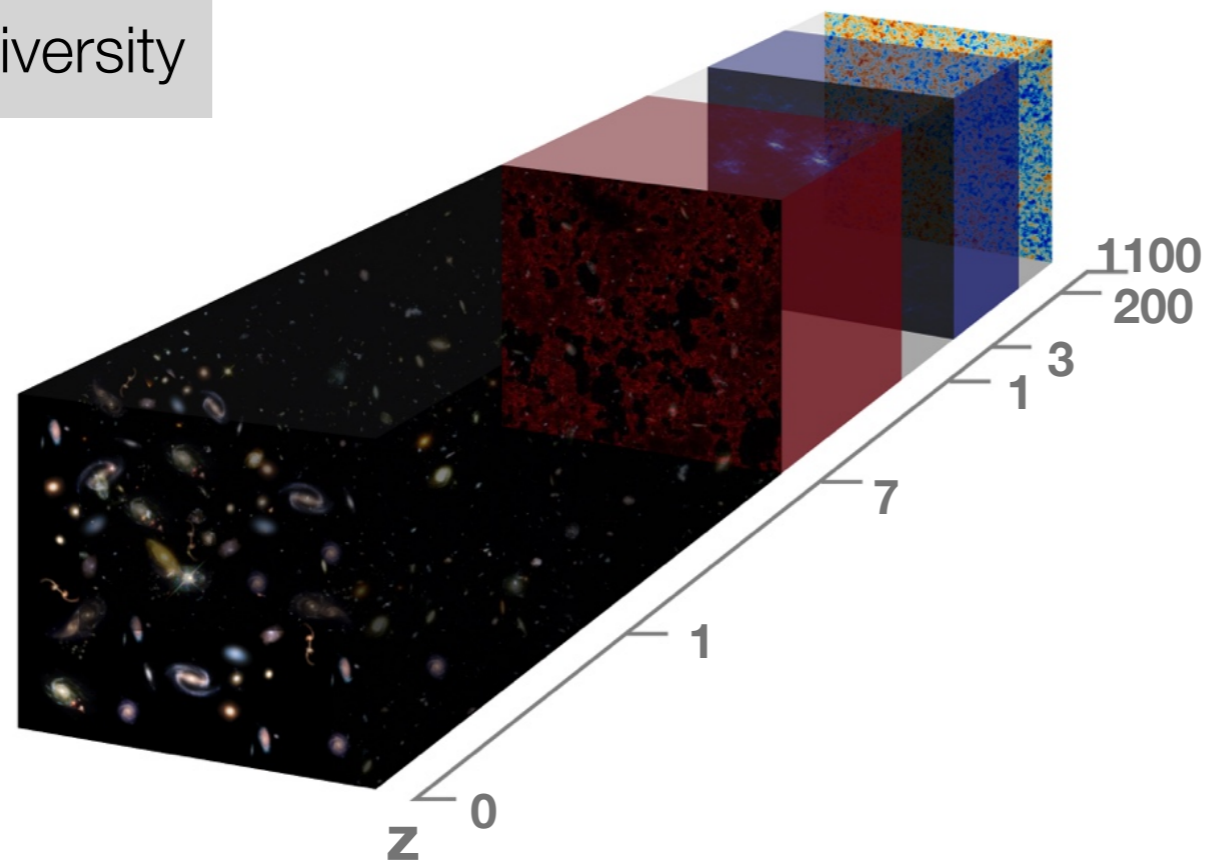


Cosmological Probes of Dark Matter off the beaten path

Ely D. Kovetz

Johns Hopkins University



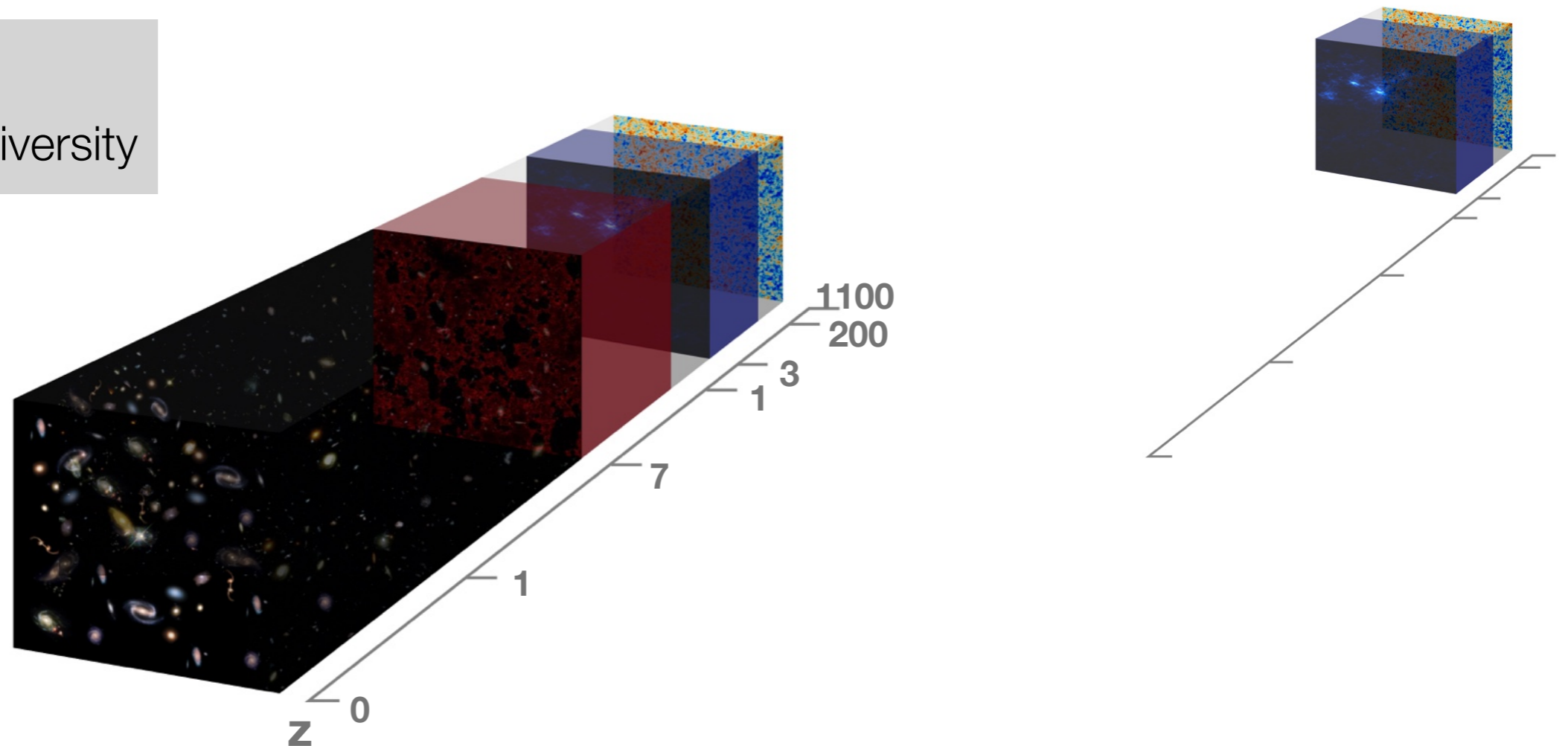
Harvard Seminar
March 1st, 2016

Based on: Muñoz, EDK and Ali-Haïmoud, Phys. Rev. D92 (2015)
Ali-Haïmoud, EDK and Silk, Phys. Rev. D93 (2016)
Bird, ..., EDK, ..., et al. - on the arXiv tomorrow

Cosmological Probes of Dark Matter off the beaten path

Ely D. Kovetz

Johns Hopkins University



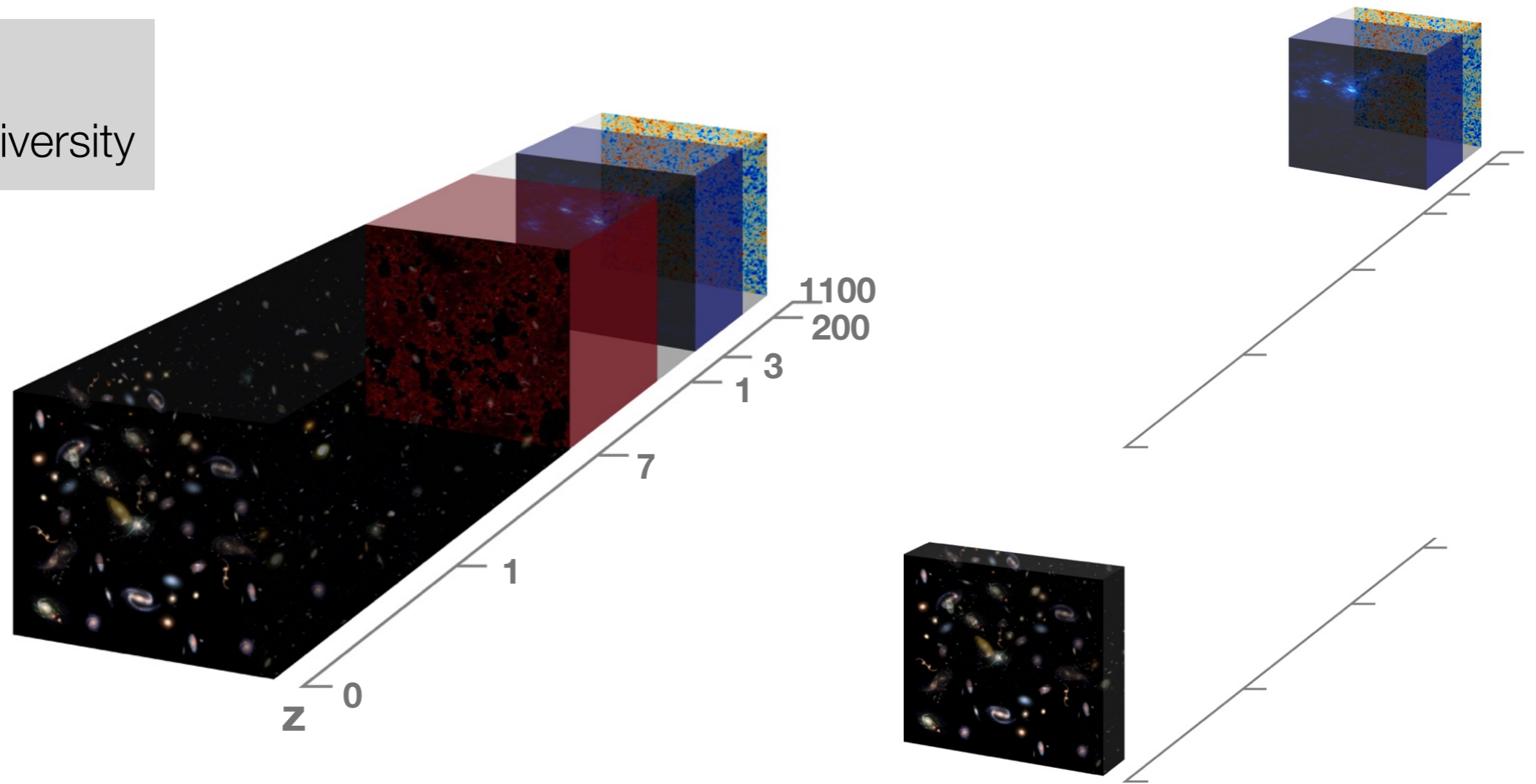
Harvard Seminar
March 1st, 2016

Based on: Muñoz, EDK and Ali-Haïmoud, Phys. Rev. D92 (2015)
Ali-Haïmoud, EDK and Silk, Phys. Rev. D93 (2016)
Bird, ..., EDK, ..., et al. - on the arXiv tomorrow

Cosmological Probes of Dark Matter off the beaten path

Ely D. Kovetz

Johns Hopkins University



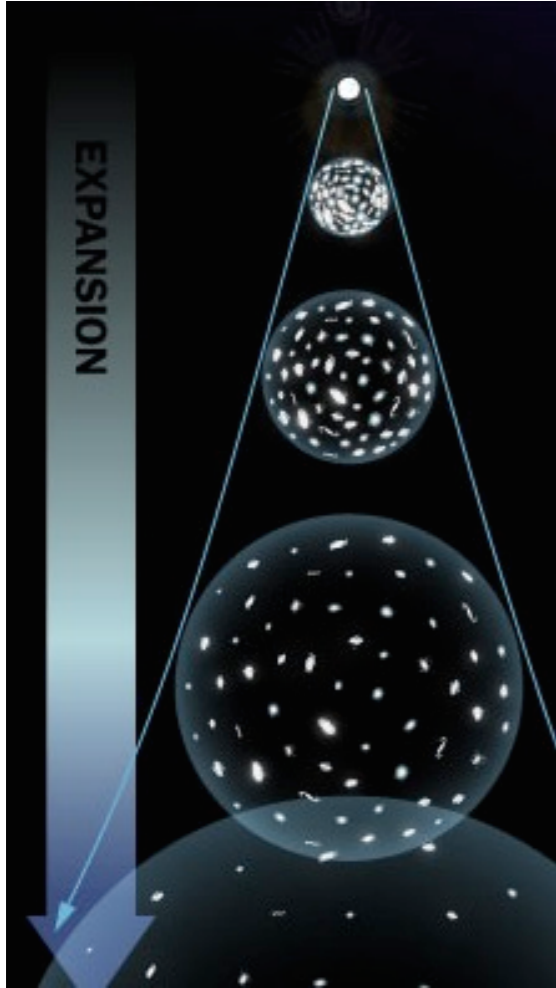
Harvard Seminar
March 1st, 2016

Based on: Muñoz, EDK and Ali-Haïmoud, Phys. Rev. D92 (2015)
Ali-Haïmoud, EDK and Silk, Phys. Rev. D93 (2016)
Bird, ..., EDK, ..., et al. - on the arXiv tomorrow

The Standard Cosmological Model

The Standard Cosmological Model

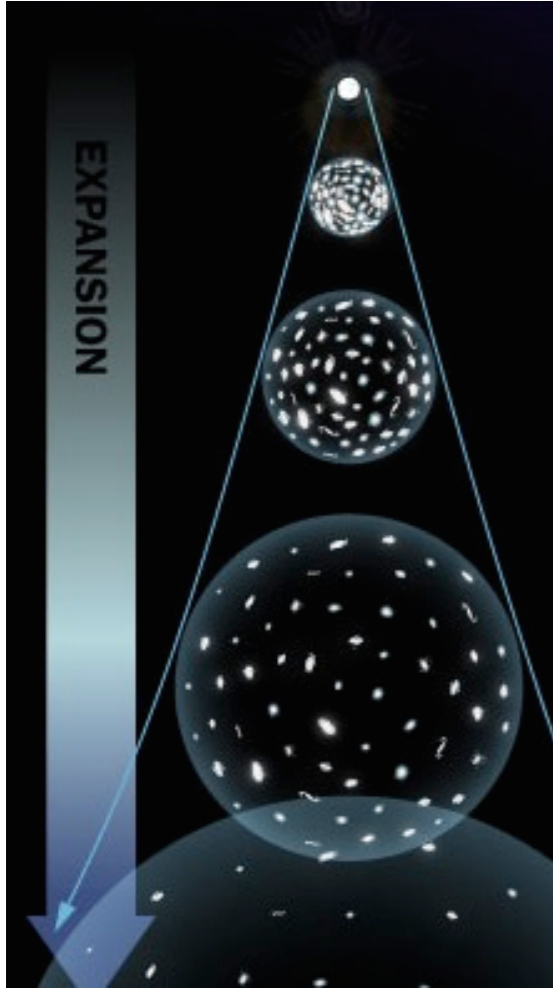
Hot big bang



The Standard Cosmological Model

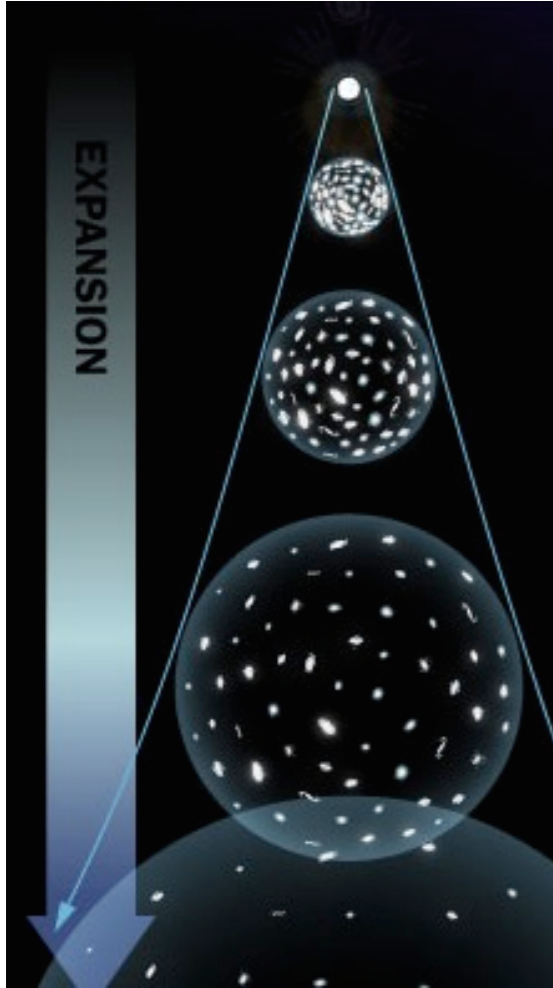
Hot big bang

Gravitational
instability

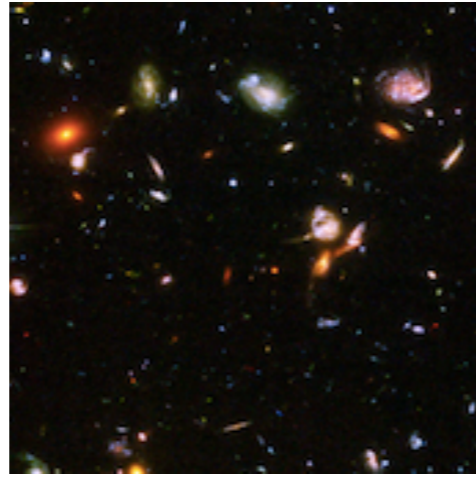


The Standard Cosmological Model

Hot big bang

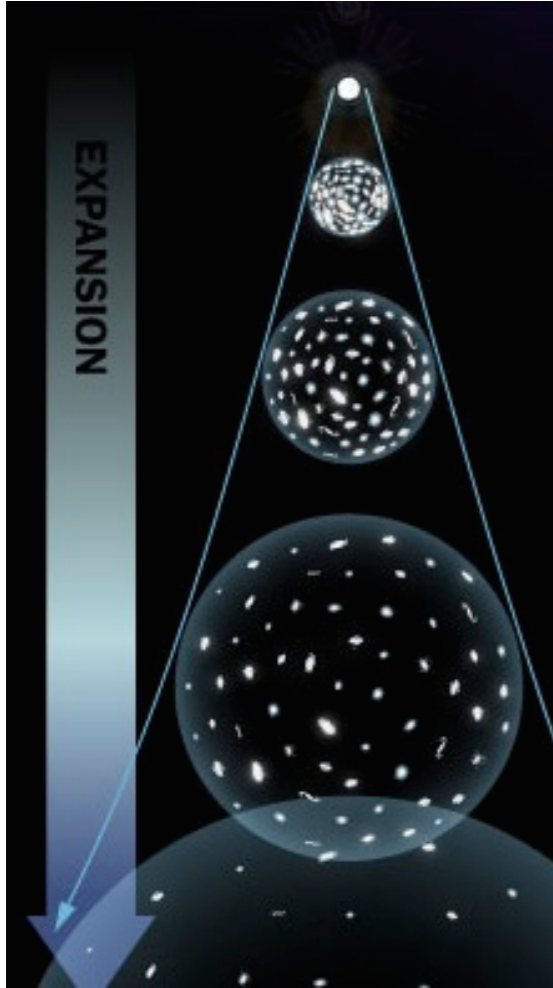


Gravitational instability

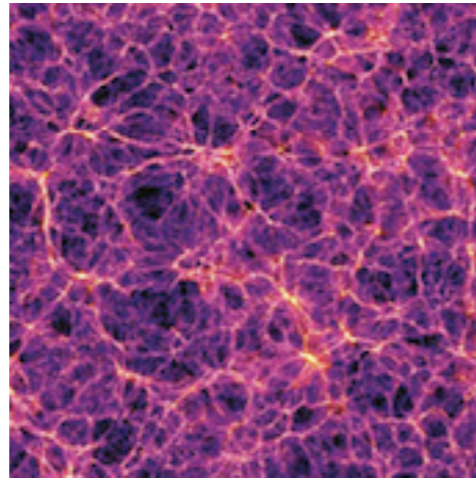
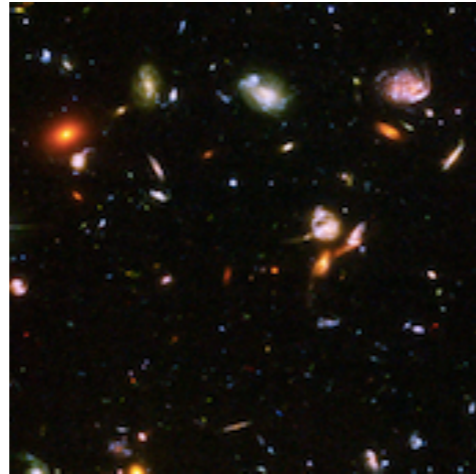


The Standard Cosmological Model

Hot big bang

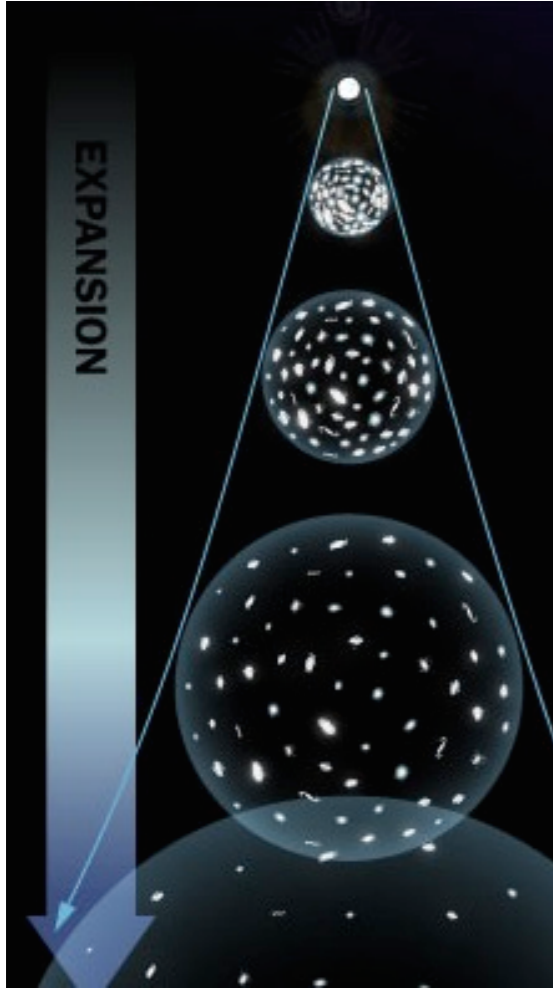


Gravitational instability

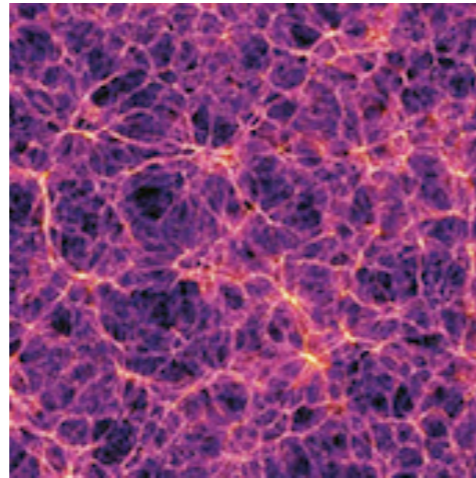
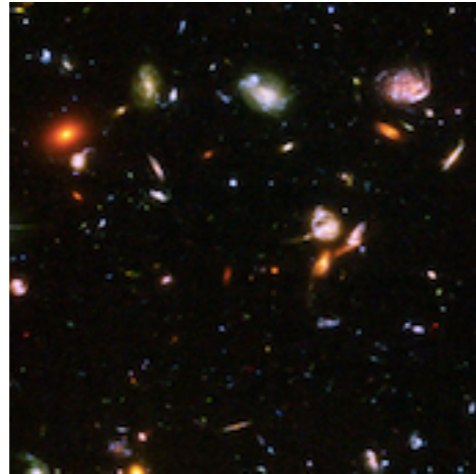


The Standard Cosmological Model

Hot big bang



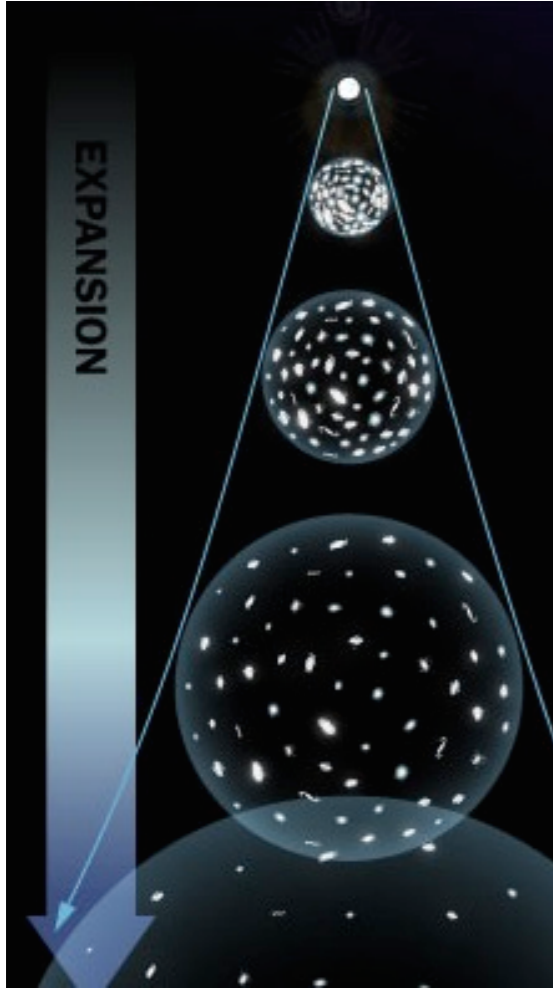
Gravitational instability



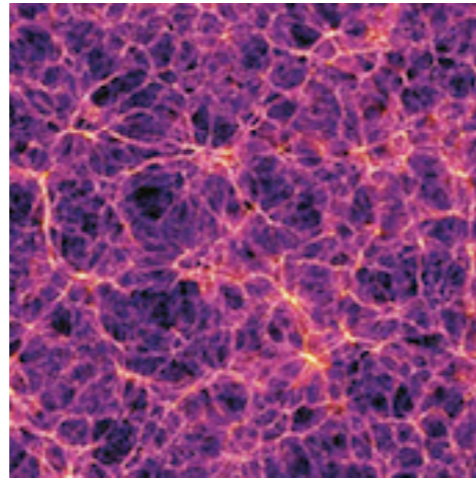
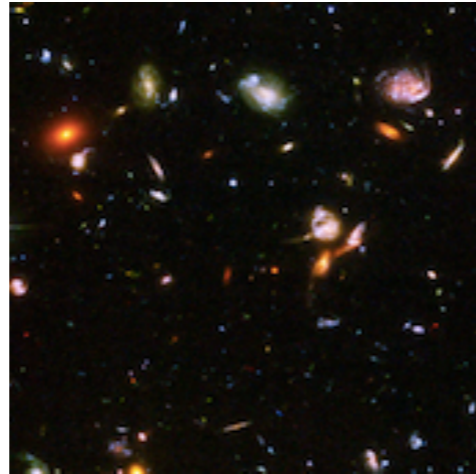
Inflation

The Standard Cosmological Model

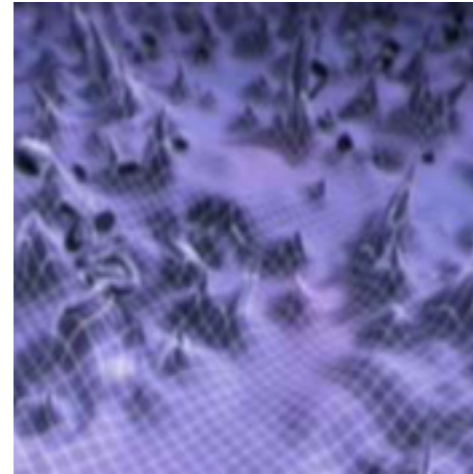
Hot big bang



Gravitational instability

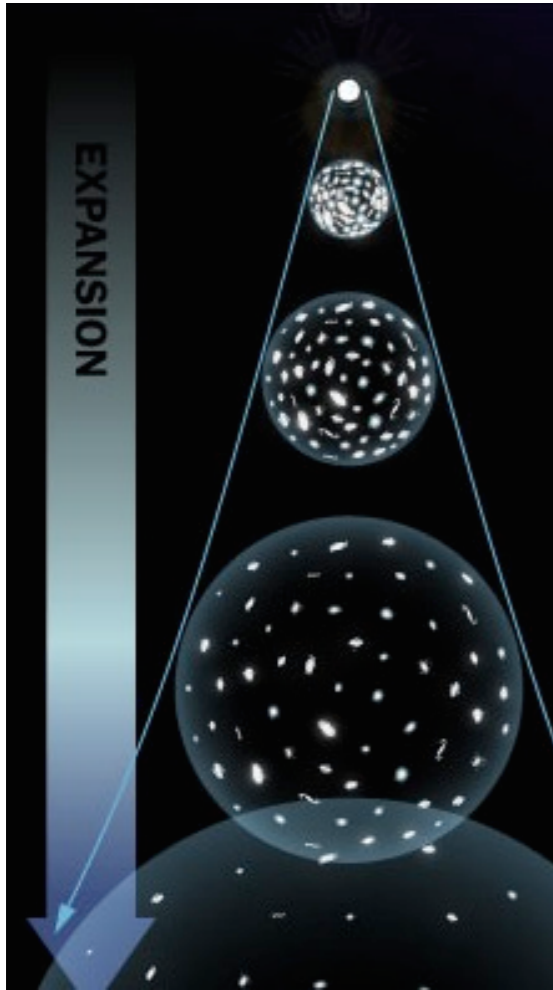


Inflation

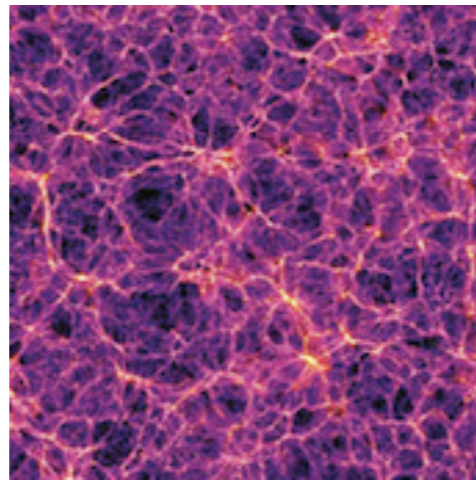
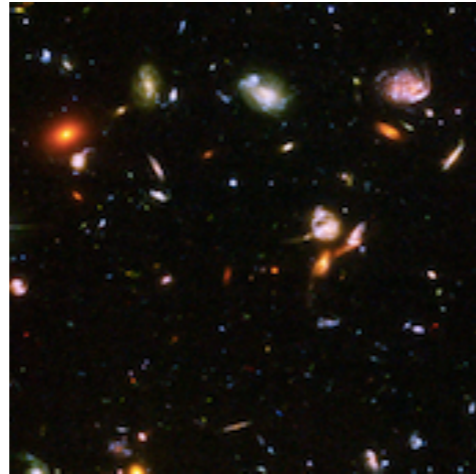


The Standard Cosmological Model

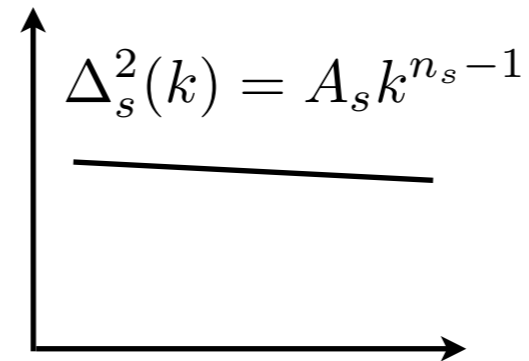
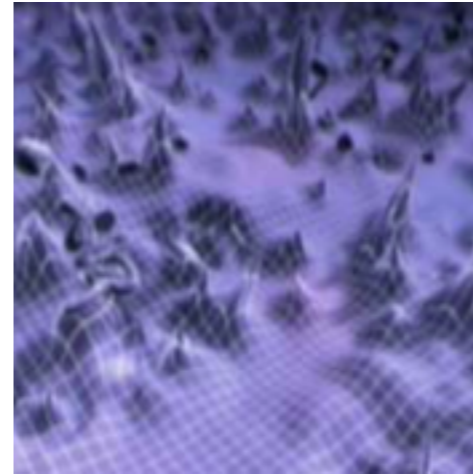
Hot big bang



Gravitational instability

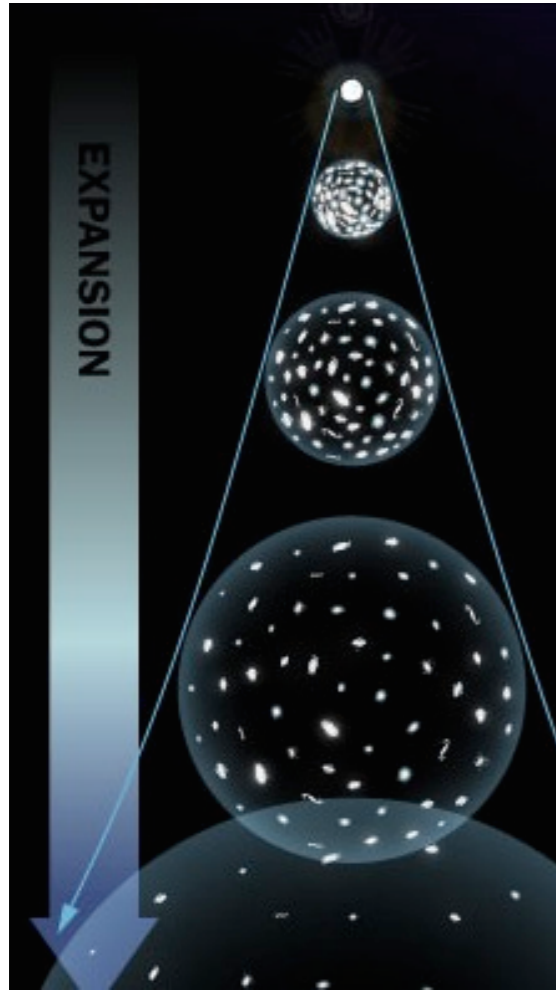


Inflation

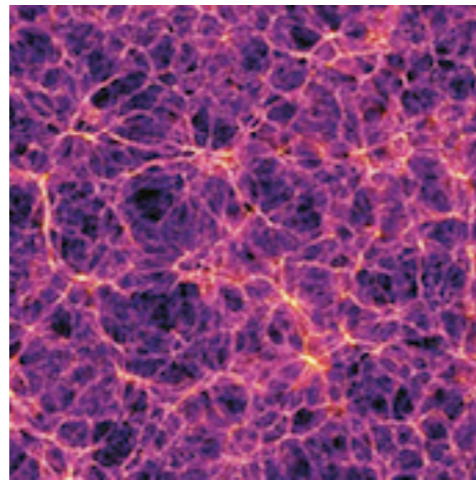
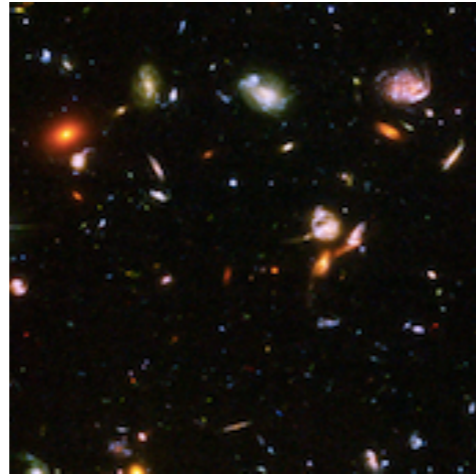


The Standard Cosmological Model

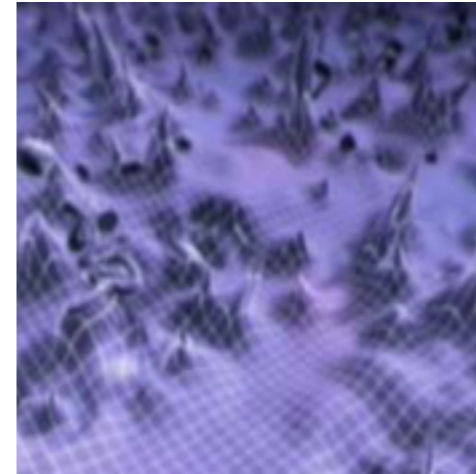
Hot big bang



Gravitational instability



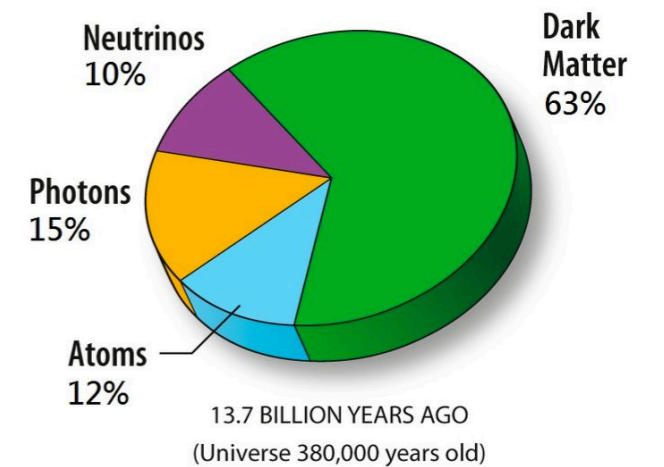
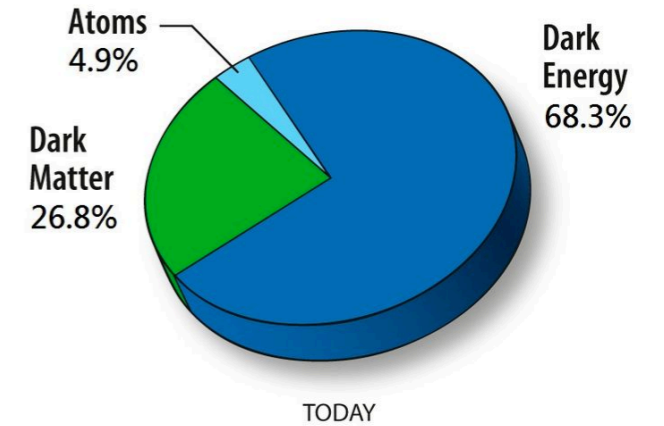
Inflation



$$\Delta_s^2(k) = A_s k^{n_s - 1}$$

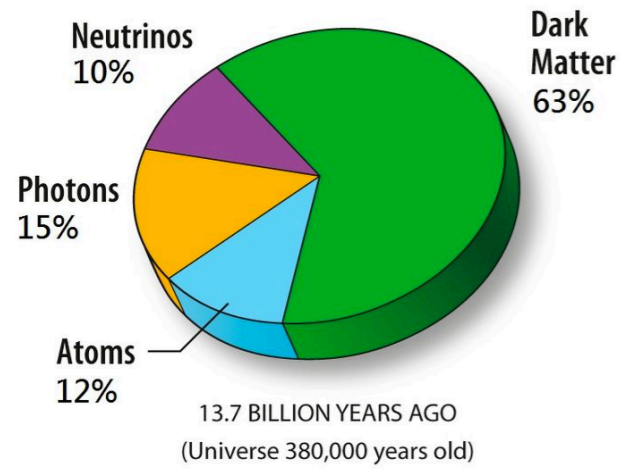
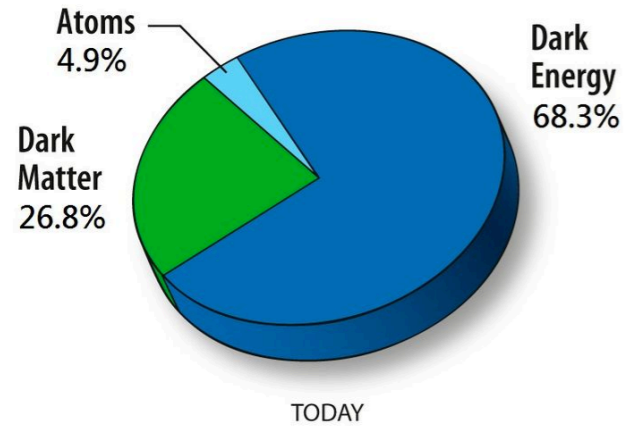
A graph showing the power spectrum of the universe. The vertical axis is labeled $\Delta_s^2(k)$ and the horizontal axis is labeled k . A horizontal line represents the power spectrum, which is slightly curved, indicating a power-law relationship between the two variables.

LCDM



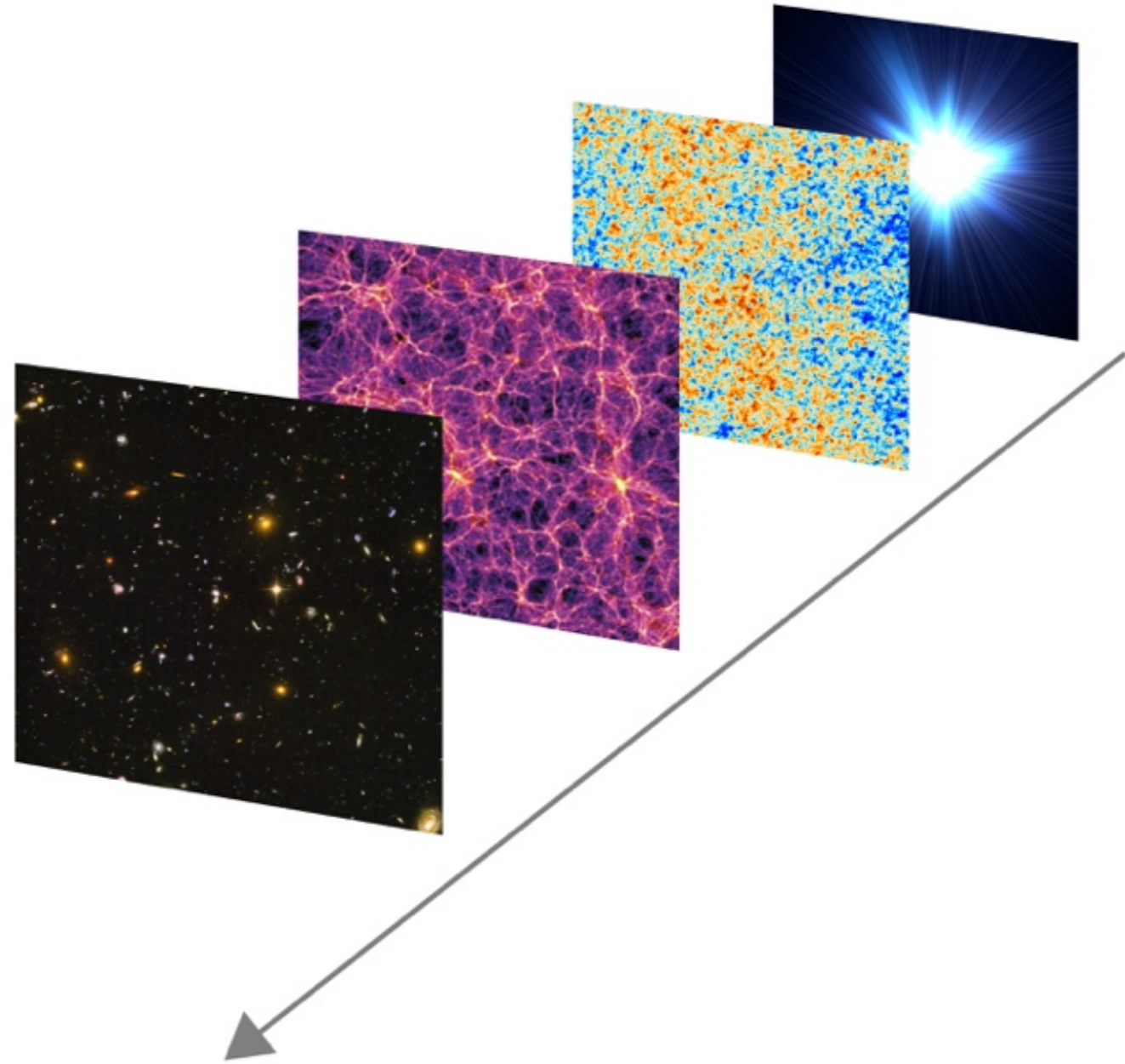
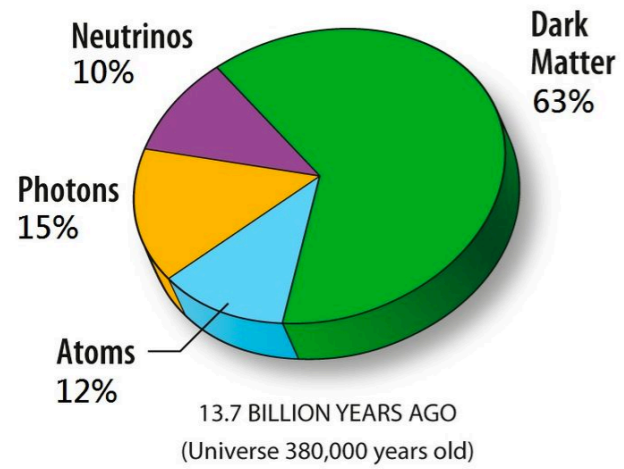
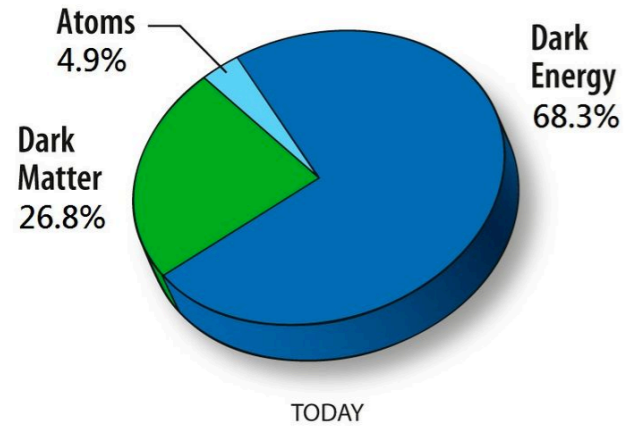
The Standard Cosmological Model

LCDM



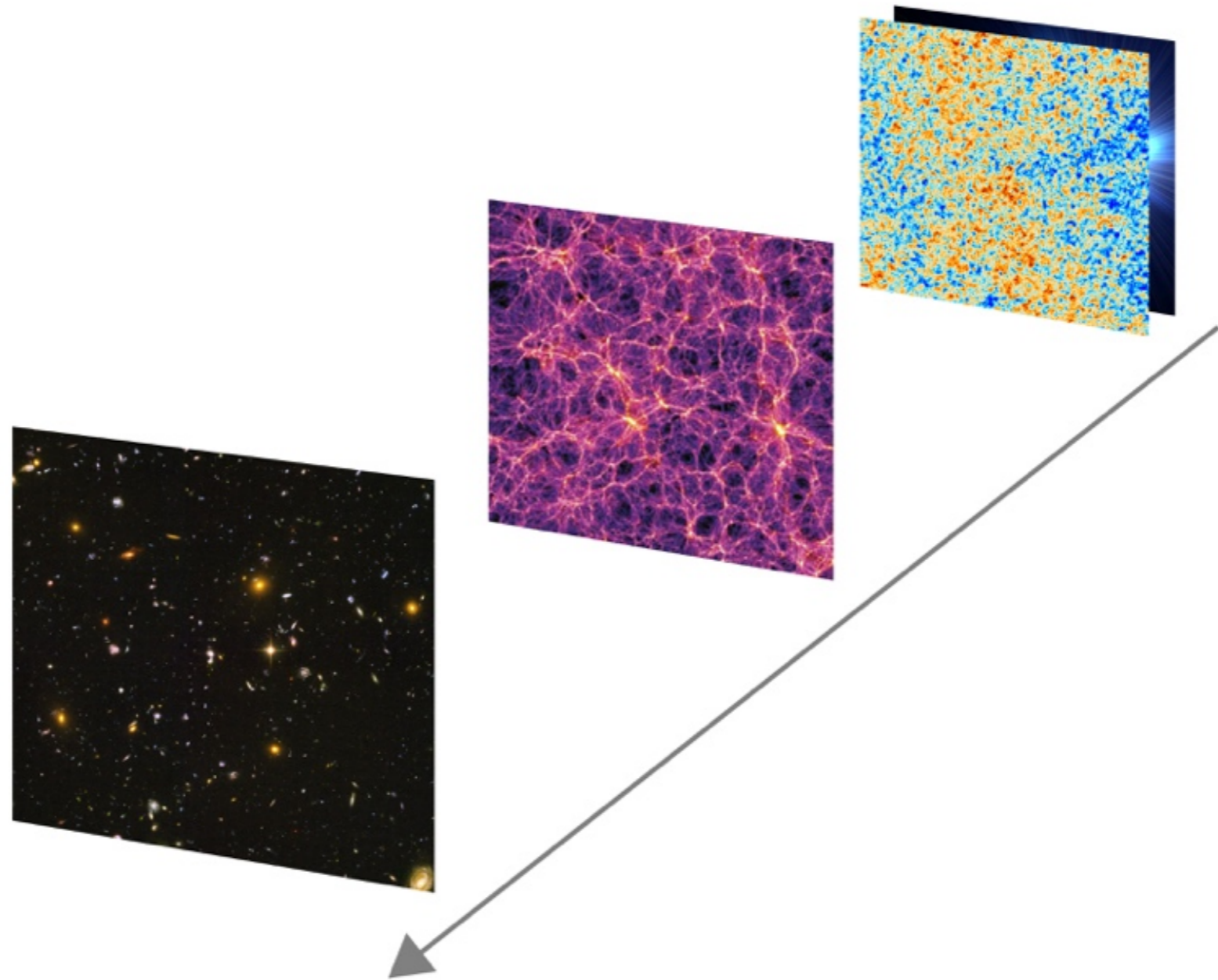
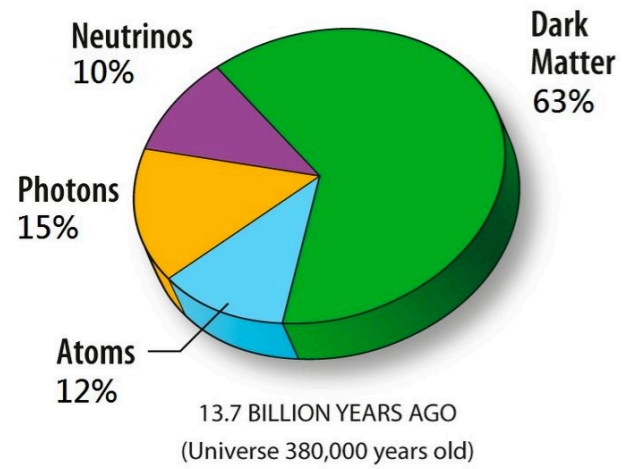
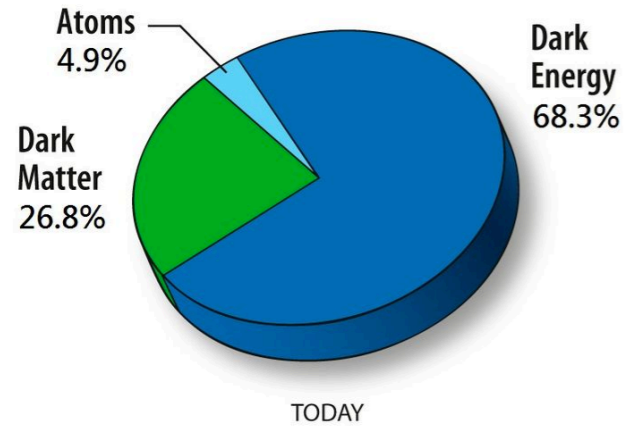
The Standard Cosmological Model

LCDM



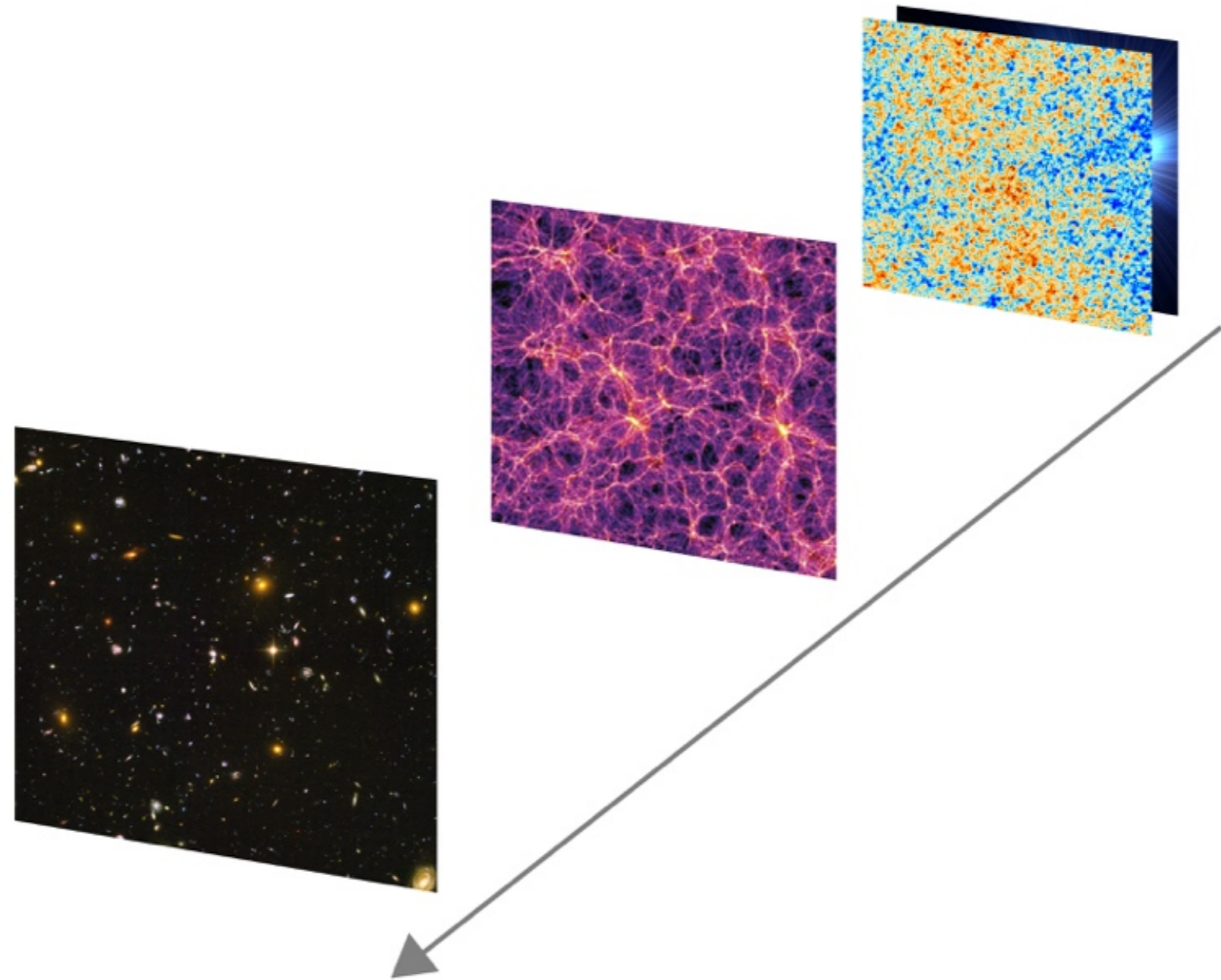
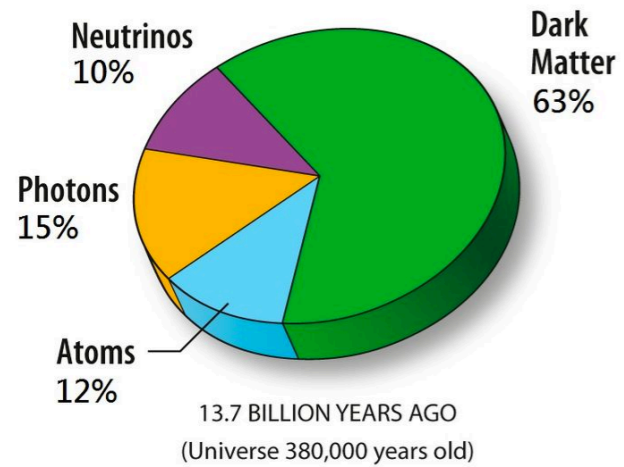
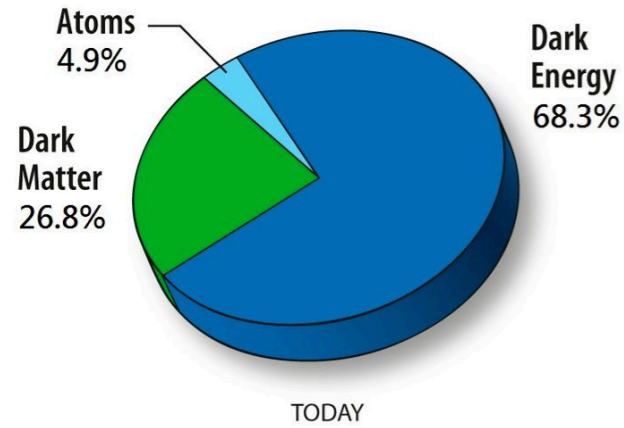
The Standard Cosmological Model

LCDM



The Standard Cosmological Model

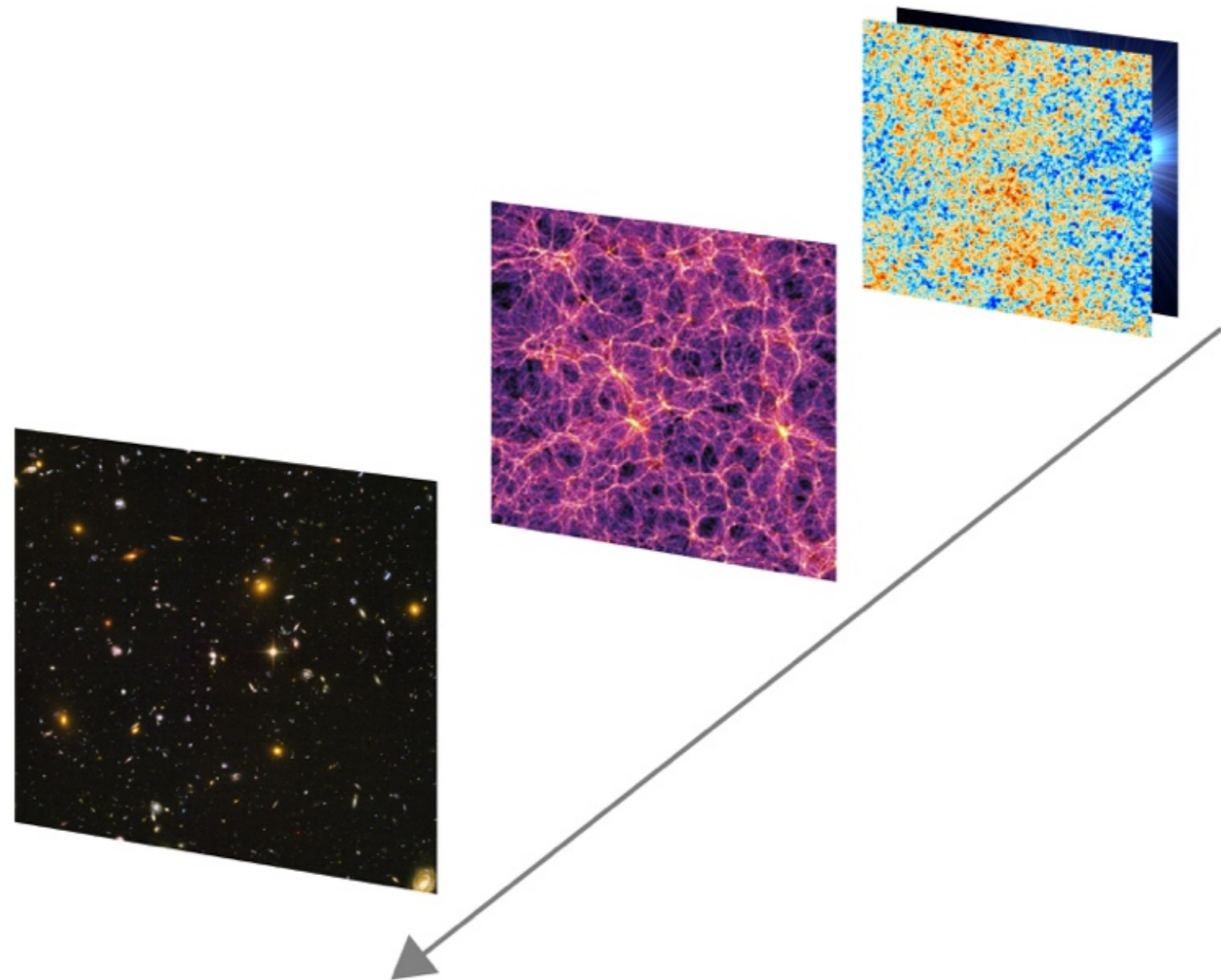
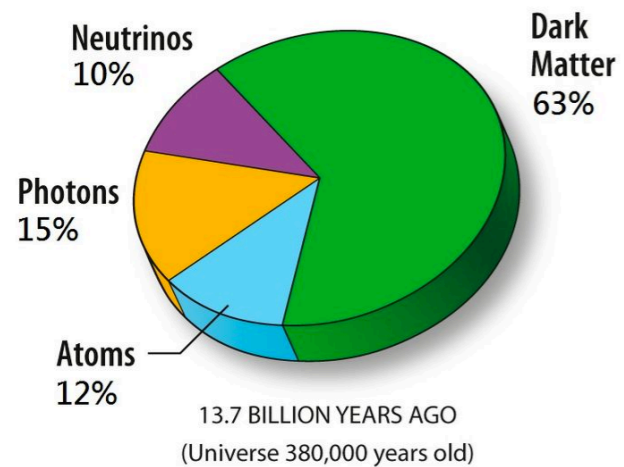
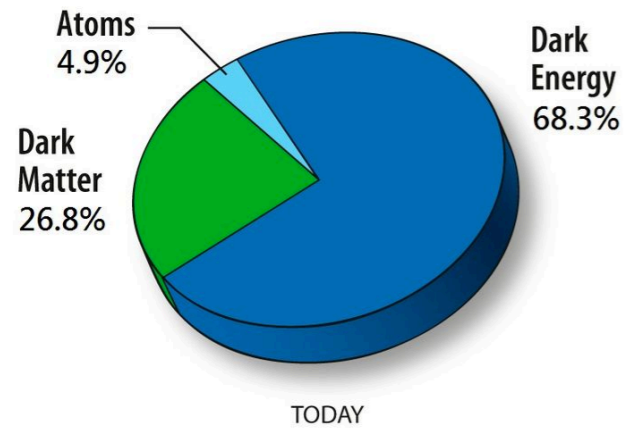
LCDM



Amazingly: just six parameters are enough to fit all existing data.

The Standard Cosmological Model

LCDM



Amazingly: just six parameters are enough to fit all existing data.

H_0	τ	A_s	n_s	Ω_b	Ω_{CDM}
-------	--------	-------	-------	------------	-----------------------

Basic Questions in Cosmology

Basic Questions in Cosmology

1

What are the
properties of
inflation?

Basic Questions in Cosmology

1

What are the properties of *inflation*?

2

What is the nature of *dark matter*?

Basic Questions in Cosmology

1

What are the properties of *inflation*?

2

What is the nature of *dark matter*?

3

What makes up *dark energy*?

Basic Questions in Cosmology

1

What are the properties of *inflation*?

2

What is the nature of *dark matter*?

3

What makes up *dark energy*?

4...

How did *large-scale structure* form and evolve?

Focus of This Talk: What is Dark Matter?

1

Inflation

2

Dark Matter

3

Dark Energy

4...

**Growth of
Structure**

Focus of This Talk: What is Dark Matter?

1

Inflation

2

Dark Matter

3

Dark Energy

4...

Growth of
Structure

Focus of This Talk: What is Dark Matter?

1

Inflation

2

Dark Matter

Is it interacting?
(WIMP?)

3

Dark Energy

4...

Growth of
Structure

Focus of This Talk: What is Dark Matter?

1

Inflation

2

Dark Matter

Is it interacting?
(WIMP?)

Self-annihilating?

3

Dark Energy

4...

Growth of
Structure

Focus of This Talk: What is Dark Matter?

1

Inflation

2

Dark Matter

Is it interacting?
(WIMP?)

Self-annihilating?

Made of particles?
(MACHOs?)

3

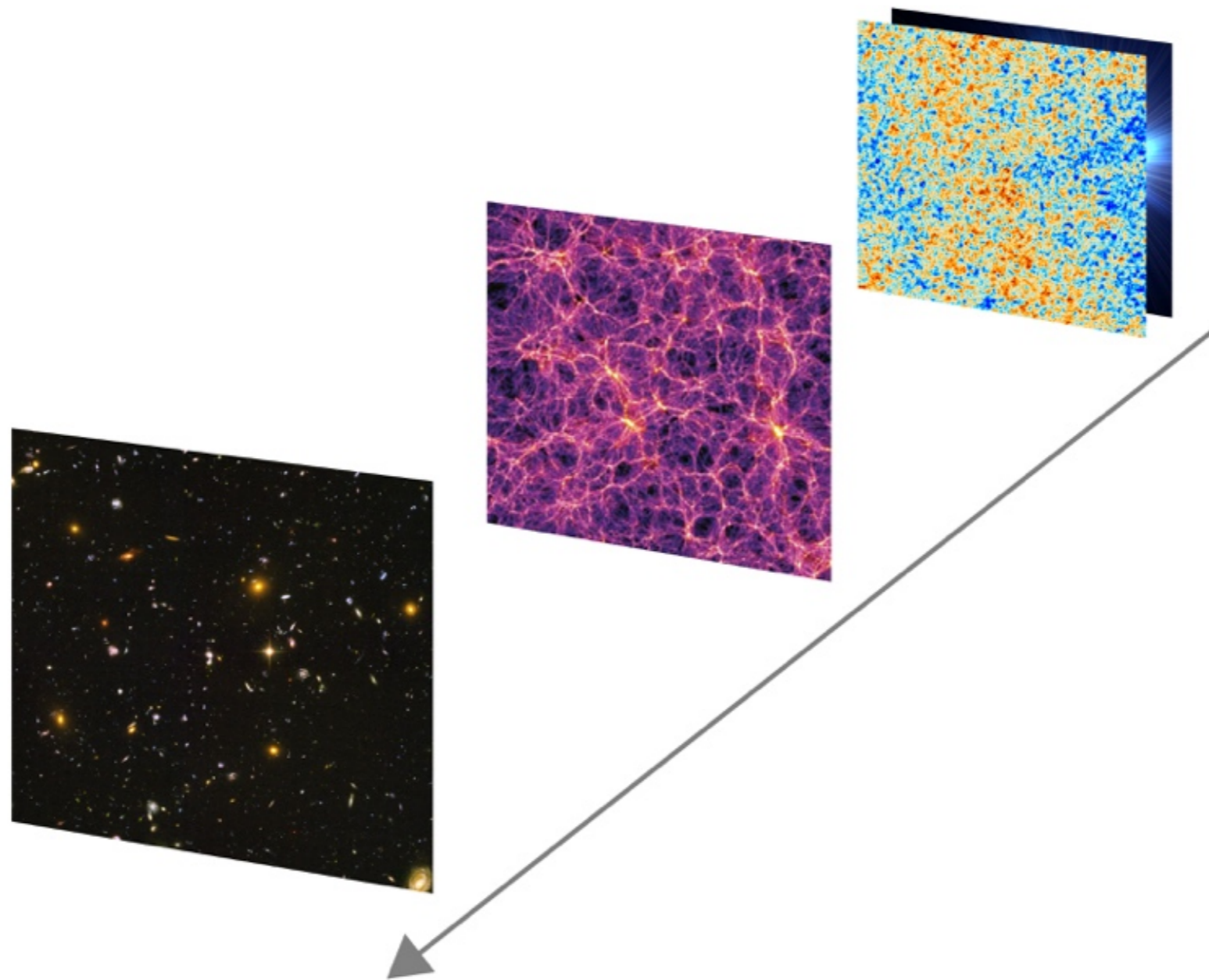
Dark Energy

4...

Growth of
Structure

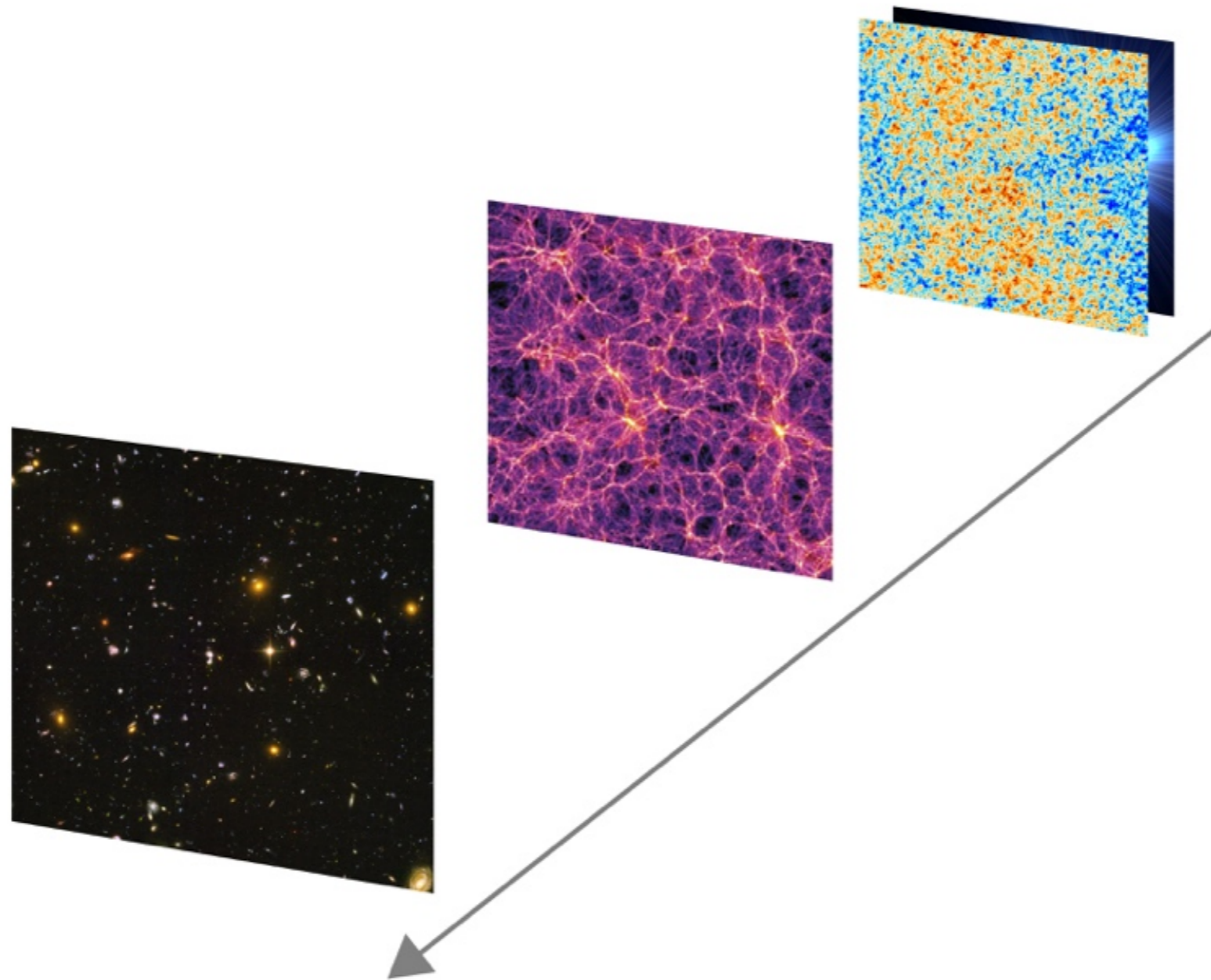
Precision Cosmology

Precision Cosmology



Precision Cosmology

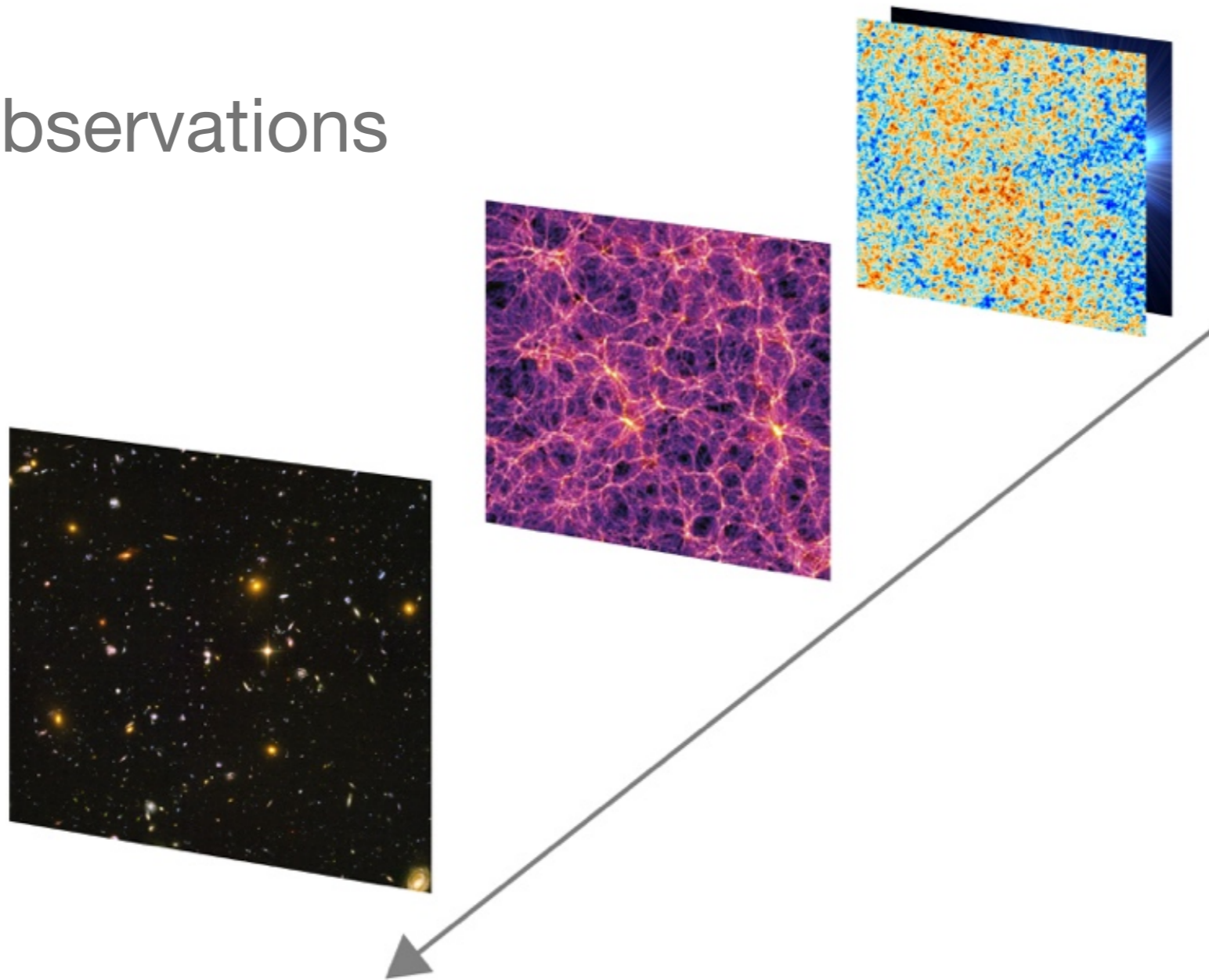
Tremendous progress in the past couple of decades:



Precision Cosmology

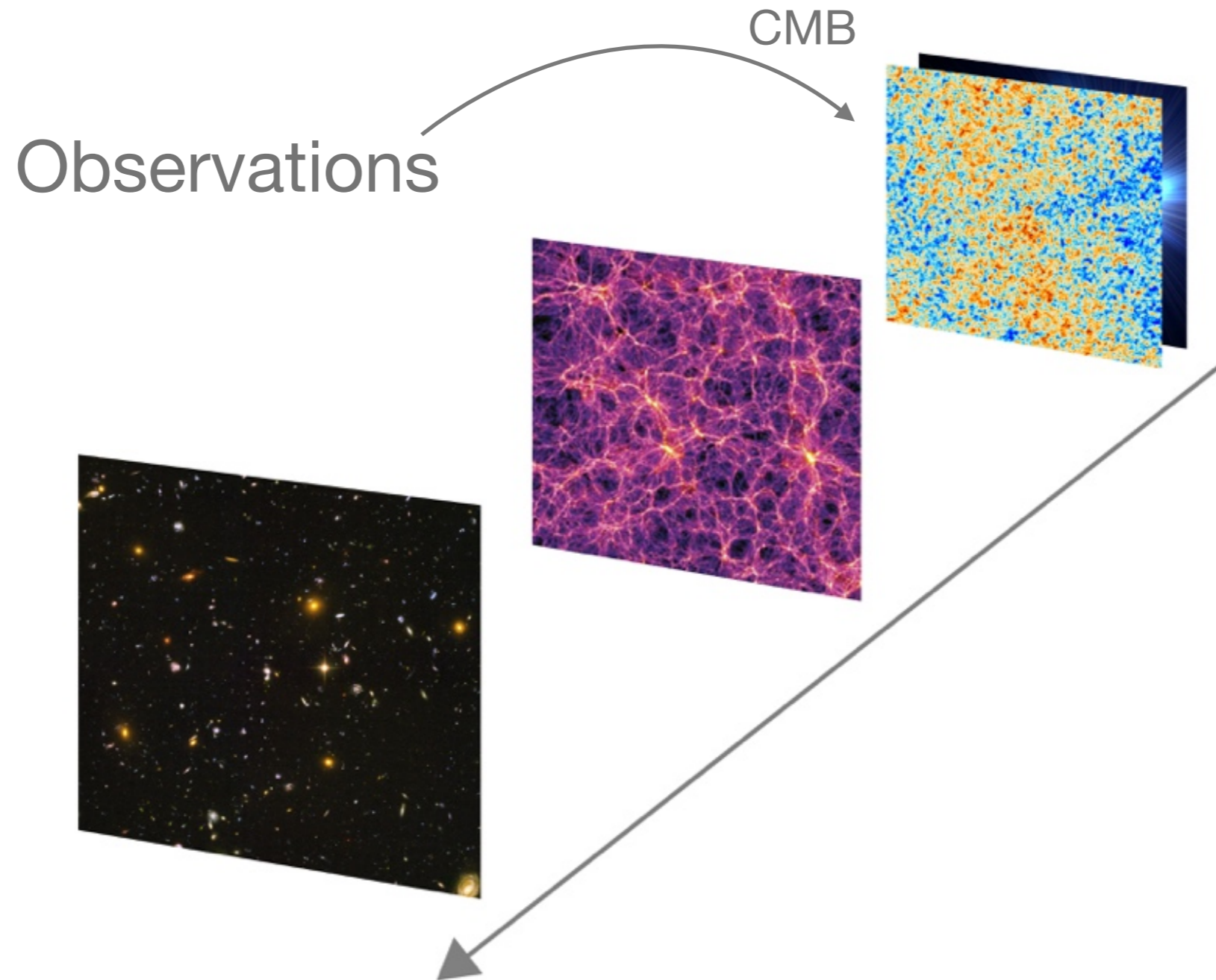
Tremendous progress in the past couple of decades:

Observations



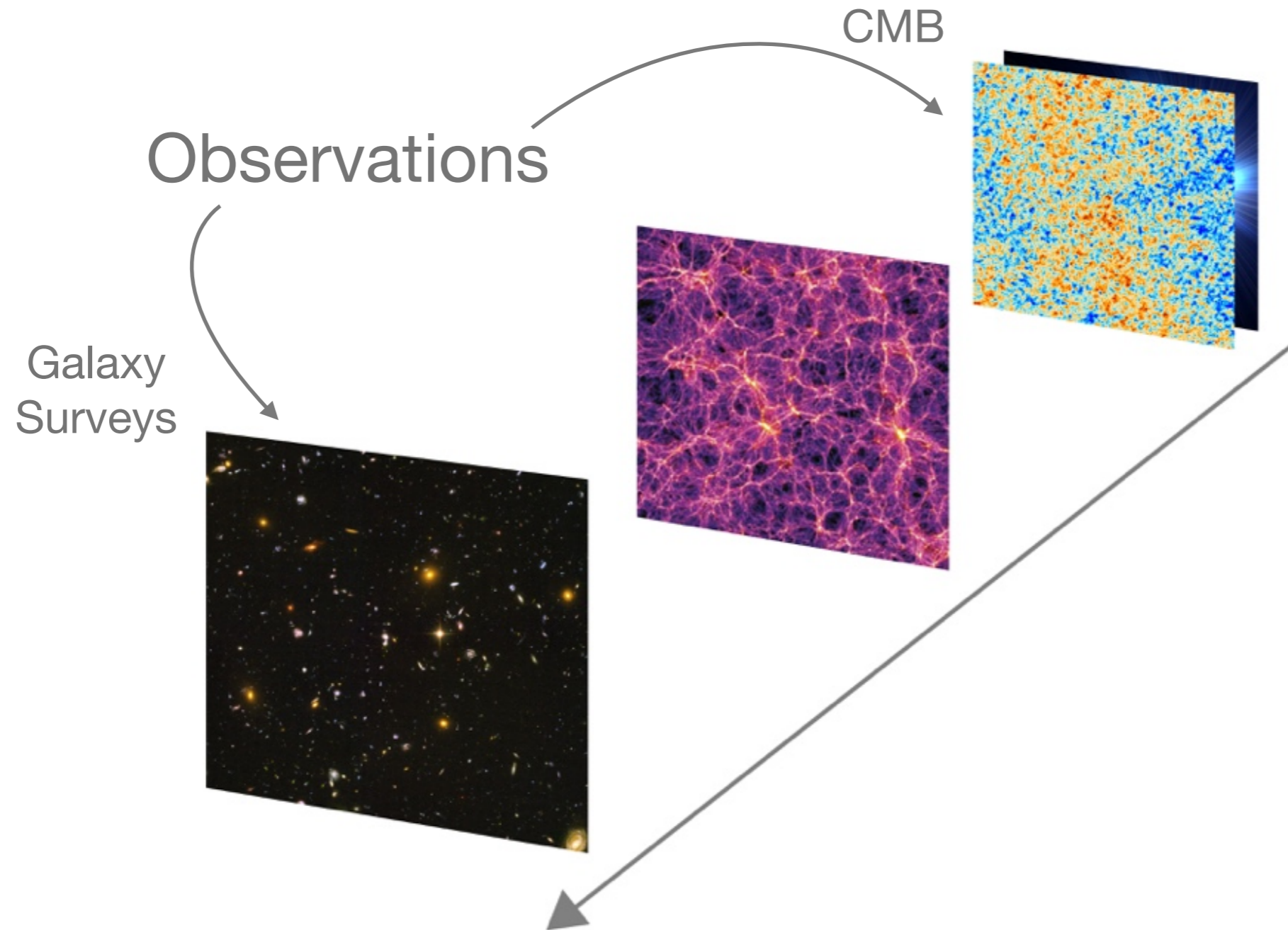
Precision Cosmology

Tremendous progress in the past couple of decades:



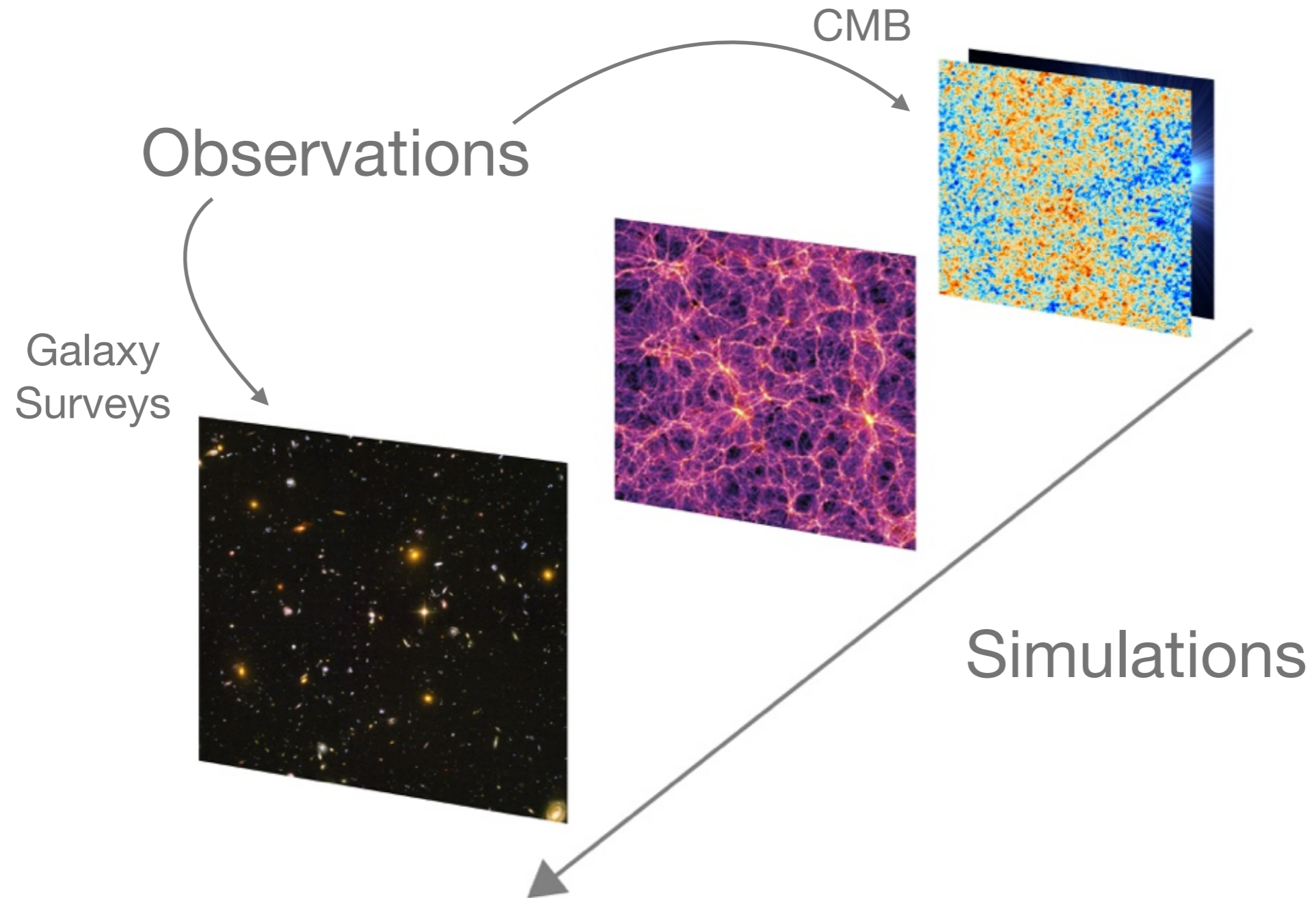
Precision Cosmology

Tremendous progress in the past couple of decades:



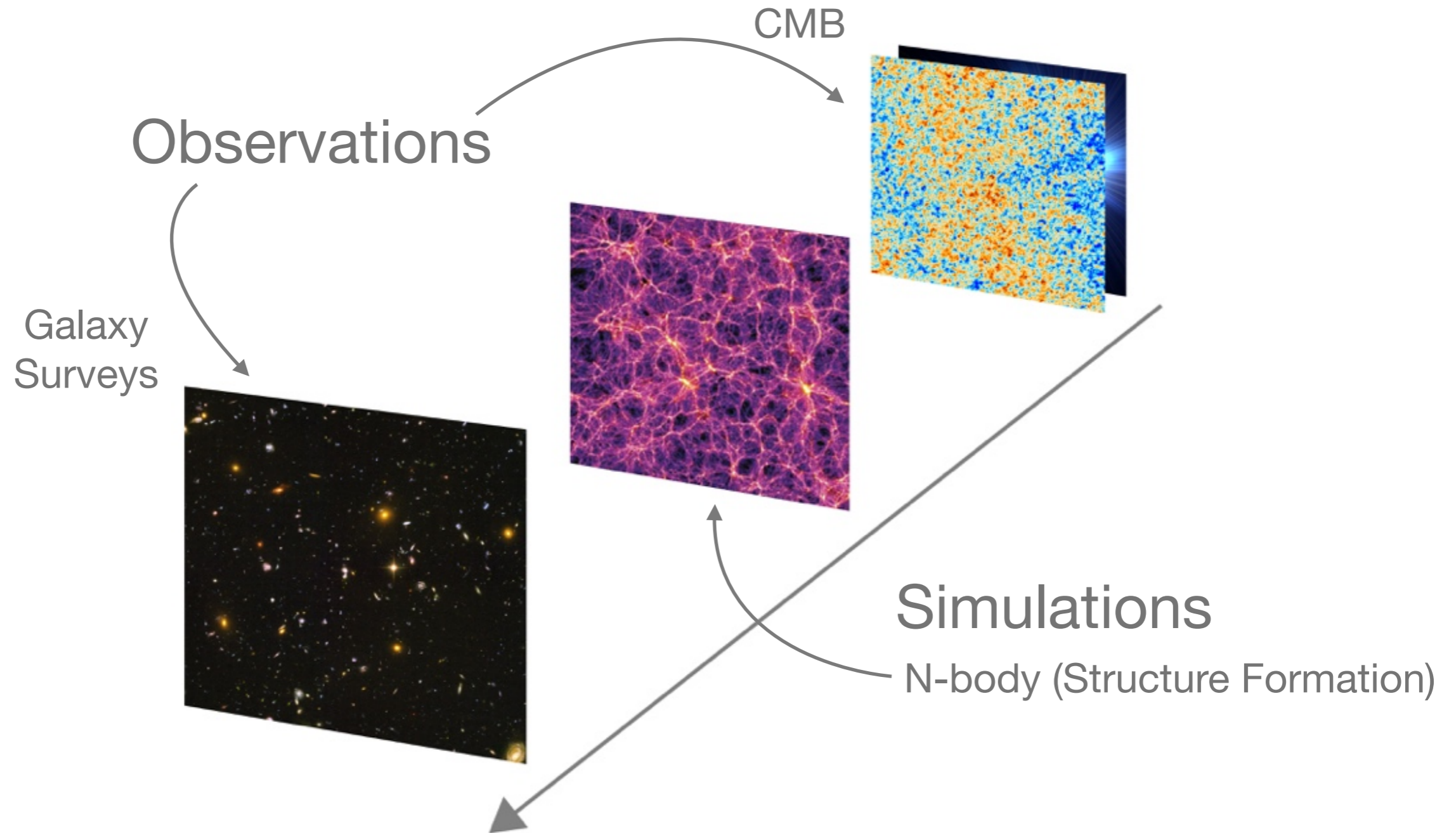
Precision Cosmology

Tremendous progress in the past couple of decades:



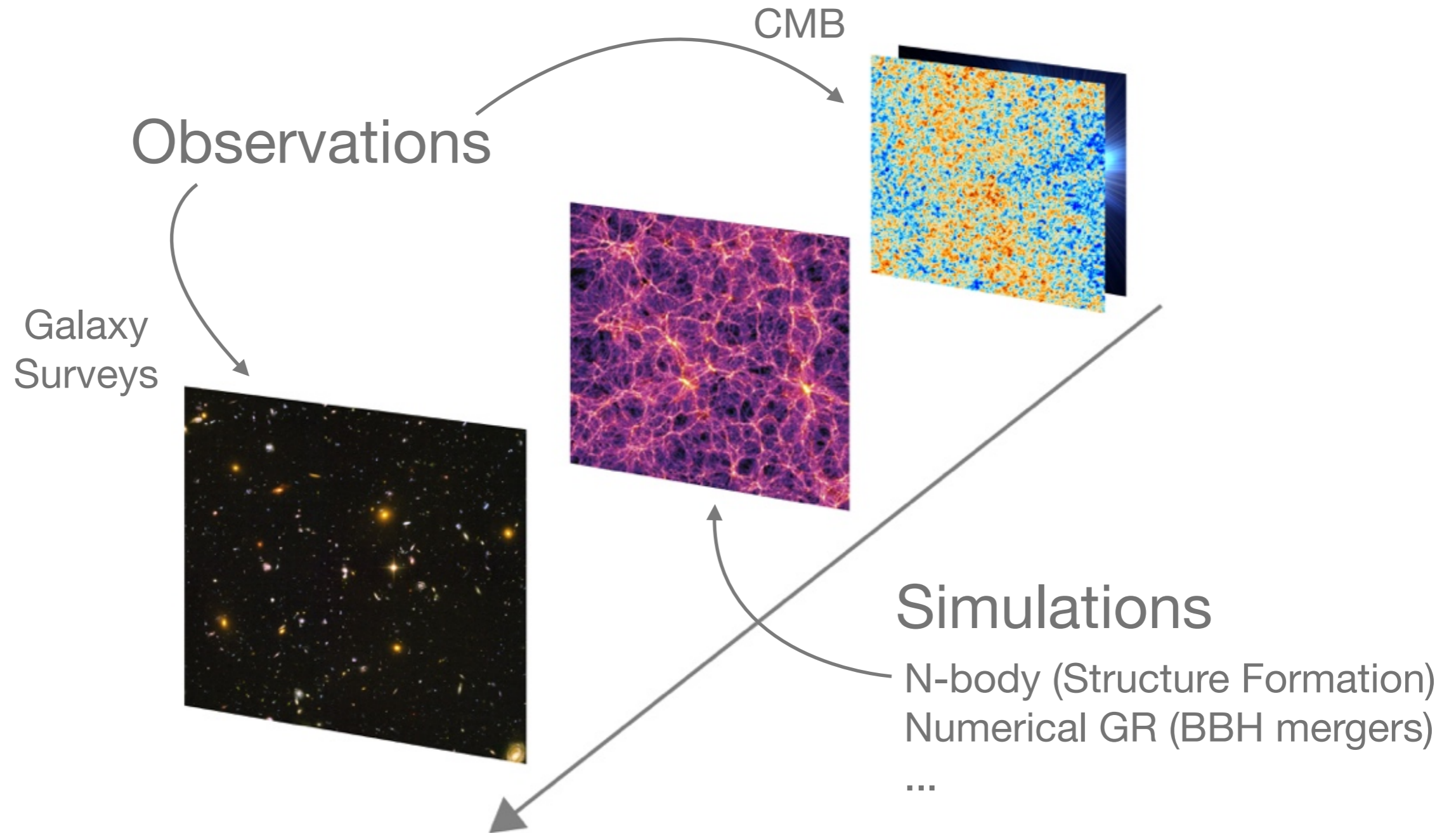
Precision Cosmology

Tremendous progress in the past couple of decades:



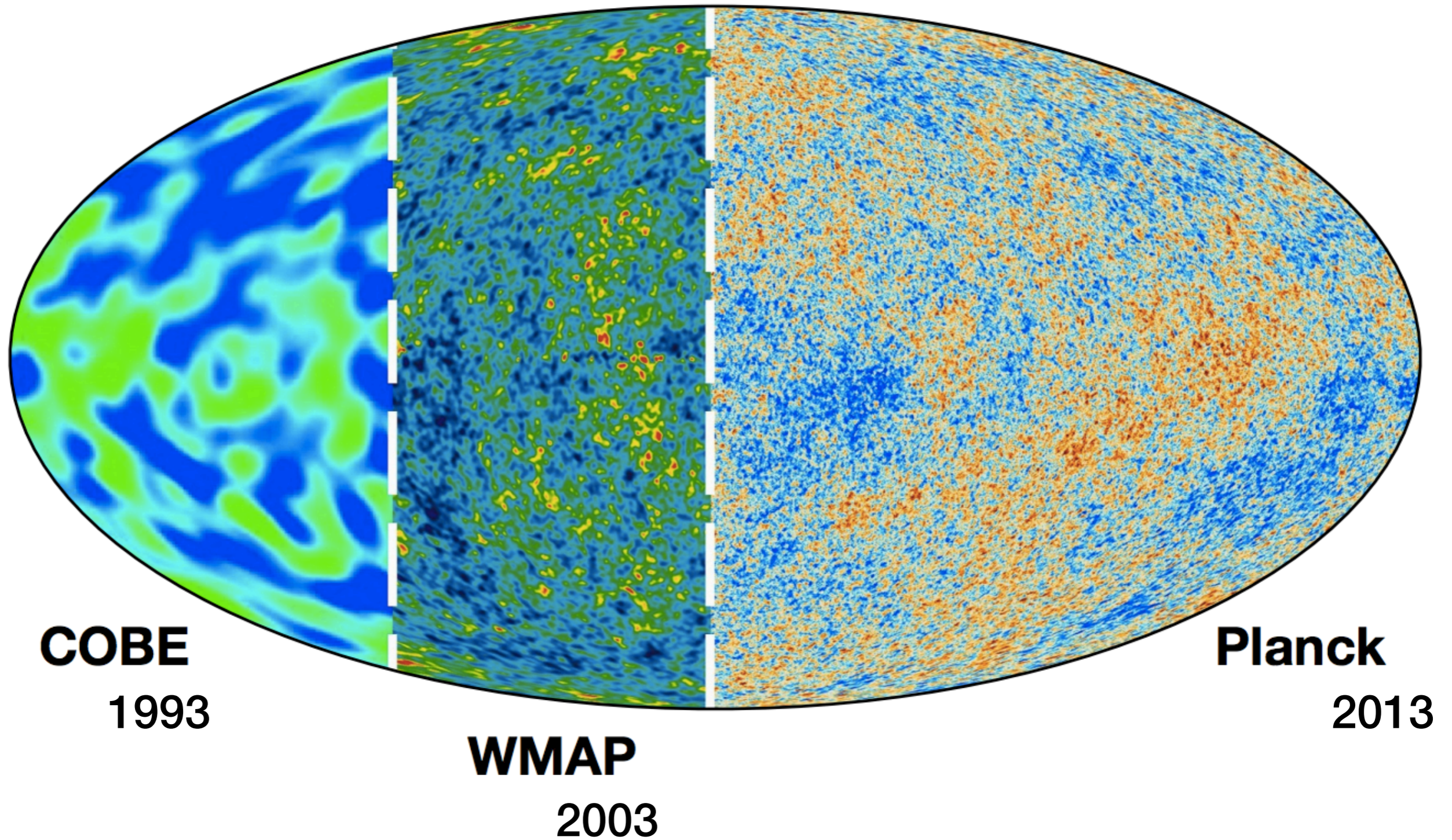
Precision Cosmology

Tremendous progress in the past couple of decades:



The Cosmic Microwave Background

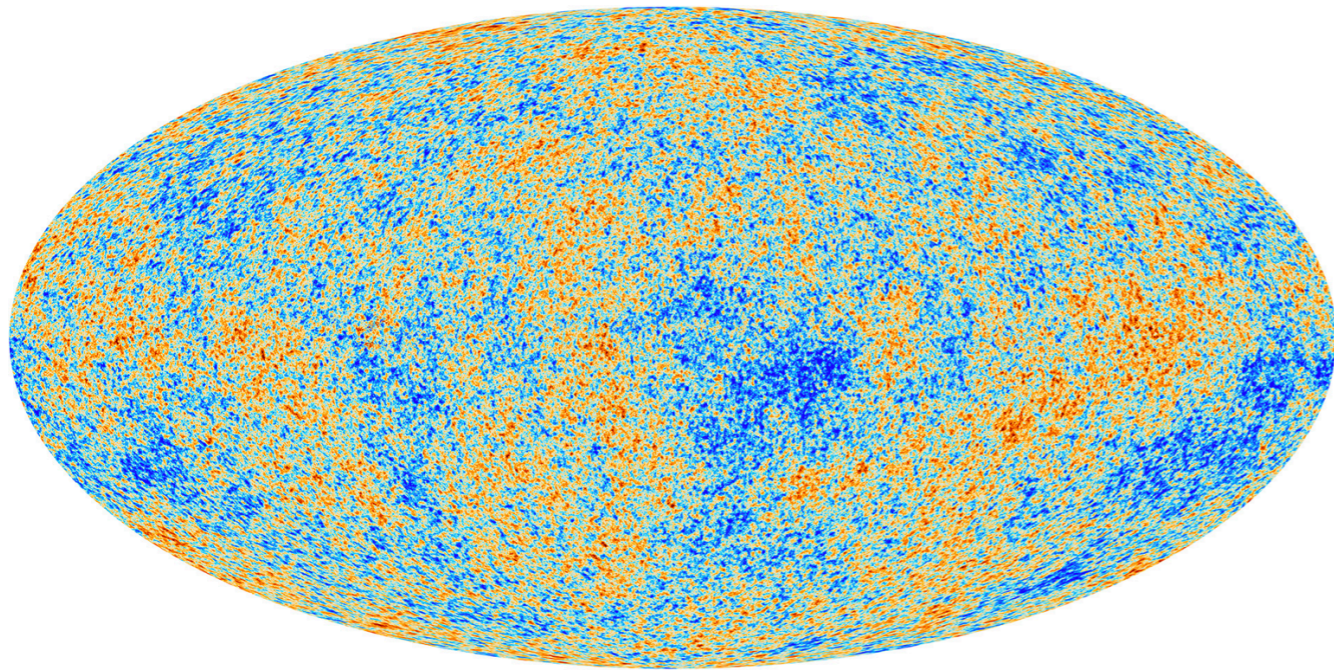
The Cosmic Microwave Background



The CMB Power Spectrum: Theory

The CMB Power Spectrum: Theory

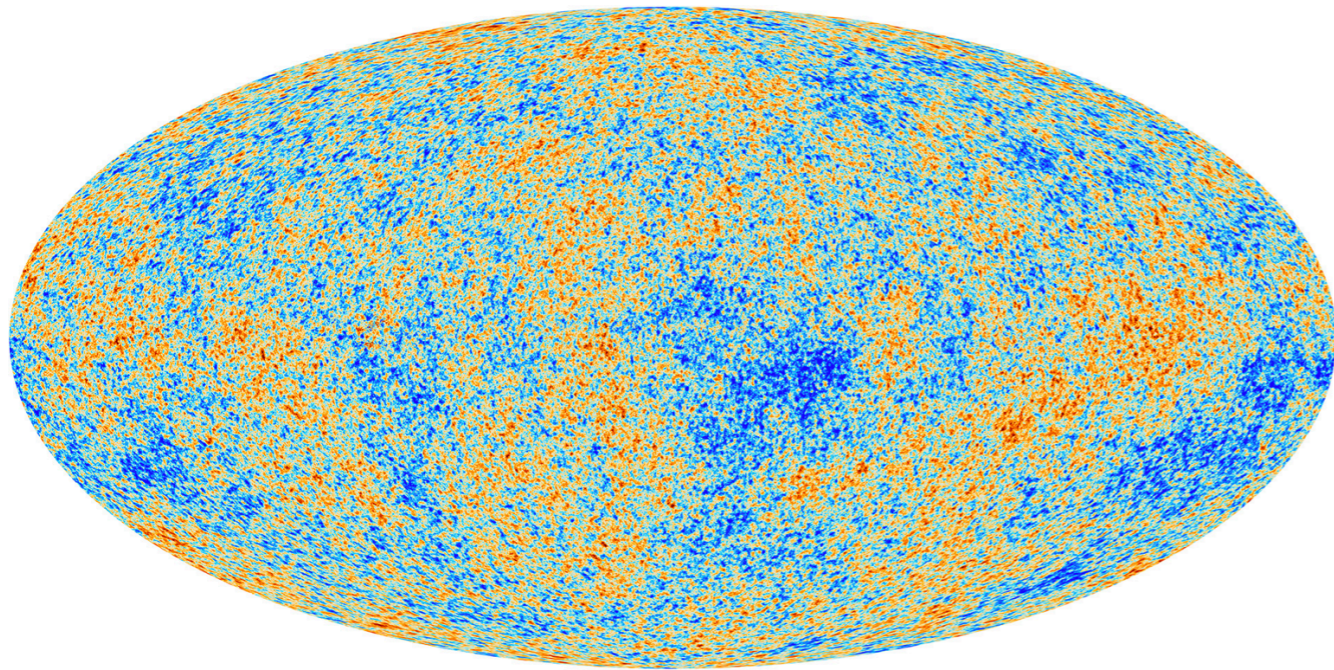
CMB fluctuations:



The CMB Power Spectrum: Theory

CMB fluctuations:

Harmonic Space: $\delta T(\hat{\mathbf{n}}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$

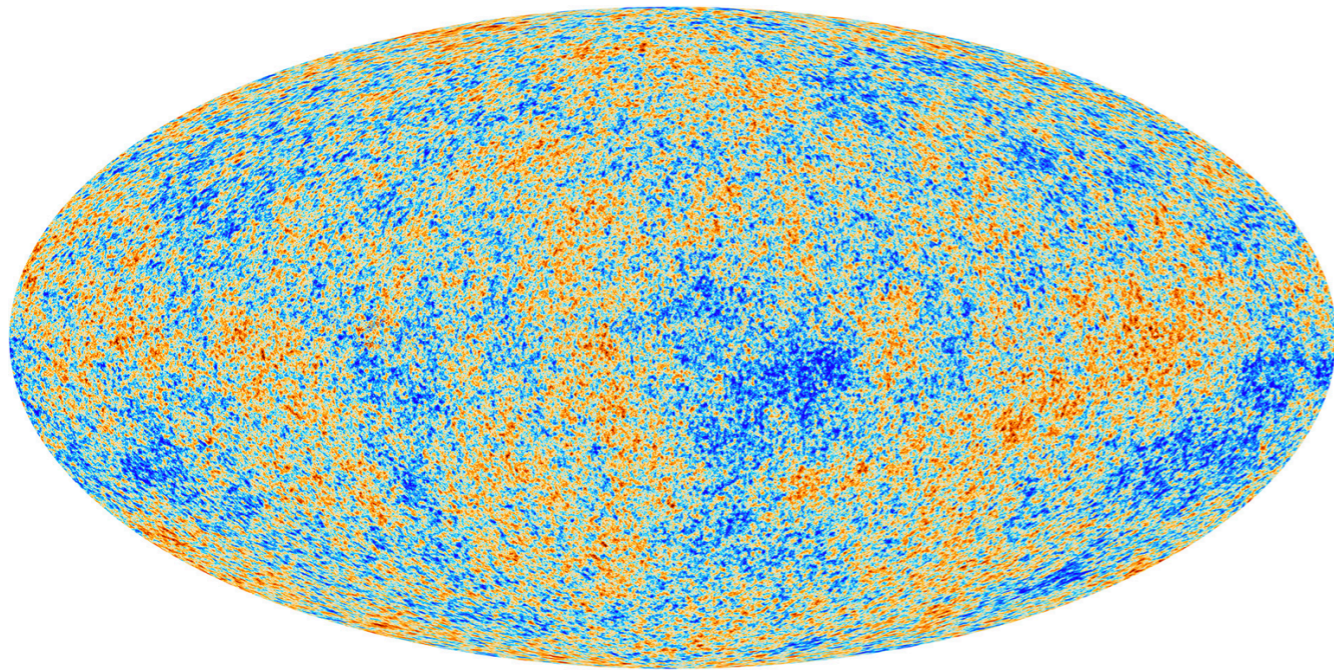


The CMB Power Spectrum: Theory

CMB fluctuations:

Harmonic Space: $\delta T(\hat{\mathbf{n}}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$

Power Spectrum: $\langle a_{\ell m}^* a_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell$

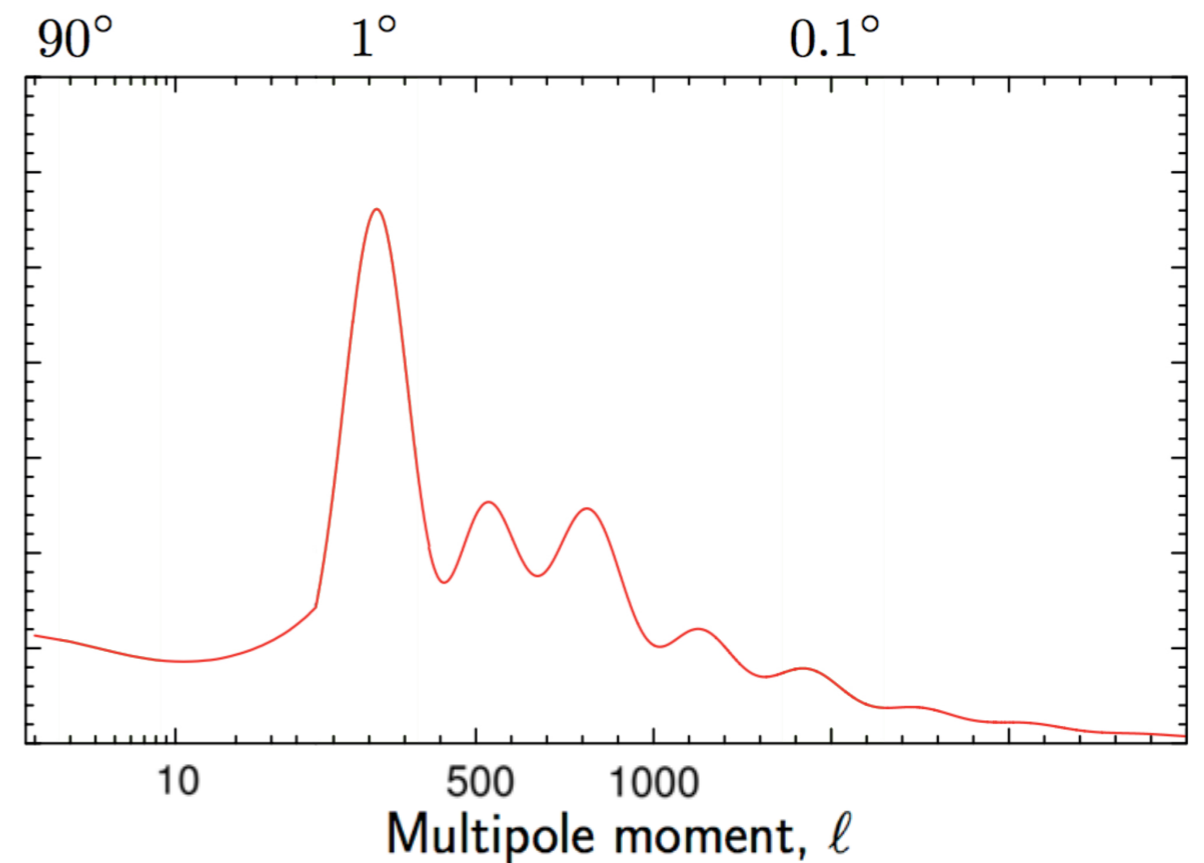
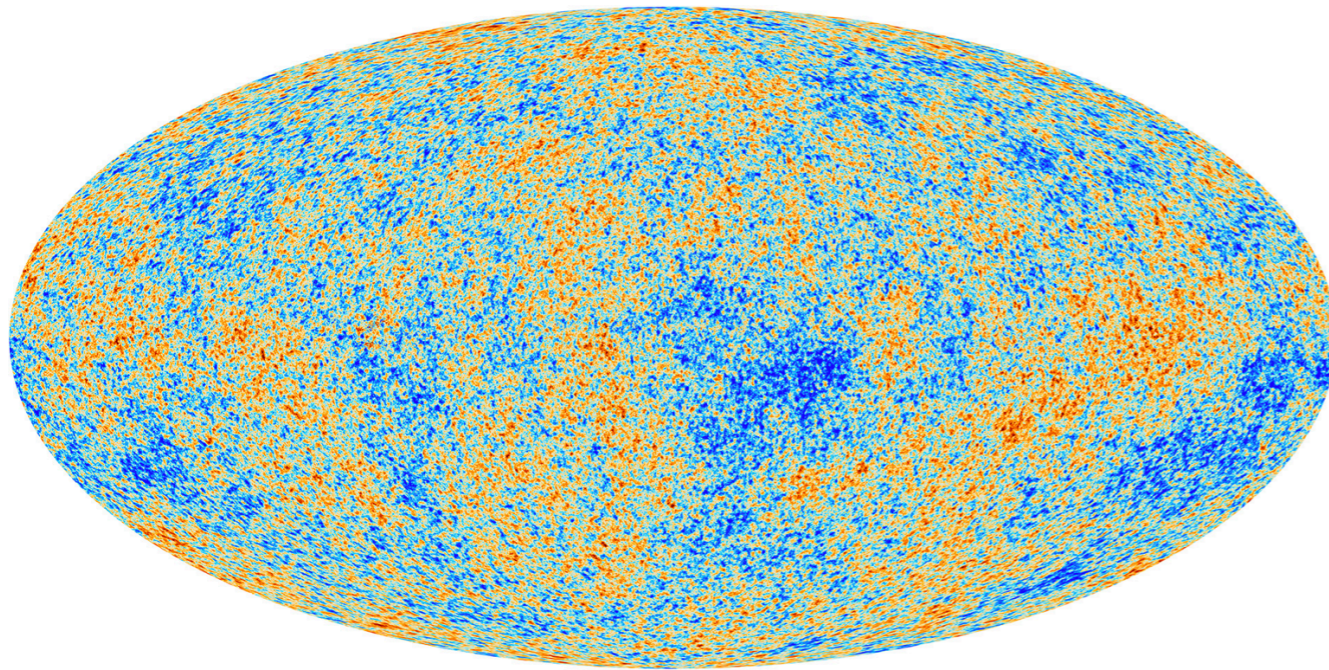


The CMB Power Spectrum: Theory

CMB fluctuations:

Harmonic Space: $\delta T(\hat{\mathbf{n}}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$

Power Spectrum: $\langle a_{\ell m}^* a_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell$

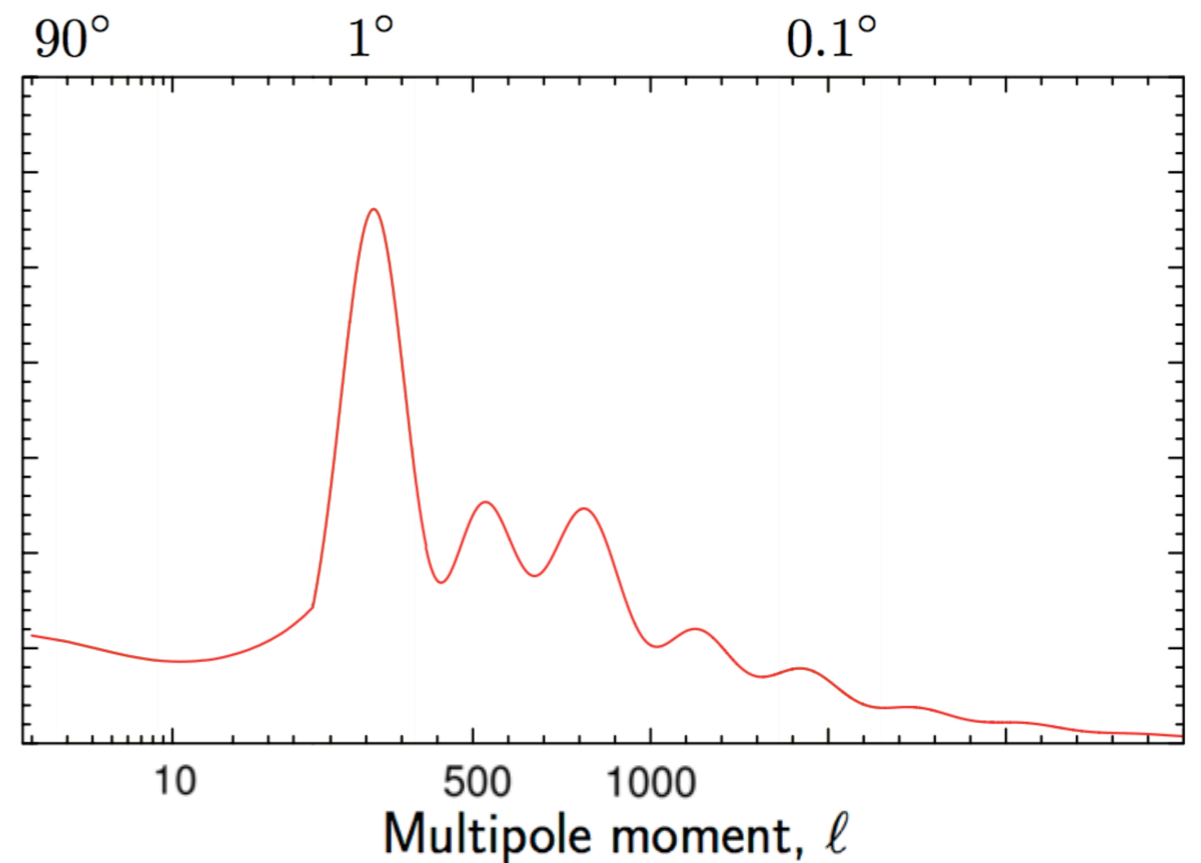
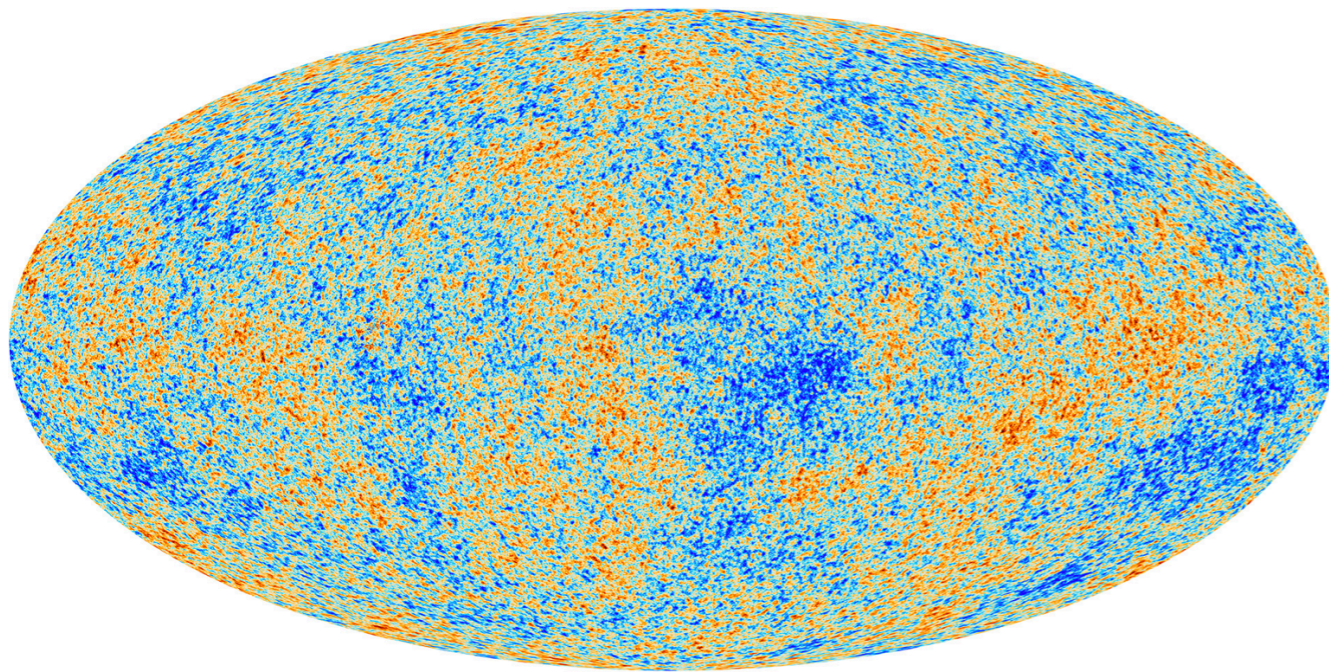


The CMB Power Spectrum: Theory

CMB fluctuations:

Harmonic Space: $\delta T(\hat{\mathbf{n}}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$

Power Spectrum: $\langle a_{\ell m}^* a_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell$



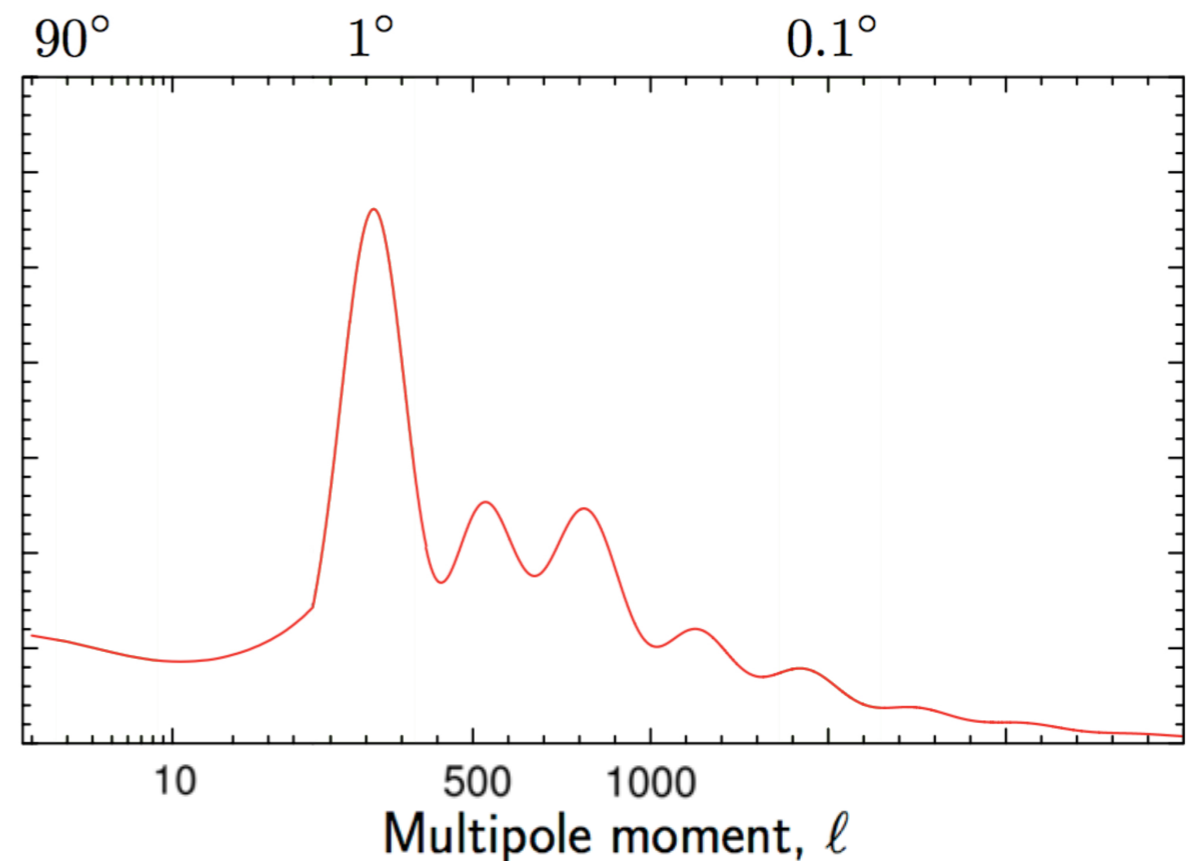
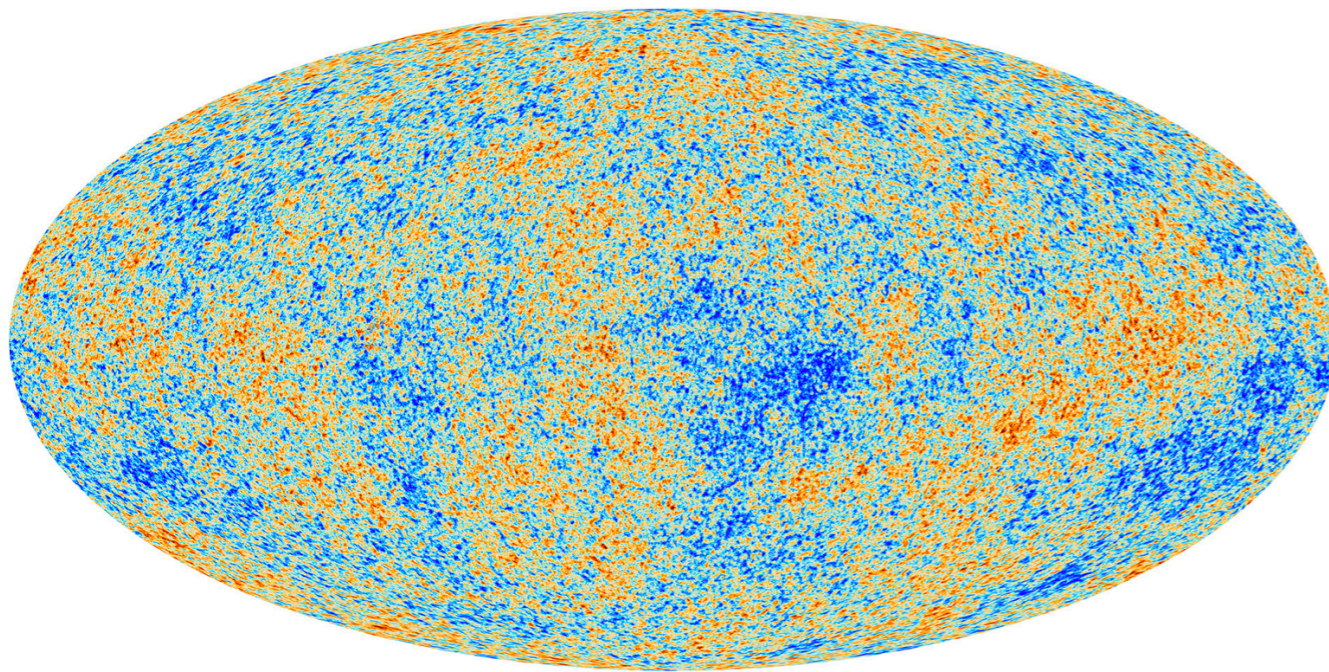
- Acoustic oscillations: basic physics described by a driven harmonic oscillator.

The CMB Power Spectrum: Theory

CMB fluctuations:

Harmonic Space: $\delta T(\hat{\mathbf{n}}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$

Power Spectrum: $\langle a_{\ell m}^* a_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell$



- Acoustic oscillations: basic physics described by a driven harmonic oscillator.
- Silk diffusion damping: exponential suppression of small scale fluctuations.

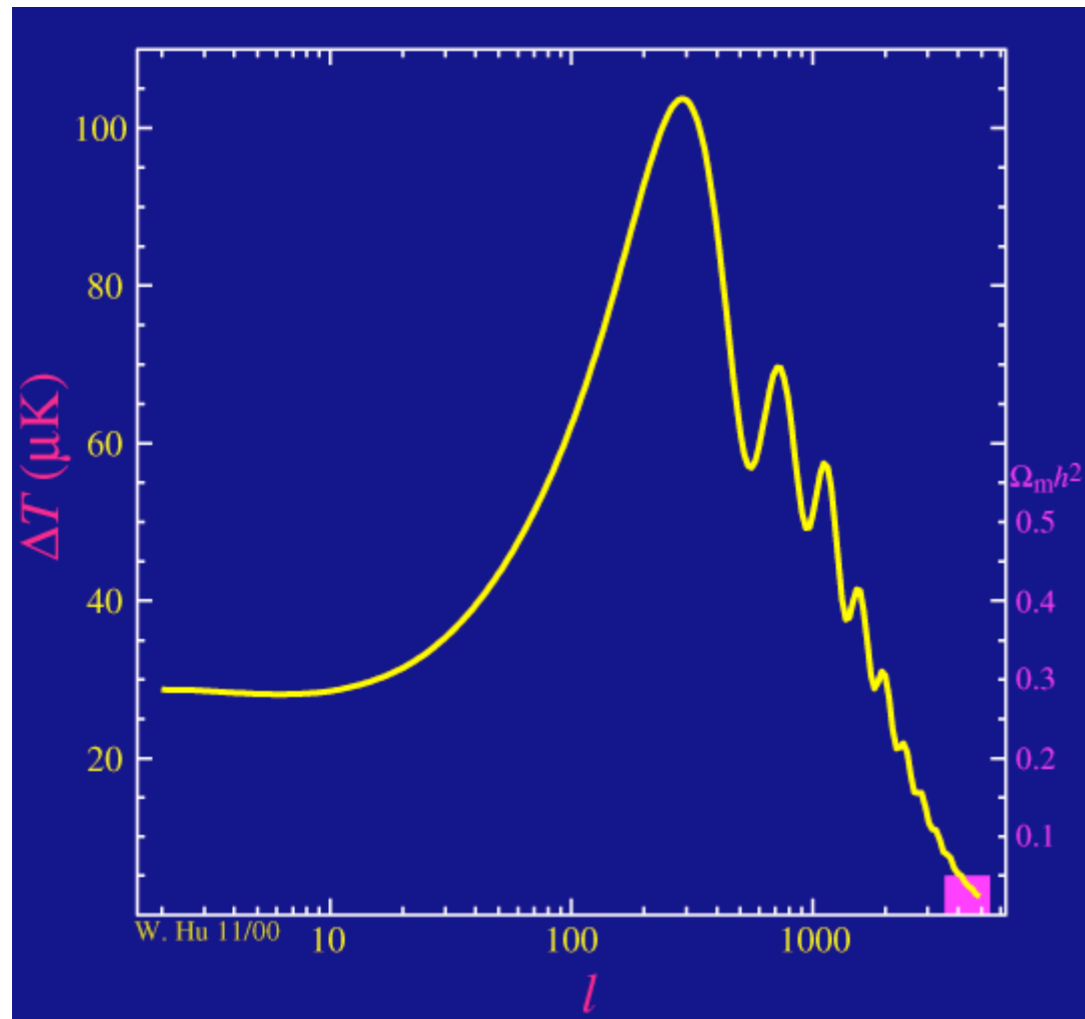
The CMB Power Spectrum: Sensitivity

Acoustic peaks are very sensitive to changes in cosmological parameters:

The CMB Power Spectrum: Sensitivity

Acoustic peaks are very sensitive to changes in cosmological parameters:

(from W. Hu's website)

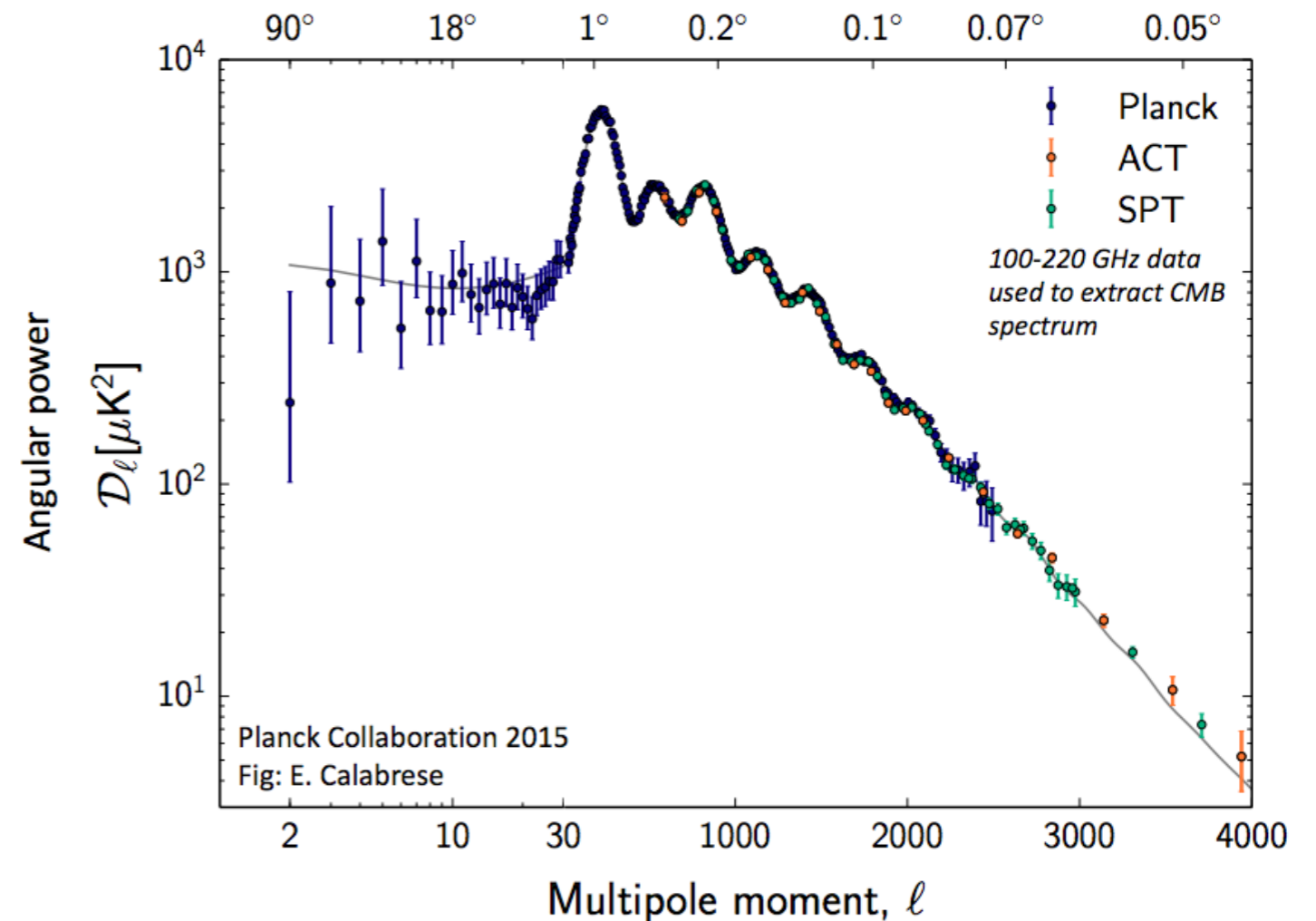
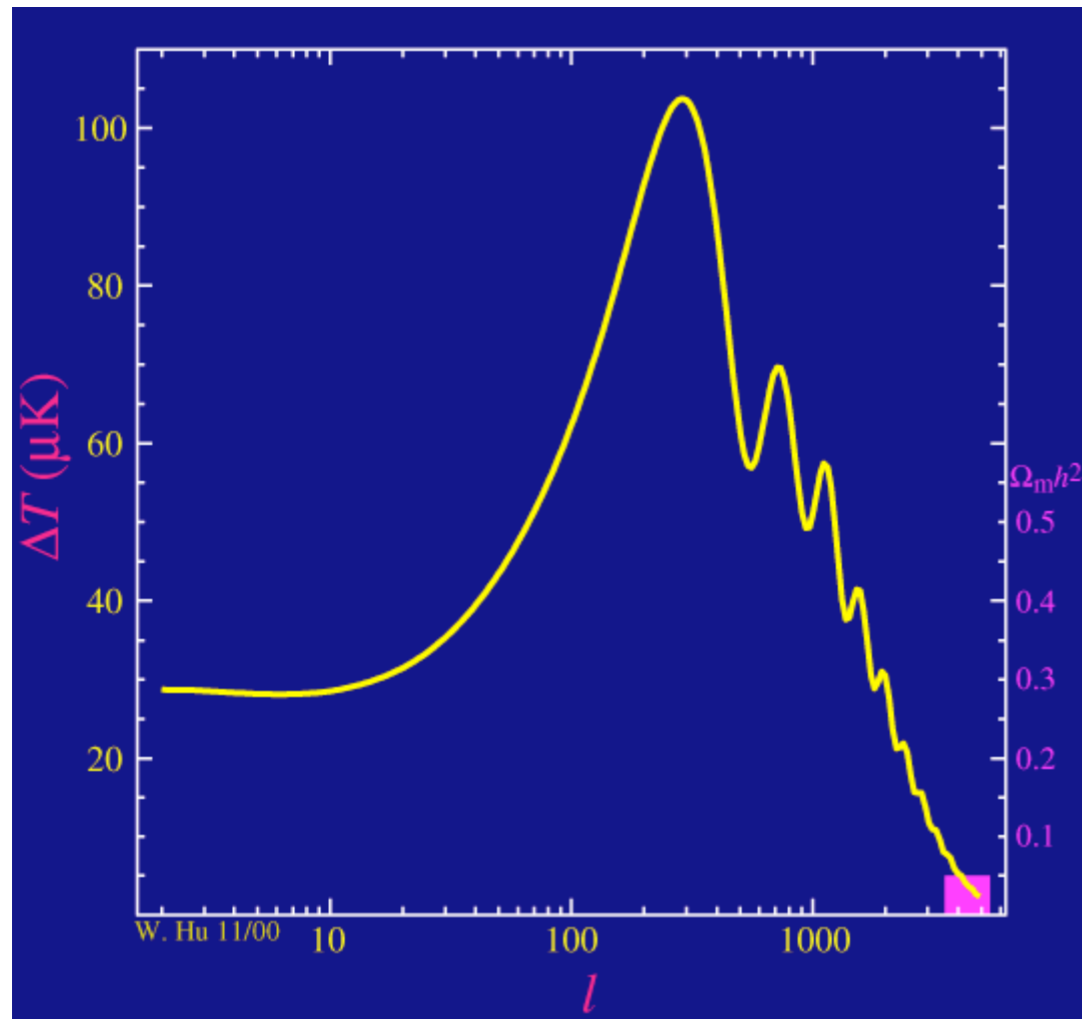


Cold dark matter: $\Omega_c h^2$

The CMB Power Spectrum: Sensitivity

Acoustic peaks are very sensitive to changes in cosmological parameters:

(from W. Hu's website)



Cold dark matter: $\Omega_c h^2$

$$\Omega_c h^2 = 0.1198 \pm 0.0015$$

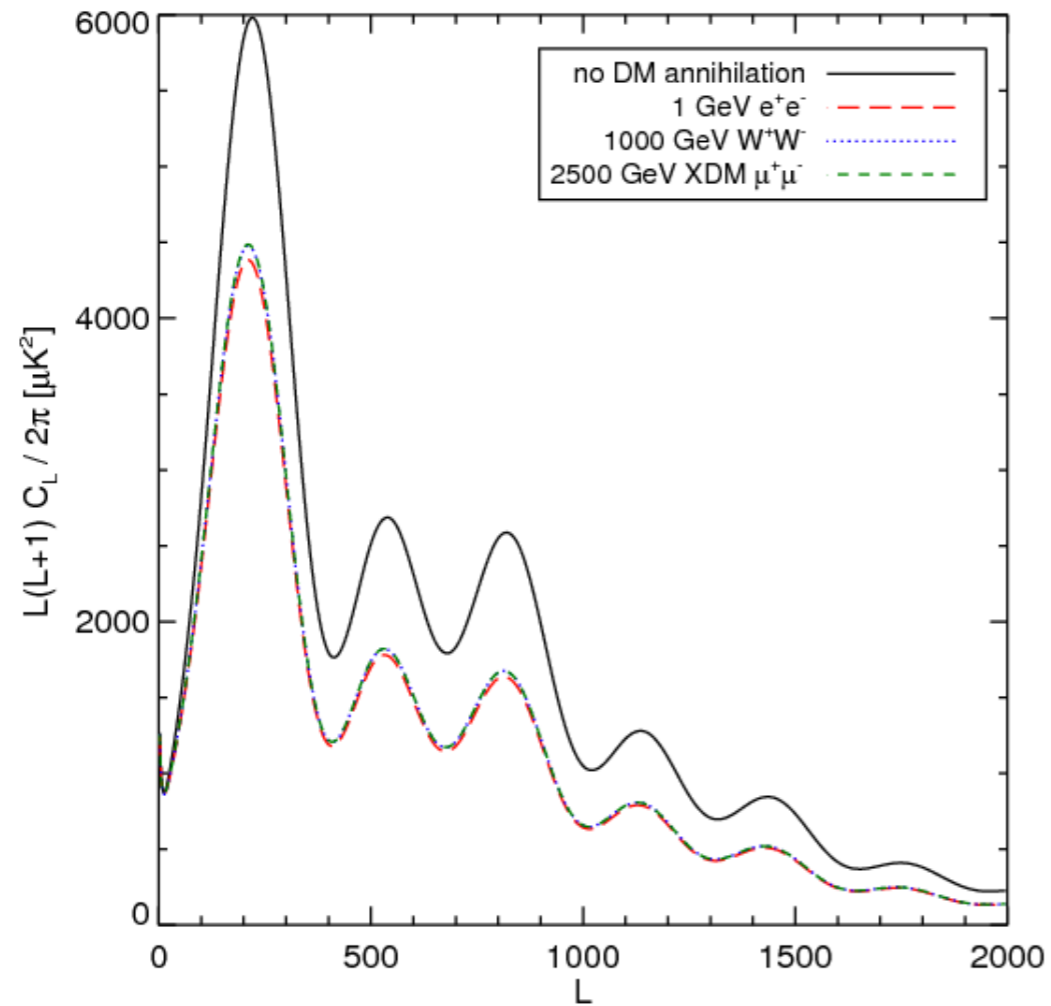
The CMB Power Spectrum: Sensitivity

Also sensitive to various dark matter signatures:

The CMB Power Spectrum: Sensitivity

Also sensitive to various dark matter signatures:

(Slatyer, Padmanabhan & Finkbeiner Phys Rev D80, 2009)

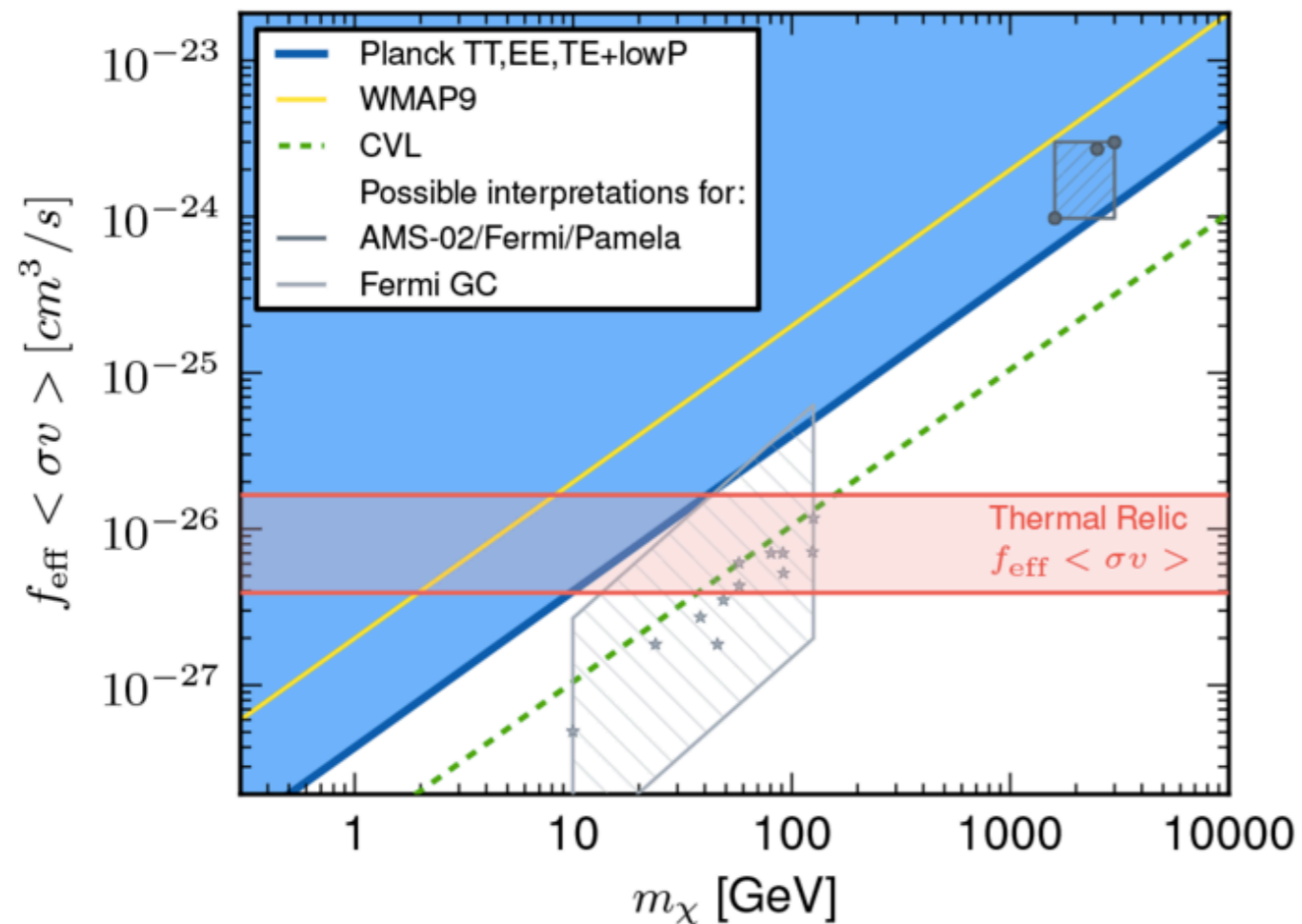


DM annihilation (energy injection)

The CMB Power Spectrum: Sensitivity

Also sensitive to various dark matter signatures:

(ESA, Planck Collaboration 2014 Press Release)

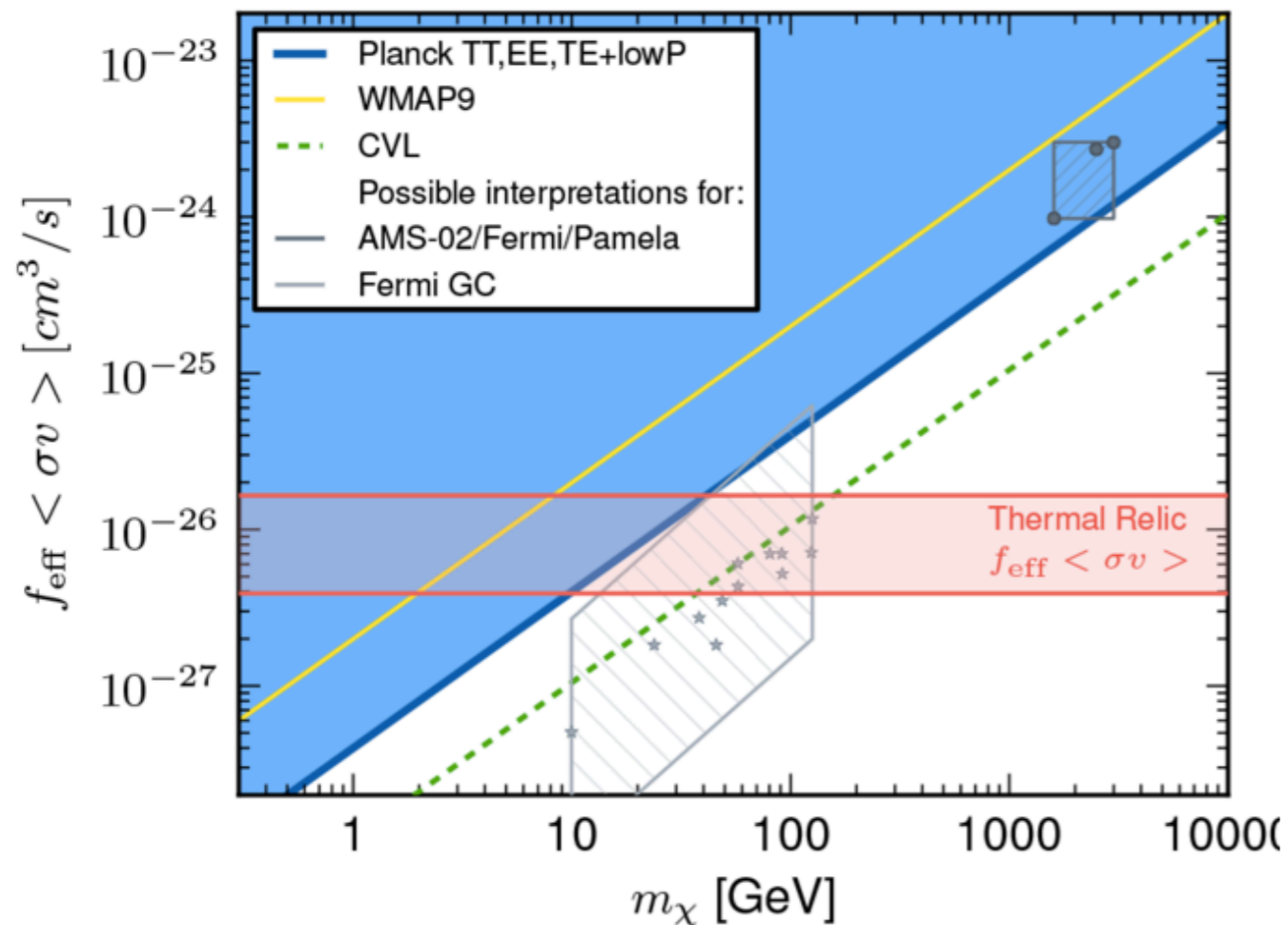


DM annihilation (energy injection)

The CMB Power Spectrum: Sensitivity

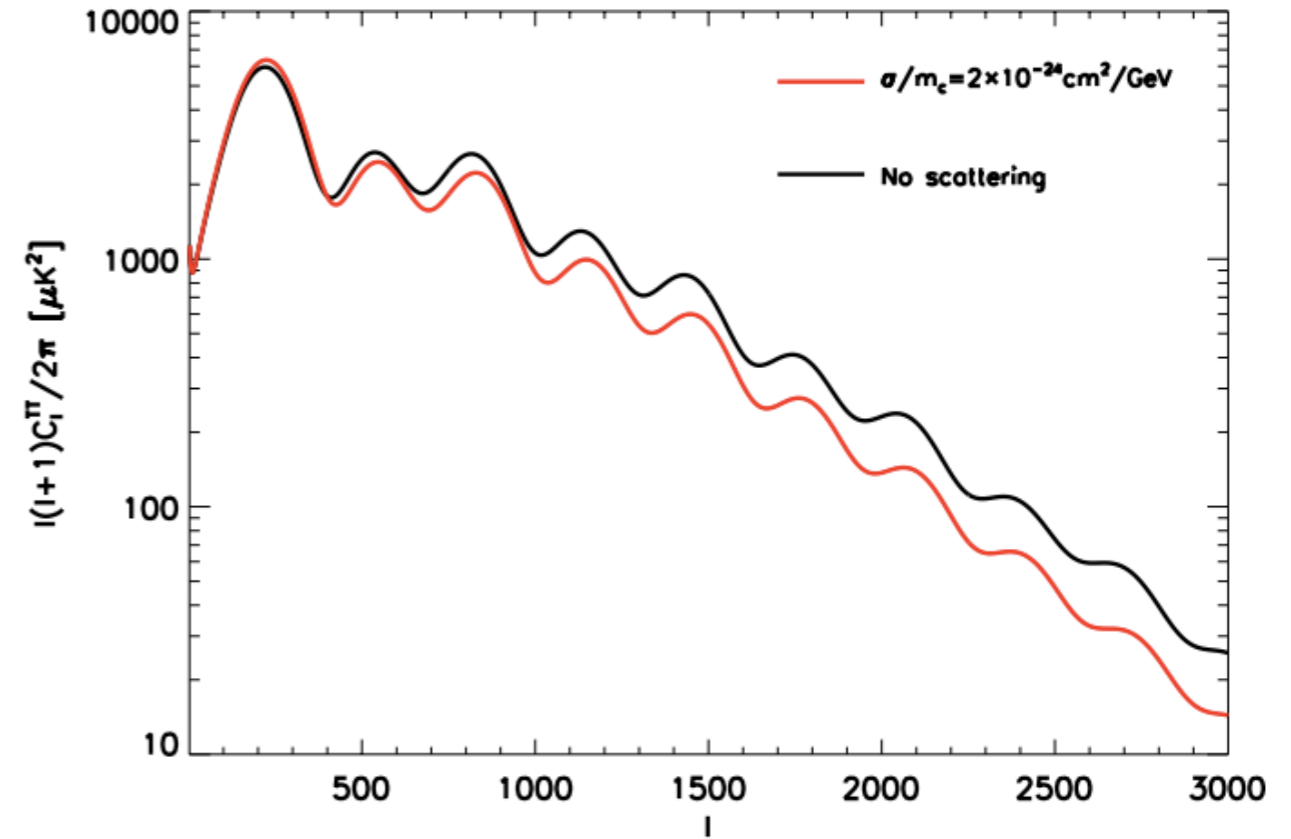
Also sensitive to various dark matter signatures:

(ESA, Planck Collaboration 2014 Press Release)



DM annihilation (energy injection)

(Courtesy of C. Dvorkin)

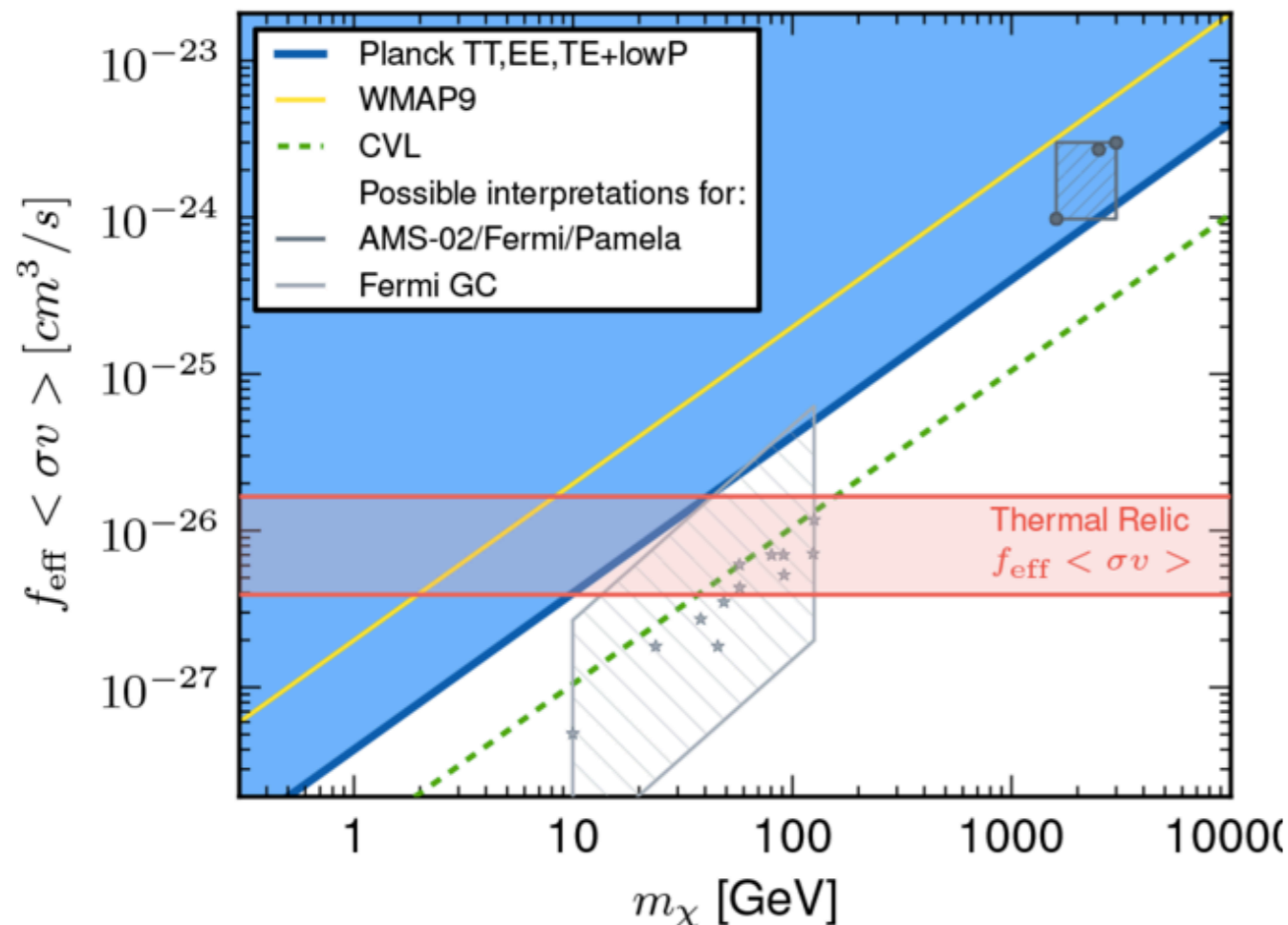


DM-baryon scattering (suppression)

The CMB Power Spectrum: Sensitivity

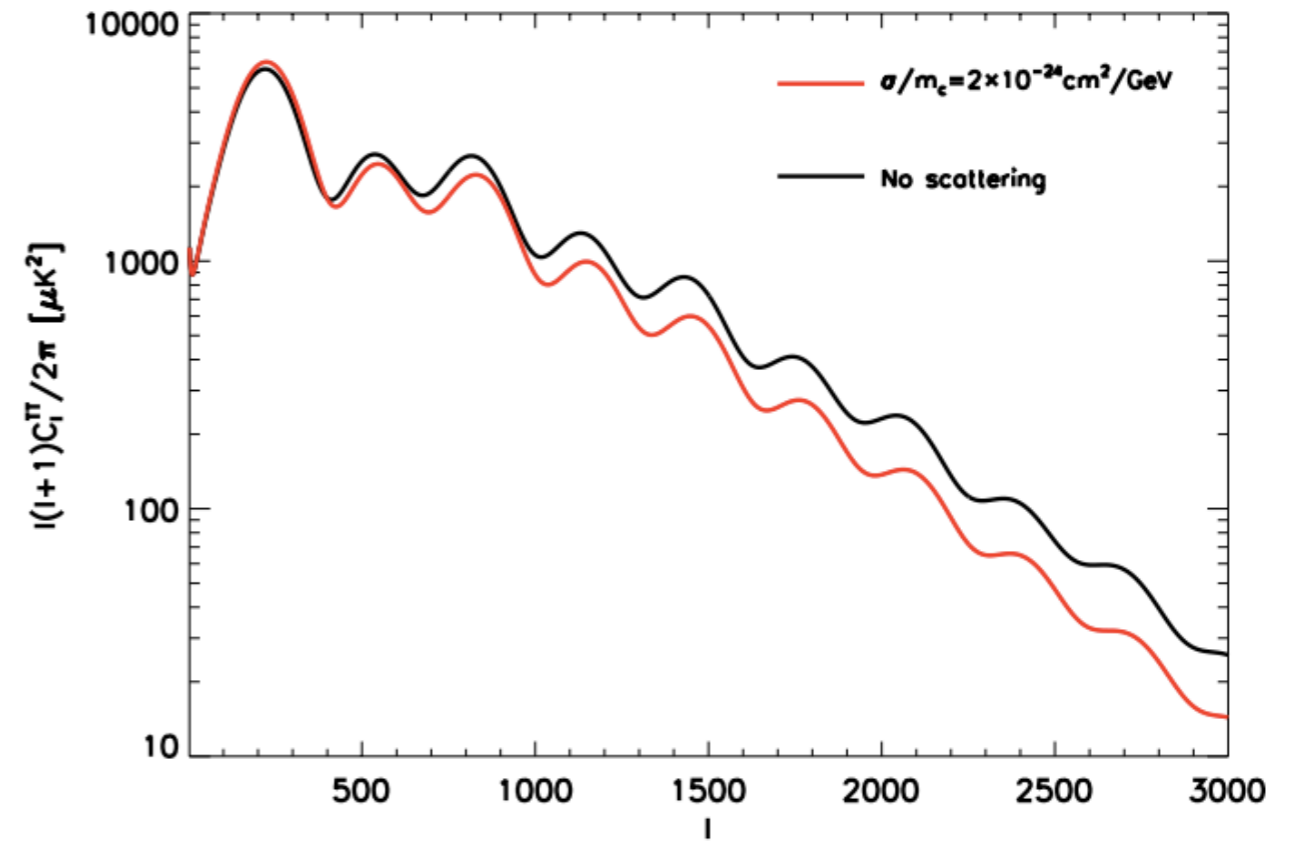
Also sensitive to various dark matter signatures:

(ESA, Planck Collaboration 2014 Press Release)



DM annihilation (energy injection)

(Courtesy of C. Dvorkin)

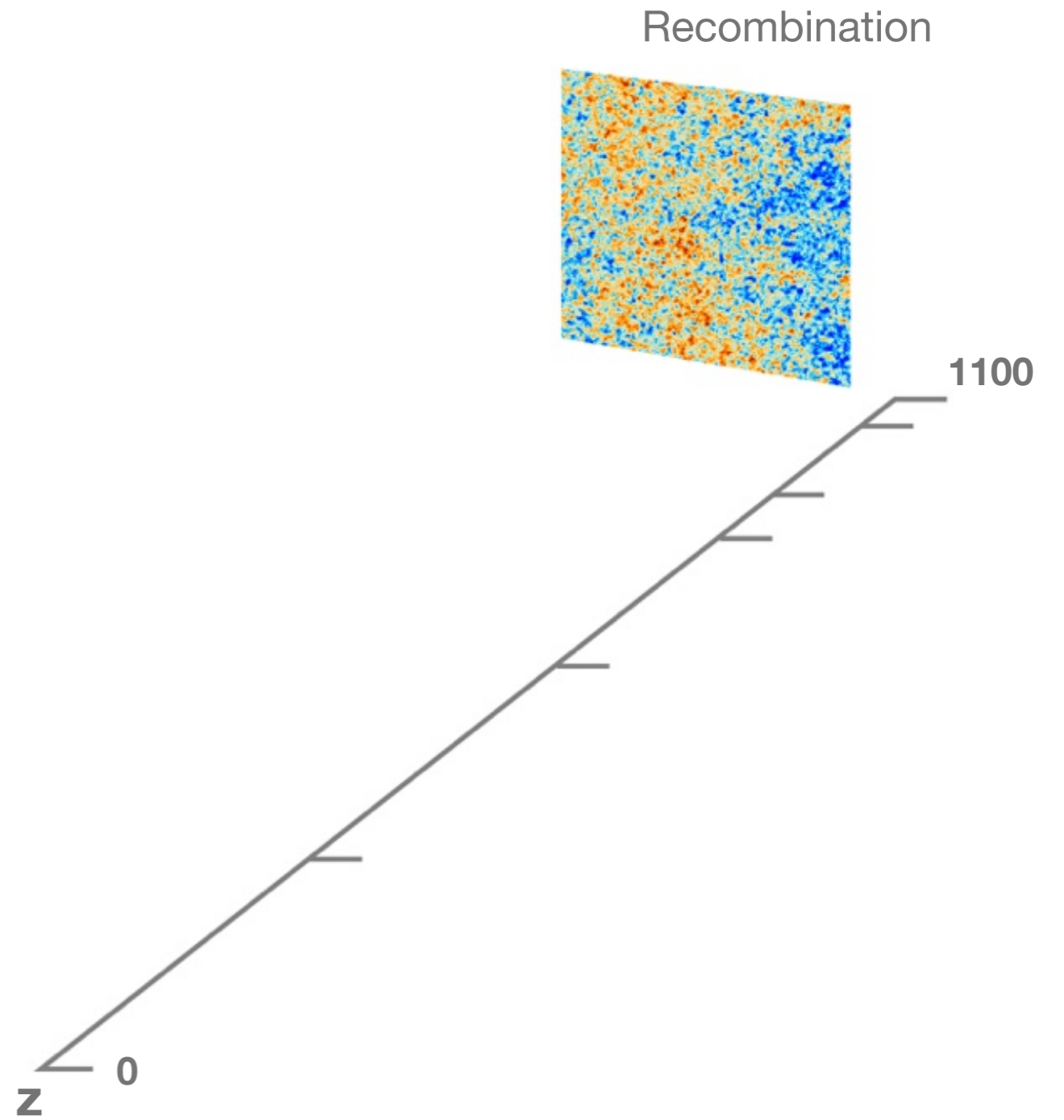


DM-baryon scattering (suppression)

more about this later...

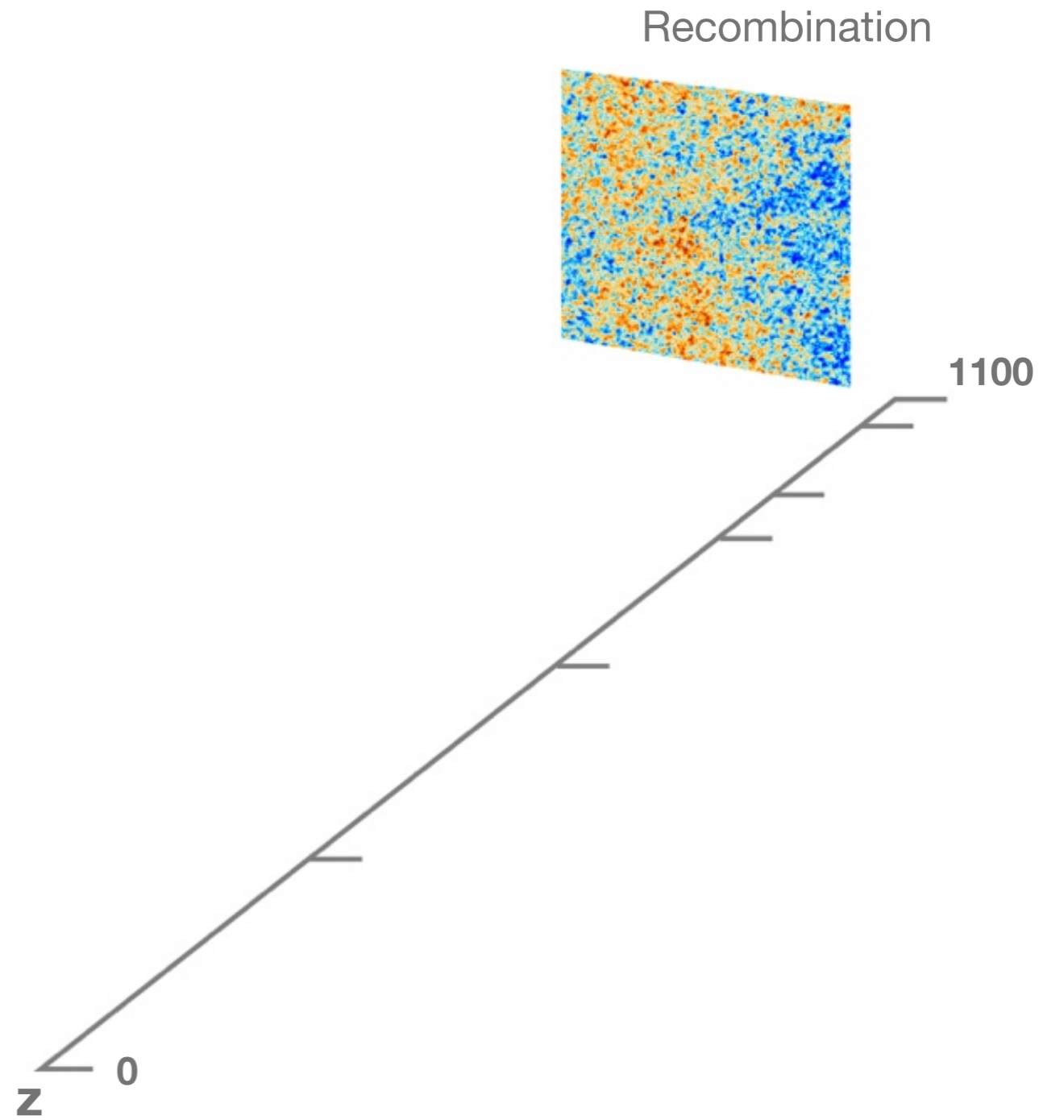
Where to Look Next?

Where to Look Next?



Where to Look Next?

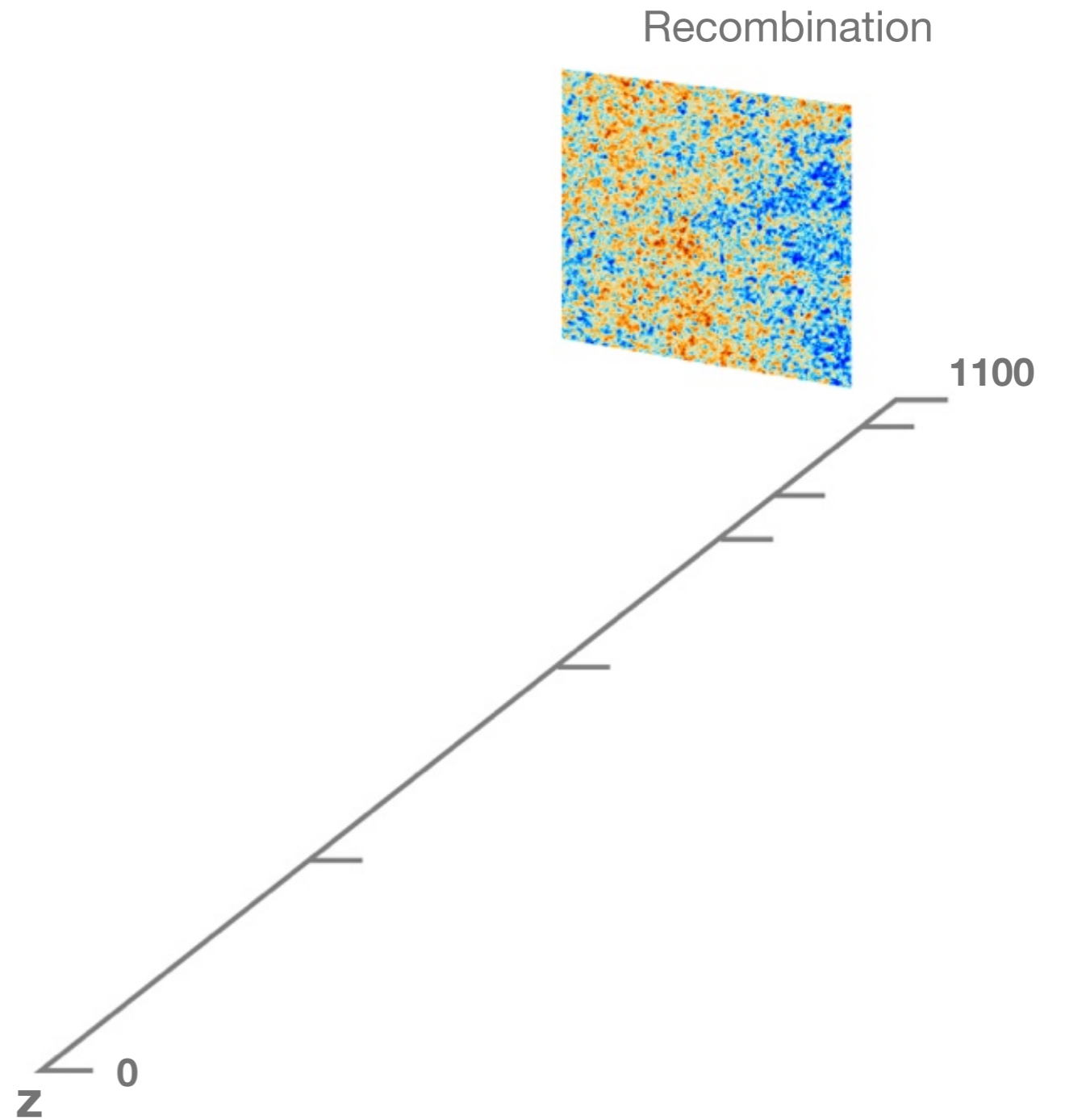
CMB weak points:



Where to Look Next?

CMB weak points:

- A good figure-of-merit: N_{modes}

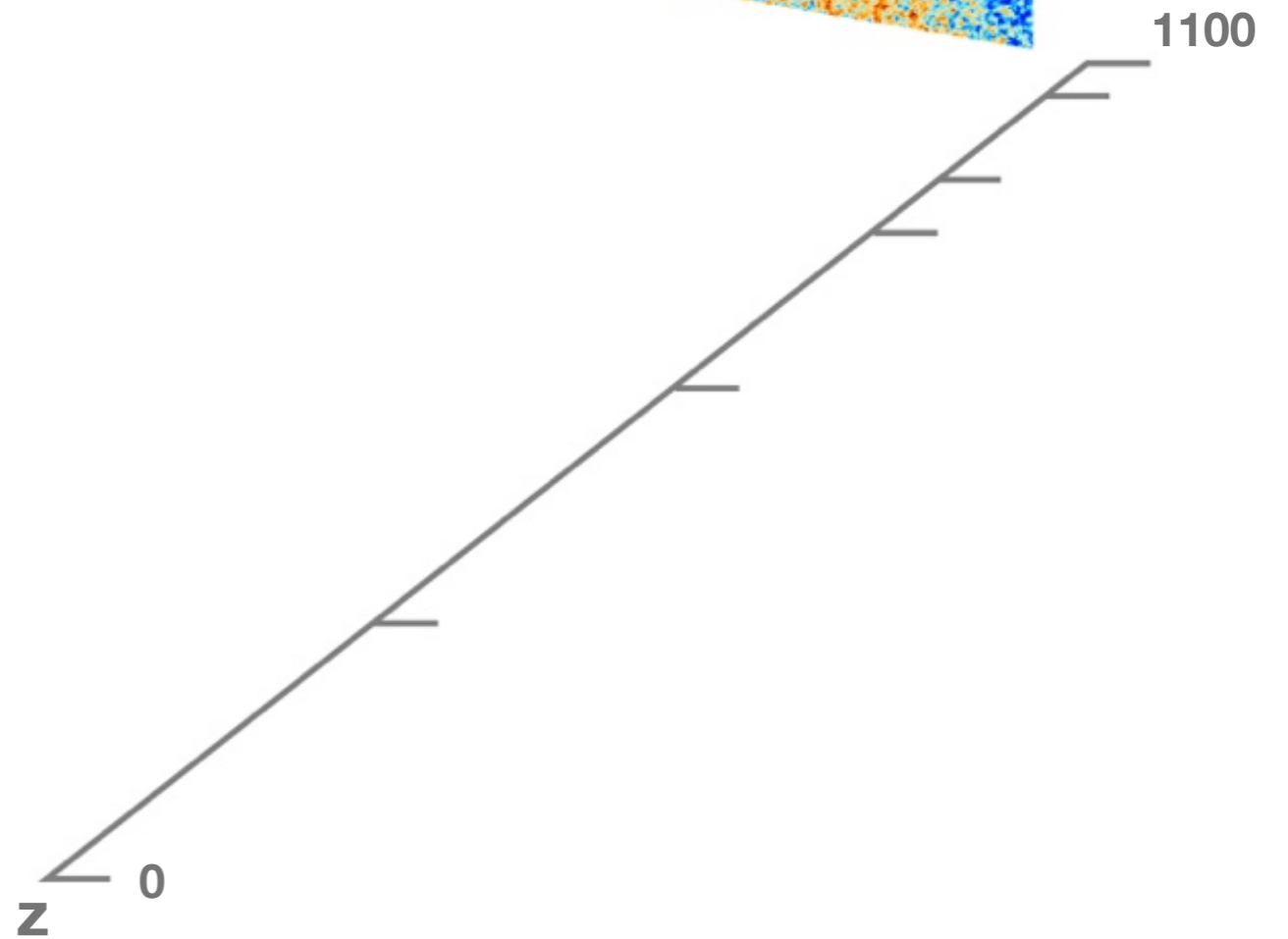
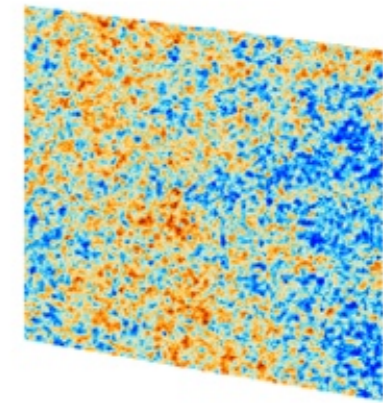


Where to Look Next?

CMB weak points:

- A good figure-of-merit: N_{modes} (constraints $\propto 1/N_{\text{modes}}^{1/2}$)

Recombination



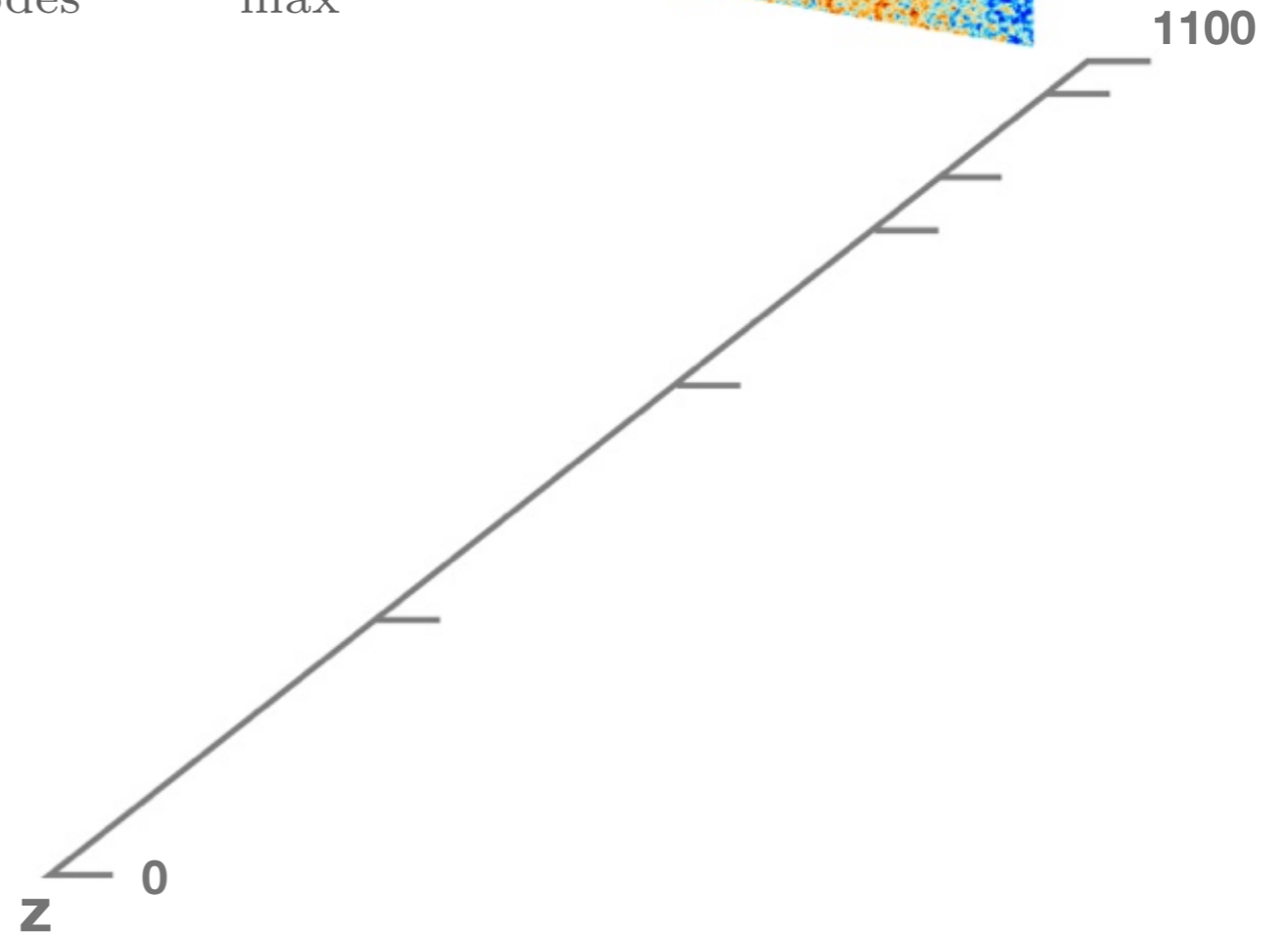
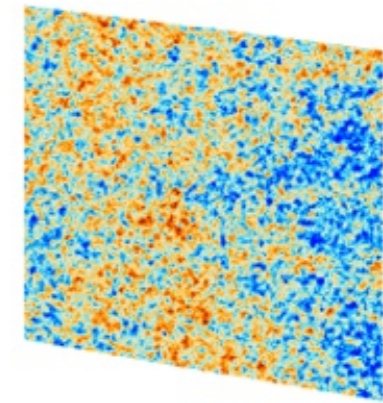
Where to Look Next?

CMB weak points:

- A good figure-of-merit: N_{modes} (constraints $\propto 1/N_{\text{modes}}^{1/2}$)

Planck and others have measured: $N_{\text{modes}}^{\text{CMB}} \sim 2\ell_{\text{max}}^2 \sim 10^7$

Recombination



Where to Look Next?

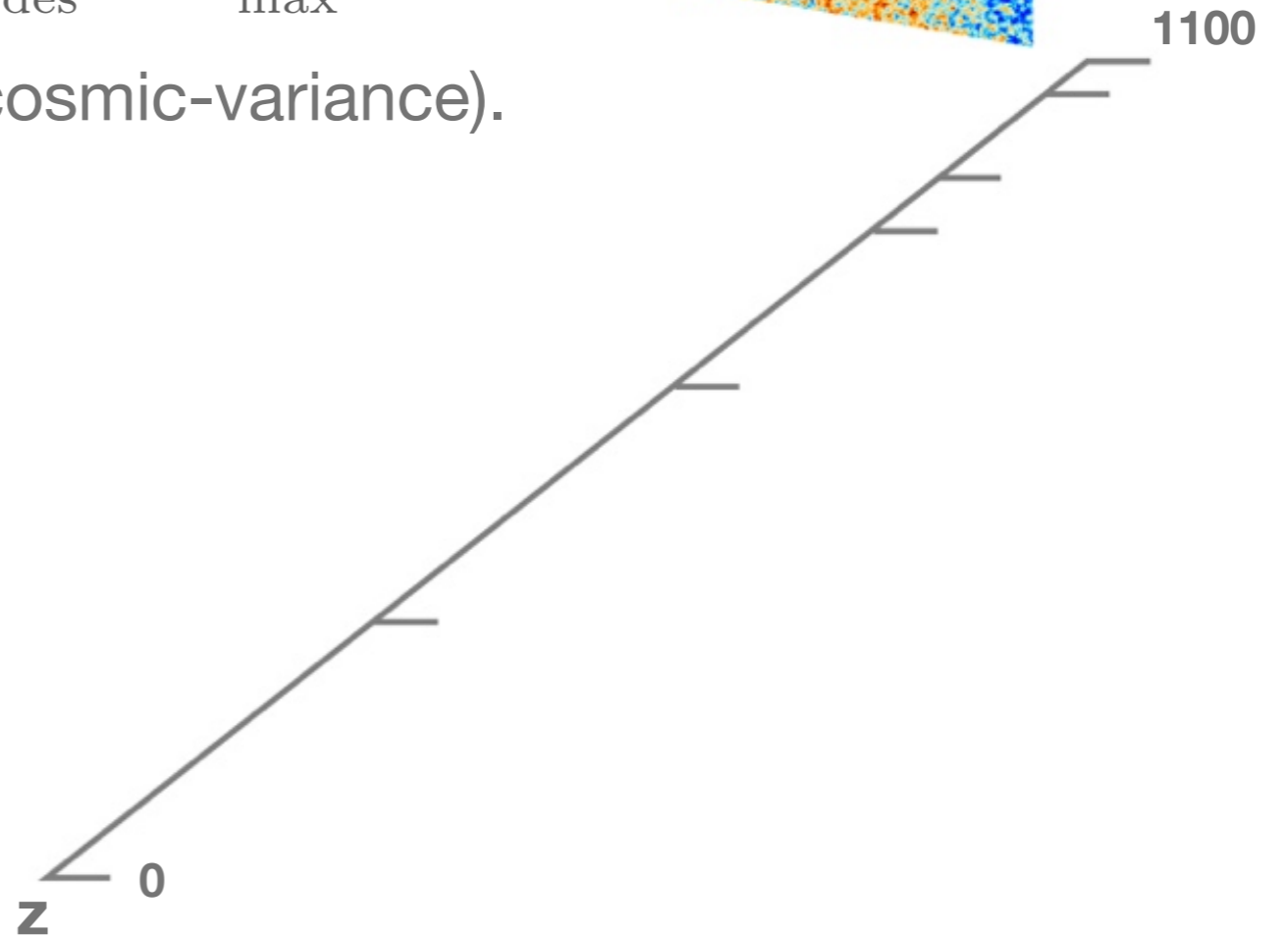
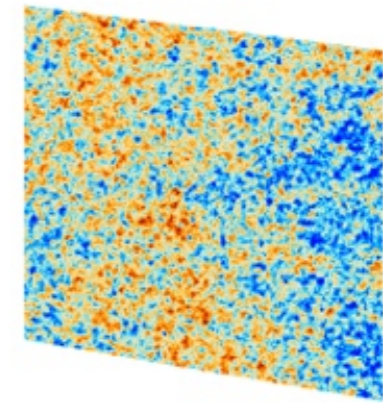
CMB weak points:

- A good figure-of-merit: N_{modes} (constraints $\propto 1/N_{\text{modes}}^{1/2}$)

Planck and others have measured: $N_{\text{modes}}^{\text{CMB}} \sim 2\ell_{\text{max}}^2 \sim 10^7$

Temperature: almost done (damping + cosmic-variance).

Recombination



Where to Look Next?

CMB weak points:

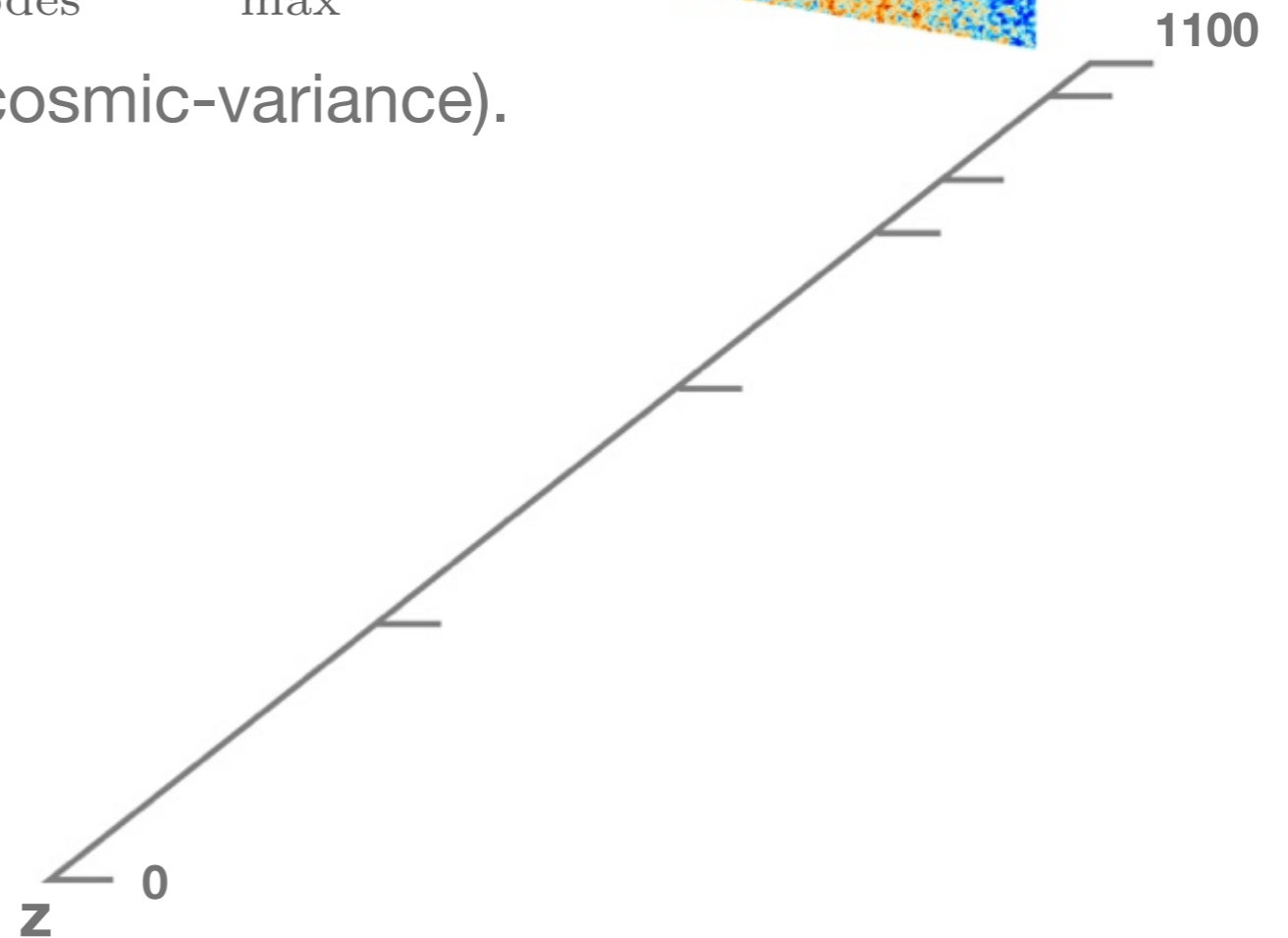
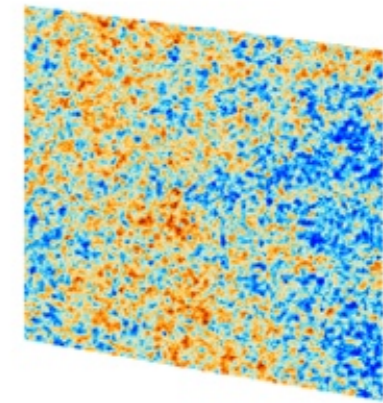
- A good figure-of-merit: N_{modes} (constraints $\propto 1/N_{\text{modes}}^{1/2}$)

Planck and others have measured: $N_{\text{modes}}^{\text{CMB}} \sim 2\ell_{\text{max}}^2 \sim 10^7$

Temperature: almost done (damping + cosmic-variance).

Polarization (E-modes): getting there.

Recombination



Where to Look Next?

CMB weak points:

- A good figure-of-merit: N_{modes} (constraints $\propto 1/N_{\text{modes}}^{1/2}$)

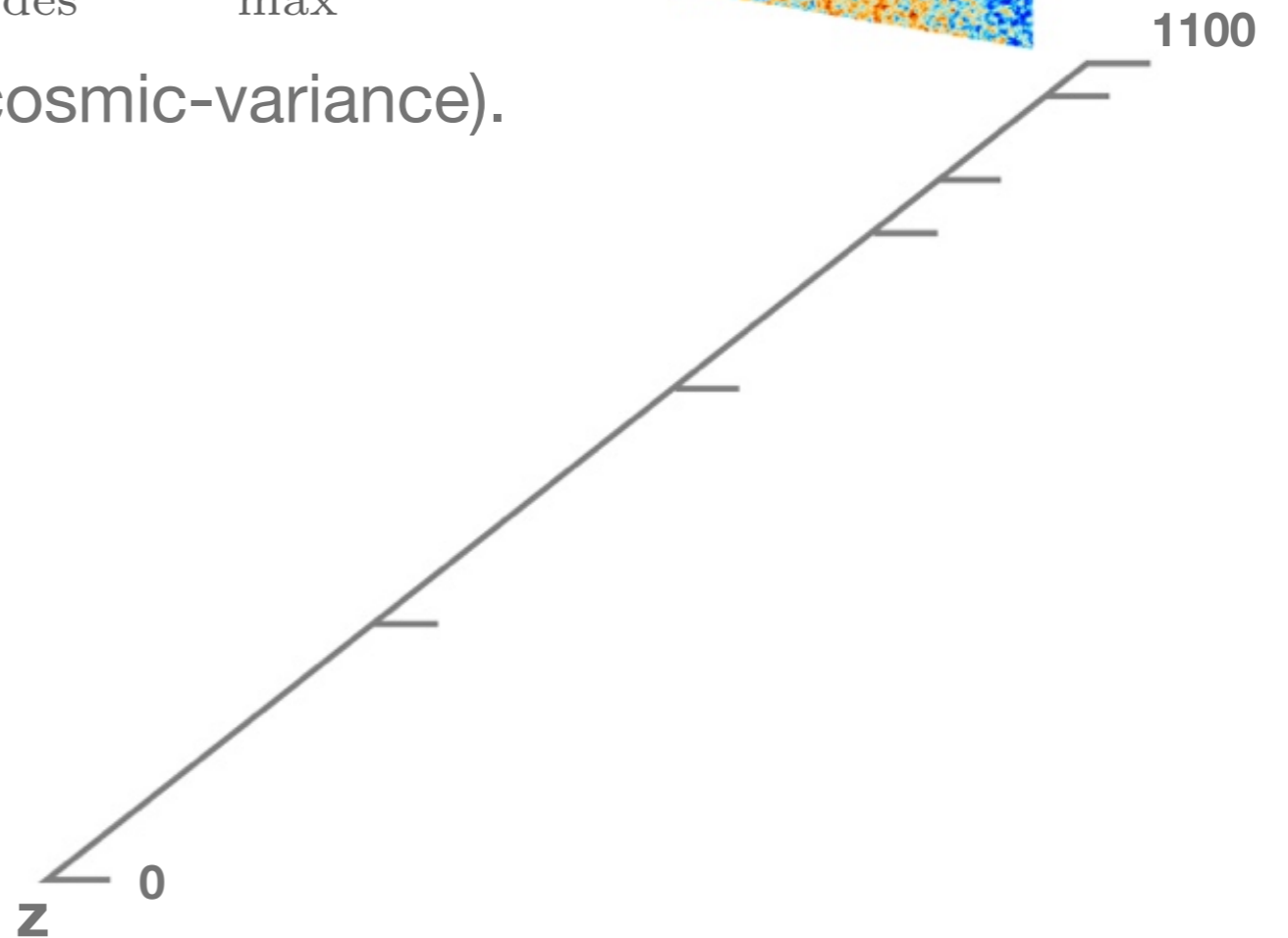
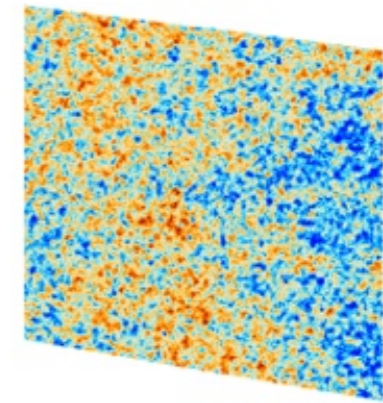
Planck and others have measured: $N_{\text{modes}}^{\text{CMB}} \sim 2\ell_{\text{max}}^2 \sim 10^7$

Temperature: almost done (damping + cosmic-variance).

Polarization (E-modes): getting there.

- Probes one very small epoch.

Recombination



Where to Look Next?

CMB weak points:

- A good figure-of-merit: N_{modes} (constraints $\propto 1/N_{\text{modes}}^{1/2}$)

Planck and others have measured: $N_{\text{modes}}^{\text{CMB}} \sim 2\ell_{\text{max}}^2 \sim 10^7$

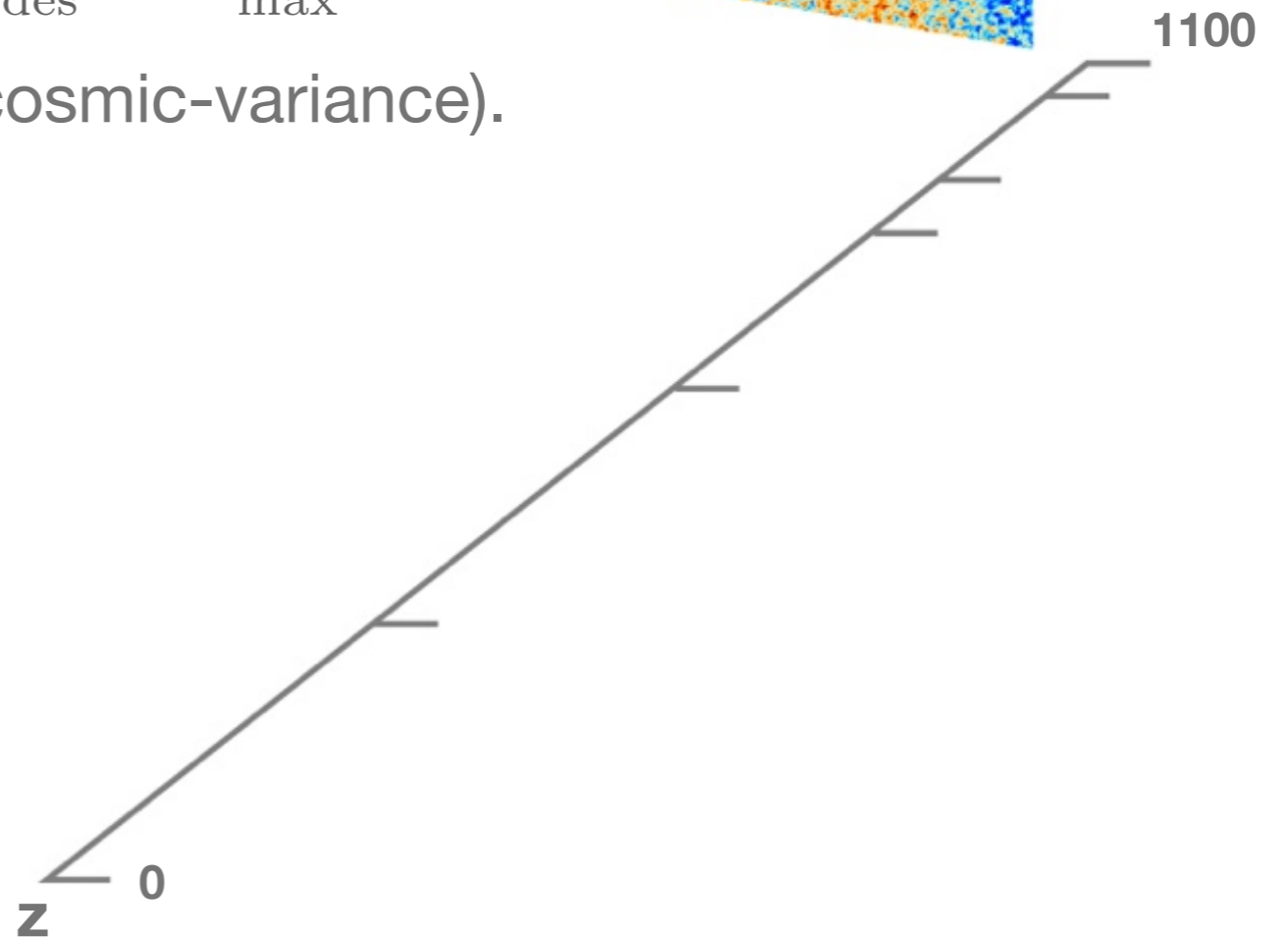
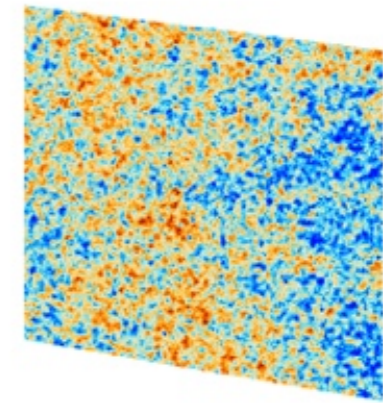
Temperature: almost done (damping + cosmic-variance).

Polarization (E-modes): getting there.

- Probes one very small epoch.

Not too sensitive to late(r) time effects.

Recombination



Where to Look Next?

CMB weak points:

- A good figure-of-merit: N_{modes} (constraints $\propto 1/N_{\text{modes}}^{1/2}$)

Planck and others have measured: $N_{\text{modes}}^{\text{CMB}} \sim 2\ell_{\text{max}}^2 \sim 10^7$

Temperature: almost done (damping + cosmic-variance).

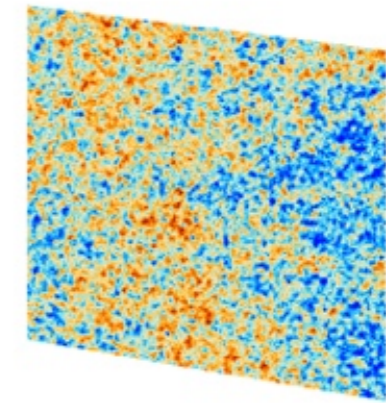
Polarization (E-modes): getting there.

- Probes one very small epoch.

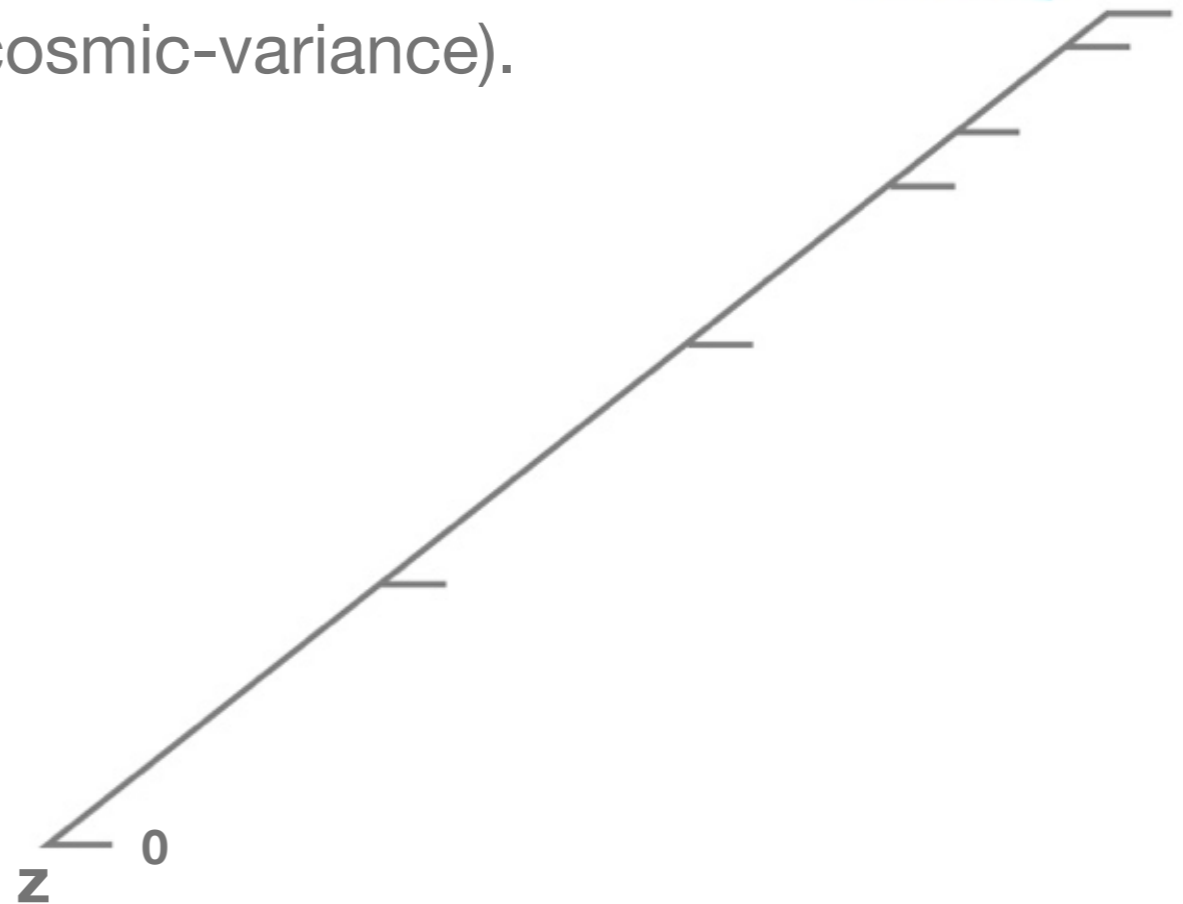
Not too sensitive to late(r) time effects.

We want access to new information.

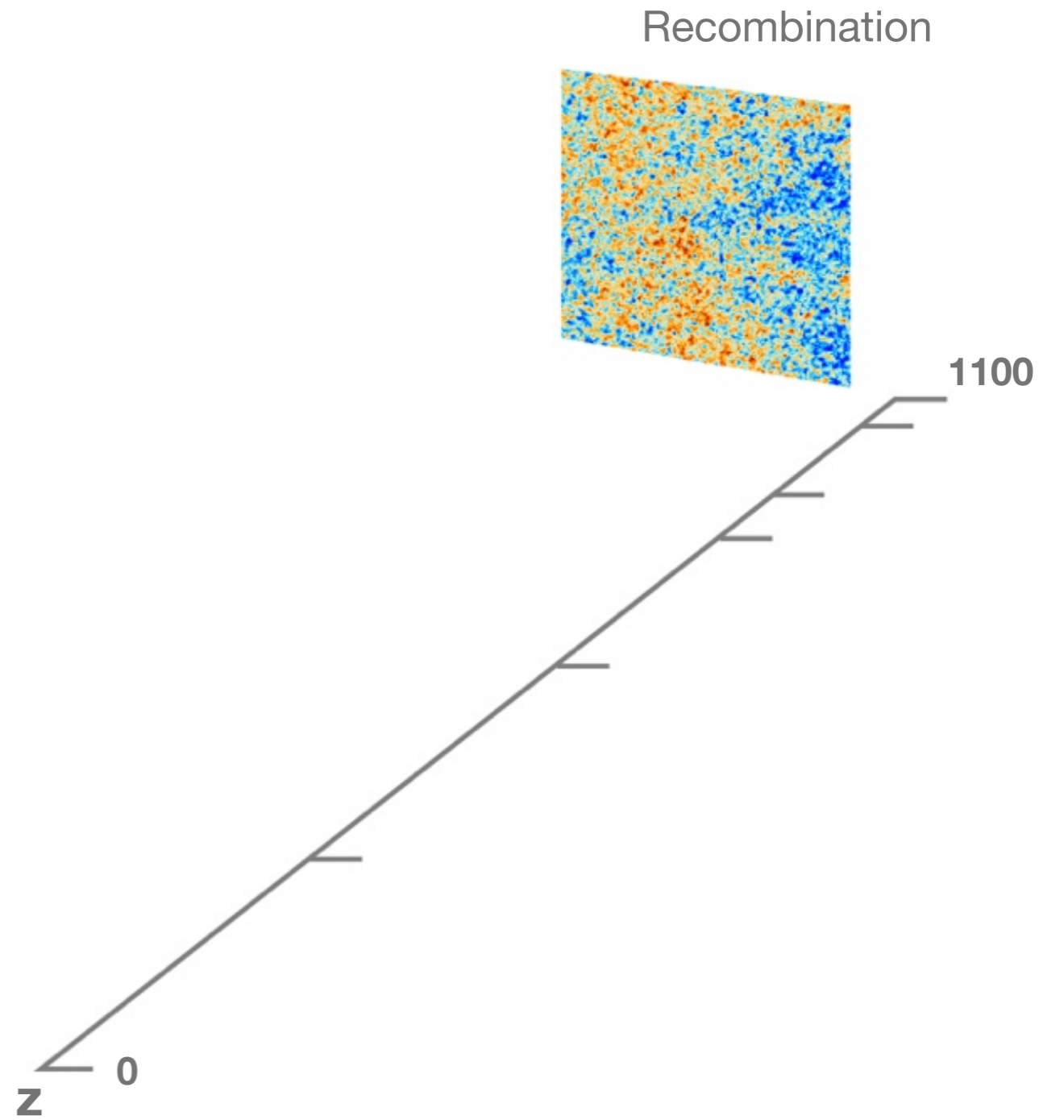
Recombination



1100

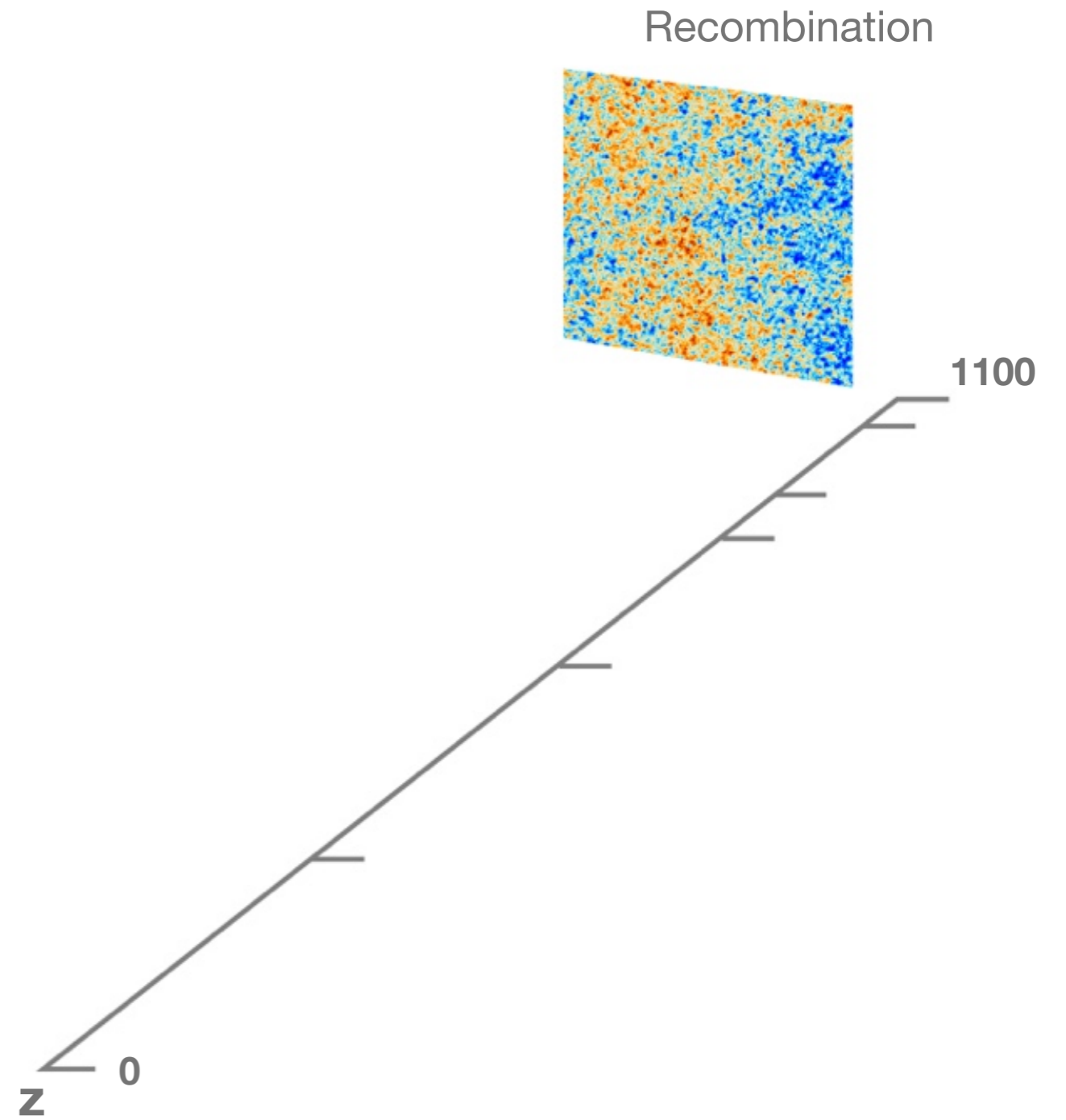


Where to Look Next?



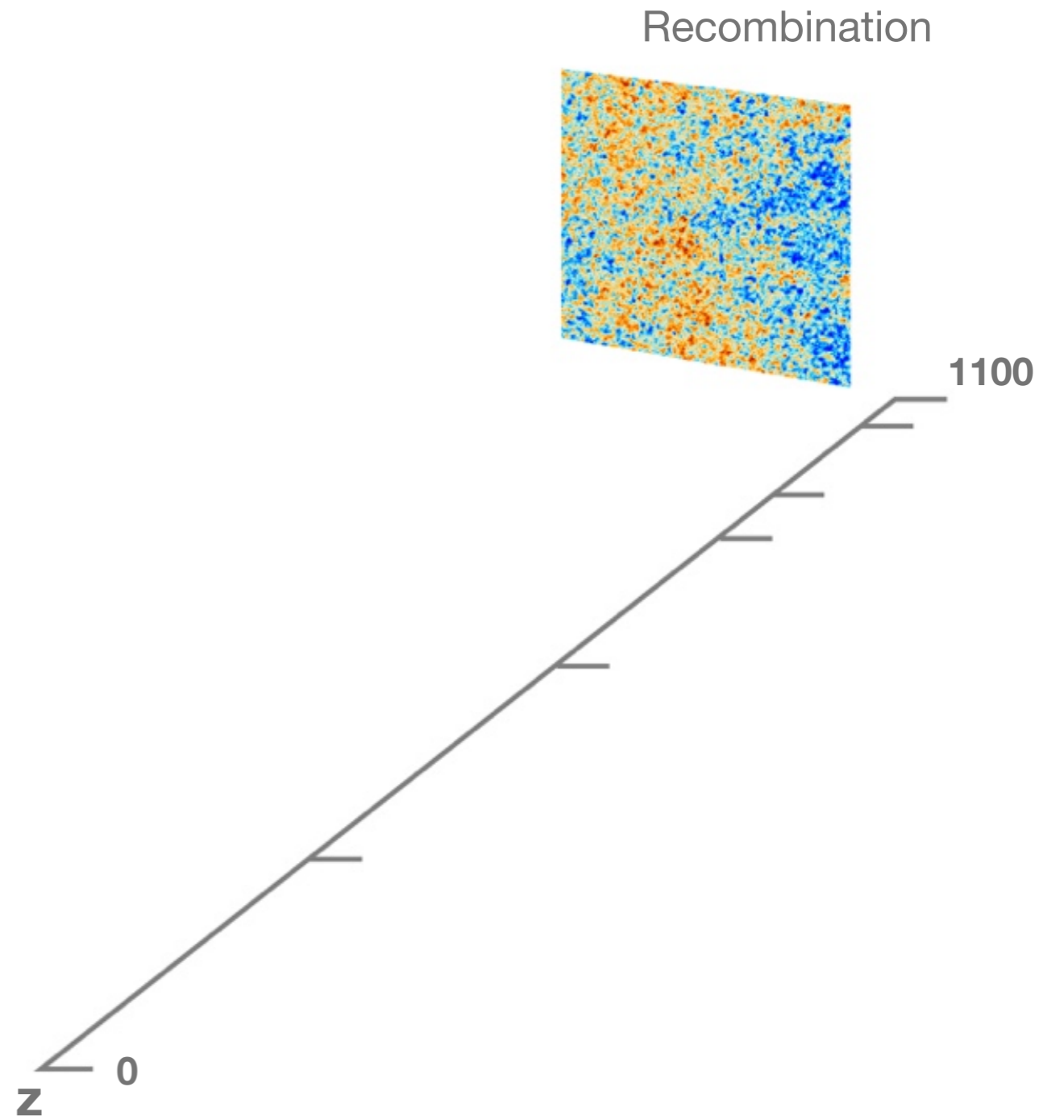
Where to Look Next?

What happens after recombination?



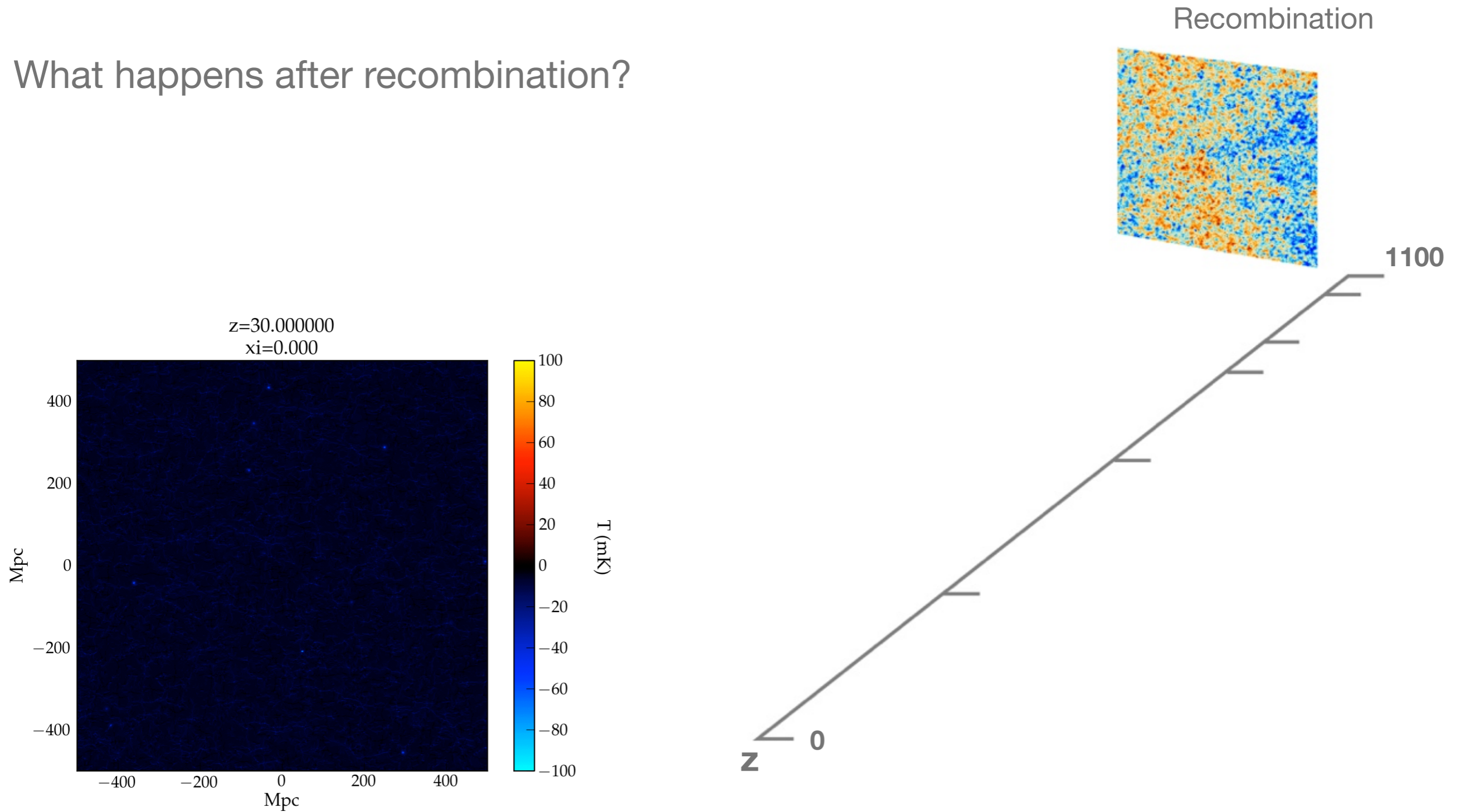
Where to Look Next?

What happens after recombination?



Where to Look Next?

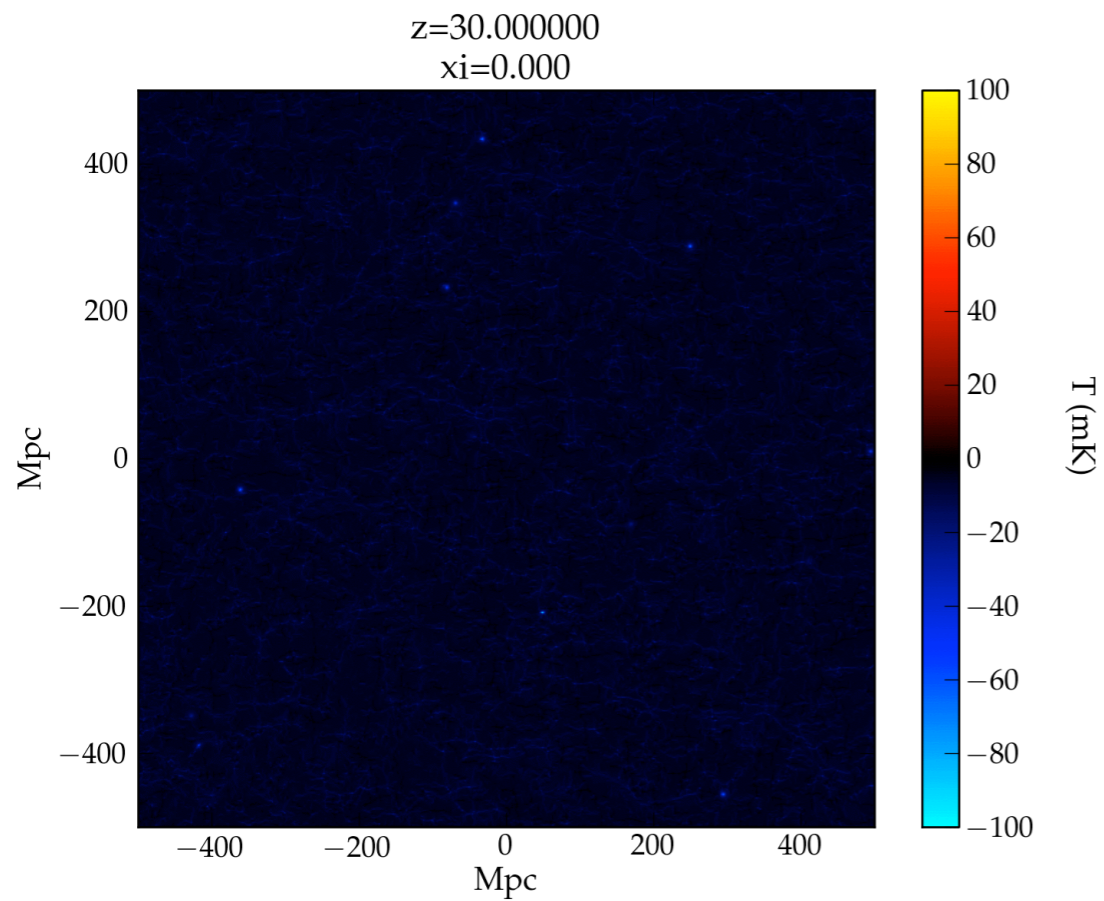
What happens after recombination?



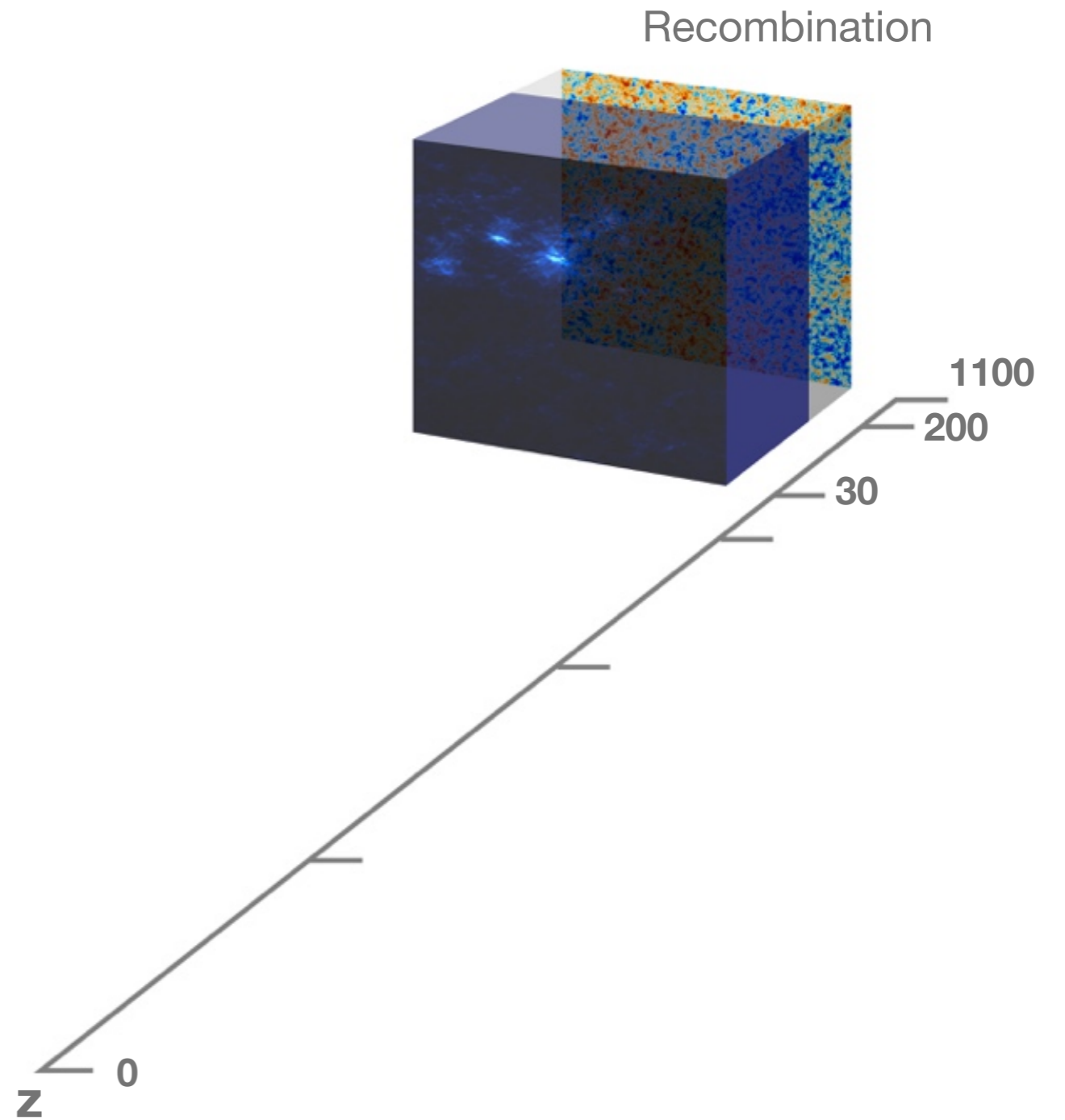
Credit:
Mário Santos (IST, Portugal)

Where to Look Next?

What happens after recombination?

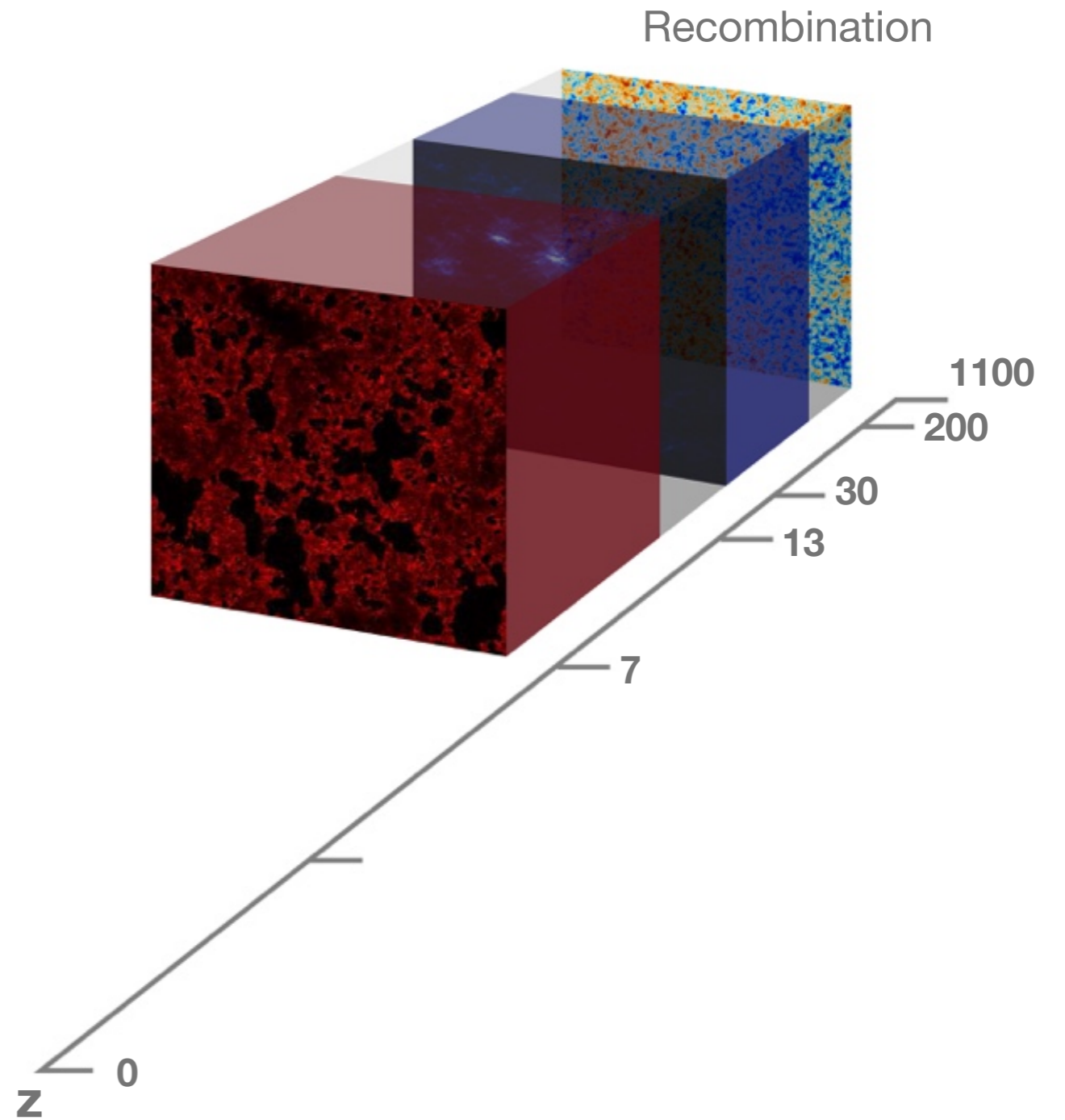
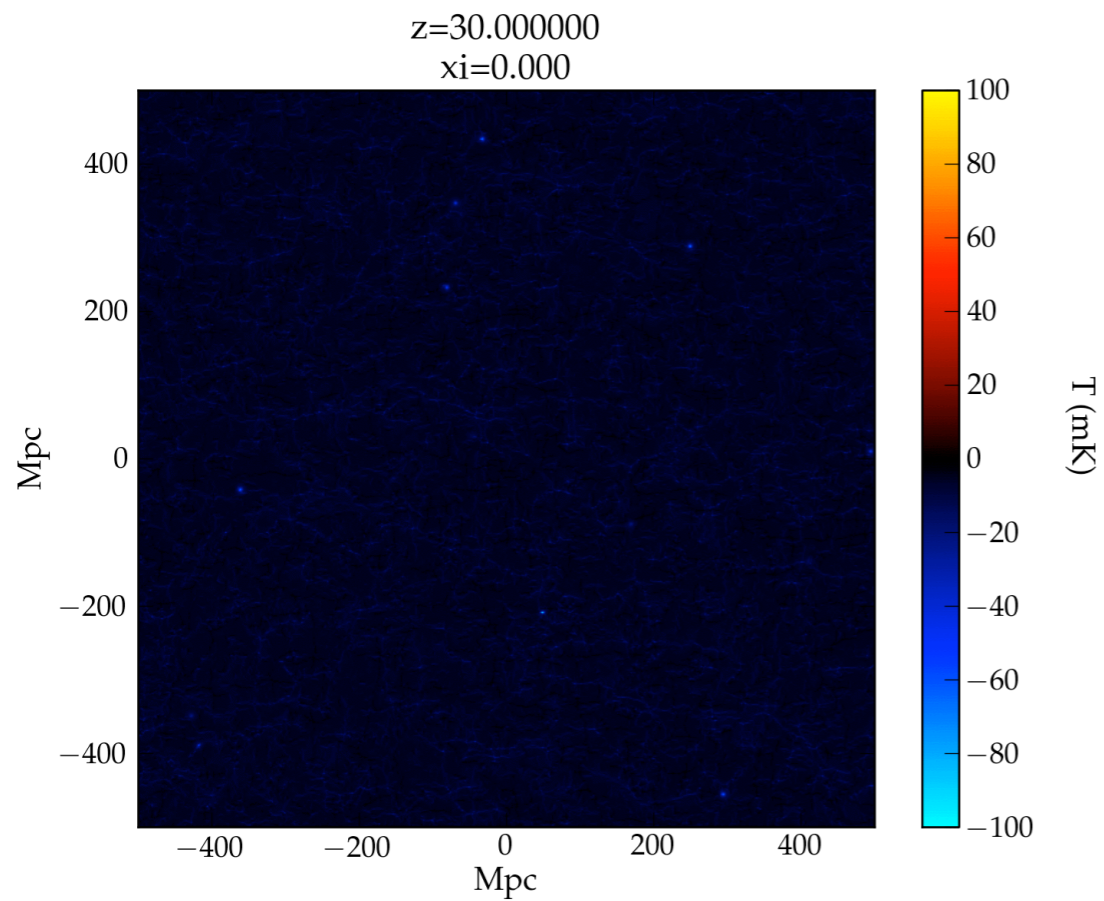


Credit:
Mário Santos (IST, Portugal)



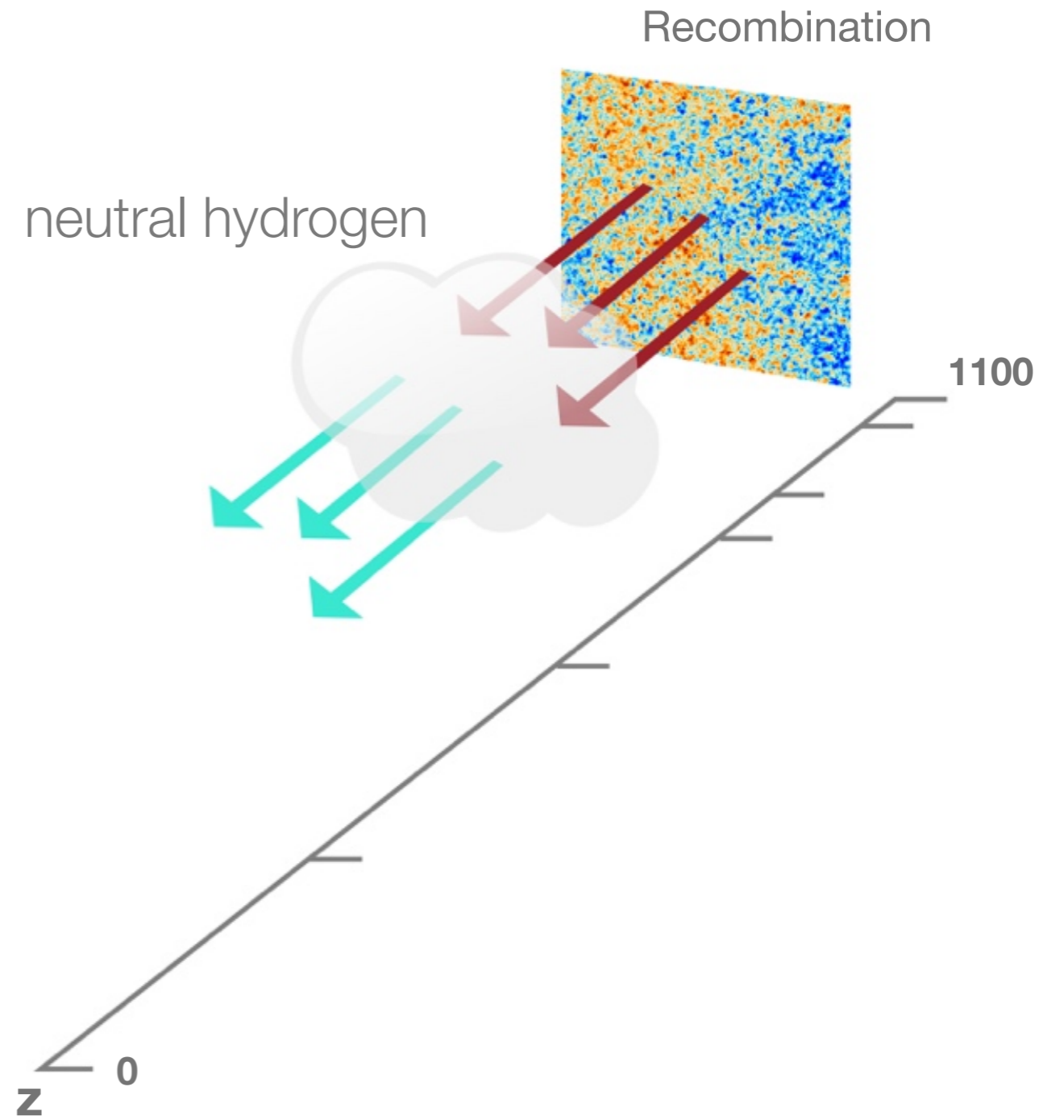
Where to Look Next?

What happens after recombination?

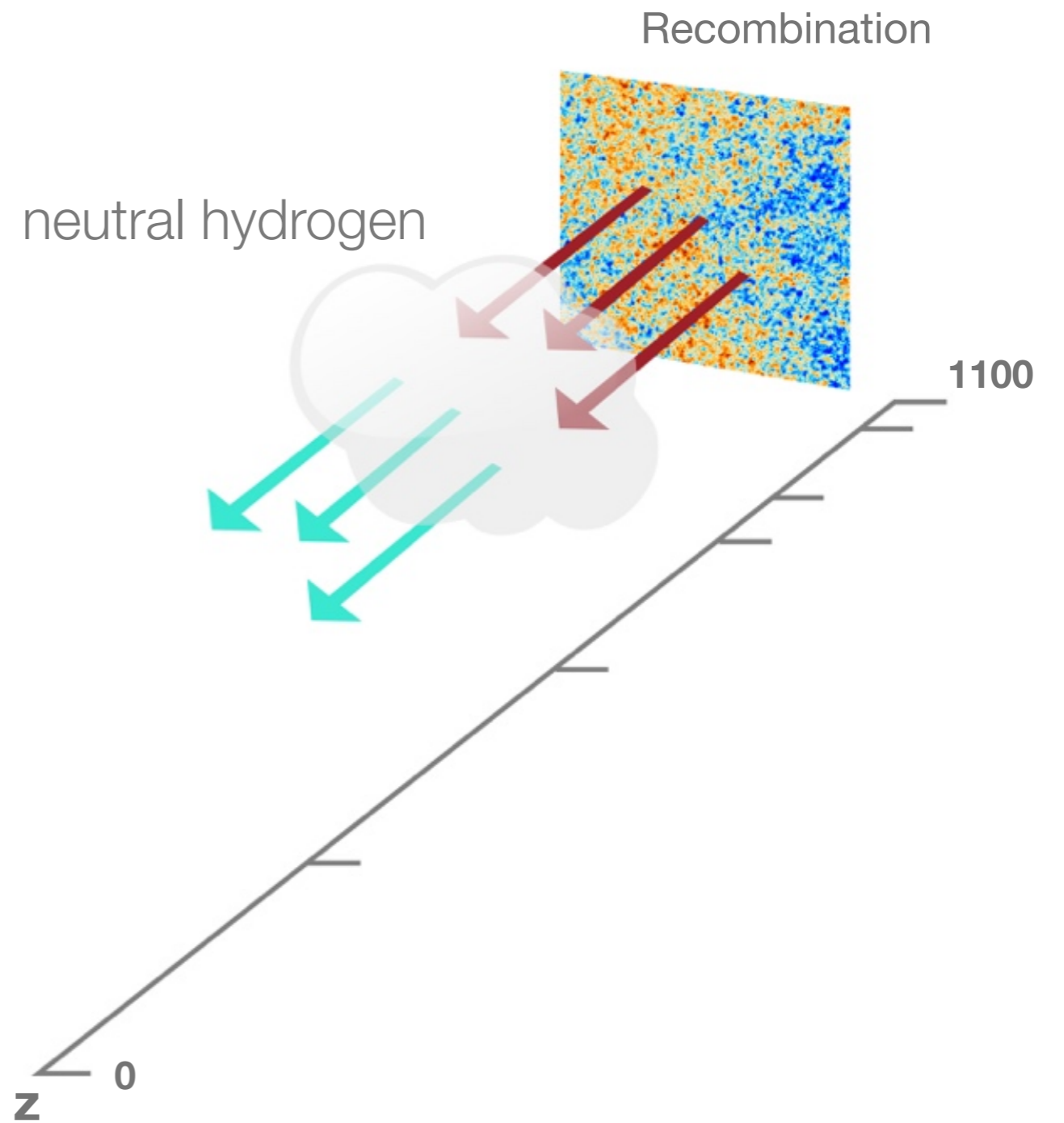
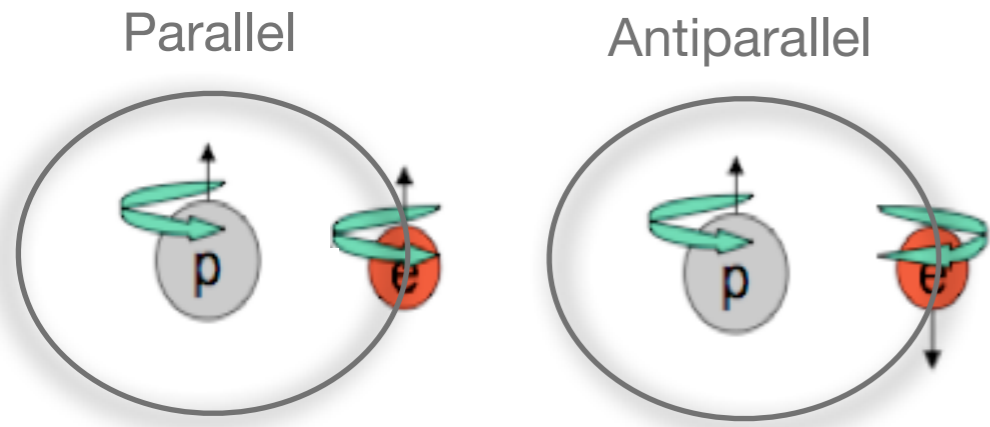


Credit:
Mário Santos (IST, Portugal)

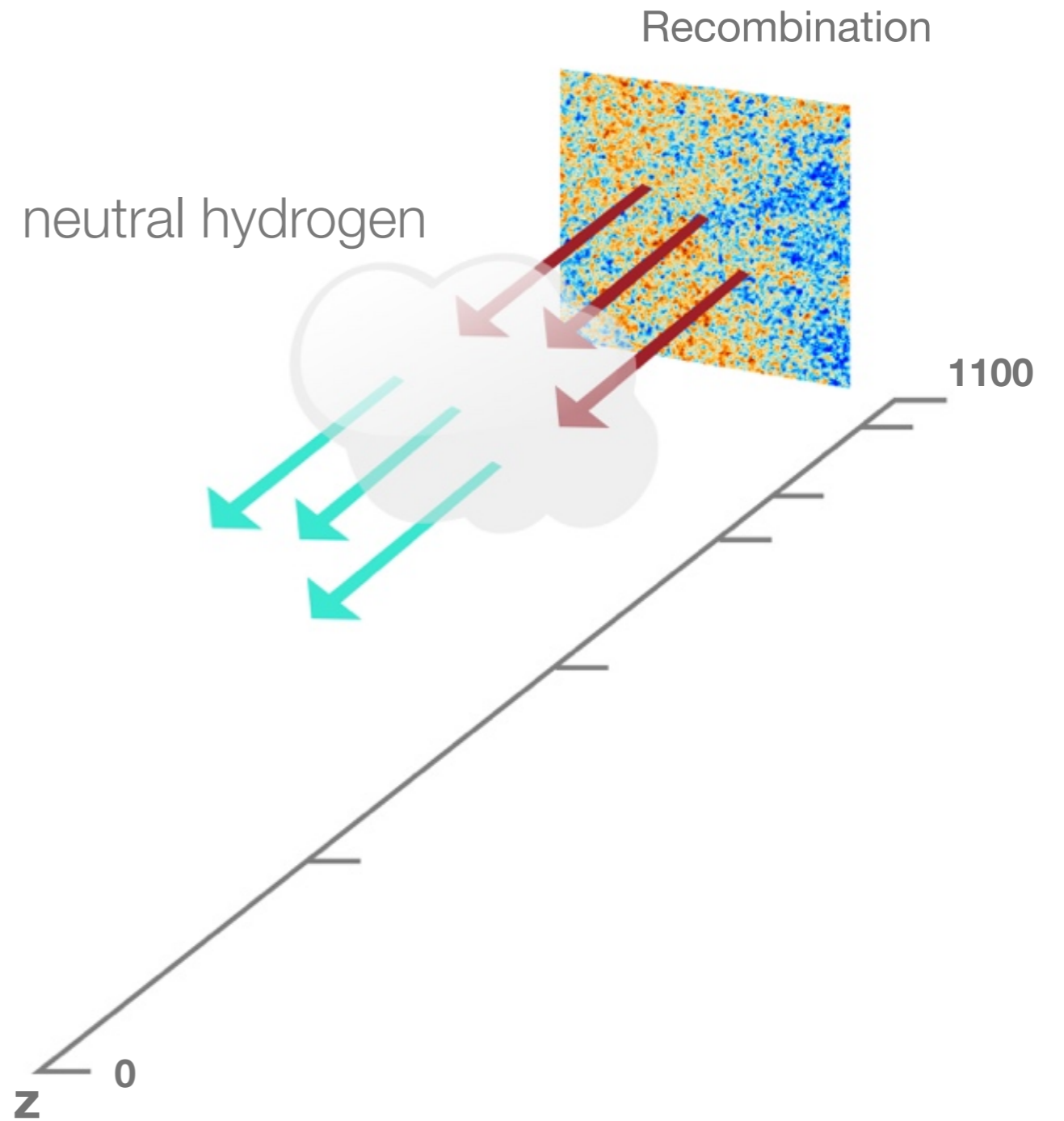
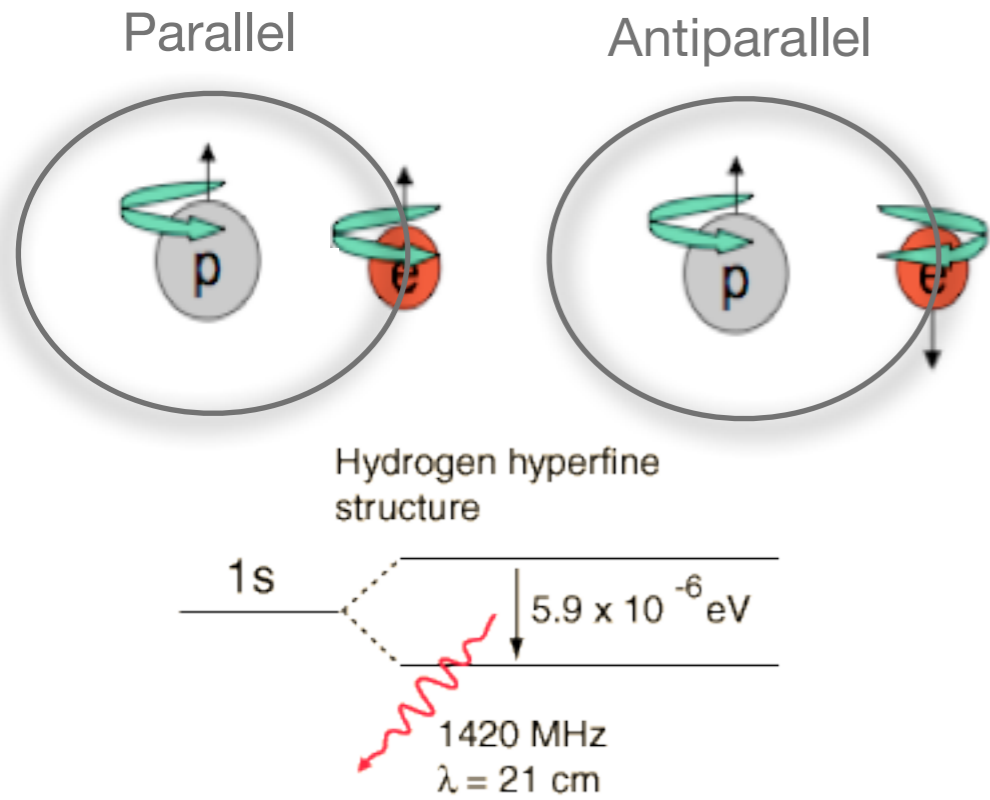
The 21-cm Signal: Lightning Review



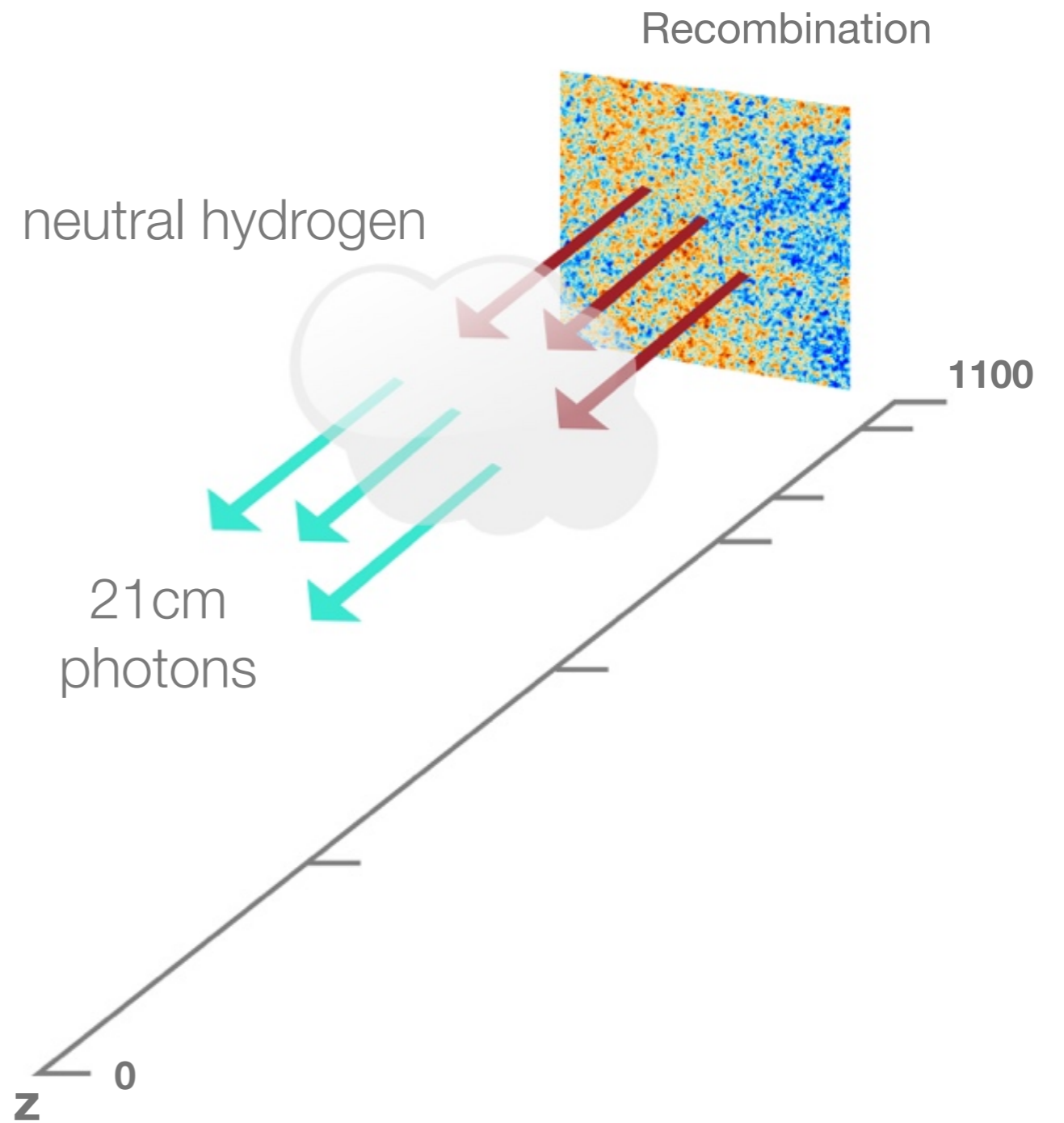
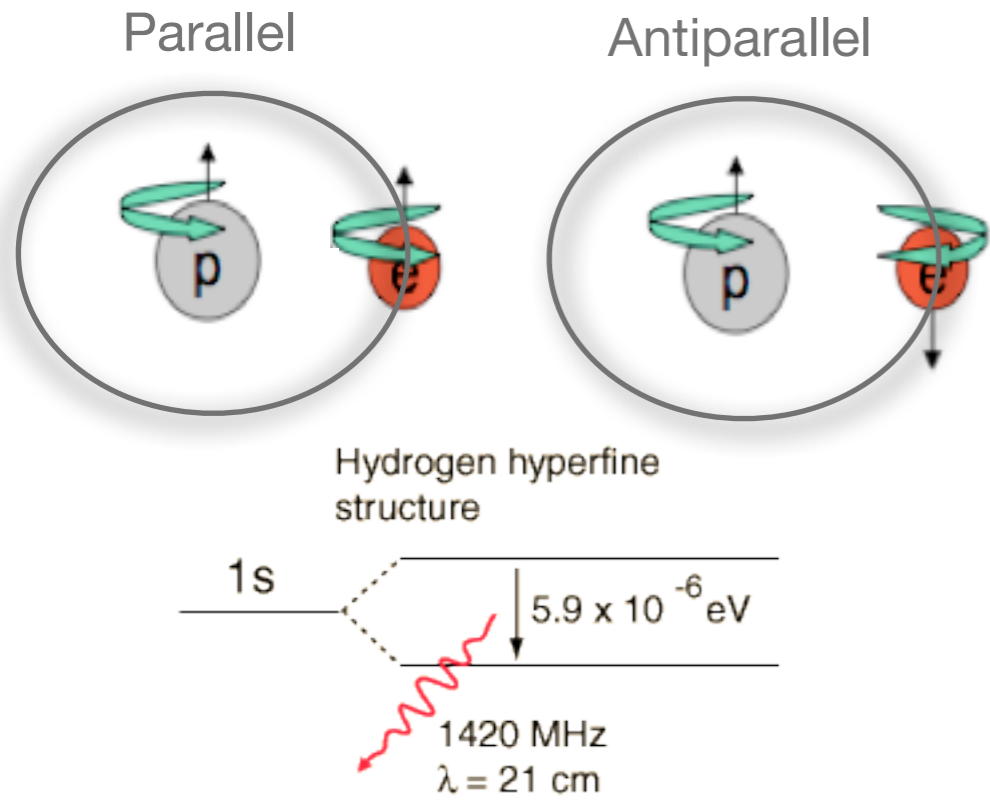
The 21-cm Signal: Lightning Review



The 21-cm Signal: Lightning Review

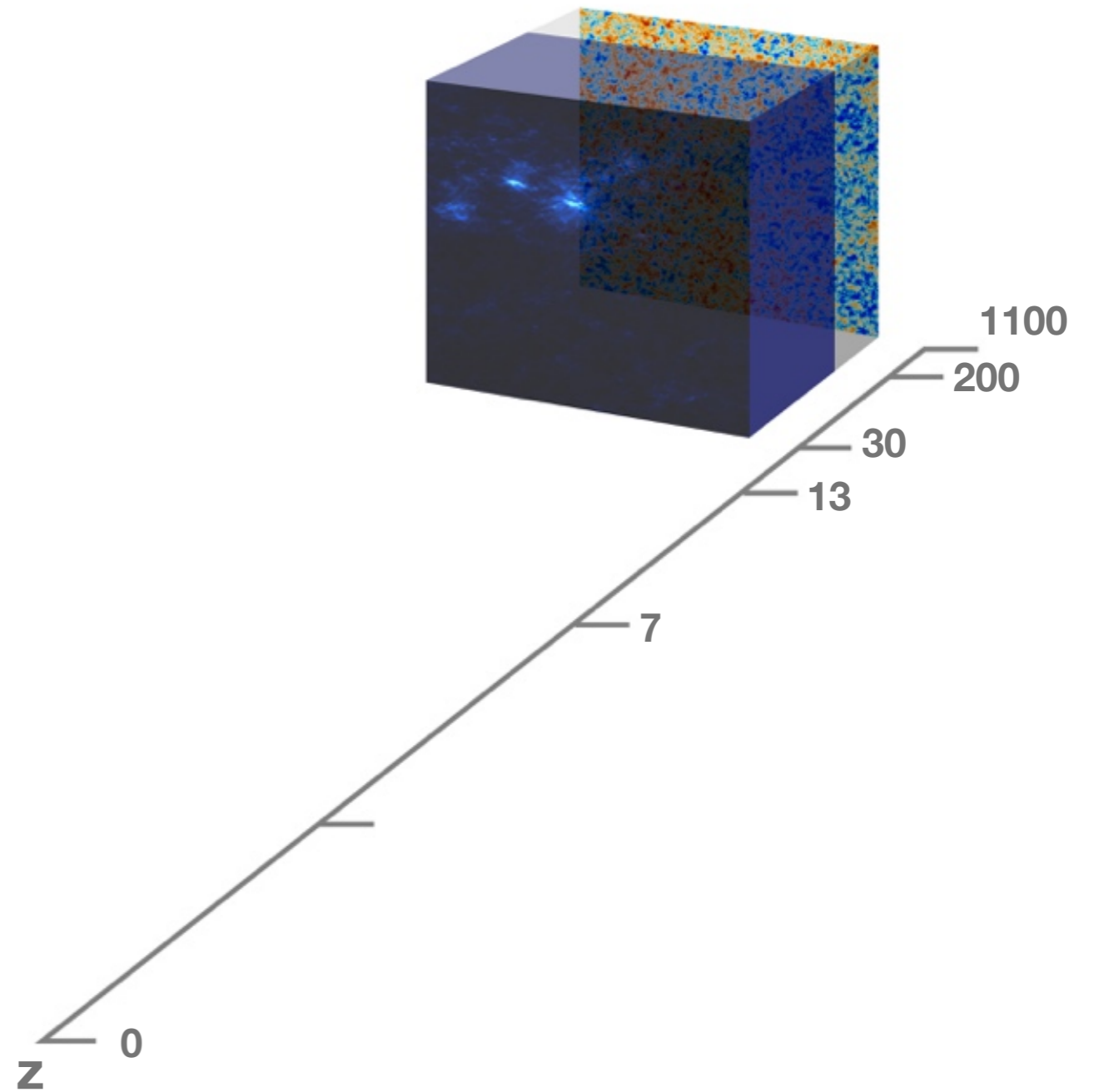


The 21-cm Signal: Lightning Review



The Dark Ages Information Trove

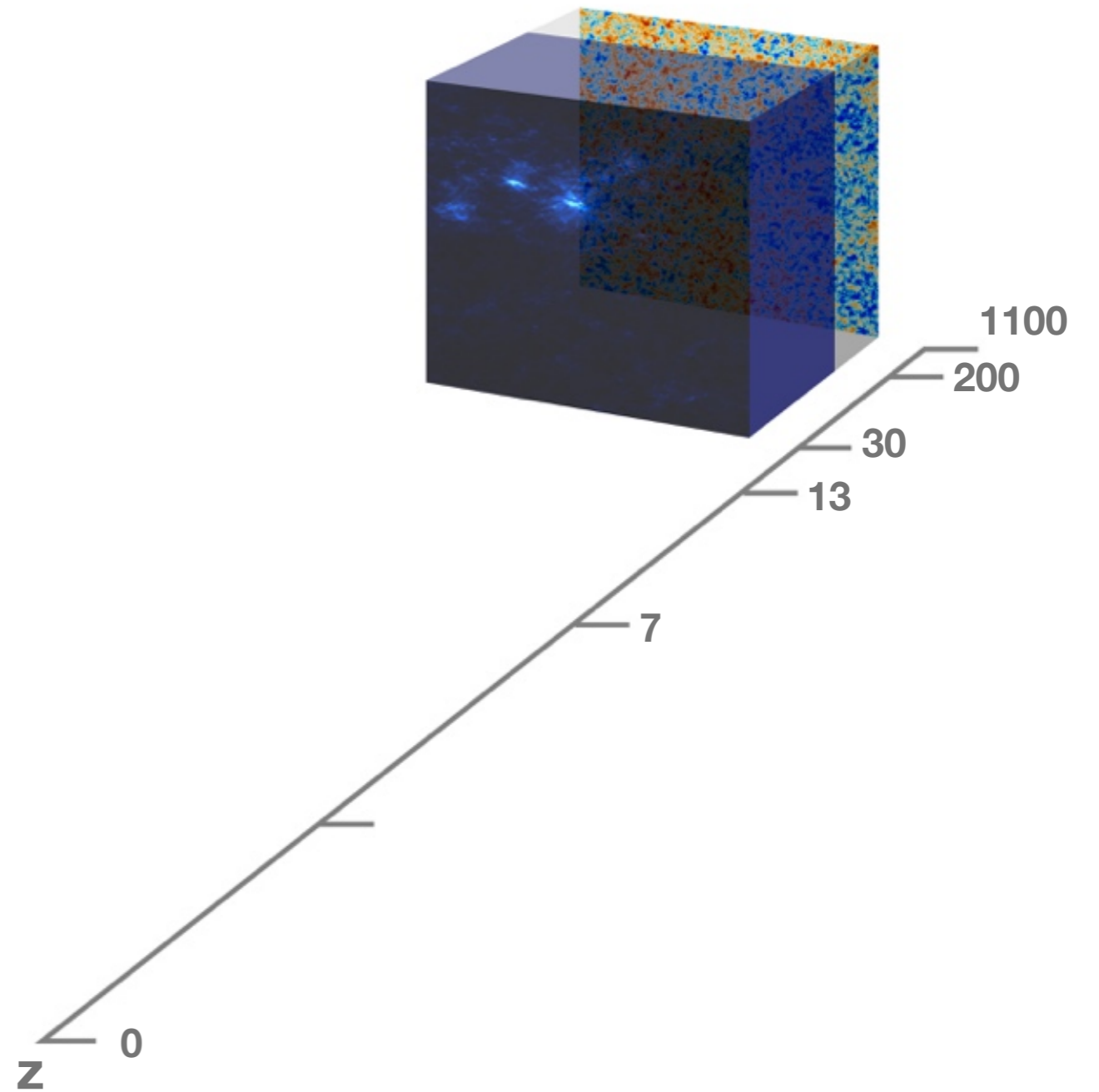
Dark ages:



The Dark Ages Information Trove

Dark ages:

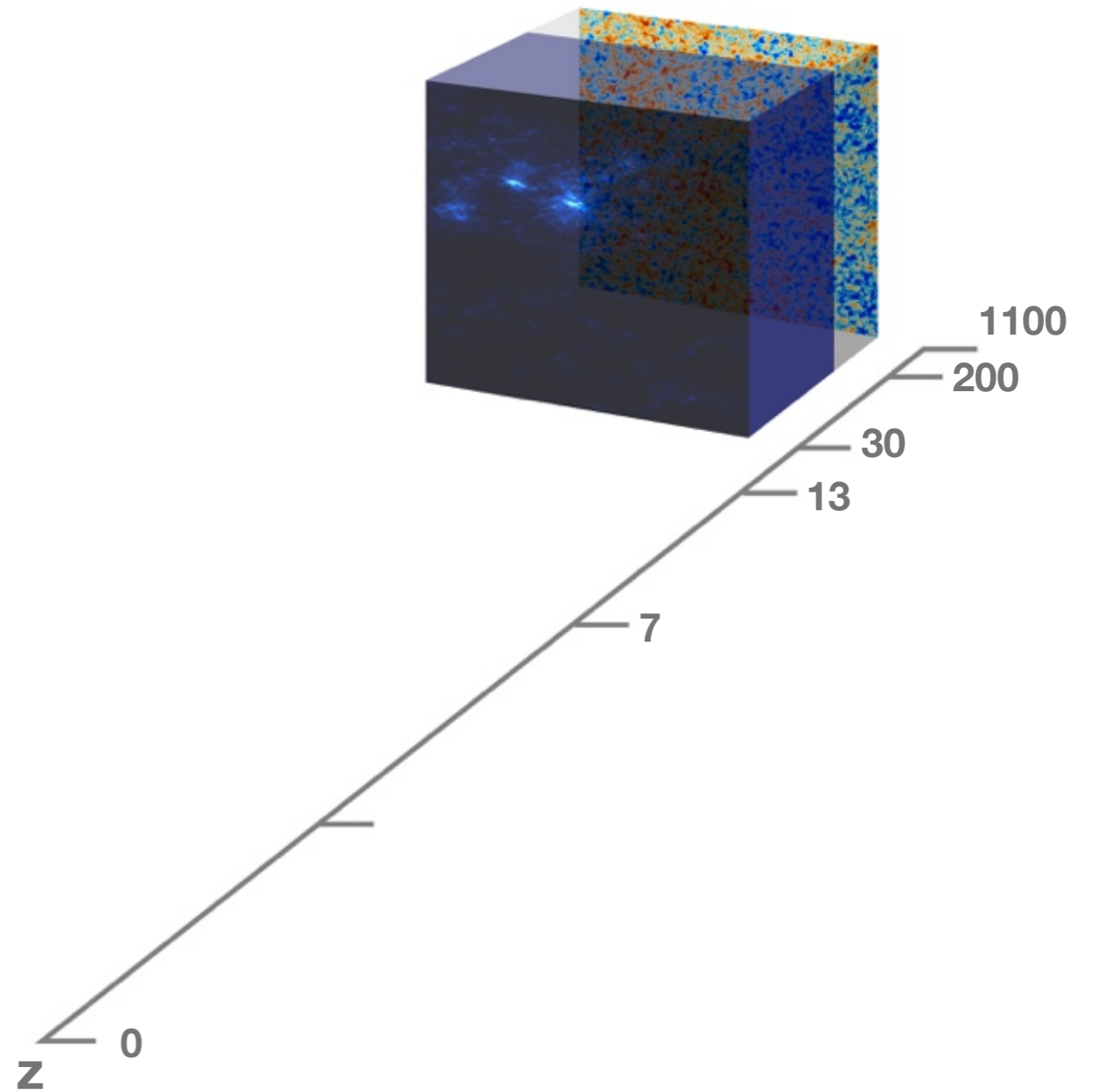
- clean of “astrophysics”



The Dark Ages Information Trove

Dark ages:

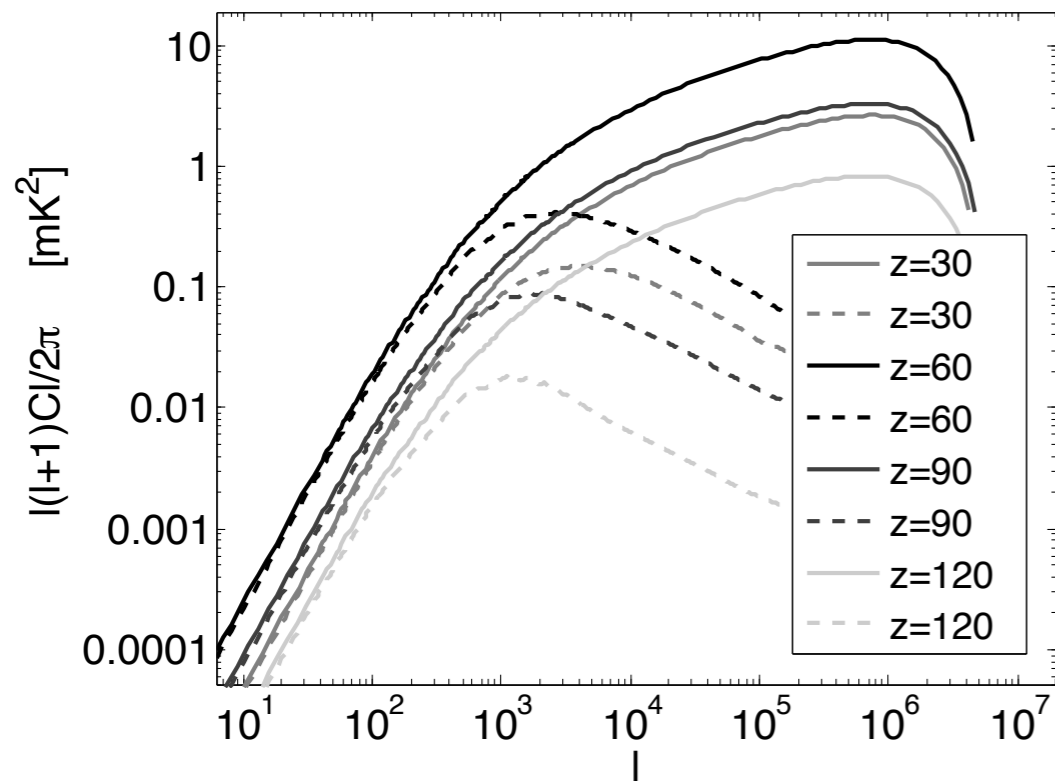
- clean of “astrophysics”
- accessible via 21cm line



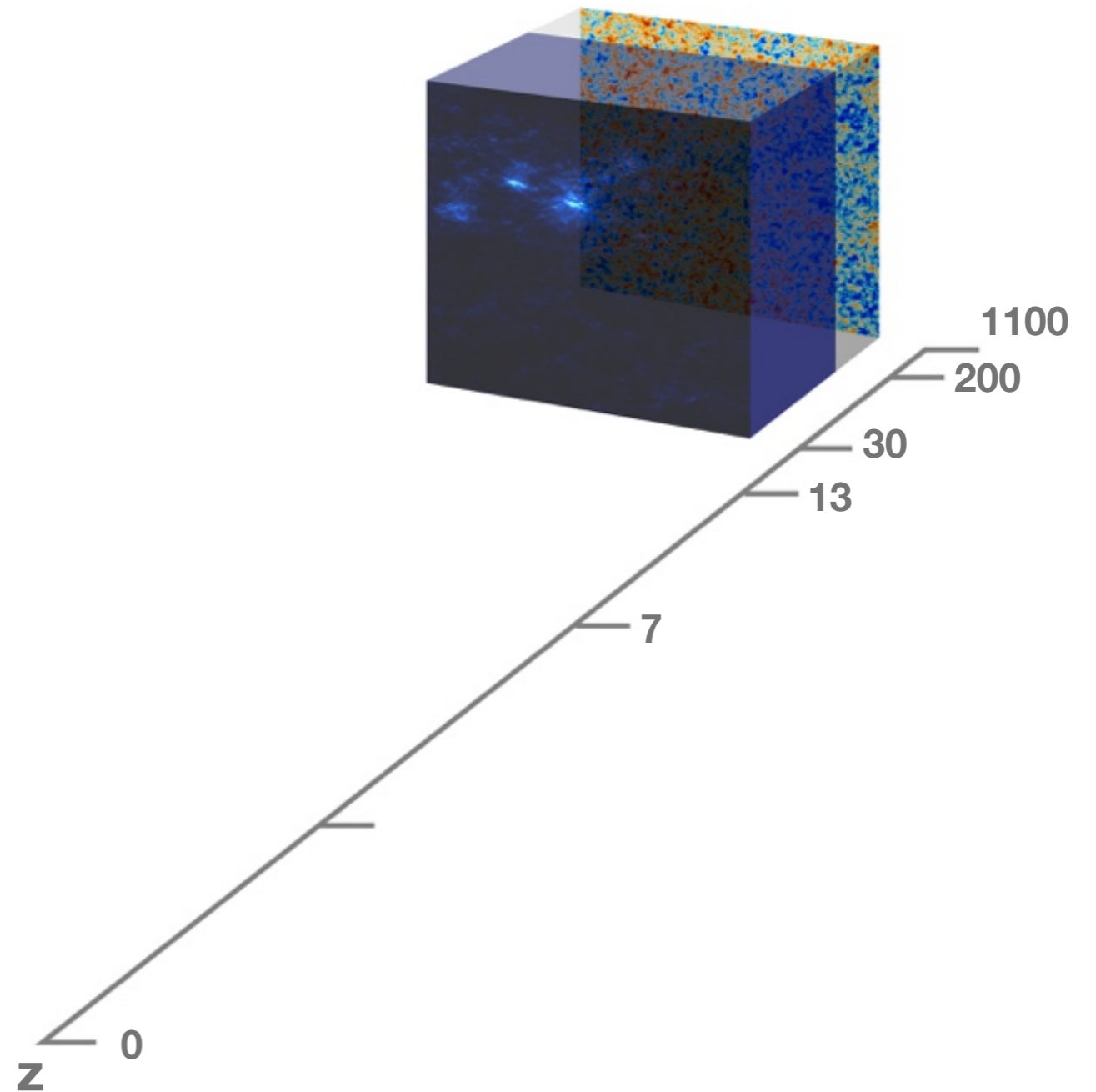
The Dark Ages Information Trove

Dark ages:

- clean of “astrophysics”
- accessible via 21cm line
- fluctuations extend down to: $l_{\max} \sim 10^6$



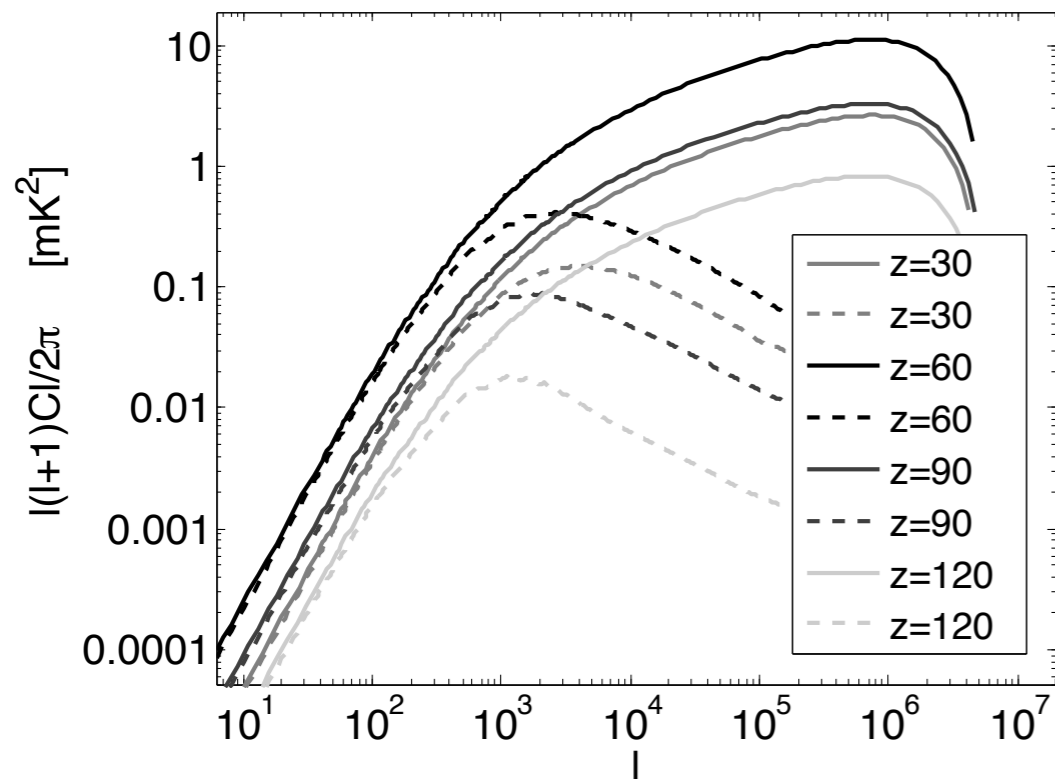
EDK and kamionkowski, Phys. Rev. D87 (2013)



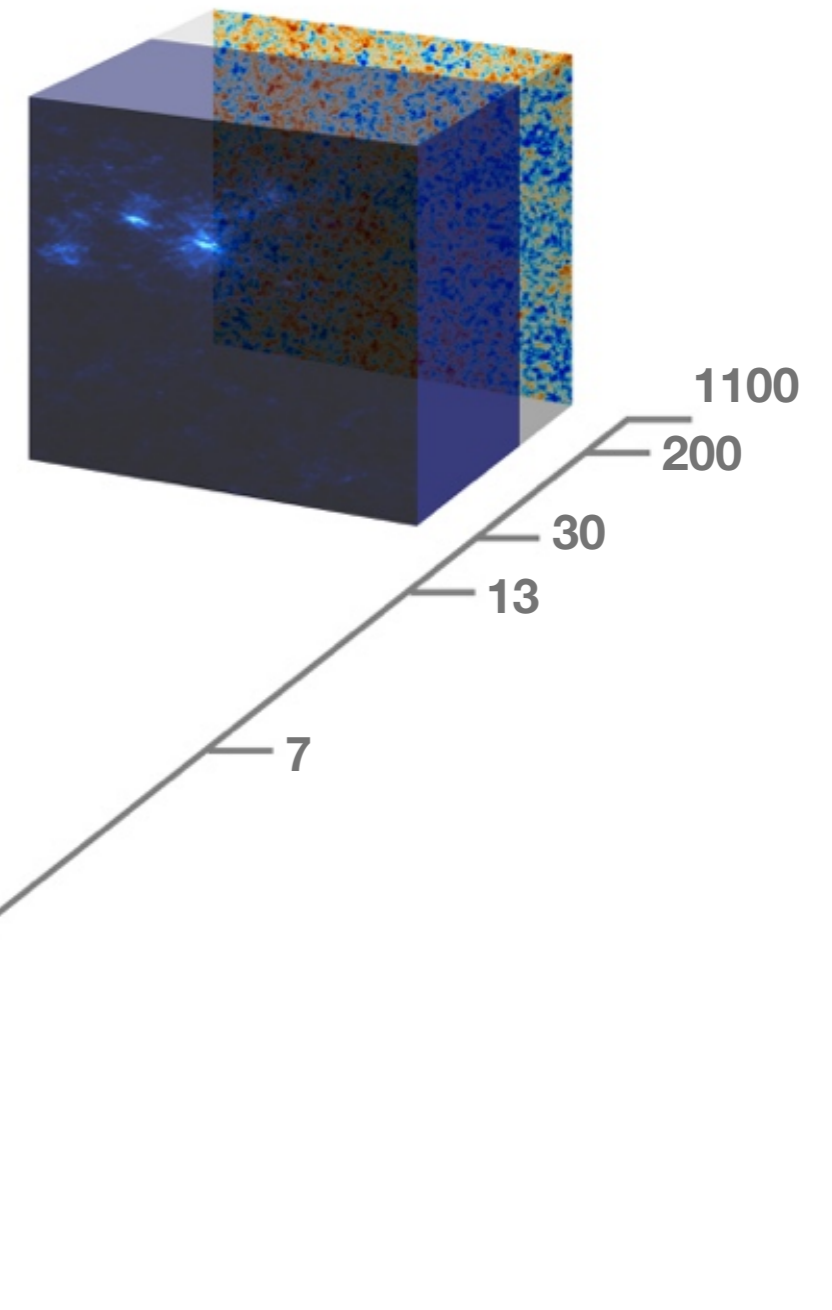
The Dark Ages Information Trove

Dark ages:

- clean of “astrophysics”
- accessible via 21cm line
- fluctuations extend down to: $l_{\max} \sim 10^6$
- many independent redshift slices: $N_z \sim 10^4$



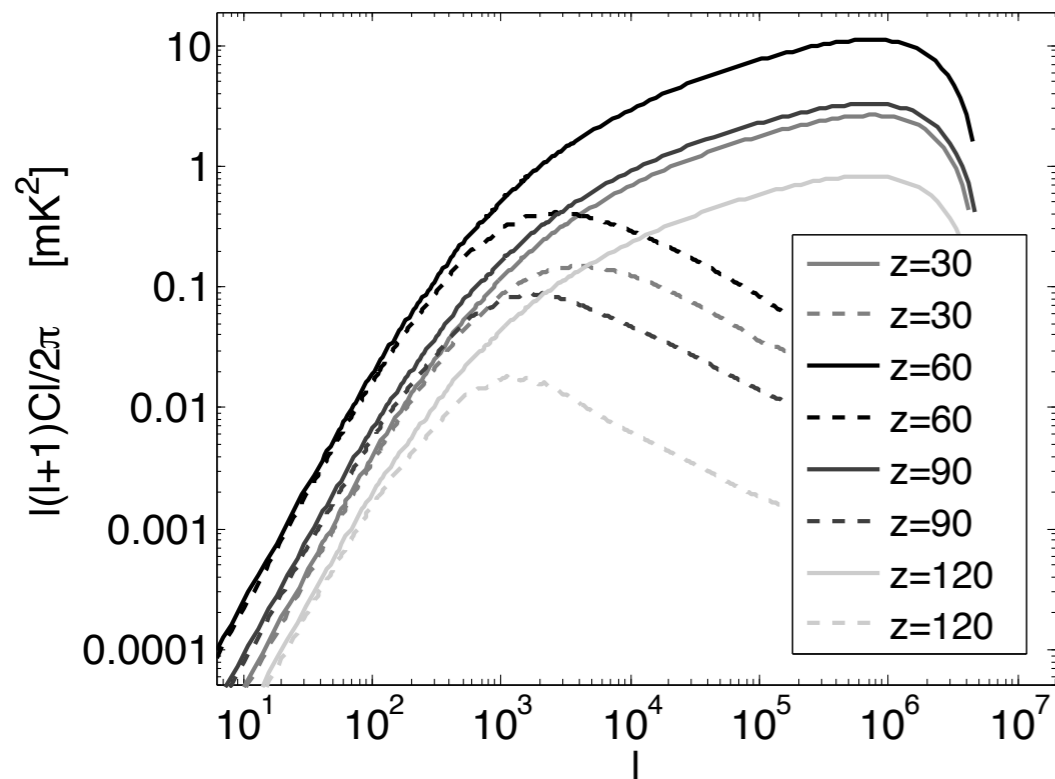
EDK and kamionkowski, Phys. Rev. D87 (2013)



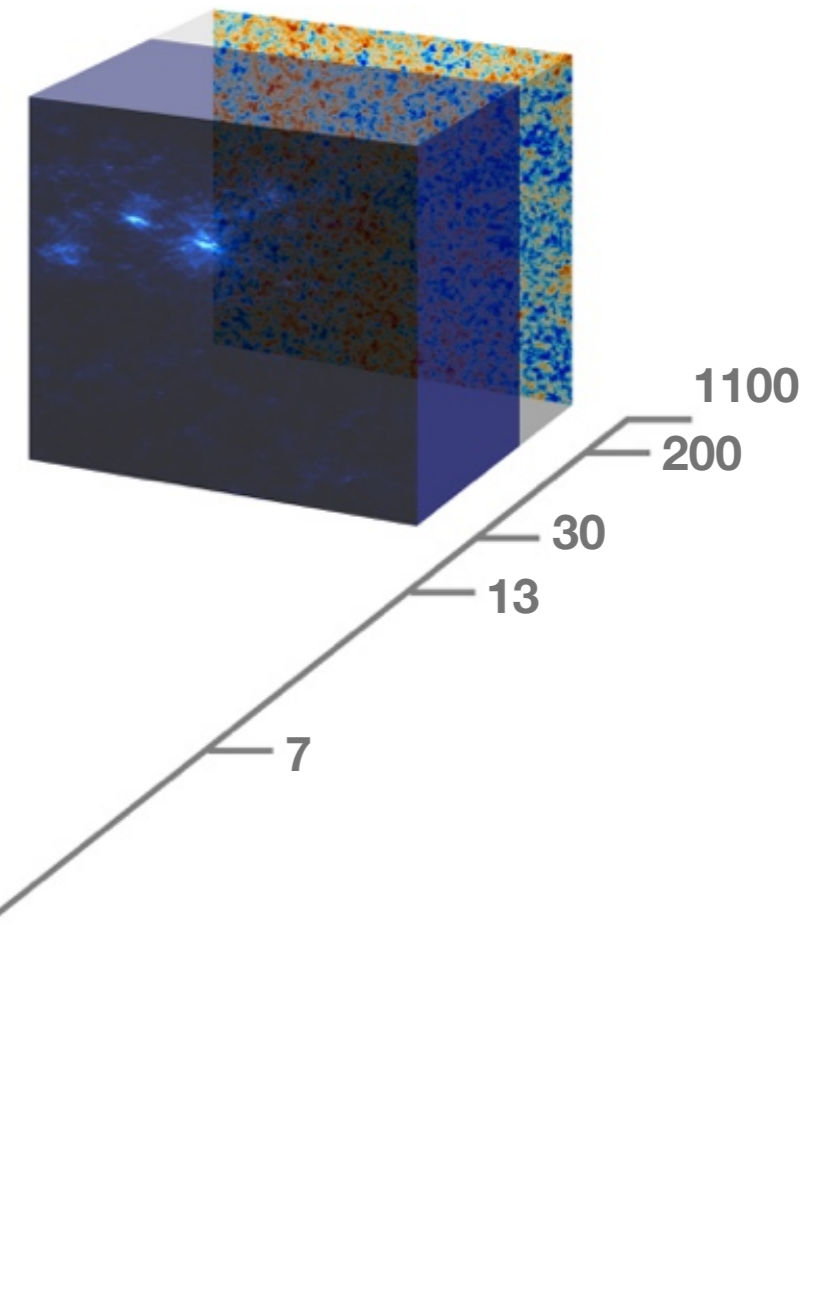
The Dark Ages Information Trove

Dark ages:

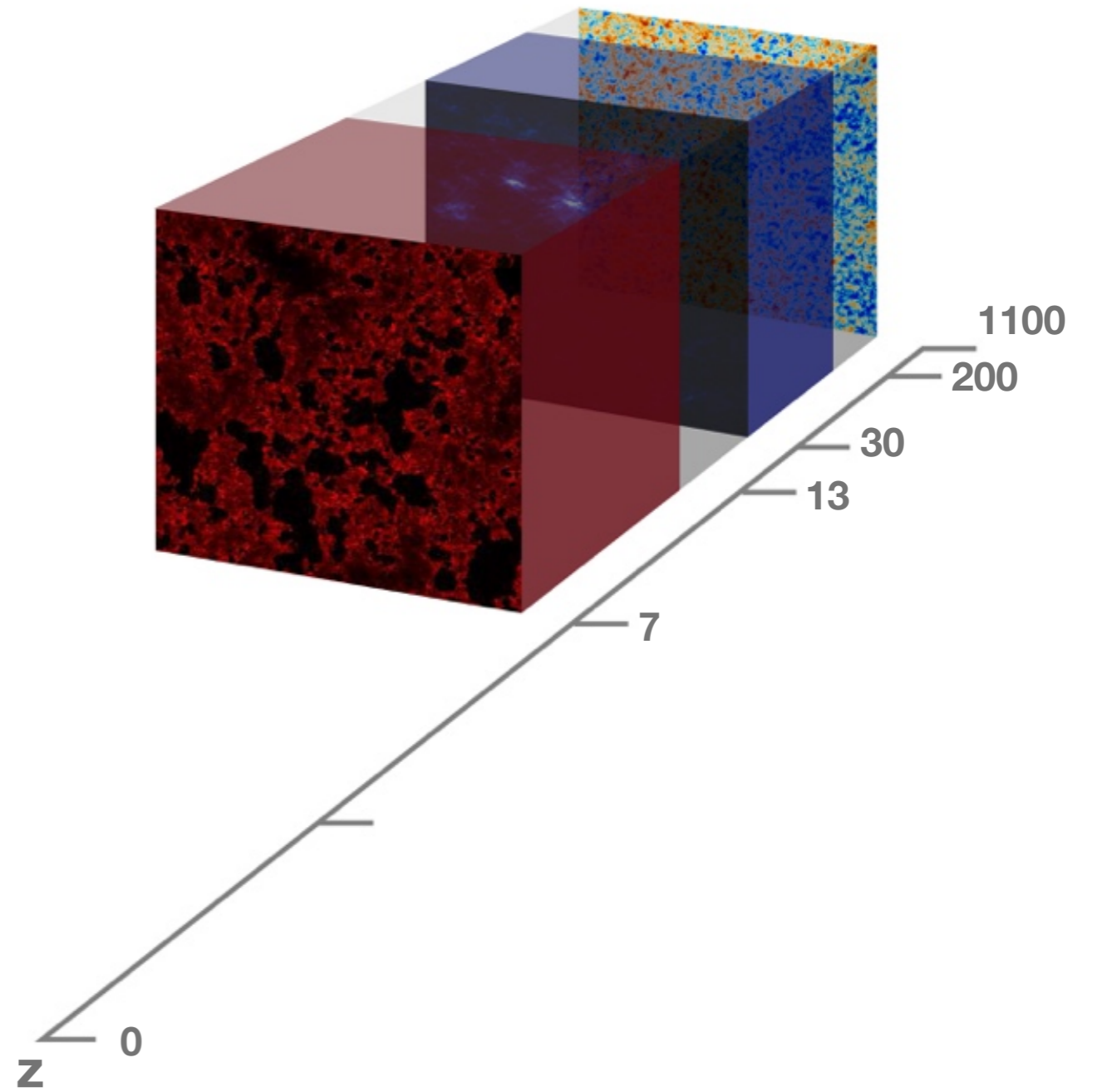
- clean of “astrophysics”
- accessible via 21cm line
- fluctuations extend down to: $l_{\max} \sim 10^6$
- many independent redshift slices: $N_z \sim 10^4$
→ in principle: $N_{\text{modes}}^{21\text{cm}} \sim 10^{16}$ (!!!)



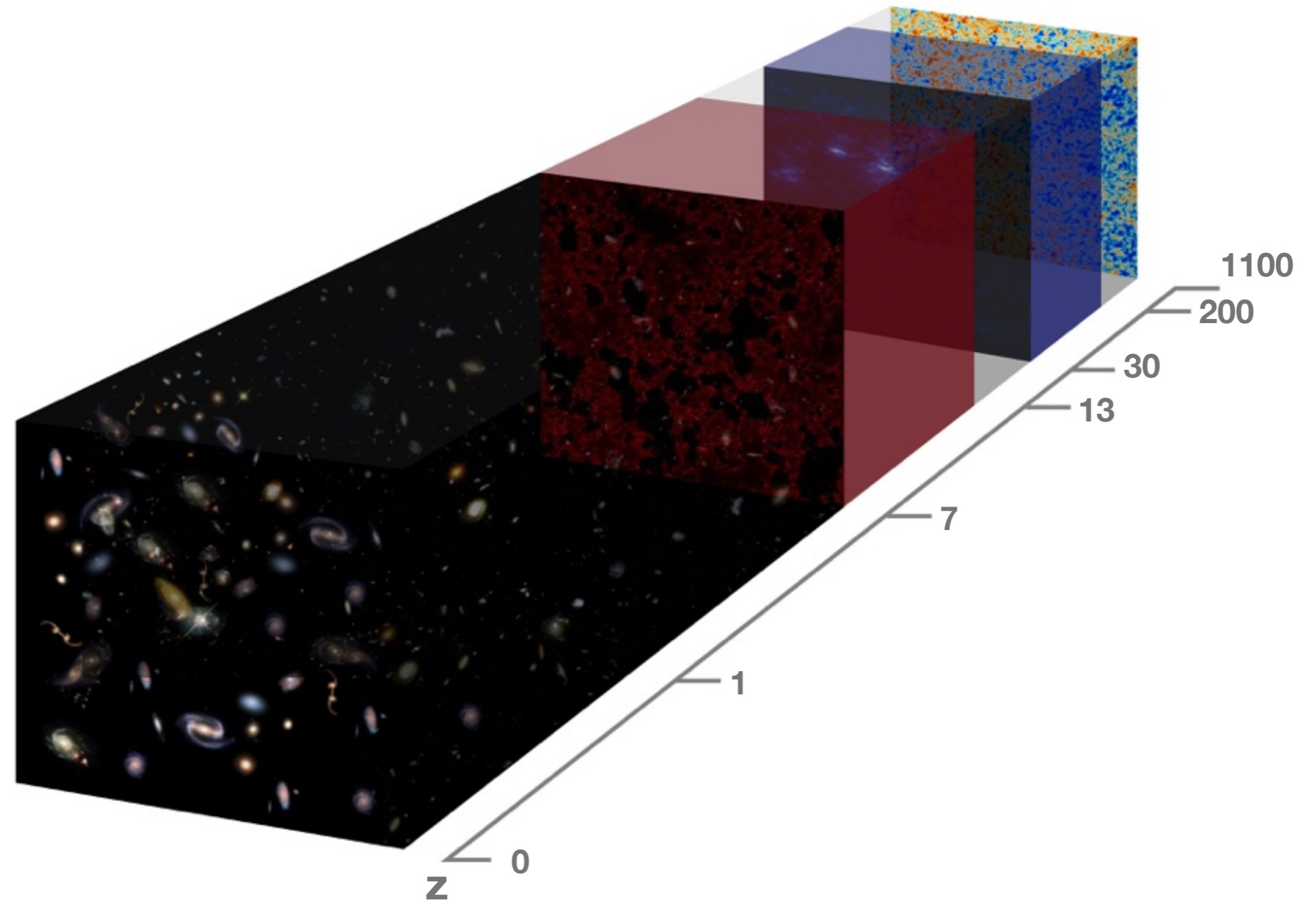
EDK and kamionkowski, Phys. Rev. D87 (2013)



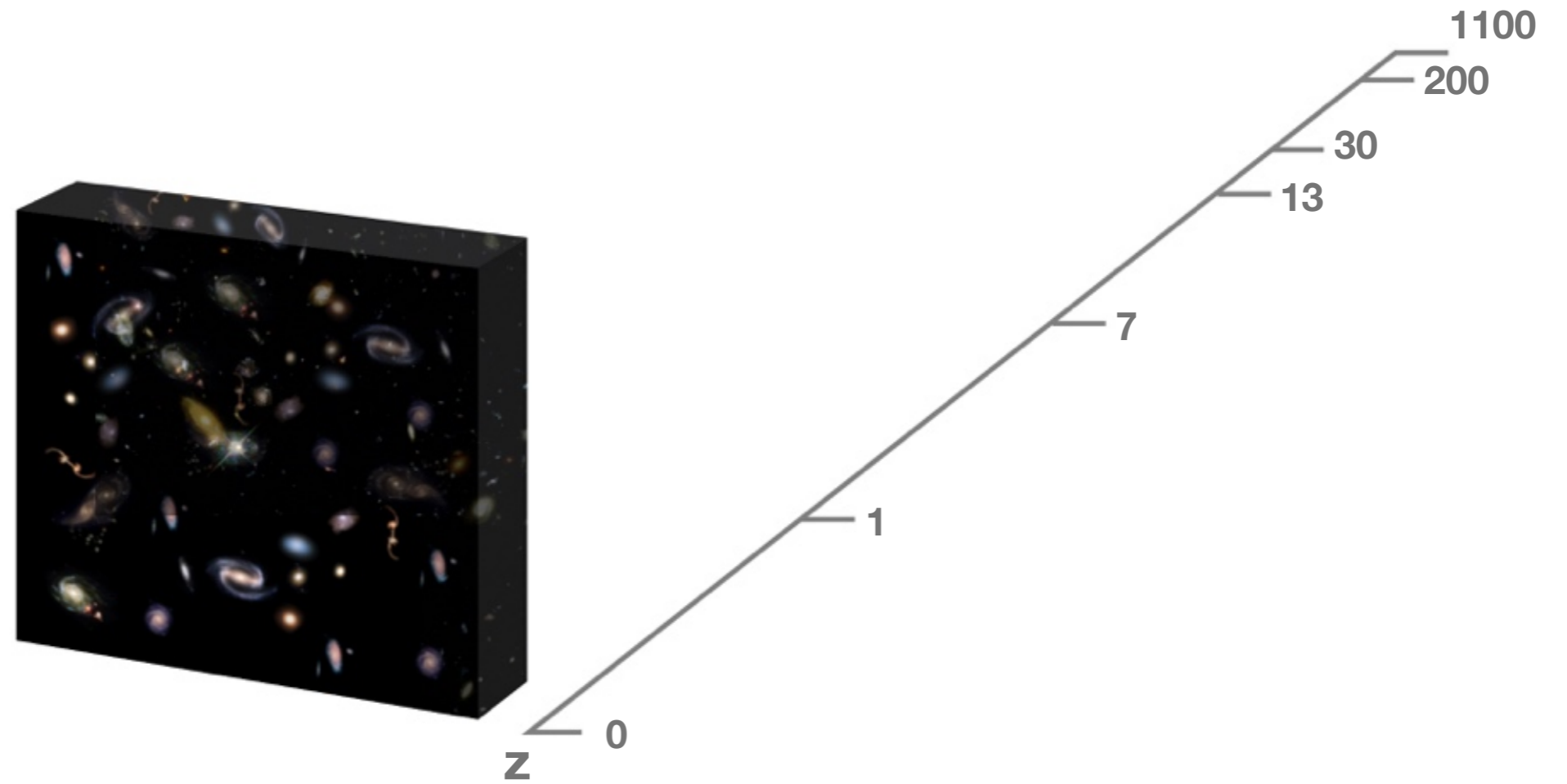
What About the Nearby Universe?



What About the Nearby Universe?

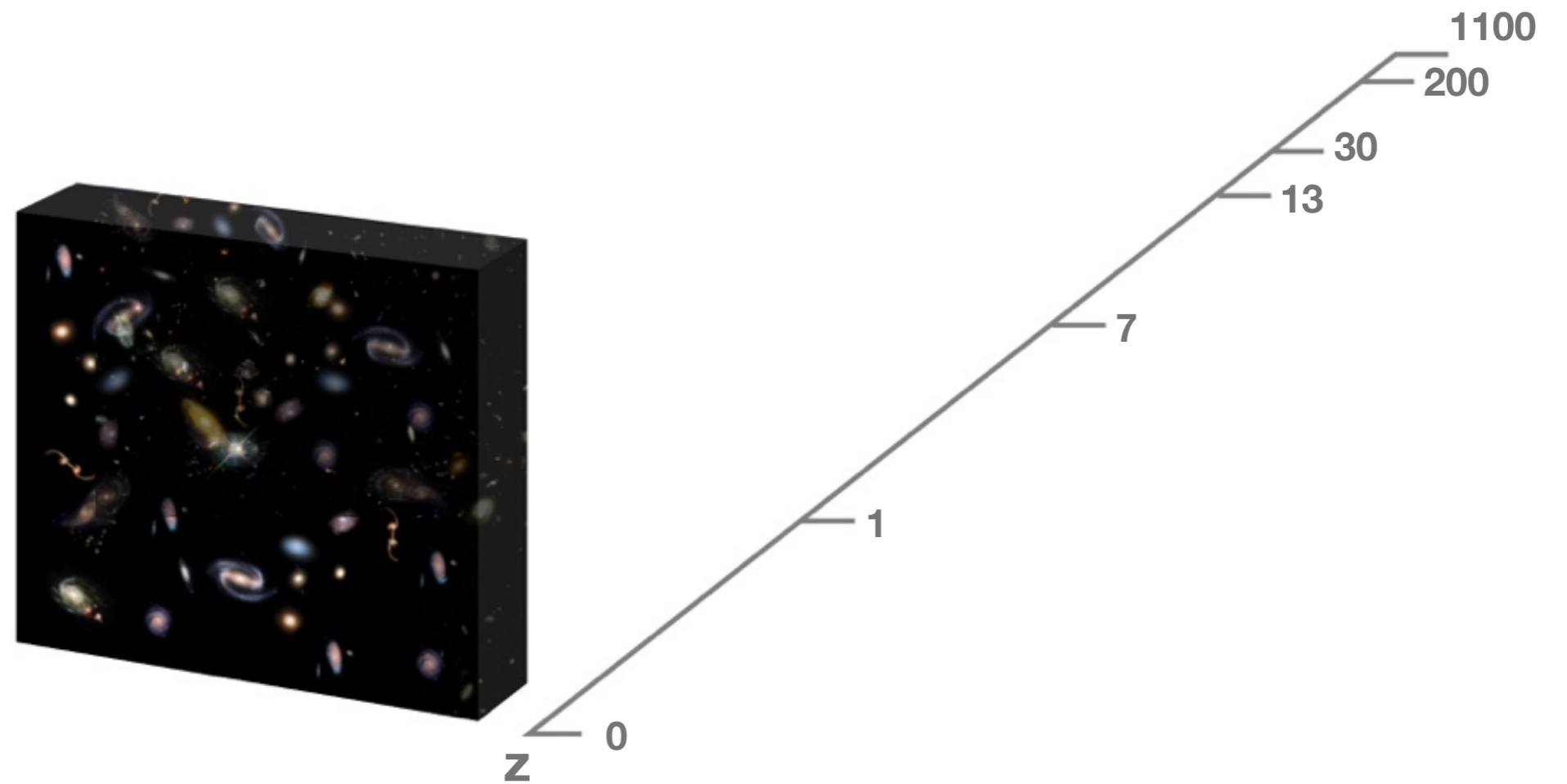


What About the Nearby Universe?



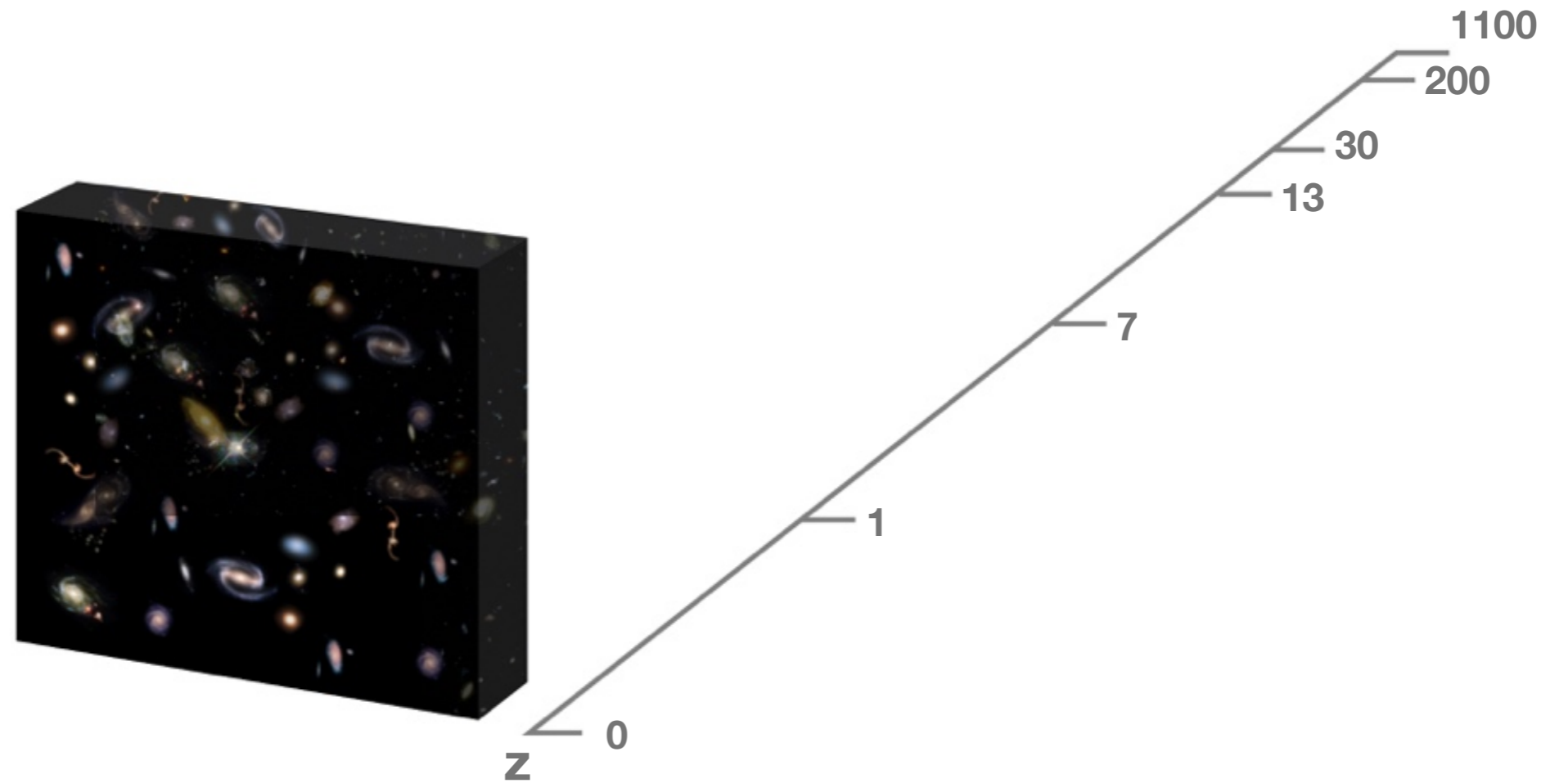
What About the Nearby Universe?

Not a lot of modes, 3D space limited



What About the Nearby Universe?

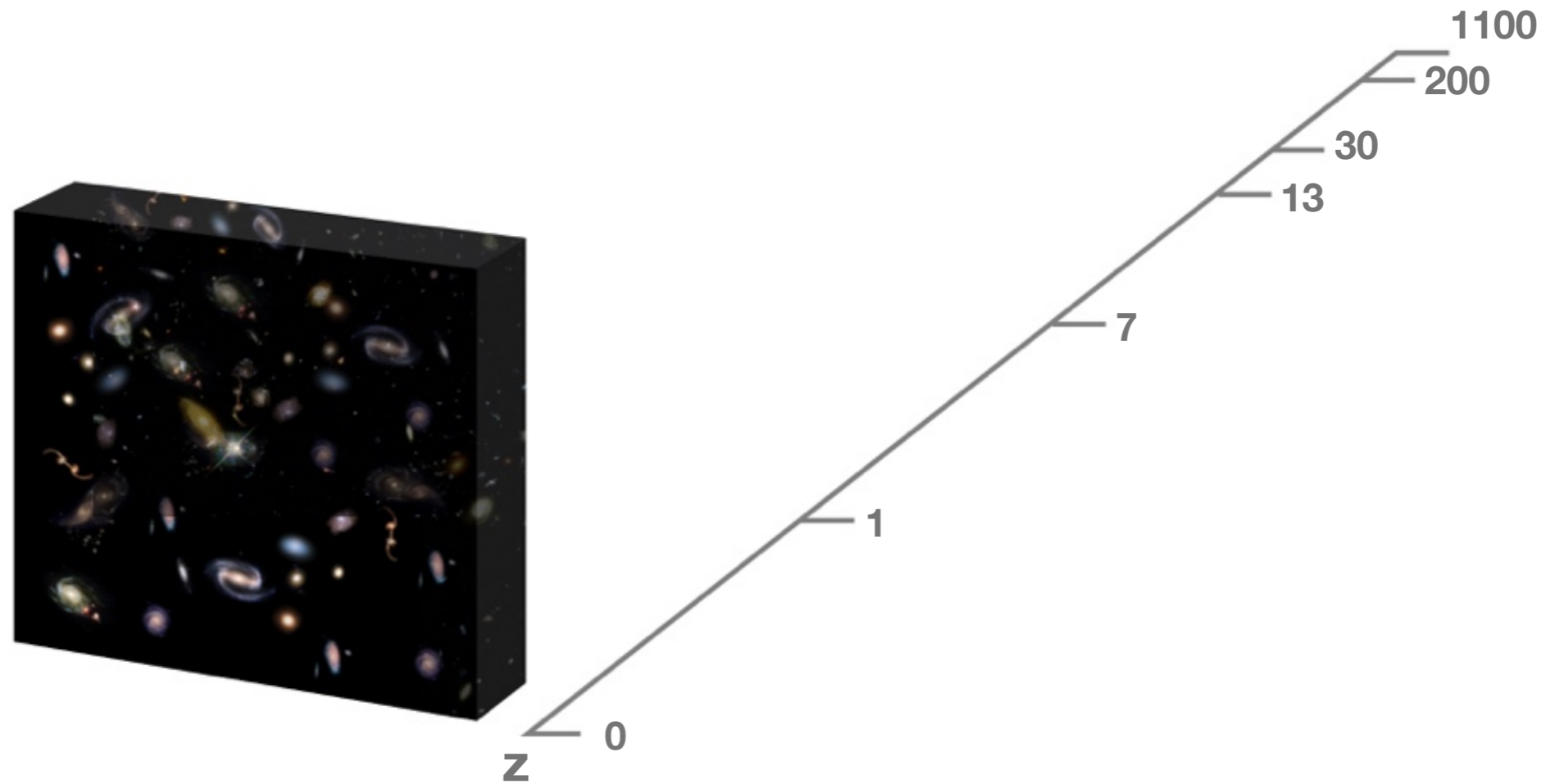
Not a lot of modes, 3D space limited \longrightarrow Transients?



What About the Nearby Universe?

Not a lot of modes, 3D space limited \longrightarrow Transients?

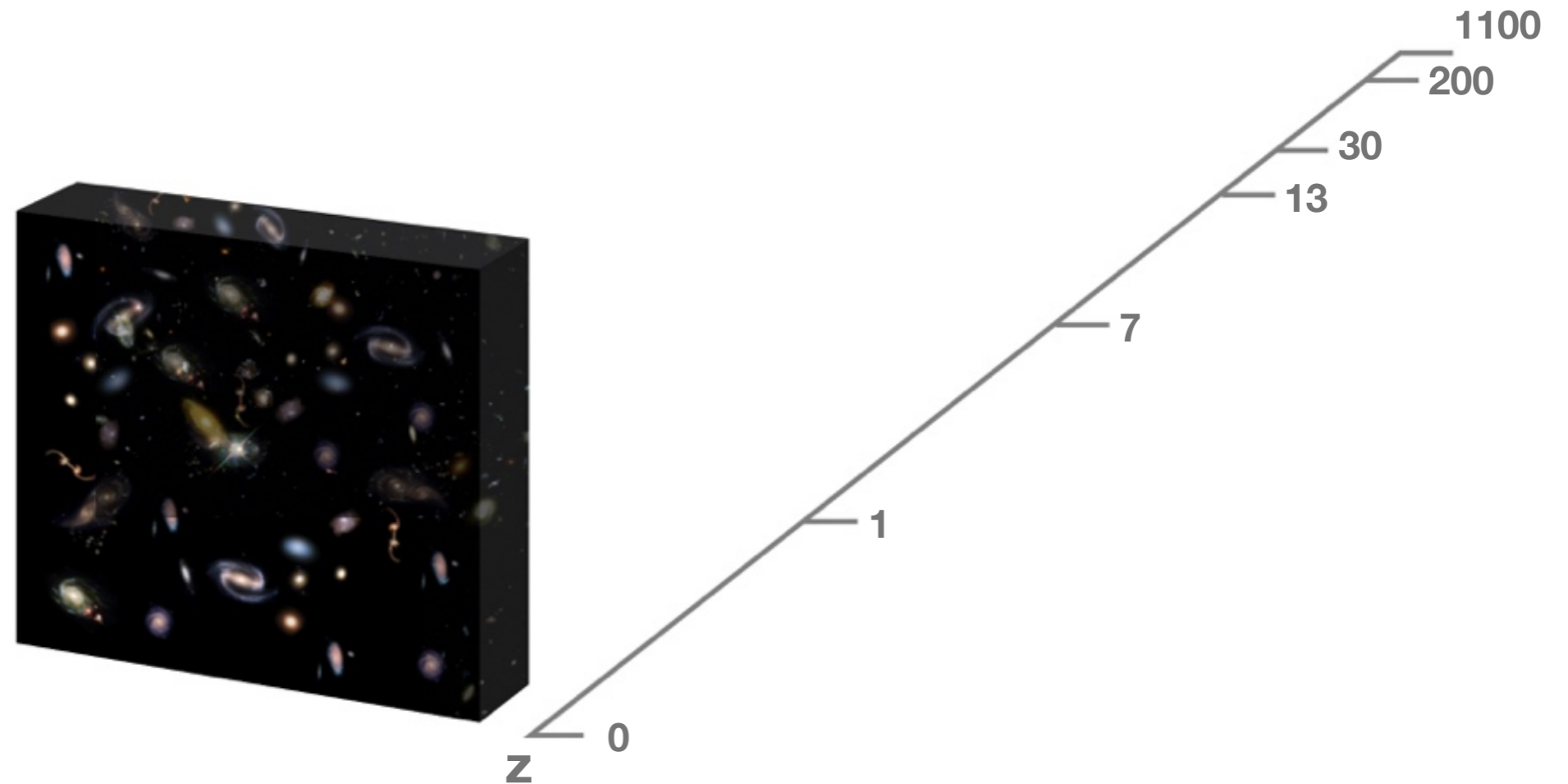
- Fermi identified >200 gamma-ray flares, $\sim 20\%$ unassociated with known sources.



What About the Nearby Universe?

Not a lot of modes, 3D space limited \longrightarrow Transients?

- Fermi identified >200 gamma-ray flares, $\sim 20\%$ unassociated with known sources.
- LIGO detected burst(s) of gravitational waves from coalescing black holes.

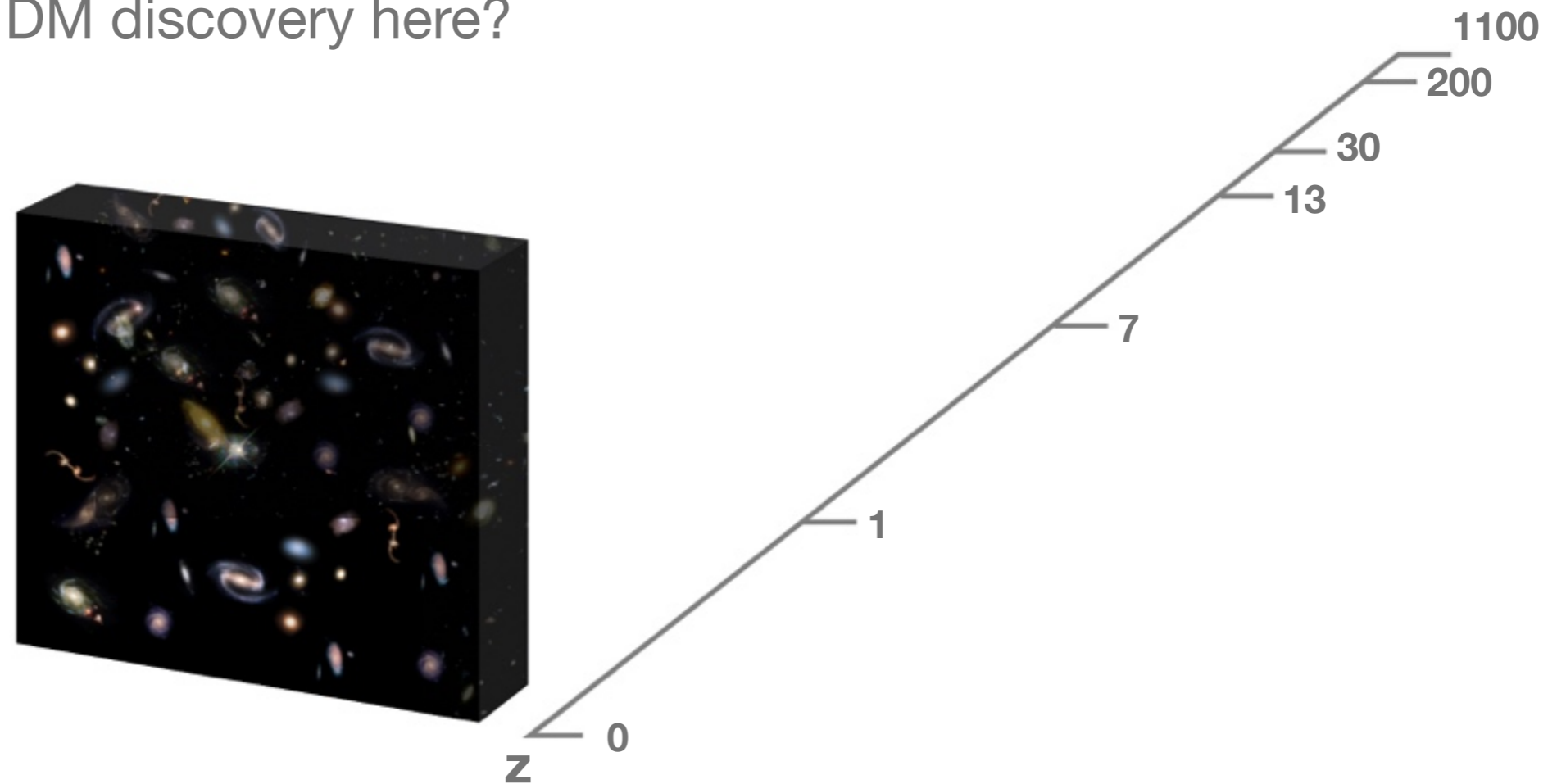


What About the Nearby Universe?

Not a lot of modes, 3D space limited \longrightarrow Transients?

- Fermi identified >200 gamma-ray flares, $\sim 20\%$ unassociated with known sources.
- LIGO detected burst(s) of gravitational waves from coalescing black holes.

Is there potential for a DM discovery here?



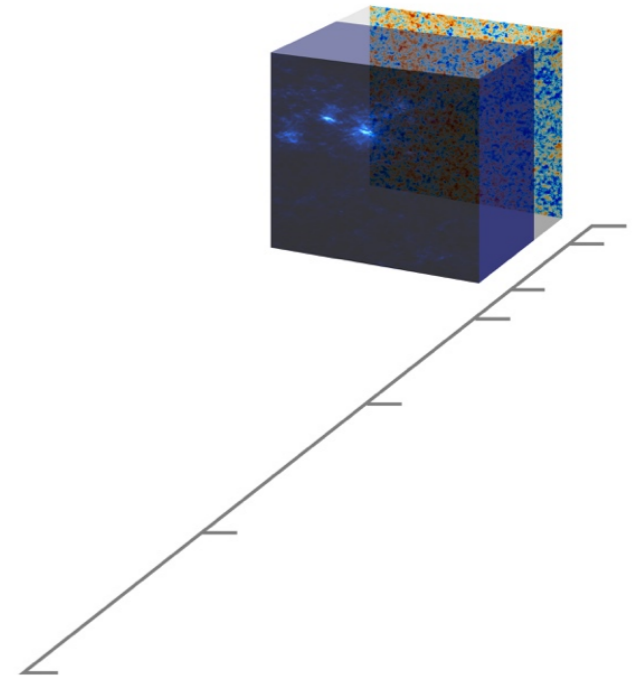
Outline

Ely D. Kovetz
Harvard, Mar. 2016

Outline

Ely D. Kovetz
Harvard, Mar. 2016

- Heat signatures of DM in the dark ages

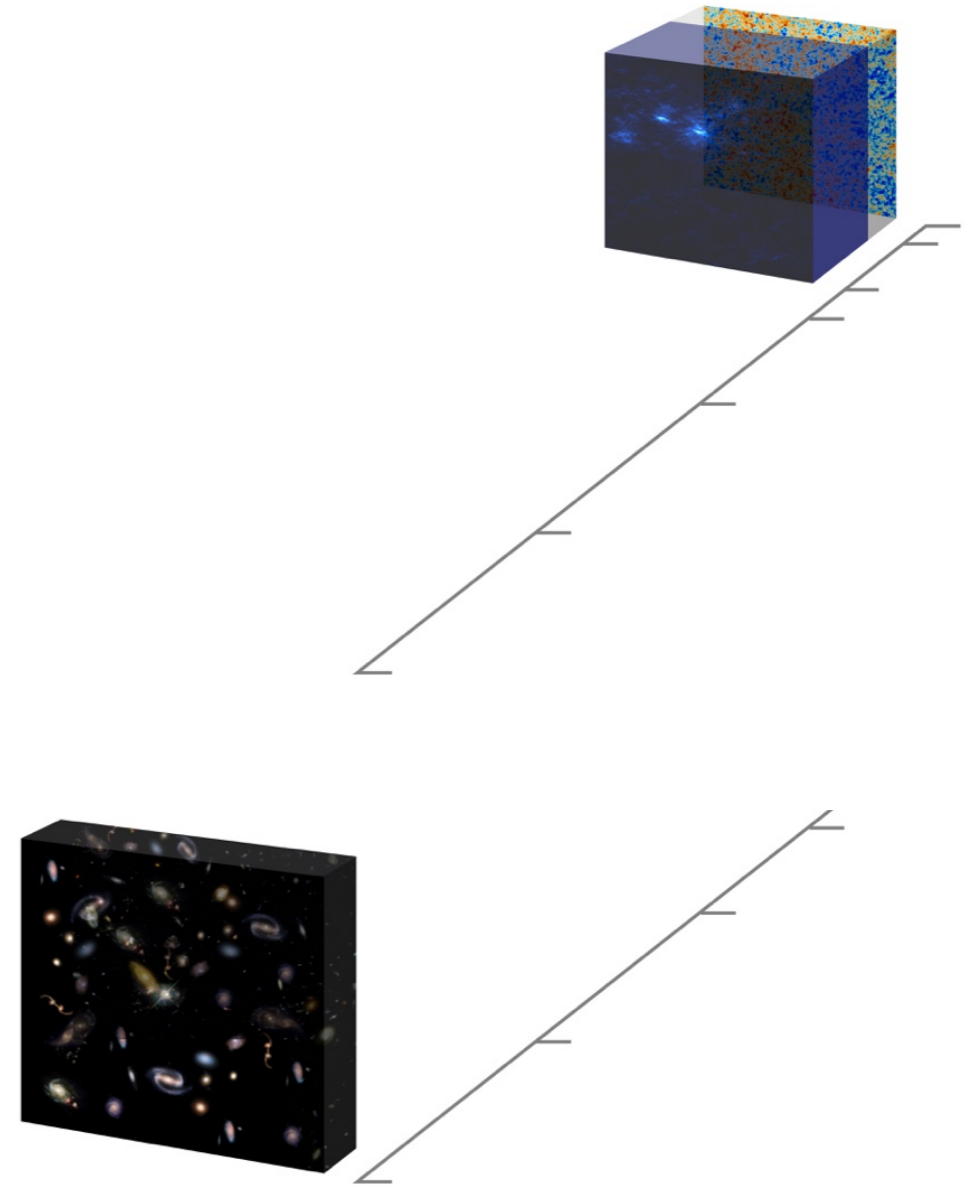


Outline

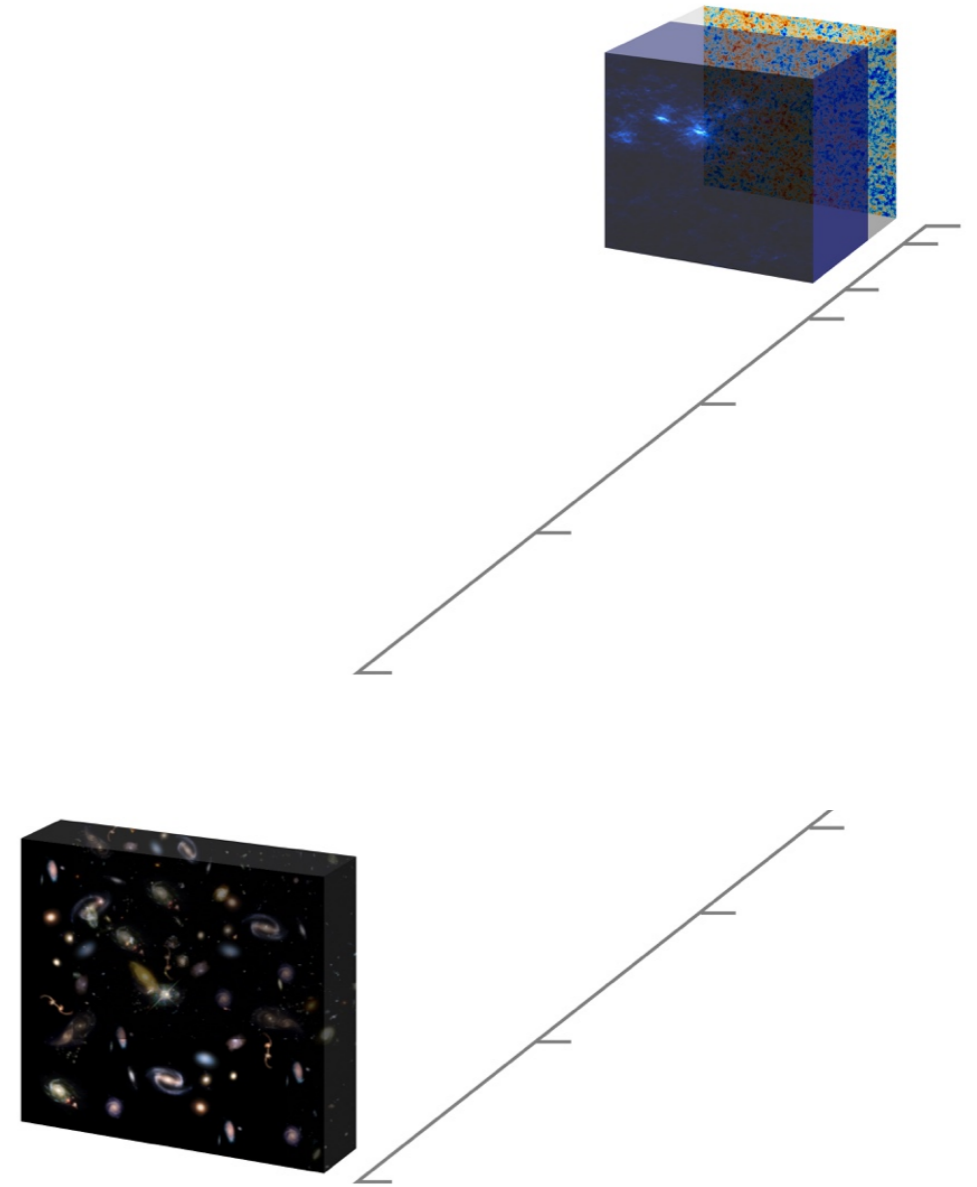
Ely D. Kovetz
Harvard, Mar. 2016

- Heat signatures of DM in the dark ages

- Flaring tidally compressed DM clumps

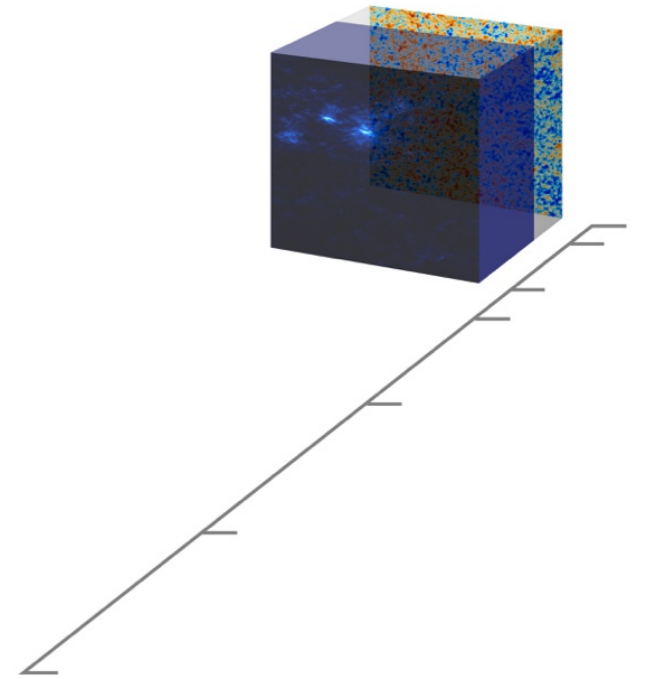


- Heat signatures of DM in the dark ages
- Flaring tidally compressed DM clumps
- Did advanced LIGO detect dark matter?



Outline

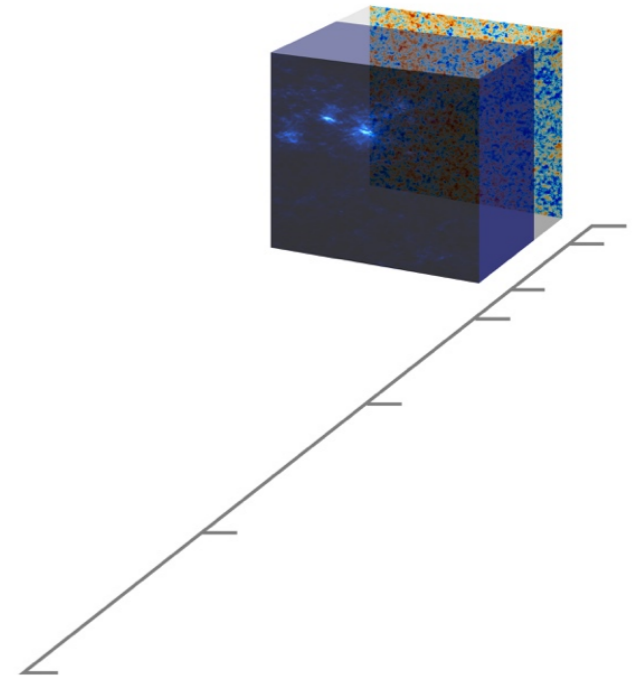
Ely D. Kovetz
Harvard, Mar. 2016



Outline

Ely D. Kovetz
Harvard, Mar. 2016

- Heat signatures of DM in the dark ages

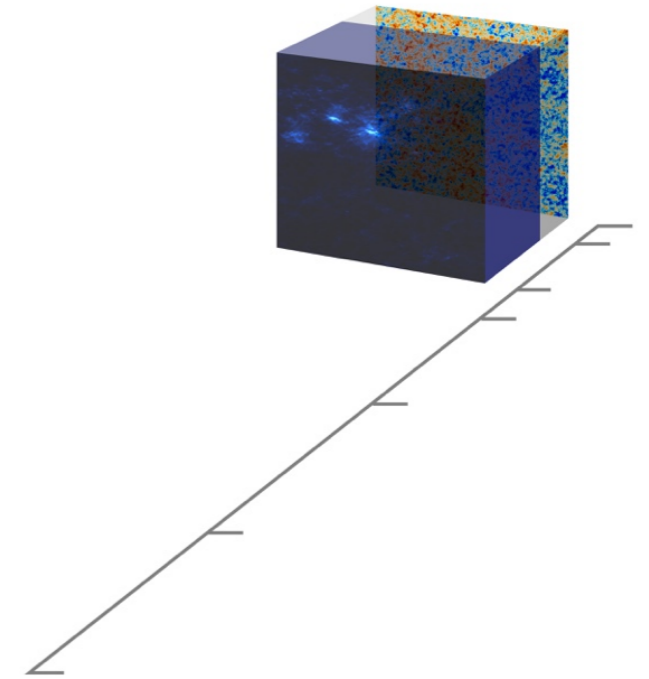


Outline

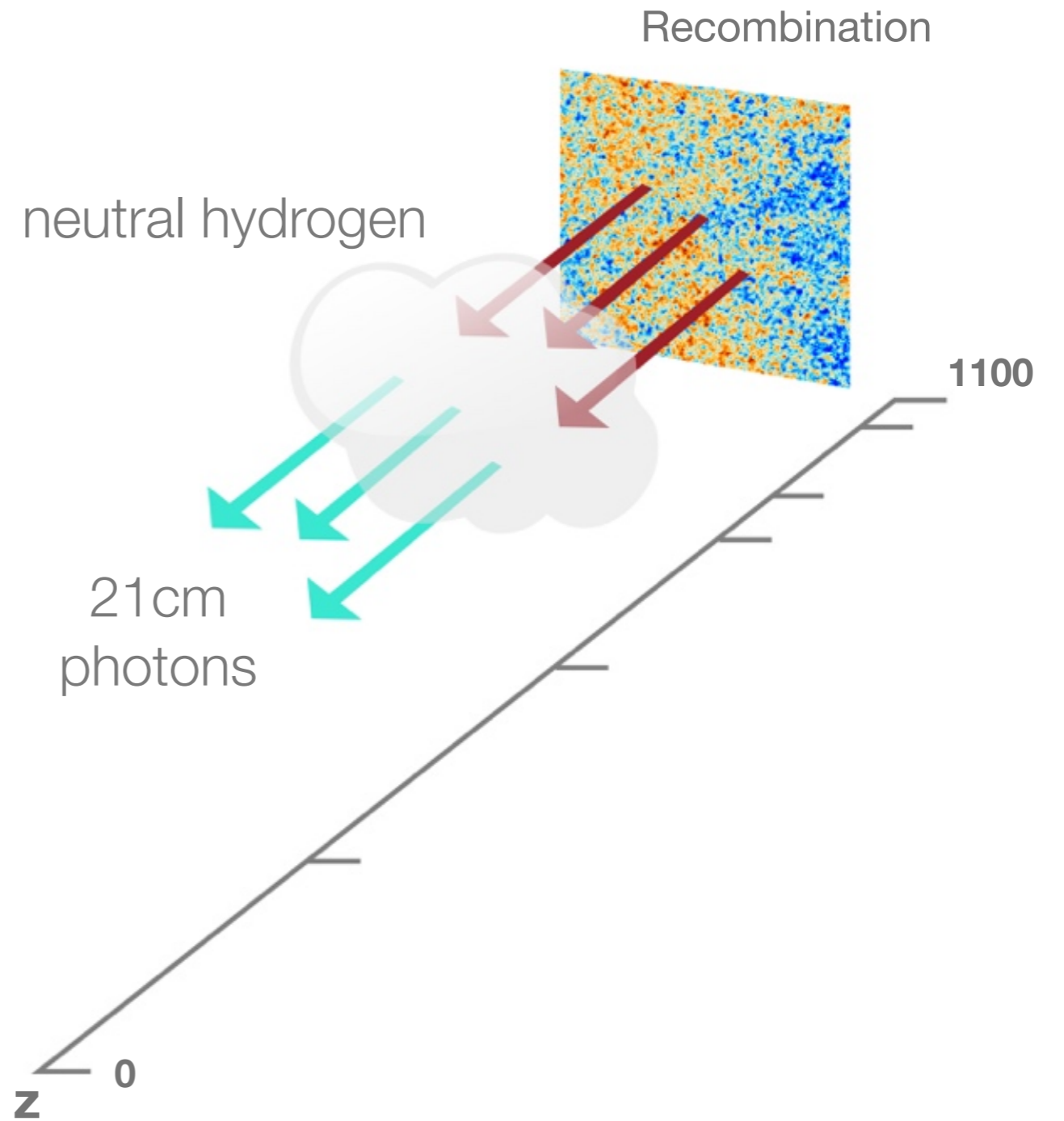
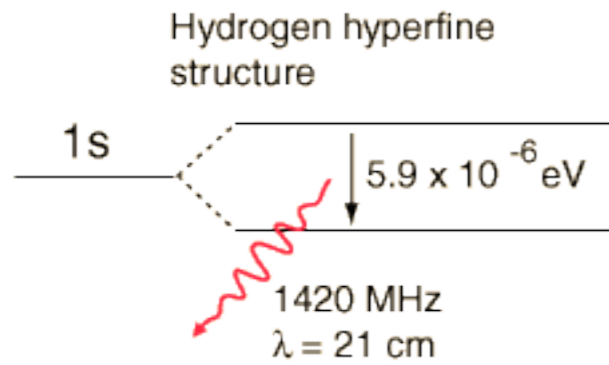
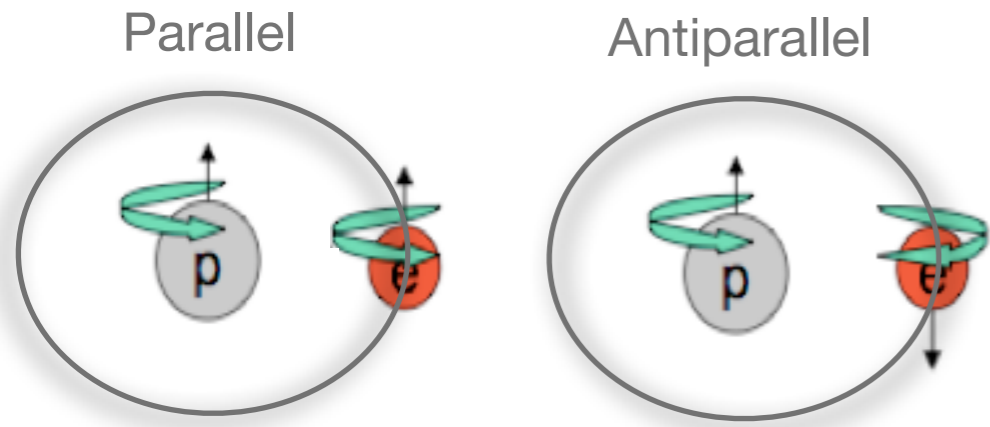
Ely D. Kovetz
Harvard, Mar. 2016

- Heat signatures of DM in the dark ages

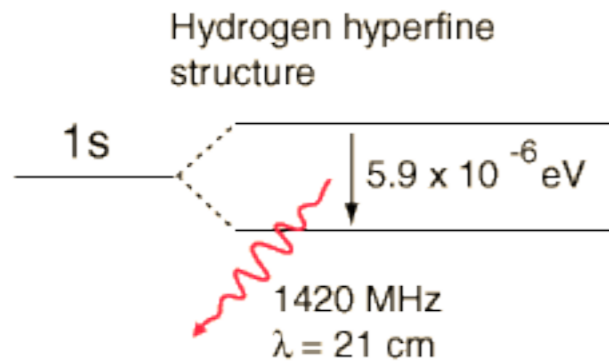
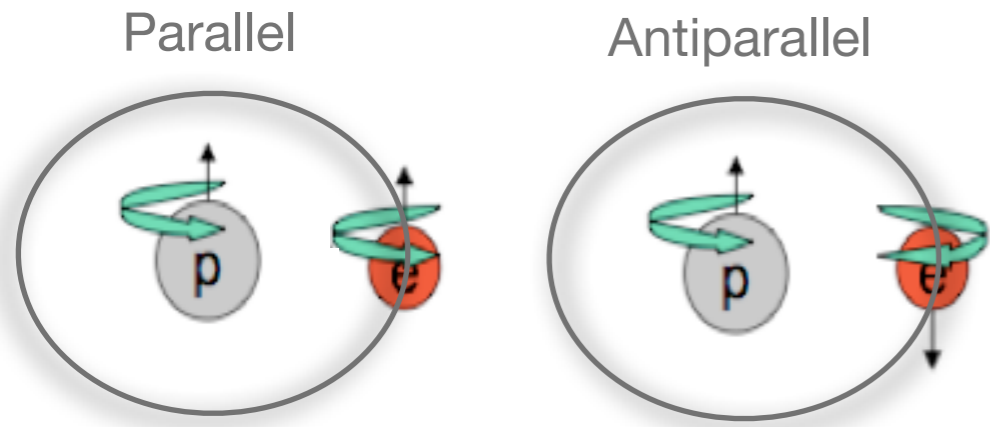
Muñoz, EDK and Ali-Haïmoud, Phys. Rev. D92 (2015)



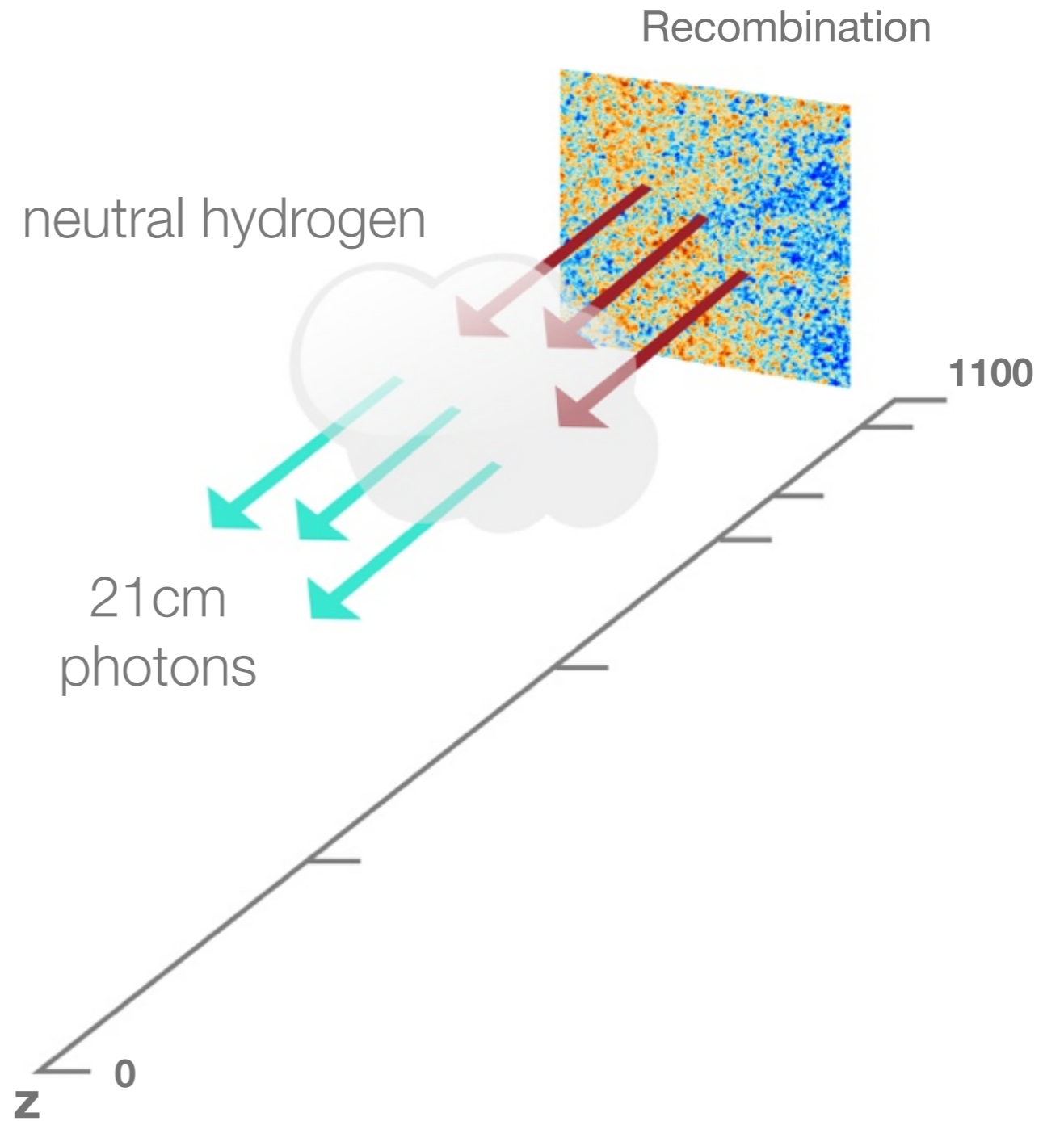
The 21-cm Signal: Lightning Review



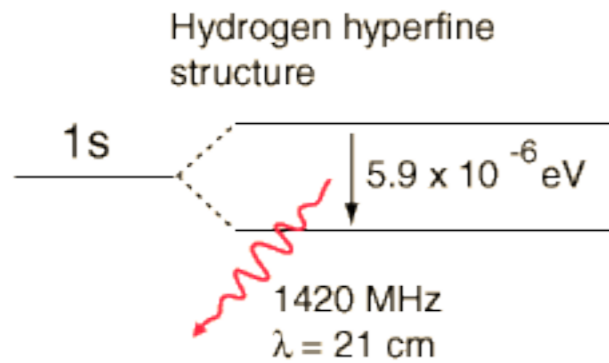
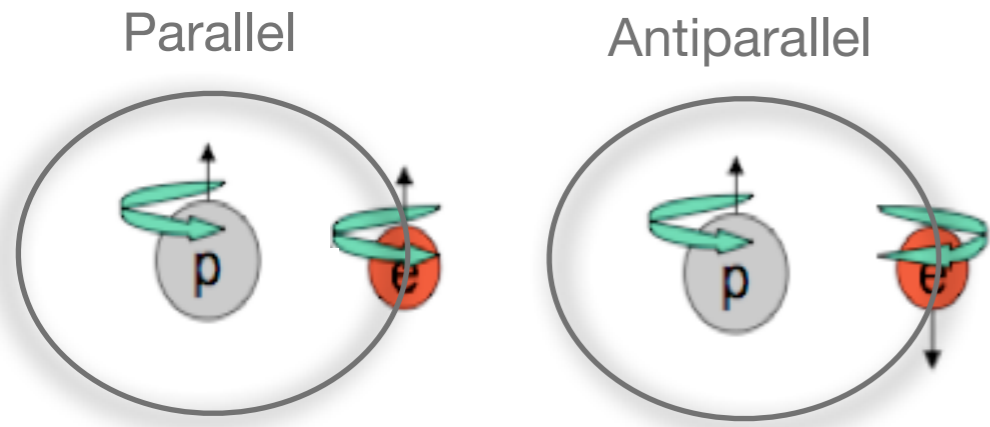
The 21-cm Signal: Lightning Review



Game of Temperatures:

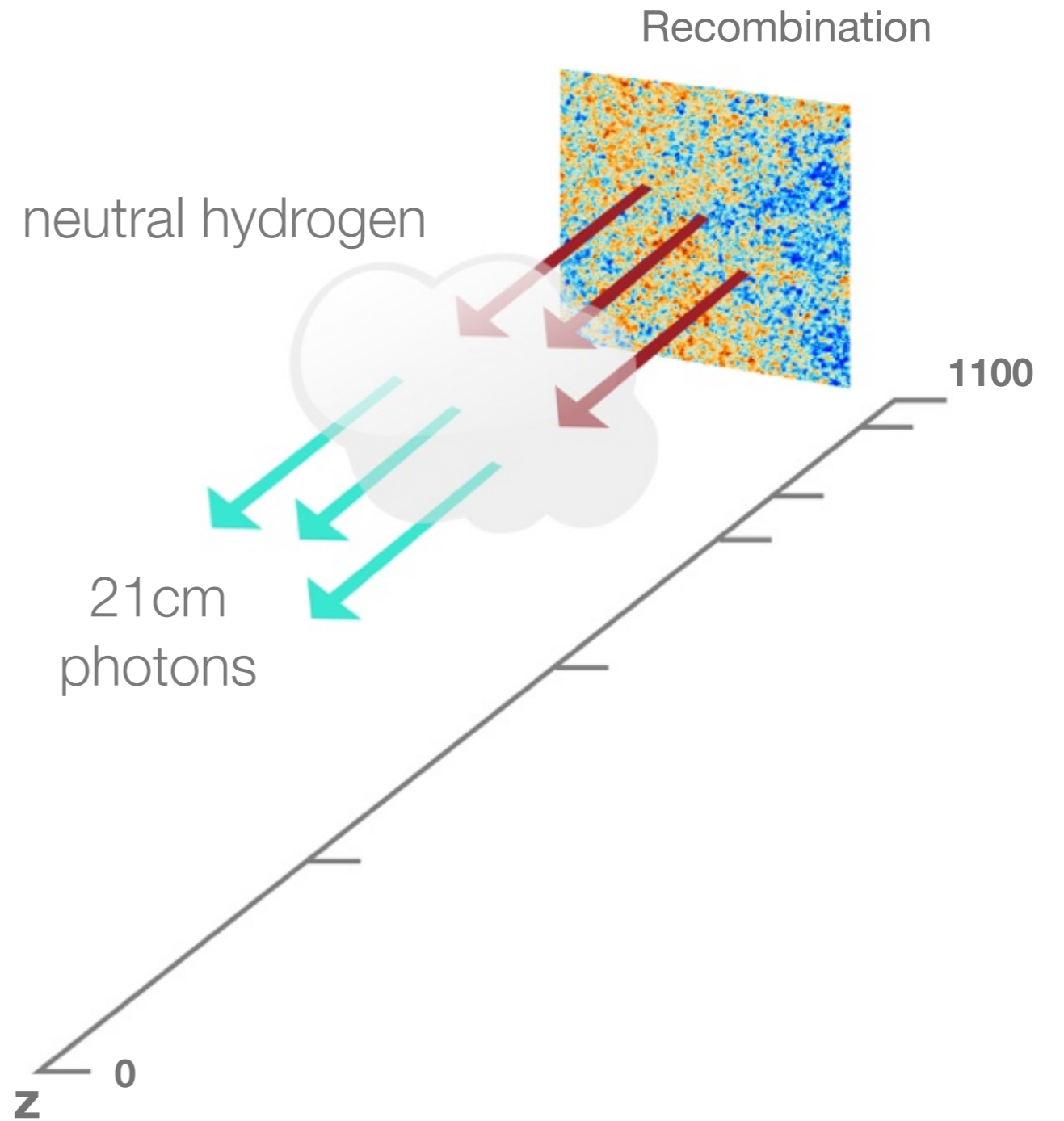


The 21-cm Signal: Lightning Review

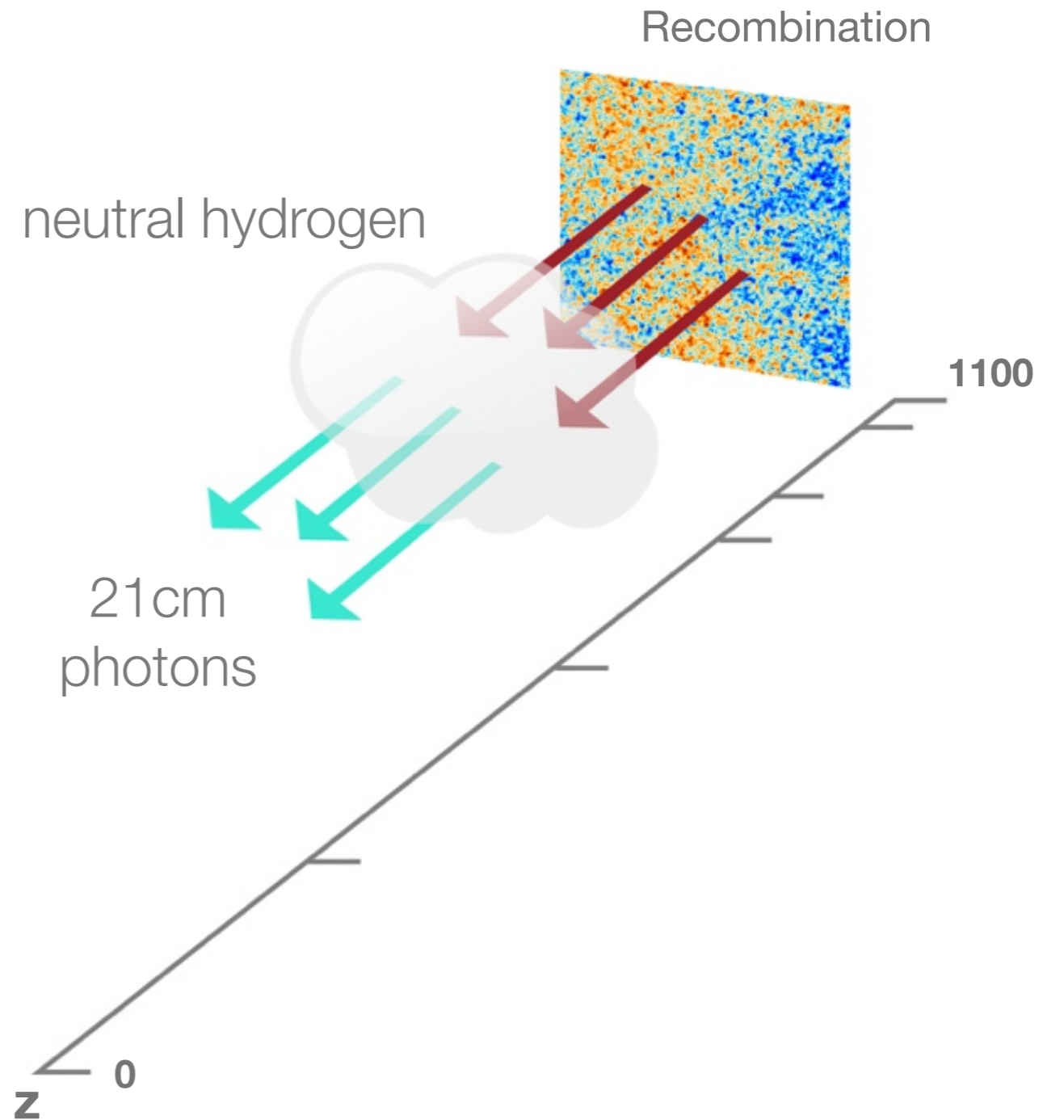
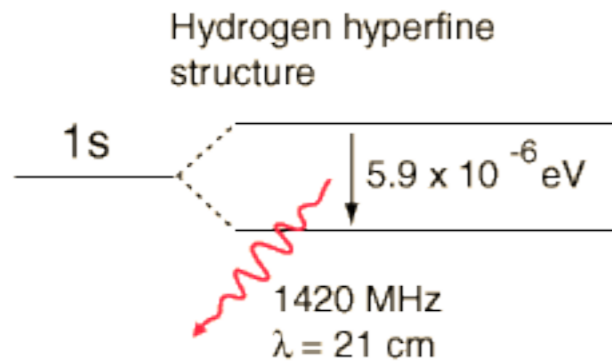
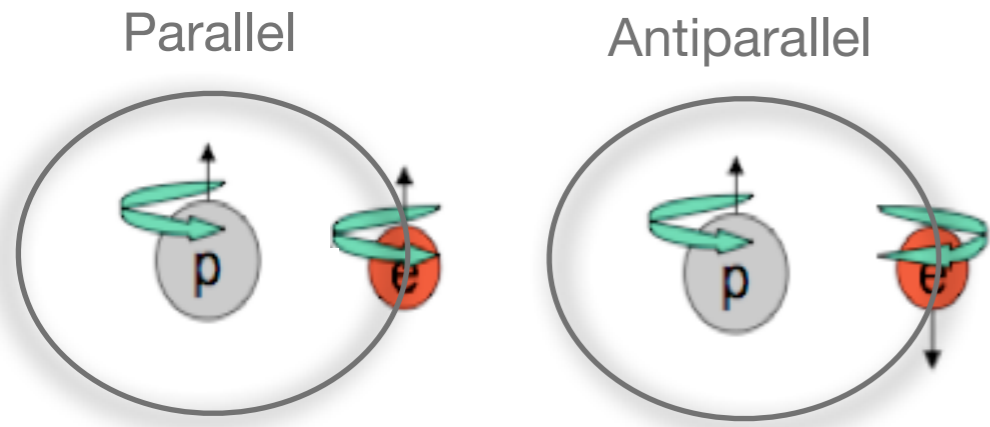


Game of Temperatures:

$$T_{\text{CMB}}$$



The 21-cm Signal: Lightning Review

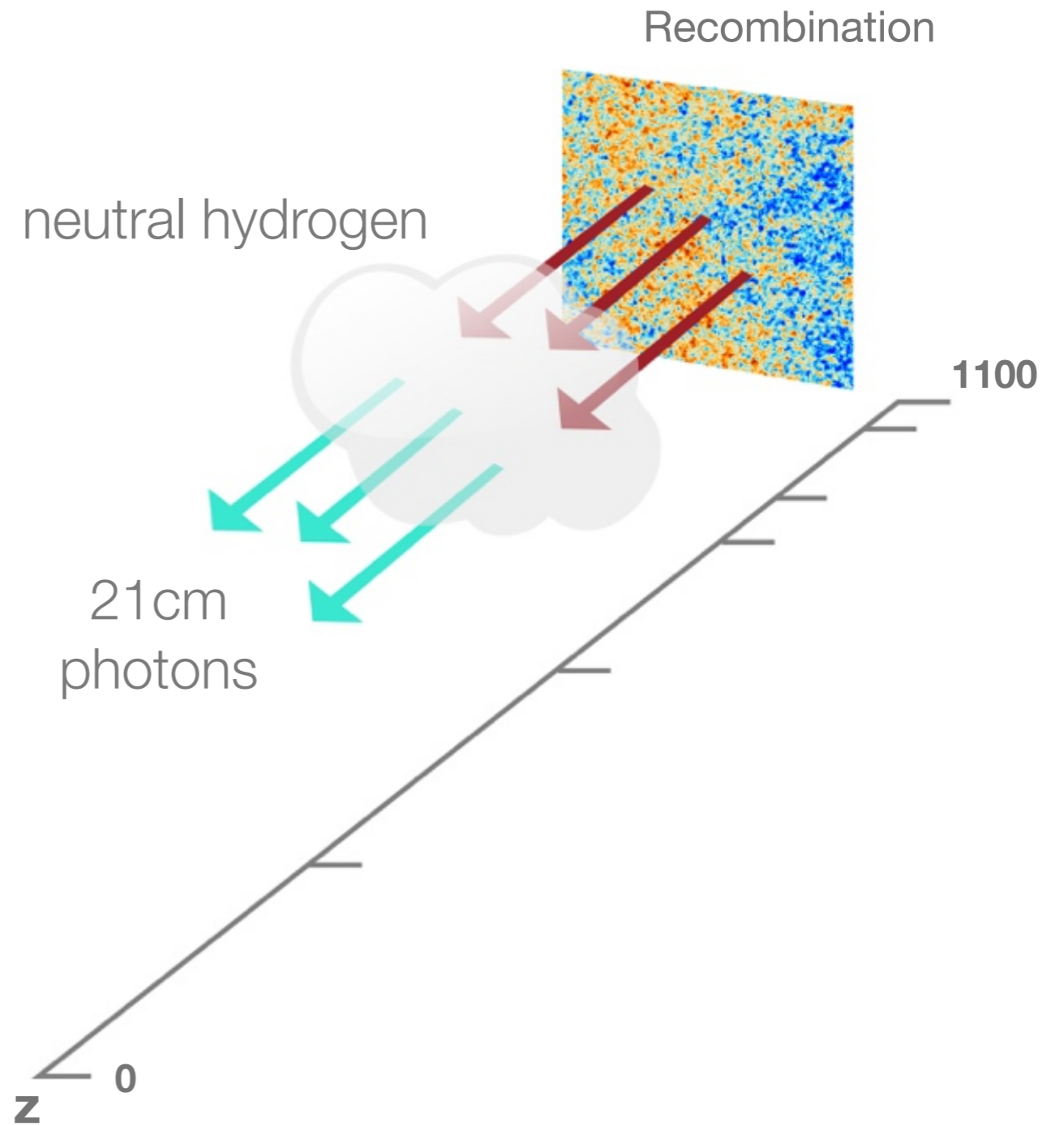
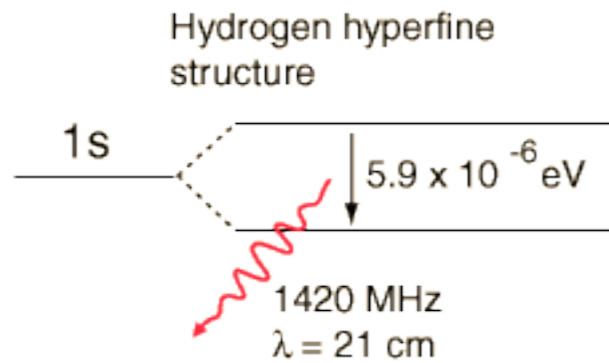
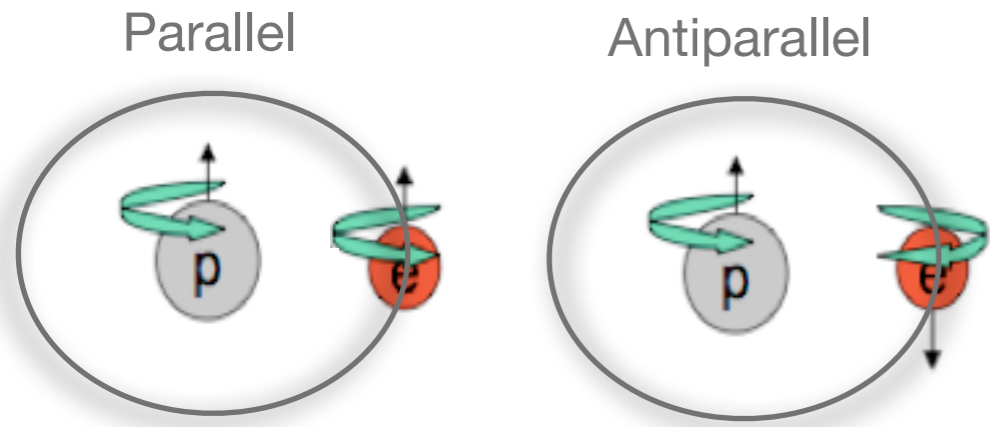


Game of Temperatures:

$$T_{\text{CMB}}$$

$$T_{\text{gas}}$$

The 21-cm Signal: Lightning Review



Game of Temperatures:

T_{CMB}

T_{gas}

Spin Temperature: $\frac{n_1}{n_0} = 3 \exp(-E_{10}/k_B T_{\text{spin}})$

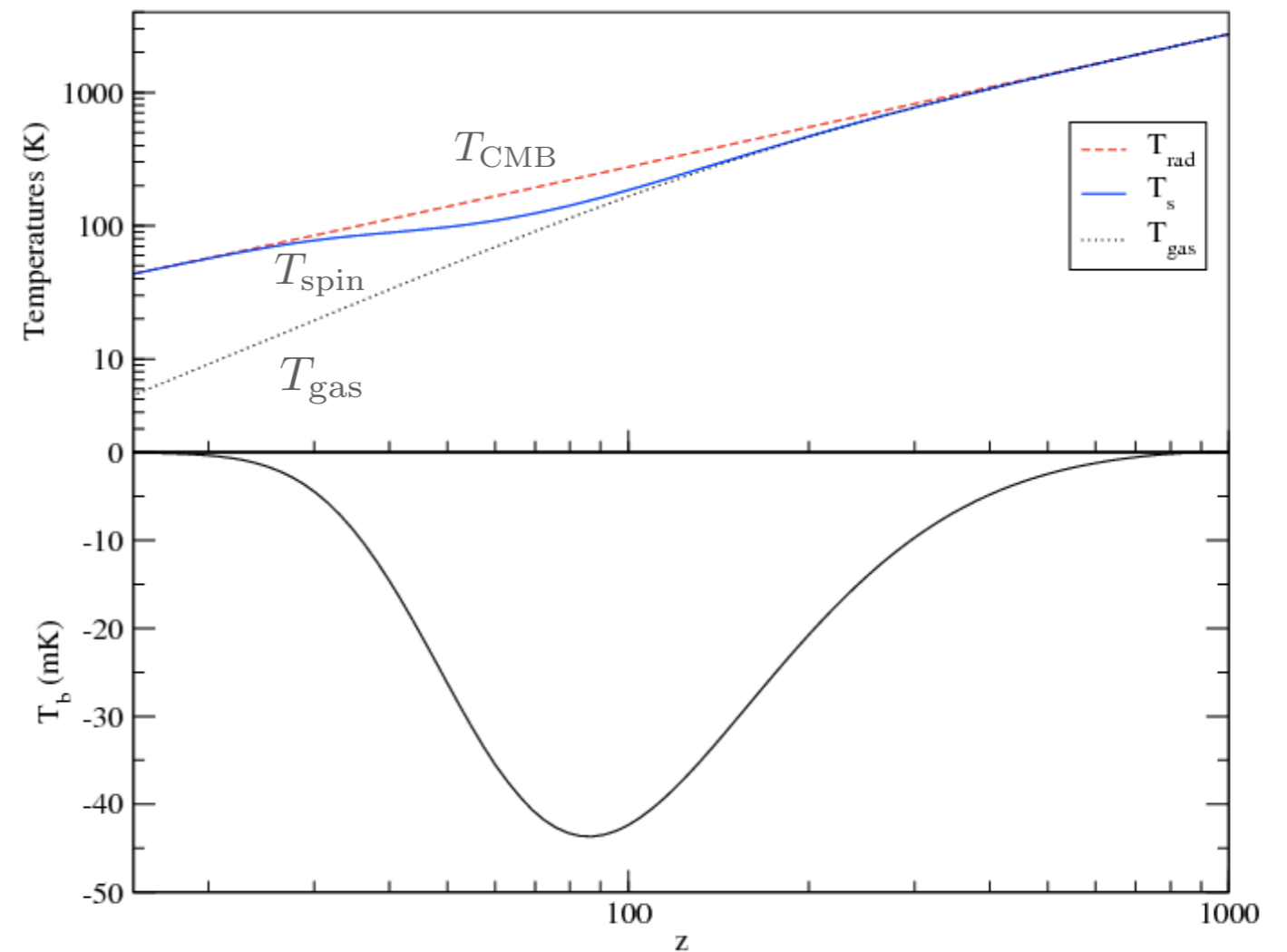
The 21-cm Signal: Lightning Review

The 21-cm Signal: Lightning Review

Time dependence of different temperatures:

The 21-cm Signal: Lightning Review

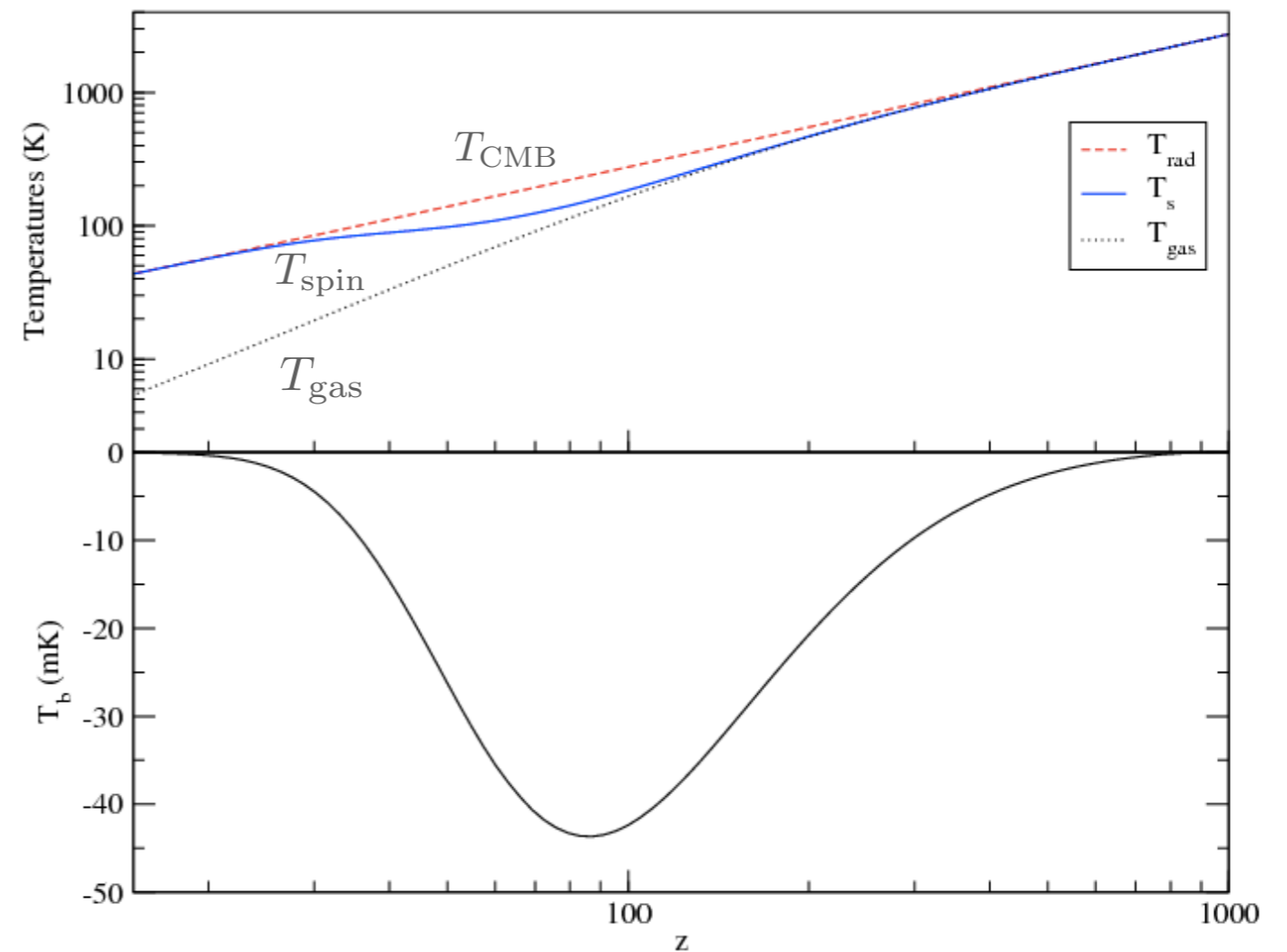
Time dependence of different temperatures:



The 21-cm Signal: Lightning Review

Time dependence of different temperatures:

At $z > 200$: $T_{\text{CMB}} \sim T_{\text{gas}} \sim T_{\text{spin}}$ (Compton scattering off remaining electrons)

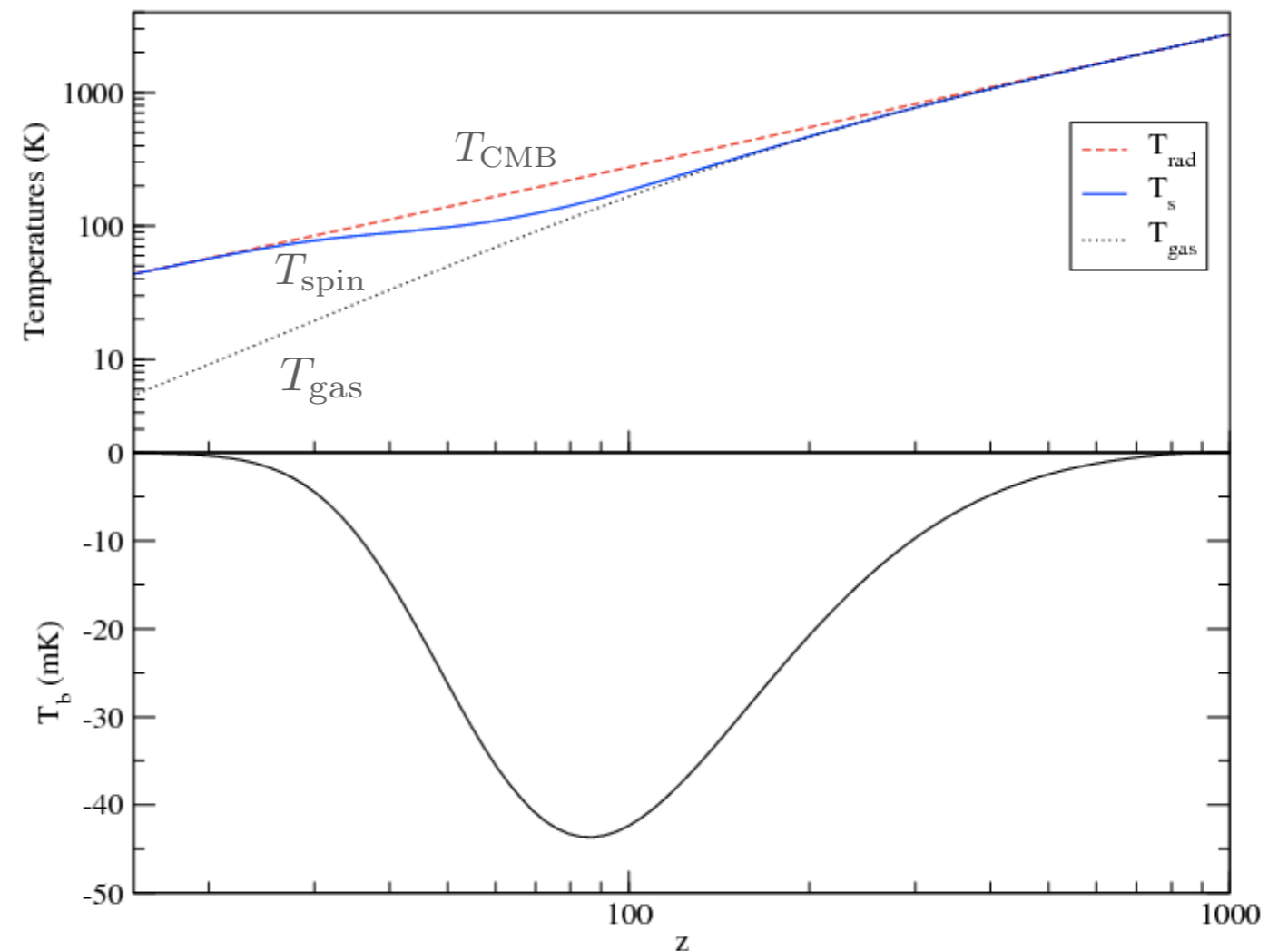


The 21-cm Signal: Lightning Review

Time dependence of different temperatures:

At $z > 200$: $T_{\text{CMB}} \sim T_{\text{gas}} \sim T_{\text{spin}}$ (Compton scattering off remaining electrons)

At $z < 200$: $T_{\text{CMB}} \sim (1+z)^{-1}$; $T_{\text{gas}} \sim (1+z)^{-2}$ (Gas decouples from CMB, cools adiabatically)



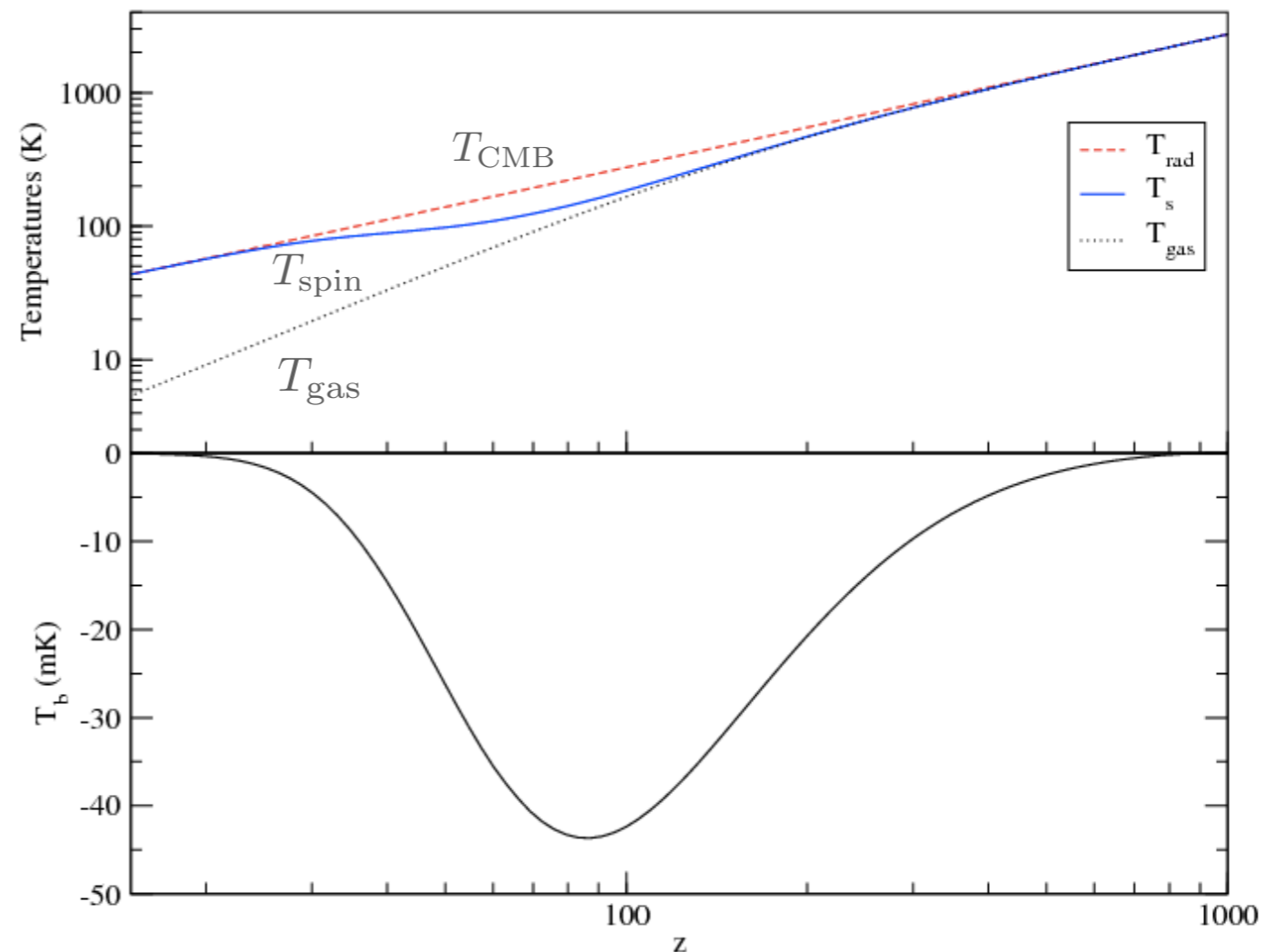
The 21-cm Signal: Lightning Review

Time dependence of different temperatures:

At $z > 200$: $T_{\text{CMB}} \sim T_{\text{gas}} \sim T_{\text{spin}}$ (Compton scattering off remaining electrons)

At $z < 200$: $T_{\text{CMB}} \sim (1+z)^{-1}$; $T_{\text{gas}} \sim (1+z)^{-2}$ (Gas decouples from CMB, cools adiabatically)

Until $z \sim 30$: First, $T_{\text{spin}} \sim T_{\text{gas}}$ (Collisions in the IGM). Then: $T_{\text{spin}} \rightarrow T_{\text{CMB}}$



The 21-cm Signal: Lightning Review

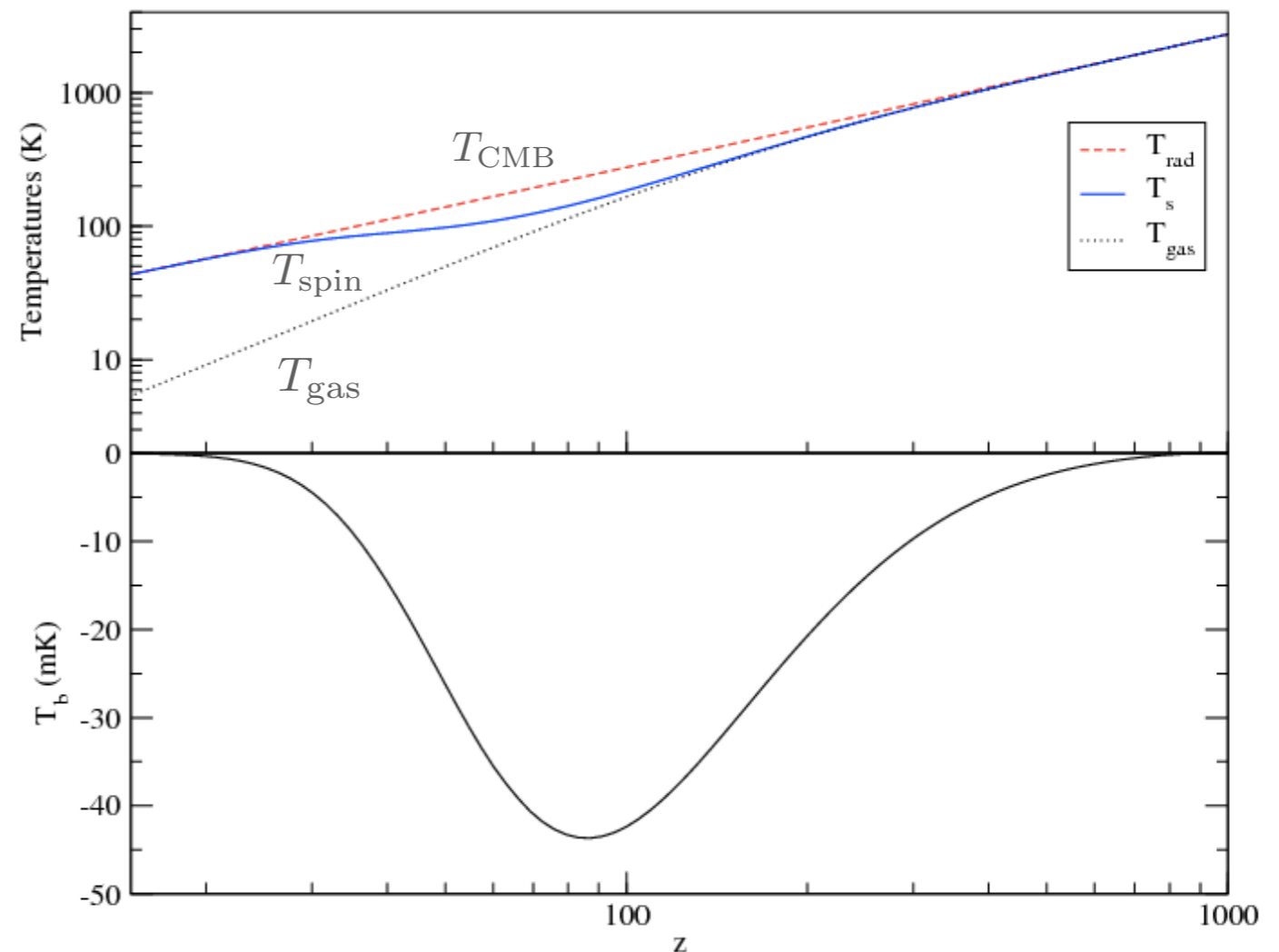
Time dependence of different temperatures:

At $z > 200$: $T_{\text{CMB}} \sim T_{\text{gas}} \sim T_{\text{spin}}$ (Compton scattering off remaining electrons)

At $z < 200$: $T_{\text{CMB}} \sim (1+z)^{-1}$; $T_{\text{gas}} \sim (1+z)^{-2}$ (Gas decouples from CMB, cools adiabatically)

Until $z \sim 30$: First, $T_{\text{spin}} \sim T_{\text{gas}}$ (Collisions in the IGM). Then: $T_{\text{spin}} \rightarrow T_{\text{CMB}}$

Absorption: $T_{\text{spin}} < T_{\text{CMB}}$



The 21-cm Signal: Lightning Review

Time dependence of different temperatures:

At $z > 200$: $T_{\text{CMB}} \sim T_{\text{gas}} \sim T_{\text{spin}}$ (Compton scattering off remaining electrons)

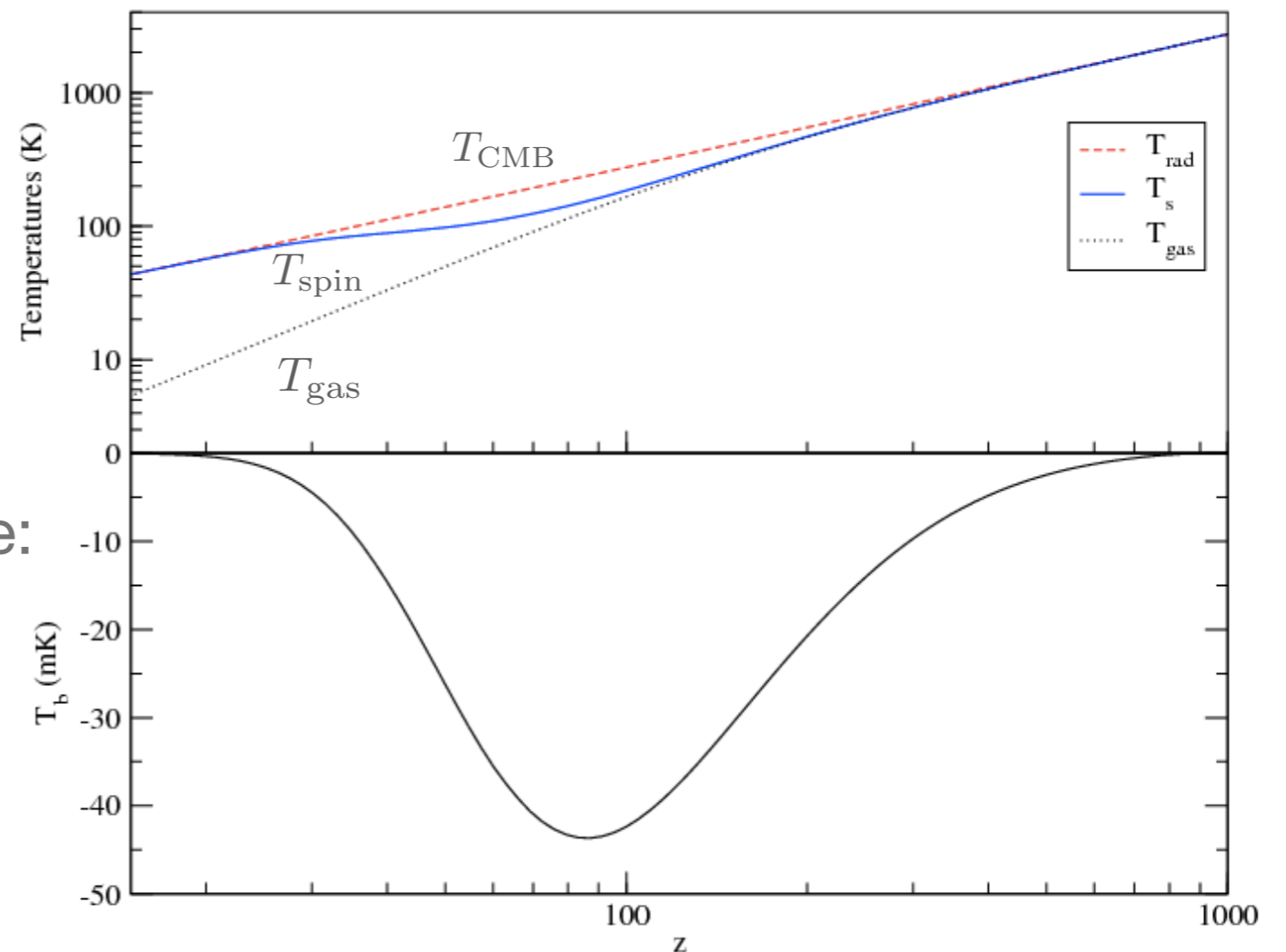
At $z < 200$: $T_{\text{CMB}} \sim (1+z)^{-1}$; $T_{\text{gas}} \sim (1+z)^{-2}$ (Gas decouples from CMB, cools adiabatically)

Until $z \sim 30$: First, $T_{\text{spin}} \sim T_{\text{gas}}$ (Collisions in the IGM). Then: $T_{\text{spin}} \rightarrow T_{\text{CMB}}$

Absorption: $T_{\text{spin}} < T_{\text{CMB}}$

We measure a brightness temperature:

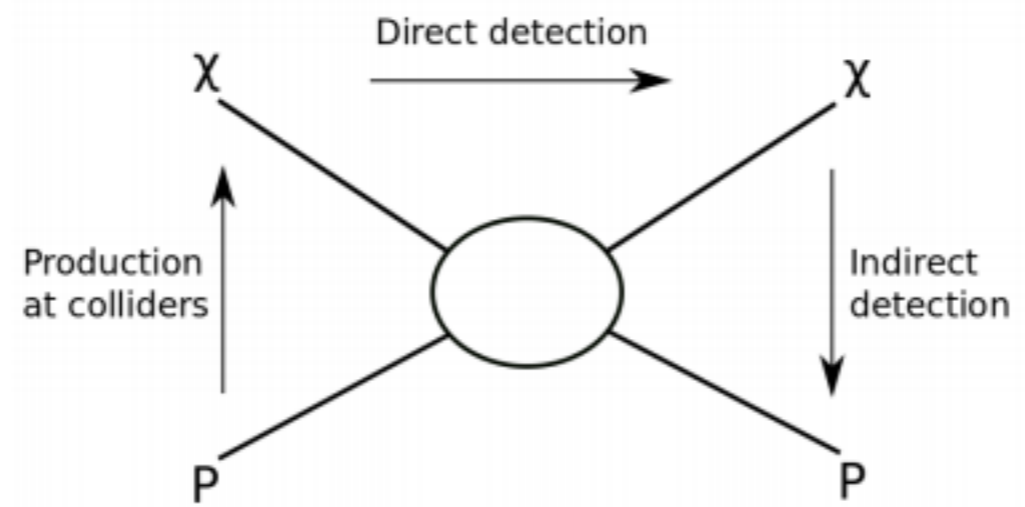
$$T_{21} \approx \frac{T_{\text{spin}} - T_{\text{CMB}}}{1+z} \tau$$



Dark Matter: Limitations of Direct Detection

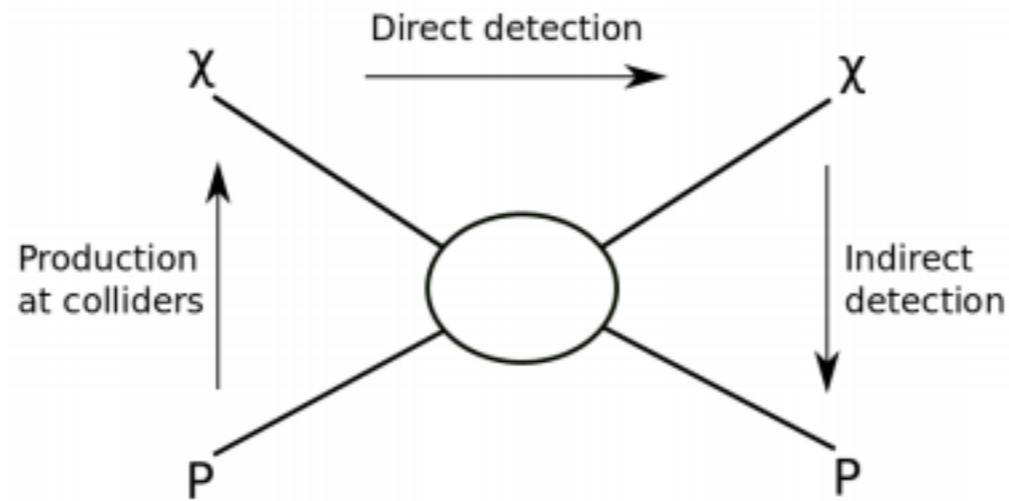
Dark Matter: Limitations of Direct Detection

Detecting DM:

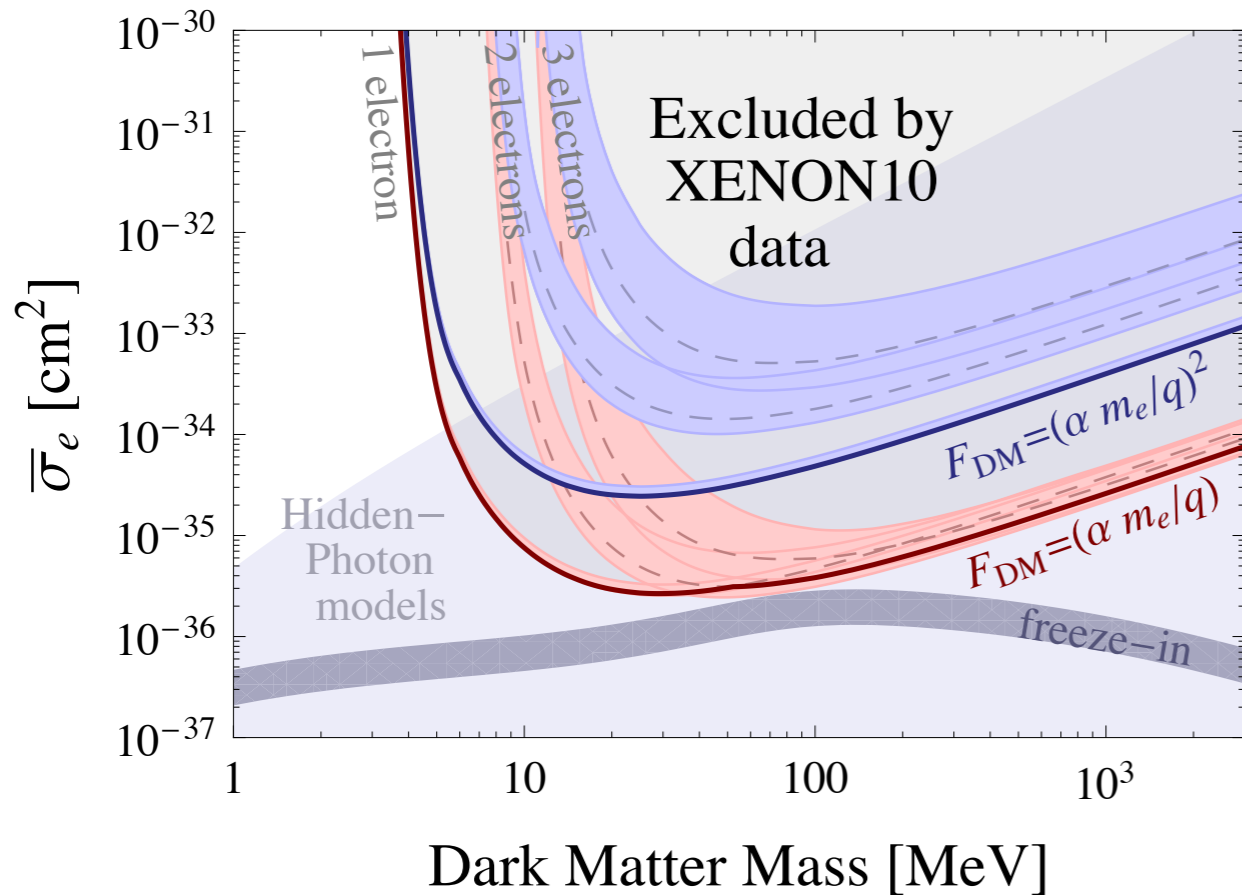


Dark Matter: Limitations of Direct Detection

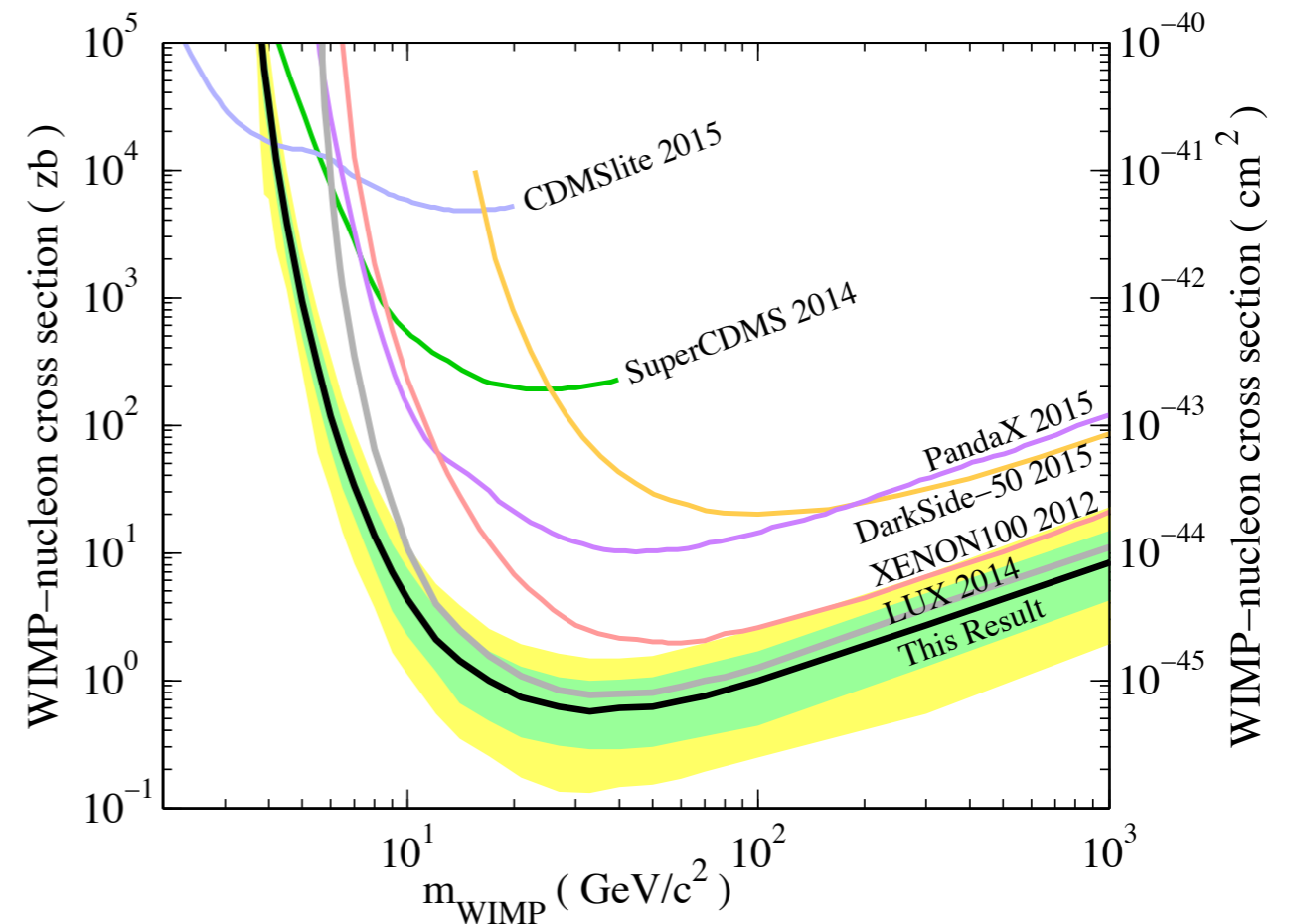
Detecting DM:



(Essig et al., PRL 109, 2012)

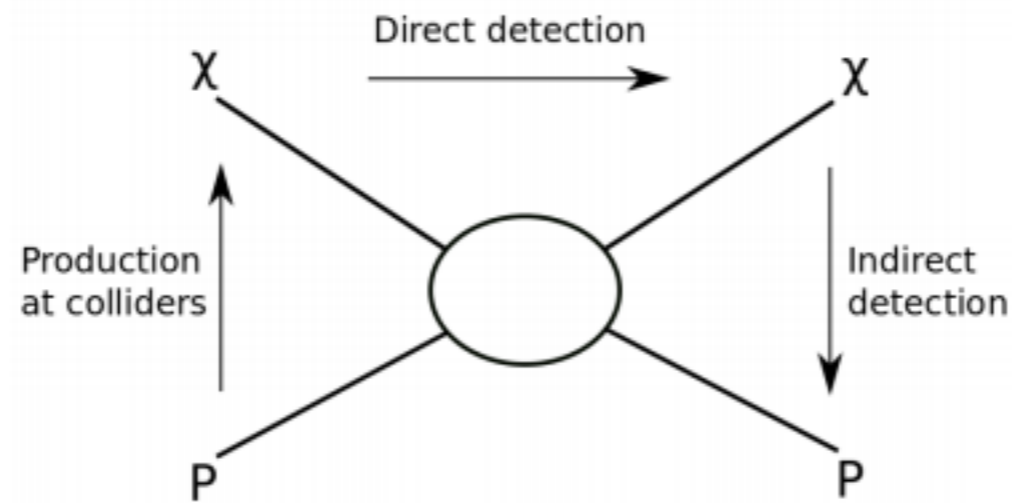


(LUX Collaboration arXiv:1512.03506)



Dark Matter: Limitations of Direct Detection

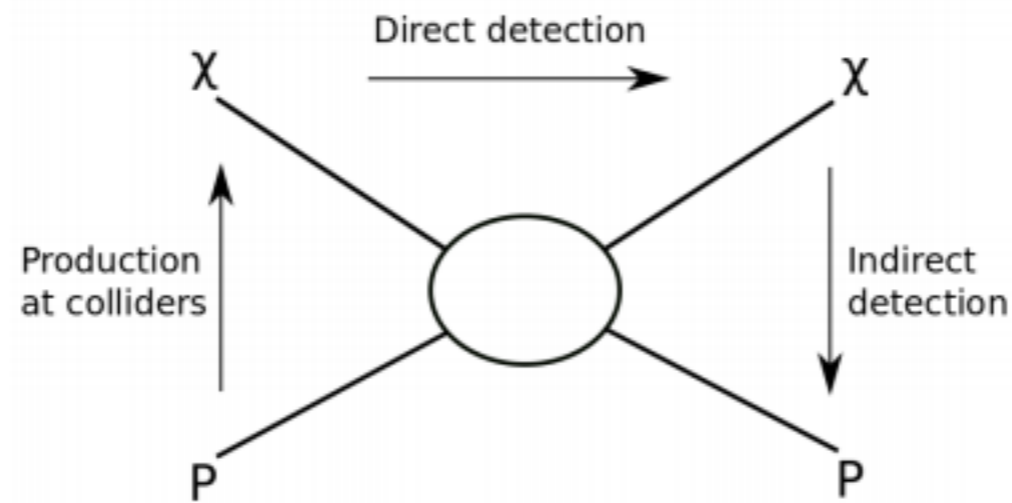
Detecting DM:



Direct detection experiments are not sensitive to low m_χ .

Dark Matter: Limitations of Direct Detection

Detecting DM:

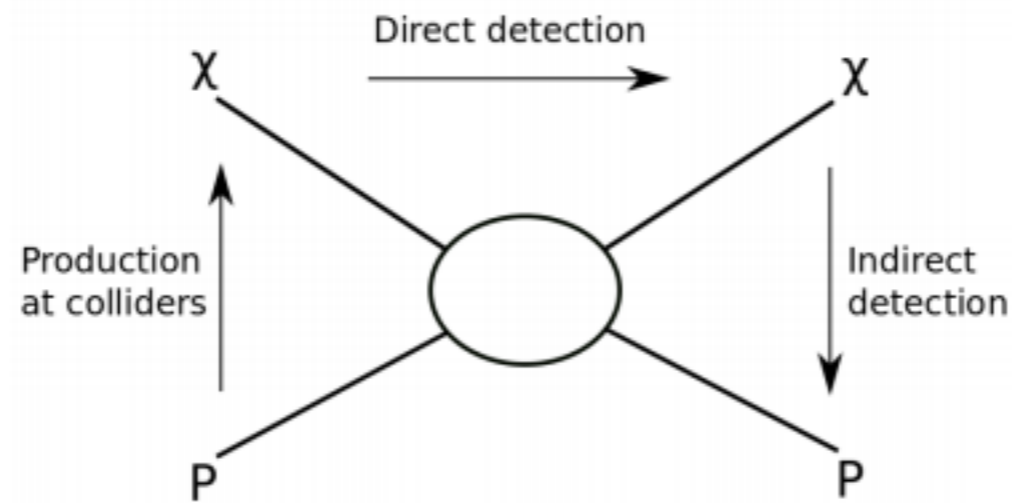


Direct detection experiments are not sensitive to low m_χ .

What about cosmological constraints?

Dark Matter: Limitations of Direct Detection

Detecting DM:



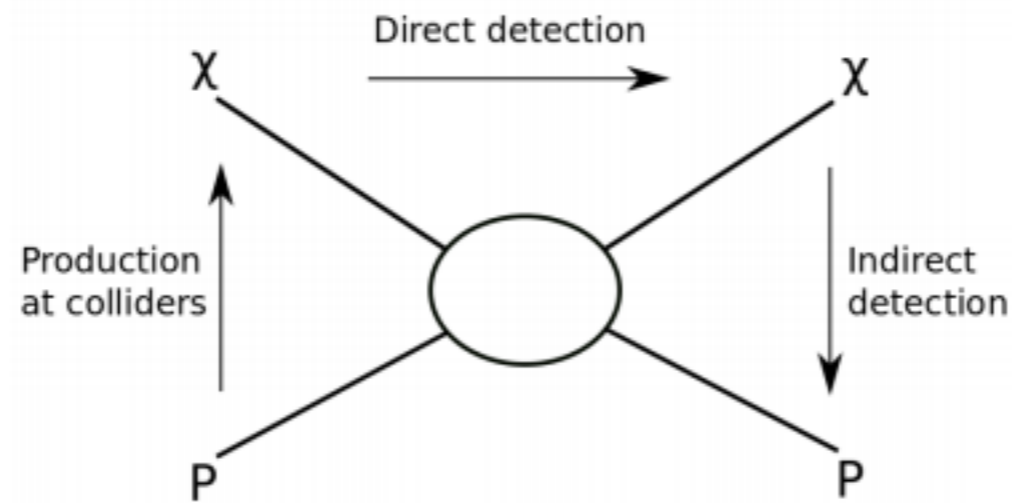
Direct detection experiments are not sensitive to low m_χ .

What about cosmological constraints?

Consider a cross-section: $\sigma = \sigma_0 v^n$

Dark Matter: Limitations of Direct Detection

Detecting DM:



Direct detection experiments are not sensitive to low m_χ .

What about cosmological constraints?

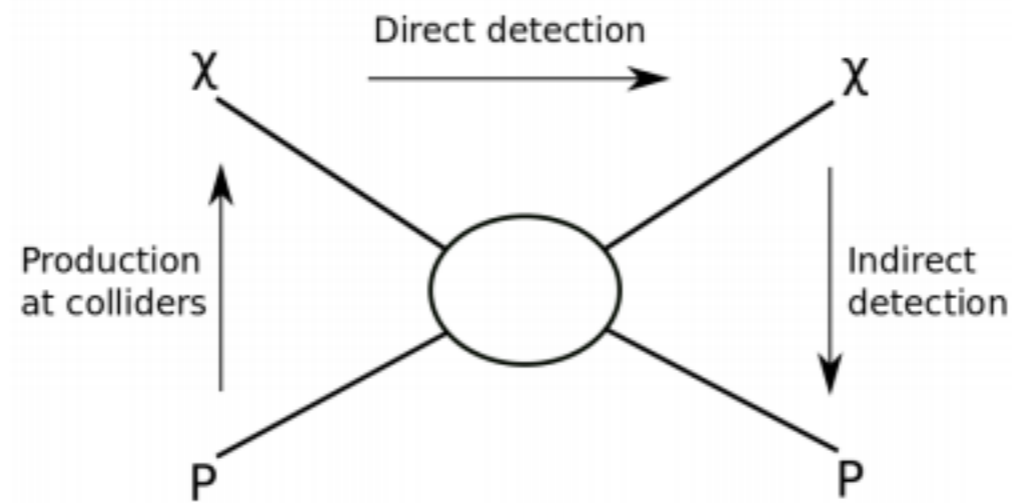
Consider a cross-section: $\sigma = \sigma_0 v^n$

Constraints have been drawn from CMB/Ly α -forest small-scale power spectra.

Dvorkin, Blum & Kamionkowski (2014)

Dark Matter: Limitations of Direct Detection

Detecting DM:



Direct detection experiments are not sensitive to low m_χ .

What about cosmological constraints?

Consider a cross-section: $\sigma = \sigma_0 v^n$

Constraints have been drawn from CMB/Ly α -forest small-scale power spectra.

Dvorkin, Blum & Kamionkowski (2014)

However, these are mostly effective for $n > -3$. What about later times?

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

- Focus on the *temperatures* of DM and baryons.

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

- Focus on the *temperatures* of DM and baryons.
- Intuitively, we expect the coupling to cool down the baryons (equilibration).

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

- Focus on the *temperatures* of DM and baryons.
- Intuitively, we expect the coupling to cool down the baryons (equilibration).
- But relative velocity is important:

$$\mathcal{P}(\mathbf{v}_{\chi b,0}) = \frac{e^{-3\mathbf{v}_{\chi b,0}^2/(2v_{\text{rms}}^2)}}{\left(\frac{2\pi}{3}v_{\text{rms}}^2\right)^{3/2}}, \quad v_{\text{rms}} = 29 \text{ km/s} \quad \text{Tseliakovich \& Hirata (2010)}$$

at decoupling, then redshifts away

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

- Focus on the *temperatures* of DM and baryons.
- Intuitively, we expect the coupling to cool down the baryons (equilibration).
- But relative velocity is important:

$$\mathcal{P}(\mathbf{v}_{\chi b,0}) = \frac{e^{-3\mathbf{v}_{\chi b,0}^2/(2v_{\text{rms}}^2)}}{\left(\frac{2\pi}{3}v_{\text{rms}}^2\right)^{3/2}}, \quad v_{\text{rms}} = 29 \text{ km/s} \quad \text{Tseliakovich \& Hirata (2010)}$$

at decoupling, then
redshifts away

- Conservation of energy: $\frac{1}{2} \frac{\rho_{\chi}\rho_b}{\rho_m} v_{\chi b}^2 + \frac{3}{2} n_{\chi} T_{\chi} + \frac{3}{2} n_b T_b = \text{const}$

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

- Focus on the *temperatures* of DM and baryons.
- Intuitively, we expect the coupling to cool down the baryons (equilibration).
- But relative velocity is important:

$$\mathcal{P}(\mathbf{v}_{\chi b,0}) = \frac{e^{-3\mathbf{v}_{\chi b,0}^2/(2v_{\text{rms}}^2)}}{\left(\frac{2\pi}{3}v_{\text{rms}}^2\right)^{3/2}}, \quad v_{\text{rms}} = 29 \text{ km/s} \quad \text{Tseliakovich \& Hirata (2010)}$$

at decoupling, then
redshifts away

- Conservation of energy: $\frac{1}{2} \frac{\rho_{\chi}\rho_b}{\rho_m} v_{\chi b}^2 + \frac{3}{2} n_{\chi} T_{\chi} + \frac{3}{2} n_b T_b = \text{const}$

→ dissipation of kinetic energy into thermal energy:

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

- Focus on the *temperatures* of DM and baryons.
- Intuitively, we expect the coupling to cool down the baryons (equilibration).
- But relative velocity is important:

$$\mathcal{P}(\mathbf{v}_{\chi b,0}) = \frac{e^{-3\mathbf{v}_{\chi b,0}^2/(2v_{\text{rms}}^2)}}{\left(\frac{2\pi}{3}v_{\text{rms}}^2\right)^{3/2}}, \quad v_{\text{rms}} = 29 \text{ km/s} \quad \text{Tseliakovich \& Hirata (2010)}$$

at decoupling, then redshifts away

- Conservation of energy: $\frac{1}{2} \frac{\rho_{\chi}\rho_b}{\rho_m} v_{\chi b}^2 + \frac{3}{2} n_{\chi} T_{\chi} + \frac{3}{2} n_b T_b = \text{const}$

→ dissipation of kinetic energy into thermal energy:

$$\dot{T}_b + 2HT_b = \Gamma_C(T_{\gamma} - T_b) + \Gamma_{\chi b}(T_{\chi} - T_b) \boxed{+F(v_{\chi b}^2)}$$

$$\dot{T}_{\chi} + 2HT_{\chi} = (n_b/n_{\chi}) \Gamma_{\chi b}(T_b - T_{\chi}) \boxed{+G(v_{\chi b}^2)}$$

Heating from DM-Baryon Scattering in Dark Ages

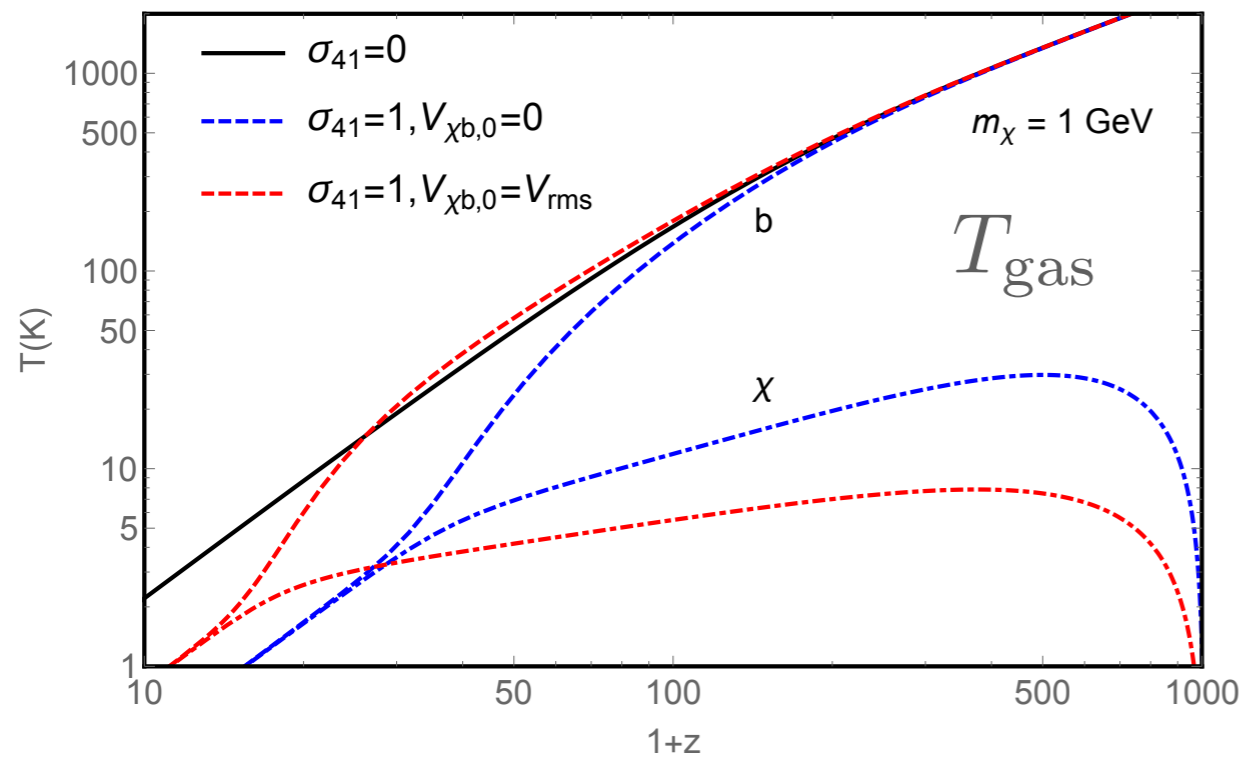
(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

Heating effect: global signal

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

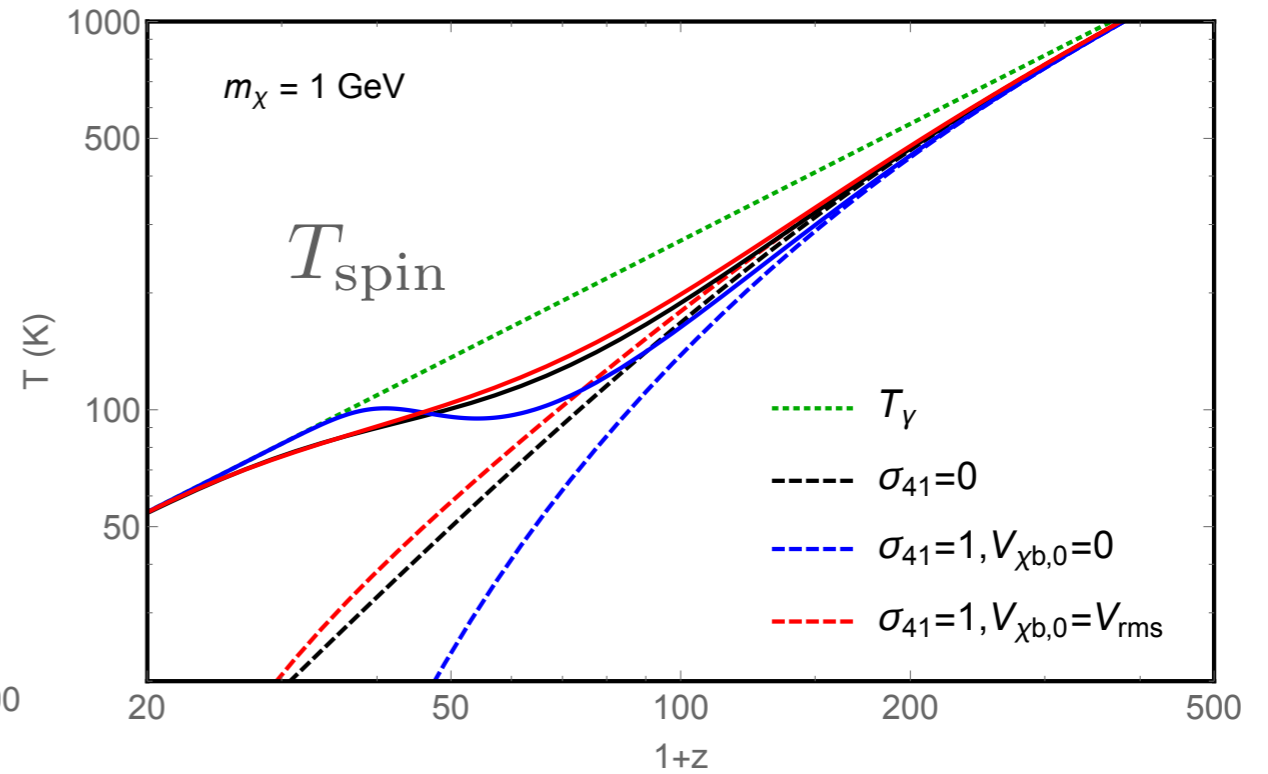
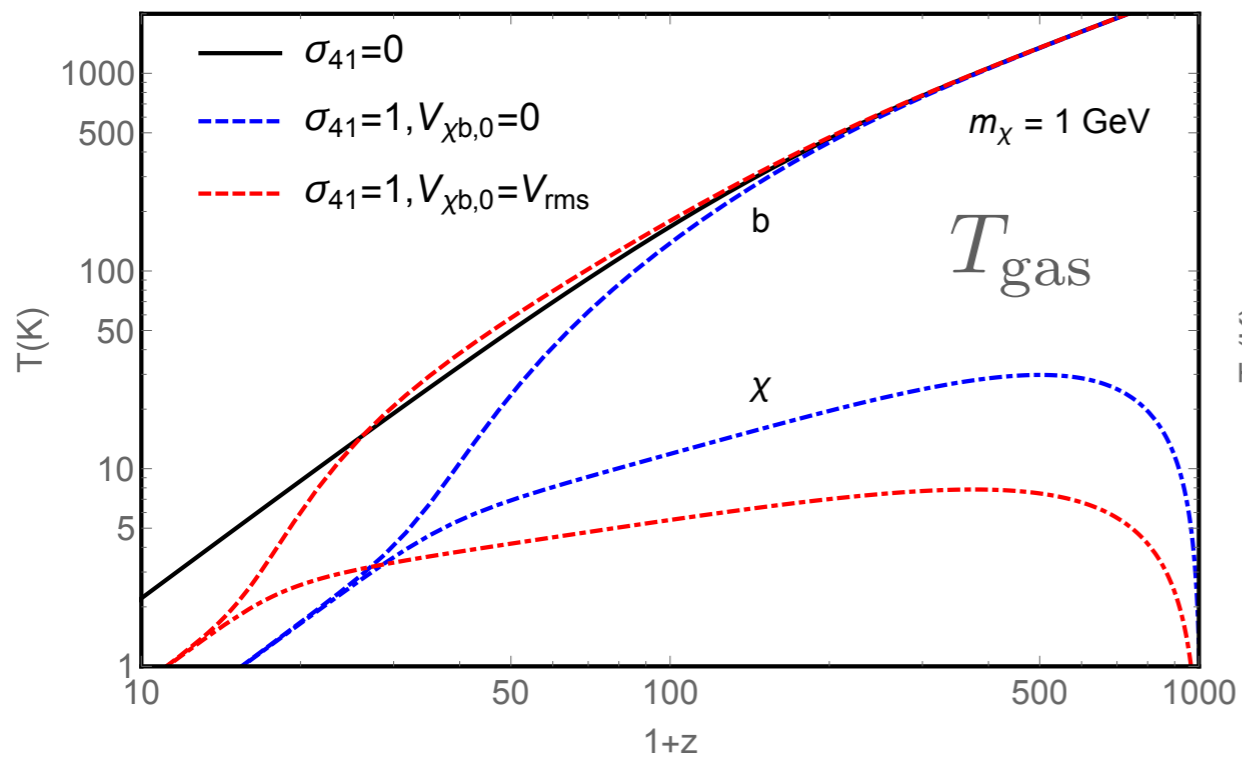
Heating effect: global signal



Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

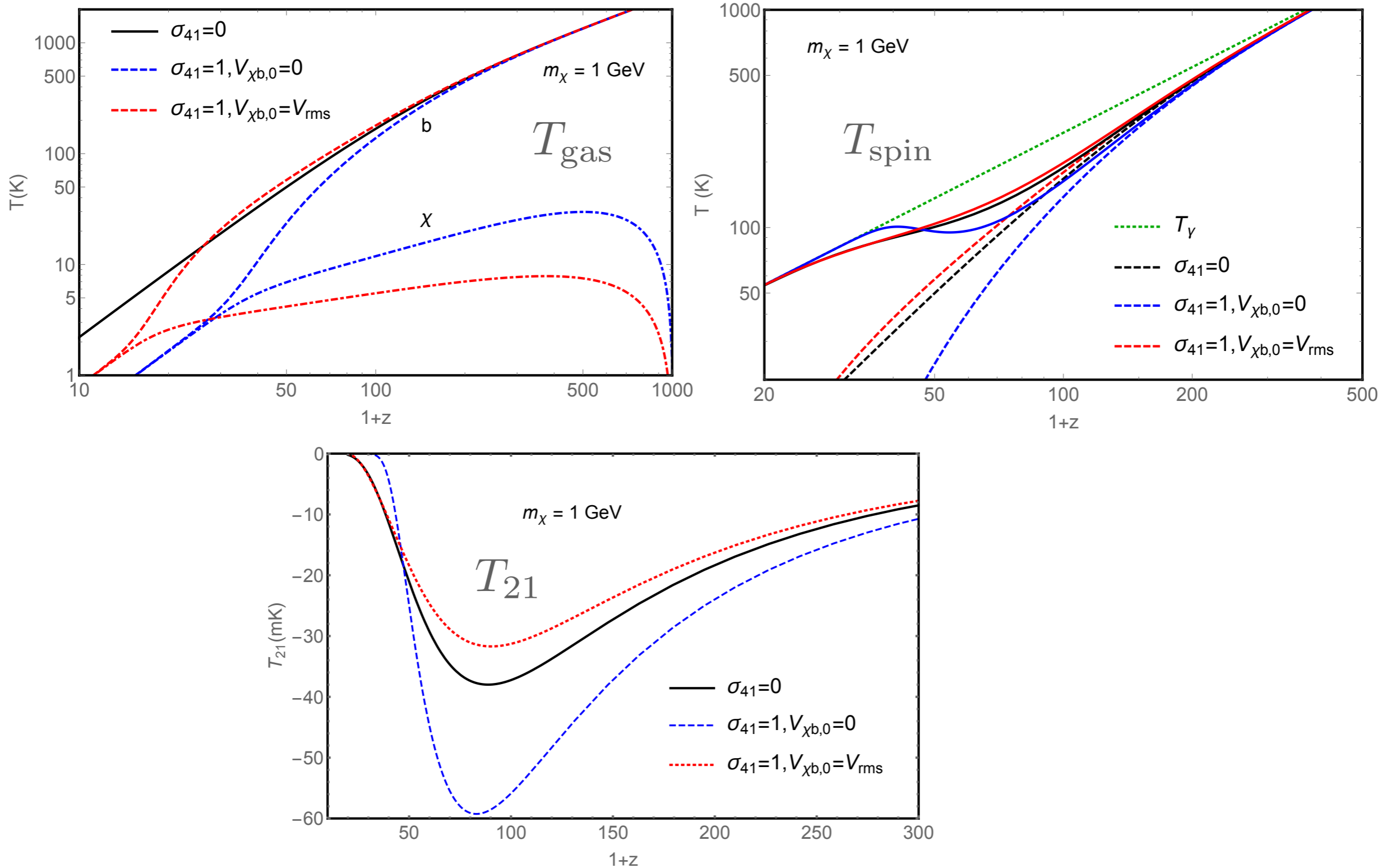
Heating effect: global signal



Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

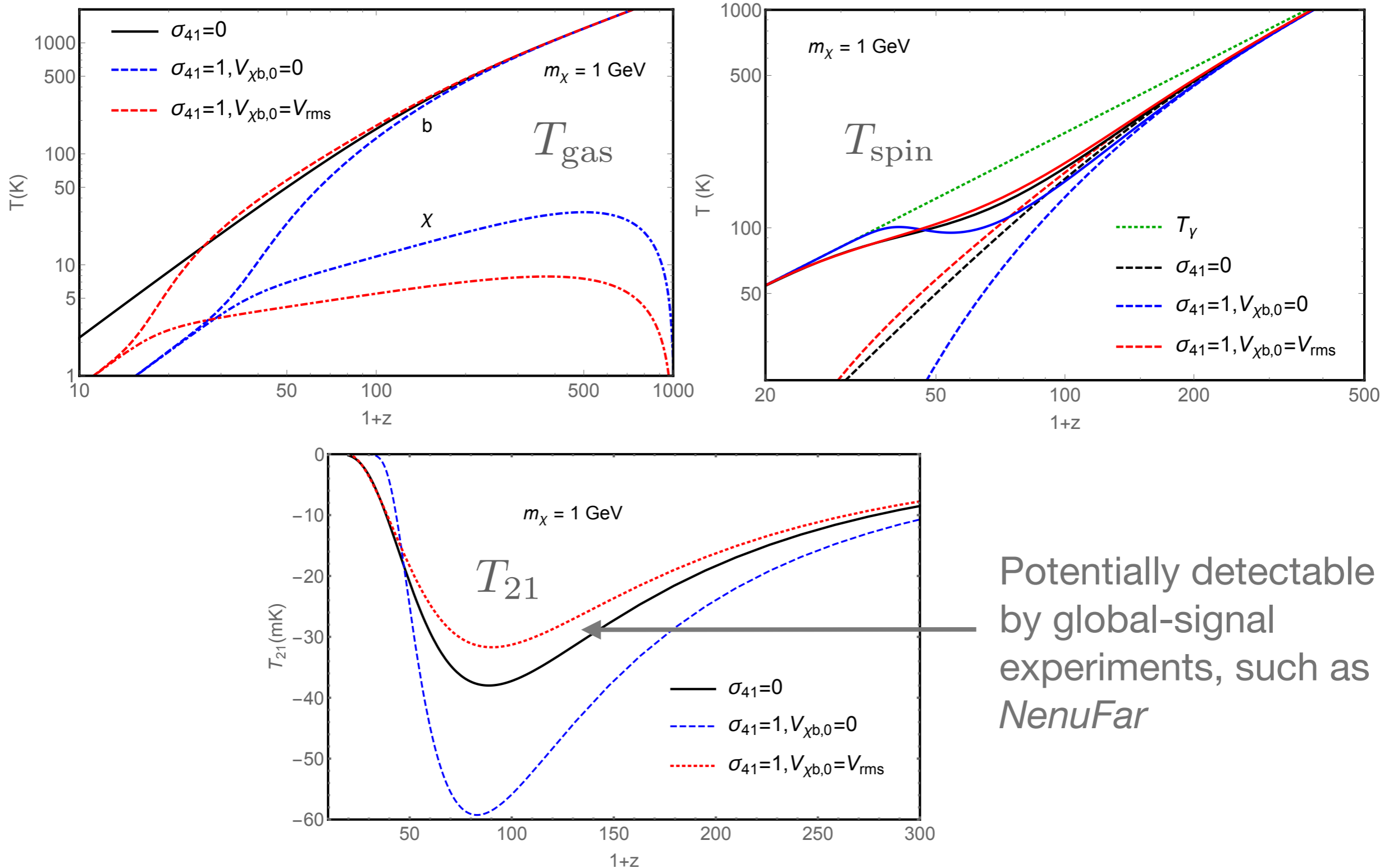
Heating effect: global signal



Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

Heating effect: global signal



Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

This is not the end of the story, though.

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

This is not the end of the story, though.

Relative velocity depends on sky position

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

This is not the end of the story, though.

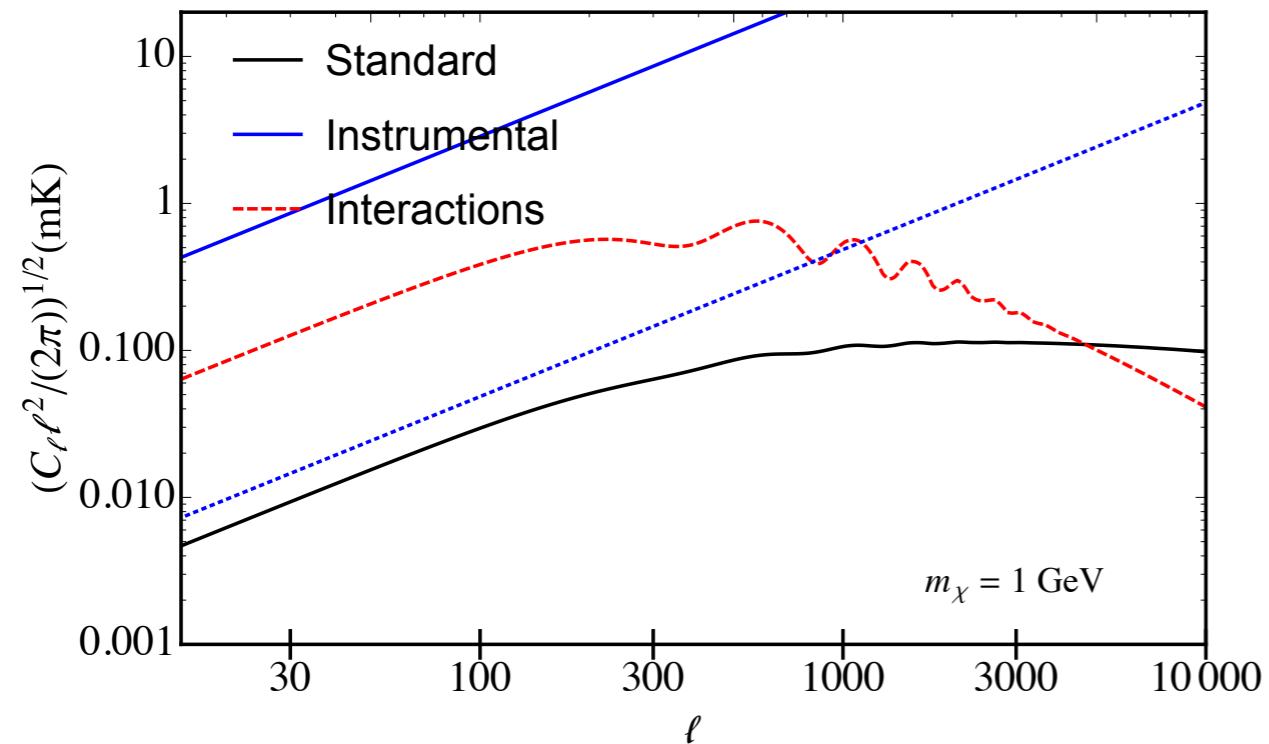
Relative velocity depends on sky position \longrightarrow new source of 21-cm fluctuations!

Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

This is not the end of the story, though.

Relative velocity depends on sky position \longrightarrow new source of 21-cm fluctuations!

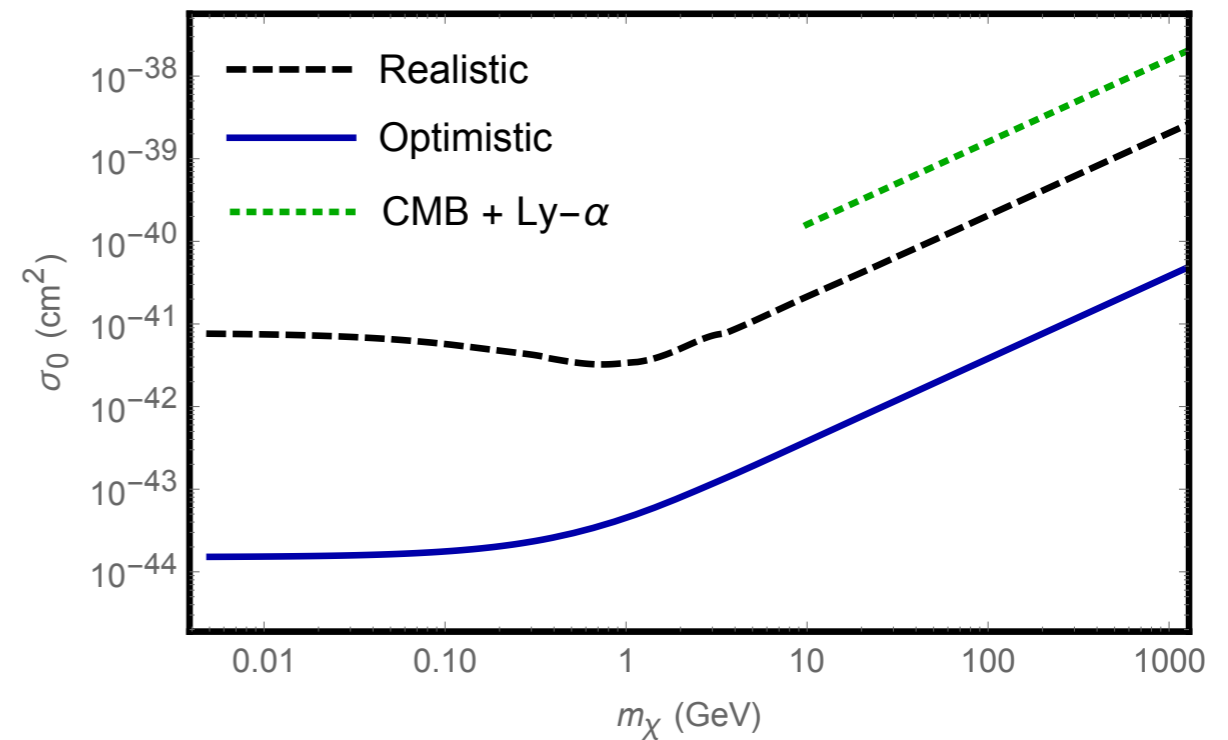
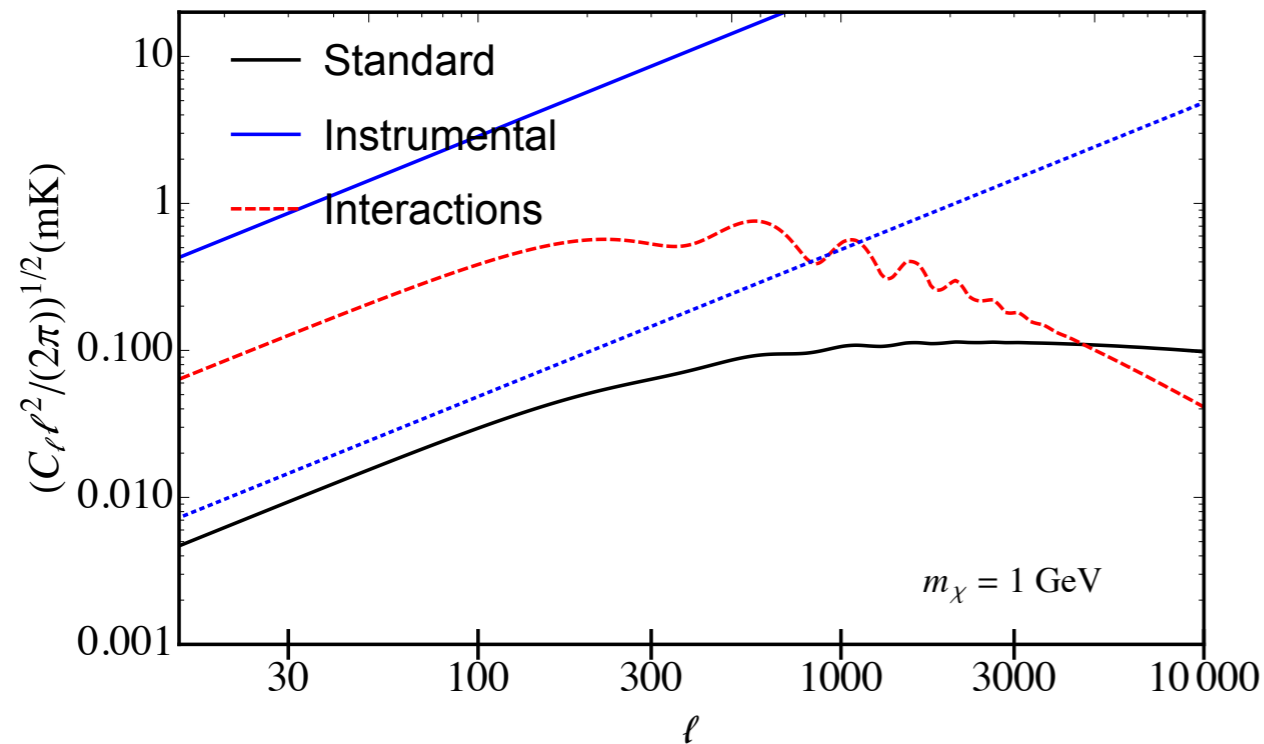


Heating from DM-Baryon Scattering in Dark Ages

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

This is not the end of the story, though.

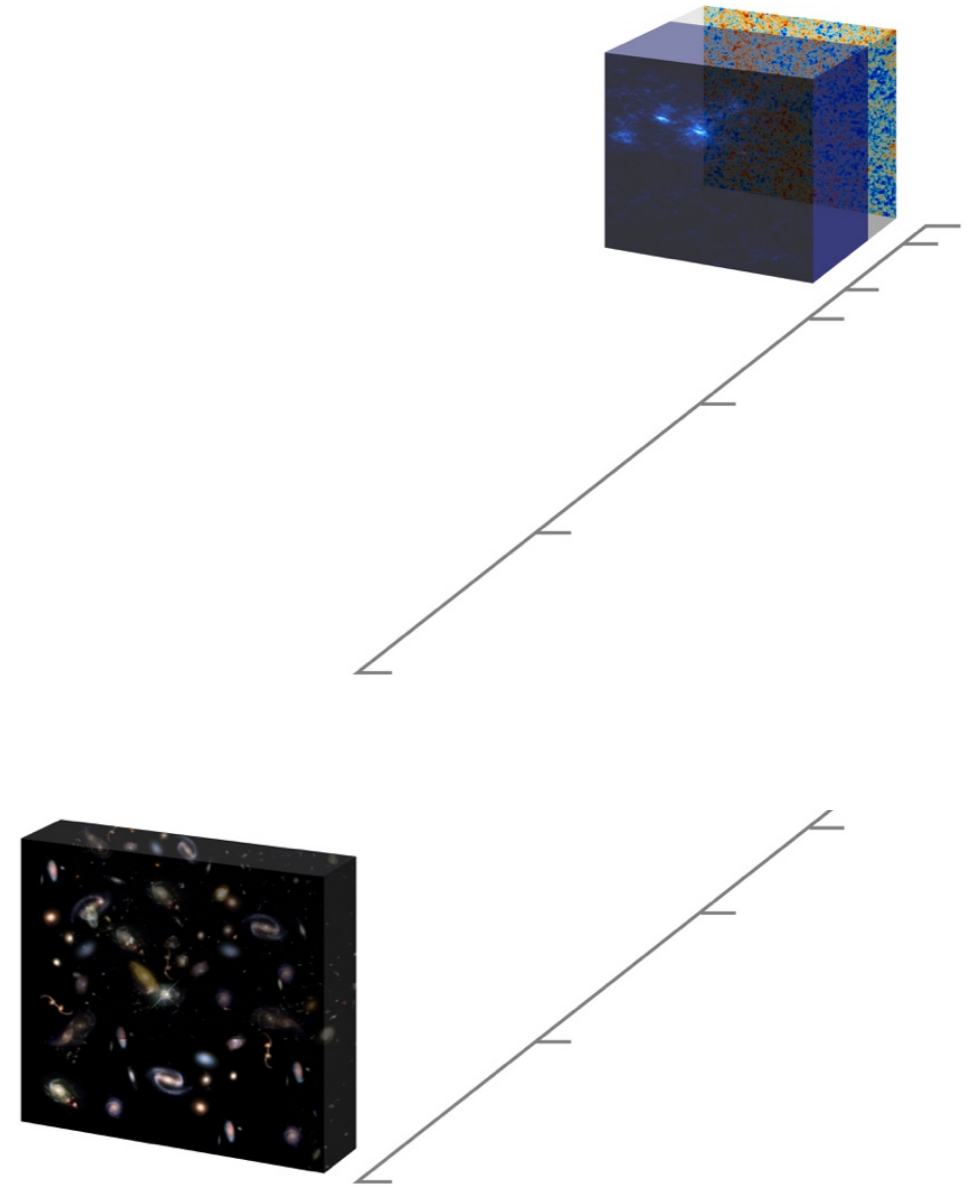
Relative velocity depends on sky position \longrightarrow new source of 21-cm fluctuations!



Realistic (SKA): 6km baseline, 2% cover fraction.

Optimistic: 50km baseline, 10% cover fraction.

- Heat signatures of DM in the dark ages

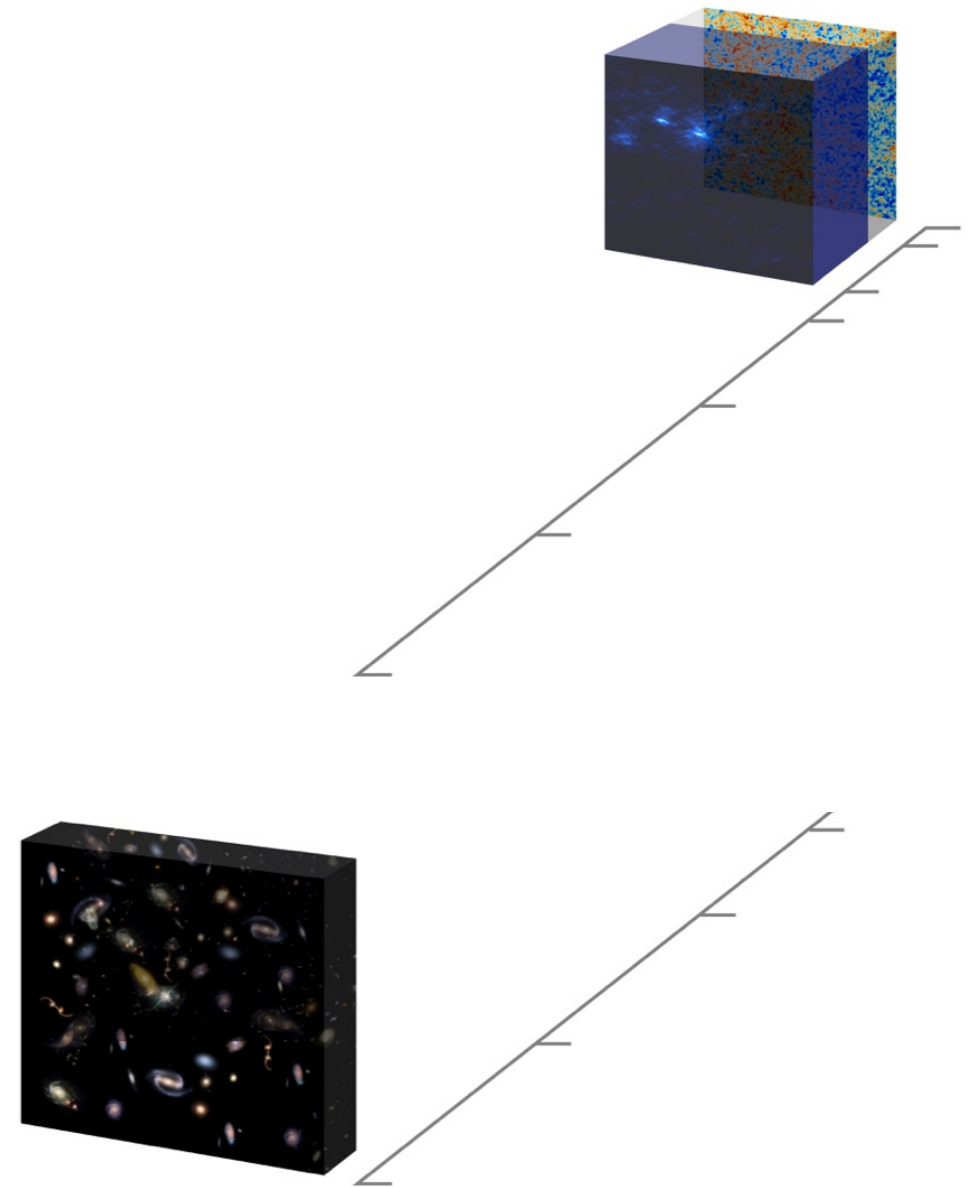


Outline

Ely D. Kovetz
Harvard, Mar. 2016

- Heat signatures of DM in the dark ages

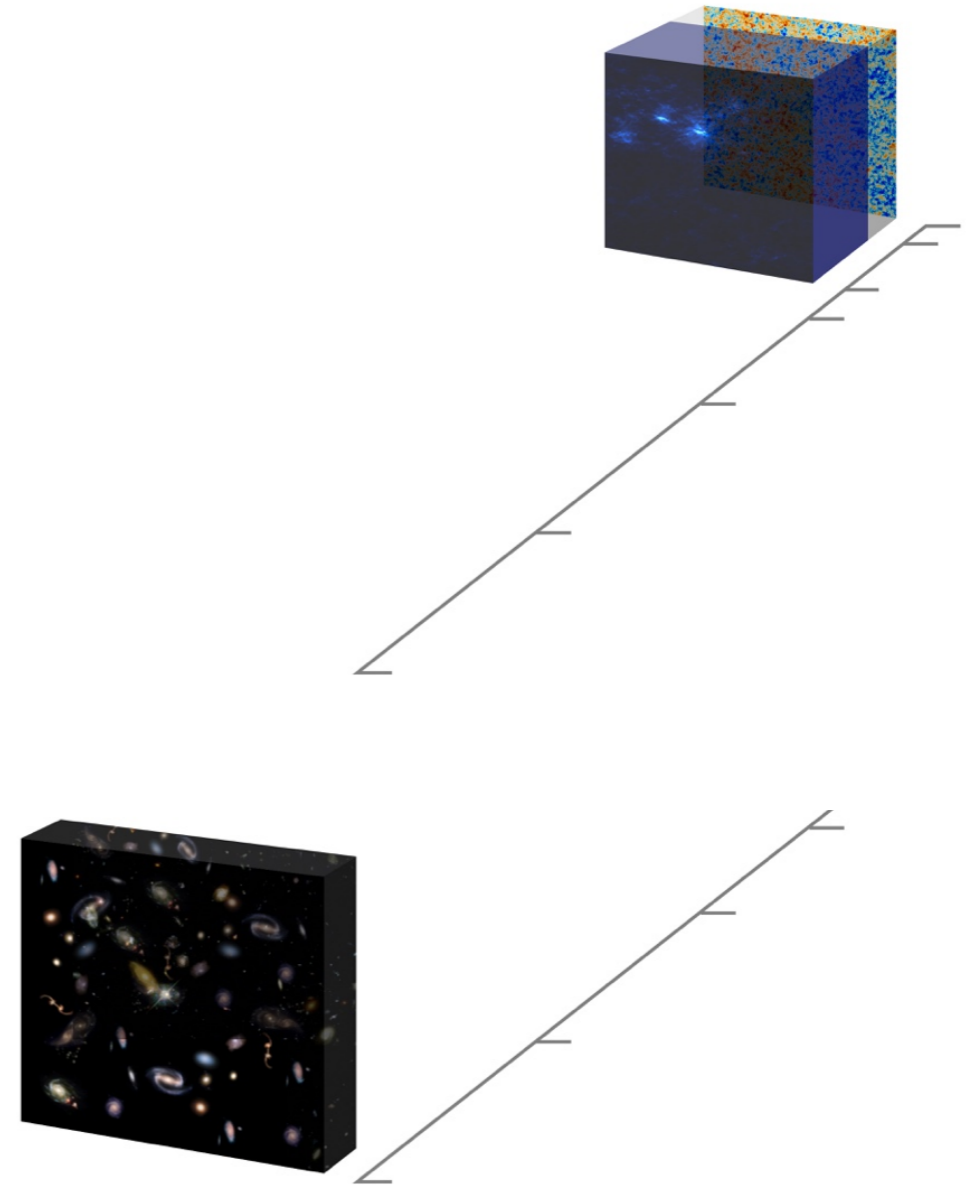
- Flaring tidally compressed DM clumps



- Heat signatures of DM in the dark ages

- Flaring tidally compressed DM clumps

Ali-Haïmoud, EDK and Silk, Phys. Rev. D93 (2016)



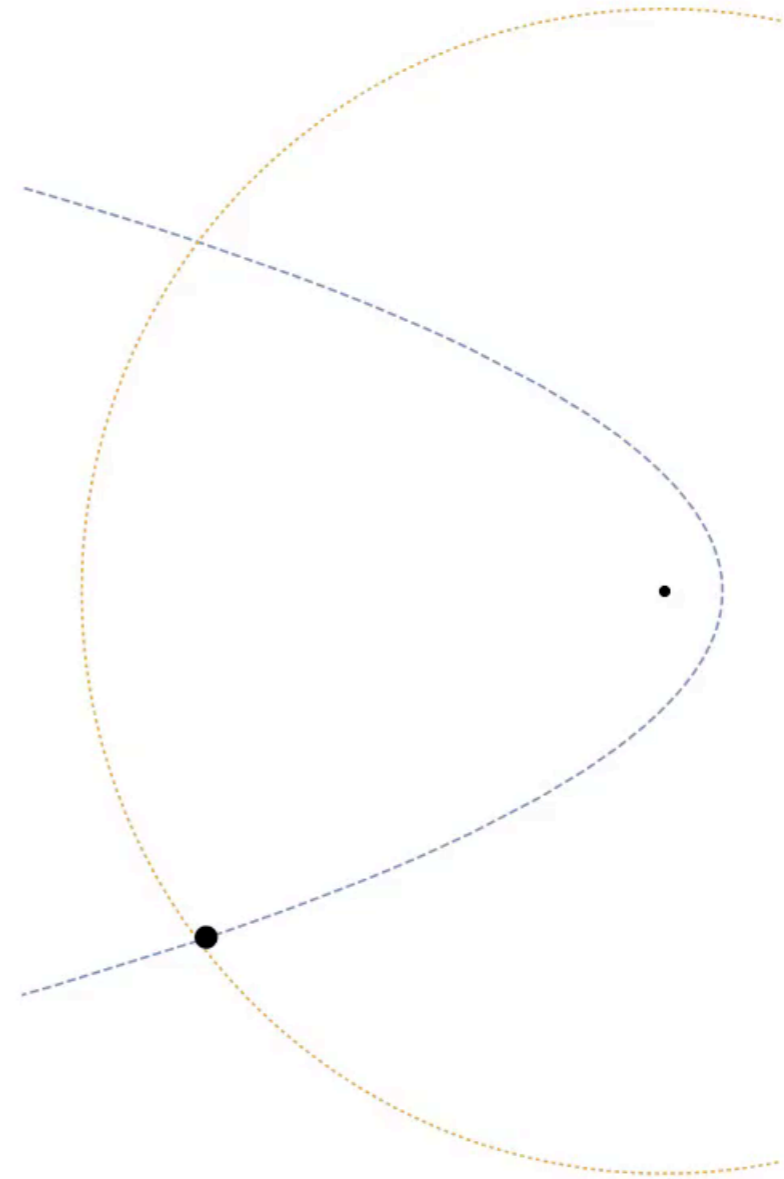
Tidal Compression of Dark Matter Clumps

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Tidal Compression of Dark Matter Clumps

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Purely phenomenological questions:

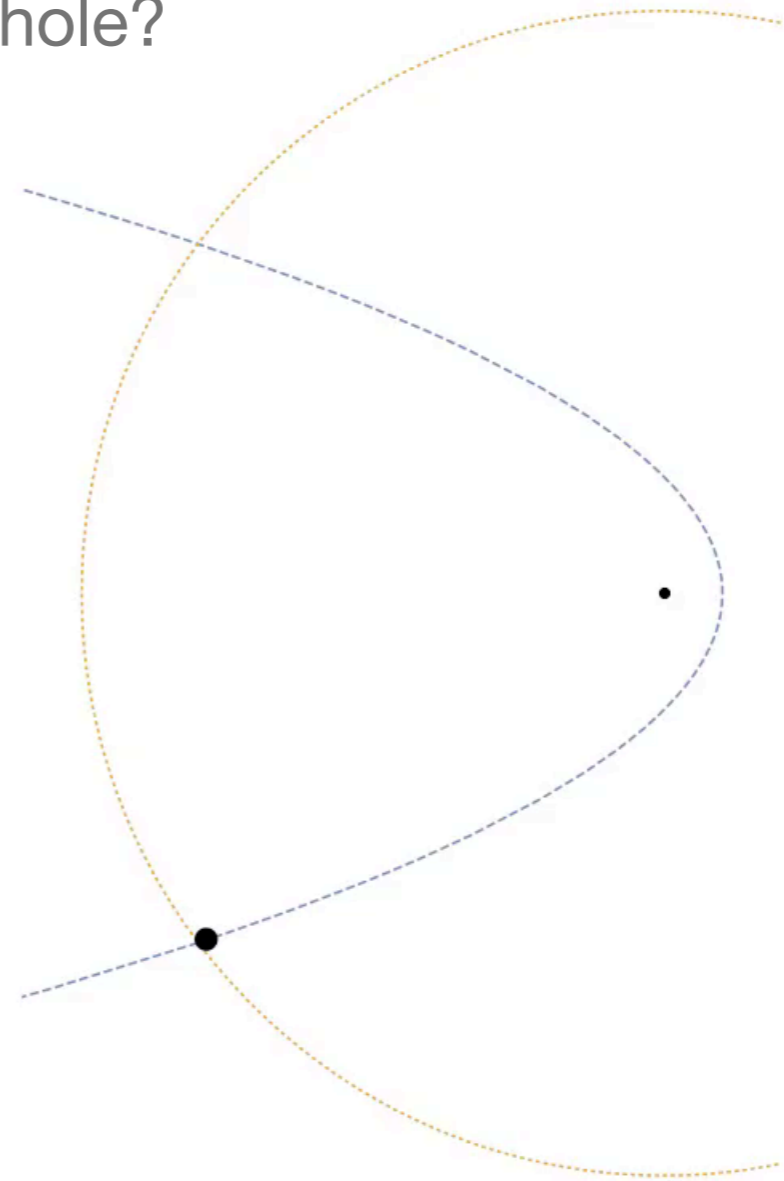


Tidal Compression of Dark Matter Clumps

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Purely phenomenological questions:

Q: What happens if a dark matter clump penetrates the tidal sphere of a super-massive black hole?



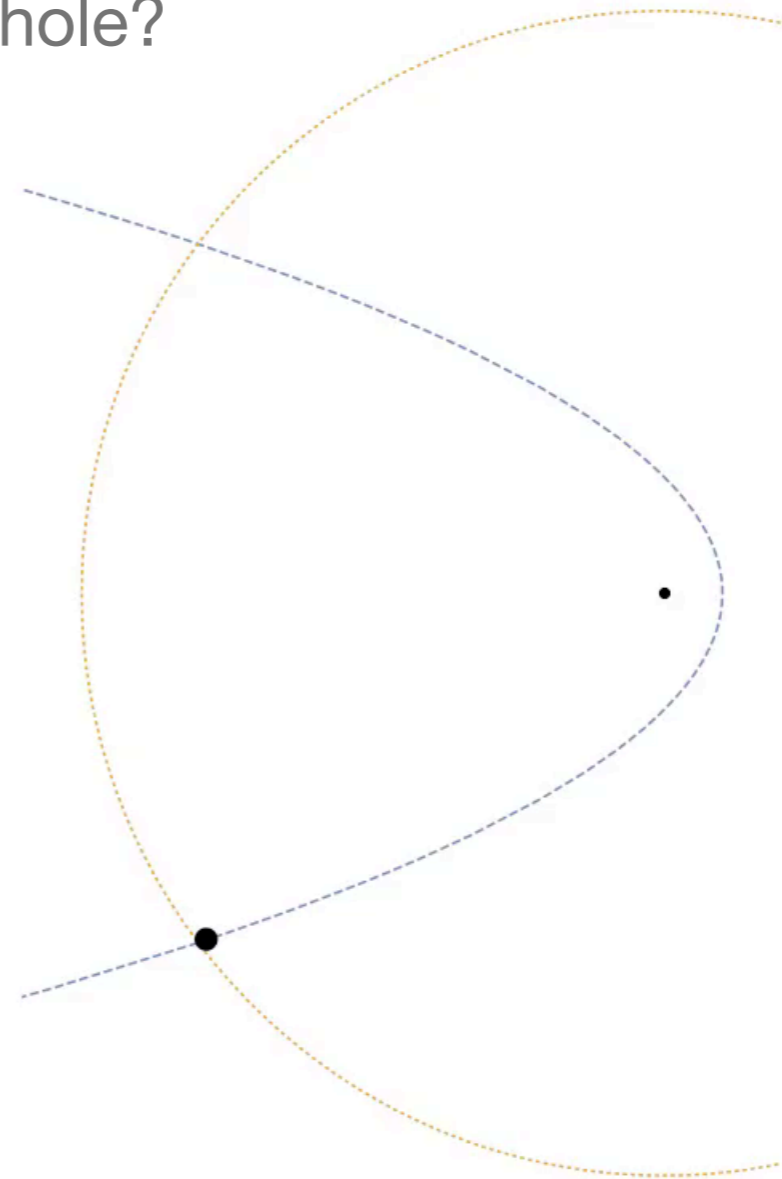
Tidal Compression of Dark Matter Clumps

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Purely phenomenological questions:

Q: What happens if a dark matter clump penetrates the tidal sphere of a super-massive black hole?

A: It will be undergo compression



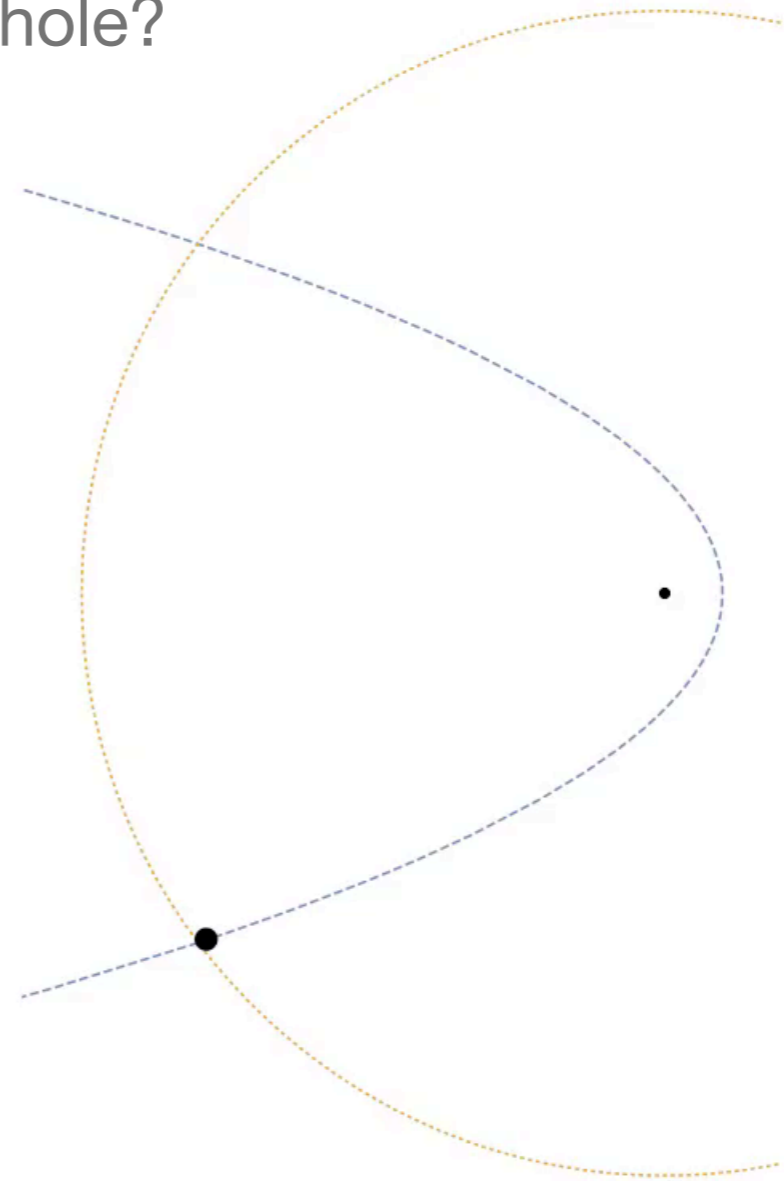
Tidal Compression of Dark Matter Clumps

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Purely phenomenological questions:

Q: What happens if a dark matter clump penetrates the tidal sphere of a super-massive black hole?

A: It will be undergo compression
orbital-plane: stretching/compression



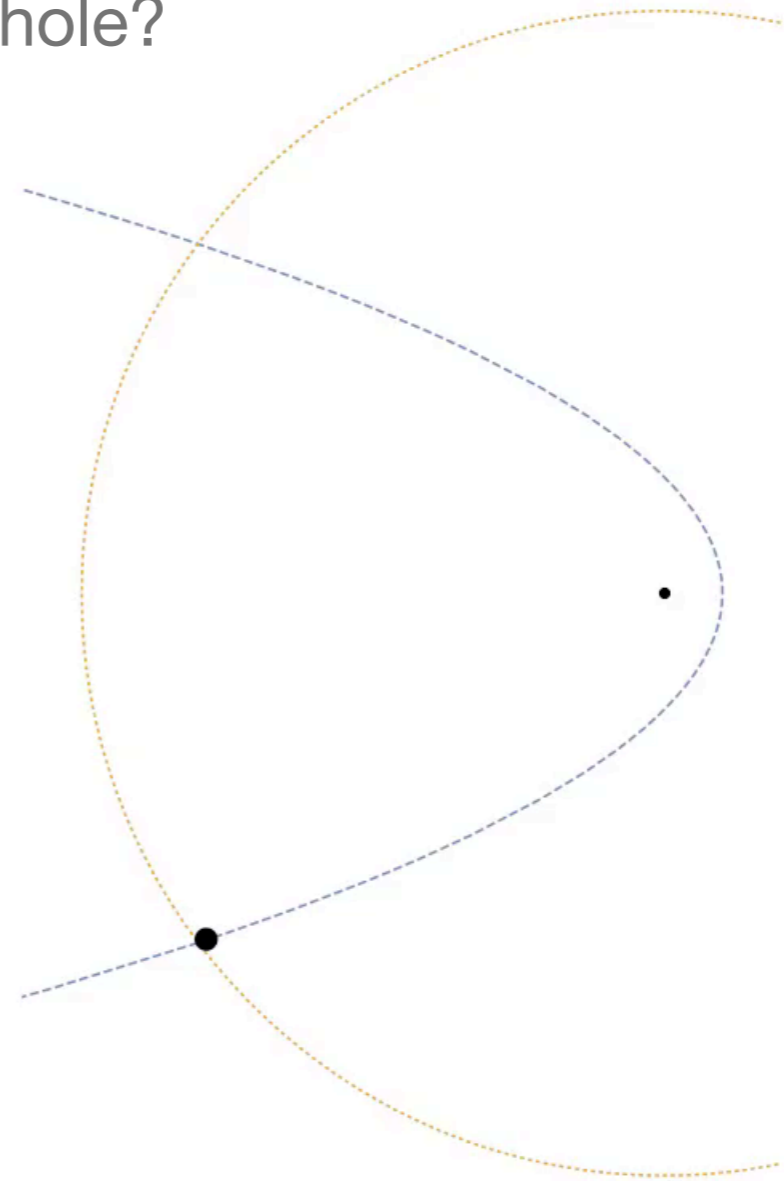
Tidal Compression of Dark Matter Clumps

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Purely phenomenological questions:

Q: What happens if a dark matter clump penetrates the tidal sphere of a super-massive black hole?

A: It will be undergo compression
orbital-plane: stretching/compression



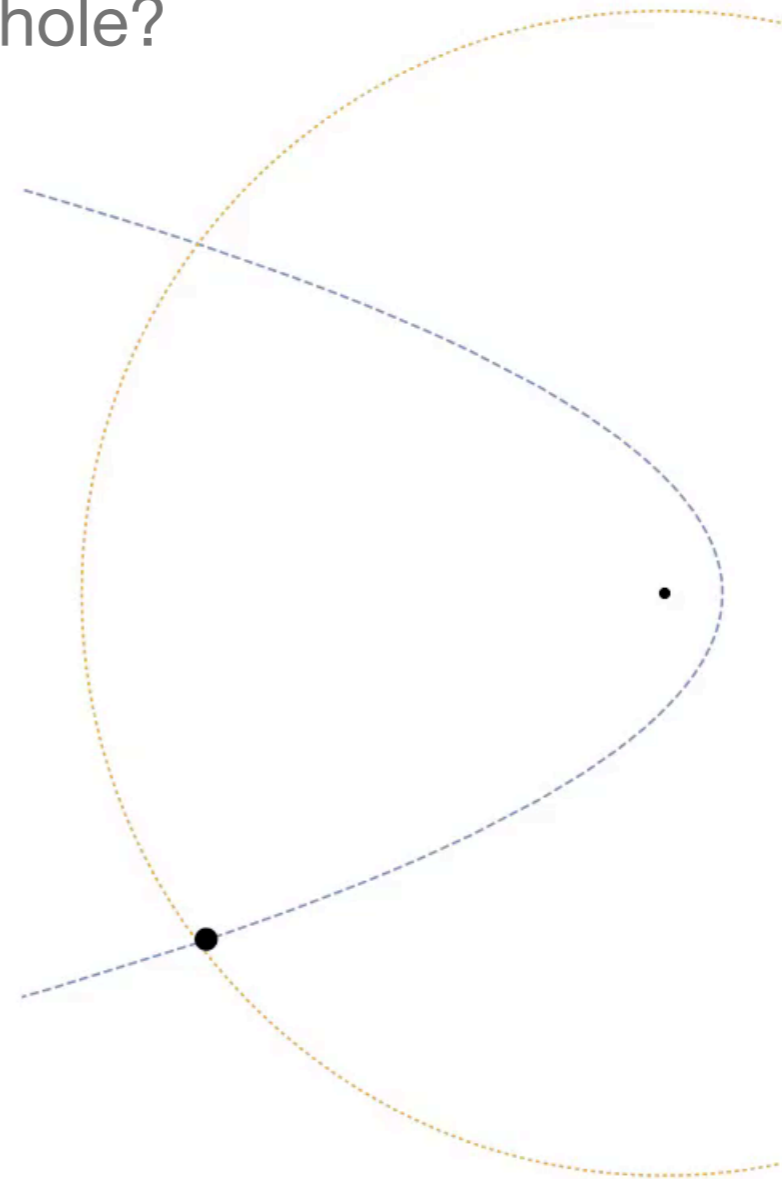
Tidal Compression of Dark Matter Clumps

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Purely phenomenological questions:

Q: What happens if a dark matter clump penetrates the tidal sphere of a super-massive black hole?

A: It will be undergo compression
orbital-plane: stretching/compression
z-direction: significant compression!



Tidal Compression of Dark Matter Clumps

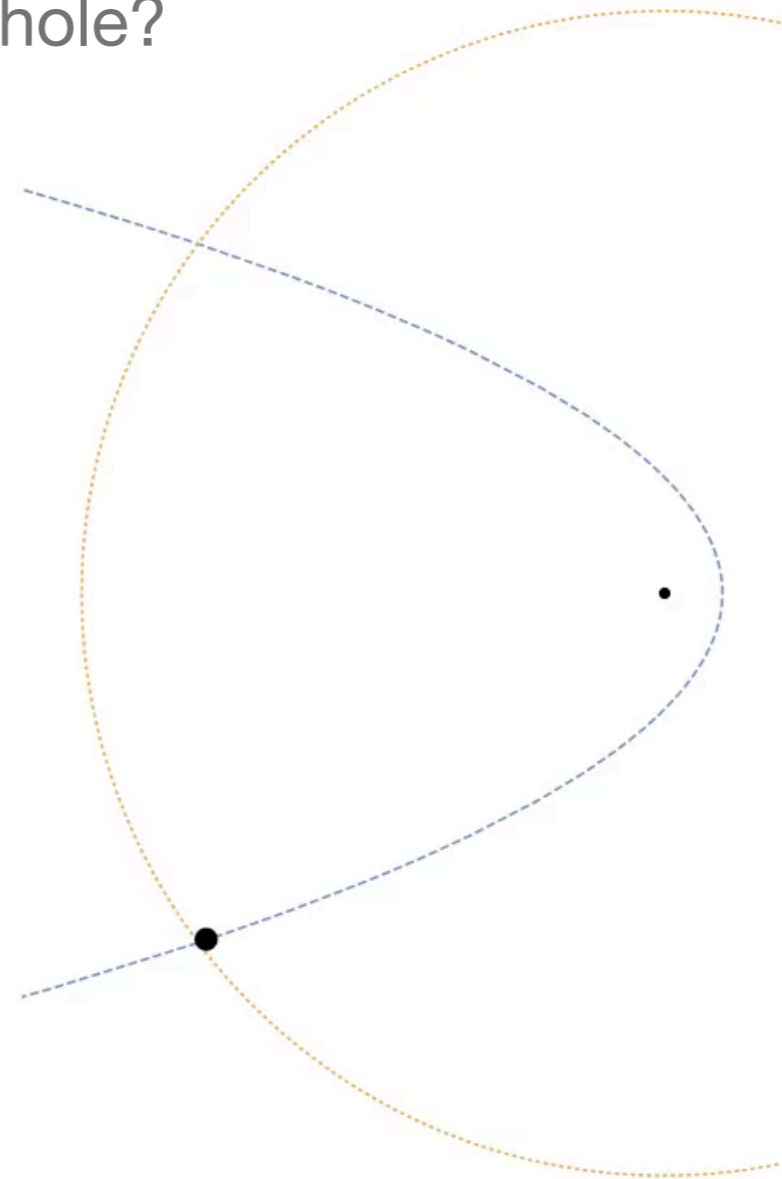
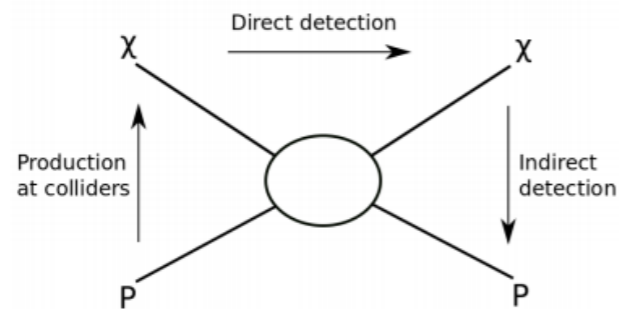
(Ali-Haïmoud, EDK and Silk, PRD 2016)

Purely phenomenological questions:

Q: What happens if a dark matter clump penetrates the tidal sphere of a super-massive black hole?

A: It will be undergo compression
orbital-plane: stretching/compression
z-direction: significant compression!

Q: What if dark matter is self-annihilating?



Tidal Compression of Dark Matter Clumps

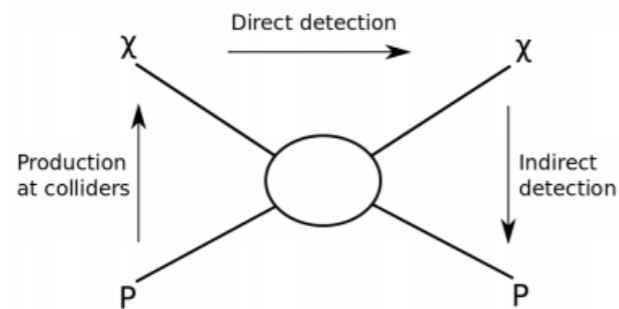
(Ali-Haïmoud, EDK and Silk, PRD 2016)

Purely phenomenological questions:

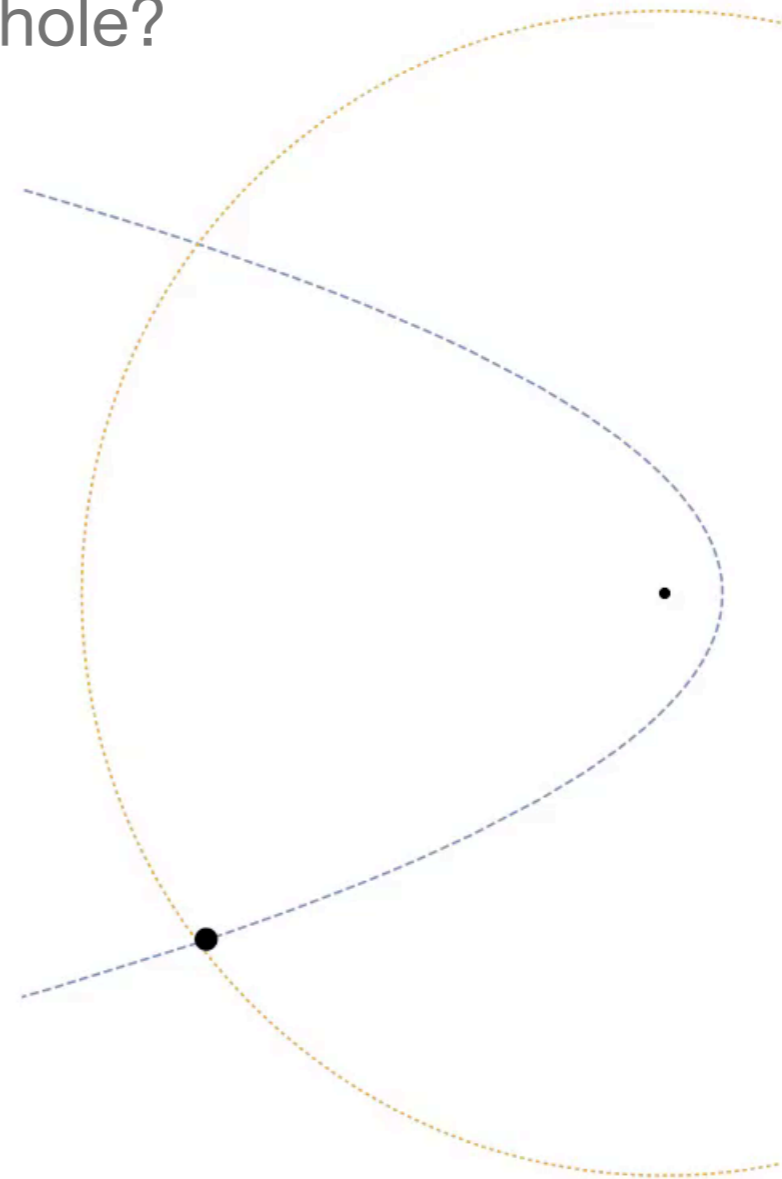
Q: What happens if a dark matter clump penetrates the tidal sphere of a super-massive black hole?

A: It will be undergo compression
orbital-plane: stretching/compression
z-direction: significant compression!

Q: What if dark matter is self-annihilating?



A: annihilation flux will be boosted



Tidal Compression of Dark Matter Clumps

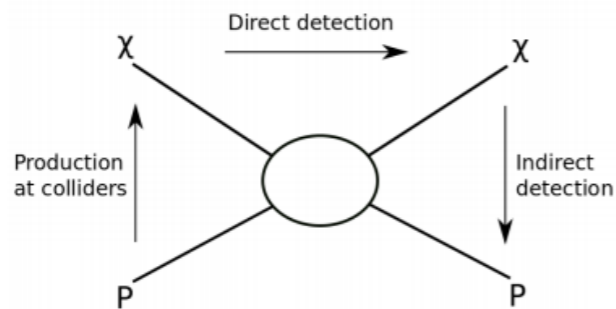
(Ali-Haïmoud, EDK and Silk, PRD 2016)

Purely phenomenological questions:

Q: What happens if a dark matter clump penetrates the tidal sphere of a super-massive black hole?

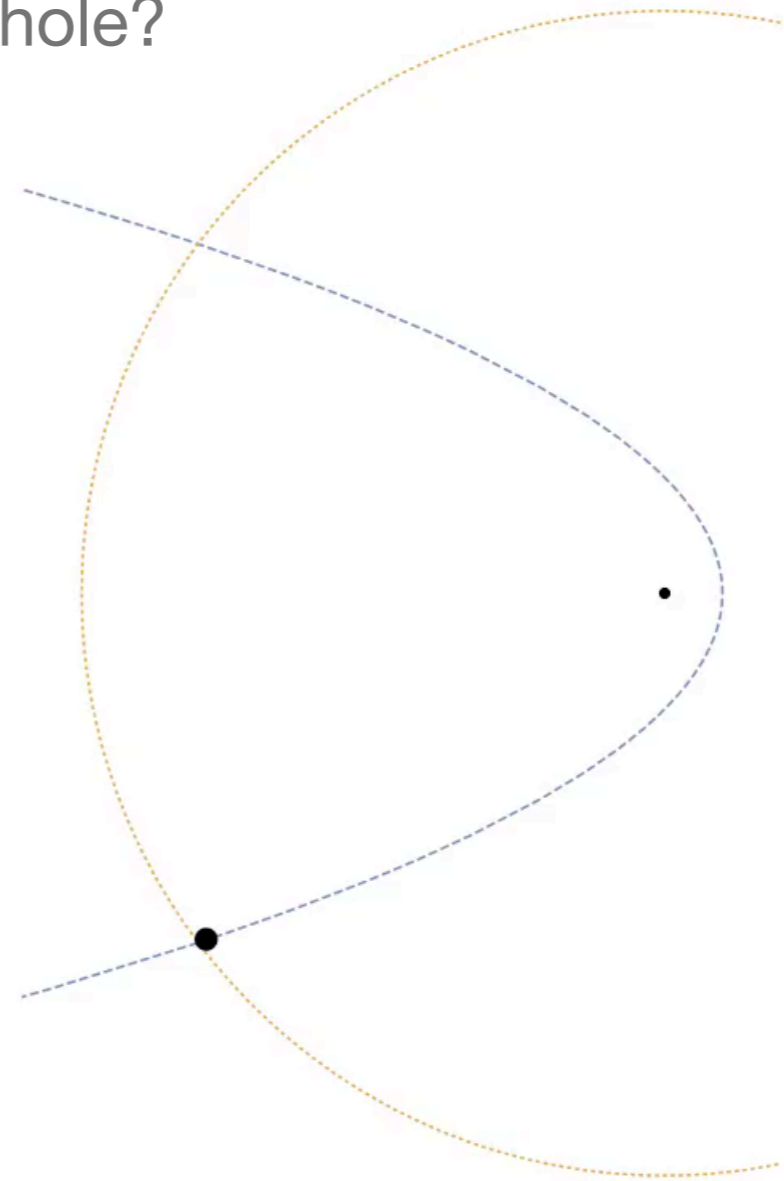
A: It will be undergo compression
orbital-plane: stretching/compression
z-direction: significant compression!

Q: What if dark matter is self-annihilating?



A: annihilation flux will be boosted

$$\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3 r \rho(r)^2$$



Tidal Compression of Dark Matter Clumps

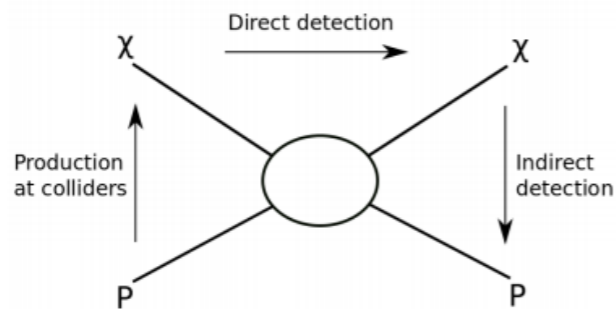
(Ali-Haïmoud, EDK and Silk, PRD 2016)

Purely phenomenological questions:

Q: What happens if a dark matter clump penetrates the tidal sphere of a super-massive black hole?

A: It will be undergo compression
orbital-plane: stretching/compression
z-direction: significant compression!

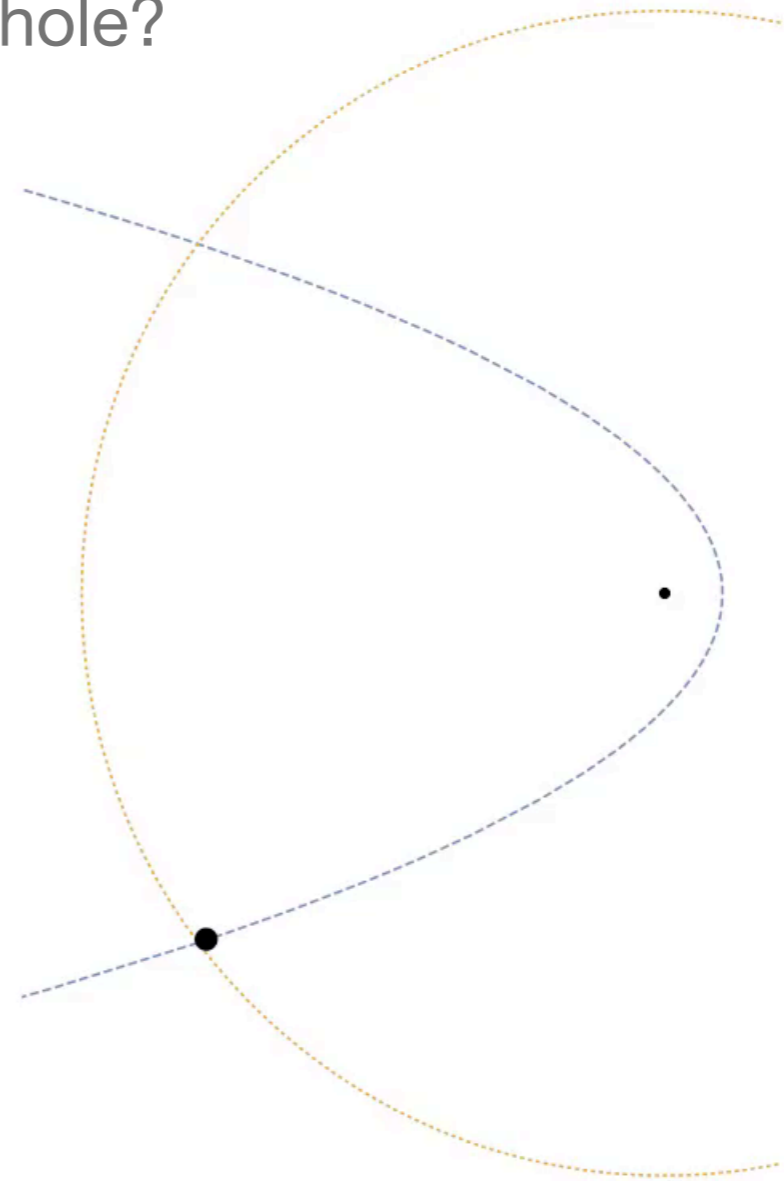
Q: What if dark matter is self-annihilating?



A: annihilation flux will be boosted

$$\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_{\chi}^2} \int d^3 r \rho(r)^2$$

Flares!



TCEs of DMCs: Ingredients

(Ali-Haïmoud, EDK and Silk, PRD 2016)

TCEs of DMCs: Ingredients

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- DM clumps:

TCEs of DMCs: Ingredients

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- DM clumps:

Could be very dense (“failed” primordial black holes).

TCEs of DMCs: Ingredients

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- DM clumps:

Could be very dense (“failed” primordial black holes).

Core could possibly survive destruction.

TCEs of DMCs: Ingredients

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- DM clumps:

Could be very dense (“failed” primordial black holes).

Core could possibly survive destruction.

- Tidal radius:

$$R_t \equiv \left(\frac{3M_{\text{BH}}}{4\pi\rho_{\text{cl}}} \right)^{1/3} \approx 6 \times 10^{-3} M_{\text{BH},6}^{1/3} \rho_{10}^{-1/3} \text{pc}$$

TCEs of DMCs: Ingredients

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- DM clumps:

Could be very dense (“failed” primordial black holes).

Core could possibly survive destruction.

- Tidal radius:

$$R_t \equiv \left(\frac{3M_{\text{BH}}}{4\pi\rho_{\text{cl}}} \right)^{1/3} \approx 6 \times 10^{-3} M_{\text{BH},6}^{1/3} \rho_{10}^{-1/3} \text{pc}$$

- Solve the equation of motion for each mass element:

$$\ddot{\mathbf{r}} = \left(\frac{R_t}{R} \right)^3 \left(3(\hat{R} \cdot \mathbf{r})\hat{R} - \mathbf{r} \right)$$

TCEs of DMCs: Ingredients

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- DM clumps:

Could be very dense (“failed” primordial black holes).

Core could possibly survive destruction.

- Tidal radius:

$$R_t \equiv \left(\frac{3M_{\text{BH}}}{4\pi\rho_{\text{cl}}} \right)^{1/3} \approx 6 \times 10^{-3} M_{\text{BH},6}^{1/3} \rho_{10}^{-1/3} \text{pc}$$

- Solve the equation of motion for each mass element:

$$\ddot{\mathbf{r}} = \left(\frac{R_t}{R} \right)^3 \left(3(\hat{R} \cdot \mathbf{r})\hat{R} - \mathbf{r} \right)$$

normalized distance to center-of-mass

center-of-mass trajectory

TCEs of DMCs: Ingredients

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- DM clumps:

Could be very dense (“failed” primordial black holes).

Core could possibly survive destruction.

- Tidal radius:

$$R_t \equiv \left(\frac{3M_{\text{BH}}}{4\pi\rho_{\text{cl}}} \right)^{1/3} \approx 6 \times 10^{-3} M_{\text{BH},6}^{1/3} \rho_{10}^{-1/3} \text{pc}$$

- Solve the equation of motion for each mass element:

$$\ddot{\mathbf{r}} = \left(\frac{R_t}{R} \right)^3 \left(3(\hat{R} \cdot \mathbf{r})\hat{R} - \mathbf{r} \right)$$

normalized distance to center-of-mass

center-of-mass trajectory

- Phase-space conservation (Liouville theorem):

TCEs of DMCs: Ingredients

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- DM clumps:

Could be very dense (“failed” primordial black holes).

Core could possibly survive destruction.

- Tidal radius:

$$R_t \equiv \left(\frac{3M_{\text{BH}}}{4\pi\rho_{\text{cl}}} \right)^{1/3} \approx 6 \times 10^{-3} M_{\text{BH},6}^{1/3} \rho_{10}^{-1/3} \text{pc}$$

- Solve the equation of motion for each mass element:

$$\ddot{\mathbf{r}} = \left(\frac{R_t}{R} \right)^3 \left(3(\hat{R} \cdot \mathbf{r})\hat{R} - \mathbf{r} \right)$$

normalized distance to center-of-mass

center-of-mass trajectory

- Phase-space conservation (Liouville theorem):

Allows to easily track the density evolution in either orbital plane or “z”-axis.

TCEs of DMCs: Ingredients

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- DM clumps:

Could be very dense (“failed” primordial black holes).

Core could possibly survive destruction.

- Tidal radius:

$$R_t \equiv \left(\frac{3M_{\text{BH}}}{4\pi\rho_{\text{cl}}} \right)^{1/3} \approx 6 \times 10^{-3} M_{\text{BH},6}^{1/3} \rho_{10}^{-1/3} \text{pc}$$

- Solve the equation of motion for each mass element:

$$\ddot{\mathbf{r}} = \left(\frac{R_t}{R} \right)^3 \left(3(\hat{R} \cdot \mathbf{r})\hat{R} - \mathbf{r} \right)$$

normalized distance to center-of-mass

center-of-mass trajectory

- Phase-space conservation (Liouville theorem):

Allows to easily track the density evolution in either orbital plane or “z”-axis.

- Initial turbulent velocities prevent DMC from reaching infinite densities.

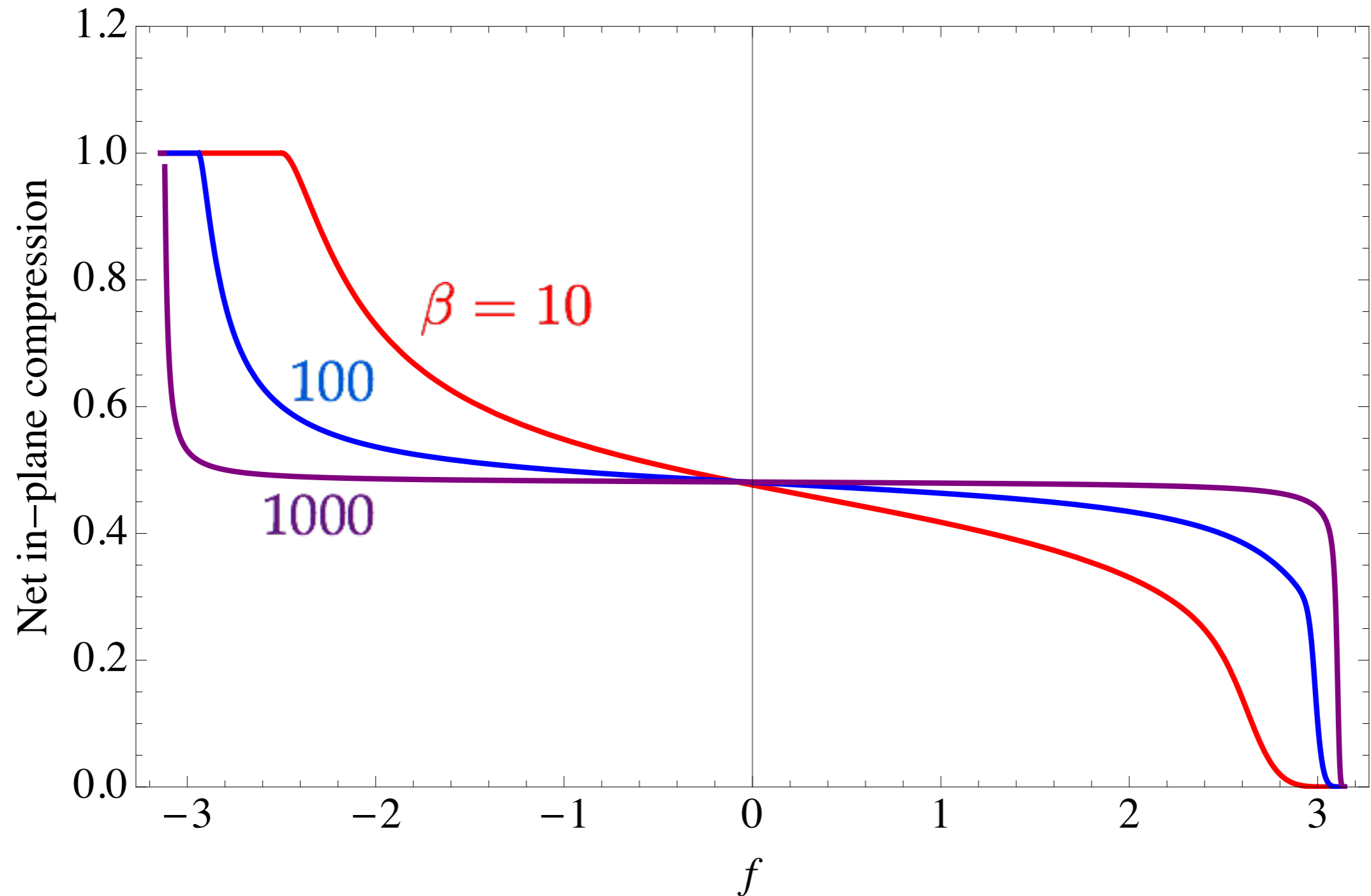
TCEs of DMCs: Orbital Plane

(Ali-Haïmoud, EDK and Silk, PRD 2016)

TCEs of DMCs: Orbital Plane

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- Marginal net dilatation in the orbital plane (factor ~ 2)



TCEs of DMCs: Time Evolution (z-axis)

(Ali-Haïmoud, EDK and Silk, PRD 2016)

TCEs of DMCs: Time Evolution (z-axis)

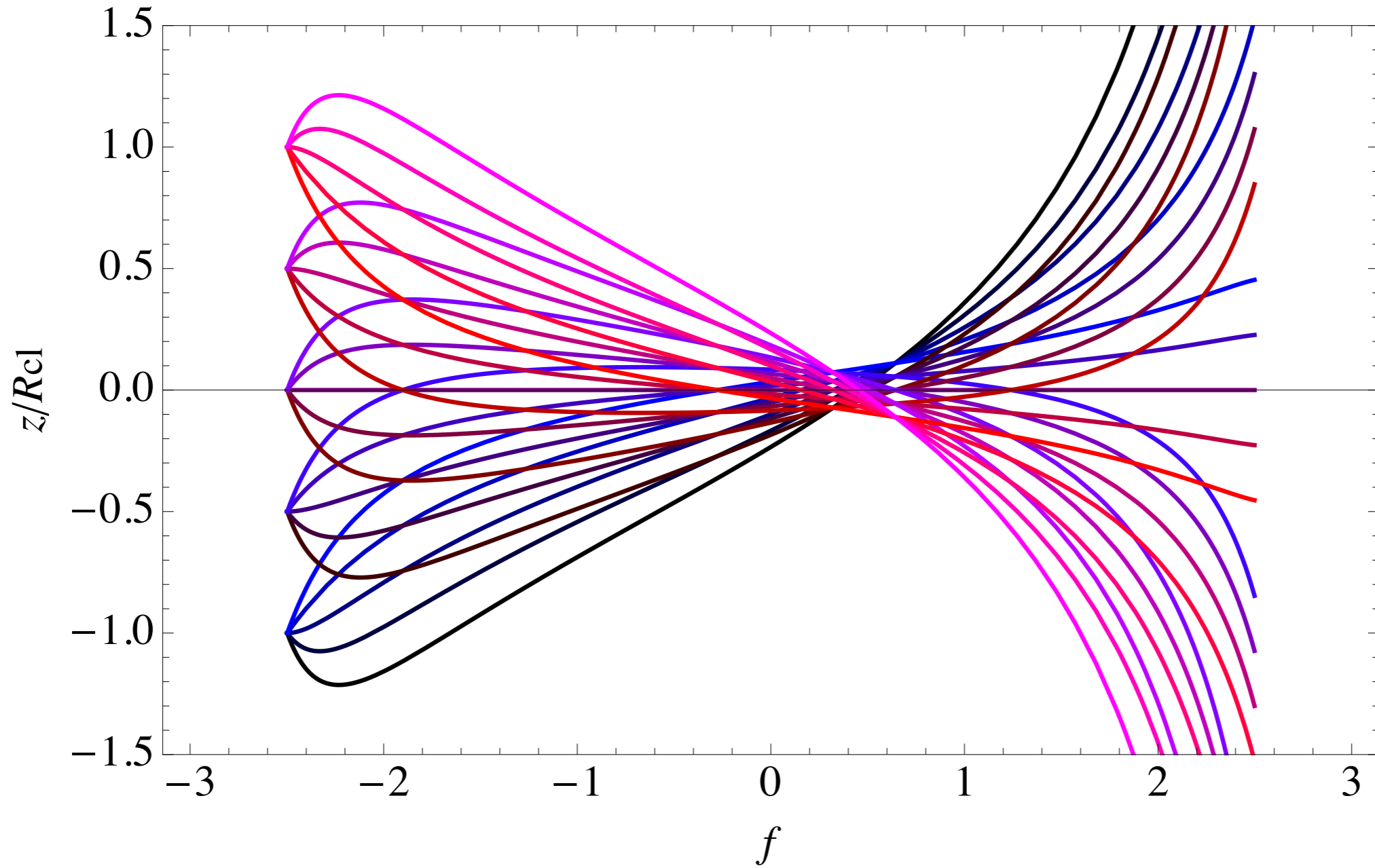
(Ali-Haïmoud, EDK and Silk, PRD 2016)

- Trajectories and velocities:

TCEs of DMCs: Time Evolution (z-axis)

(Ali-Haïmoud, EDK and Silk, PRD 2016)

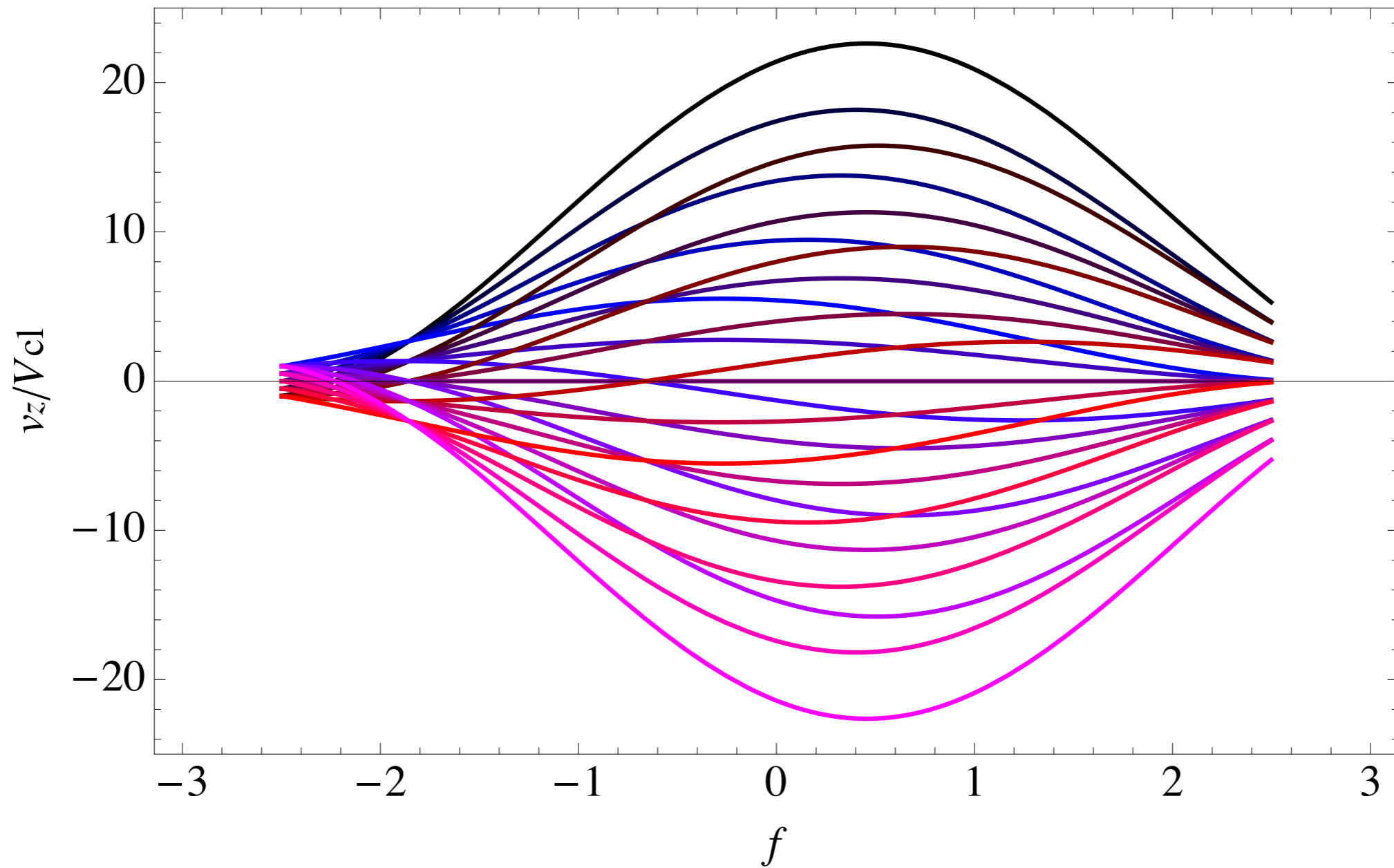
- Trajectories and velocities:



TCEs of DMCs: Time Evolution (z-axis)

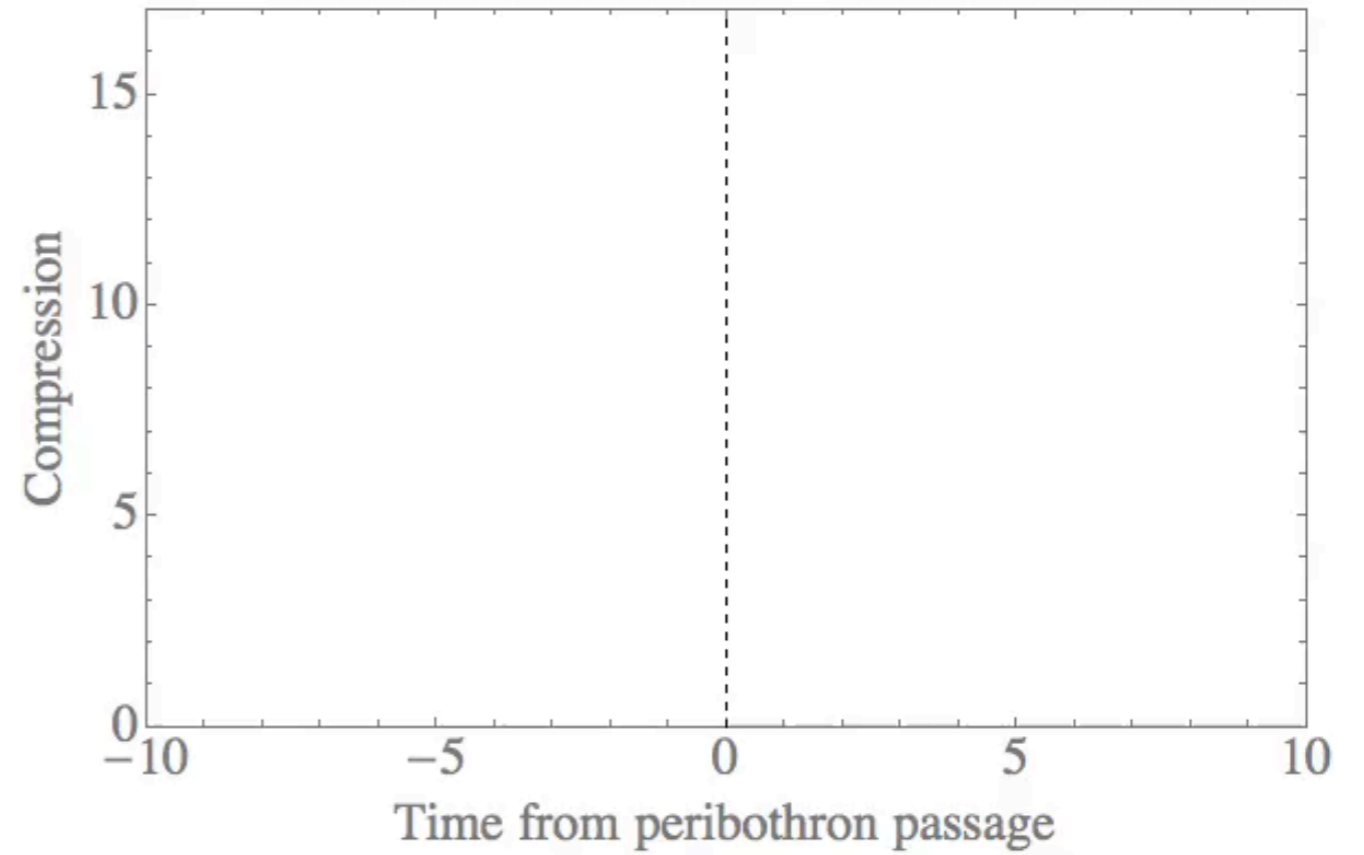
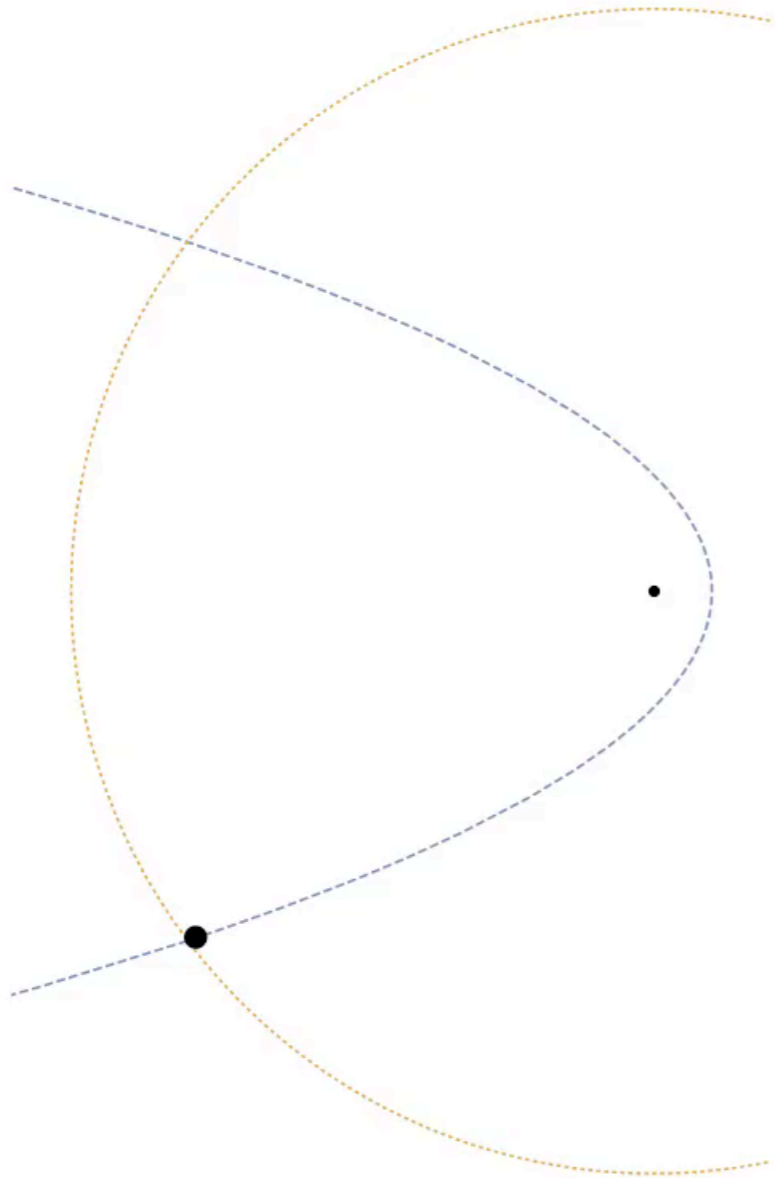
(Ali-Haïmoud, EDK and Silk, PRD 2016)

- Trajectories and velocities:



TCEs of DMCs: Time Evolution (z-axis)

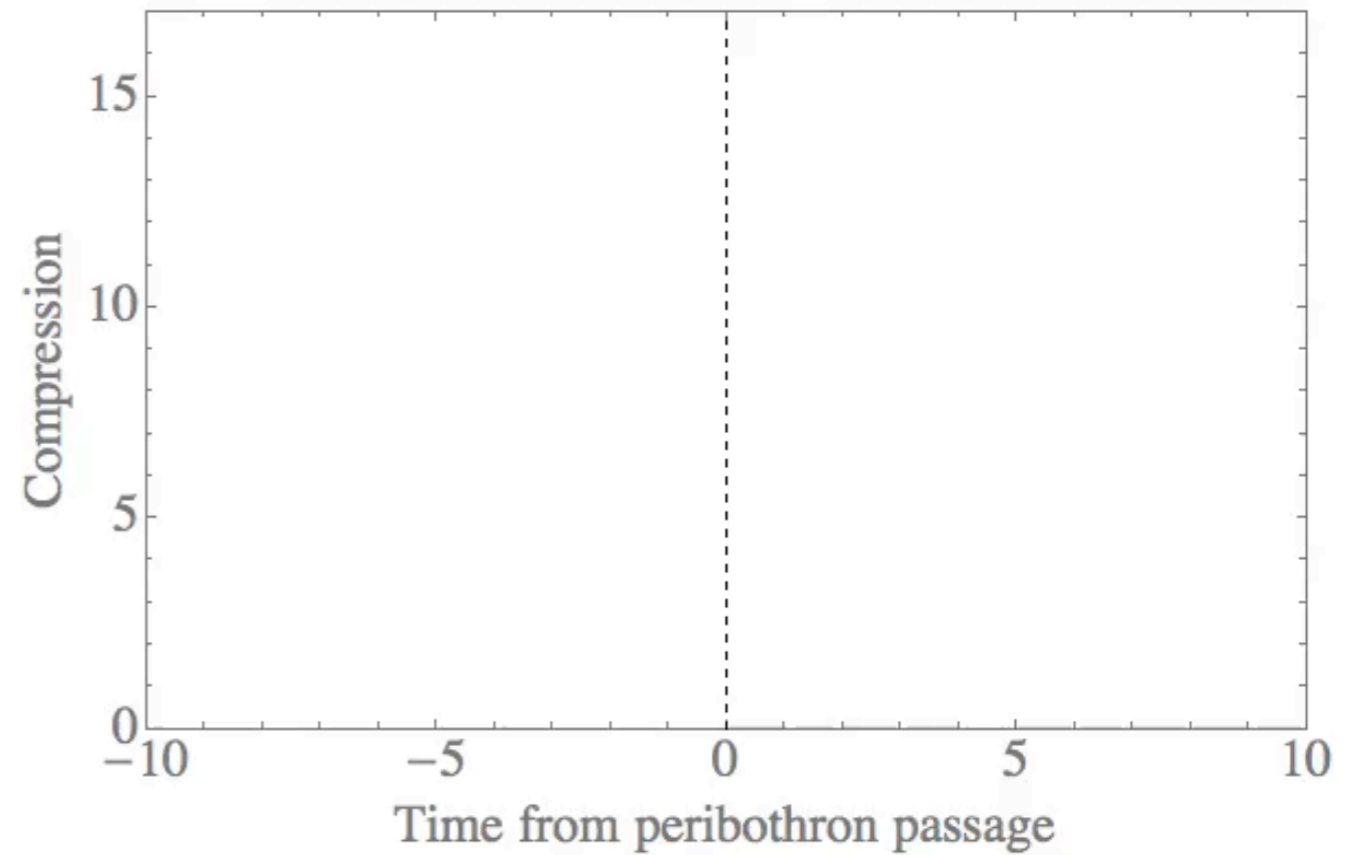
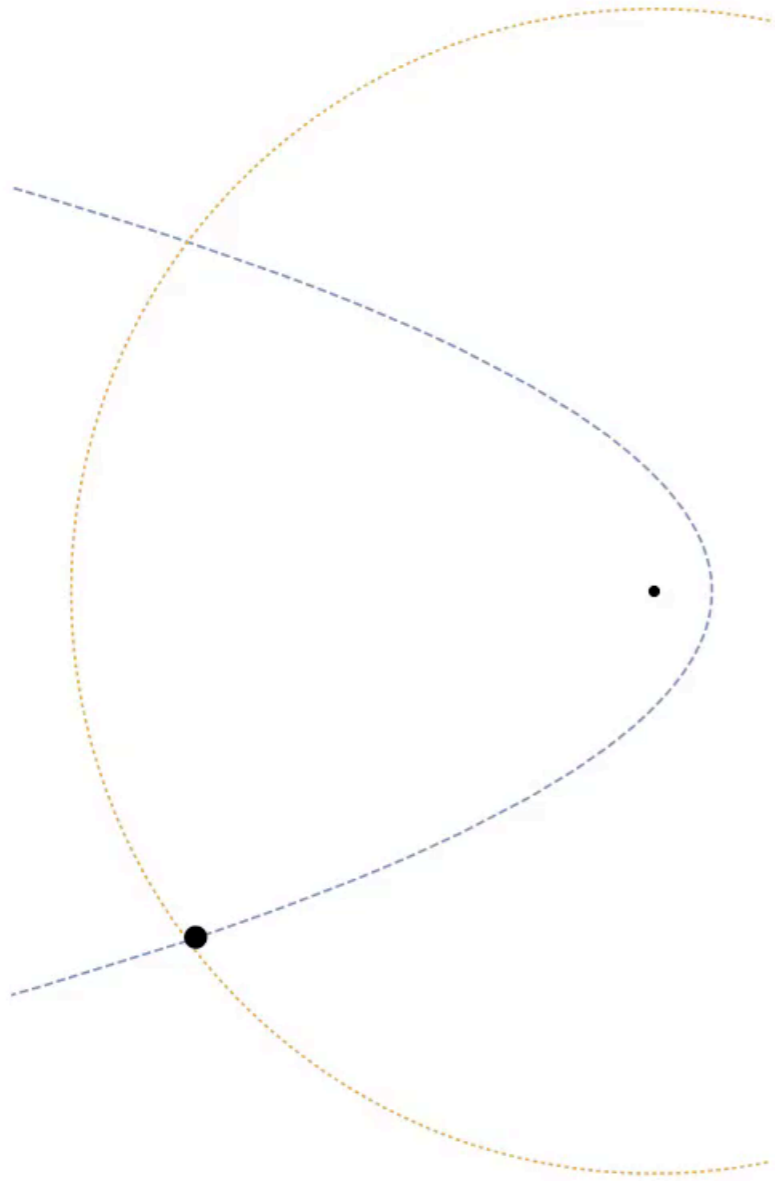
(Ali-Haïmoud, EDK and Silk, PRD 2016)



TCEs of DMCs: Time Evolution (z-axis)

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- Compression peaks shortly after pericenter.



TCEs of DMCs: Compression (z-axis)

(Ali-Haïmoud, EDK and Silk, PRD 2016)

TCEs of DMCs: Compression (z-axis)

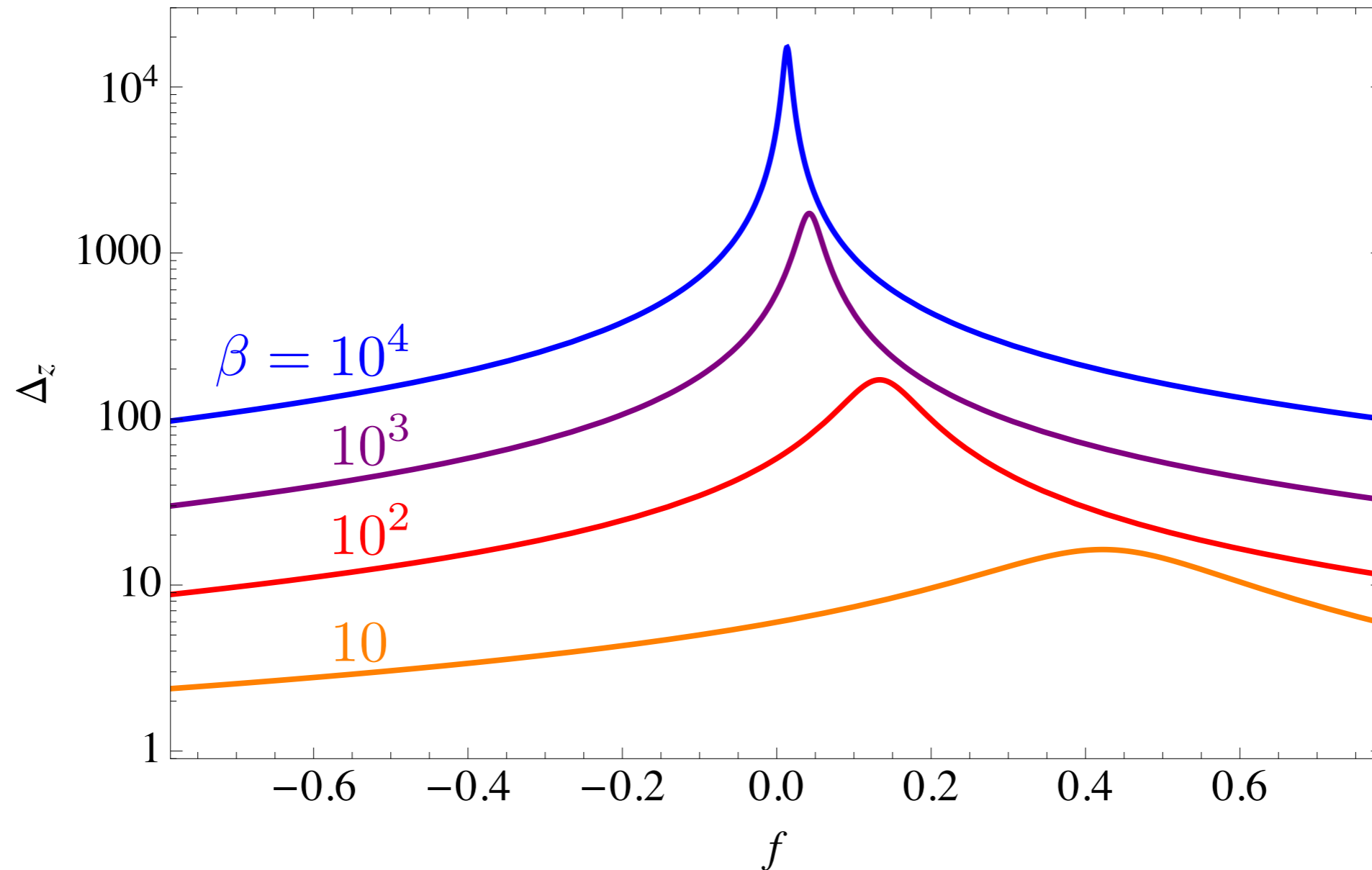
(Ali-Haïmoud, EDK and Silk, PRD 2016)

- Scalings of peak compression with penetration factor $\beta \equiv \frac{R_p}{R_t}$:

TCEs of DMCs: Compression (z-axis)

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- Scalings of peak compression with penetration factor $\beta \equiv \frac{R_p}{R_t}$:



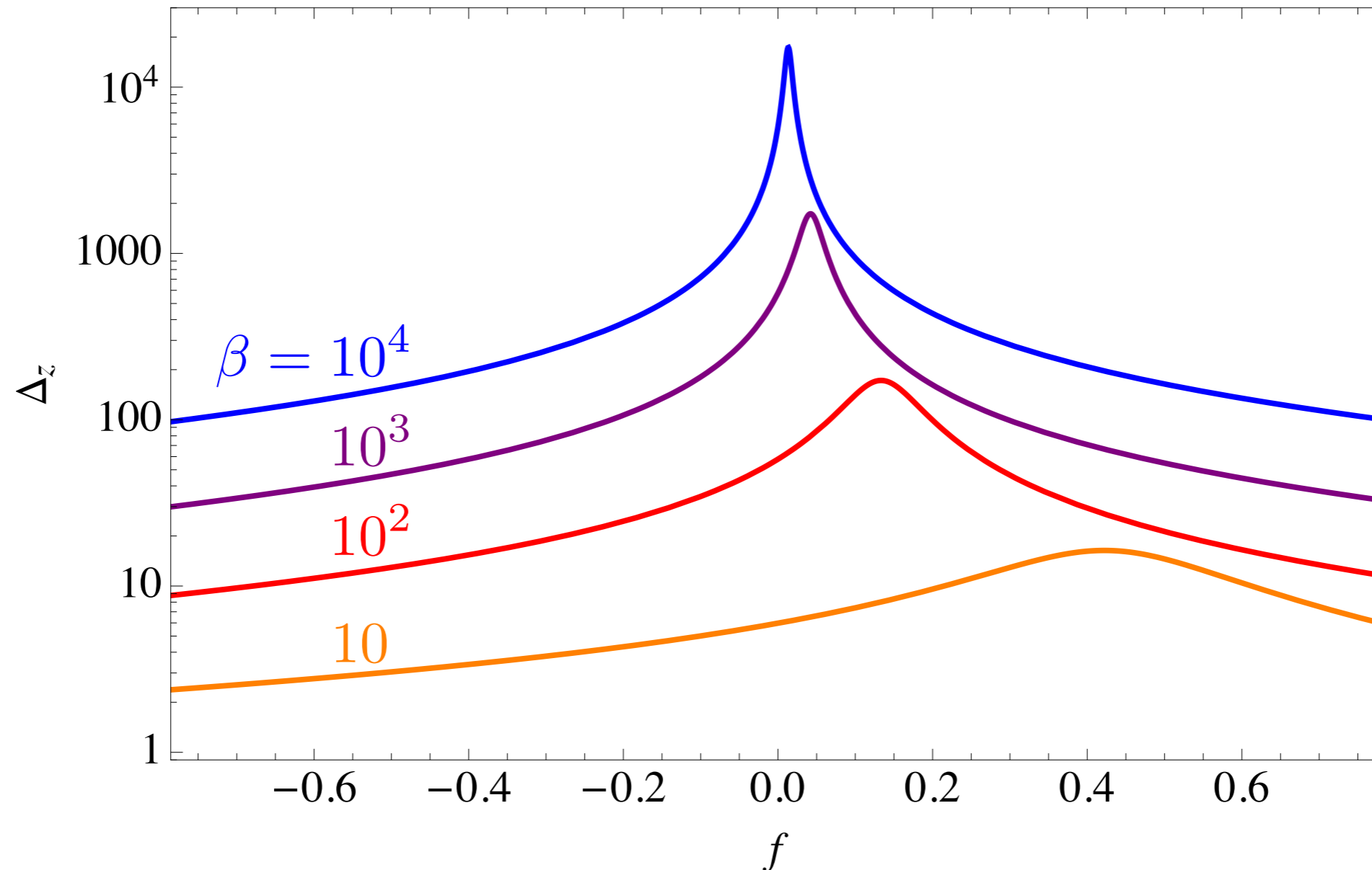
TCEs of DMCs: Compression (z-axis)

(Ali-Haïmoud, EDK and Silk, PRD 2016)

- Scalings of peak compression with penetration factor $\beta \equiv \frac{R_p}{R_t}$:

$$\Delta_t \propto 1/\beta^2$$

$$\max[\Delta_z] \propto \beta$$



TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation:

TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3r \rho(r)^2$

TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3 r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}}$

TCEs of DMCs: Gamma-Ray Flares

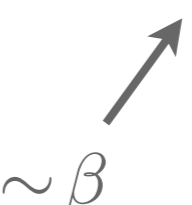
(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation:
$$\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$$

TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3 r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$

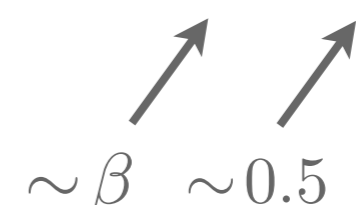


$\sim \beta$

TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3 r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$



$\sim \beta$ ~ 0.5

TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3 r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$

$\sim \beta$ ~ 0.5 $\left\{ \begin{array}{l} 1 \quad \text{s-wave} \\ \beta^2 \quad \text{p-wave} \\ \beta^4 \quad \text{d-wave} \end{array} \right.$

TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3 r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$

Fermi flares?

$\sim \beta$ ~ 0.5 $\propto \begin{cases} 1 & \text{s-wave} \\ \beta^2 & \text{p-wave} \\ \beta^4 & \text{d-wave} \end{cases}$

TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$

Fermi flares?

→ ~1000 photons per week for certain parameter choices.

$\sim \beta$ ~ 0.5 $\left\{ \begin{array}{l} 1 \quad \text{s-wave} \\ \beta^2 \quad \text{p-wave} \\ \beta^4 \quad \text{d-wave} \end{array} \right.$

\propto

TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$

Fermi flares?

→ ~1000 photons per week for certain parameter choices.

$$\begin{array}{c} \nearrow \quad \nearrow \quad \nwarrow \\ \sim \beta \quad \sim 0.5 \quad \left\{ \begin{array}{l} 1 \quad \text{s-wave} \\ \beta^2 \quad \text{p-wave} \\ \beta^4 \quad \text{d-wave} \end{array} \right. \\ \propto \end{array}$$

$$\left(M_{\text{cl}} = 0.1 M_\odot, \quad \rho_{\text{cl}} = 10^{-10} \text{g cm}^{-3}, \quad m_\chi = 1 \text{ GeV}, \quad d = 100 \text{ Mpc}, \quad N_\gamma = \int dE (dN_\gamma/dE) \sim 10 \right)$$

TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

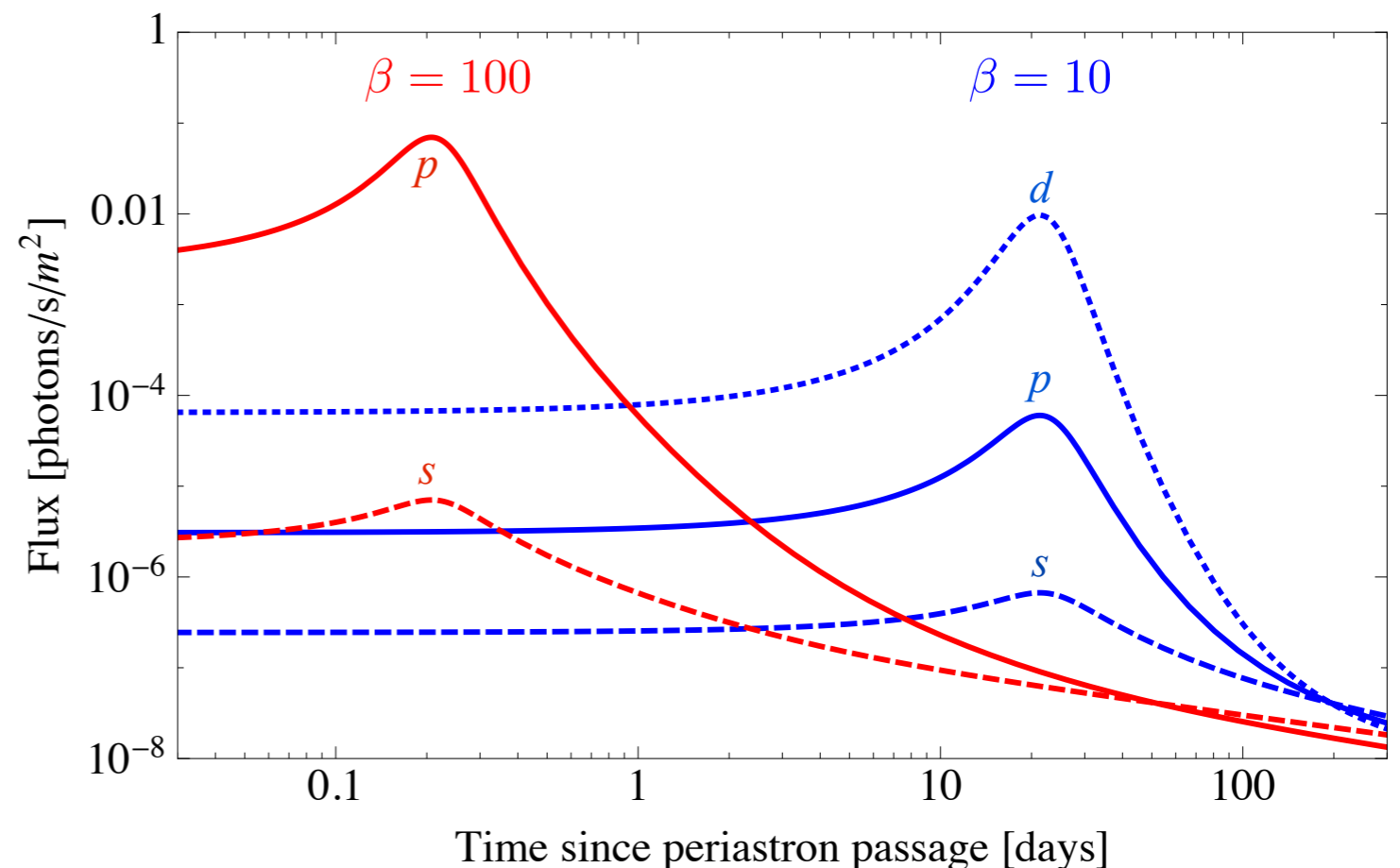
DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3 r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$

$\sim \beta$ ~ 0.5 $\propto \begin{cases} 1 & \text{s-wave} \\ \beta^2 & \text{p-wave} \\ \beta^4 & \text{d-wave} \end{cases}$

Fermi flares?

→ ~1000 photons per week for certain parameter choices.

$\left(M_{\text{cl}} = 0.1 M_\odot, \quad \rho_{\text{cl}} = 10^{-10} \text{g cm}^{-3}, \quad m_\chi = 1 \text{ GeV}, \quad d = 100 \text{ Mpc}, \quad N_\gamma = \int dE (dN_\gamma/dE) \sim 10 \right)$



TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3 r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$

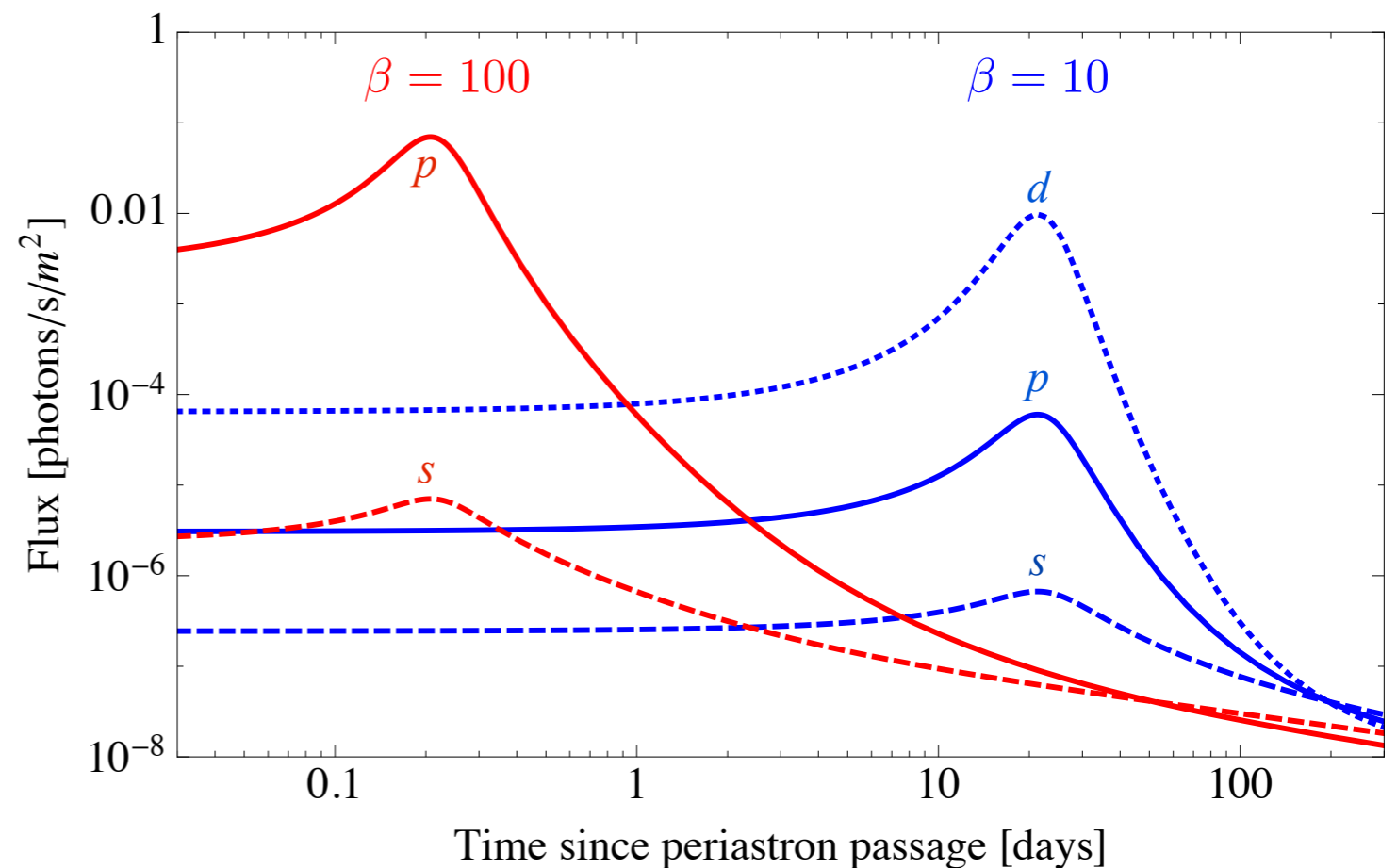
Fermi flares?

→ ~1000 photons per week for certain parameter choices.

$$\begin{matrix} \nearrow & \nearrow & \nwarrow \\ \sim \beta & \sim 0.5 & \\ \propto \begin{cases} 1 & \text{s-wave} \\ \beta^2 & \text{p-wave} \\ \beta^4 & \text{d-wave} \end{cases} \end{matrix}$$

$$\left(M_{\text{cl}} = 0.1 M_\odot, \quad \rho_{\text{cl}} = 10^{-10} \text{g cm}^{-3}, \quad m_\chi = 1 \text{ GeV}, \quad d = 100 \text{ Mpc}, \quad N_\gamma = \int dE (dN_\gamma/dE) \sim 10 \right)$$

Unique predictions:



TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$

$\begin{matrix} \nearrow & \nearrow & \nwarrow \\ \sim \beta & \sim 0.5 & \end{matrix} \propto \begin{cases} 1 & \text{s-wave} \\ \beta^2 & \text{p-wave} \\ \beta^4 & \text{d-wave} \end{cases}$

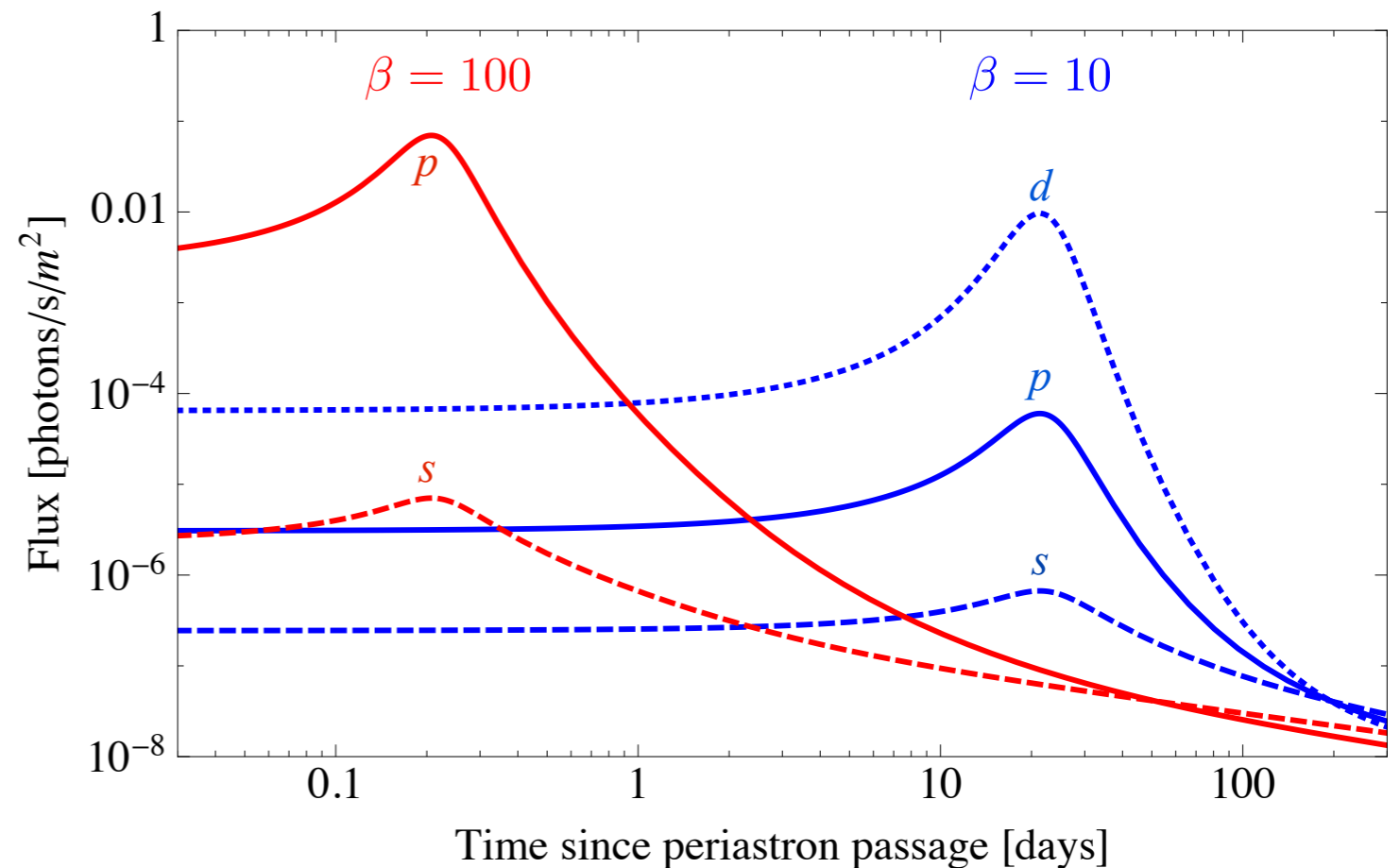
Fermi flares?

→ ~1000 photons per week for certain parameter choices.

$\left(M_{\text{cl}} = 0.1 M_\odot, \rho_{\text{cl}} = 10^{-10} \text{g cm}^{-3}, m_\chi = 1 \text{ GeV}, d = 100 \text{ Mpc}, N_\gamma = \int dE (dN_\gamma/dE) \sim 10 \right)$

Unique predictions:

- Universal *energy spectrum*.



TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$

$$\begin{matrix} \nearrow & \nearrow & \nwarrow \\ \sim \beta & \sim 0.5 & \end{matrix} \propto \begin{cases} 1 & \text{s-wave} \\ \beta^2 & \text{p-wave} \\ \beta^4 & \text{d-wave} \end{cases}$$

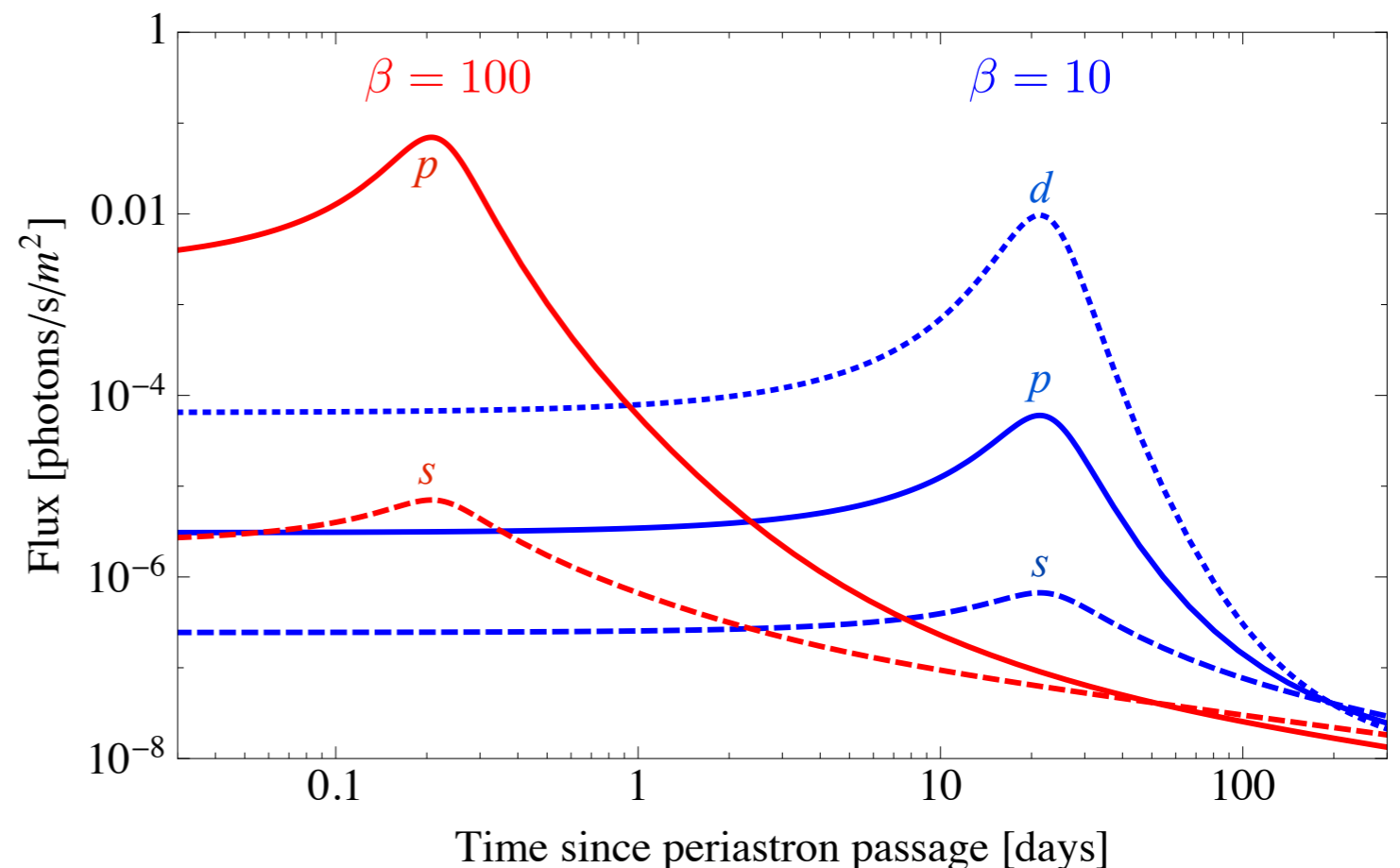
Fermi flares?

→ ~1000 photons per week for certain parameter choices.

$$\left(M_{\text{cl}} = 0.1 M_\odot, \quad \rho_{\text{cl}} = 10^{-10} \text{g cm}^{-3}, \quad m_\chi = 1 \text{ GeV}, \quad d = 100 \text{ Mpc}, \quad N_\gamma = \int dE (dN_\gamma/dE) \sim 10 \right)$$

Unique predictions:

- Universal *energy spectrum*.
- Flares on *various timescales*.



TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle\sigma v\rangle}{m_\chi^2} \int d^3r \rho(r)^2 \propto \frac{\langle\sigma v\rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$

$$\begin{matrix} \nearrow & \nearrow & \nwarrow \\ \sim \beta & \sim 0.5 & \end{matrix} \propto \begin{cases} 1 & \text{s-wave} \\ \beta^2 & \text{p-wave} \\ \beta^4 & \text{d-wave} \end{cases}$$

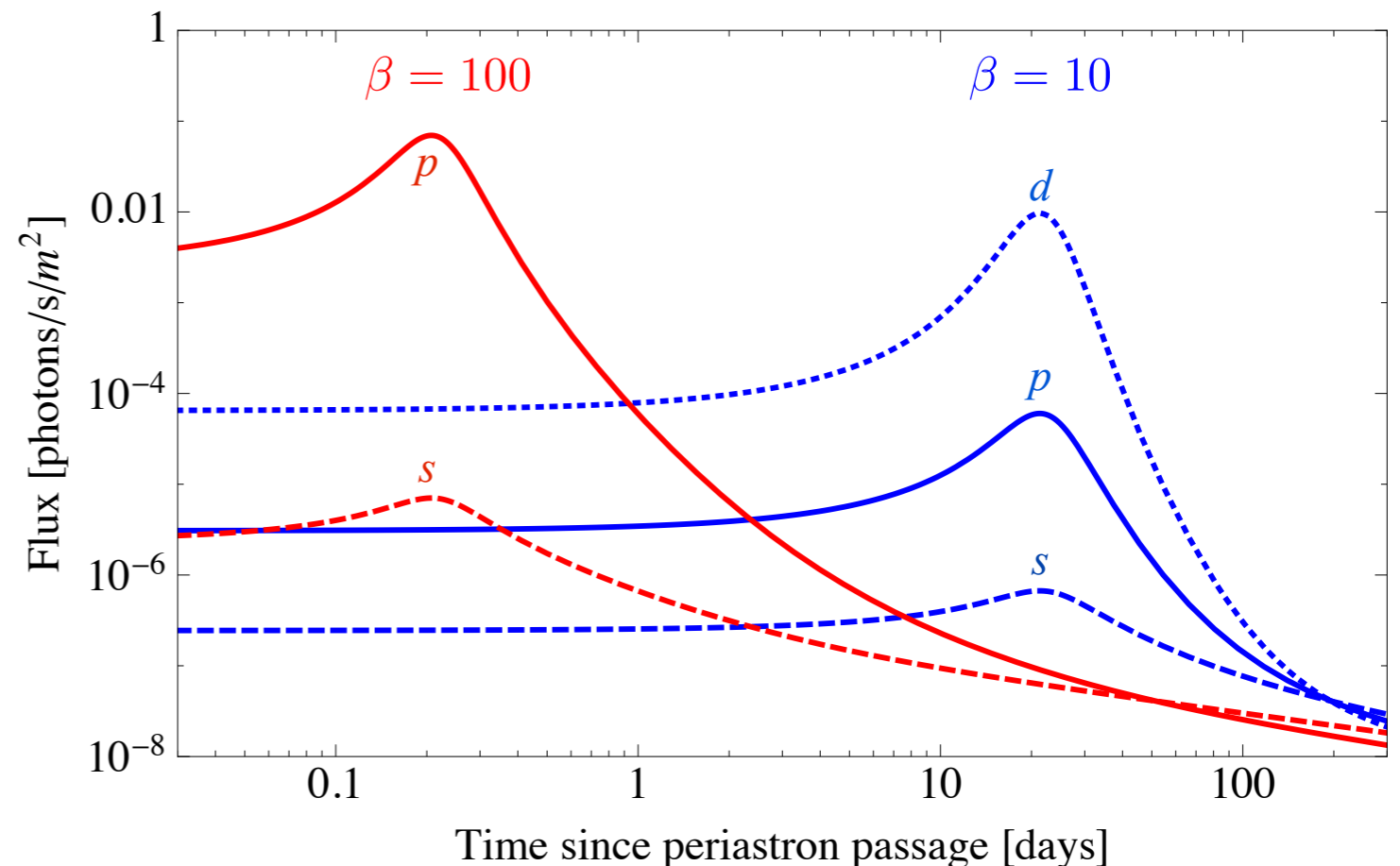
Fermi flares?

→ ~1000 photons per week for certain parameter choices.

$$\left(M_{\text{cl}} = 0.1 M_\odot, \quad \rho_{\text{cl}} = 10^{-10} \text{g cm}^{-3}, \quad m_\chi = 1 \text{ GeV}, \quad d = 100 \text{ Mpc}, \quad N_\gamma = \int dE (dN_\gamma/dE) \sim 10 \right)$$

Unique predictions:

- Universal *energy spectrum*.
- Flares on *various timescales*.
- *Isotropic* sky distribution.



TCEs of DMCs: Gamma-Ray Flares

(Ali-Haïmoud, EDK and Silk, PRD 2016)

DM annihilation: $\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi^2} \int d^3 r \rho(r)^2 \propto \frac{\langle \sigma v \rangle_0}{m_\chi^2} \rho_{\text{cl}} M_{\text{cl}} \times \Delta_z \Delta_{||} \Delta_v$

$$\begin{matrix} \nearrow & \nearrow & \nwarrow \\ \sim \beta & \sim 0.5 & \begin{cases} 1 & \text{s-wave} \\ \beta^2 & \text{p-wave} \\ \beta^4 & \text{d-wave} \end{cases} \end{matrix} \propto$$

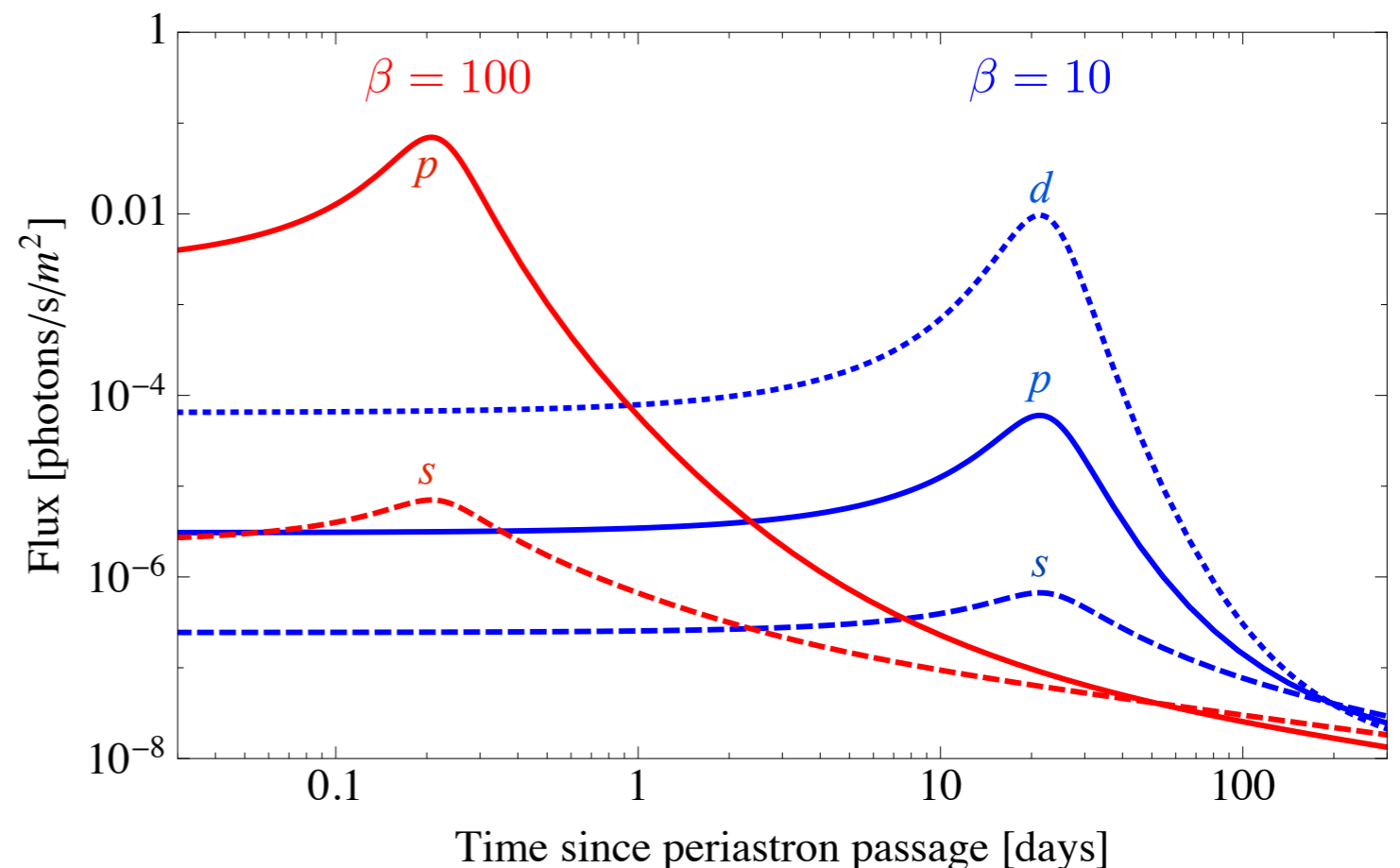
Fermi flares?

→ ~1000 photons per week for certain parameter choices.

$$\left(M_{\text{cl}} = 0.1 M_\odot, \quad \rho_{\text{cl}} = 10^{-10} \text{g cm}^{-3}, \quad m_\chi = 1 \text{ GeV}, \quad d = 100 \text{ Mpc}, \quad N_\gamma = \int dE (dN_\gamma/dE) \sim 10 \right)$$

Unique predictions:

- Universal *energy spectrum*.
- Flares on *various timescales*.
- *Isotropic* sky distribution.
- Full *light curve* prediction.
(in principle)



TCEs of DMCs: Gravitational Wave Bursts

(Ali-Haïmoud, EDK and Silk, PRD 2016)

TCEs of DMCs: Gravitational Wave Bursts

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Two sources of GWs:

TCEs of DMCs: Gravitational Wave Bursts

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Two sources of GWs:

- The orbital motion of the DMC around the SMBH (similar to stellar TDEs):

TCEs of DMCs: Gravitational Wave Bursts

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Two sources of GWs:

- The orbital motion of the DMC around the SMBH (similar to stellar TDEs):

$$h_{\text{orb}} \sim \frac{GM_{\text{cl}}R_p^2}{c^4 d t_{\text{orb}}^2} \sim \frac{GM_{\text{cl}}R_p^2}{c^4 d T_{\text{cl}}^2} \beta^3 \qquad t_{\text{orb}} \sim \left(\frac{GM_{\text{BH}}}{R_p^3} \right)^{-1/2} \sim T_{\text{cl}} \times \beta^{-3/2}$$

TCEs of DMCs: Gravitational Wave Bursts

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Two sources of GWs:

- The orbital motion of the DMC around the SMBH (similar to stellar TDEs):

$$h_{\text{orb}} \sim \frac{GM_{\text{cl}}R_p^2}{c^4 d t_{\text{orb}}^2} \sim \frac{GM_{\text{cl}}R_p^2}{c^4 d T_{\text{cl}}^2} \beta^3 \quad t_{\text{orb}} \sim \left(\frac{GM_{\text{BH}}}{R_p^3} \right)^{-1/2} \sim T_{\text{cl}} \times \beta^{-3/2}$$

- The tidal compression of the (asymmetric) DMC:

$$h_{\text{tce}} \sim \frac{G\ddot{Q}}{c^4 d} \sim \frac{GM_{\text{cl}}R_{\text{cl}}^2}{c^4 d T_{\text{cl}}^2} \beta^3$$

TCEs of DMCs: Gravitational Wave Bursts

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Two sources of GWs:

- The orbital motion of the DMC around the SMBH (similar to stellar TDEs):

$$h_{\text{orb}} \sim \frac{GM_{\text{cl}}R_p^2}{c^4 d t_{\text{orb}}^2} \sim \frac{GM_{\text{cl}}R_p^2}{c^4 d T_{\text{cl}}^2} \beta^3 \quad t_{\text{orb}} \sim \left(\frac{GM_{\text{BH}}}{R_p^3} \right)^{-1/2} \sim T_{\text{cl}} \times \beta^{-3/2}$$

- The tidal compression of the (asymmetric) DMC:

$$h_{\text{tce}} \sim \frac{G\ddot{Q}}{c^4 d} \sim \frac{GM_{\text{cl}}R_{\text{cl}}^2}{c^4 d T_{\text{cl}}^2} \beta^3$$

This is $\sim (R_{\text{cl}}/R_p)^2$ smaller, but at: $f_{\text{tce}} \sim \Delta t_{\text{tce}}^{-1} \sim 30 \text{ Hz} \left(\frac{\rho_{\text{cl}}}{1 \text{ g cm}^{-3}} \right)^{1/2} \left(\frac{\beta}{100} \right)^2$

TCEs of DMCs: Gravitational Wave Bursts

(Ali-Haïmoud, EDK and Silk, PRD 2016)

Two sources of GWs:

- The orbital motion of the DMC around the SMBH (similar to stellar TDEs):

$$h_{\text{orb}} \sim \frac{GM_{\text{cl}}R_p^2}{c^4 d t_{\text{orb}}^2} \sim \frac{GM_{\text{cl}}R_p^2}{c^4 d T_{\text{cl}}^2} \beta^3 \quad t_{\text{orb}} \sim \left(\frac{GM_{\text{BH}}}{R_p^3} \right)^{-1/2} \sim T_{\text{cl}} \times \beta^{-3/2}$$

- The tidal compression of the (asymmetric) DMC:

$$h_{\text{tce}} \sim \frac{G\ddot{Q}}{c^4 d} \sim \frac{GM_{\text{cl}}R_{\text{cl}}^2}{c^4 d T_{\text{cl}}^2} \beta^3$$

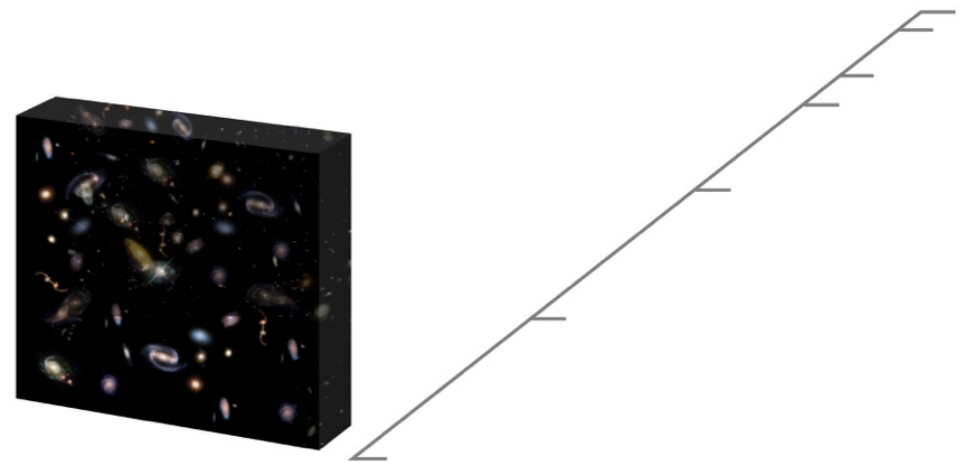
This is $\sim (R_{\text{cl}}/R_p)^2$ smaller, but at: $f_{\text{tce}} \sim \Delta t_{\text{tce}}^{-1} \sim 30 \text{ Hz} \left(\frac{\rho_{\text{cl}}}{1 \text{ g cm}^{-3}} \right)^{1/2} \left(\frac{\beta}{100} \right)^2$

which is potentially detectable by aLIGO:

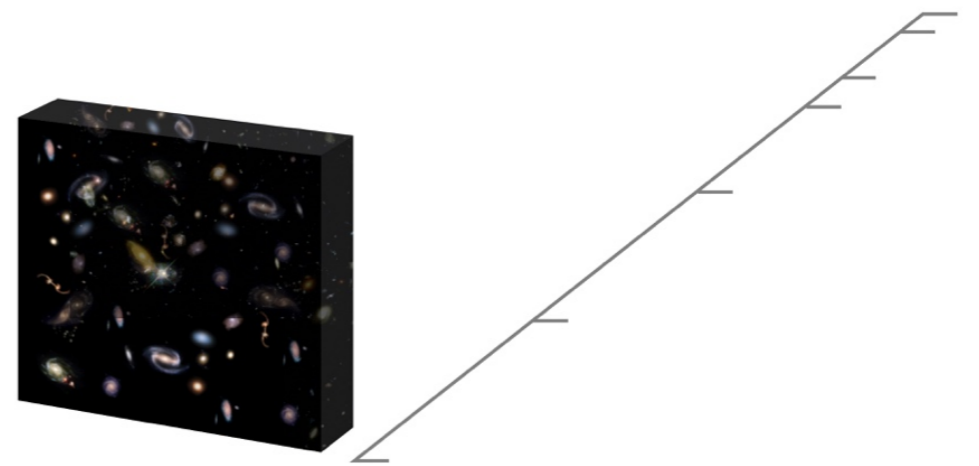
$$h_{\text{tce}} \sim 10^{-23} \left(\frac{M_{\text{cl}}}{0.1 M_{\odot}} \right)^{5/3} \left(\frac{\rho_{\text{cl}}}{1 \text{ g cm}^{-3}} \right)^{1/3} \frac{(\beta/100)^3}{d_{100}}$$

- Heat signatures of DM in the dark ages
- Flaring tidally compressed DM clumps

- Heat signatures of DM in the dark ages
- Flaring tidally compressed DM clumps
- Did advanced LIGO detect dark matter?

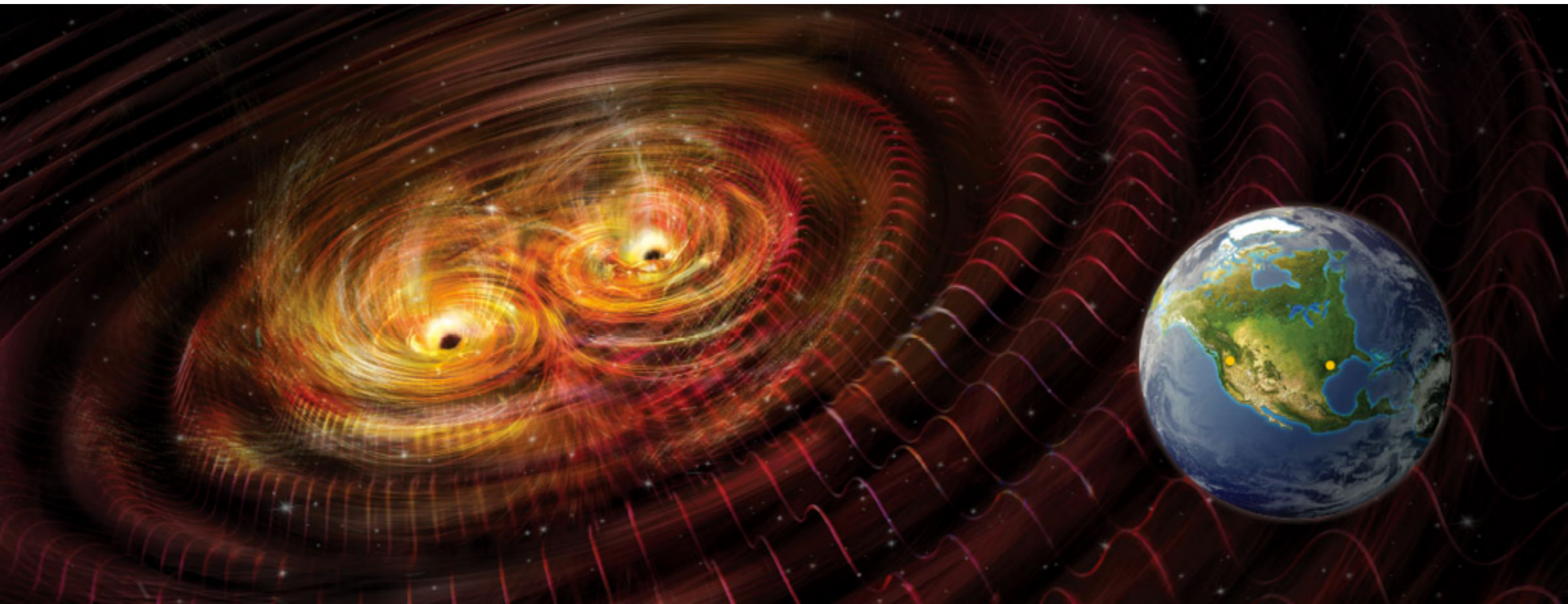


- Heat signatures of DM in the dark ages
- Flaring tidally compressed DM clumps
- Did advanced LIGO detect dark matter?

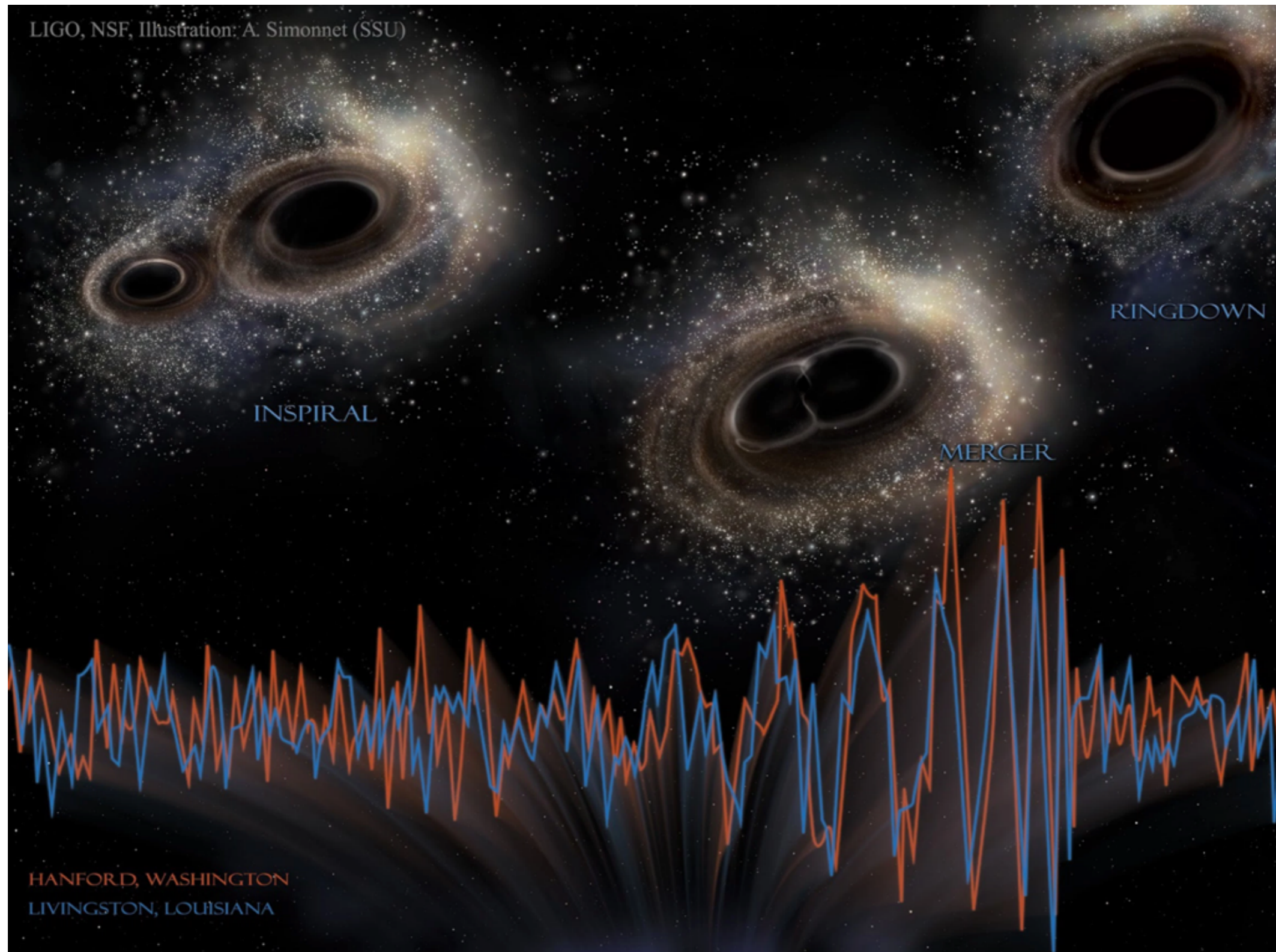


What Did LIGO See?

What Did LIGO See?



What Did LIGO See?



Coalescing Black Holes: Primordial Dark Matter?

(Bird et al., arXiv:1503.XXXXX)

Coalescing Black Holes: Primordial Dark Matter?

(Bird et al., arXiv:1503.XXXXX)

Guiding questions:

Coalescing Black Holes: Primordial Dark Matter?

(Bird et al., arXiv:1503.XXXXX)

Guiding questions:

Q: Can the LIGO detection have anything to do with dark matter?

Coalescing Black Holes: Primordial Dark Matter?

(Bird et al., arXiv:1503.XXXXX)

Guiding questions:

Q: Can the LIGO detection have anything to do with dark matter?

A: Sure, these could be primordial DM black holes.

Coalescing Black Holes: Primordial Dark Matter?

(Bird et al., arXiv:1503.XXXXX)

Guiding questions:

Q: Can the LIGO detection have anything to do with dark matter?

A: Sure, these could be primordial DM black holes. (MACHOS)

Coalescing Black Holes: Primordial Dark Matter?

(Bird et al., arXiv:1503.XXXXX)

Guiding questions:

Q: Can the LIGO detection have anything to do with dark matter?

A: Sure, these could be primordial DM black holes. (MACHOS)

Q: Aren't these ruled out already?

Coalescing Black Holes: Primordial Dark Matter?

(Bird et al., arXiv:1503.XXXXX)

Guiding questions:

Q: Can the LIGO detection have anything to do with dark matter?

A: Sure, these could be primordial DM black holes. (MACHOS)

Q: Aren't these ruled out already?

A: Not in the mass range $10 - 100 M_{\odot}$.

Coalescing Black Holes: Primordial Dark Matter?

(Bird et al., arXiv:1503.XXXXX)

Guiding questions:

Q: Can the LIGO detection have anything to do with dark matter?

A: Sure, these could be primordial DM black holes. (MACHOS)

Q: Aren't these ruled out already?

A: Not in the mass range $10 - 100 M_{\odot}$.

($\lesssim 10 M_{\odot}$: ruled out by Microlensing; $\gtrsim 100 M_{\odot}$: ruled out by wide binaries)

Coalescing Black Holes: Primordial Dark Matter?

(Bird et al., arXiv:1503.XXXXX)

Guiding questions:

Q: Can the LIGO detection have anything to do with dark matter?

A: Sure, these could be primordial DM black holes. (MACHOS)

Q: Aren't these ruled out already?

A: Not in the mass range $10 - 100 M_{\odot}$.

($\lesssim 10 M_{\odot}$: ruled out by Microlensing; $\gtrsim 100 M_{\odot}$: ruled out by wide binaries)

Q: How do the binaries form?

Coalescing Black Holes: Primordial Dark Matter?

(Bird et al., arXiv:1503.XXXXX)

Guiding questions:

Q: Can the LIGO detection have anything to do with dark matter?

A: Sure, these could be primordial DM black holes. (MACHOS)

Q: Aren't these ruled out already?

A: Not in the mass range $10 - 100 M_{\odot}$.

($\lesssim 10 M_{\odot}$: ruled out by Microlensing; $\gtrsim 100 M_{\odot}$: ruled out by wide binaries)

Q: How do the binaries form?

A: The relevant capture mechanism is through GW emission in close encounter:

$$\sigma \propto R_s^2 \left(\frac{v}{c}\right)^{-18/7} \quad R_s = 2GM_{\text{pbh}}/c^2 \quad v \text{ is the relative velocity}$$

Coalescing Black Holes: Primordial Dark Matter?

(Bird et al., arXiv:1503.XXXXX)

Guiding questions:

Q: Can the LIGO detection have anything to do with dark matter?

A: Sure, these could be primordial DM black holes. (MACHOS)

Q: Aren't these ruled out already?

A: Not in the mass range $10 - 100 M_{\odot}$.

($\lesssim 10 M_{\odot}$: ruled out by Microlensing; $\gtrsim 100 M_{\odot}$: ruled out by wide binaries)

Q: How do the binaries form?

A: The relevant capture mechanism is through GW emission in close encounter:

$$\sigma \propto R_s^2 \left(\frac{v}{c}\right)^{-18/7} \quad R_s = 2GM_{\text{pbh}}/c^2 \quad v \text{ is the relative velocity}$$

Q: Do the event rates work out?

Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

To calculate the event rate:

Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

To calculate the event rate:

- The PBH merger rate within each halo:

Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

To calculate the event rate:

- The PBH merger rate within each halo:

$$\mathcal{R} = 4\pi \int_0^{R_{\text{vir}}} r^2 \frac{1}{2} \left(\frac{\rho_{\text{nfw}}(r)}{M_{\text{pbh}}} \right)^2 \langle \sigma v_{\text{pbh}} \rangle dr$$

Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

To calculate the event rate:

- The PBH merger rate within each halo:

$$\mathcal{R} = 4\pi \int_0^{R_{\text{vir}}} r^2 \frac{1}{2} \left(\frac{\rho_{\text{nfw}}(r)}{M_{\text{pbh}}} \right)^2 \langle \sigma v_{\text{pbh}} \rangle dr$$

Navarro-Frenk-White
density profile



Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

To calculate the event rate:

- The PBH merger rate within each halo:

$$\mathcal{R} = 4\pi \int_0^{R_{\text{vir}}} r^2 \frac{1}{2} \left(\frac{\rho_{\text{nfw}}(r)}{M_{\text{pbh}}} \right)^2 \langle \sigma v_{\text{pbh}} \rangle dr$$

Navarro-Frenk-White density profile

Relative velocity MB distribution

Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

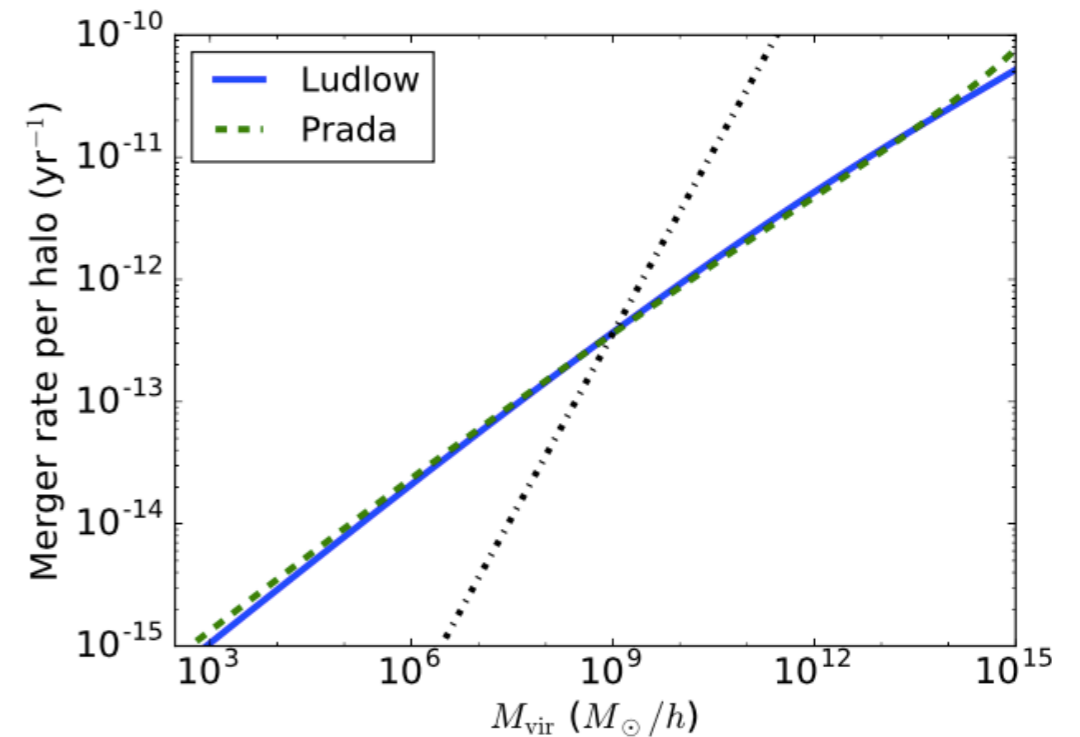
To calculate the event rate:

- The PBH merger rate within each halo:

$$\mathcal{R} = 4\pi \int_0^{R_{\text{vir}}} r^2 \frac{1}{2} \left(\frac{\rho_{\text{nfw}}(r)}{M_{\text{pbh}}} \right)^2 \langle \sigma v_{\text{pbh}} \rangle dr$$

Navarro-Frenk-White density profile

Relative velocity MB distribution



Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

To calculate the event rate:

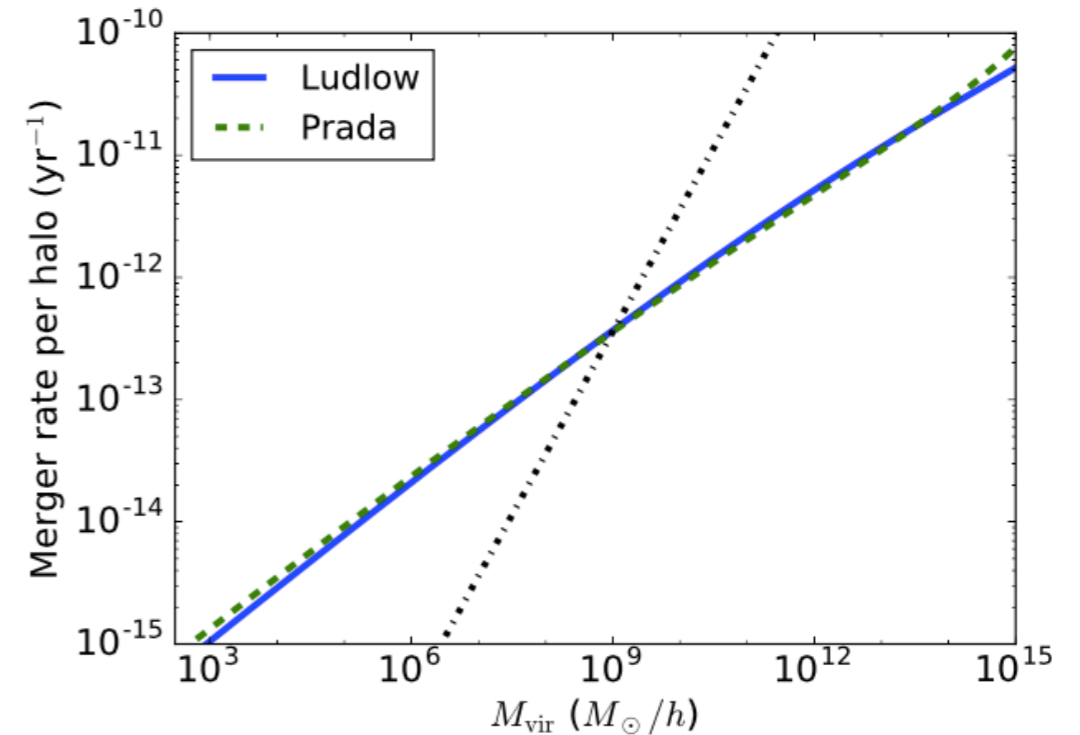
- The PBH merger rate within each halo:

$$\mathcal{R} = 4\pi \int_0^{R_{\text{vir}}} r^2 \frac{1}{2} \left(\frac{\rho_{\text{nfw}}(r)}{M_{\text{pbh}}} \right)^2 \langle \sigma v_{\text{pbh}} \rangle dr$$

Navarro-Frenk-White density profile

Relative velocity MB distribution

- Total merger rate as a function of halo mass:



Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

To calculate the event rate:

- The PBH merger rate within each halo:

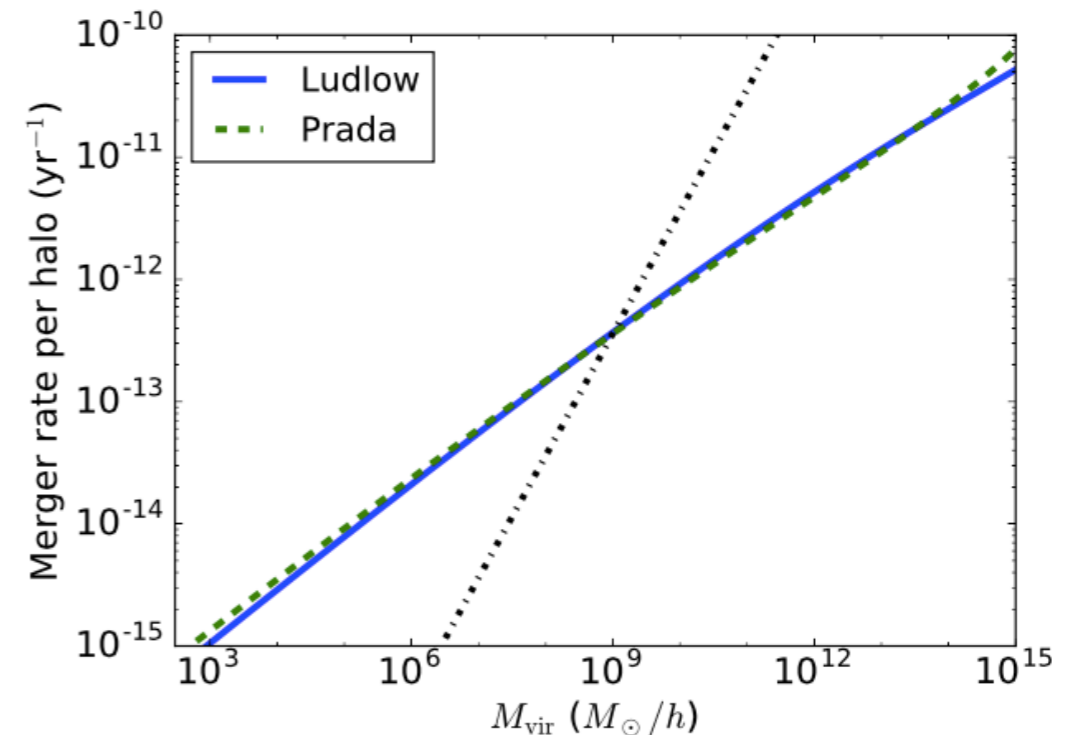
$$\mathcal{R} = 4\pi \int_0^{R_{\text{vir}}} r^2 \frac{1}{2} \left(\frac{\rho_{\text{nfw}}(r)}{M_{\text{pbh}}} \right)^2 \langle \sigma v_{\text{pbh}} \rangle dr$$

Navarro-Frenk-White density profile

Relative velocity MB distribution

- Total merger rate as a function of halo mass:

$$\mathcal{V} = \int (dn/dM)(M) \mathcal{R}(M) dM$$



Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

To calculate the event rate:

- The PBH merger rate within each halo:

$$\mathcal{R} = 4\pi \int_0^{R_{\text{vir}}} r^2 \frac{1}{2} \left(\frac{\rho_{\text{nfw}}(r)}{M_{\text{pbh}}} \right)^2 \langle \sigma v_{\text{pbh}} \rangle dr$$

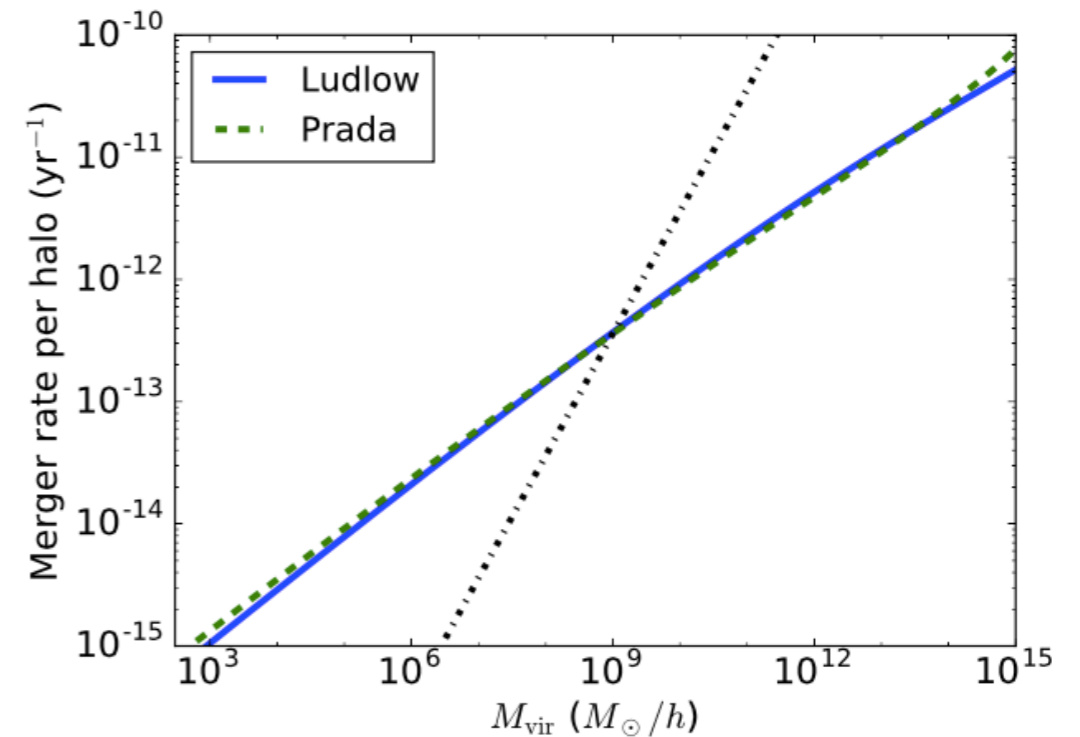
Navarro-Frenk-White density profile

Relative velocity MB distribution

- Total merger rate as a function of halo mass:

$$\mathcal{V} = \int (dn/dM)(M) \mathcal{R}(M) dM$$

Halo Mass Function



Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

To calculate the event rate:

- The PBH merger rate within each halo:

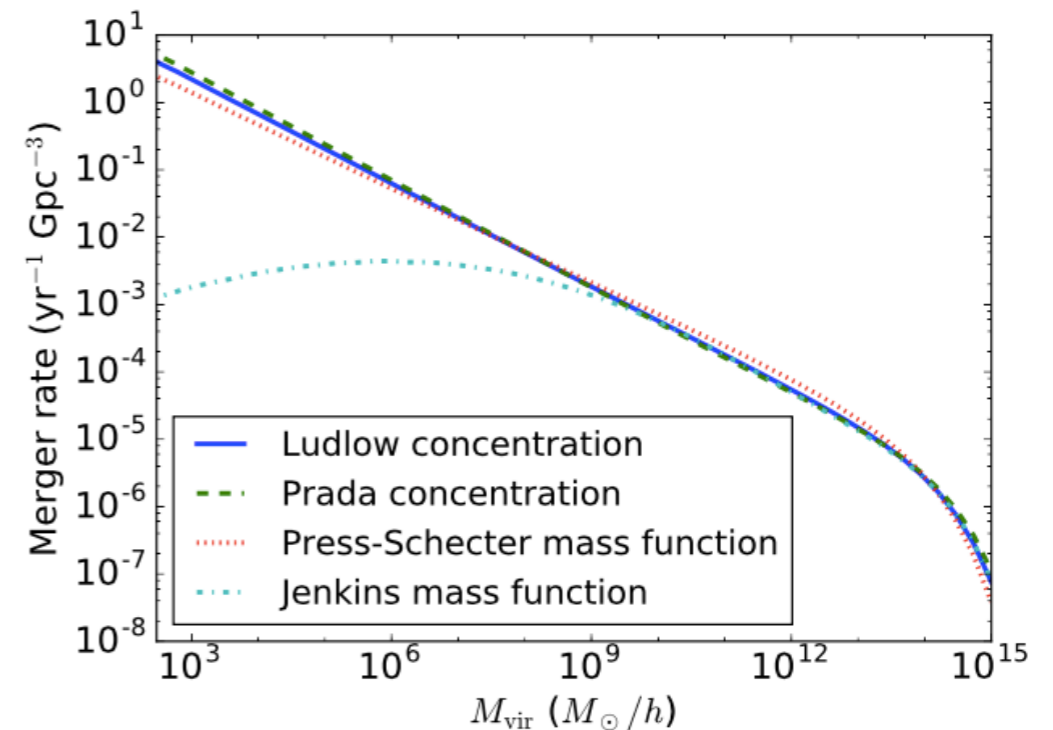
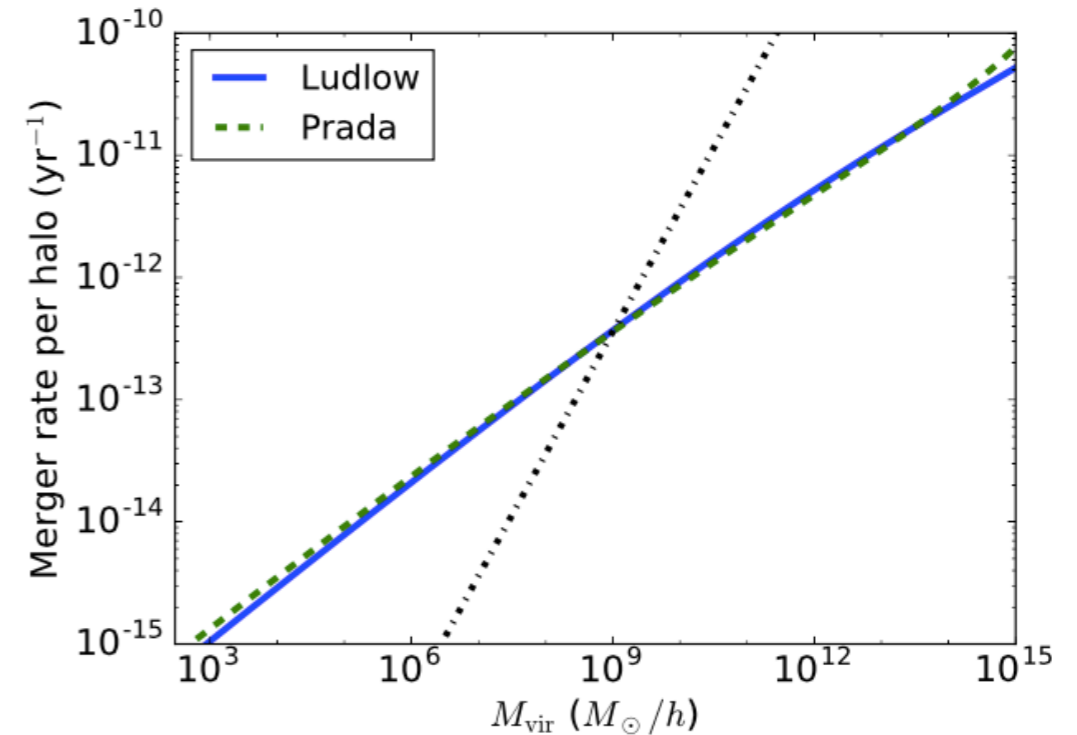
$$\mathcal{R} = 4\pi \int_0^{R_{\text{vir}}} r^2 \frac{1}{2} \left(\frac{\rho_{\text{nfw}}(r)}{M_{\text{pbh}}} \right)^2 \langle \sigma v_{\text{pbh}} \rangle dr$$

Navarro-Frenk-White density profile
Relative velocity MB distribution

- Total merger rate as a function of halo mass:

$$\mathcal{V} = \int (dn/dM)(M) \mathcal{R}(M) dM$$

Halo Mass Function



Coalescing DM PBHs: Event Rate Calculation

(Bird et al., arXiv:1503.XXXXX)

To calculate the event rate:

- The PBH merger rate within each halo:

$$\mathcal{R} = 4\pi \int_0^{R_{\text{vir}}} r^2 \frac{1}{2} \left(\frac{\rho_{\text{nfw}}(r)}{M_{\text{pbh}}} \right)^2 \langle \sigma v_{\text{pbh}} \rangle dr$$

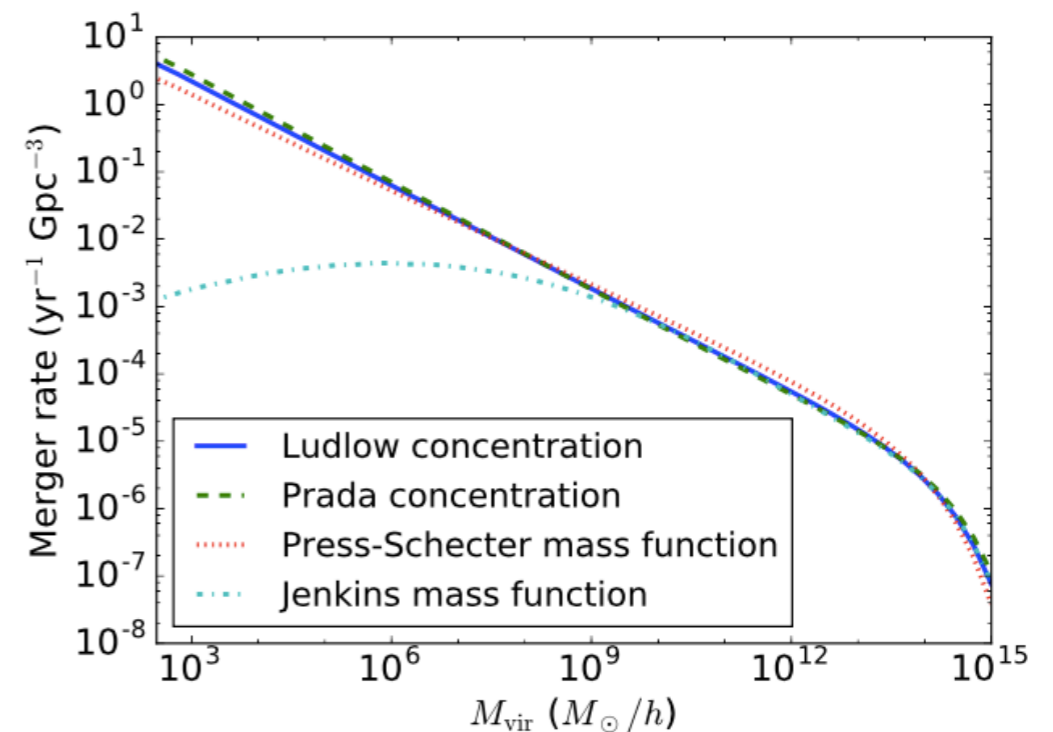
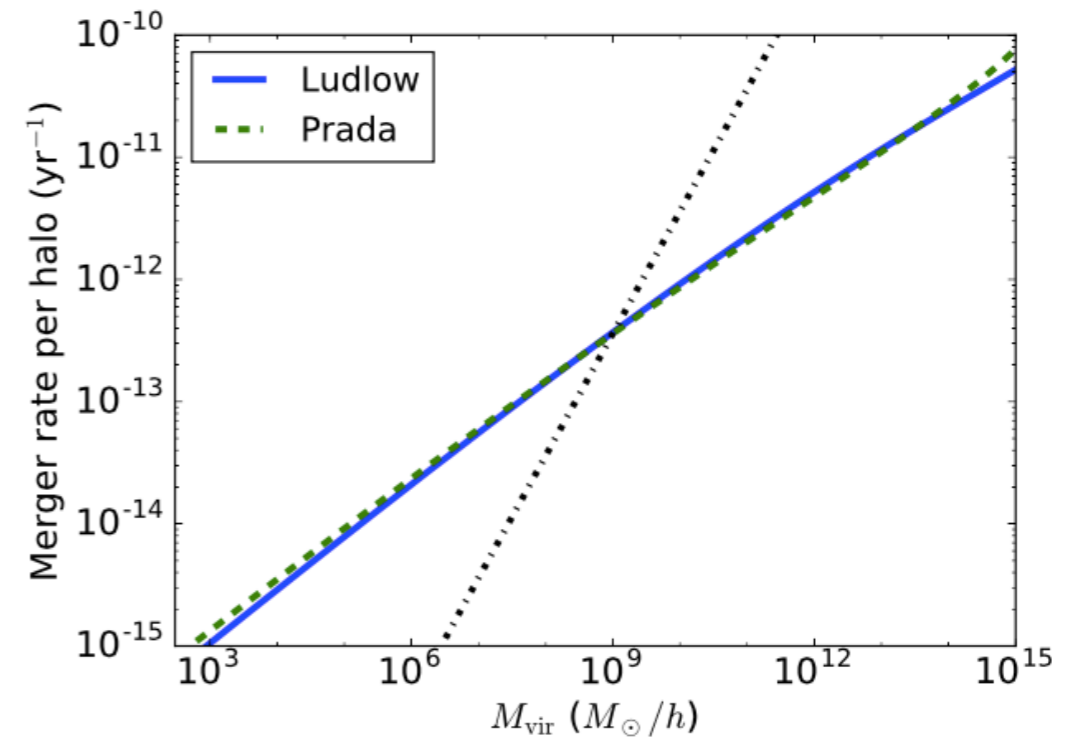
Navarro-Frenk-White density profile
Relative velocity MB distribution

- Total merger rate as a function of halo mass:

$$\mathcal{V} = \int (dn/dM)(M) \mathcal{R}(M) dM$$

Halo Mass Function

Dominated by smallest halos!!



Coalescing DM PBHs: Results and Prospects

(Bird et al., arXiv:1503.XXXXX)

Coalescing DM PBHs: Results and Prospects

(Bird et al., arXiv:1503.XXXXX)

We get a total LIGO event rate of:

$$\mathcal{V} = 5 f(M_c/500 M_\odot)^{-11/21} \text{Gpc}^{-3} \text{yr}^{-1}$$

Coalescing DM PBHs: Results and Prospects

(Bird et al., arXiv:1503.XXXXX)

We get a total LIGO event rate of:

$$\mathcal{V} = 5 f(M_c/500 M_\odot)^{-11/21} \text{Gpc}^{-3} \text{yr}^{-1}$$

- Within the LIGO estimated event rate!

$$2 - 53 \text{Gpc}^{-3} \text{yr}^{-1}$$

Coalescing DM PBHs: Results and Prospects

(Bird et al., arXiv:1503.XXXXX)

We get a total LIGO event rate of:

$$\mathcal{V} = 5 f(M_c/500 M_\odot)^{-11/21} \text{Gpc}^{-3} \text{yr}^{-1}$$

- Within the LIGO estimated event rate!

$$2 - 53 \text{Gpc}^{-3} \text{yr}^{-1}$$

- Extrapolation to low masses not as bad as it may seem.

Coalescing DM PBHs: Results and Prospects

(Bird et al., arXiv:1503.XXXXX)

We get a total LIGO event rate of:

$$\mathcal{V} = 5 f(M_c/500 M_\odot)^{-11/21} \text{Gpc}^{-3} \text{yr}^{-1}$$

- Within the LIGO estimated event rate!

$$2 - 53 \text{Gpc}^{-3} \text{yr}^{-1}$$

- Extrapolation to low masses not as bad as it may seem.

Predictions (some unique):

Coalescing DM PBHs: Results and Prospects

(Bird et al., arXiv:1503.XXXXX)

We get a total LIGO event rate of:

$$\mathcal{V} = 5 f(M_c/500 M_\odot)^{-11/21} \text{Gpc}^{-3} \text{yr}^{-1}$$

- Within the LIGO estimated event rate!

$$2 - 53 \text{Gpc}^{-3} \text{yr}^{-1}$$

- Extrapolation to low masses not as bad as it may seem.

Predictions (some unique):

- Originate in the middle of nowhere (small halos are not luminous).

Coalescing DM PBHs: Results and Prospects

(Bird et al., arXiv:1503.XXXXX)

We get a total LIGO event rate of:

$$\mathcal{V} = 5 f(M_c/500 M_\odot)^{-11/21} \text{Gpc}^{-3} \text{yr}^{-1}$$

- Within the LIGO estimated event rate!

$$2 - 53 \text{Gpc}^{-3} \text{yr}^{-1}$$

- Extrapolation to low masses not as bad as it may seem.

Predictions (some unique):

- Originate in the middle of nowhere (small halos are not luminous).
- No EM or neutrino counterparts.

Coalescing DM PBHs: Results and Prospects

(Bird et al., arXiv:1503.XXXXX)

We get a total LIGO event rate of:

$$\mathcal{V} = 5 f(M_c/500 M_\odot)^{-11/21} \text{Gpc}^{-3} \text{yr}^{-1}$$

- Within the LIGO estimated event rate!

$$2 - 53 \text{Gpc}^{-3} \text{yr}^{-1}$$

- Extrapolation to low masses not as bad as it may seem.

Predictions (some unique):

- Originate in the middle of nowhere (small halos are not luminous).
- No EM or neutrino counterparts.
- High initial eccentricities (orbit circularizes by the time it enters LIGO band).

Coalescing DM PBHs: Results and Prospects

(Bird et al., arXiv:1503.XXXXX)

We get a total LIGO event rate of:

$$\mathcal{V} = 5 f(M_c/500 M_\odot)^{-11/21} \text{Gpc}^{-3} \text{yr}^{-1}$$

- Within the LIGO estimated event rate!

$$2 - 53 \text{Gpc}^{-3} \text{yr}^{-1}$$

- Extrapolation to low masses not as bad as it may seem.

Predictions (some unique):

- Originate in the middle of nowhere (small halos are not luminous).
- No EM or neutrino counterparts.
- High initial eccentricities (orbit circularizes by the time it enters LIGO band).
- Potential peak in mass distribution of detected events (at PBH scale).

Coalescing DM PBHs: Results and Prospects

(Bird et al., arXiv:1503.XXXXX)

We get a total LIGO event rate of:

$$\mathcal{V} = 5 f(M_c/500 M_\odot)^{-11/21} \text{Gpc}^{-3} \text{yr}^{-1}$$

- Within the LIGO estimated event rate!

$$2 - 53 \text{Gpc}^{-3} \text{yr}^{-1}$$

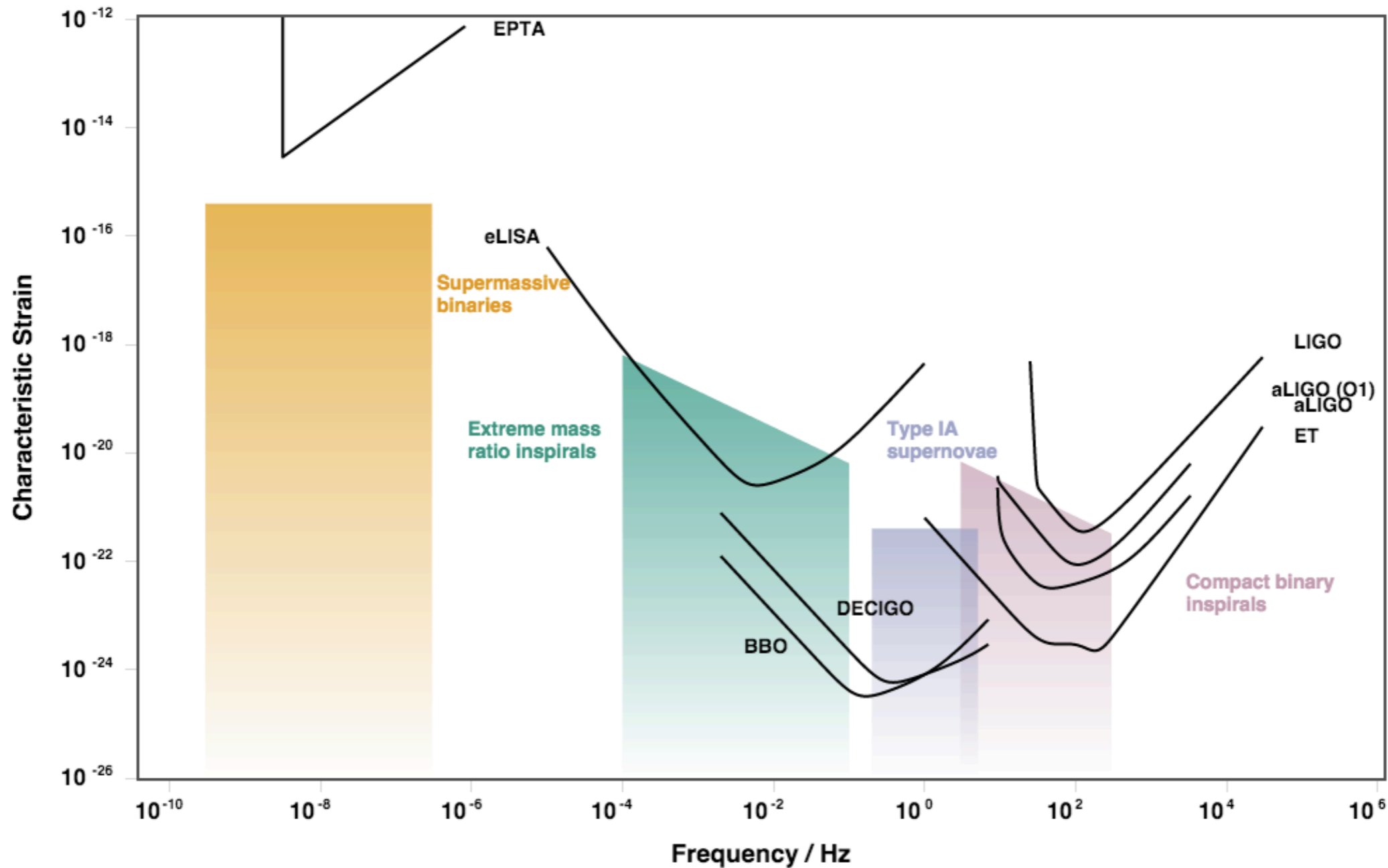
- Extrapolation to low masses not as bad as it may seem.

Predictions (some unique):

- Originate in the middle of nowhere (small halos are not luminous).
- No EM or neutrino counterparts.
- High initial eccentricities (orbit circularizes by the time it enters LIGO band).
- Potential peak in mass distribution of detected events (at PBH scale).
- Stochastic GW background (all the way to high redshifts \longrightarrow low frequencies).

Coalescing DM PBHs: Results and Prospects

(Bird et al., arXiv:1503.XXXXX)



Even more motivation for aLIGO (full), ET, DECIGO, BBO...

Conclusion: Lots to Look Forward To

Conclusion: Lots to Look Forward To

Upcoming cosmological probes of dark matter include:

Conclusion: Lots to Look Forward To

Upcoming cosmological probes of dark matter include:



Conclusion: Lots to Look Forward To

Upcoming cosmological probes of dark matter include:

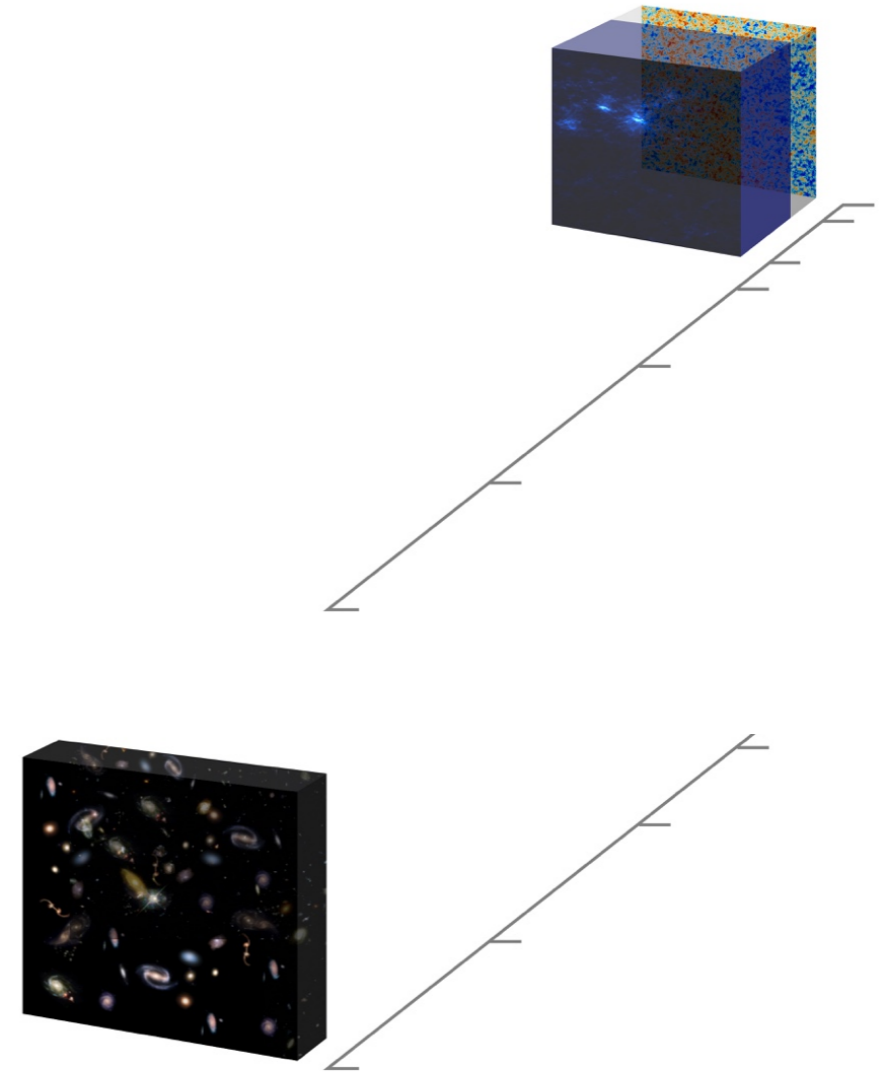


Thank you!

Ely D. Kovetz

Johns Hopkins University

LOFAR MWA
eLISA
SKA LIGO
NenuFar aLIGO
BOFIT
DECIGO
CHIME



Harvard Seminar
March 1st, 2016

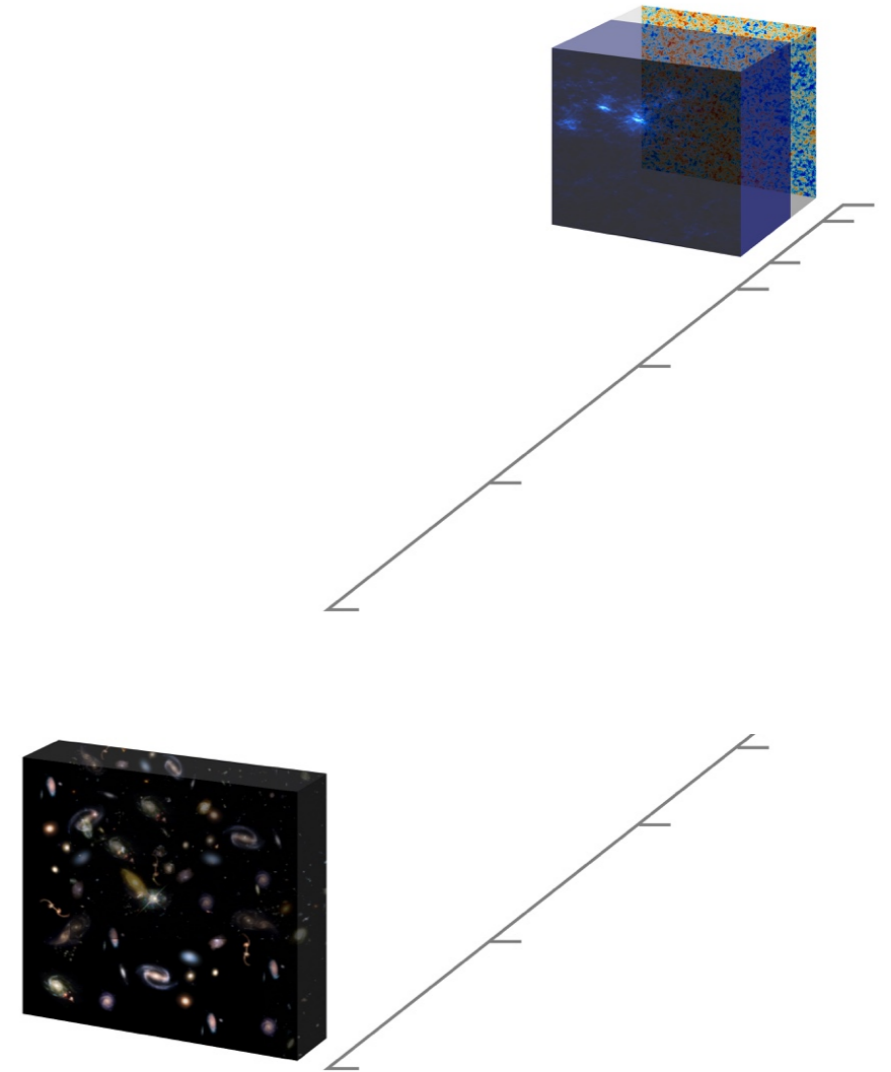
Based on: Muñoz, EDK and Ali-Haïmoud, Phys. Rev. D92 (2015)
Ali-Haïmoud, EDK and Silk, Phys. Rev. D93 (2016)
Bird et al. - on the arXiv tonight!

Thank you!

Ely D. Kovetz

Johns Hopkins University

LOFAR MWA
eLISA
SKA LIGO
NenuFar aLIGO
BOFIT
DECIGO
CHIME



Harvard Seminar
March 1st, 2016

Based on: Muñoz, EDK and Ali-Haïmoud, Phys. Rev. D92 (2015)
Ali-Haïmoud, EDK and Silk, Phys. Rev. D93 (2016)
Bird et al. - on the arXiv tonight!

Coalescing DM PBHs: Ellipticities

(Bird et al., arXiv:1503.XXXXX)

Predictions (some unique):

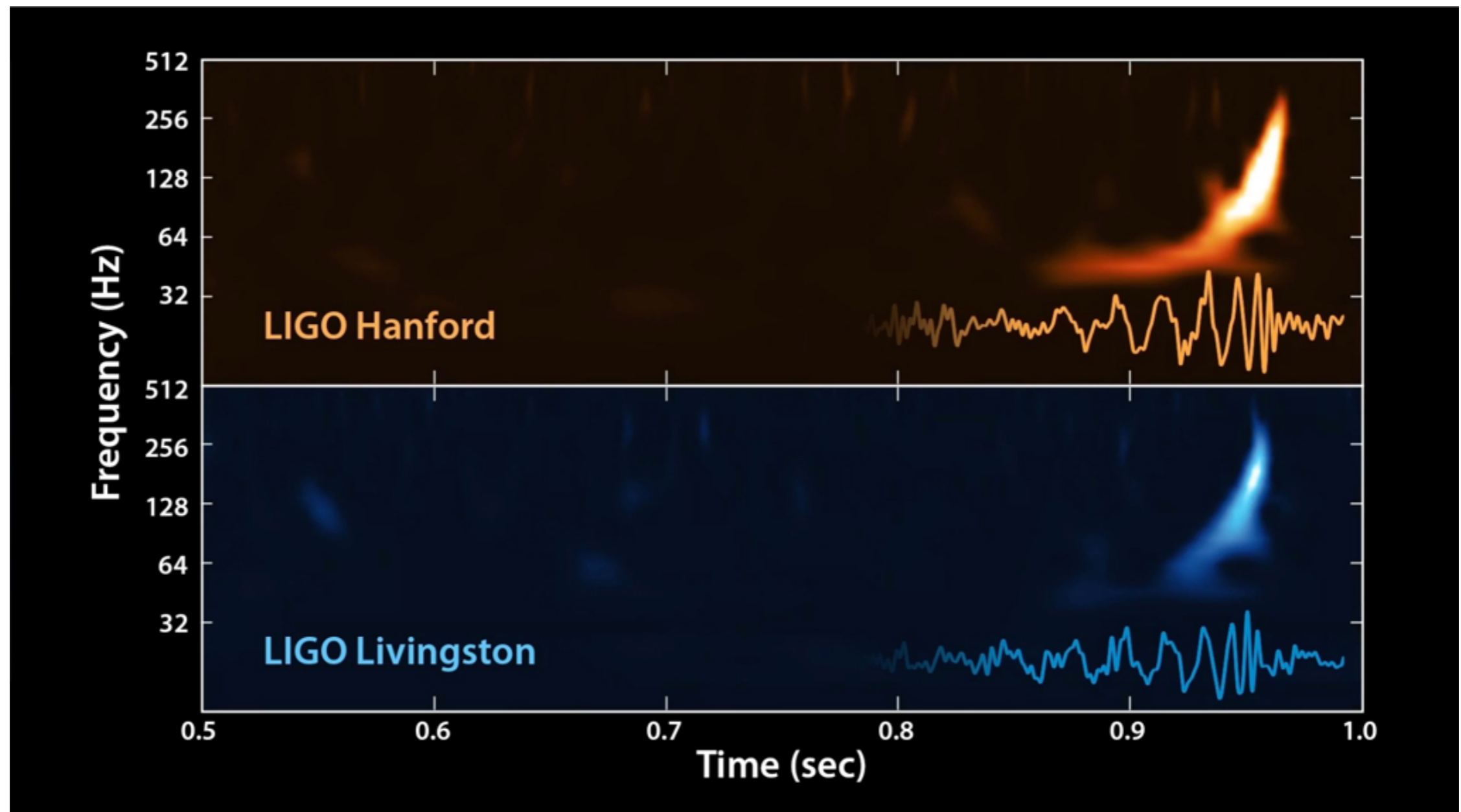
- High initial eccentricities (orbit circularizes by the time it enters LIGO band).

Coalescing DM PBHs: Ellipticities

(Bird et al., arXiv:1503.XXXXX)

Predictions (some unique):

- High initial eccentricities (orbit circularizes by the time it enters LIGO band).

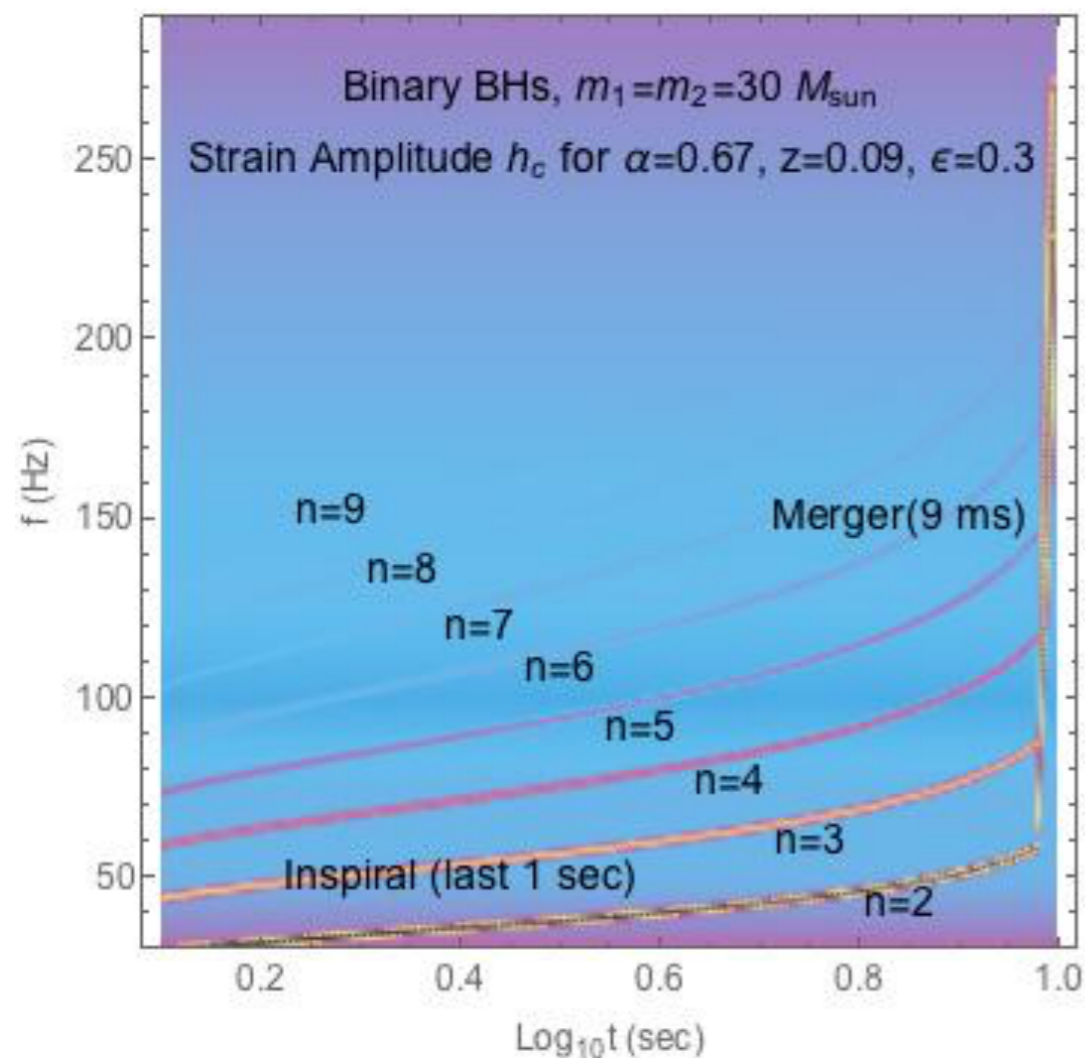


Coalescing DM PBHs: Ellipticities

(Bird et al., arXiv:1503.XXXXX)

Predictions (some unique):

- High initial eccentricities (orbit circularizes by the time it enters LIGO band).



(Courtesy of I. Cholis)

$\text{Log}_{10}((h_c+h_n)\times 10^{21})$

