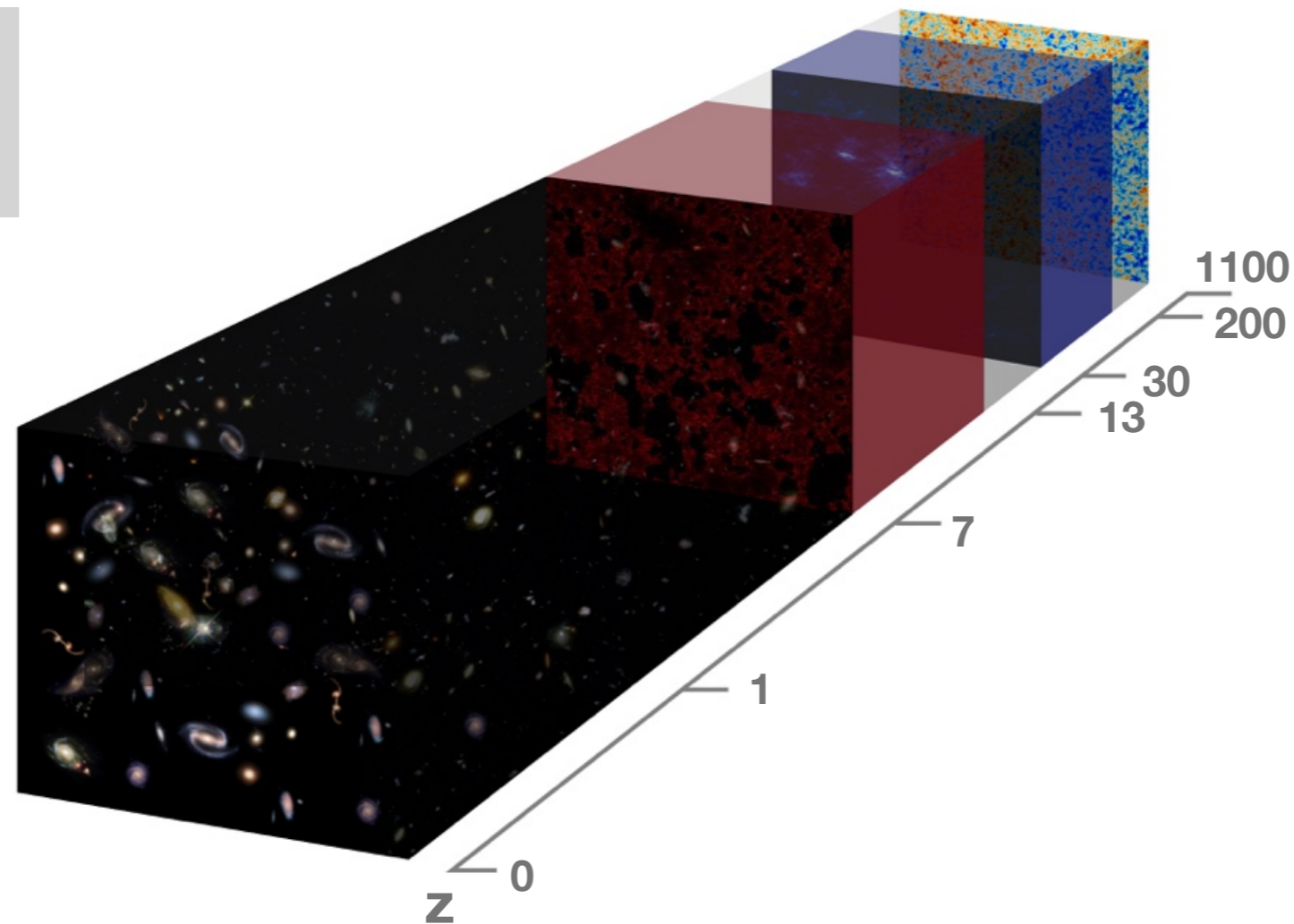


# Signals and Interlopers: Exhausting Cosmological Information from the Depths of the Observable Universe

**Ely D. Kovetz**

Johns Hopkins University



WIS Seminar  
Jan. 24th, 2016

Based on works with: P. Breysse, J. Muñoz, L. Dai  
Y. Ali-Haïmoud, A. Raccanelli,  
M. Kamionkowski, J. Silk

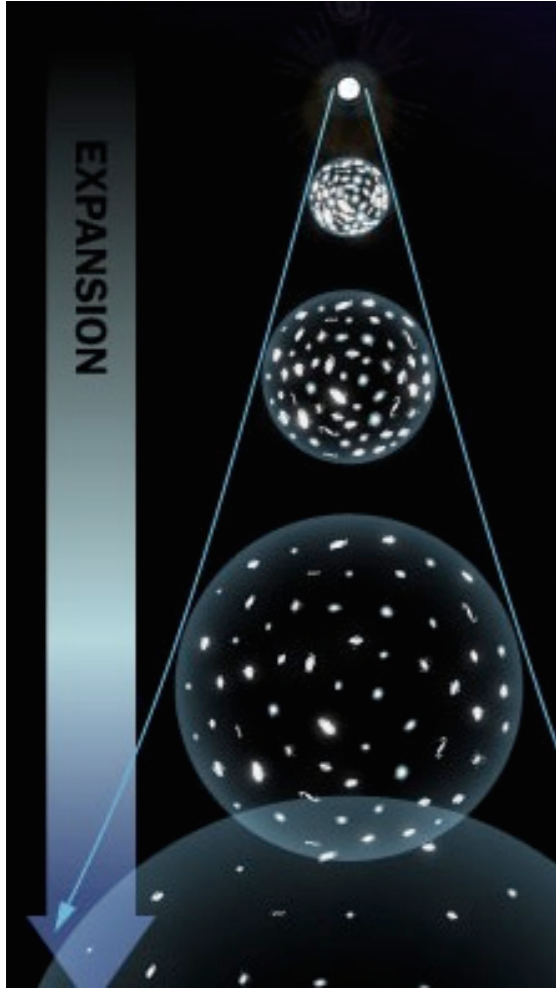
# The Standard Cosmological Model

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Hot big bang

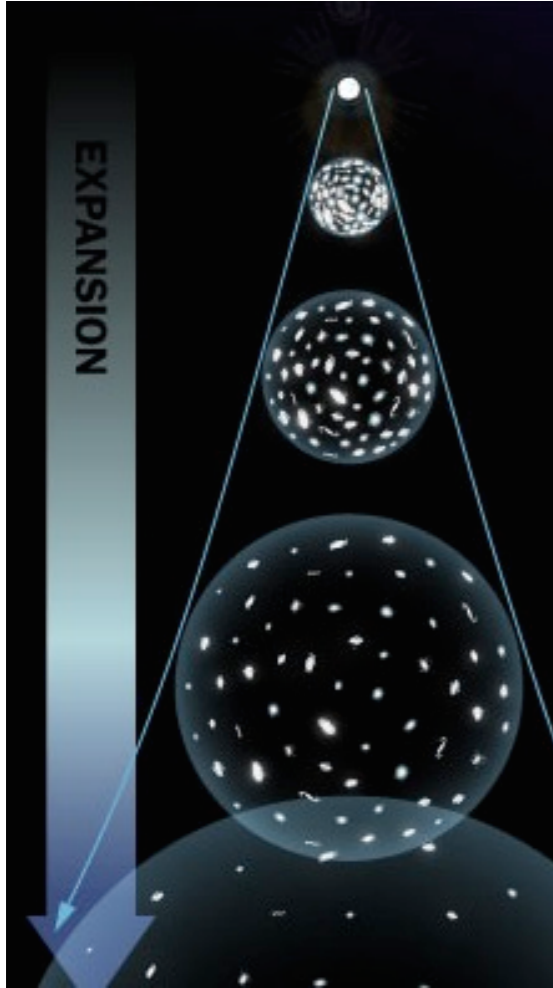


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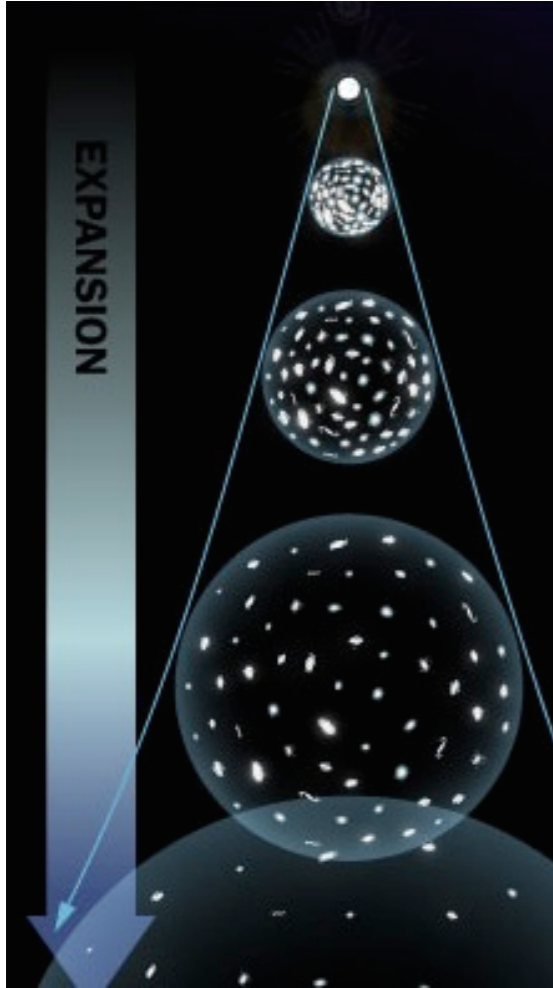
Gravitational  
instability



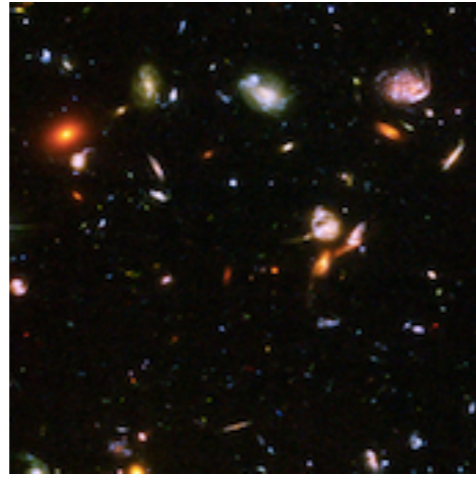
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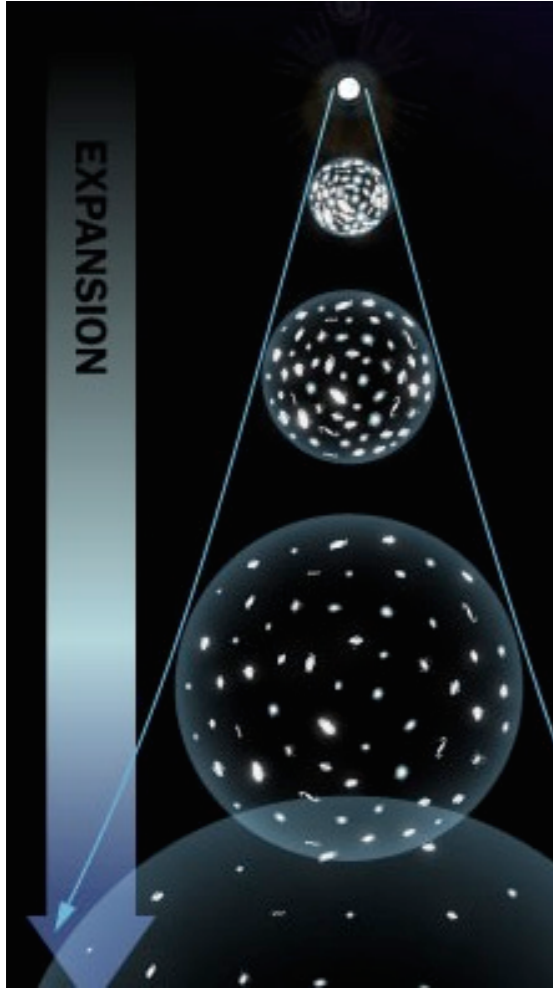
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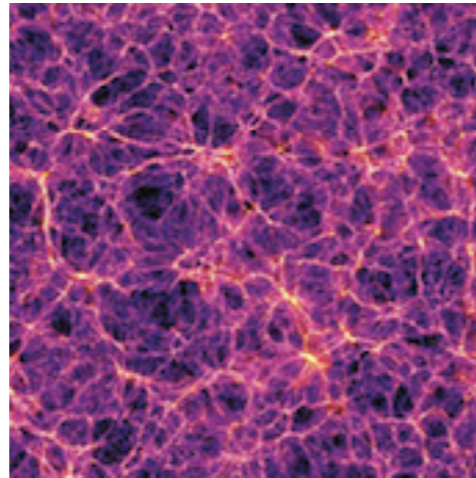
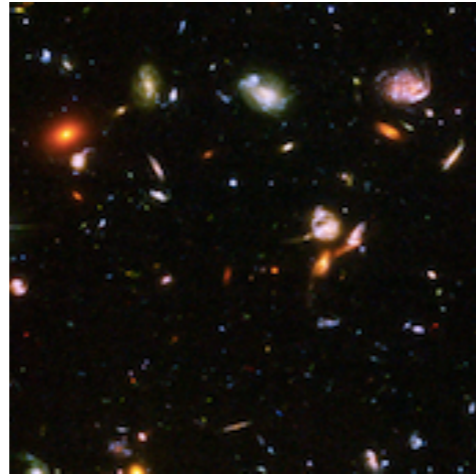
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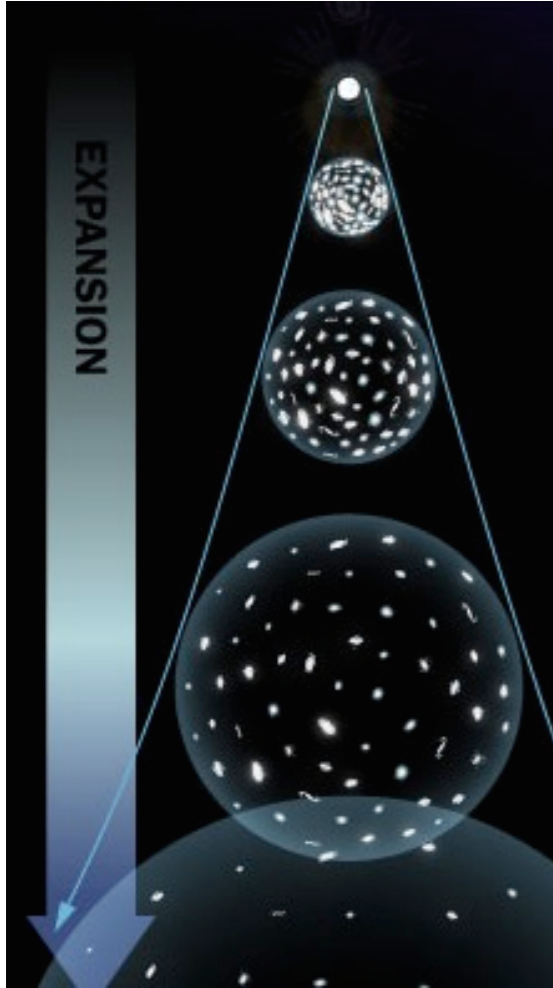
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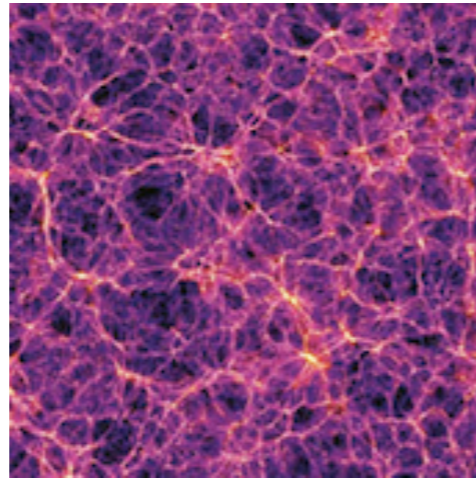
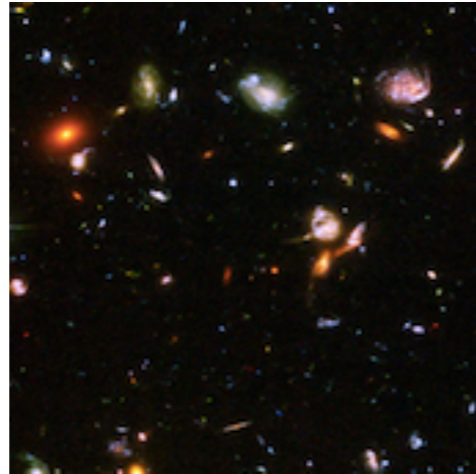
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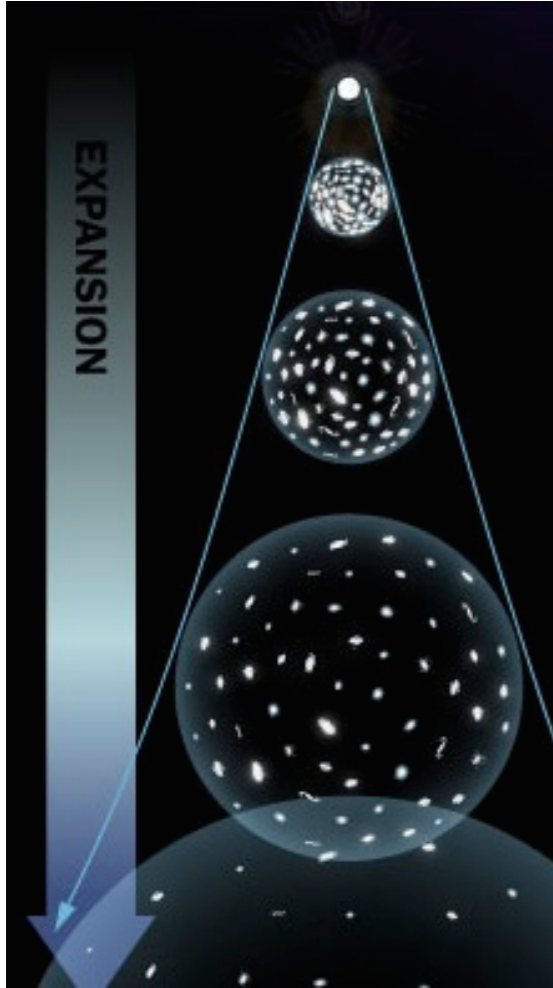


Inflation

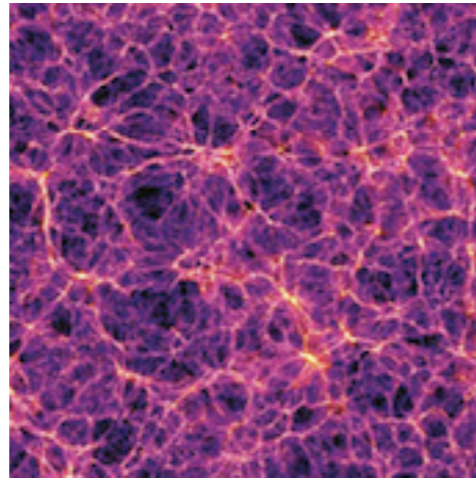
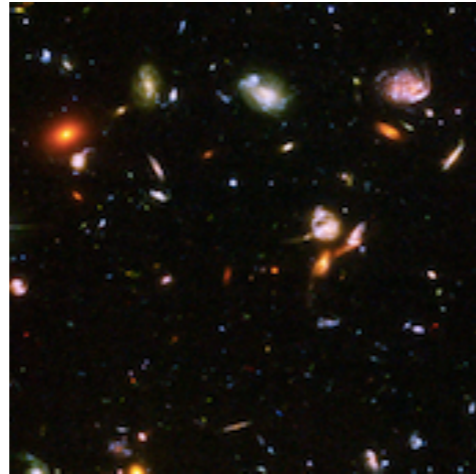
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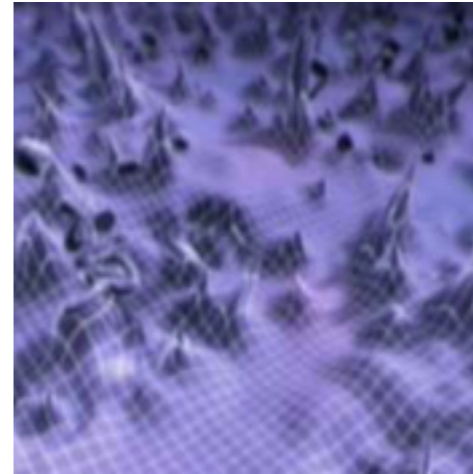
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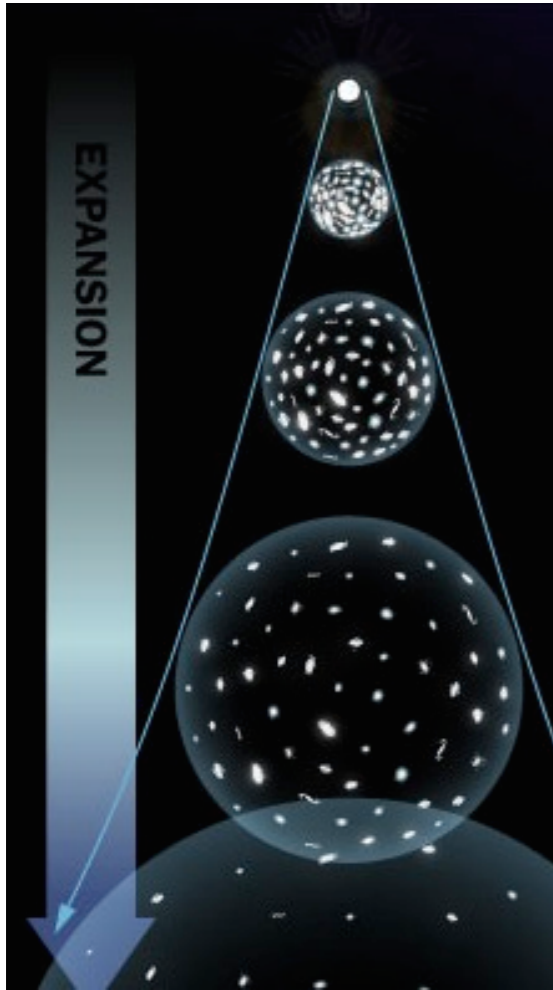
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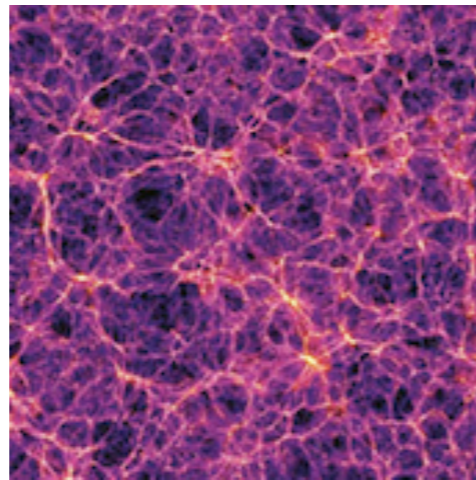
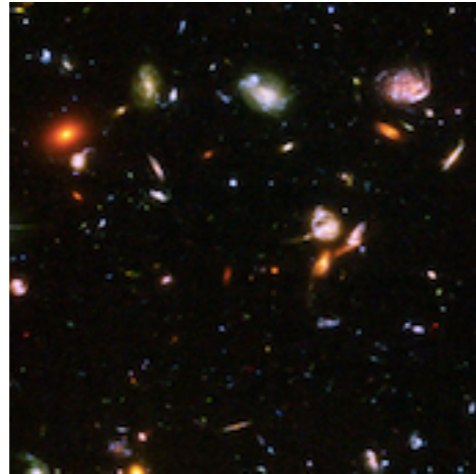
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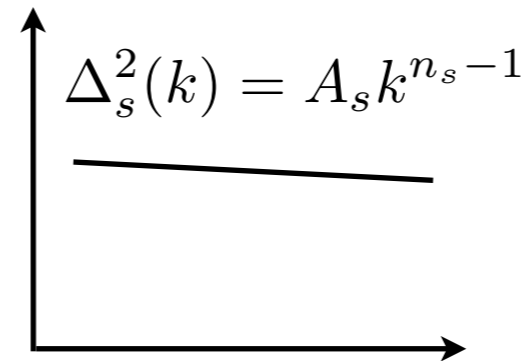
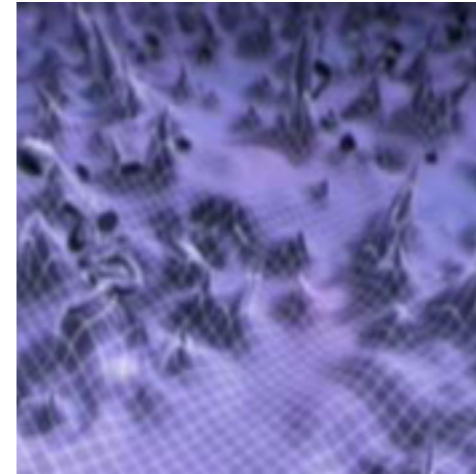
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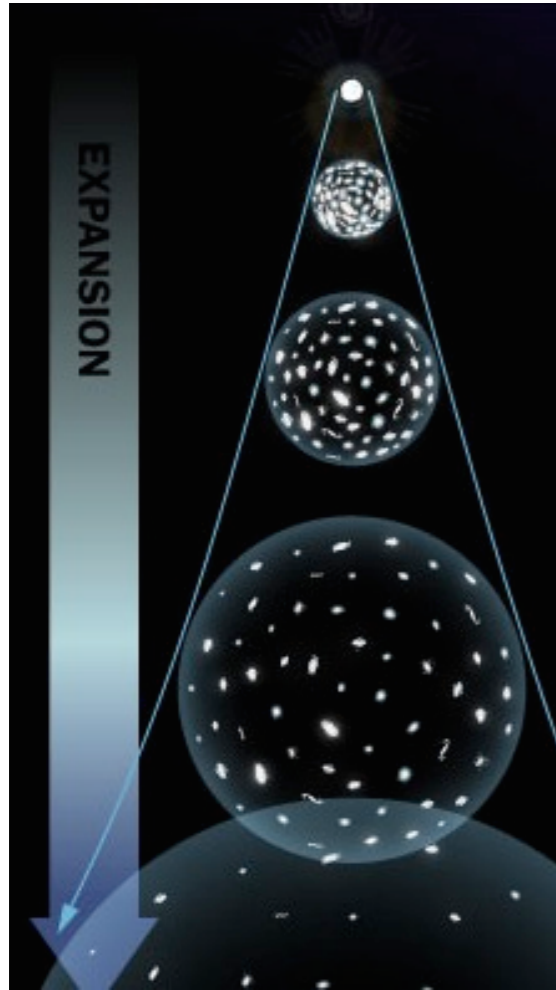


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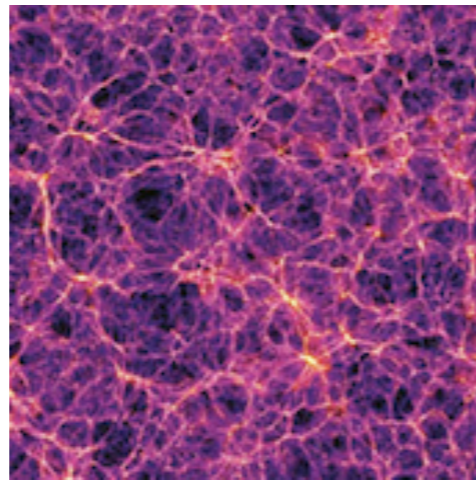
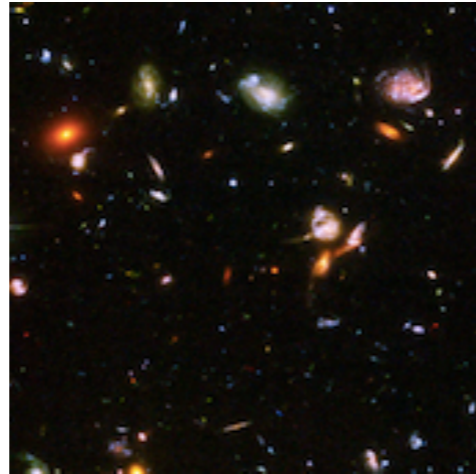


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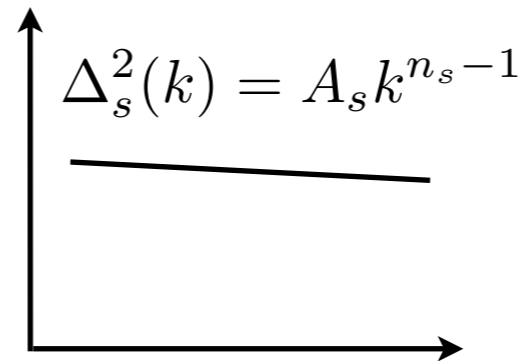
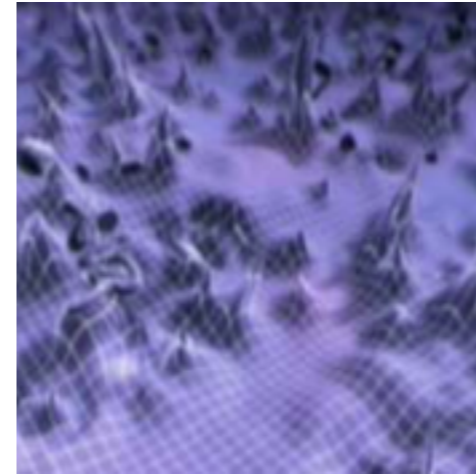
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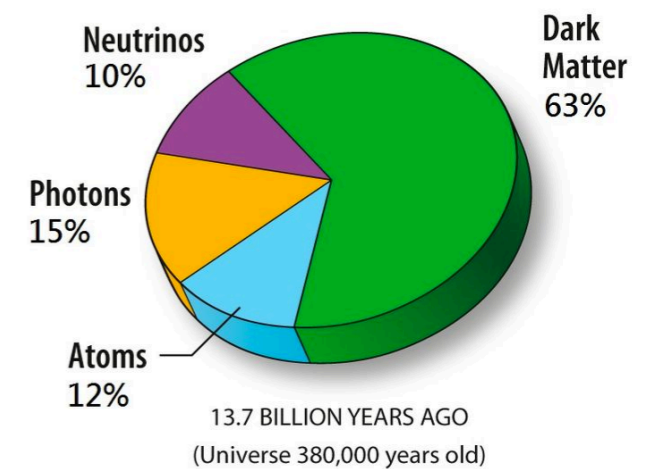
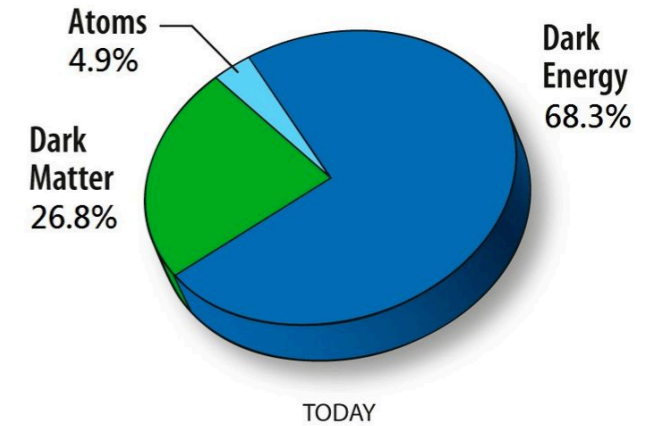
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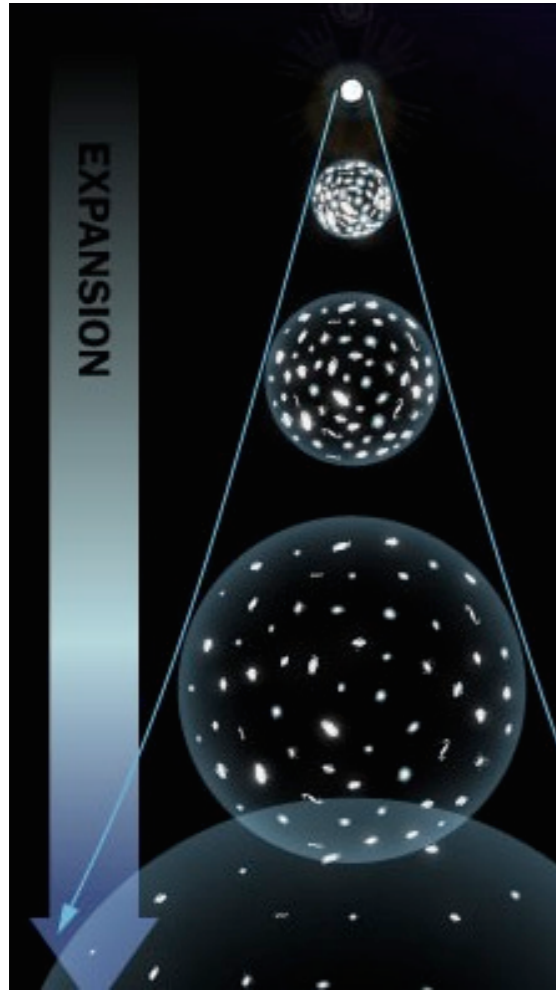


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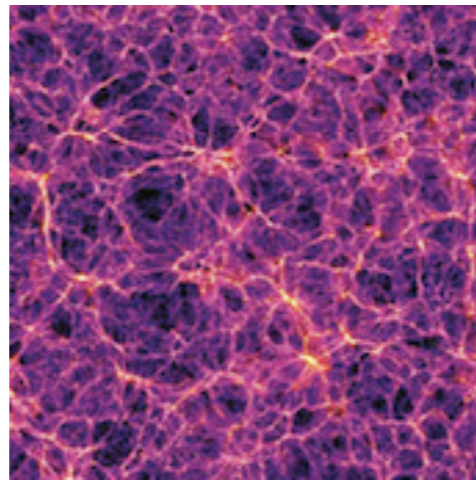
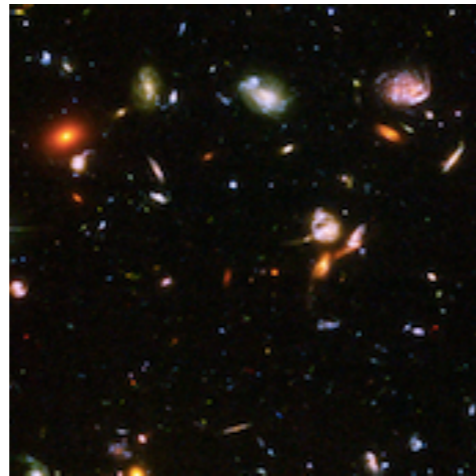


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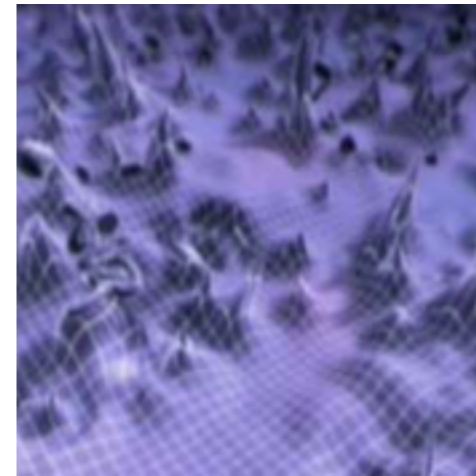
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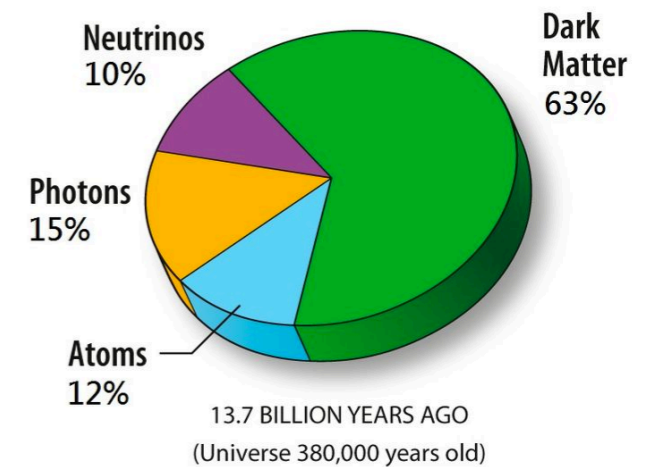
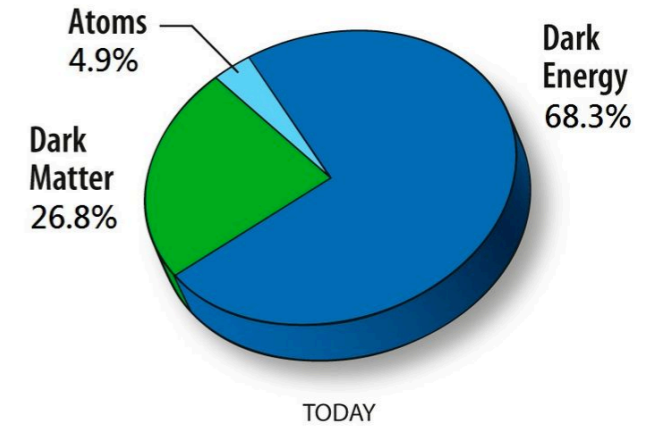
## Inflation



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

A graph showing the power spectrum  $\Delta_s^2(k)$  as a function of wavenumber  $k$ . The vertical axis is labeled  $\Delta_s^2(k)$  and the horizontal axis is labeled  $k$ . A horizontal line is drawn across the graph, indicating a constant power spectrum, which is characteristic of the inflationary epoch.

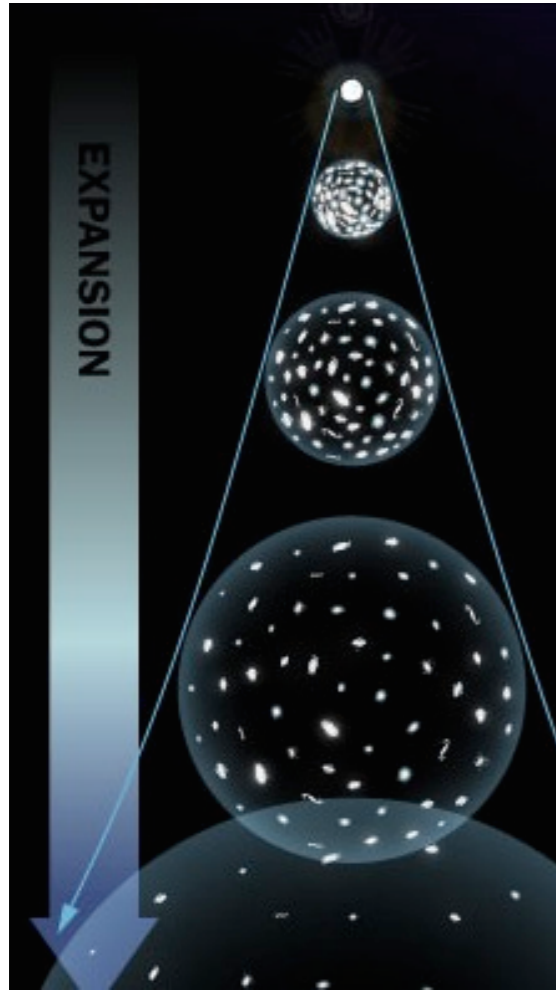
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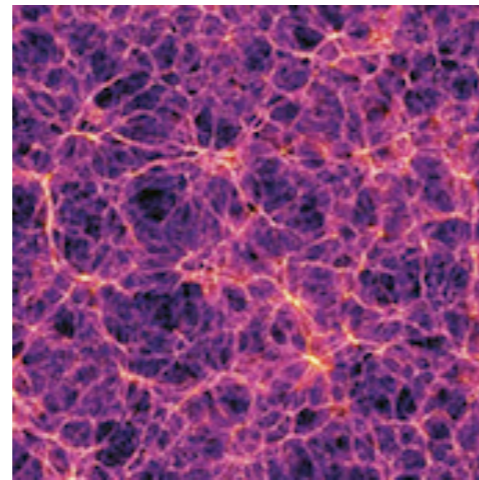
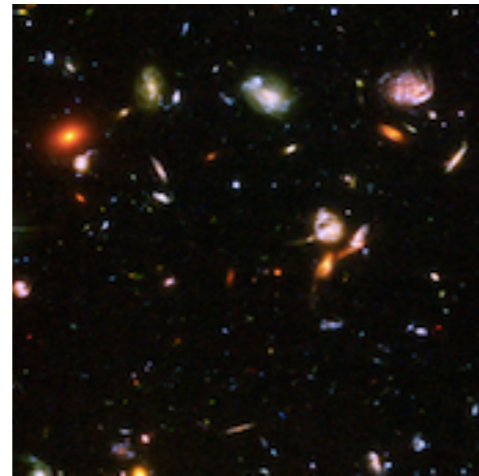
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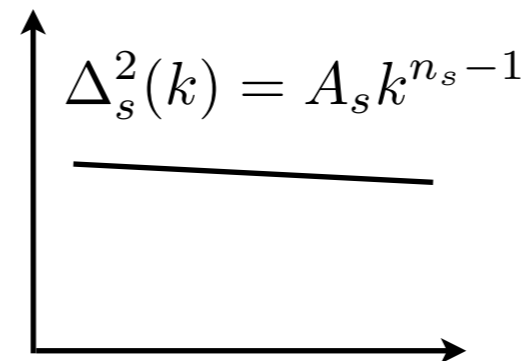
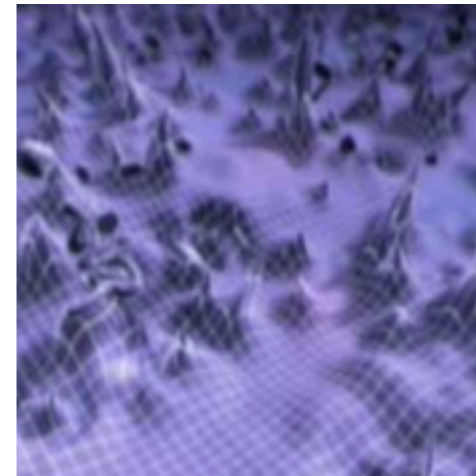
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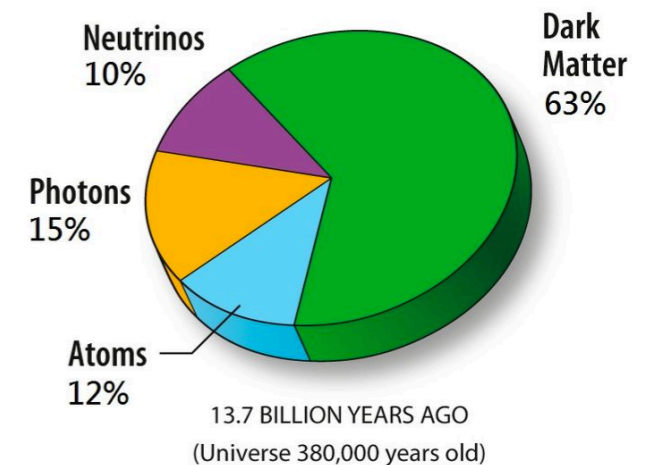
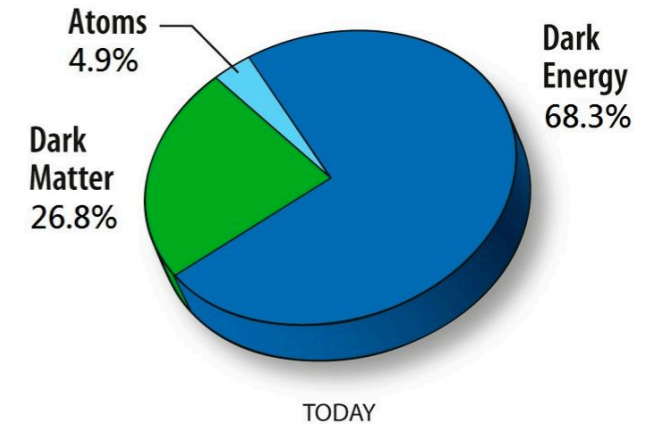
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Inflation



ΛCDM



$H_0$

$\tau$

$A_s$

$n_s$

$\Omega_{\text{CDM}}$

$\Omega_b$

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# Basic Questions in Cosmology

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What are the  
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# Basic Questions in Cosmology

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What are the properties of *inflation*?

2

What is the nature of *dark matter*?

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What makes up *dark energy*?

4

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

# Source of Answers: Precision Cosmology

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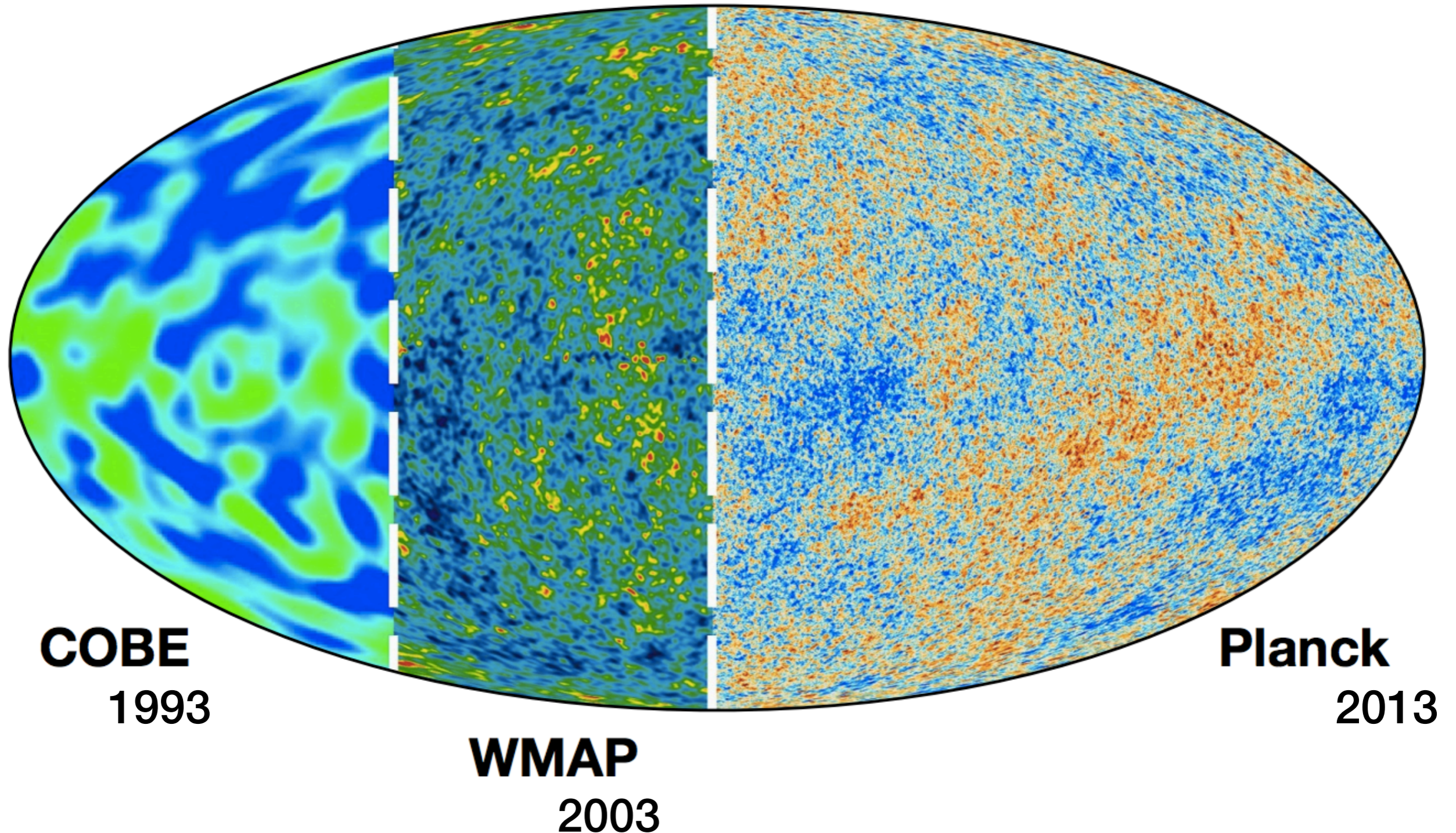
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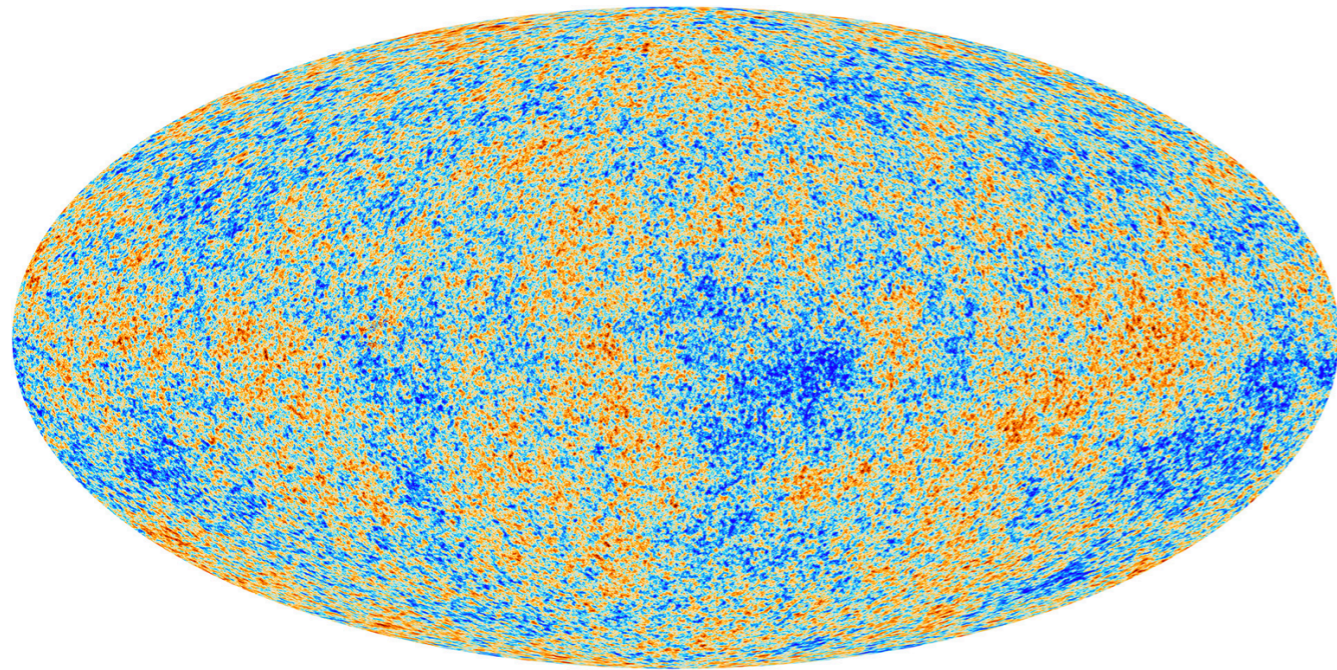
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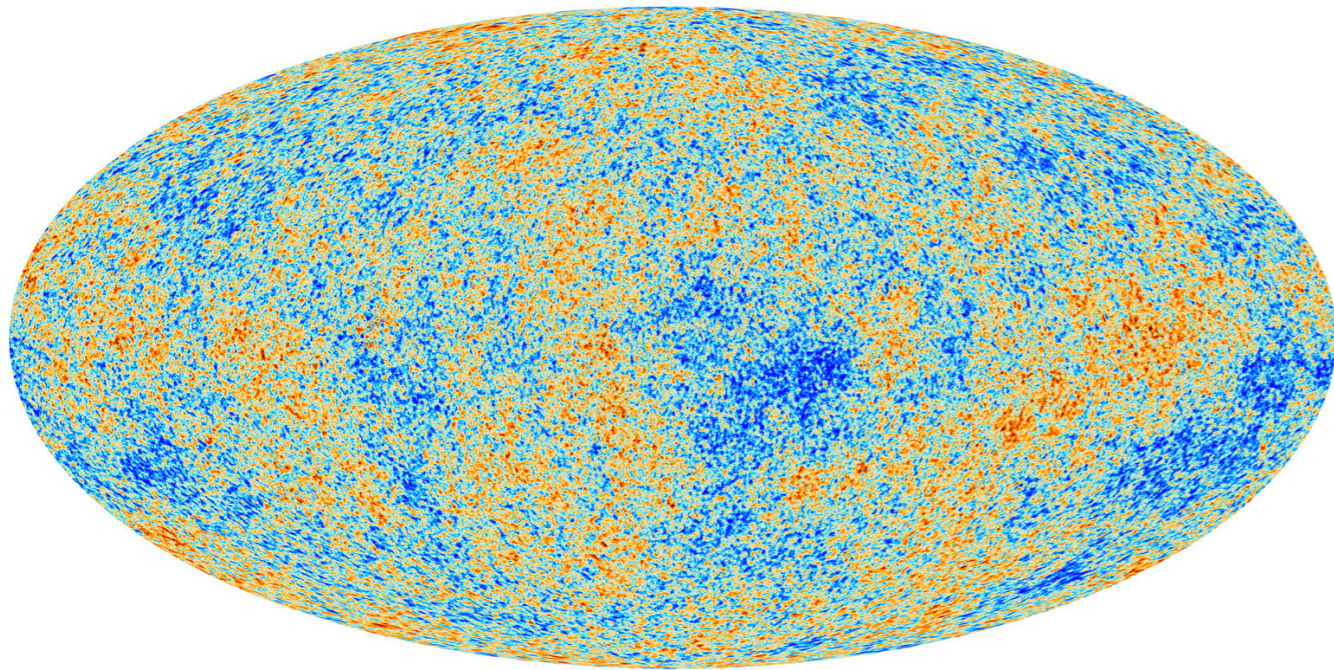


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$$\delta T(\hat{\mathbf{n}}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$



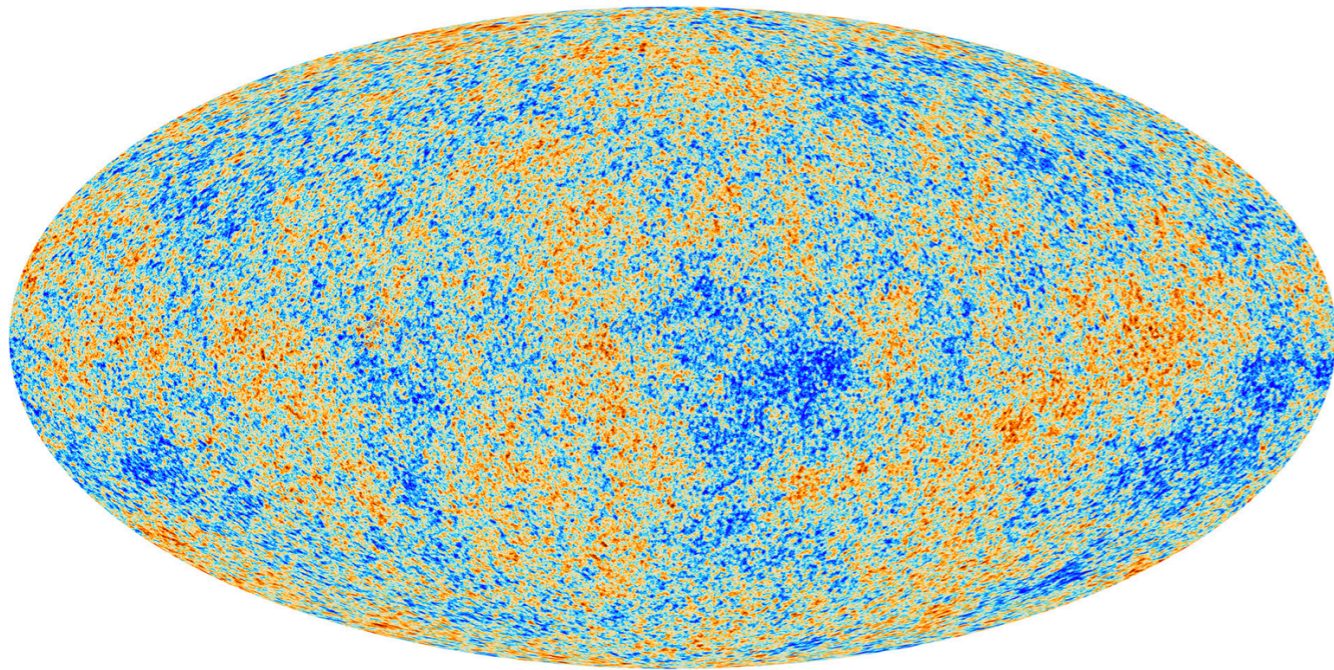
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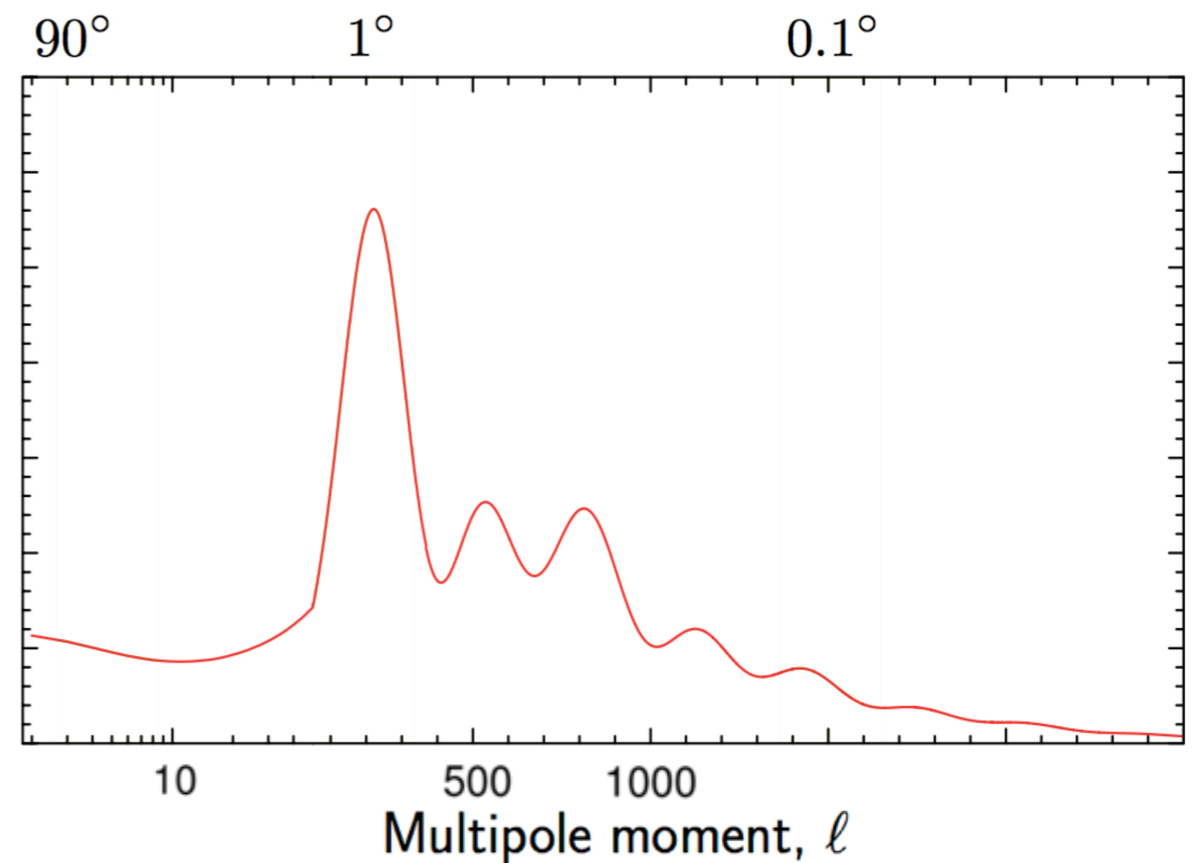
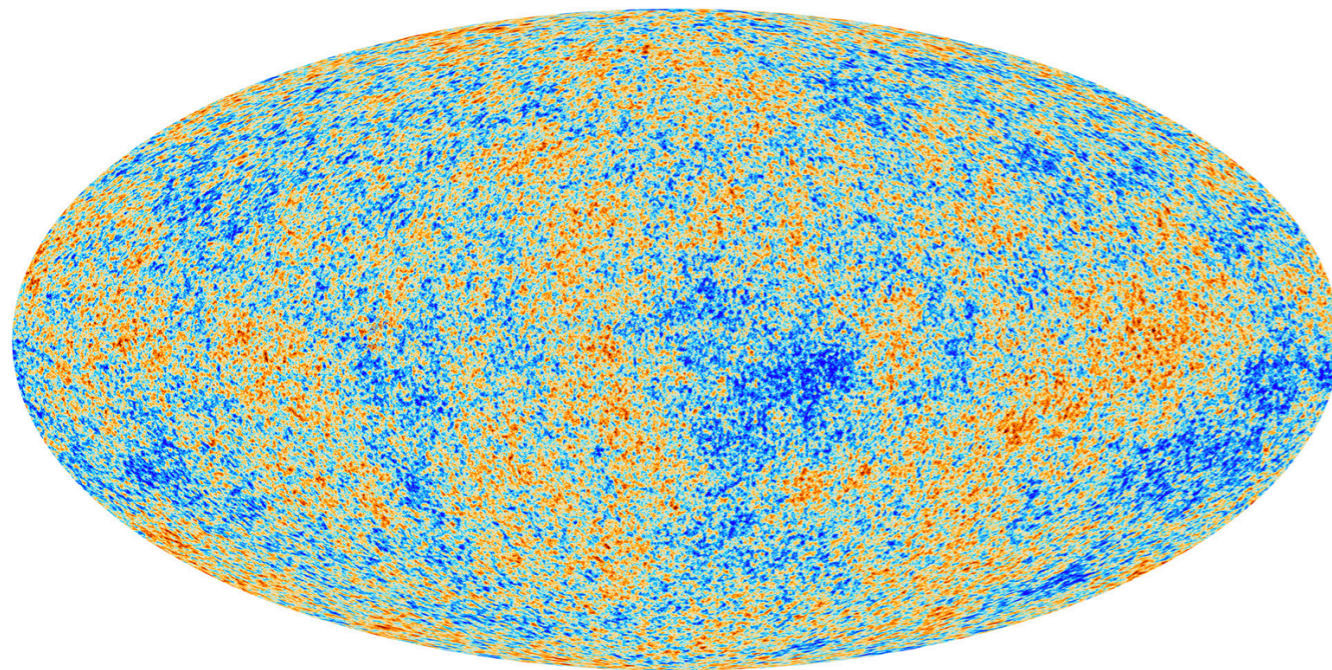
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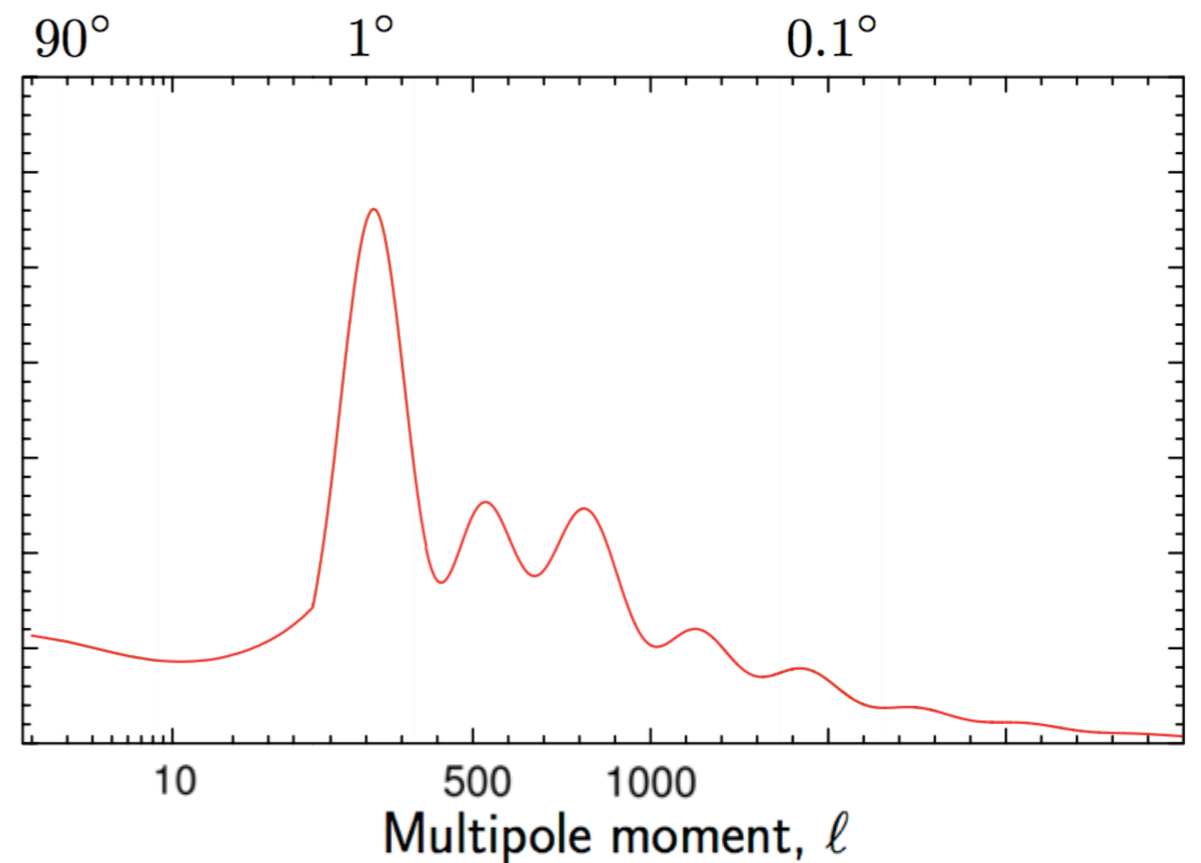
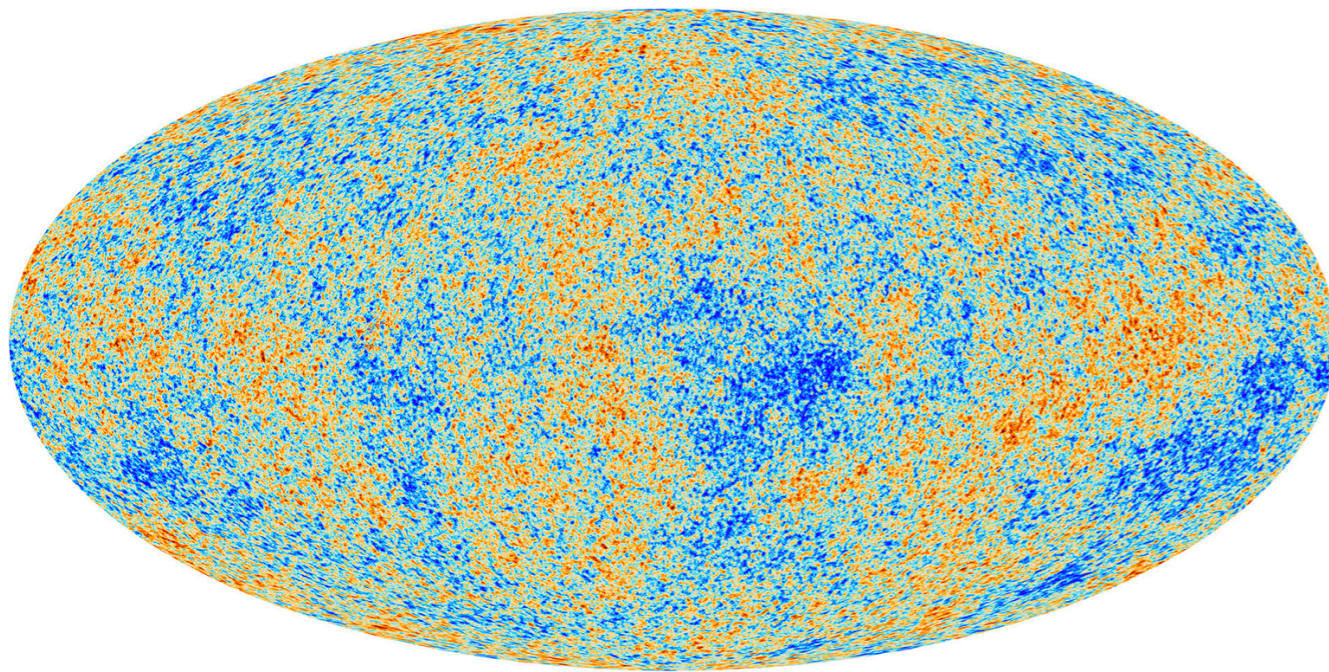
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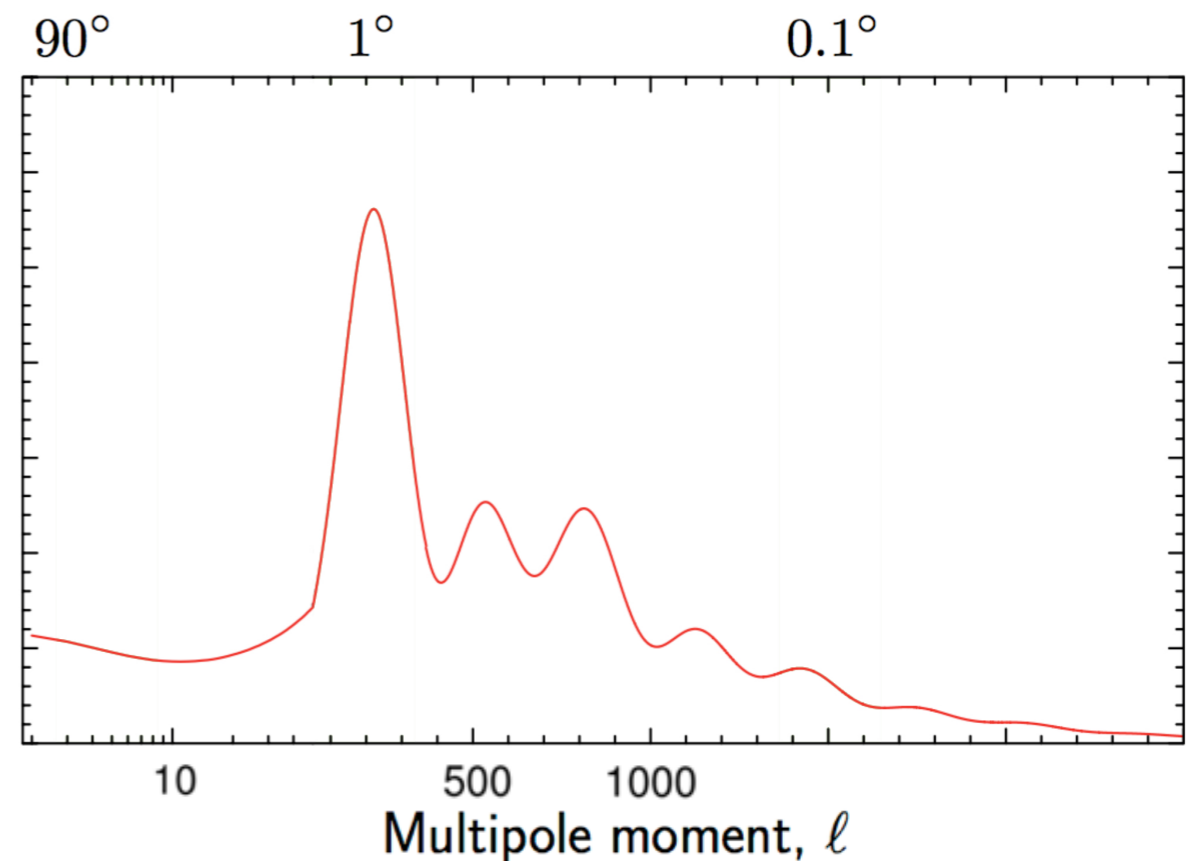
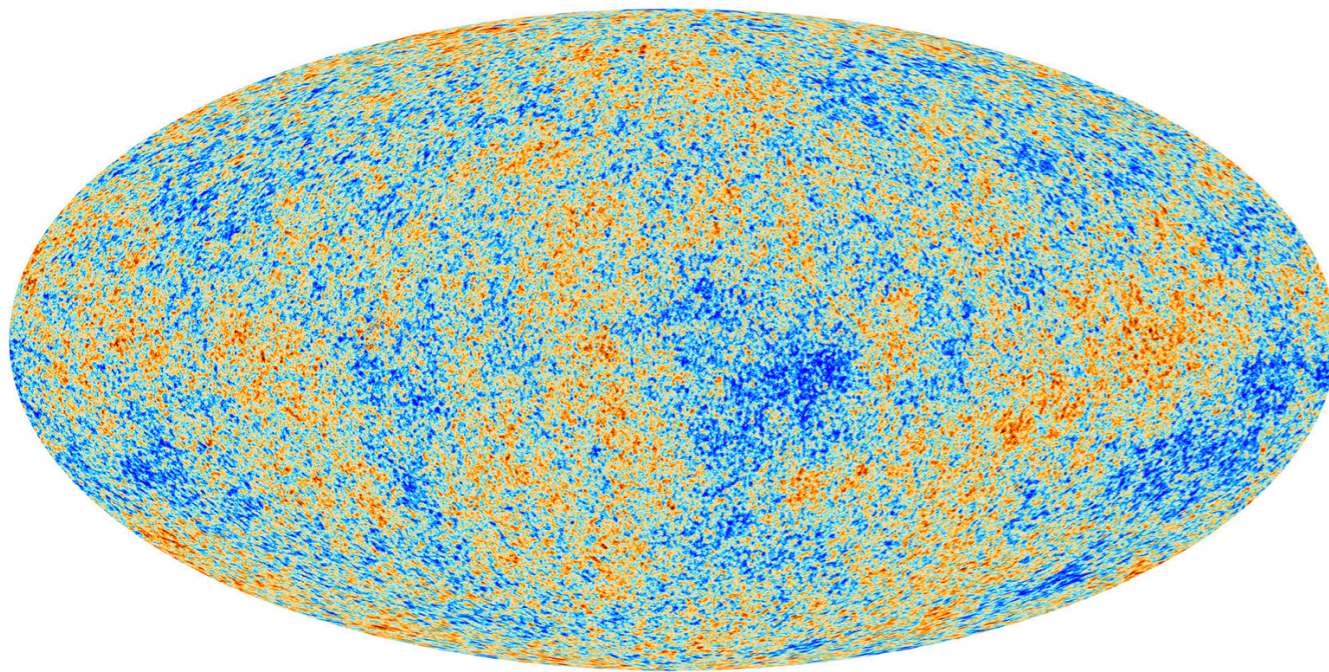
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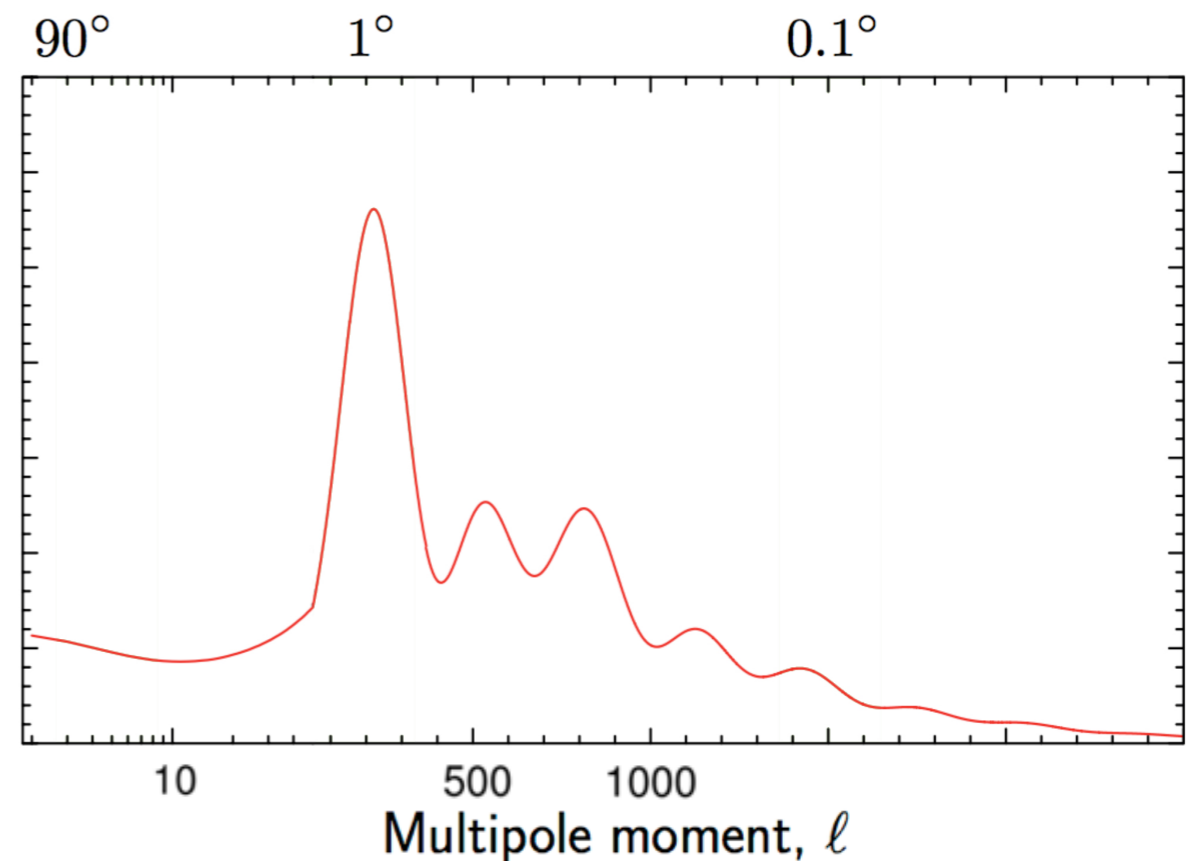
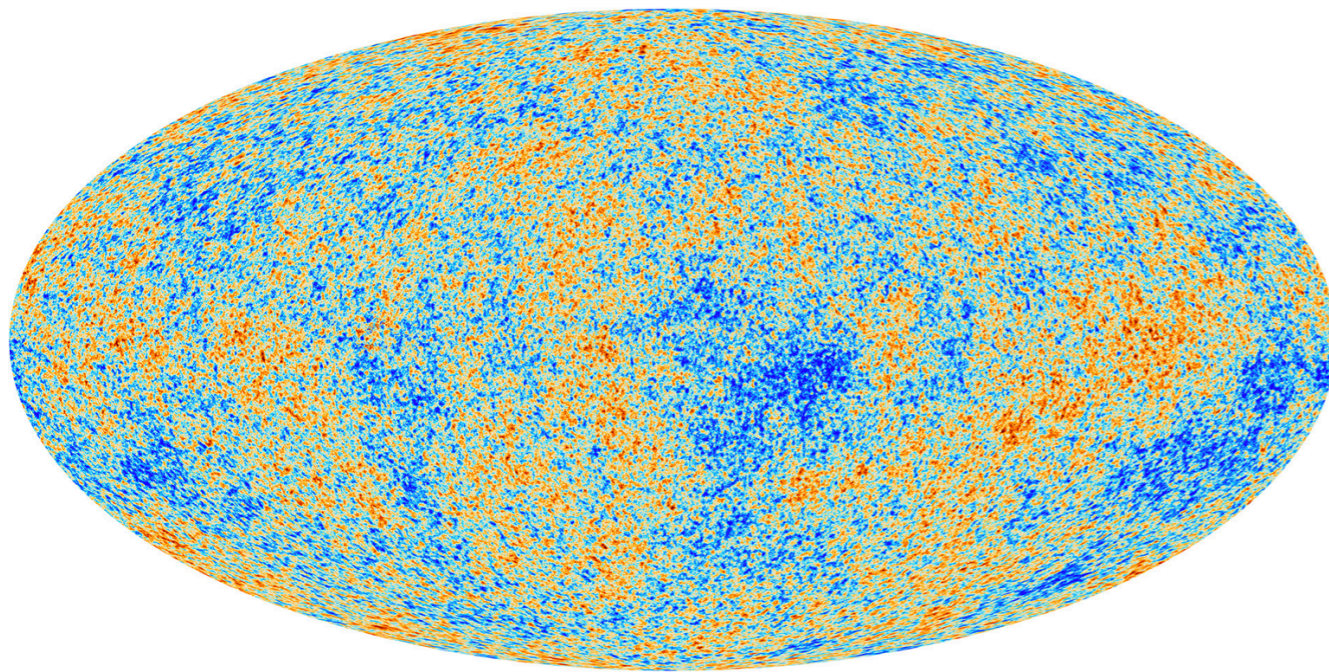
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Gravitational driving force generated by dark-matter potential wells.  
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- Silk diffusion damping: exponential suppression of small scale fluctuations.

# The CMB Power Spectrum: Sensitivity

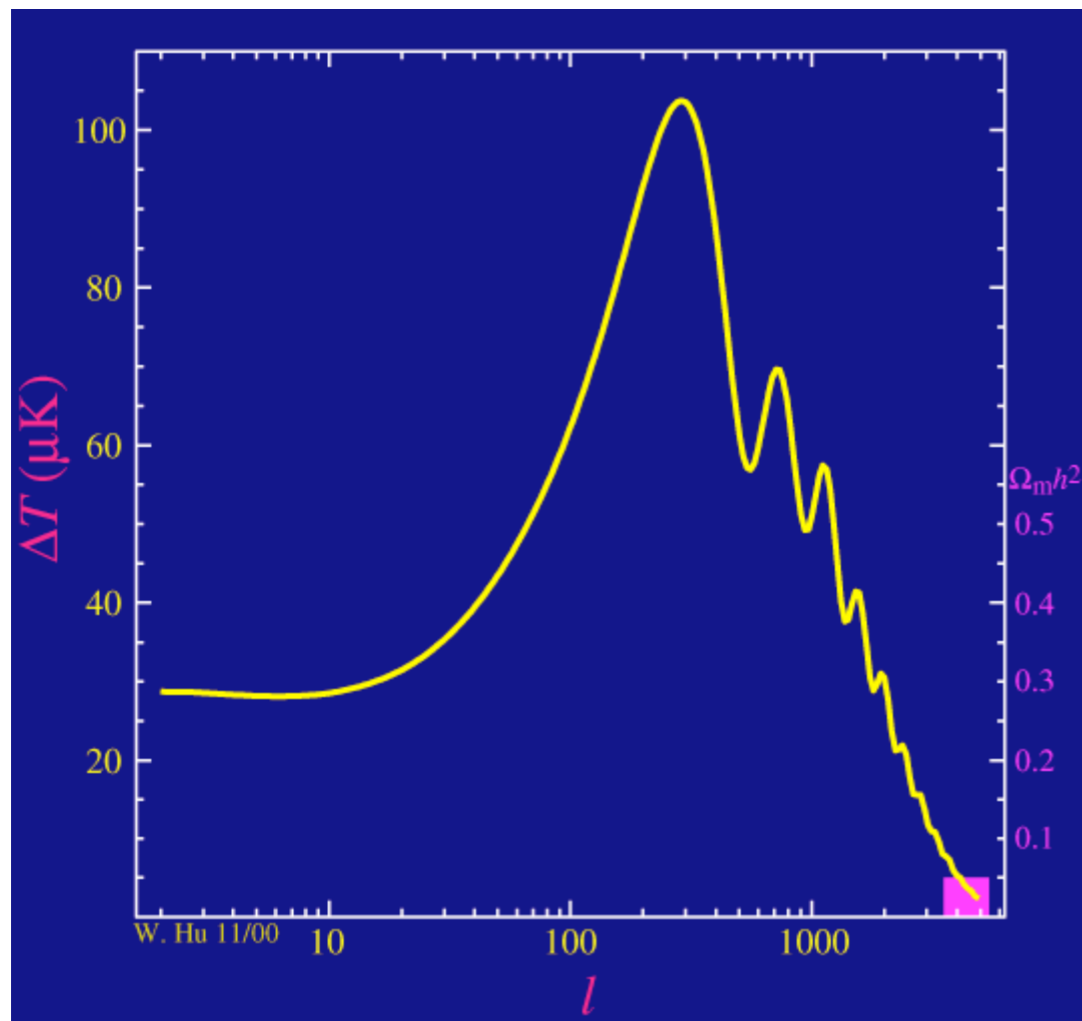
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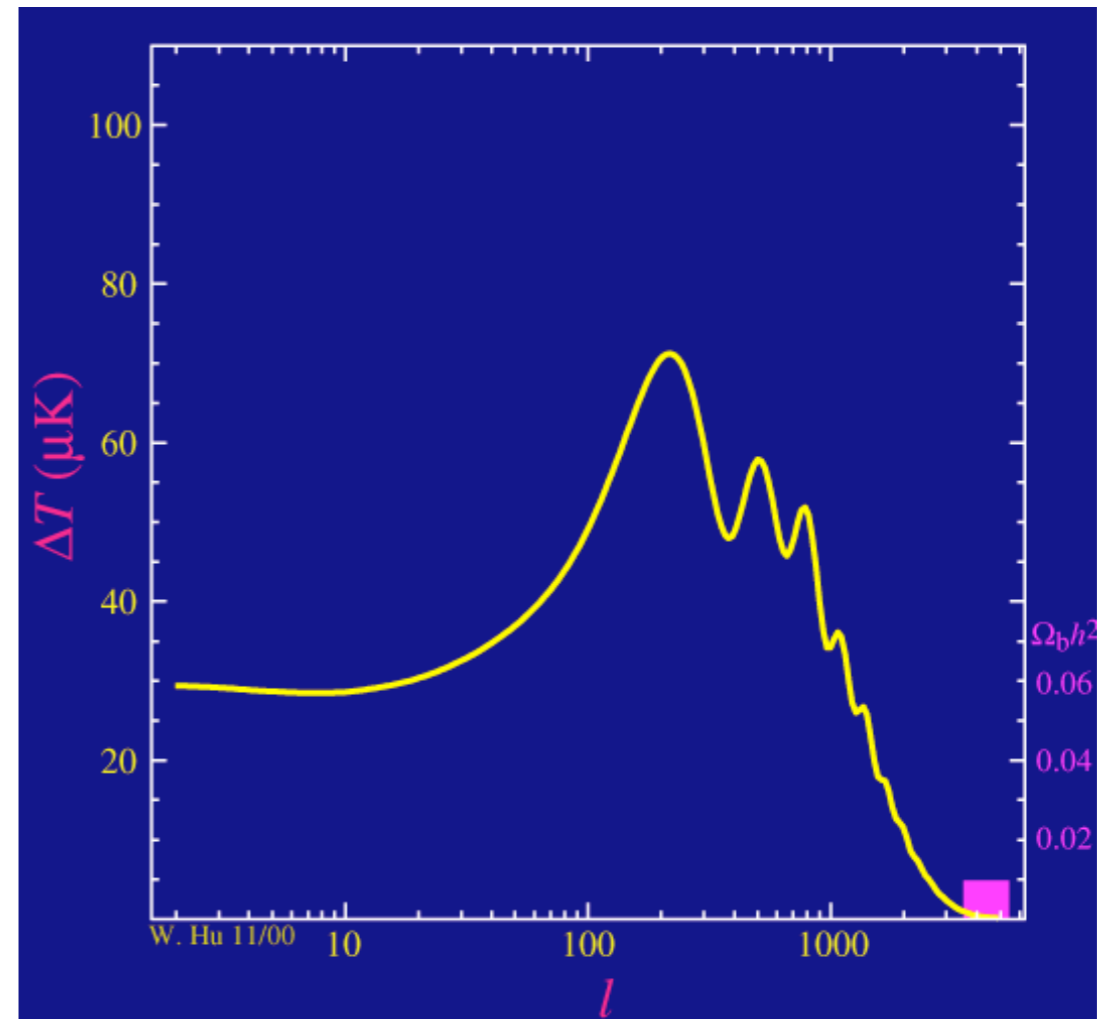
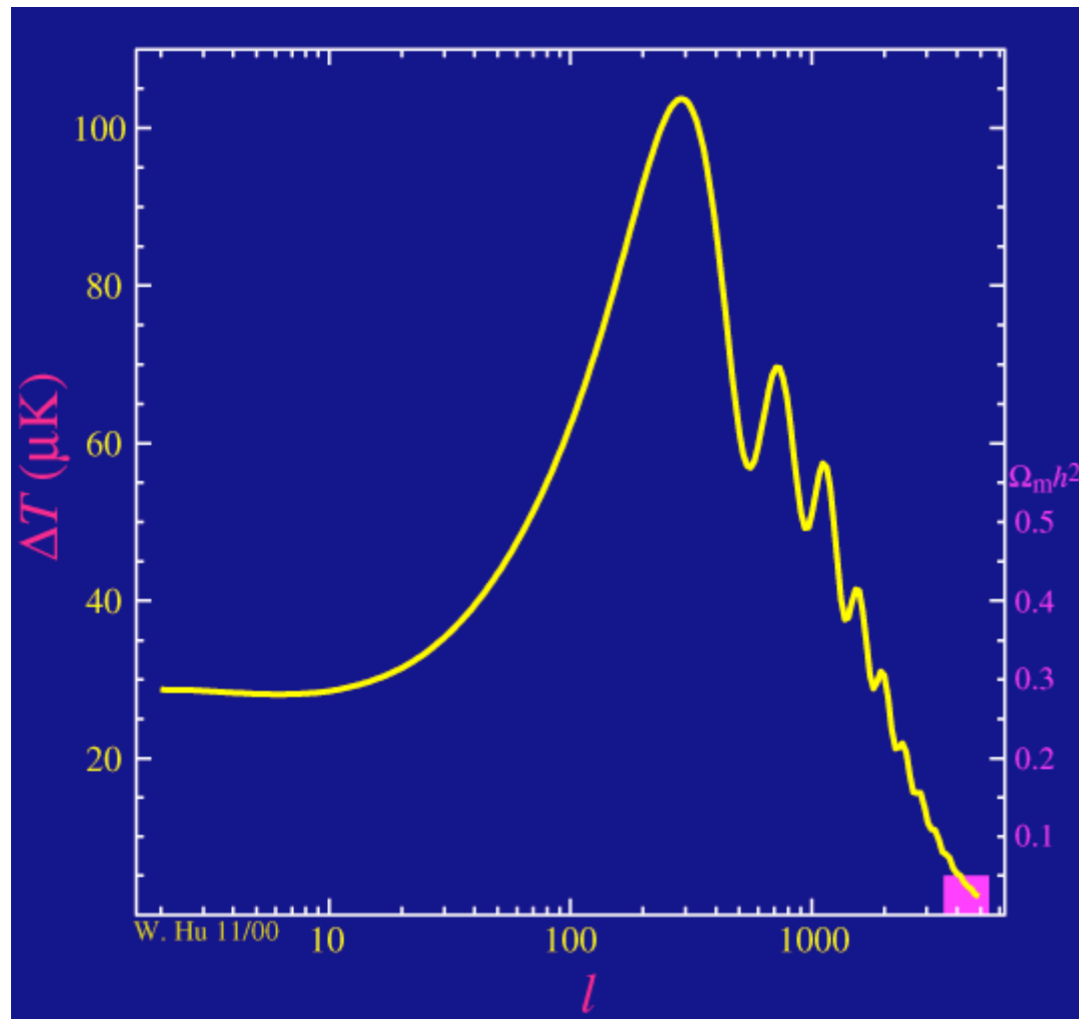


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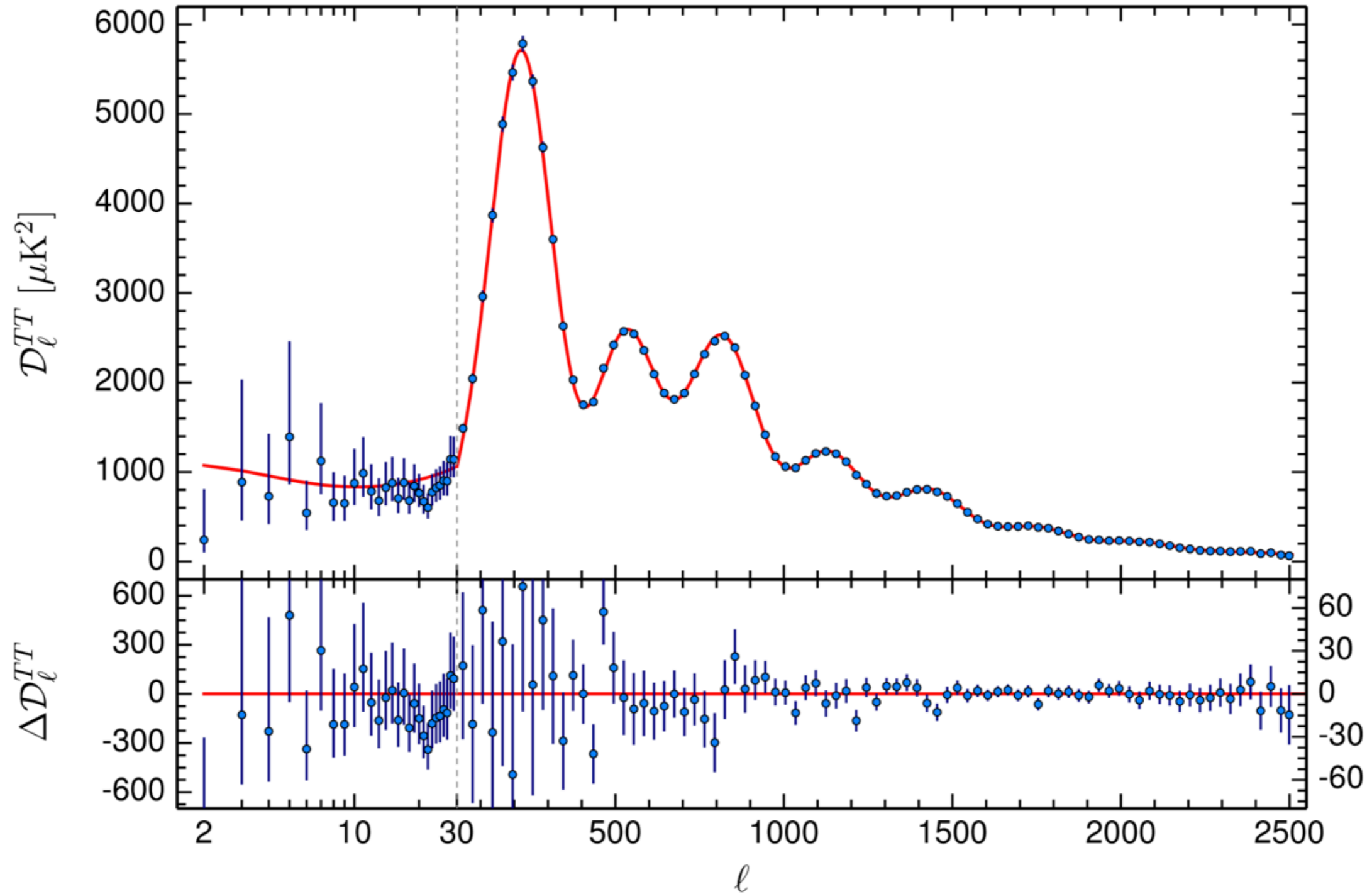
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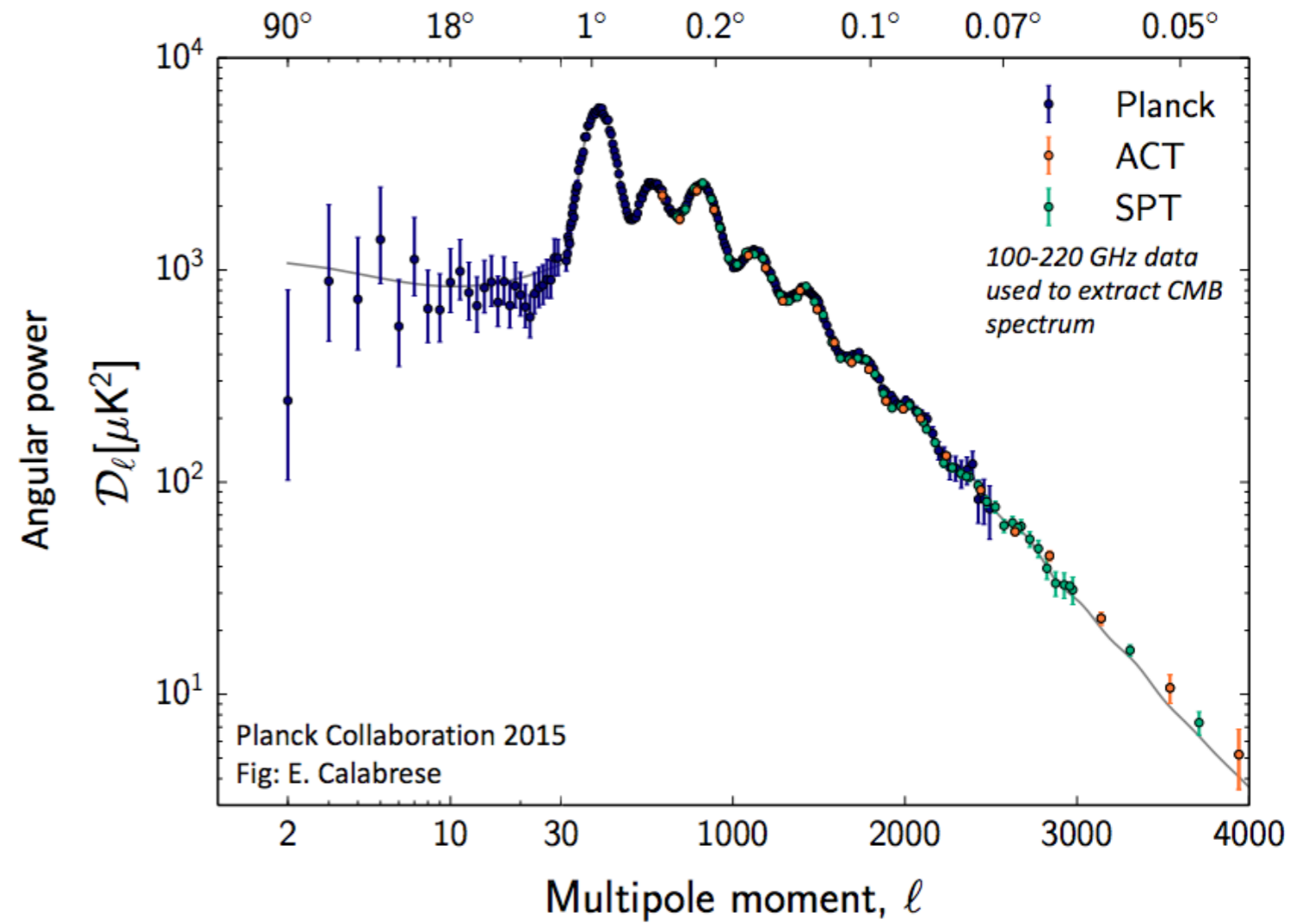
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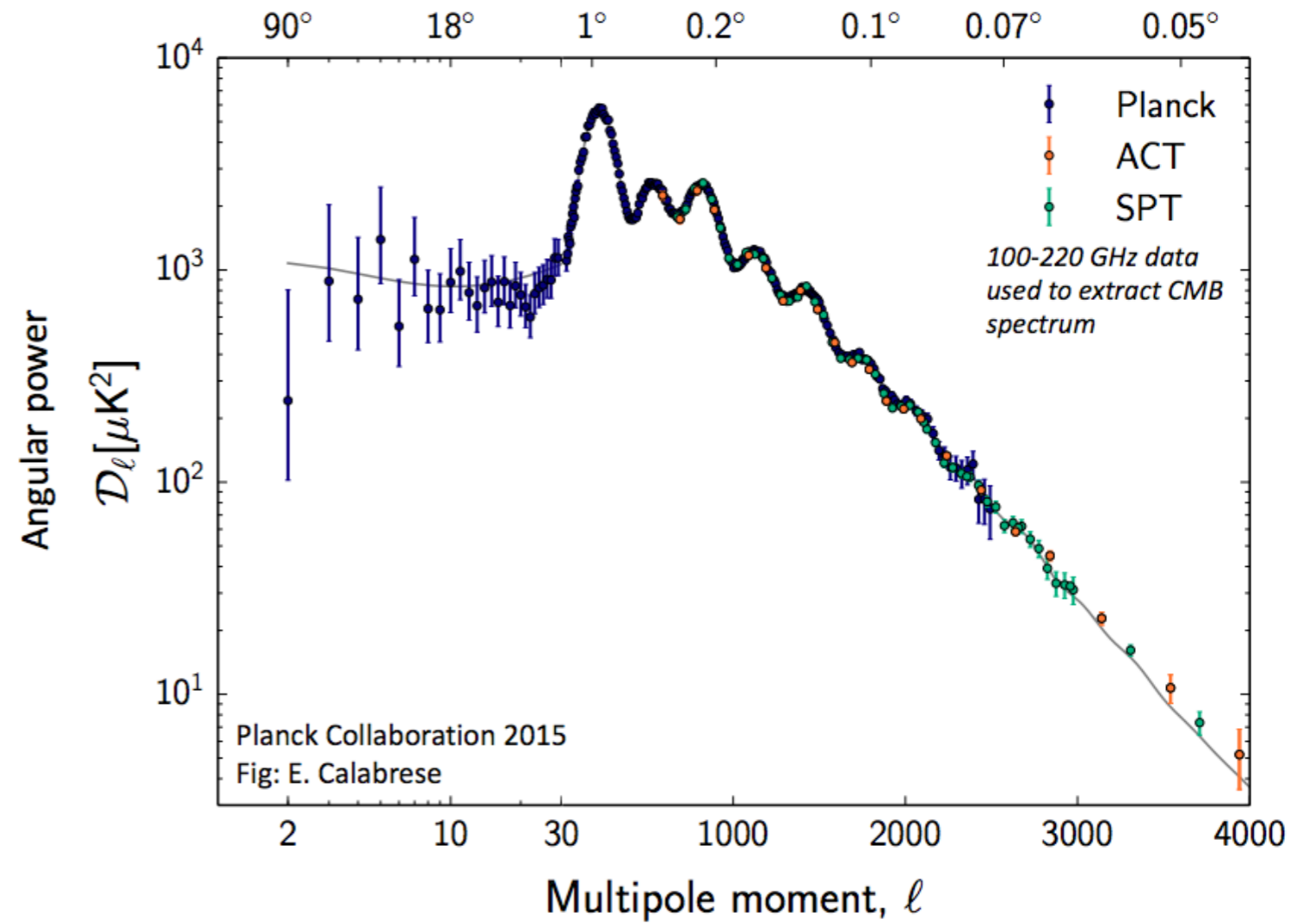


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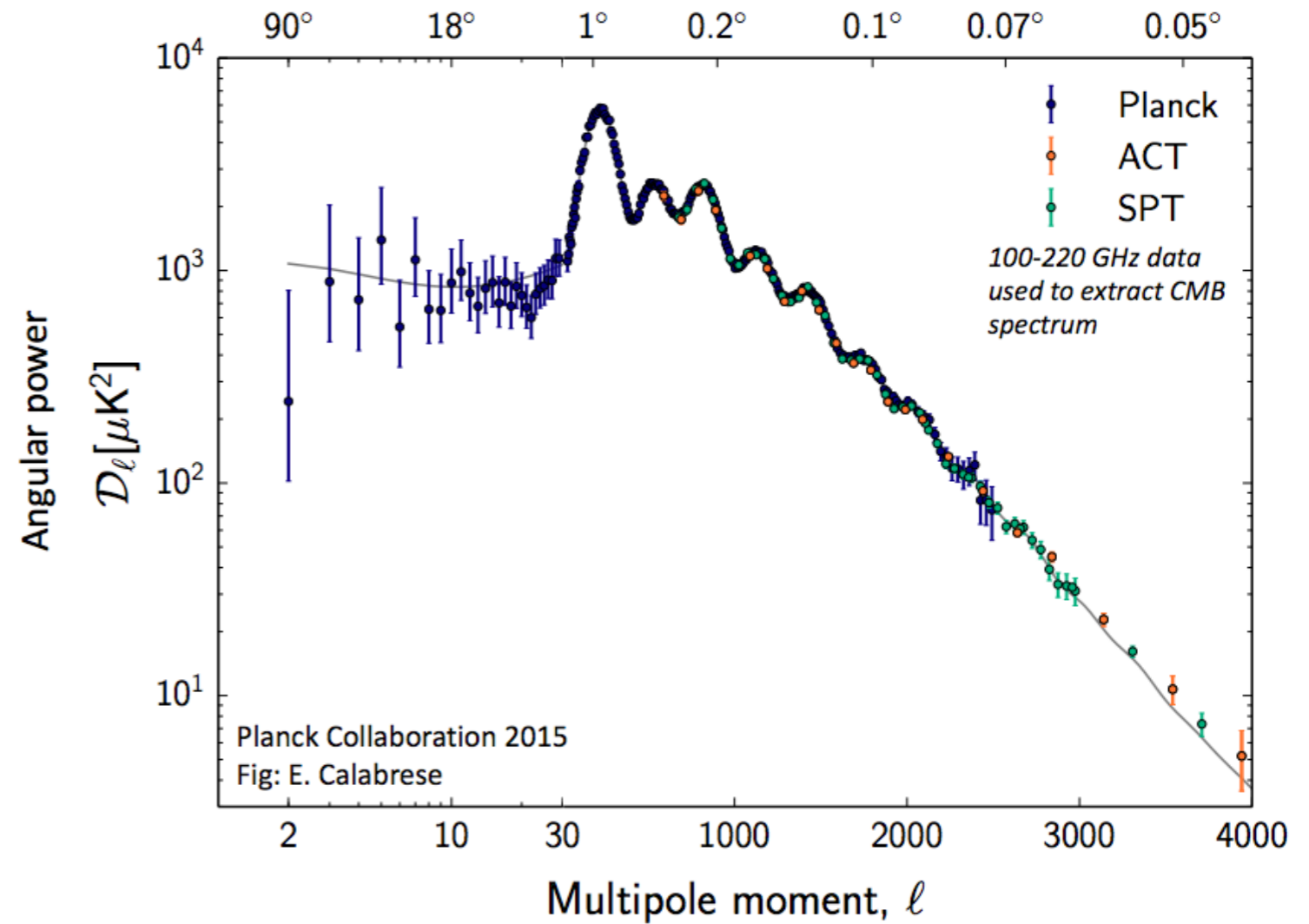
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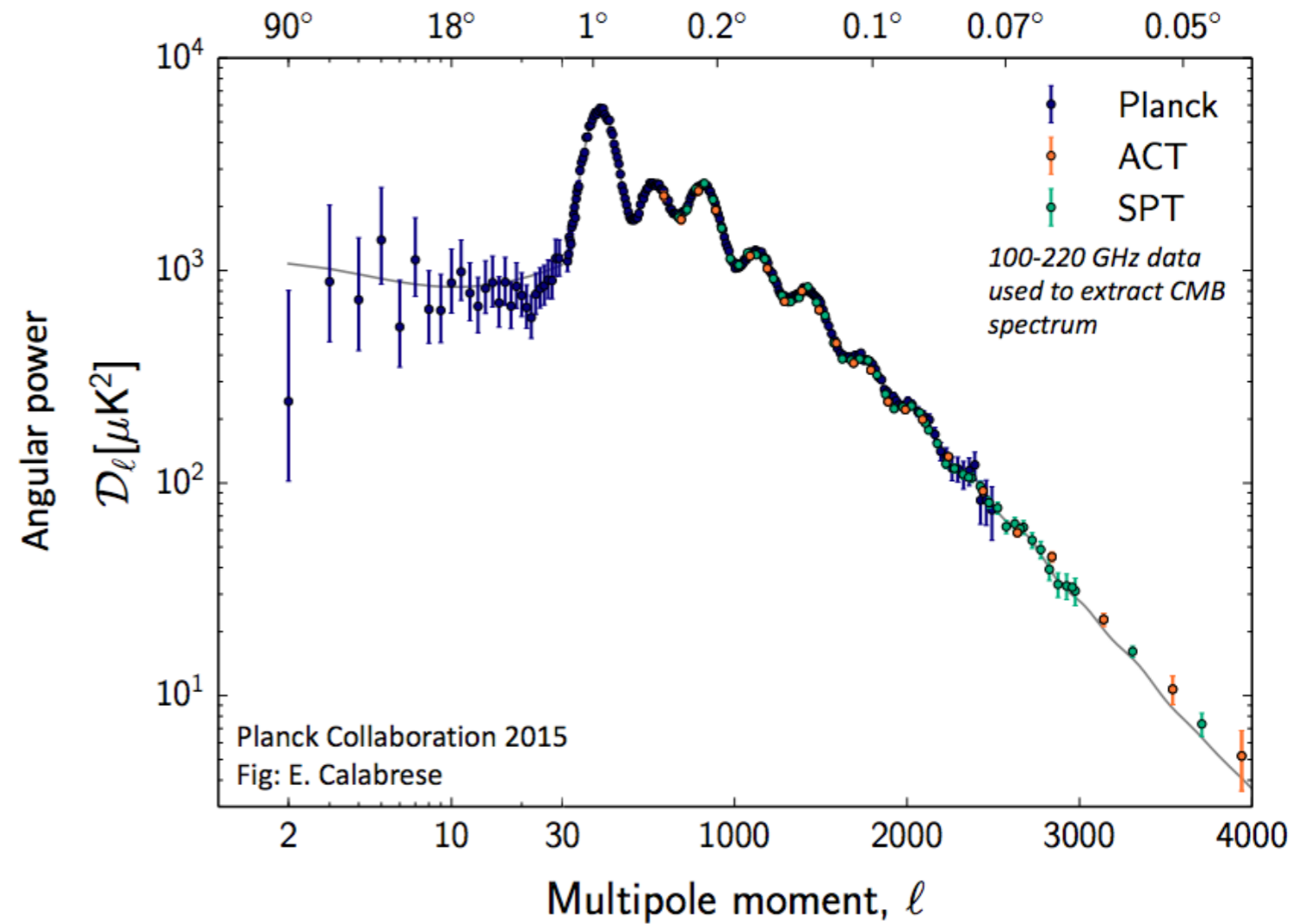
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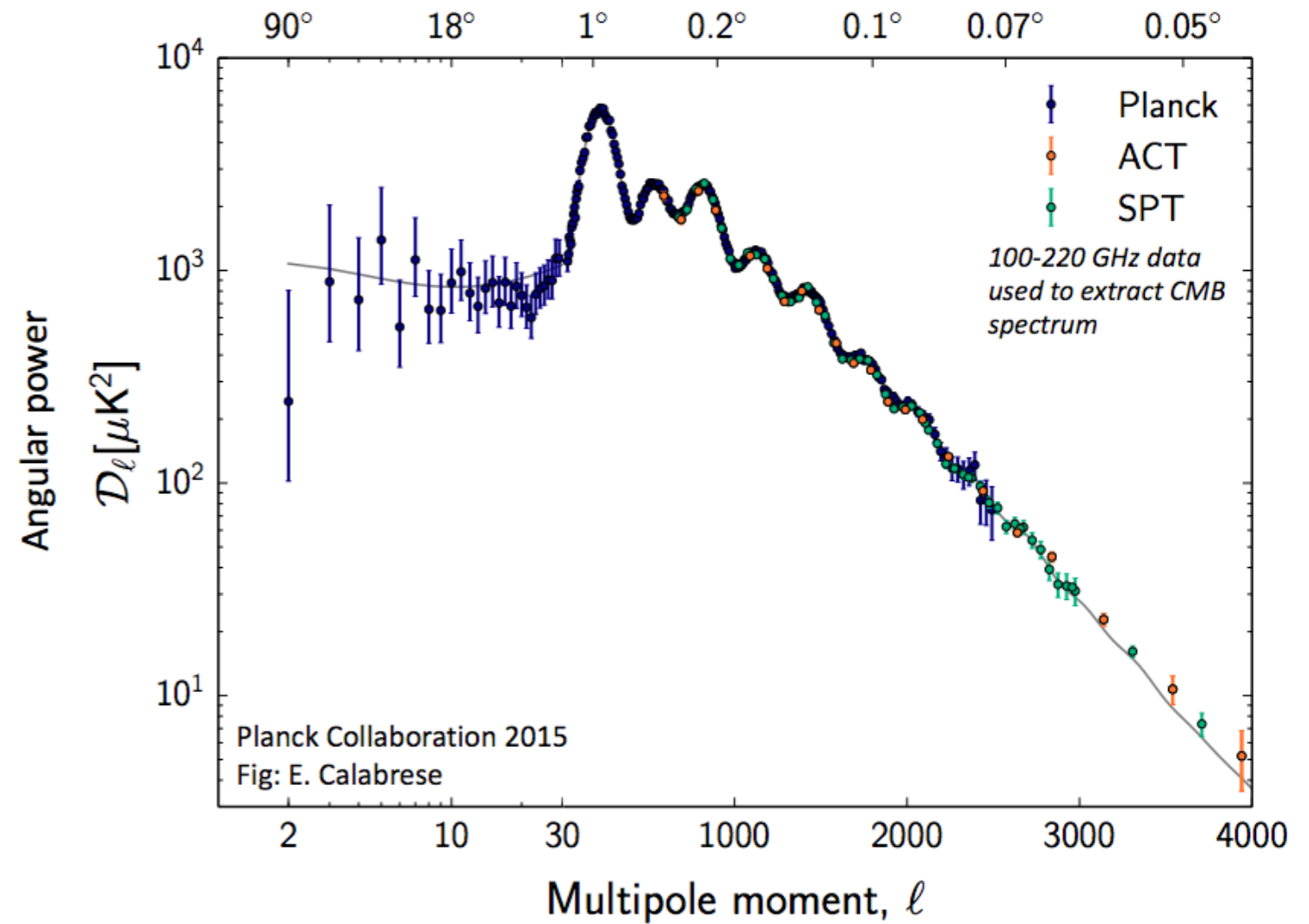
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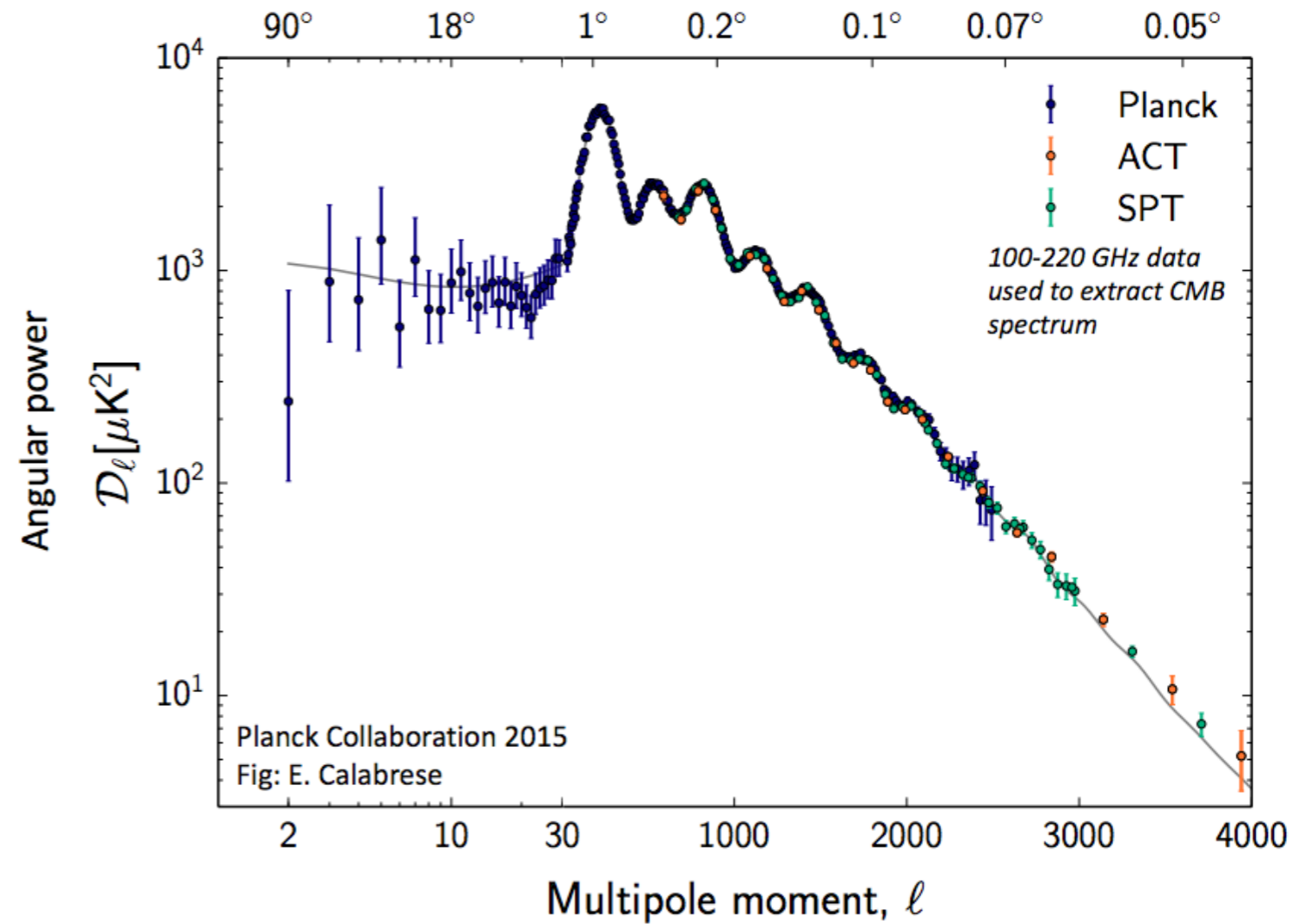
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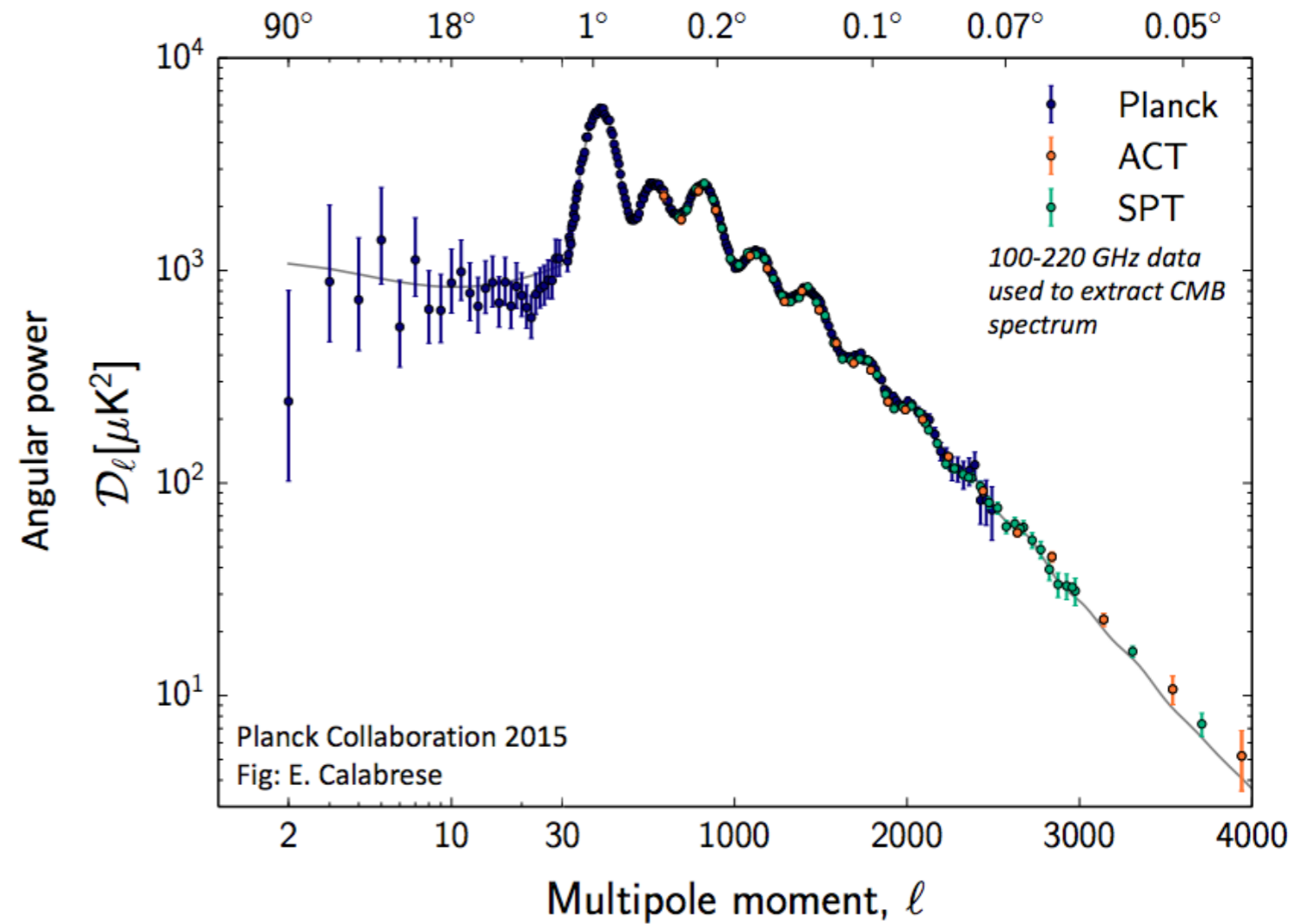
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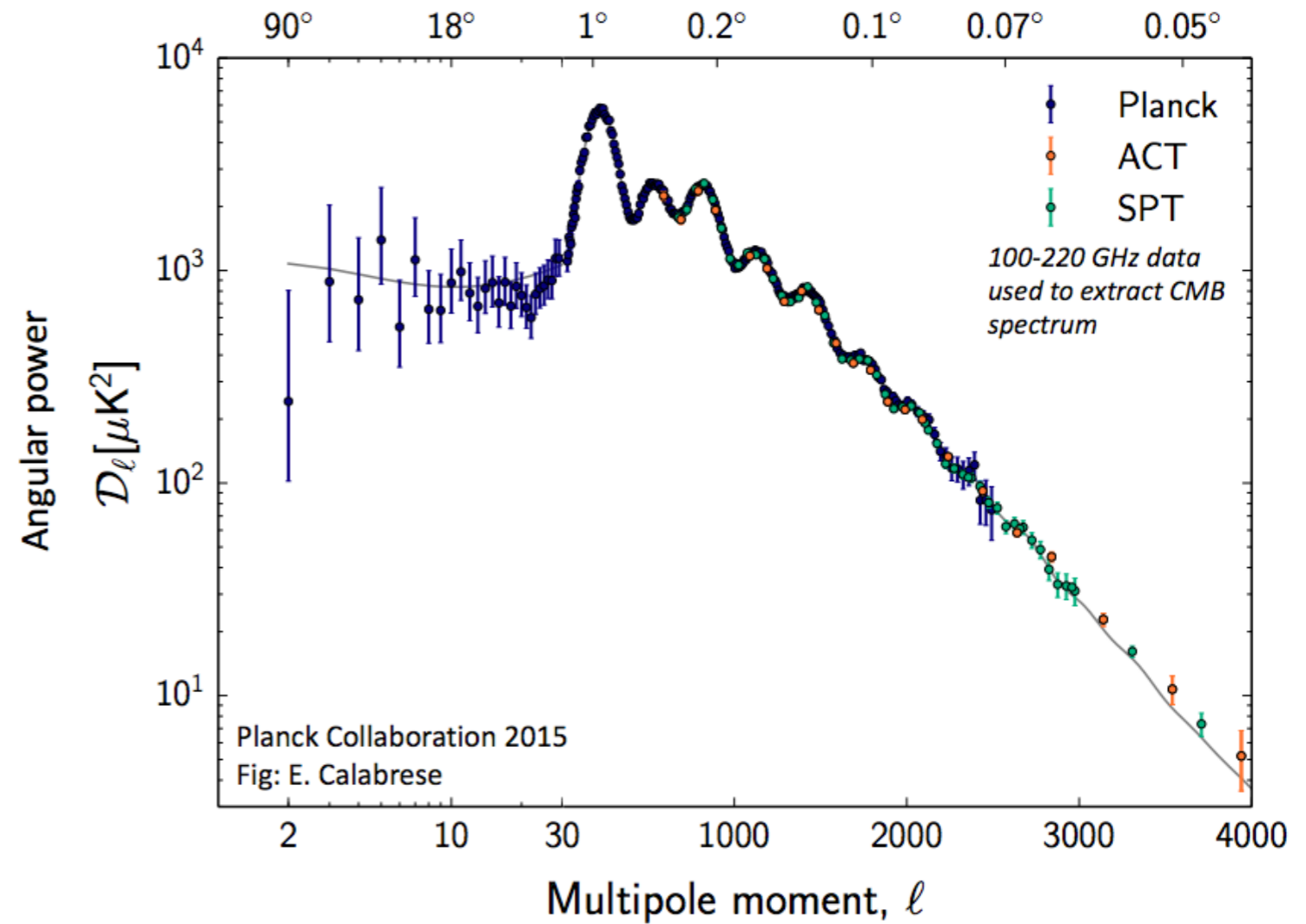


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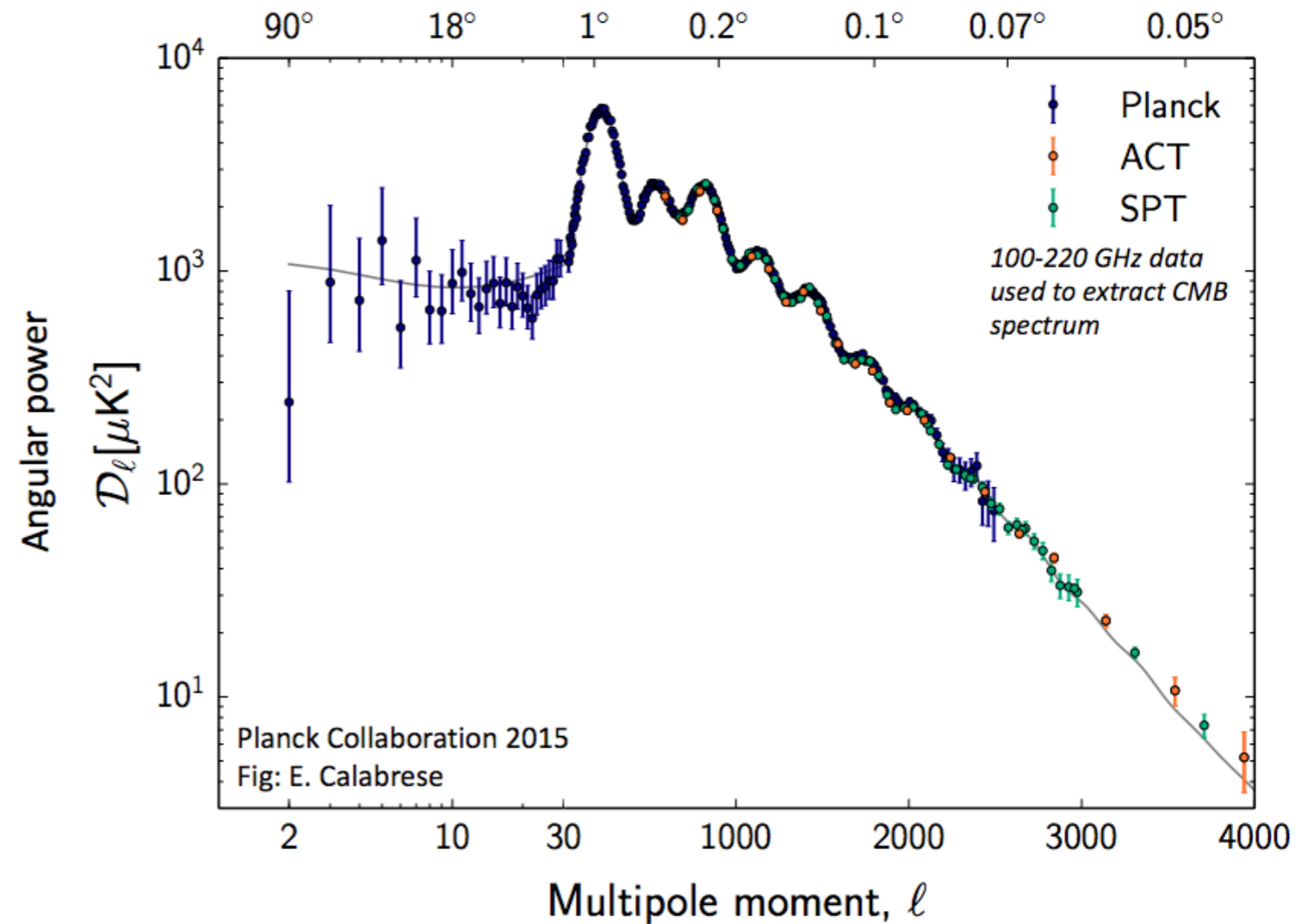
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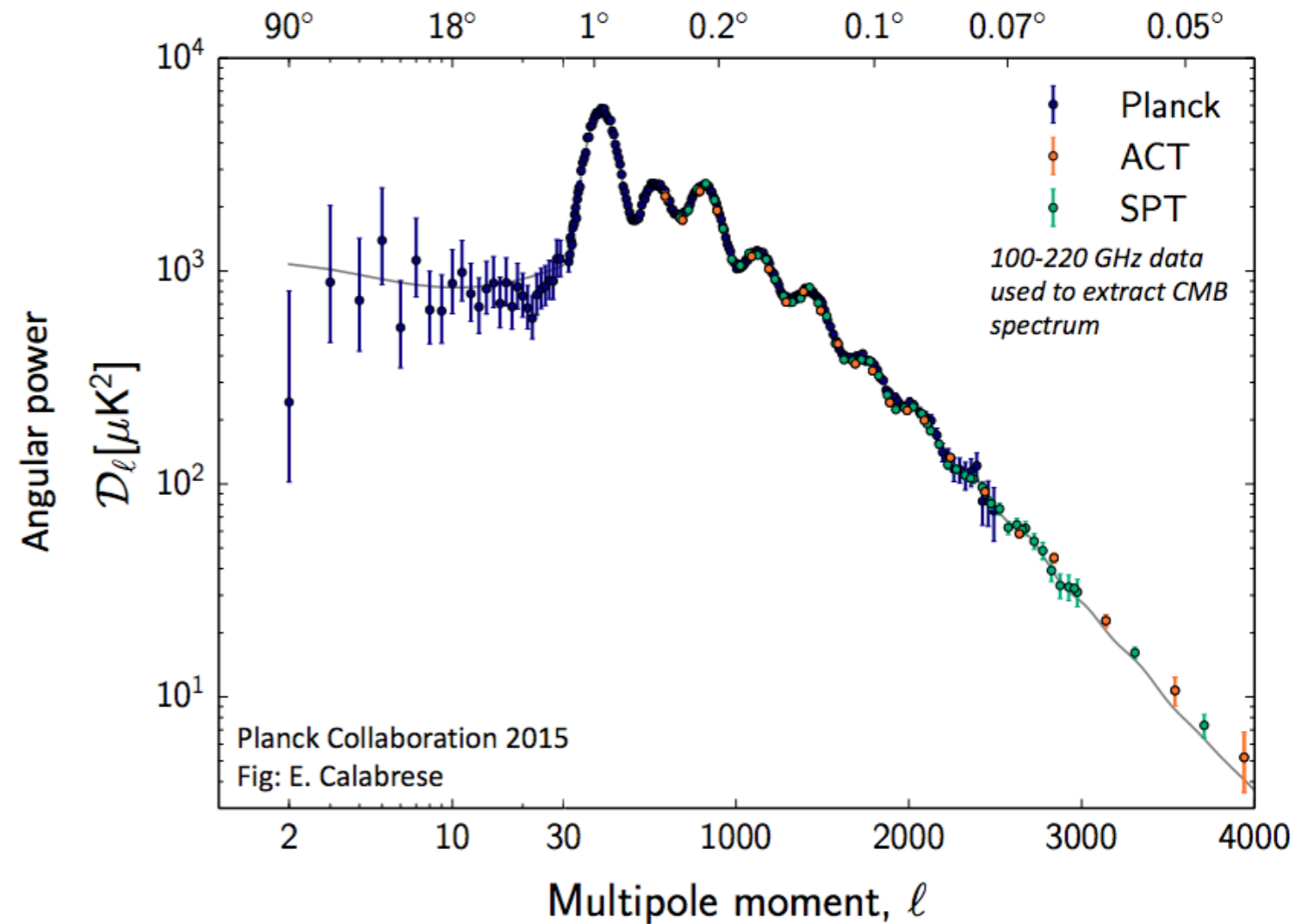
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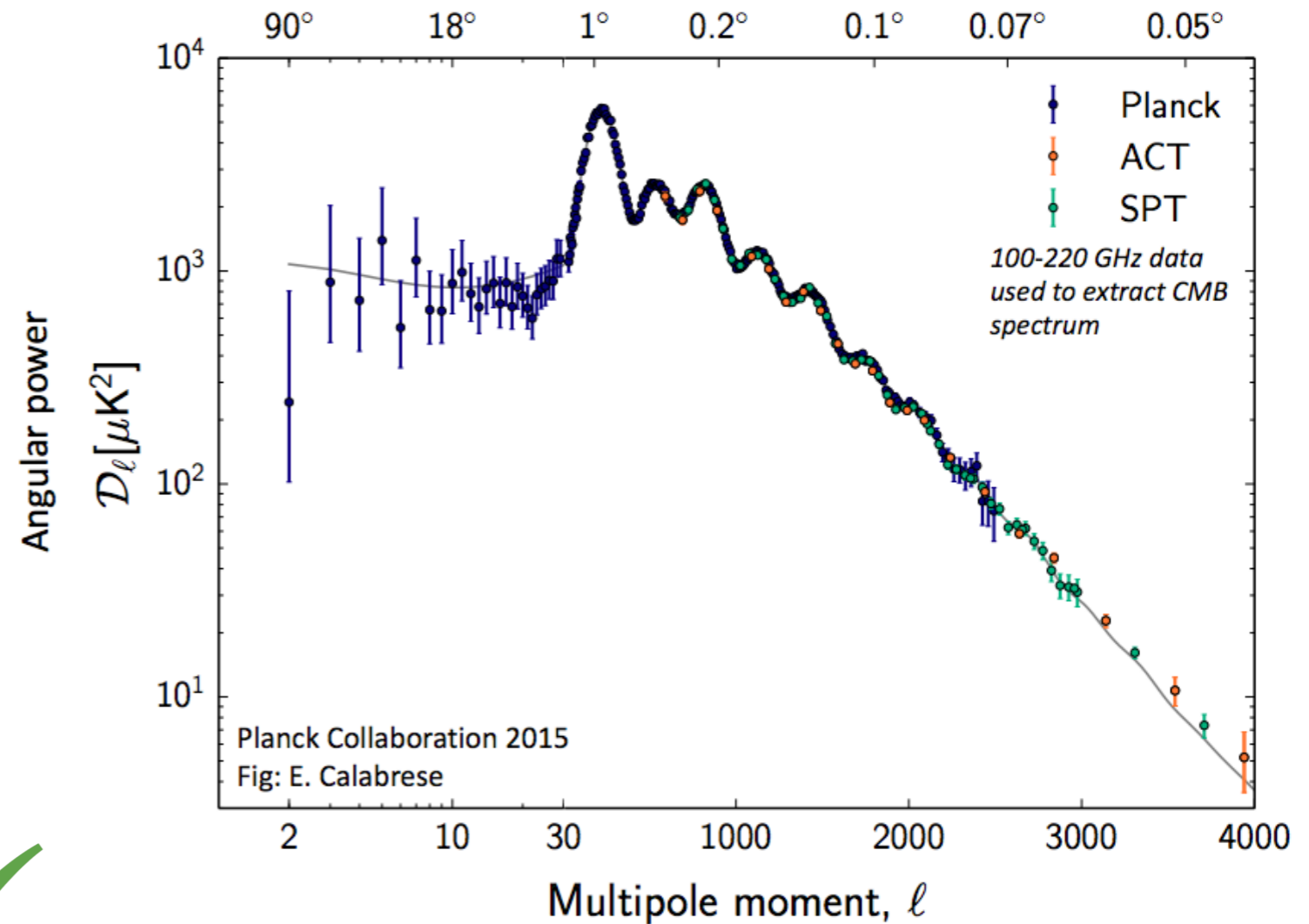
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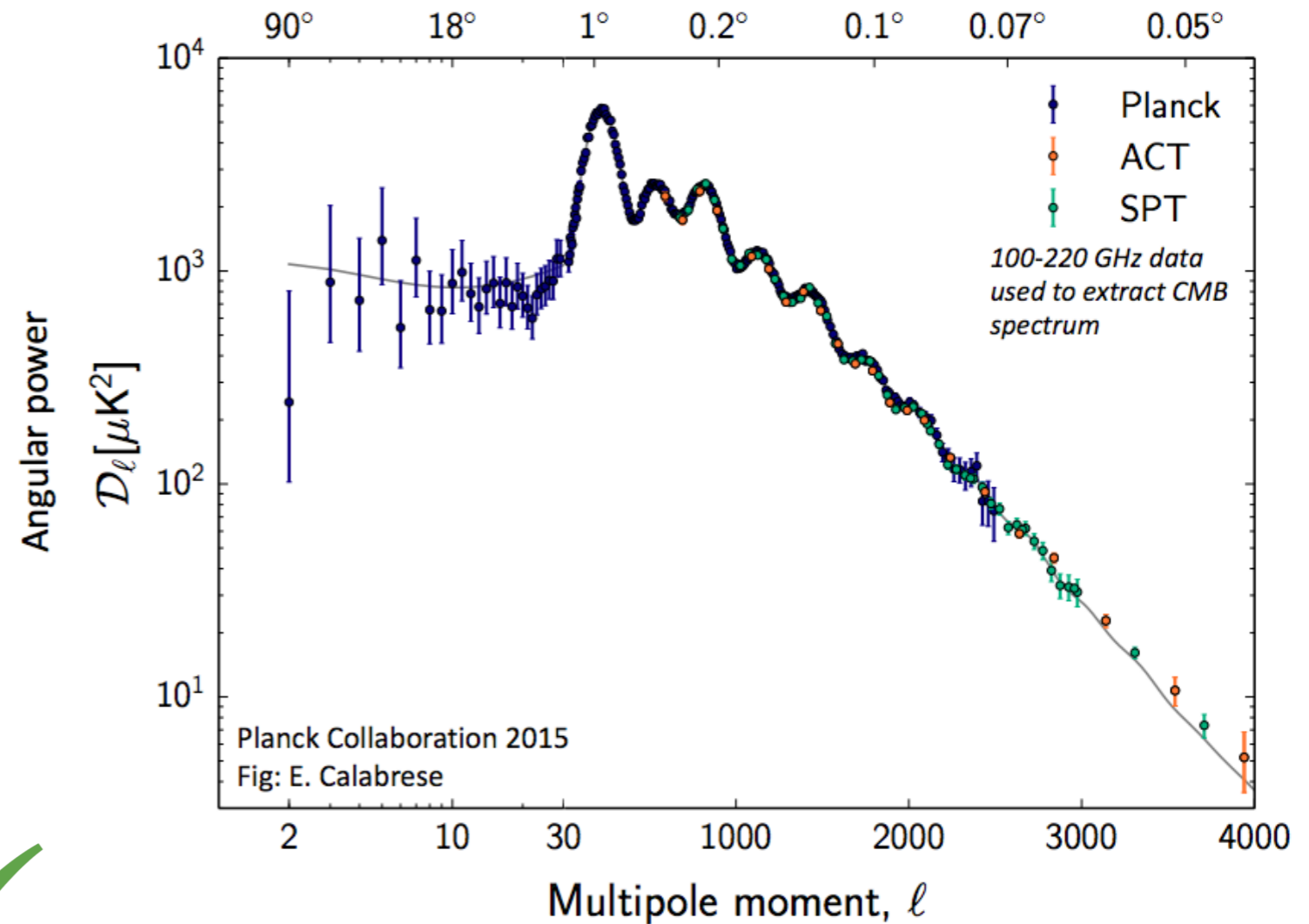
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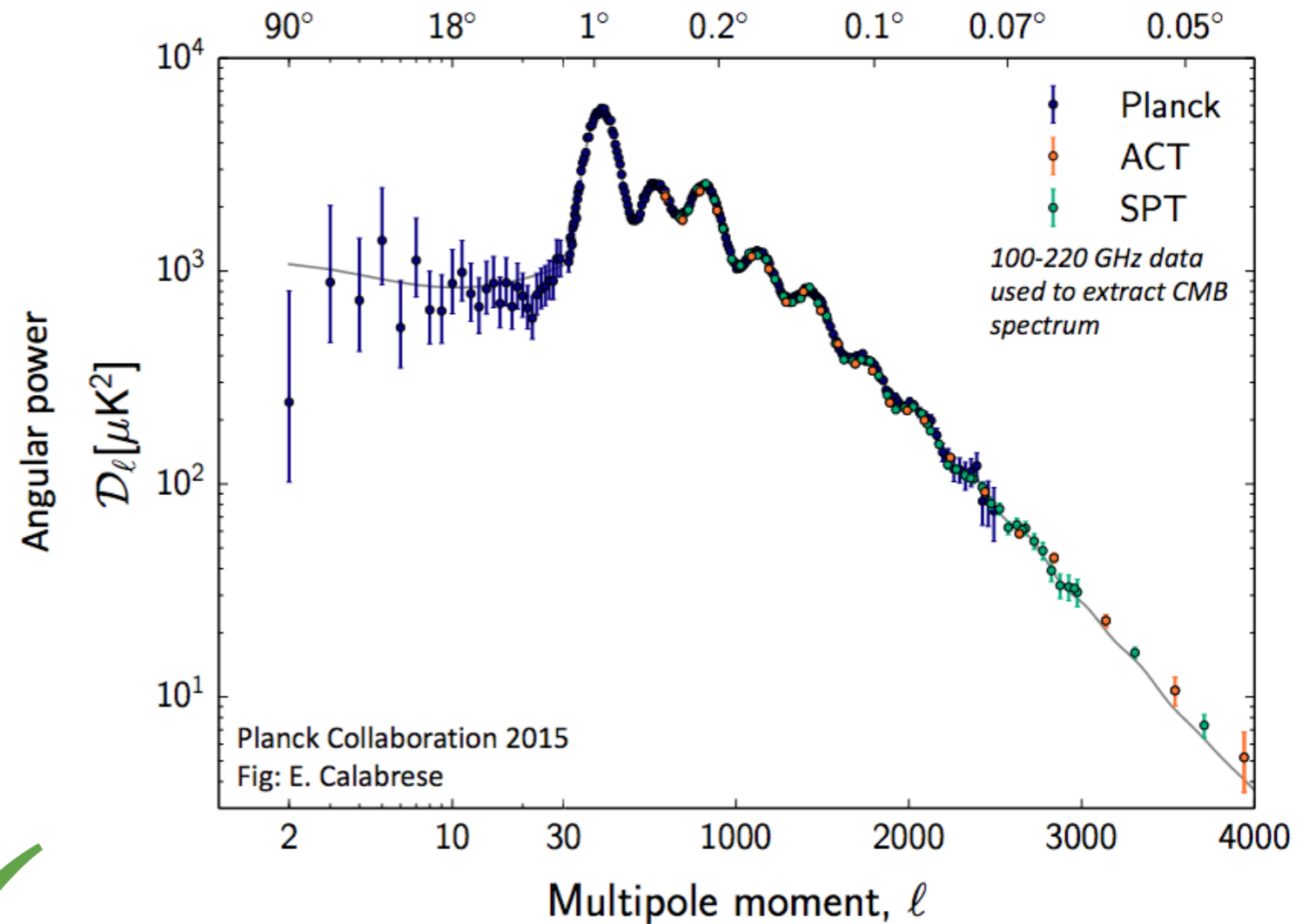
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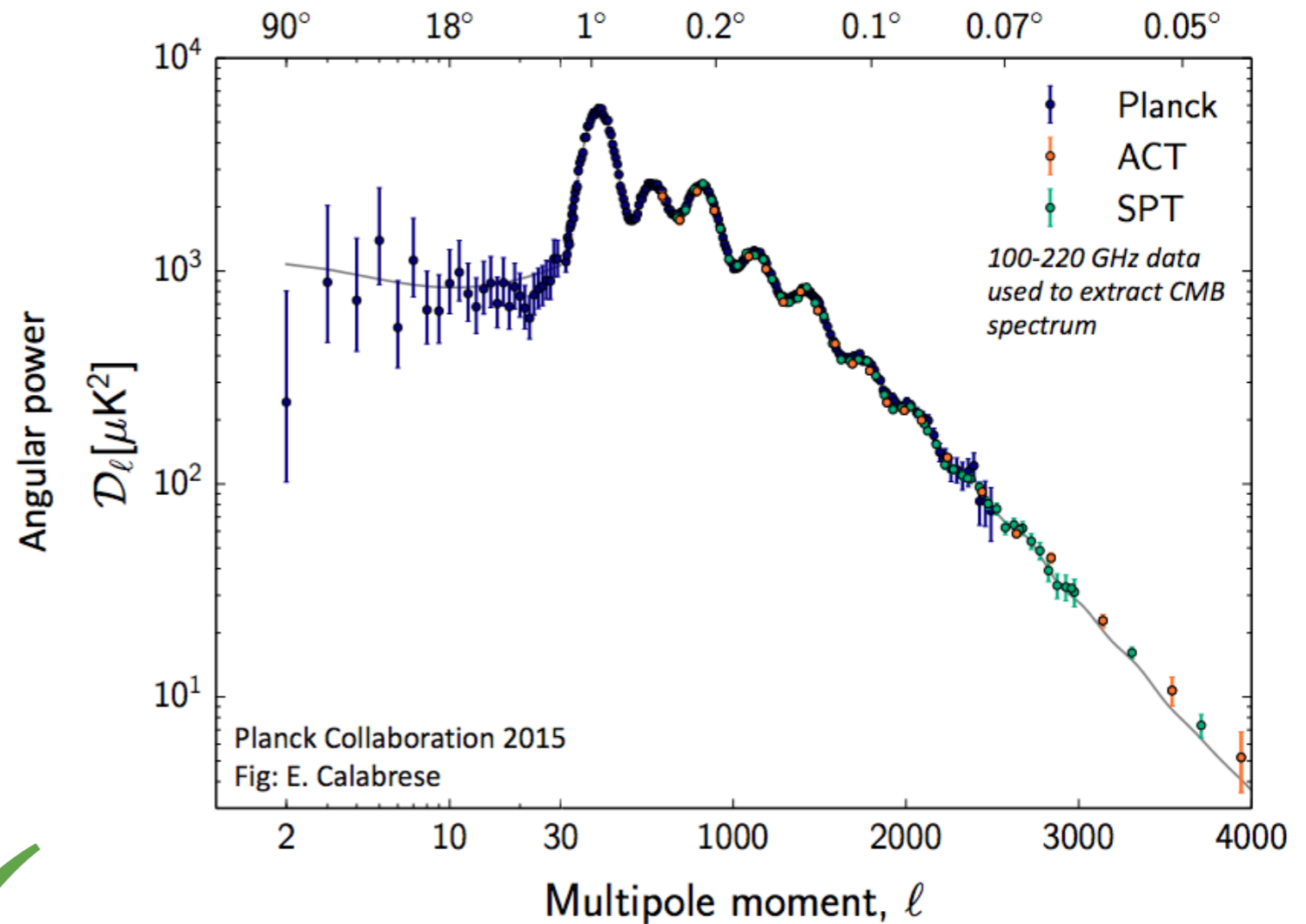
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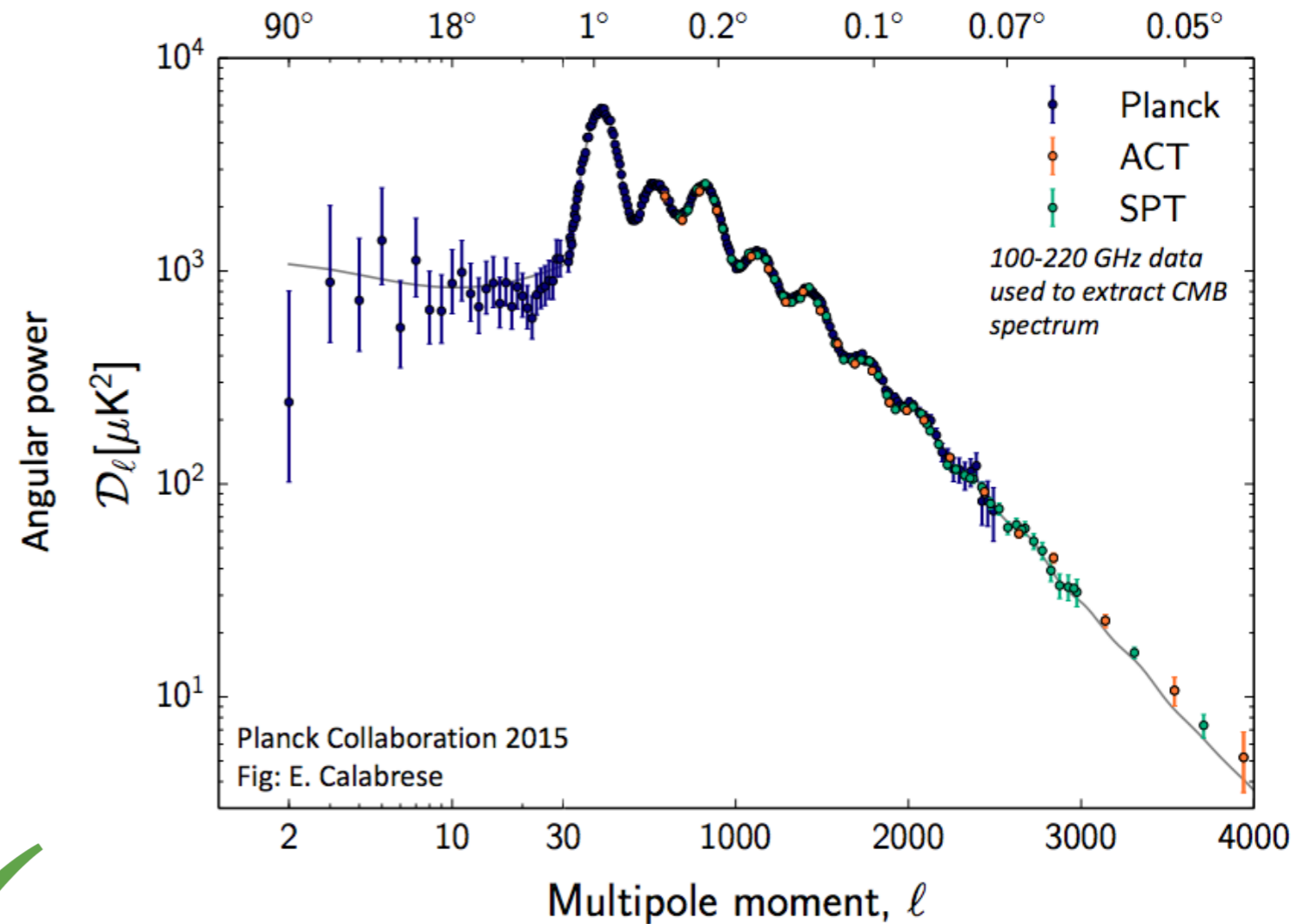
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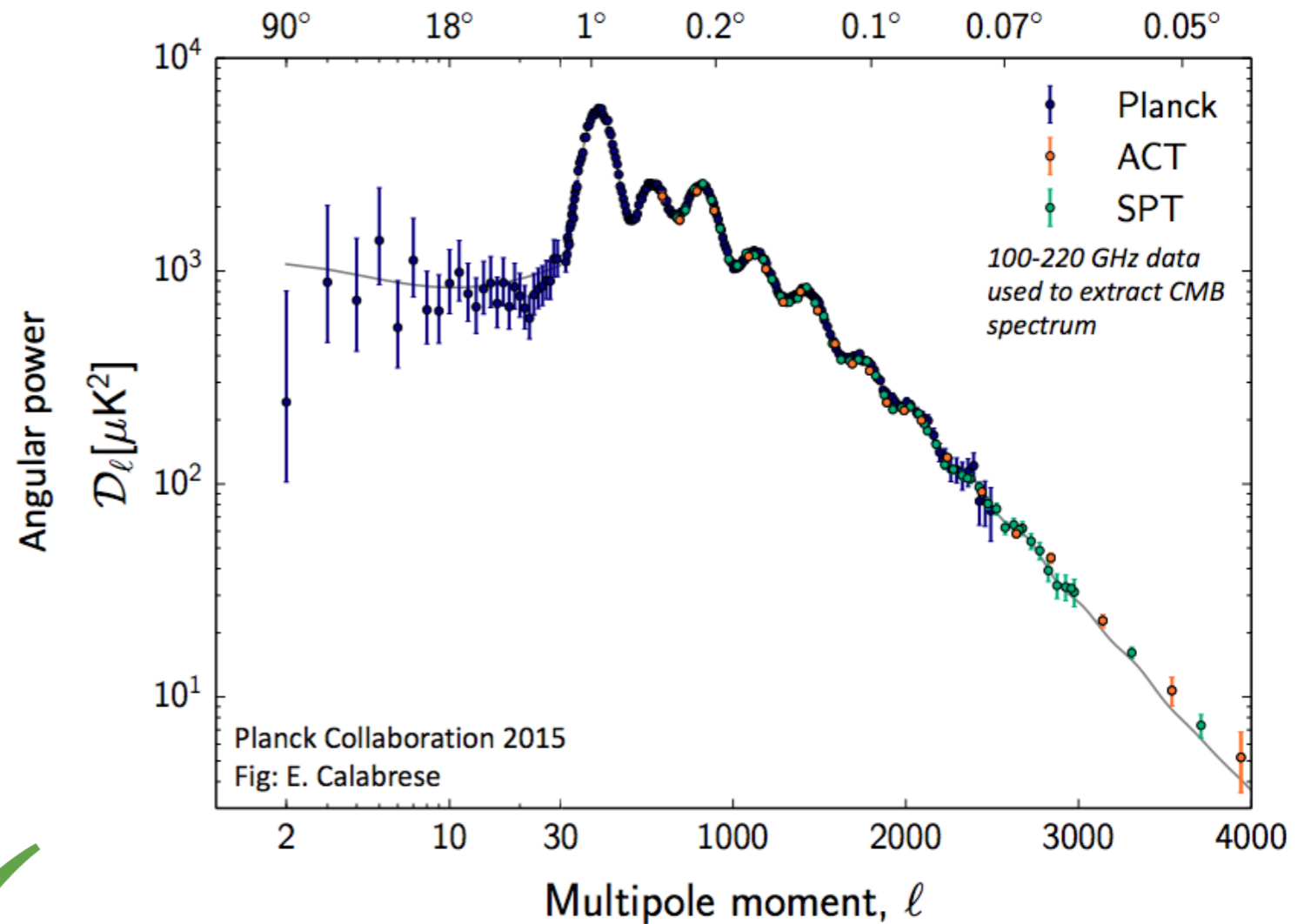
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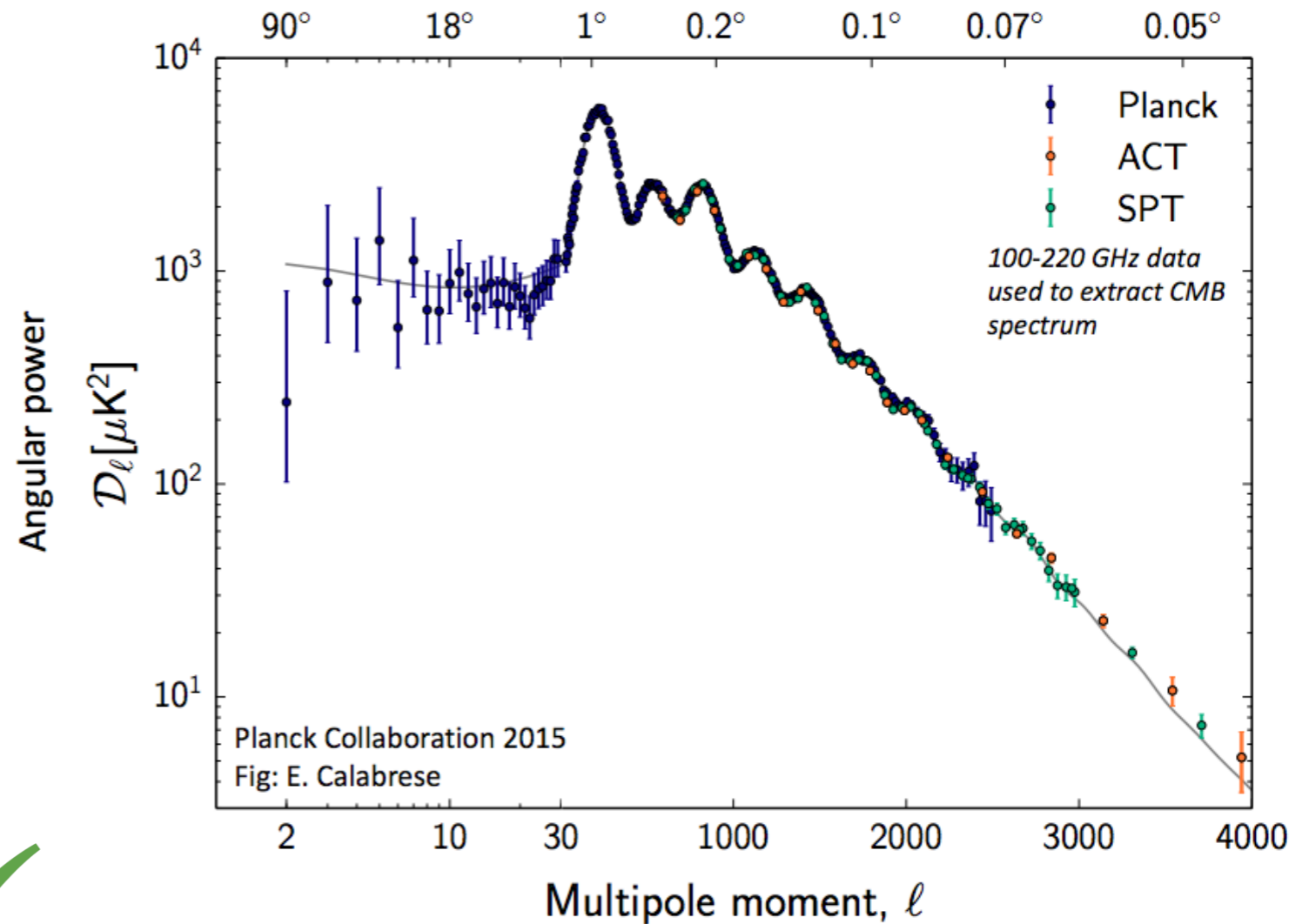
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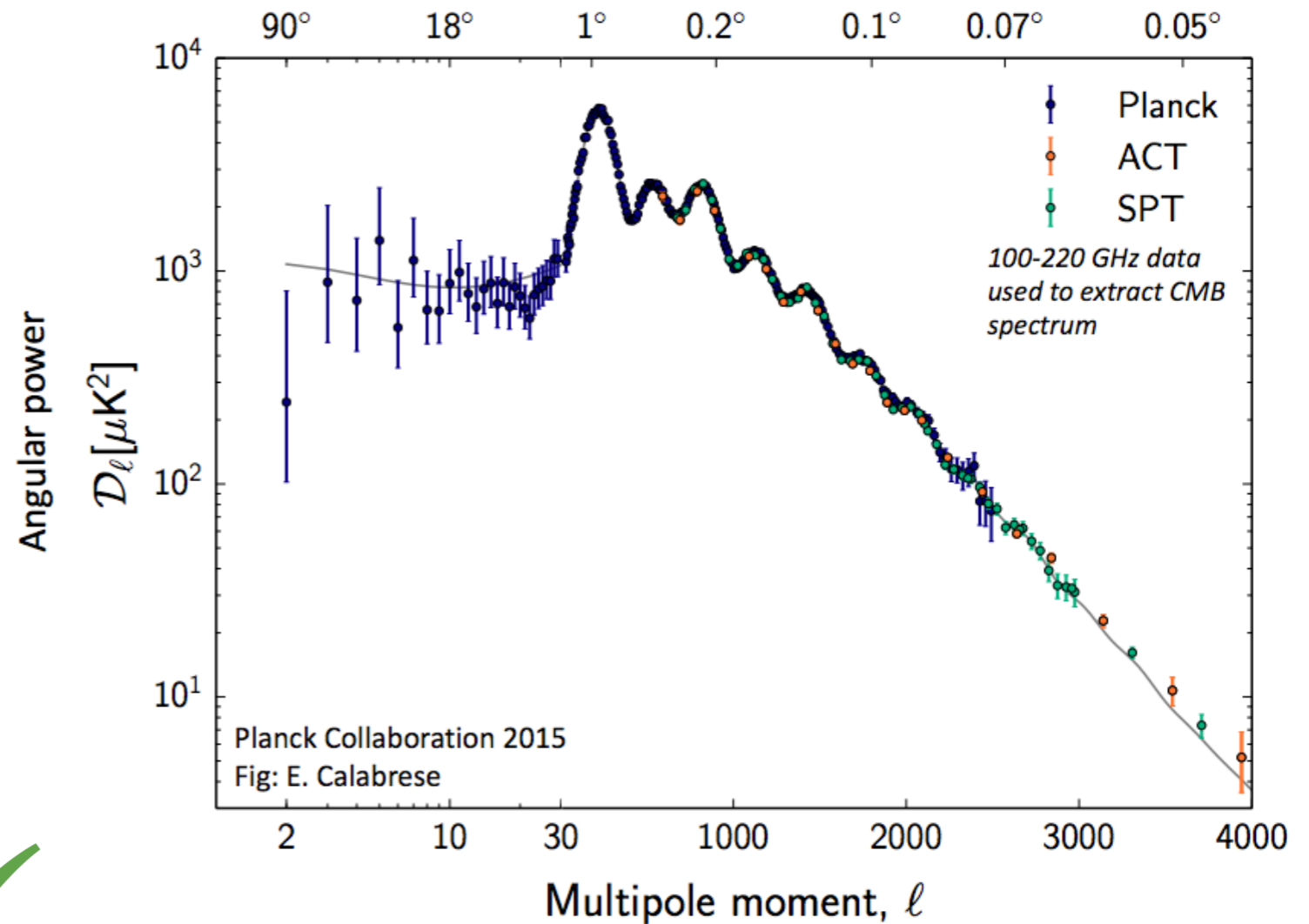
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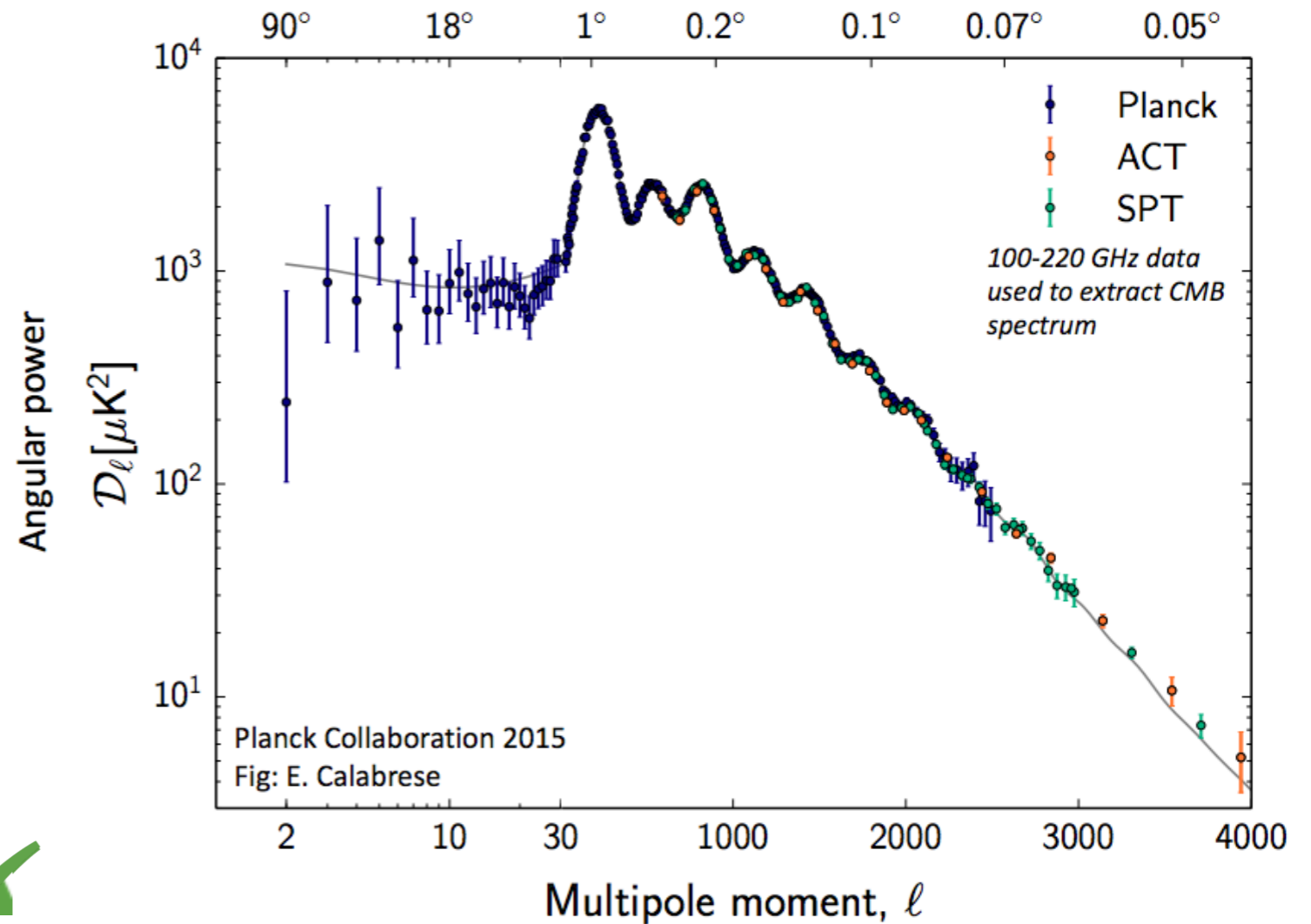
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# Open Questions in Cosmology

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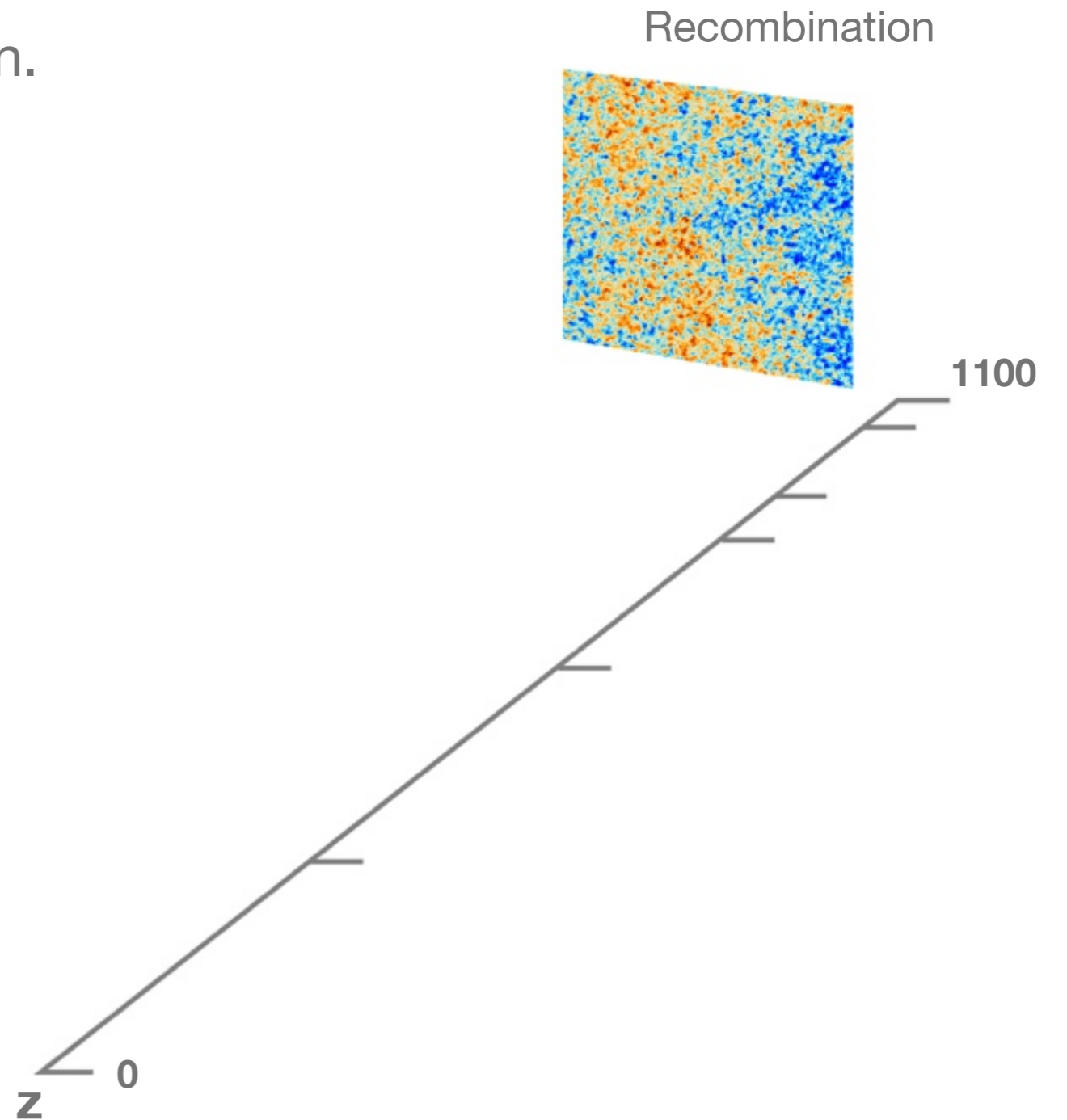
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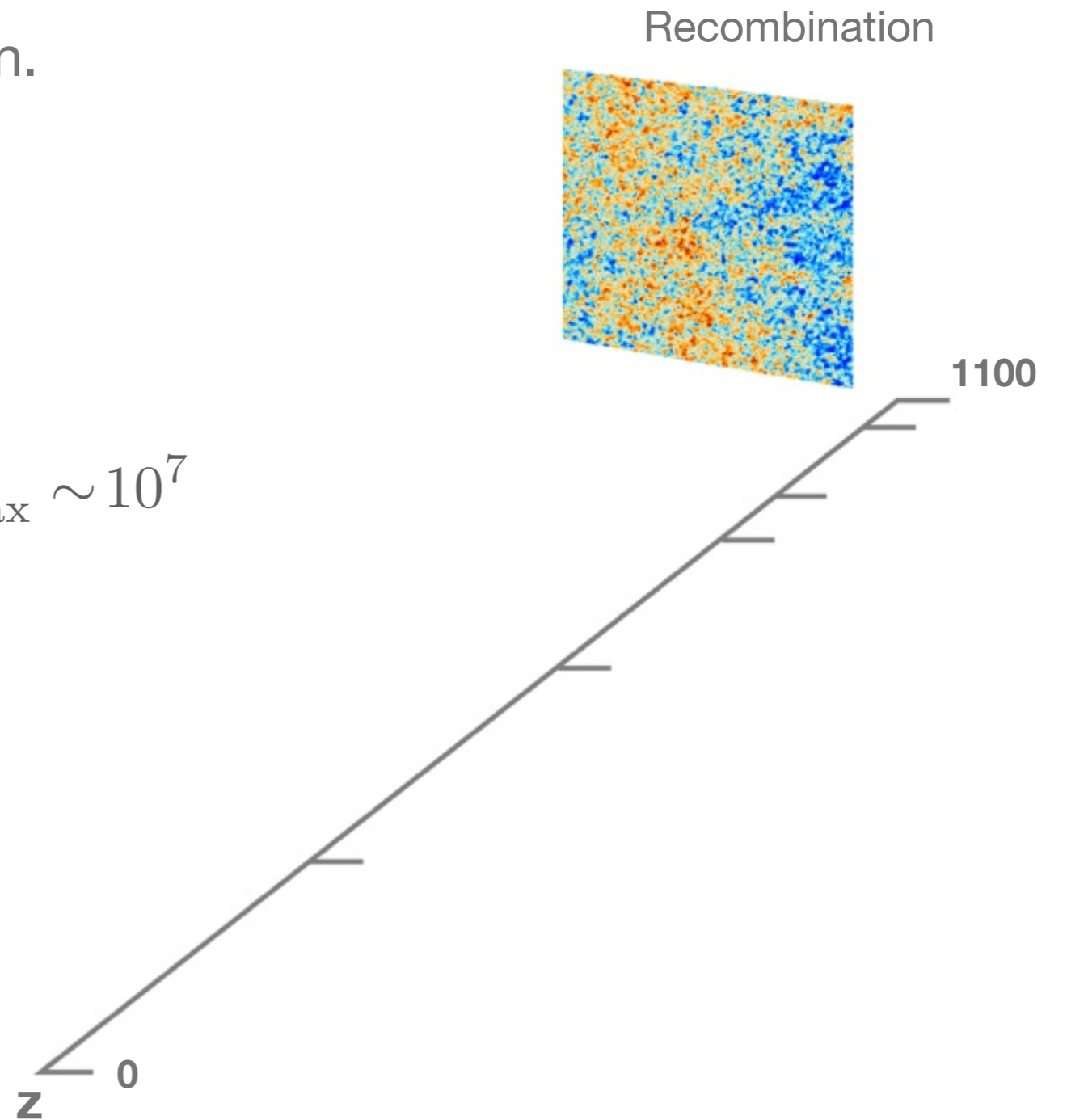


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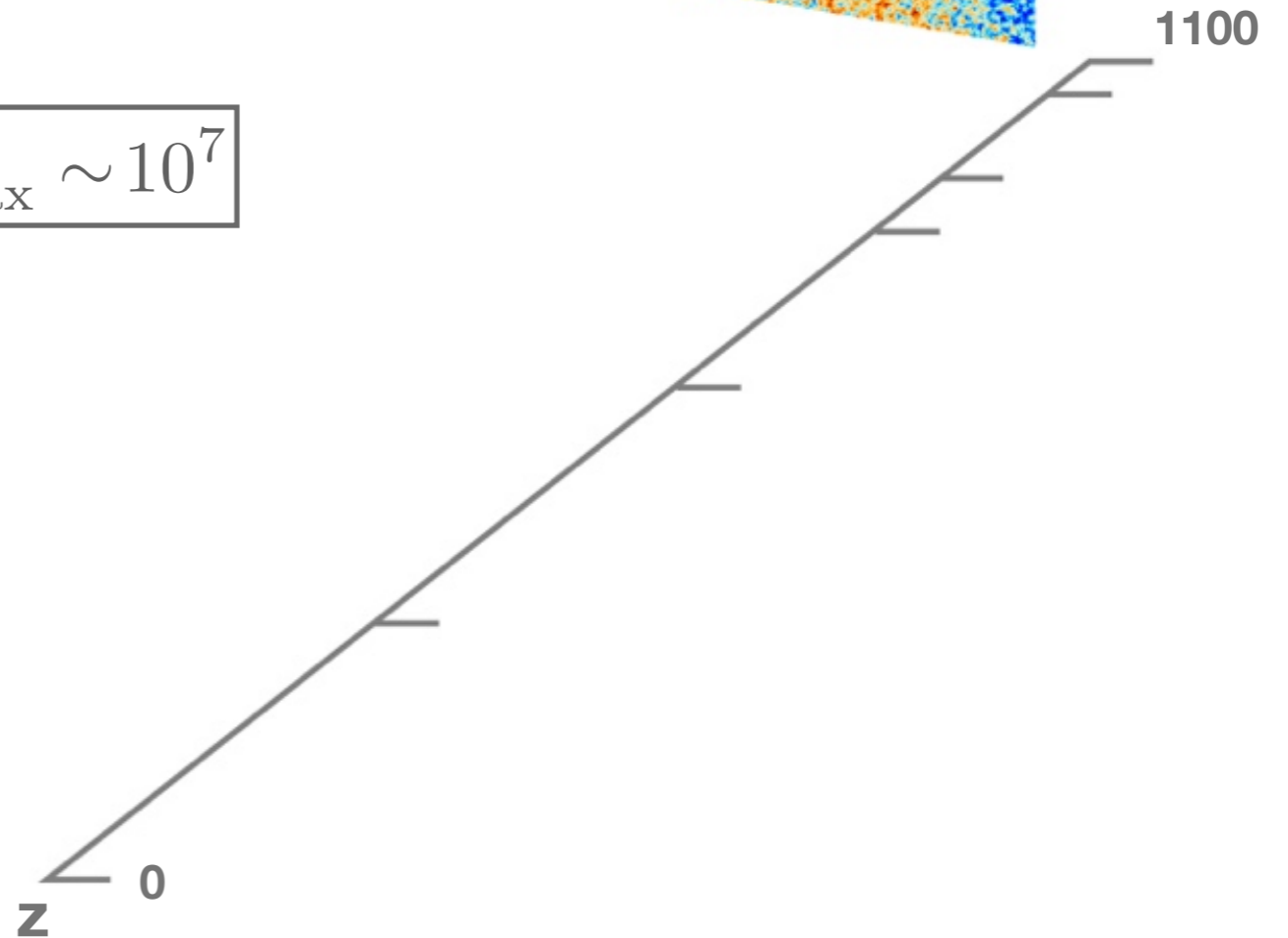
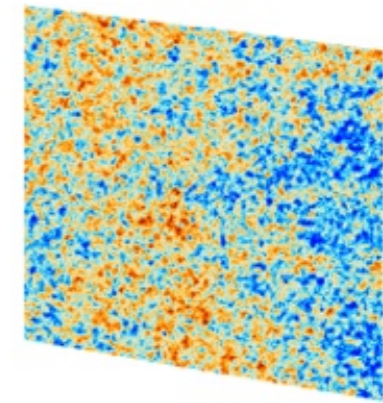
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Recombination



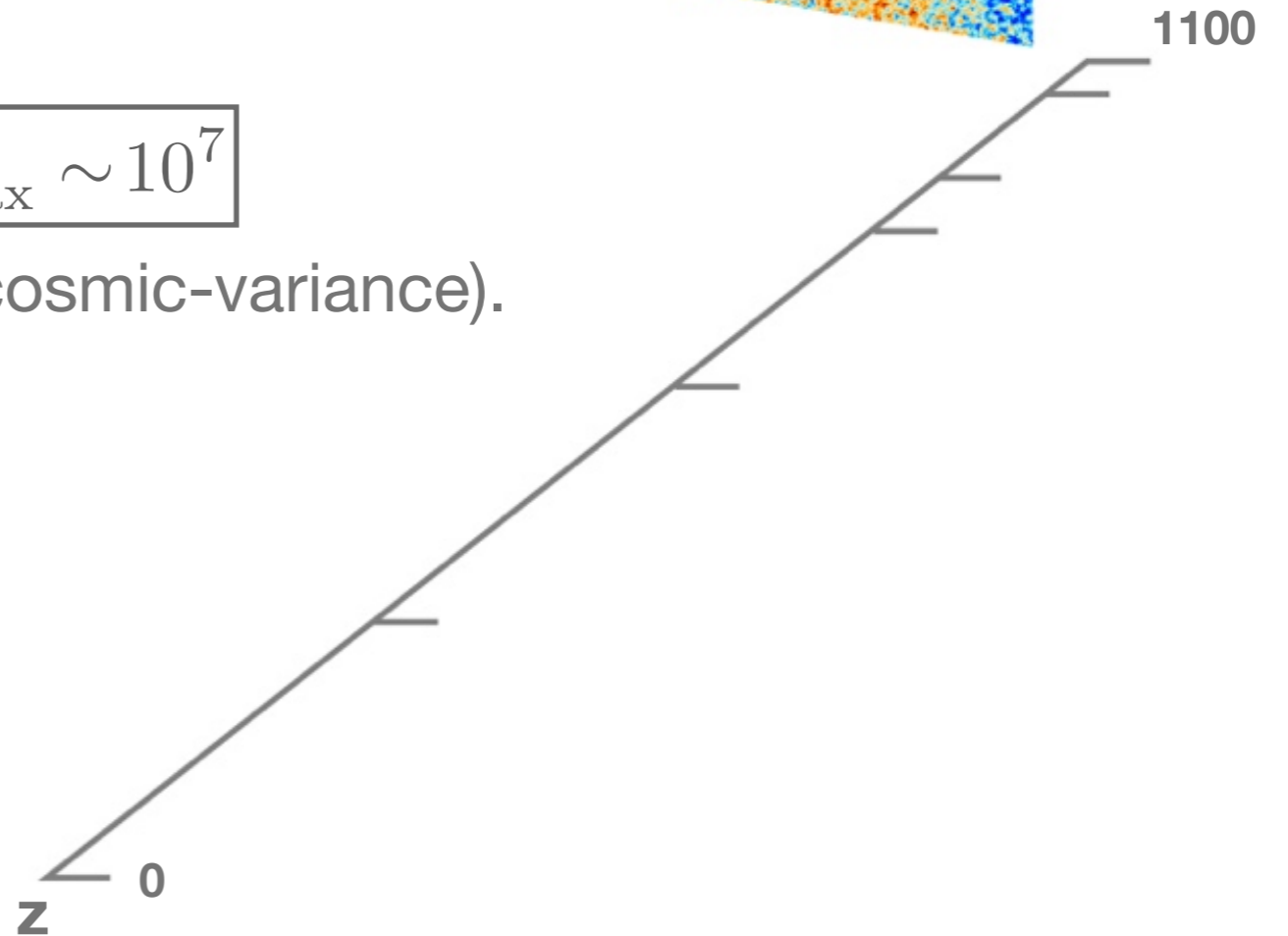
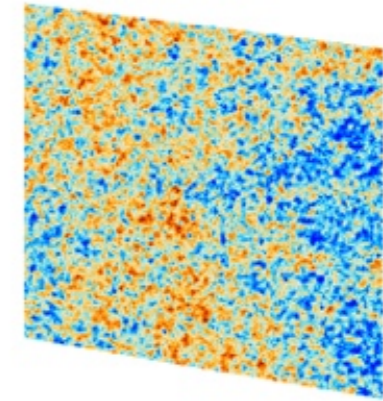
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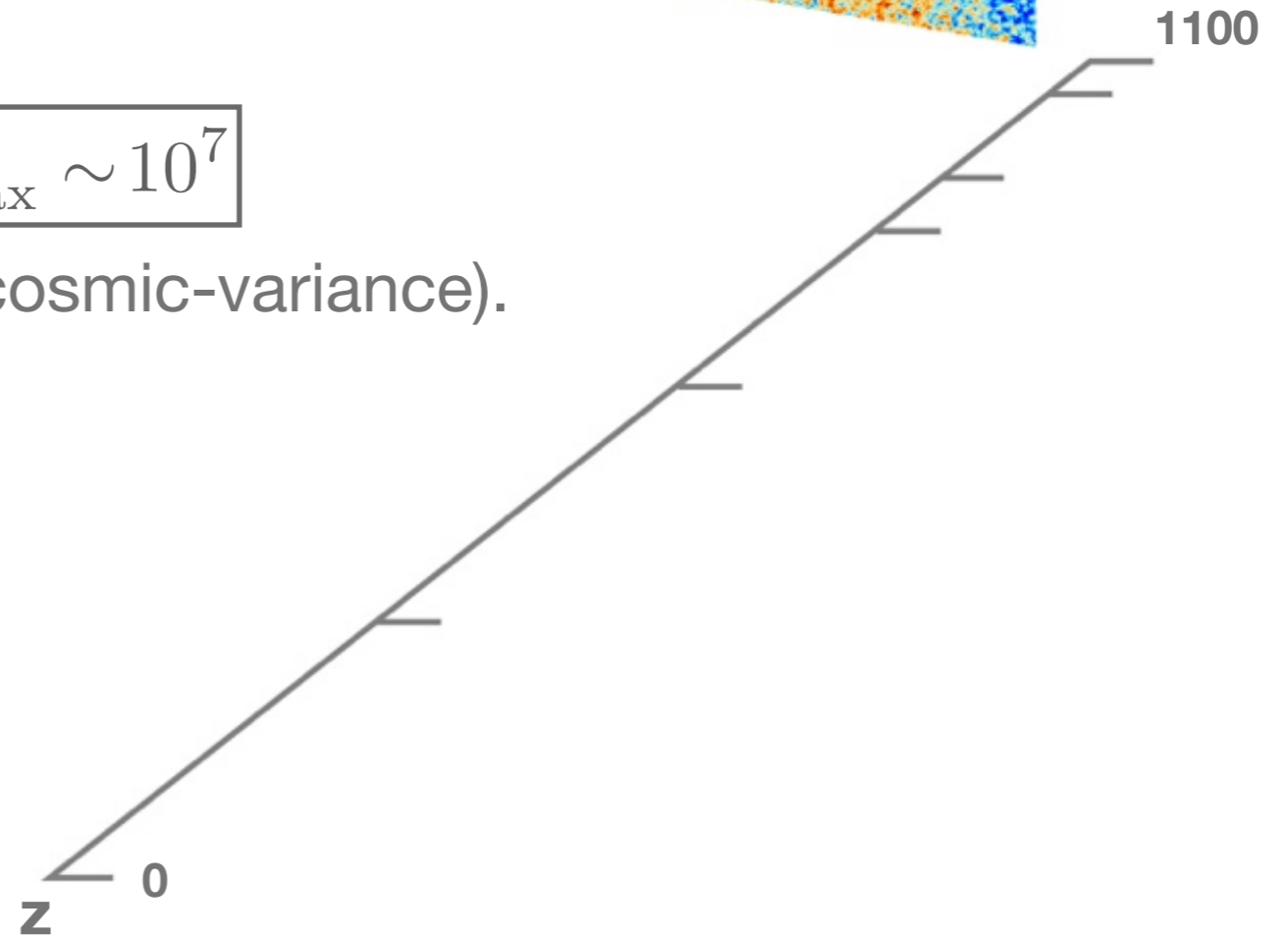
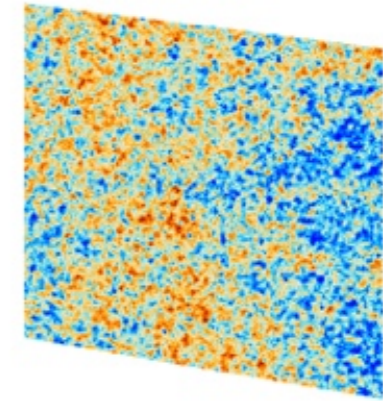
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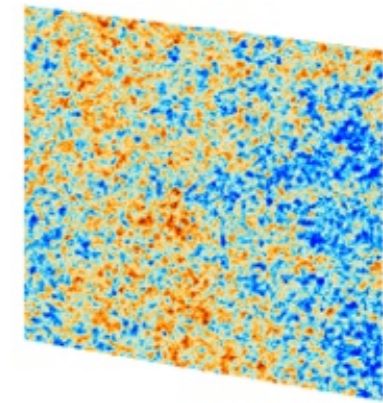
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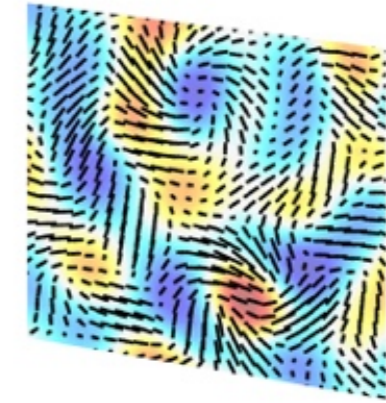
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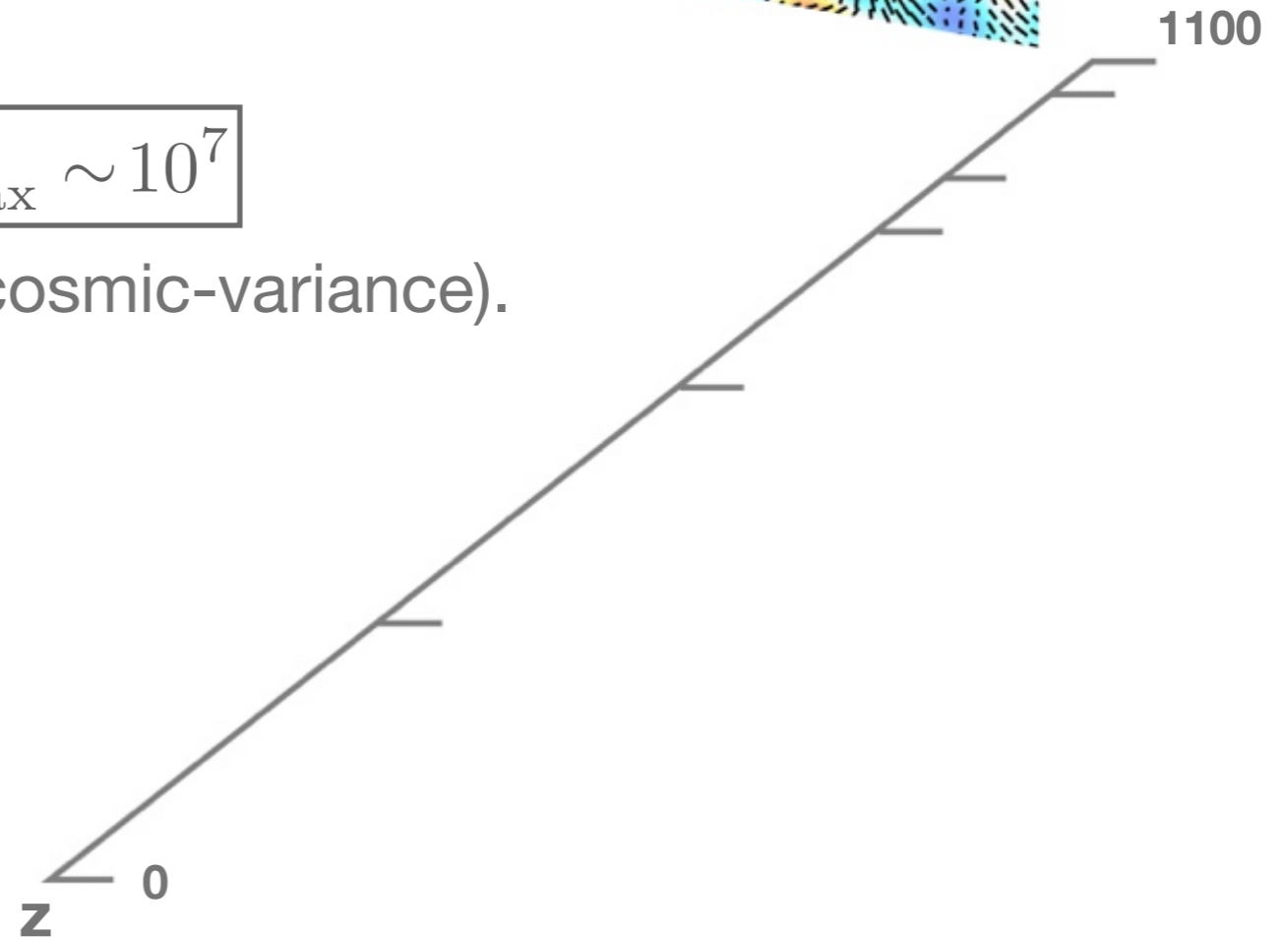
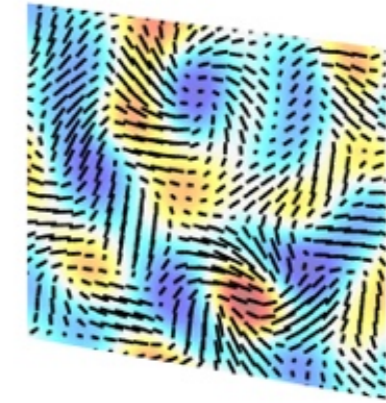
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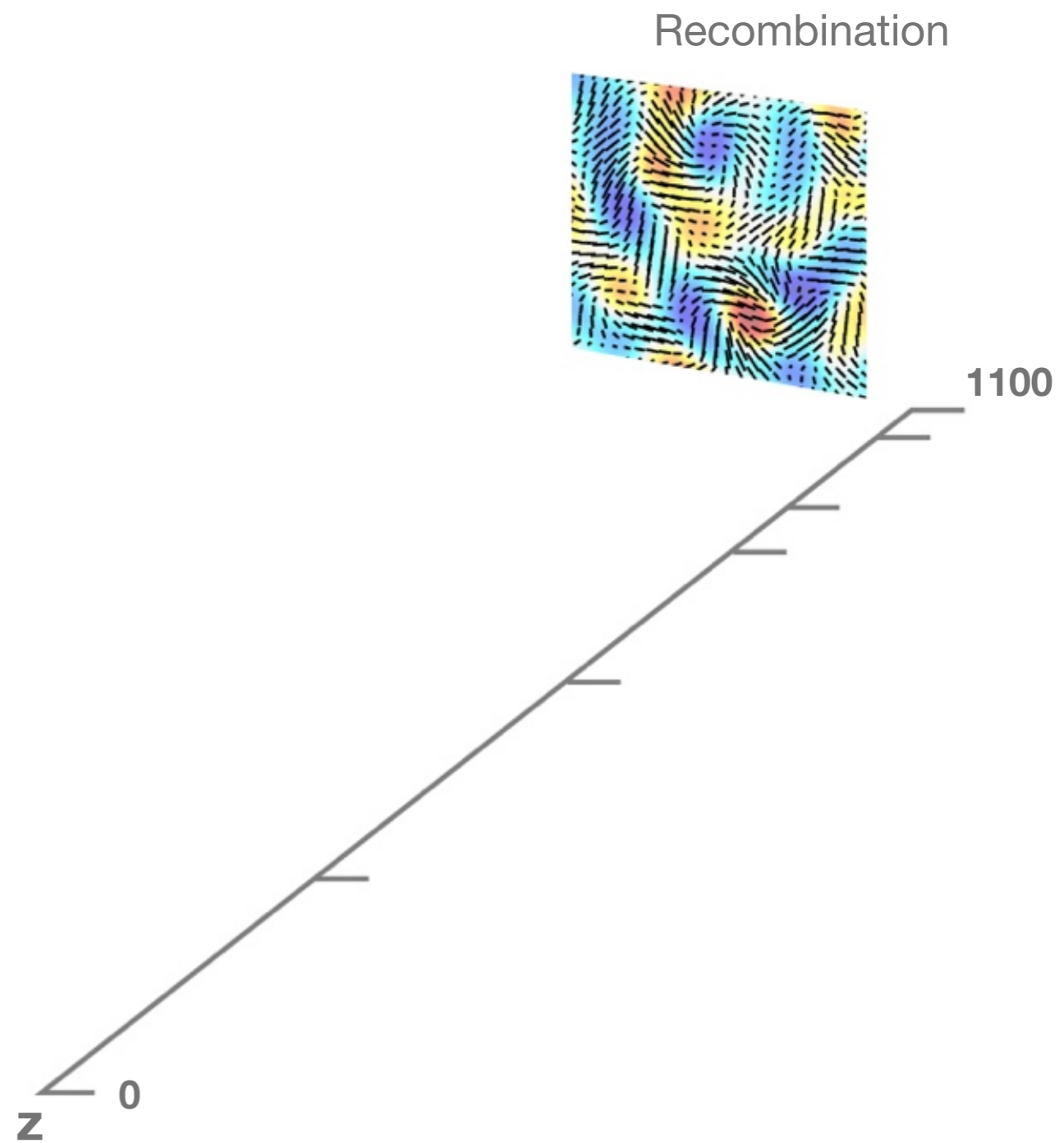
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More about that later....

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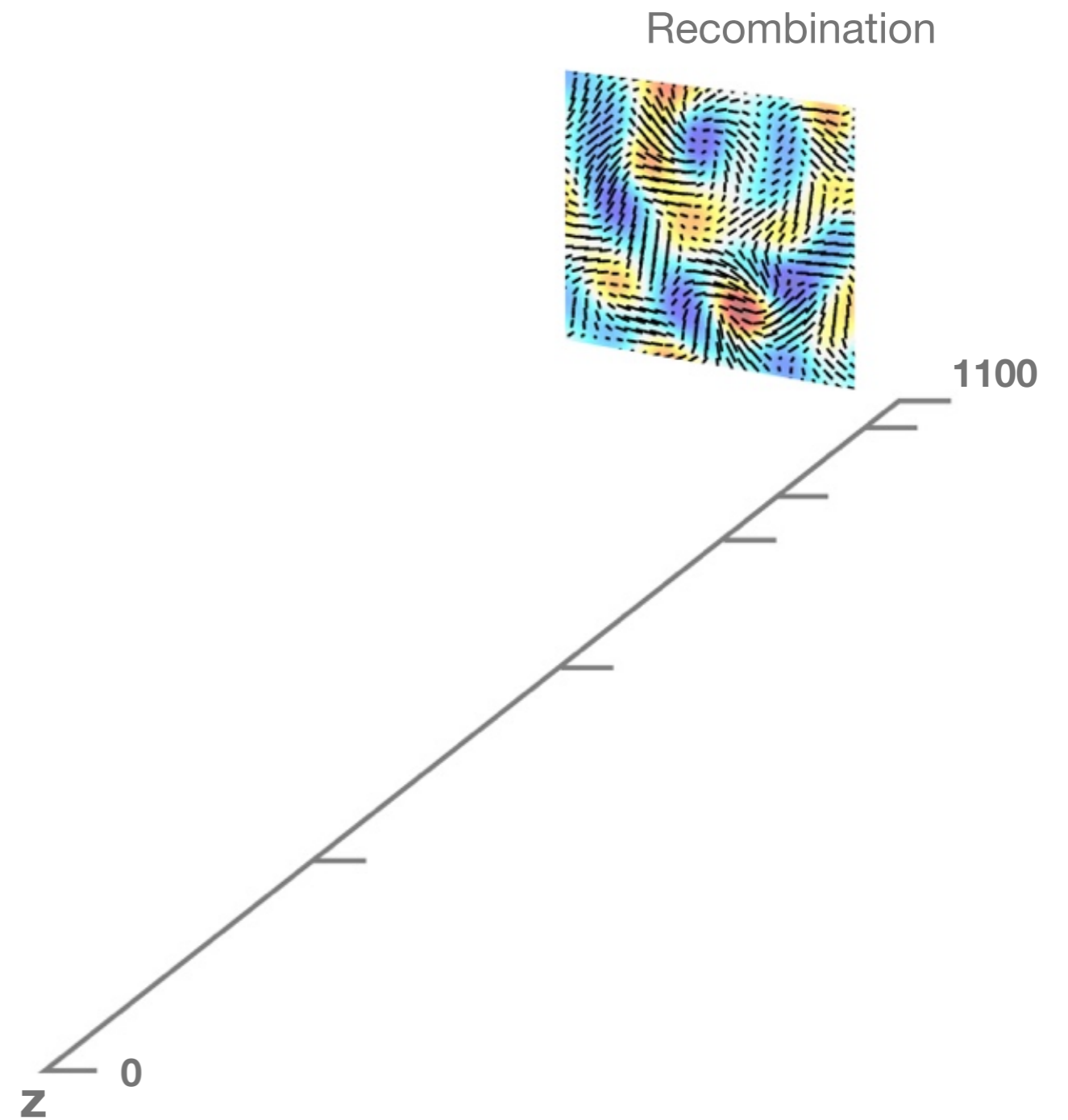
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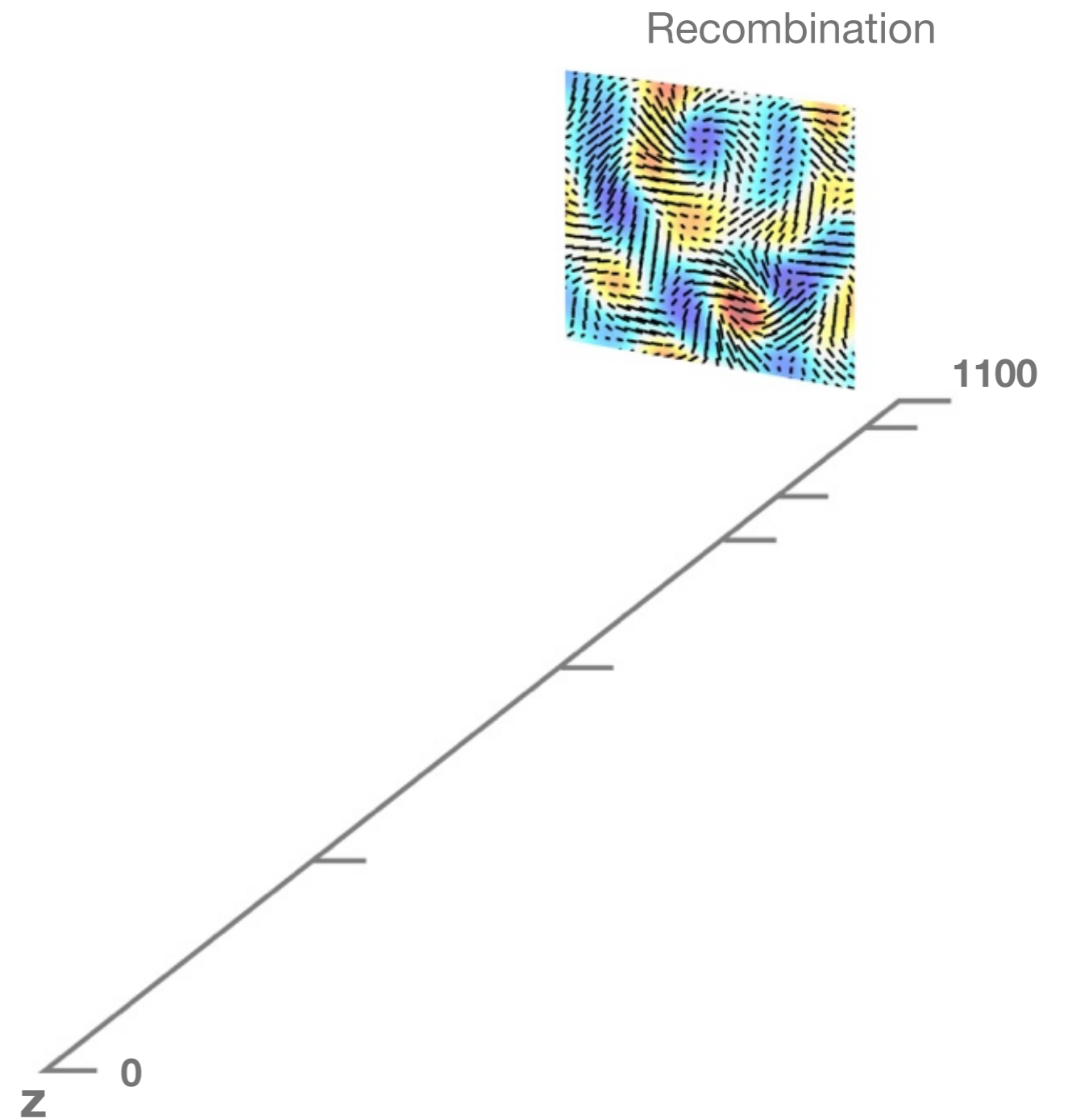
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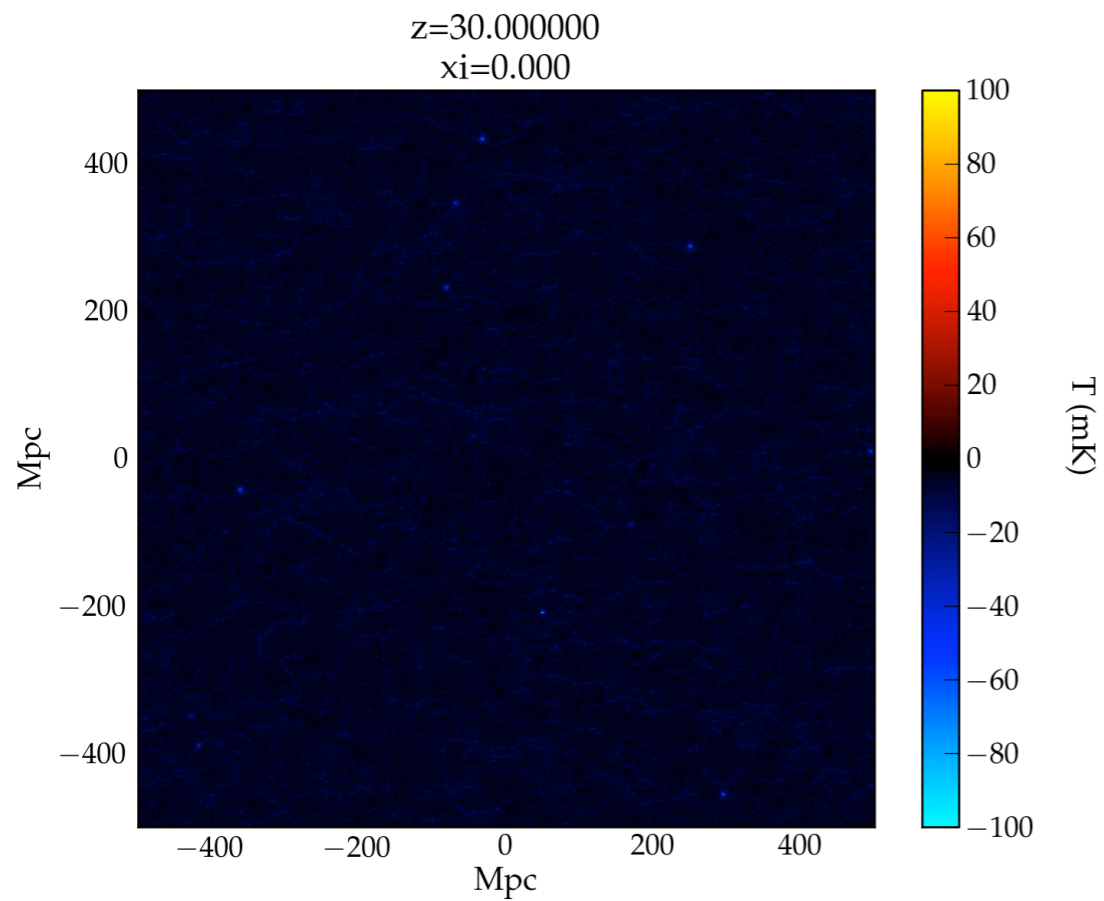
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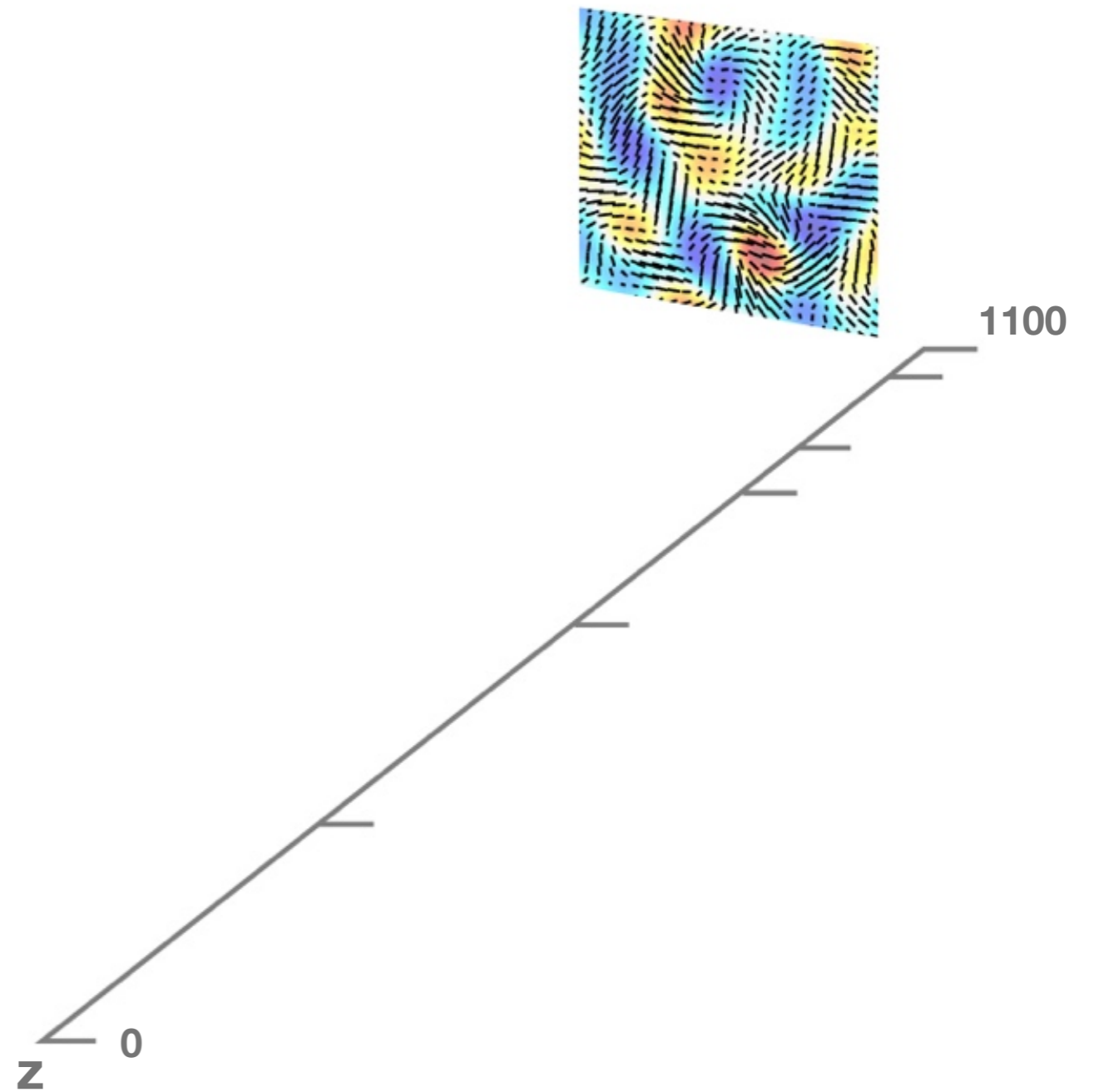
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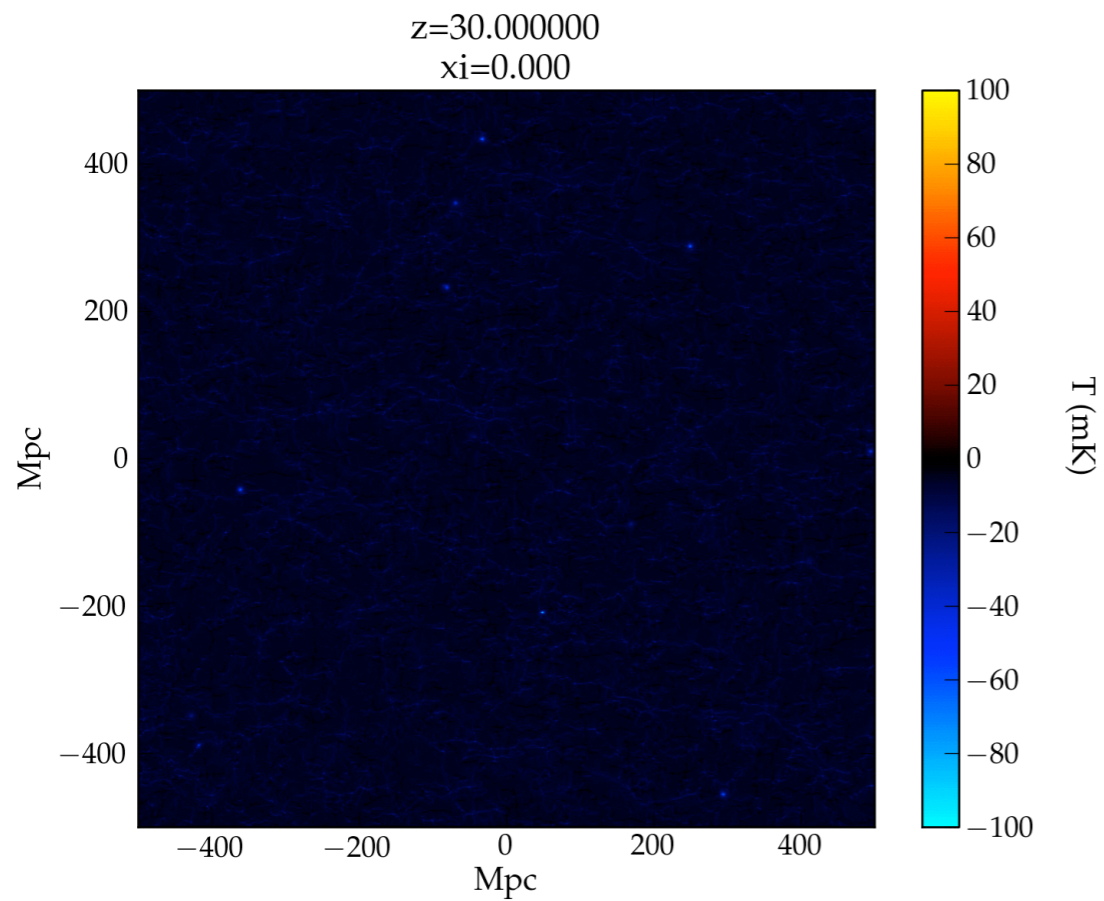
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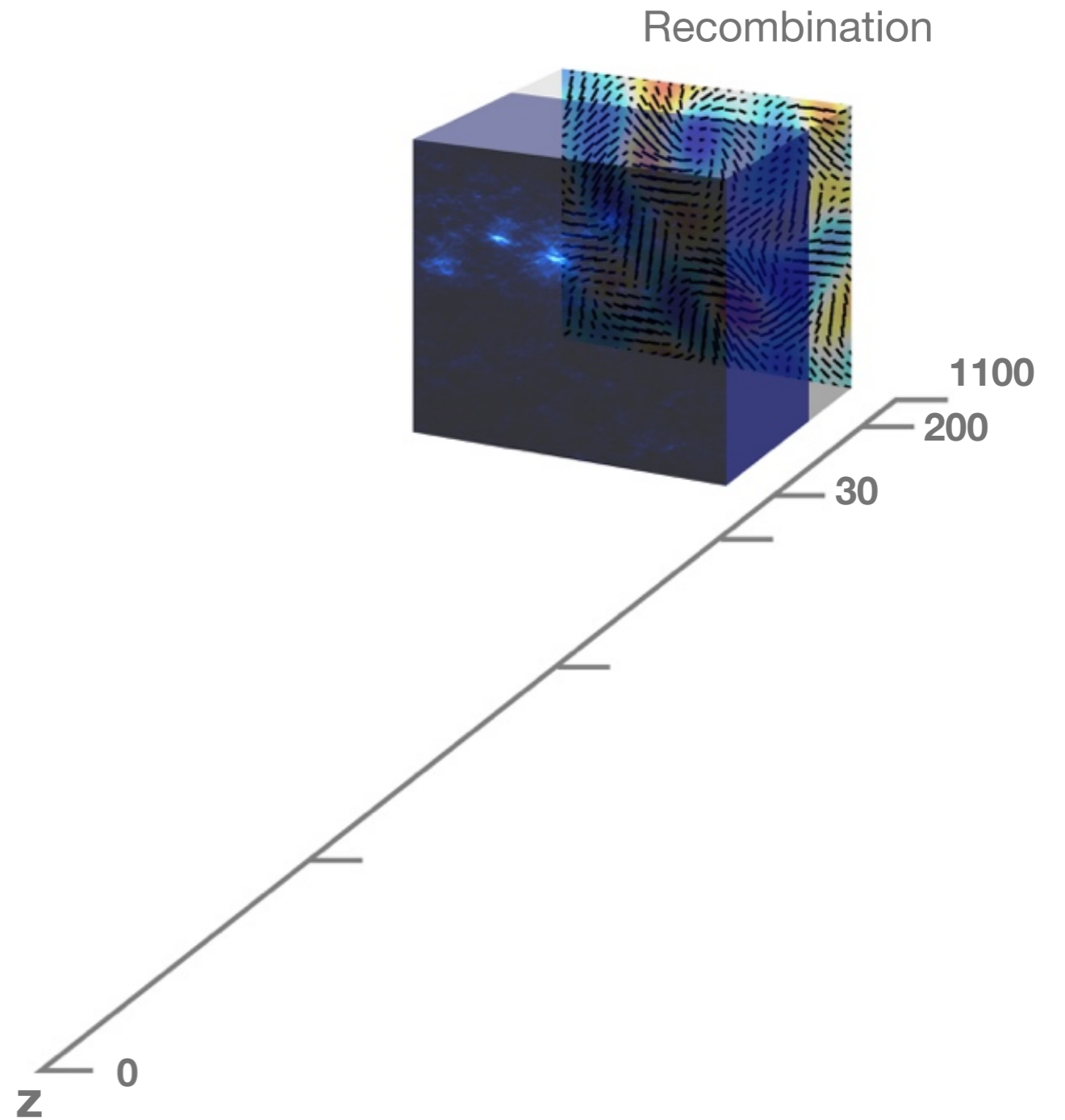


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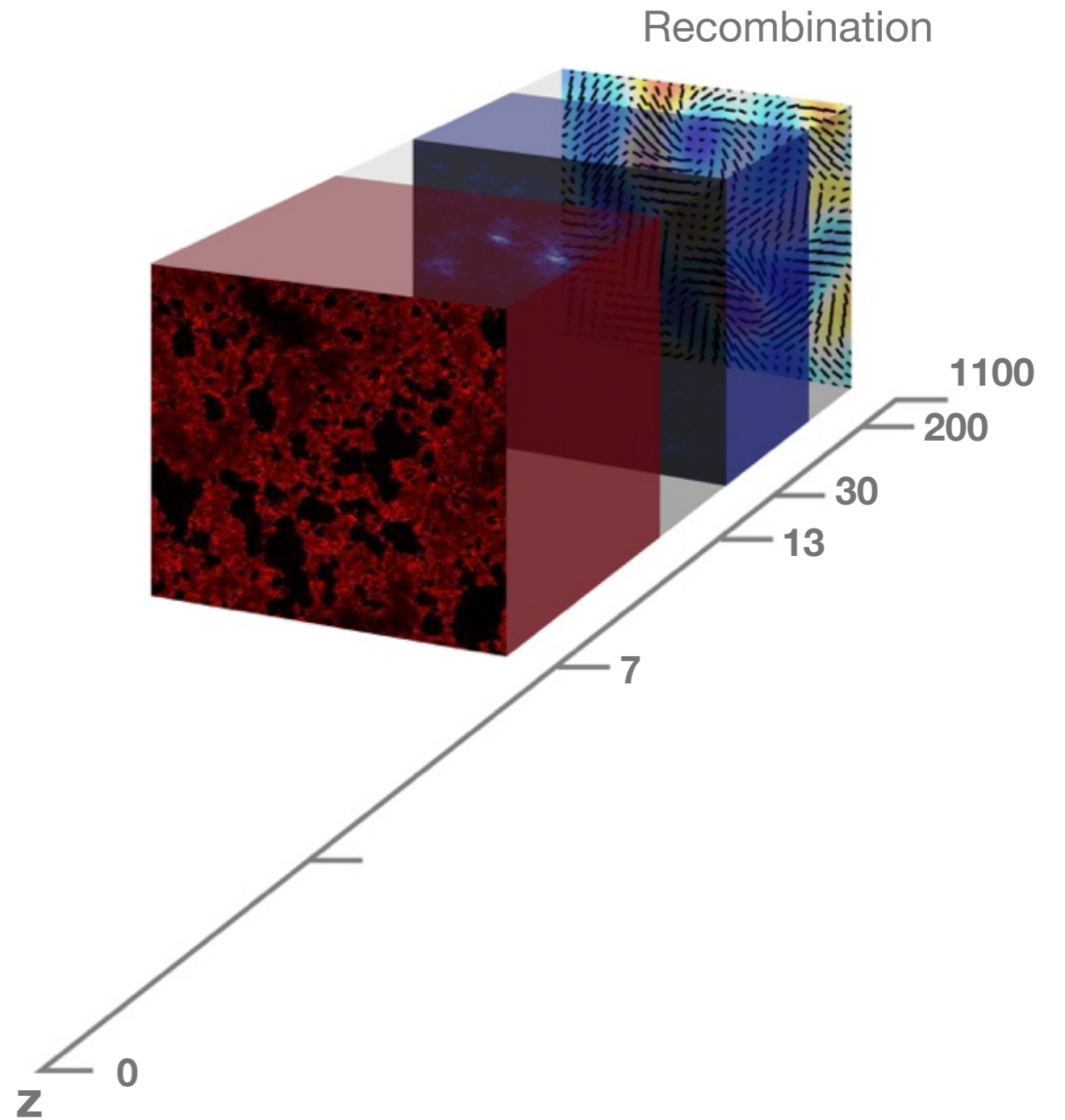
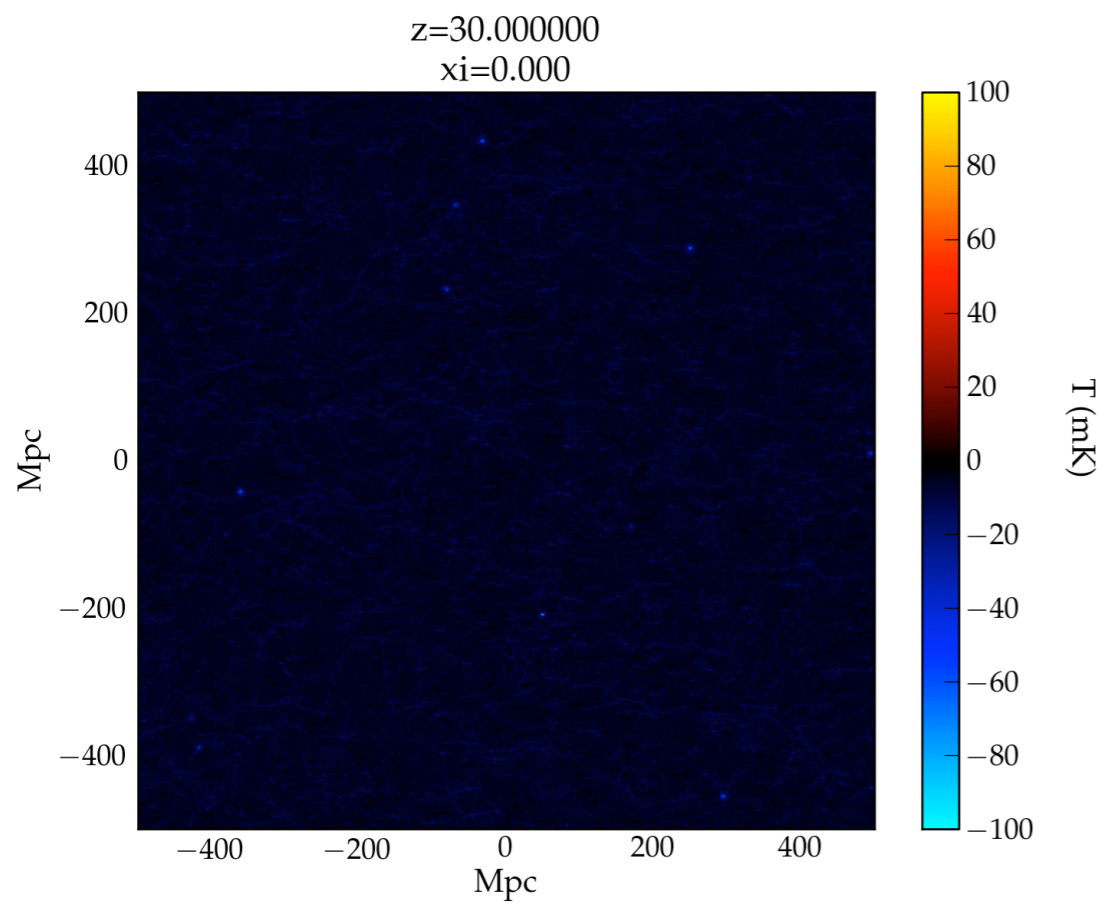


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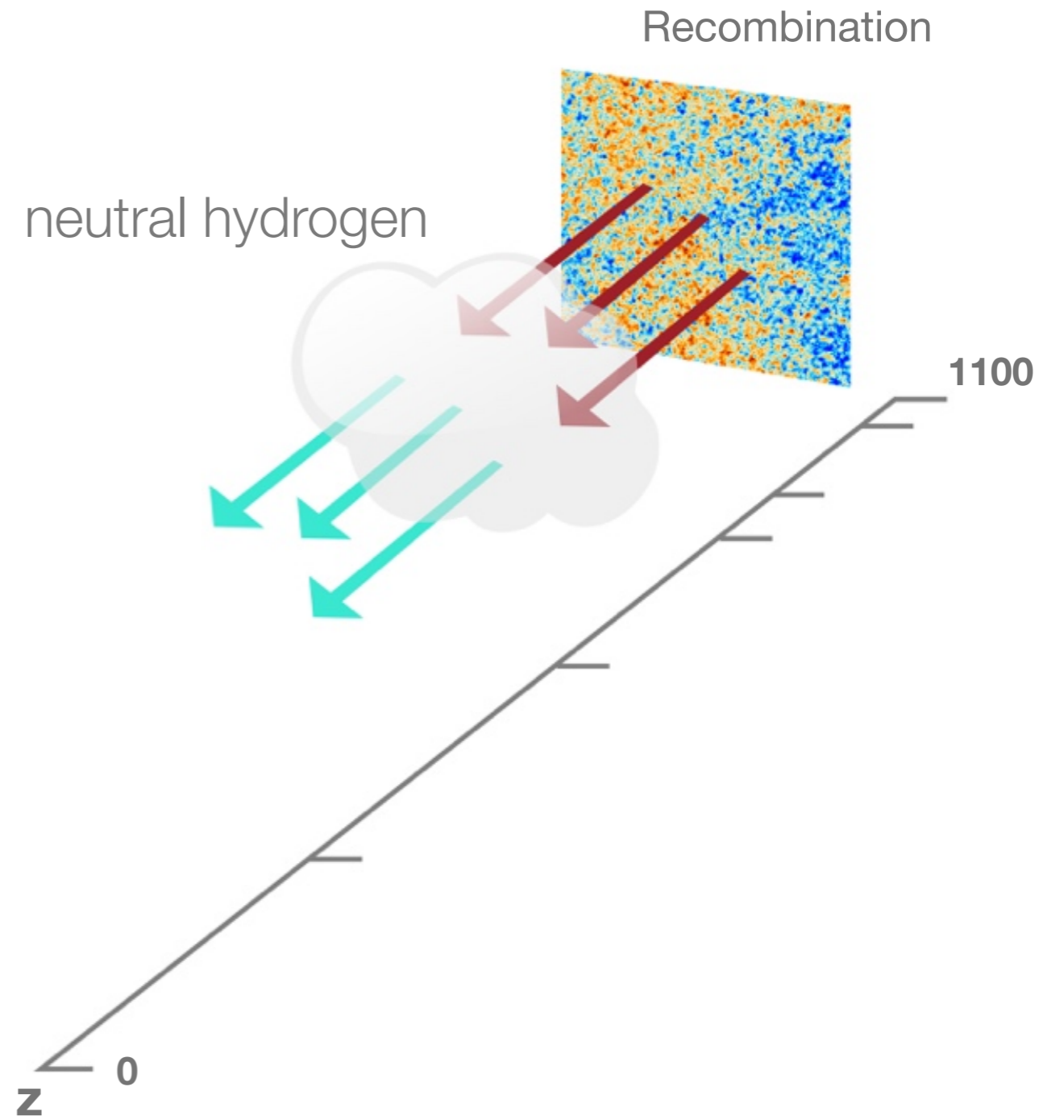
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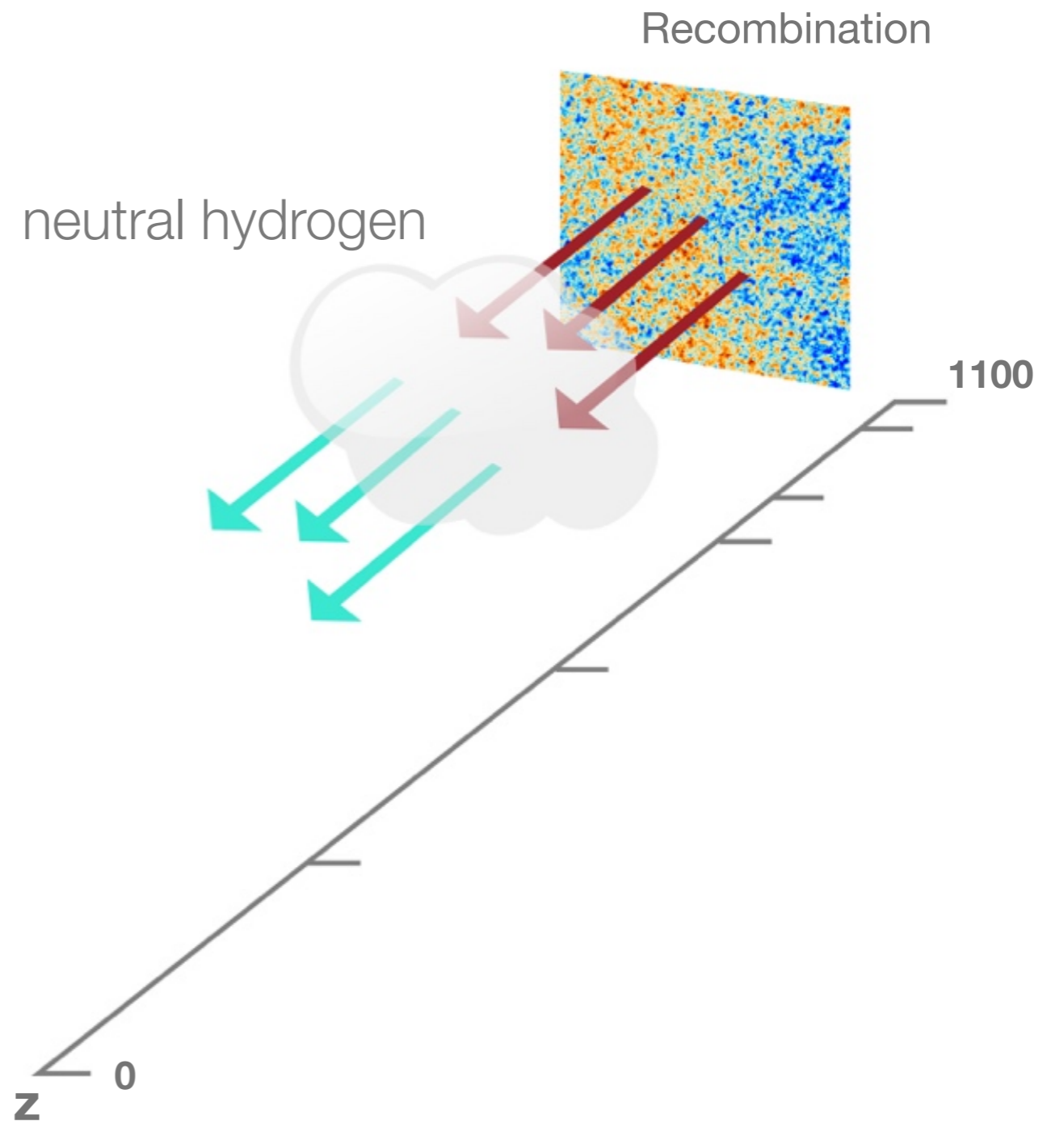
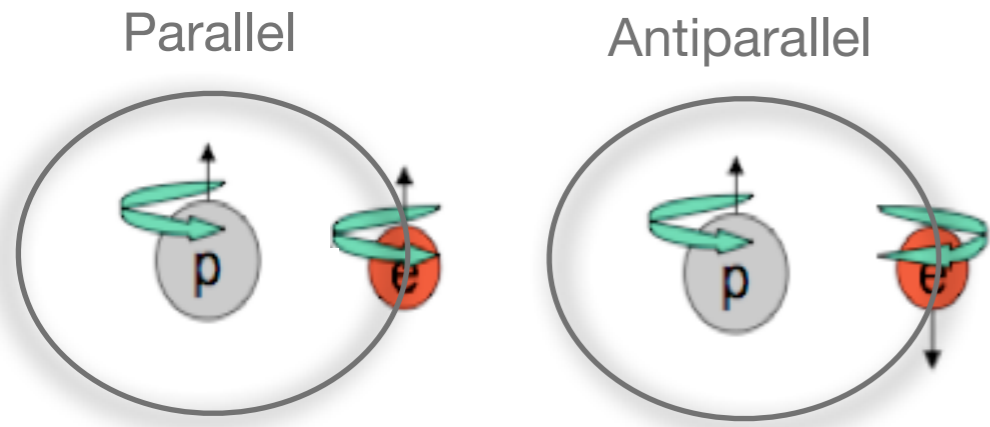
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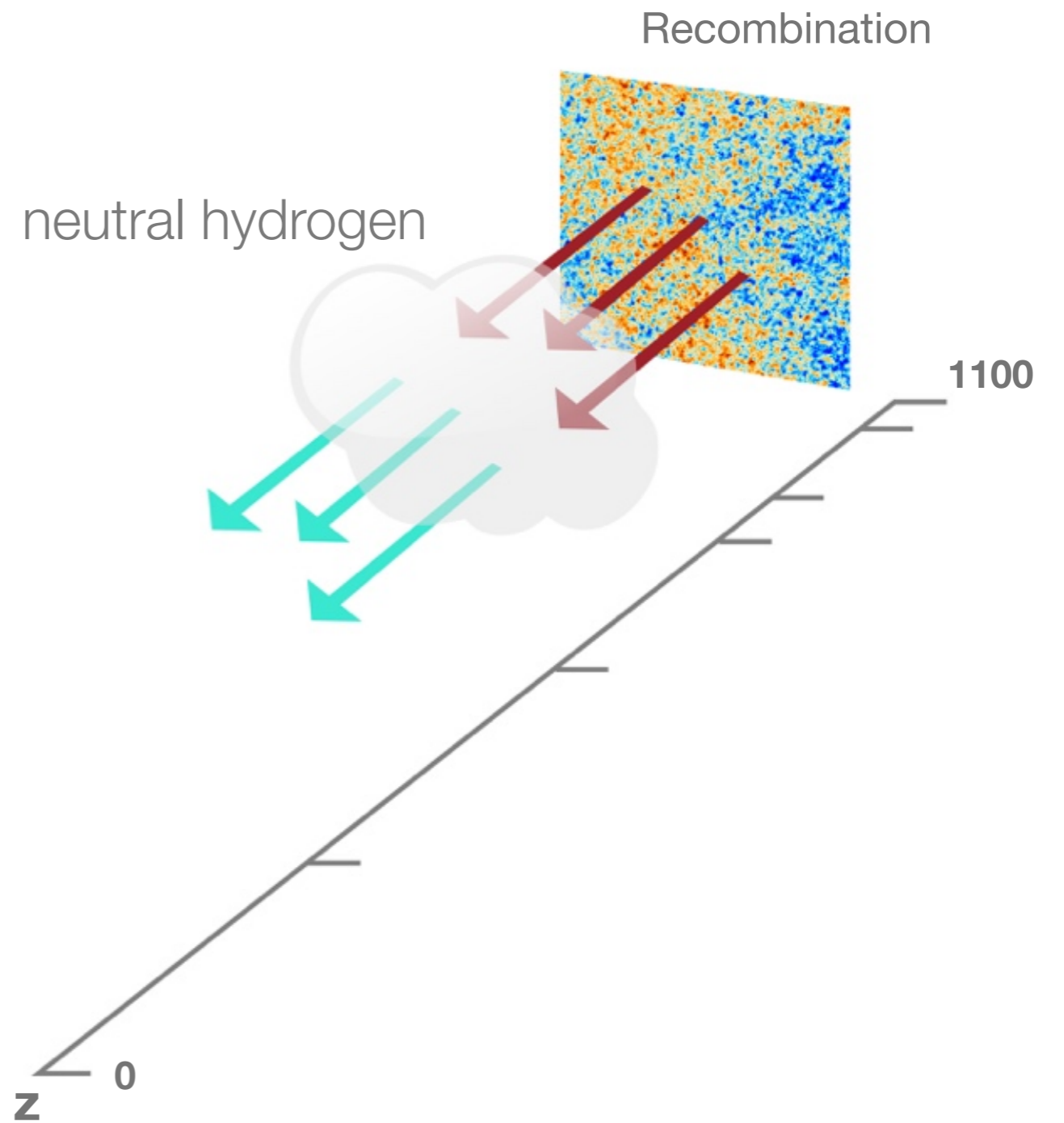
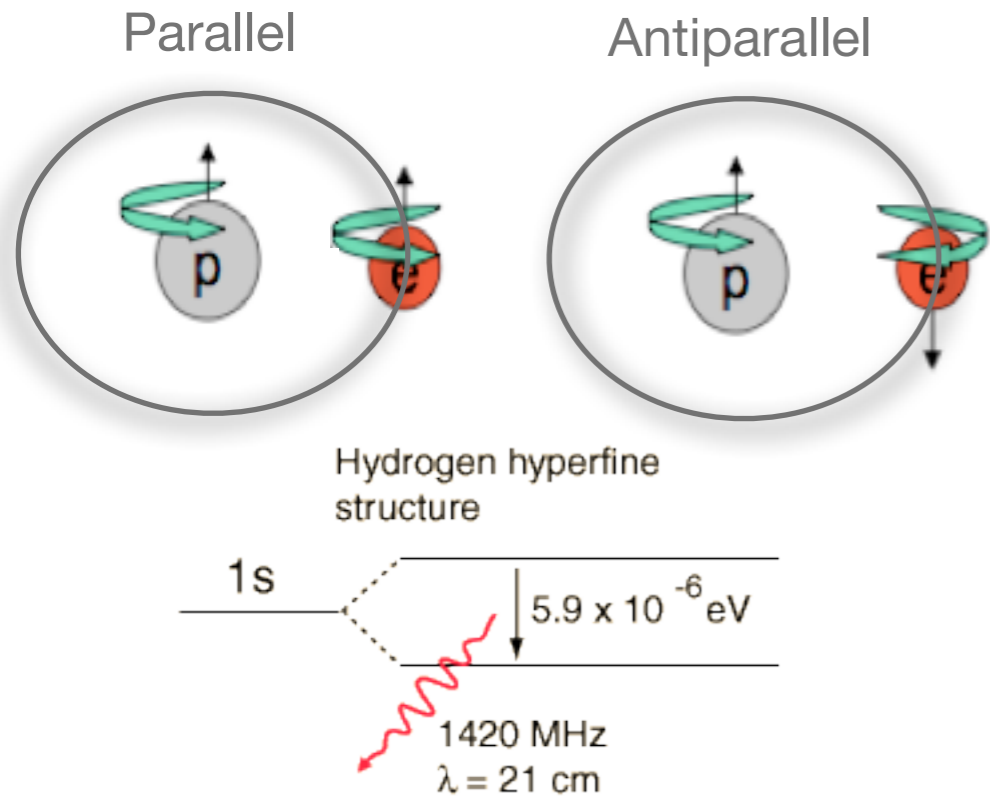
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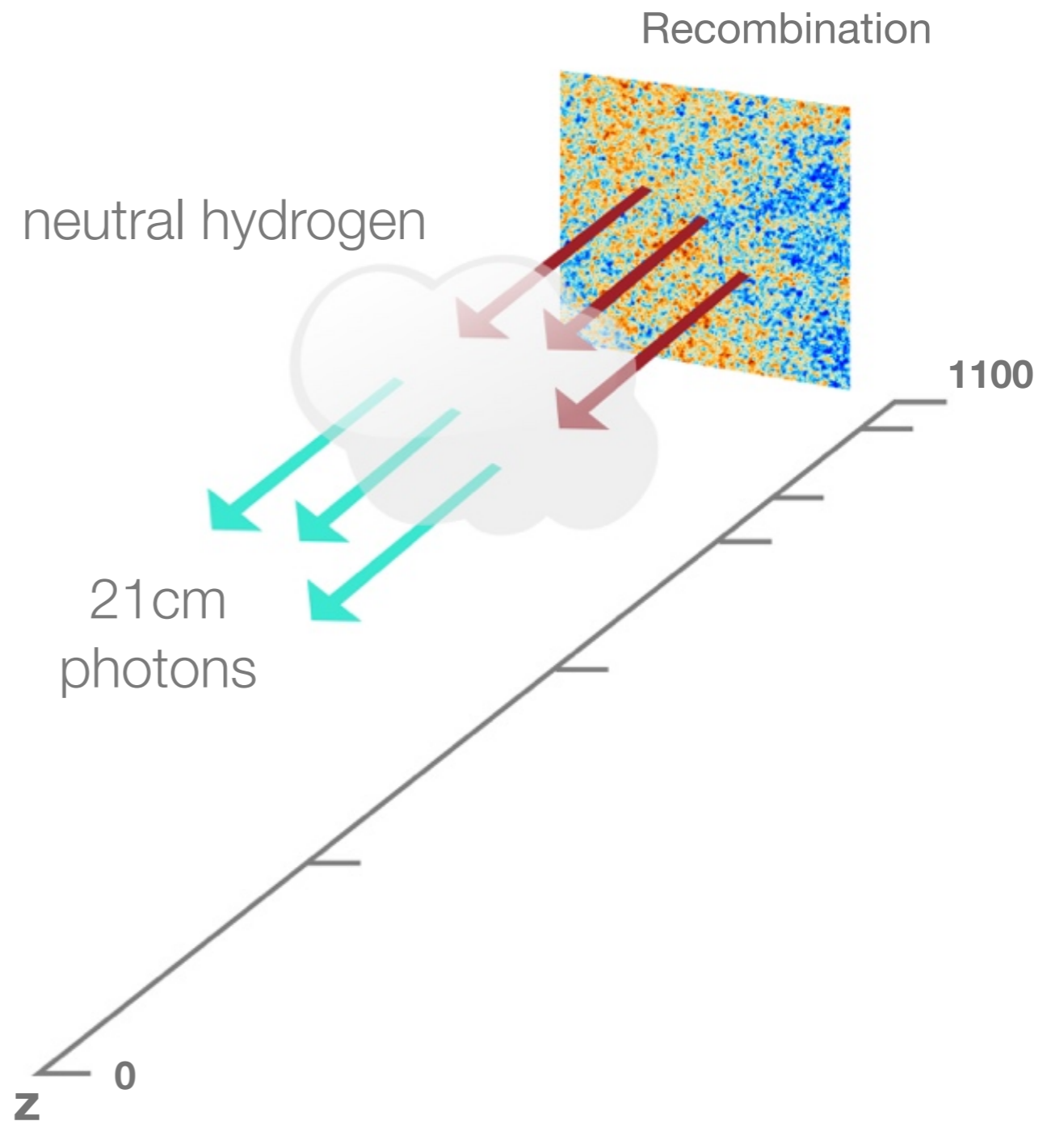
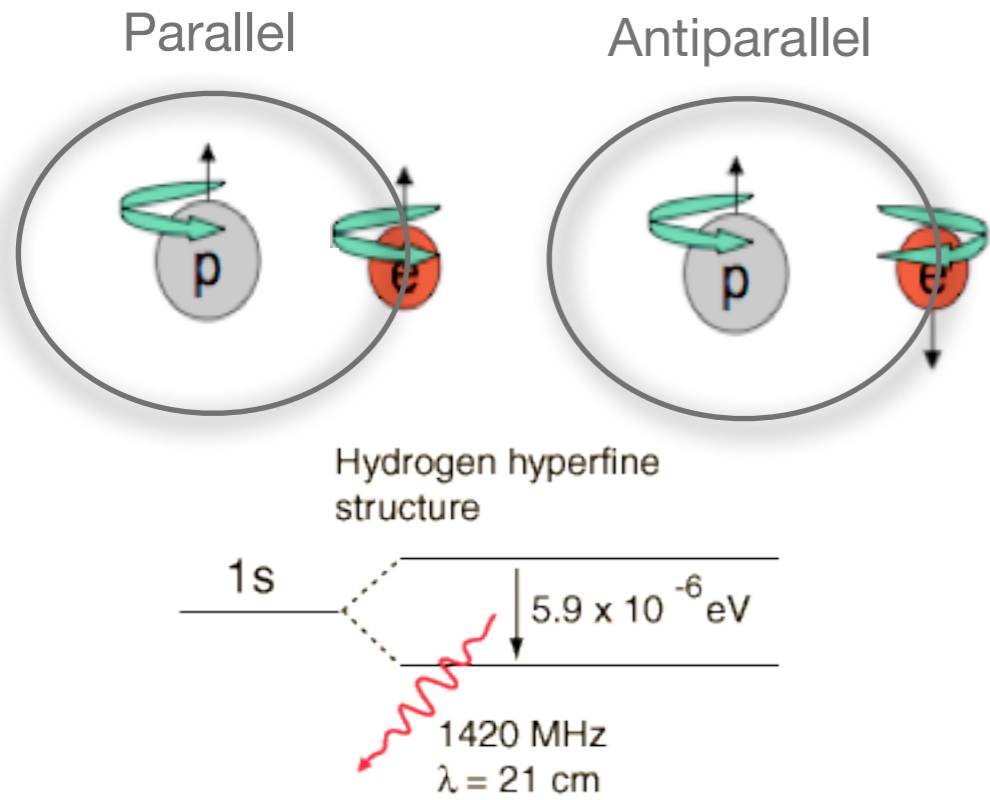
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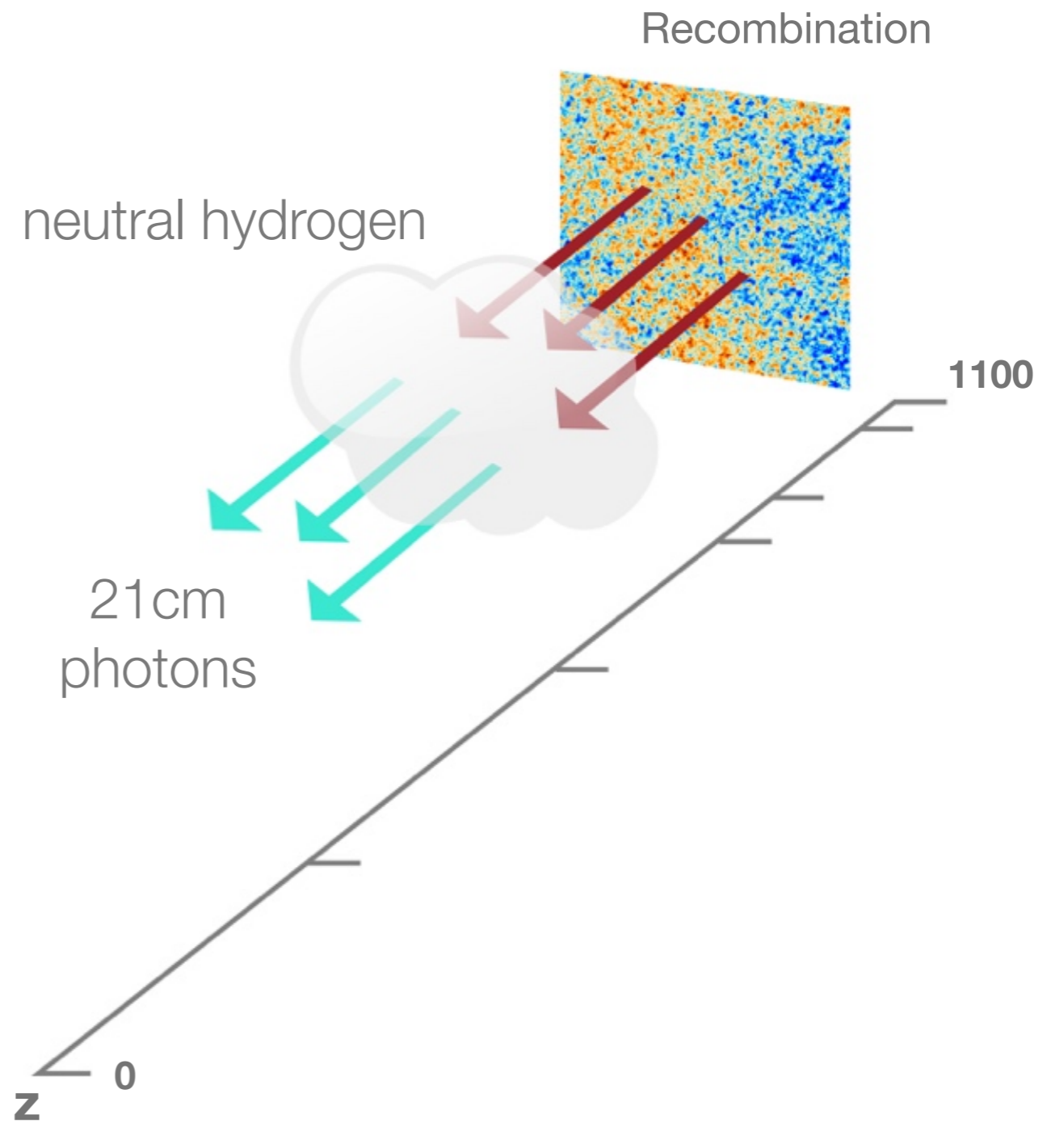
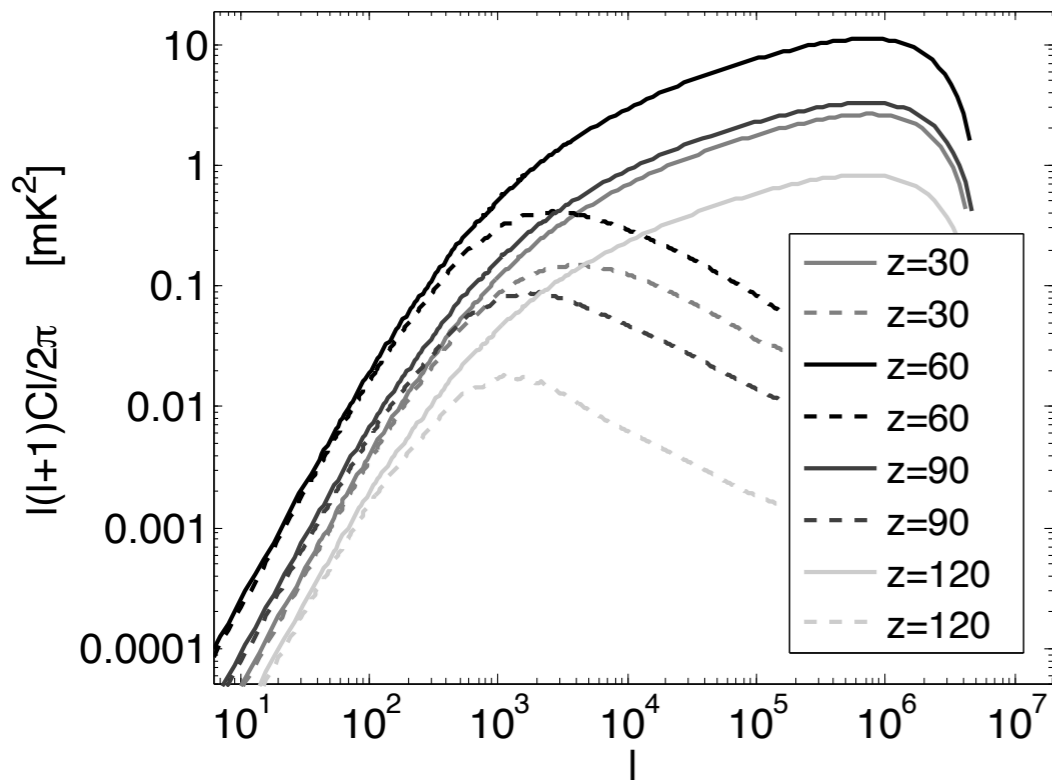
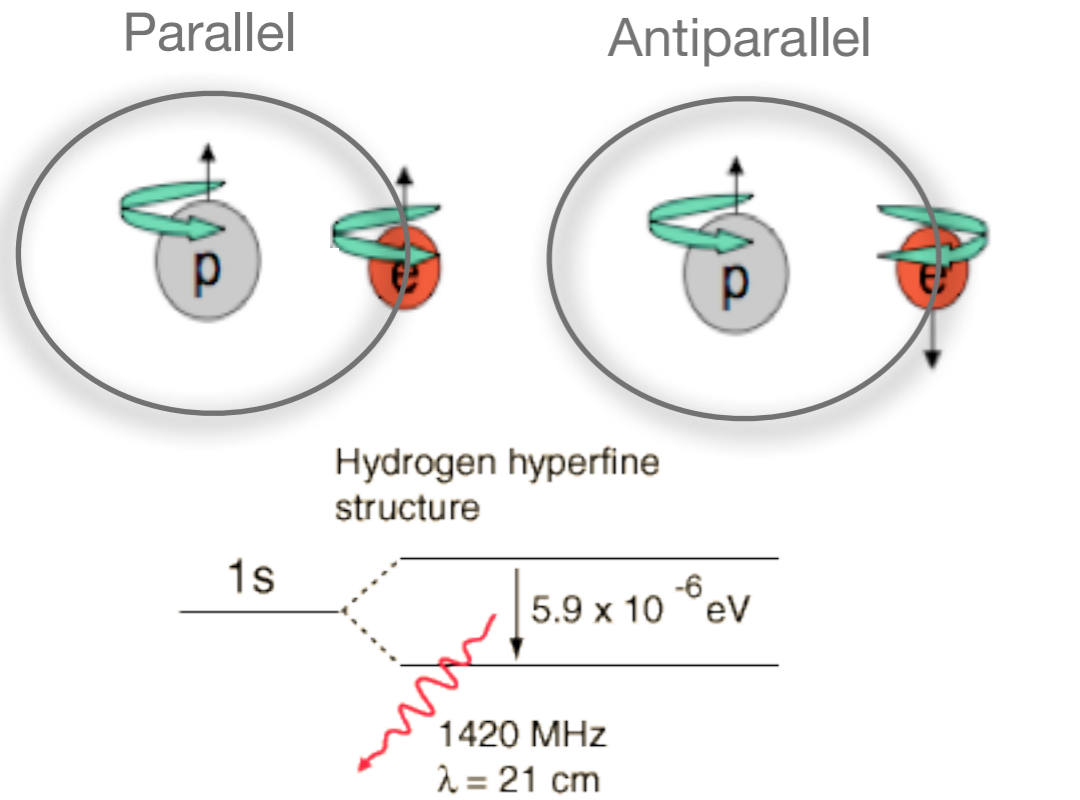
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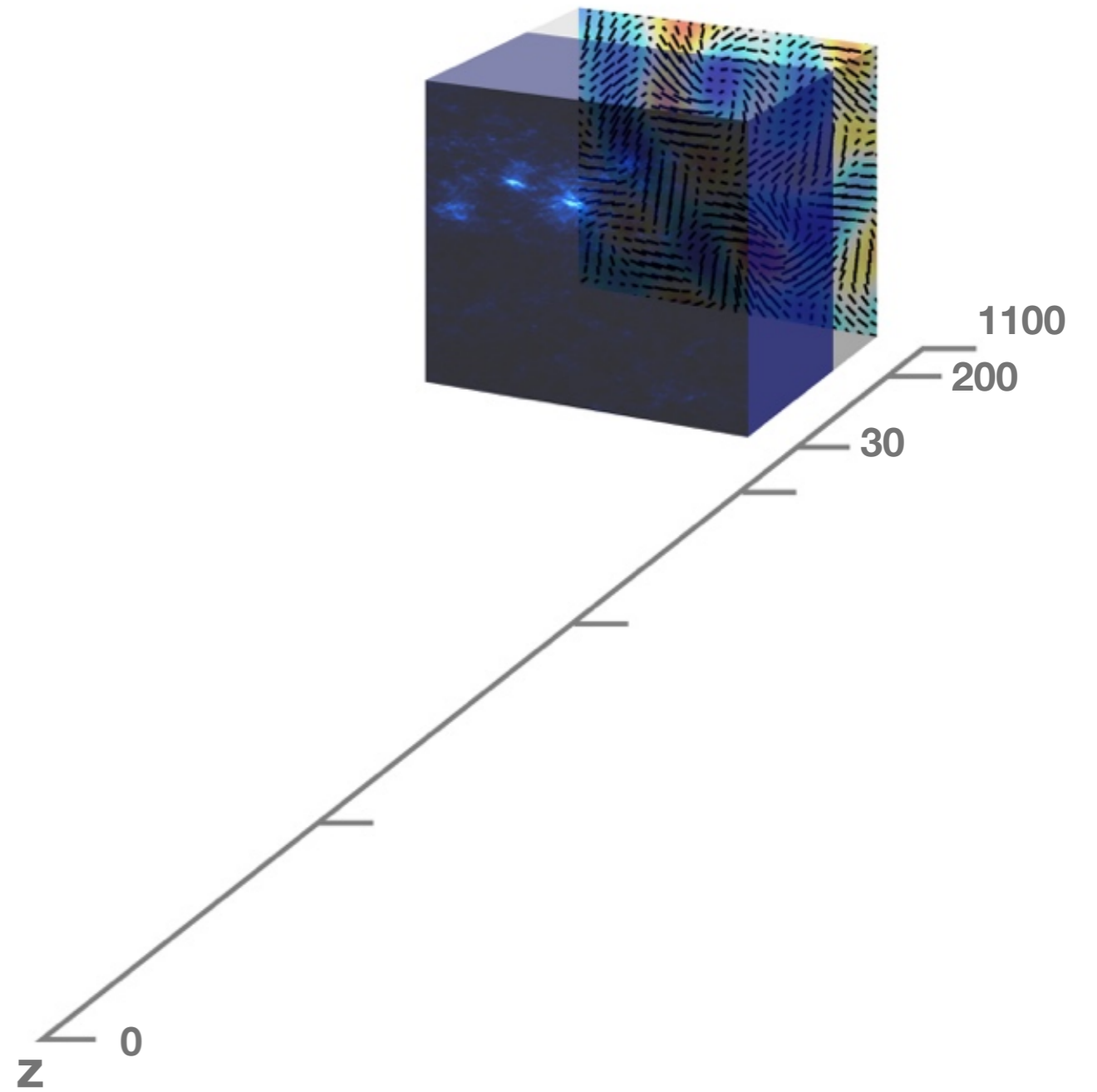


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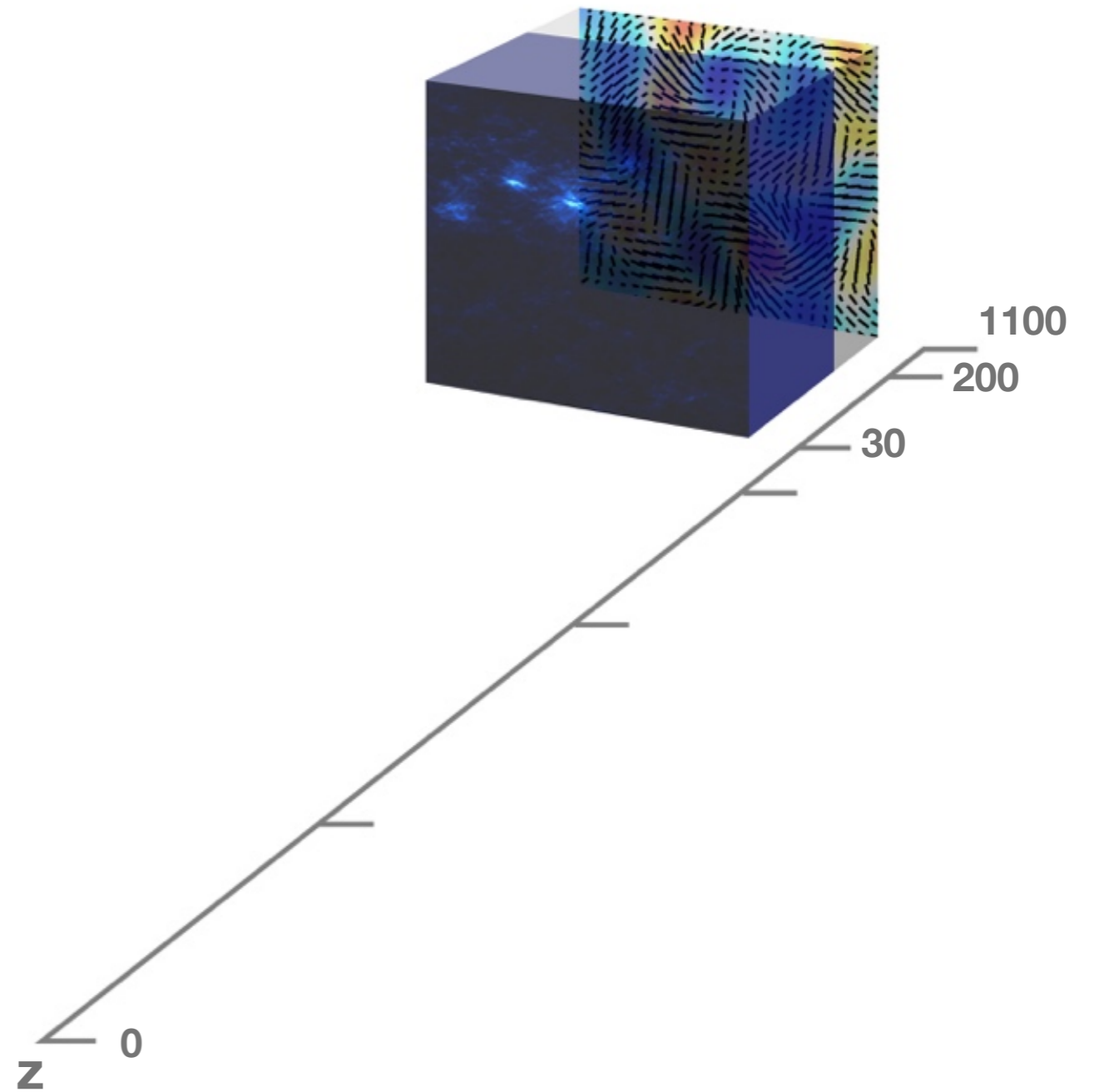
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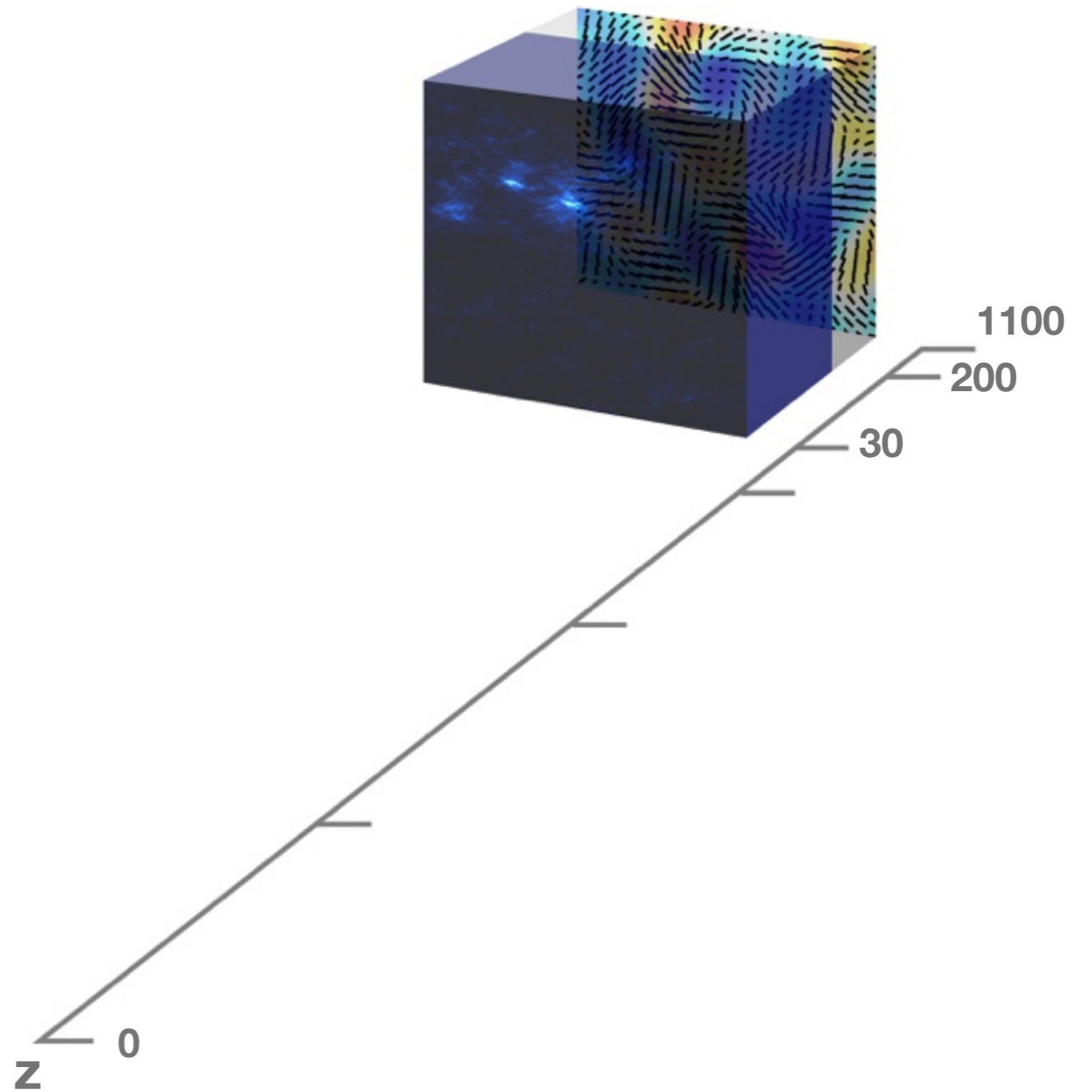
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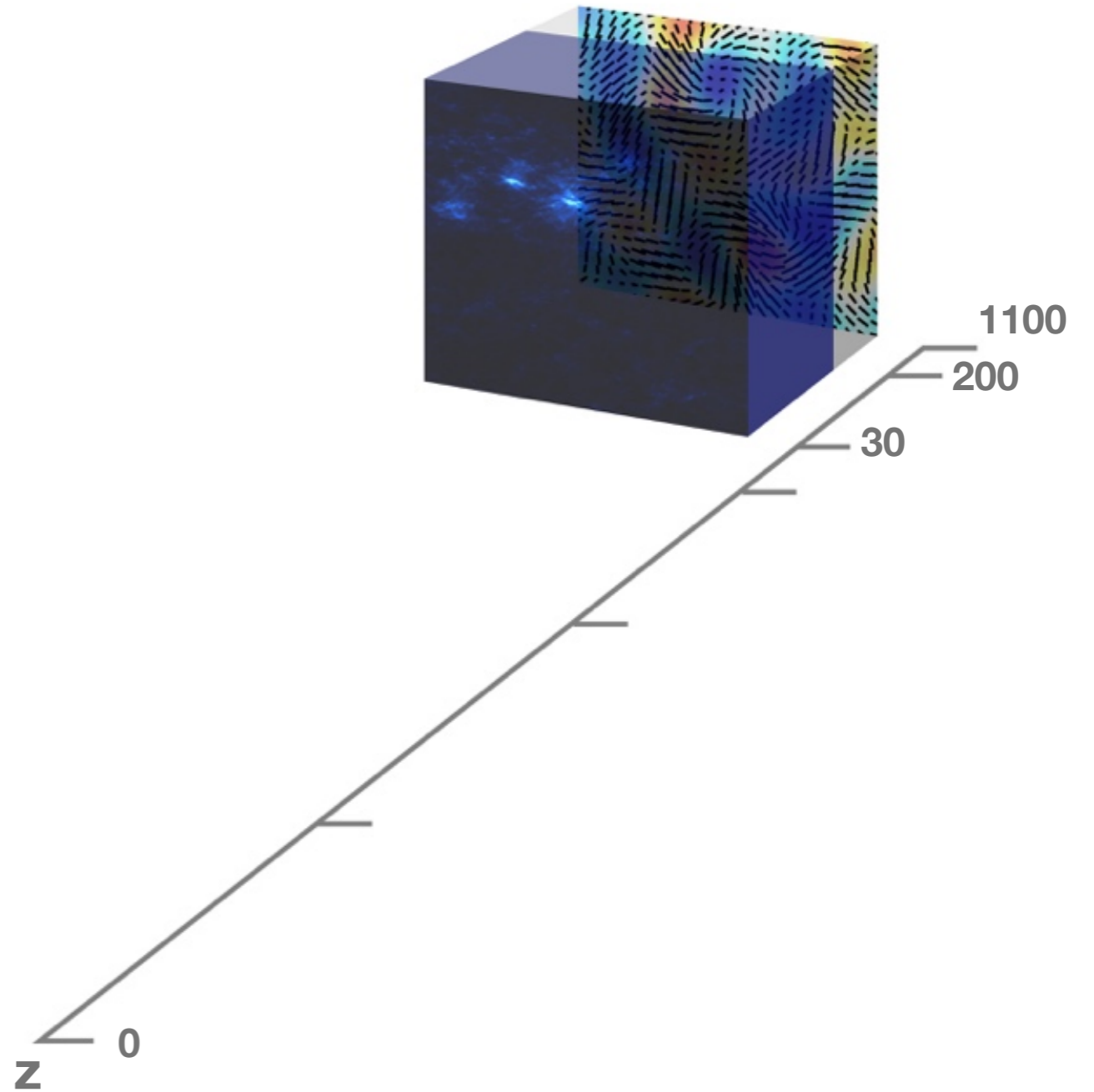
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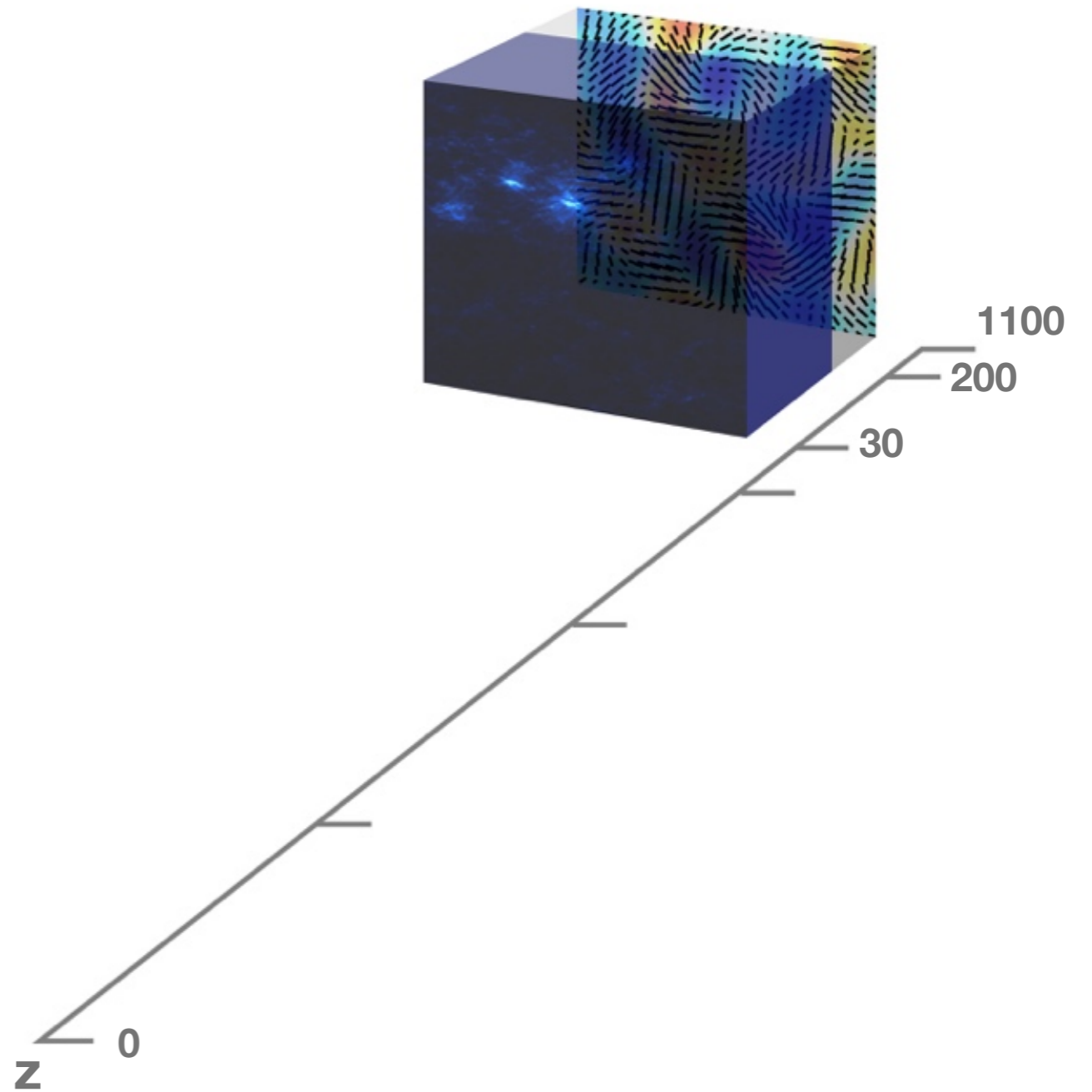
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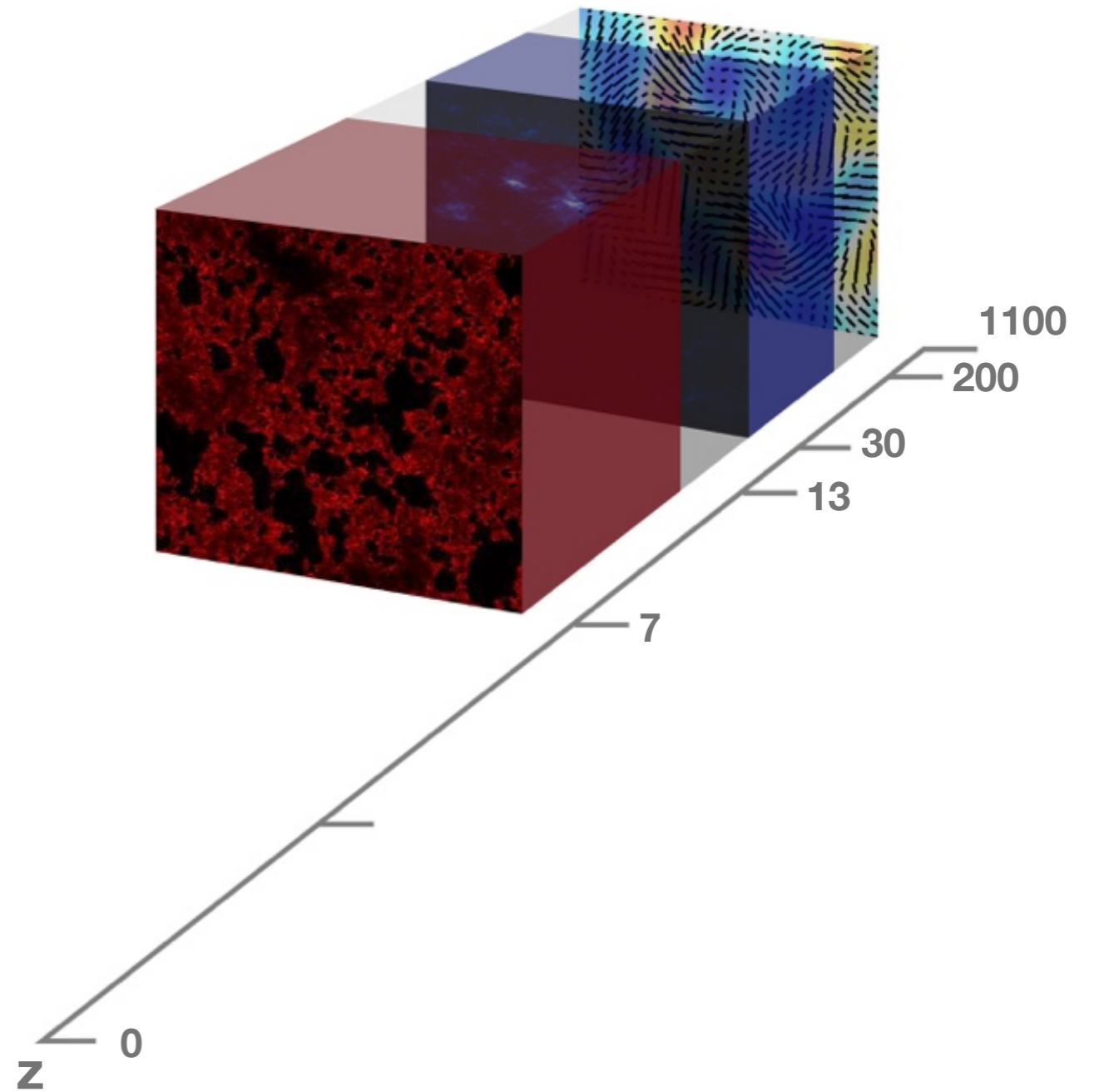
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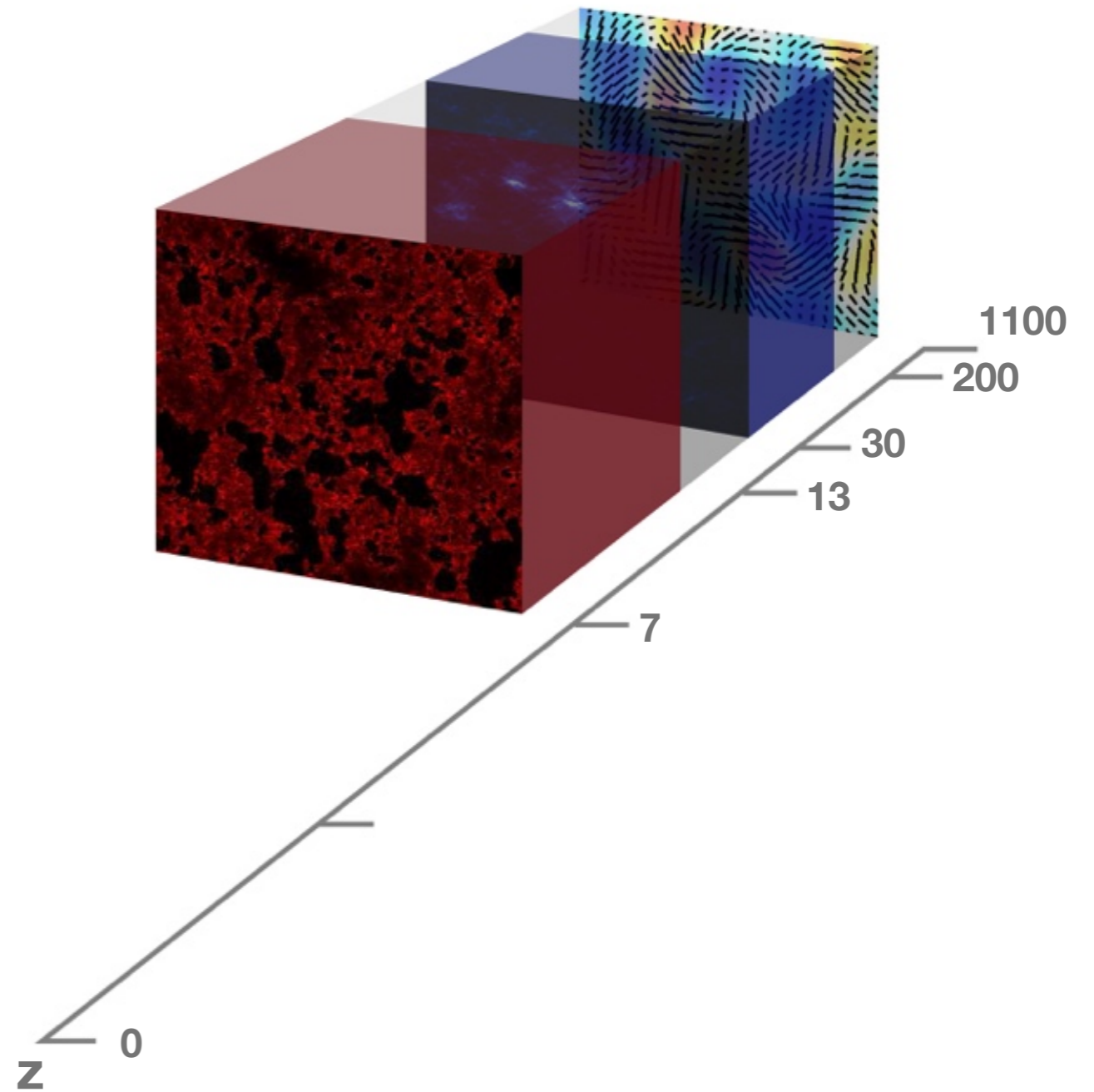
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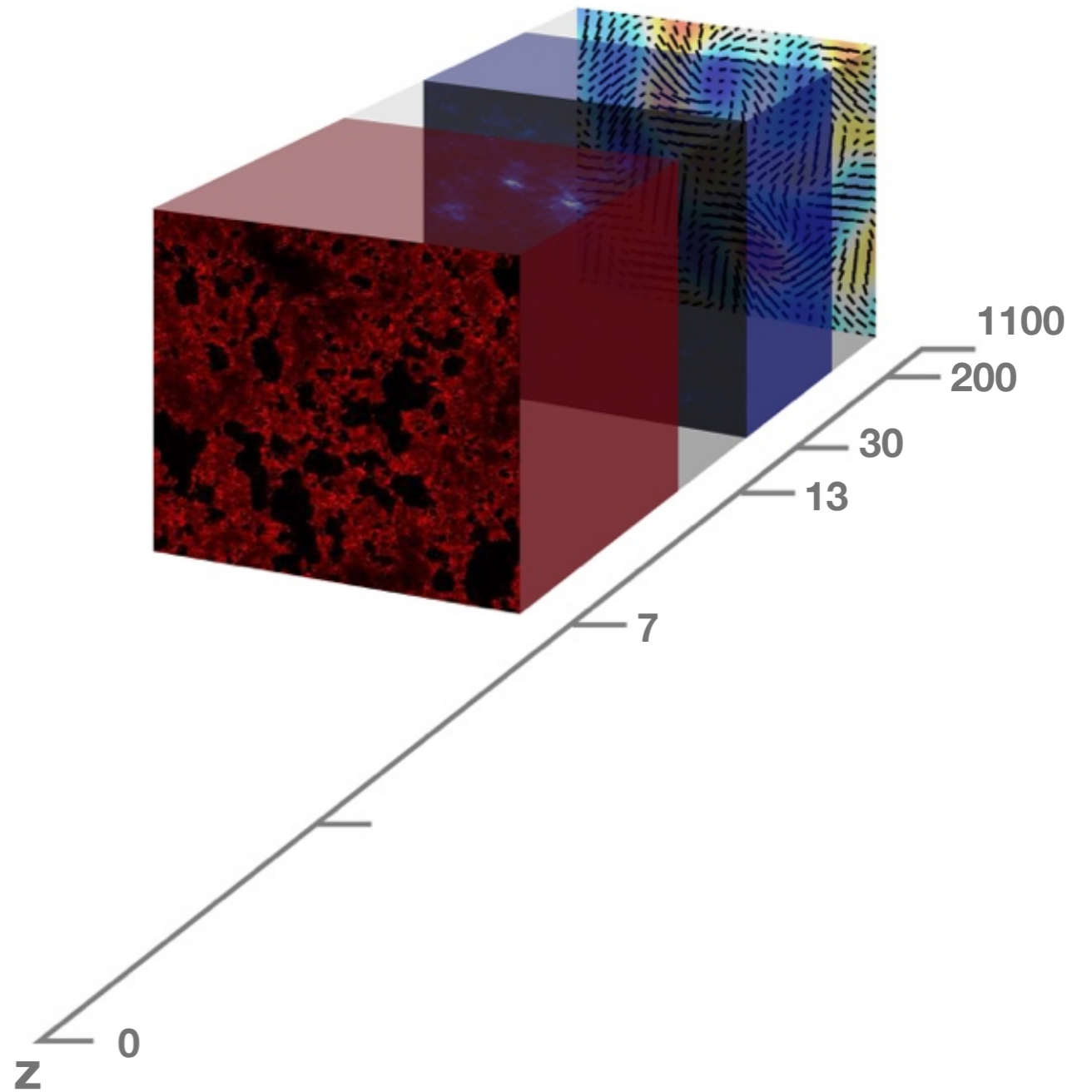
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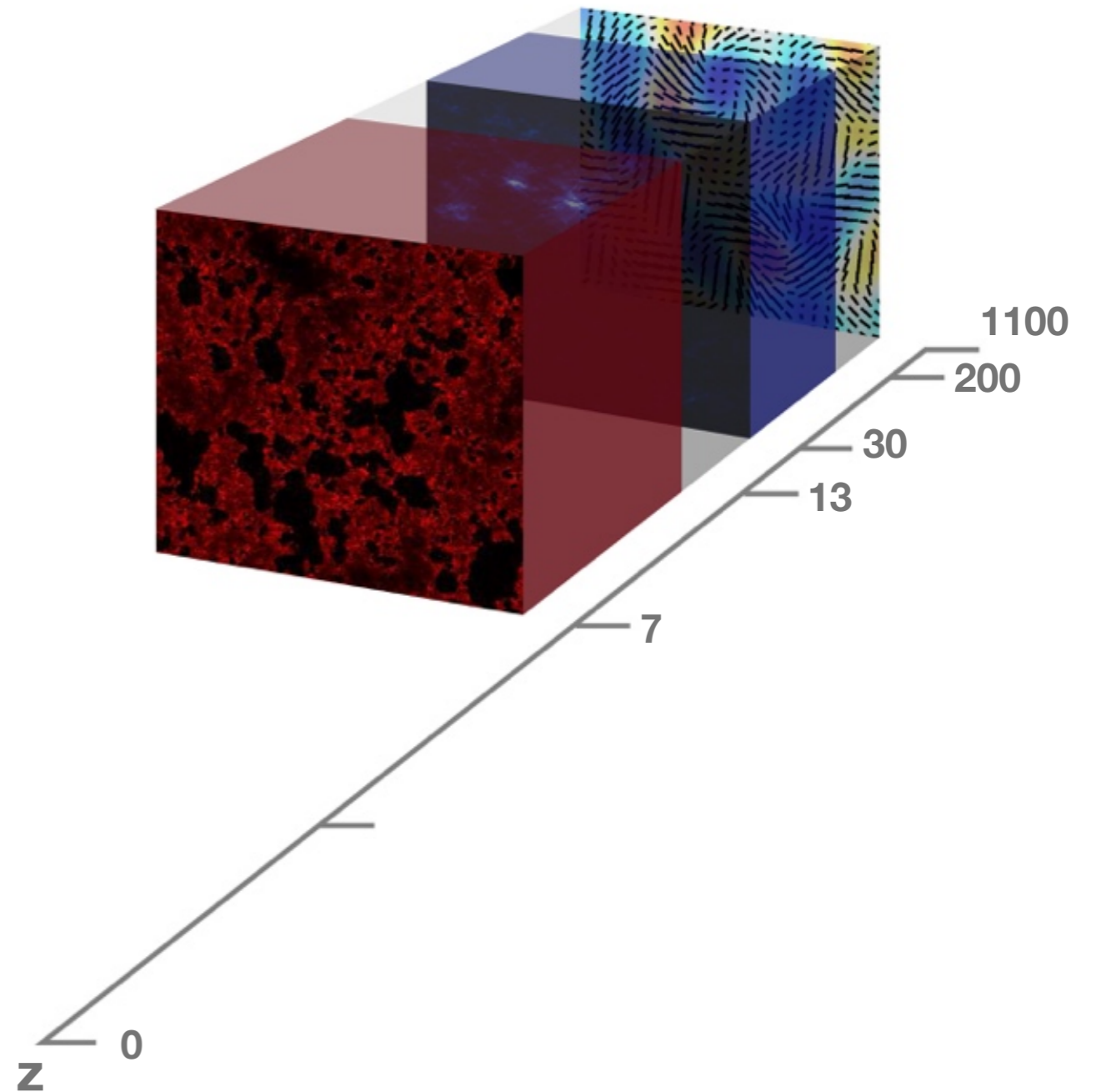
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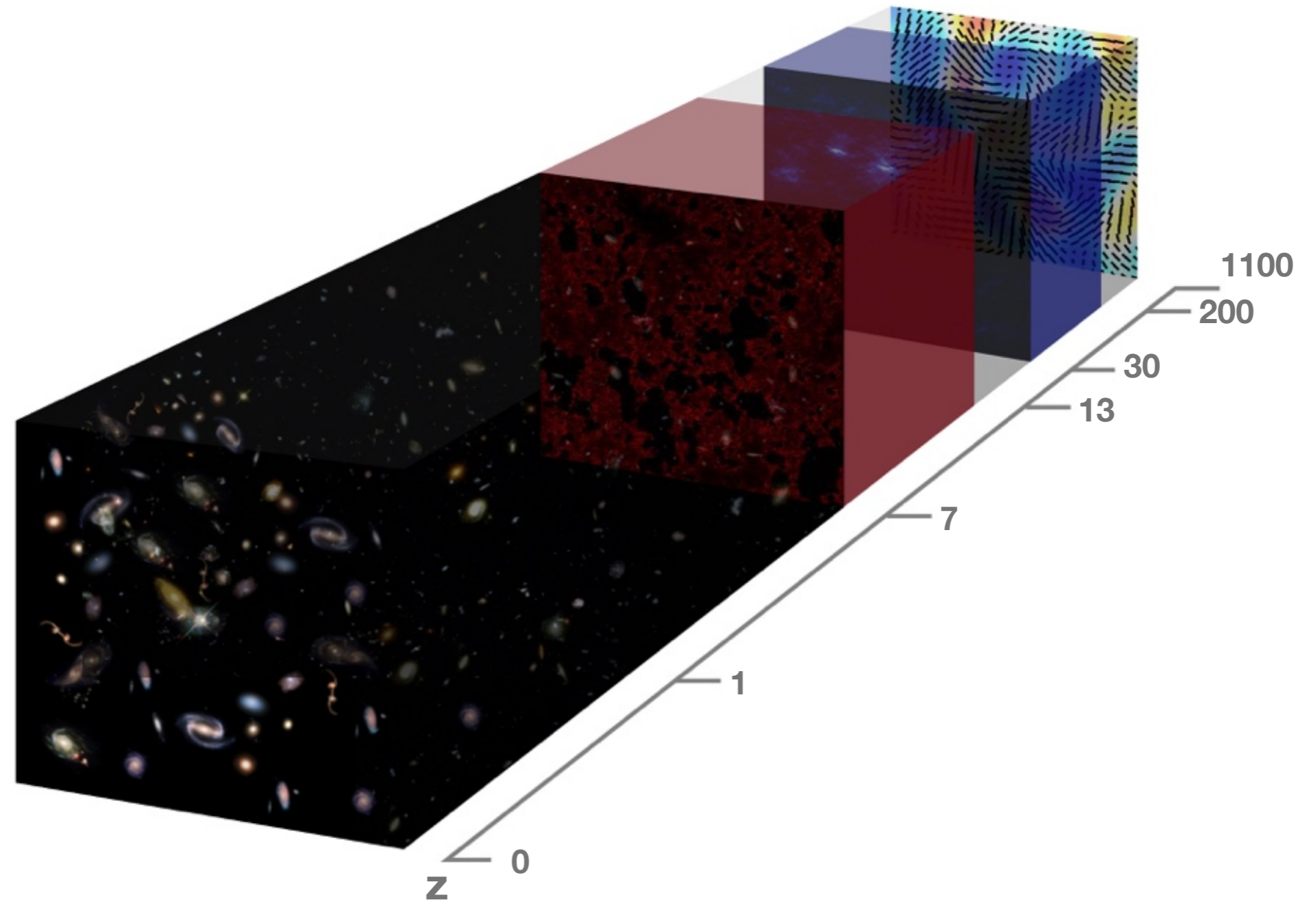




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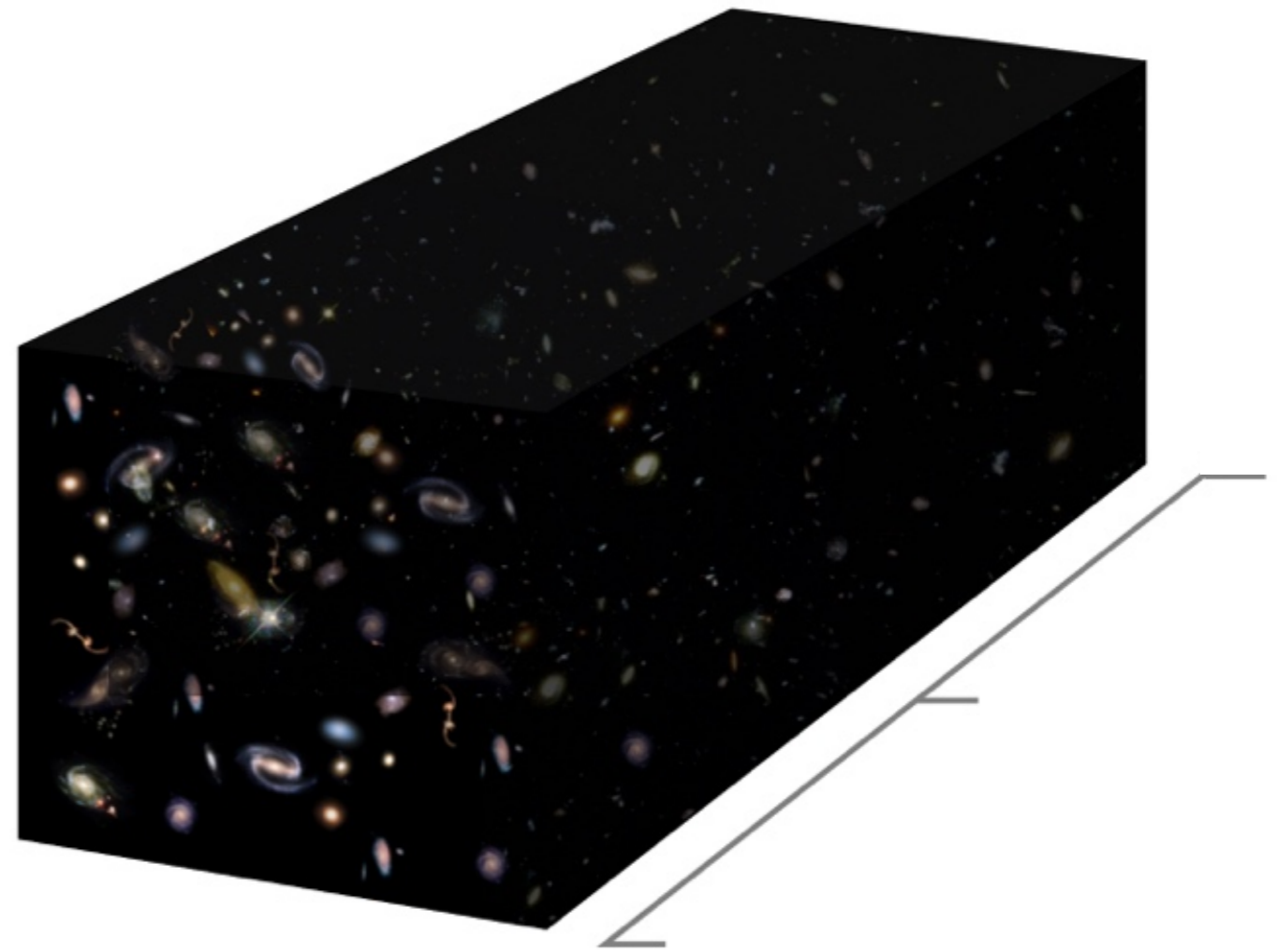
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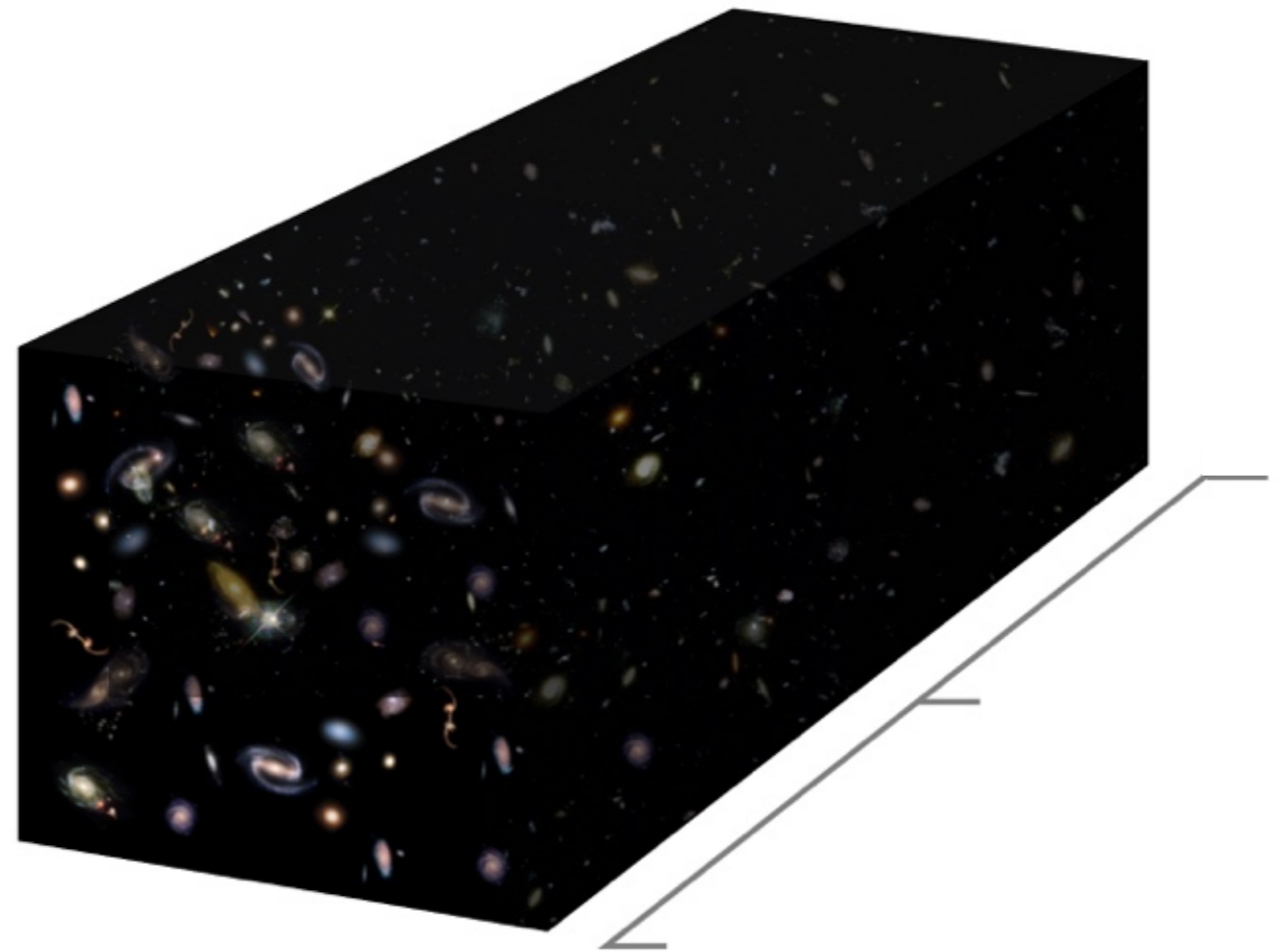


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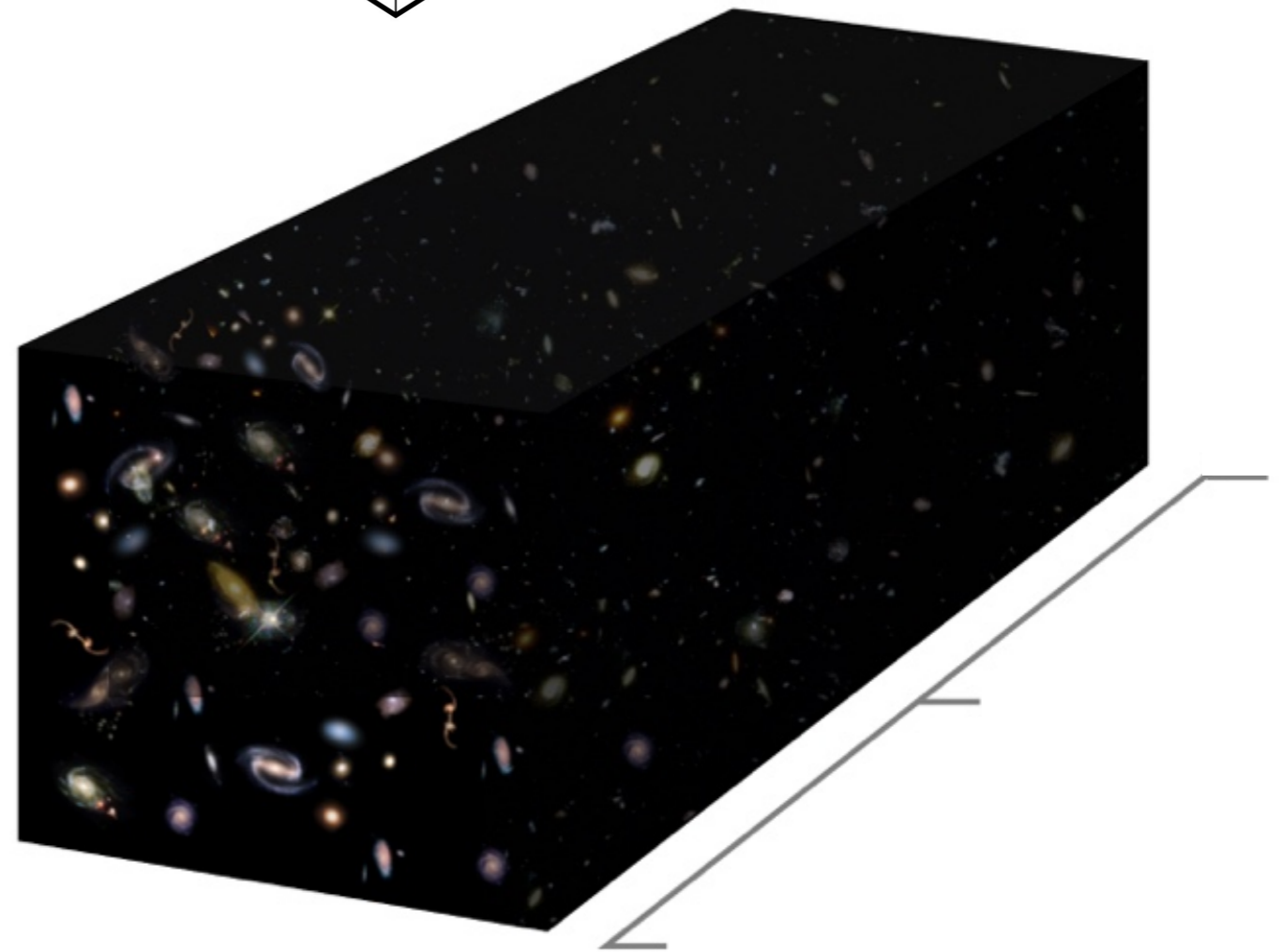
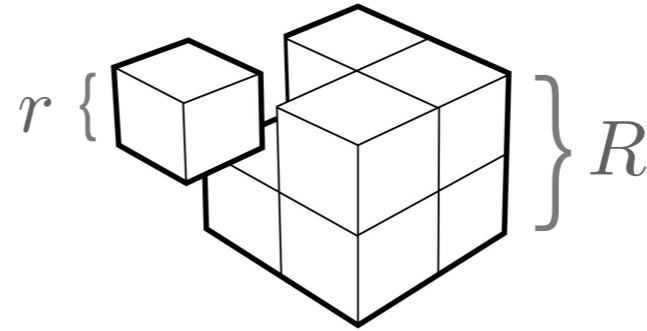


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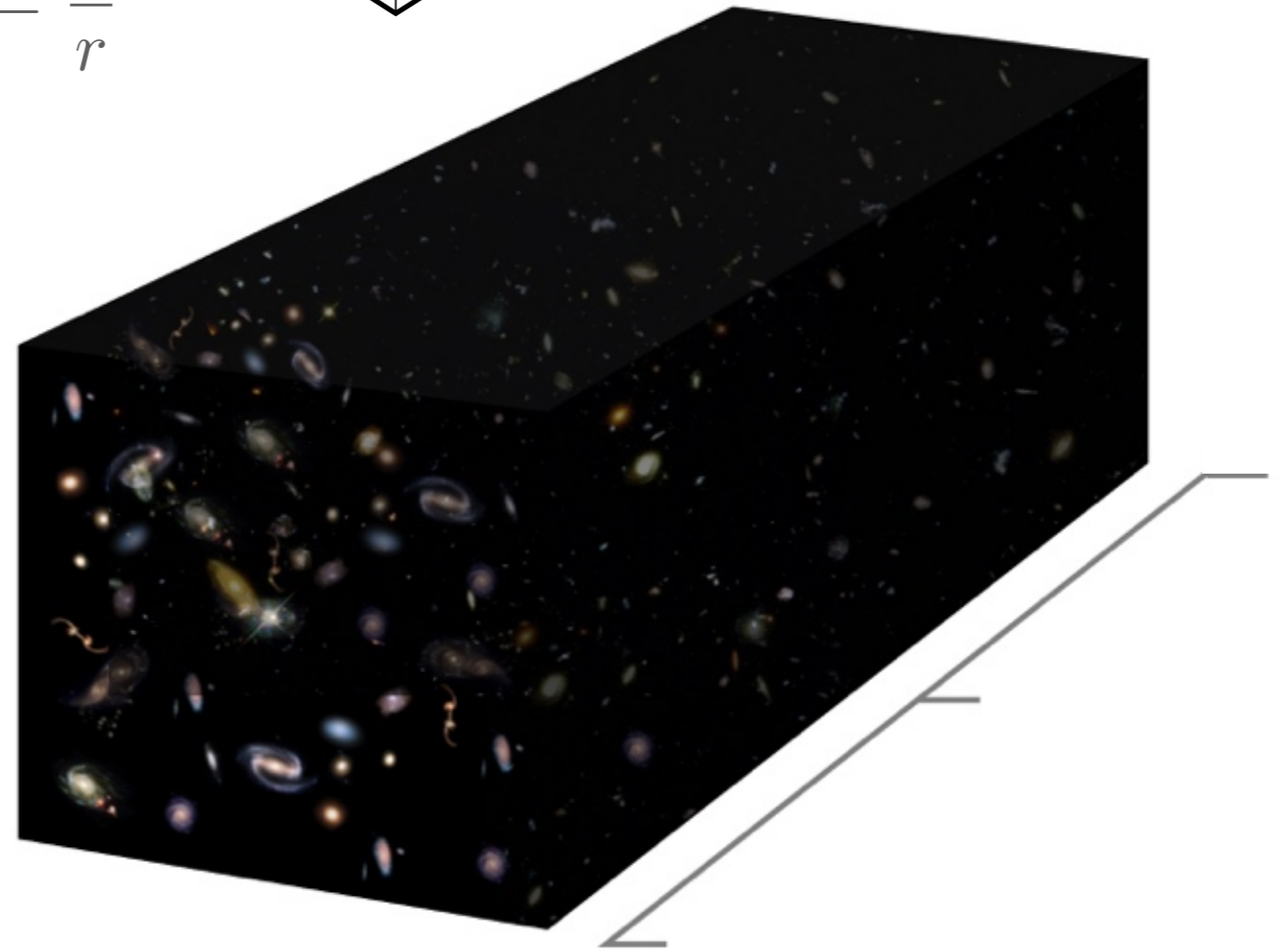
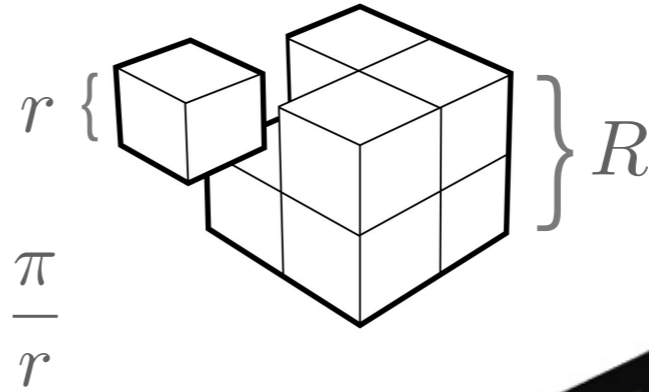
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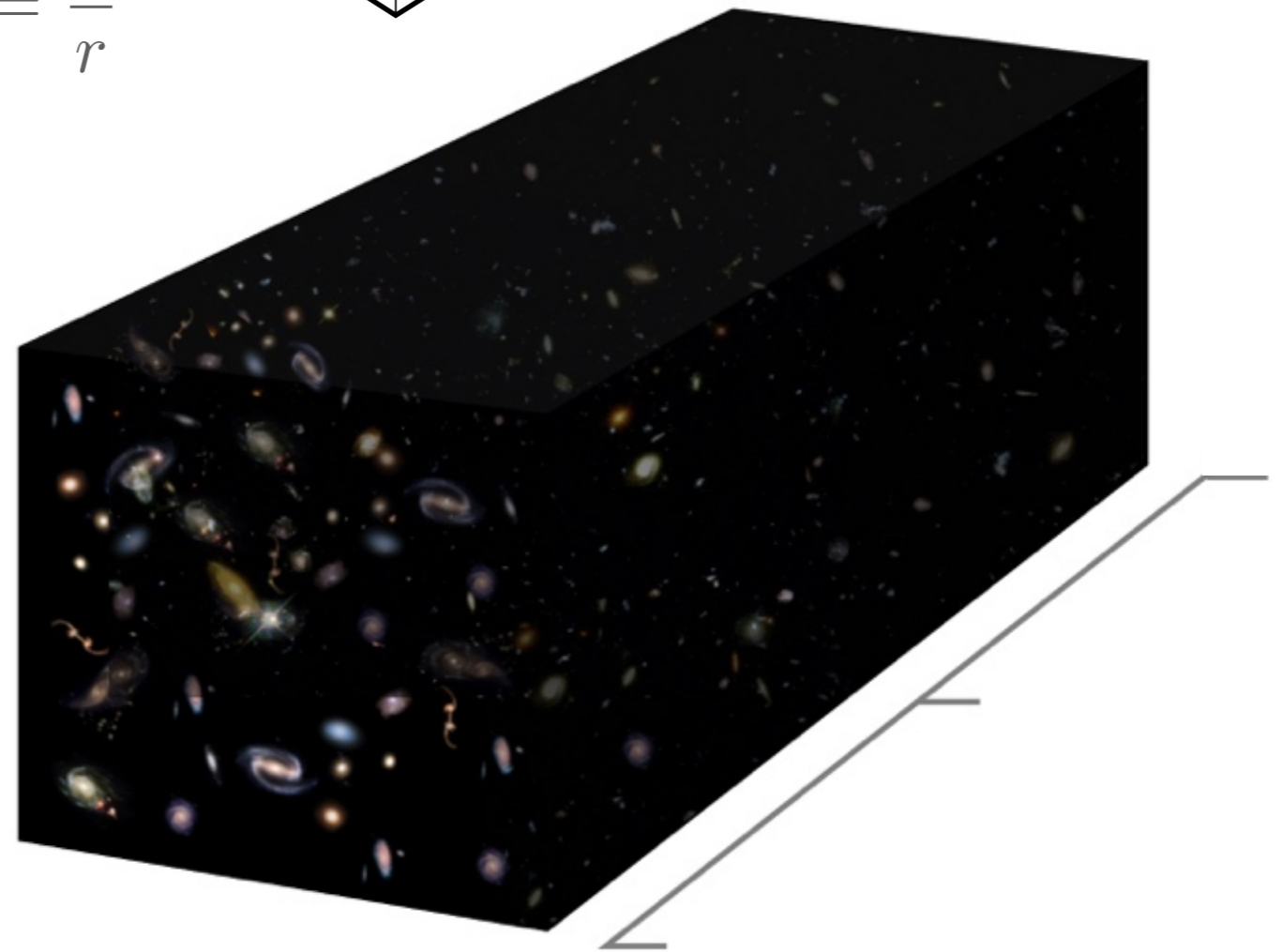
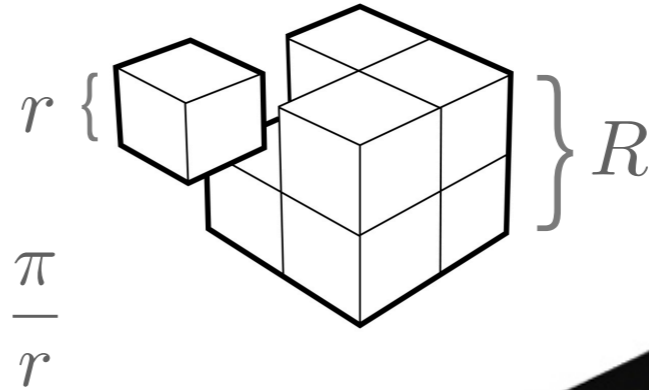
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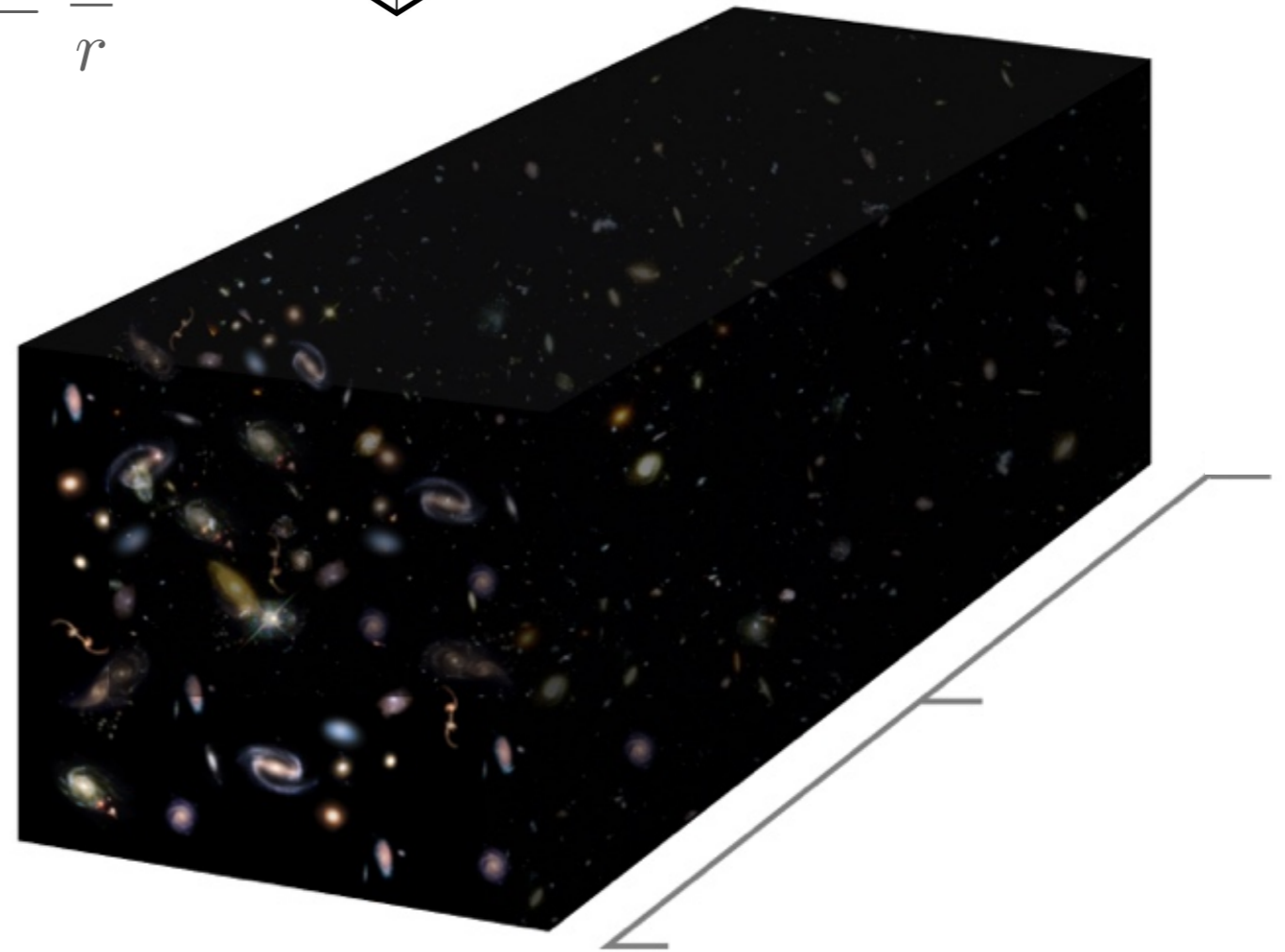
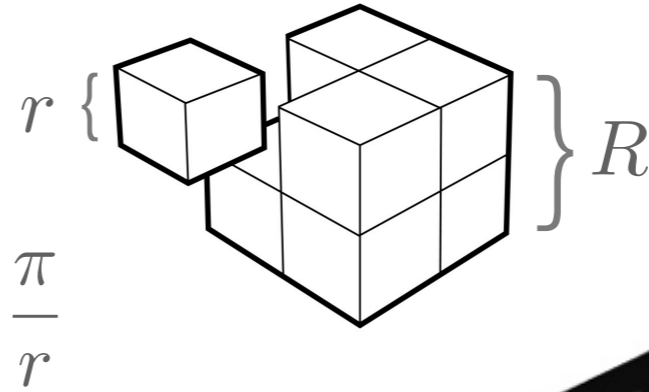
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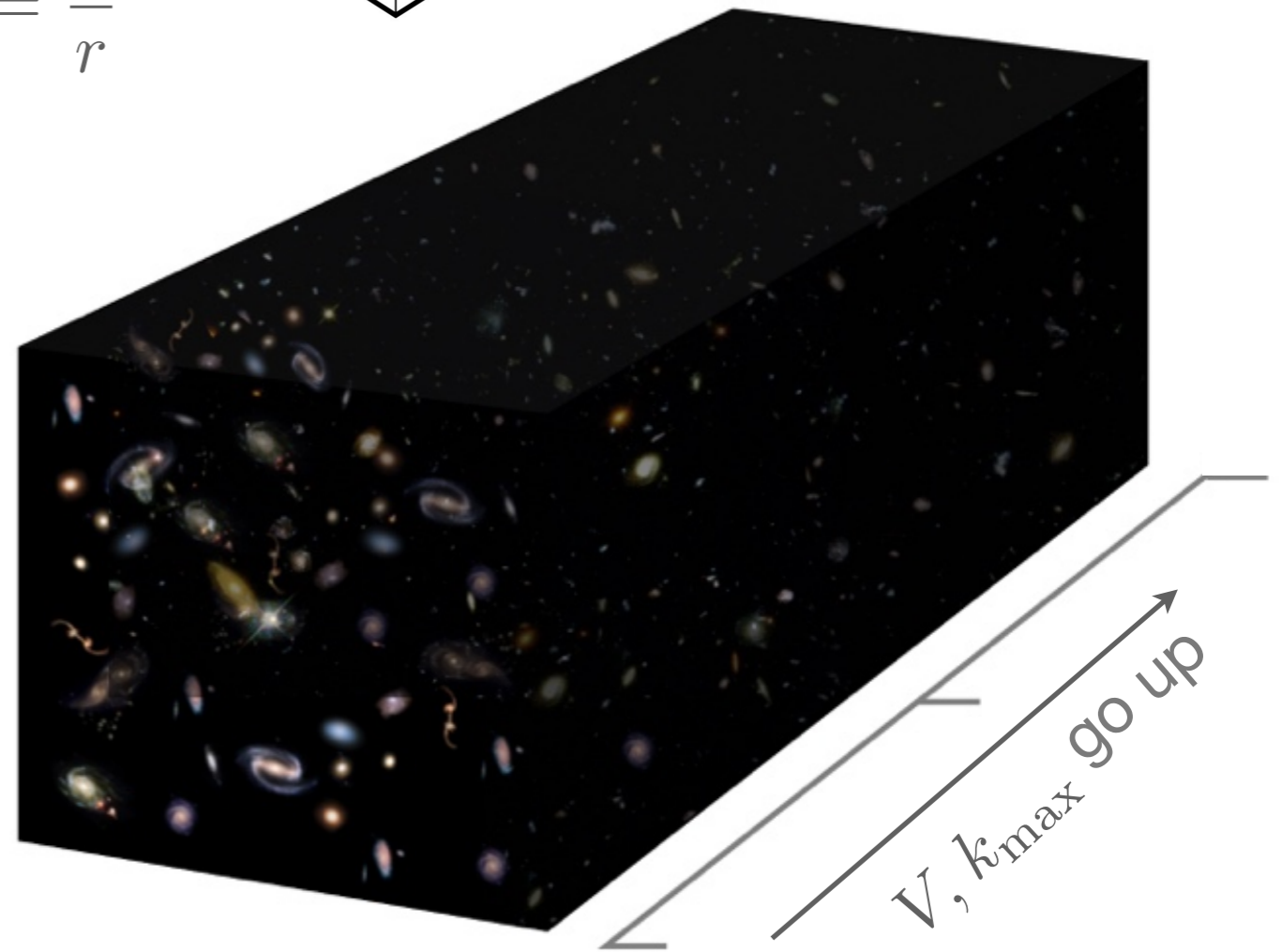
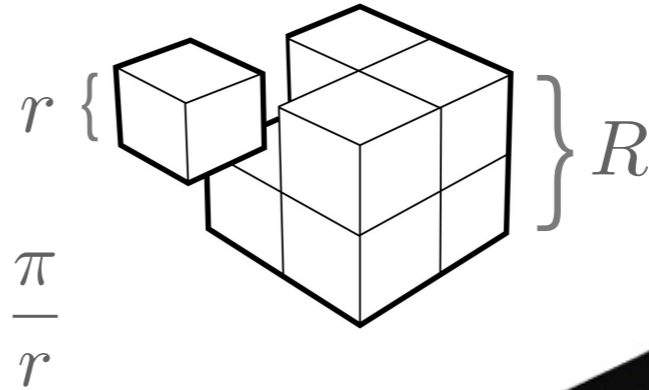
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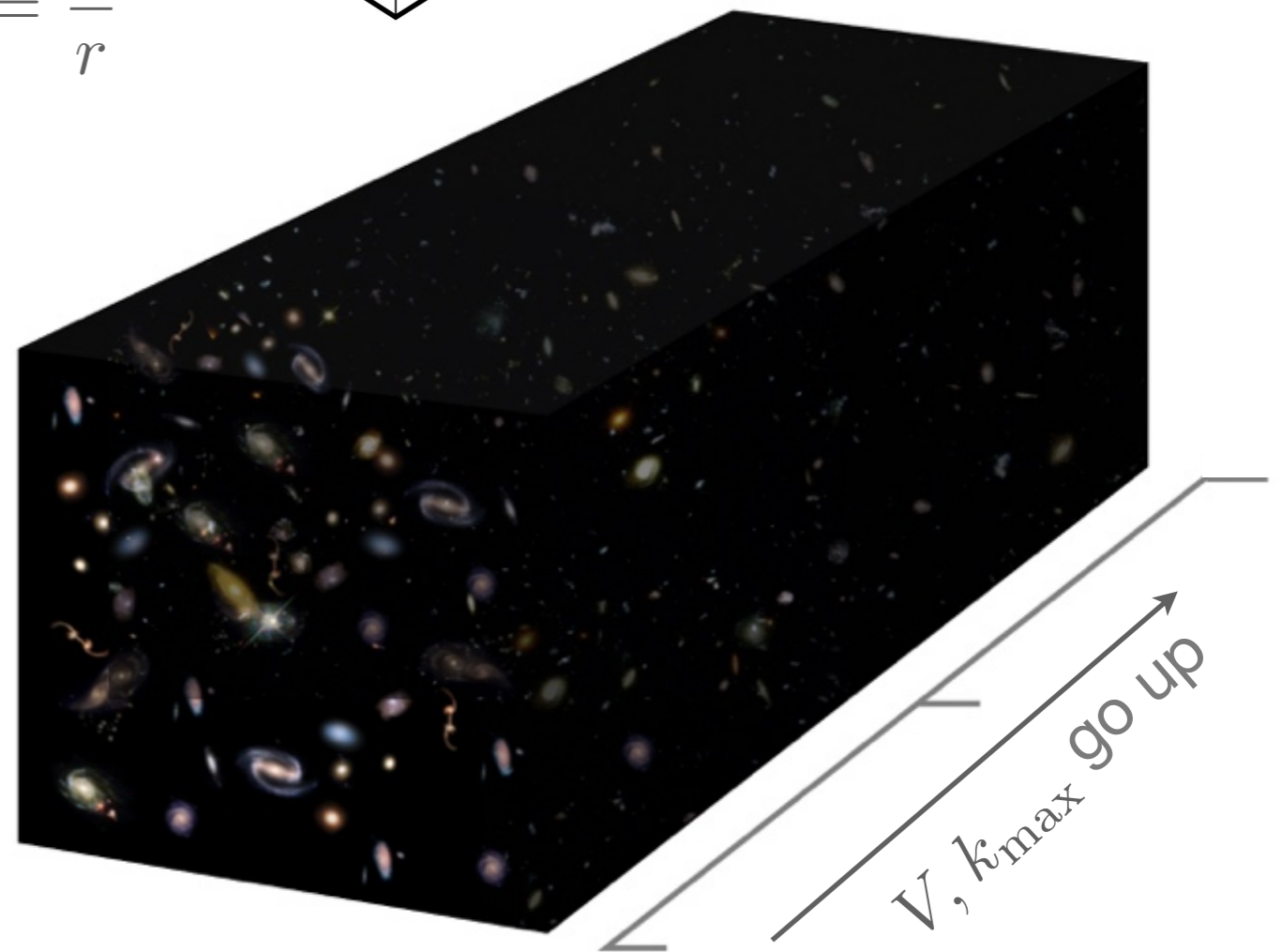
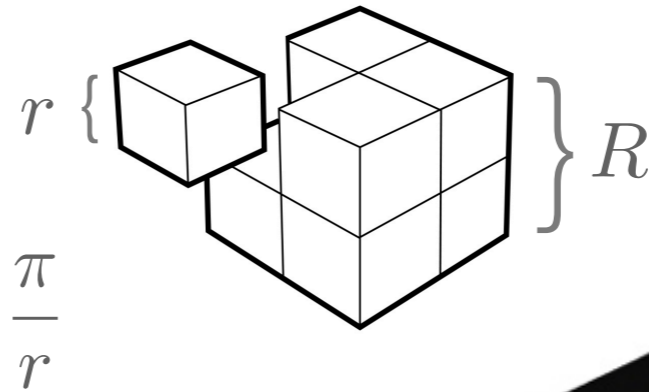
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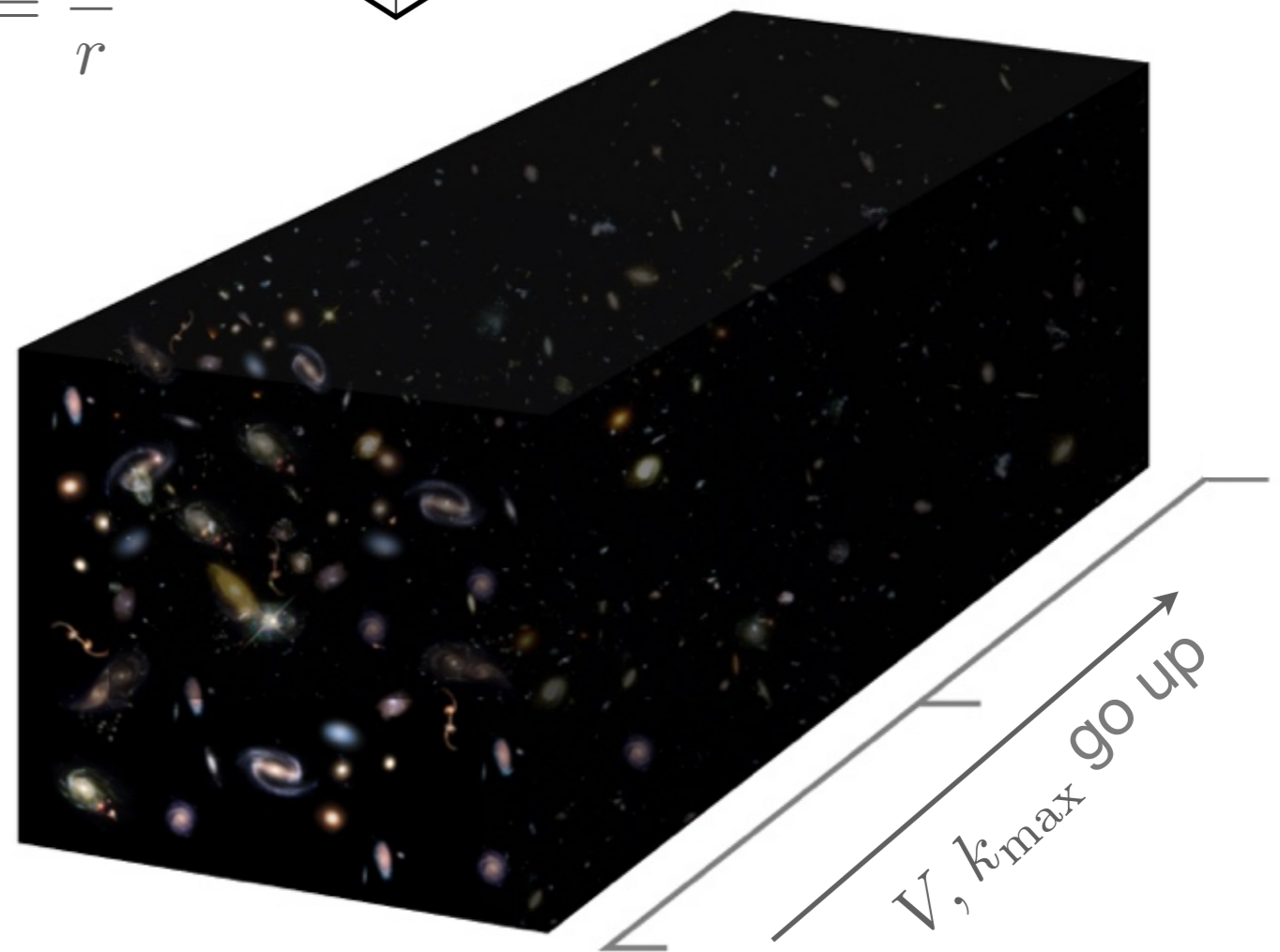
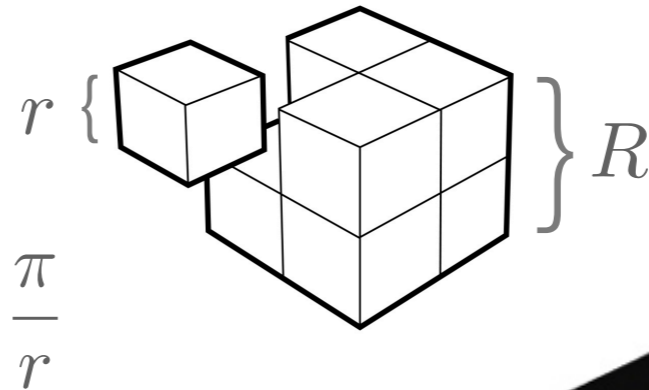
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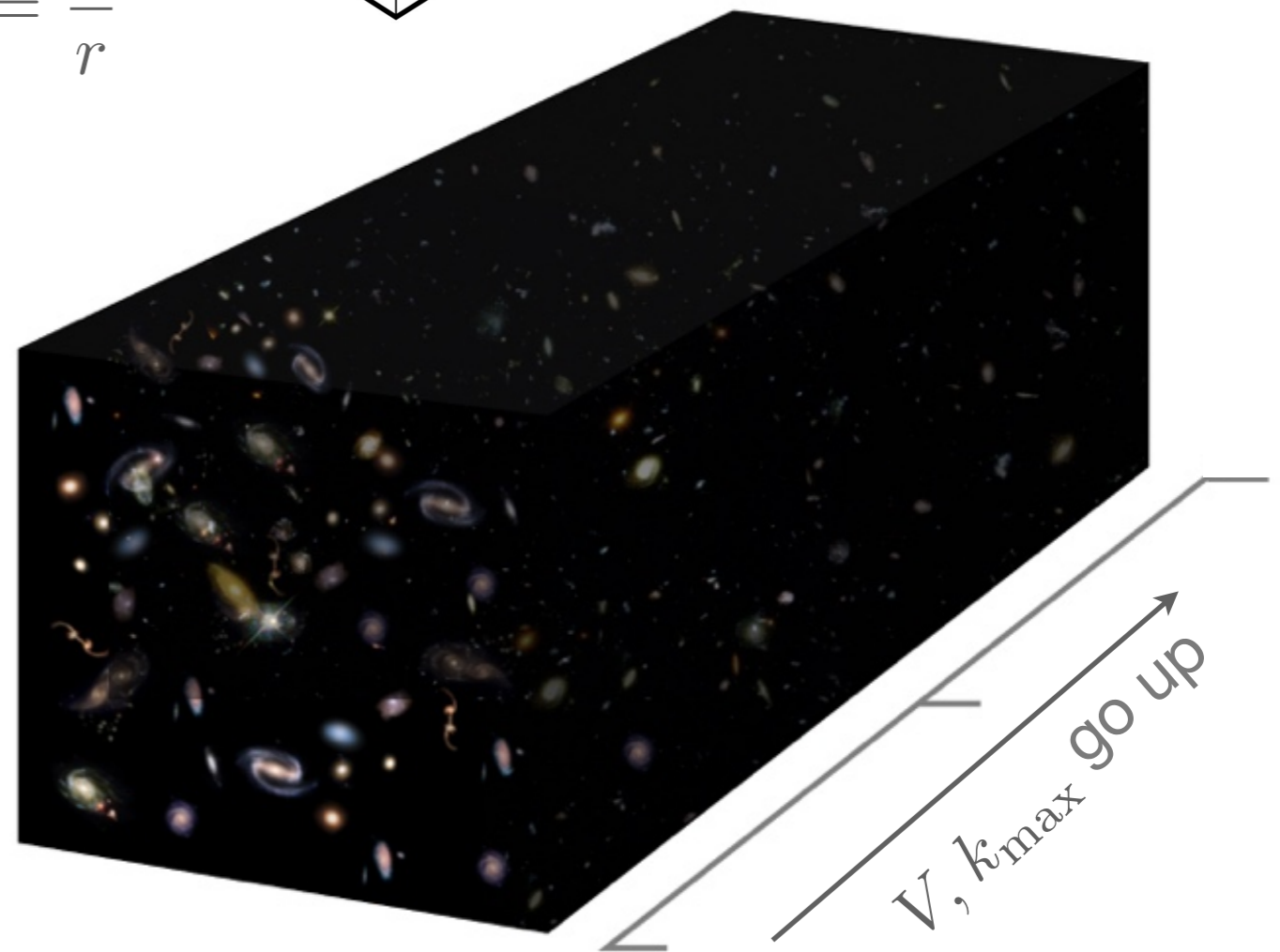
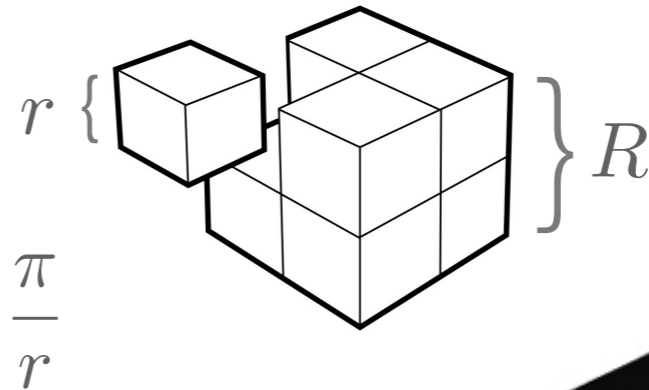
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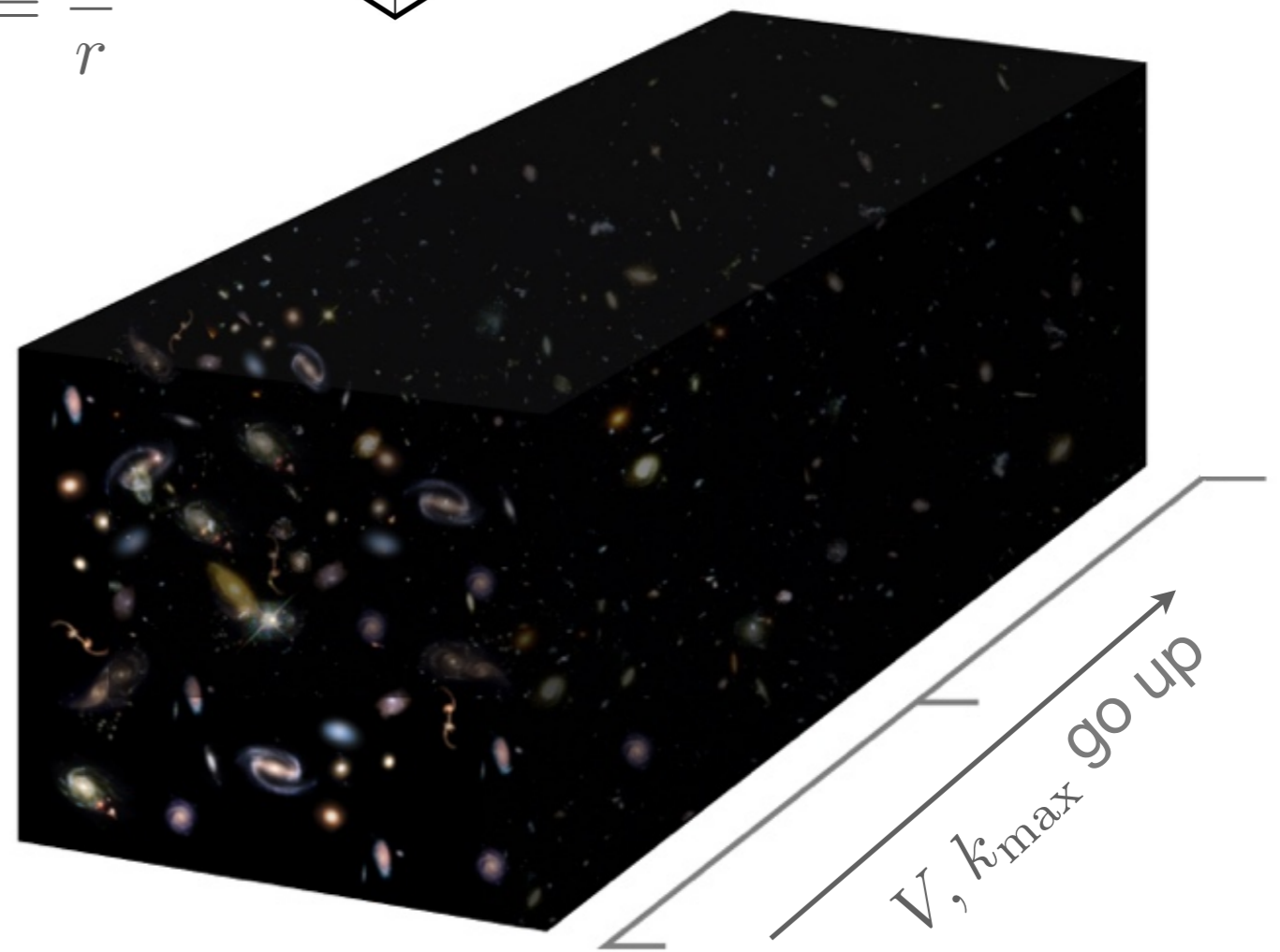
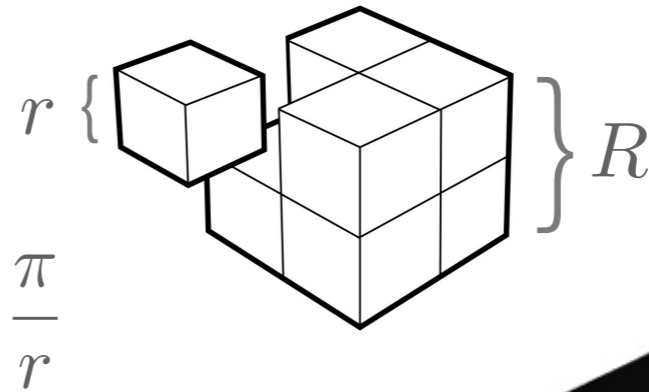
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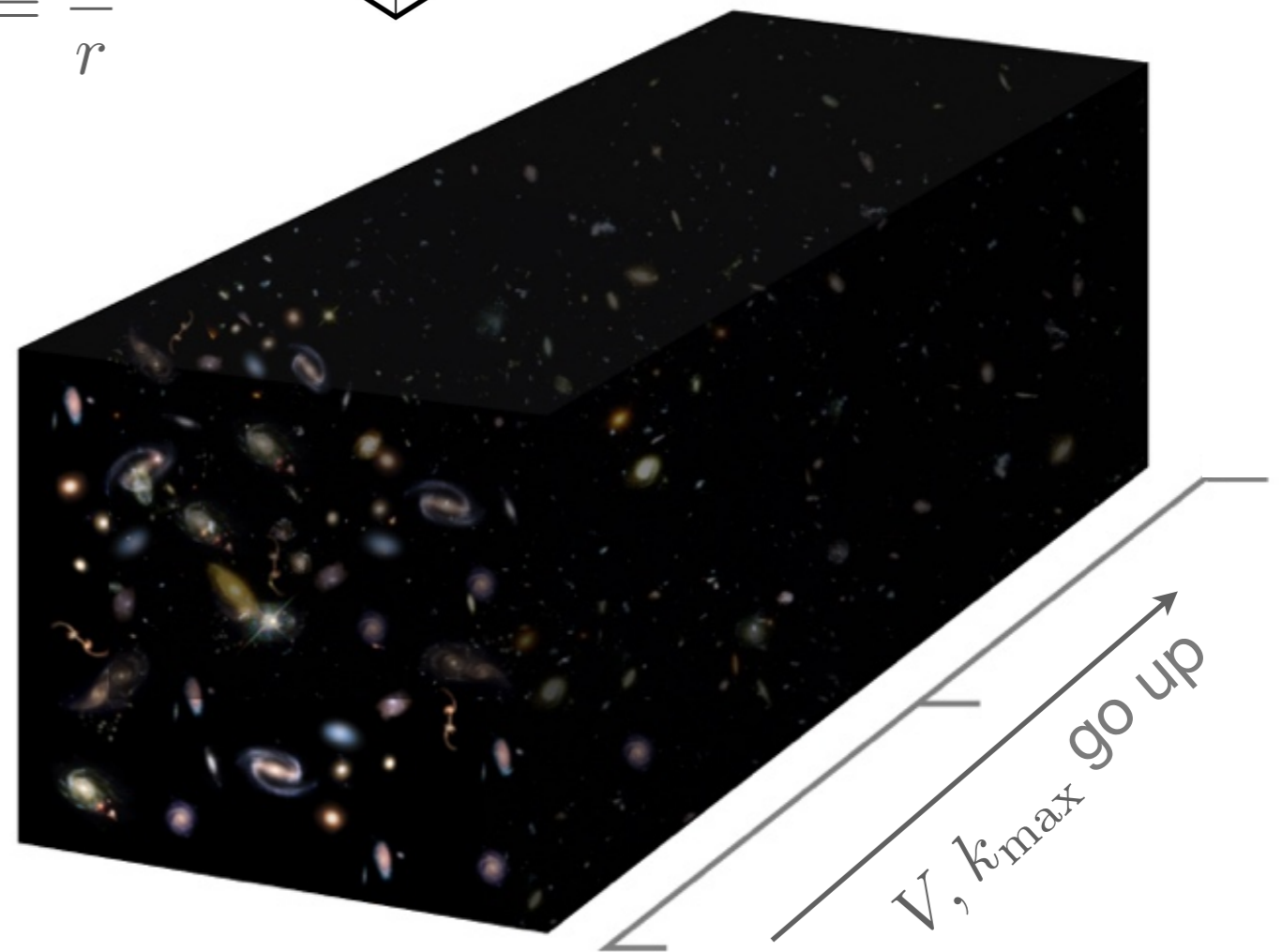
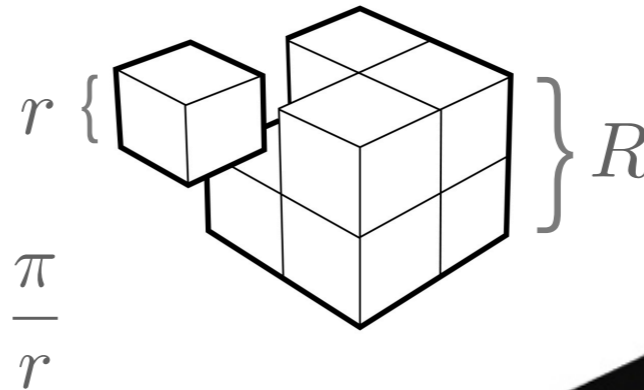
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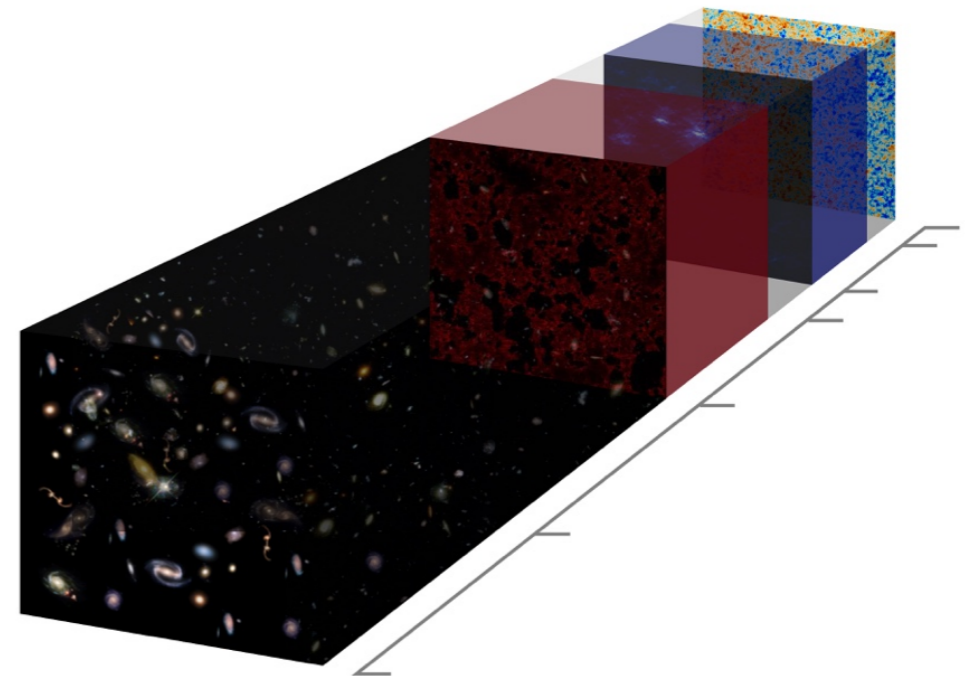
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LSST, Euclid - both target  $10^9$  sources, but not with spectroscopy...



# Outline

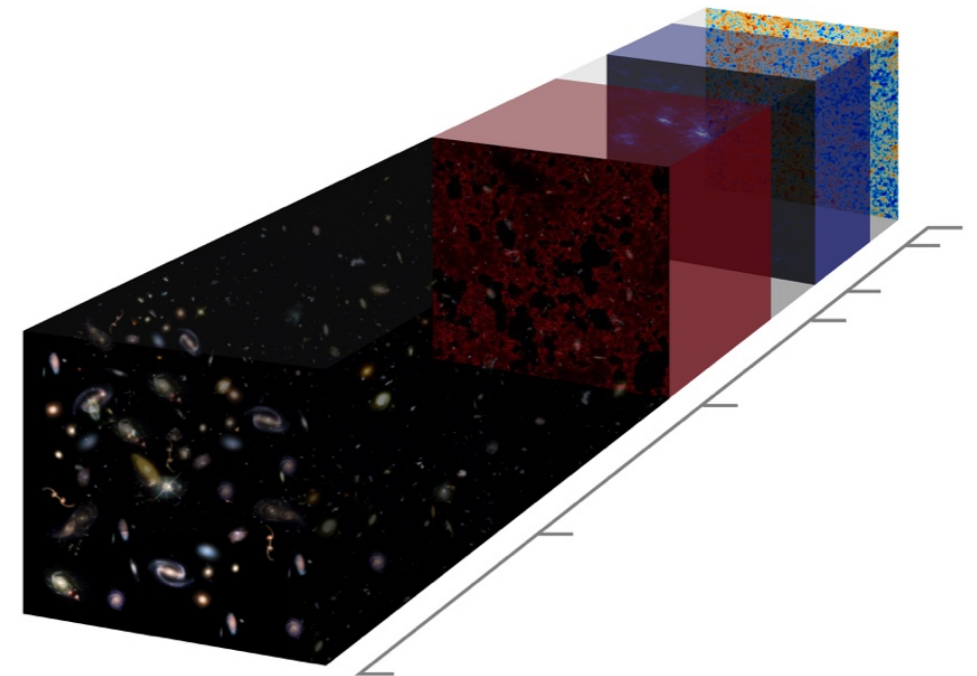
Ely D. Kovetz  
WIS, Jan. 2016



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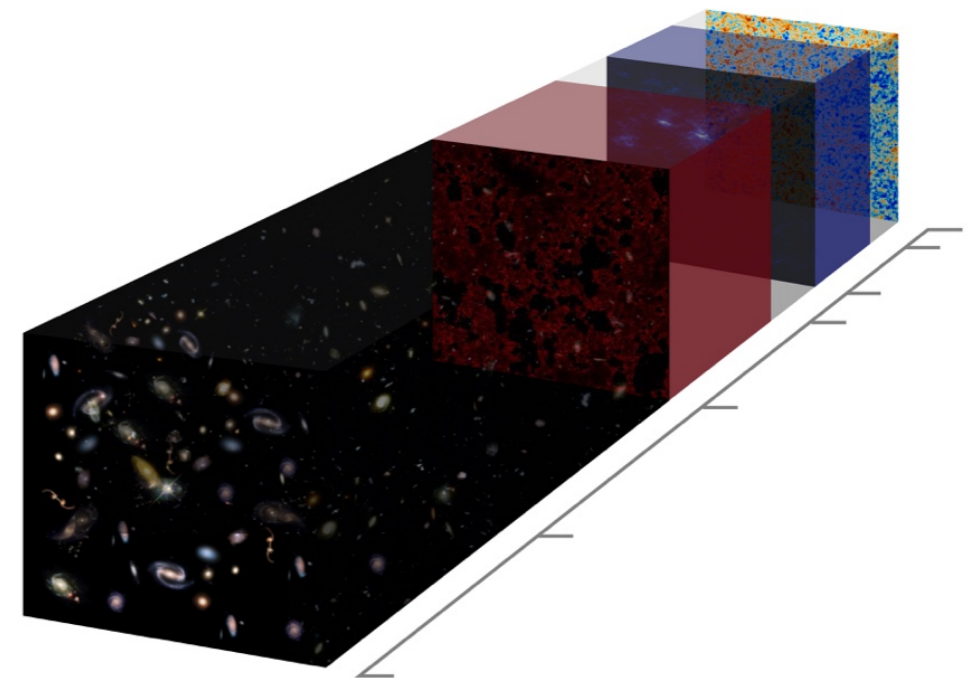


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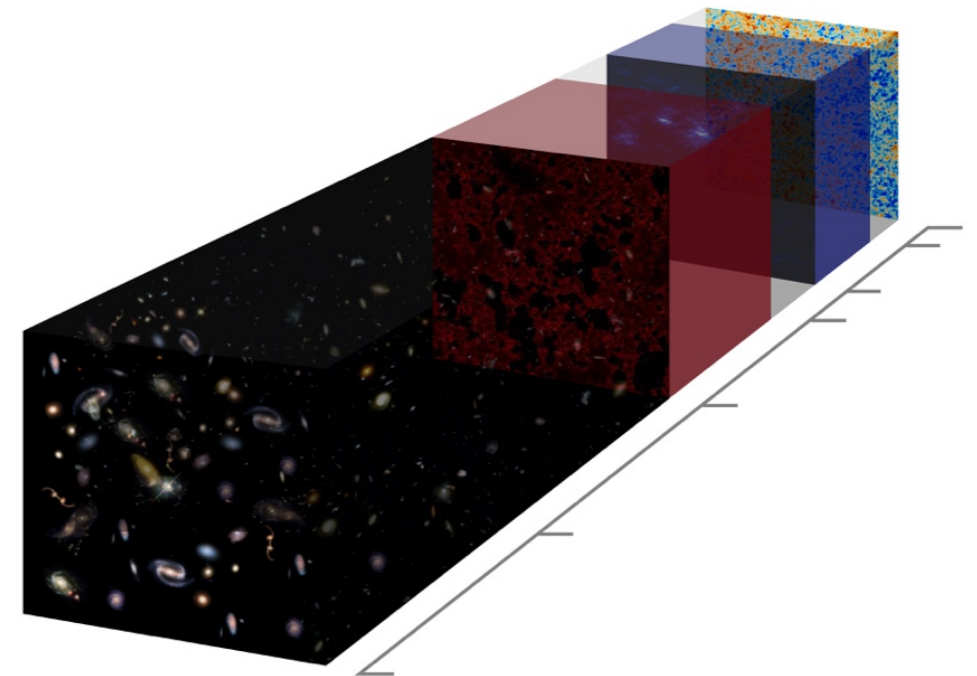
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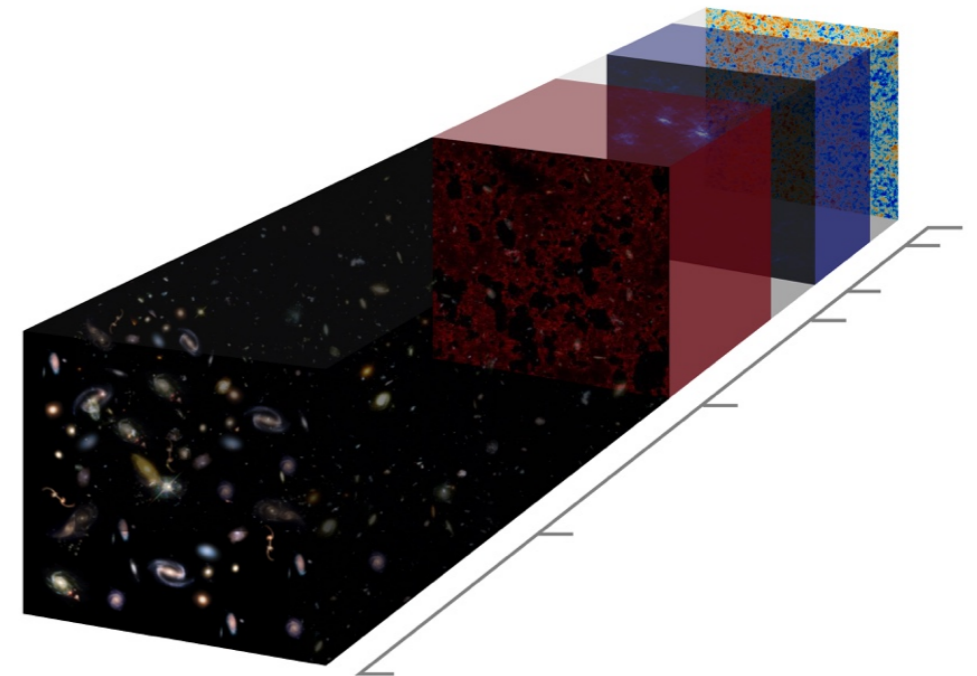
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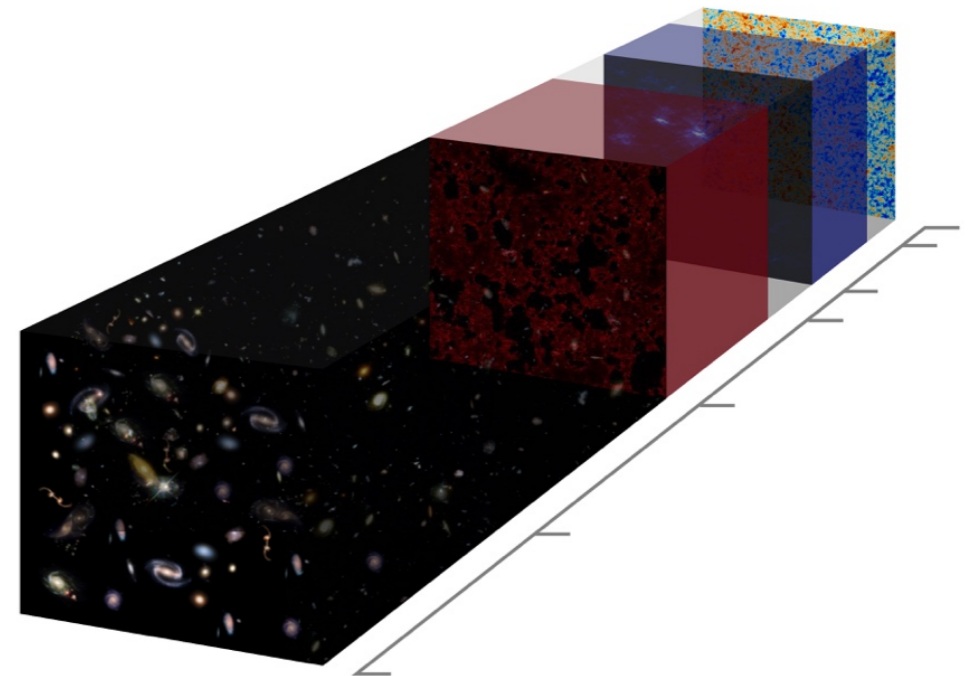


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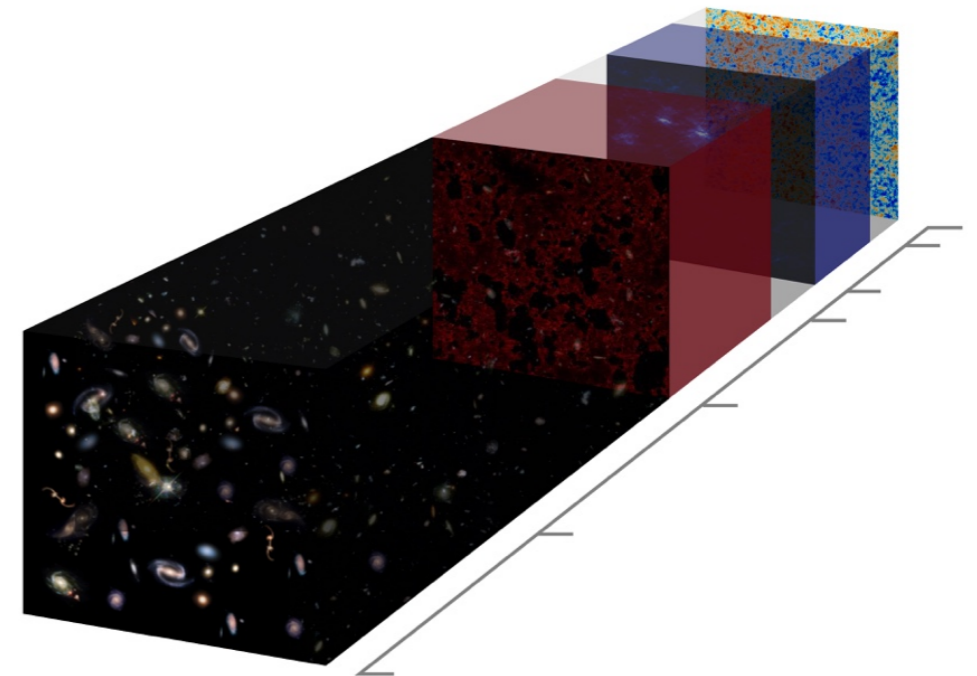
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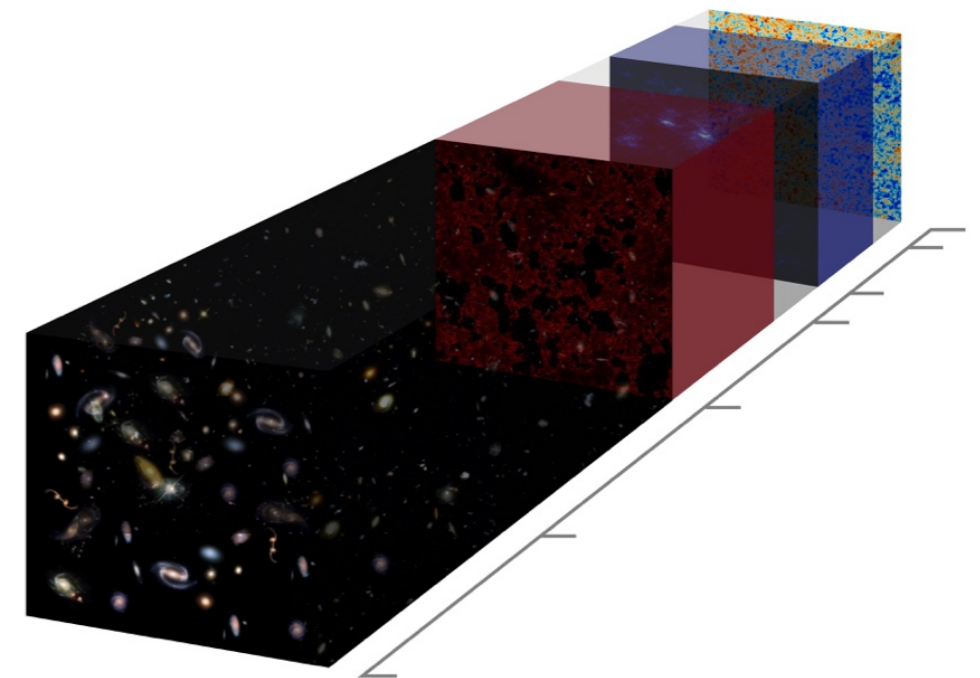
Kamionkowski and EDK, Phys. Rev. Lett. 113 (2014)

EDK and kamionkowski, Phys. Rev. D91 (2015)

Kamionkowski and EDK, Annual Review of A&A, in press (2016)

EDK and Kamionkowski, New Astronomy 43 (2016)

EDK, Dvorkin and Kamionkowski, in preparation



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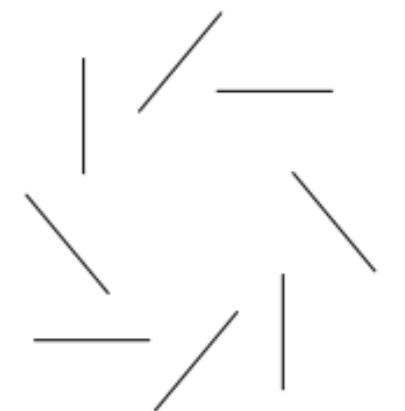
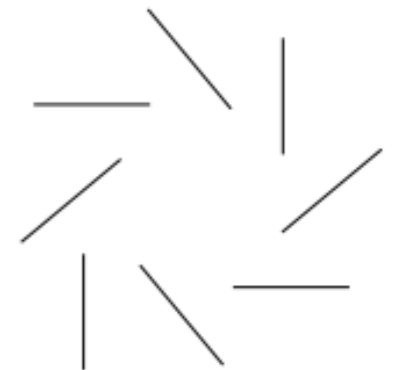
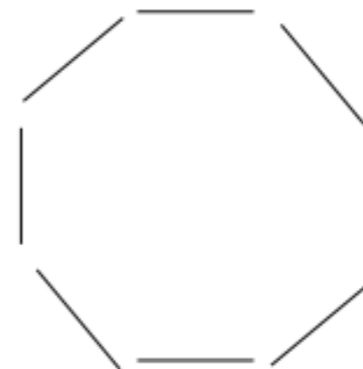
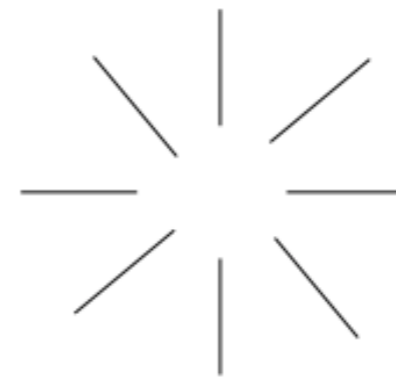
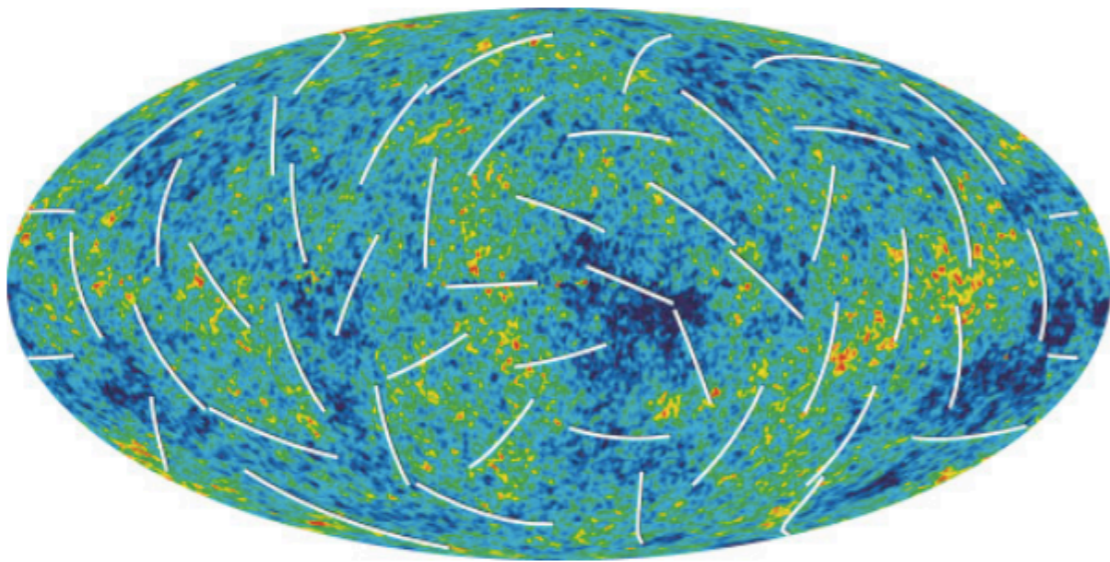
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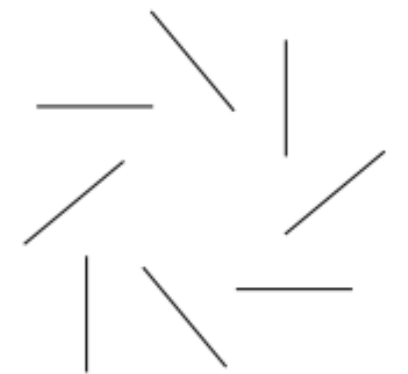
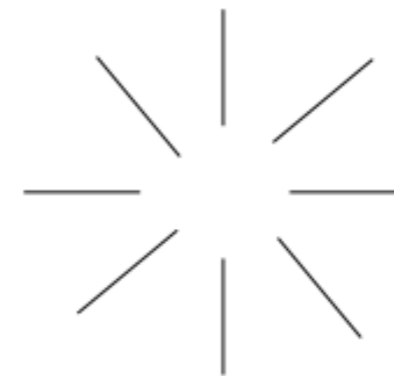
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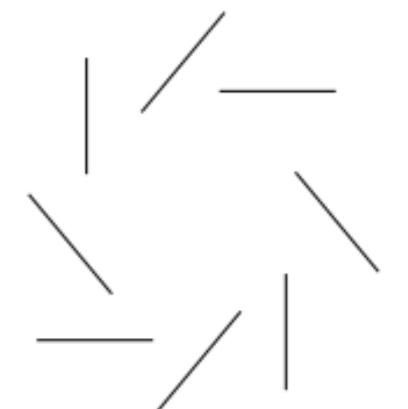
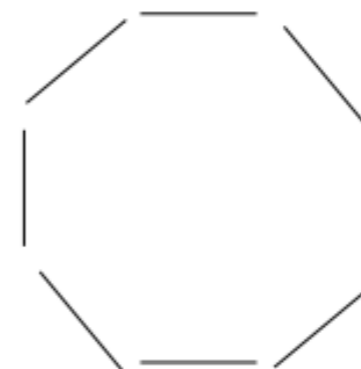
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Inflationary gravitational waves (IGWs) create both!



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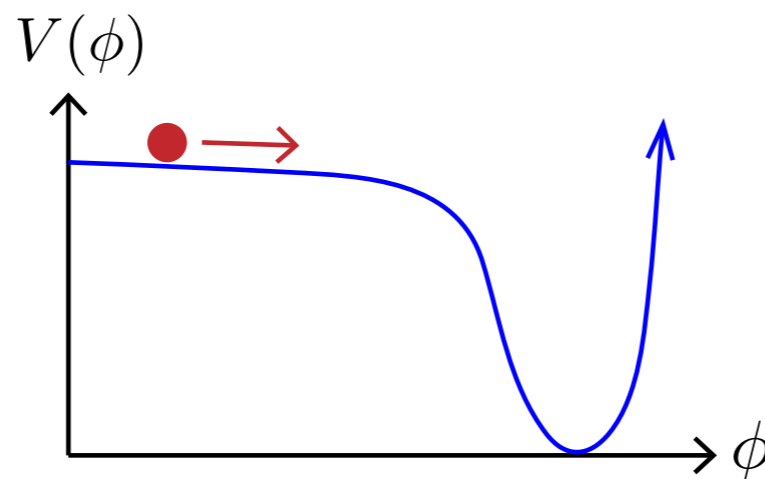
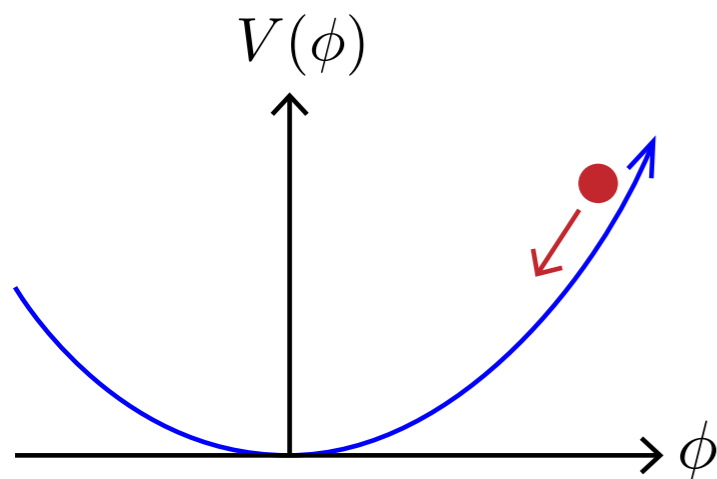
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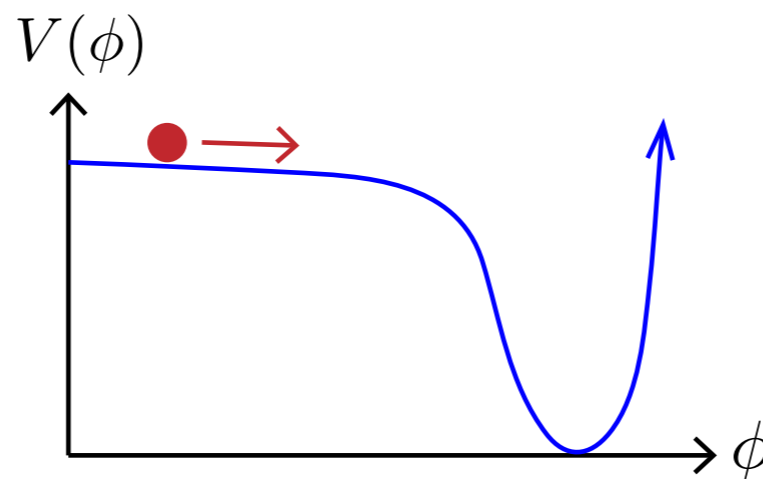
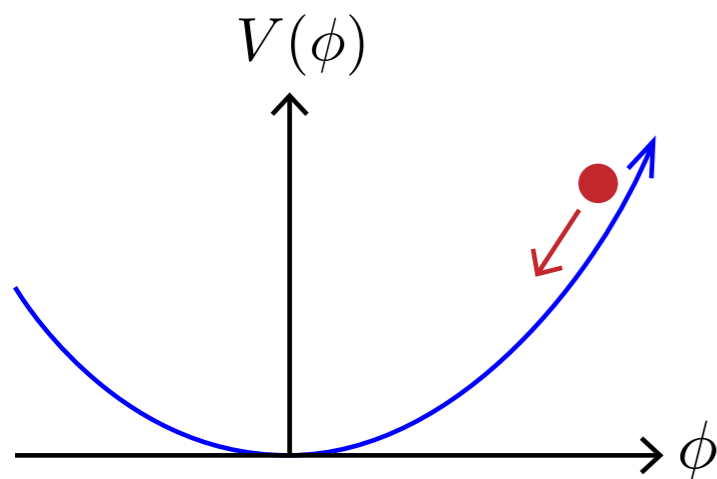
GUT scale  $\longrightarrow r \sim 0.01 - 0.1$

Slow-roll potential parameters:

$$\epsilon \simeq \frac{M_{\text{pl}}^2}{2} \left( \frac{V'}{V} \right)^2 \quad \eta \simeq M_{\text{pl}}^2 \frac{V''}{V}$$

$$n_s - 1 = 2\eta - 6\epsilon \quad r = 16\epsilon$$

what does  $n_s \simeq 0.968 \pm 0.006$  imply?



**$\phi^2$  Inflation:**  
 best-fit  $r$  |  $3\sigma$  bound  
 0.13 | 0.057

**$R^2$  Inflation:**  
 best-fit  $r$  |  $3\sigma$  bound  
 0.003 |  $6 \times 10^{-4}$

**Monodromy  $\phi$ :**  
 best-fit  $r$  |  $3\sigma$  bound  
 0.087 | 0.038

**Natural Inflation:**  
 $3\sigma$  bound  
 0.04

**Monodromy  $\phi^{2/3}$ :**  
 best-fit  $r$  |  $3\sigma$  bound  
 0.065 | 0.028

**Higgs-like Potential:**  
 $3\sigma$  bound  
 0.03

# B-modes and IGWs: Review

(Kamionkowski and EDK, Annual Review of A&A 2016)

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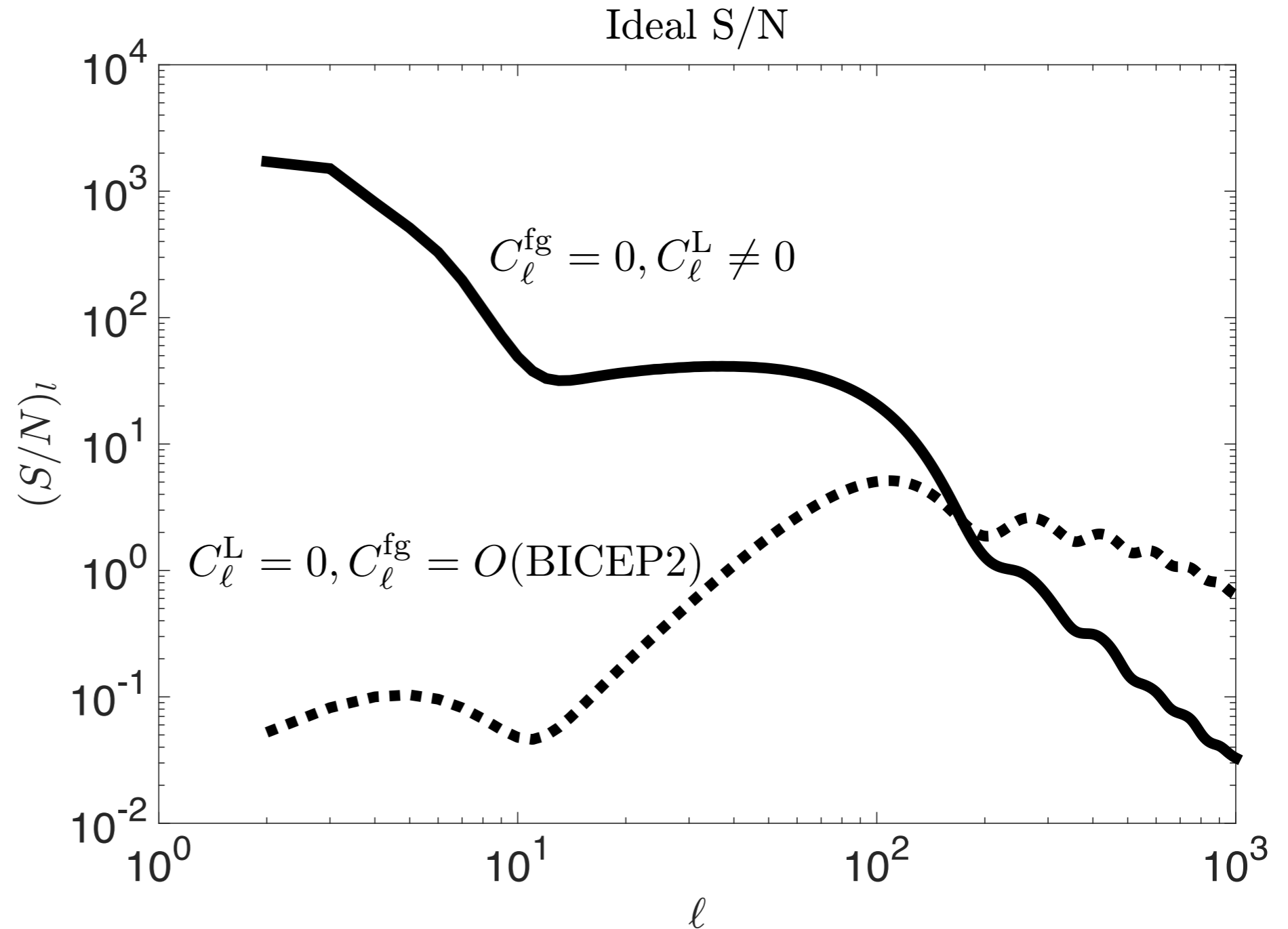
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- Biggest obstacle: Dust B-modes

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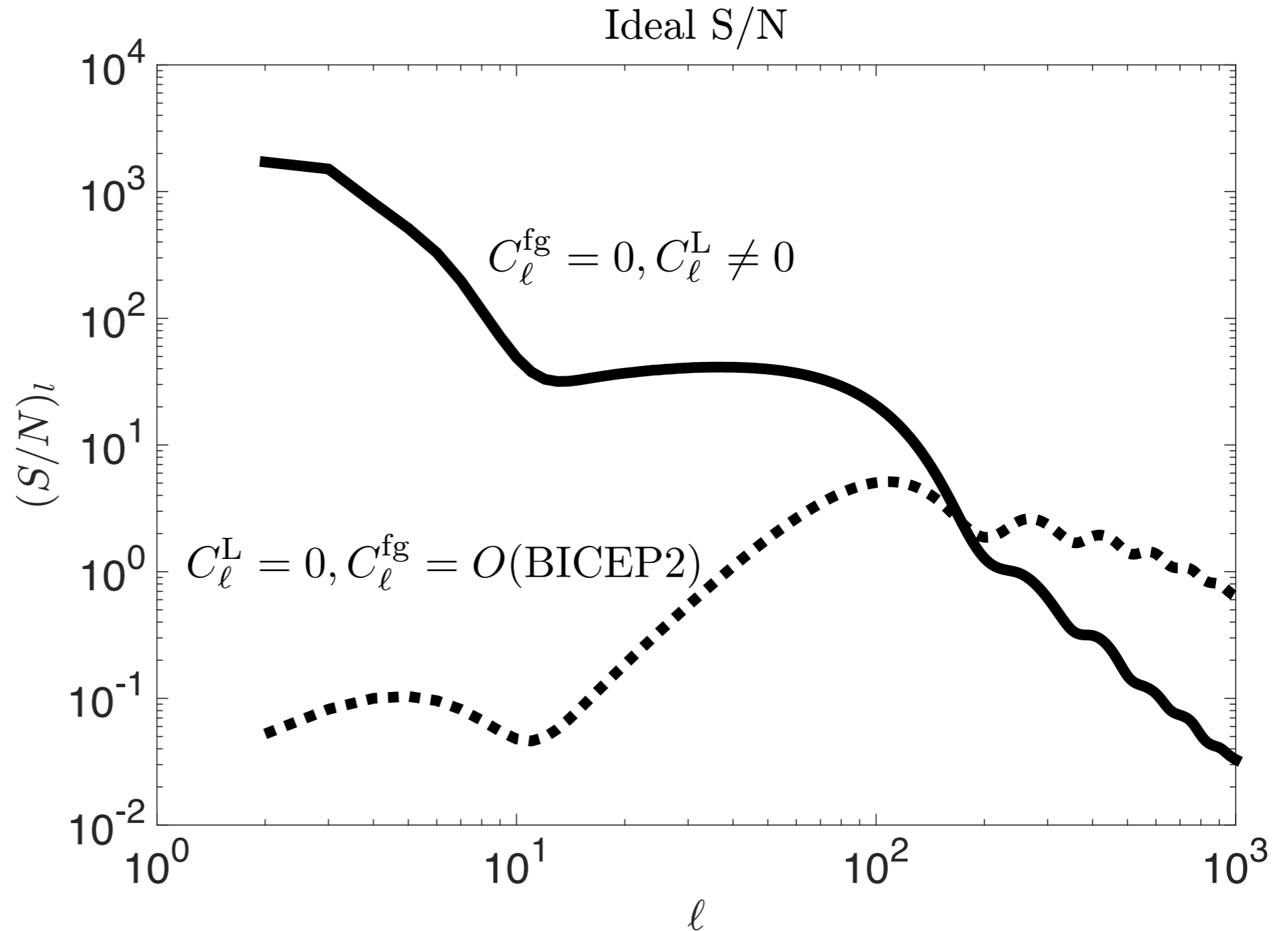


# B-modes and IGWs: Review

(Kamionkowski and EDK, Annual Review of A&A 2016)

- Biggest obstacle: Dust B-modes

Q: How rare is the BICEP2 field?



# Confronting Dust B-modes: Before (or During)

(EDK and Kamionkowski, PRD 2015; EDK and Kamionkowski, New Astronomy 2016)

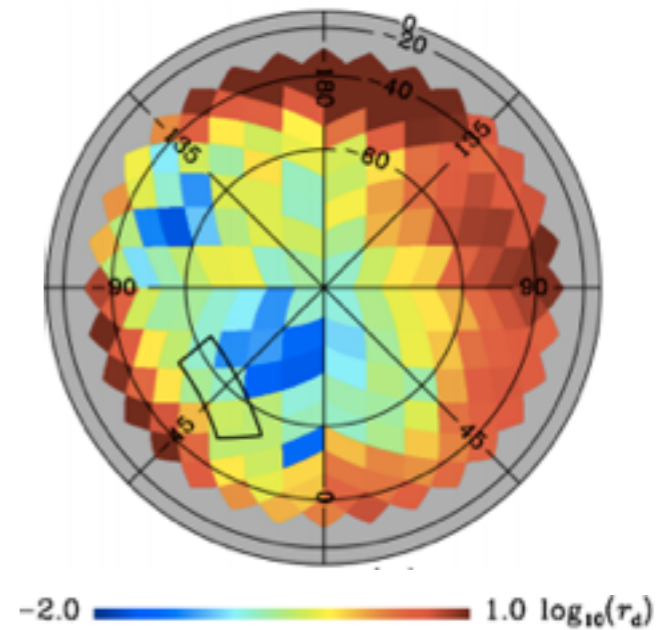
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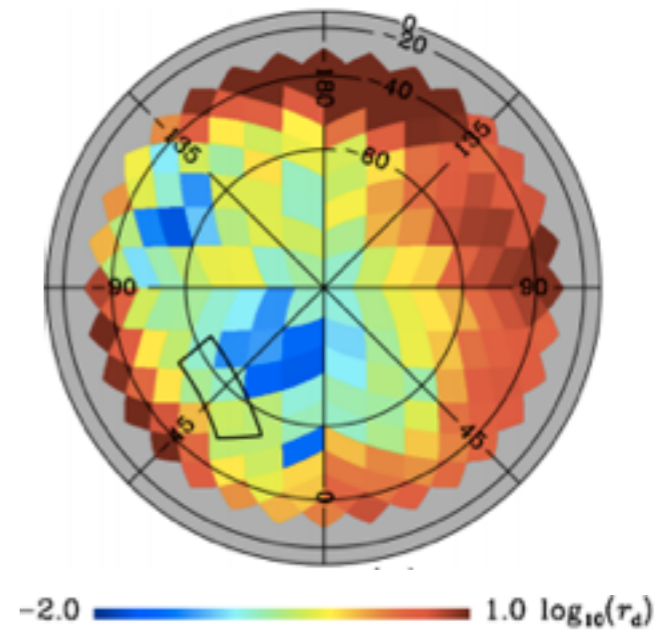


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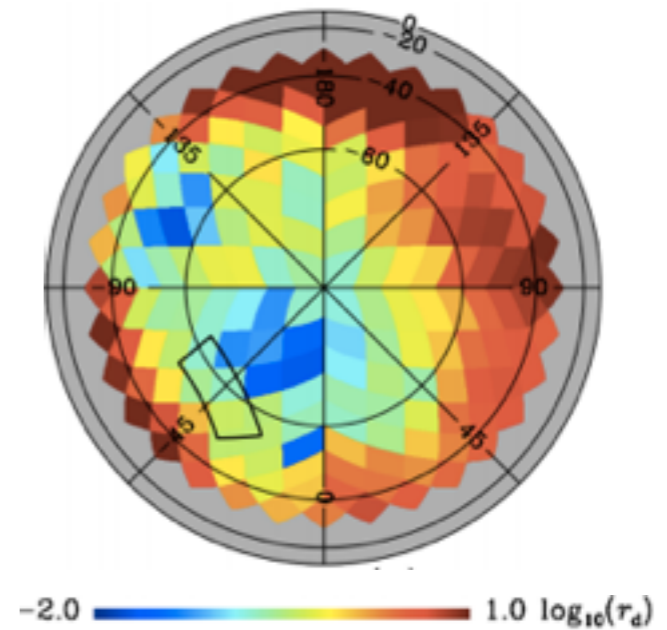
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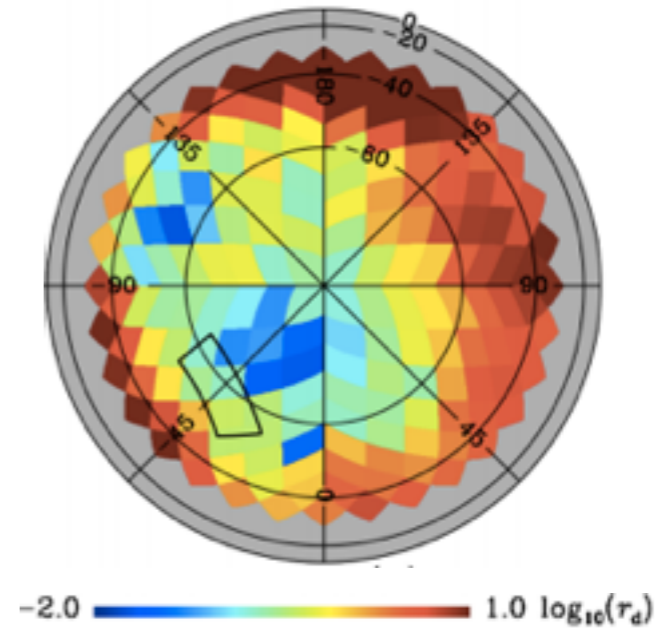


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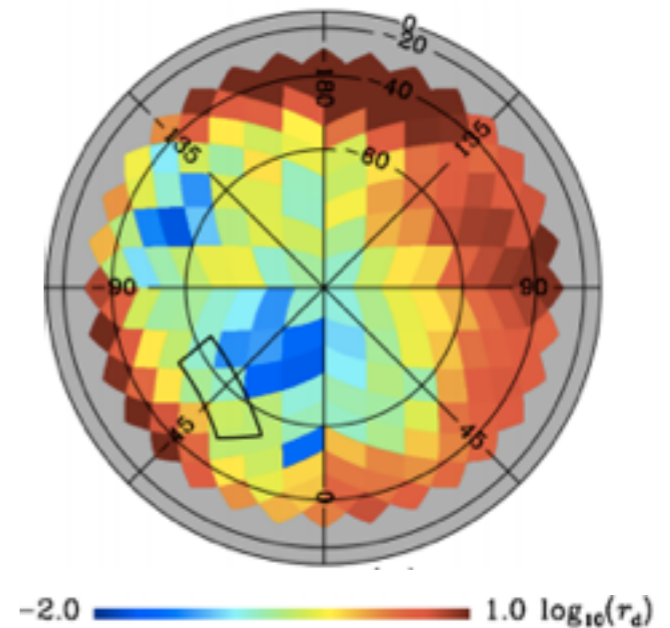
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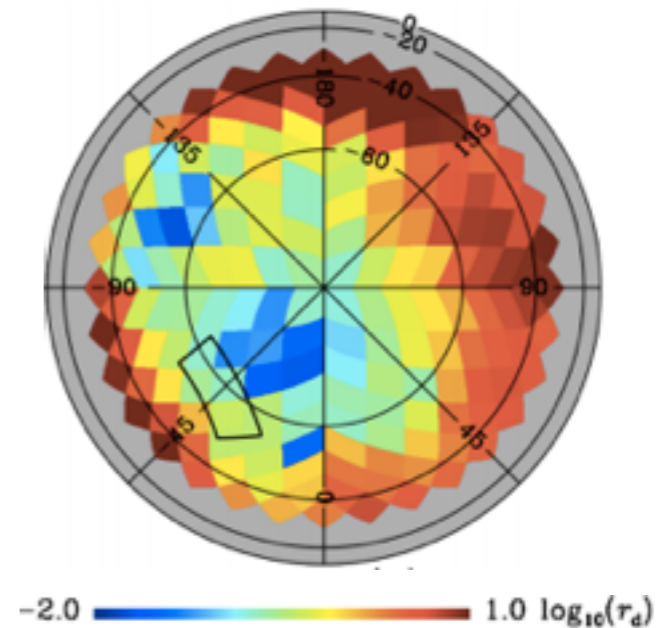
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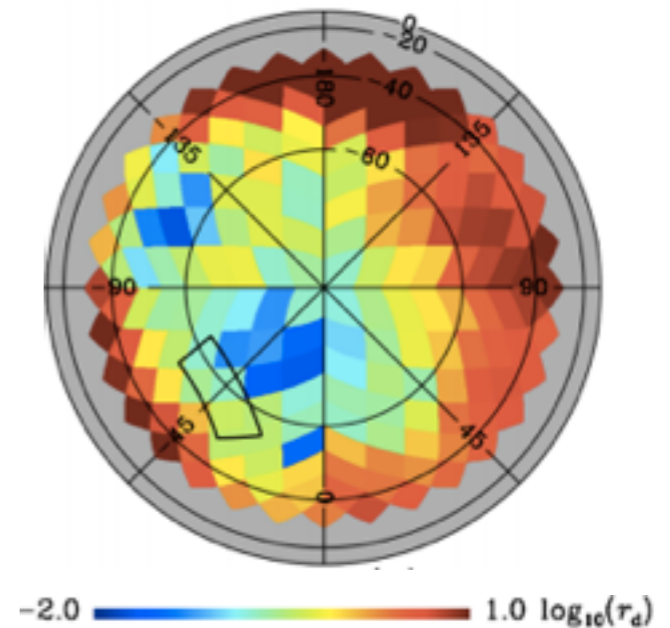
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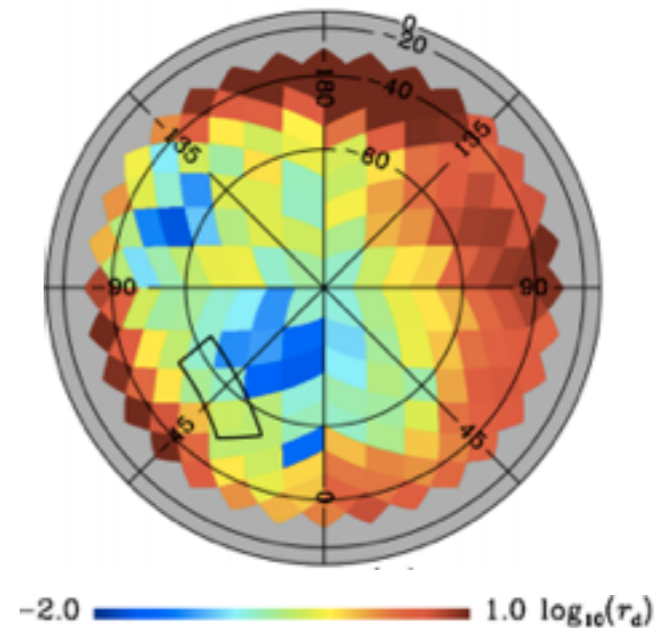


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→ On average, improvement factors of 50%.

→ Method can be implemented elsewhere.



# Confronting Dust B-modes: After

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What do we do after the fact?

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Can we identify the presence of dust B-modes in a given map?

Dust B-modes are far from statistically isotropic:



It would be useful to develop an estimator to detect this!

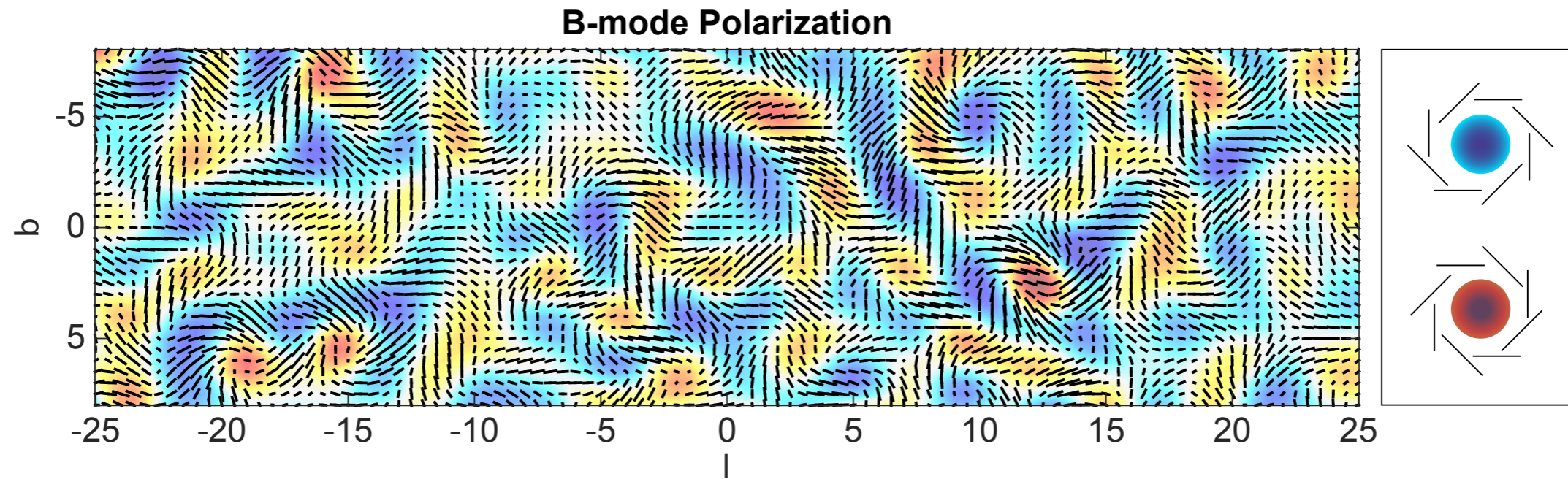
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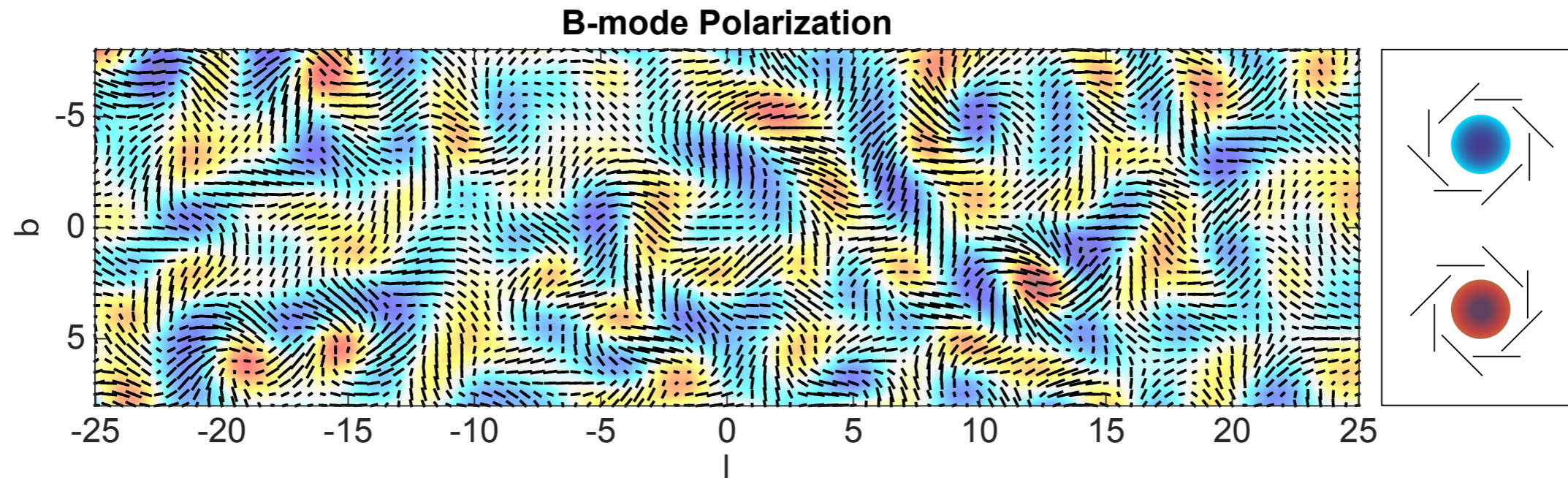
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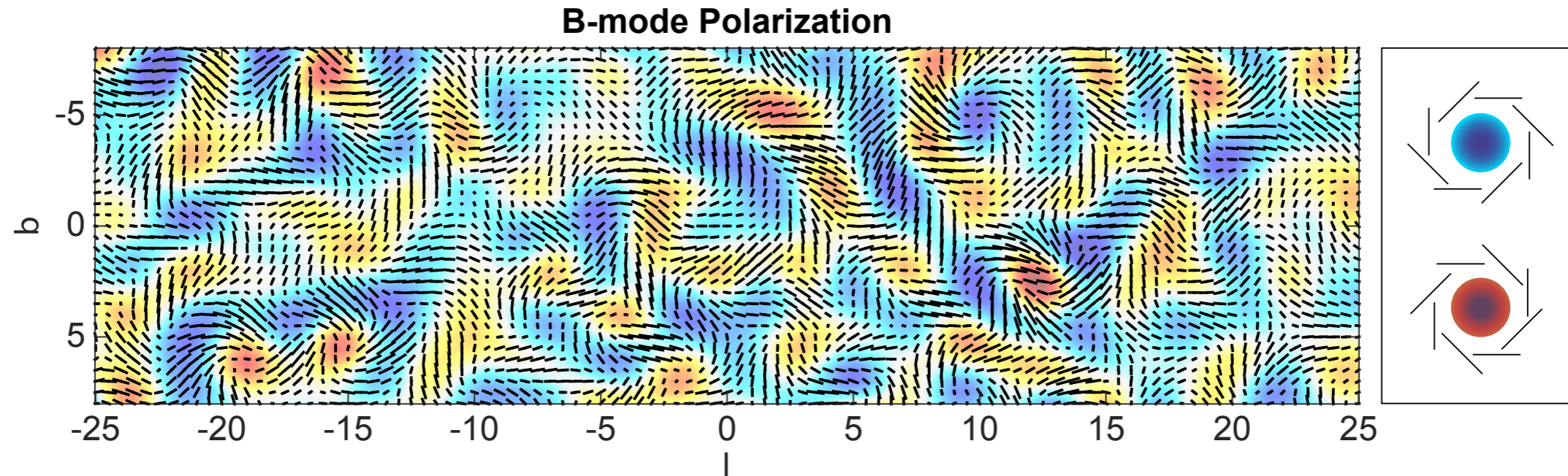
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A simple case: *uniform* polarization orientation angle

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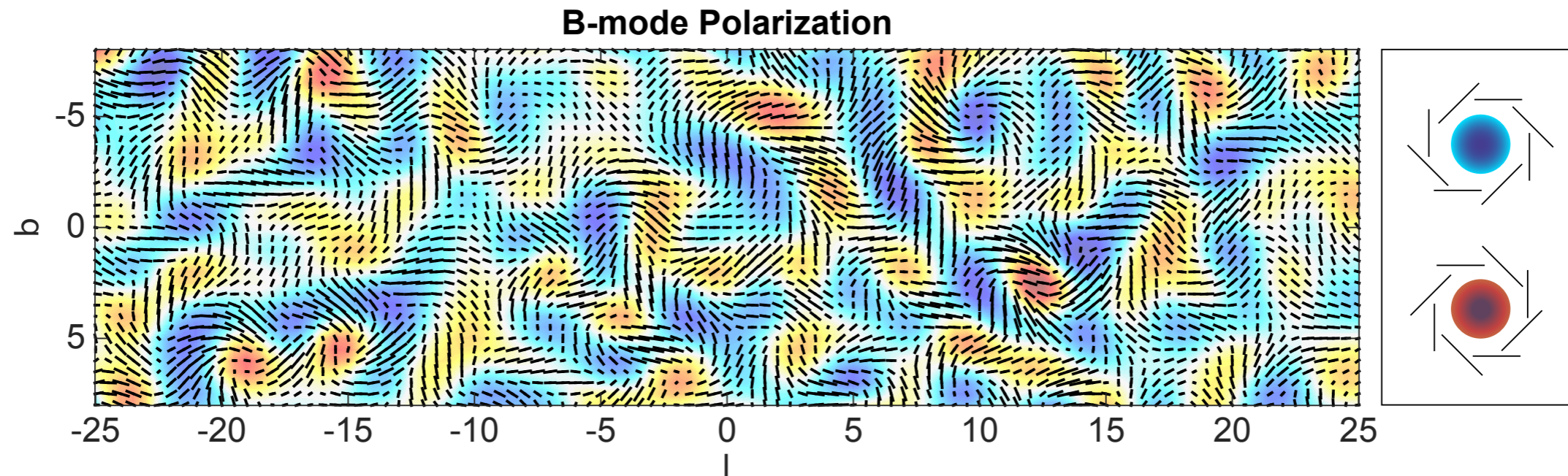


A simple case: *uniform* polarization orientation angle

→ B-modes exhibit local hexadecapolar departure from statistical isotropy.

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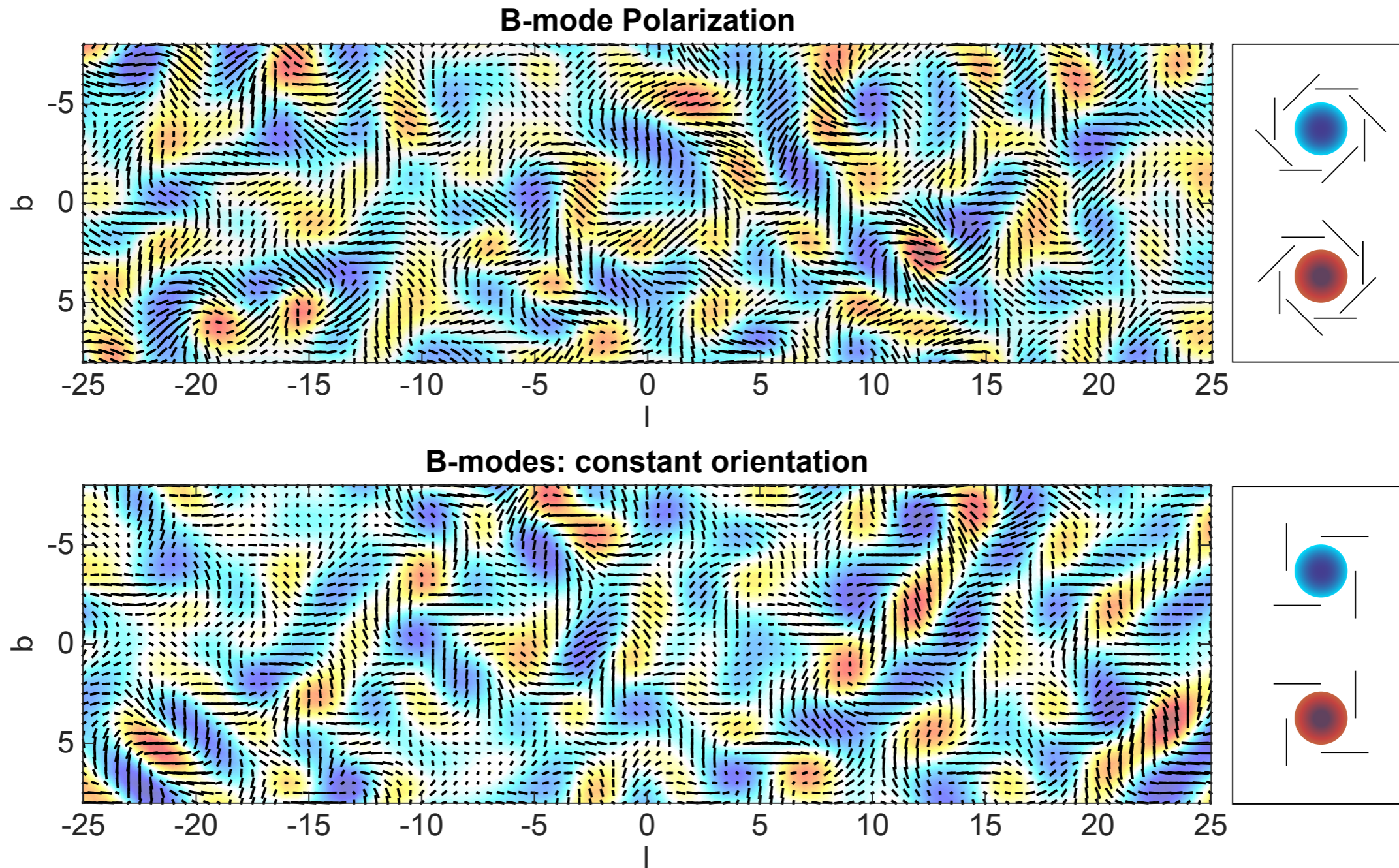
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Translation: map is dominated by Fourier modes oriented at  $45^\circ$  with respect to the polarization orientation.

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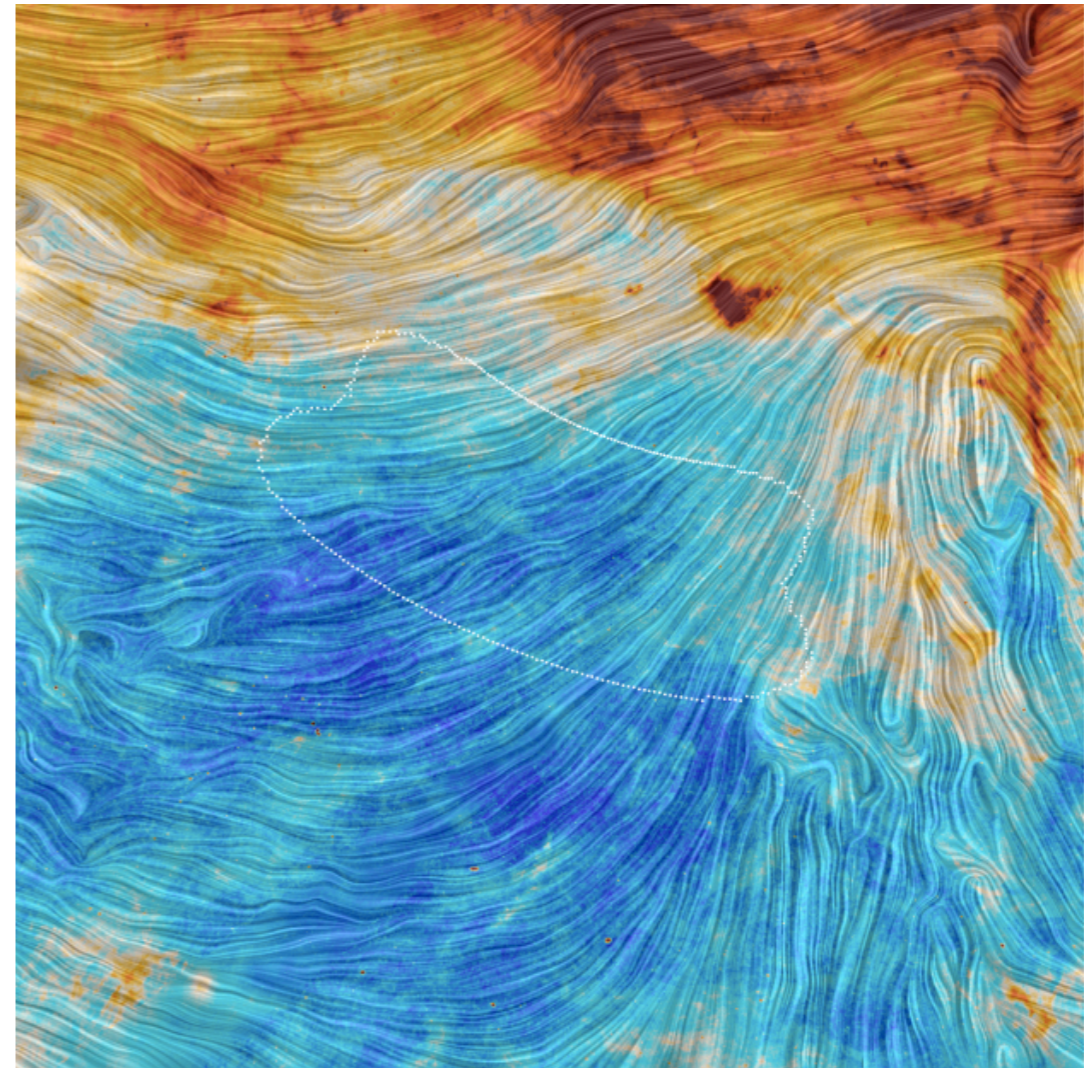
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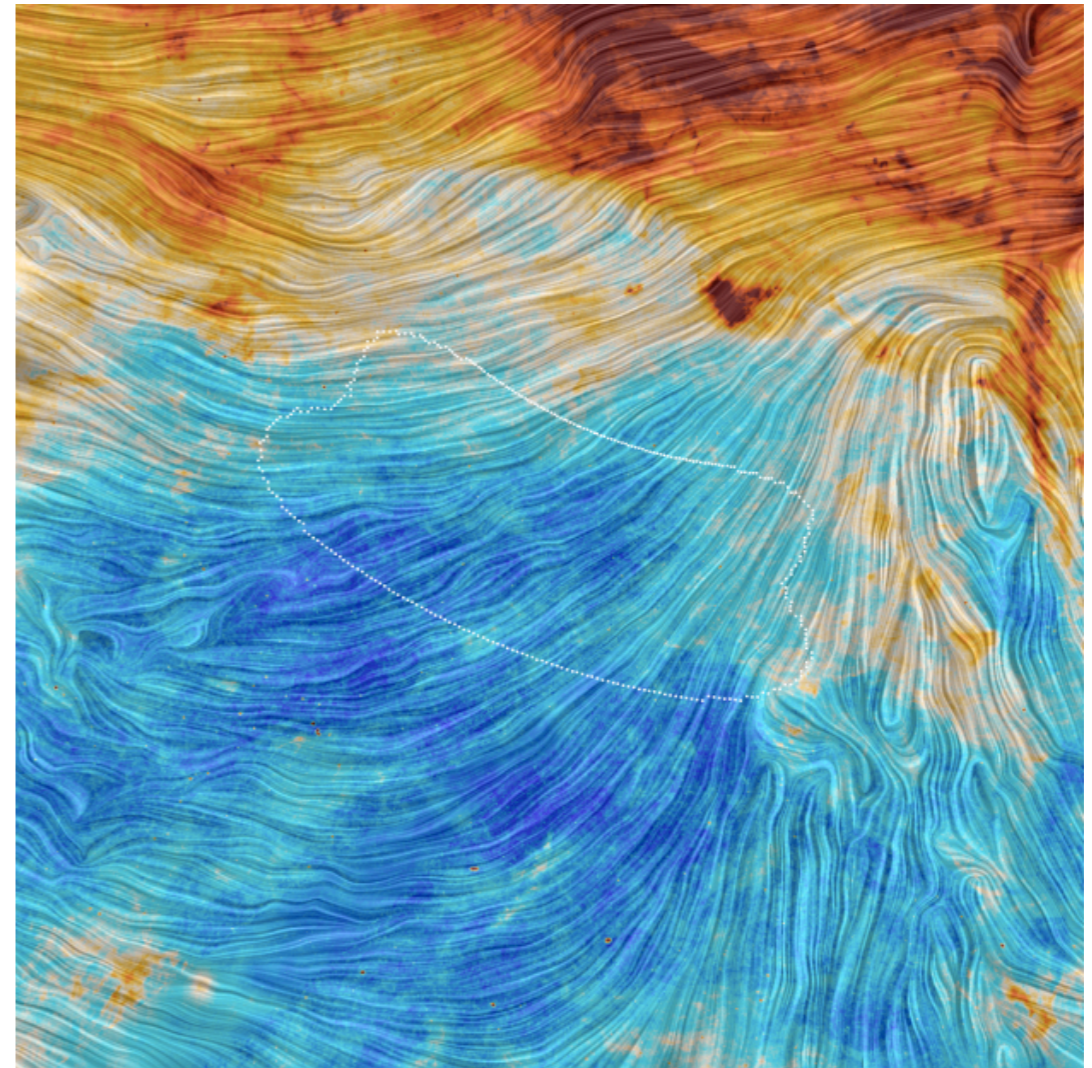
BICEP2/Keck sky patch

# Confronting Dust B-modes: After

(Kamionkowski and EDK, PRL 2014)

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Flat-sky estimator, constant orientation:



BICEP2/Keck sky patch

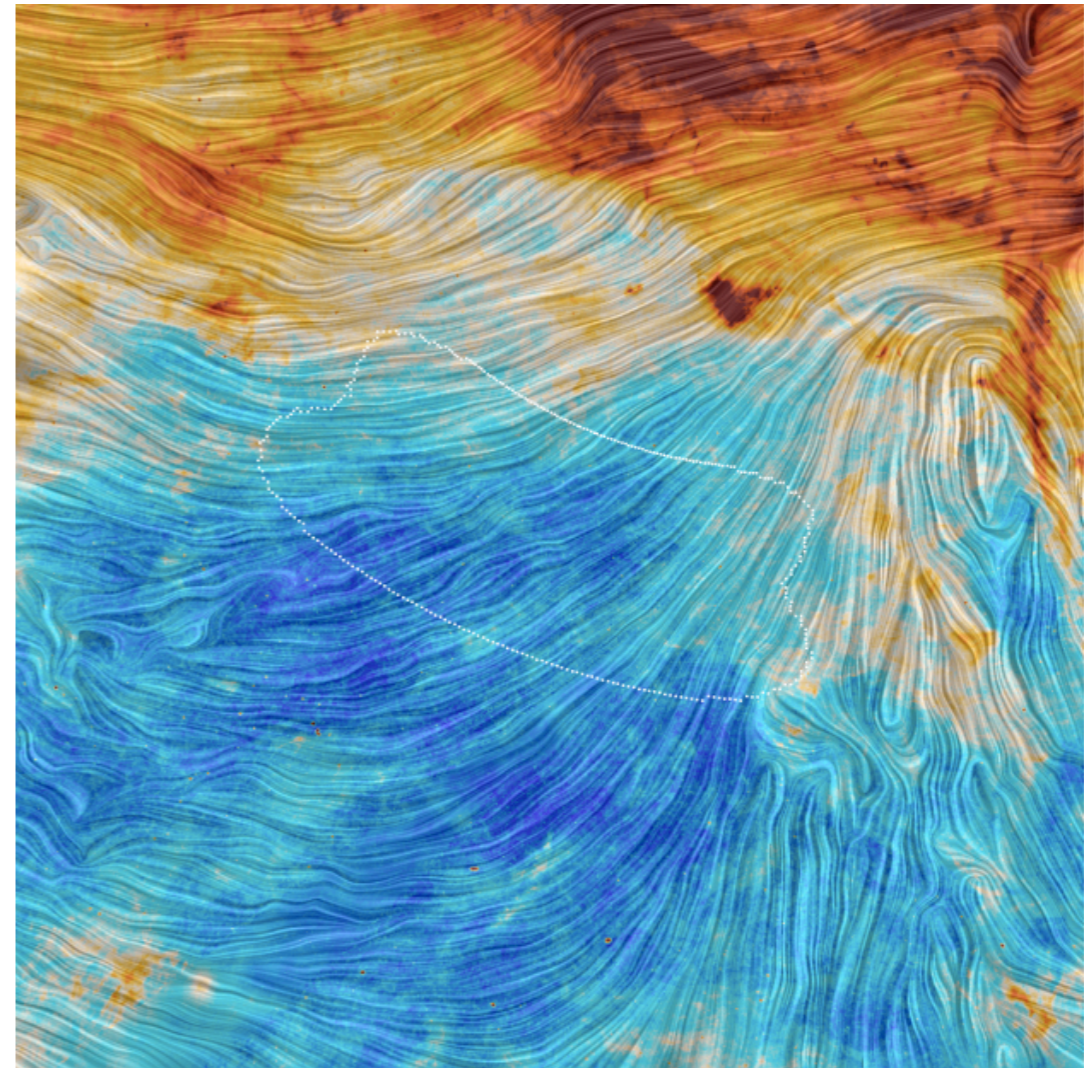
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Flat-sky estimator, constant orientation:

$$\hat{A} = \frac{\sum_{\vec{l}} |\tilde{B}_{\vec{l}}|^2 C_l^f / \sigma_l^2}{\sum_{\vec{l}} (C_l^f)^2 / \sigma_l^2}$$



BICEP2/Keck sky patch

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(Kamionkowski and EDK, PRL 2014; EDK, Dvorkin and Kamionkowski, in preparation)

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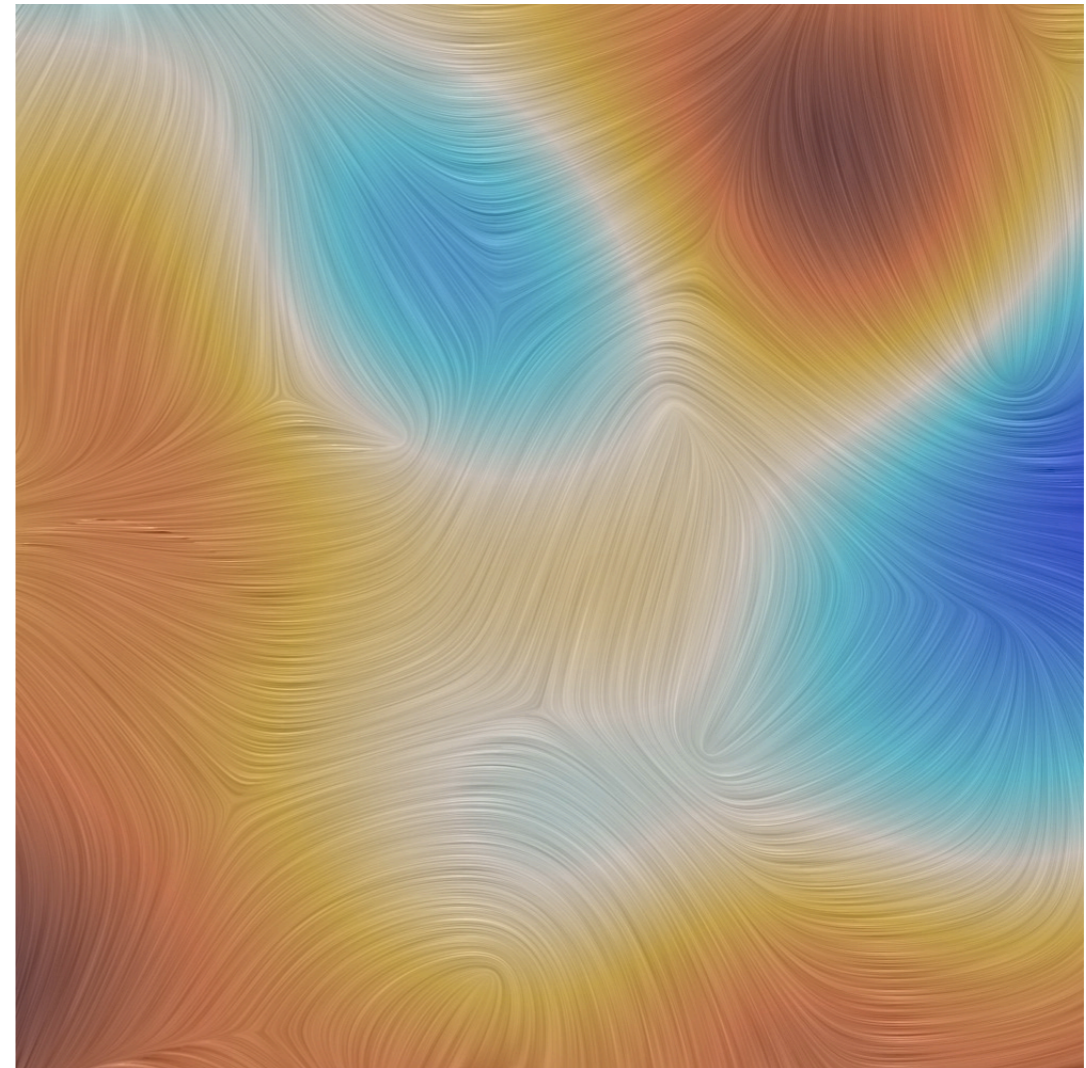
Flat-sky estimator, general case:

$$\widehat{(R_L)}^2 = A(L) \int \frac{d^2l}{(2\pi)^2} \tilde{B}(\vec{l}) \tilde{B}^*(\vec{l}') W(\vec{l}, \vec{l}')$$

$$A(L) = \left[ \int \frac{d^2l}{(2\pi)^2} w(\vec{l}, \vec{l}') W(\vec{l}, \vec{l}') \right]^{-1}$$

$$w(\vec{l}, \vec{l}') = -\frac{1}{4} C_{|\vec{l}' - \vec{l}|/2}^\phi e^{2i(\varphi_{\vec{l}'} + \varphi_{\vec{l}})}$$

$$W(\vec{l}, \vec{l}') = \frac{w(\vec{l}, \vec{l}')^*}{C_l^B C_{l'}^B}$$

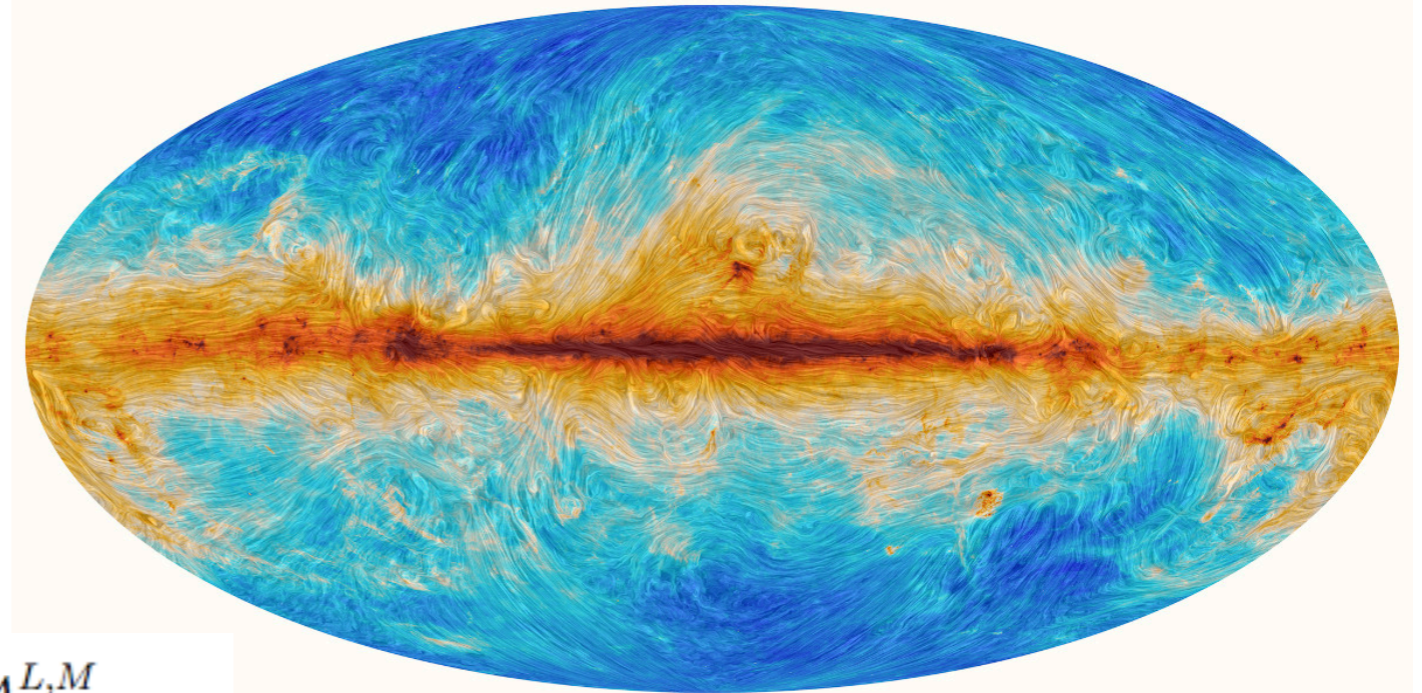


Random sky patch

# Confronting Dust B-modes: After

(EDK, Dvorkin and Kamionkowski, in preparation)

Full-sky estimator:



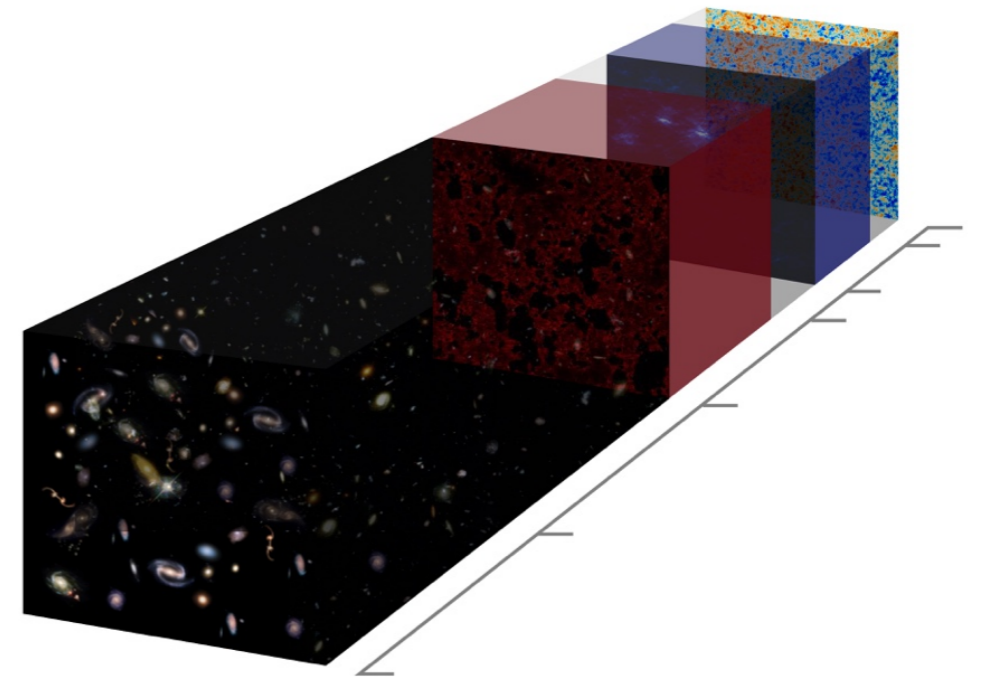
$$\hat{B}_{LM}^{2(0)} = \sum_{\ell_1 m_1} \sum_{\ell_2 m_2} B_{\ell_1 m_1} B_{\ell_2 m_2} F(\ell_1, \ell_2, L, m_1, m_2, M) A_{\ell_1, m_1, \ell_2, m_2}^{L, M}$$

$$F(\ell_1, \ell_2, L, m_1, m_2, M) = \frac{16\pi}{(-1)^{m_1+m_2} \sum_{\ell'_1 m'_1} C_{\ell'_1}^{\phi\phi} \sqrt{(2\ell_1+1)(2\ell_2+1)(2L+1)(2\ell'_1+1)}} \\ \times \frac{1}{\begin{pmatrix} \ell_1 & L & \ell'_1 \\ -m_1 & M & m'_1 \end{pmatrix} \begin{pmatrix} \ell_2 & L & \ell'_1 \\ -m_2 & M & -m'_1 \end{pmatrix} \begin{pmatrix} \ell_1 & L & \ell'_1 \\ 2 & -2 & 0 \end{pmatrix} \begin{pmatrix} \ell_2 & L & \ell'_1 \\ 2 & -2 & 0 \end{pmatrix}} \\ \times \frac{1}{[1 + (-1)^{\ell_2+L+\ell'_1} + (-1)^{\ell_1+L+\ell'_1} + (-1)^{\ell_1+\ell_2}]},$$

$$A_{\ell_1, m_1, \ell_2, m_2}^{L, M} = \frac{\sum_{\ell'_1 m'_1 \ell'_2 m'_2} \langle B_{\ell_1 m_1} B_{\ell_2 m_2} B_{\ell'_1 m'_1} B_{\ell'_2 m'_2} \rangle^{-1} F^{-1}(\ell_1, \ell_2, L, m_1, m_2, M) F^{-1}(\ell'_1, \ell'_2, L, m'_1, m'_2, M)}{\sum_{\ell_1 m_1 \ell_2 m_2 \ell'_1 m'_1 \ell'_2 m'_2} \langle B_{\ell_1 m_1} B_{\ell_2 m_2} B_{\ell'_1 m'_1} B_{\ell'_2 m'_2} \rangle^{-1} F^{-1}(\ell_1, \ell_2, L, m_1, m_2, M) F^{-1}(\ell'_1, \ell'_2, L, m'_1, m'_2, M)}$$

# Outline

Ely D. Kovetz  
WIS, Jan. 2016

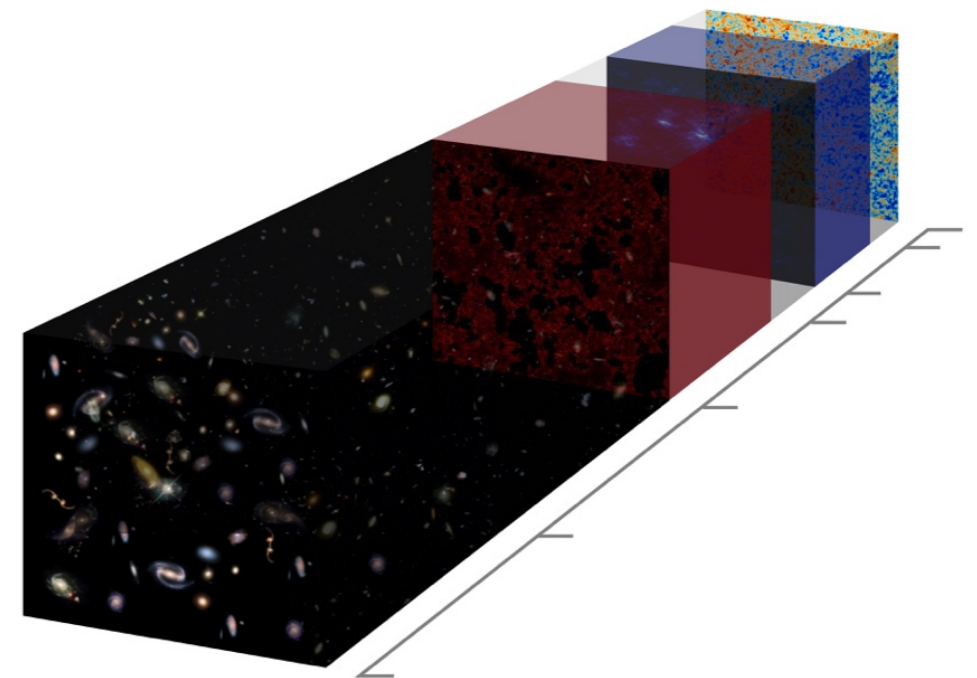


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WIS, Jan. 2016

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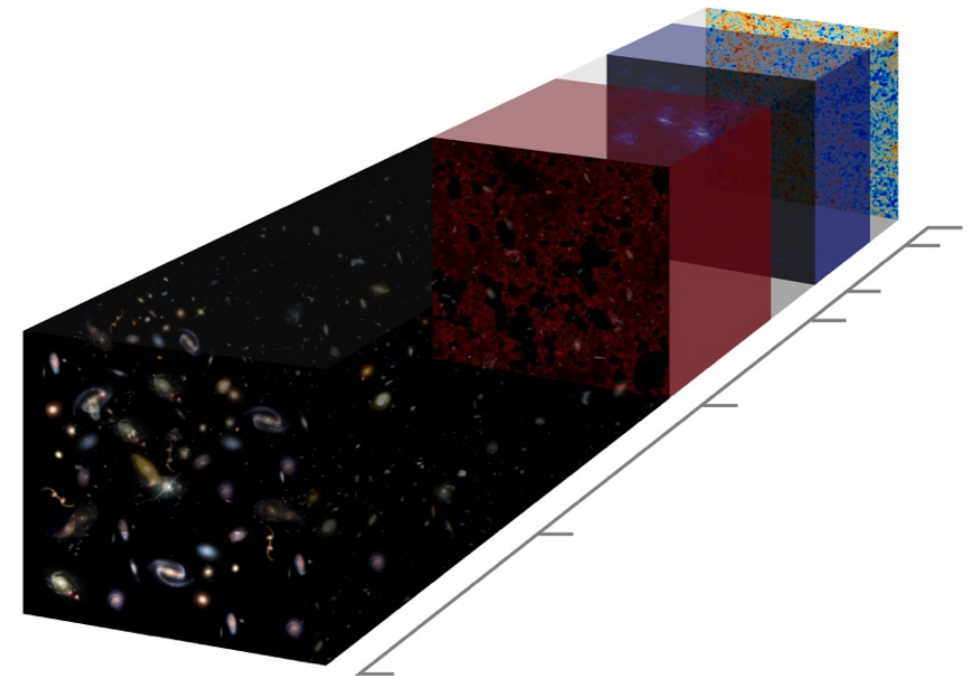
- Heat signatures of DM in the dark ages



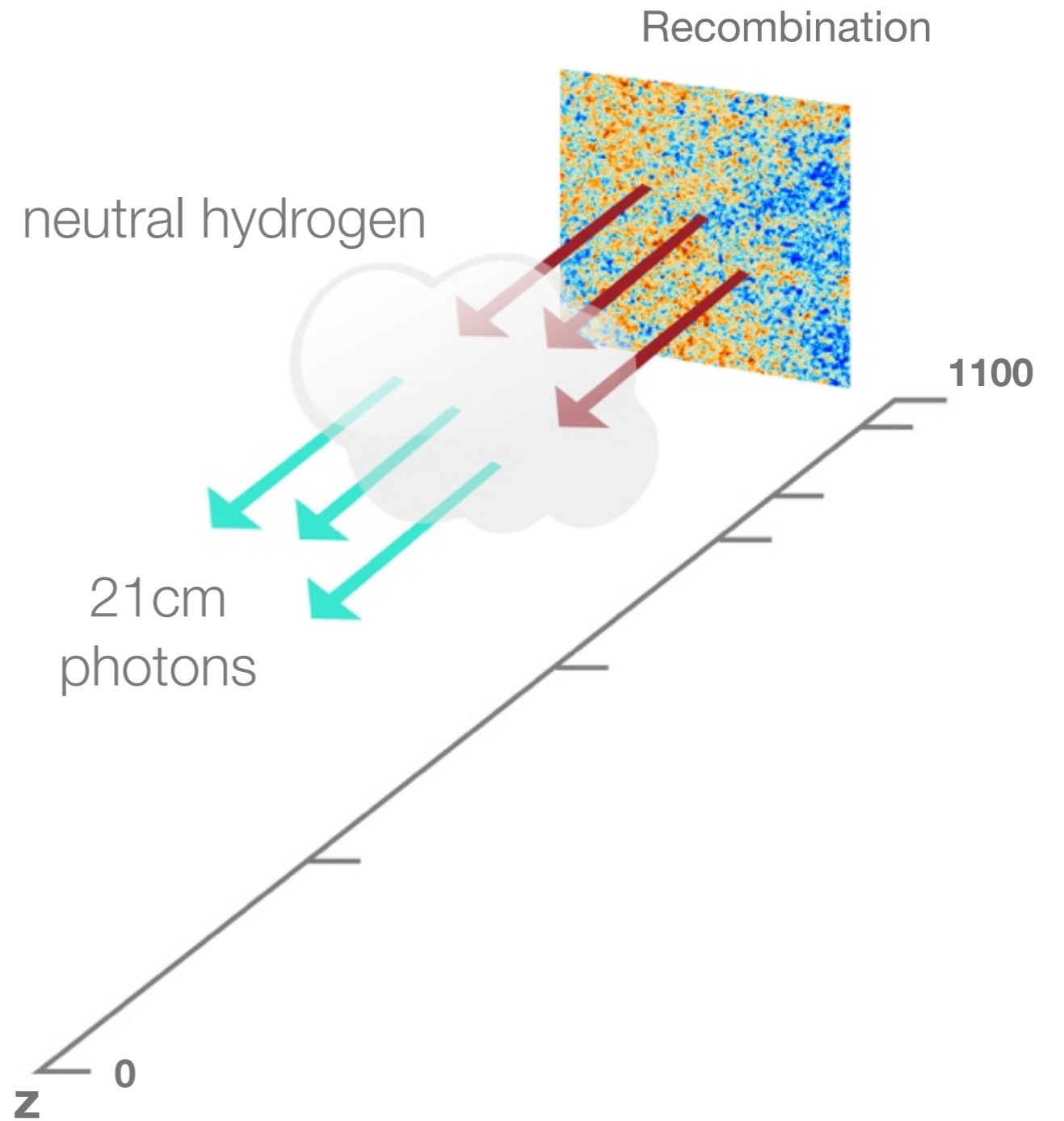
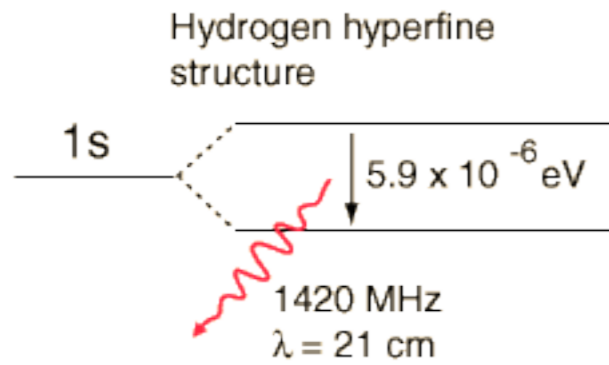
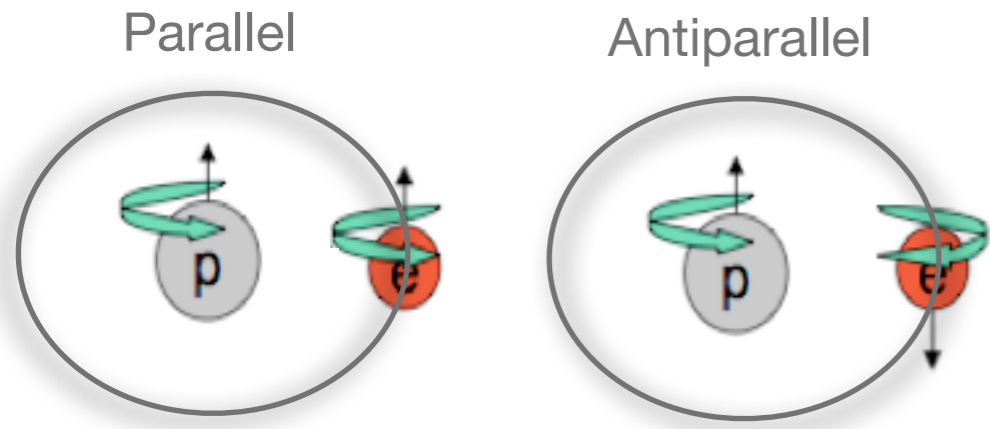
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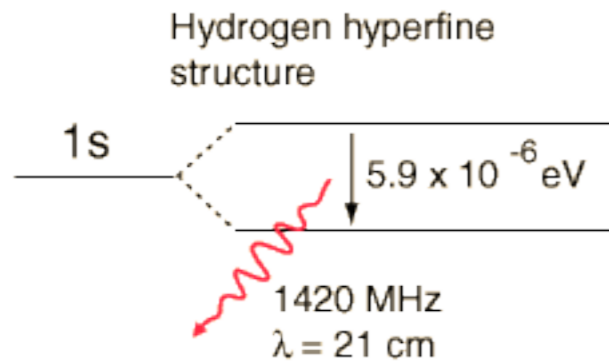
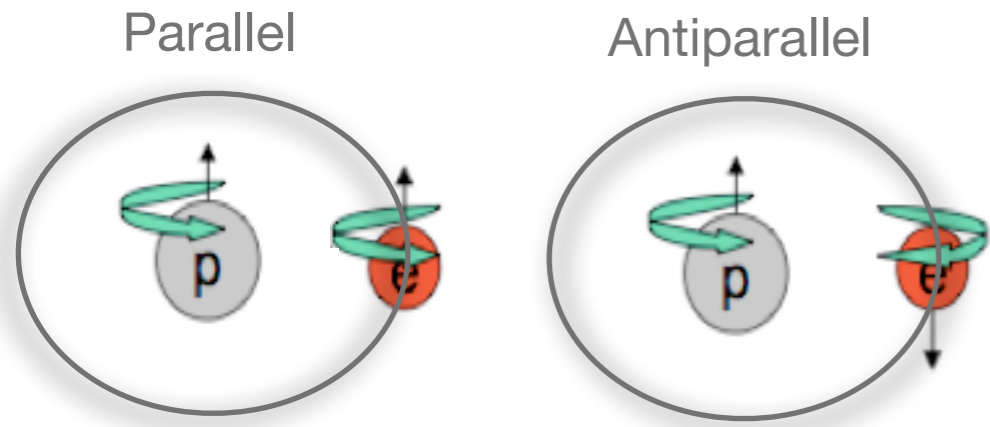
Muñoz, EDK and Ali-Haïmoud, Phys. Rev. D92 (2015)



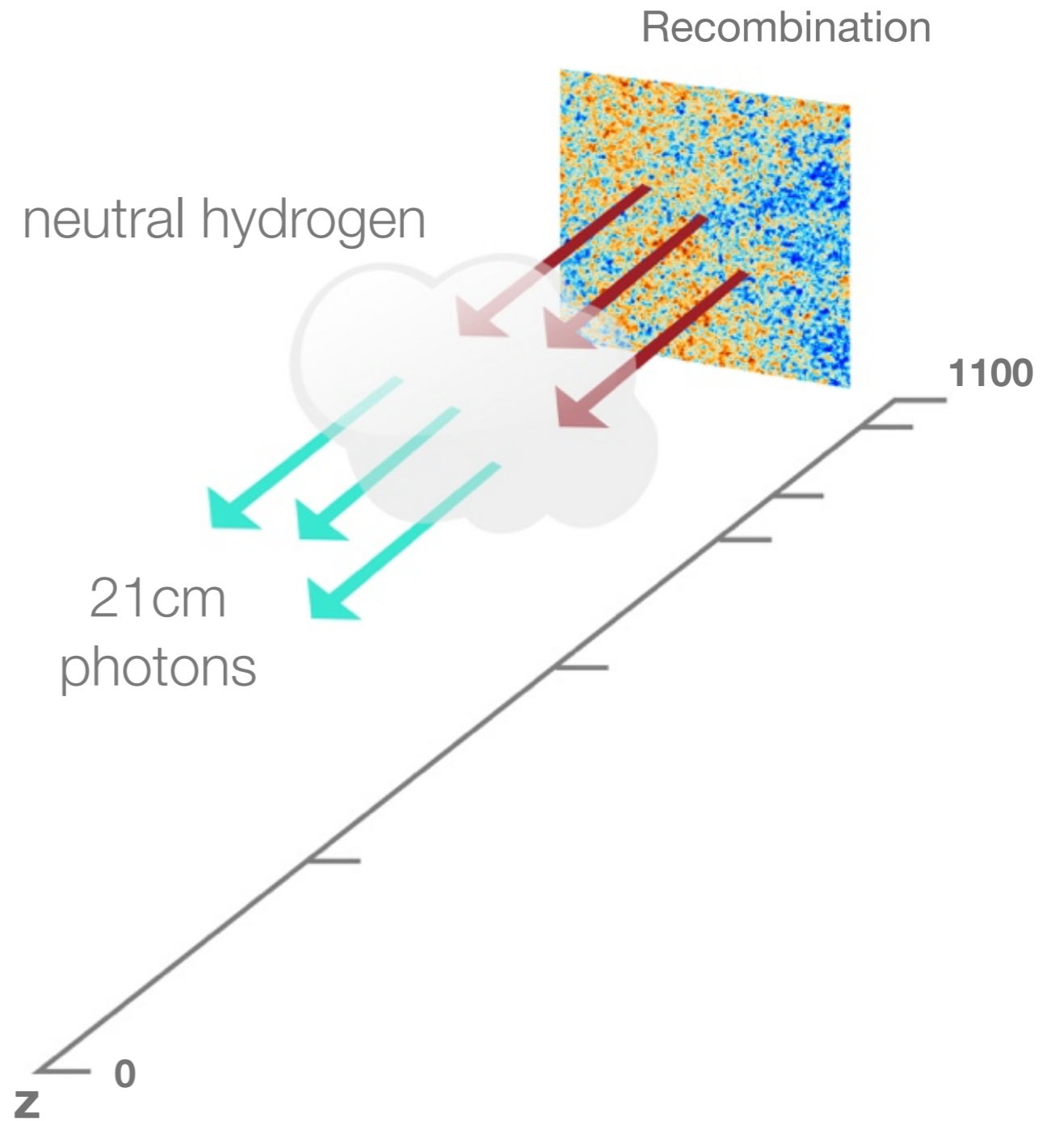
# The 21-cm Signal: Lightning Review



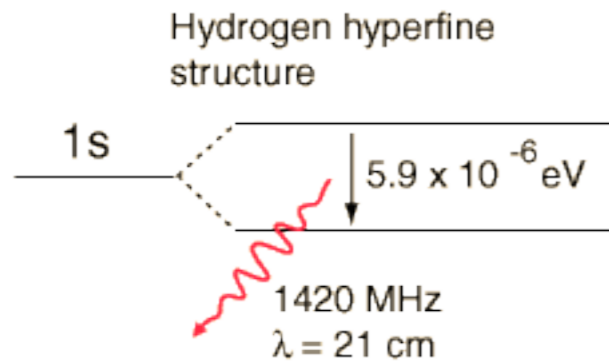
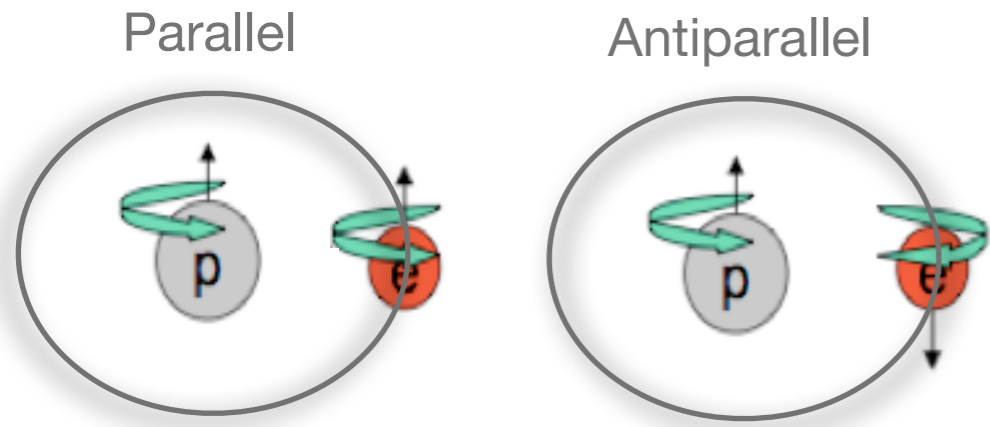
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Game of Temperatures:

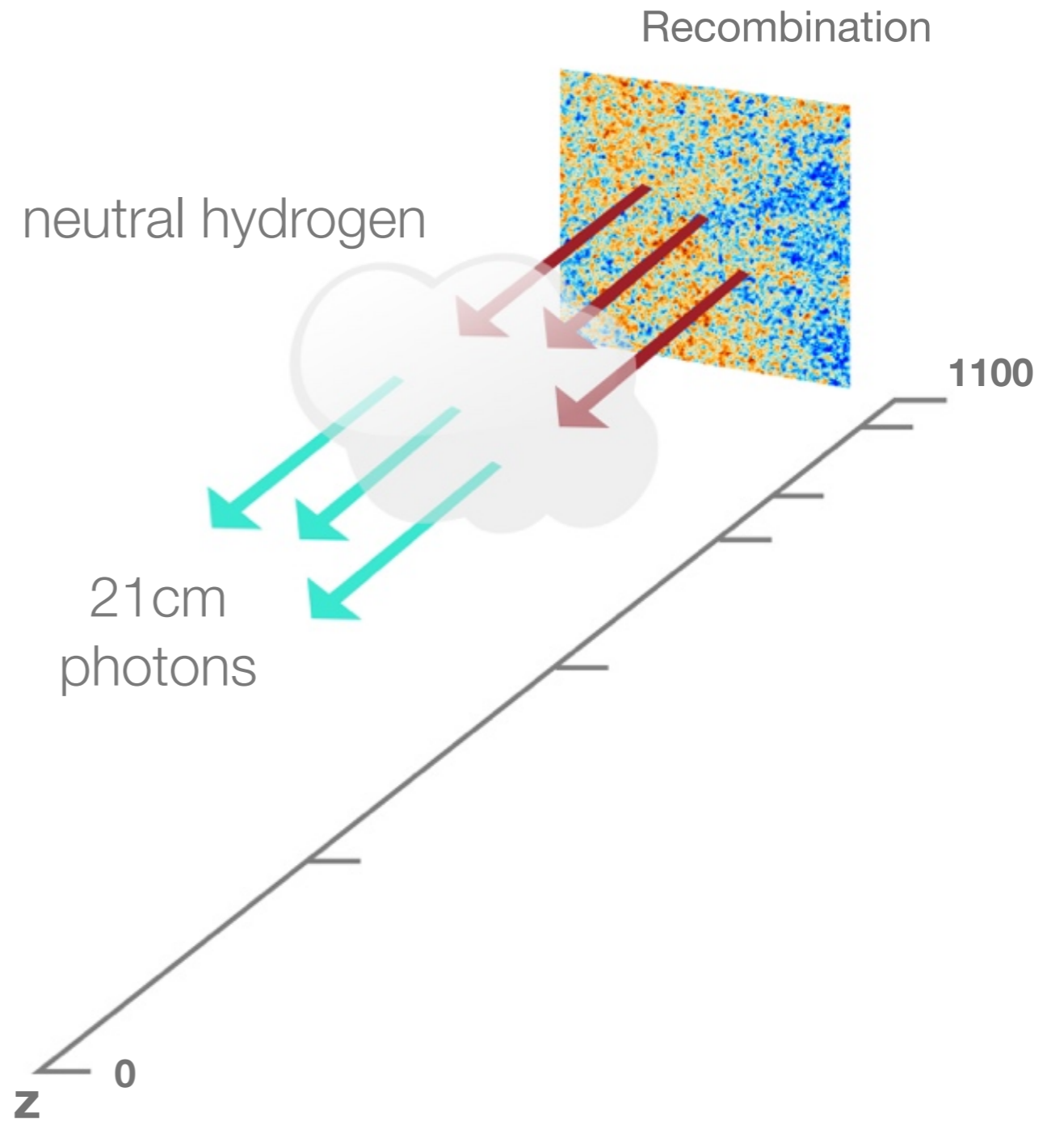


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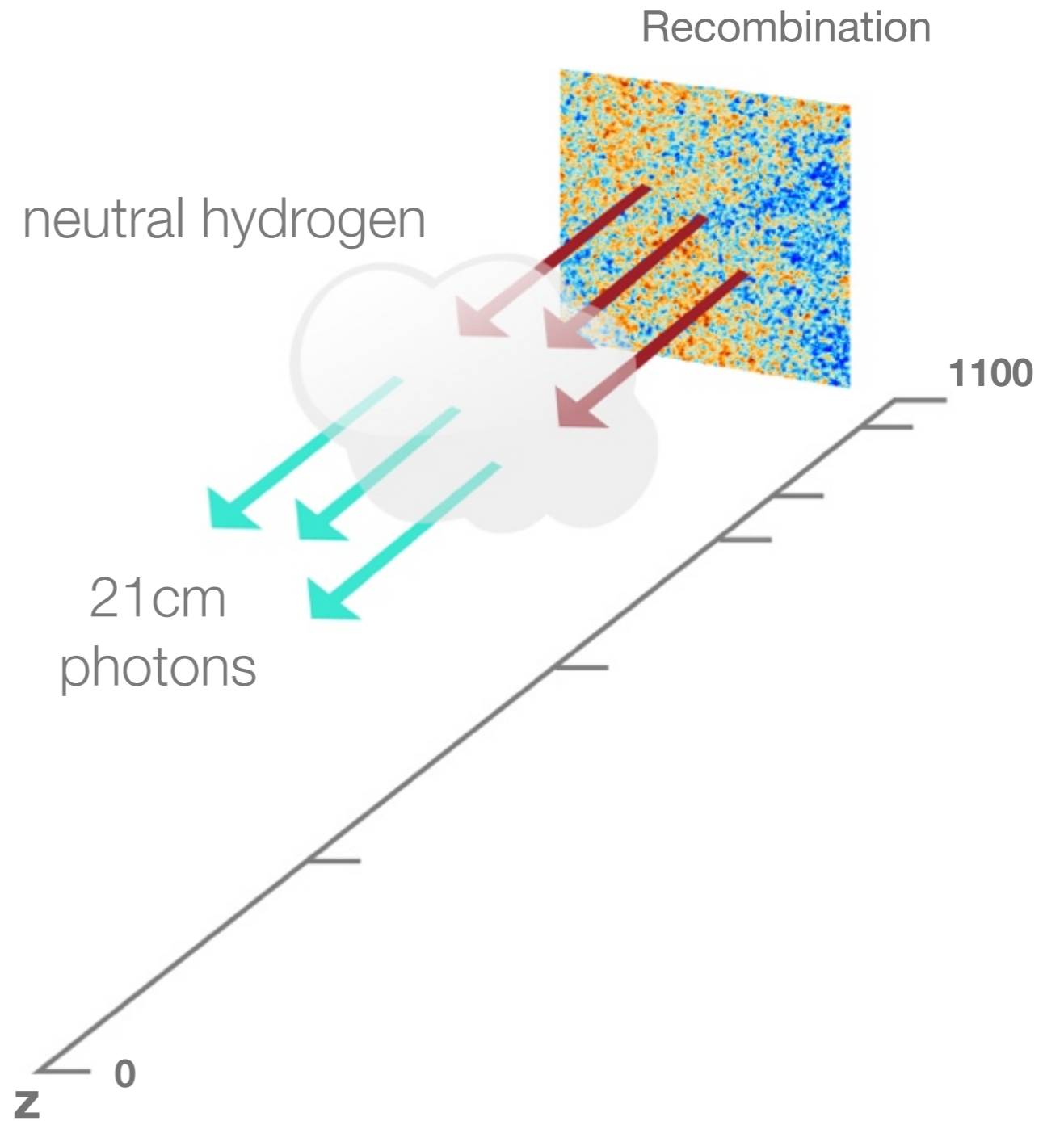
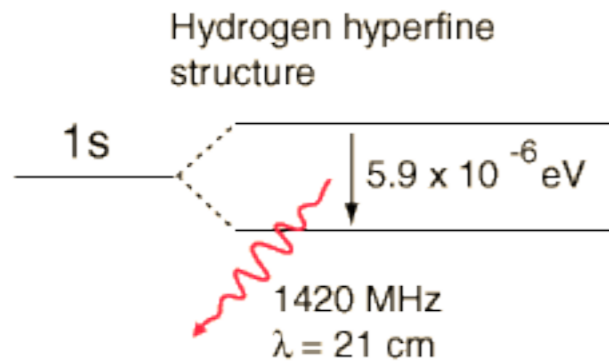
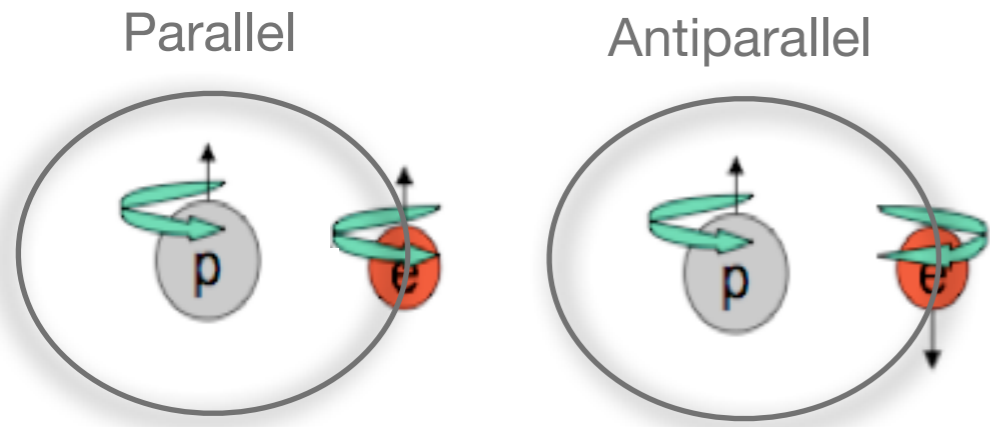


Game of Temperatures:

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



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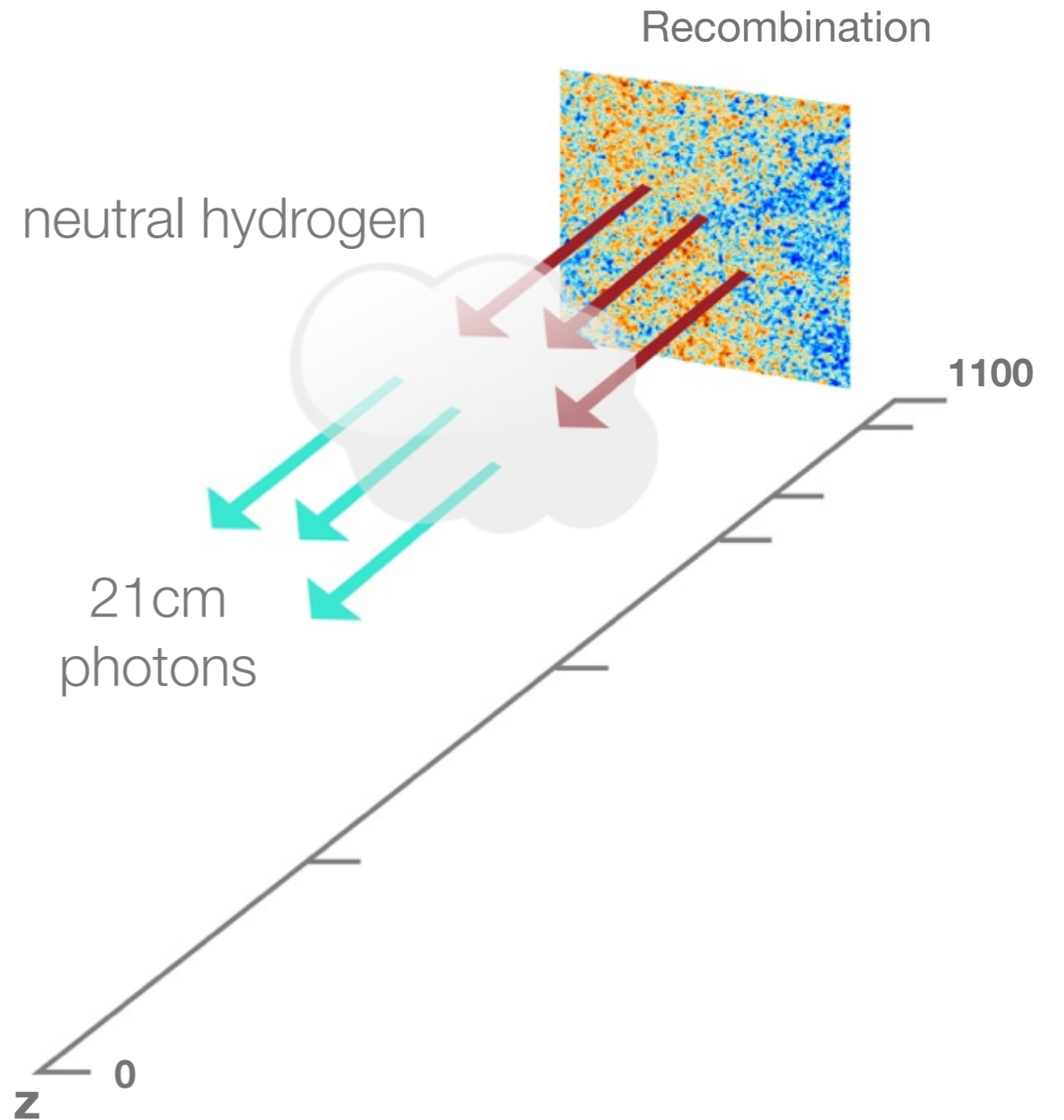
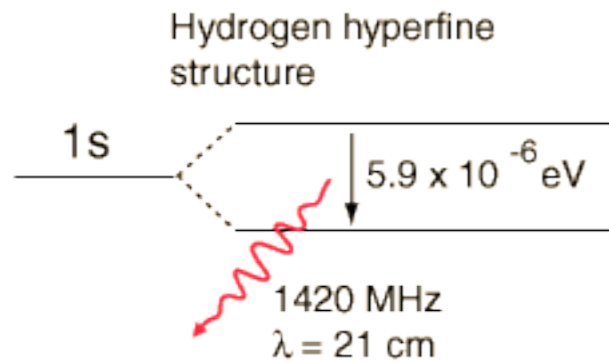
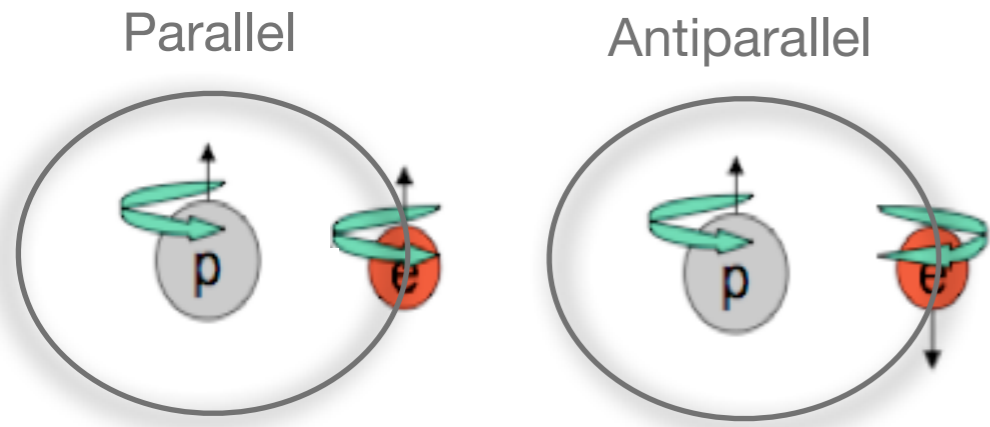


Game of Temperatures:

$T_{\text{CMB}}$

$T_{\text{gas}}$

# The 21-cm Signal: Lightning Review



## Game of Temperatures:

$T_{\text{CMB}}$

$T_{\text{gas}}$

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

# The 21-cm Signal: Lightning Review

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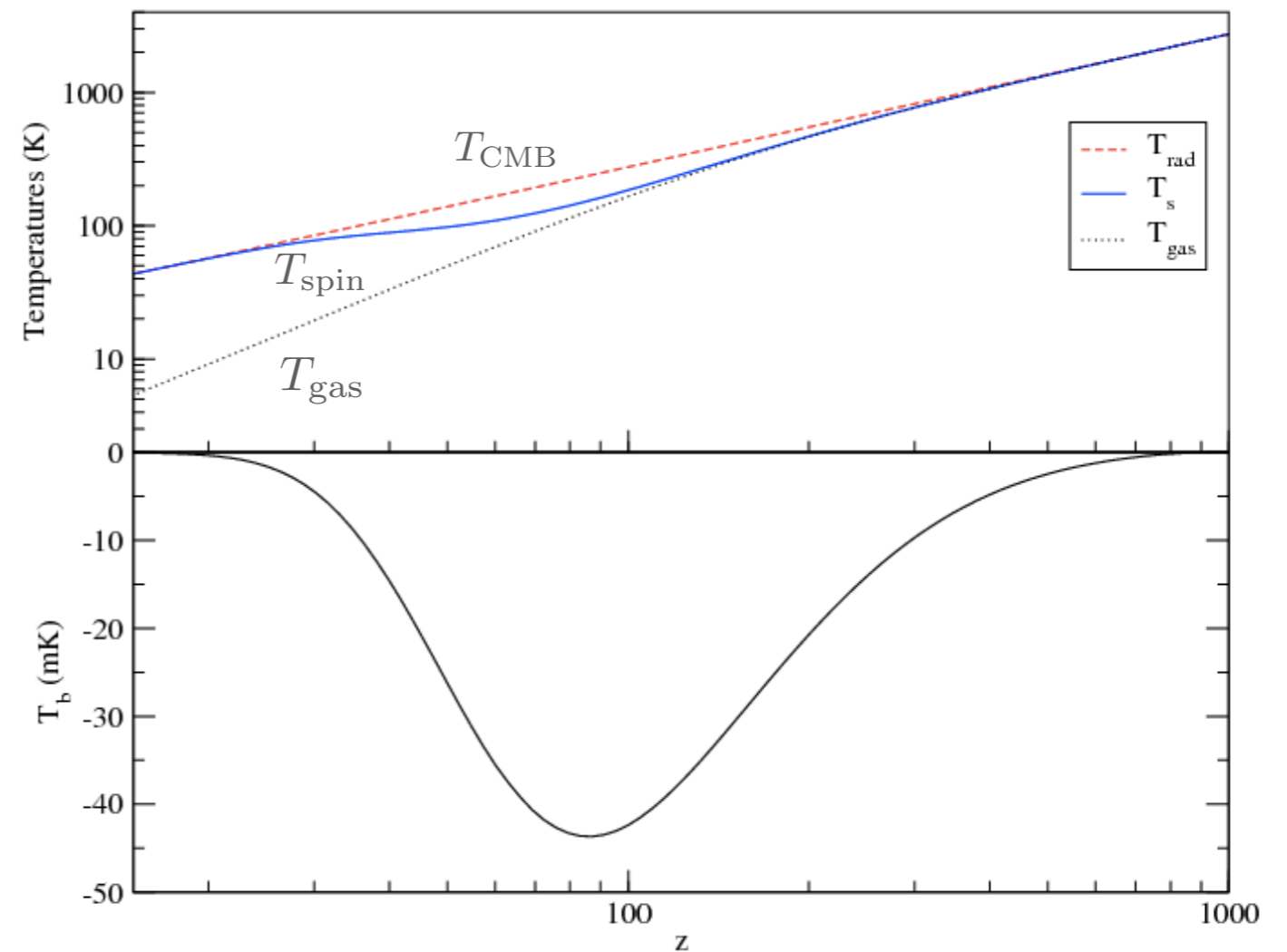
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Time dependence of different temperatures:

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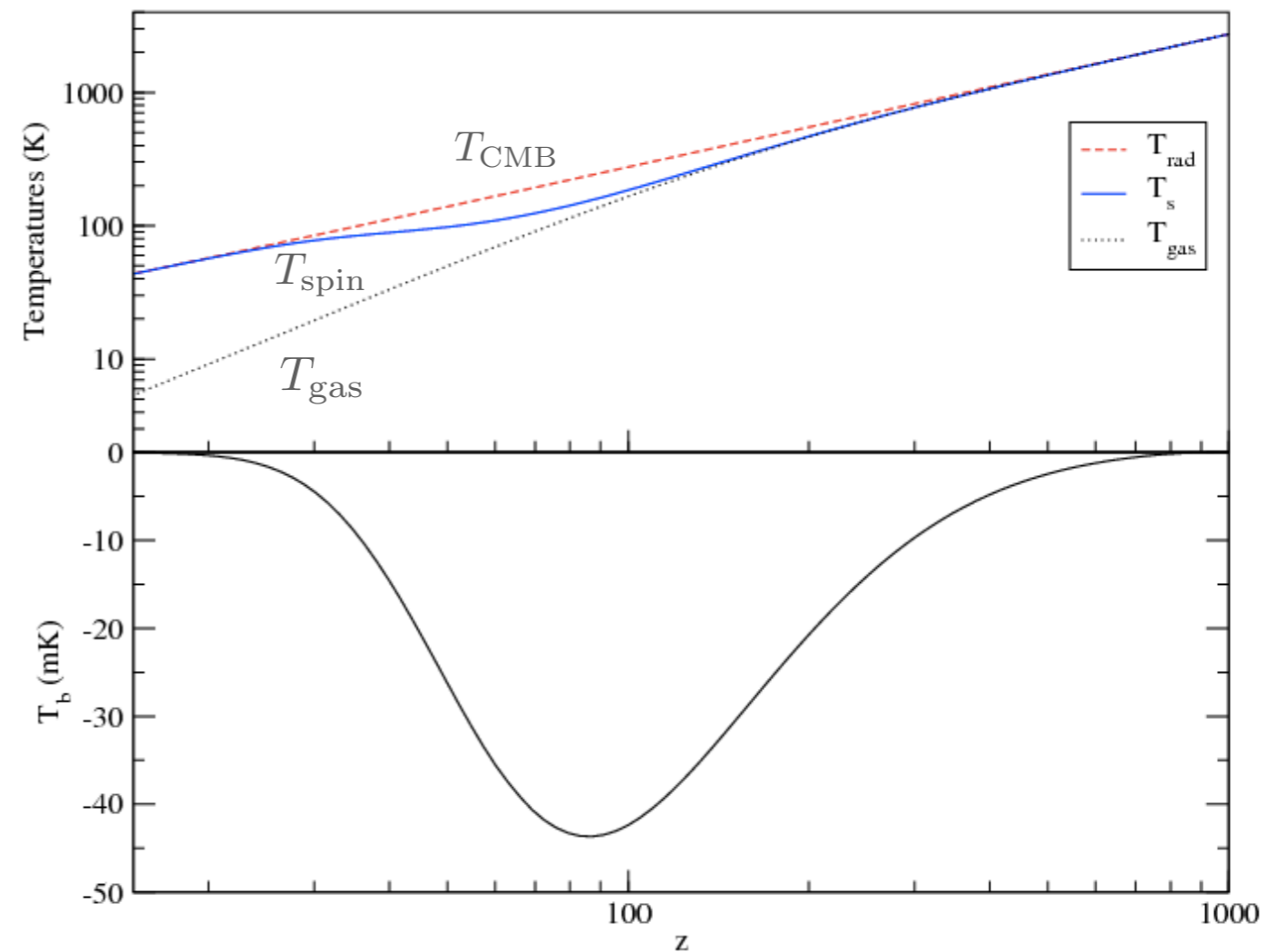
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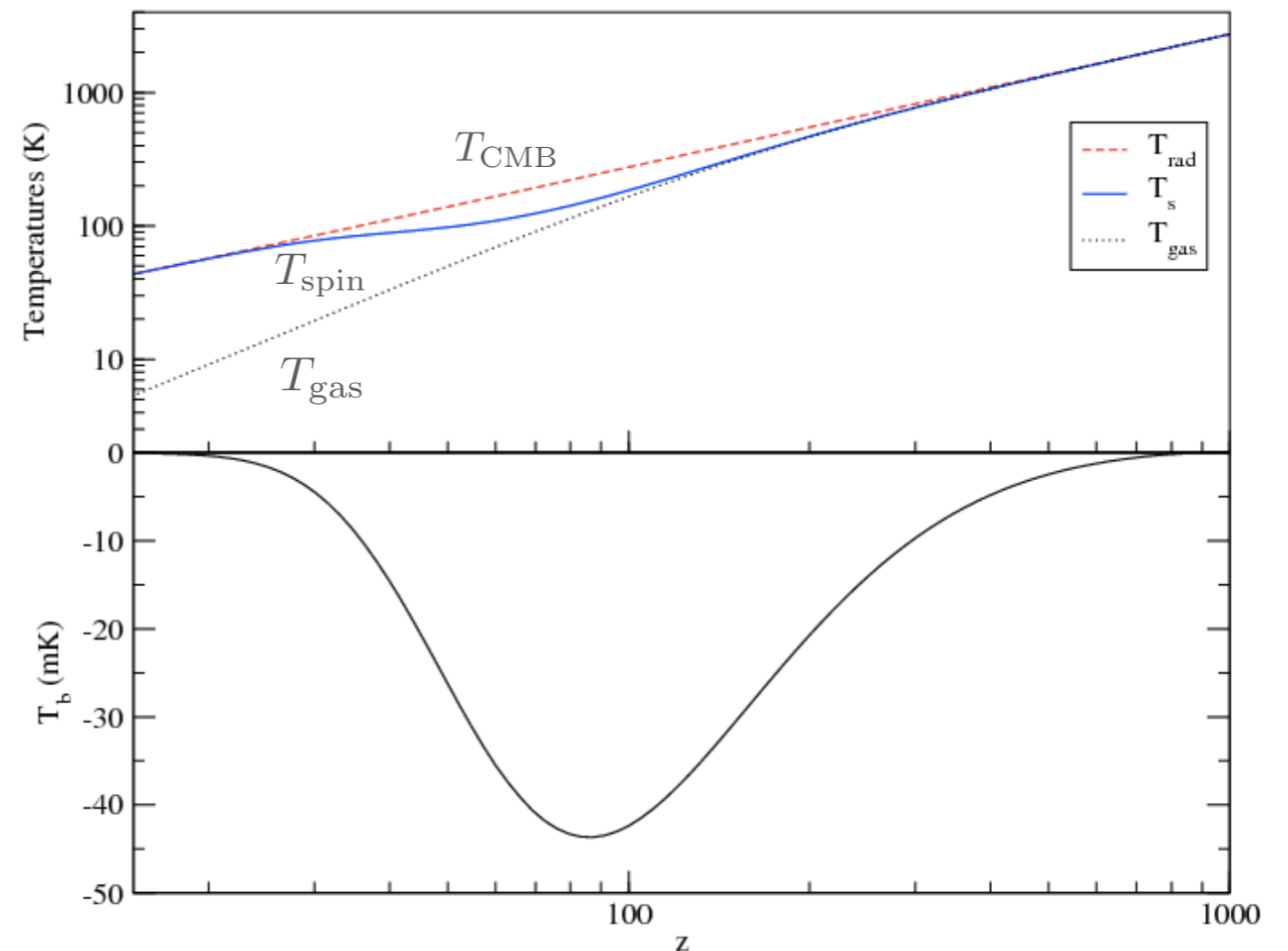


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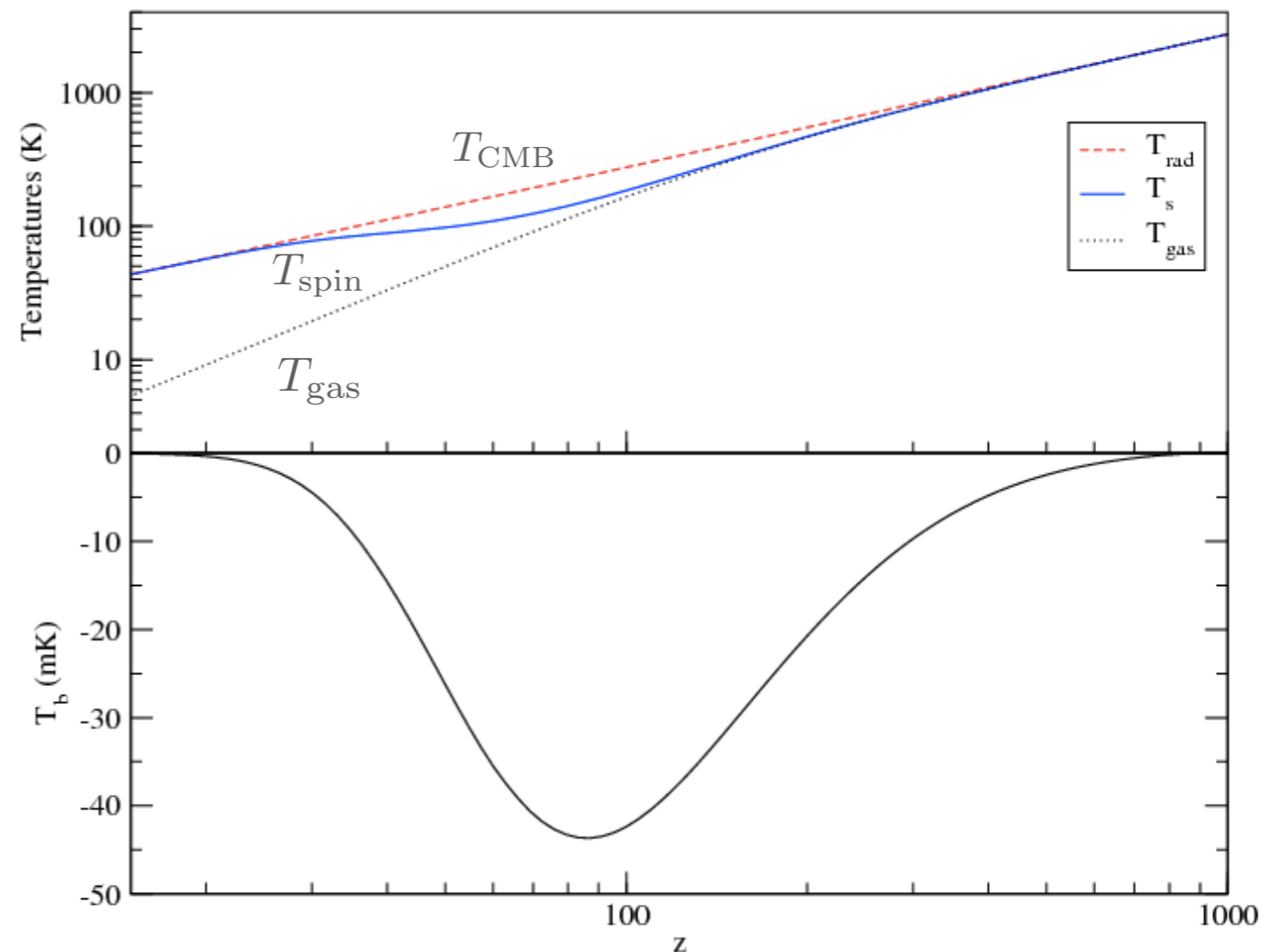
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Until  $z \sim 30$ : First,  $T_{\text{spin}} \sim T_{\text{gas}}$  (Collisions in the IGM). Then:  $T_{\text{spin}} \rightarrow T_{\text{CMB}}$



# The 21-cm Signal: Lightning Review

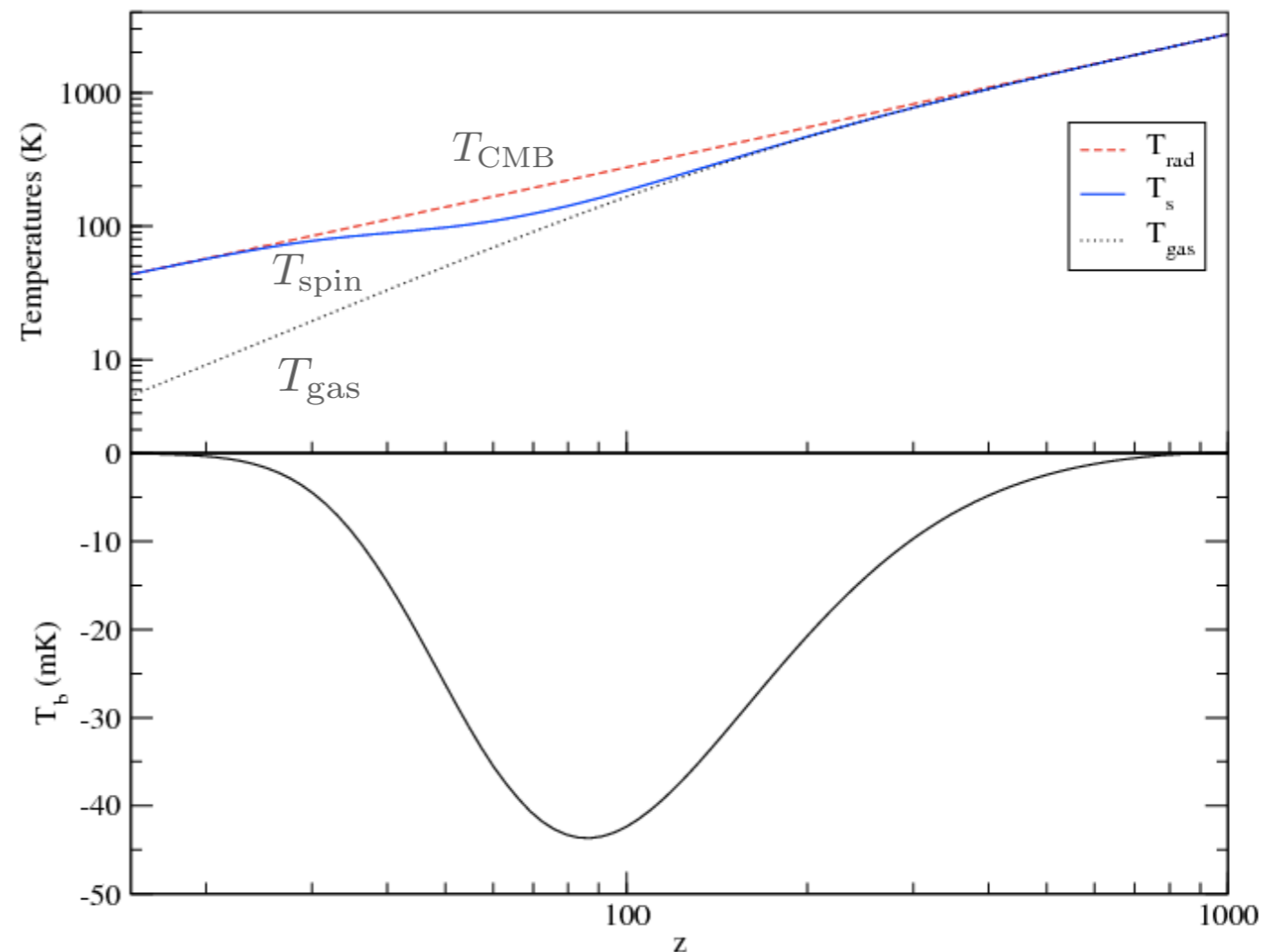
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Until  $z \sim 30$ : First,  $T_{\text{spin}} \sim T_{\text{gas}}$  (Collisions in the IGM). Then:  $T_{\text{spin}} \rightarrow T_{\text{CMB}}$

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# The 21-cm Signal: Lightning Review

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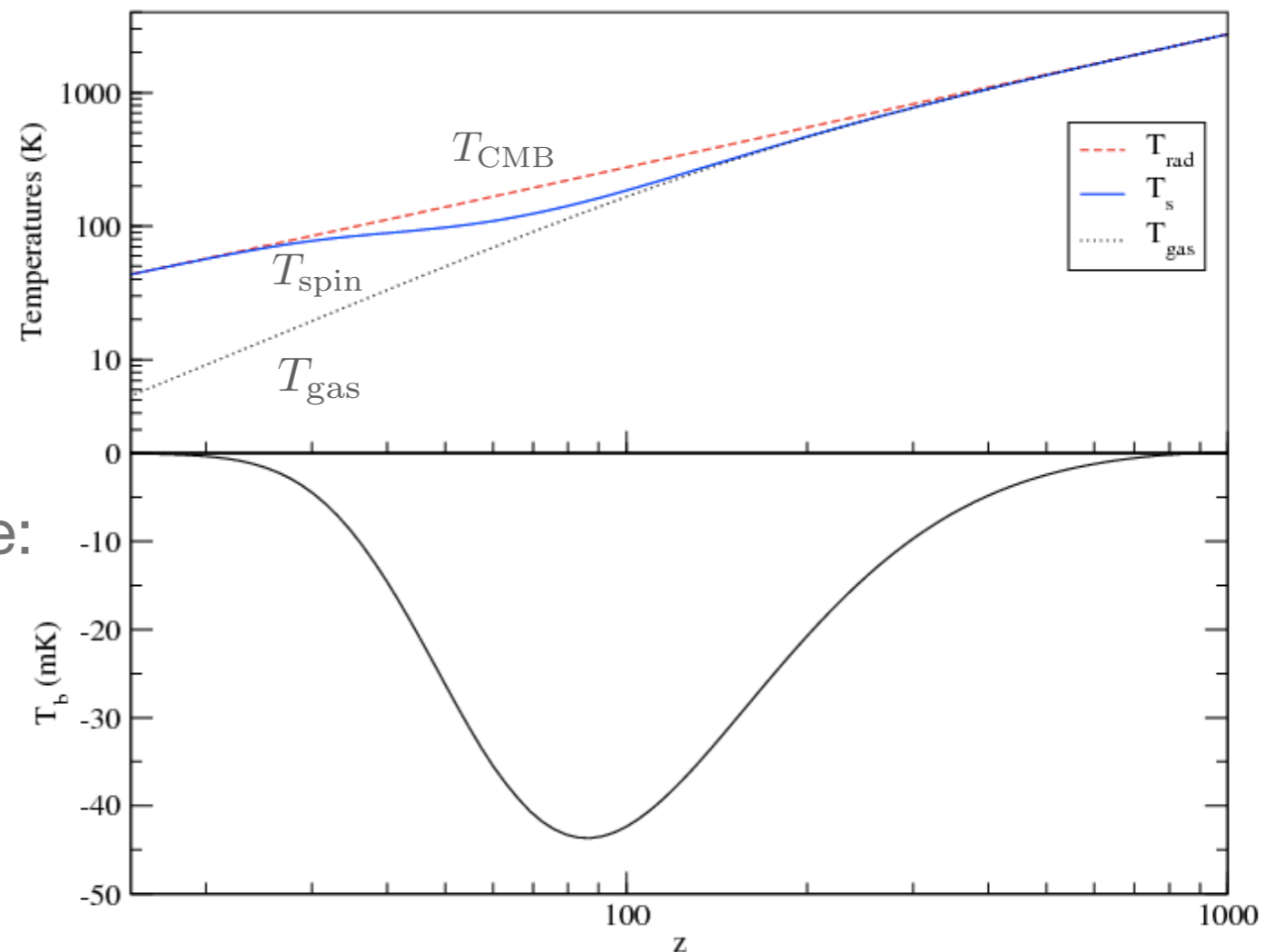
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We measure a brightness temperature:

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



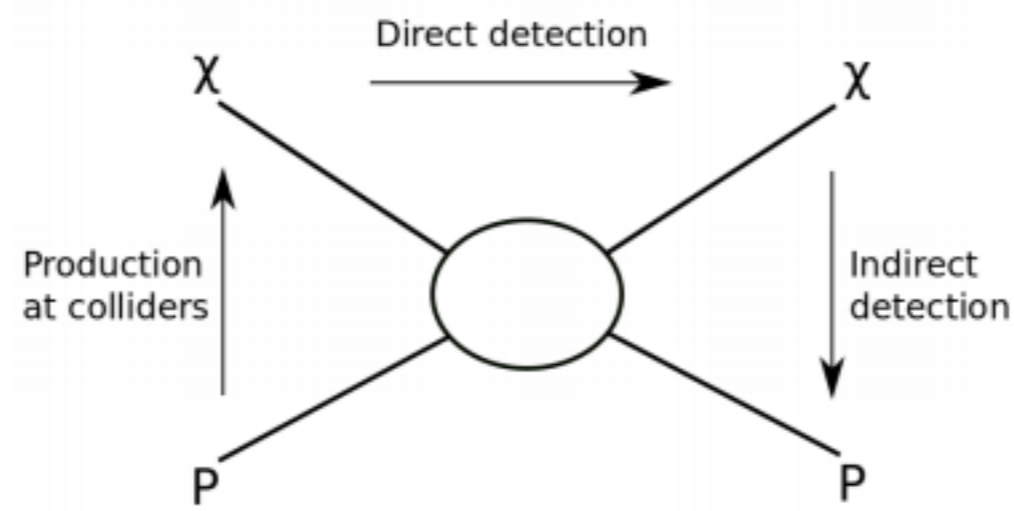
# Dark Matter: Direct and Indirect detection

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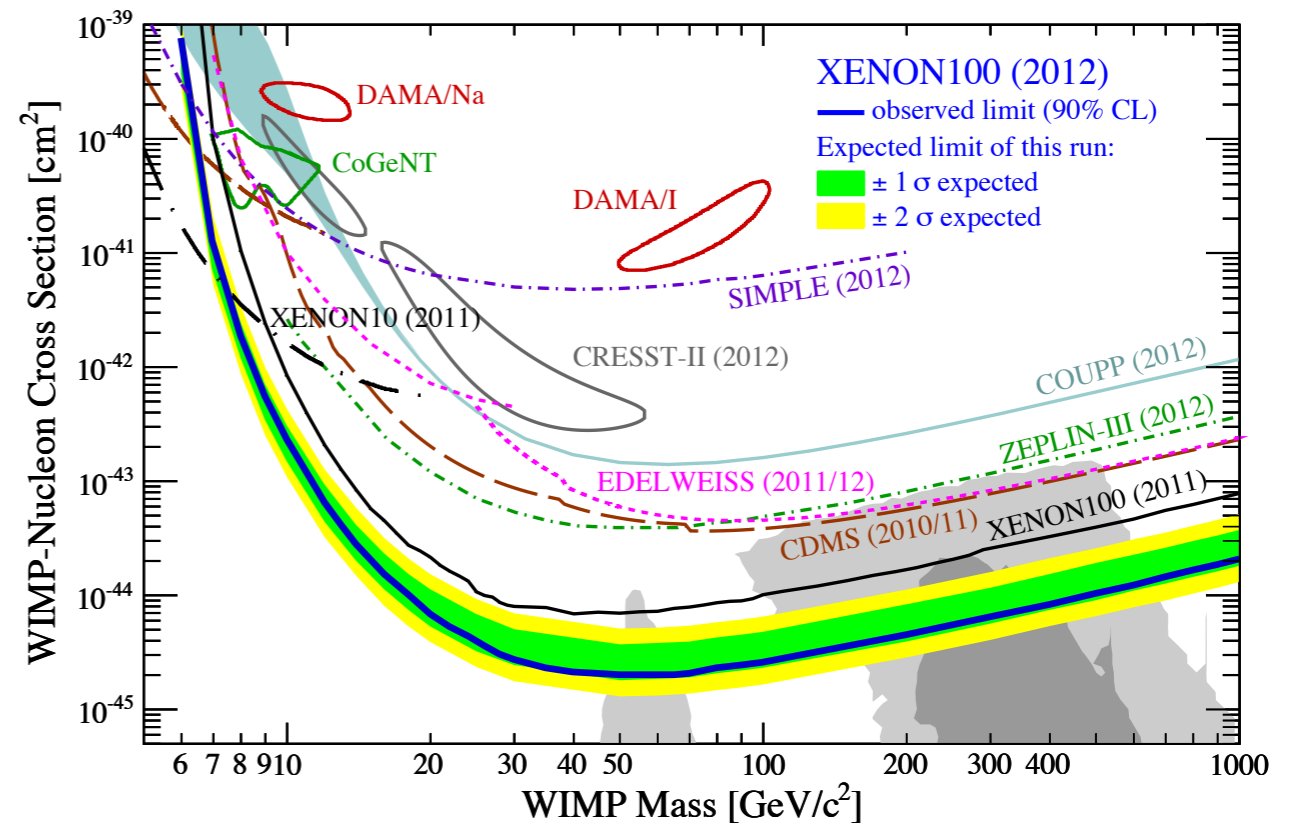
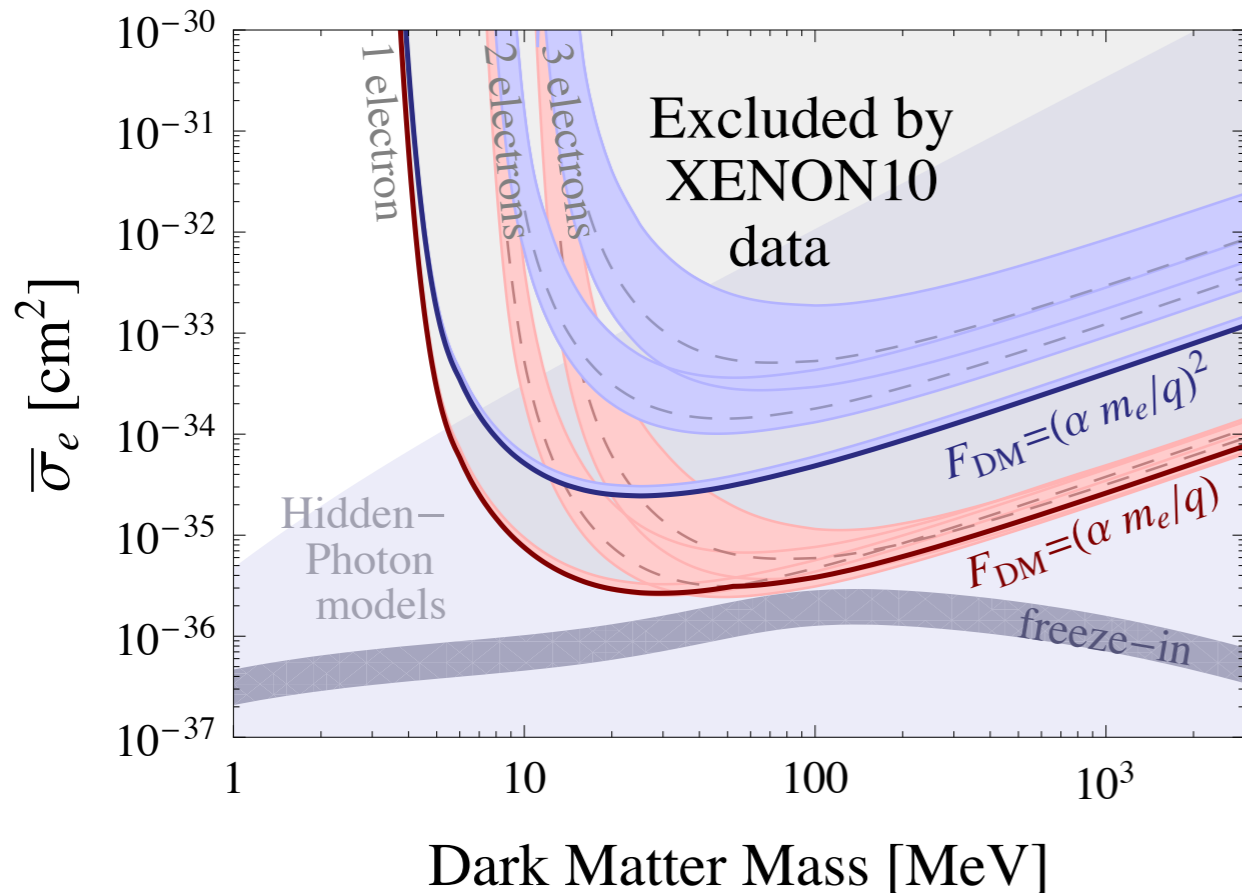
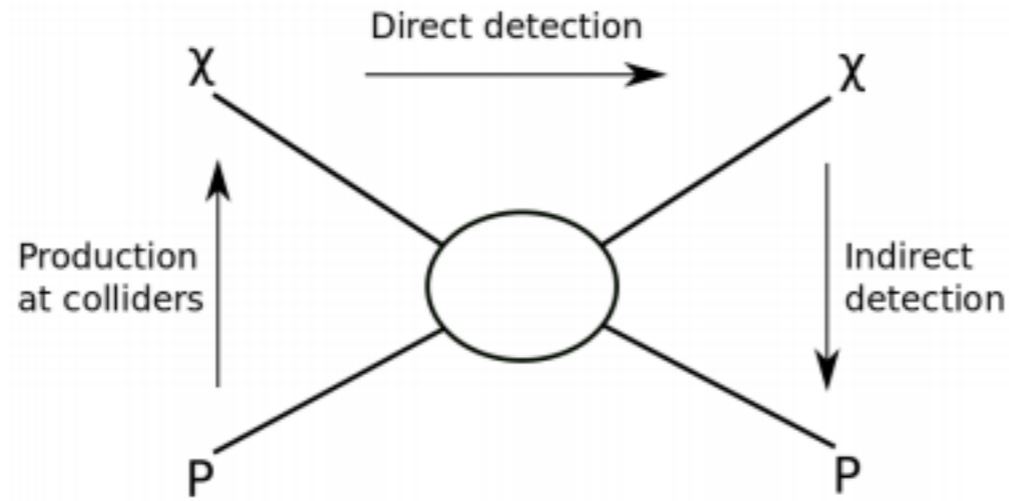
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Detecting DM:



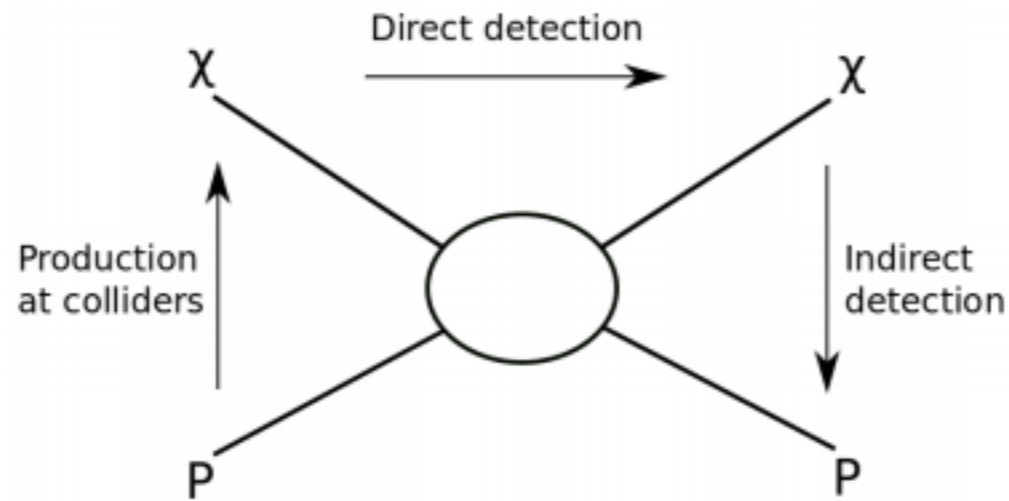
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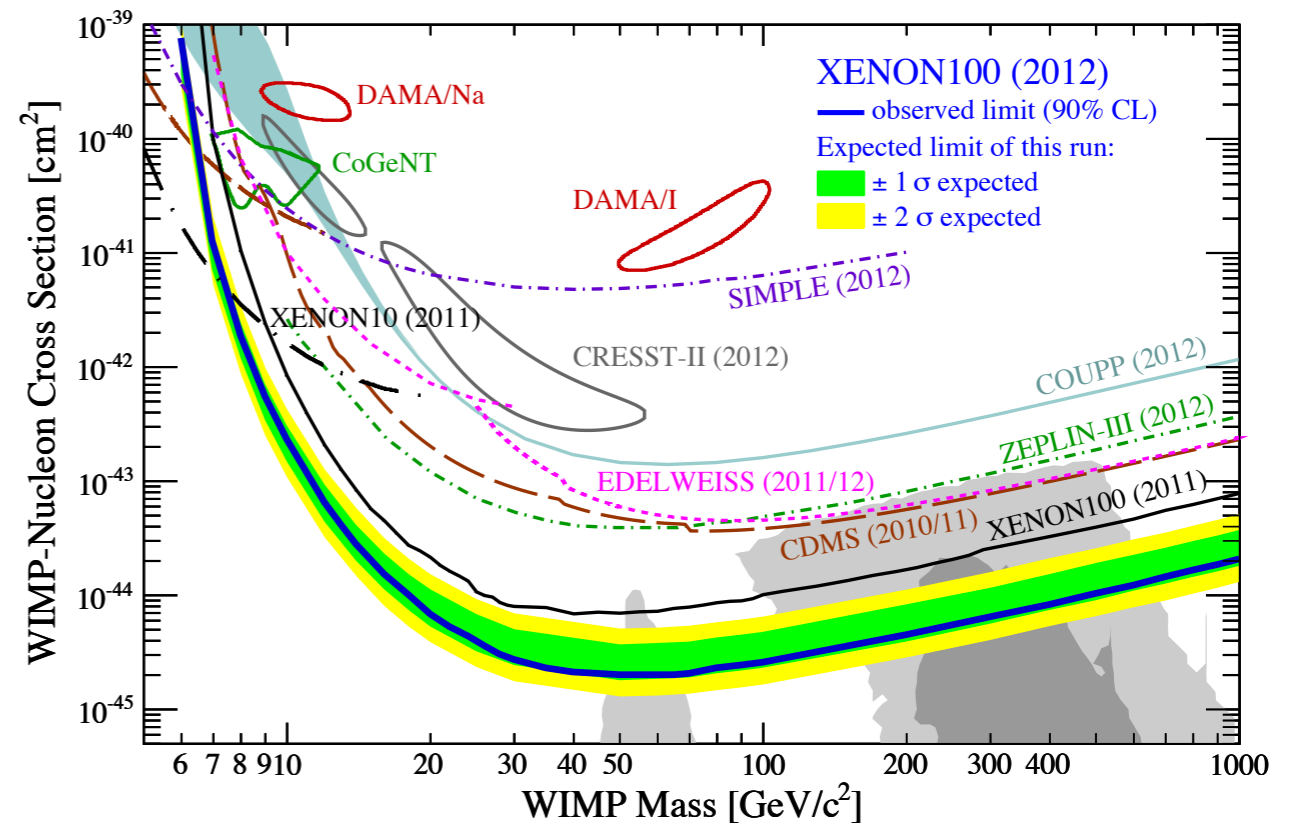
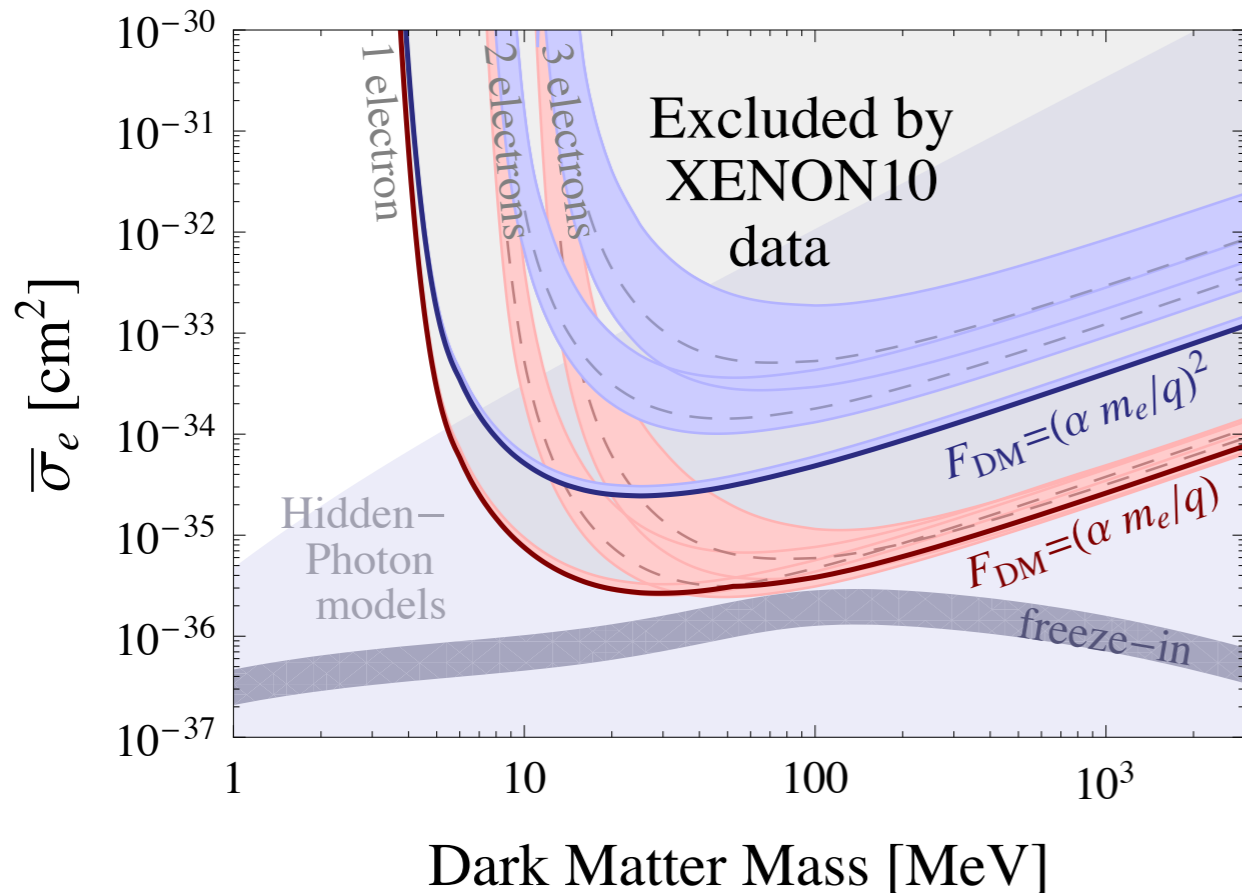


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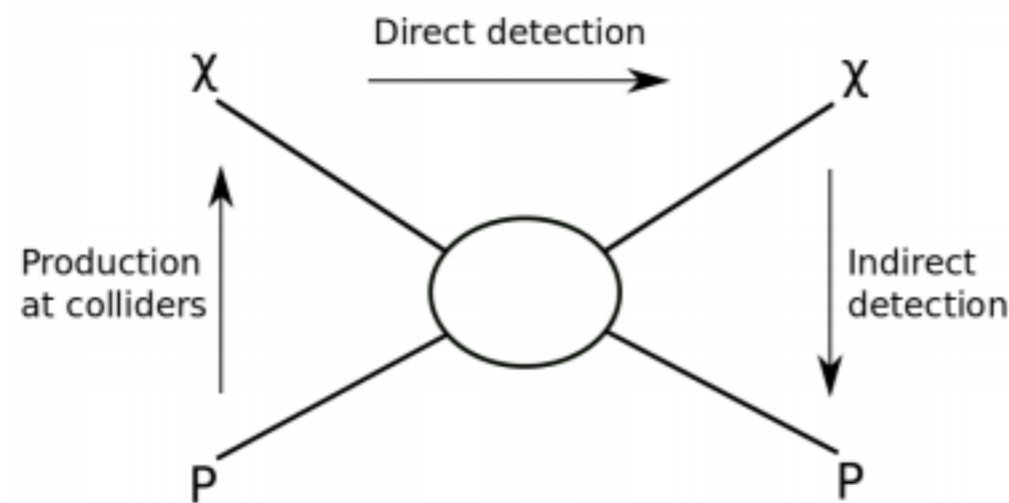
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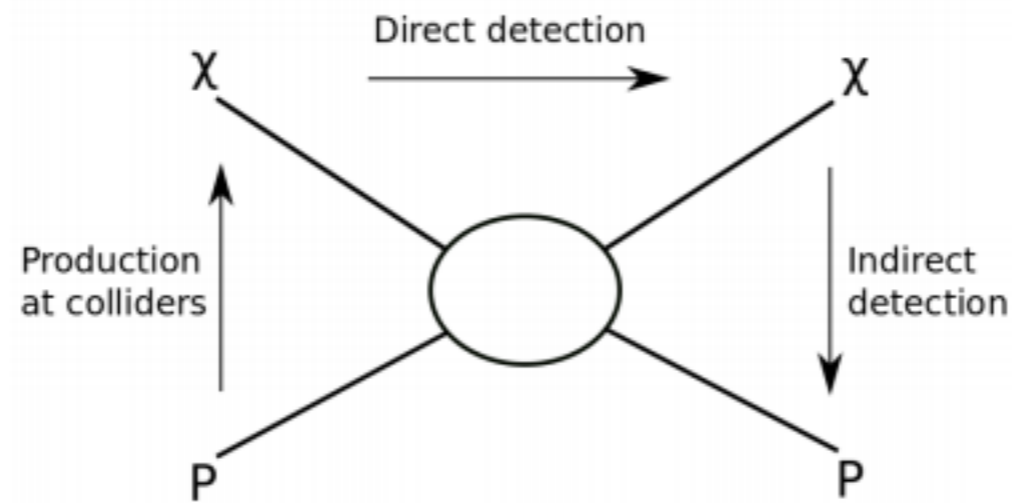
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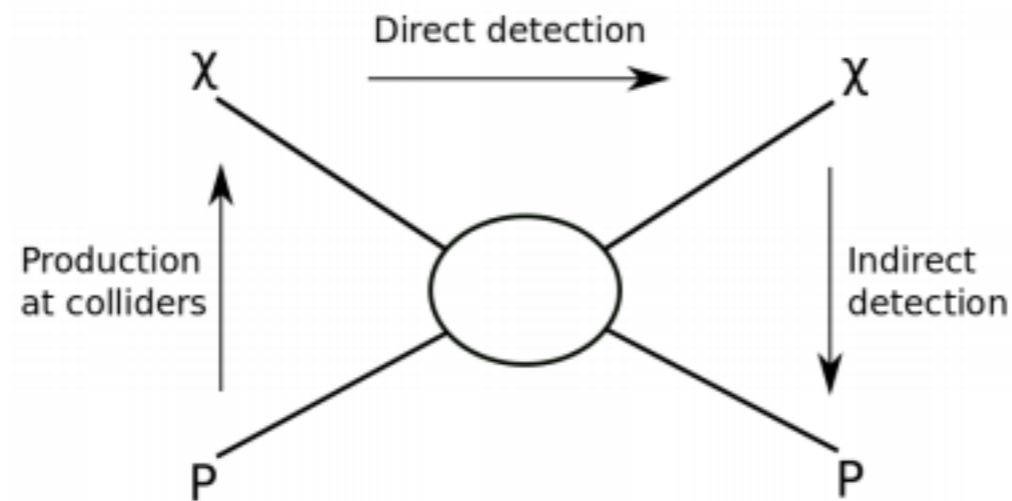
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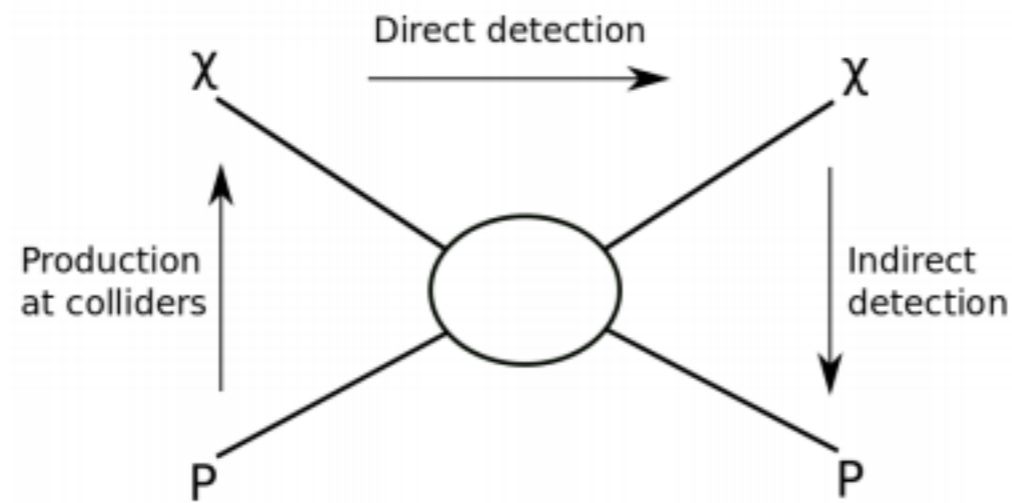
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However, these are mostly effective for  $n > -3$ . What about later times?

# Heating from DM-Baryon Scattering in Dark Ages

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

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→ dissipation of kinetic energy into thermal energy:

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

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

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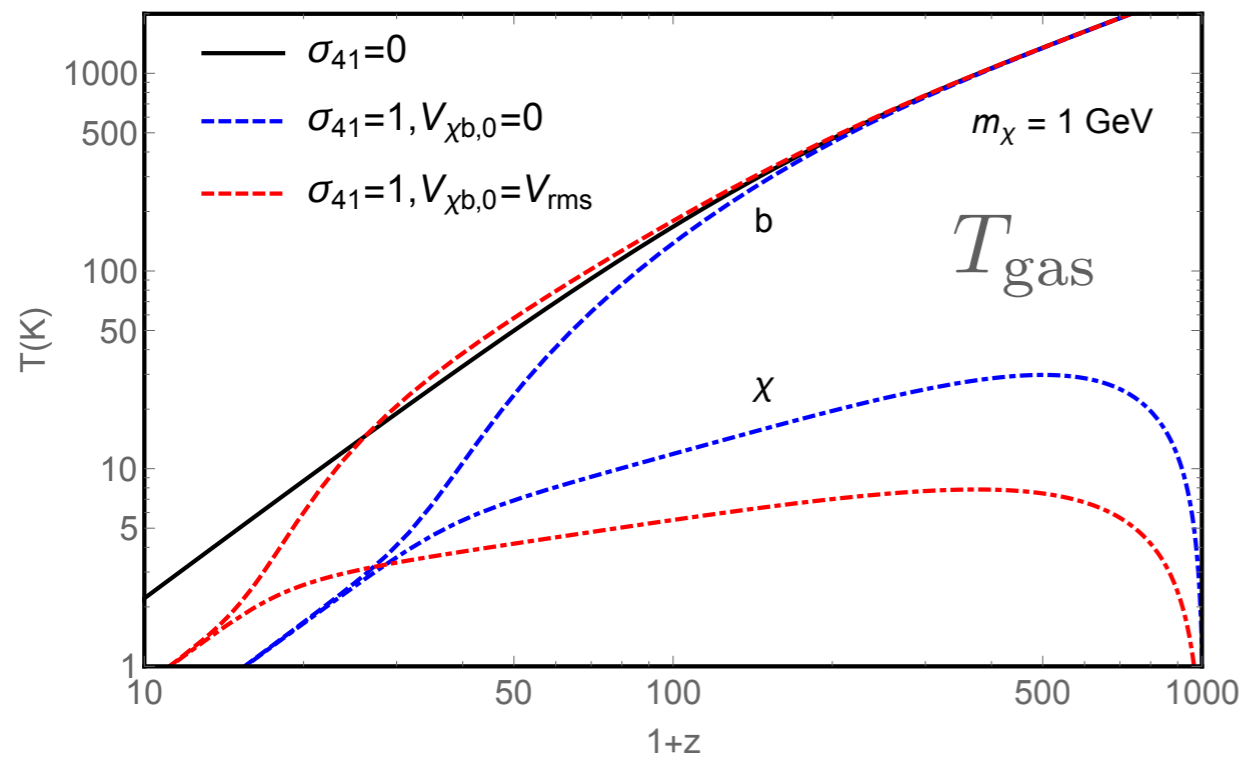
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Heating effect: global signal

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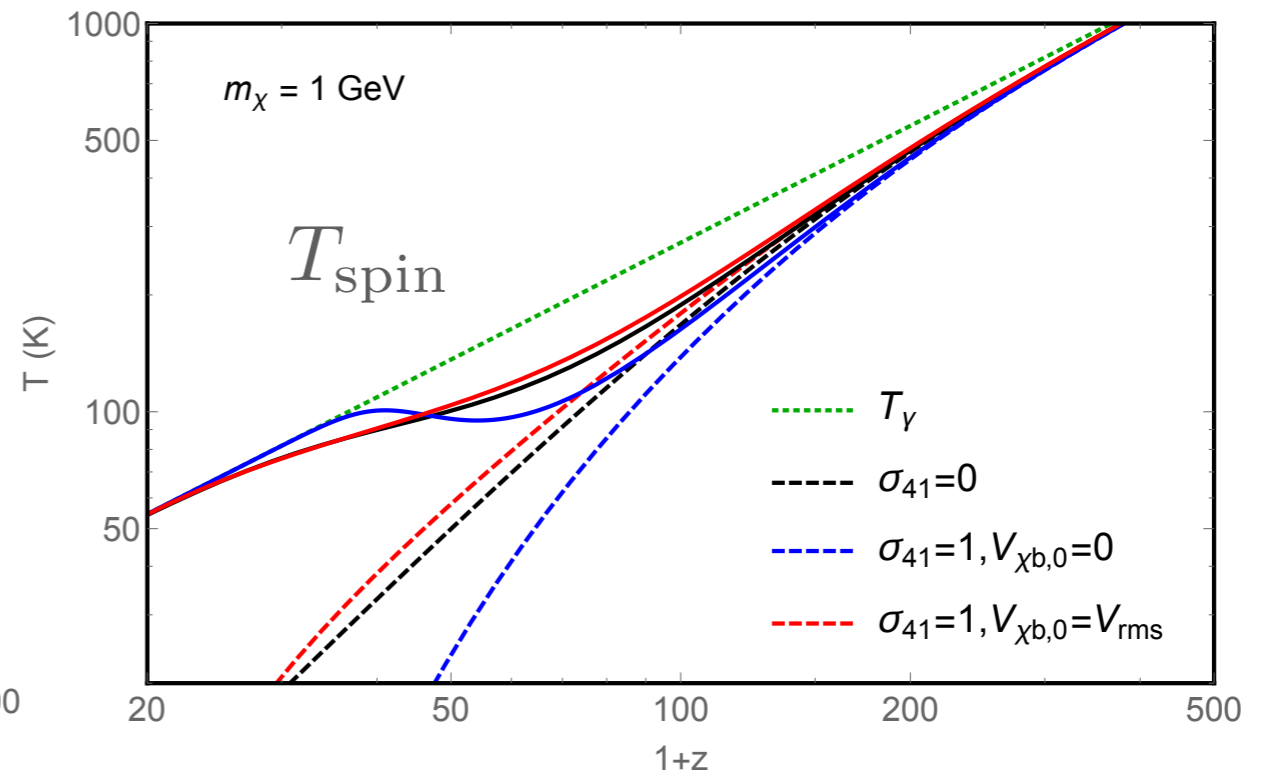
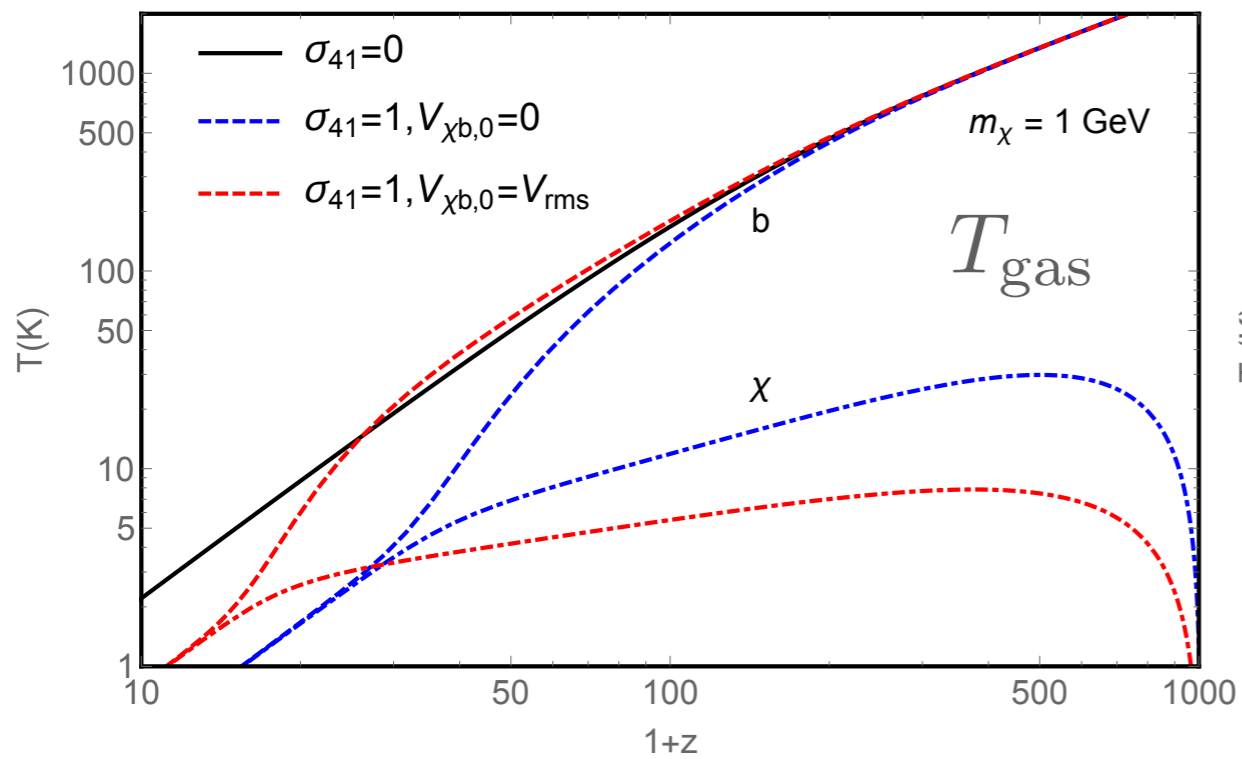
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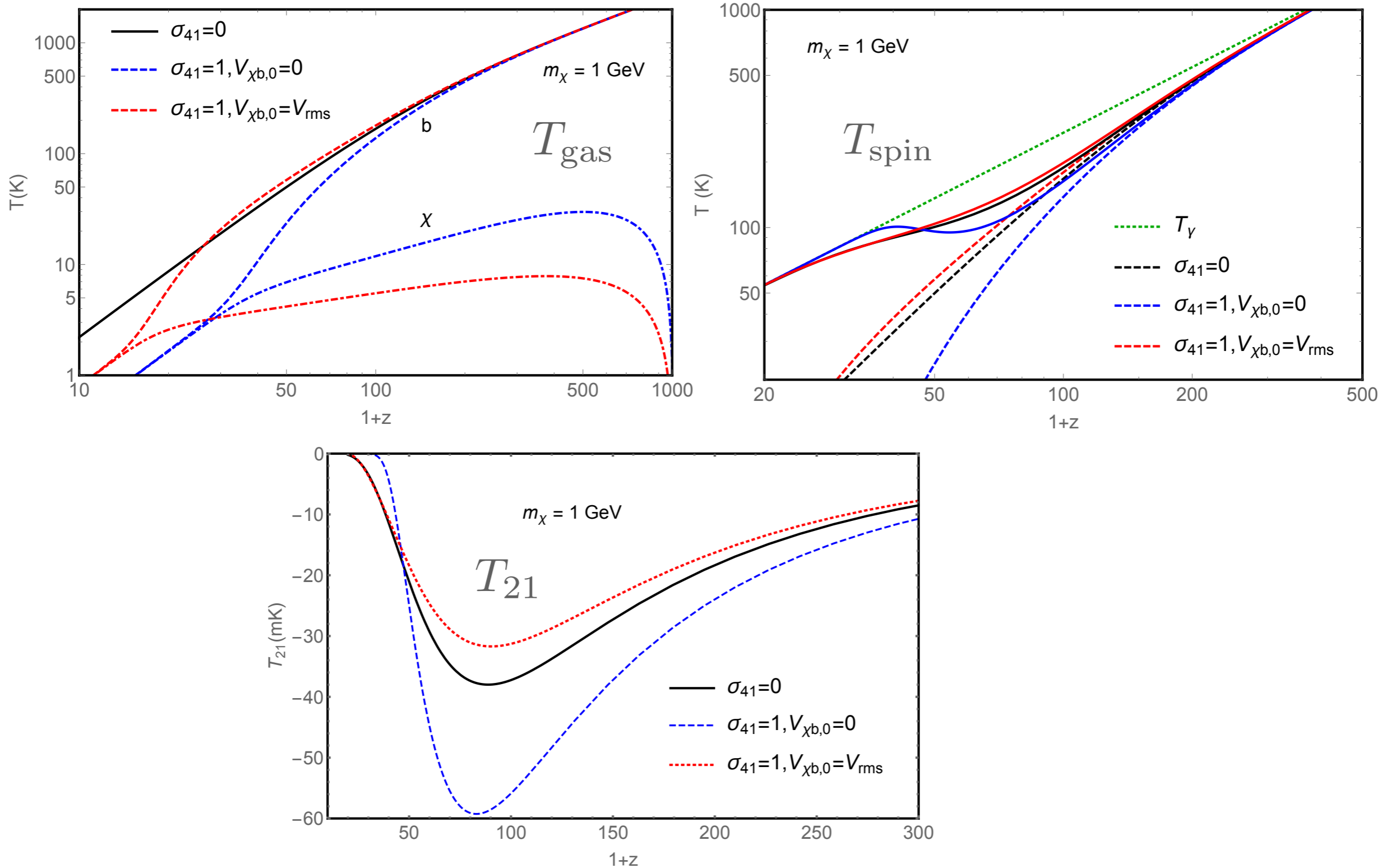
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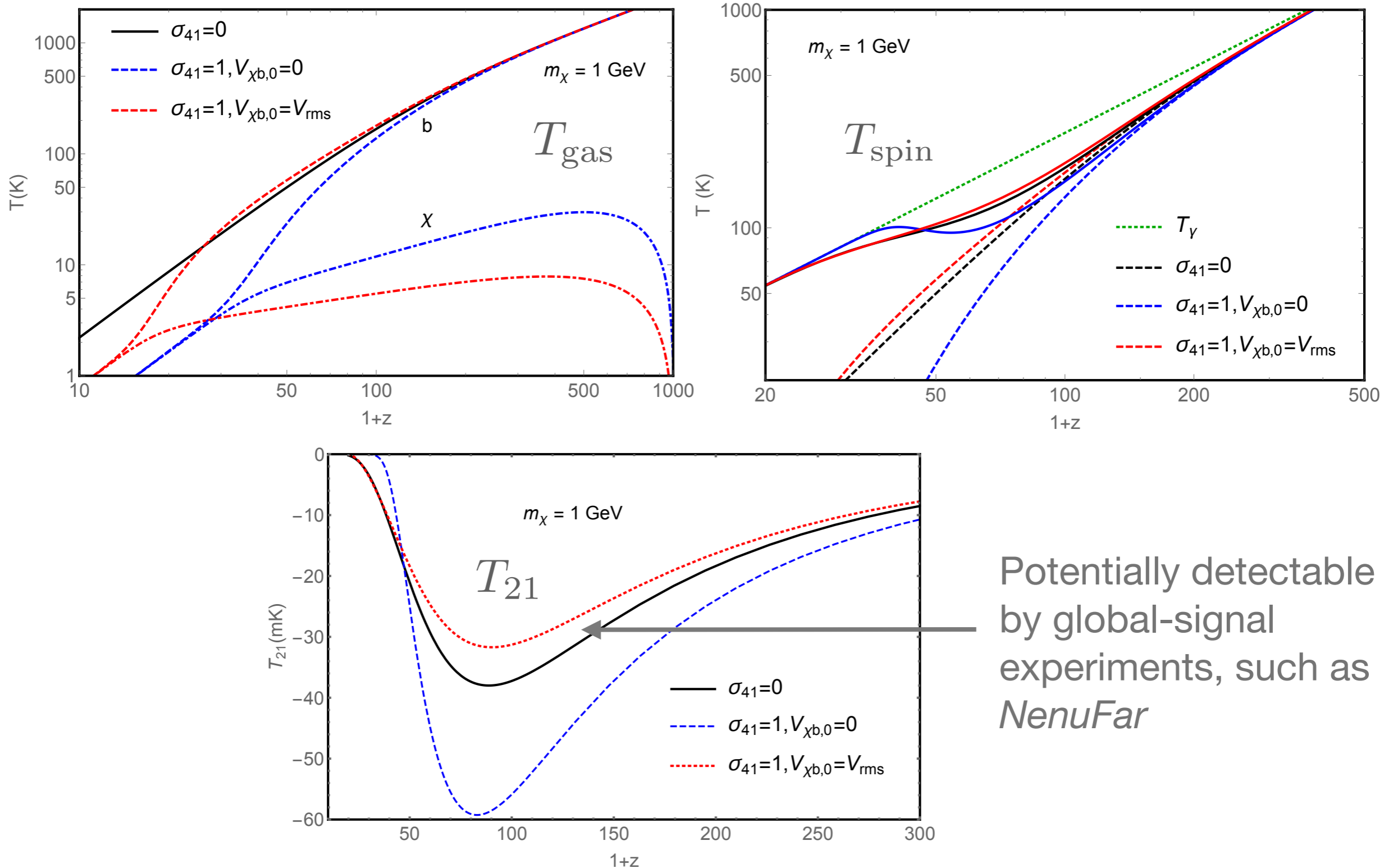
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Potentially detectable by global-signal experiments, such as *NenuFar*

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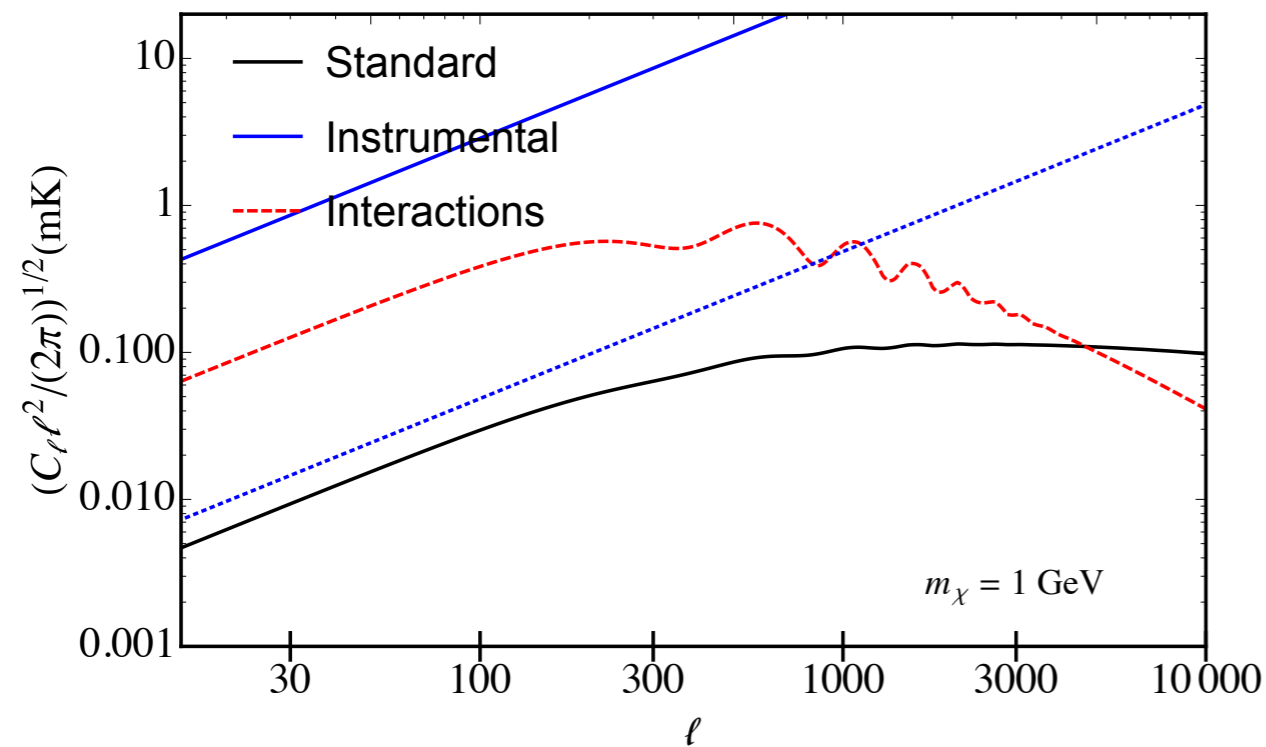
Dependence on the initial relative velocity means that the brightness temperature will depend on position on the sky, yielding a new source of 21-cm fluctuations.

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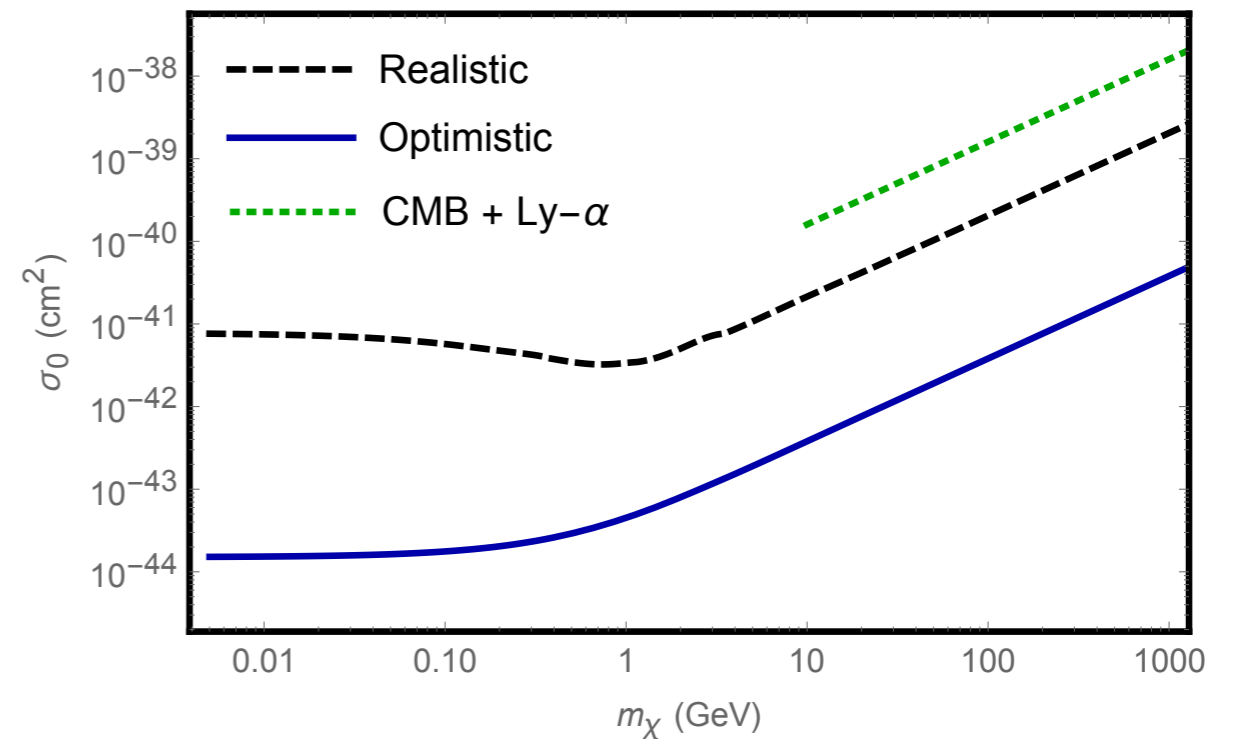
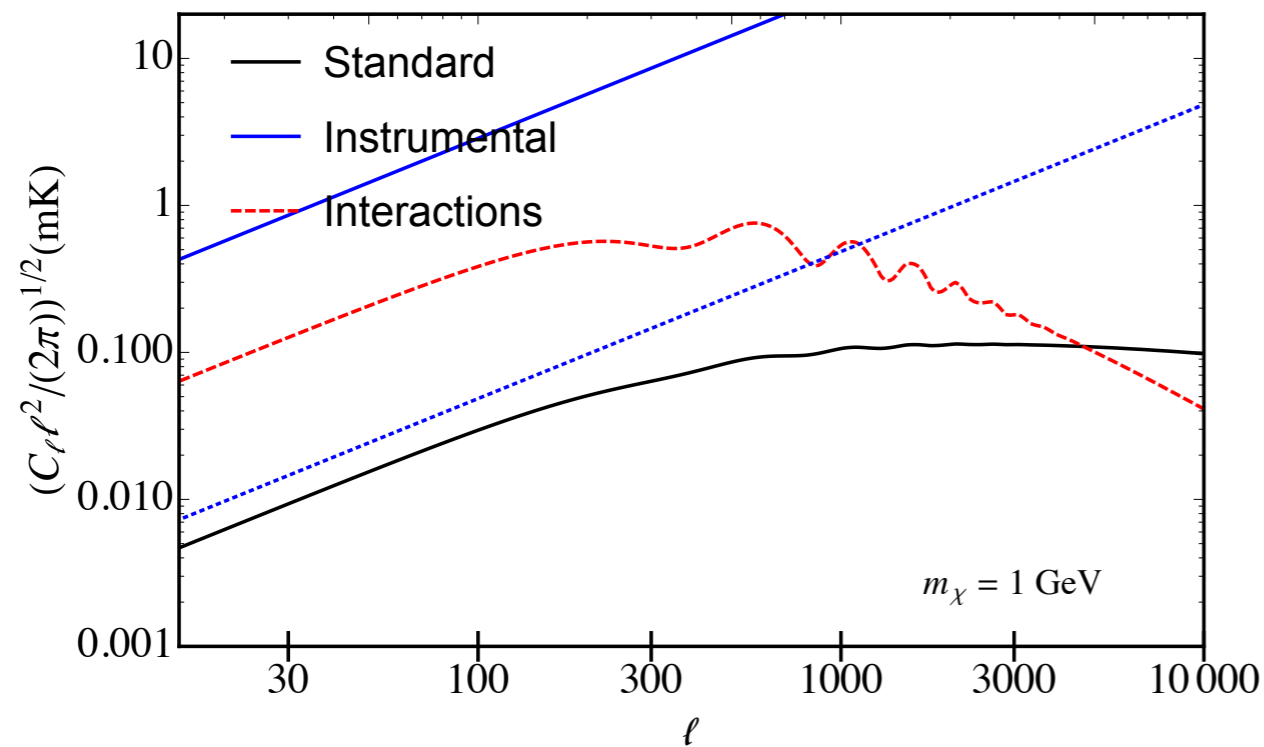


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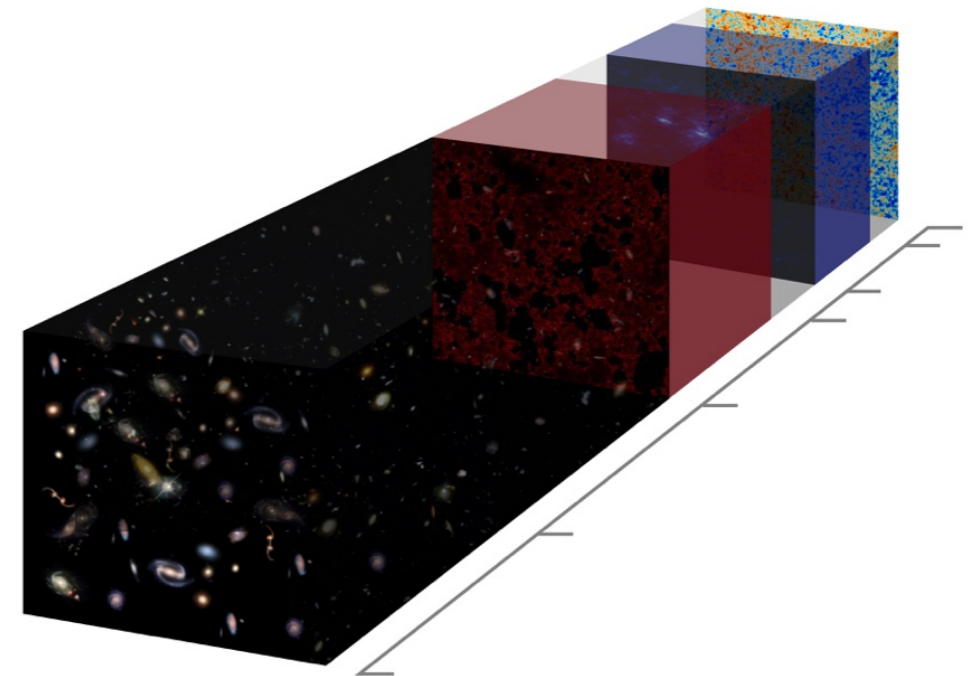


Realistic: SKA, 6-km baseline, 2% cover fraction.

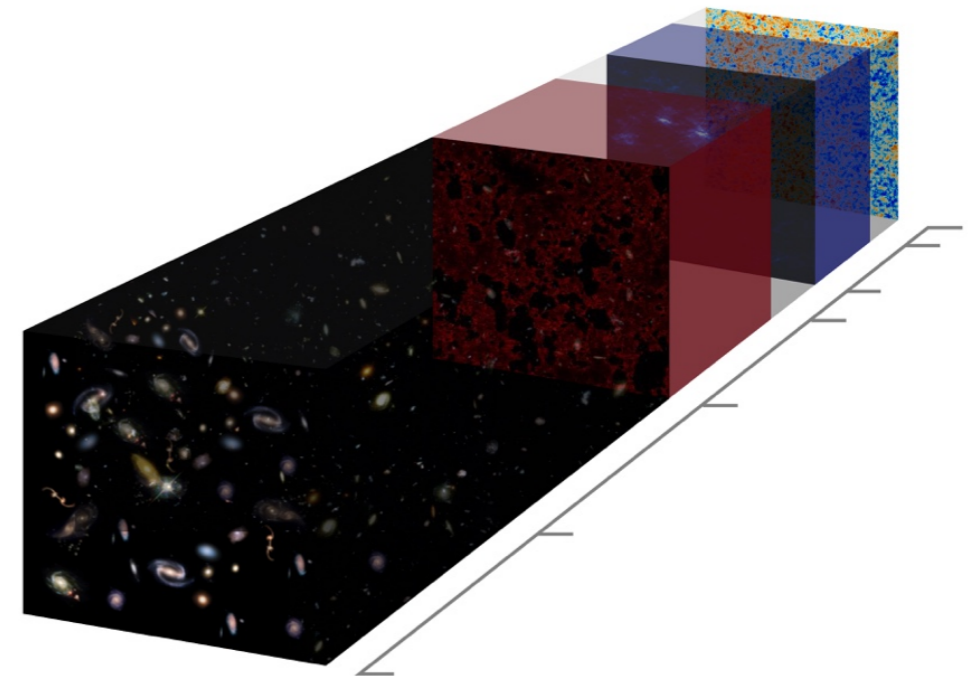
Optimistic: 50-km baseline, 10% cover fraction.

# Outline

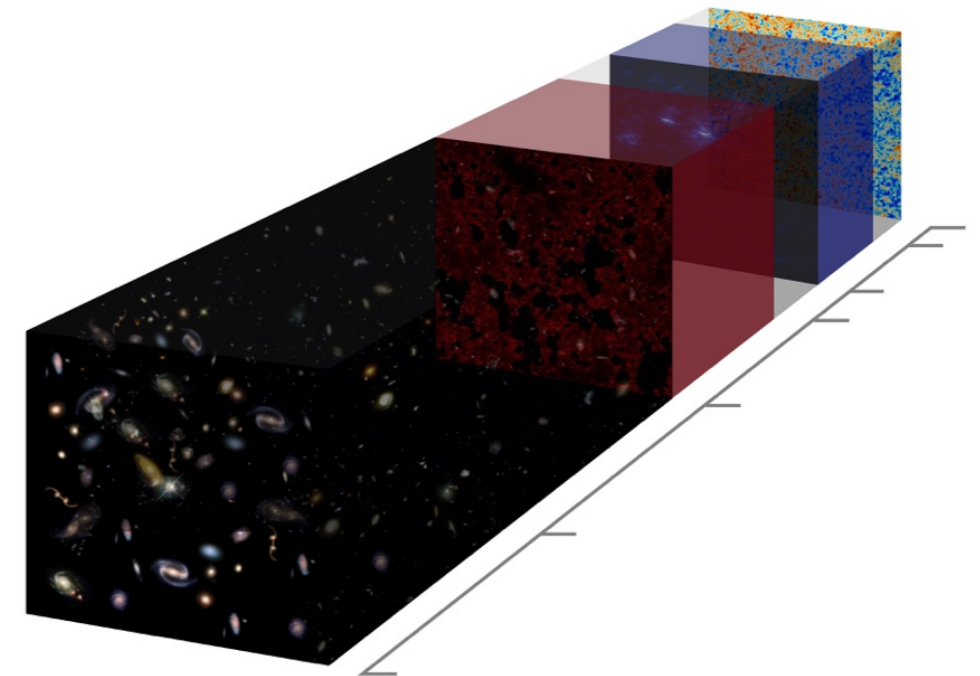
Ely D. Kovetz  
WIS, Jan. 2016



- The quest for B-modes from Inflationary GWs
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Breysse, EDK and Kamionkowski, MNRAS 443 (2014)

Breysse, EDK and Kamionkowski, MNRAS 452 (2015)

Breysse, EDK and Kamionkowski, MNRAS Letters, in press (2016)

# Intensity Mapping

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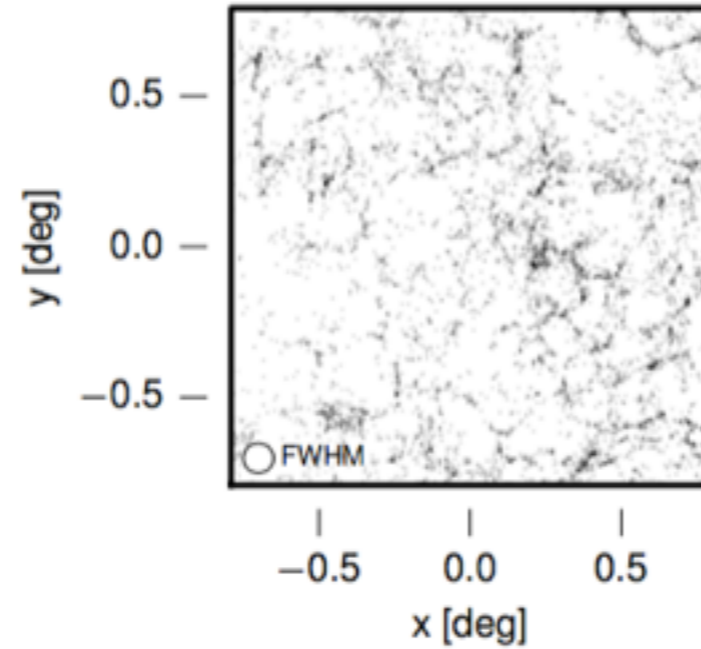
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Definition: 3D mapping of the specific intensity due to line emission.

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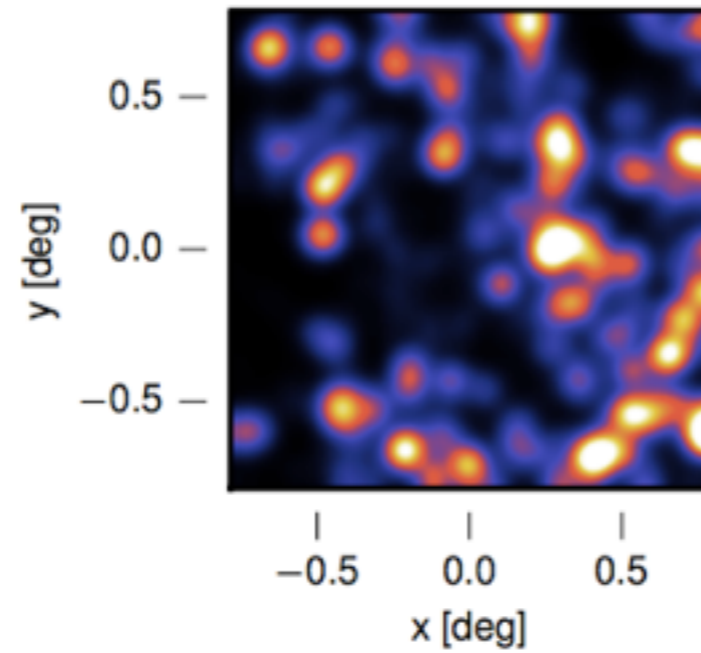
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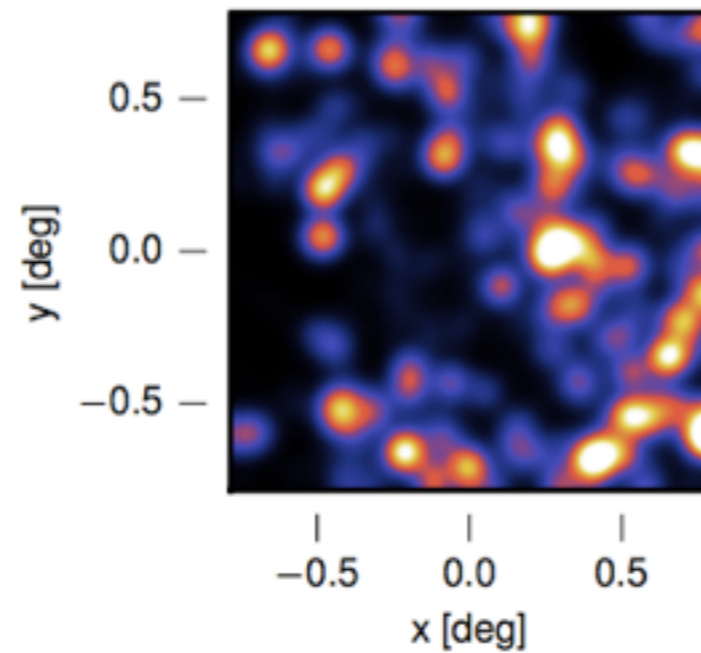
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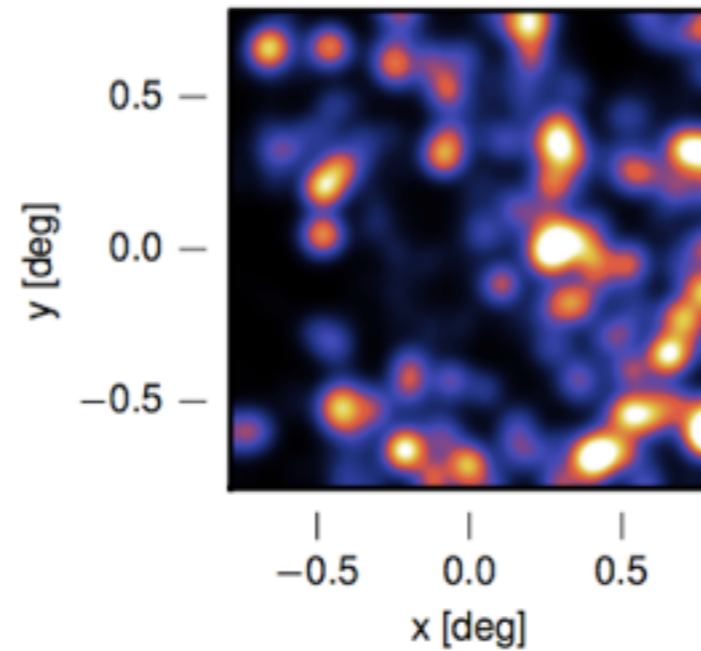


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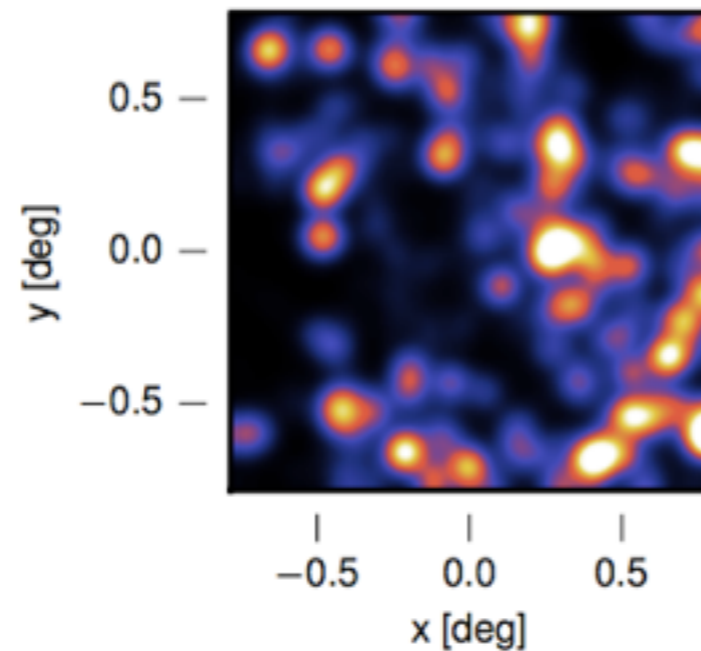
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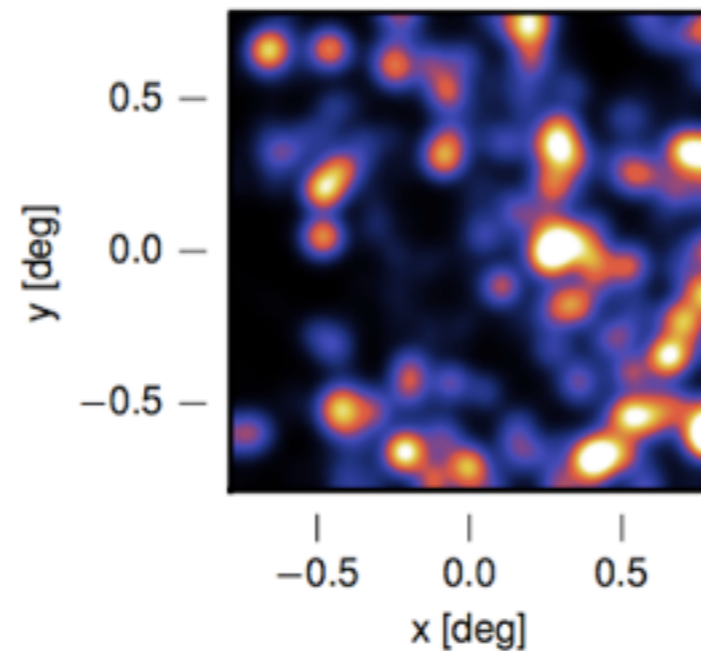
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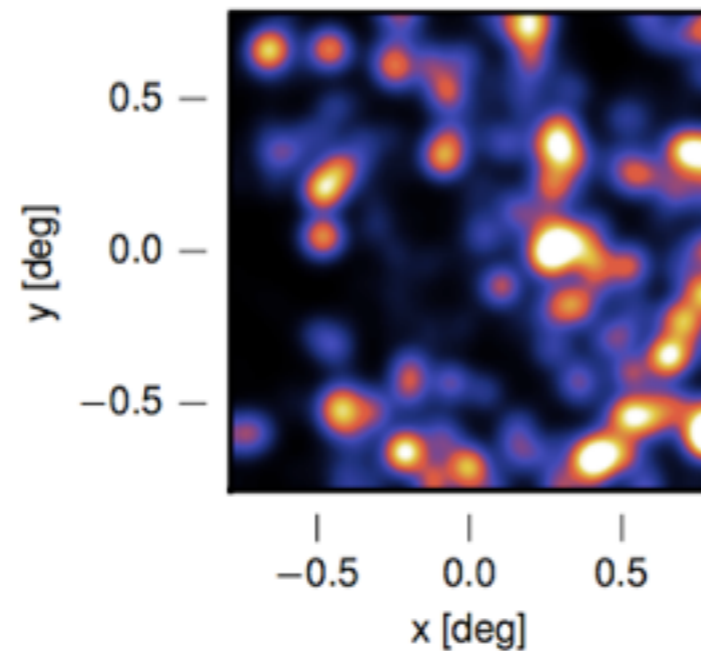
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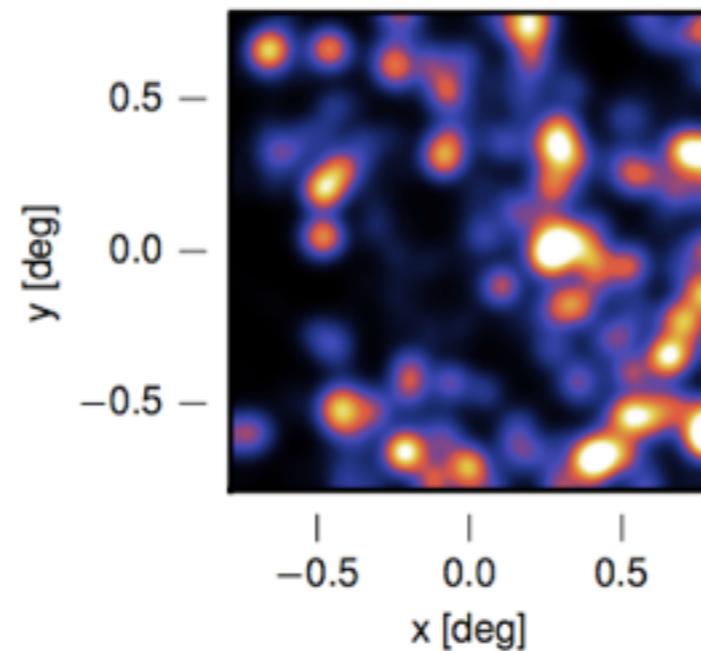
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Emitters trace the  
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The predicted form of the power spectrum:

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Galaxies are  
biased tracers  
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The predicted form of the power spectrum:

$$P_{\text{line}}(k, z) = \langle T_{\text{line}} \rangle^2(z) b^2(z) P_m(k, z)$$



Convert from  
galaxy spectrum  
to line spectrum

# Intensity Mapping: Power Spectrum

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The predicted form of the power spectrum:

$$P_{\text{line}}(k, z) = \langle T_{\text{line}} \rangle^2(z) b^2(z) P_m(k, z) + P_{\text{shot}}(z)$$



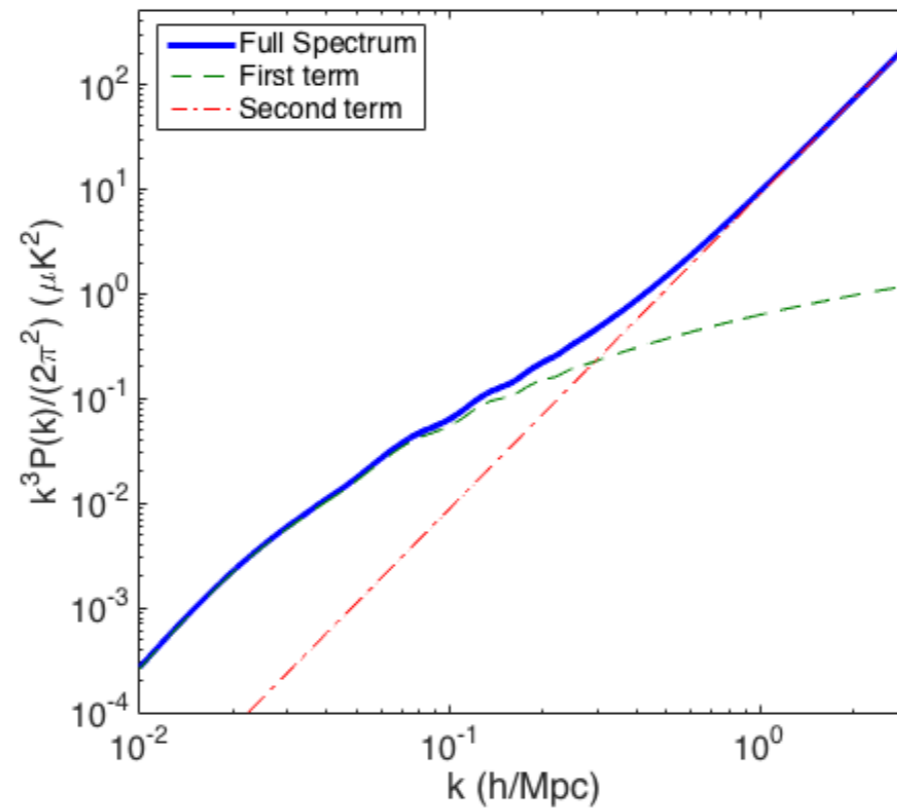
We measure emission  
from discrete sources

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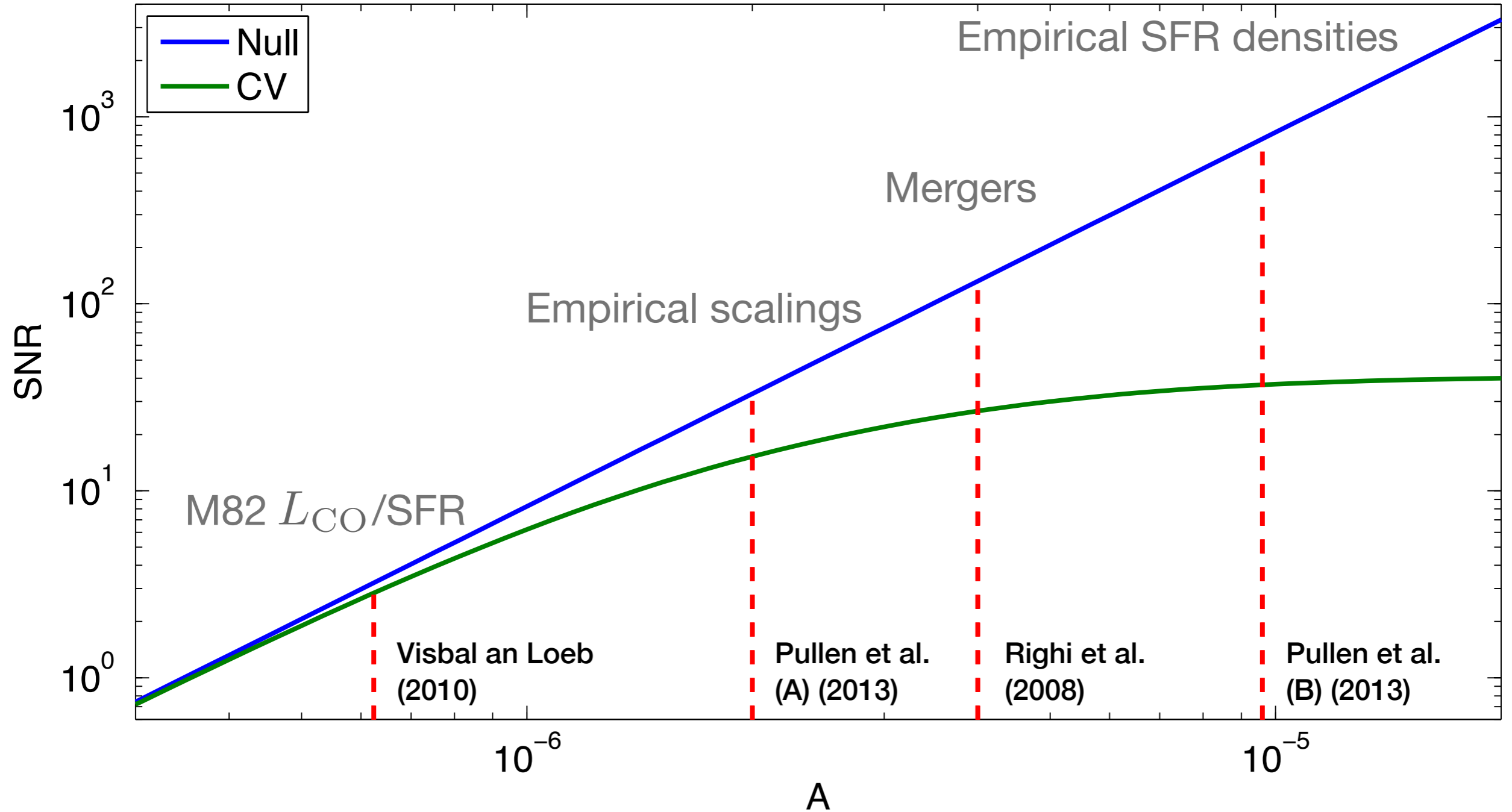
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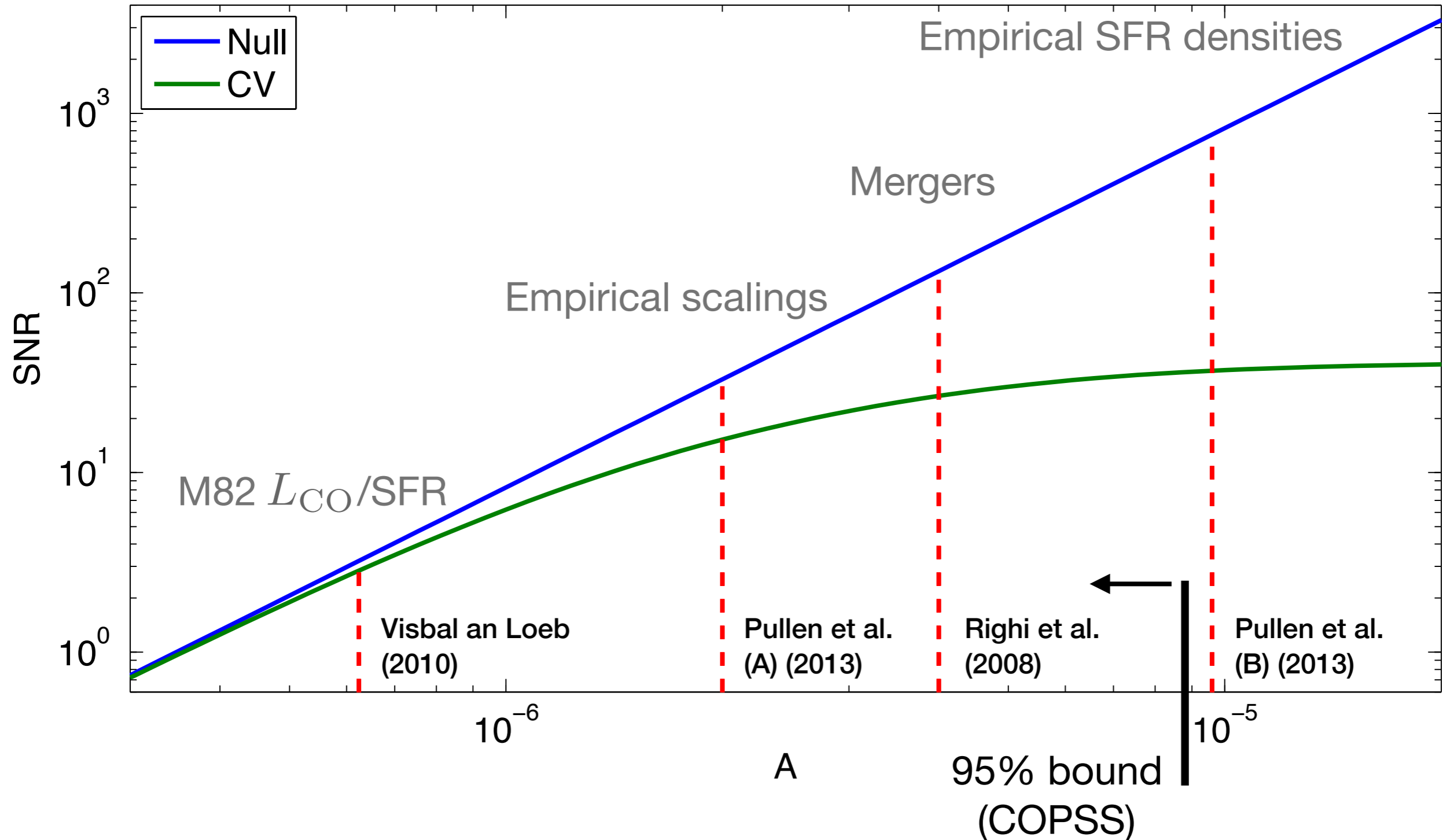
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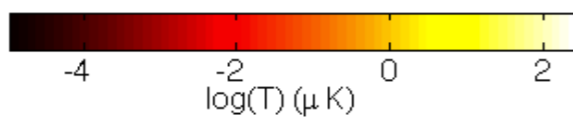
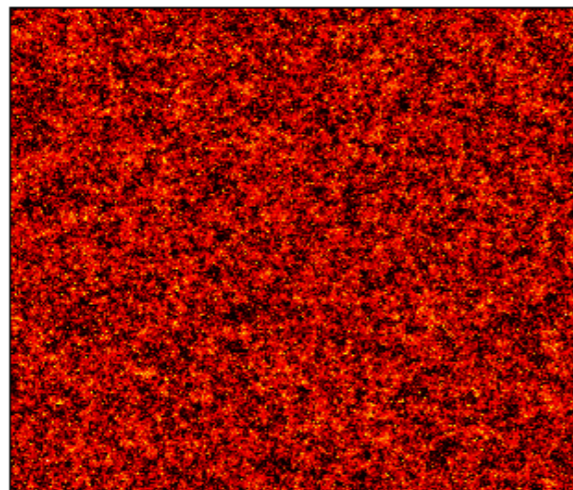
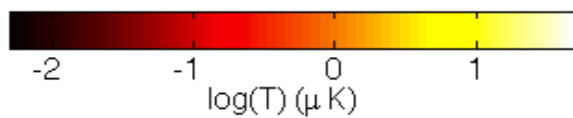
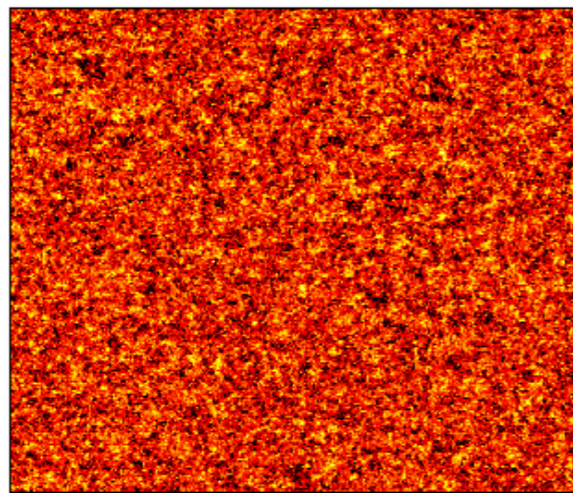
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CO (HCN)



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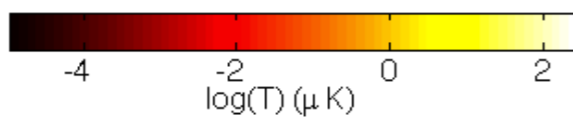
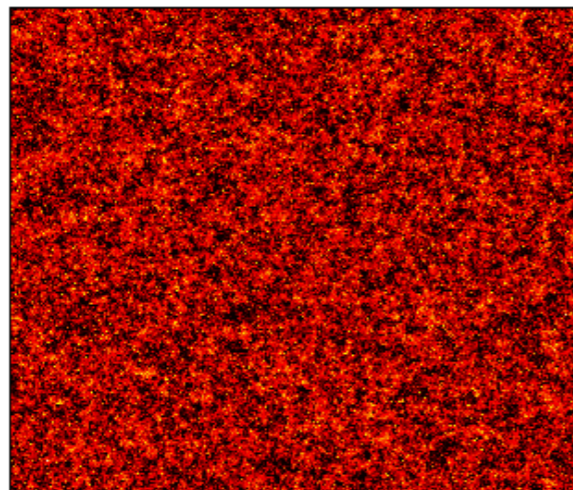
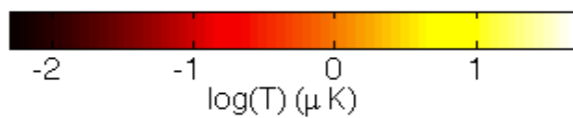
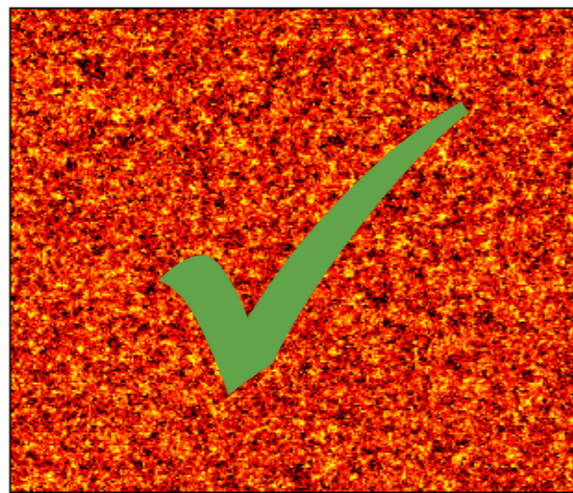
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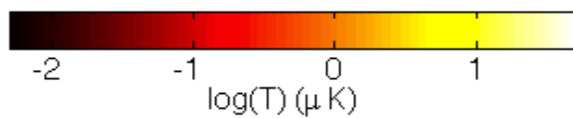
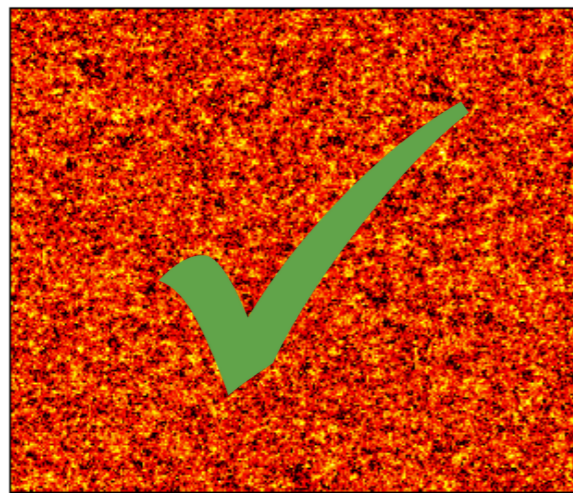
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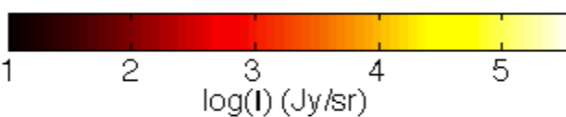
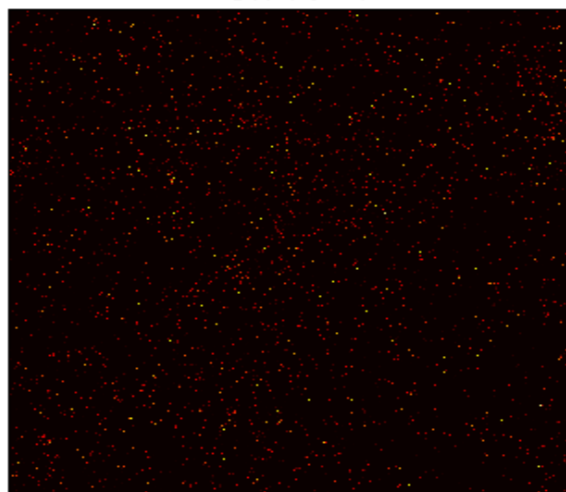
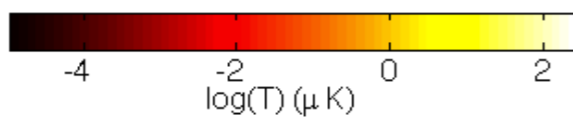
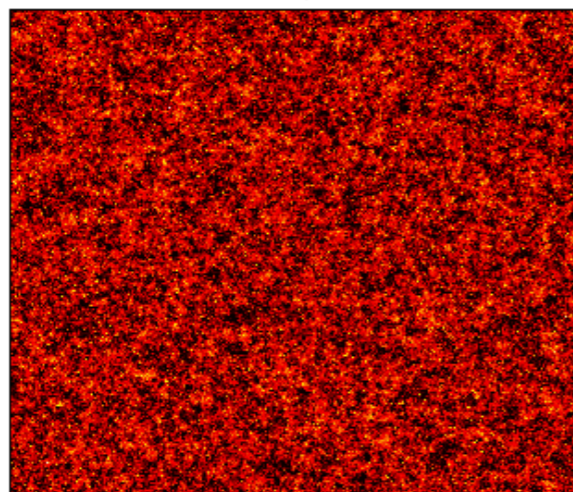
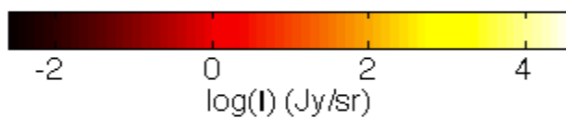
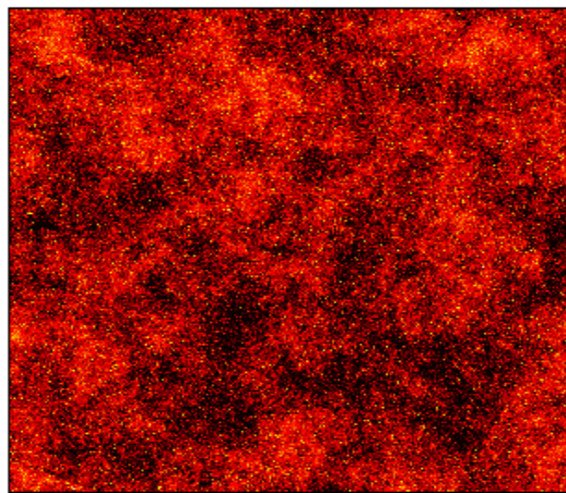
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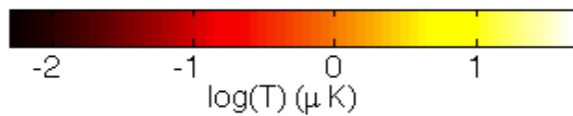
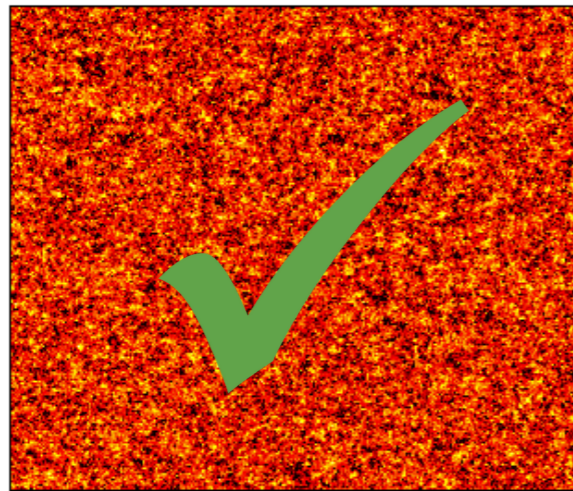
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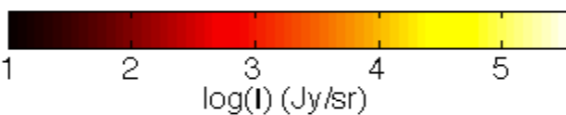
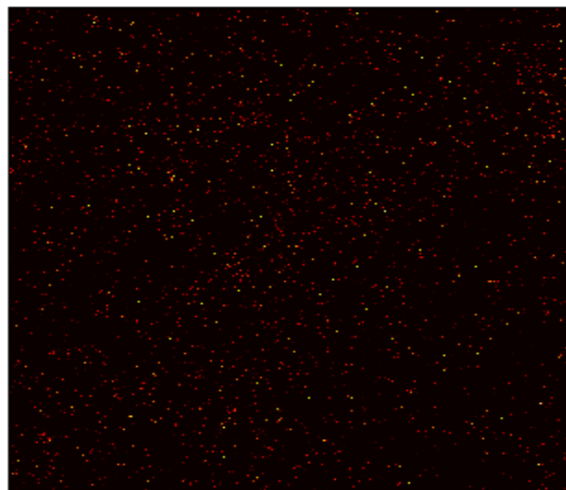
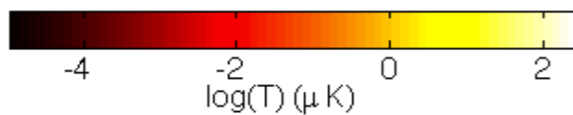
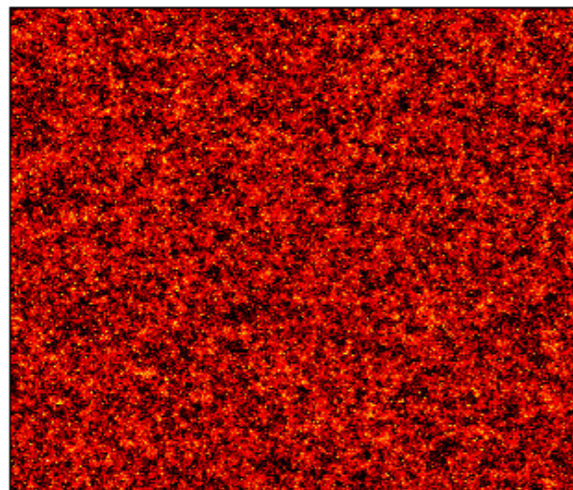
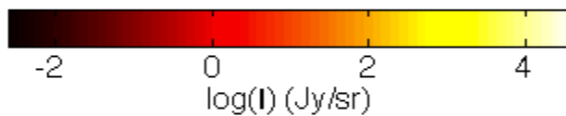
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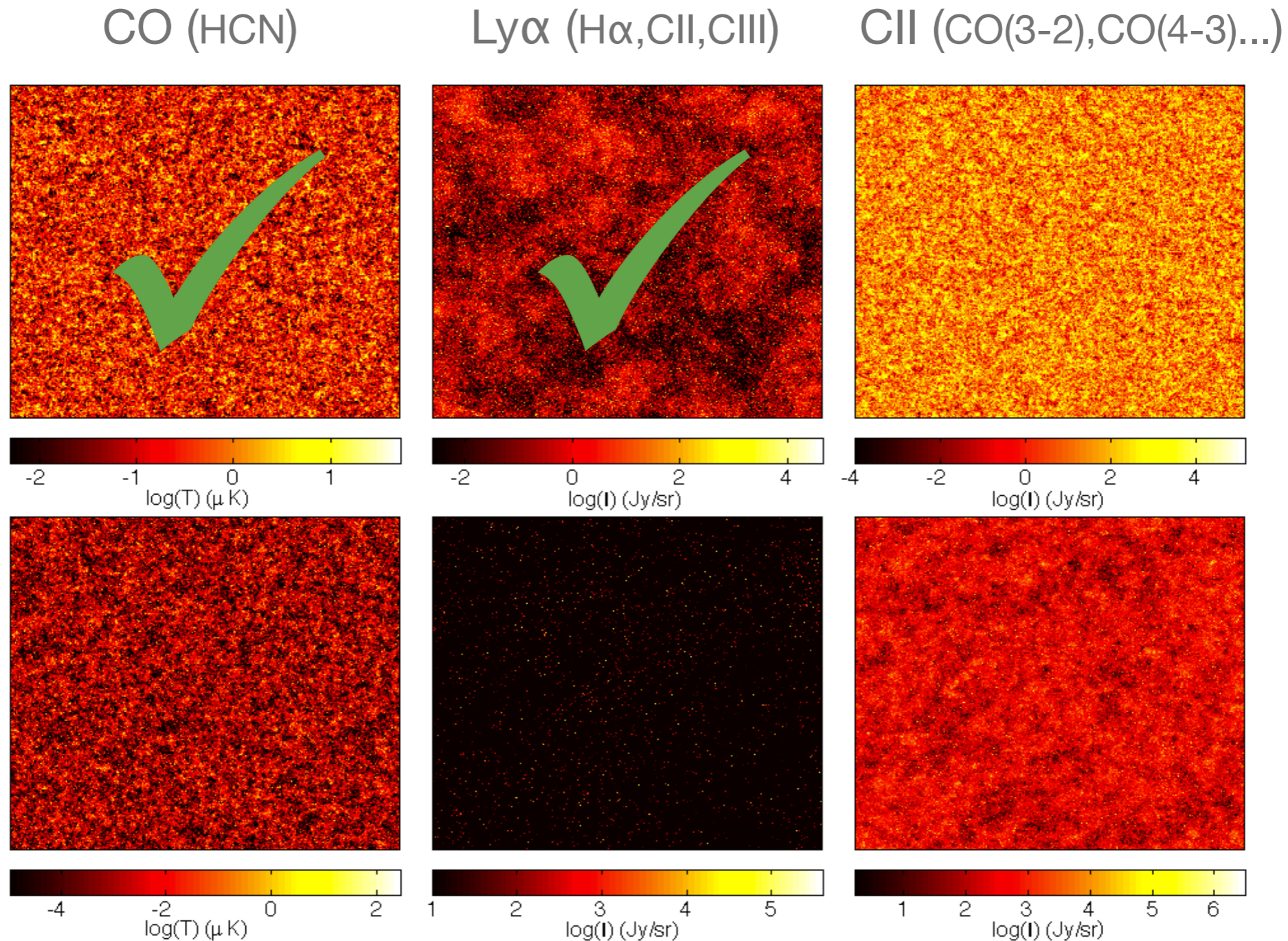


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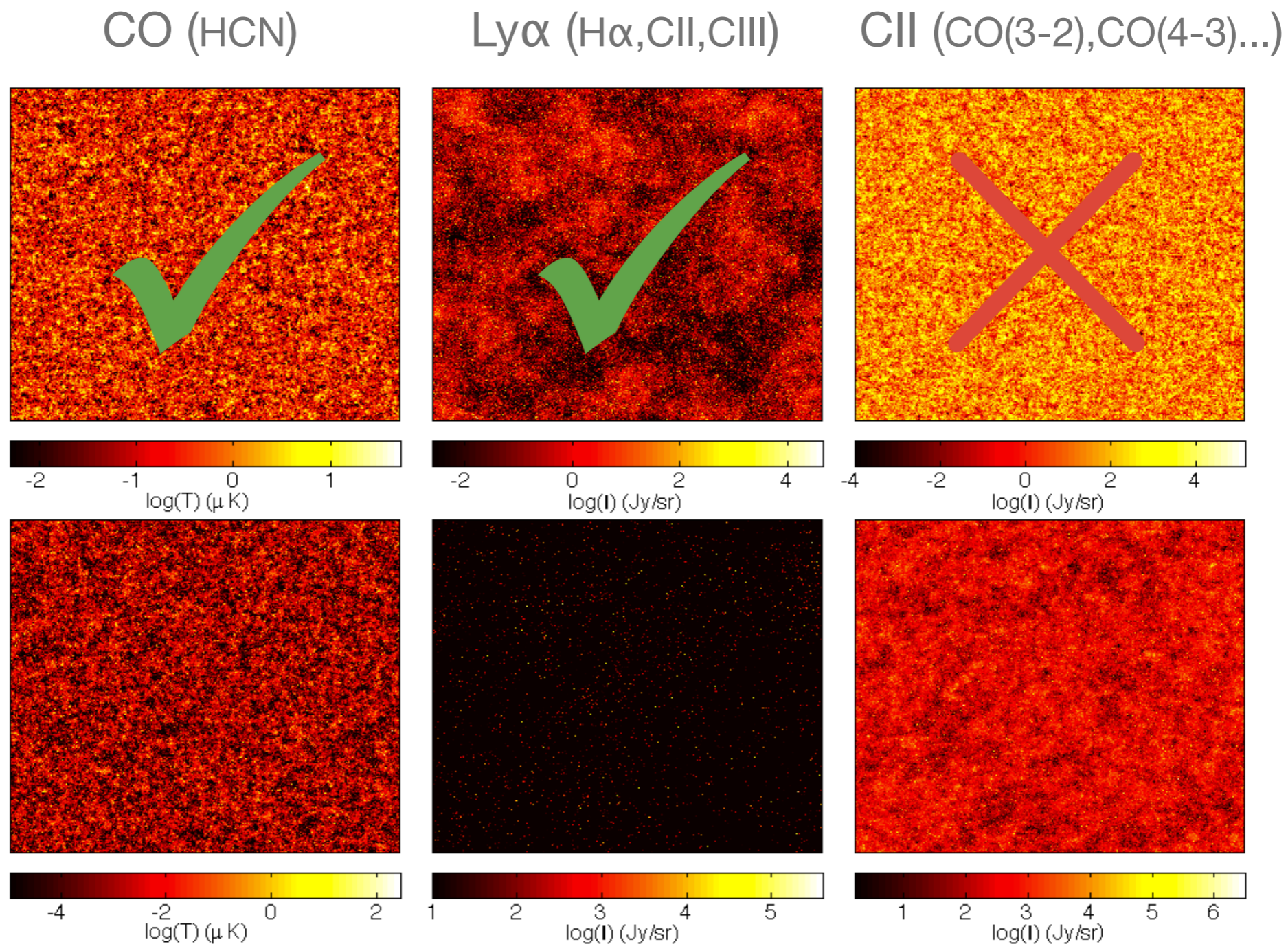


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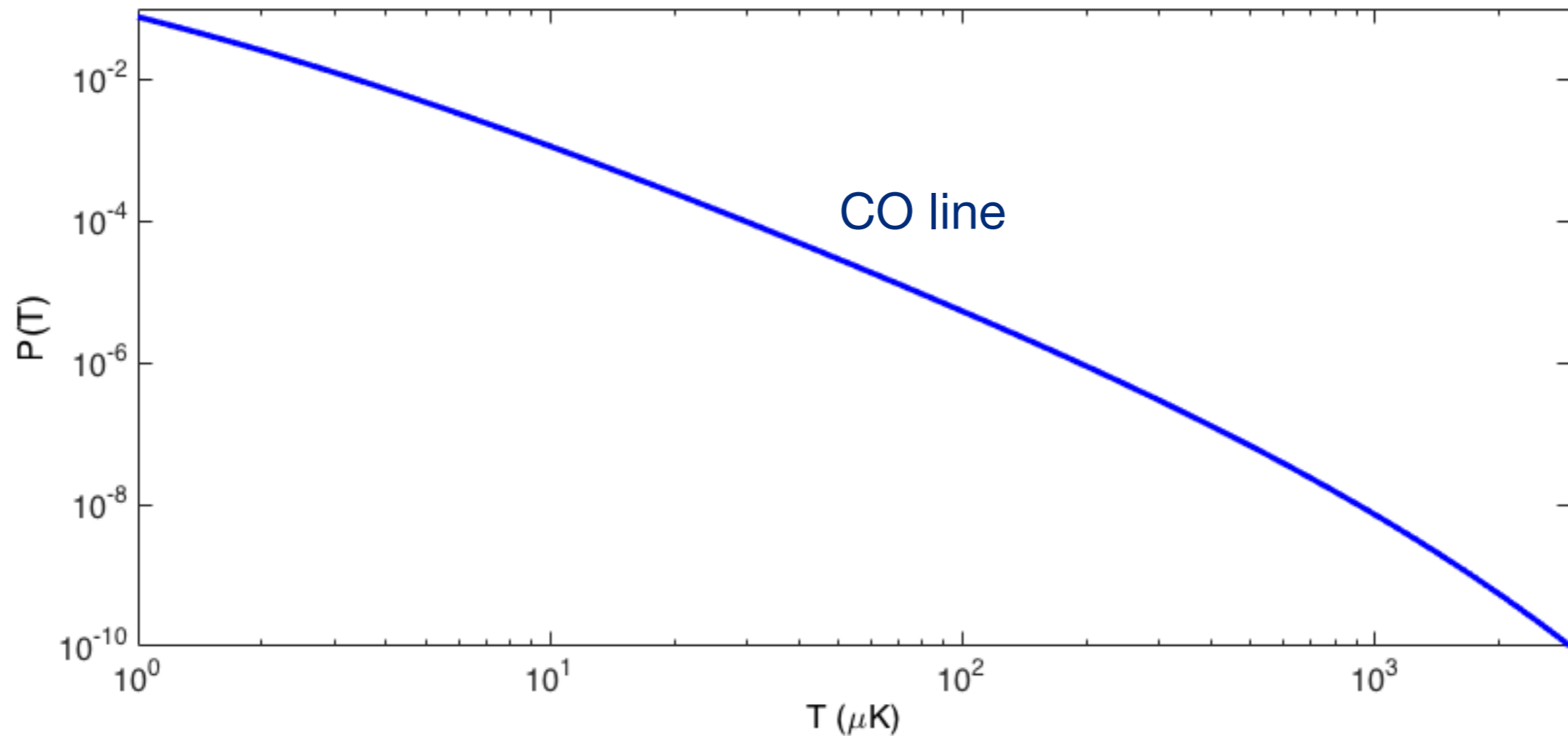
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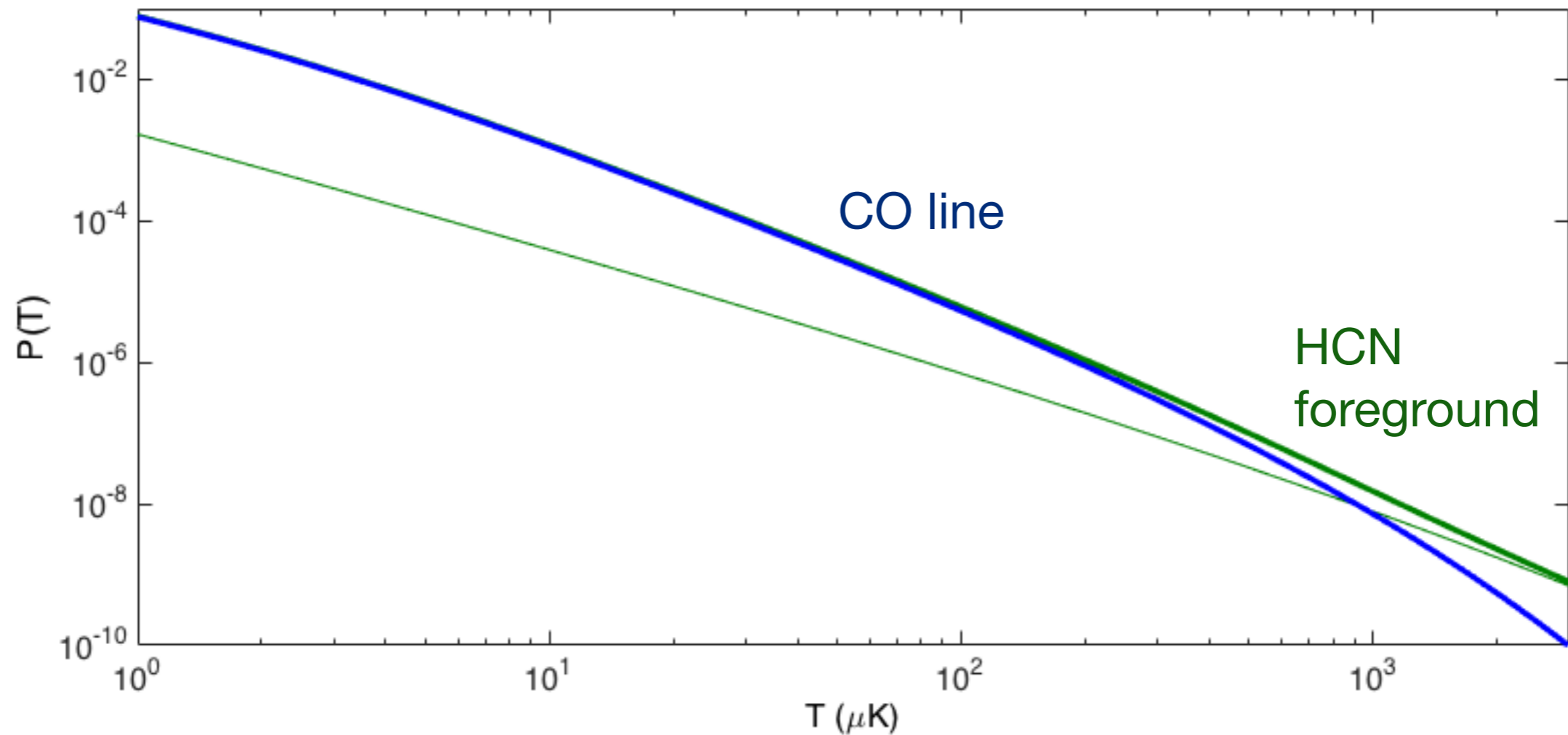
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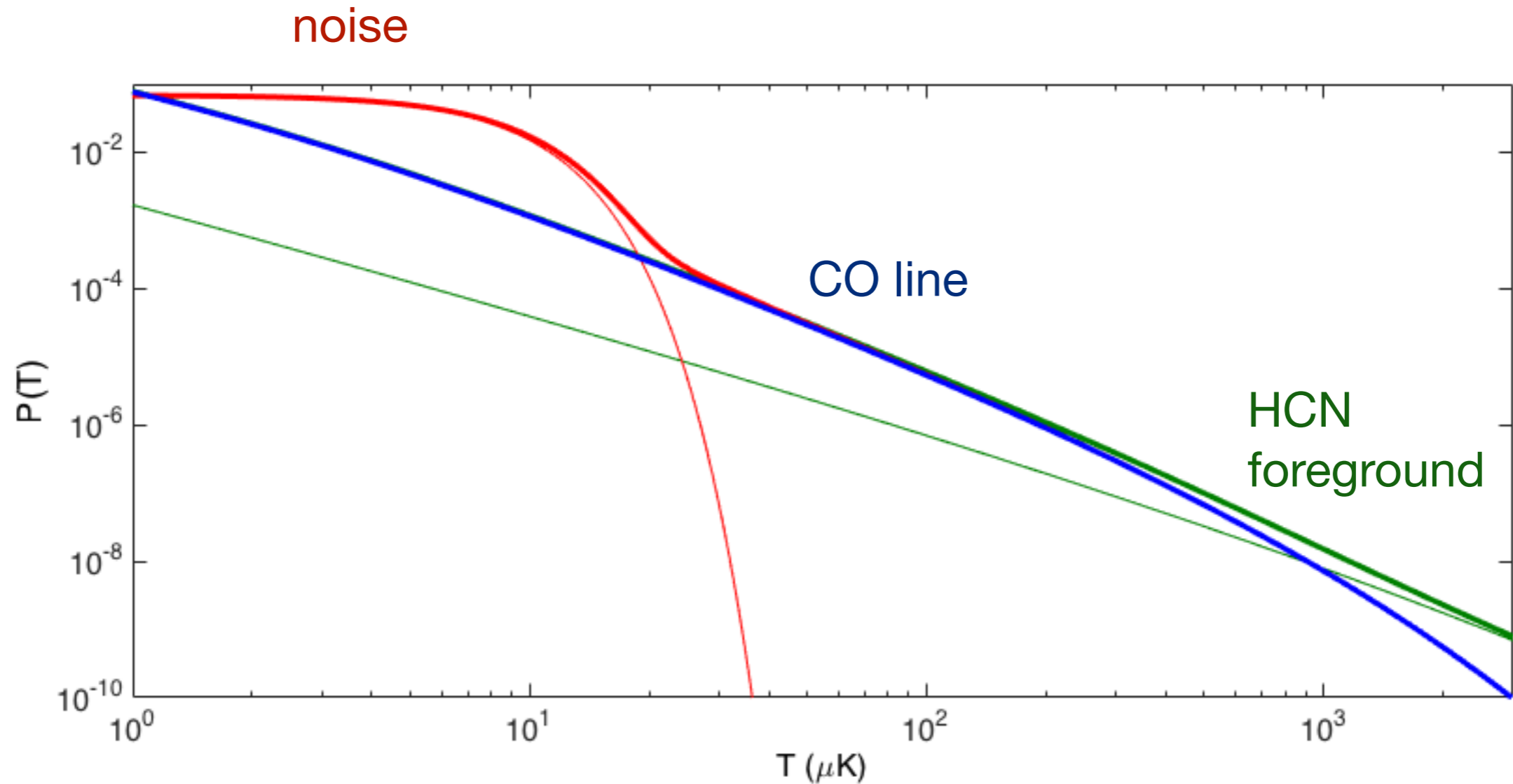
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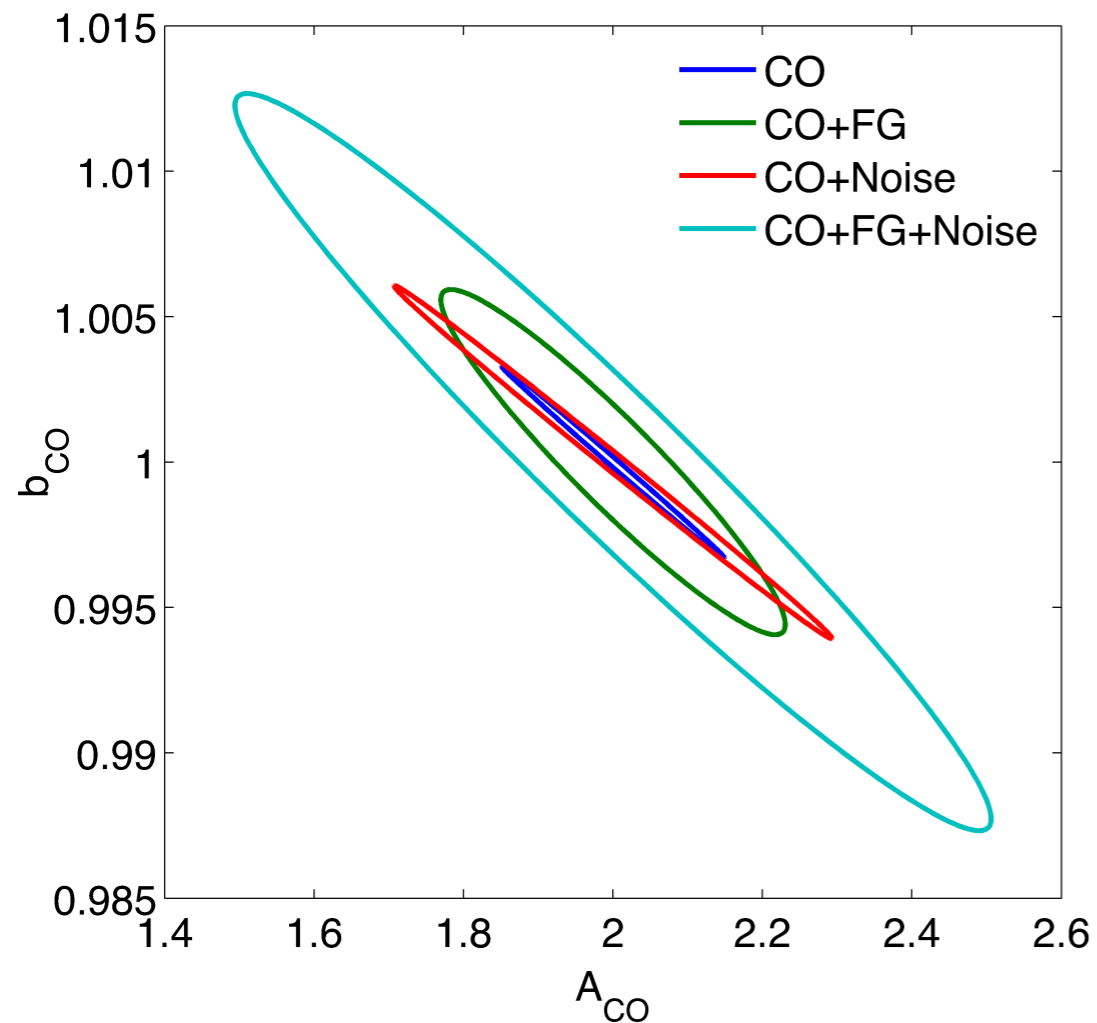
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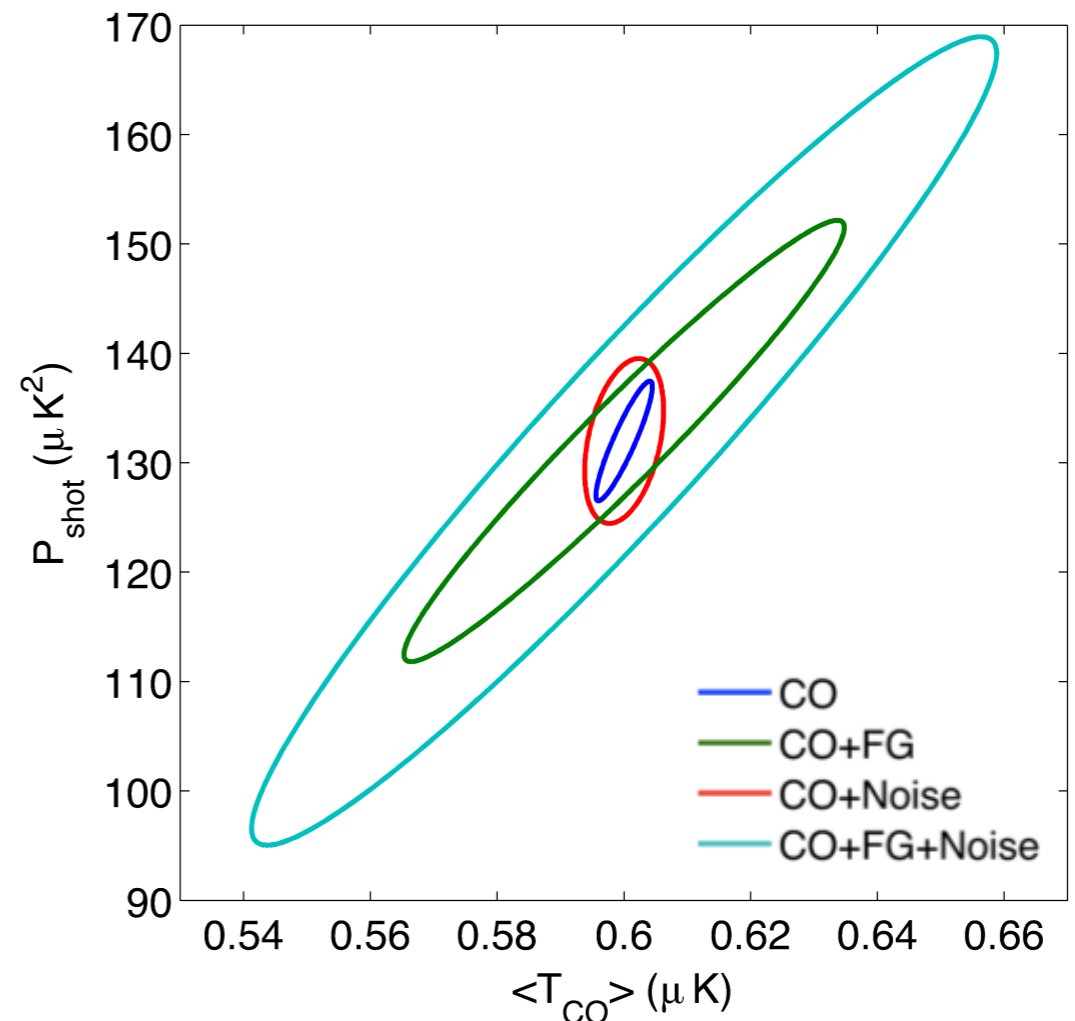
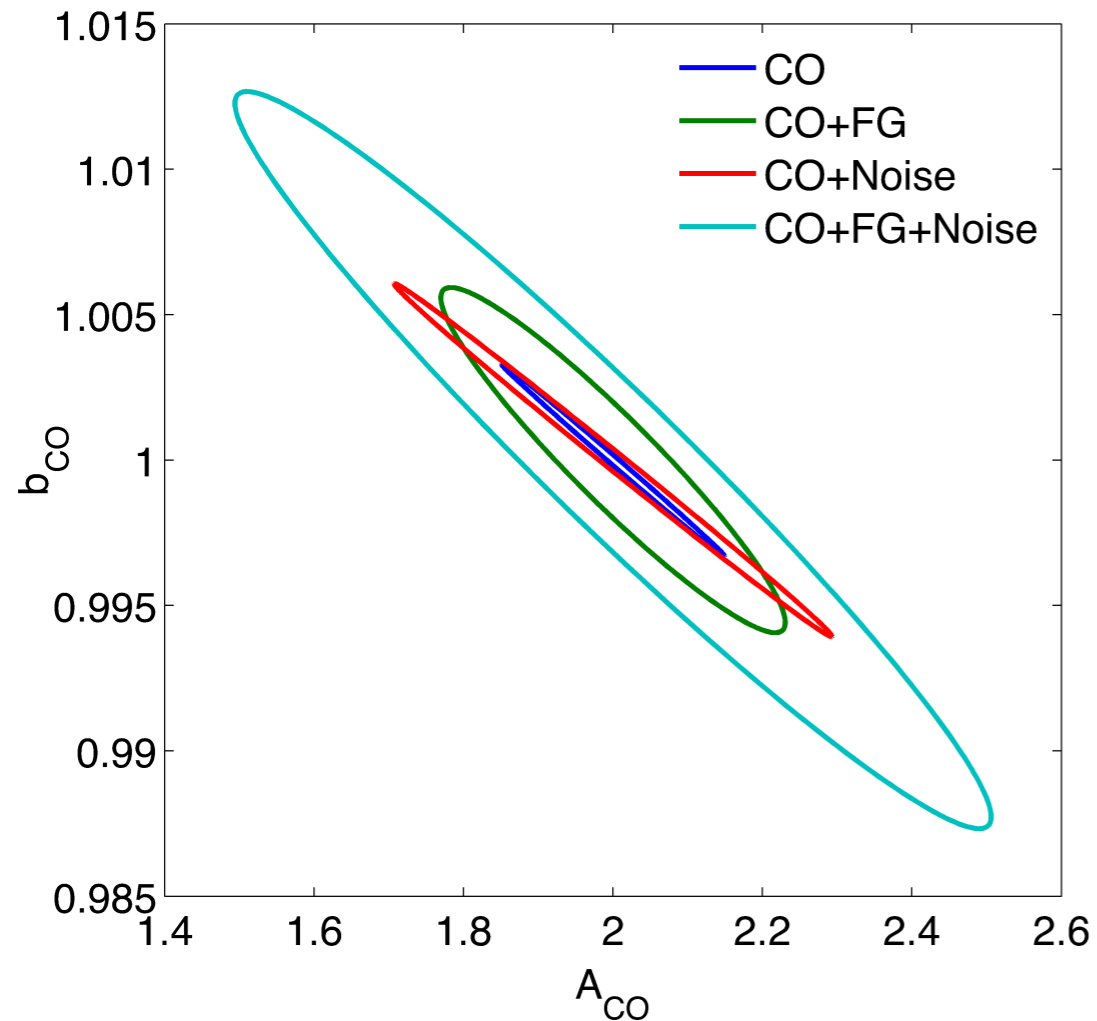
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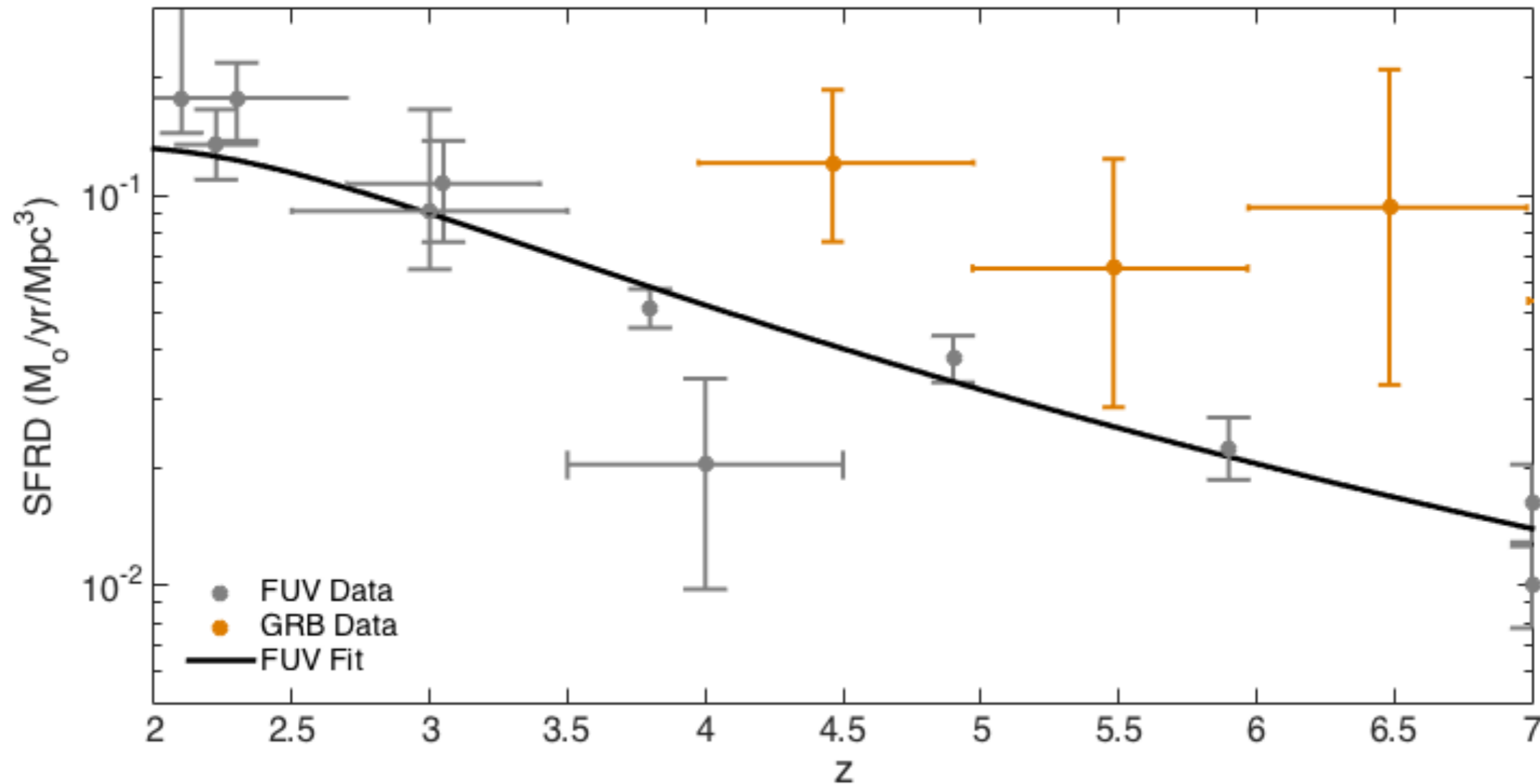
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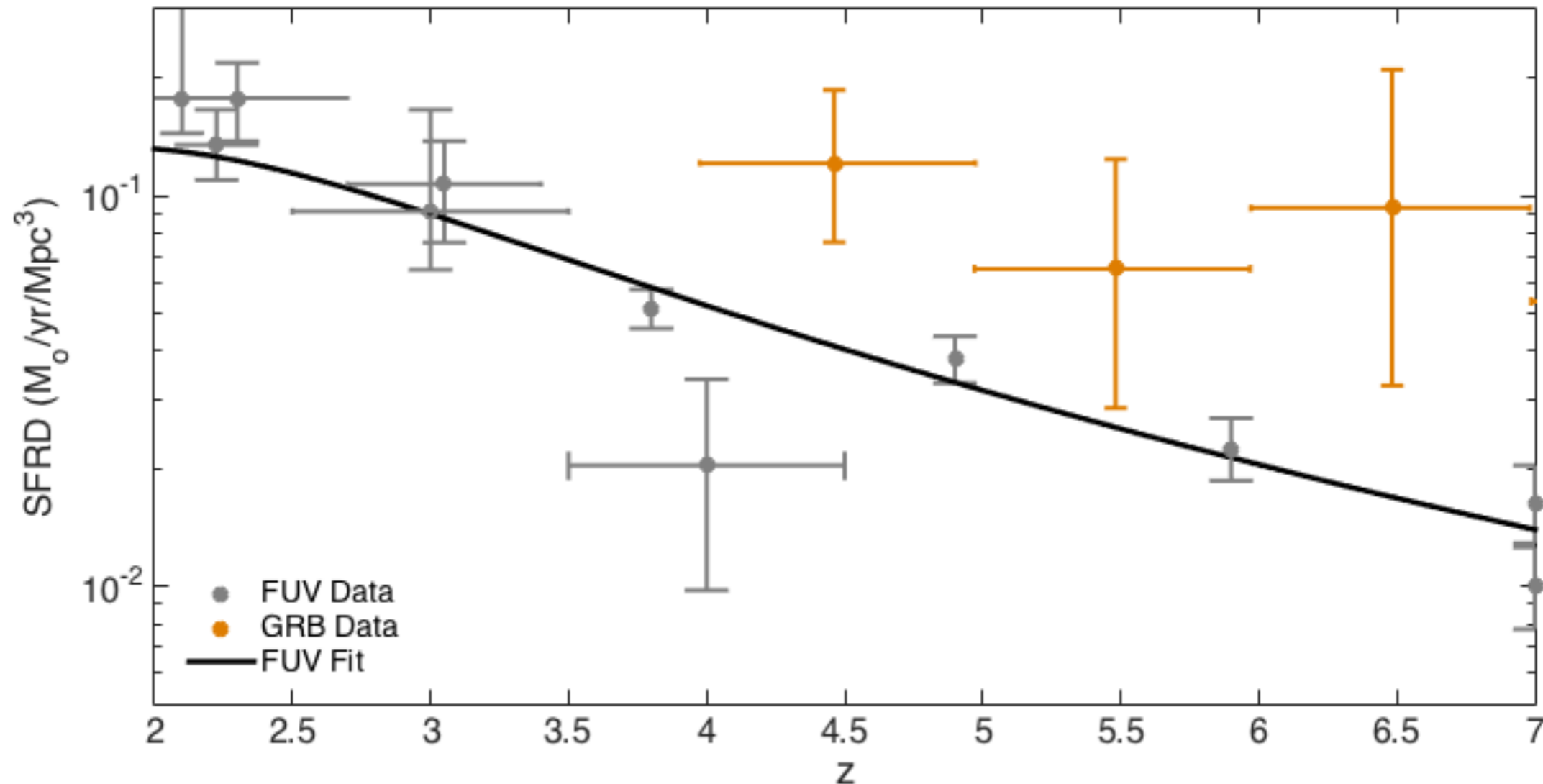


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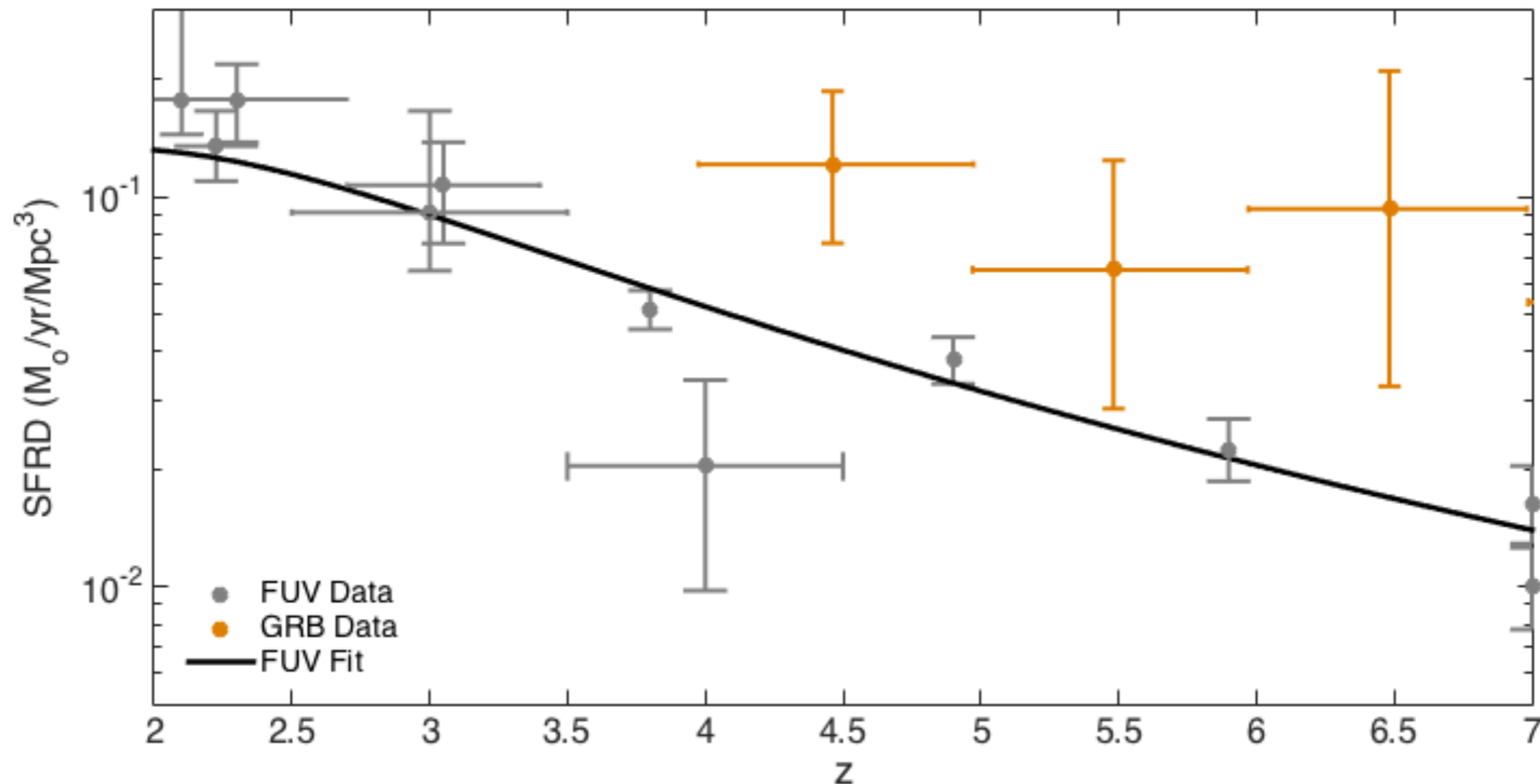


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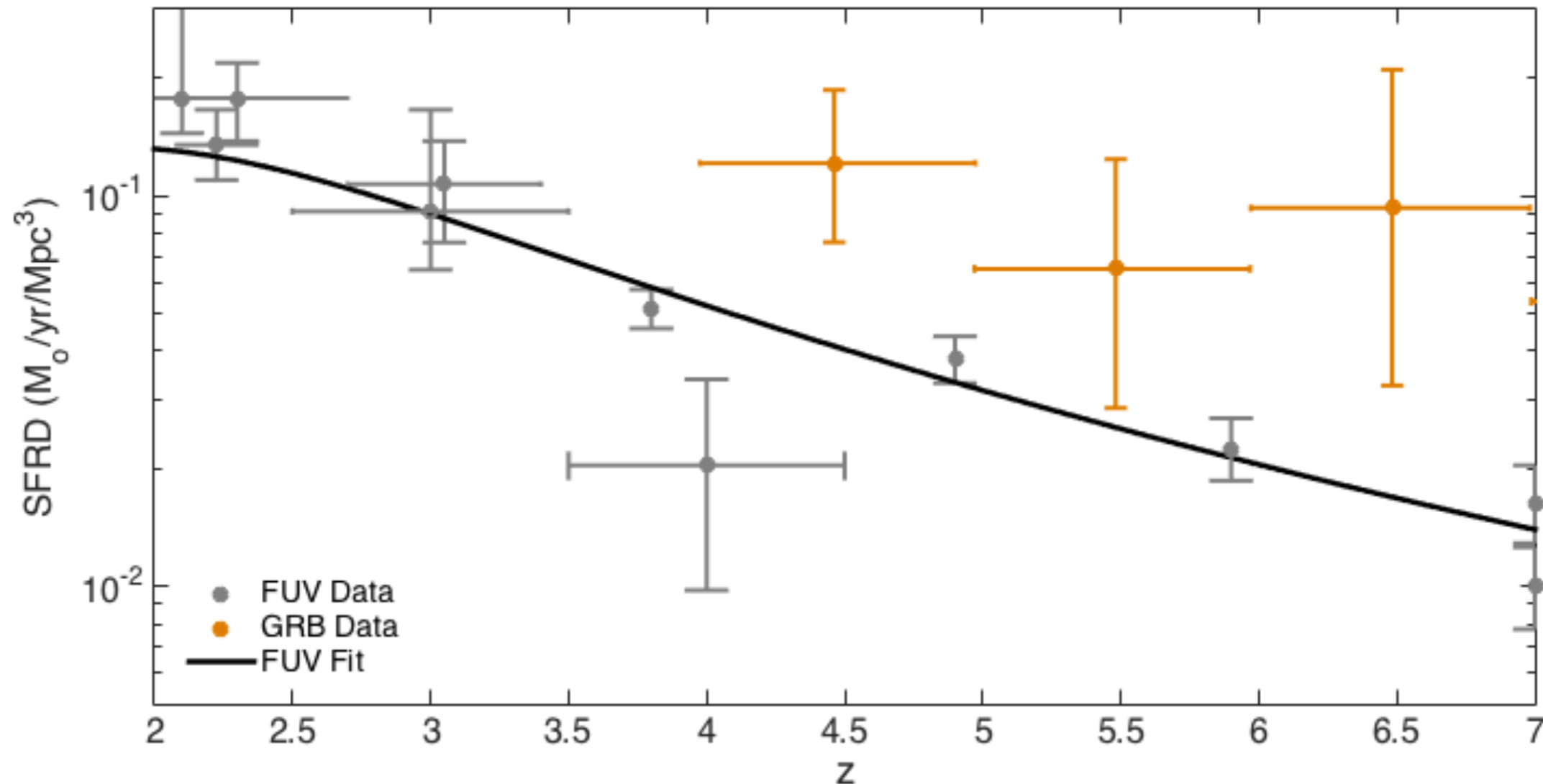


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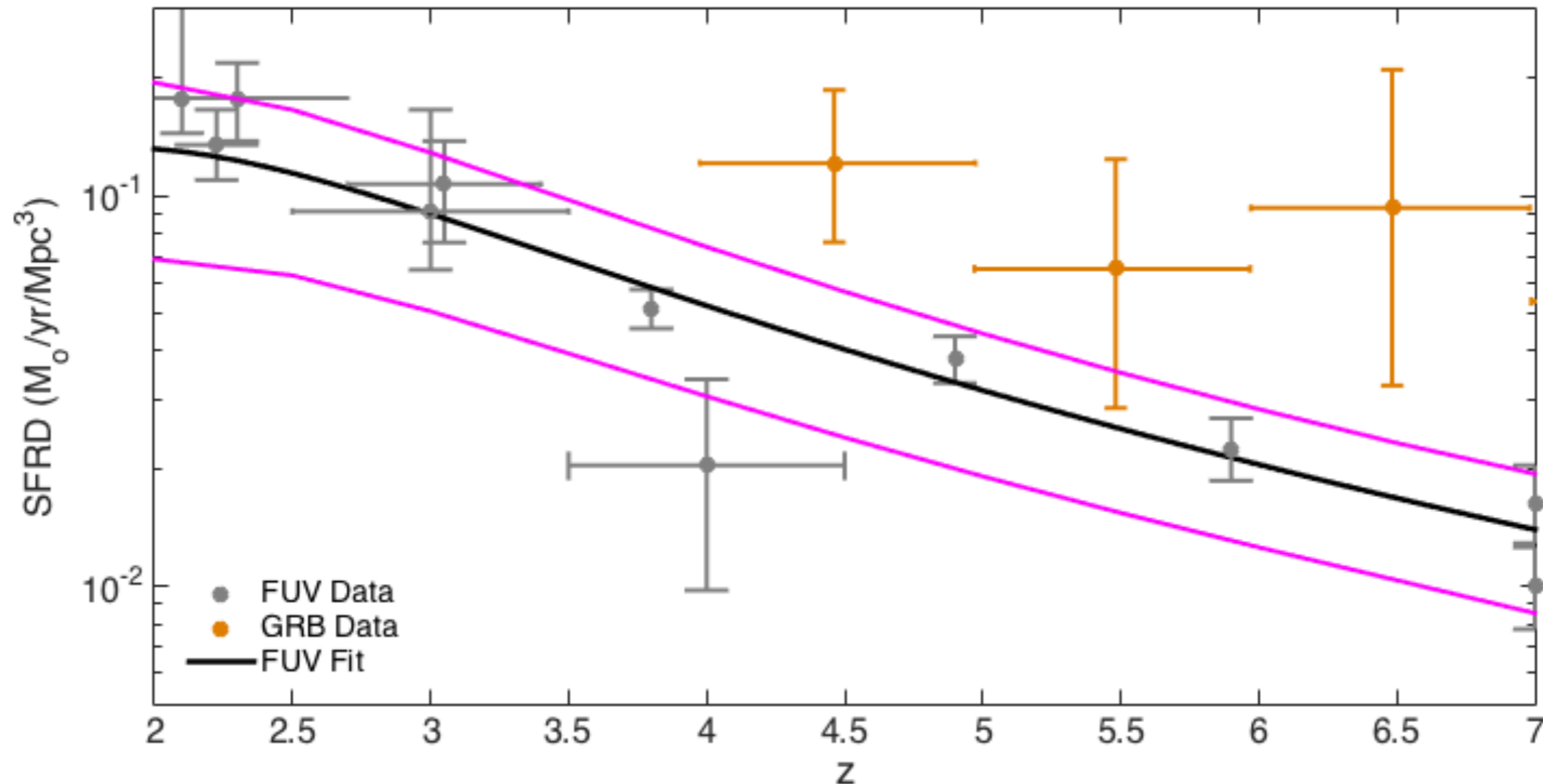


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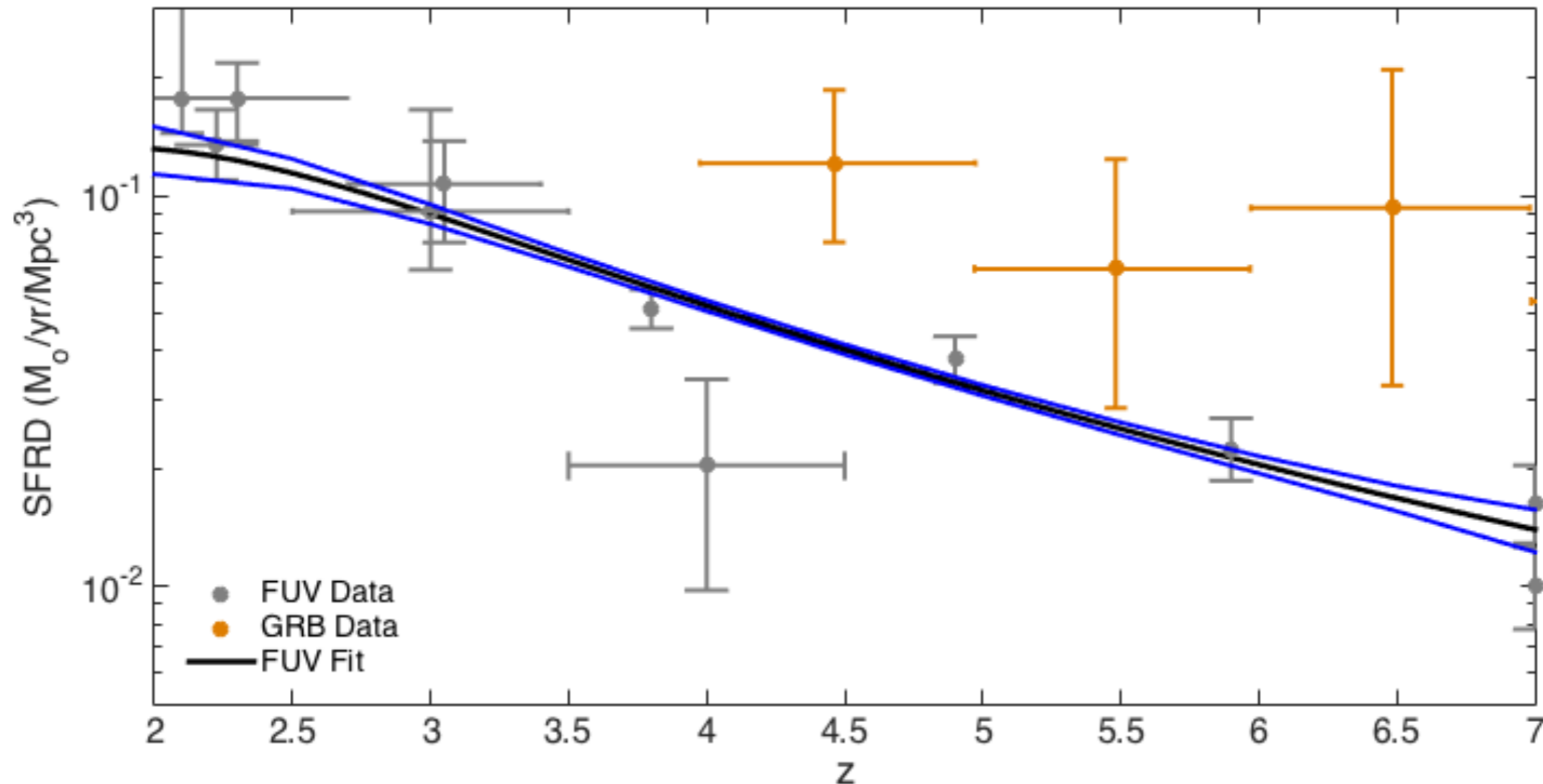


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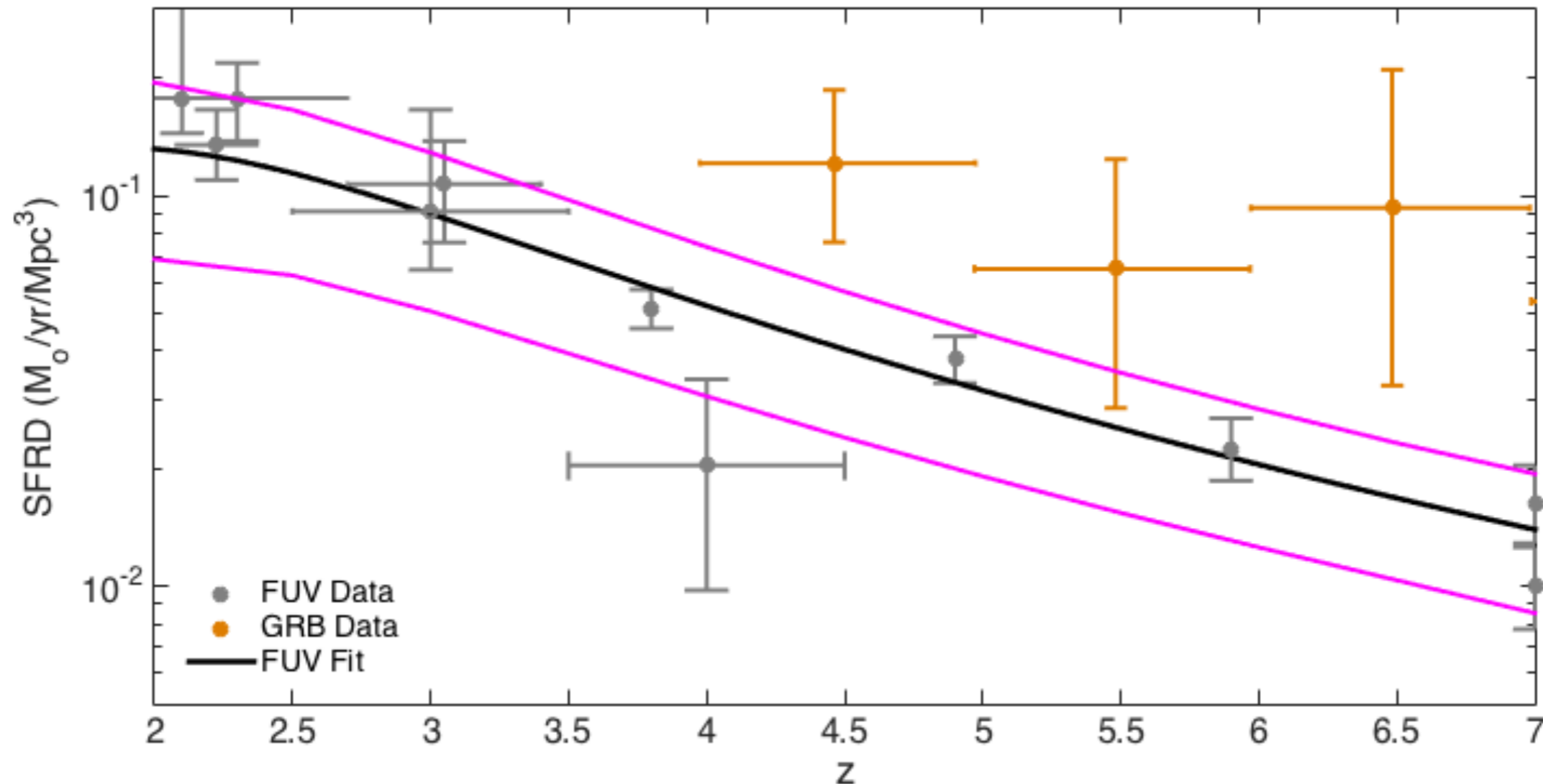


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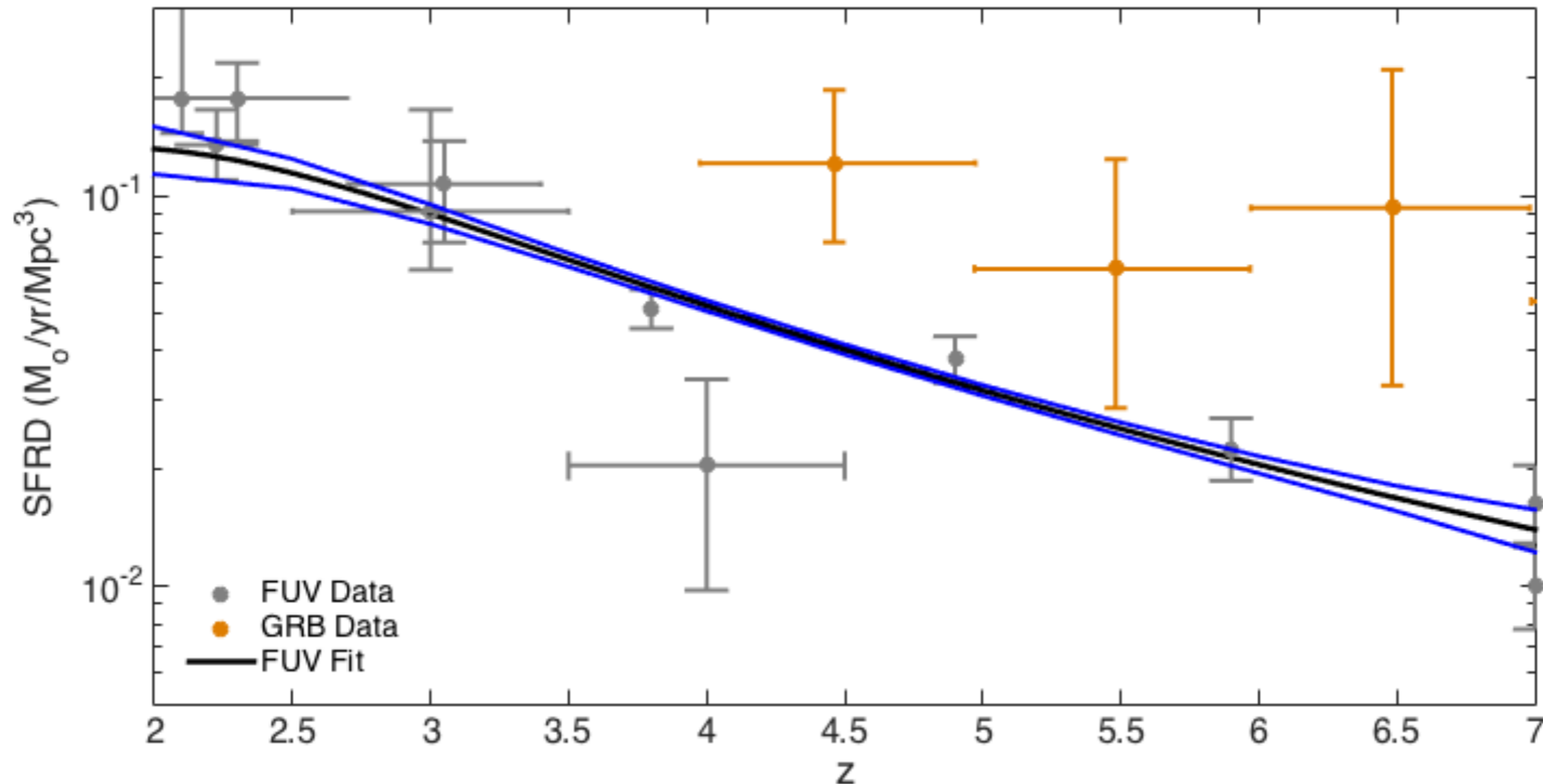


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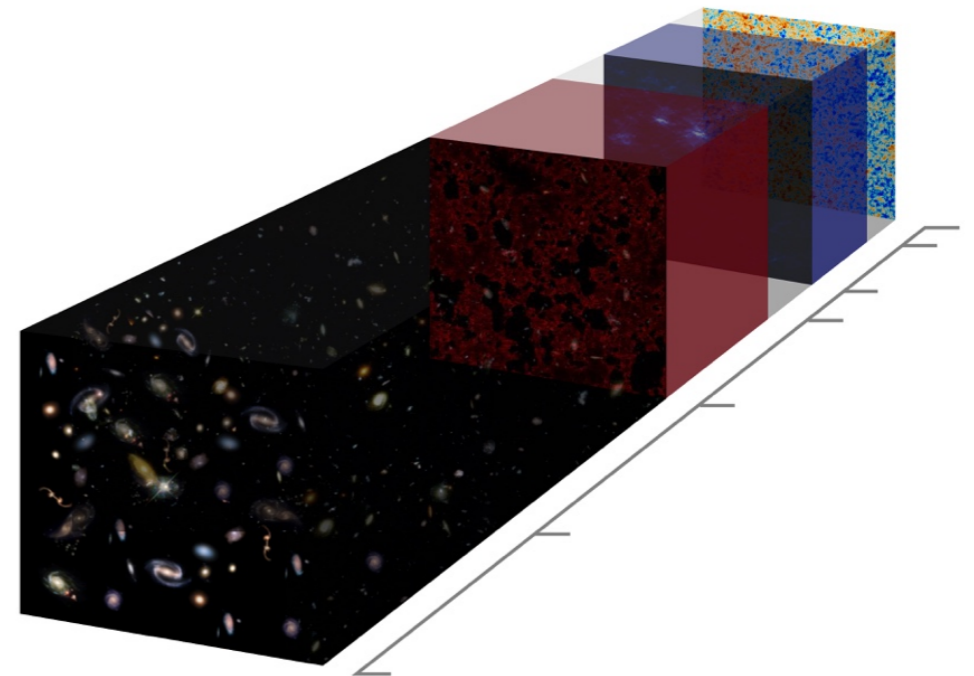
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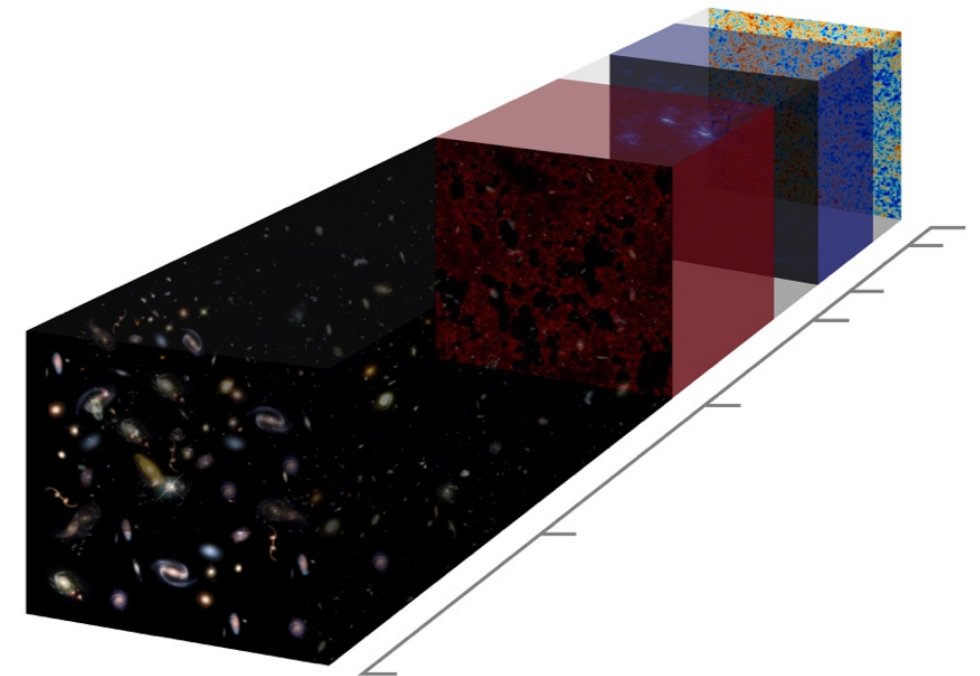


# Outline

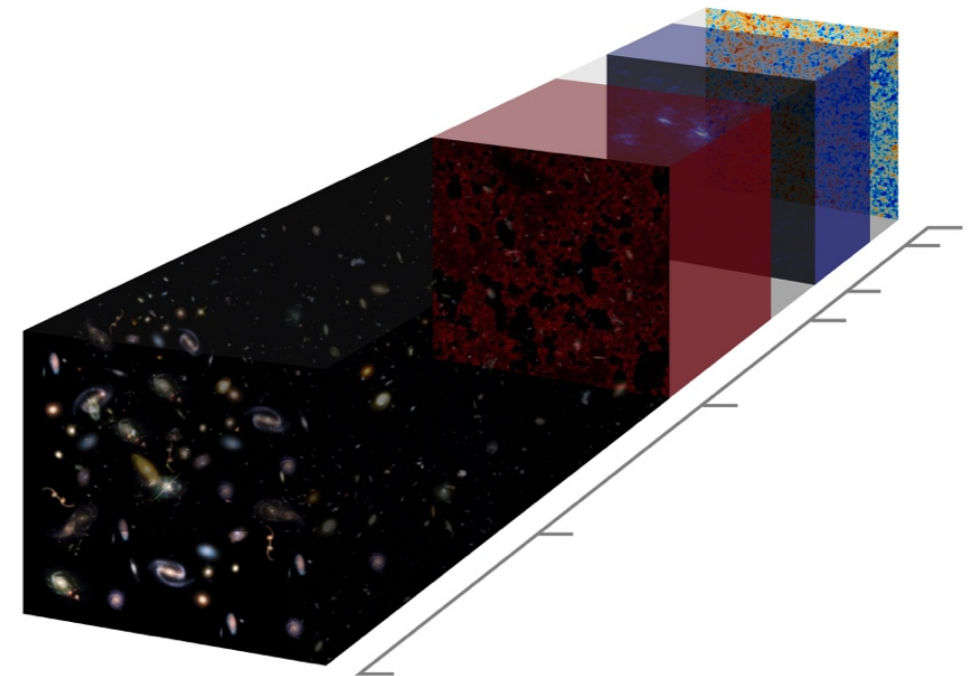
Ely D. Kovetz  
WIS, Jan. 2016



- The quest for B-modes from Inflationary GWs
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# Probing the dark sector in new dimensions: $z$

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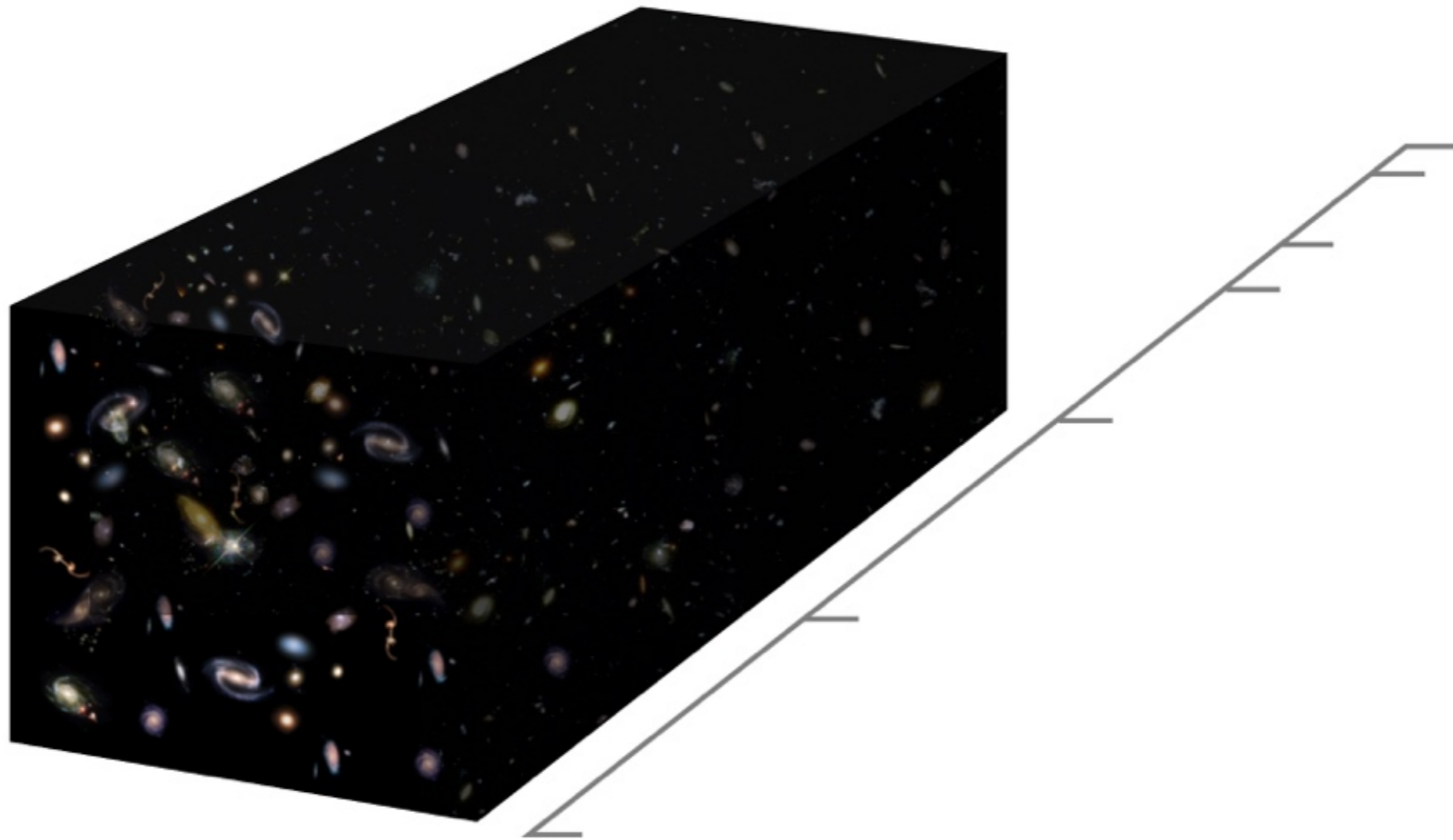
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Large deep surveys lack redshift information.

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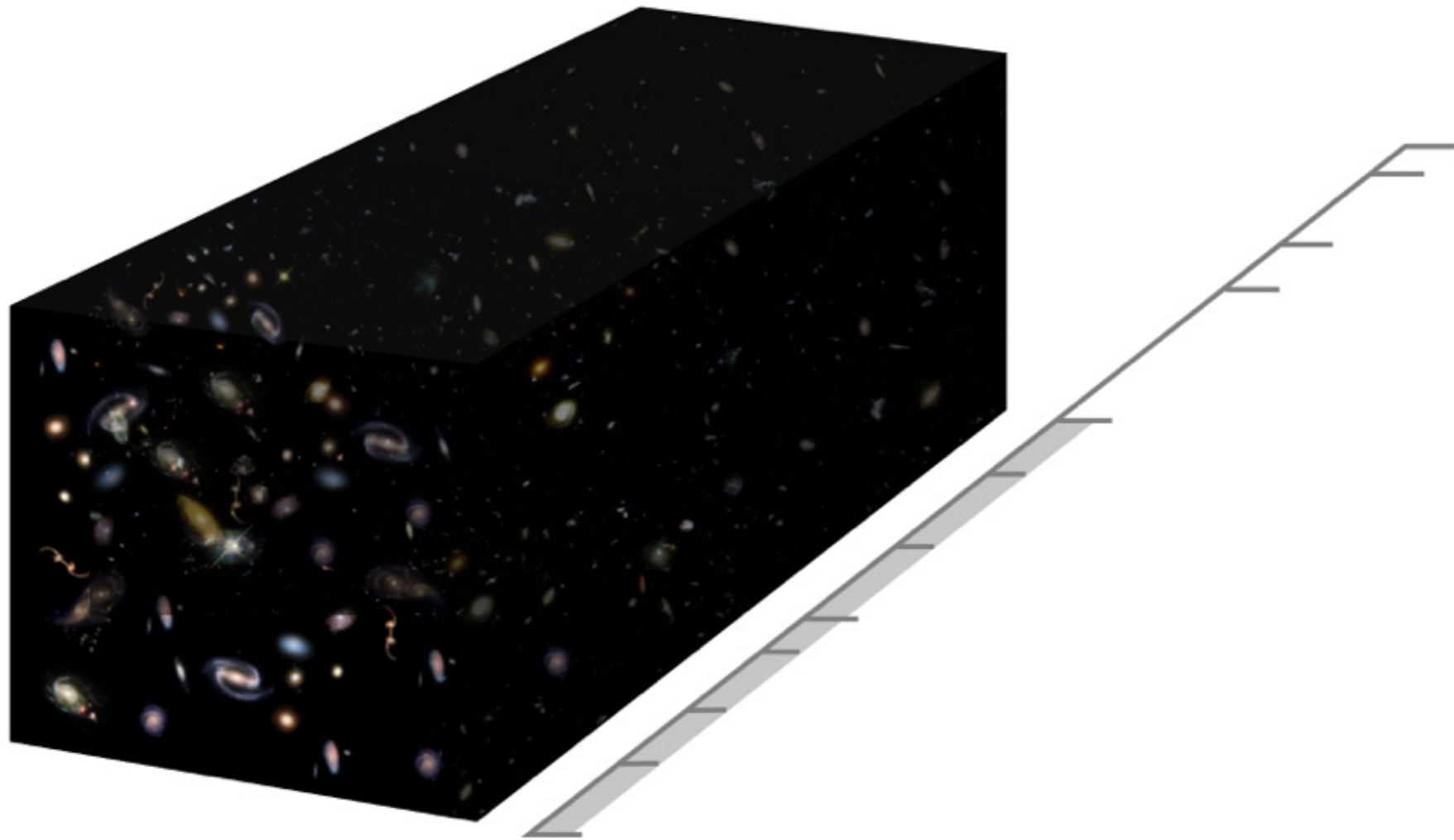
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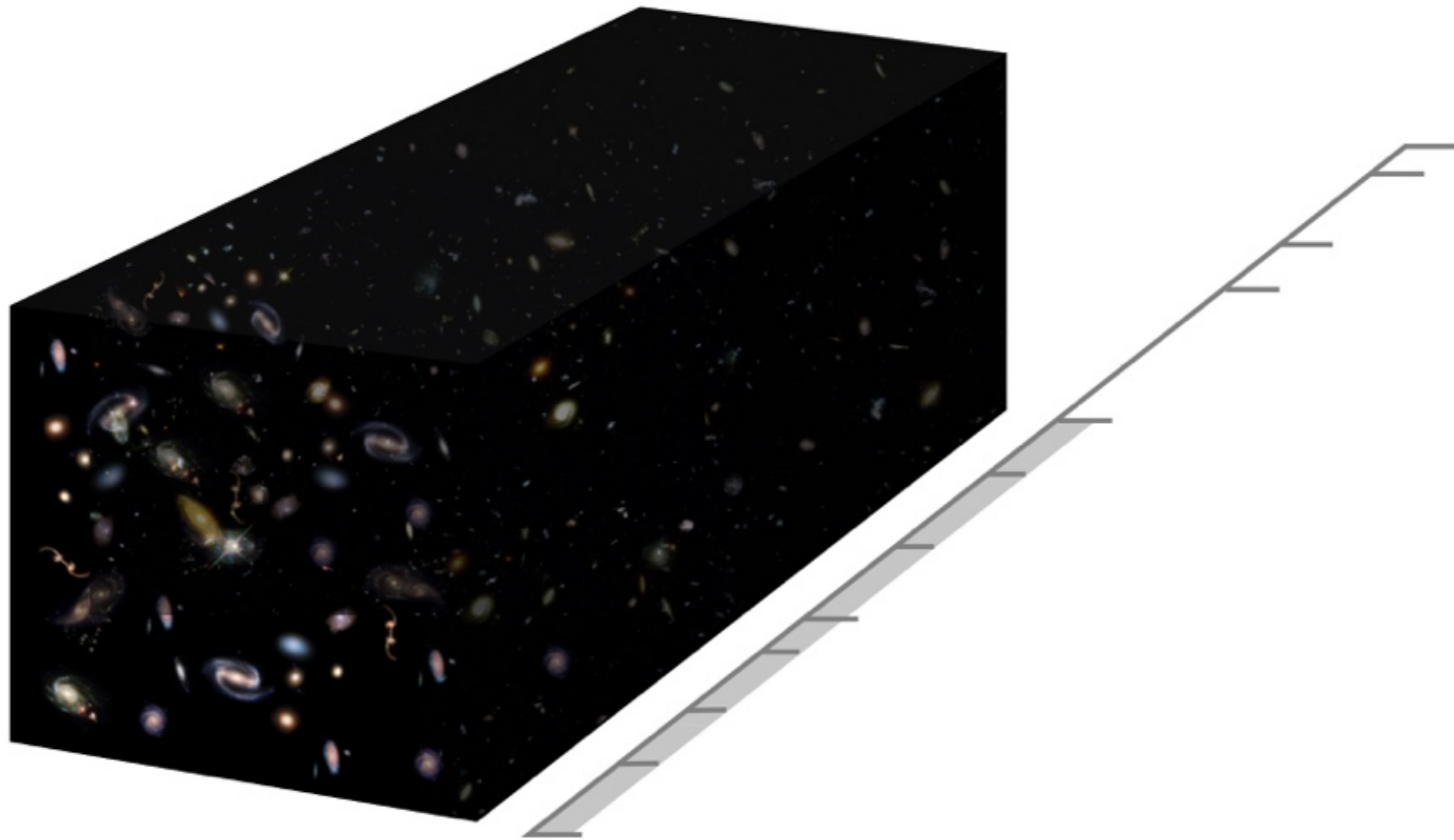


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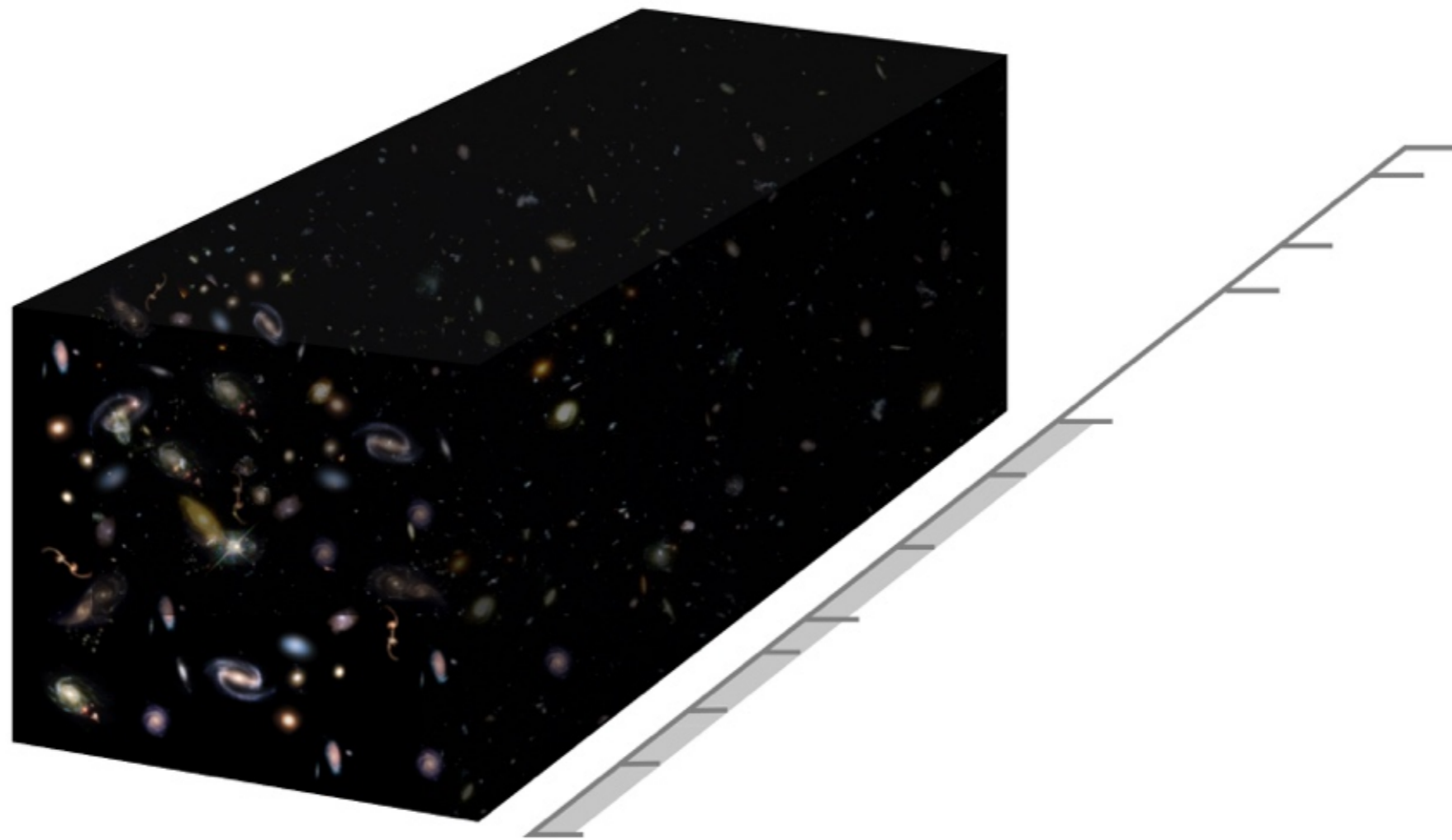


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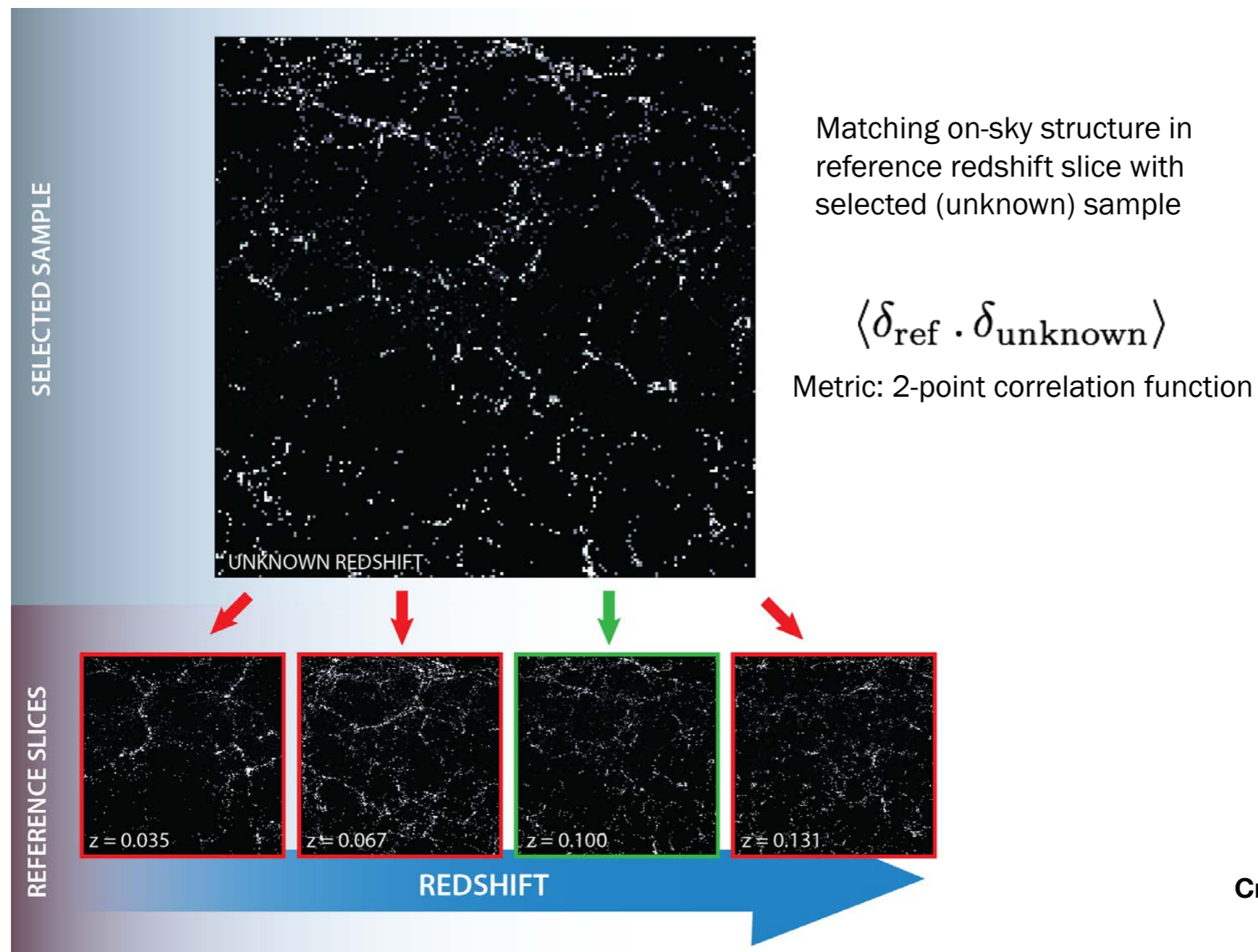
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Credit: M. Rahman

# Cosmology with Clustering Redshift Estimation

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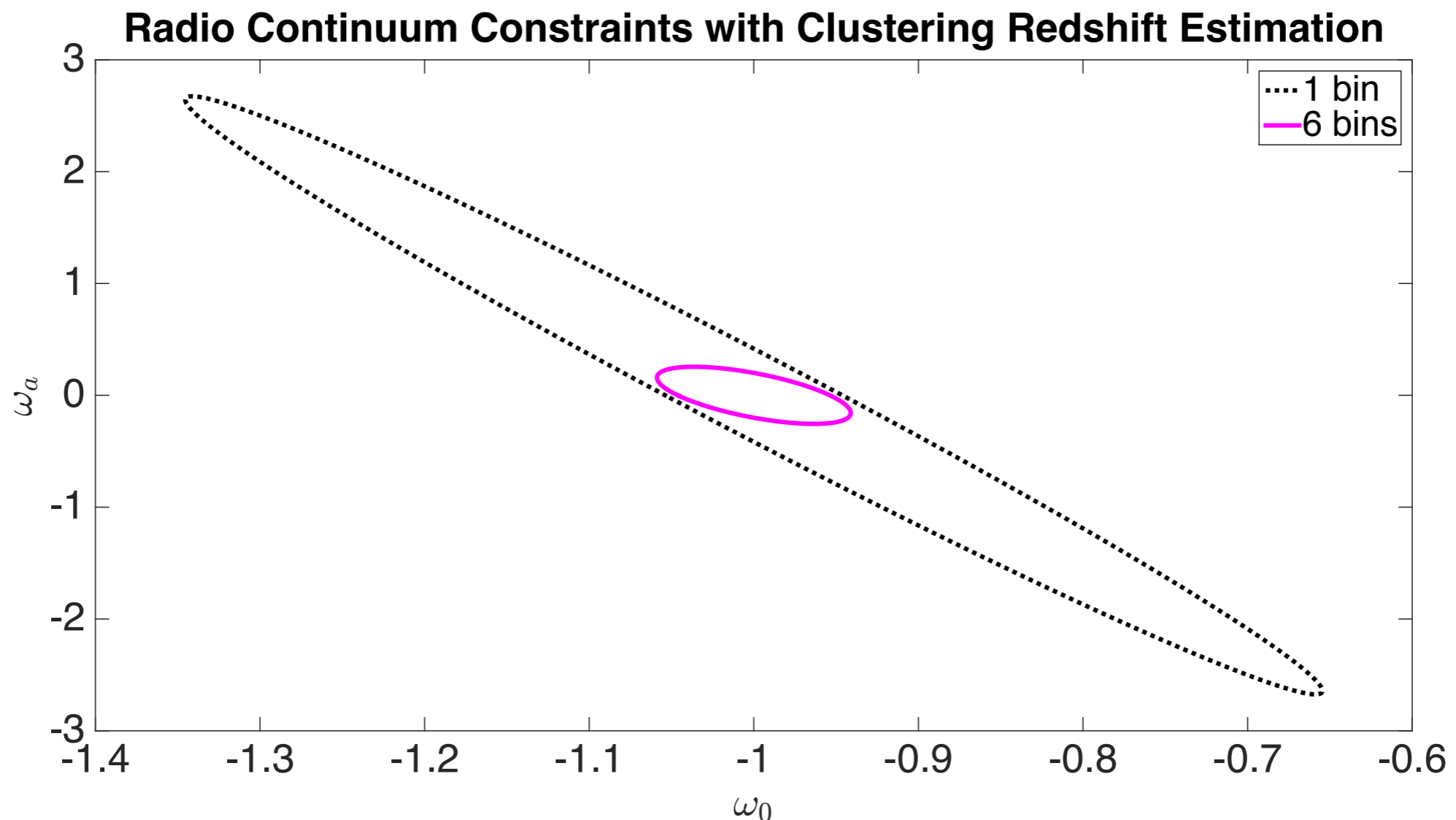
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Our error forecast:  $\omega_0 = 1 \pm 0.038841$  (better than combined CMB + low-z)



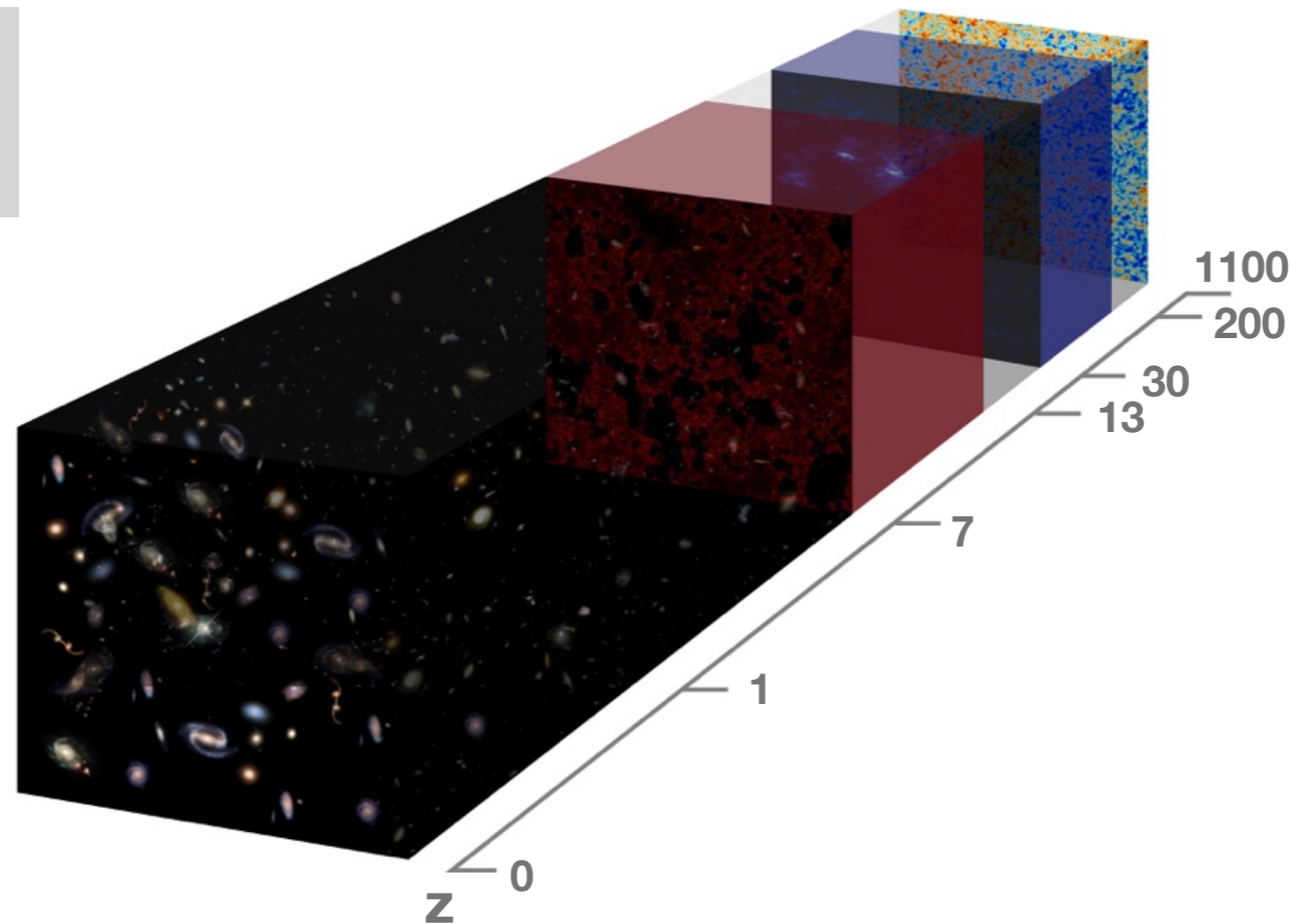




# Thank you!

**Ely D. Kovetz**

Johns Hopkins University



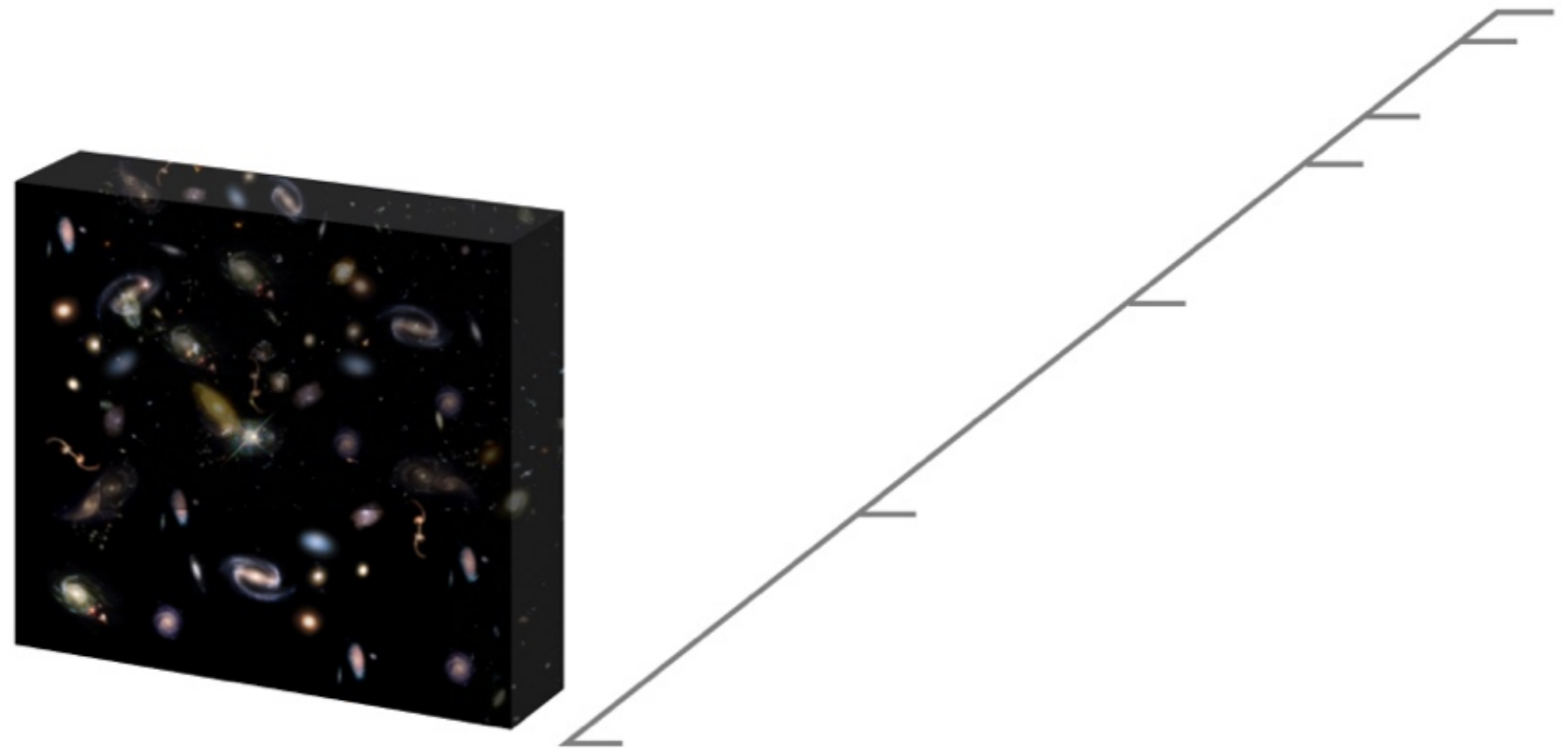
WIS Seminar  
Jan. 24th, 2016

Based on works with: P. Breysse, J. Munoz, L. Dai  
Y. Ali-Haïmoud, A. Raccanelli,  
M. Kamionkowski, J. Silk

One more thing...

# Probing the dark sector in new dimensions: t

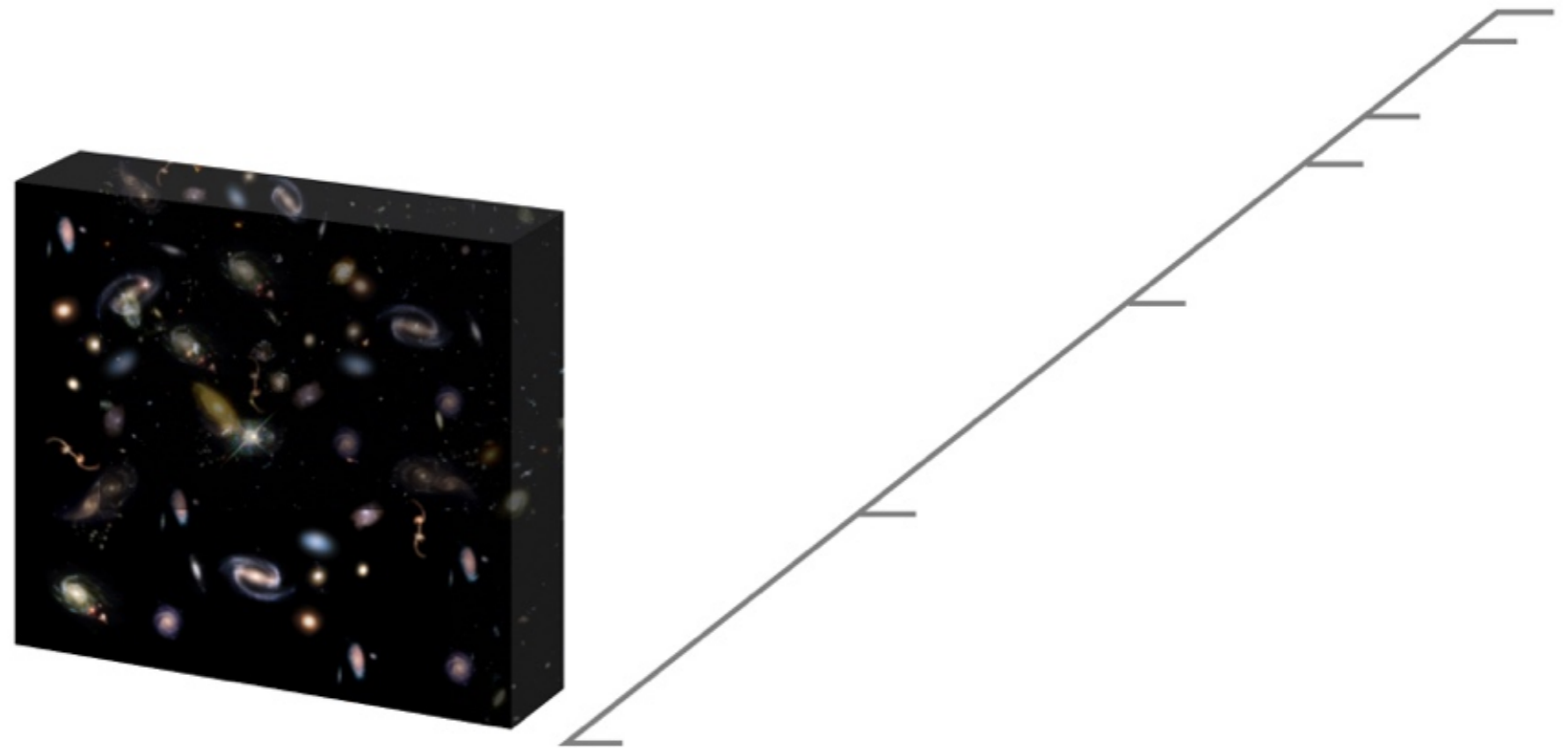
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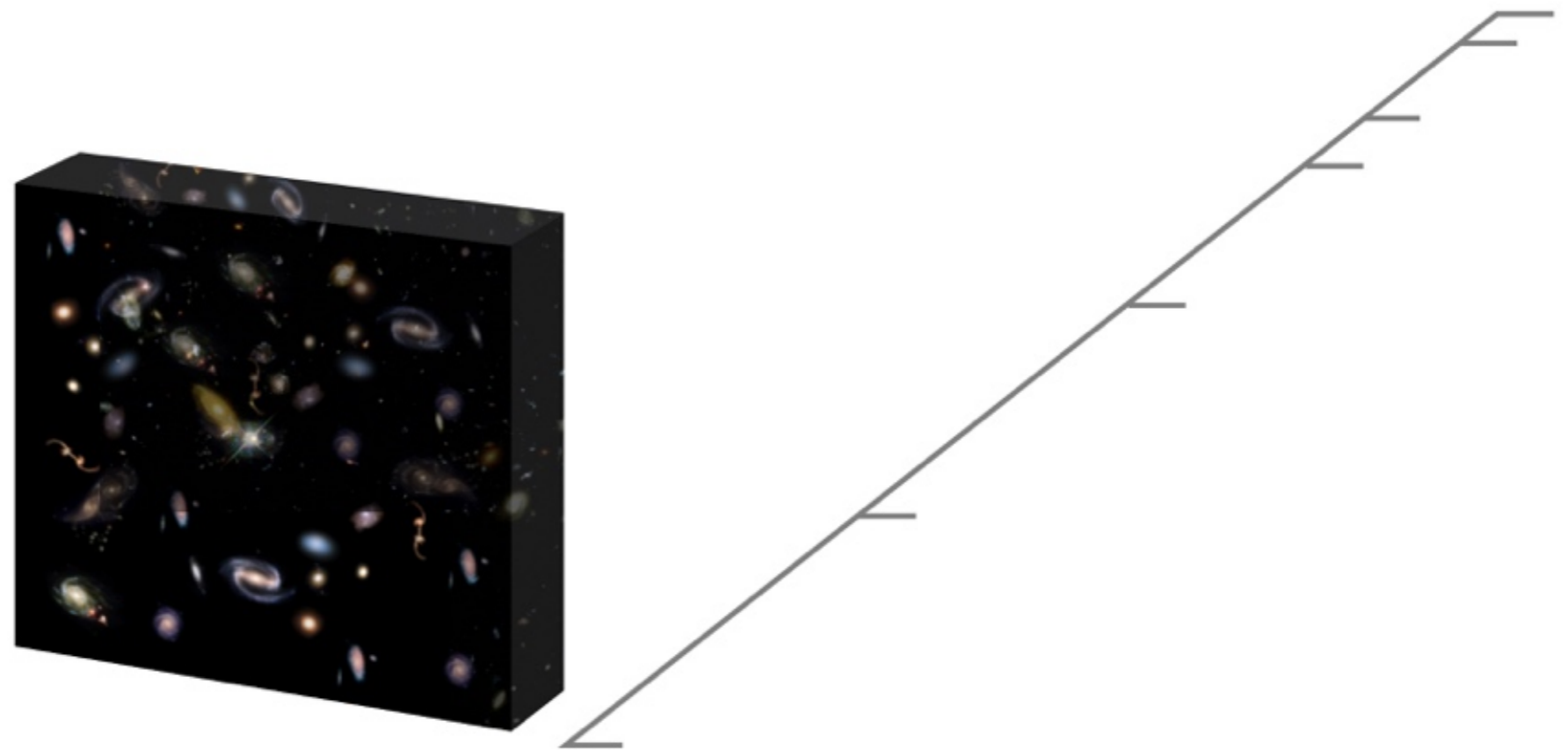


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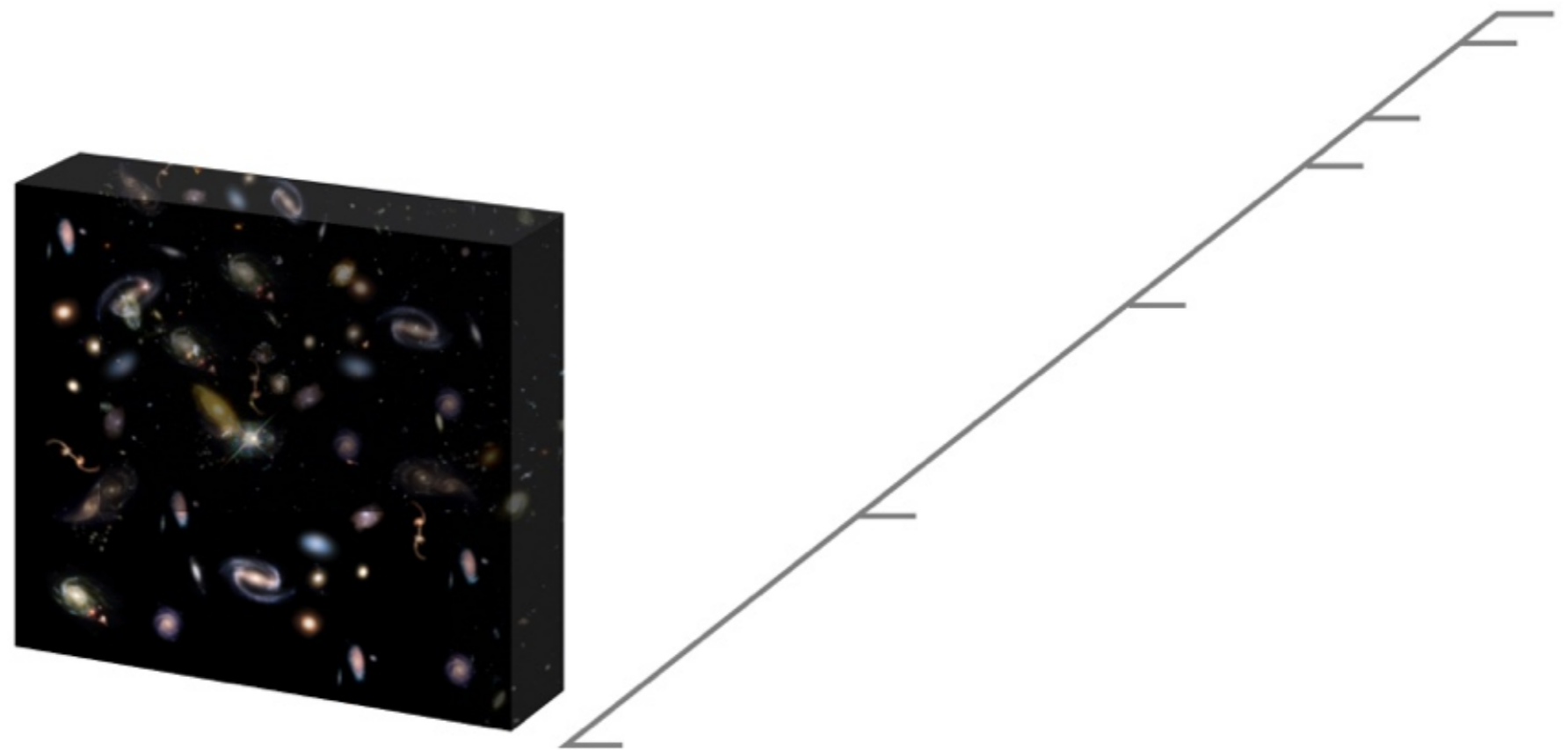
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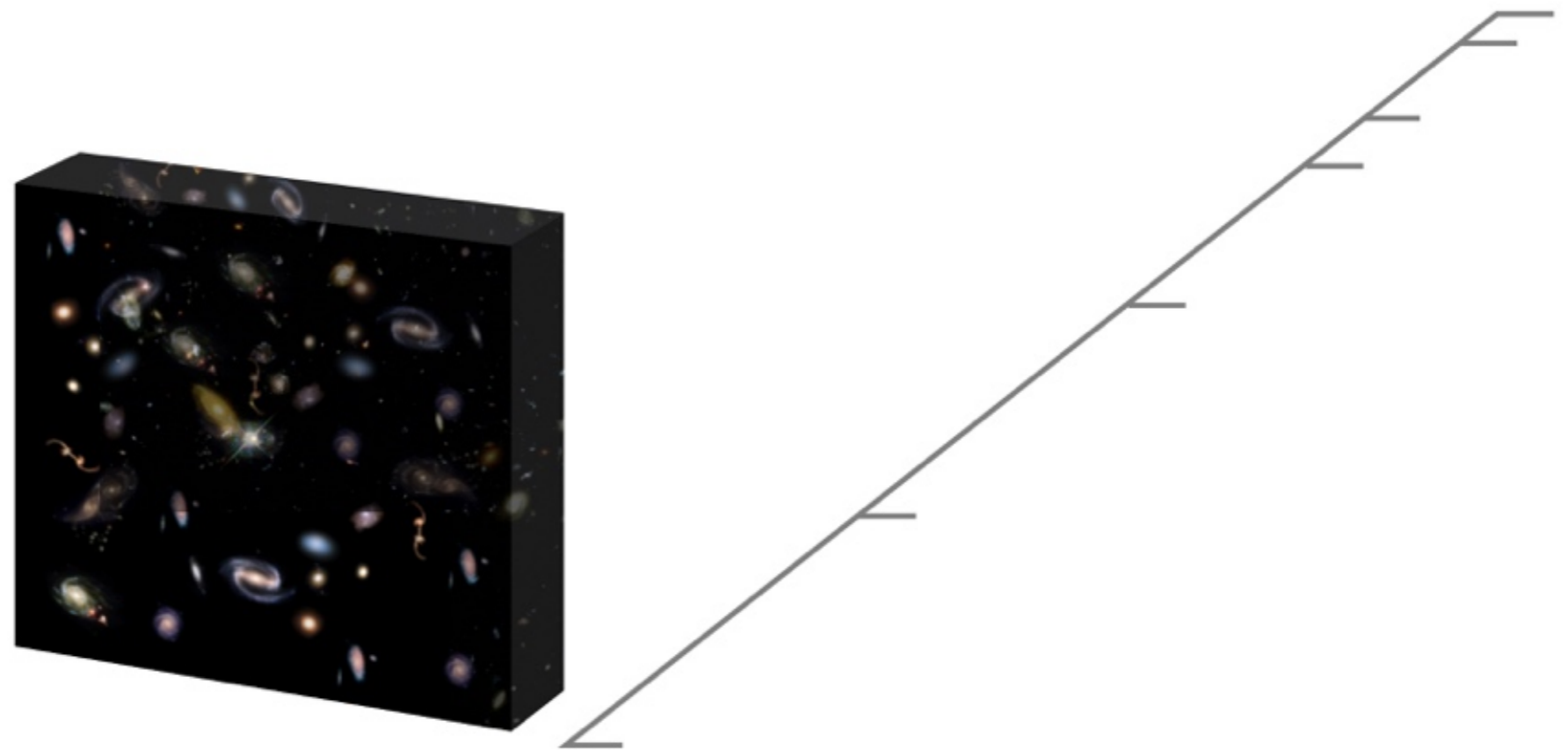
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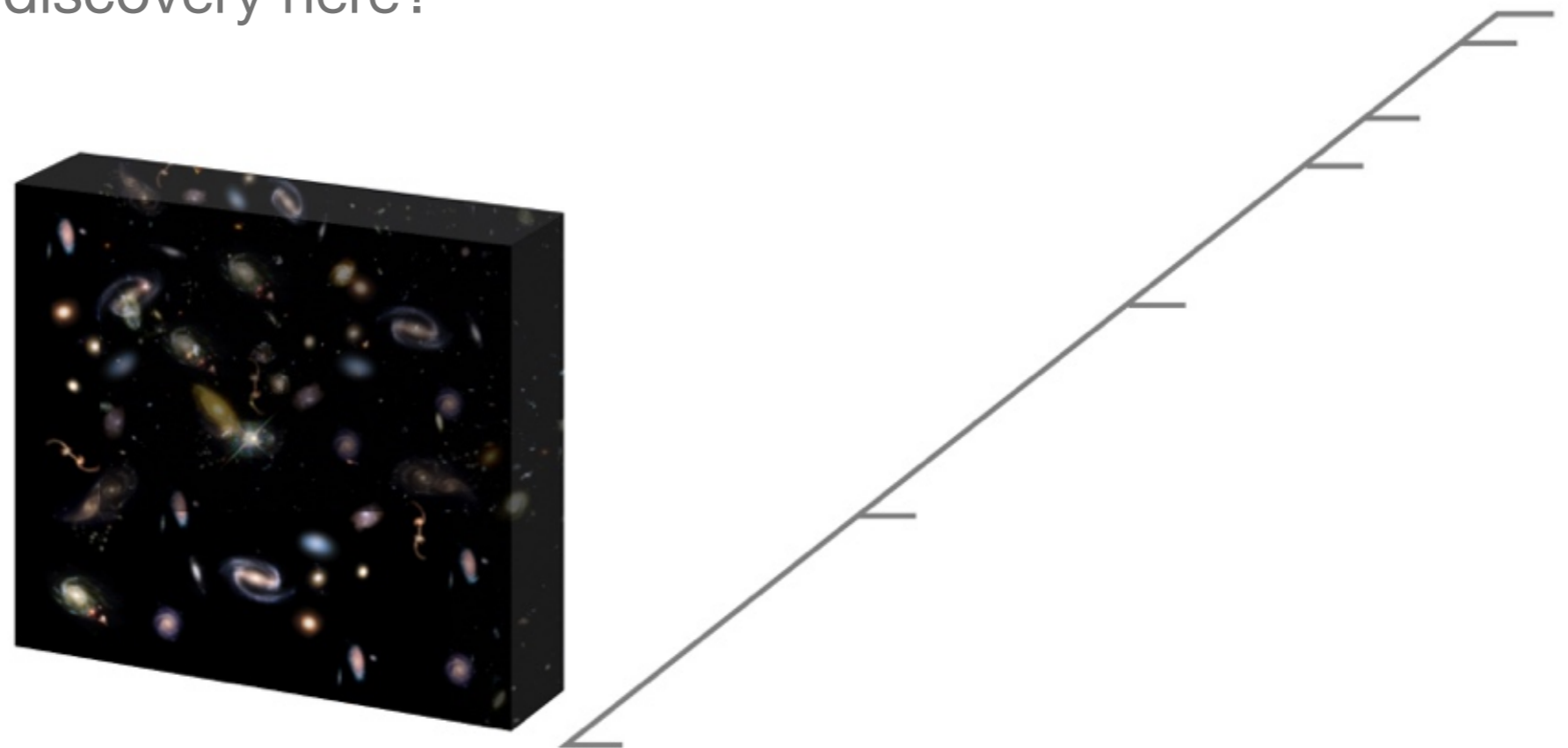
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(Ali-Haïmoud, EDK and Silk, PRD 2016)

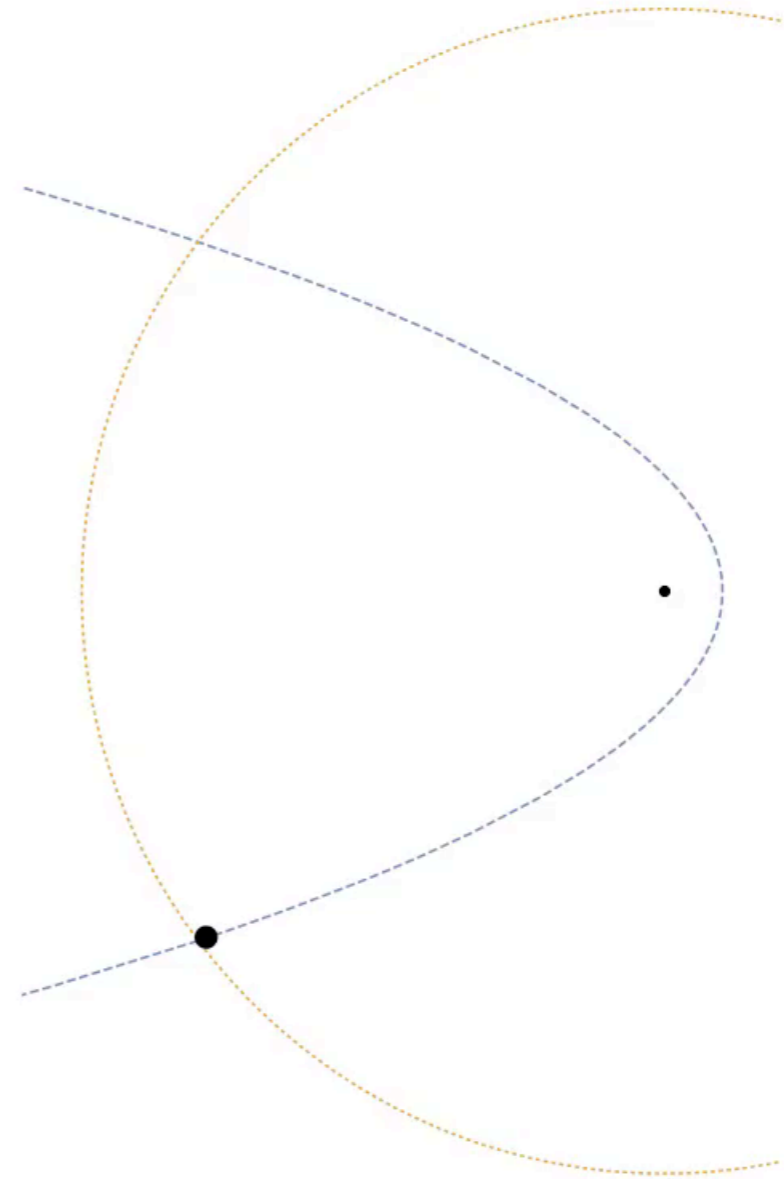
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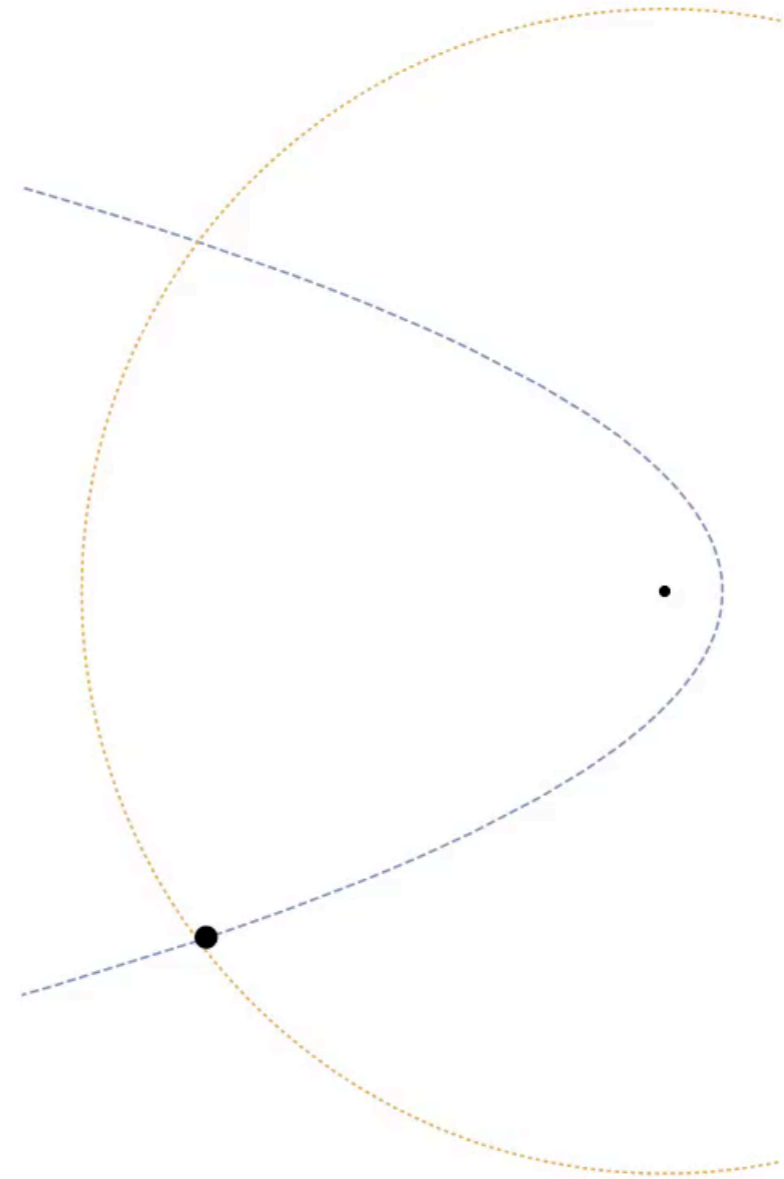


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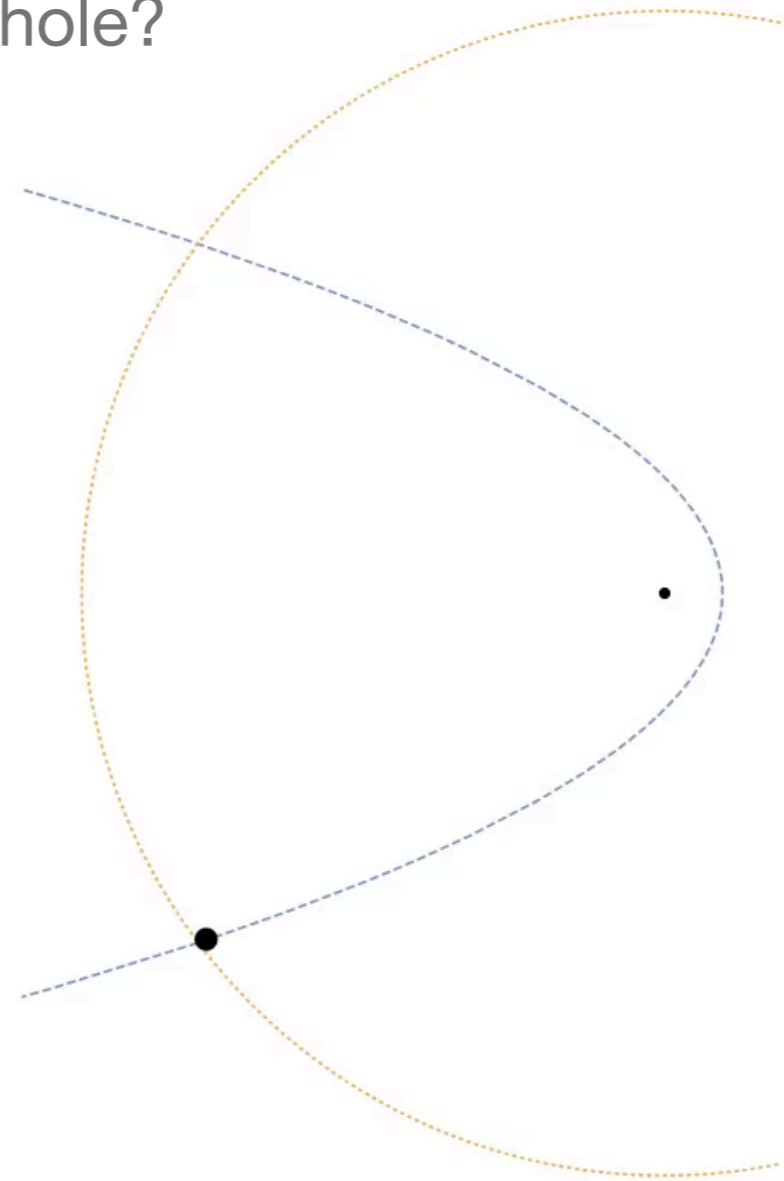
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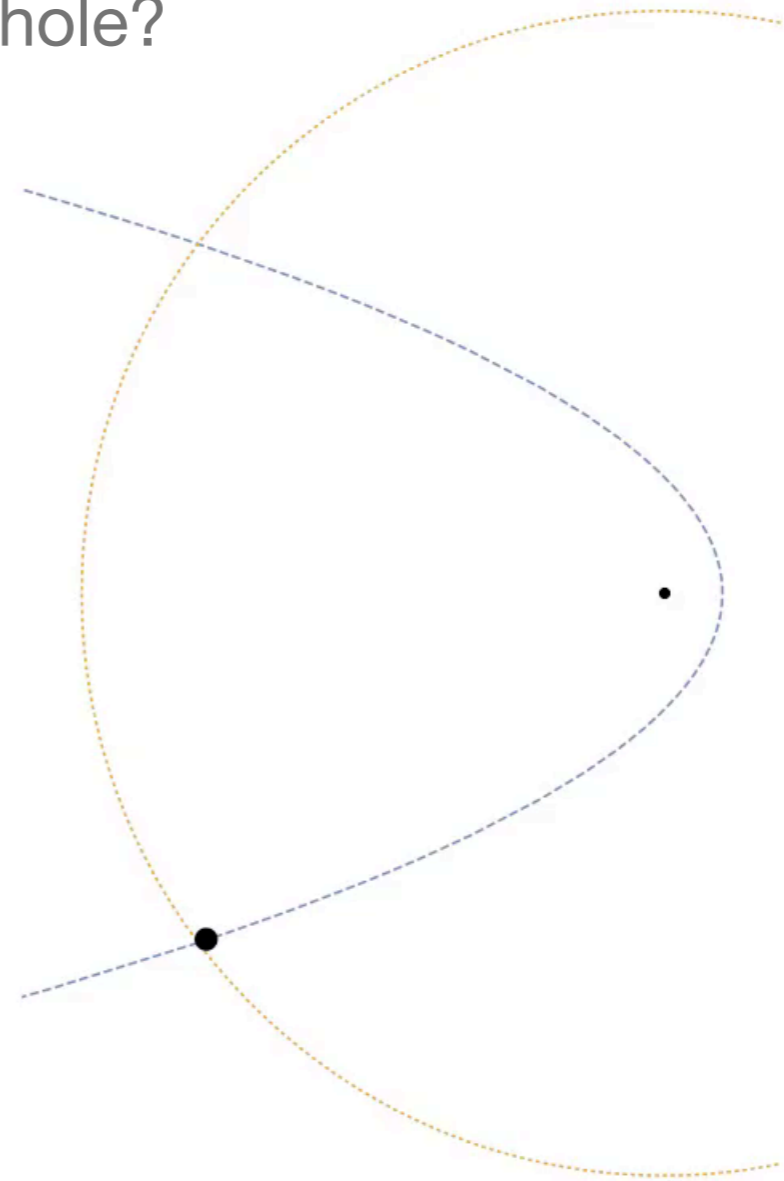
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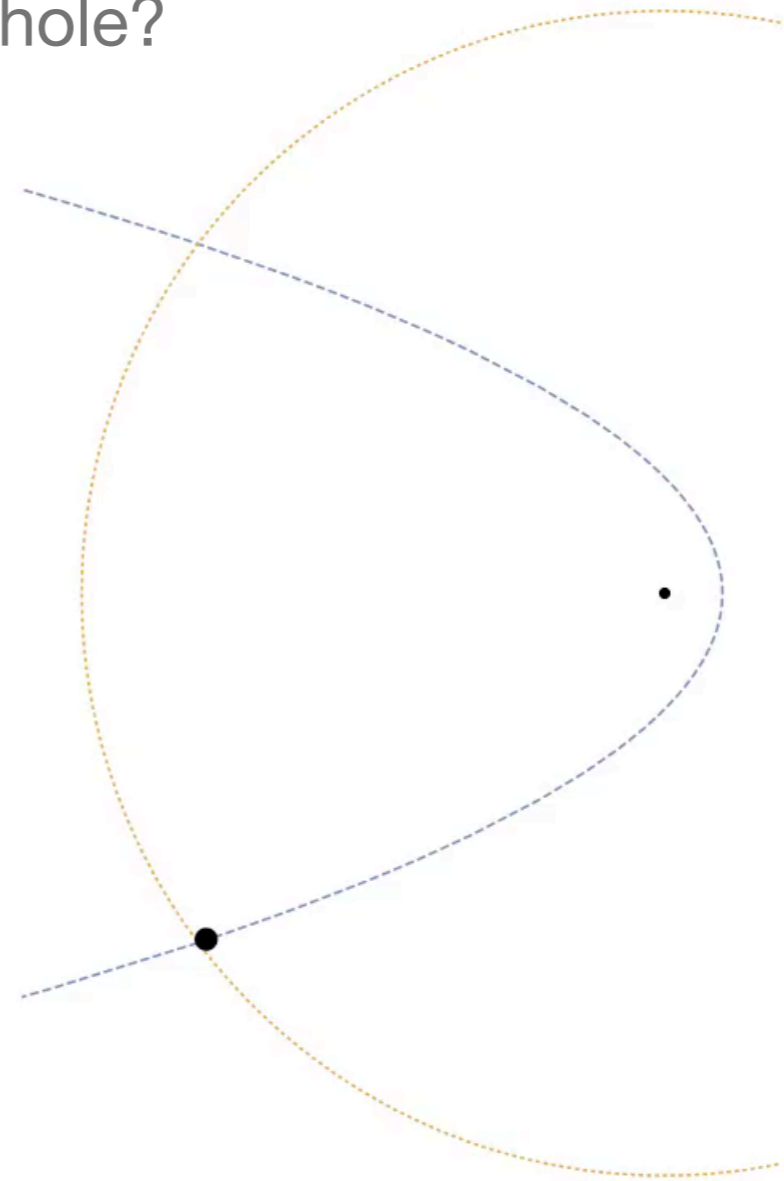
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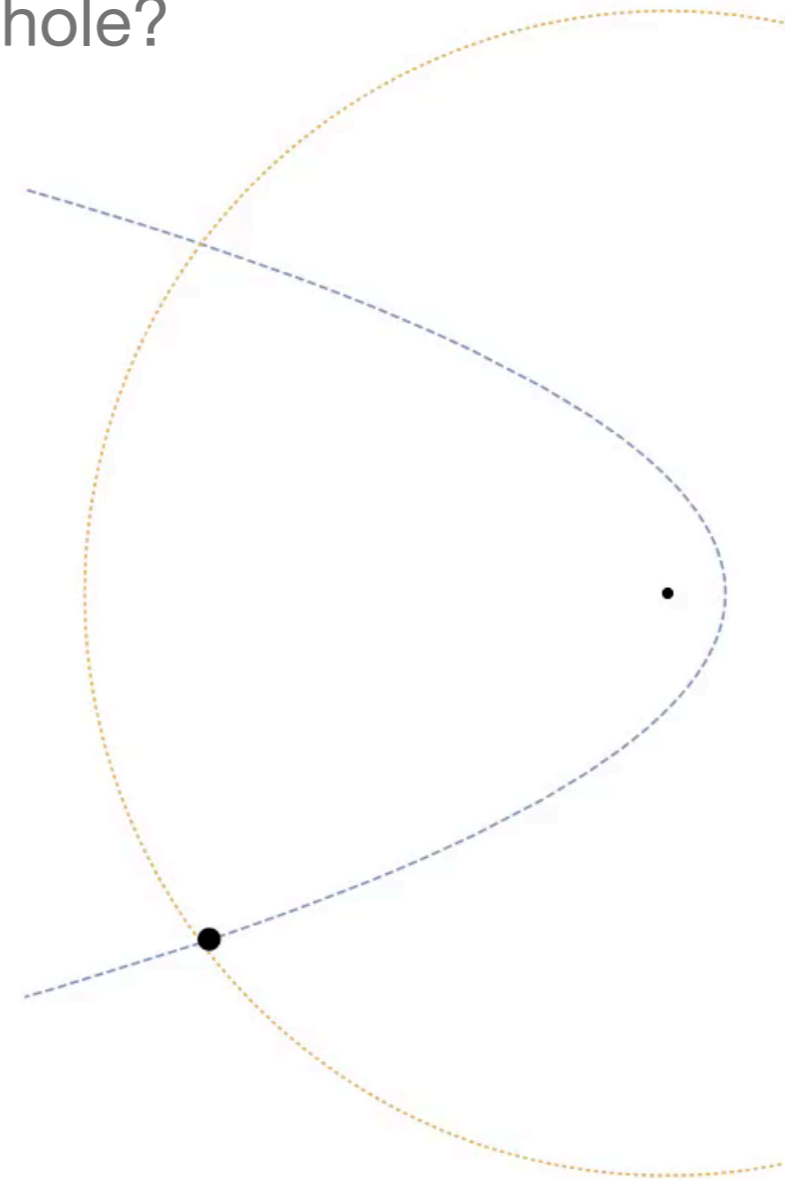
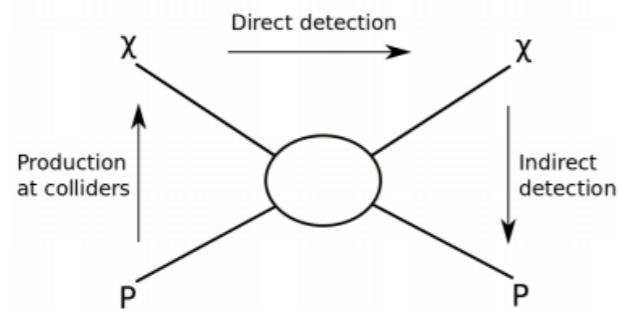
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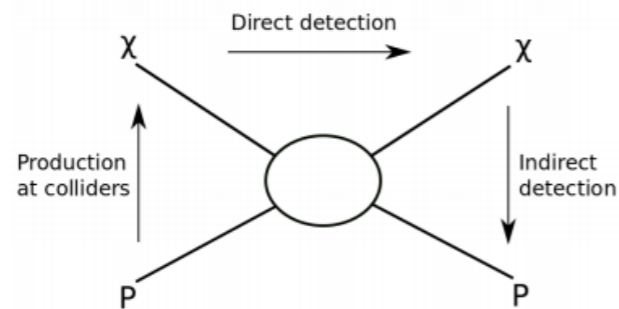
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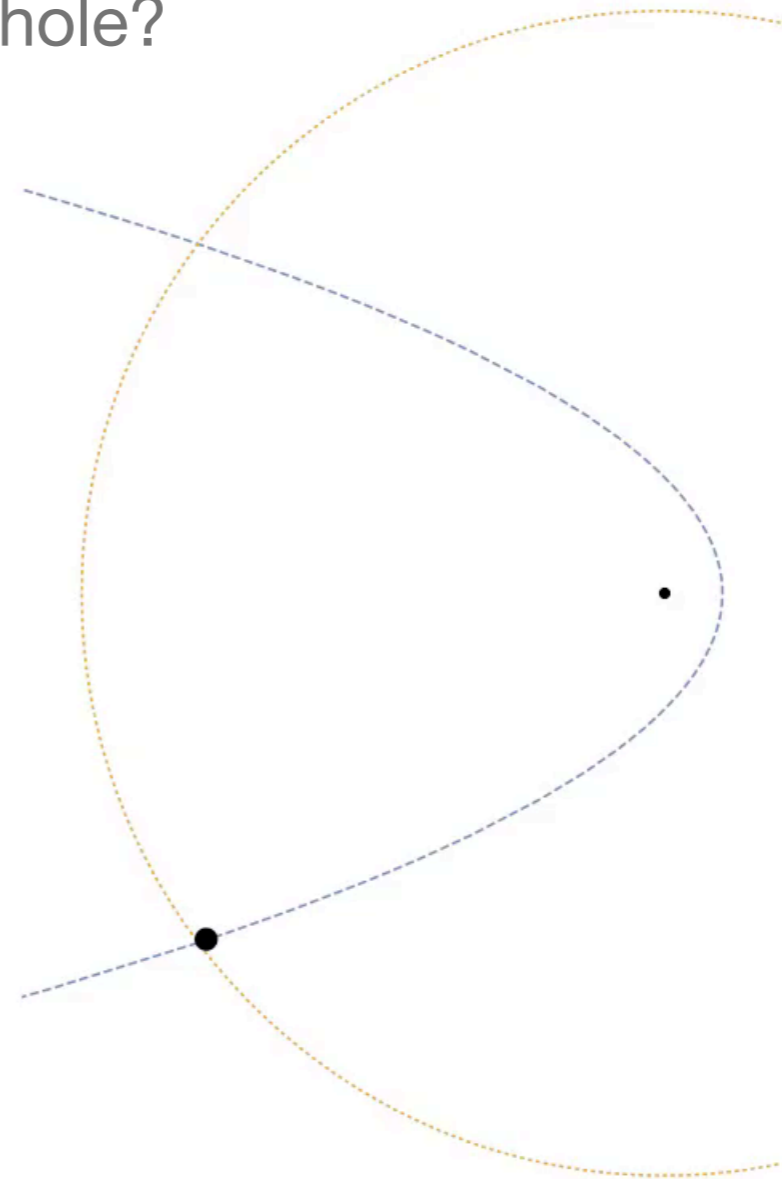
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A: annihilation flux will be boosted:



# Tidal Compression of Dark Matter Clumps

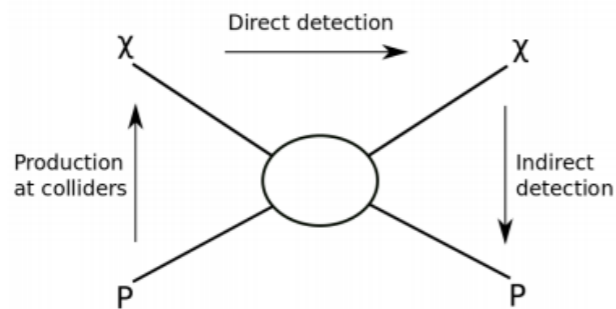
(Ali-Haïmoud, EDK and Silk, PRD 2016)

Purely phenomenological questions:

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

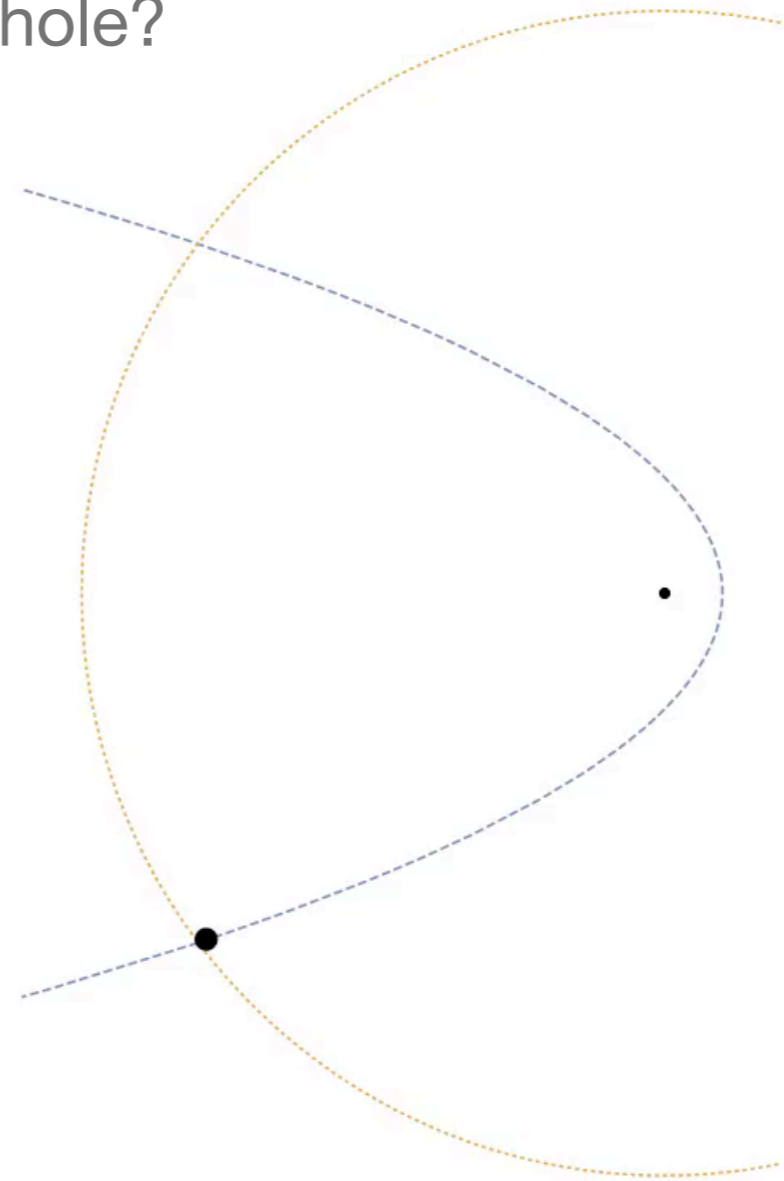
A: It will be undergo compression!  
orbital-plane: stretching/compression  
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$$\dot{N}_{\text{ann}} = \frac{\langle \sigma v \rangle}{m_{\chi}^2} \int d^3 r \rho(r)^2$$



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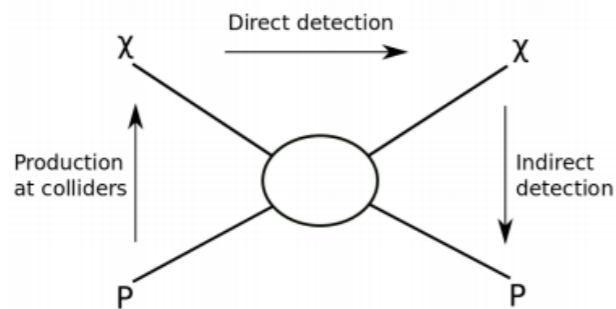
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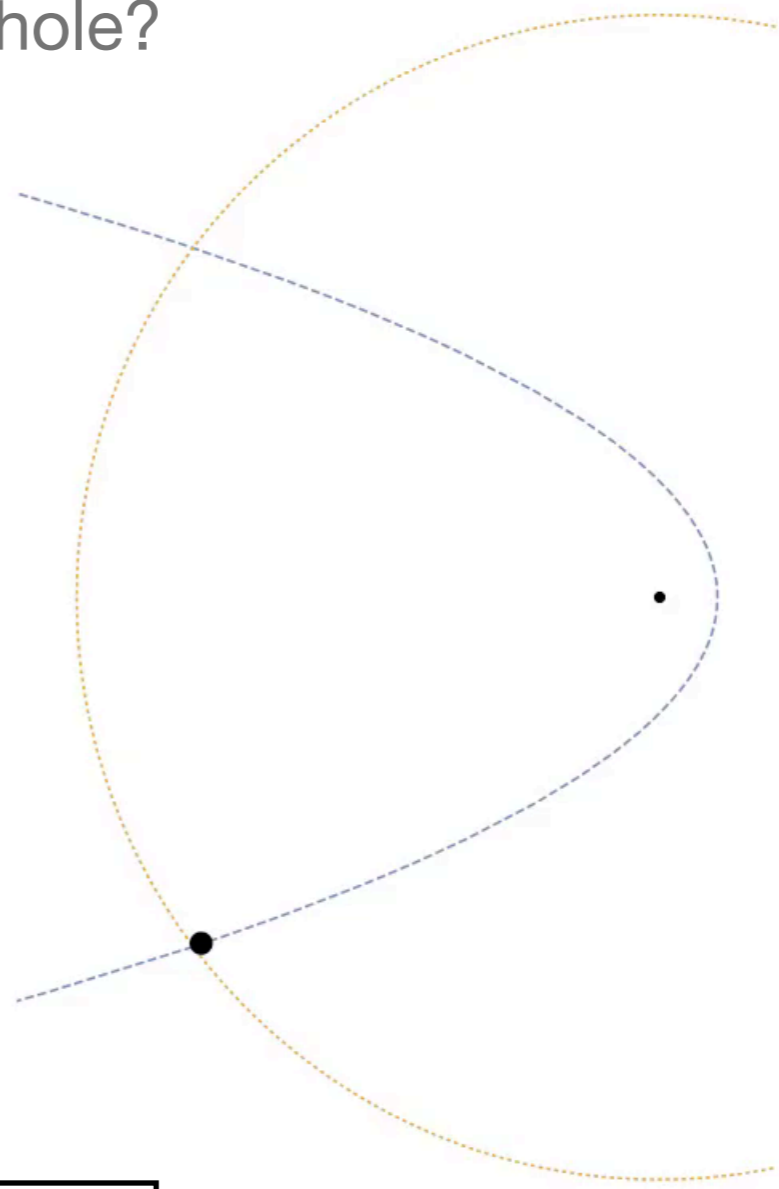
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**Flares!**



# TCEs of DMCs: Gamma-Ray Flares

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

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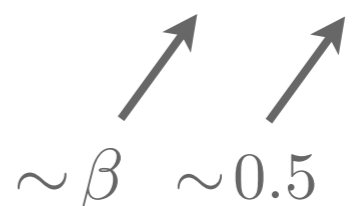
$\sim \beta$  

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

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→ ~1000 photons per week for certain parameter choices.

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$\longrightarrow \sim 1000$  photons per week for certain parameter choices.

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

$\sim \beta$     $\sim 0.5$

Predictions for gamma-ray flares from TCEs of DMCs:

- Universal *energy spectrum*.

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- Flares on *various timescales*.

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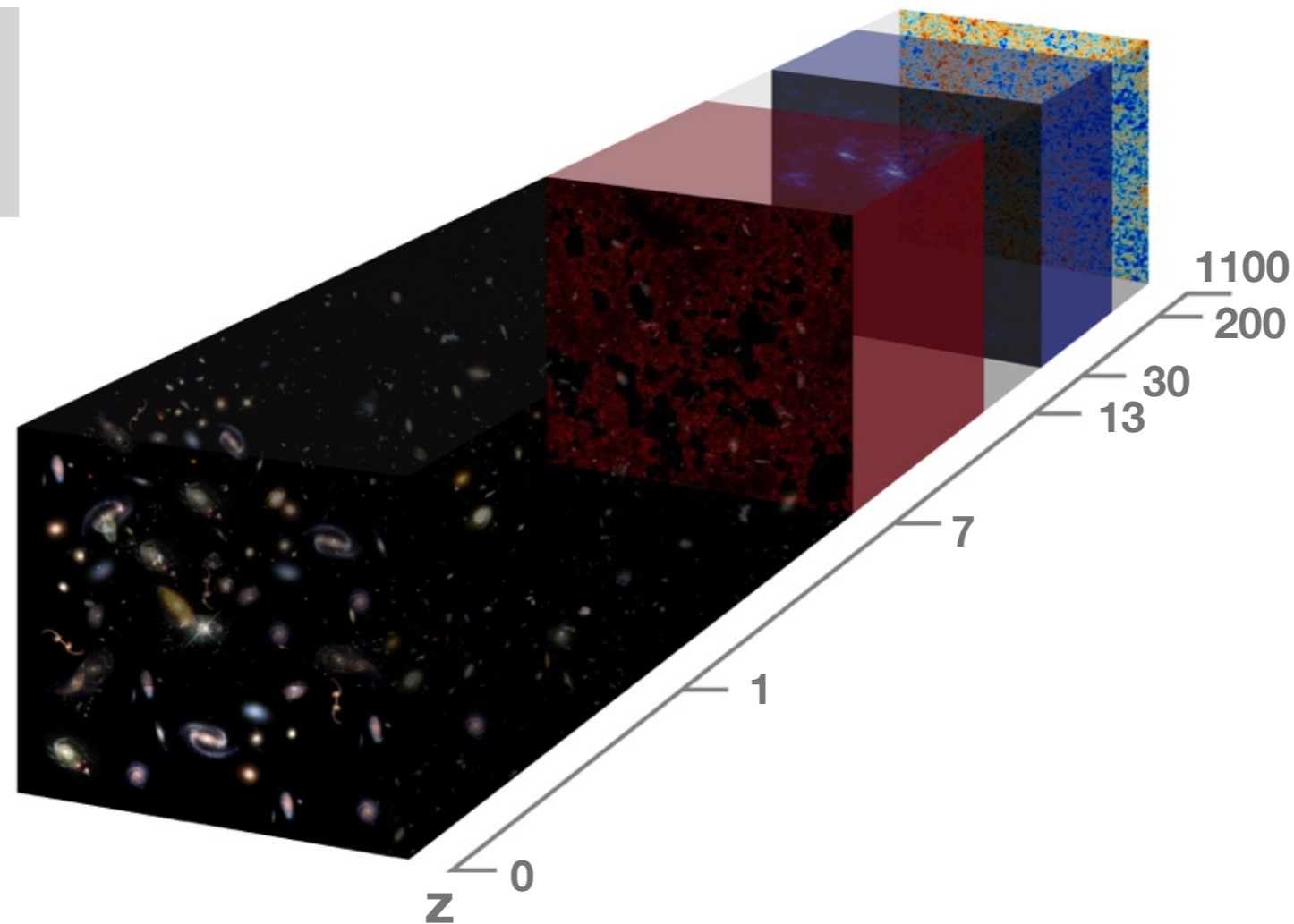
Predictions for gamma-ray flares from TCEs of DMCs:

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

# Thank you!

**Ely D. Kovetz**

Johns Hopkins University



WIS Seminar  
Jan. 24th, 2016

Based on works with: P. Breysse, J. Munoz, L. Dai  
Y. Ali-Haïmoud, A. Raccanelli,  
M. Kamionkowski, J. Silk