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APC

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et de physique des particules

IAP

Relativistic magnetohydrodynamical simulations of the resonant corrugation of a fast shock front

Demidem et al, 2018, Mon. Not. R. Astron. Soc. 475, 2713–2723

Camilia DEMIDEM, 2nd year PhD student
« PIC-MHD simulations of particle acceleration in a magnetized turbulence »
Supervisors: Fabien CASSE & Martin LEMOINE

Isradynamics 2018: Dynamical Processes in Space Plasmas

27th April 2018

Plan

I. Introduction: motivations & object of this study

II. Results from SRMHD simulations of shock interacting with fast magnetosonic or entropy waves

III. Conclusion

Motivations

Energy dissipation processes in non-thermal (relativistic) sources?

Supernova remnants

IR
X
X
X

shock

Image Credit: MPIA/NASA/Calar Alto Observatory

Active Galactic Nuclei

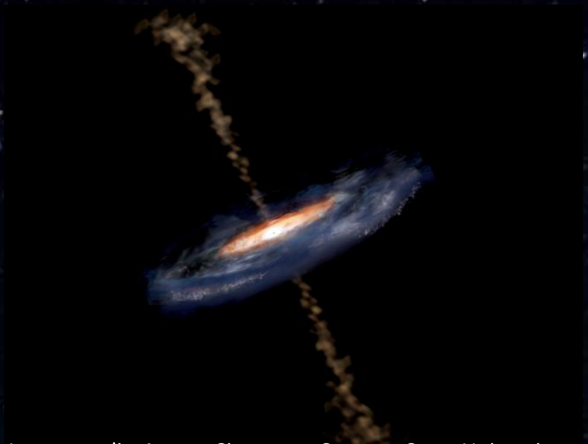


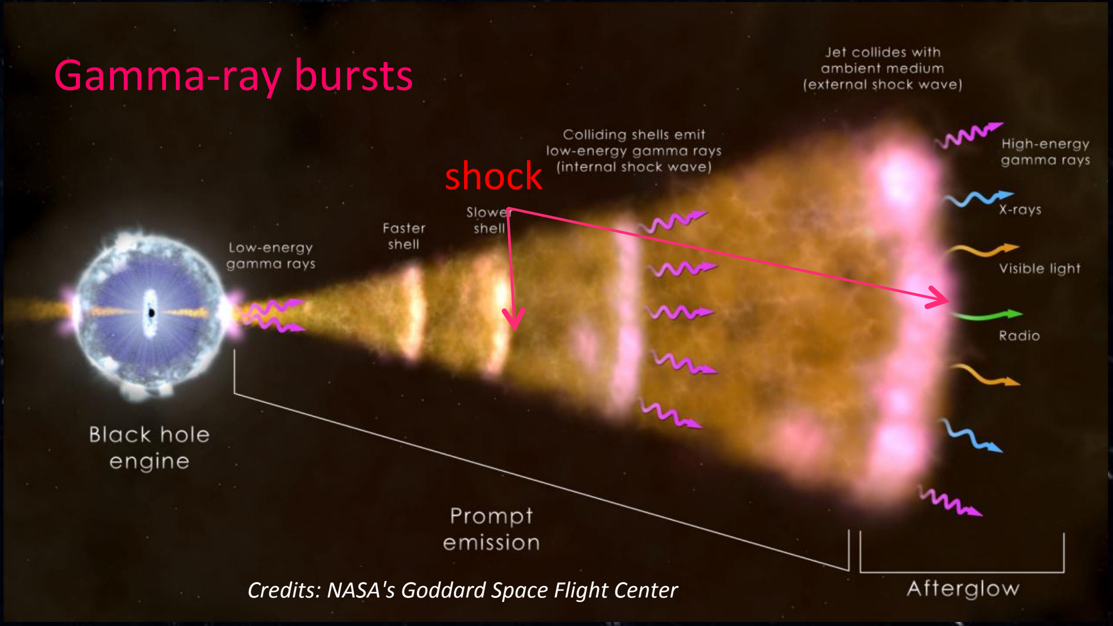
Image credit: Aurore Simonnet, Sonoma State University

pulsar magnetosphere & nebula

R
IR
O
UV
X

shock

Credits: NASA, ESA, G. Dubner (IAFE, CONICET-University of Buenos Aires) et al.; A. Loll et al.; T. Temim et al.; F. Seward et al.; VLA/NRAO/AUI/NSF; Chandra/CXC; Spitzer/JPL-Caltech; XMM-Newton/ESA; and Hubble/STScI

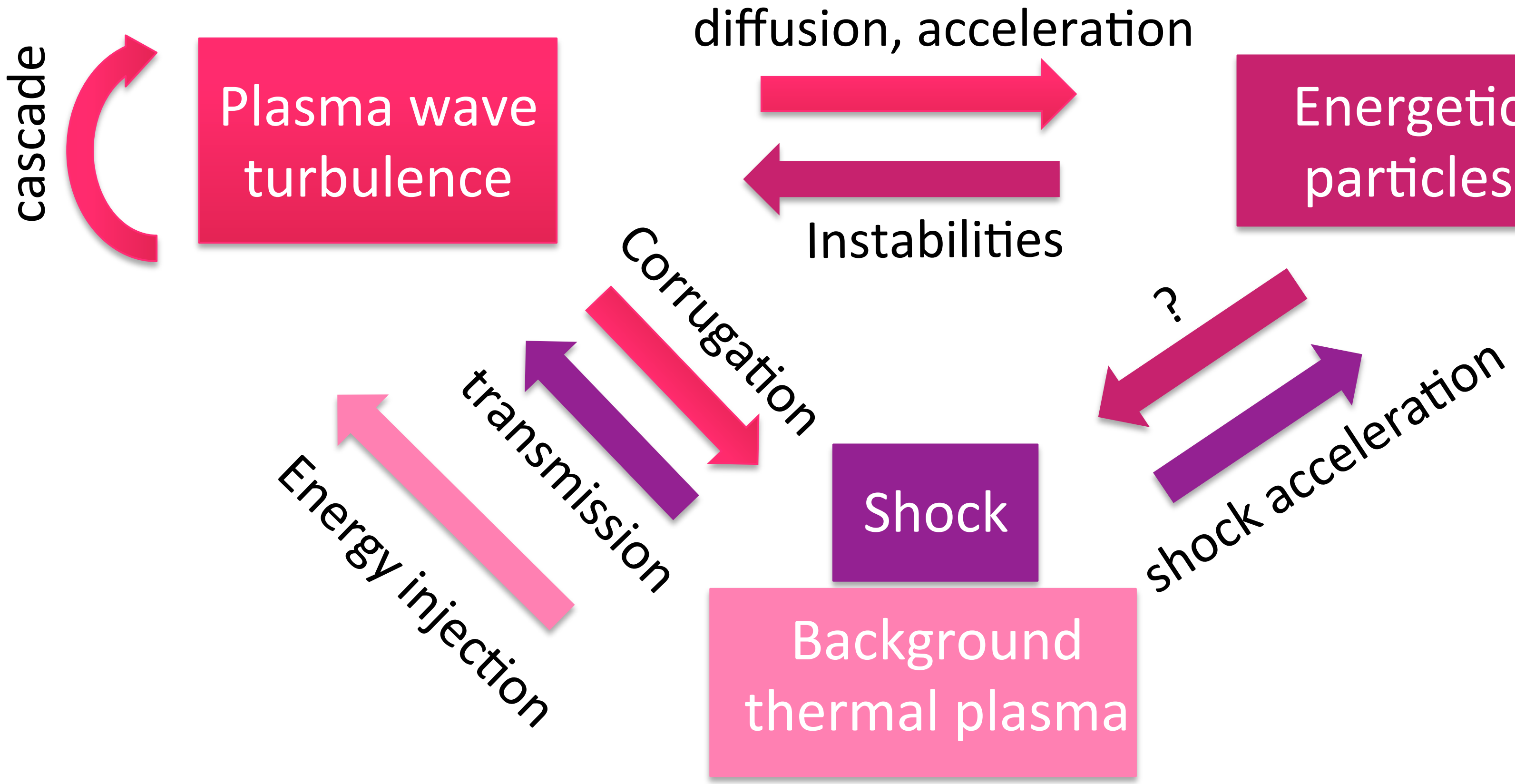


Gamma-ray bursts

shock

Credits: NASA's Goddard Space Flight Center

Motivations



cascade

Plasma wave turbulence

diffusion, acceleration

Instabilities

Energetic particles

Corrugation

transmission

Energy injection

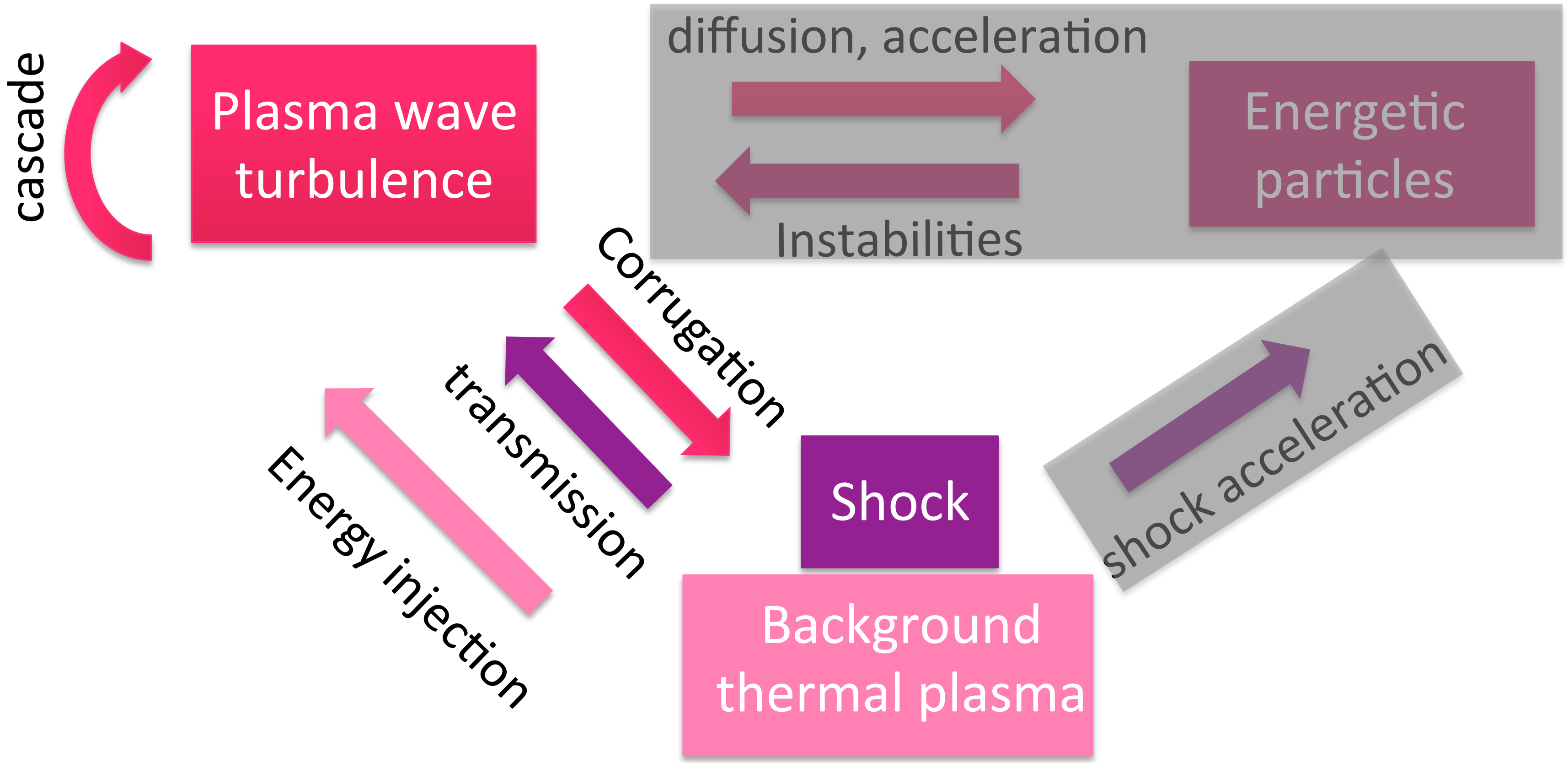
?

shock acceleration

Shock

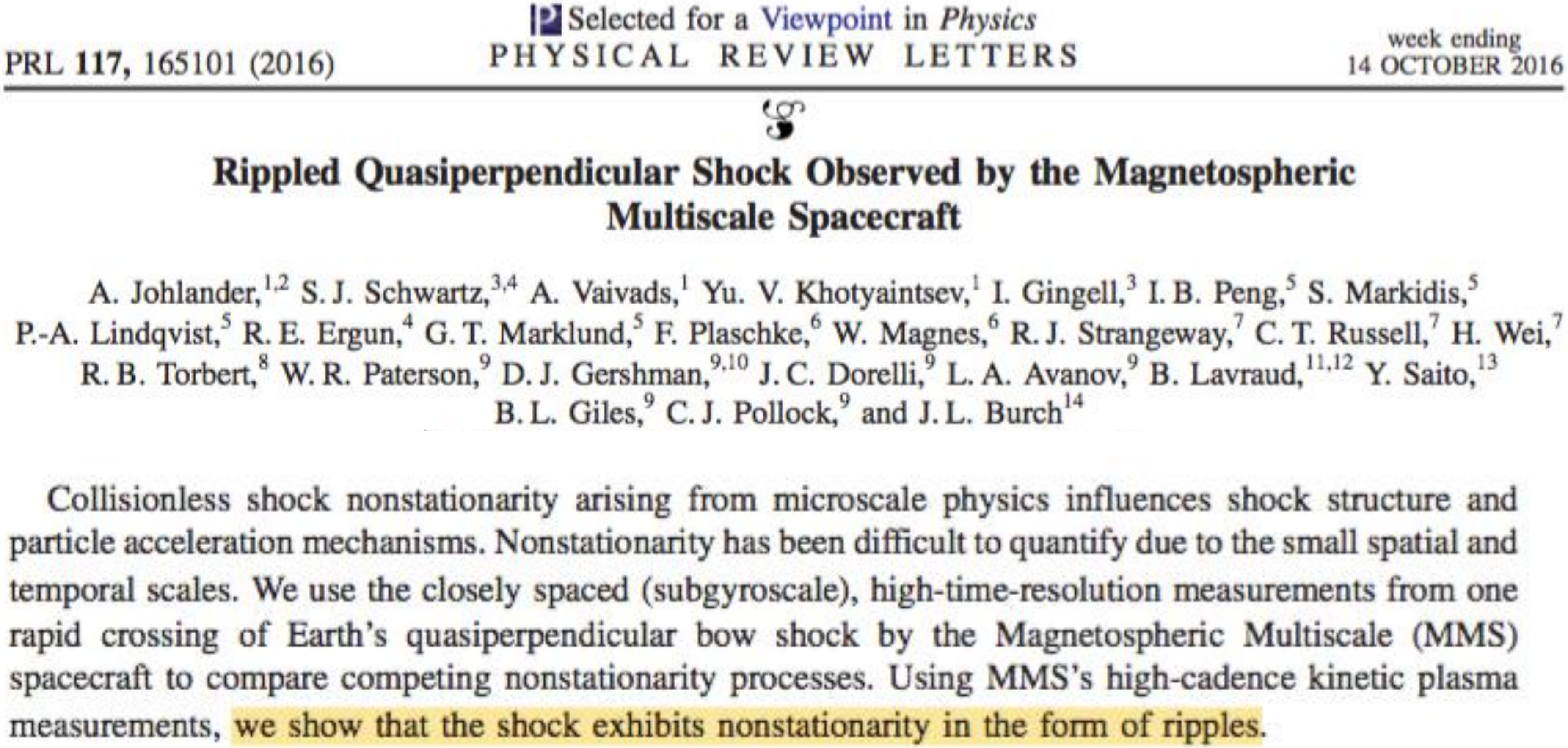
Background thermal plasma

Motivations



- **Next part**: work related to the issue of shock-turbulence interactions, in the framework of MHD

Motivations



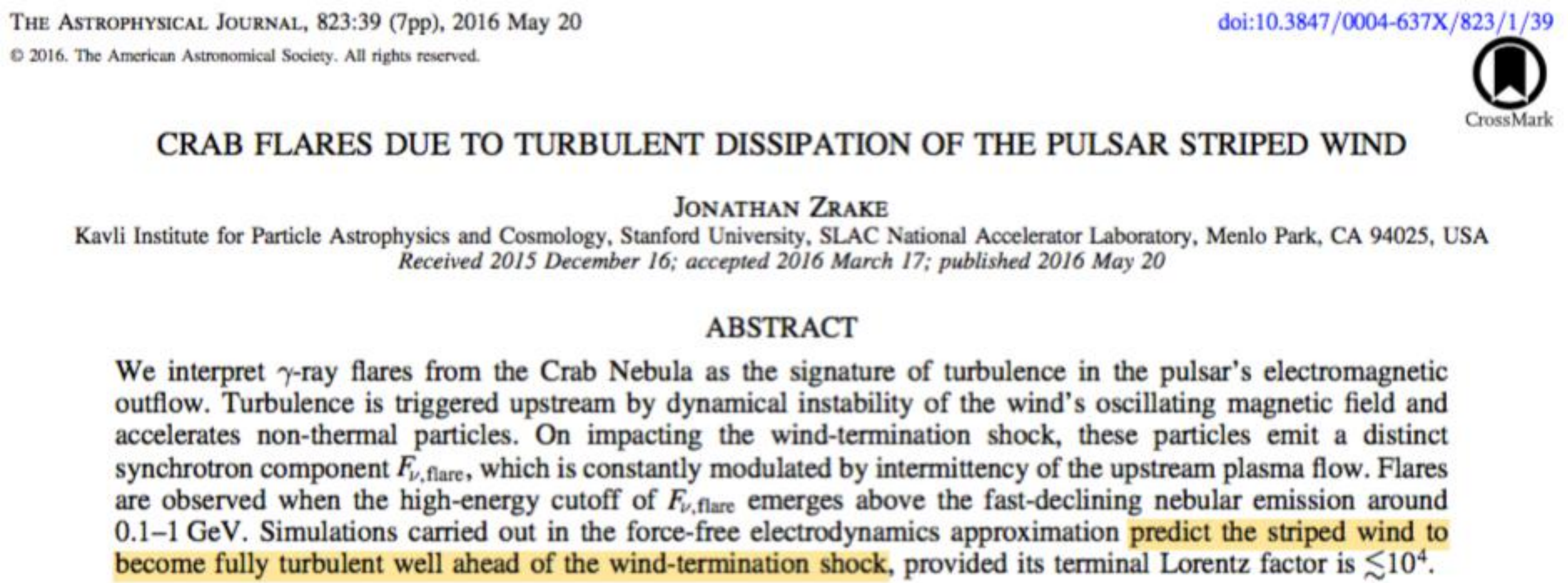
Selected for a Viewpoint in *Physics*

PRL **117,** 165101 (2016) PHYSICAL REVIEW LETTERS week ending 14 OCTOBER 2016

Rippled Quasiperpendicular Shock Observed by the Magnetospheric Multiscale Spacecraft

A. Johlander,[1,2] S. J. Schwartz,[3,4] A. Vaivads,[1] Yu. V. Khotyaintsev,[1] I. Gingell,[3] I. B. Peng,[5] S. Markidis,[5] P.-A. Lindqvist,[5] R. E. Ergun,[4] G. T. Marklund,[5] F. Plaschke,[6] W. Magnes,[6] R. J. Strangeway,[7] C. T. Russell,[7] H. Wei,[7] R. B. Torbert,[8] W. R. Paterson,[9] D. J. Gershman,[9,10] J. C. Dorelli,[9] L. A. Avanov,[9] B. Lavraud,[11,12] Y. Saito,[13] B. L. Giles,[9] C. J. Pollock,[9] and J. L. Burch[14]

Collisionless shock nonstationarity arising from microscale physics influences shock structure and particle acceleration mechanisms. Nonstationarity has been difficult to quantify due to the small spatial and temporal scales. We use the closely spaced (subgyroscale), high-time-resolution measurements from one rapid crossing of Earth's quasiperpendicular bow shock by the Magnetospheric Multiscale (MMS) spacecraft to compare competing nonstationarity processes. Using MMS's high-cadence kinetic plasma measurements, we show that the shock exhibits nonstationarity in the form of ripples.



The Astrophysical Journal, 823:39 (7pp), 2016 May 20
doi:10.3847/0004-637X/823/1/39

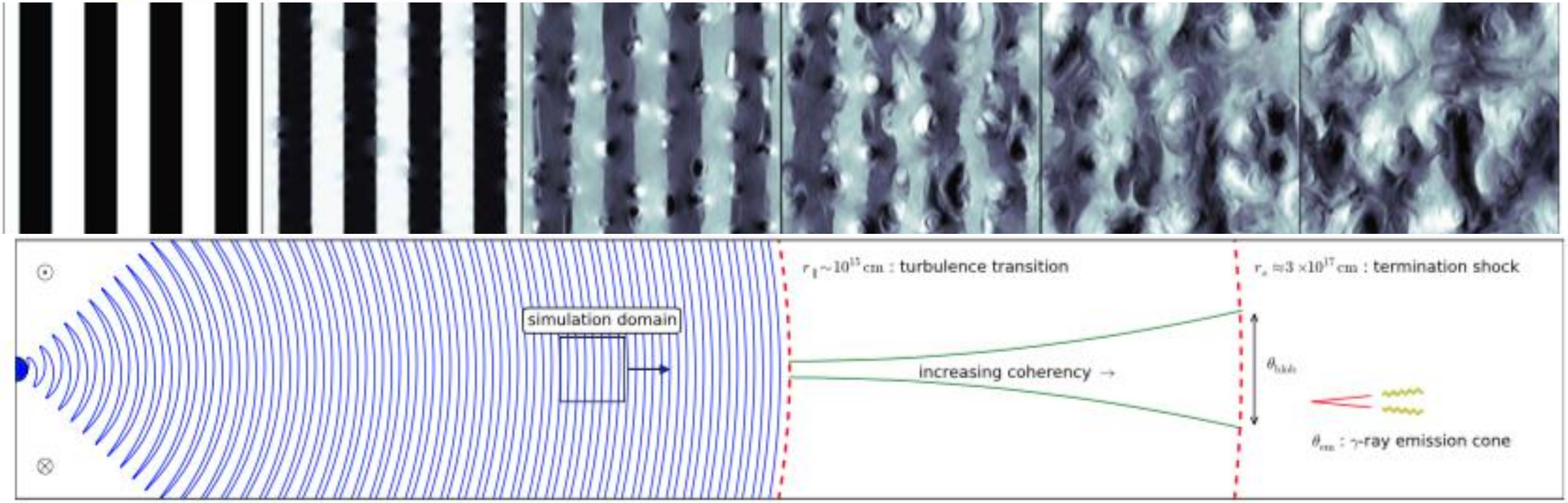
CRAB FLARES DUE TO TURBULENT DISSIPATION OF THE PULSAR STRIPED WIND

Jonathan Zrake
Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Received 2015 December 16; accepted 2016 March 17; published 2016 May 20

ABSTRACT

We interpret γ-ray flares from the Crab Nebula as the signature of turbulence in the pulsar's electromagnetic outflow. Turbulence is triggered upstream by dynamical instability of the wind's oscillating magnetic field and accelerates non-thermal particles. On impacting the wind-termination shock, these particles emit a distinct synchrotron component $F_{\nu,\mathrm{flare}}$, which is constantly modulated by intermittency of the upstream plasma flow. Flares are observed when the high-energy cutoff of $F_{\nu,\mathrm{flare}}$ emerges above the fast-declining nebular emission around 0.1–1 GeV. Simulations carried out in the force-free electrodynamics approximation predict the striped wind to become fully turbulent well ahead of the wind-termination shock, provided its terminal Lorentz factor is $\lesssim 10^4$.



FFE simulations

Frawework: special relativistic ideal MHD (SRMHD)

- Ideal MHD: fluid description of perfectly conducting plasma
- Governing equations: mass, energy, momentum conservation equations + evolution equation of ***B*** + div(***B***)=0 constraint
- SRMHD → need covariant formalism

c=1, μ_0=1.

Introducing $b^\mu = \left[u^i B_i, \left(\boldsymbol{B} + u^i B_i \boldsymbol{u}\right)/u^0\right],$

$$T^{\mu\nu} = \left(w + b_\alpha b^\alpha\right) u^\mu u^\nu + \left(p + \frac{b_\alpha b^\alpha}{2}\right) \eta^{\mu\nu} - b^\mu b^\nu,$$

$$^*F^{\mu\nu} = u^\mu b^\nu - u^\nu b^\mu,$$

the governing equations read: $\nabla_\alpha(\rho u^\alpha) = 0,$

$$\nabla_\alpha T^{\alpha\beta} = 0,$$

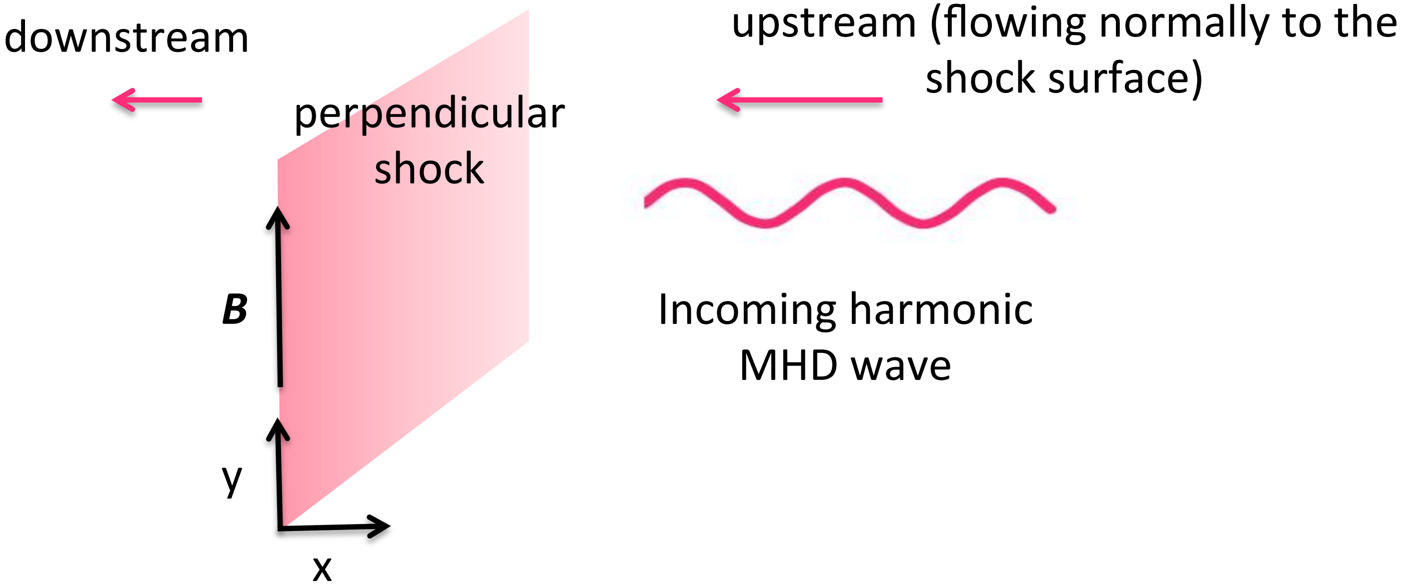
$$\nabla_\alpha {}^*F^{\alpha\beta} = 0.$$

<u>Notations</u>:
u^μ: 4-velocity
B: magnetic field
p: thermal pressure
w: enthalpy density
ρ: proper density
$\eta^{\mu\nu}$: Minkowsky metric

- 7 eigenmodes: 1 entropy + 2 Alfvén + 2 slow magnetosonic+
  2 fast magnetosonic

Framework: shocks interacting with perturbations

- Theoretical study of the linear response of a relativistic shock to an harmonic MHD wave (Lemoine et al, 2016, ApJ 827)



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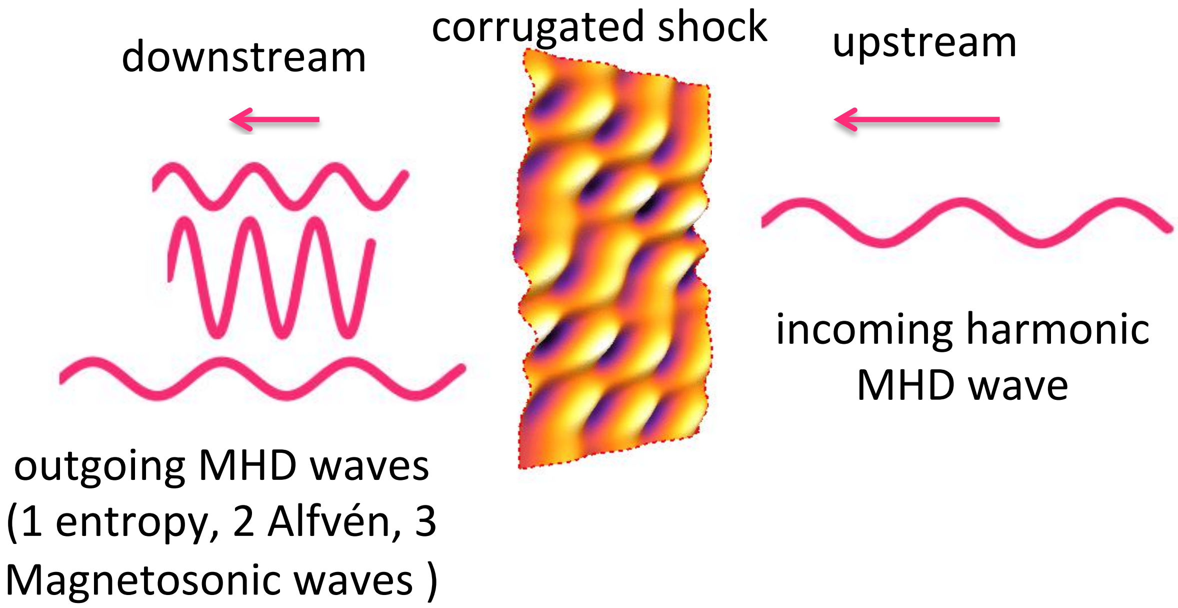

downstream

corrugated shock

upstream

incoming harmonic
MHD wave

outgoing MHD waves
(1 entropy, 2 Alfvén, 3
Magnetosonic waves)

➔ resonance for some wave vectors.

Observable in simulations of finite amplitude incoming waves?

Framework: simulation program

MPI-AMRVAC (van der Holst et al, 2008, Comp. Phys. Commun., 179, 617)

finite volumes solver + constrained transport algorithm

Ensures div(***B***)=0

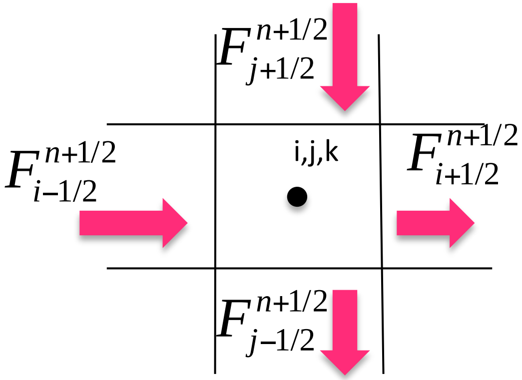
Updates cell centered quanties by computing flux at the cell borders

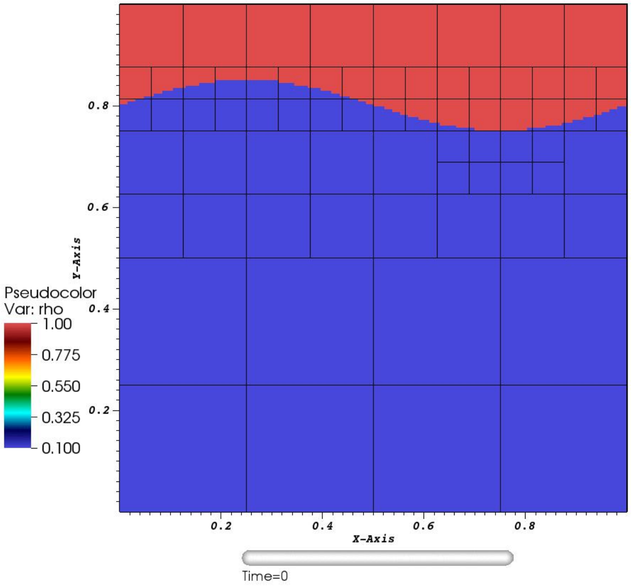
Adaptive Mesh Refinement: adapts grid to zone of interest

Volume & time average

$$\frac{\partial D(t,\mathbf{r})}{\partial t} + \nabla\cdot\mathbf{f}(t,\mathbf{r},D) = 0$$

$$\langle D\rangle_i^{n+1} - \langle D\rangle_i^{n} + \frac{\Delta t}{\Delta V}\left(F_{i+1/2}^{n+1/2} - F_{i-1/2}^{n+1/2} + \dots\right) = 0$$





Example of simulation of the Rayleigh-Taylor instability

Initial set up: shock in its rest frame

- 2D problem (incoming wave vector in (x y) plane)

- **Initial state** = solution of the Rankine-Hugoniot jump relations for given upstream state and relative Lorentz factor Γ_{rel}

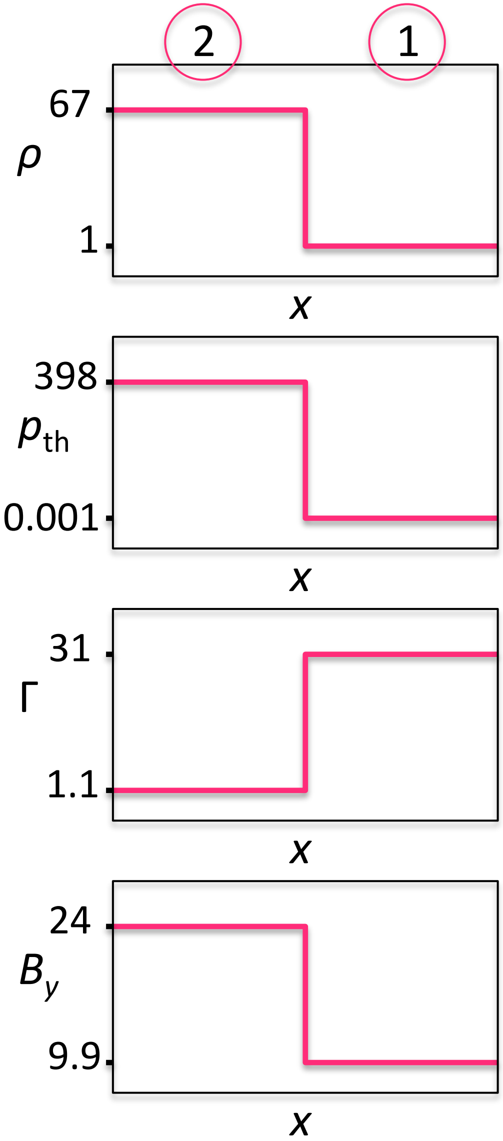
$$\rho_1\Gamma_1 v_1 = \rho_2\Gamma_2 v_2$$

$$B_1 v_1 = B_2 v_2$$

$$W_1{\Gamma_1}^2{v_1}^2 + P_1 = W_2{\Gamma_2}^2{v_2}^2 + P_2$$

$$W_1{\Gamma_1}^2 v_1 = W_2{\Gamma_2}^2 v_2$$

with $P = p_{\mathrm{th}} + B^2/\Gamma^2$, the total pressure and $W = w + B^2/\Gamma^2$, the total enthalpy, associated to an adiabatic ideal gas EOS.



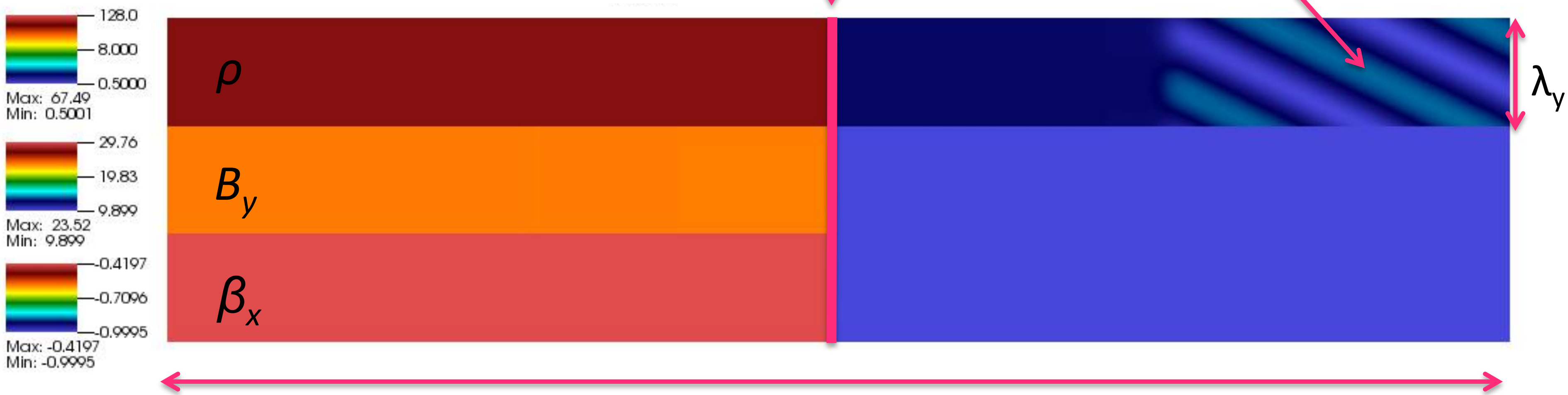
Relativistic shocks: incoming entropy wave

- Entropy wave: pertubations in ρ
- Perturbation amplitude: $\delta\rho/\rho$ = 45%
- Relative Lorentz factor: 20
- Upstream magnetization: σ=0.1

$$\boxed{\sigma \equiv \frac{\text{magn. energy}}{\text{enthalpy}}}$$

Incoming entropy wave

Shock front



λ_y

$12.4\ \lambda_y$

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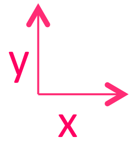
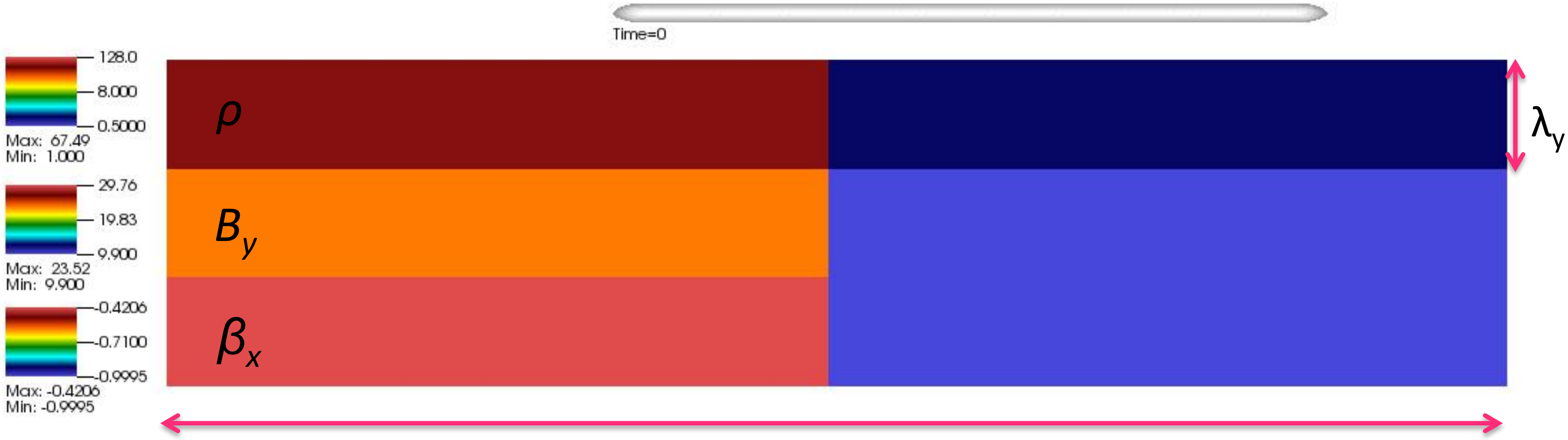




$12.4\ \lambda_y$

Relativistic shocks: incoming entropy wave

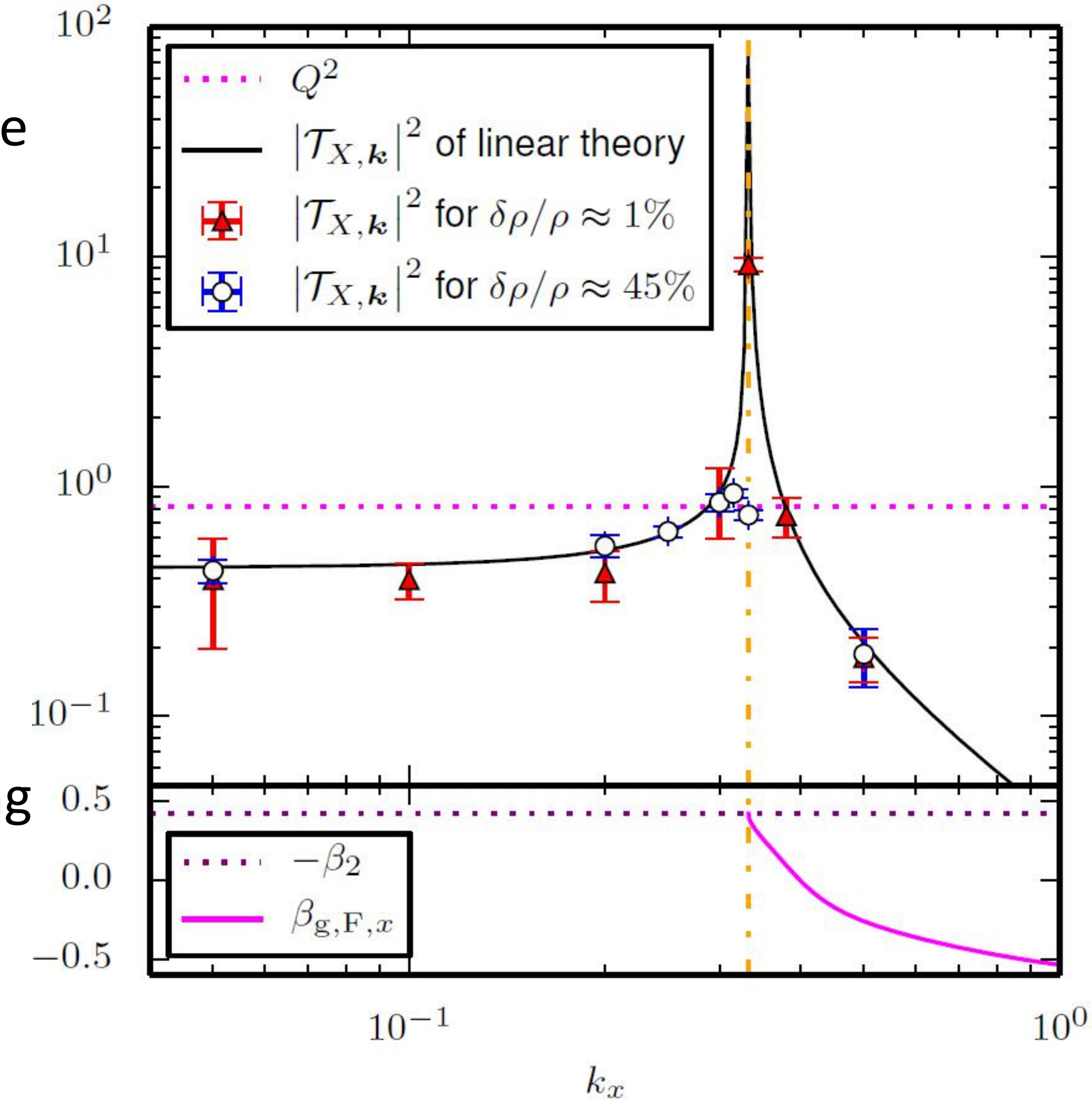
- In downstream rest frame

- Transfer function

$$\boxed{\mathcal{T}_{X,\boldsymbol{k}} \propto \frac{\text{ampli of corrugation}}{\text{ampli of wave}}}$$

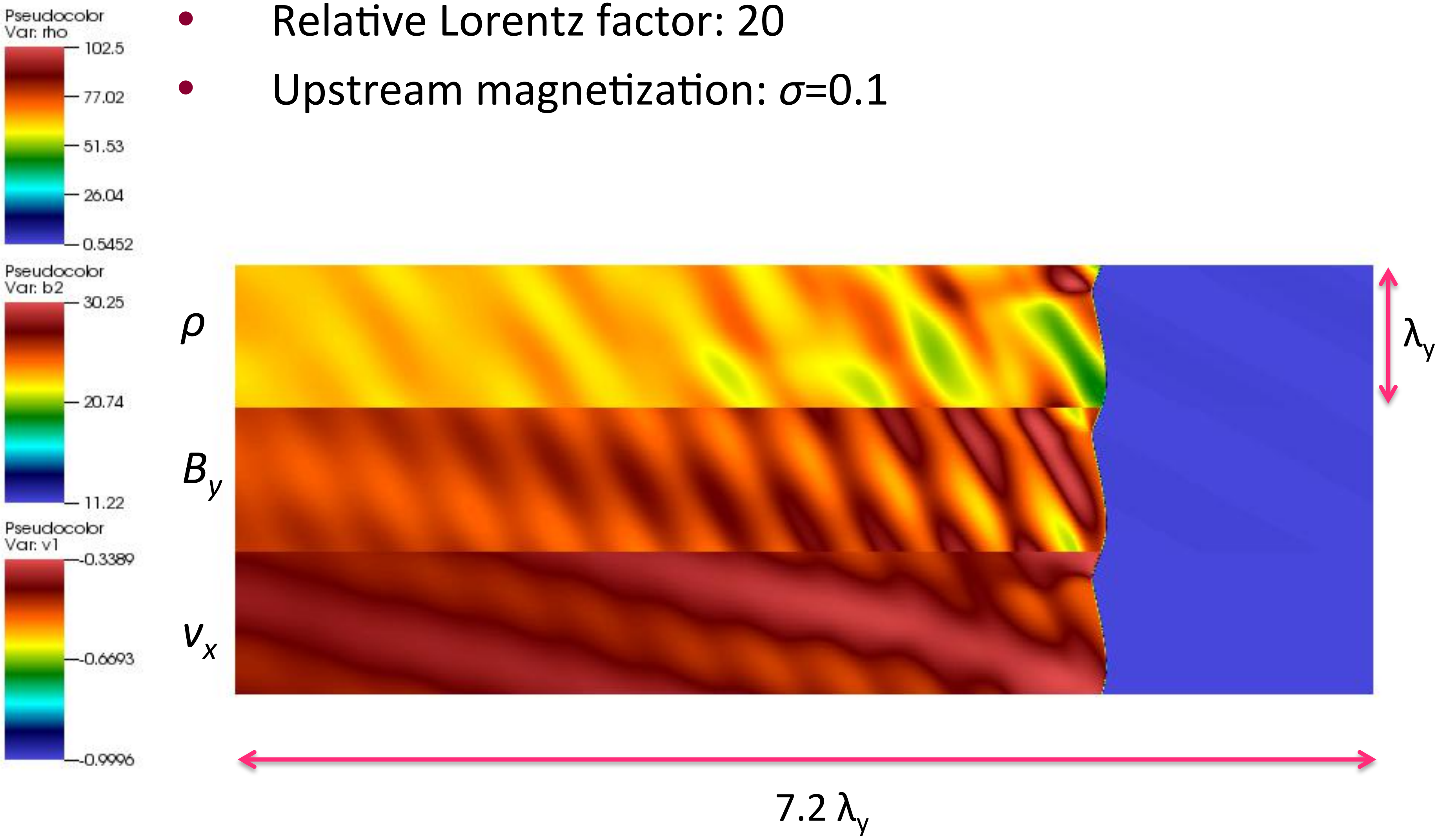
- Resonance: longitudinal group velocity of outgoing F mode= shock velocity

Demidem et al, 2018, Mon. Not. R. Astron. Soc. 475, 2713–2723



Relativistic shocks: incoming FMS wave

- Perturbation amplitude: $\delta\rho/\rho$ = 45 %
- Relative Lorentz factor: 20
- Upstream magnetization: σ=0.1



Relativistic shocks: incoming FMS wave

- In downstream rest frame

- Transfer function

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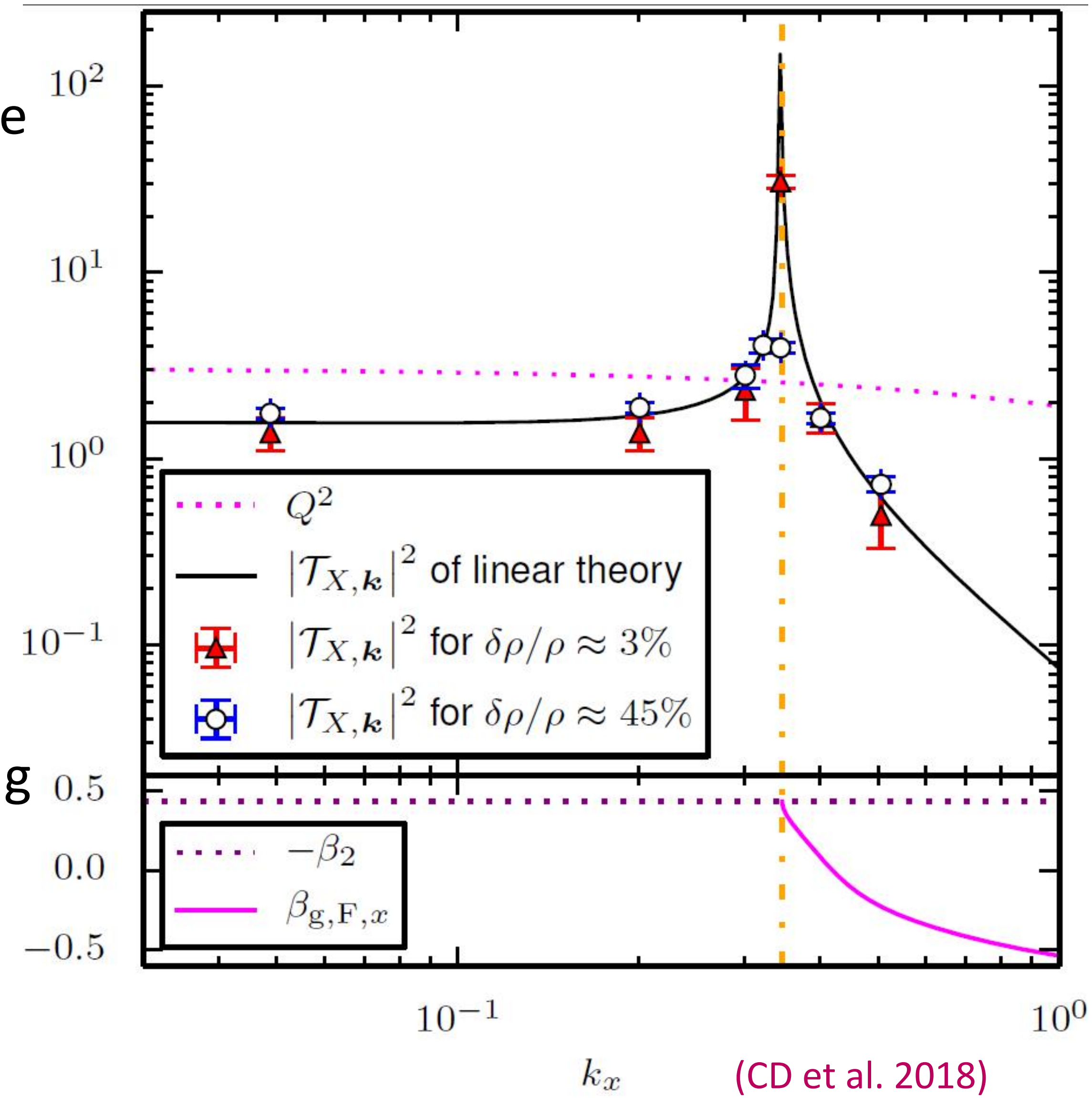
- Resonance: longitudinal group velocity of outgoing F mode= shock velocity



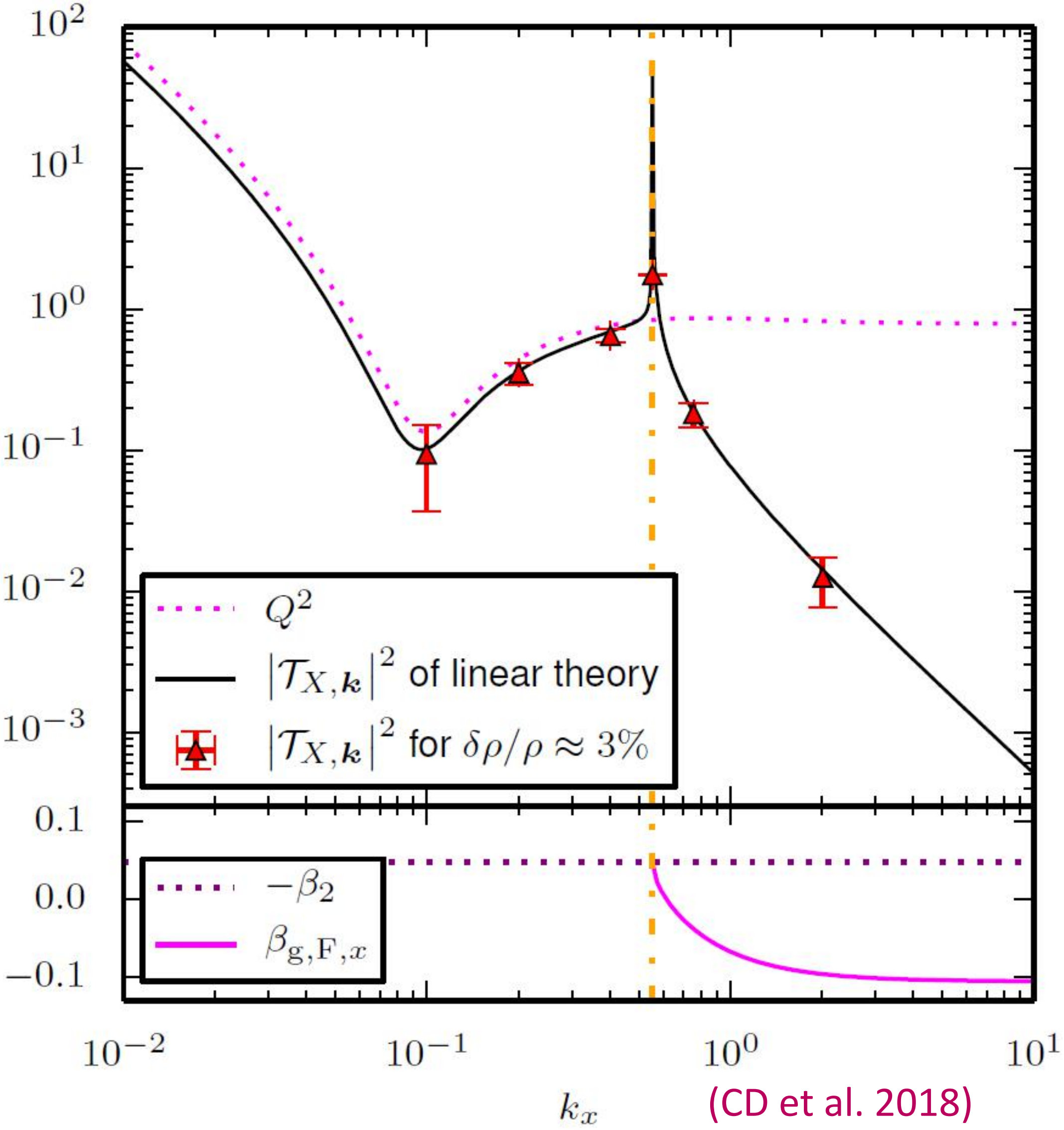
(CD et al. 2018)

Sub-relativistic shocks ($\beta_{sh/up}$≈0.2, σ≈10^{-4}): incoming FMS wave

- In downstream rest frame
- Transfer function

$$\boxed{\mathcal{T}_{X,\boldsymbol{k}} \propto \frac{\text{ampli of corrugation}}{\text{ampli of wave}}}$$

- Resonance: longitudinal group velocity of outgoing F mode= shock velocity



(CD et al. 2018)

Conclusion

Summary (Demidem et al, 2018, Mon. Not. R. Astron. Soc. 475, 2713–2723):

SRMHD simulations of interaction of upstream monoλ MHD mode with shock show existence of **universal** (i.e. for both relativistic/sub-relativistic velocities & strong/weak magnetizations) **resonant response of shock** to perturbations.

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Summary (Demidem et al, 2018, Mon. Not. R. Astron. Soc. 475, 2713–2723):

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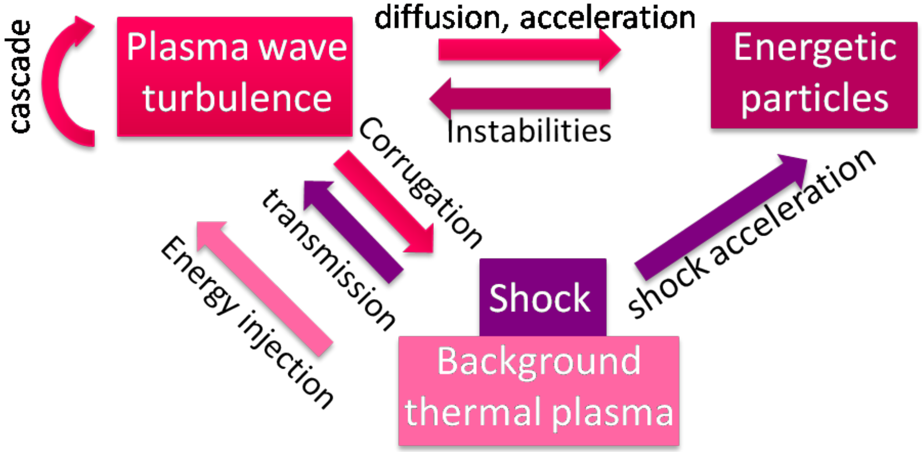

Outlook:

- Impact of the corrugation on particle acceleration?
- PI[MHD]C simulations of **non-relativistic** shocks: → corrugation induced by the accelerated particles which in turn affect particle acceleration efficiency. (Van Marle et al. 2018, MNRAS Vol. 473, 3394)