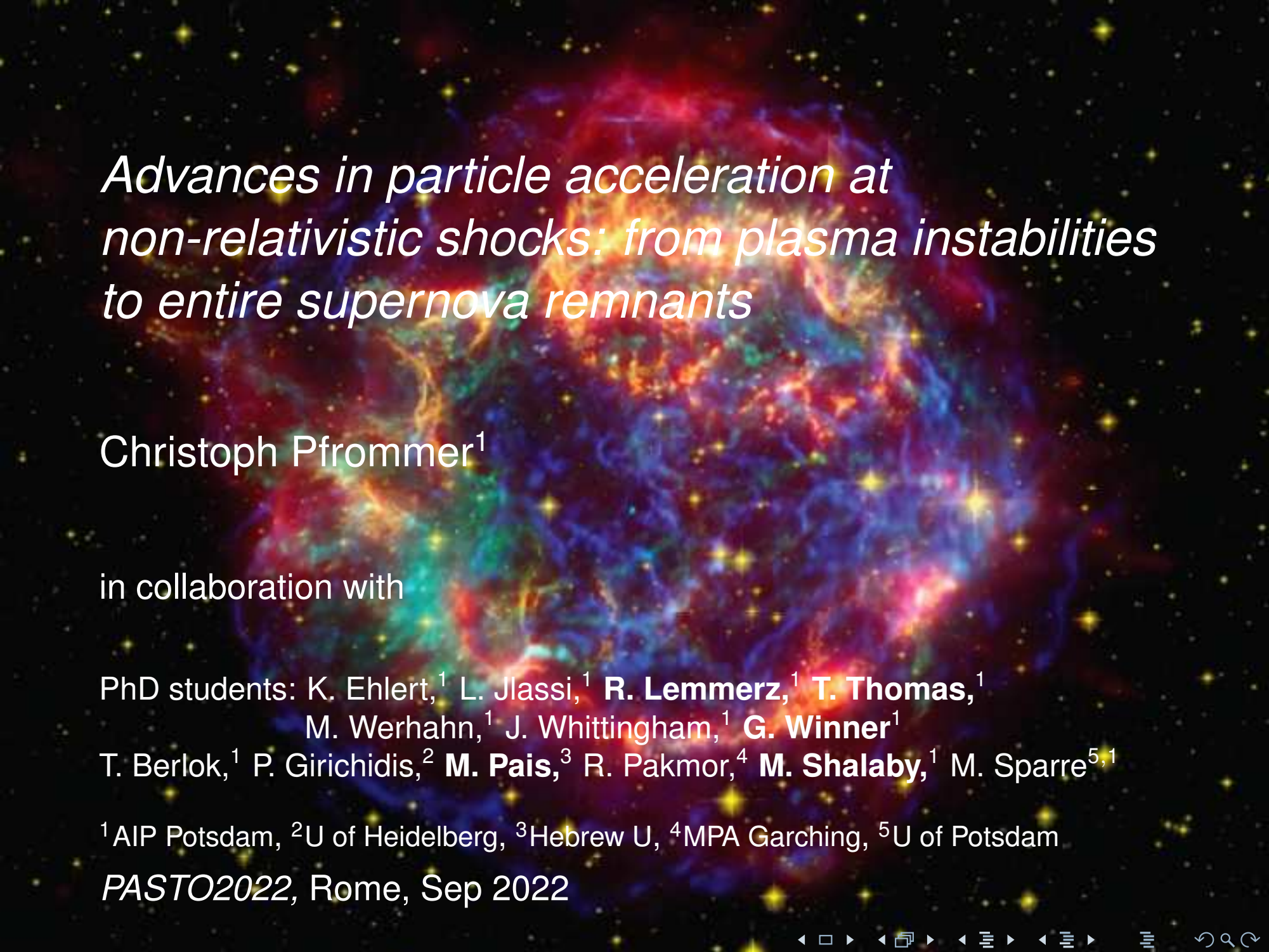


Advances in particle acceleration at non-relativistic shocks: from plasma instabilities to entire supernova remnants

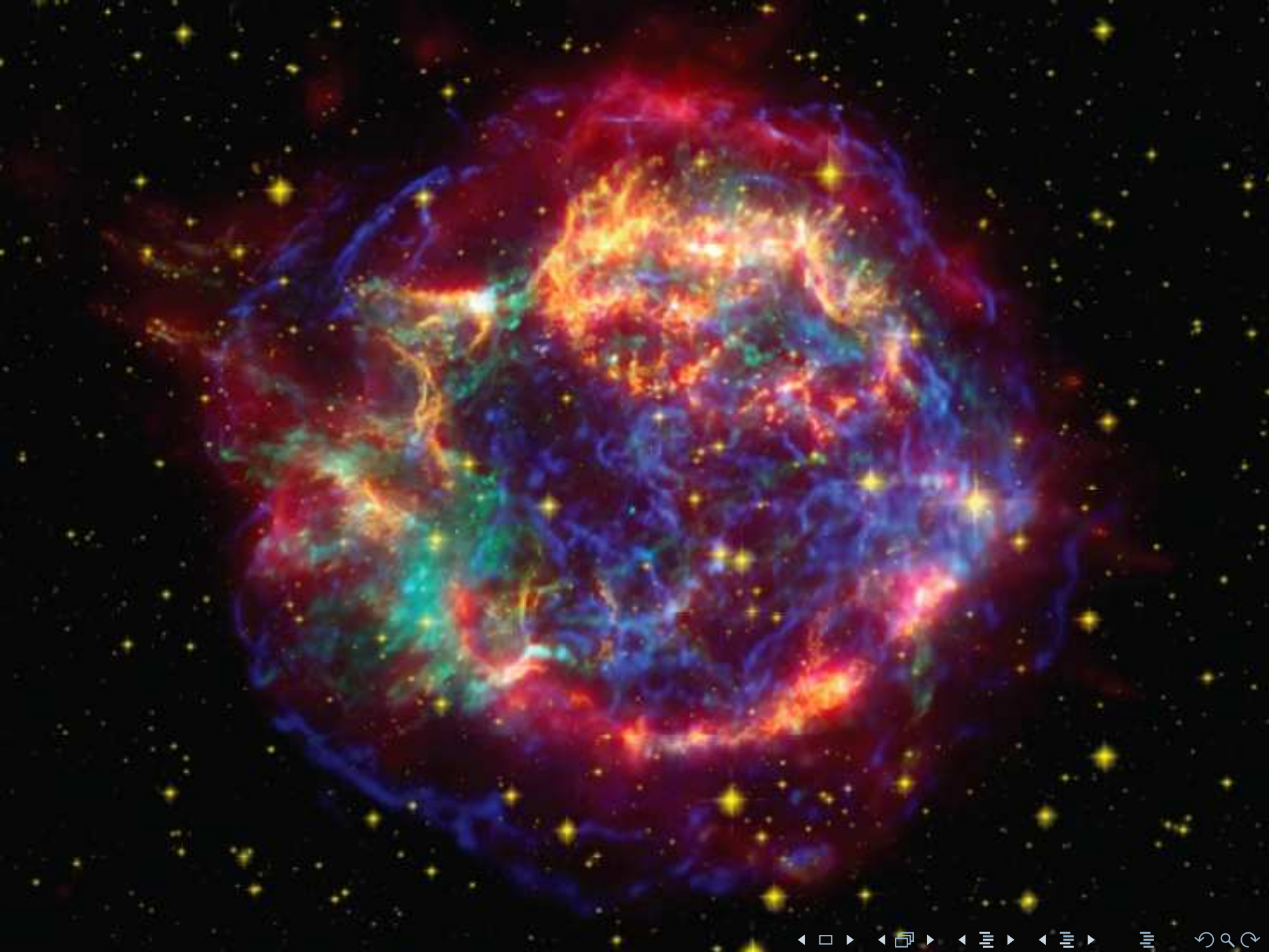
Christoph Pfrommer[1]

in collaboration with

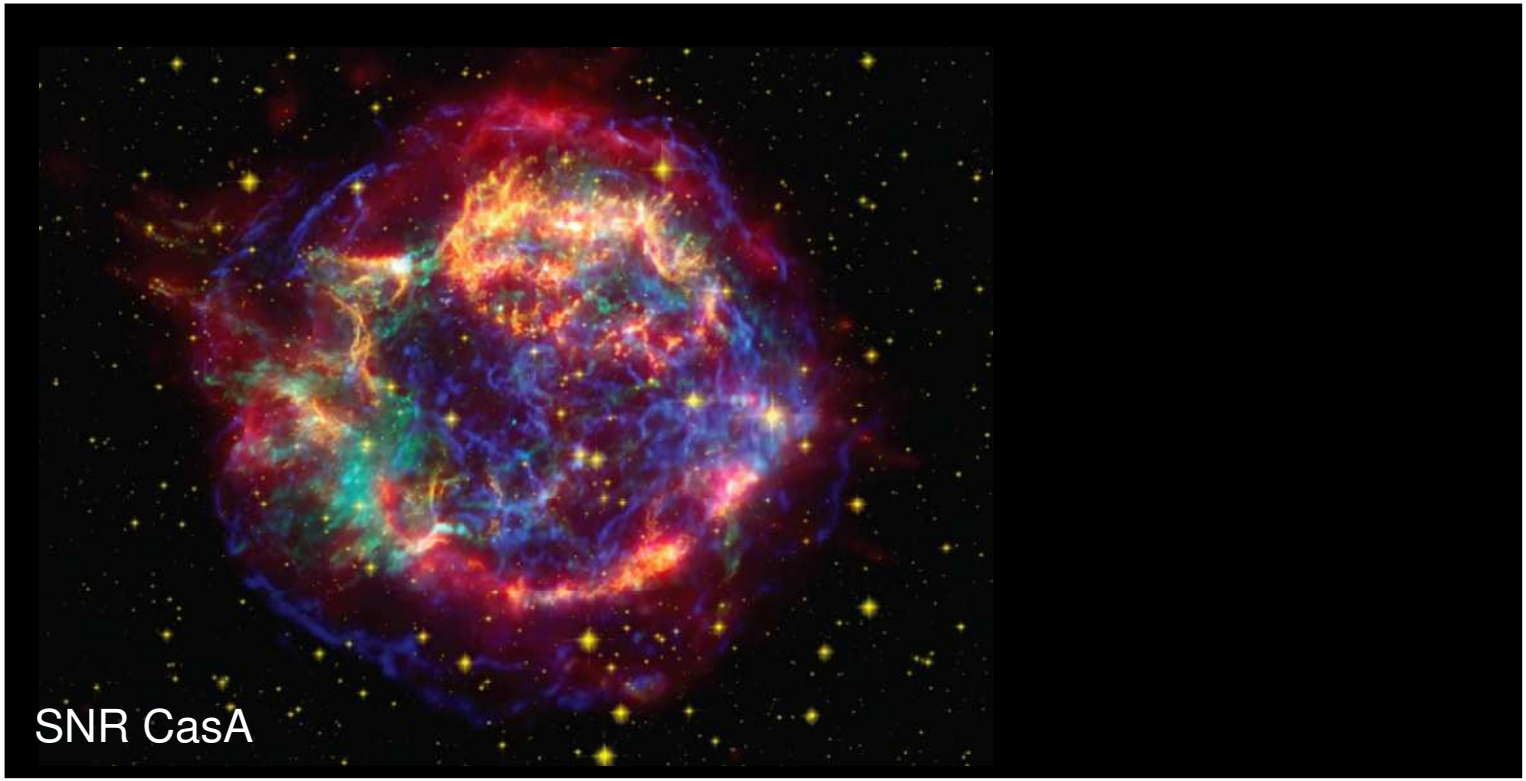
PhD students: K. Ehlert,[1] L. Jlassi,[1] **R. Lemmerz,**[1] **T. Thomas,**[1]
M. Werhahn,[1] J. Whittingham,[1] **G. Winner**[1]
T. Berlok,[1] P. Girichidis,[2] **M. Pais,**[3] R. Pakmor,[4] **M. Shalaby,**[1] M. Sparre[5,1]

[1]AIP Potsdam, [2]U of Heidelberg, [3]Hebrew U, [4]MPA Garching, [5]U of Potsdam

PASTO2022, Rome, Sep 2022



Particle acceleration: an extreme multi-scale problem



supernova remnant:

$r_{\mathrm{SNR}} \sim 3\ \mathrm{pc} \sim 1 \times 10^{19}\ \mathrm{cm},$

AIP

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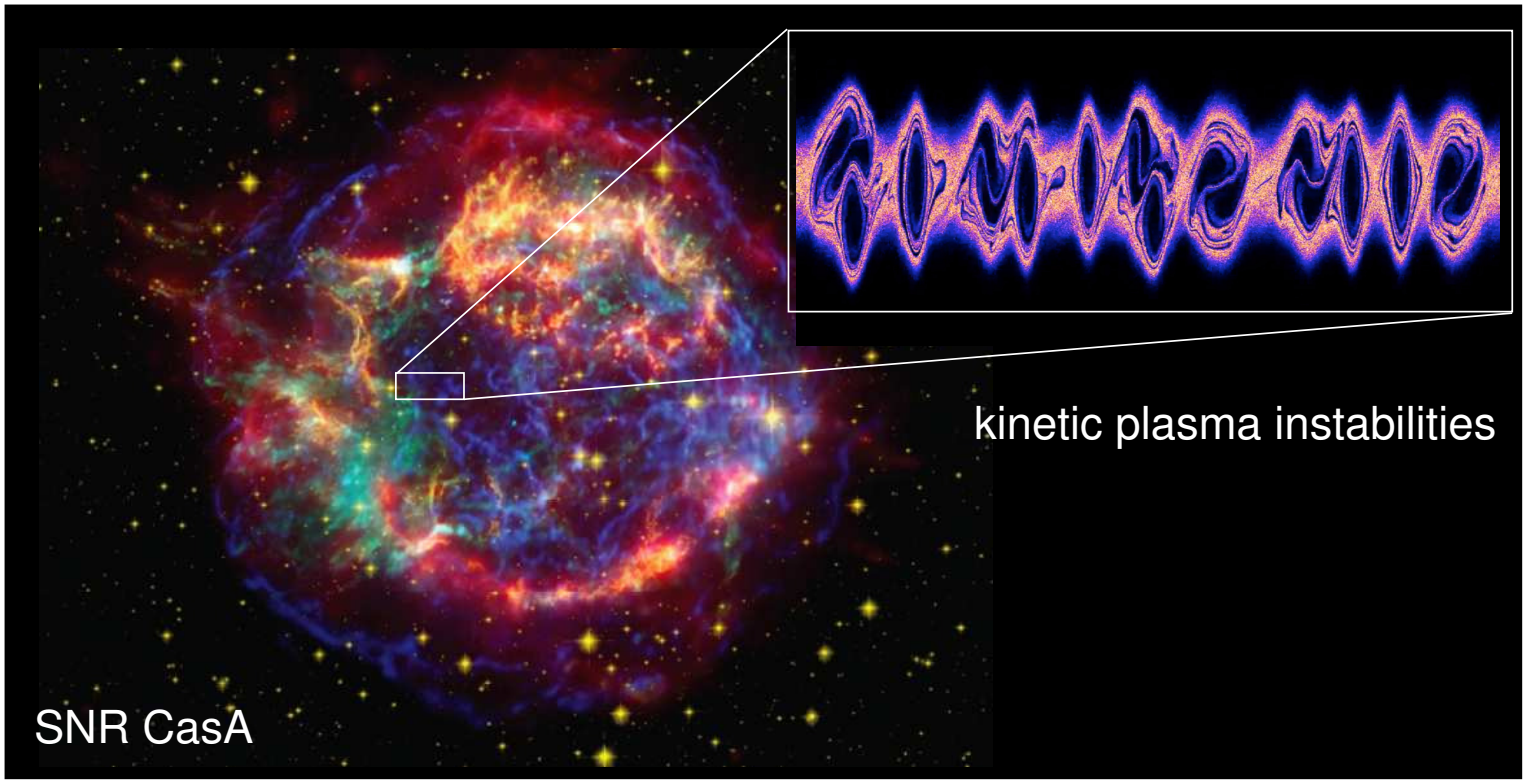

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plasma skin depth:

$$\lambda_{\mathrm{i}} = \frac{c}{\omega_{\mathrm{i}}} \sim 2 \times 10^{7} \left(\frac{n}{1\ \mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{cm}$$

AIP

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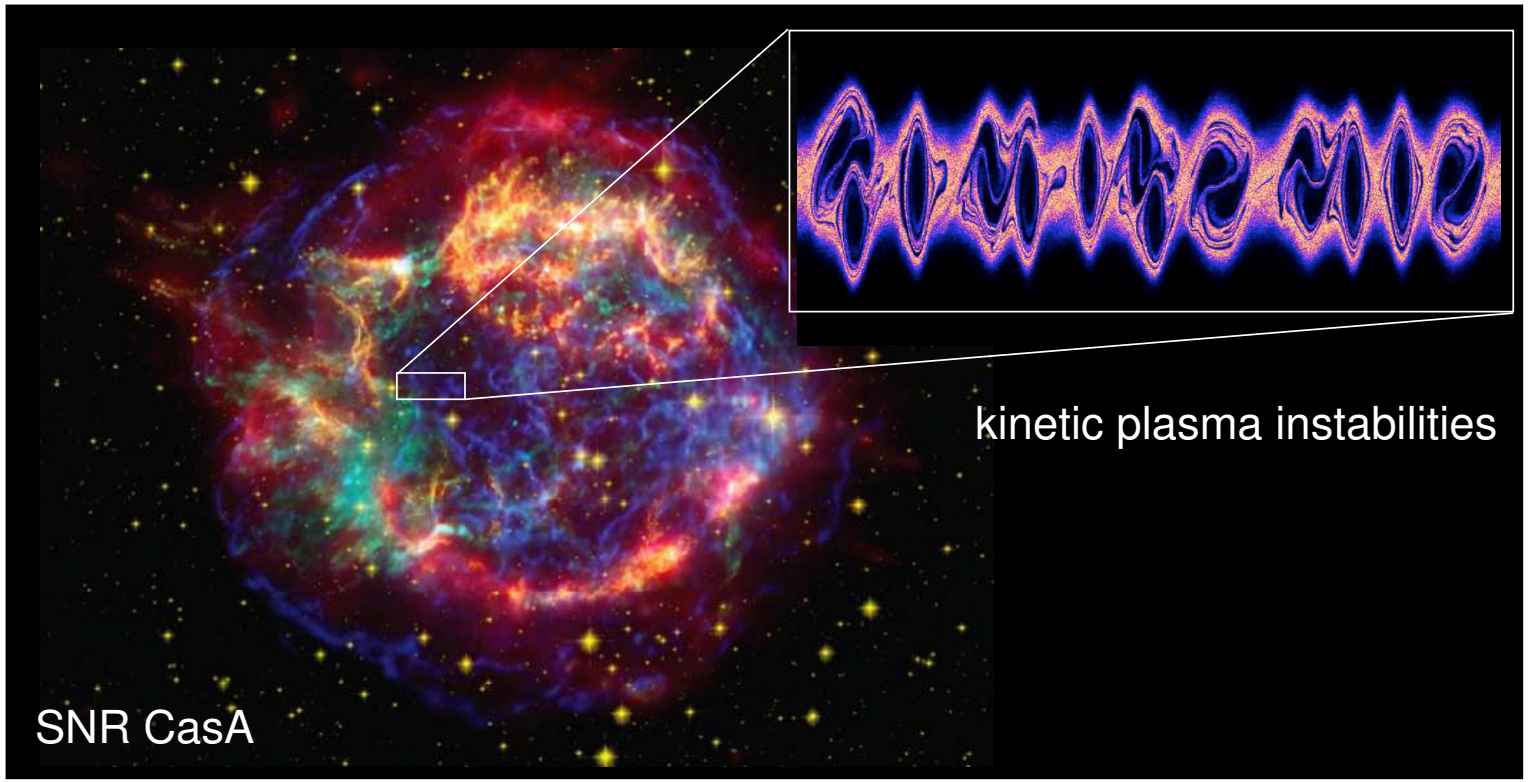

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$\Rightarrow$ need to develop a **multi-scale approach: PIC and MHD models!**

Outline

AIP

Cosmic ray scattering with background plasma

- extrinsic confinement: scattering off of turbulence injected on the driving scale and cascaded to smaller scales
  $\Rightarrow$ important for confinement of TeV CRs

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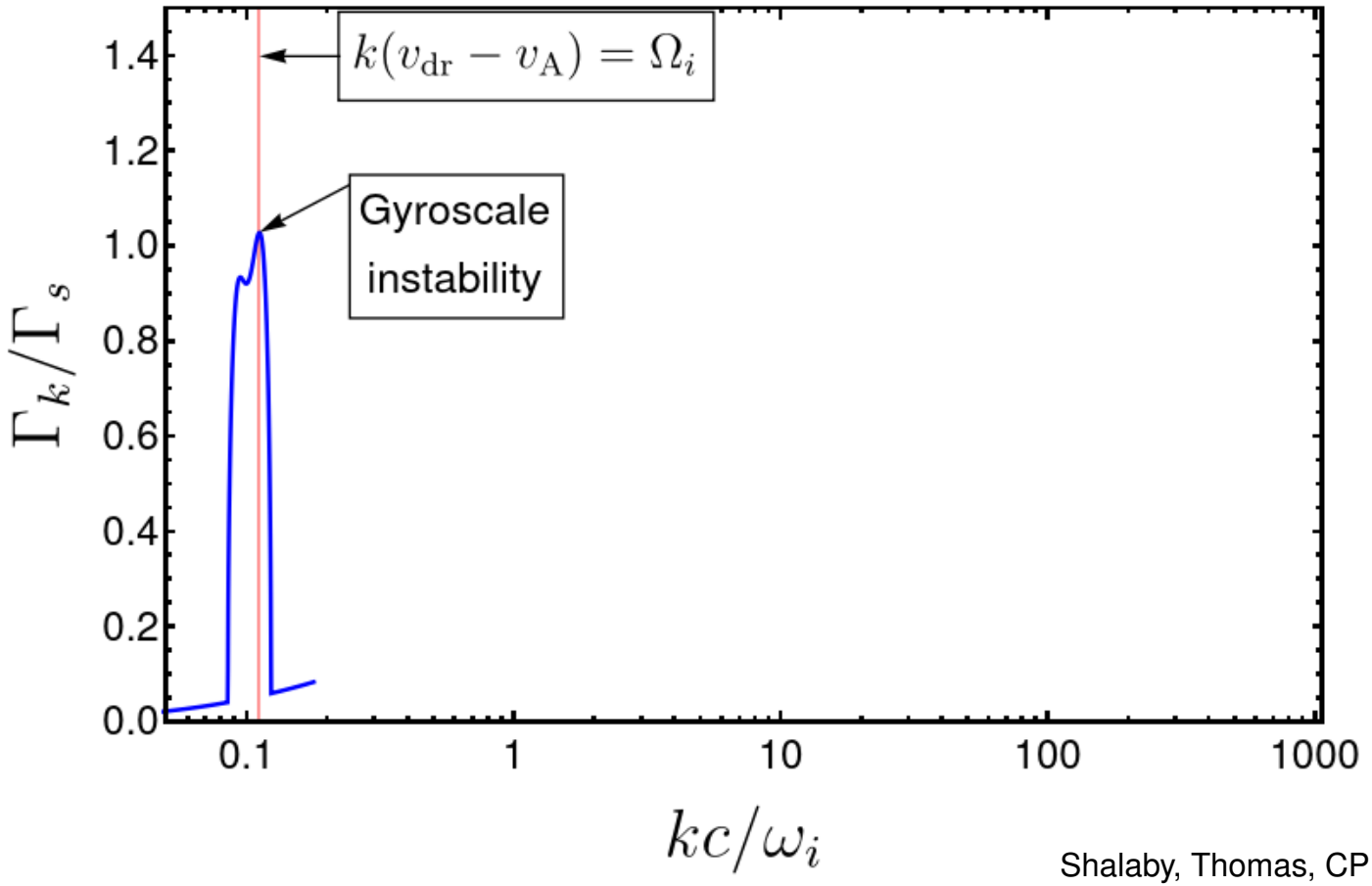
- intrinsic confinement: CRs drive unstable plasma wave modes (e.g., Alfvén waves), and then scatter off of them
  $\Rightarrow$ most important mechanism for GeV CR confinement
- dispersion relation ($\Omega_{e,0} = -m_i/m_e \times \Omega_{i,0}$, $\alpha = n_{cr}/n_i$): gyrotropic CR ion + electron beam propagates in background plasma

$$\frac{k^2c^2}{\omega^2} - 1 = \frac{\omega_i^2}{\omega\left(-\omega \pm \Omega_{i,0}\right)} + \frac{\omega_e^2}{\omega\left(-\omega \pm \Omega_{e,0}\right)} \quad \Leftarrow \text{ background}$$

$$\text{CRe} \Rightarrow \quad + \frac{\alpha\omega_e^2}{\gamma_e\omega^2}\left\{\frac{\omega - kv_{dr}}{kv_{dr} - \omega \mp \Omega_{e,0}/\gamma_e}\right\}$$

$$\text{CRi} \Rightarrow \quad + \frac{\alpha\omega_i^2}{\gamma_i\omega^2}\left\{\frac{\omega - kv_{dr}}{kv_{dr} - \omega \pm \Omega_i} - \frac{v_\perp^2\left(k^2c^2 - \omega^2\right)/c^2}{2\left(kv_{dr} - \omega \pm \Omega_i\right)^2}\right\}$$

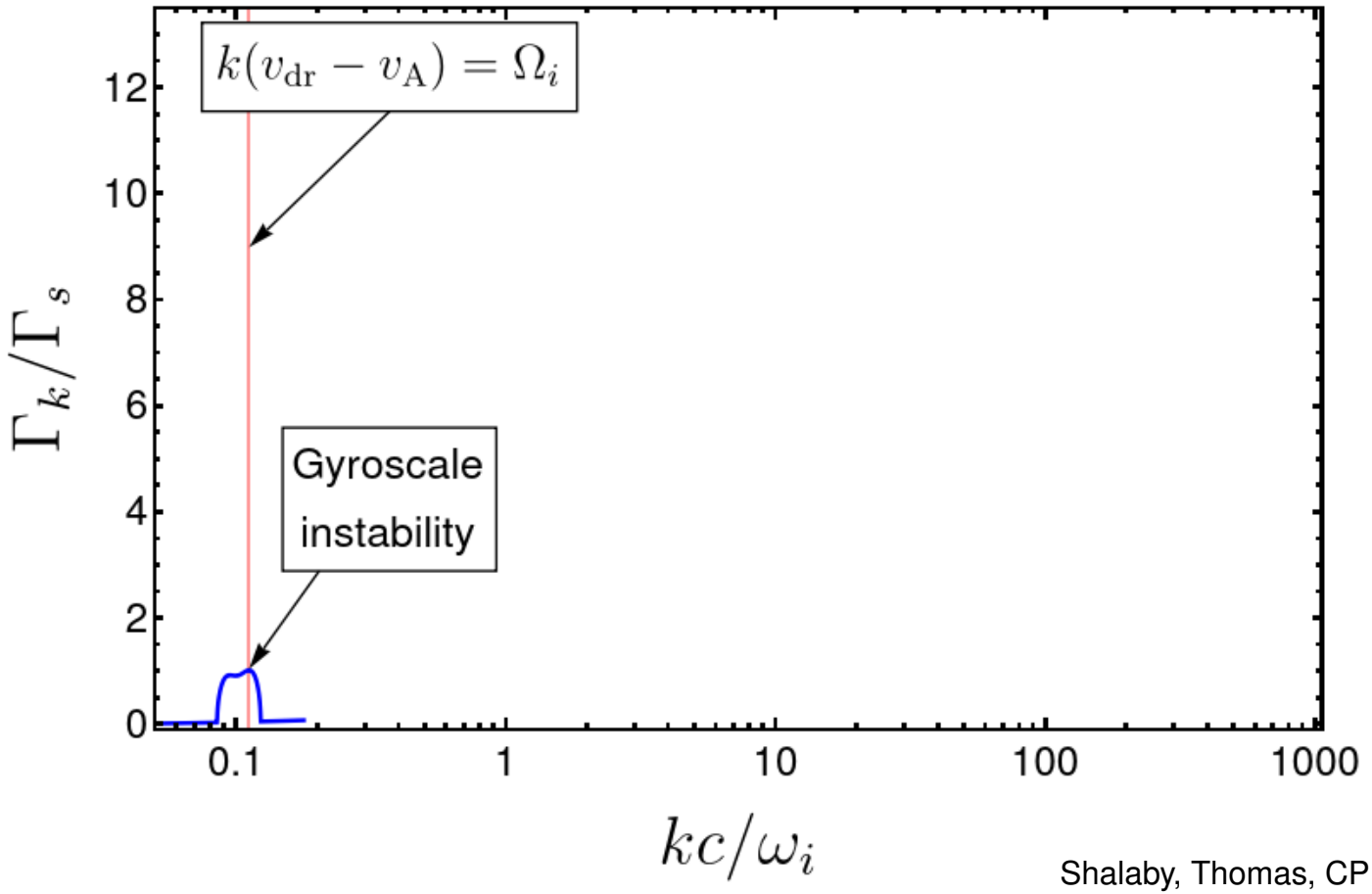
CR driven instabilities – growth rates



Shalaby, Thomas, CP (2021)

- gyro-resonant instability of gyrotropic CR population

CR driven instabilities – growth rates



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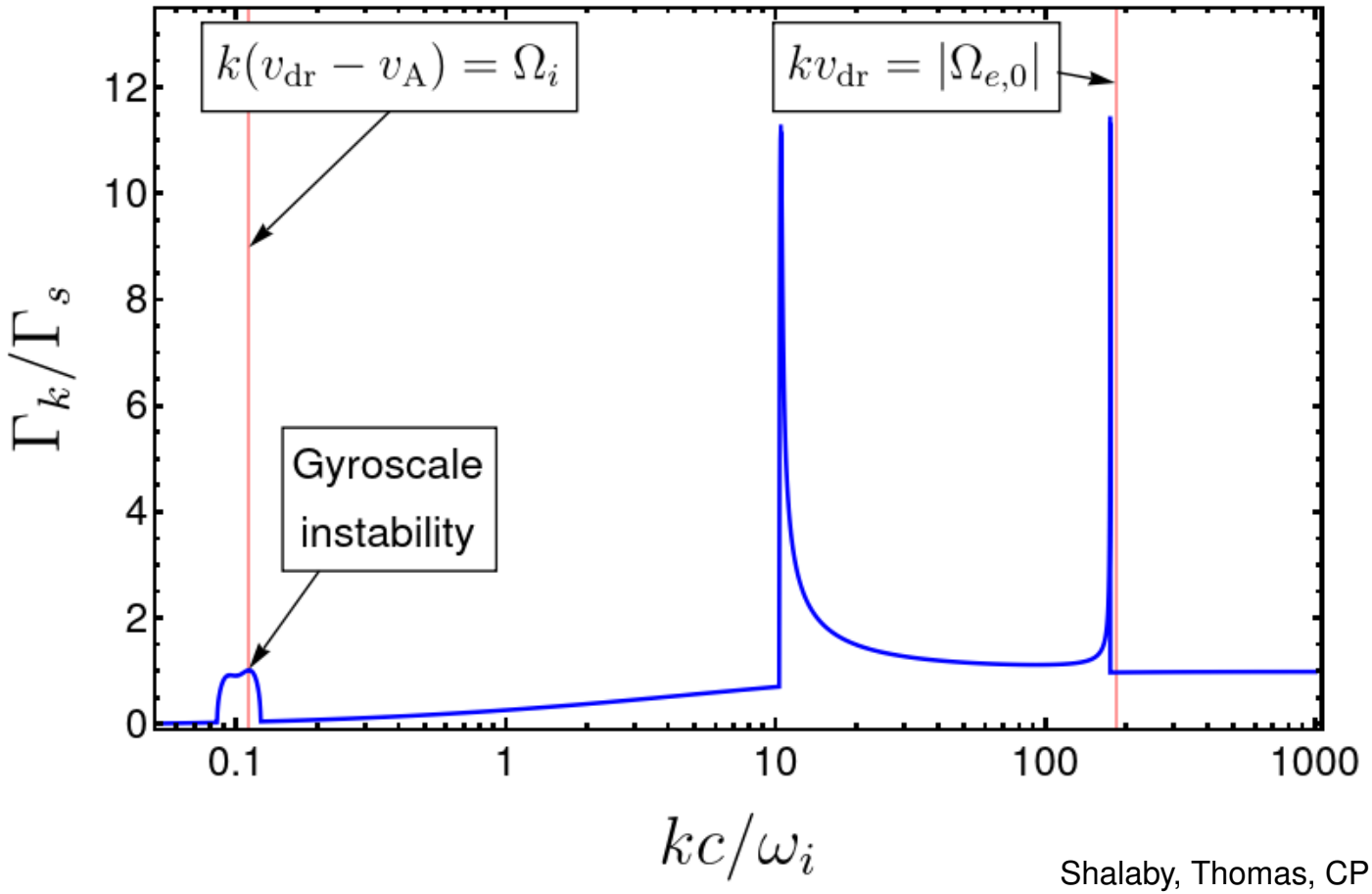

Shalaby, Thomas, CP (2021)

- **new intermediate-scale instability** of gyrotropic CR population

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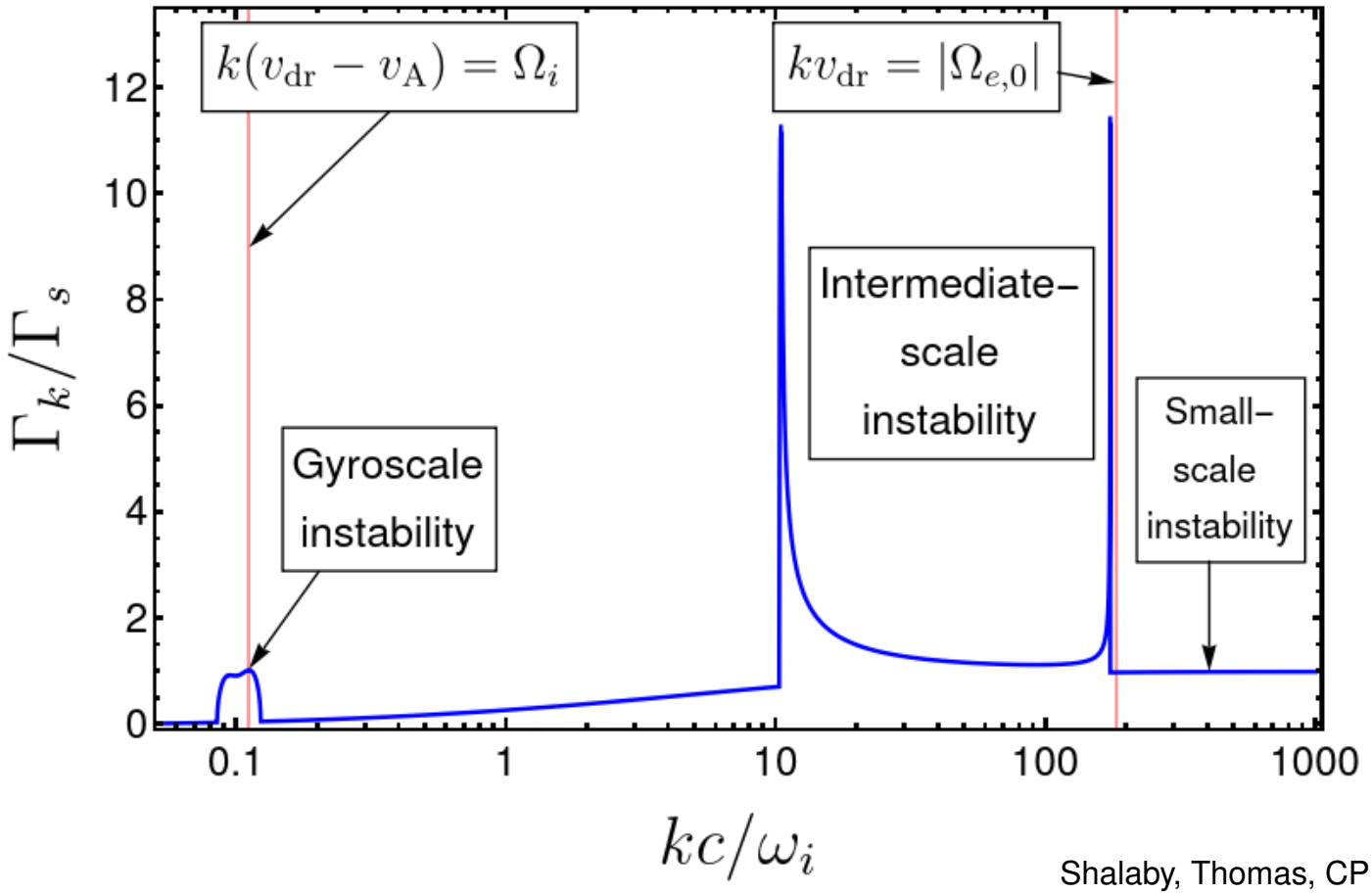

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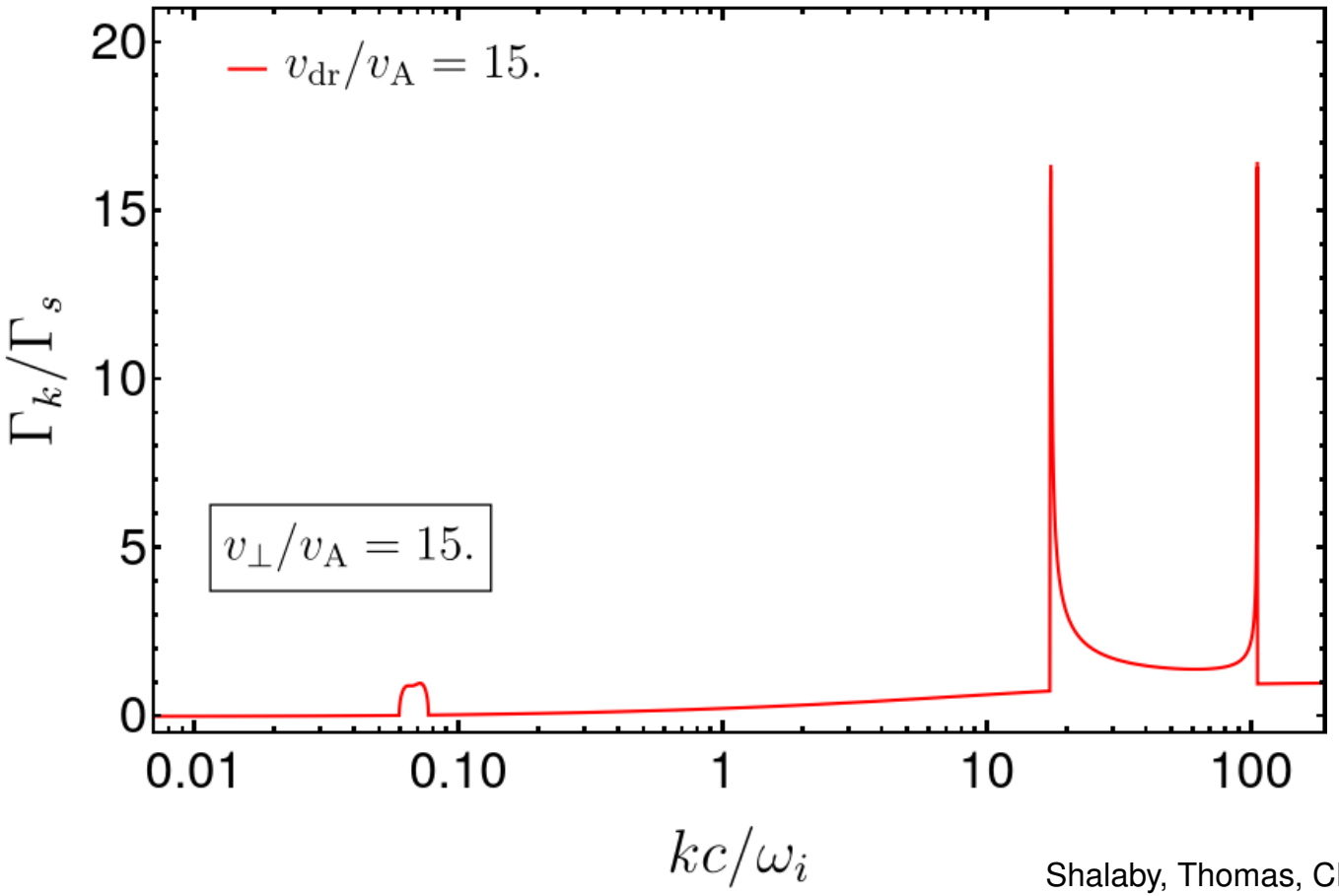
CR driven intermediate-scale instability



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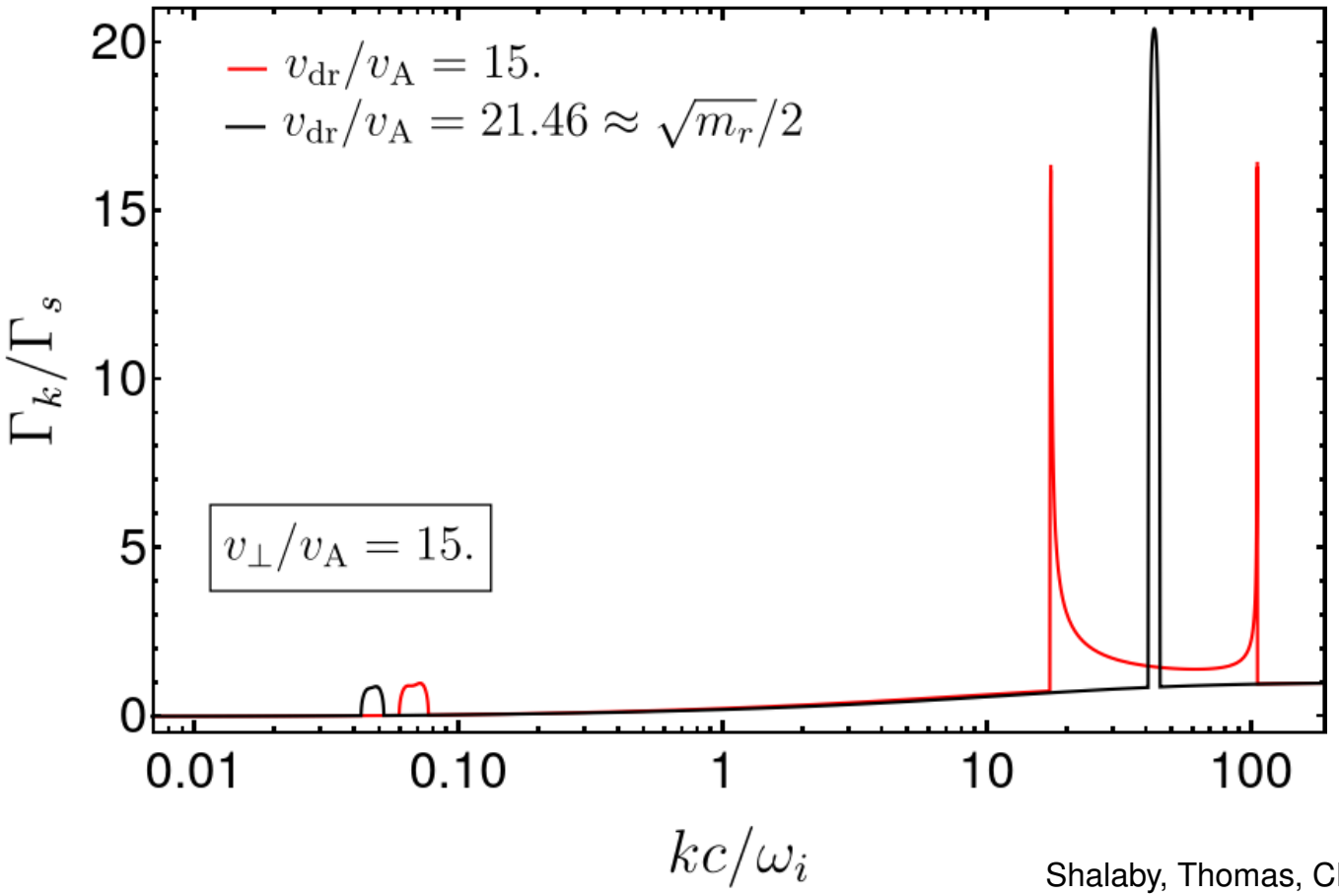
- low CR drift speed: two instability peaks

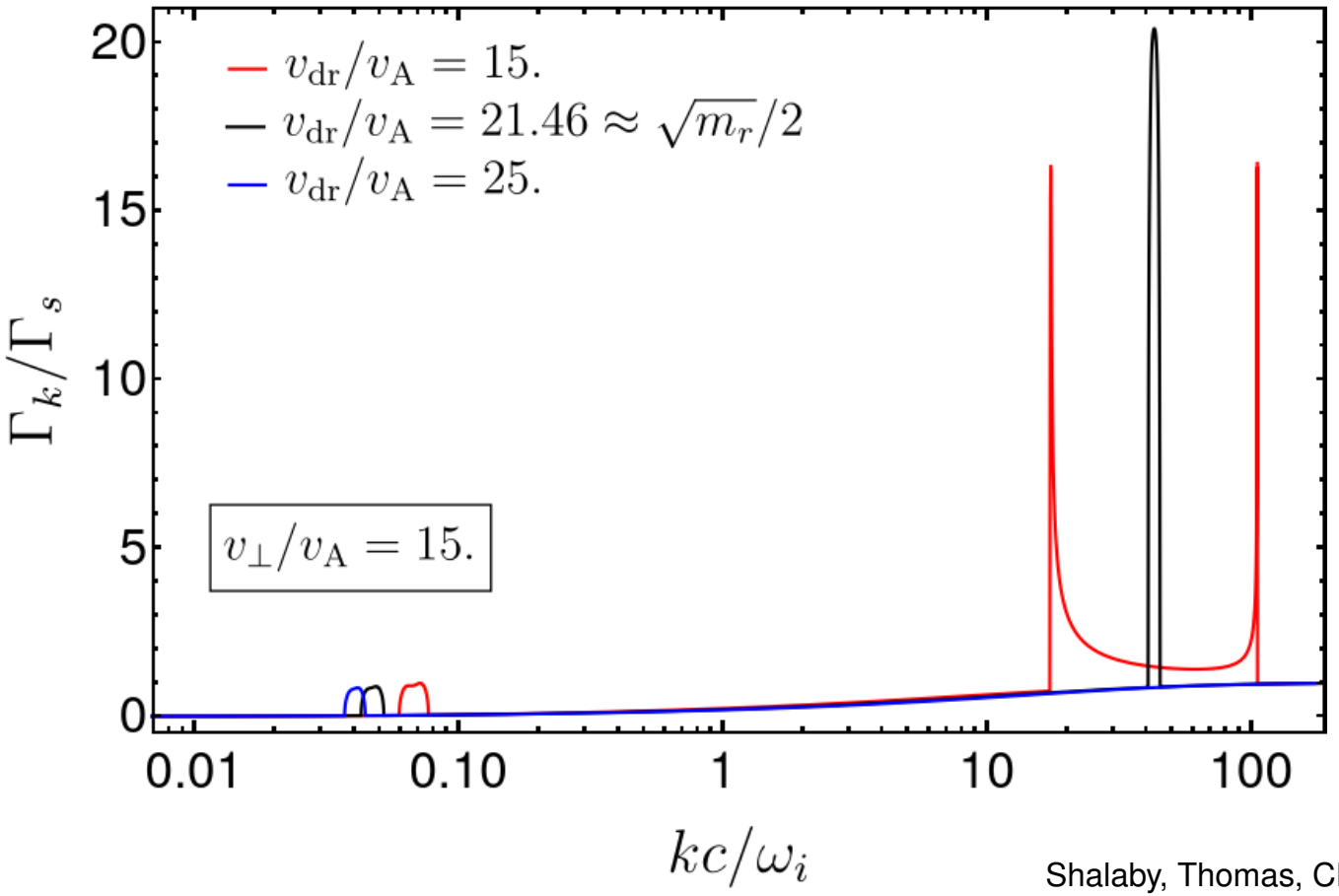
CR driven intermediate-scale instability



Shalaby, Thomas, CP (2021)

- for CR drift speed $v_{\rm dr} \approx \sqrt{\frac{m_{\rm i}}{m_{\rm e}}}\frac{v_{\rm A}}{2}$: two instability peaks merge

CR driven intermediate-scale instability



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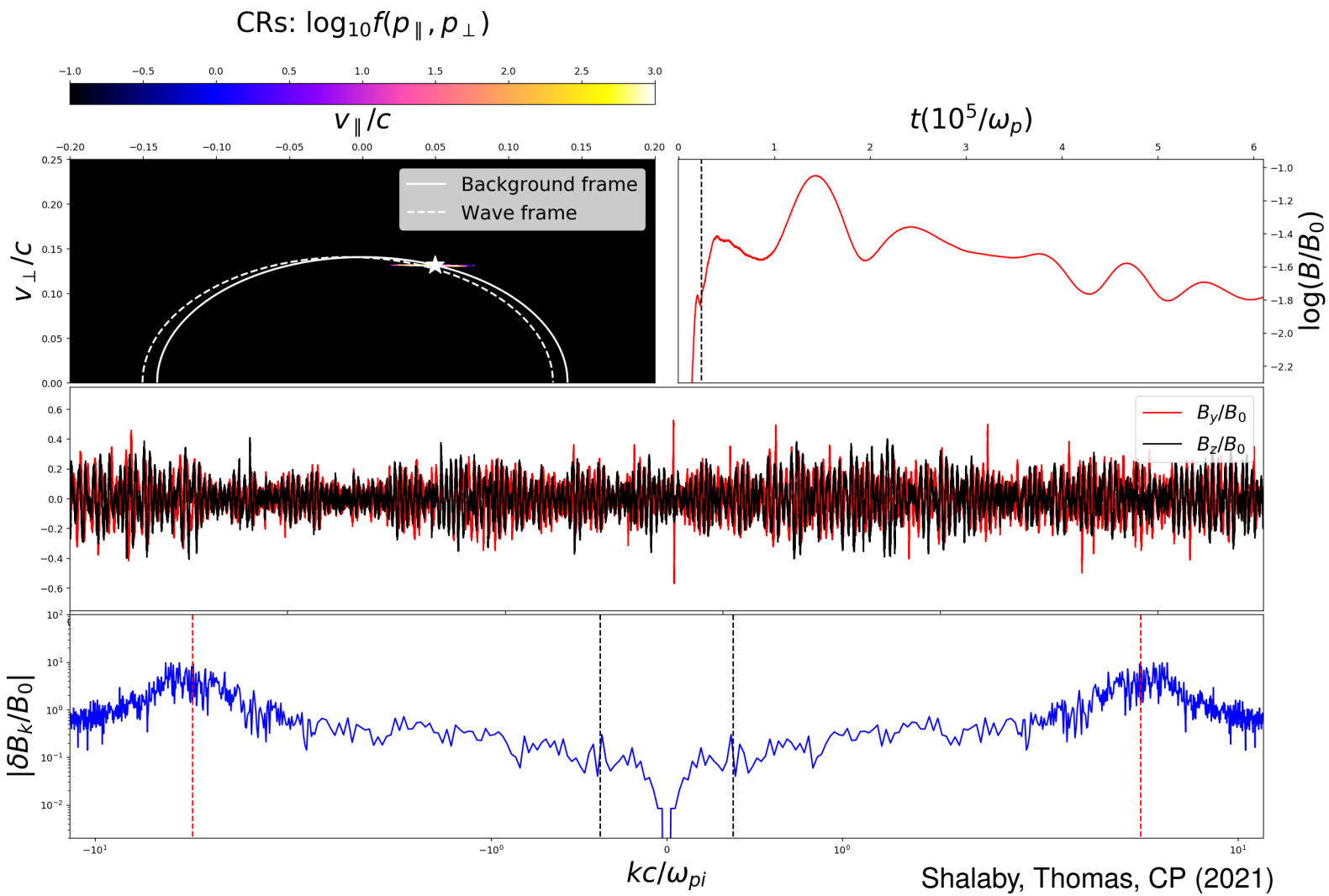
- for $v_{\rm dr} > \sqrt{\frac{m_{\rm i}}{m_{\rm e}}}\frac{v_{\rm A}}{2}$: intermediate-scale instability quenched

Cosmic ray driven instabilities

Growth of the intermediate-scale and the gyro-resonant instability



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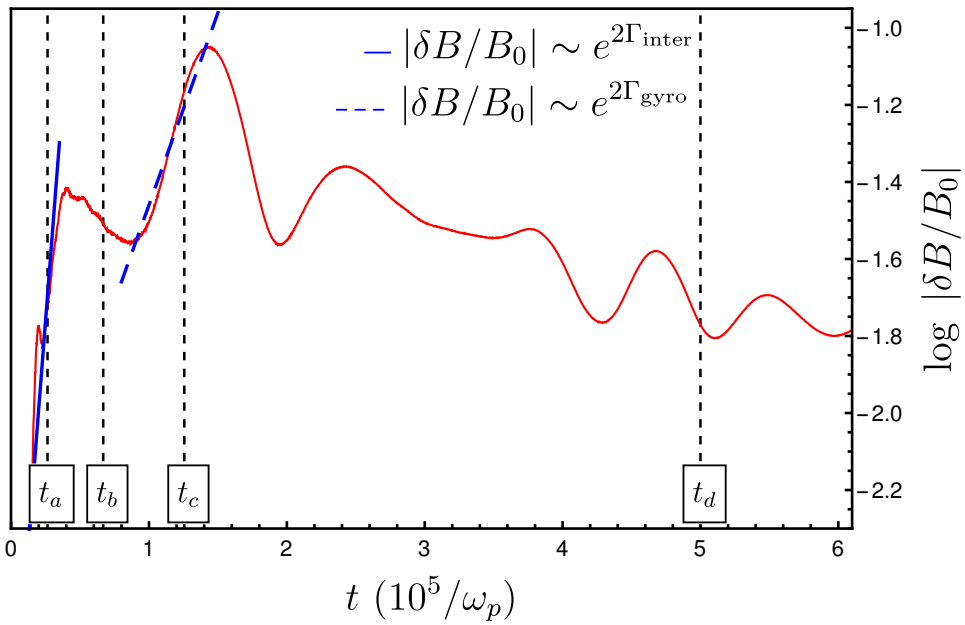
CR driven instabilities: magnetic field growth



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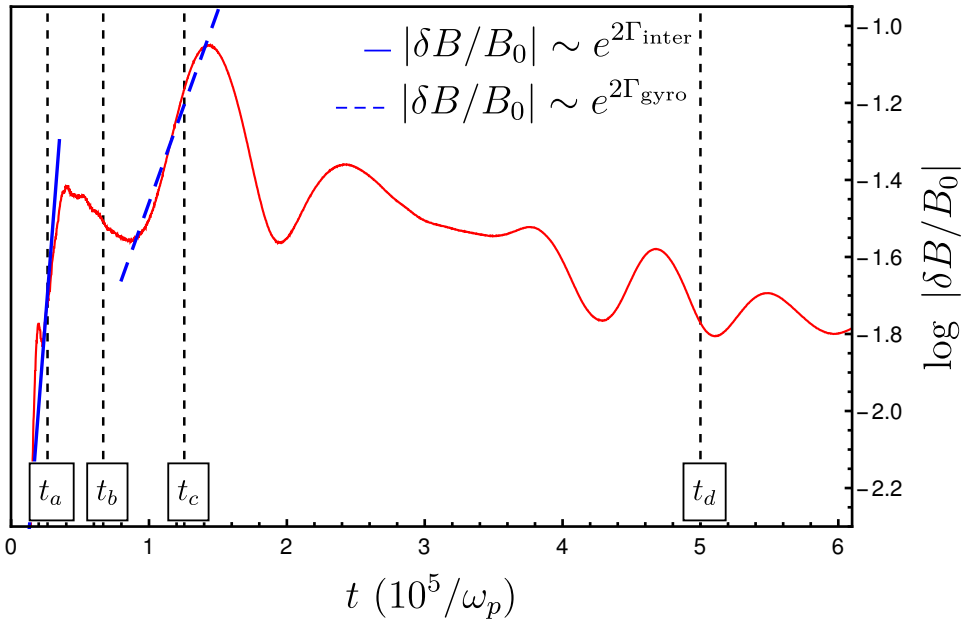

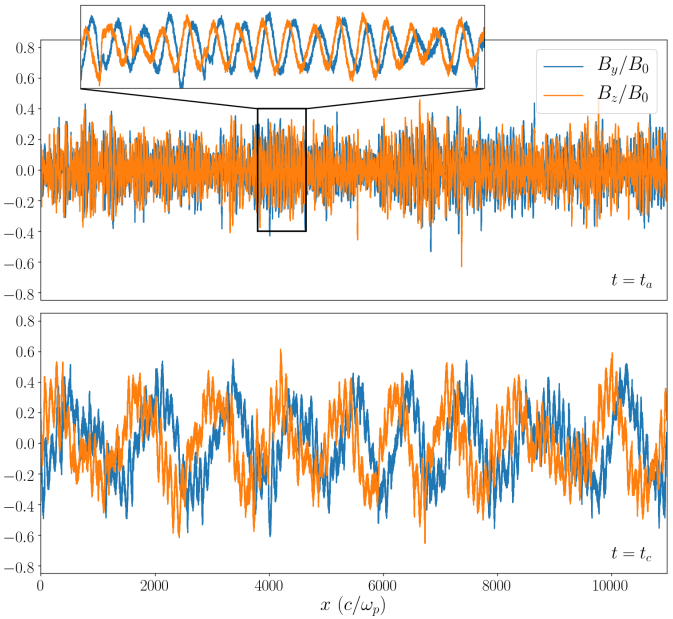

Shalaby, Thomas, CP (2021)

- $t \sim t_{\rm a}$: fast magnetic field amplification at scales $< d_{\rm i}$

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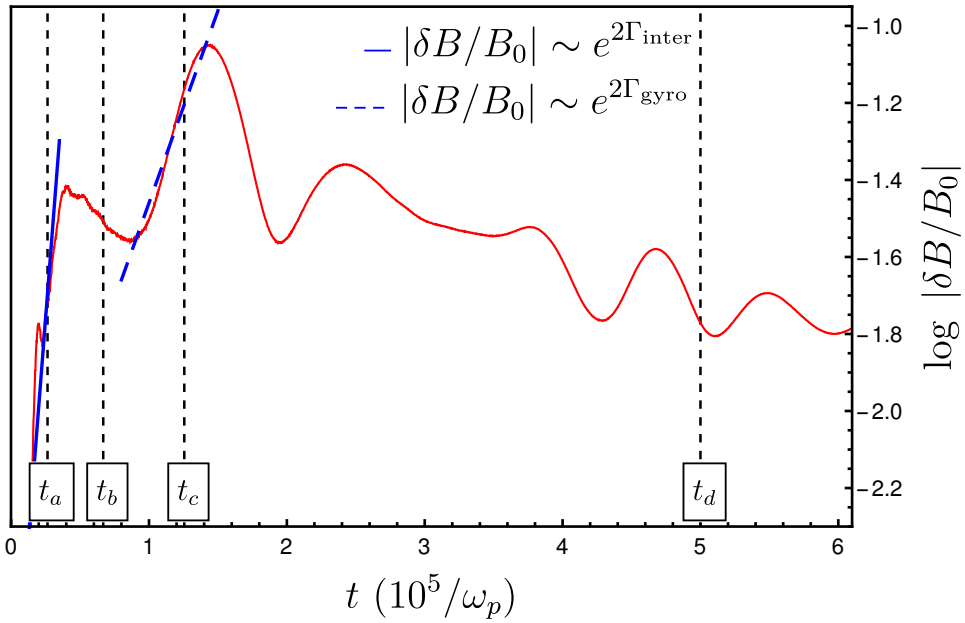
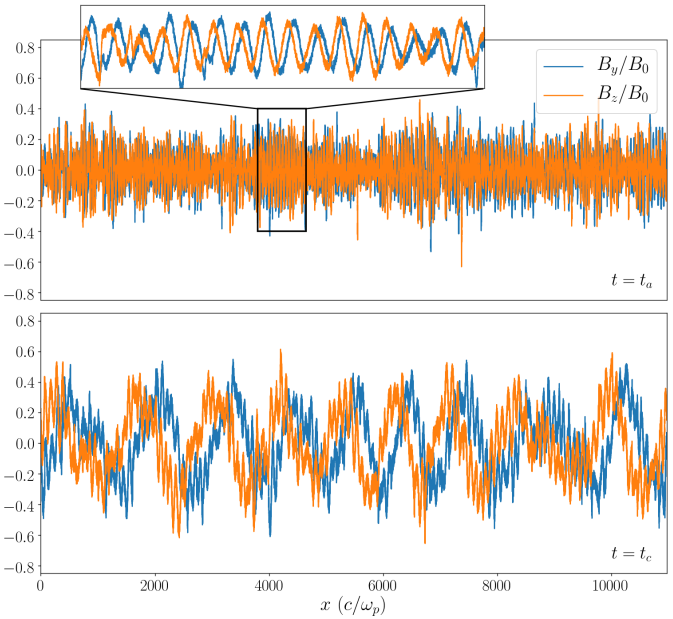
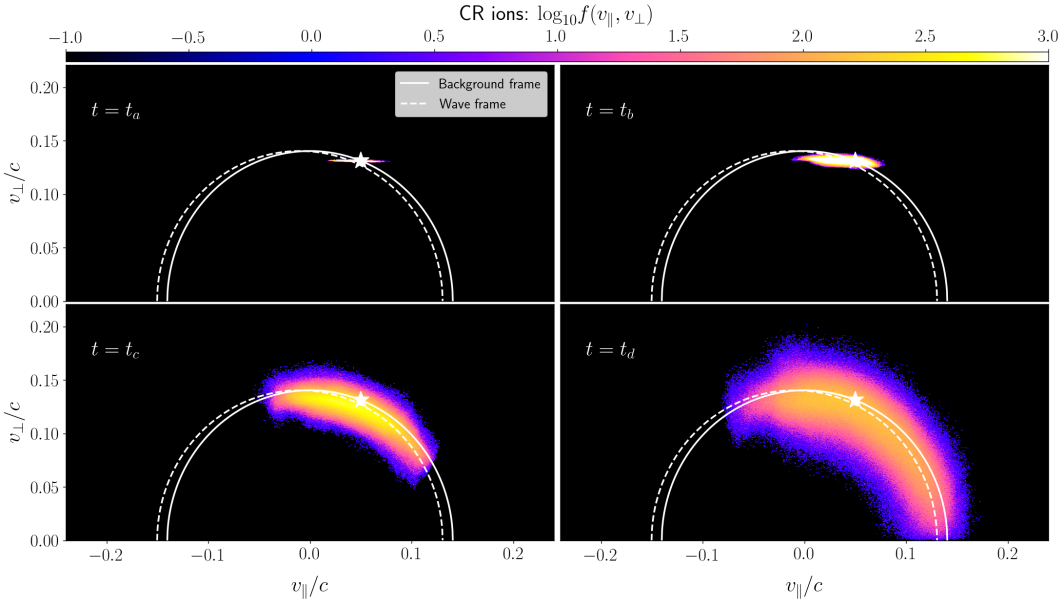




Shalaby, Thomas, CP (2021)

- $t \sim t_{\rm a}$: fast magnetic field amplification at scales $< d_{\rm i}$
- $t \sim t_{\rm c}$: instability starts to grow on larger, gyro-resonant scale $d_{\rm i}$

CR driven instabilities: momentum distribution



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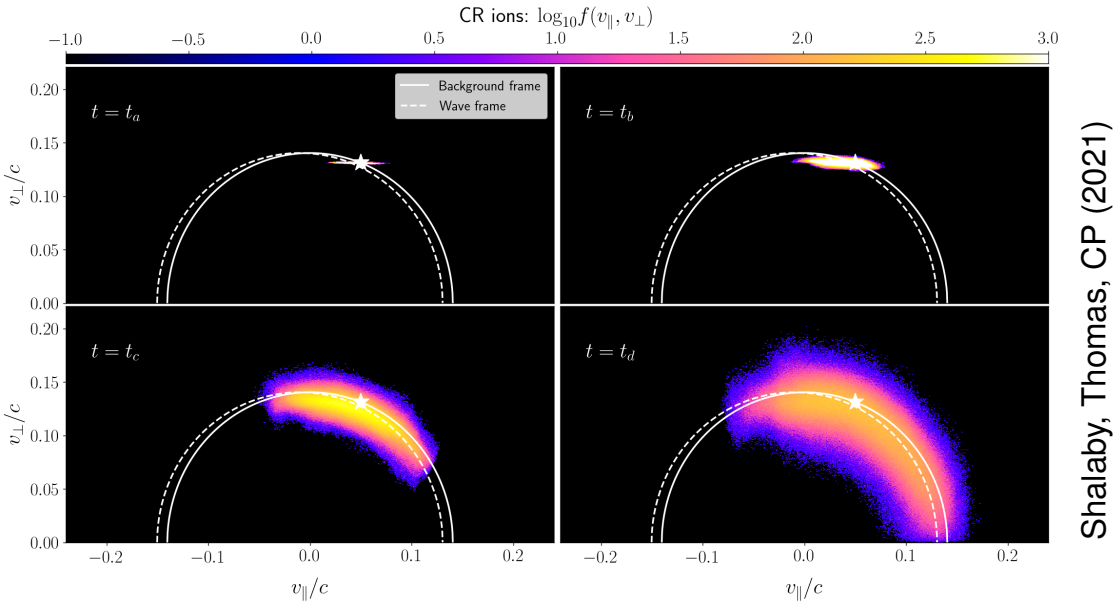

Shalaby, Thomas, CP (2021)

electromagnetic wave with $v_{\rm ph}$ interacting with particle of velocity (v_x, v_y, v_z):

$$\dot{K}_\parallel = \frac{m}{2}\frac{dv_x^2}{dt} = q v_x (v_y B_z - v_z B_y)$$

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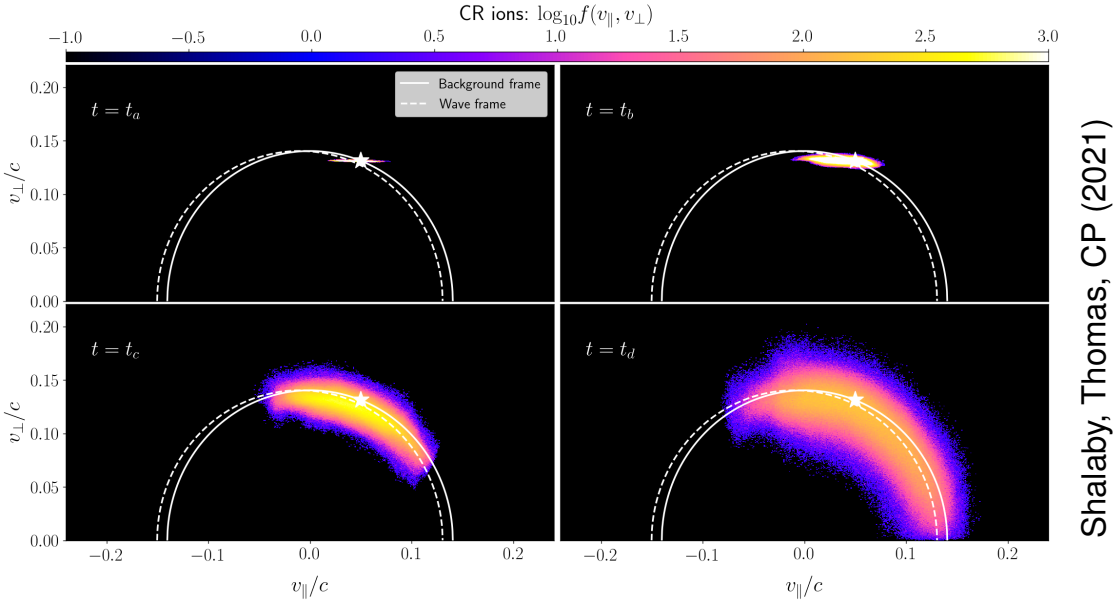

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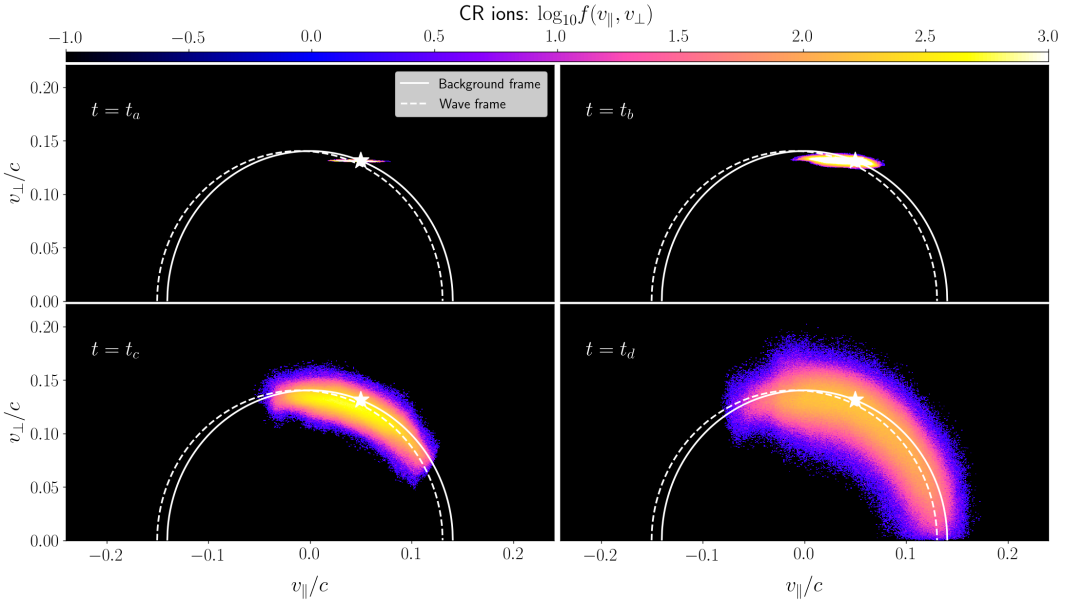

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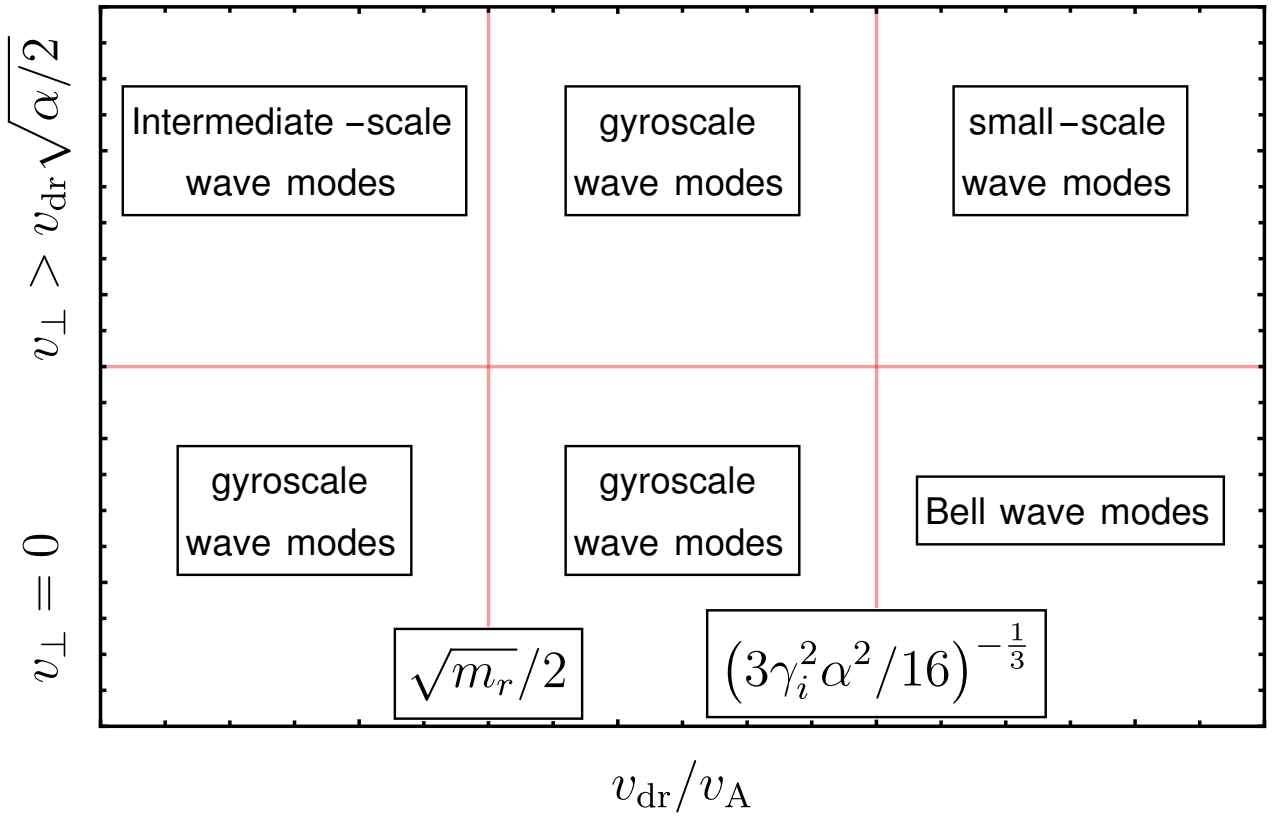
Regimes of CR driven instabilities



Shalaby, Thomas, CP (2021)

- where $\alpha = \frac{n_{\rm cr}}{n_{\rm i}}$ is the CR number fraction, $m_{\rm r} = \frac{m_{\rm i}}{m_{\rm e}}$ is the mass ratio, and $\gamma_{\rm i}$ is the Lorentz factor of CR ions

The intermediate-scale instability

Properties of the intermediate-scale instability:

- growth rate $\Gamma_{\text{inter}} \gg \Gamma_{\text{gyro}}$ and excites broad spectral support
- unstable modes are background ion-cyclotron waves in the comoving CR frame
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Possible implications of this new instability:

- enables electron heating at shocks and injection into diffusive shock acceleration
- couples CRs more tightly to background plasma and strengthens CR feedback in galaxies and galaxy clusters
- slows down CR escape from the sites of particle acceleration $\rightarrow$ brighter gamma-ray halos

Electron acceleration at non-relativistic shocks

electron injection problem:

- gyro-radii: $r_e = \frac{m_e}{m_i} r_i \Rightarrow$ electrons do *random walk* through the shock transition; no coherent electrostatic shock potential

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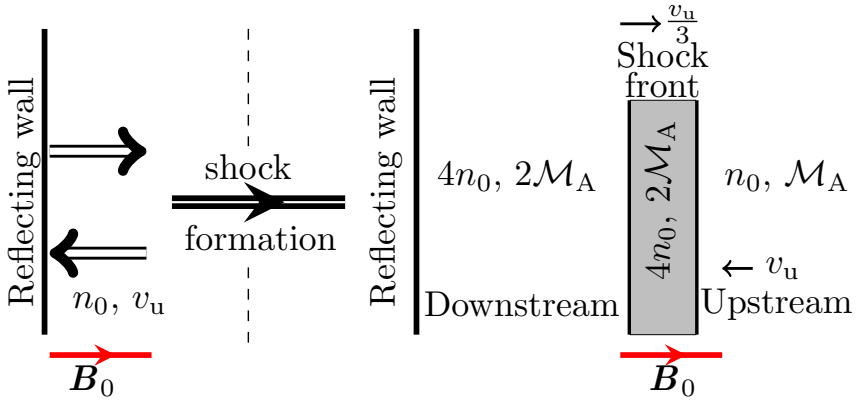

Shalaby, Lemmerz, Thomas, CP (2022):
quasi-parallel, non-relativistic shock with PIC code SHARP

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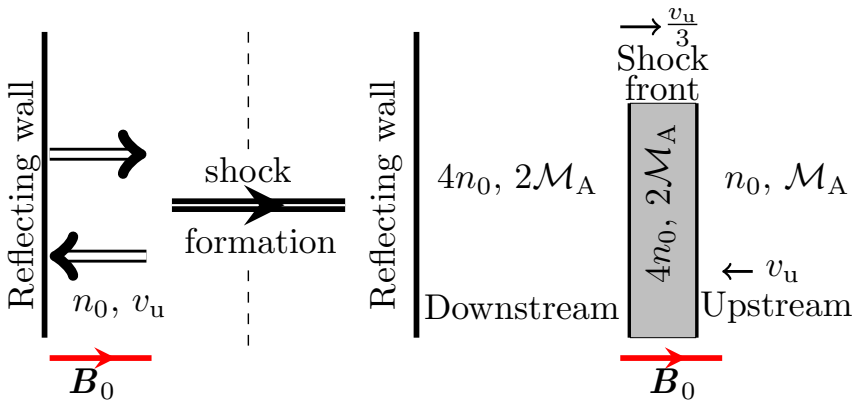

Shalaby, Lemmerz, Thomas, CP (2022):
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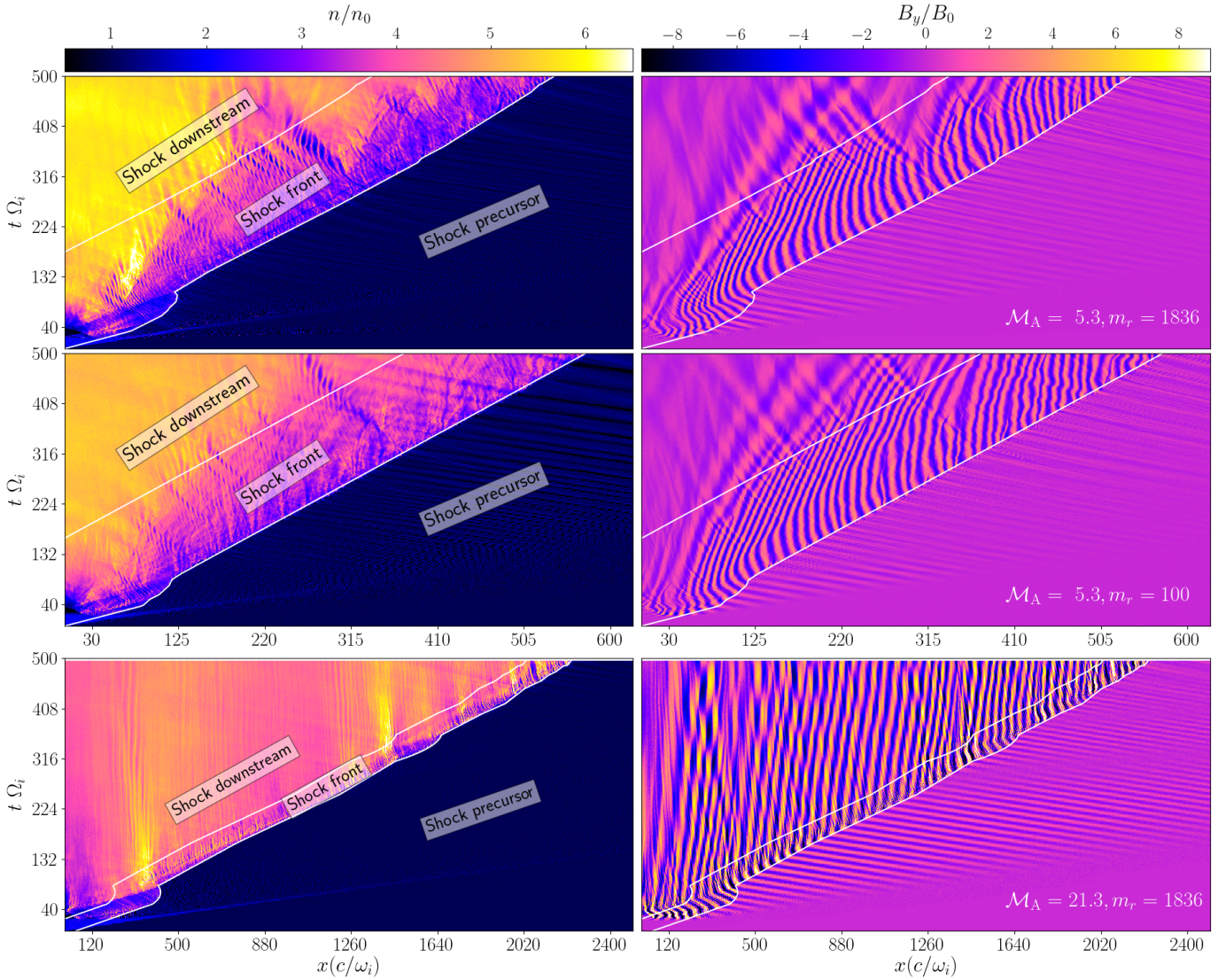
Table 1
Parameters of our electron-ion parallel shock simulations

Name	v_u/c[a]	$\mathcal{M}_A$[b]	$\mathcal{M}_s$[c]	m_i/m_e	Condition[d]
Ma5Mr1836	-0.1	5.3	365	1836	✓
Ma5Mr100	-0.1	5.3	365	100	×
Ma21Mr1836	-0.1	21.3	365	1836	×

condition in front/downstream:

$$\mathcal{M}_A \lesssim \frac{1}{4}\sqrt{\frac{m_i}{m_e}}$$

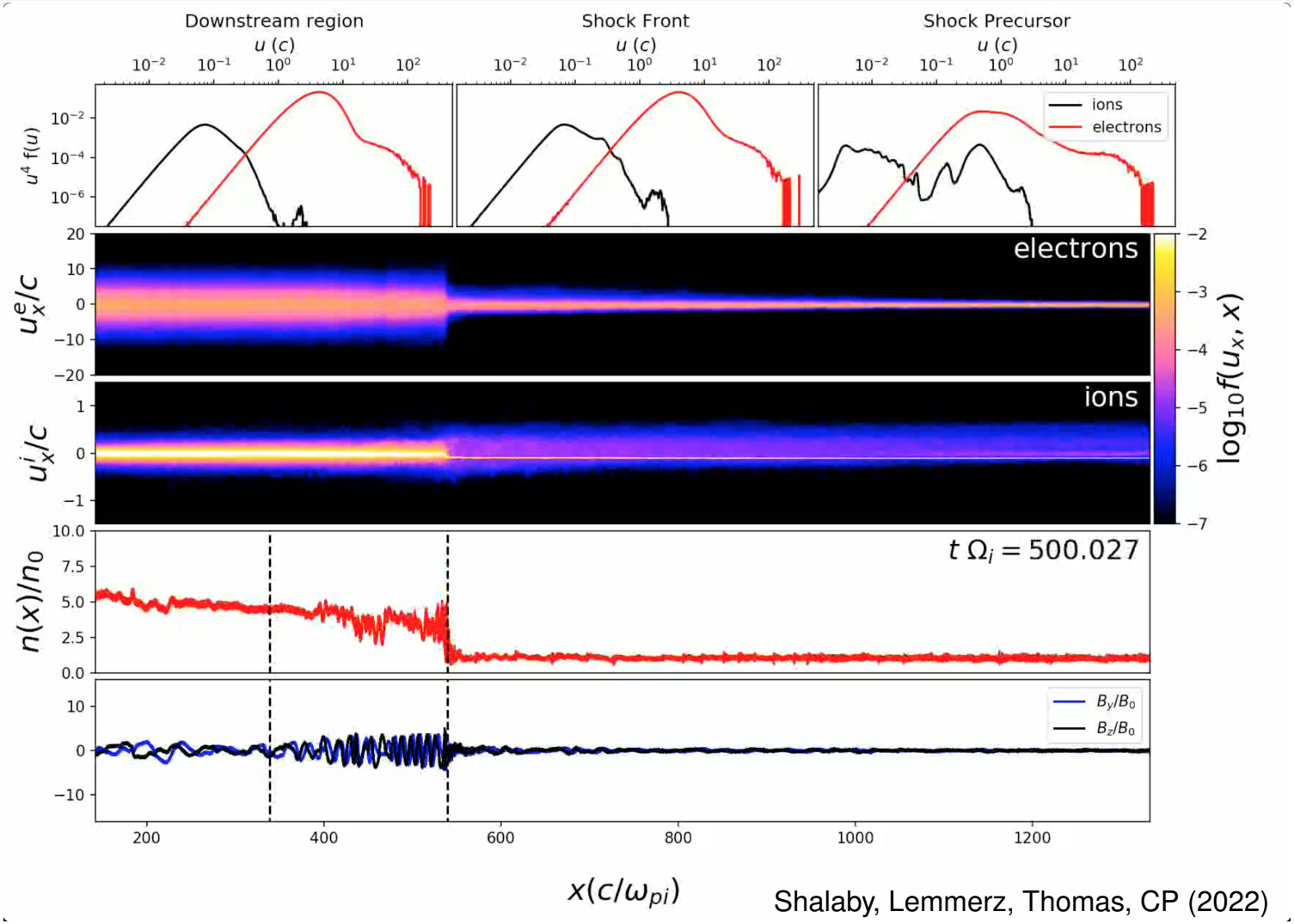
Shock physics: magnetic amplification



Shalaby, Lemmerz, Thomas, CP (2022)

Particle acceleration at a non-relativistic shock

The intermediate-scale and the gyro-resonant instabilities mediate particle scattering



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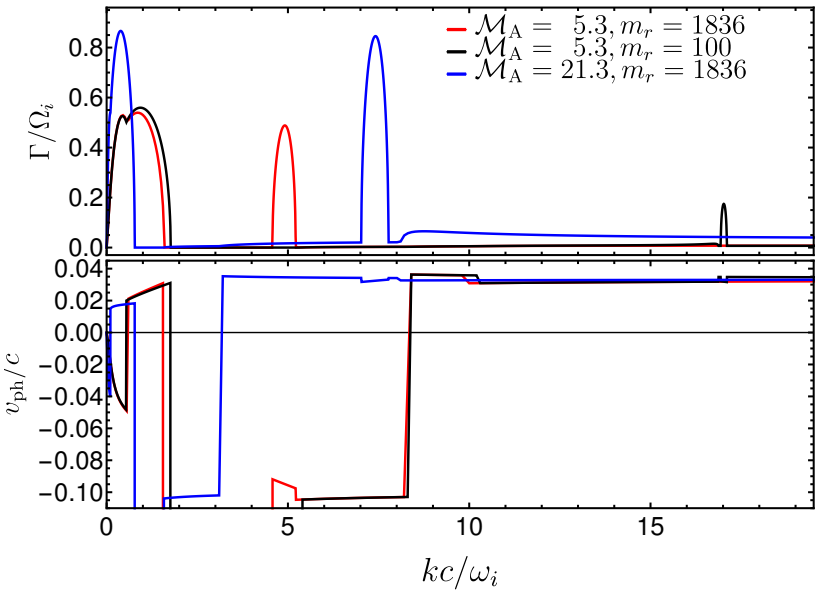
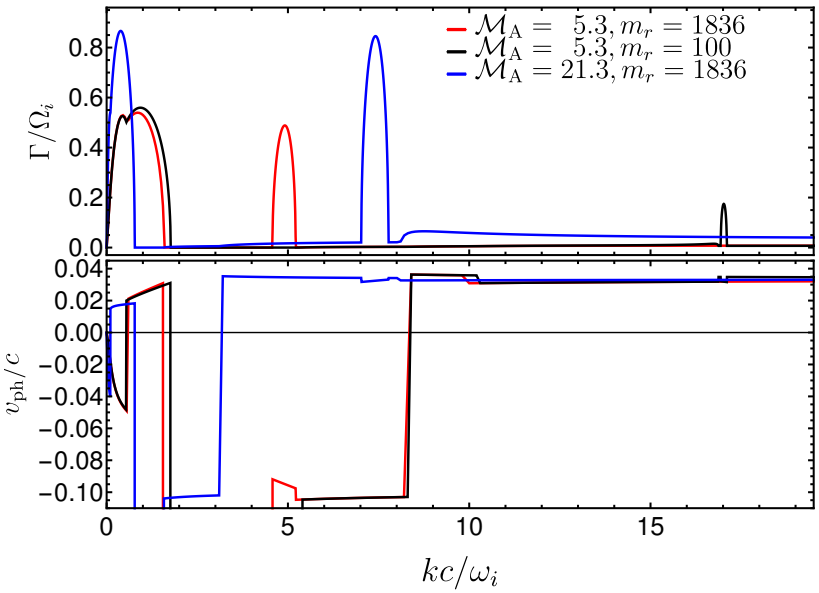
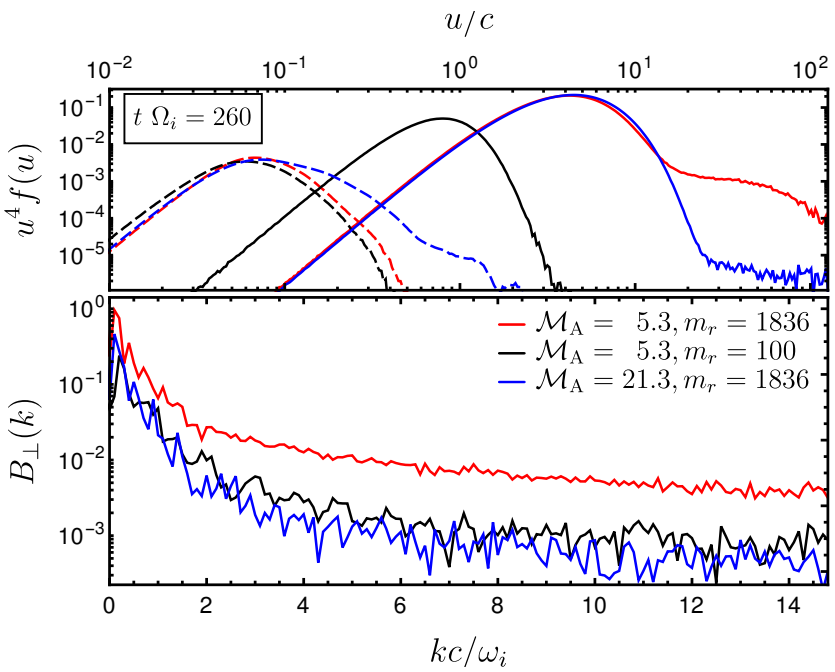
Shock acceleration: intermediate-scale instability



- solution of dispersion relation at shock front (in the contact discontinuity rest frame)

Shock acceleration: intermediate-scale instability





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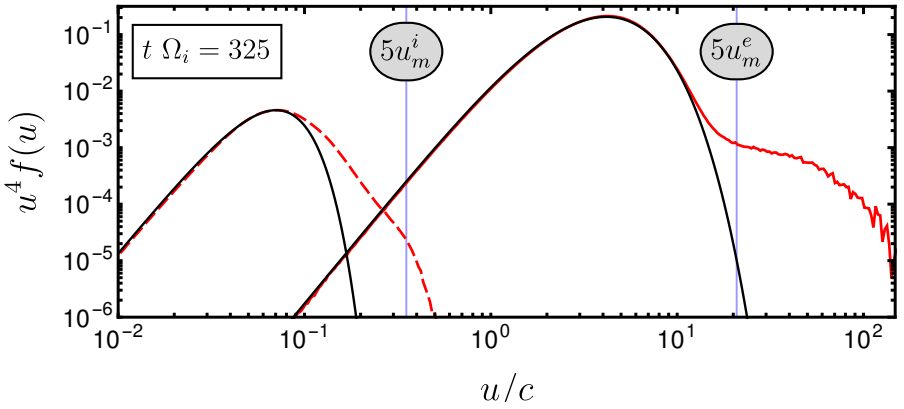
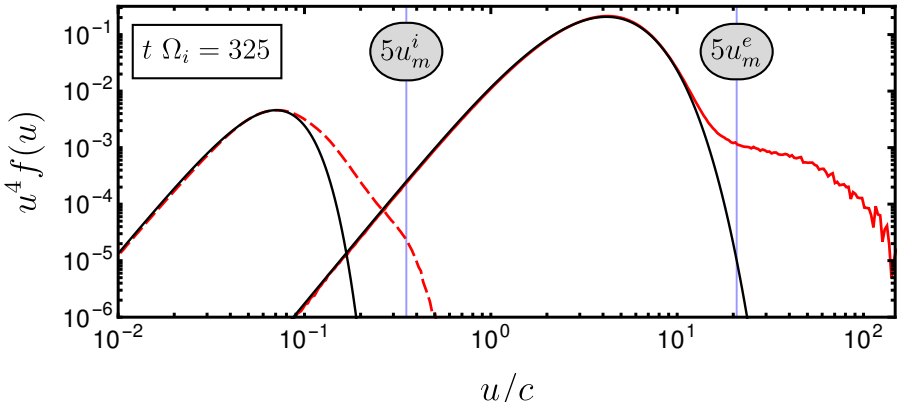
- solution of dispersion relation at shock front (in the contact discontinuity rest frame)
- only red simulation, which grows intermediate-scale instability, accelerates electrons and amplifies magnetic field

Shock acceleration efficiency: K_{ei}



- rest-frame momentum distribution of ions and electrons
- analytical Maxwell-Jüttner distribution normalized to u_m, for which $u^4 f(u)$ is maximum

Shock acceleration efficiency: K_{ei}



- rest-frame momentum distribution of ions and electrons
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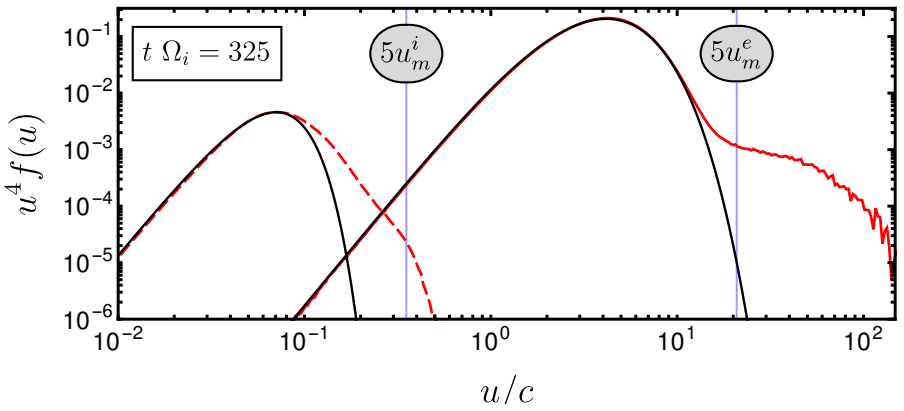
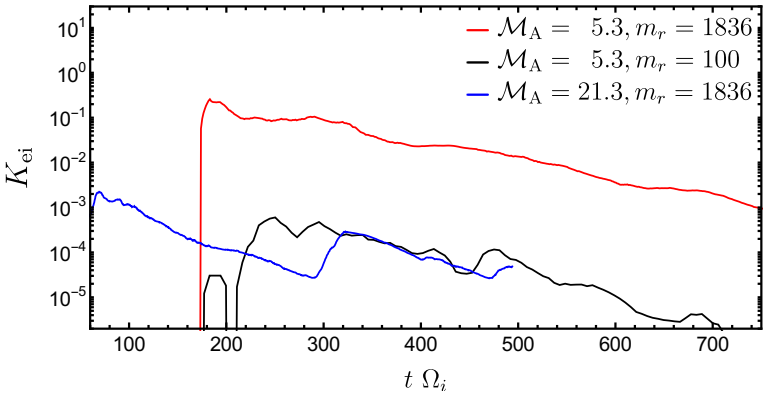
- non-thermal electron-to-ion energy:

$$K_{ei} = \frac{E_e(u > 5u_m^e)}{E_i(u > 5u_m^i)}$$

Shock acceleration efficiency: K_{ei}





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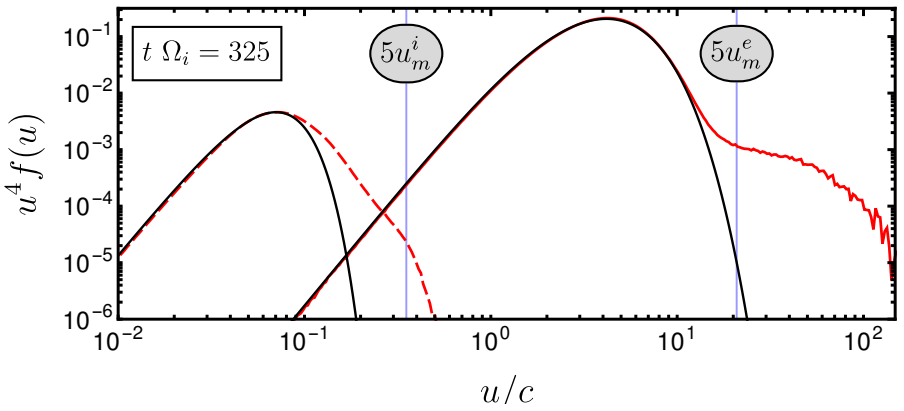
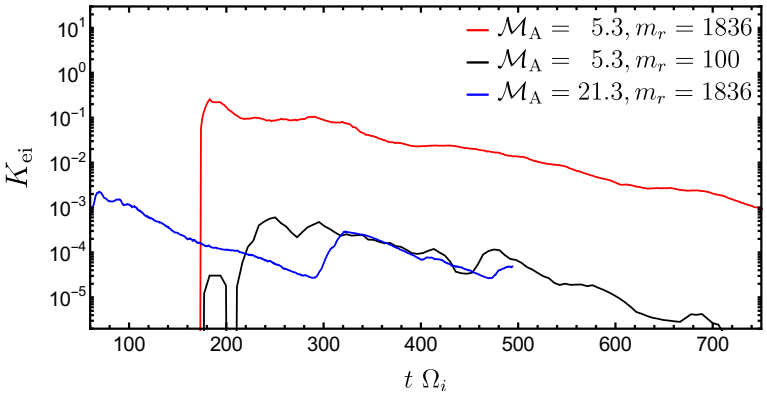
- non-thermal electron-to-ion energy:

$$K_{ei} = \frac{E_e(u > 5u_m^e)}{E_i(u > 5u_m^i)}$$

- downstream evolution of K_{ei} (non-thermal ion distribution still growing)
- $\mathcal{M}_s$ and v_{sh} identical for all runs, only $\mathcal{M}_A$ differs

Shock acceleration efficiency: K_{ei}





Shalaby, Lemmerz, Thomas, CP (2022)

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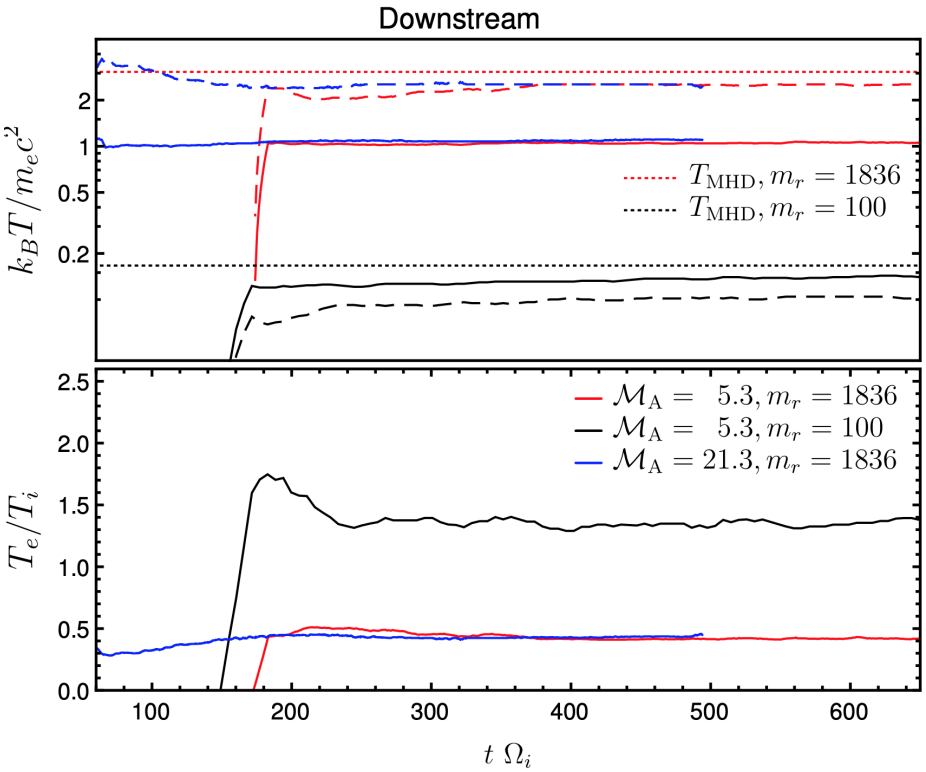
- $\mathcal{M}_s$ and v_{sh} identical for all runs, only $\mathcal{M}_A$ differs
- ***presence of intermediate-scale instability increases K_{ei} by more than 100!***

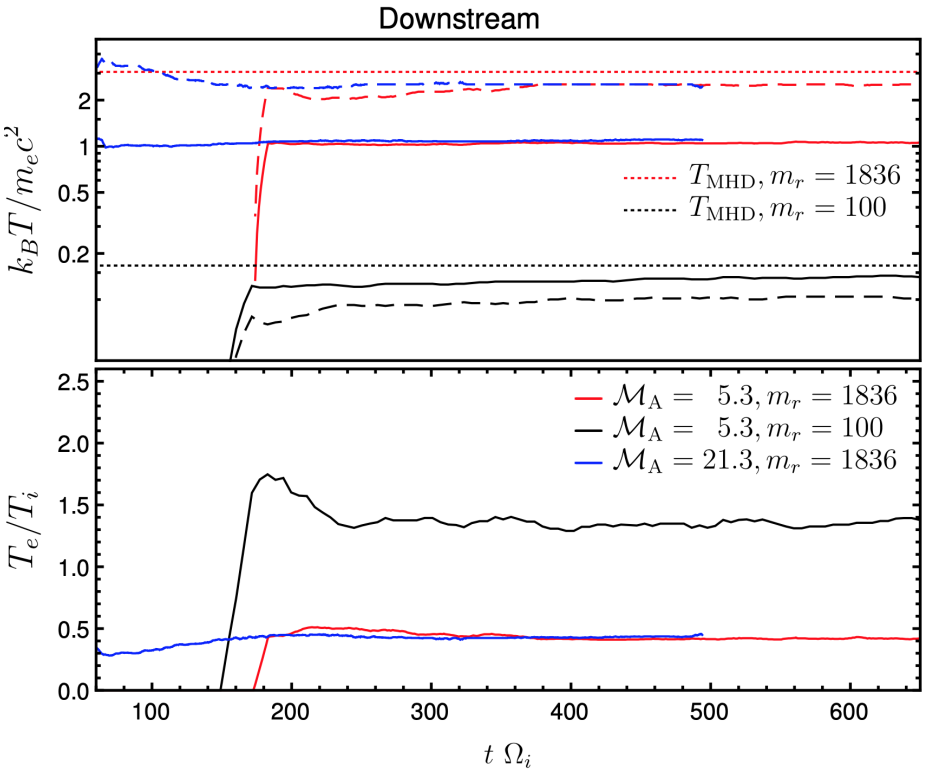
Shock dissipation: electron and ion temperatures



Shalaby, Lemmerz, Thomas, CP (2022)

- time evolution of downstream $T_{\rm i}$ (dashed) and $T_{\rm e}$ (solid)

Shock dissipation: electron and ion temperatures



Shalaby, Lemmerz, Thomas, CP (2022)

- runs with $m_{\rm i}/m_{\rm e} = 1836$ have different efficiencies $K_{\rm ei}$ but same temperatures
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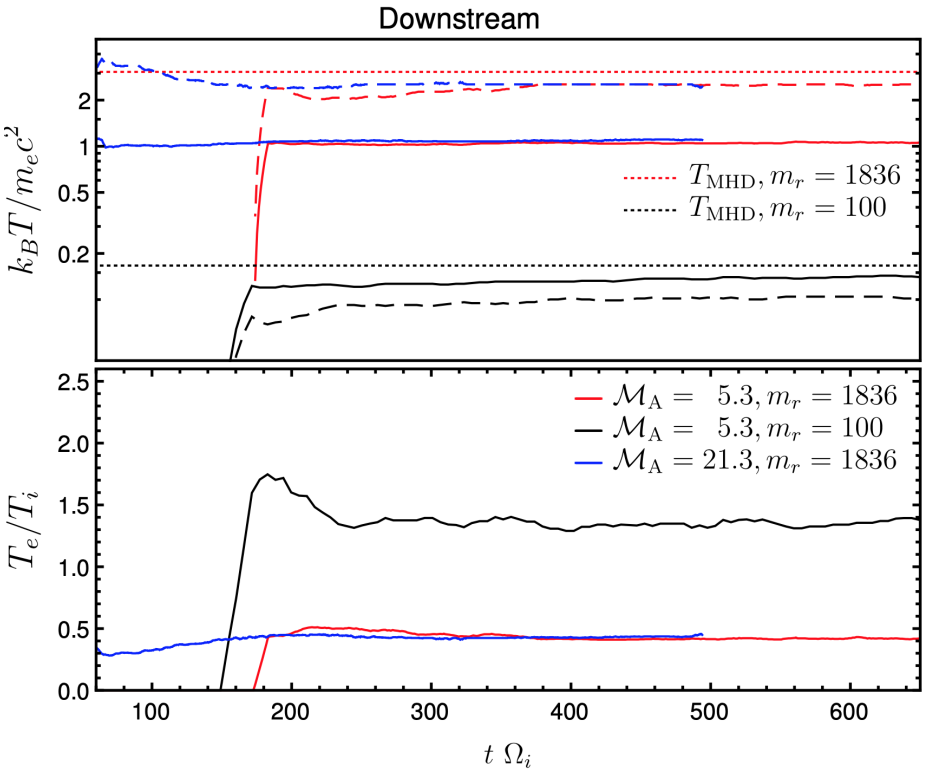

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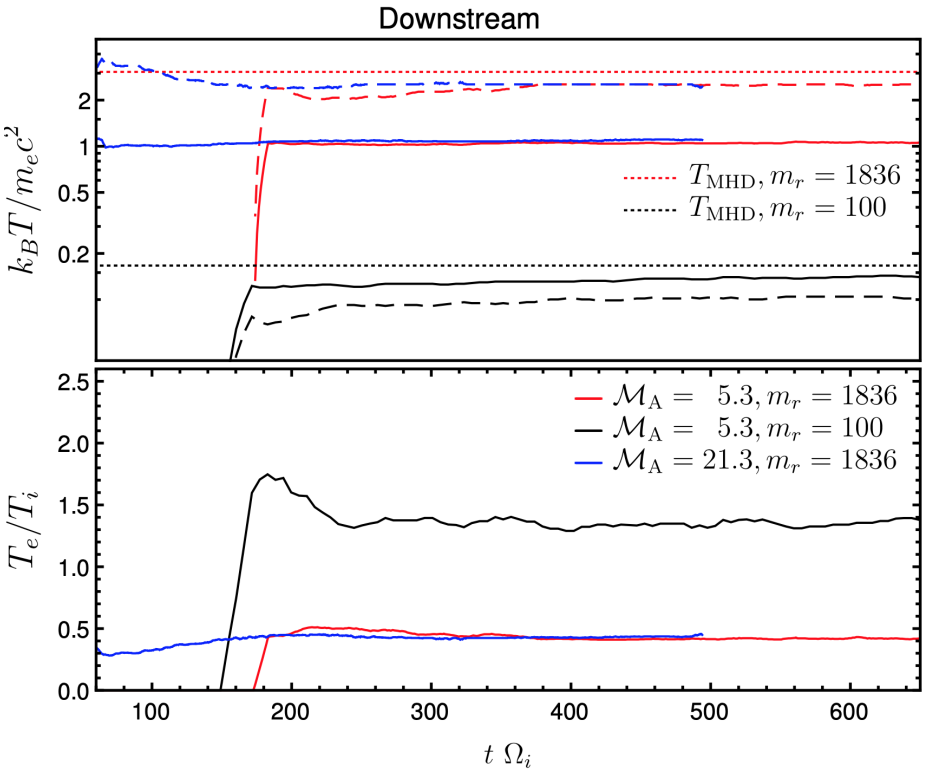

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- $T_{\rm e} \approx 0.4\,T_{\rm i}$ (1D vs. 3D or missing instabilities?)
- true $m_{\rm i}/m_{\rm e}$ required for correct heating physics

Electron acceleration at non-relativistic shocks

Intermediate-scale instability at shocks:

- provides efficient pre-acceleration that scatters and accelerates electrons on scales much shorter than the ion gyro radius
- instability drives comoving ion-cyclotron waves (with the upstream plasma) at the shock front
- condition for growth: $\frac{v_{\mathrm{sh}}}{v_{\mathrm{A},0}} < \frac{1}{4}\sqrt{\frac{m_{\mathrm{i}}}{m_{\mathrm{e}}}}, \quad \text{for} \quad n = 4n_0$

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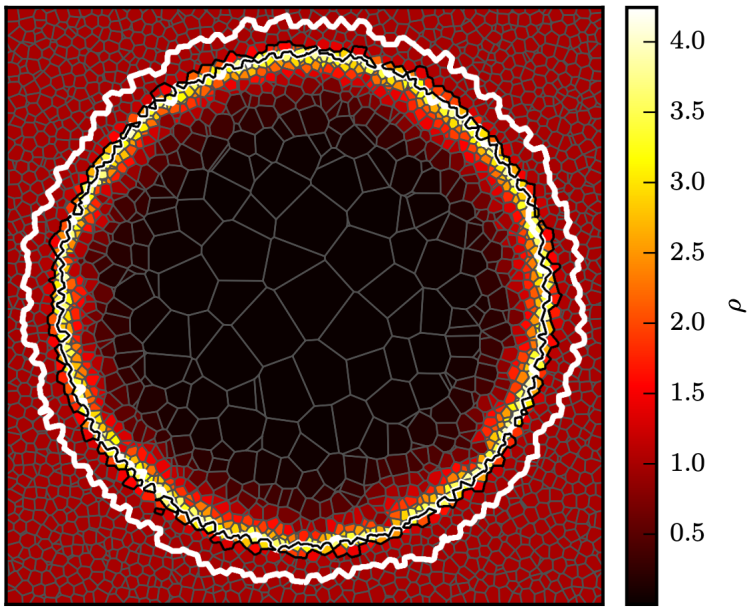
Electron shock acceleration and heating:

- intermediate-scale instability increases electron acceleration efficiency (by factor > 100)
- ion thermalization in line with MHD (accounting for E_B and E_{CR}), but $T_{\mathrm{e}} \approx 0.4\,T_{\mathrm{i}}$ remains open question
- reduced $m_{\mathrm{i}}/m_{\mathrm{e}}$ suppresses intermediate instability, precludes electron acceleration, results in erroneous electron and ion heating

Global MHD simulations of SNRs with CR physics

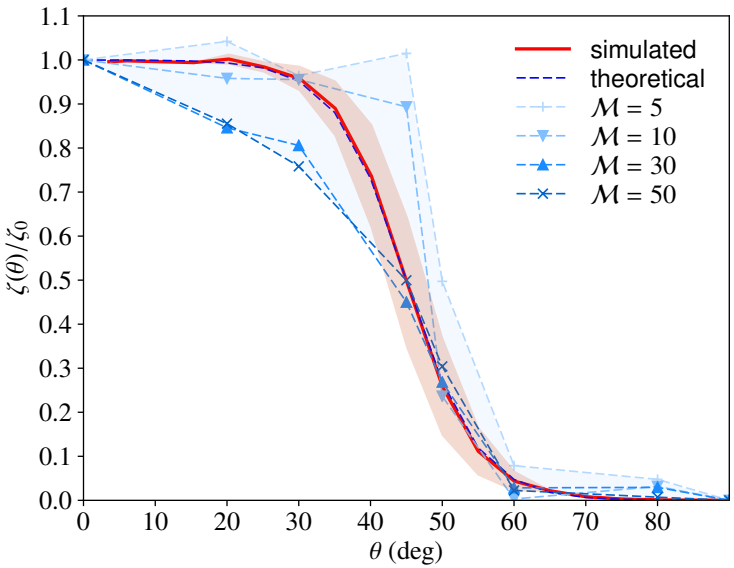


- detect and characterize shocks and jump conditions on the fly

Mach number finder with CRs

CP+ (2017)

Global MHD simulations of SNRs with CR physics



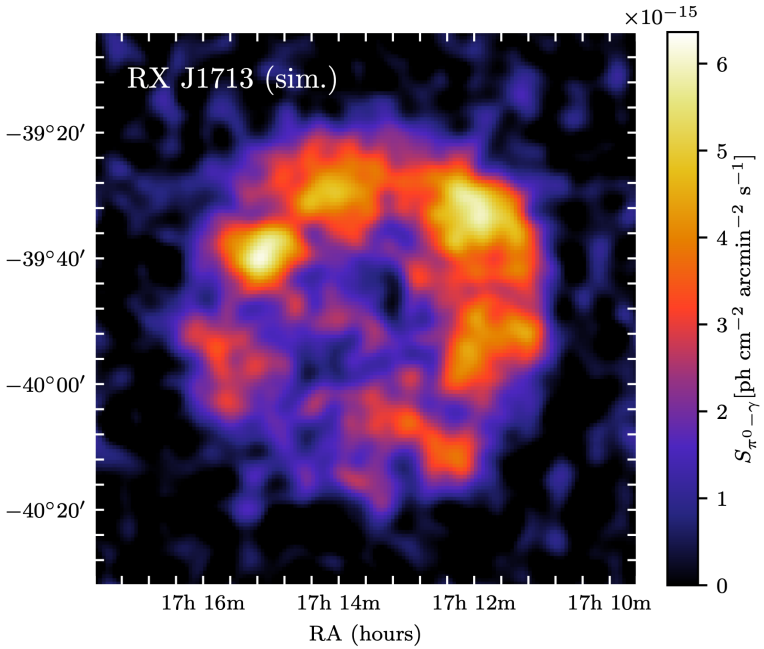
- detect and characterize shocks and jump conditions on the fly
- measure Mach number $\mathcal{M}$ and magnetic obliquity θ_B

obliquity-dep. acceleration efficiency

Pais, CP+ (2018) based on
hybrid PIC sim.'s by Caprioli & Spitkovsky (2015)

AIP

Global MHD simulations of SNRs with CR physics



simulated TeV gamma-ray map

Pais & CP (2020)

- detect and characterize shocks and jump conditions on the fly
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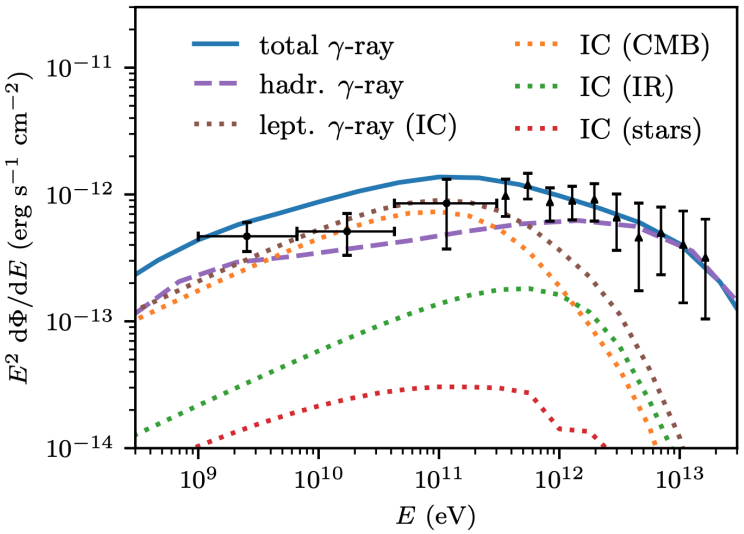
- inject and transport CR protons $\Rightarrow$ dynamical back reaction on gas flow, hadronic emission

AIP

Global MHD simulations of SNRs with CR physics

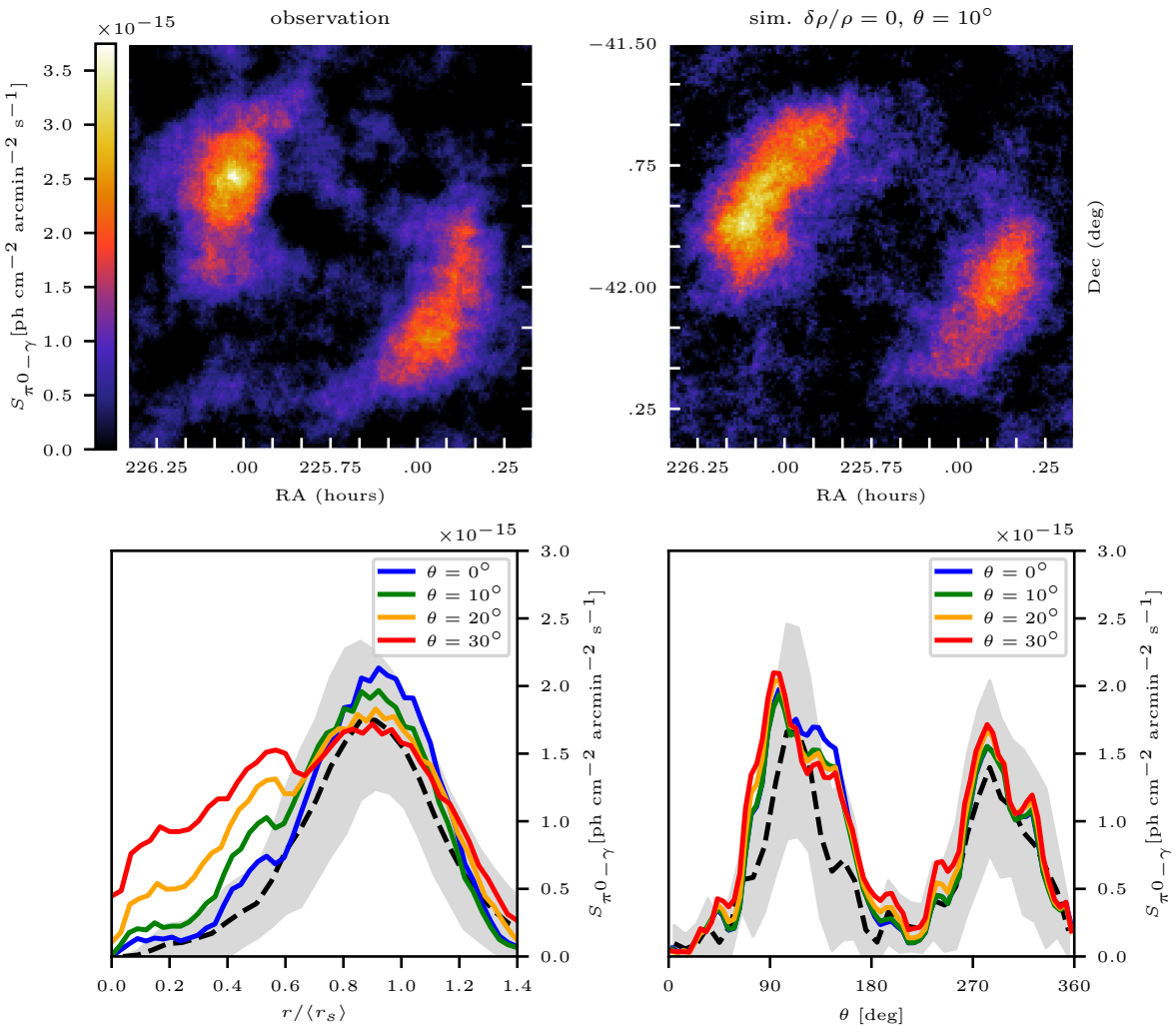


simulated gamma-ray spectrum

Winner, CP+ (2019, 2020)

- detect and characterize shocks and jump conditions on the fly
- measure Mach number $\mathcal{M}$ and magnetic obliquity θ_B
- inject and transport CR protons $\Rightarrow$ dynamical back reaction on gas flow, hadronic emission
- inject and transport CR electrons
- calculate non-thermal radio, X-ray, γ-ray emission

Hadronic TeV γ rays: SN 1006



Pais & CP (2020)

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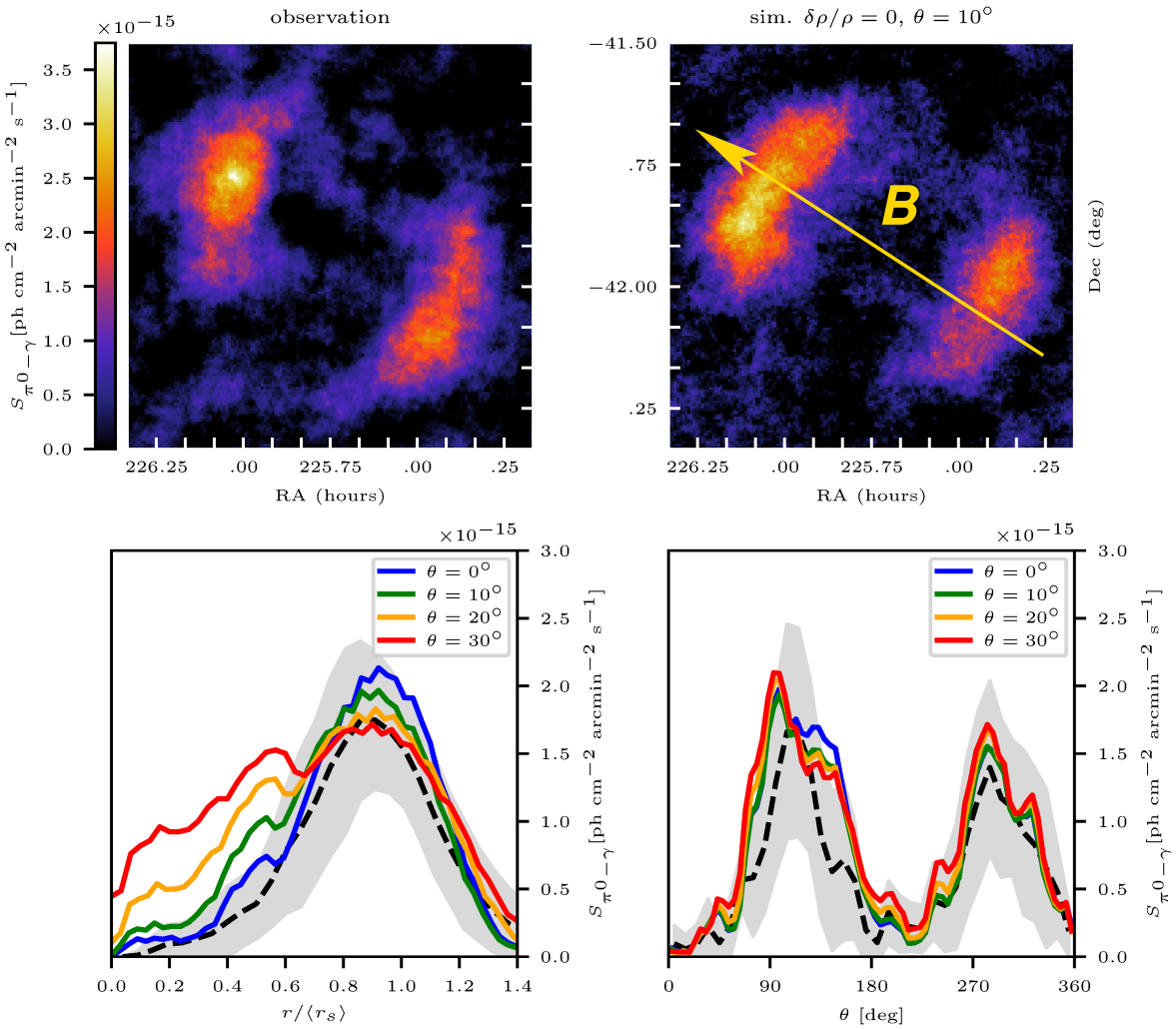
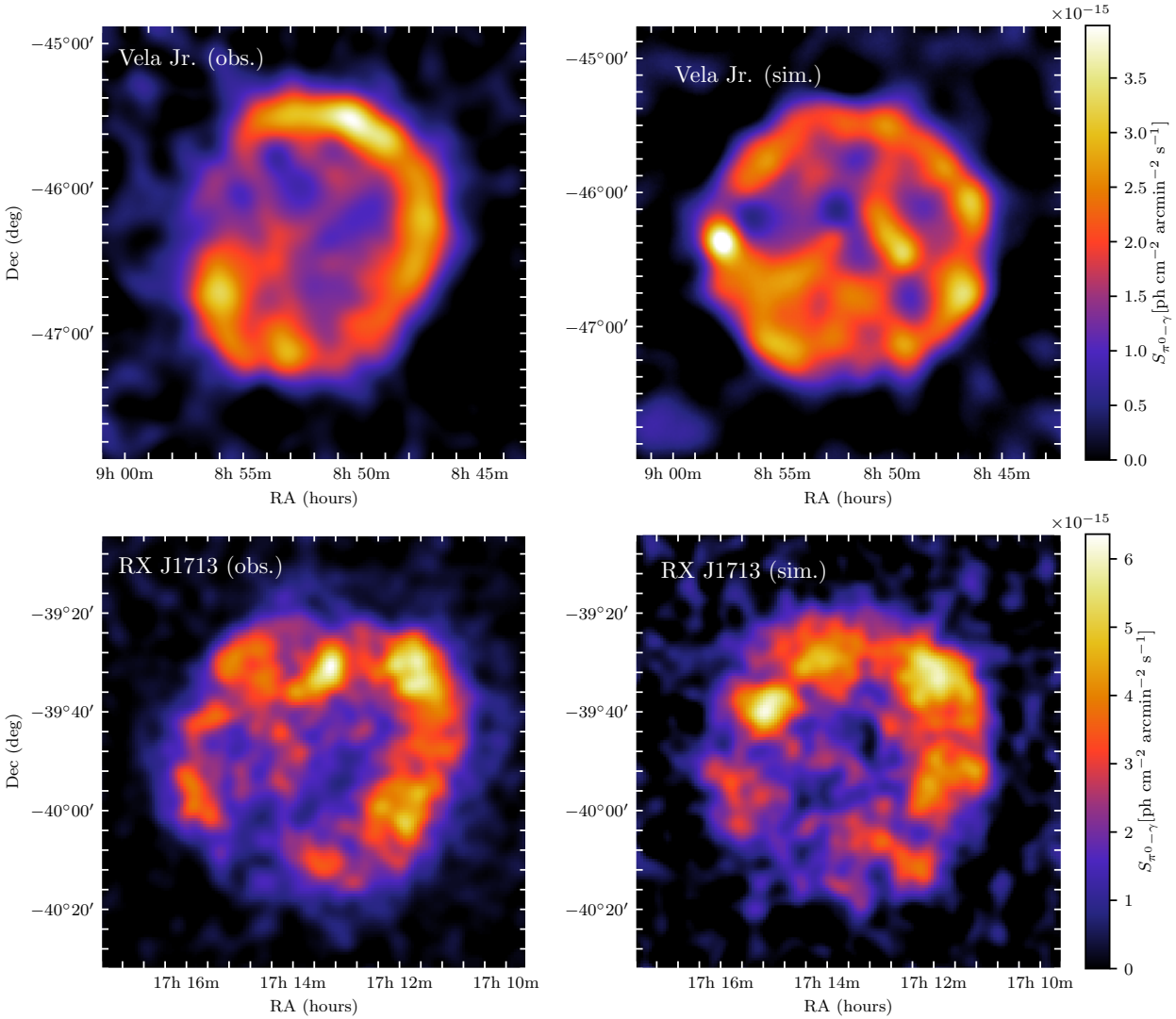


Pais & CP (2020)

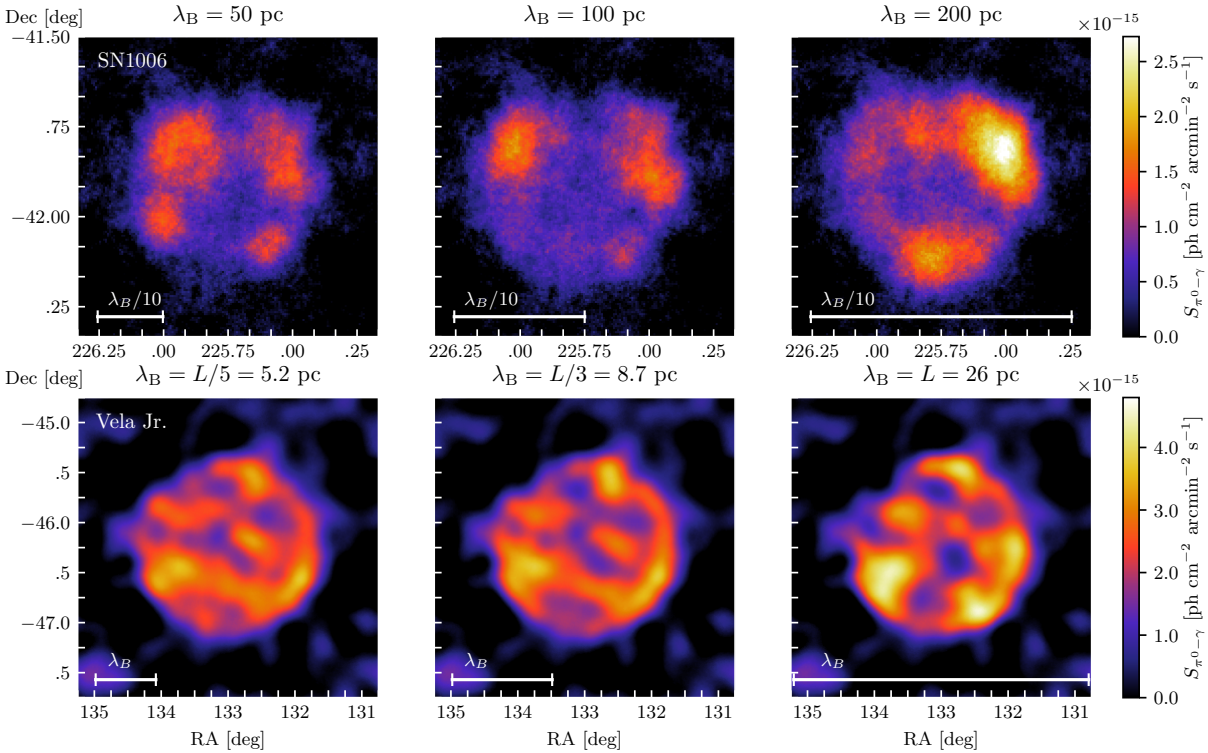
Hadronic TeV γ rays: Vela Jr. and RXJ 1713



Pais & CP (2020)

TeV γ rays from shell-type supernova remnants

Varying magnetic coherence scale in simulations of SN 1006 and Vela Junior



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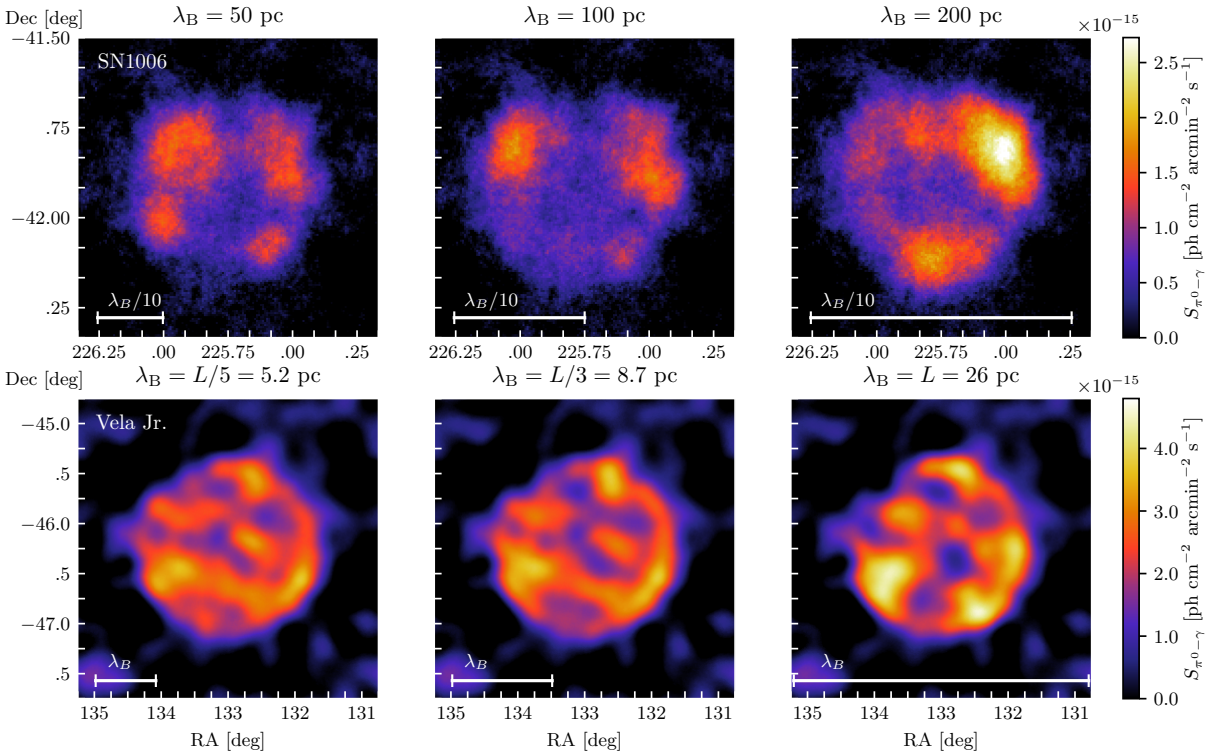
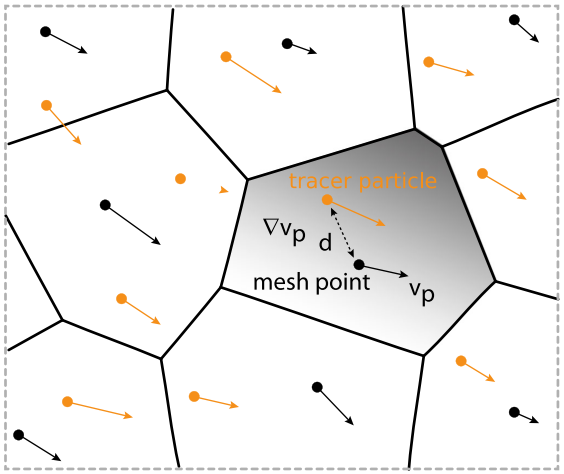


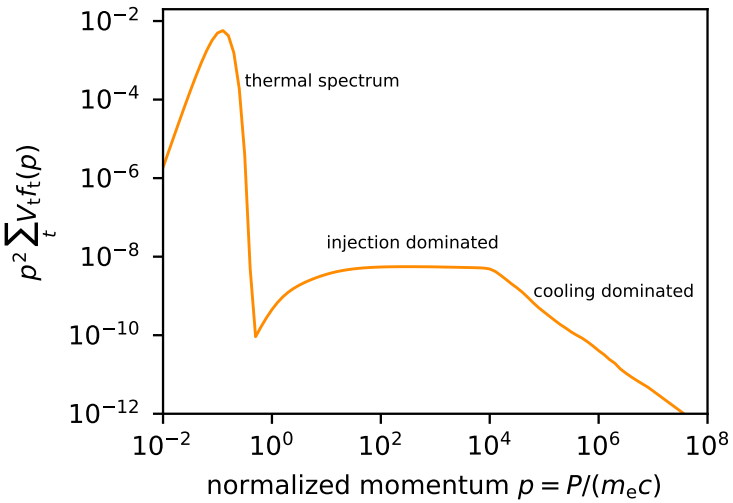
Pais, CP+ (2020)

$\Rightarrow$ Correlation structure of patchy TeV γ-rays constrains magnetic coherence scale in ISM:

SN 1006: $\lambda_B > 200^{+80}_{-10}$ pc Vela Junior: $\lambda_B = 13^{+13}_{-4.3}$ pc

CREST - Cosmic Ray Electron Spectra evolved in Time





CREST code (Winner, CP+ 2019)

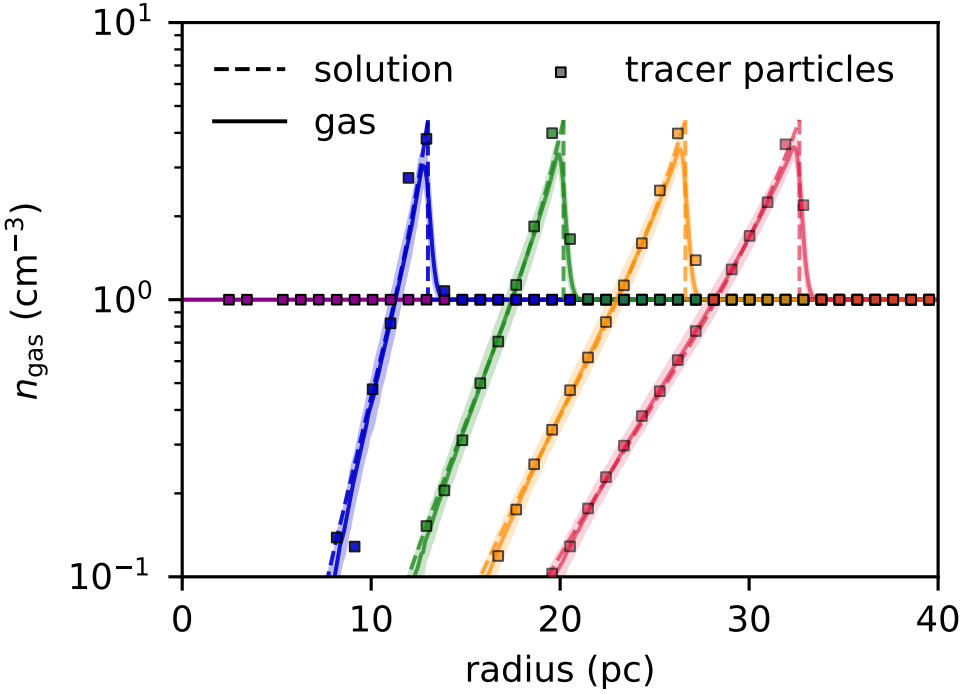
- post-processing MHD simulations
- on Lagrangian particles
  - adiabatic processes
  - Coulomb and radiative losses
  - Fermi-I (re-)acceleration
  - Fermi-II reacceleration
  - secondary electrons

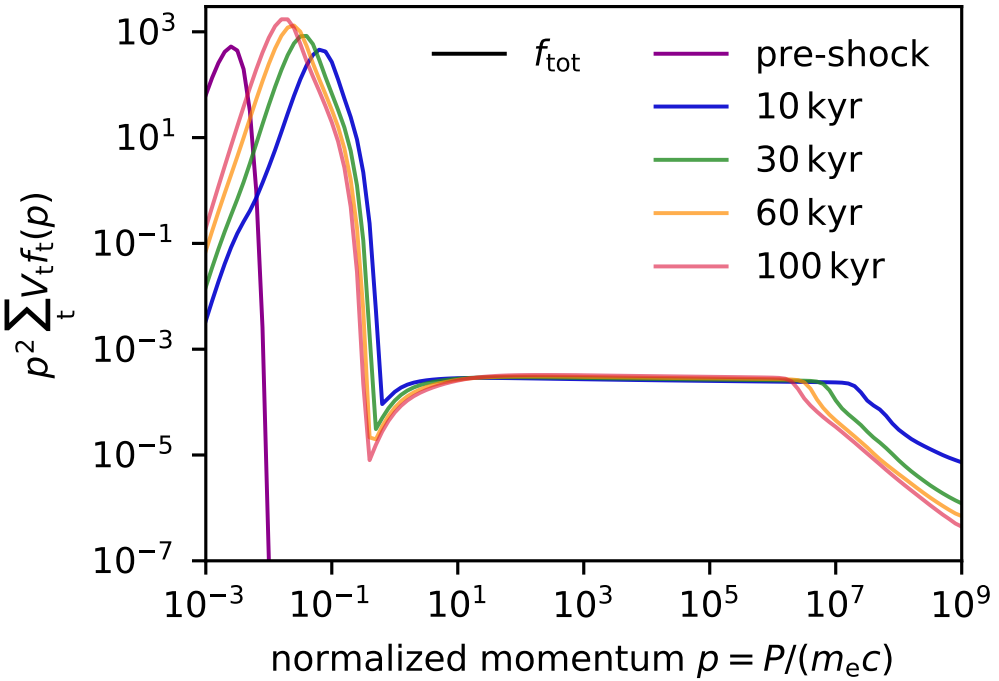
Link to observations

- radio synchrotron
- inverse Compton (IC) γ-ray

AIP

Sedov–Taylor blast wave: spectral evolution

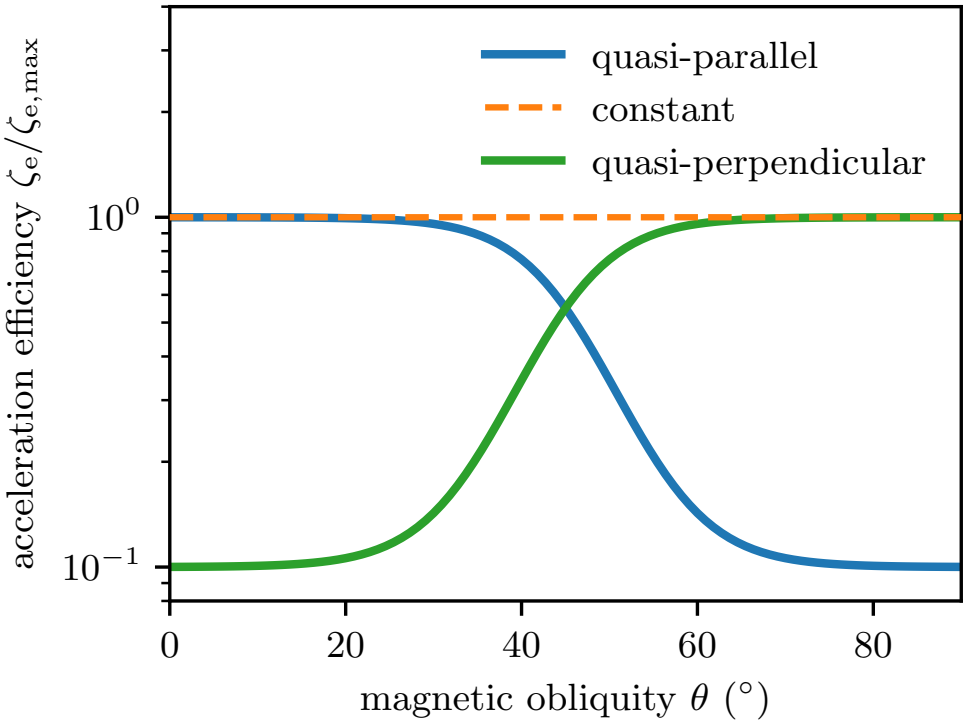




Winner, CP+ (2019)

$E_0 = 10^{51}\,\mathrm{erg},\ n_{\mathrm{gas}} = 1\,\mathrm{cm}^{-3},\ T_0 = 10^4\,\mathrm{K},\ B = 1\,\mu\mathrm{G}$

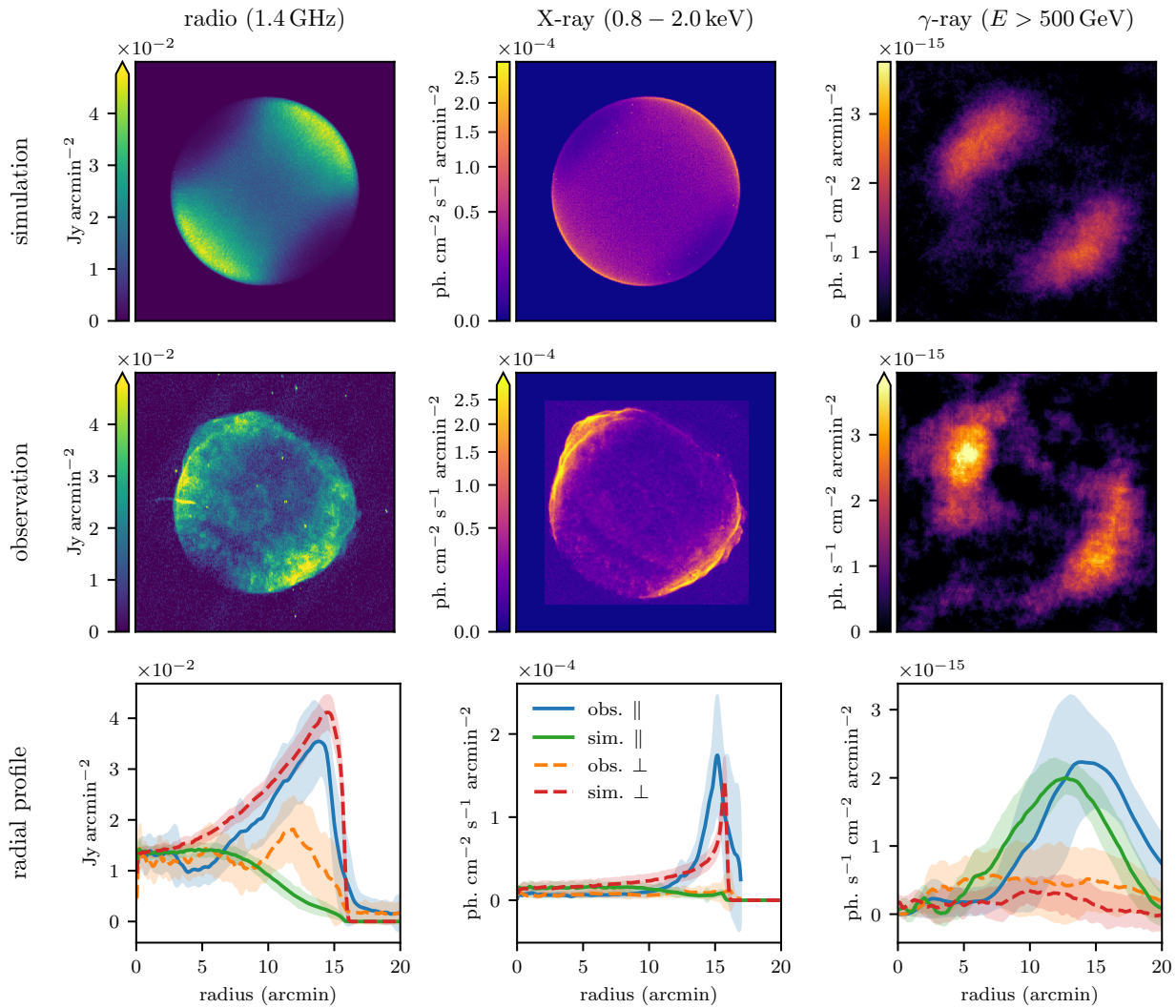
SN 1006: CR electron acceleration models



Winner, CP+ (2020)

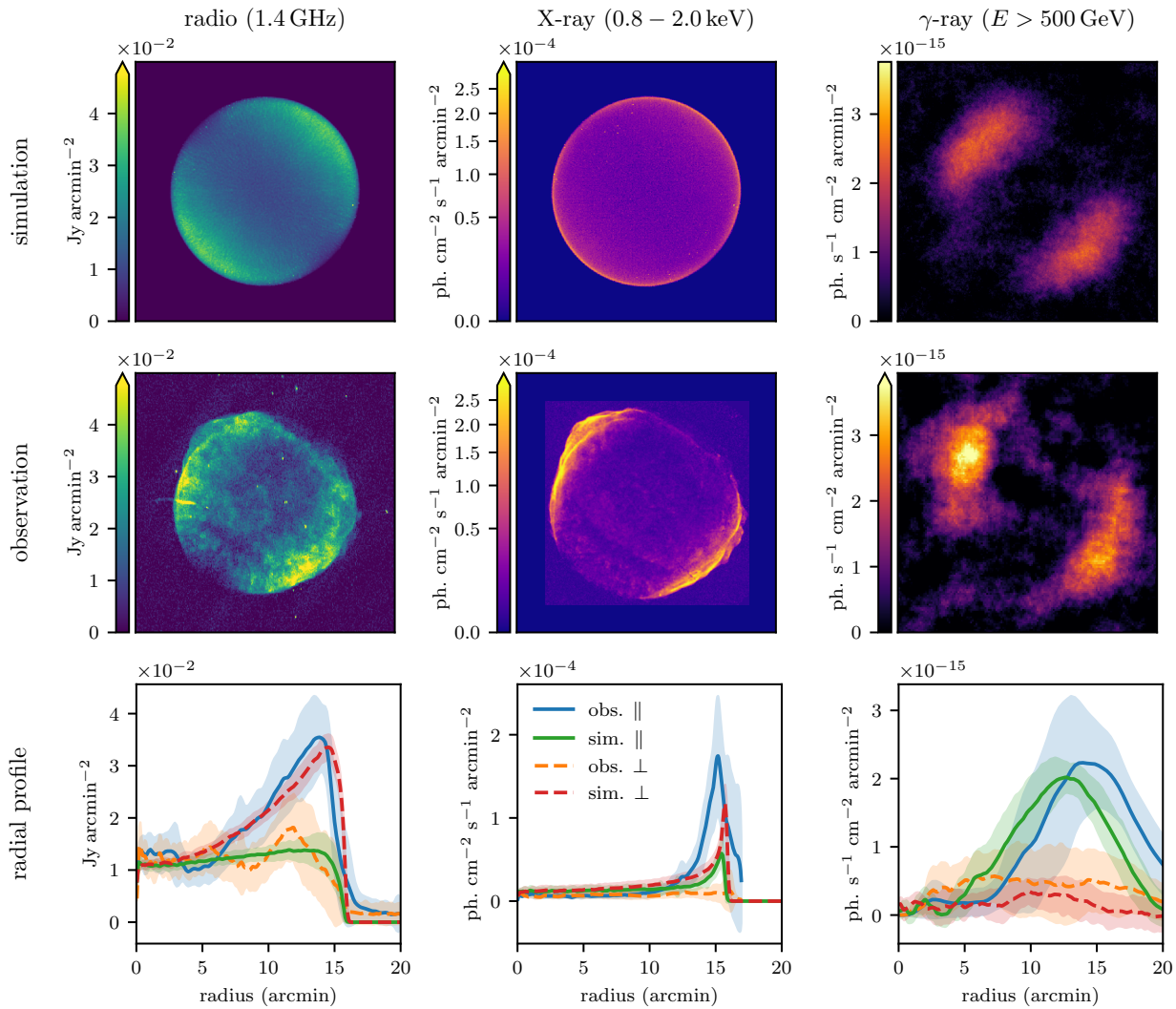
- different obliquity dependent electron acceleration efficiencies:
  1. preferred quasi-perpendicular acceleration (previous PIC)
  2. constant acceleration efficiency (a straw man's model)
  3. preferred quasi-parallel acceleration (like CR protons)

CR electron acceleration: quasi-perpendicular shocks



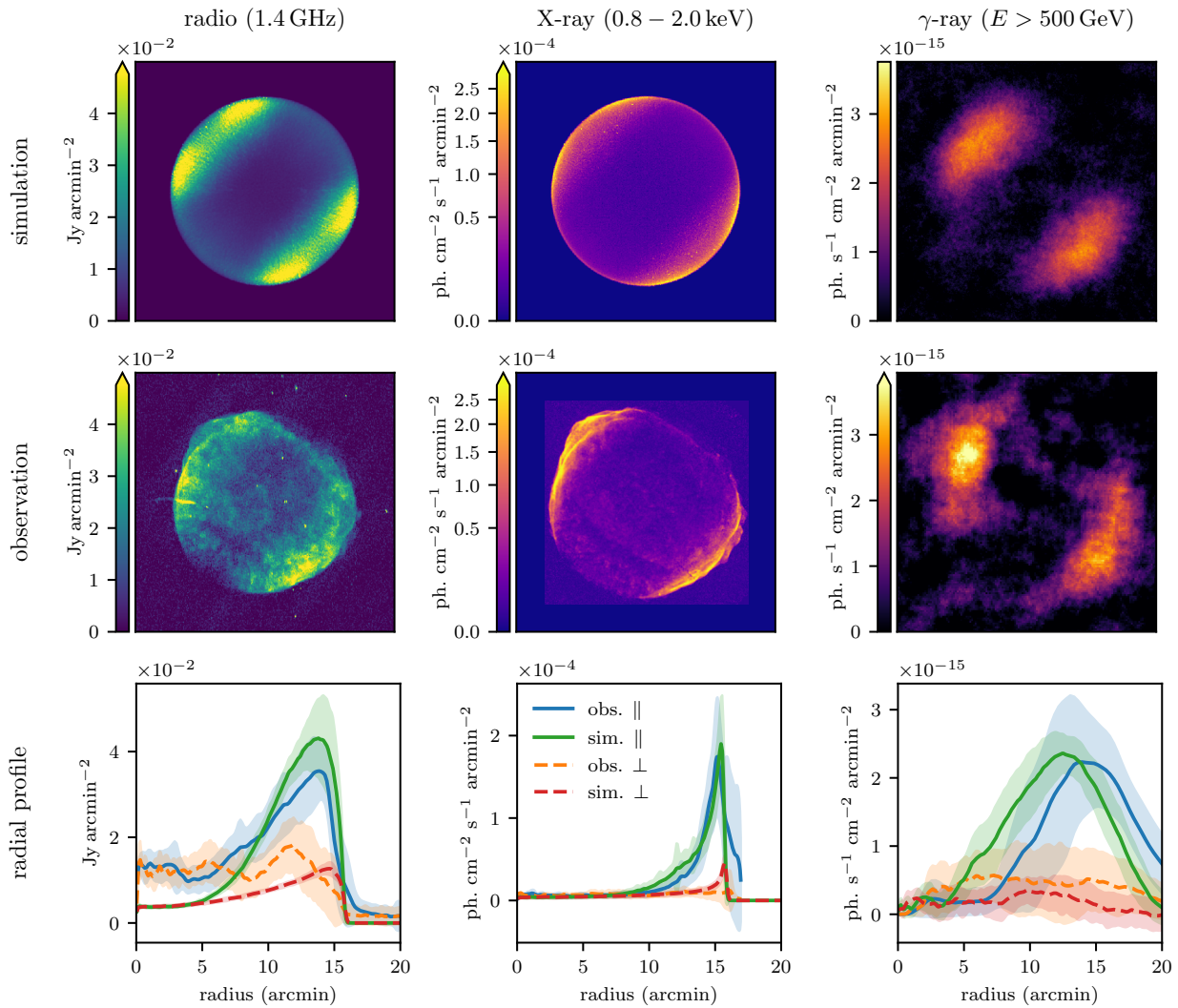
Winner, CP+ (2020)

CR electron acceleration: constant efficiency



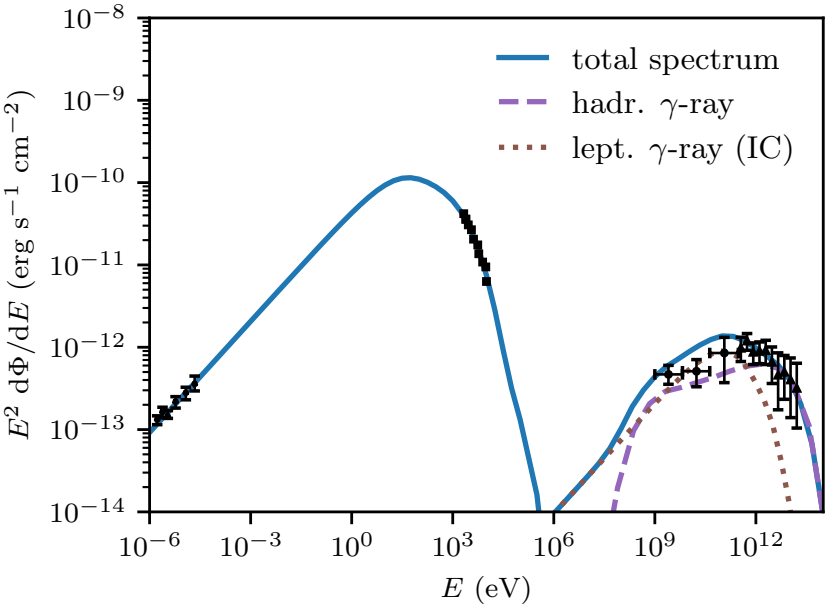
Winner, CP+ (2020)

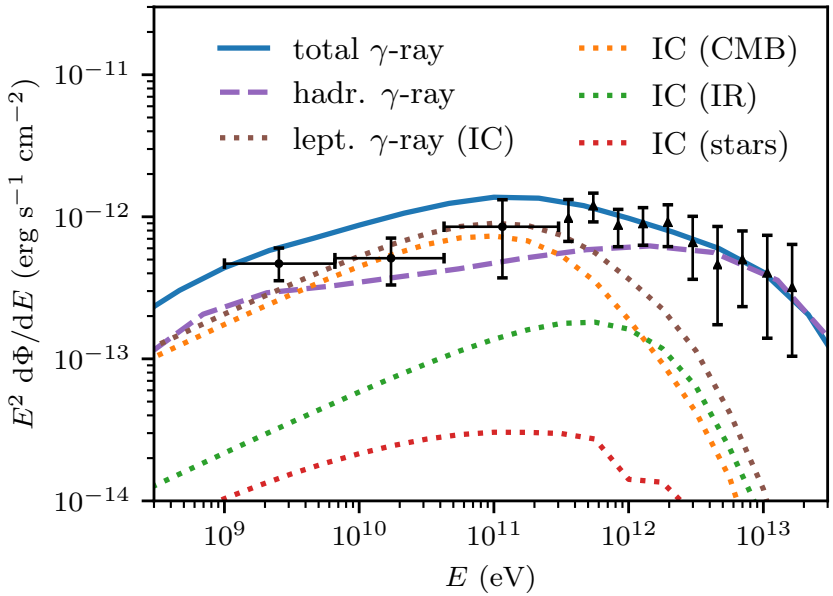
CR electron acceleration: quasi-parallel shocks



Winner, CP+ (2020)

SN 1006: multi-frequency spectrum

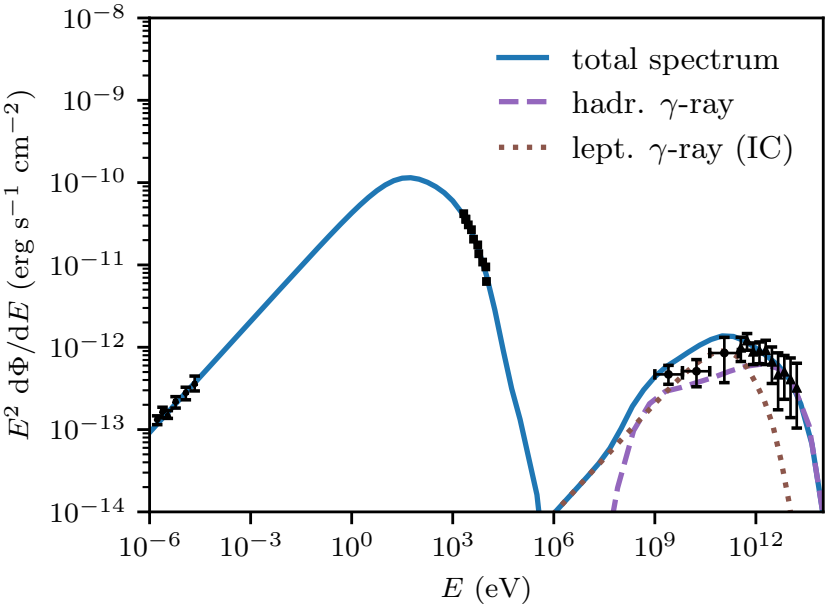


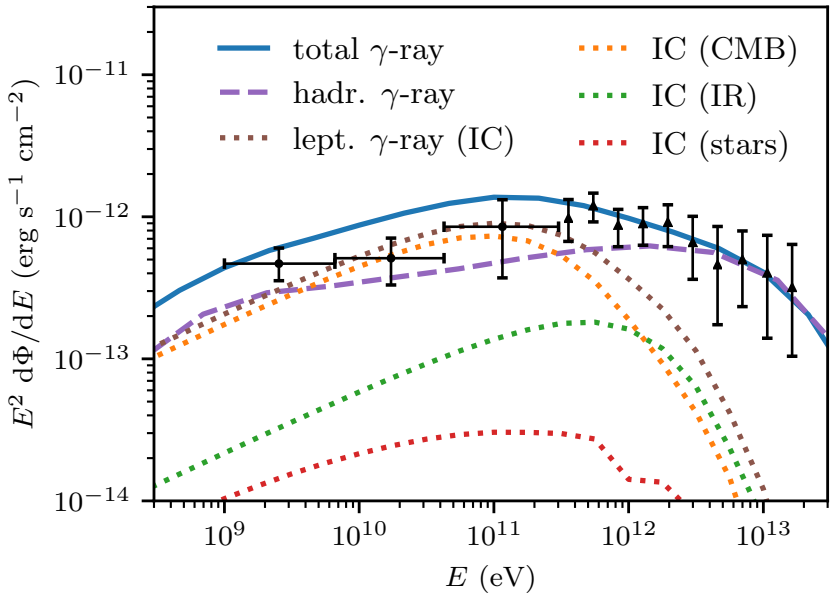


Winner, CP+ (2020)

- quasi-parallel acceleration model fits multi-frequency spectrum

SN 1006: multi-frequency spectrum





Winner, CP+ (2020)

- quasi-parallel acceleration model fits multi-frequency spectrum
- GeV regime: leptonic inverse Compton dominates
- TeV regime: hadronic pion decay

Conclusions for CR hydrodynamics at SNRs

CR hydrodynamics with kinetic plasma physics:

- Shock finder enables CR acceleration in MHD simulations
- CR proton transport in MHD enables dynamic backreaction
- CR electron spectral transport (CREST): multi-frequency spectra and emission maps

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CR acceleration constraints by MHD models:

- TeV shell-type SNRs probe magnetic coherence scale in ISM
- hybrid-PIC simulations of p^+ acceleration agree with global SNR simulations
- global SNR simulations imply preferred quasi-parallel e^- acceleration: new intermediate instability enables e^- (pre-)acceleration

PICOGAL: From Plasma KInetics to COsmological GALaxy Formation

This project has received funding from the European Research Counsil (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No PICOGAL–101019746).

AIP

Literature for the talk – 1

Cosmic ray driven instabilities:

- Shalaby, Thomas, Pfrommer, *A new cosmic ray-driven instability,* 2021, ApJ, 908, 206.
- Shalaby, Lemmerz, Thomas, Pfrommer, *The mechanism of efficient electron acceleration at parallel non-relativistic shocks,* 2022, ApJ, 932, 86.

Cosmic ray hydrodynamics and shock acceleration:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh* 2017, MNRAS, 465, 4500.

Literature for the talk – 2

Cosmic ray electron spectra in MHD:

- Winner, Pfrommer, Girichidis, Pakmor, *Evolution of cosmic ray electron spectra in magnetohydrodynamical simulations,* 2019, MNRAS, 488, 2235.
- Winner, Pfrommer, Girichidis, Werhahn, Pais, *Evolution and observational signatures of the cosmic ray electron spectrum in SN 1006,* 2020, MNRAS, 499, 2785.

Cosmic ray proton acceleration at SNRs:

- Pais, Pfrommer, Ehlert, Pakmor, *The effect of cosmic-ray acceleration on supernova blast wave dynamics,* 2018, MNRAS, 478, 5278.
- Pais, Pfrommer, Ehlert, Werhahn, Winner, *Constraining the coherence scale of the interstellar magnetic field using TeV gamma-ray observations of supernova remnants,* 2020, MNRAS, 496, 2448.
- Pais, Pfrommer, *Simulating TeV gamma-ray morphologies of shell-type supernova remnants,* 2020, MNRAS, 498, 5557.