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Cosmic Ray Acceleration on Bow Shocks

Dynamical impact on its evolution and emission

Keito Watanabe, Stefanie Walch-Gassner, Tim-Eric Rathjen, Jonathan Mackey,
Pierre Nürnberger, Philipp Girichidis

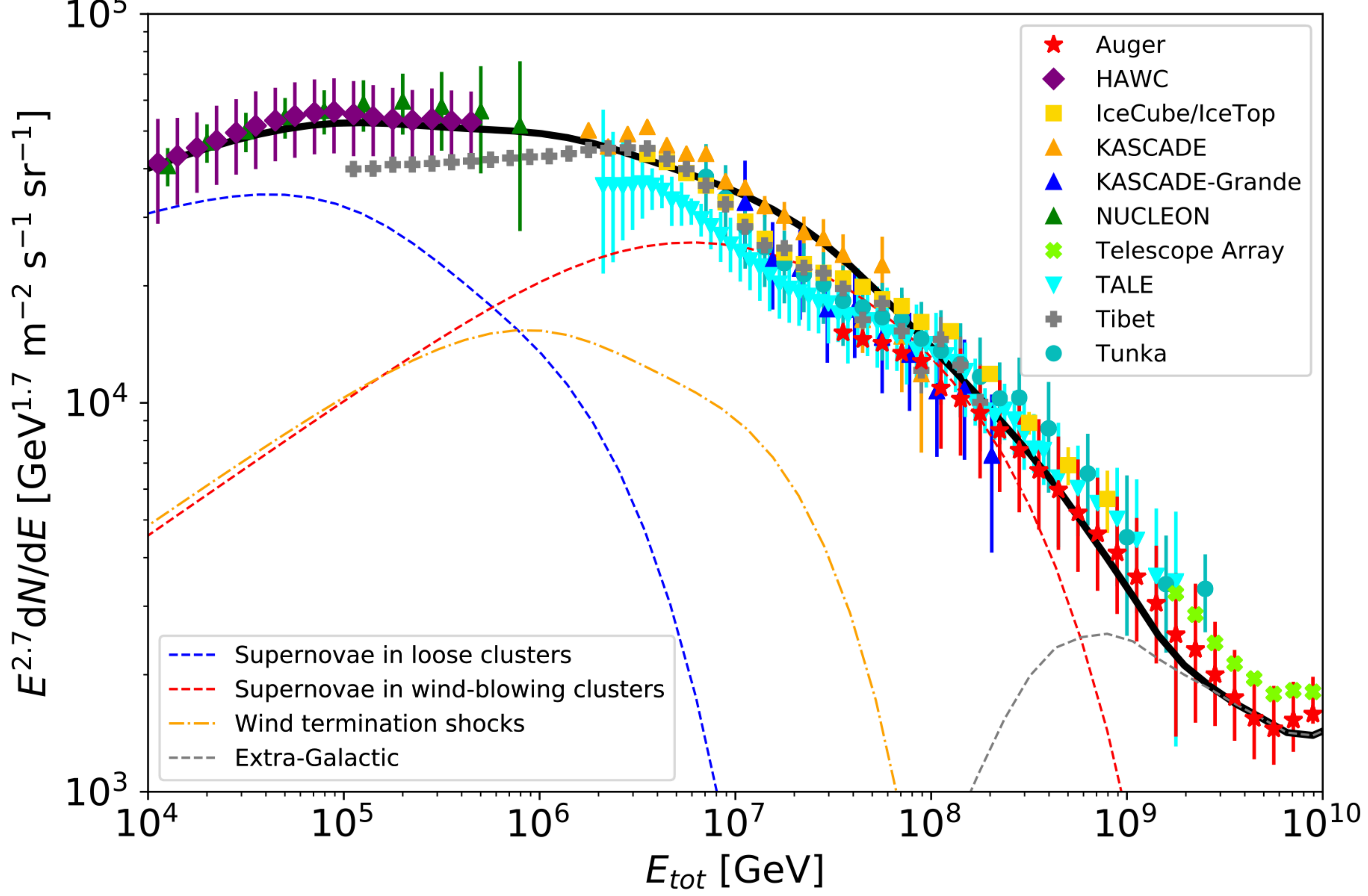
KIT Seminar, 22nd January, 2026

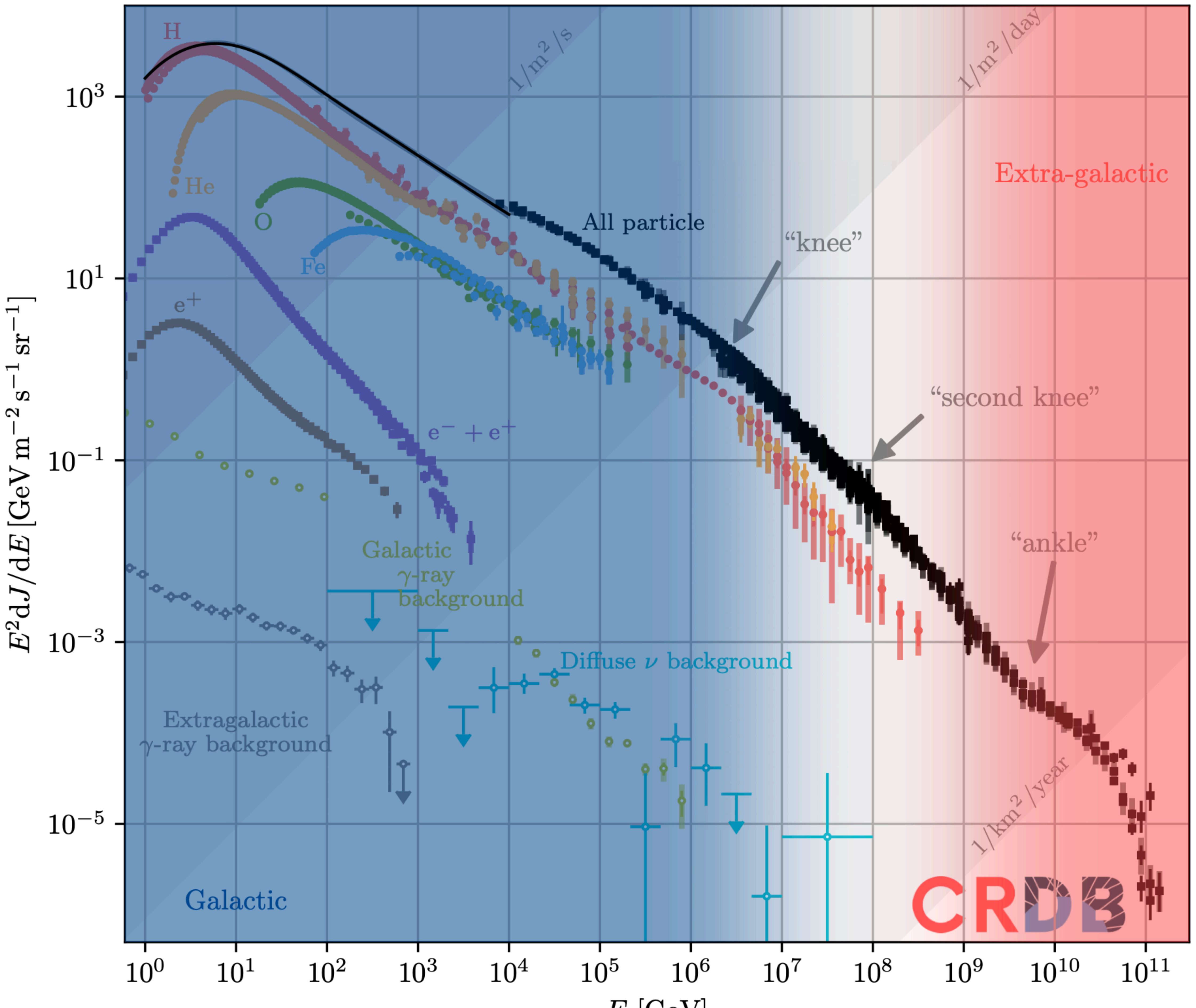
arXiv: https://arxiv.org/abs/2510.11988

Galactic Cosmic Rays

- Cosmic rays $\lesssim 10^{18}\text{eV}$
- Originate from **within** our Galaxy
- Spectrum tells us:
  - Contributions of possible source populations
  - Acceleration mechanisms of sources
  - CR diffusion process

T. Vieu & B. Reville (2023)





P. Mertsch, ICRC2025

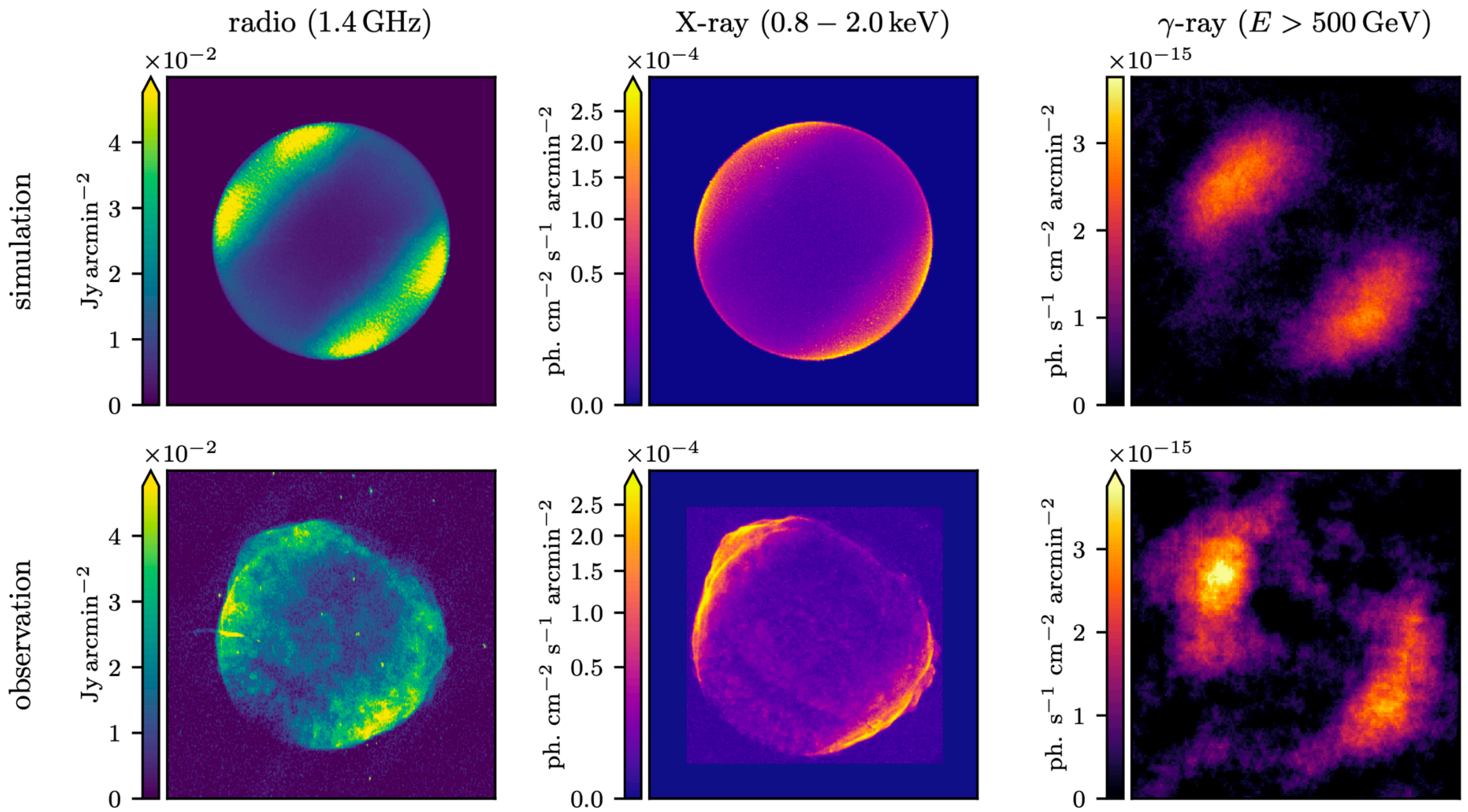
(Potential) Cosmic Ray Accelerators in the Galaxy

- Supernova remnants (e.g. SN1006)
- Young Massive Stellar clusters (e.g. Westerlund 1)
- Pulsar wind nebula
- Stellar winds from massive stars

Indirect indicators through:

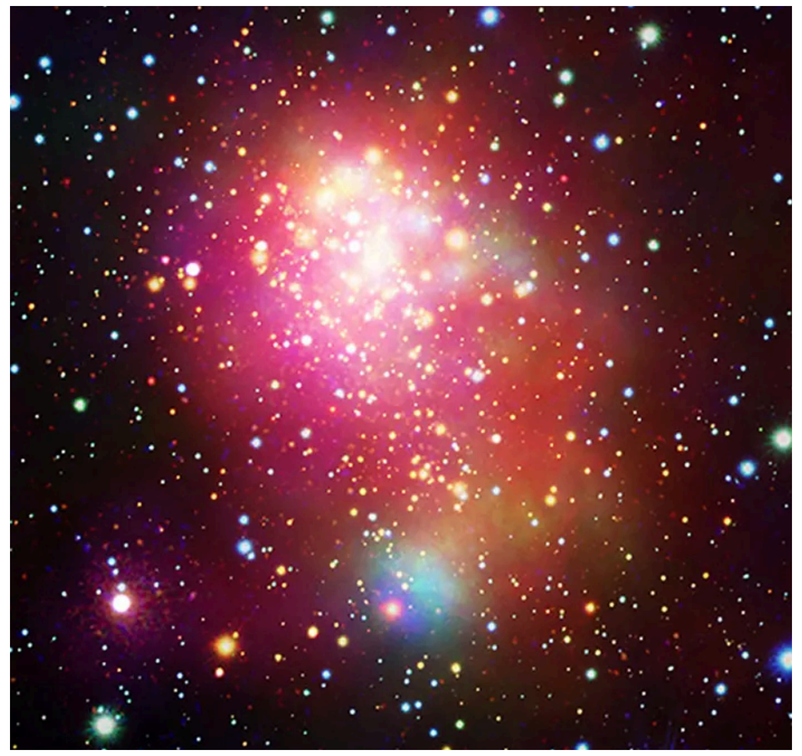
- Synchrotron emission (radio, X-ray)
- Inverse Compton scattering (X-ray, γ-ray)

G. Winner+2020



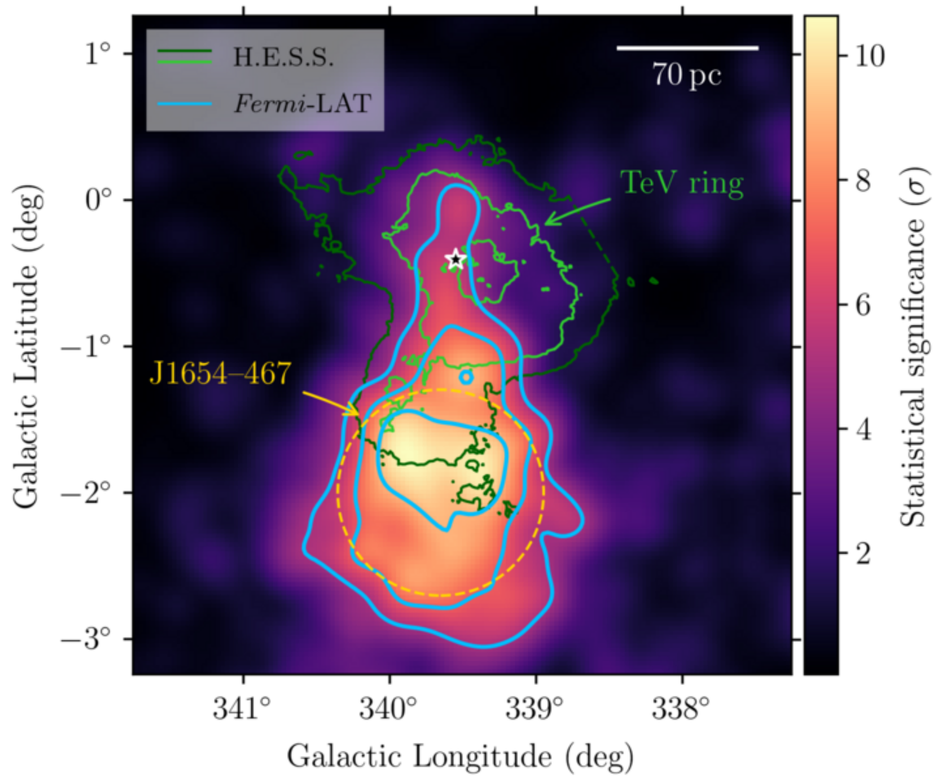
Multi-wavelength emission study of SN1006

X-Ray, and γ-ray emission from Westerlund 1



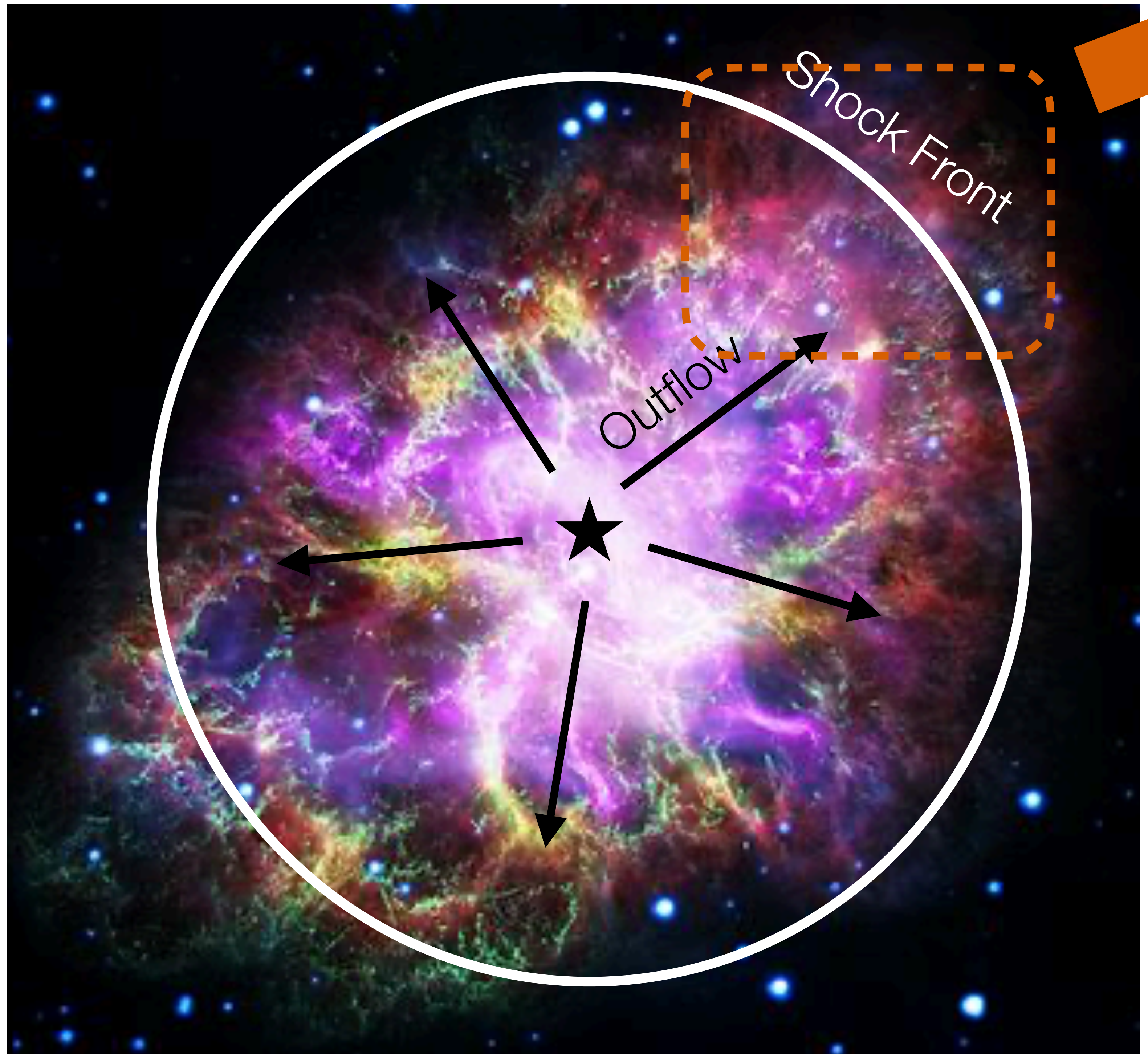
NASA/CXC/INAF/M. Guarcello et al., NASA/ESA/STScI; NASA/CSC/SAO/L. Frattare

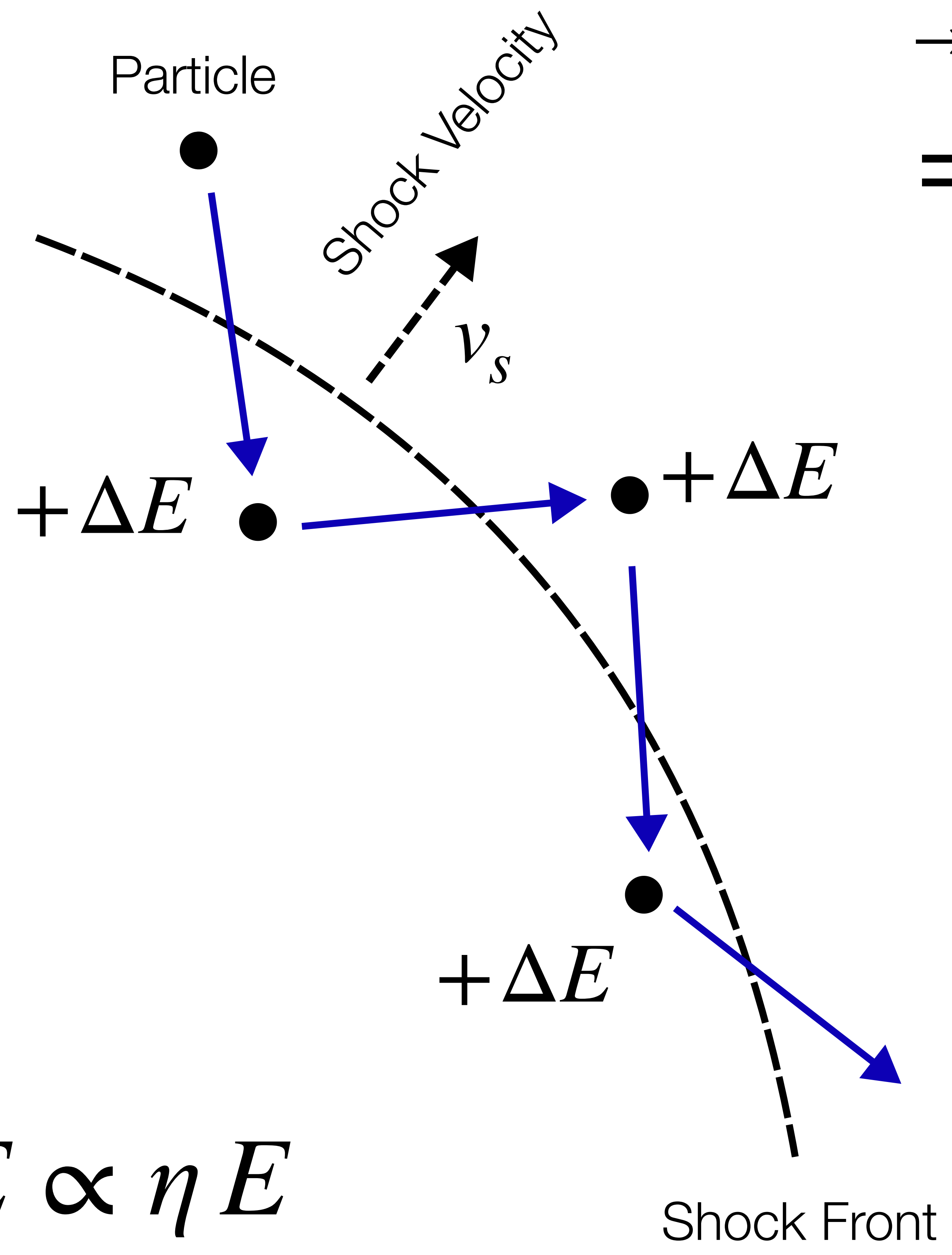
Lemoine-Goumard+2025



Cosmic Ray Acceleration in Astrophysical Objects

- Standard paradigm: diffusive shock acceleration



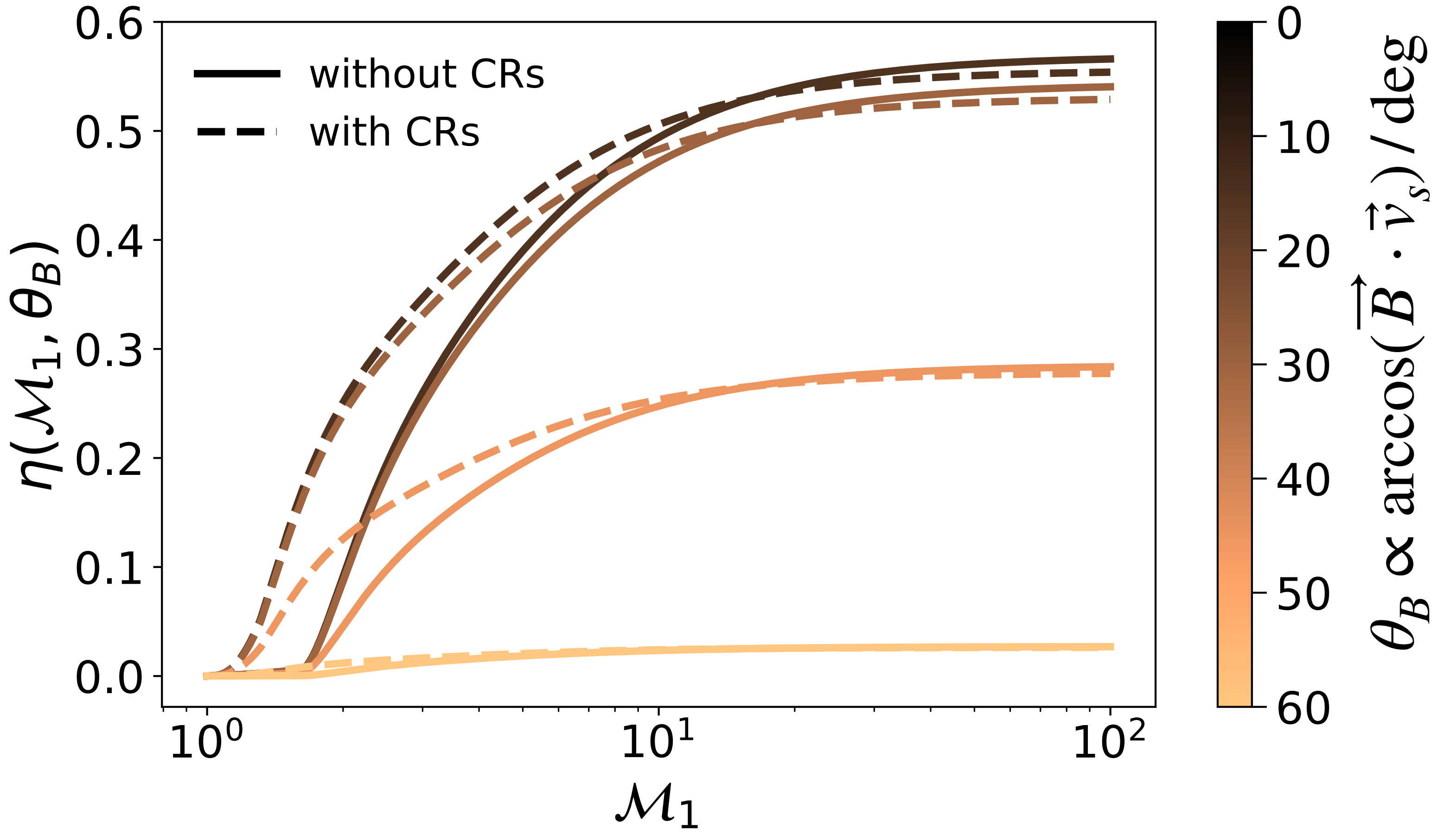


$$\Delta E \propto \eta E$$

$\rightarrow n_{\mathrm{part}}$

$$\Longrightarrow \quad n(E) \propto E^{-\alpha_{\mathrm{inj}}}$$

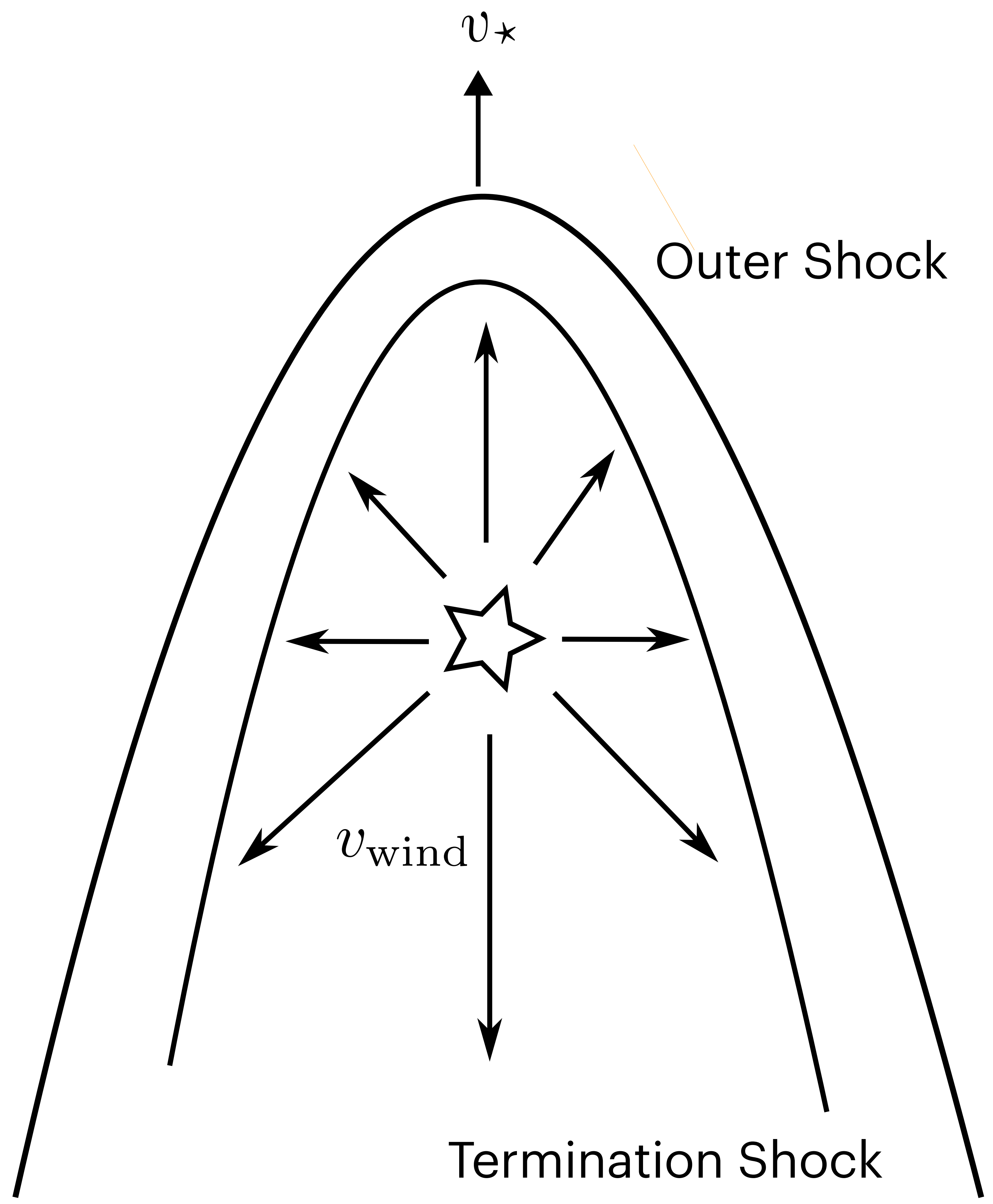
- Depends on Mach number & density of material
- Acceleration efficiency η scales with e.g. Mach number, magnetic field direction



→ CR acceleration depends heavily on magnetohydrodynamic simulations!

Bow Shocks around Massive Runaway Stars

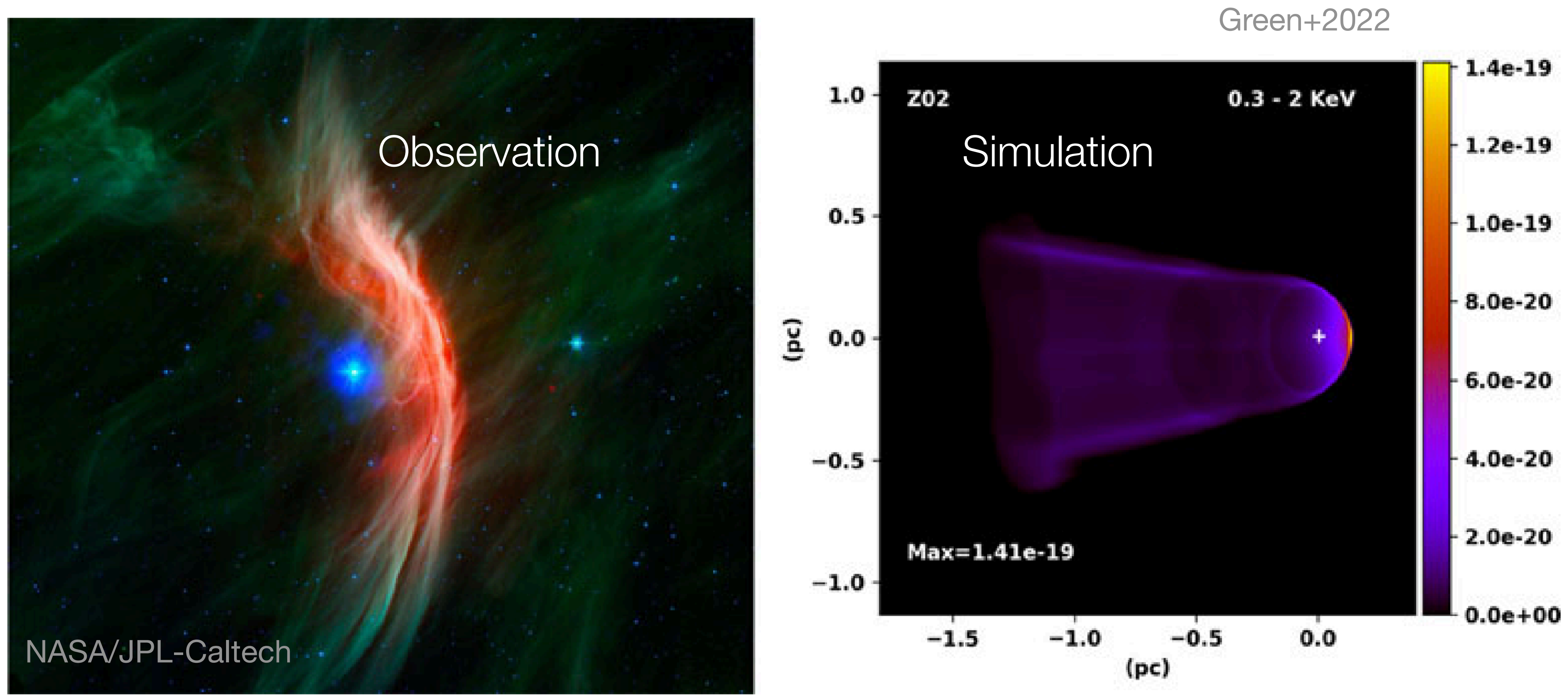
- Generated by interaction from stellar winds + ISM
  - Stellar winds ejected from star ($v_{\rm wind}$ ~ 1000 km/s) with masses > $\gtrsim 10 M_\odot$
  - Star moves with velocities $v_\star \gtrsim$ 30 km/s within medium
  - Interaction generates mixture of fluids -> formation of shock at two regions:
    - **Termination shock / reverse shock**: between winds & mixed medium
    - **Outer shock / forward shock** : between mixed & ambient medium



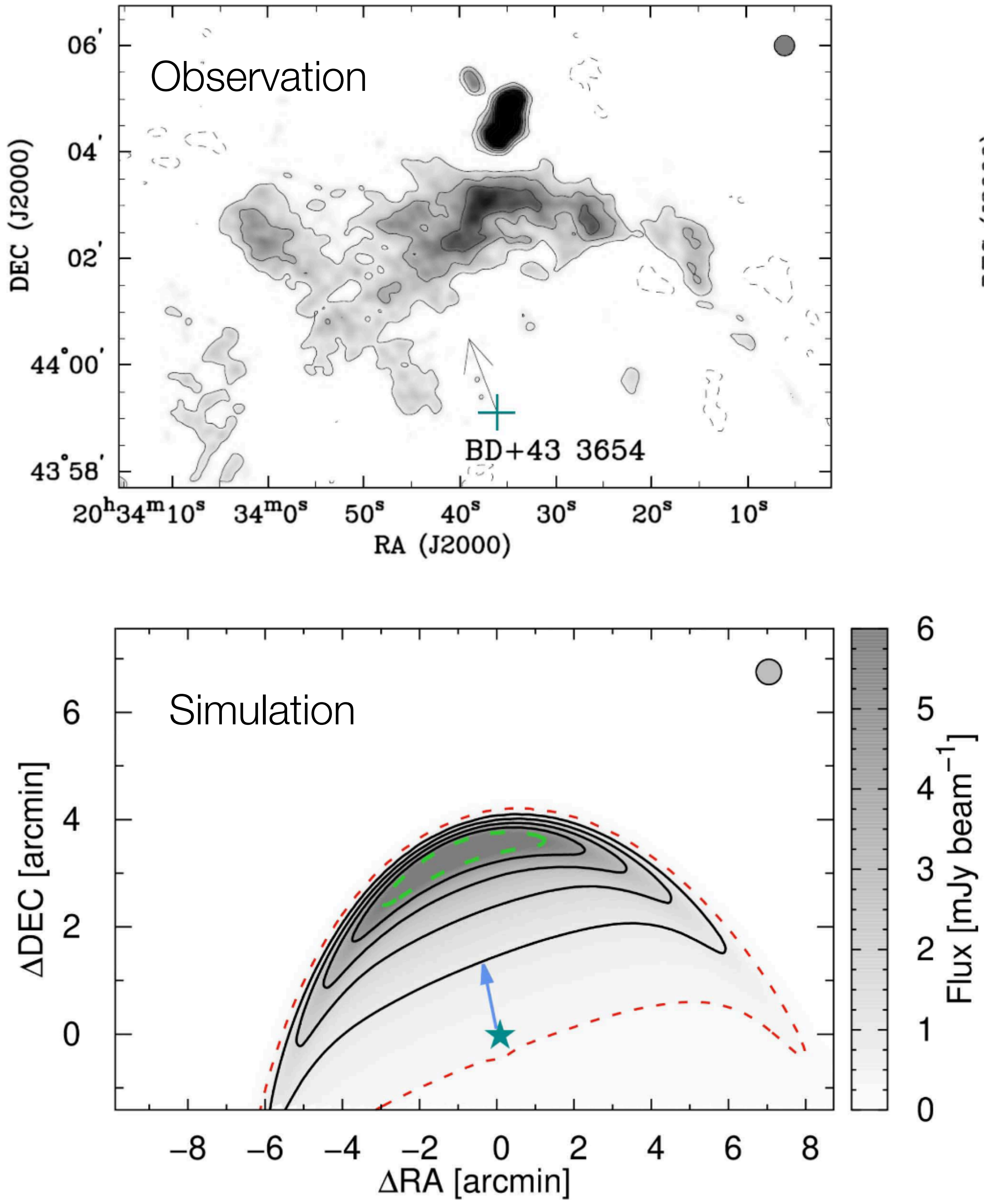
- Features
  - Short dynamical lifetime ($t_{\rm dyn} \sim$ 100 kyr)
  - Axisymmetric morphology - effects of non-uniformity
  - Magnetic fields "drape" around shock
  - Pressure balance between winds and ISM : constant pressure in bubble
  - Potential acceleration sites for cosmic rays

Bow Shocks around Massive Runaway Stars

- Already several simulation studies / observations!
  - Thermal emission from e.g. ζ Ophiuchi
  - Radio synchrotron / Inverse Compton emission from r.g. BD+43 3654



Thermal X-ray emission from ζ Ophiuchi



Radio Flux maps from BD+43 3654

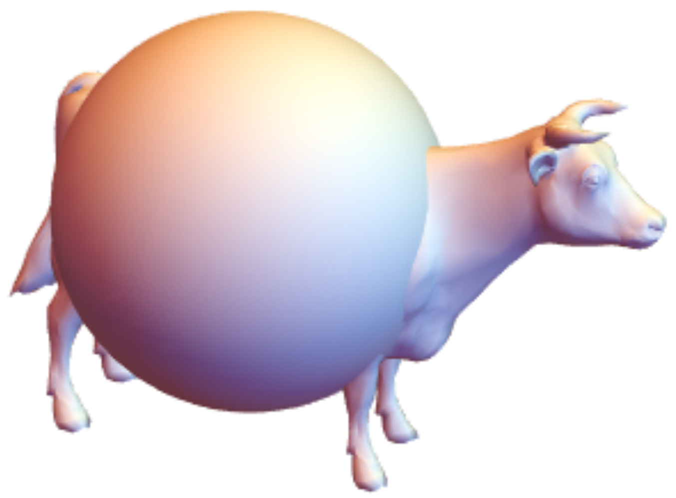
→ Great laboratory to study behaviour of CR acceleration!

Progress on Bow Shock Simulations

All-inclusive simulation (3D MHD + Wind Injection + Full CR Transport + synthetic emission)

MHD simulations + Wind Injection

CR Transport + Synthetic Emission



MHD simulations + Wind Injection + Momentum-integrated CR Transport + complete CR acceleration treatment

Simplified synthetic emission

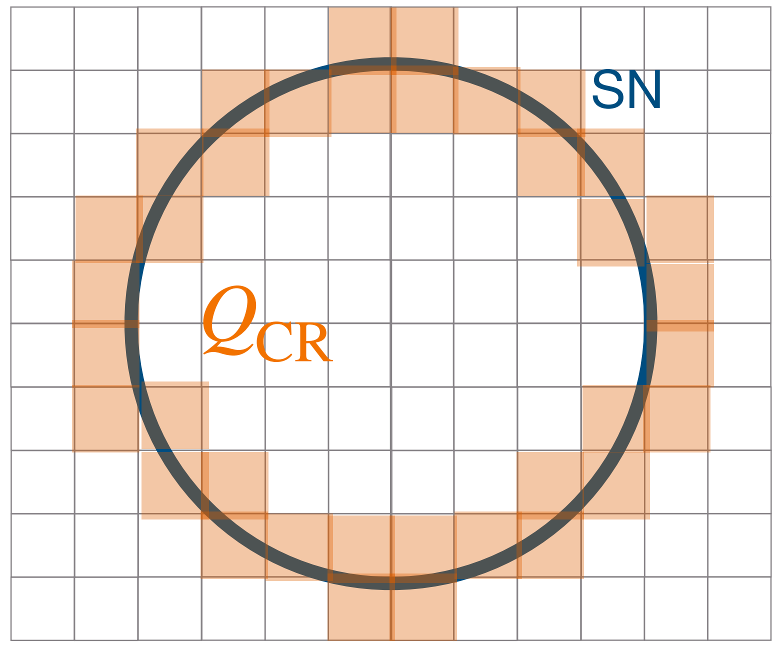
Goal!

- 1/2D (M)HD simulations
- One-zone models for wind injection
- Momentum-integrated CR Transport equation
- Neglecting CR transport processes (streaming etc.)
- Simplified emission models (no radiative transfer, inclination angles etc)
- Simplified CR acceleration modelling
- And more…

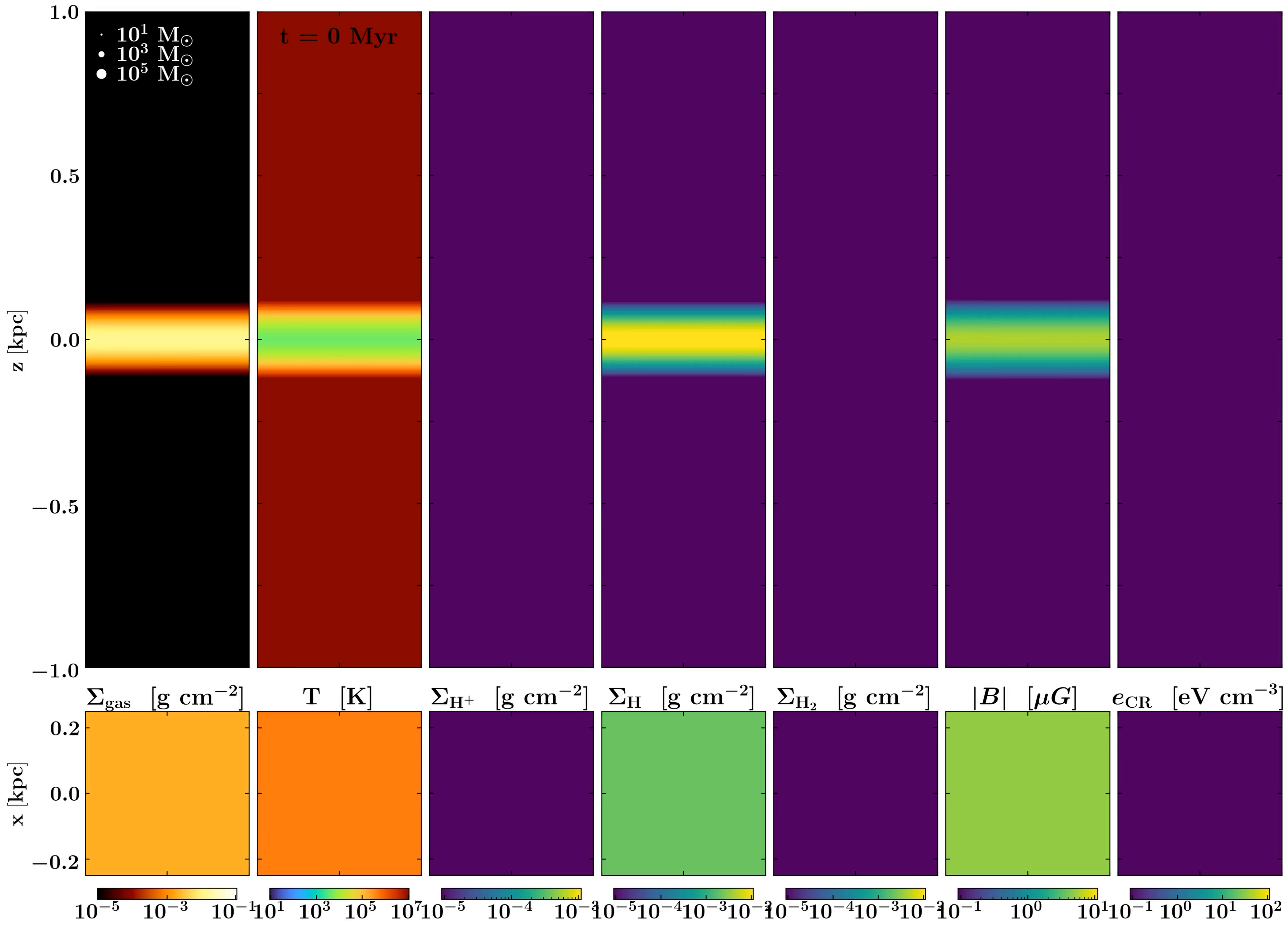
Simulation Framework

- Using **FLASH** : Hydrodynamic grid-based solver
  - Solves CRMHD equations at each timestep
  - Includes:
    - Gas heating / cooling from chemical species
    - Molecular formation / destruction
    - Self-gravity
    - Massive star formation through accretion
    - Stellar feedback from supernovae, stellar winds, ionising radiation
    - Cosmic ray as an additional fluid with adiabatic EoS
- **Additionally: CR dynamically injected at resolved shocks**
  - Gradient-based shock detection

    + CR injection with efficiency at each timestep



T.-E. Rathjen+2025



Time evolution of realistic ISM simulation using FLASH (SILCC Project)

Outline

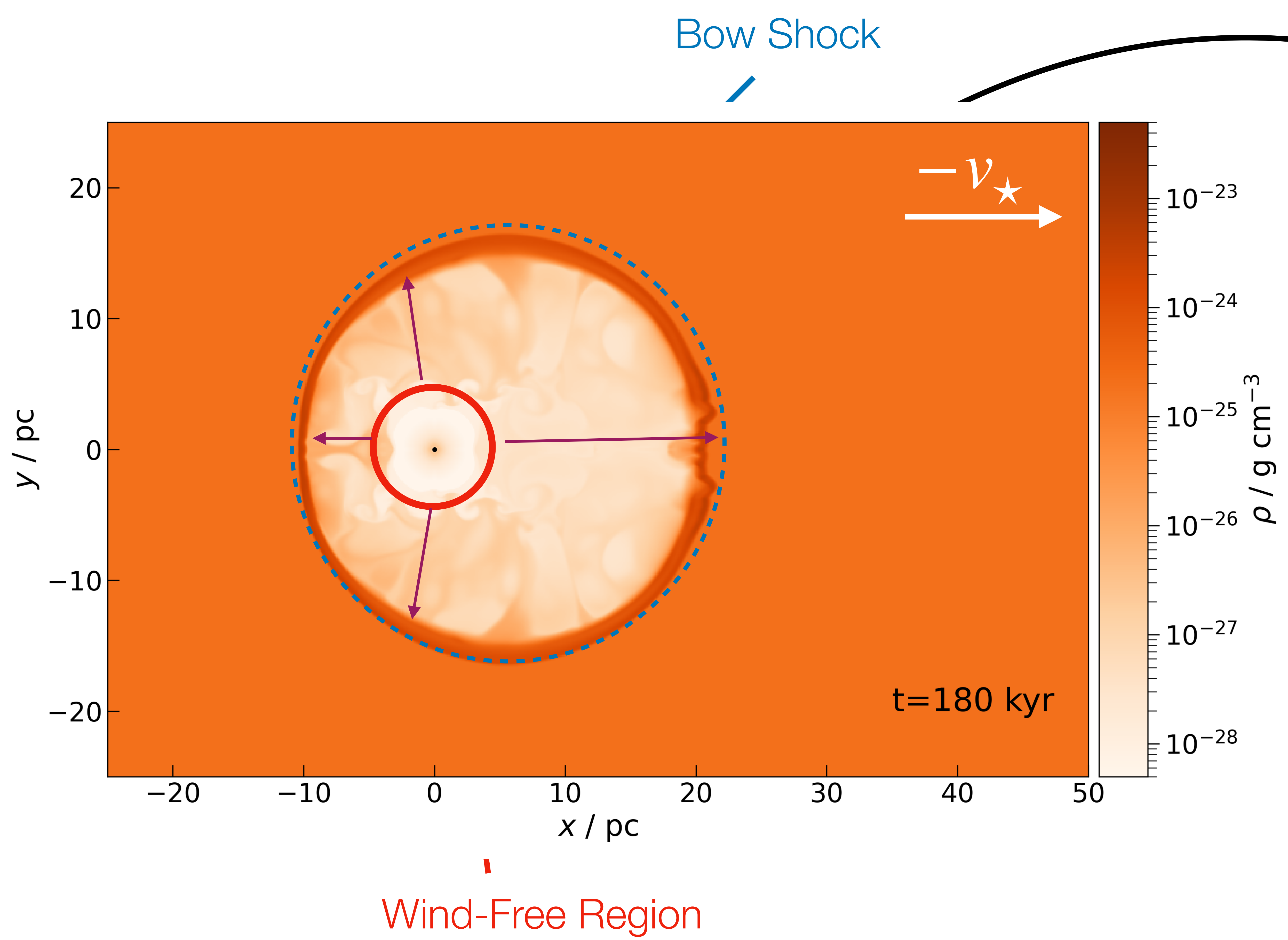
Comparison with MHD → CR Acceleration at the Shock → Synthetic Emission

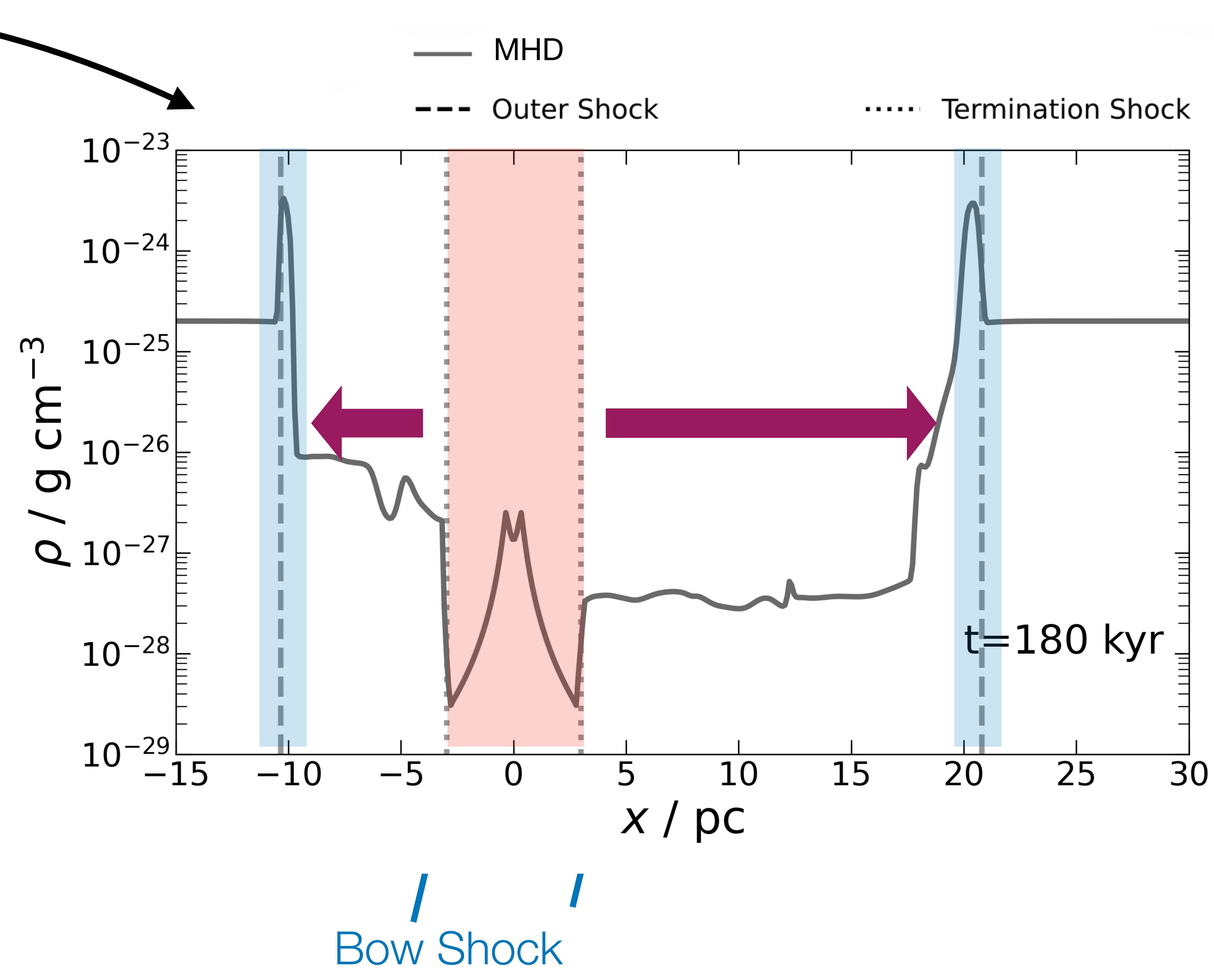
Outline

Comparison with MHD → CR Acceleration at the Shock → Synthetic Emission

Result - MHD Only

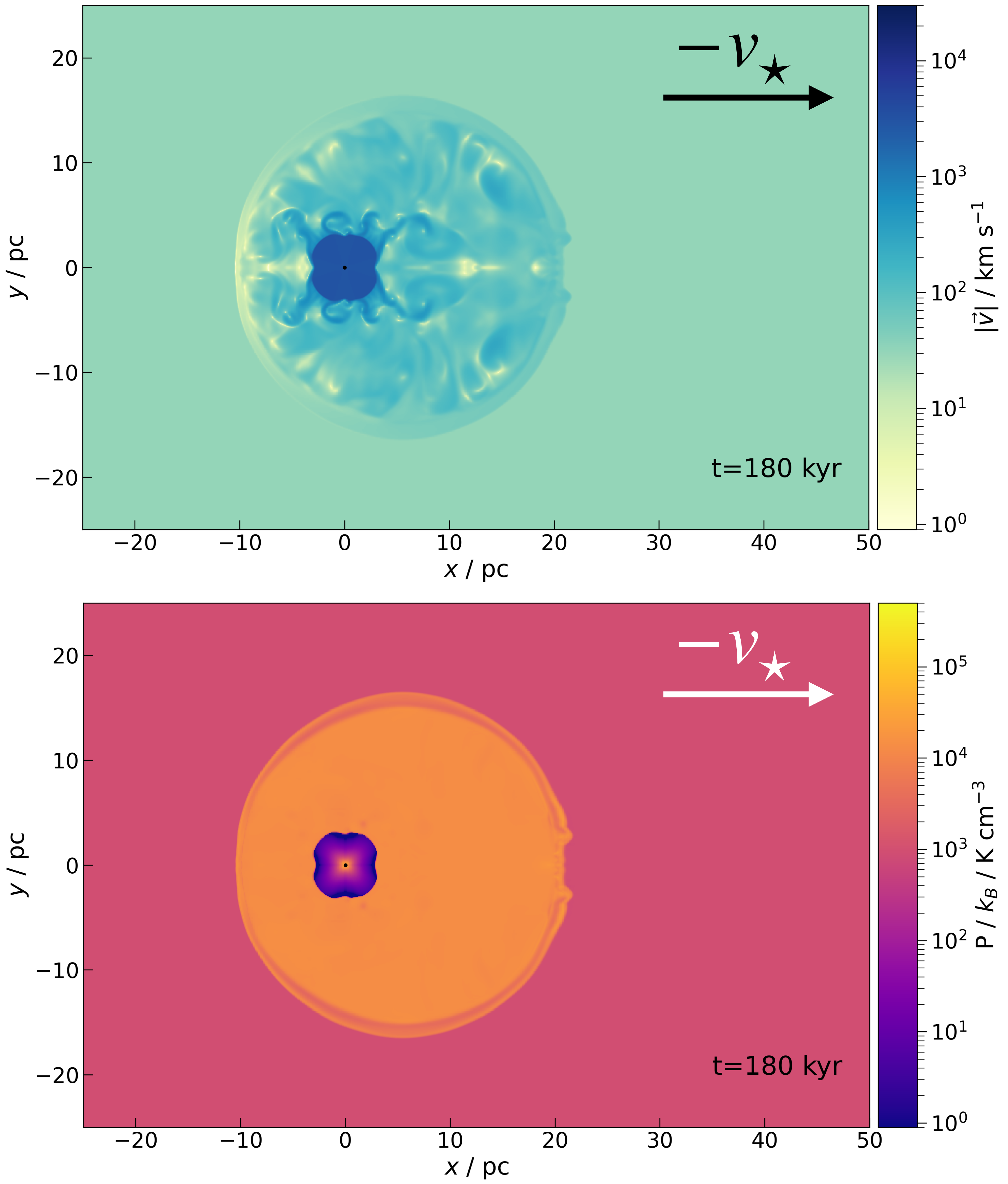
- Verify that we simulate a bow shock

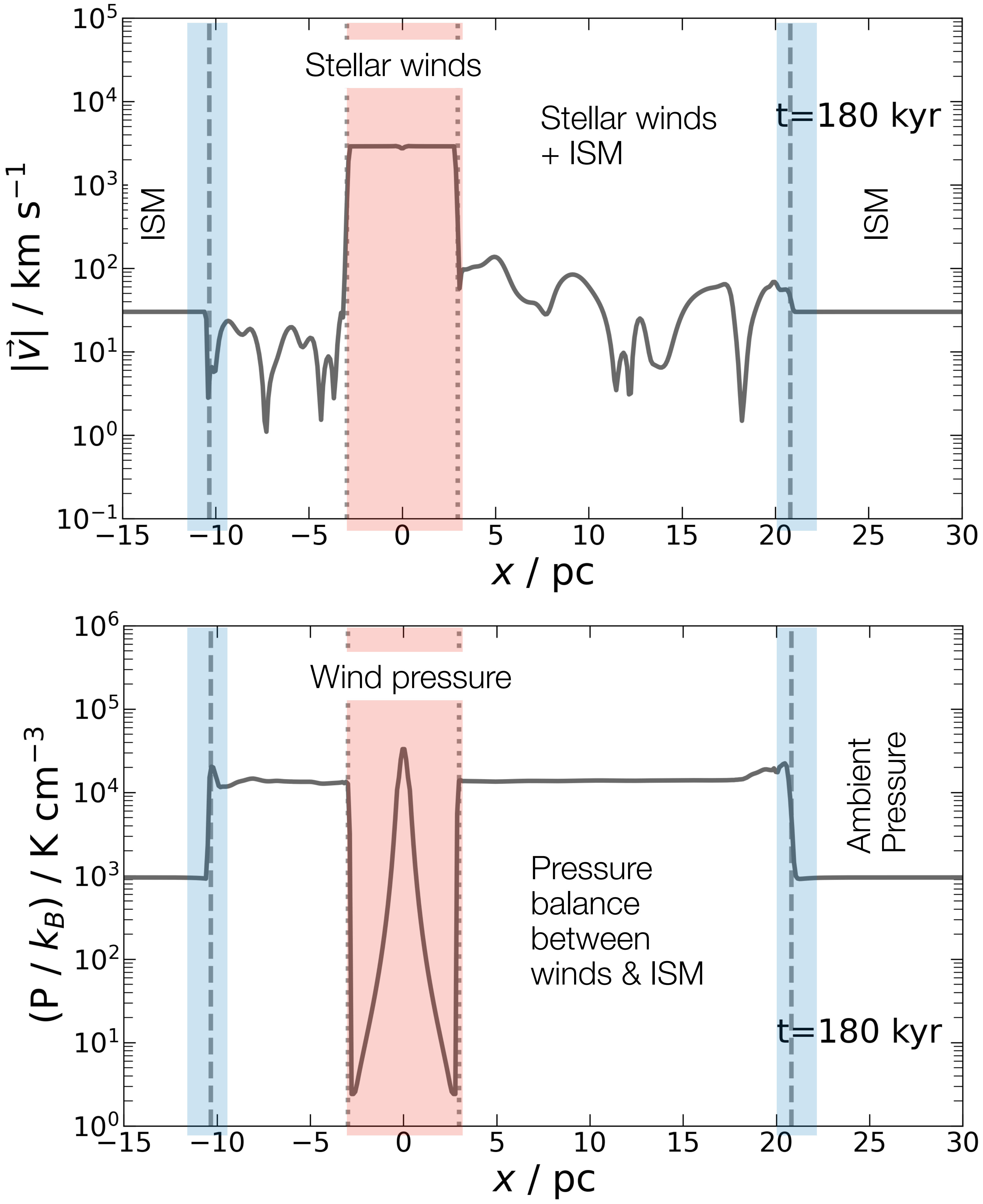




Result - MHD Only

- Other relevant thermodynamic parameters

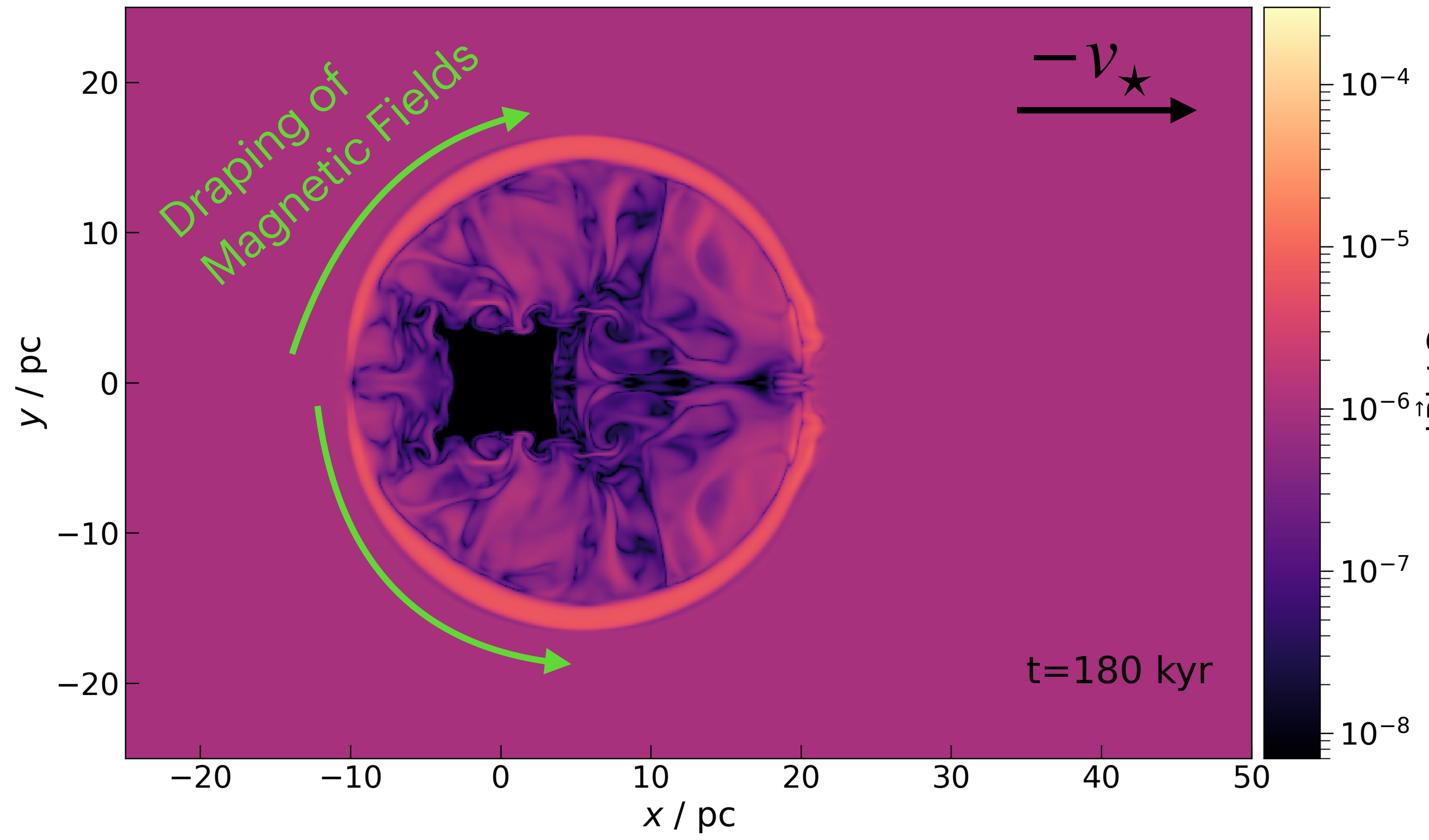




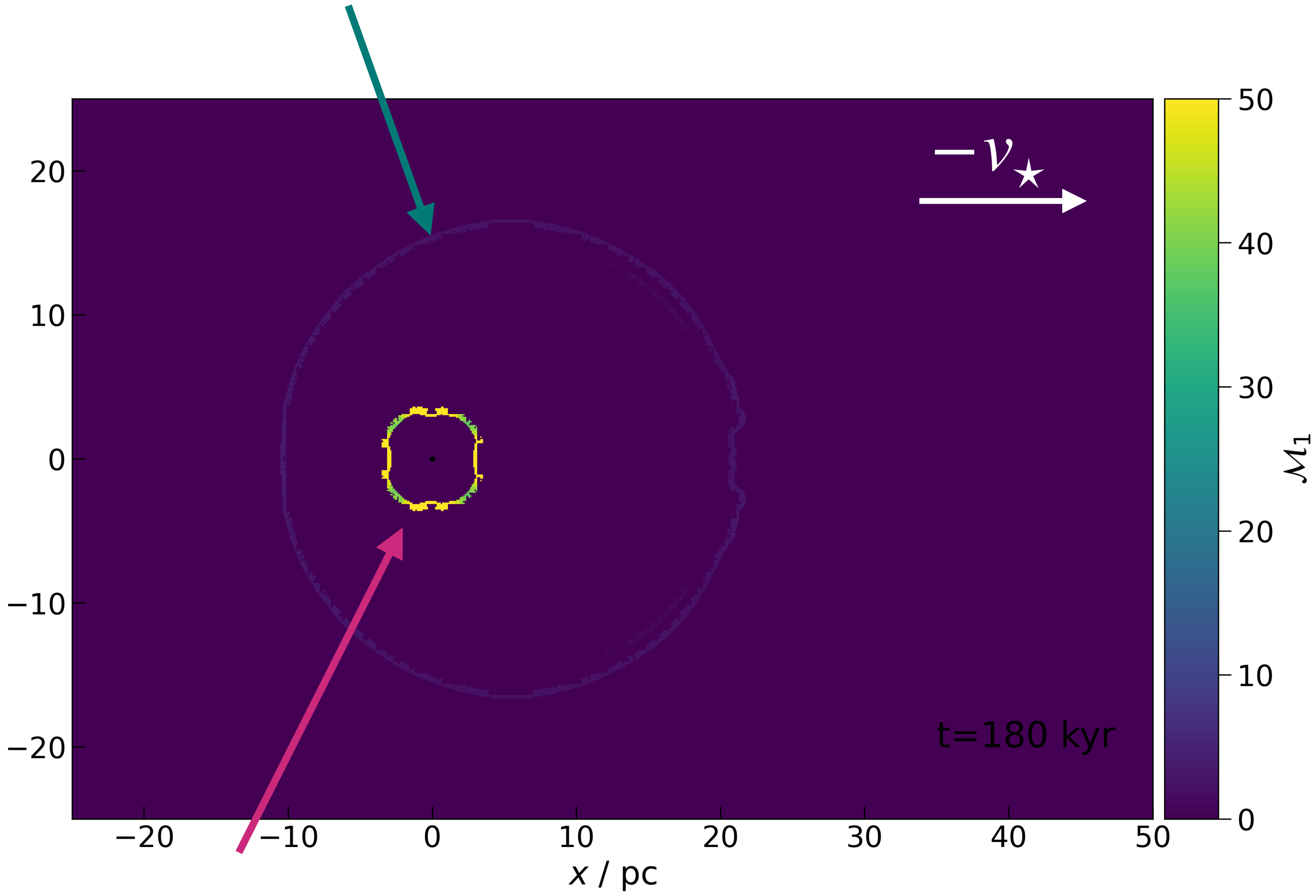
Result - MHD Only

Mach number: $\mathscr{M} = v/c_s$

- Other relevant thermodynamic parameters



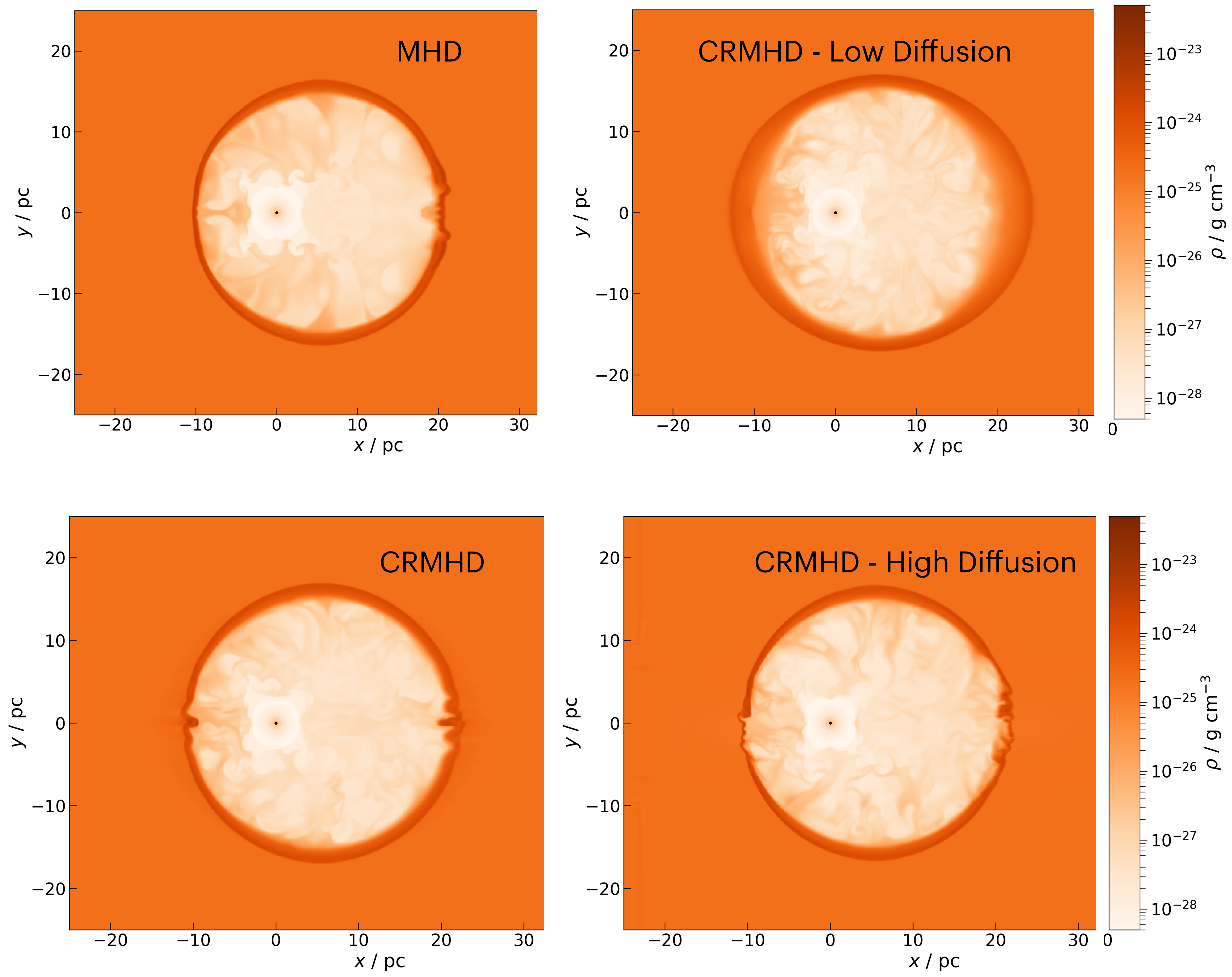
Slow shocks at outer shock

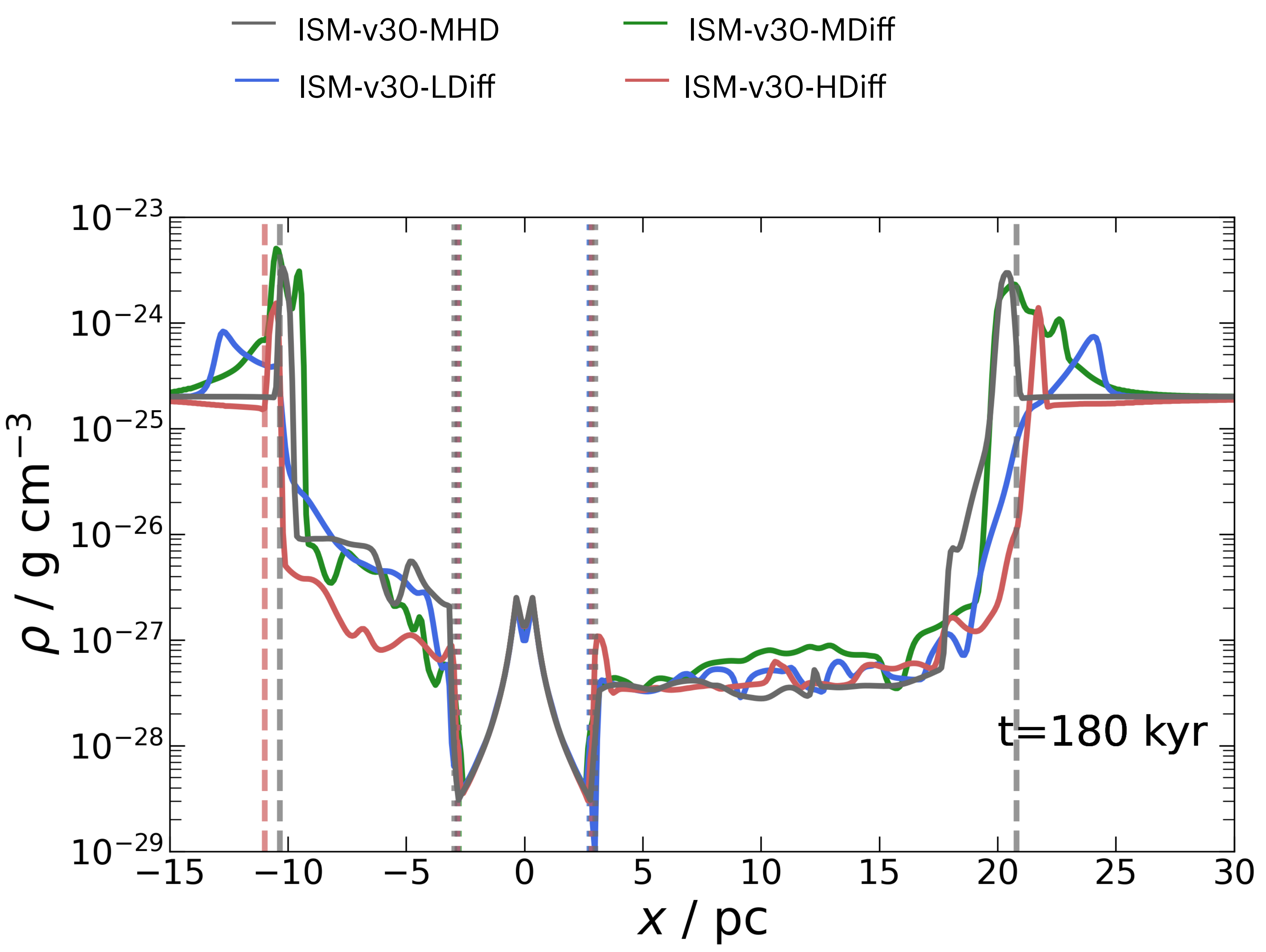


High-velocity shocks at termination shock

Results - CRMHD vs MHD

- Comparing between varying diffusion coefficients, $t = 180$kyr

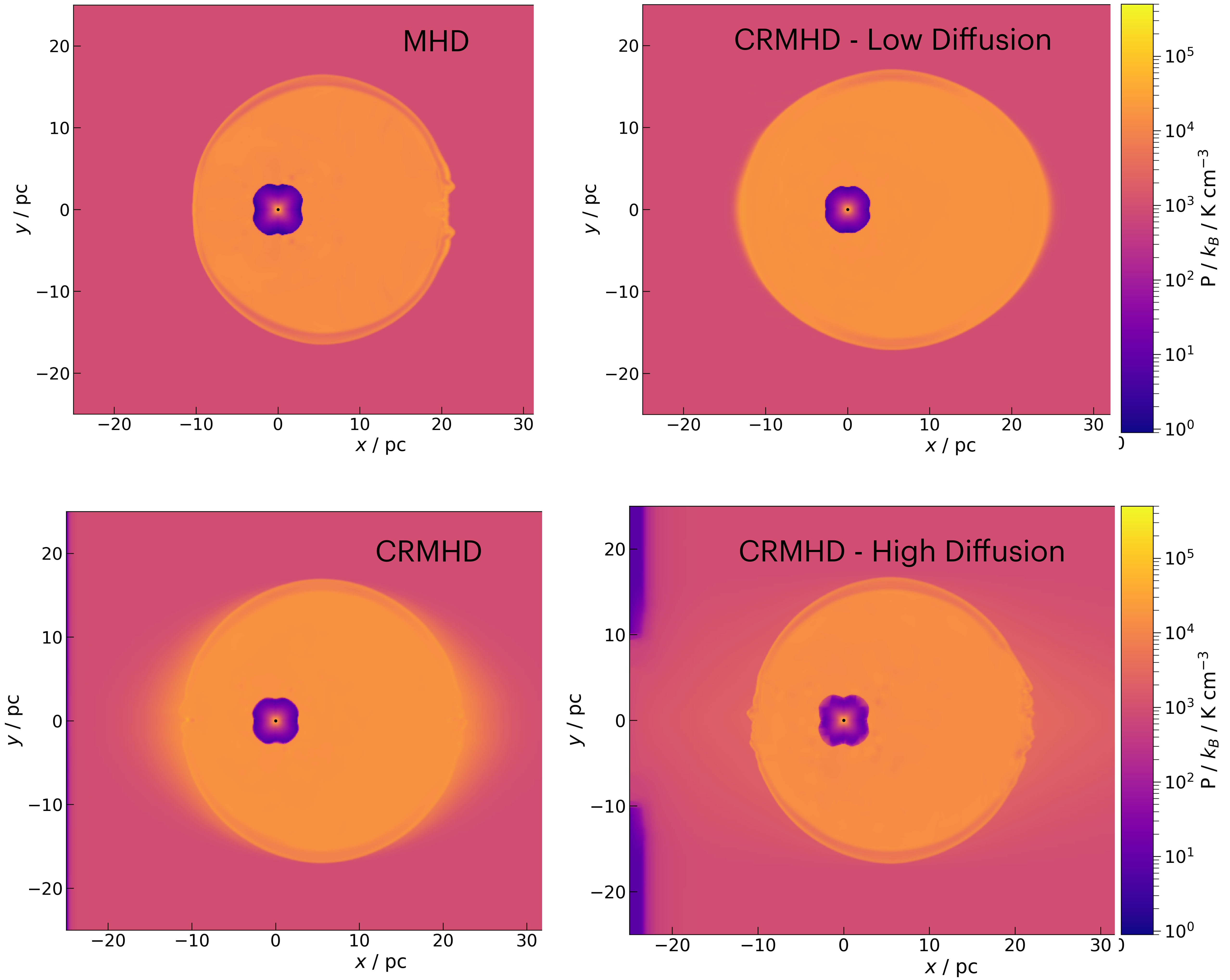


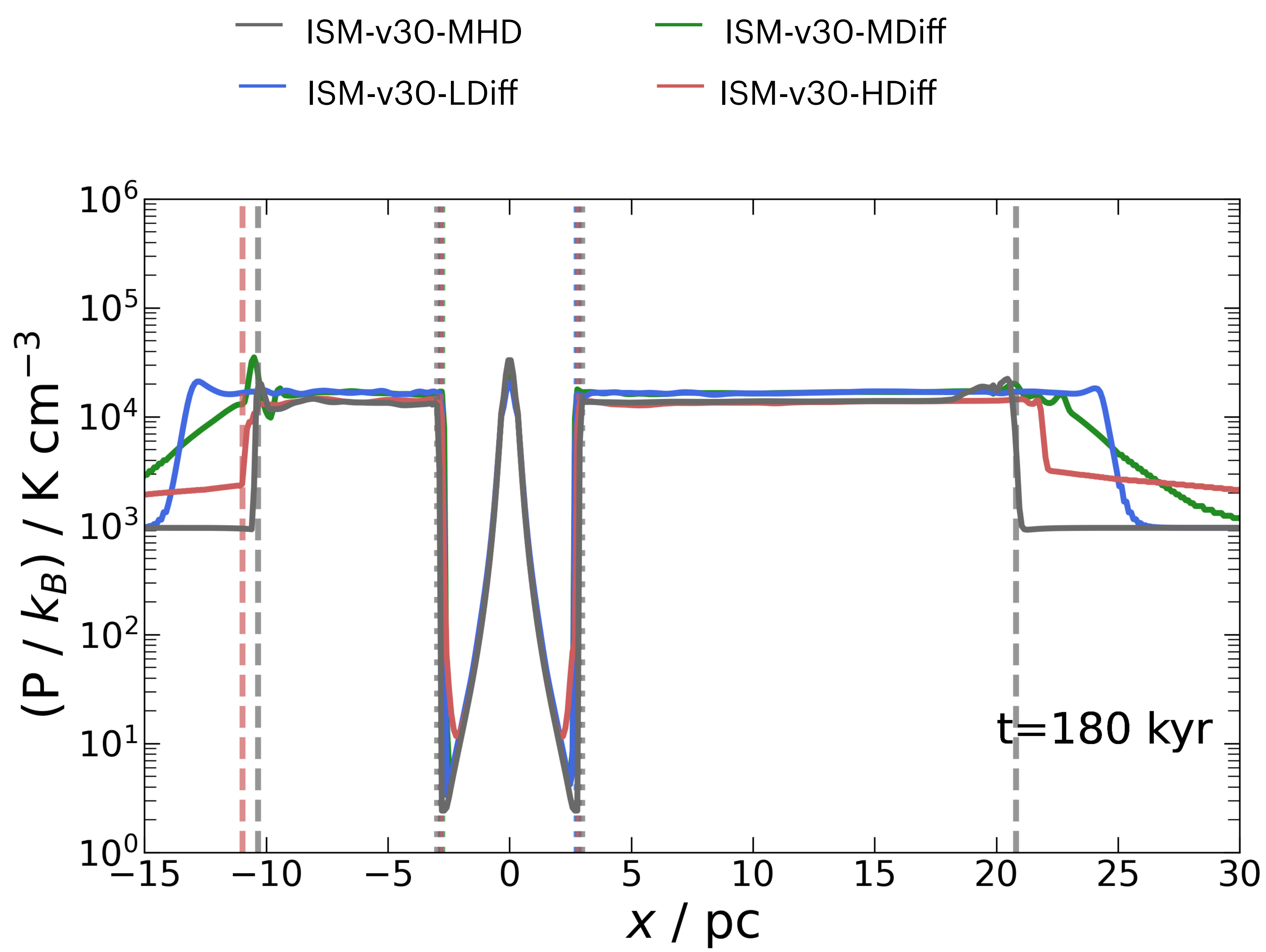


- Only low diffusion case has different morphology: outer shock is “smeared out”

Results - CRMHD vs MHD

- Comparing between varying diffusion coefficients, $t = 180$kyr





- Low diffusion case changes morphology - due to additional CR pressure within bubble
- Higher diffusion -> CRs escape bubble -> less contribution to morphology

Interim Summary

- MHD-only bow shock simulation makes sense :)
- Inclusion of CRs indeed affect the dynamics of the bow shock!
  - Stronger diffusion → CRs diffuse outside faster : effective morphology ~ MHD case
  - Weaker diffusion → CRs within bubble : additional CR pressure smears out / elongates shock

Outline

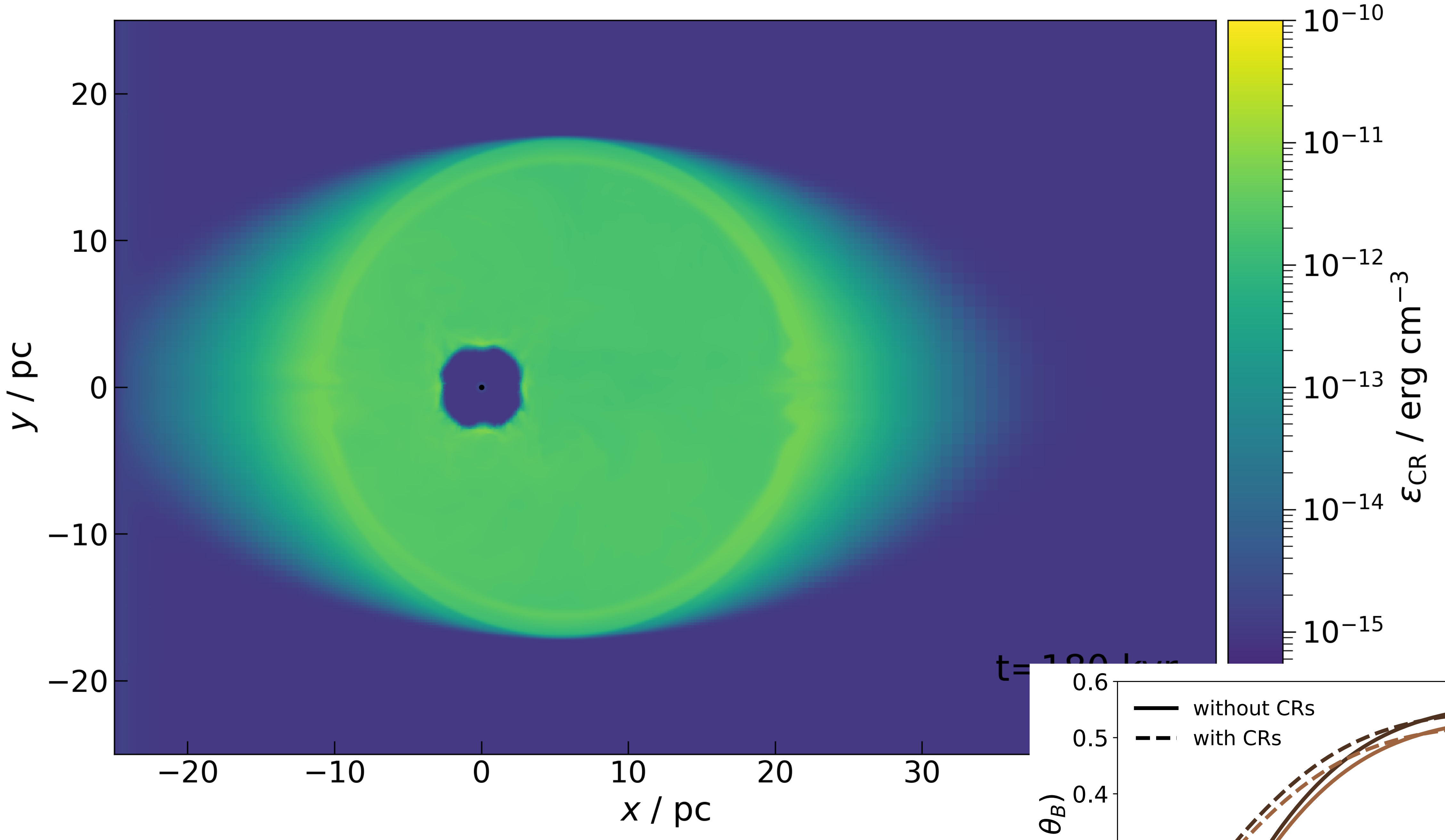
Comparison with MHD

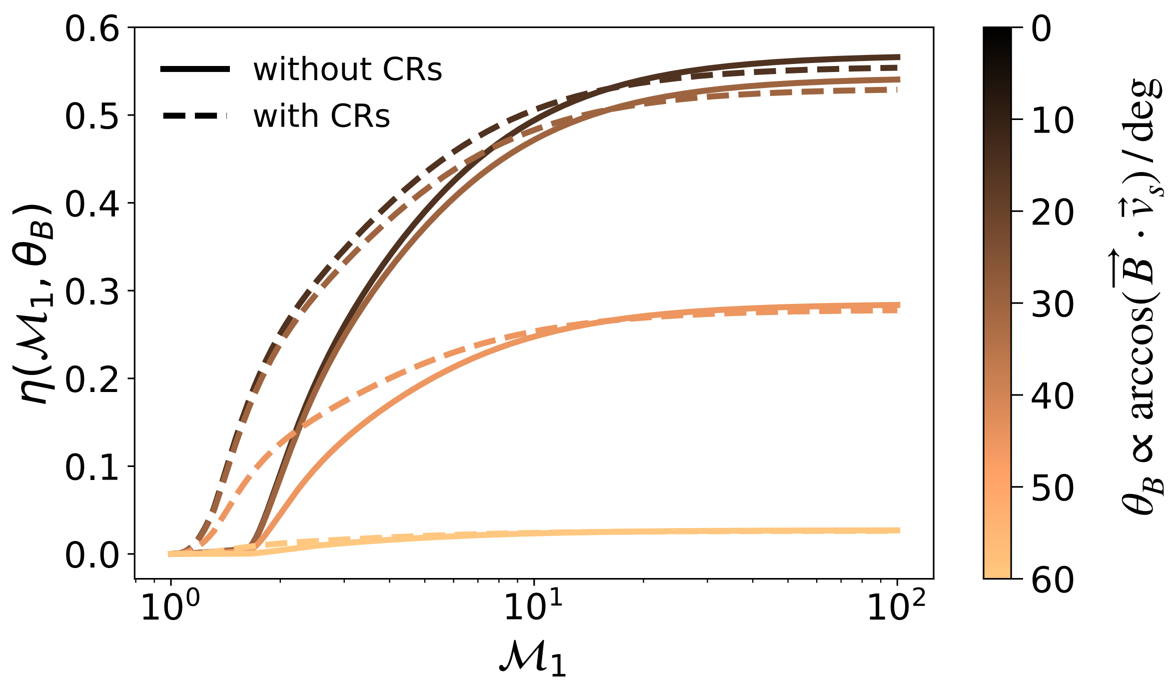
CR Acceleration at the Shock

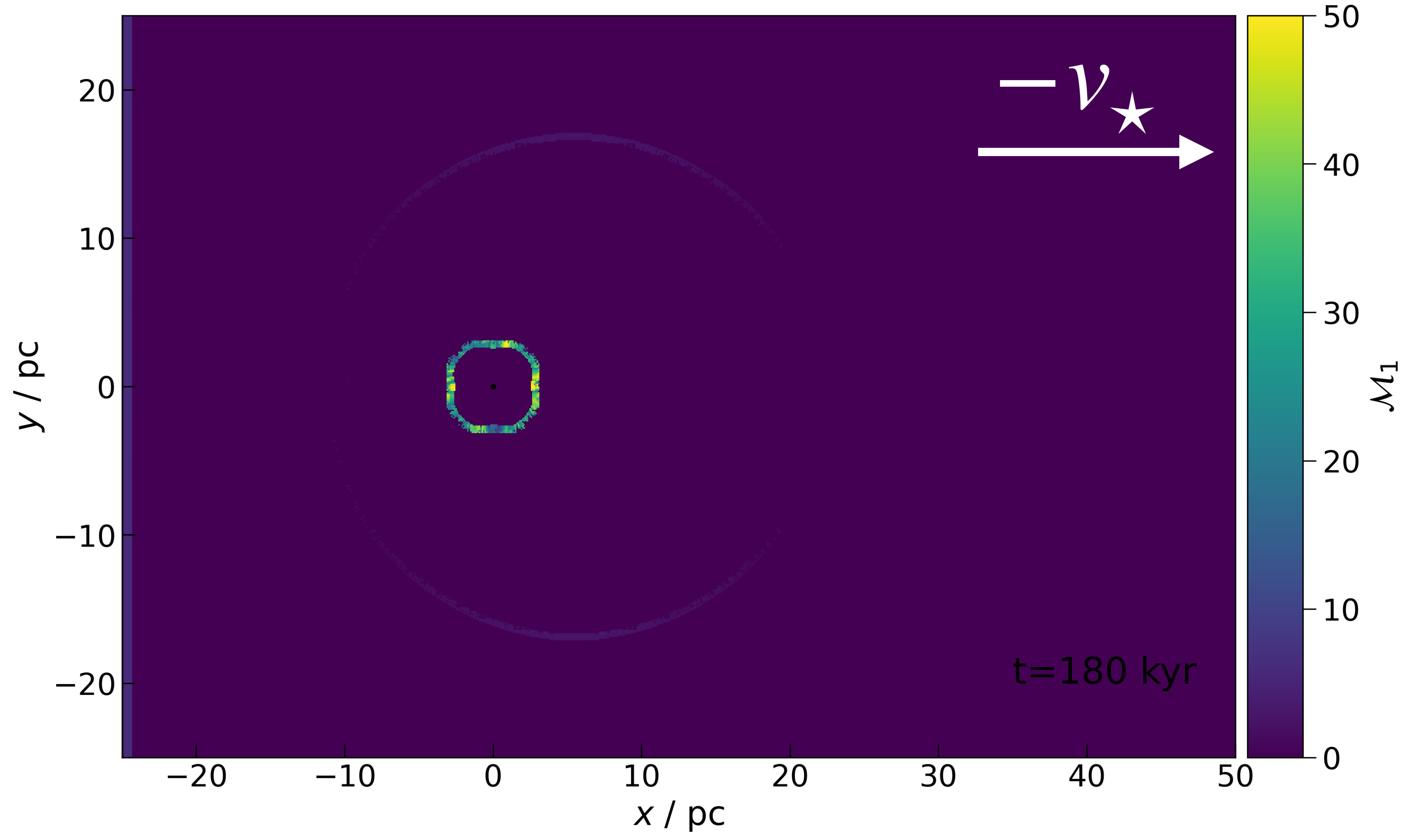
Synthetic Emission

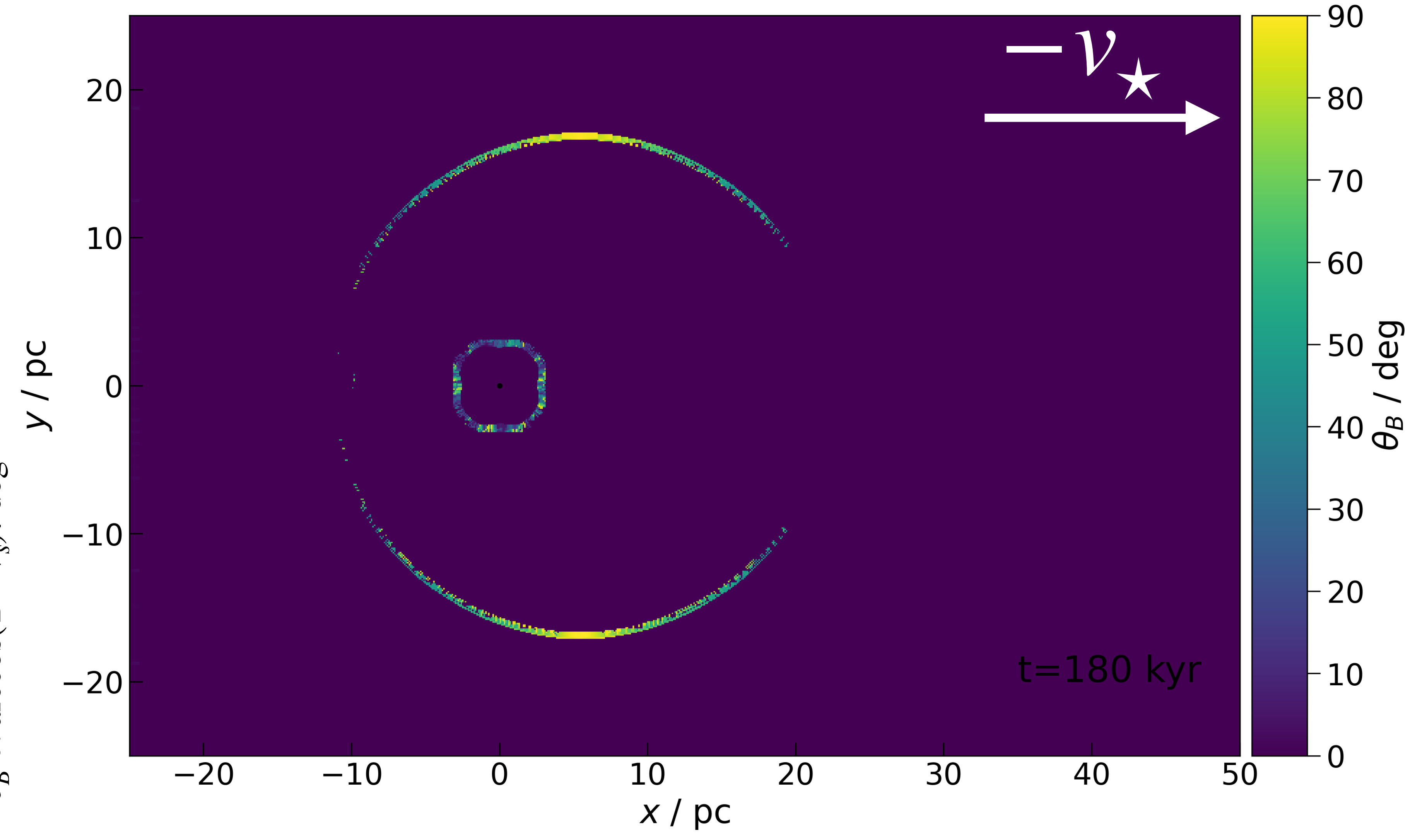
CR Acceleration on CR Energy Distribution

- Distribution of CR Energy density depends on CR acceleration
  - Dependence on Mach number & magnetic obliquity θ_B, & pre-existing CR population
  - Efficient particle acceleration from outer shock, only at termination shock at later times









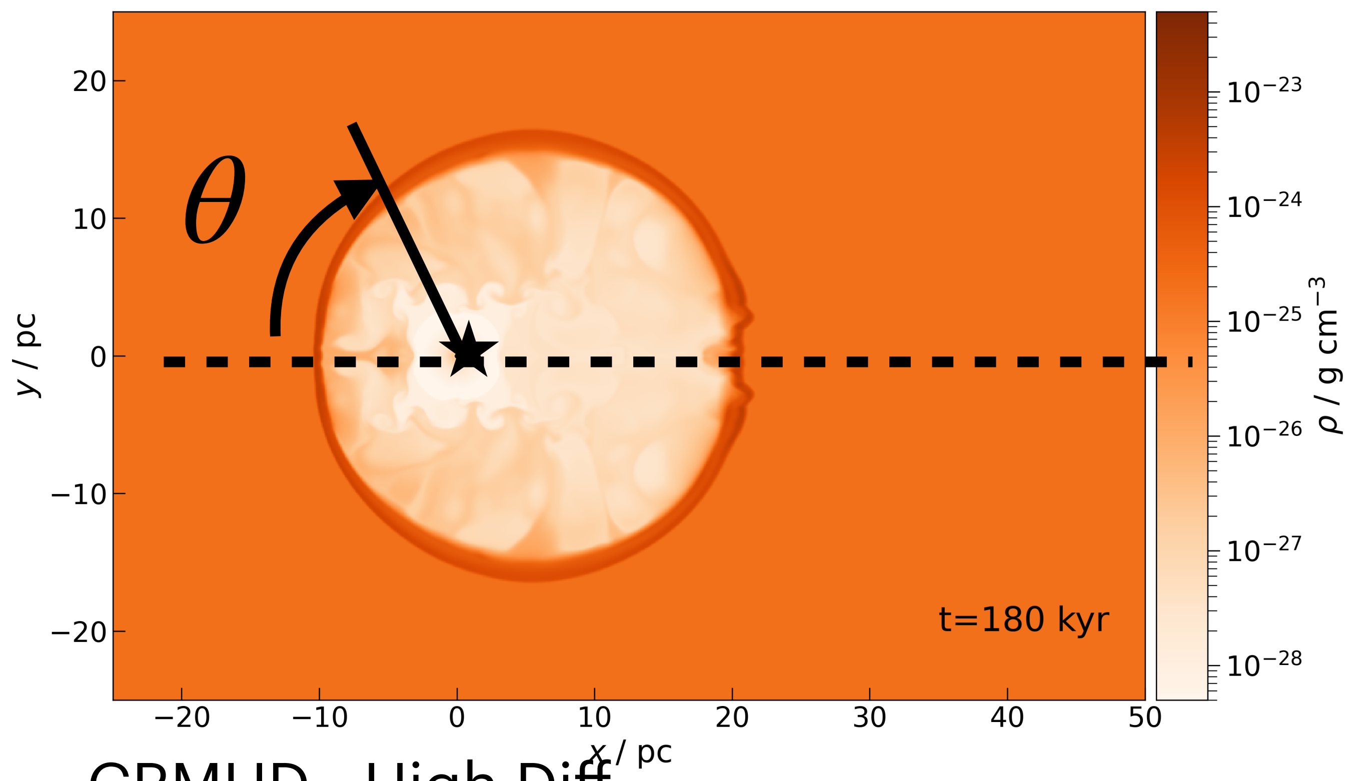
CR Energy Density

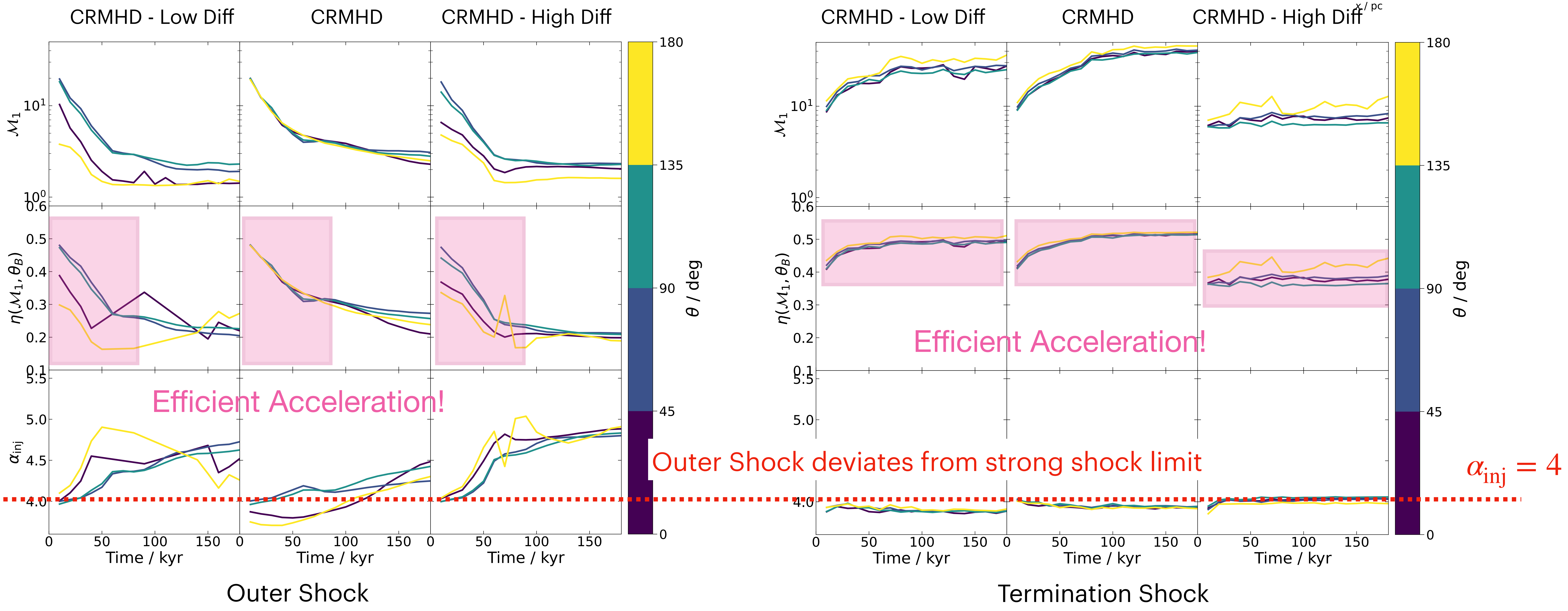
- CR Energy Density with varying diffusion coefficients, $t = 180$ kyr

- Diffusion plays a prominent role in CR population
  - Magnetic fields oriented || star - prominent CR transport along star
  - Weaker diffusion : CRs within bubble → can additionally induce particle acceleration from termination shock => higher CR population
  - Stronger diffusion : CRs escape bubble → less CR population

Morphology of CR Shock Parameters

- Polar angle & Time-dependence on CR Shock Parameters
  - α_{inj} calculated in post-processing through Mach number





Interim Summary

- MHD-only bow shock simulation makes sense :)
- Inclusion of CRs indeed affect the dynamics of the bow shock!
    - Stronger diffusion → CRs diffuse outside faster : effective CR population ~ MHD case
    - Weaker diffusion → CRs within bubble : additional CR pressure smears out shock
- Efficient particle acceleration at outer shock, only at termination shock at later times
    - Diffusion modifies pressure & CR population within bubble : impacts further particle acceleration
    - Modified injection index at outer shock due to mixing with thermal components
    - Over-efficient due to overestimated CR efficiency & lack of slow-shock treatment

Outline

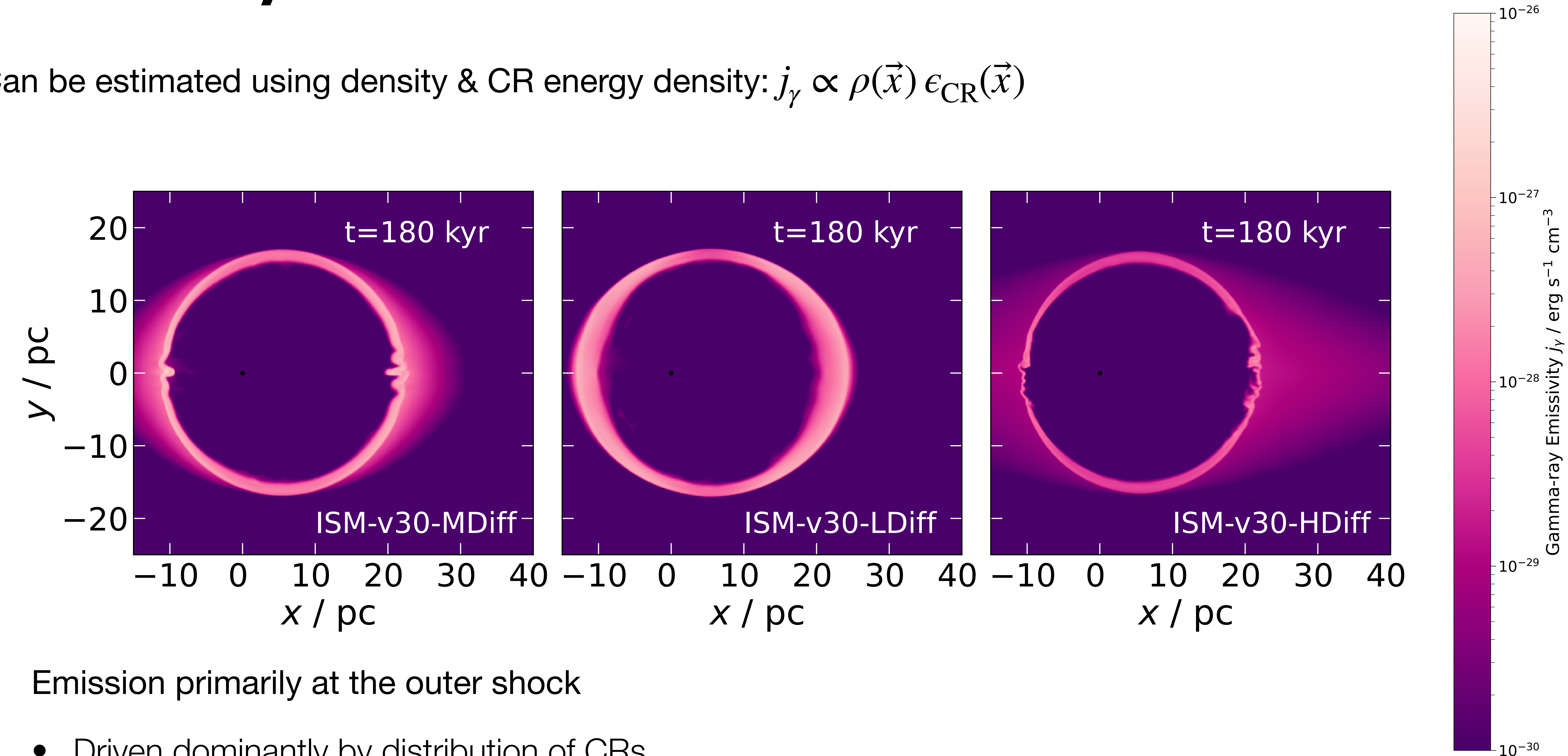
Comparison with MHD

CR Acceleration at the Shock

Synthetic Emission

Gamma-ray Emission

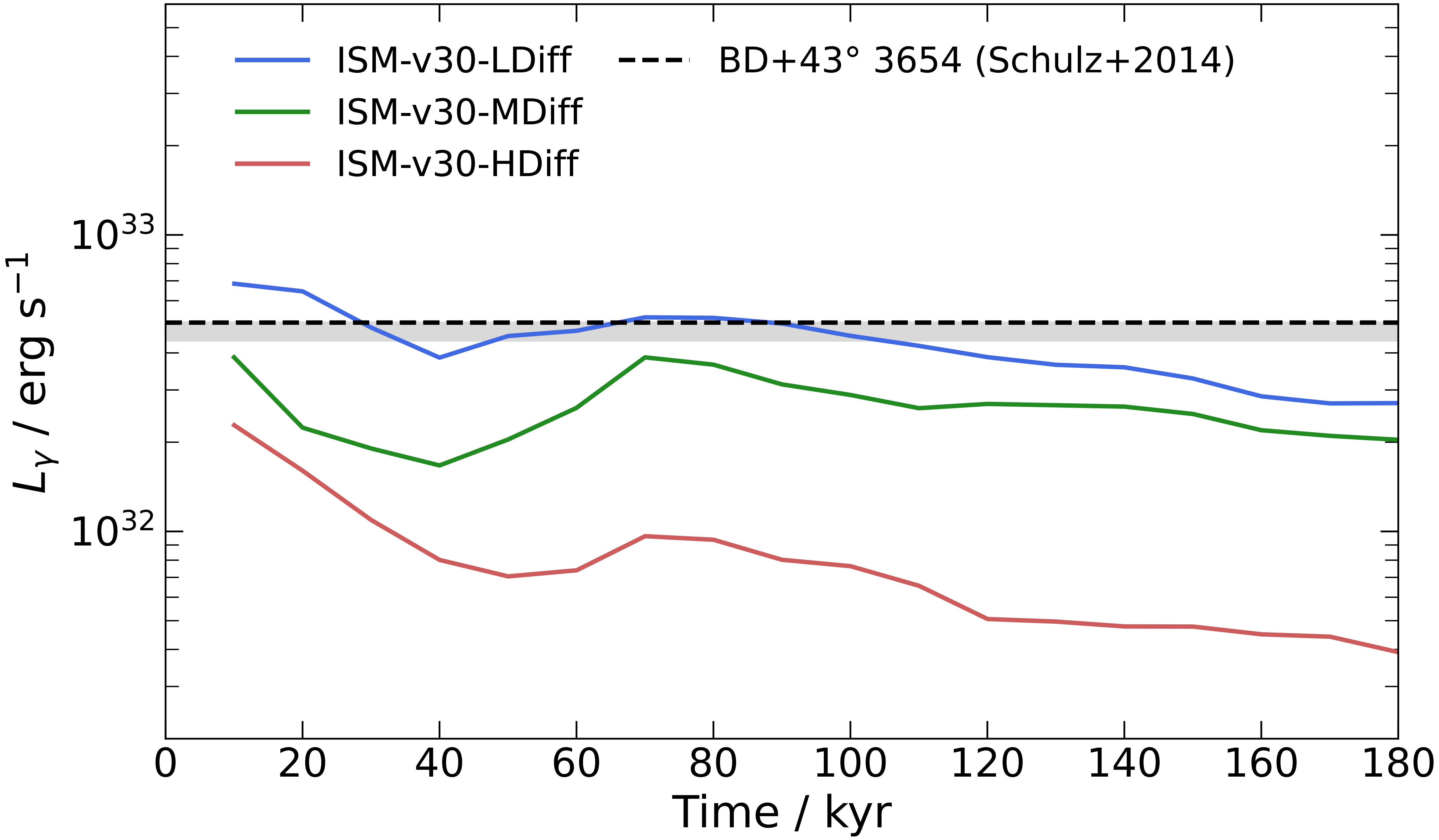
- Can be estimated using density & CR energy density: $j_\gamma \propto \rho(\vec{x})\, \epsilon_{\rm CR}(\vec{x})$



- Emission primarily at the outer shock
  - Driven dominantly by distribution of CRs
  - Low density regions reduce emission within bubble

Gamma-Ray Emission

- Comparison with current upper limits from BD+433654 (Schultz+2014)



- Compatible at earliest times, despite different stellar mass & velocity in simulations
- Decreases at later times due to expansion of bubbles -> less CRs for gamma production
- Diffusion-dependent : less CRs with higher diffusion coefficient

Longer Runtimes Required for further analysis!

BD+43 3654 : observed bow shock with high stellar mass (~ 70 $M_\odot$) with $v_\star$~ 80 km/s

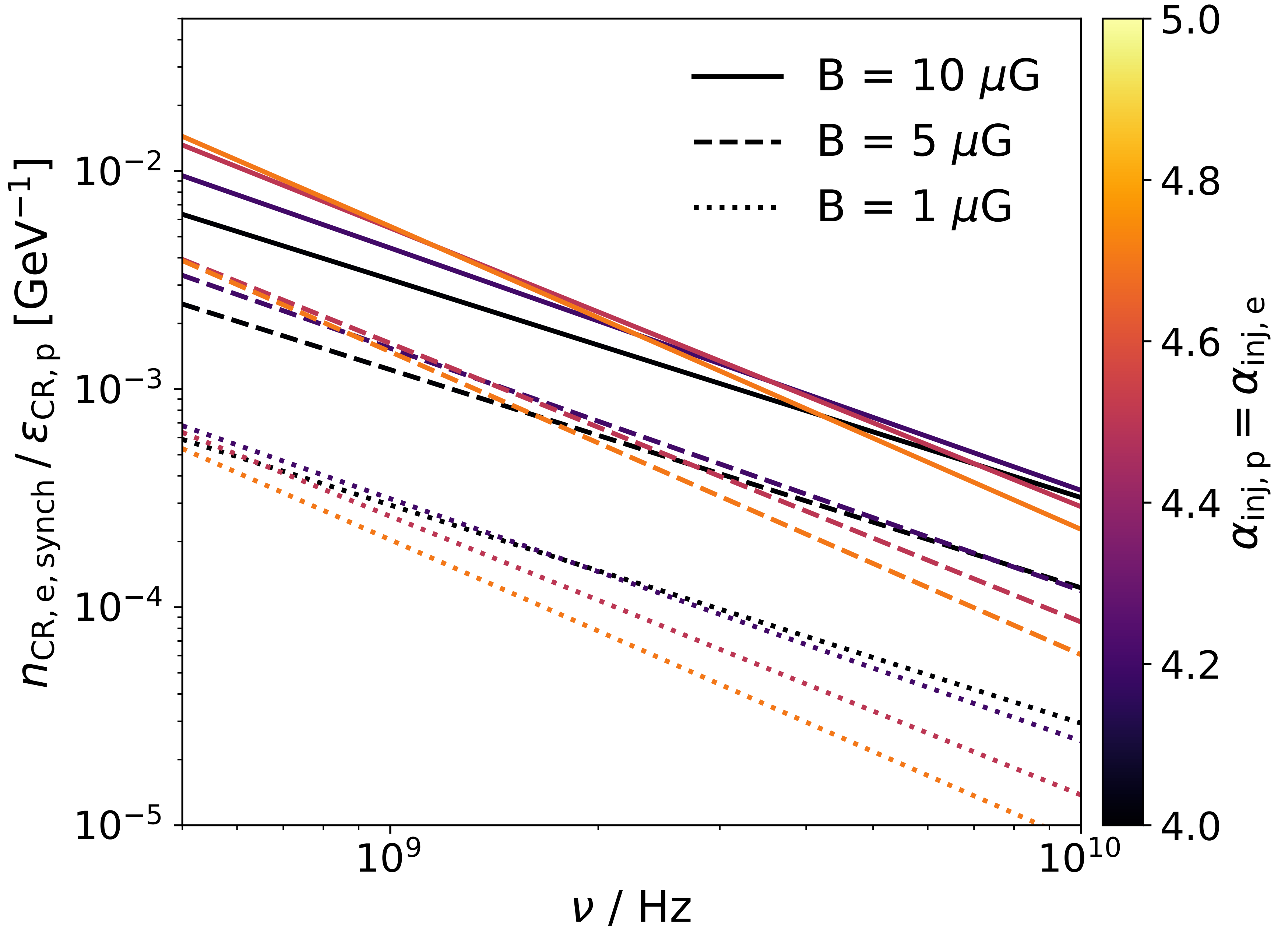
Radio Synchrotron Emission

- Synchrotron emissivity: $j_{\text{syn}}(\vec{x}, \nu) \propto \vec{B}(\vec{x})\, n_{\text{syn,ele}}(\vec{x})$
  - Depends heavily on magnetic field & CR electron density that participate in synchrotron emission

- No immediate approximation available for $n_{\text{syn,ele}}$
  - Only CR protons traced within CRMHD simulation - CR electrons dominate synchrotron emission
  - Emission is momentum-dependent - not included within CRMHD equations

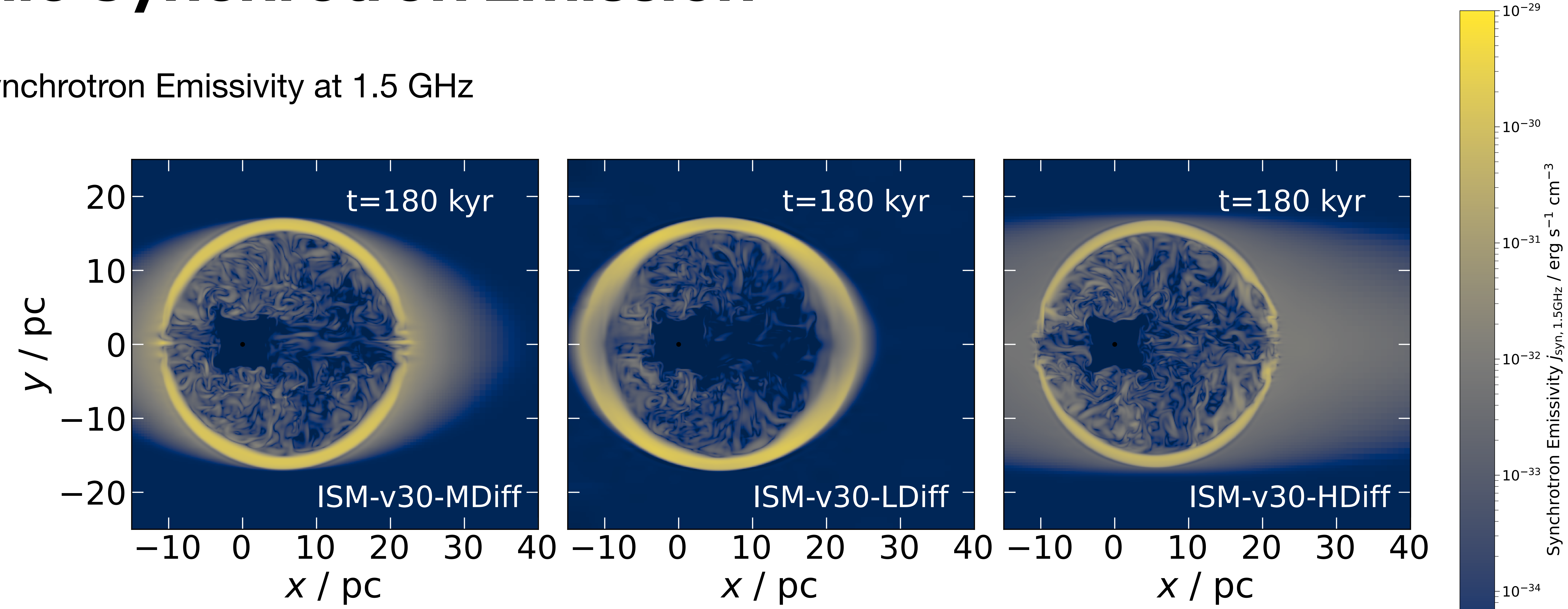
- Simplified approach: Convert $\epsilon_{\text{CR}} \to n_{\text{syn,ele}}$ through pre-calculated ratio
  - Steady-state (+ rescaling) to obtain CR proton (electron) spectrum
  - Integrate both sides over momentum to obtain desired ratio

$$\frac{n_{\text{CR,e,syn}}}{\epsilon_{\text{CR,p}}} = \frac{\int_0^\infty \mathrm{d}p_e 4\pi p_e^2\, f_e(p_e) F(\nu/\nu_c)}{\int_0^\infty \mathrm{d}p_p\, 4\pi p_p^2 T_p(p) f_p(p_p)},$$



Radio Synchrotron Emission

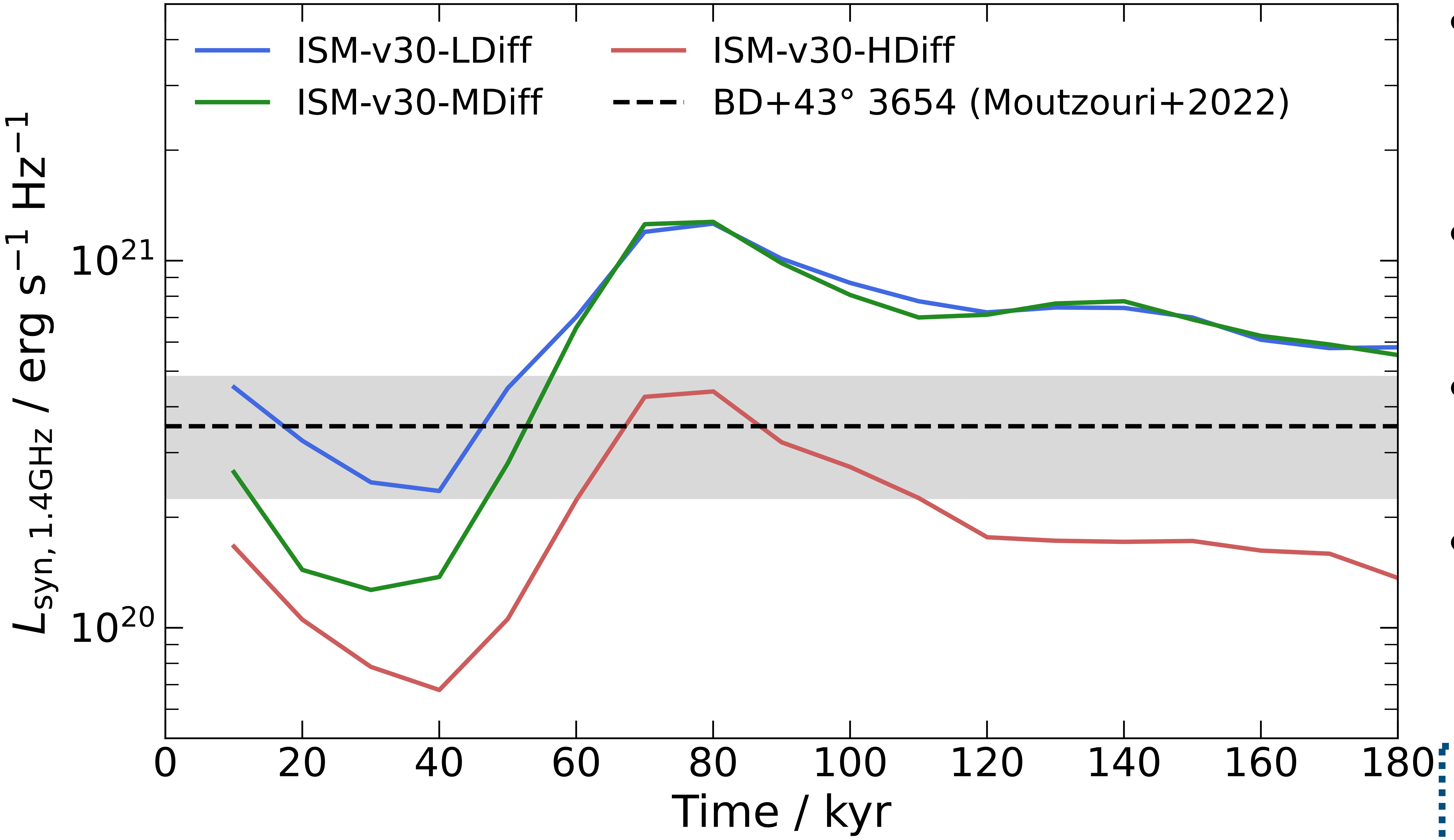
- Synchrotron Emissivity at 1.5 GHz



- As with gamma-rays, emission predominantly at outer shock!
  - Most CR population at outer shock -> drives the emission since $\propto \epsilon_{CR}$
  - Turbulent features within bubble due to lack of stellar magnetic fields

Radio Synchrotron Emission

- Comparison with current observed flux values from radio observations



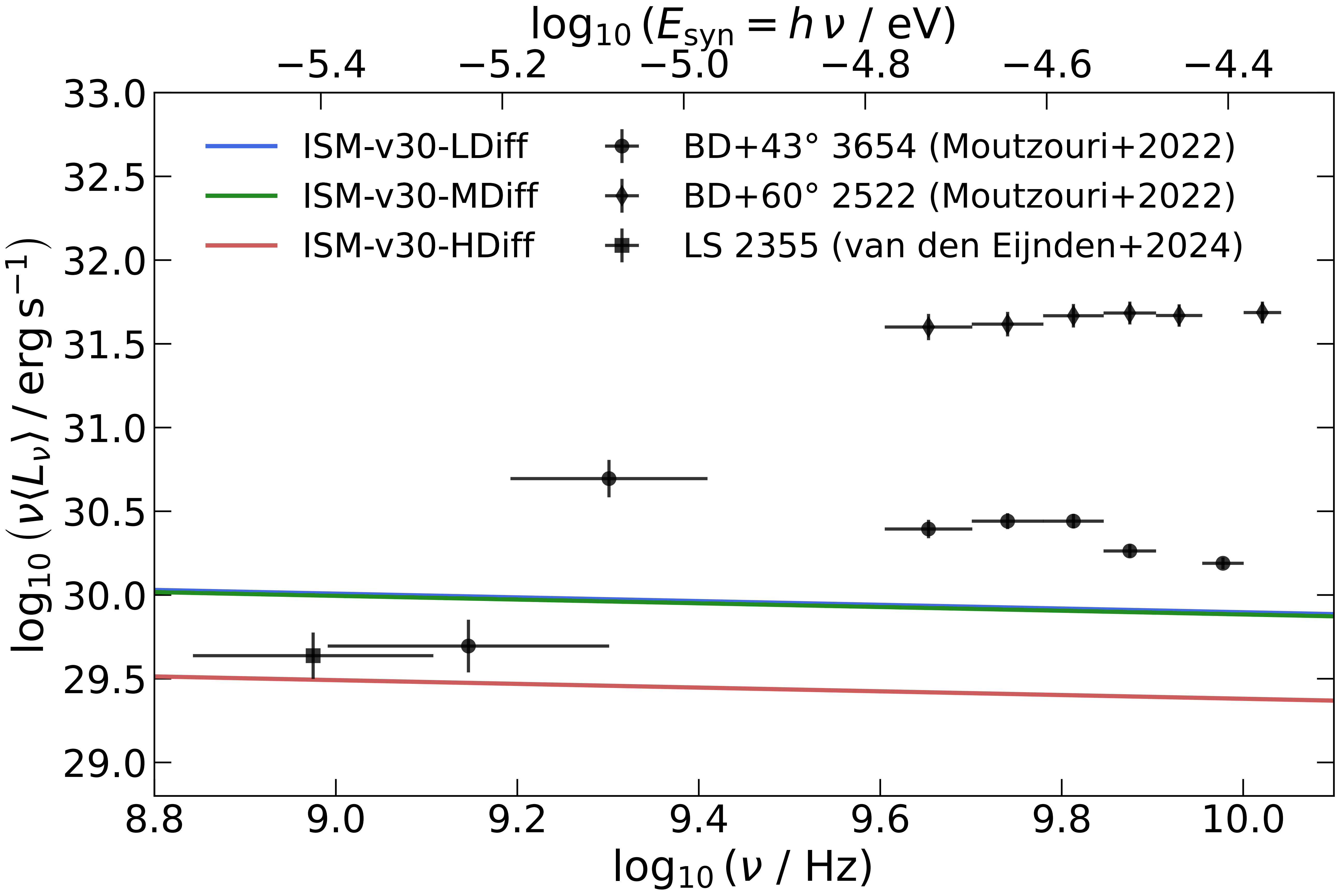
- Comparable to observed flux (order of magnitude), again despite varying initial parameters
- Increase in luminosity at t ~ 50 kyr : due to compression in magnetic fields
- Saturation for t > 140 kyr : driven by bubble expansion
- High-diffusion case varies strongly : due to lack of CR population

Longer Runtimes Required for further analysis!

BD+43 3654 : observed bow shock with high stellar mass (~ 70 $M_\odot$) with $v_\star$~ 80 km/s

Radio Synchrotron Emission

- Comparison with current observed flux values from radio observations
  - Average luminosity over different frequency bins



- Comparable with current observations, despite:
  - Less dense medium (~ 1 order less dense)
  - Lighter stellar mass (~ 3 times smaller)
  - Lower stellar velocities (~ 3 times slower)

- Primary reasoning: efficient particle acceleration at outer shock
  - All particles (even shocks with $\mathscr{M} \lesssim 3$) can accelerate
  - CR acceleration efficiency is overestimated (maximum from observation : ~ 0.2)

Caveats and how to fix them

- Analysis for early evolution only
  - Bow shock has not yet reached “equilibrium” yet - can run for longer

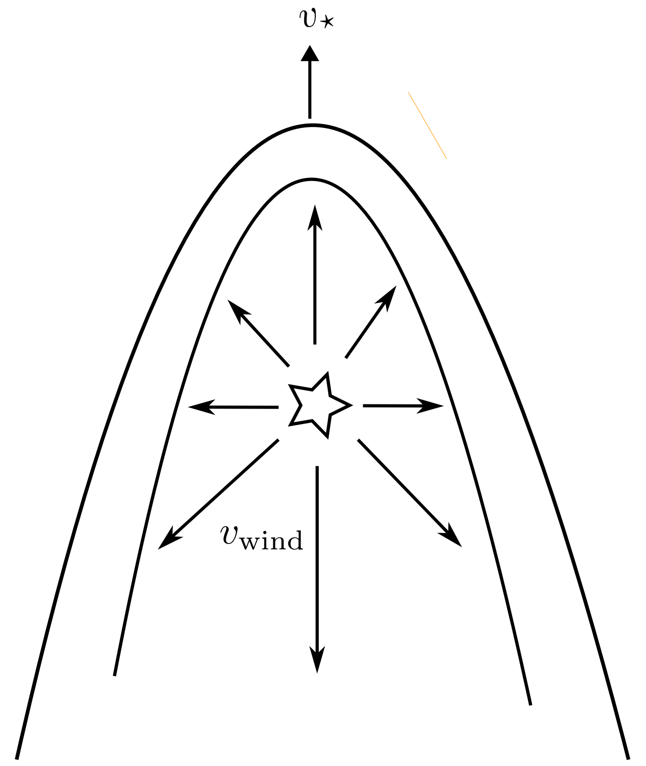
Run simulations for longer

- Over-efficient particle acceleration at outer shock
  - Outer shock is radiative - adiabatic only for hyper-velocity stars (> 500 km/s)
  - Mach numbers at outer shock are low => should not be this efficient for particle acceleration
  - Drives resulting gamma-ray / synchrotron emission
  - Maximal energy of CRs unknown -> even low-velocity shocks can contribute to shock
  - Old parameteric function used for CR acceleration efficiency - recent results show $\eta_{\text{max}} \sim 0.2$

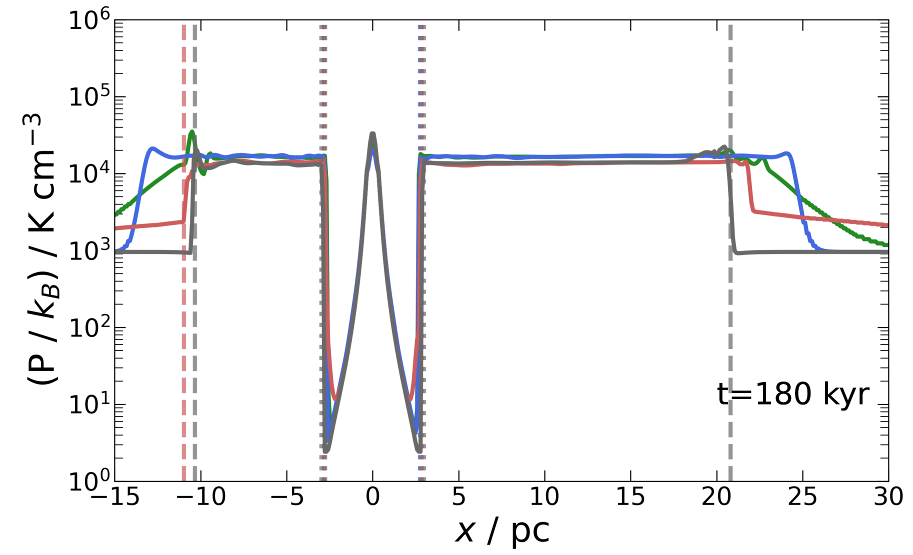
Focus on termination shock : an efficient particle acceleration region

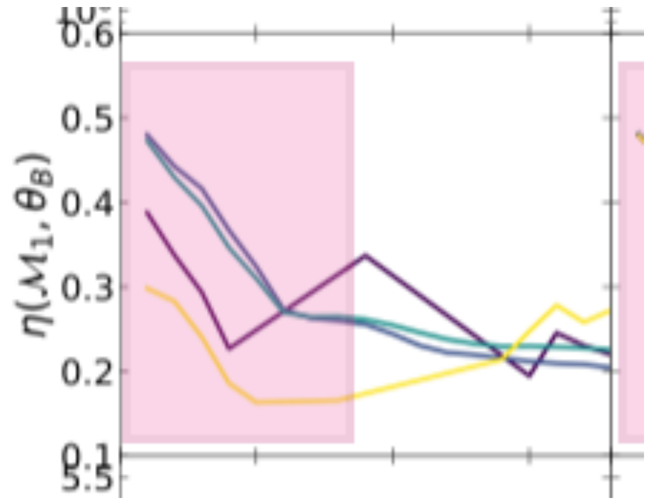
Renormalise current function to correct maximum

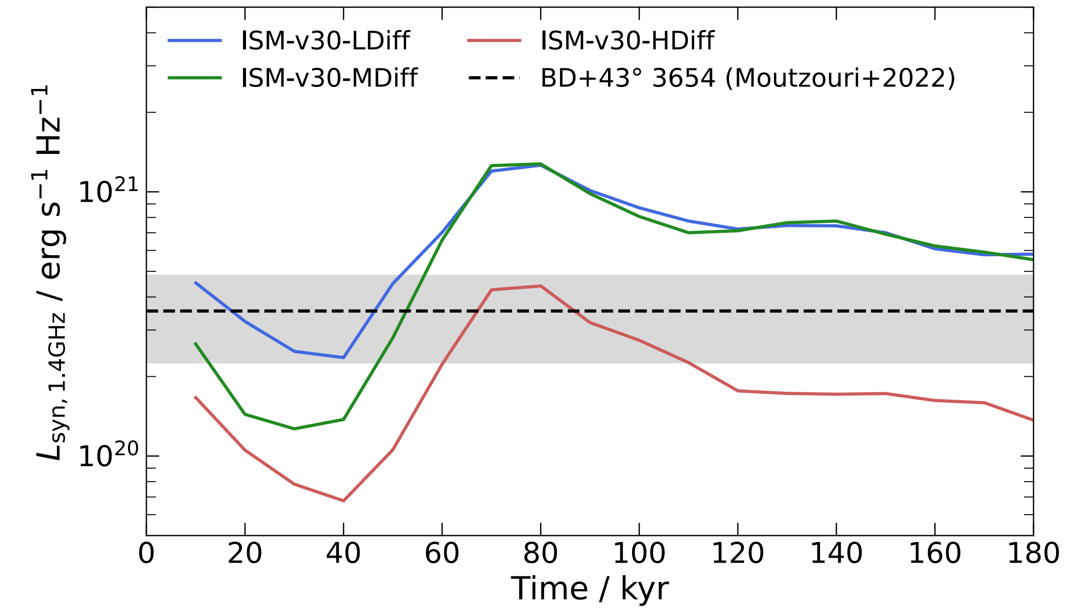
Conclusion



- Investigate impact of **cosmic ray acceleration** on **bow shocks** generated from massive stars
    - Bow shocks are great laboratories for CR acceleration studies - short lifetime & non-uniform morphology
    - Conduct via CRMHD simulations with dynamical injection of CRs through DSA
- Comparison with MHD shows strong impact on morphology through CR diffusion
    - CR diffusion controls pressure within bubble -> impacts overall morphology
- Efficient particle acceleration happens in outer shock
    - Highly efficient acceleration at earlier times, termination shock dominates at later times
    - CR population driven by magnetic field orientation (injection) + diffusion
- Simplified emission model shows comparable results to current observations
    - …but primarily due to highly efficient acceleration in outer shock
    - Emission driven by CR population & diffusion







Paper currently in review process : fixes on the way for corrections!

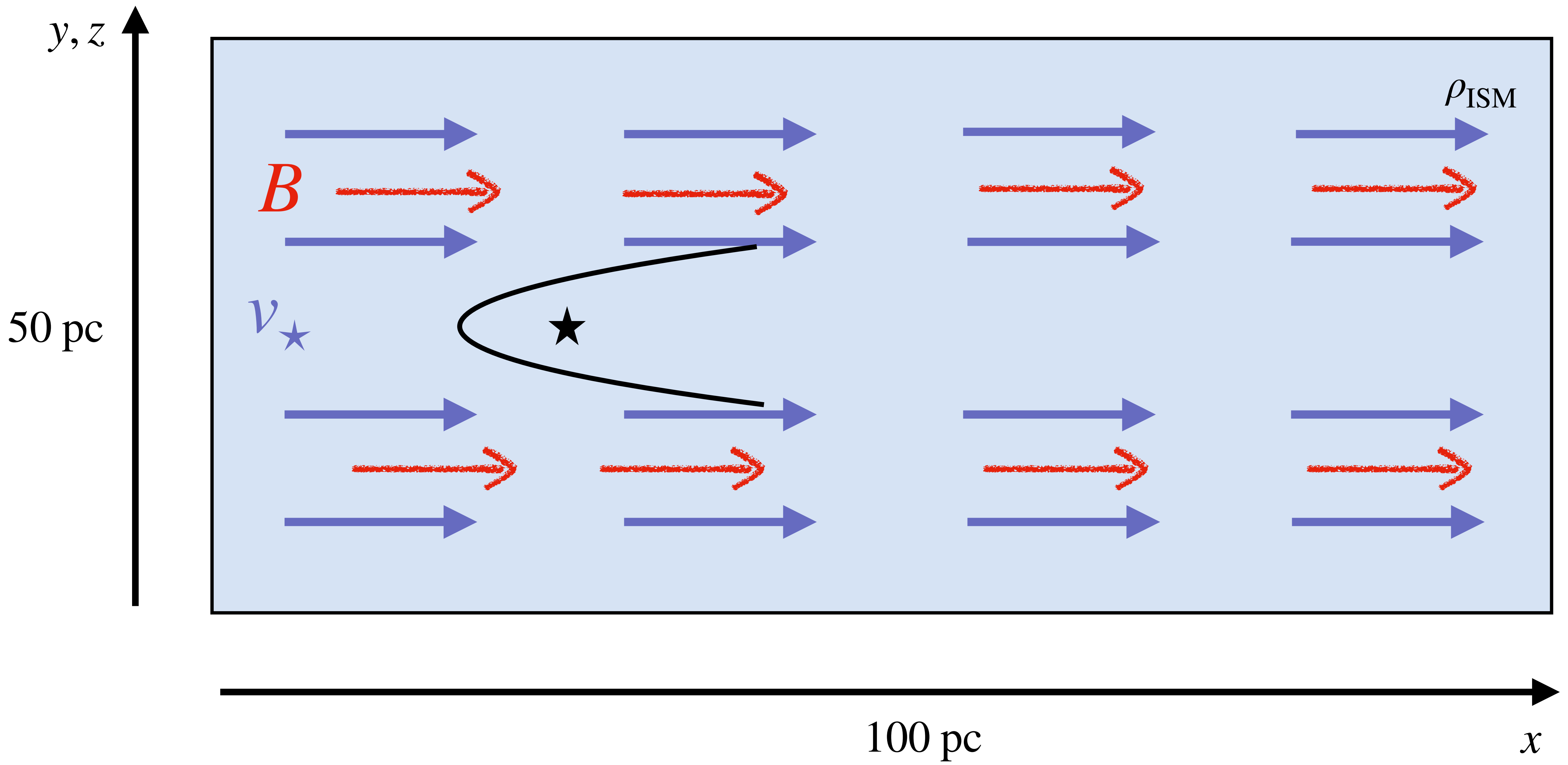
Thank you!

Backup Slides

Simulation Setup

- Single, massive star ($M = 20 M_\odot$) in uniform medium with uni-directional ambient velocity $-v_\star$
  - Maximum resolution of **0.048 pc**
  - Simulation time until **180 kyr**
  - **Weak, ionized ISM**-like ambient environment:

Density	$2 \times 10^{-25}\,\mathrm{g\,cm^{-3}}$
Temperature	$10^4\,\mathrm{K}$
Magnetic Field	$10^{-6}\,\mathrm{G}$



- **Vary** CR diffusion coefficient & analyse behaviour for stronger / weaker diffusion:

$$\kappa_\| = 3 \times 10^{24}\,\mathrm{cm\,s^{-2}},\ 3 \times 10^{25}\,\mathrm{cm\,s^{-2}},\ 3 \times 10^{26}\,\mathrm{cm\,s^{-2}}$$

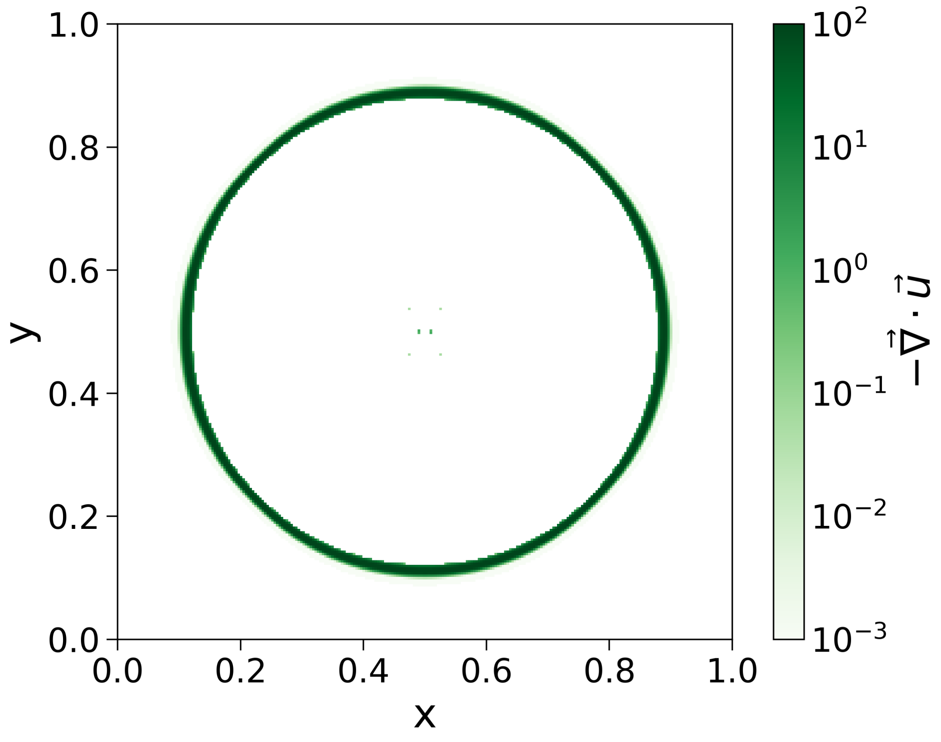
- Also simulate: one case **without CRs** for comparison (MHD only)

Shock Finding - Algorithm

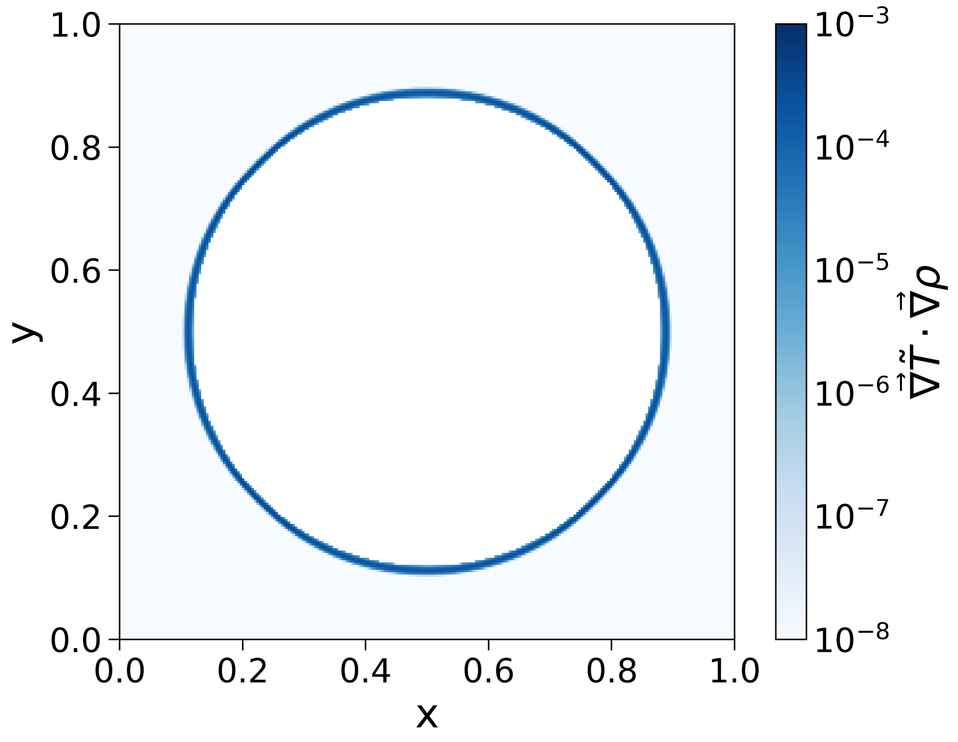
- Following Pfrommer+2017

1. Get "shock zone"

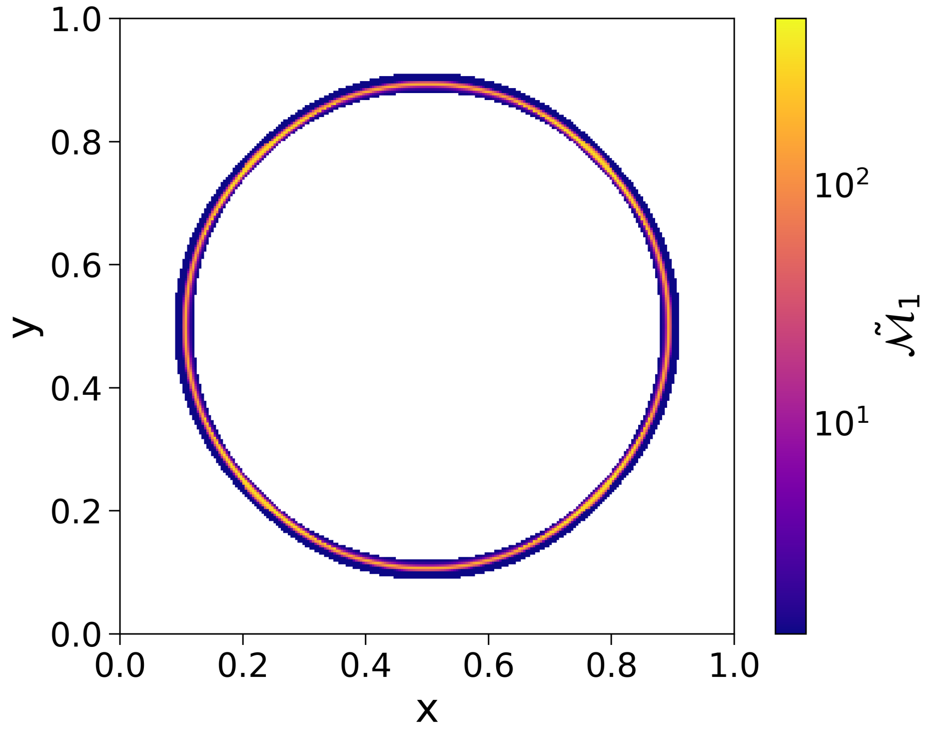
$-\vec{\nabla} \cdot \vec{u} > 0$

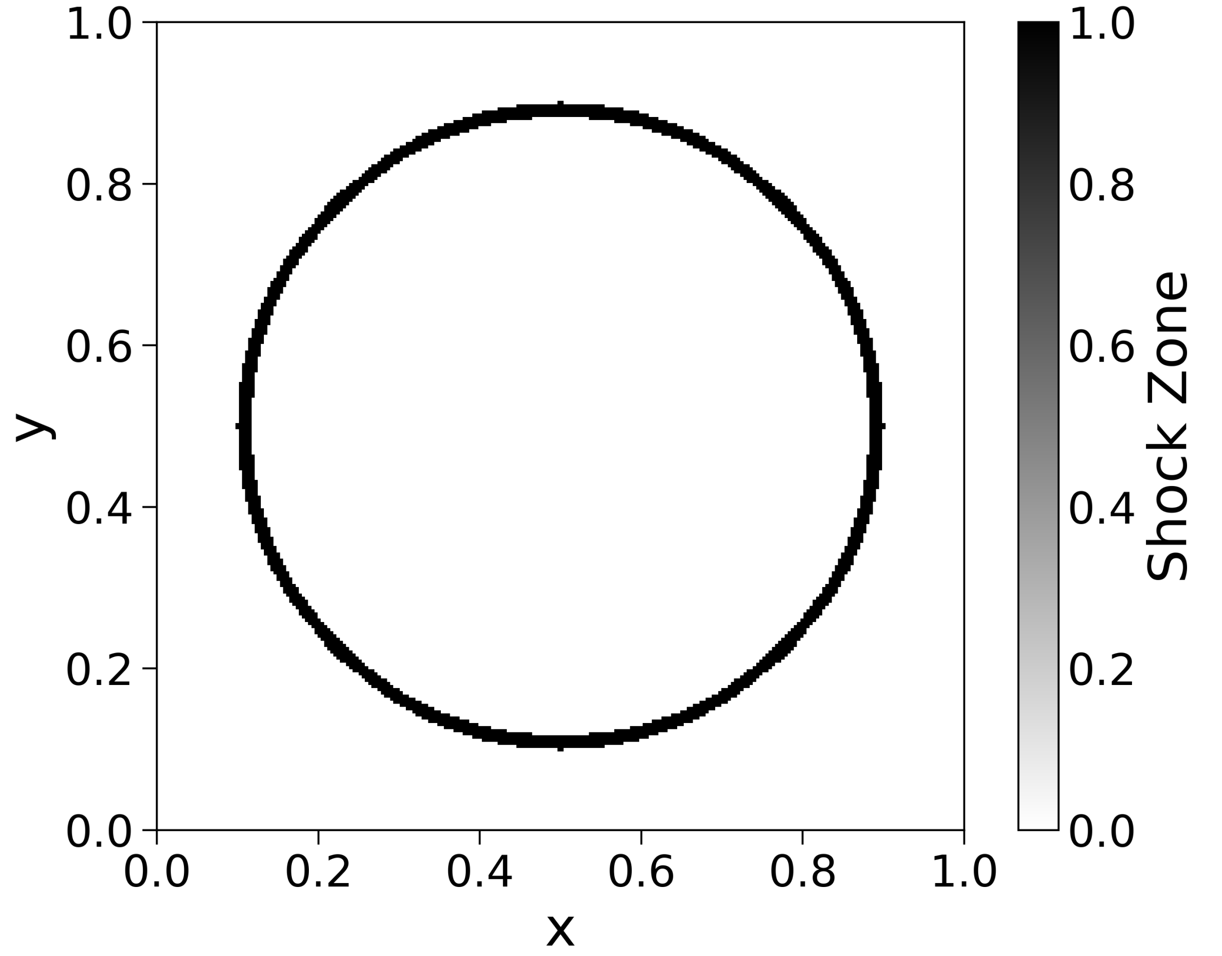


$\vec{\nabla}\tilde{T} \cdot \vec{\nabla}\rho > 0$



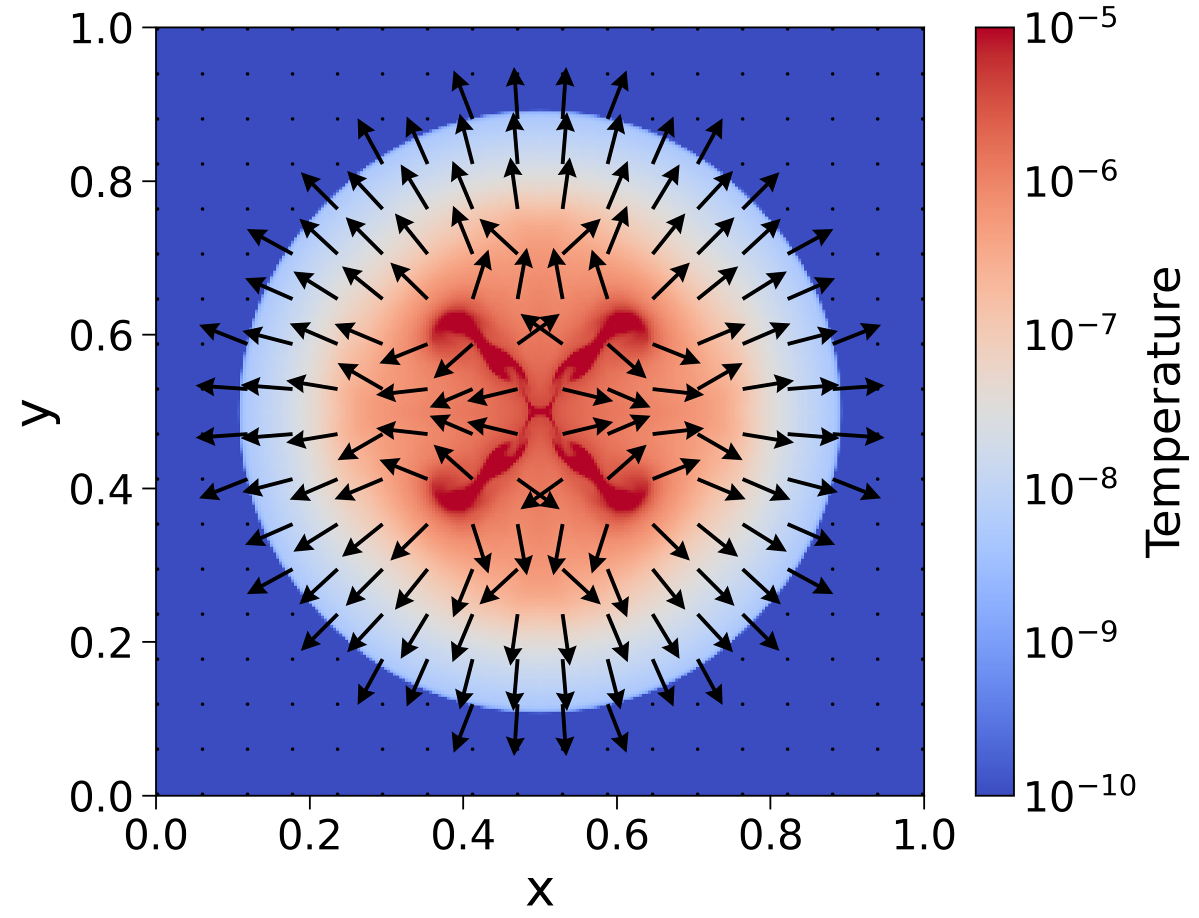
$\tilde{\mathscr{M}}_1 > \tilde{\mathscr{M}}_{1,\mathrm{min}}$



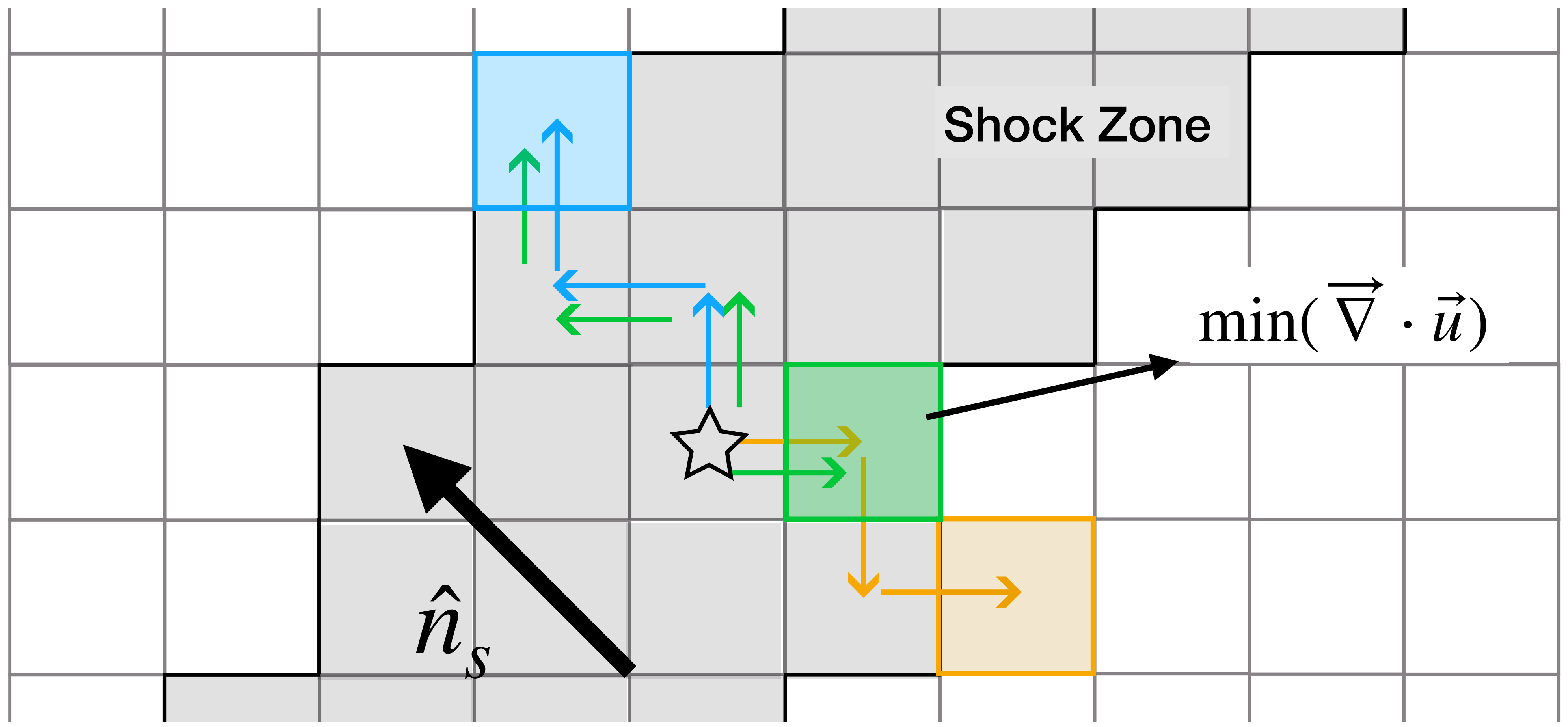


2. Get Shock Direction

$$\hat{n}_s = -\frac{\vec{\nabla}\tilde{T}}{|\vec{\nabla}\tilde{T}|}$$



3. Determine Pre- , Post-Shock, and Shock Surface Cells



CR Injection - Algorithm

ϵ: energy density γ: adiabatic index

ρ: density u : gas velocity

Adapted from implementation from Pfrommer et al. 2017

1. Obtain dissipated flux f_{diss} from pre- and post-shock cells ($x_s = \rho_2/\rho_1$):

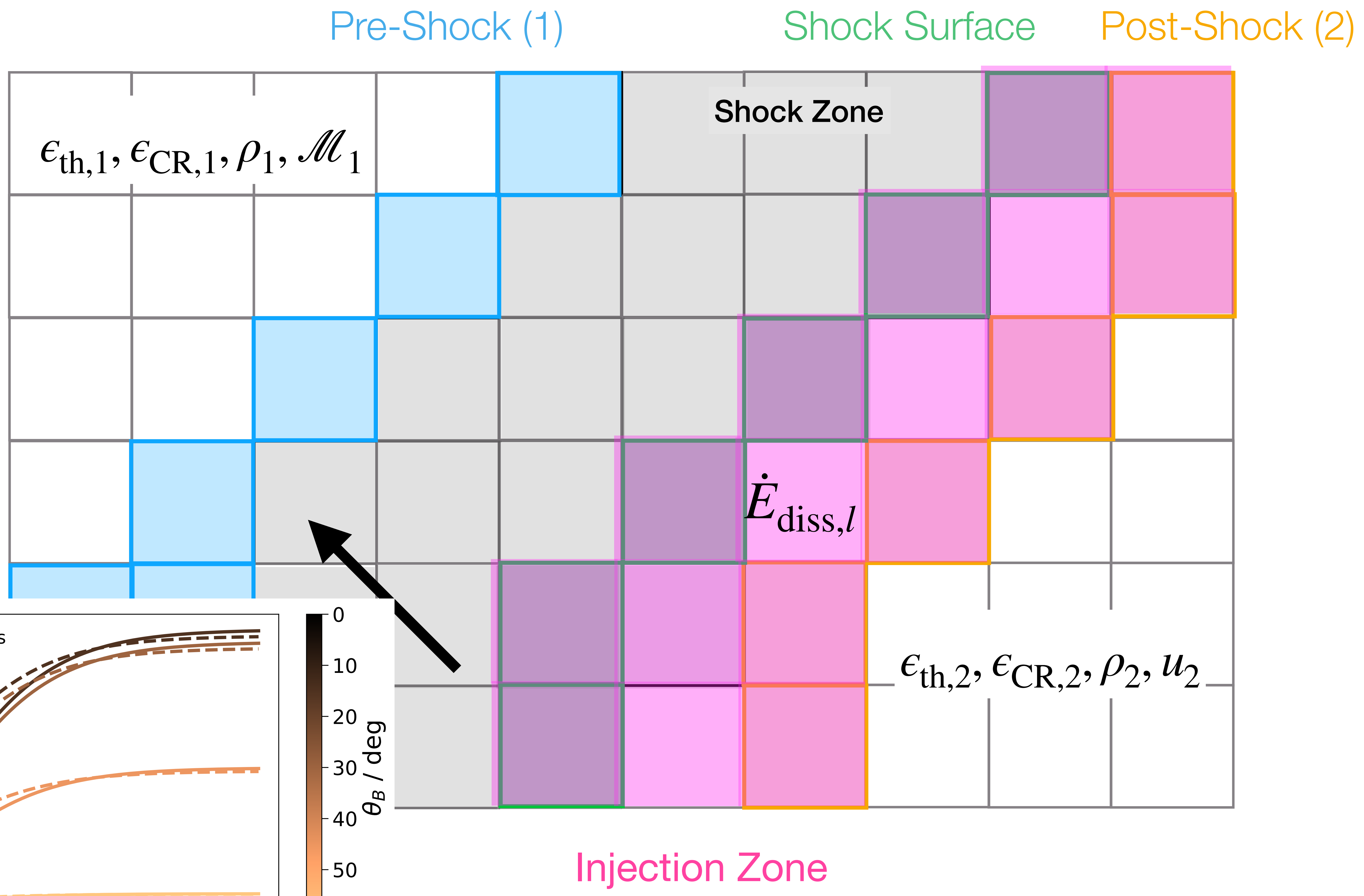
$$f_{\mathrm{diss}} = \left[\left(\epsilon_{\mathrm{th},2} - \epsilon_{\mathrm{th},1} x_s^{\gamma_{\mathrm{th}}} \right) + \left(\epsilon_{\mathrm{CR},2} - \epsilon_{\mathrm{CR},1} x_s^{\gamma_{\mathrm{CR}}} \right) \right] u_2$$

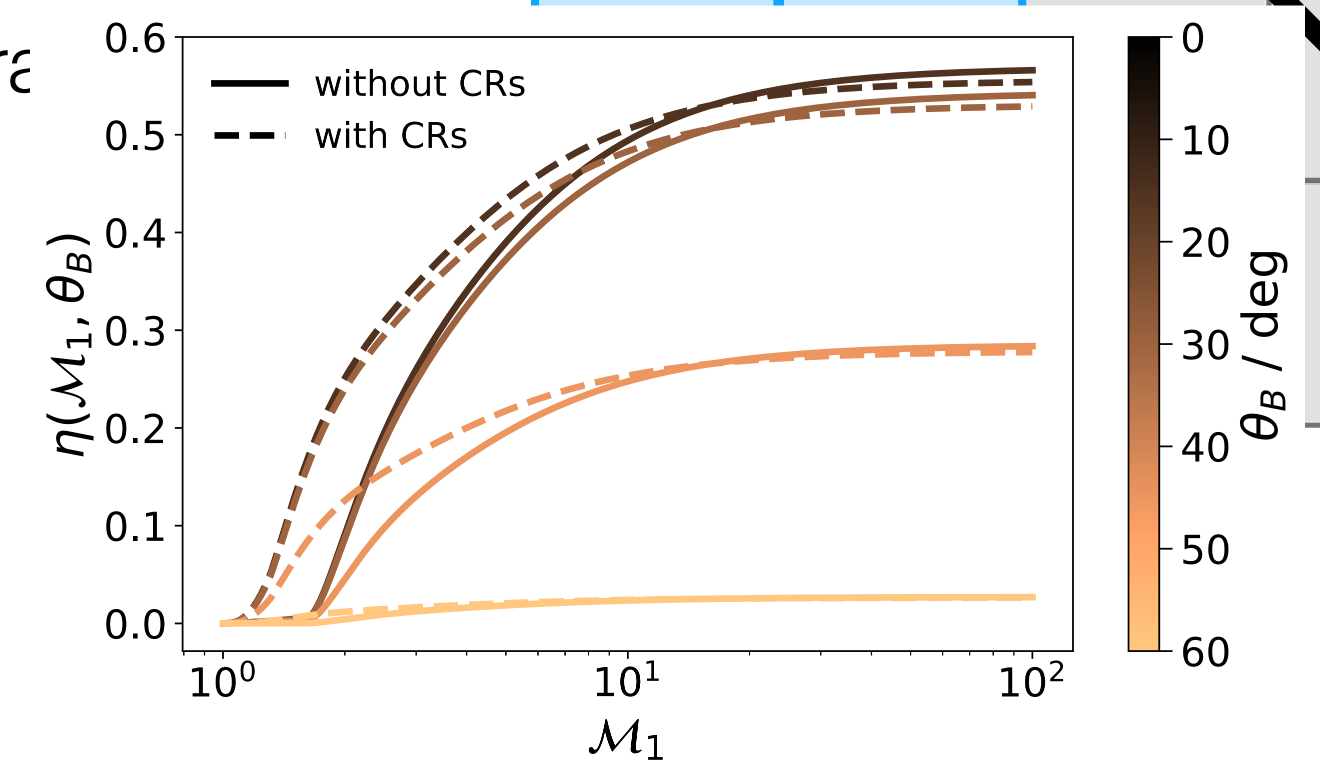
2. Calculate dissipated energy rate $\dot{E}_{\mathrm{diss},l}$ for each cell l in injection zone ($\vec{S}_l$: surface area of each cell):

$$\dot{E}_{\mathrm{diss}} \propto f_{\mathrm{diss}} \, \vec{S}_l \cdot \hat{n}_s$$

3. Calculate CR injection energy using CR accelera efficiency η:

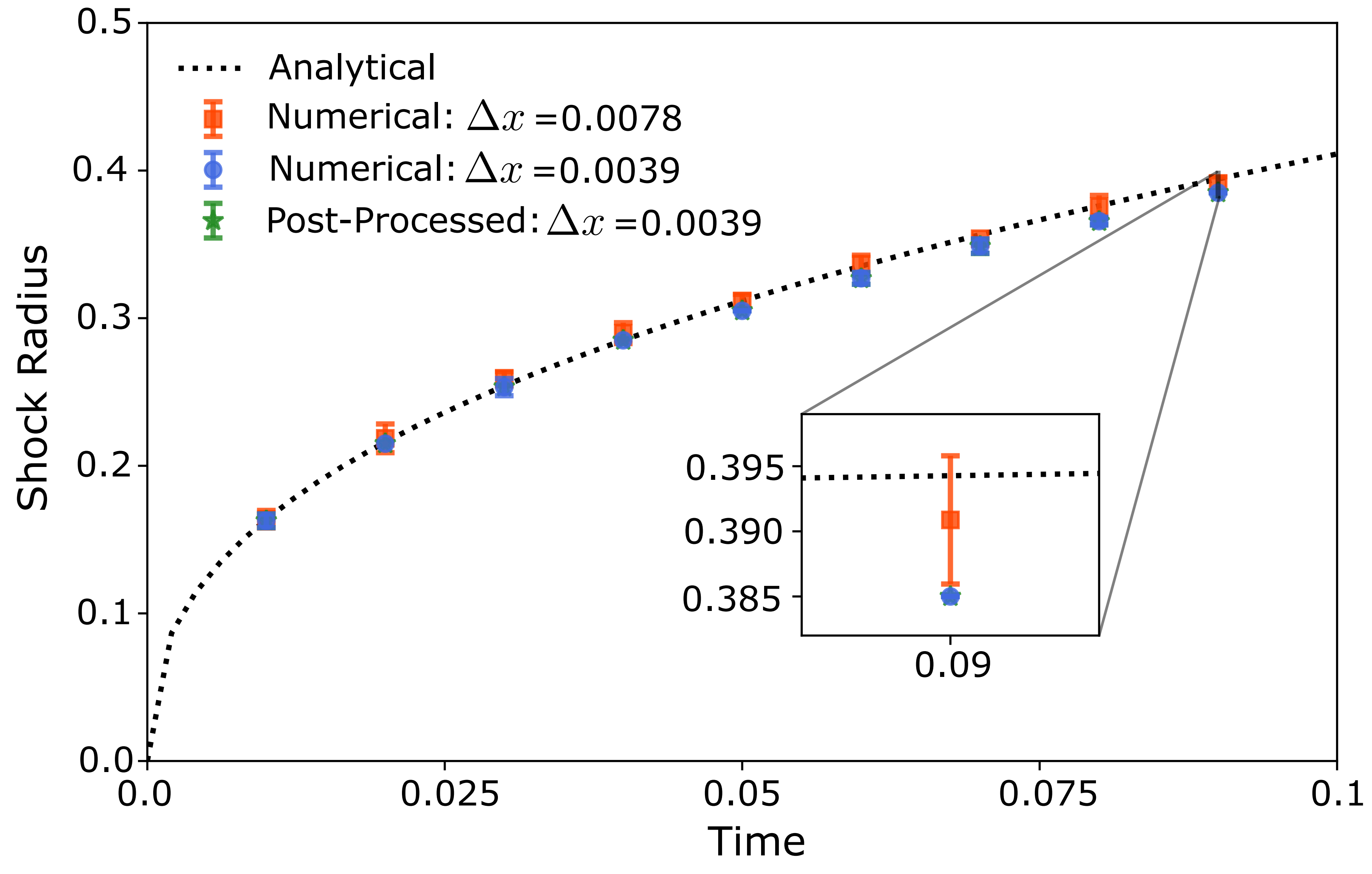
$$E_{\mathrm{inj},l} = \eta(\mathscr{M}_1, \theta_B) \dot{E}_{\mathrm{diss},l} \Delta t$$



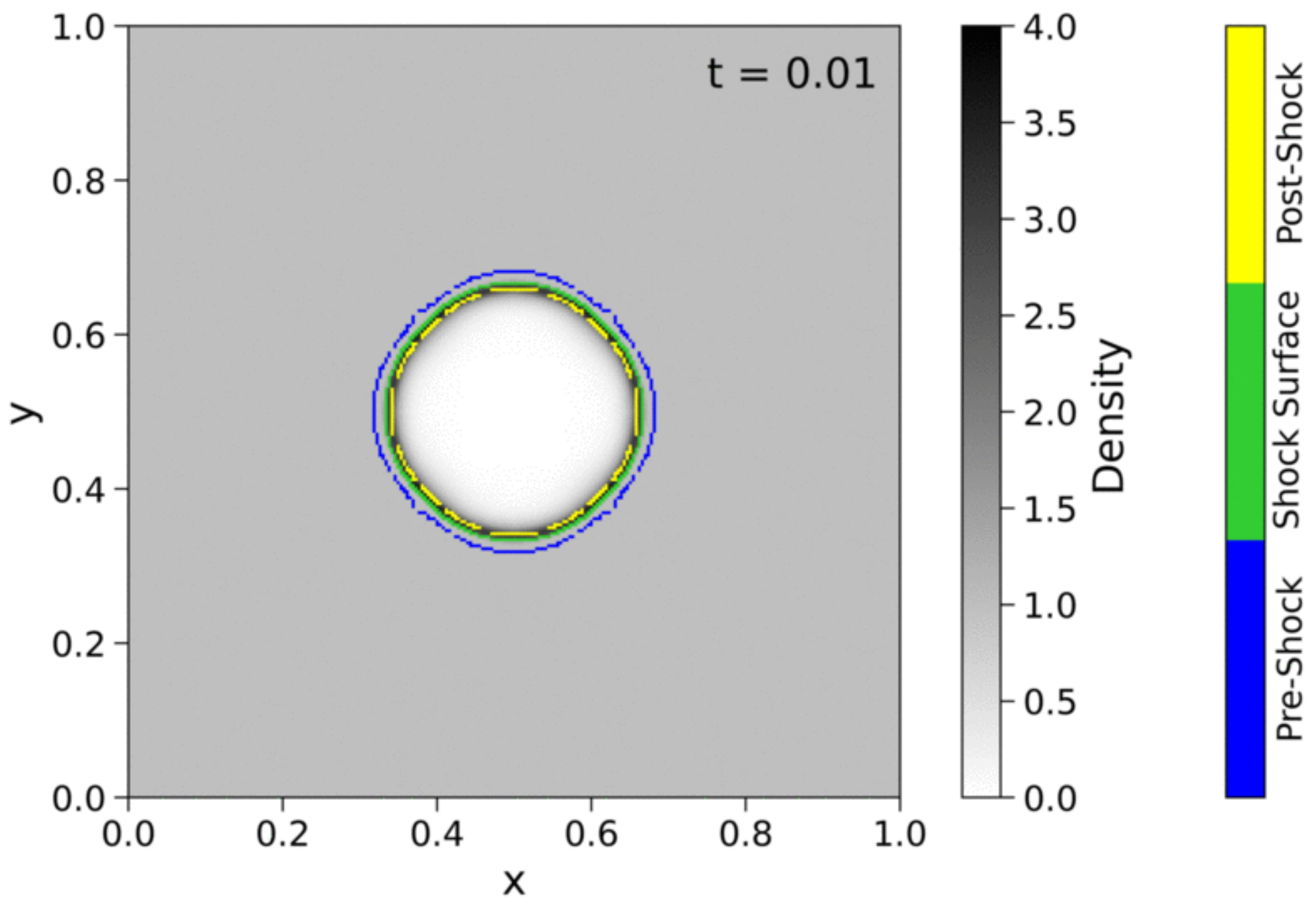


Validation - Sedov Test

- Standard test for hydrodynamic simulations to benchmark performance of solver
  - Spherical explosion with injected energy initially near center
  - Assess quality of solver to capture shocks in realistic scenarios



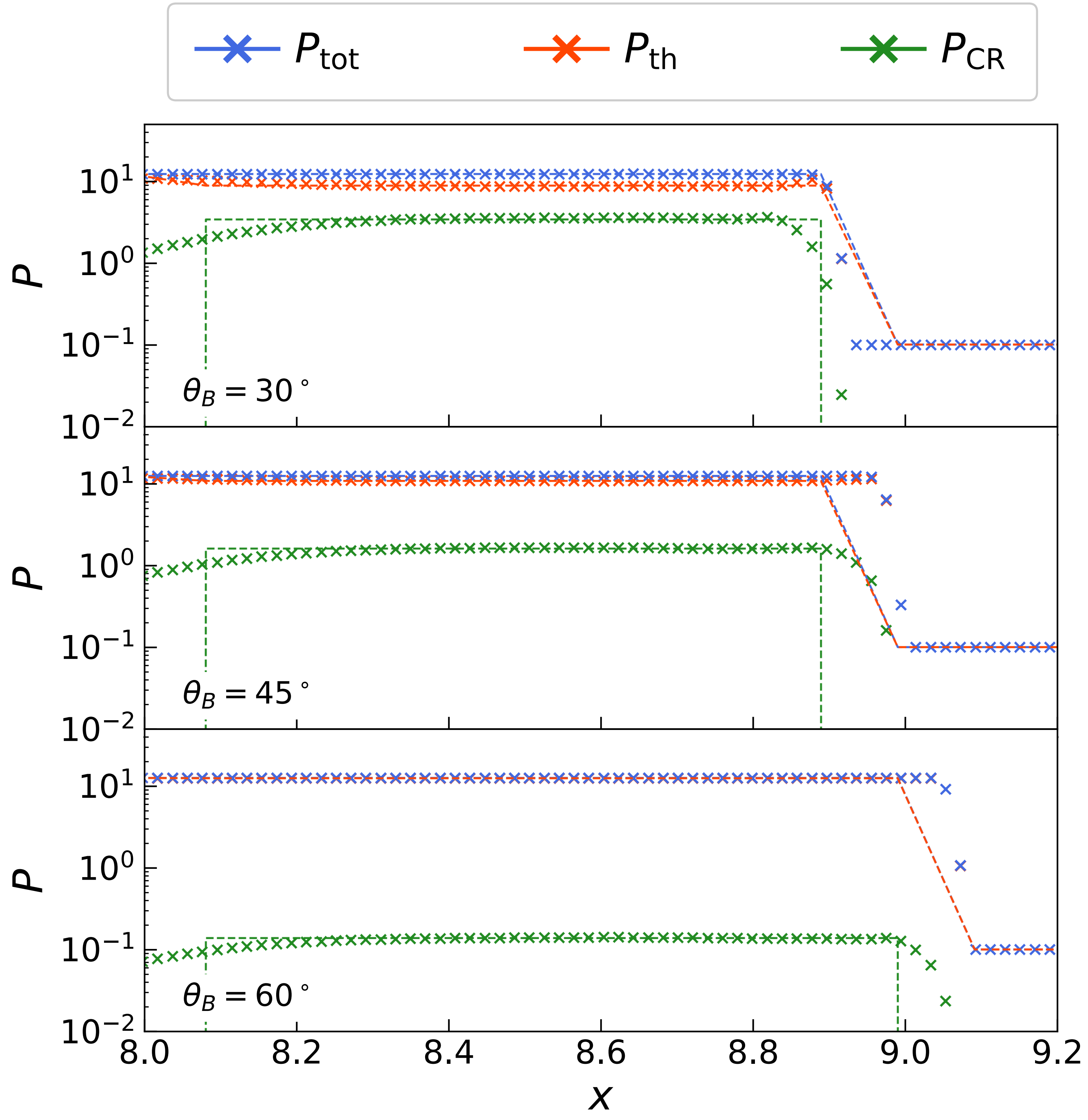
Time evolution of shock radius



Density & Shock detection regions, $\Delta x = 0.0039$

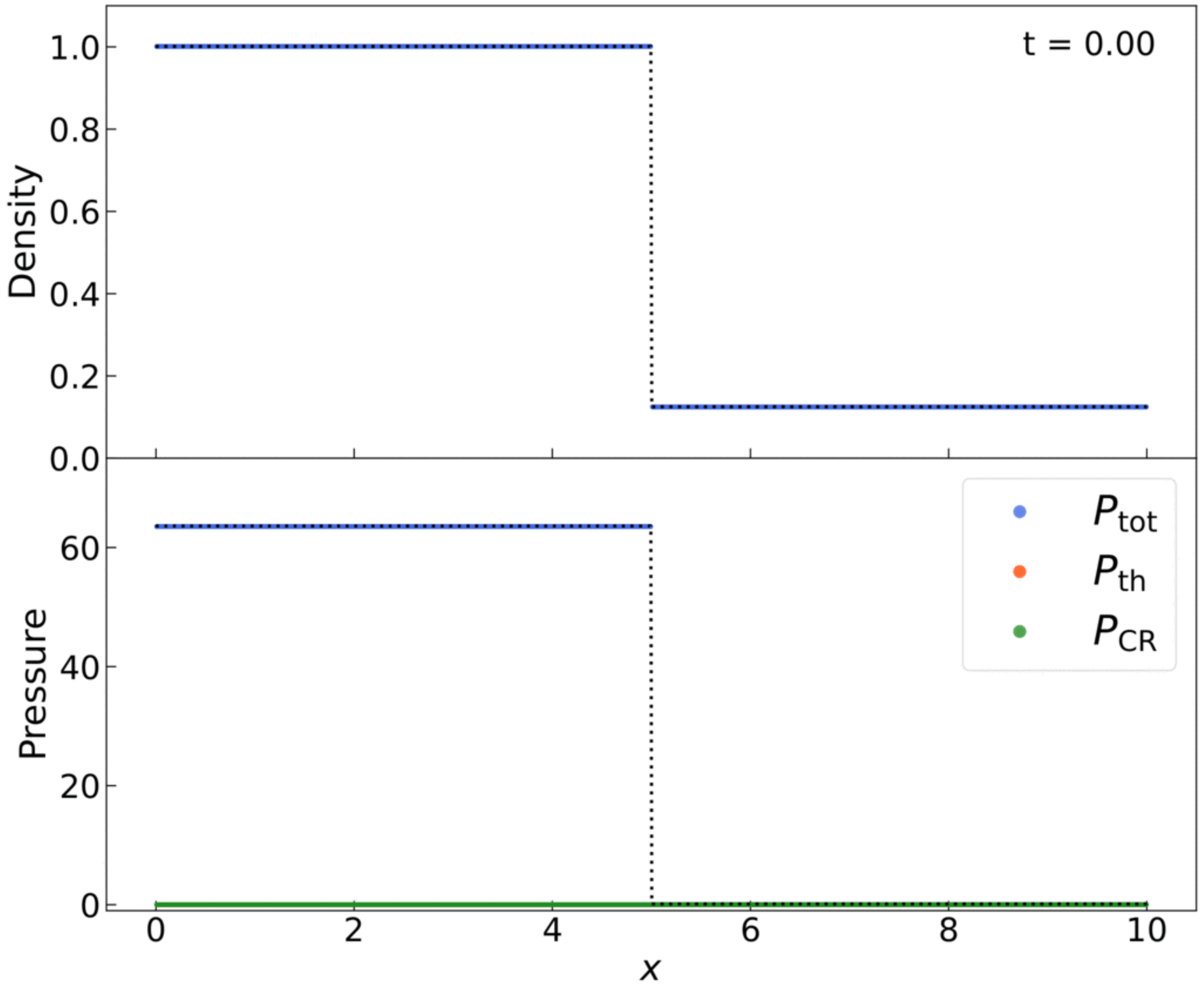
Validation - Sod Shock Tube Test

- Standard test for hydrodynamic simulations to benchmark performance of solver
  - Varying density & pressure at each side initially -> let shock evolve
  - Here with added (constant) contribution of CRs at each step
  - Analytical solution known - can directly compare



Pressure distribution for varying magnetic obliquity

Dashed : Analytical Solution



Density & Pressure distribution with CR injection, $\eta = 0.5$

CRMHD Equations

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = \dot{\rho}_{\rm wind}$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \vec{\nabla} \cdot \left(\rho \vec{u} \vec{u}^T - \frac{\vec{B}\,\vec{B}^T}{4\pi} \right) + \vec{\nabla} P_{\rm tot} = \dot{\vec{q}}_{\rm wind}$$

$$\frac{\partial \epsilon}{\partial t} + \vec{\nabla} \cdot \left[(\epsilon + P_{\rm tot}) \vec{u} - \frac{\vec{B}(\vec{B} \cdot \vec{u})}{4\pi} \right] = \Lambda_{\rm cool} + \vec{\nabla} \cdot \left[\mathsf{K} \vec{\nabla} \epsilon_{\rm CR} \right] + \Lambda_{\rm hadr} + Q_{\rm CR}$$

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times (\vec{u} \times \vec{B}) = 0$$

$$\frac{\partial \epsilon_{\rm CR}}{\partial t} = \vec{\nabla} \cdot (\mathsf{K} \vec{\nabla} \epsilon_{\rm CR}) - \vec{\nabla} \cdot (\vec{u}\, \epsilon_{\rm CR}) - P_{\rm CR} (\vec{\nabla} \cdot \vec{u}) + \Lambda_{\rm hadr} + Q_{\rm CR}$$

$$P_{\rm th} = (\gamma_{\rm th} - 1)\epsilon_{\rm th}, \quad P_{\rm CR} = (\gamma_{\rm CR} - 1)\epsilon_{\rm CR}$$

- $\dot{\vec{q}}_{\rm wind}$, $\dot{\rho}_{\rm wind}$: Momentum / Mass injection through stellar feedback (*Gatto+ 2017*)
- $\Lambda_{\rm cool}$: Radiative cooling at solar metallicity (*Koyama & Inutsuka 2002, Plewa 1995*)
- Contributions from $\epsilon_{\rm CR}, P_{\rm CR}$ included in $\epsilon, P_{\rm tot}$

- **Anisotropic diffusion** and **advection** of CRs
- Adiabatic EoS with CR index $\gamma_{\rm CR}$
- $\Lambda_{\rm hadr}$: Hadronic losses from proton-proton collisions
- $Q_{\rm CR}$: CR injection at astrophysical shocks

Not self-consistently included!

CR Transport Equation - the 'grey' approach

- Simplified CR transport equation based on **integrated CR energy density:**

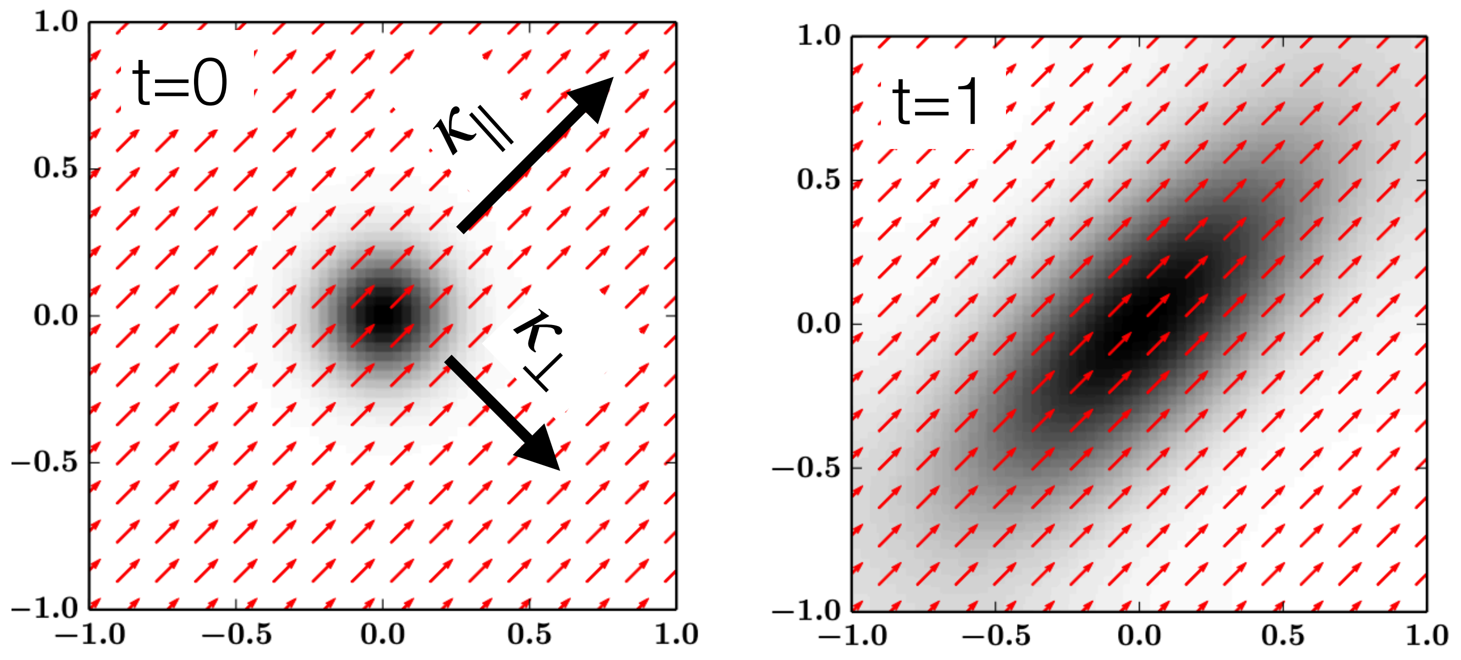
$$\frac{\partial \epsilon_{CR}}{\partial t} = \vec{\nabla} \cdot (\mathrm{K}\, \vec{\nabla}\, \epsilon_{CR}) - \vec{\nabla} \cdot (\vec{u}\, \epsilon_{CR}) - P_{CR}\, (\vec{\nabla} \cdot \vec{u}) + \Lambda_{hadr} + Q_{CR}$$

Spatial diffusion Advection Losses Sources

- Treated as a mono-energetic fluid
- Integrated over all energies : i.e. energy-independent
- Defined with adiabatic equation of state: $P_{CR} = (\gamma_{CR} - 1)\epsilon_{CR}, \gamma_{CR} \sim 4/3$

- Energy-independent anisotropic diffusion depending on magnetic field direction b_i:

$$\mathrm{K} := \kappa_{ij} = \kappa_{\perp}\delta_{ij} + (\kappa_{||} - \kappa_{\perp})b_i b_j$$

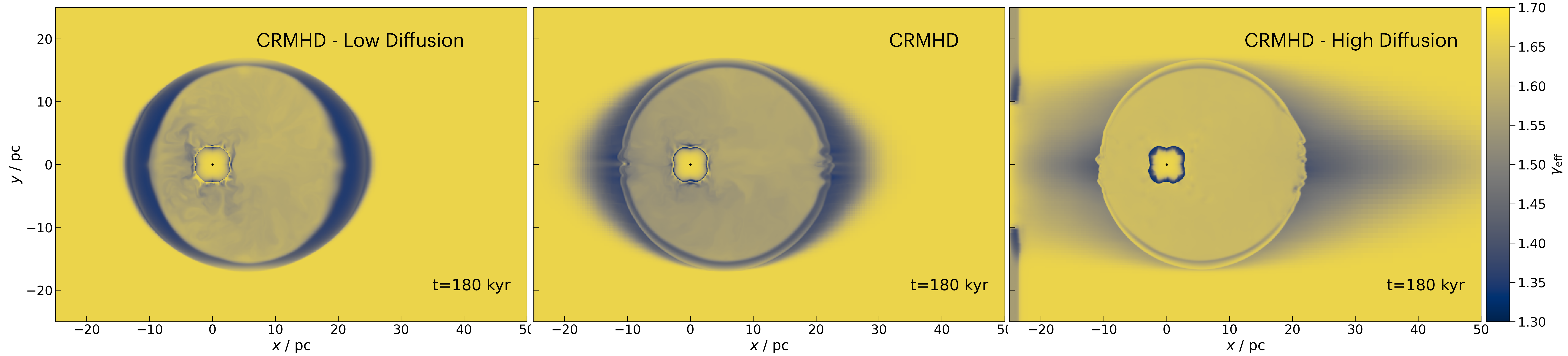


Example of anisotropic diffusion

- Losses Λ_{CR} : only energy-independent losses -> hadronic losses from proton-proton collisions

Effective adiabatic index

- $\gamma_{\rm eff} = (\gamma_{\rm th} P_{\rm th} + \gamma_{\rm CR} P_{\rm CR}) / P_{\rm tot}$: describes how “mixed” the fluids are



- Low diffusion case : pile-up of CRs on the outer shock
- Nominal case : equilibrium between CR pressure & thermal pressure?
- High diffusion case : no CRs in the bubble as they all escape

Fluid Treatment of CRs

- Galactic CRs can be treated as a fluid since $r_g \sim 10^{-4}\mathrm{pc} \ll \sim \mathcal{O}(\mathrm{pc})$

Depends on **mean free path of CR**

- Smaller than system: fluid approach
- Larger than system: particle approach
- Can be checked using gyroradius of CRs:

$$r_g = \frac{p_\perp}{|q|B}$$

For **Galactic CRs**, $p_\perp c \sim 10^{12}\ \mathrm{eV}$, $B_{\mathrm{ISM}} \sim 10^{-5}\ \mathrm{G}$

$\Longrightarrow r_g \sim 10^{-4}\ \mathrm{pc}$

Since system considered are on order pc scales, $r_g \ll r_{\mathrm{sys}}$

$\Longrightarrow$ Fluid approach is valid

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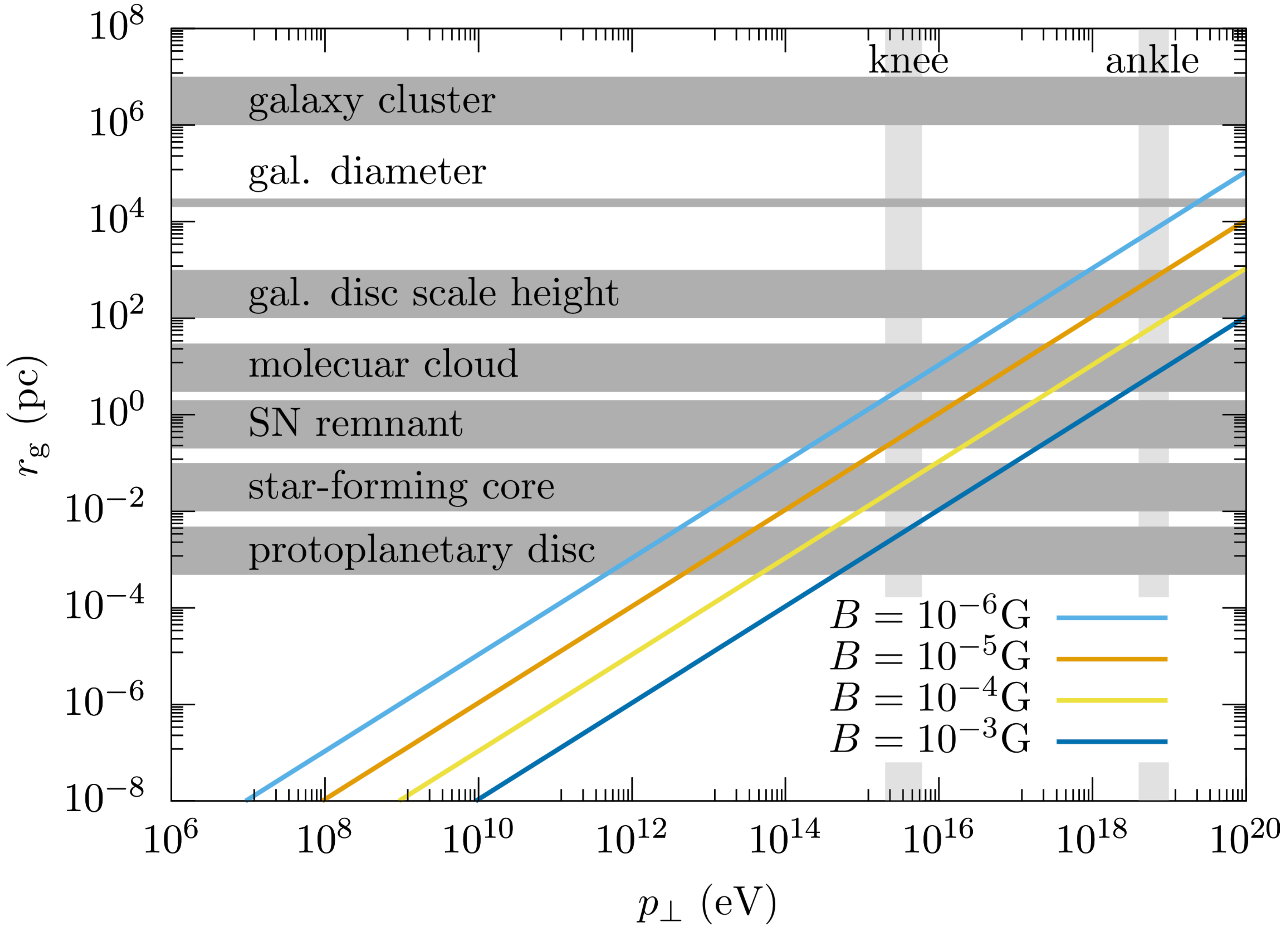

Results - CRMHD vs MHD

- Polar & time-dependence of thermodynamic parameters at the outer shock