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Are SNRs Cosmic Ray Factories? Yes, but…

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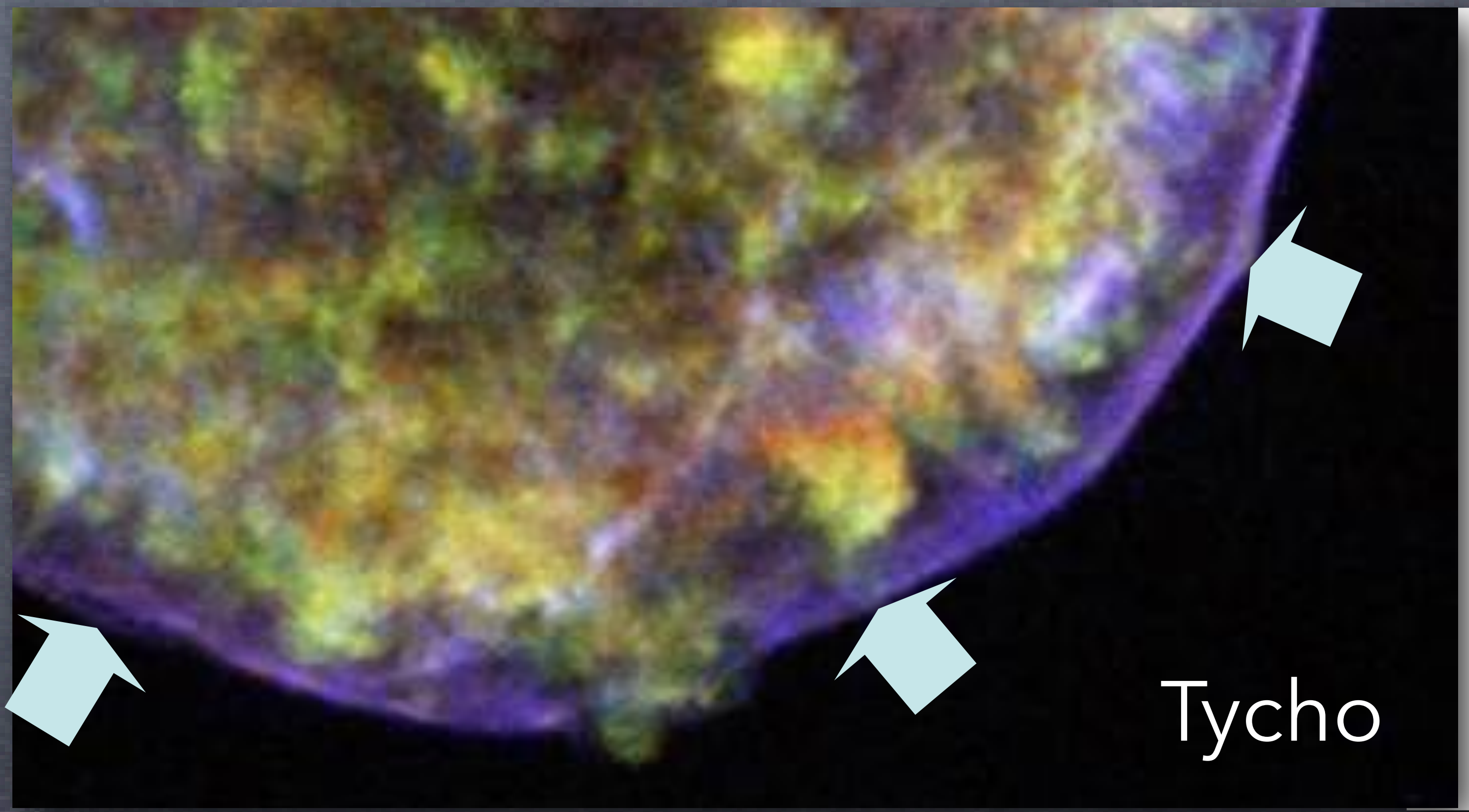
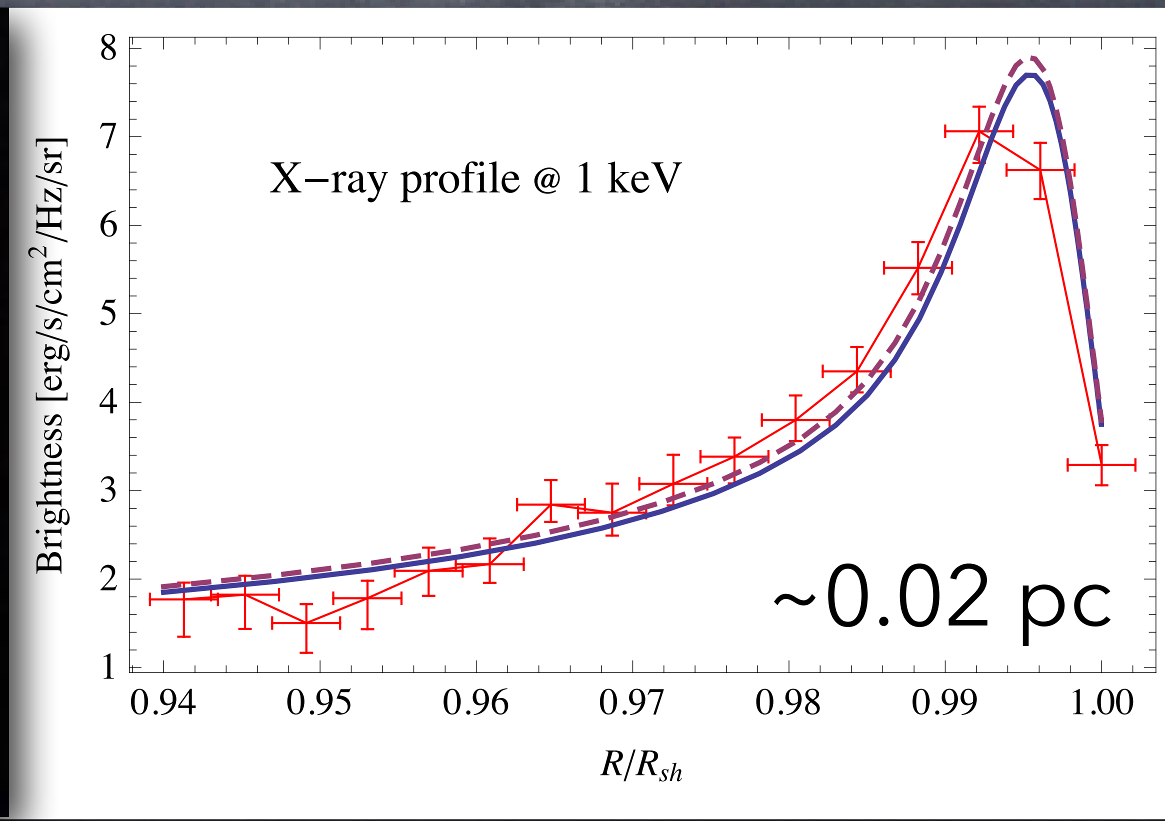
The SNR paradigm for the origin of CRs

- **Mechanism**: Fermi acceleration at SNR shocks is *first-order* and produces power-laws. Diffusive Shock Acceleration (DSA) (Krimskii77,Axford+78,Bell78,Blandford-Ostriker78)

- Evidence of **B field amplification**: self-generated scattering enhances the energization rate (e.g., Bamba+05, Völk+05, Parizot+06, Morlino+12, Ressler+14, etc)





- Reaching the knee depends on the properties of CR-driven instabilities (e.g., Bell+13, Cardillo+15, Cristofari+21,22, …)

B-Amplification in Shocks

A Multi-scale Approach

Micro

PIC Plasma Simulations
electron + ion dynamics

Meso

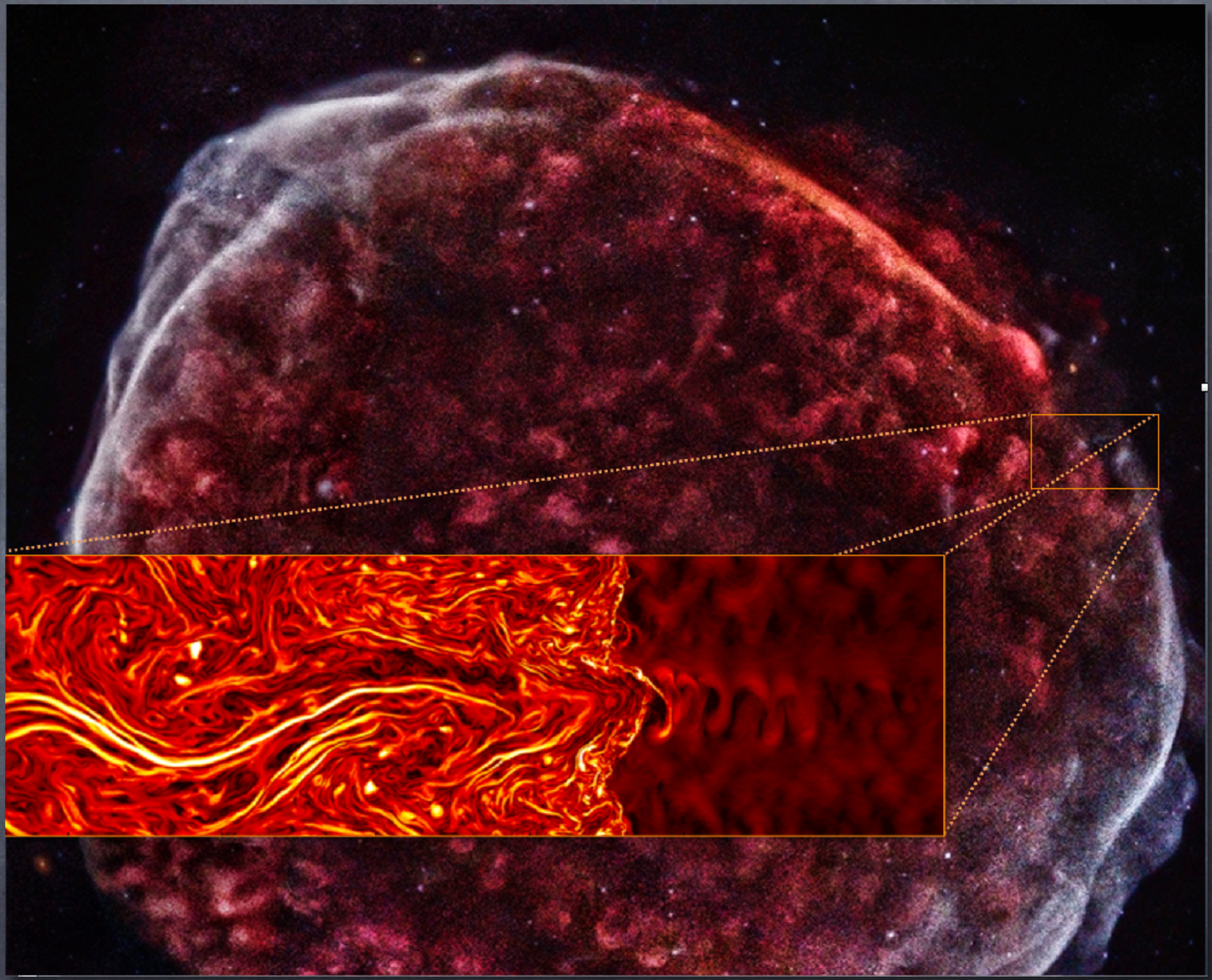
Hybrid: ion dynamics, magnetic field amplification

Macro

Super-Hybrid (MHD+hybrid)
Large/long scales
High-Mach numbers

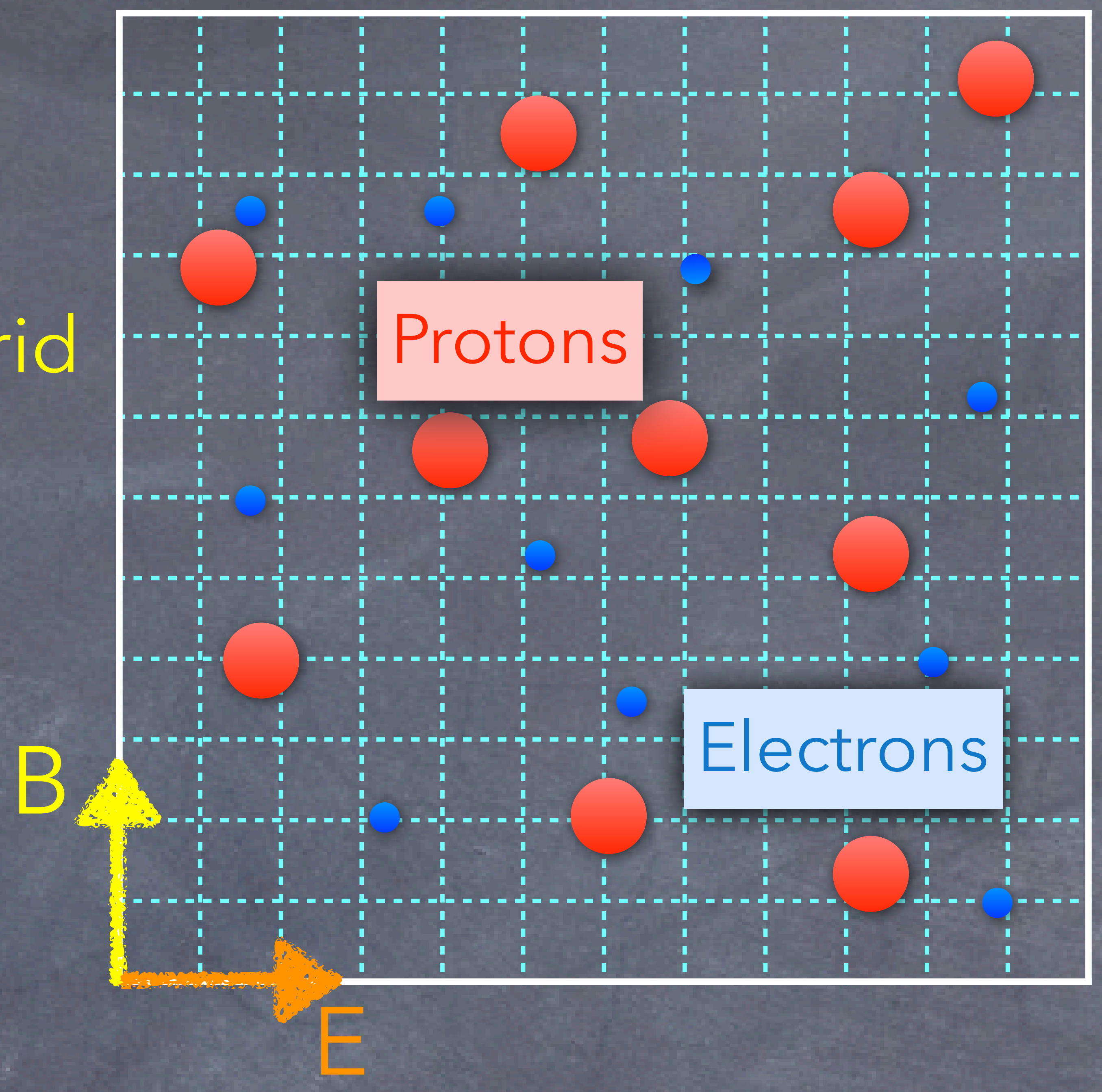
Astro

Semi-Analytical
CRAFT = *Cosmic Ray Analytical Fast Tool*



Astroplasmas from first principles

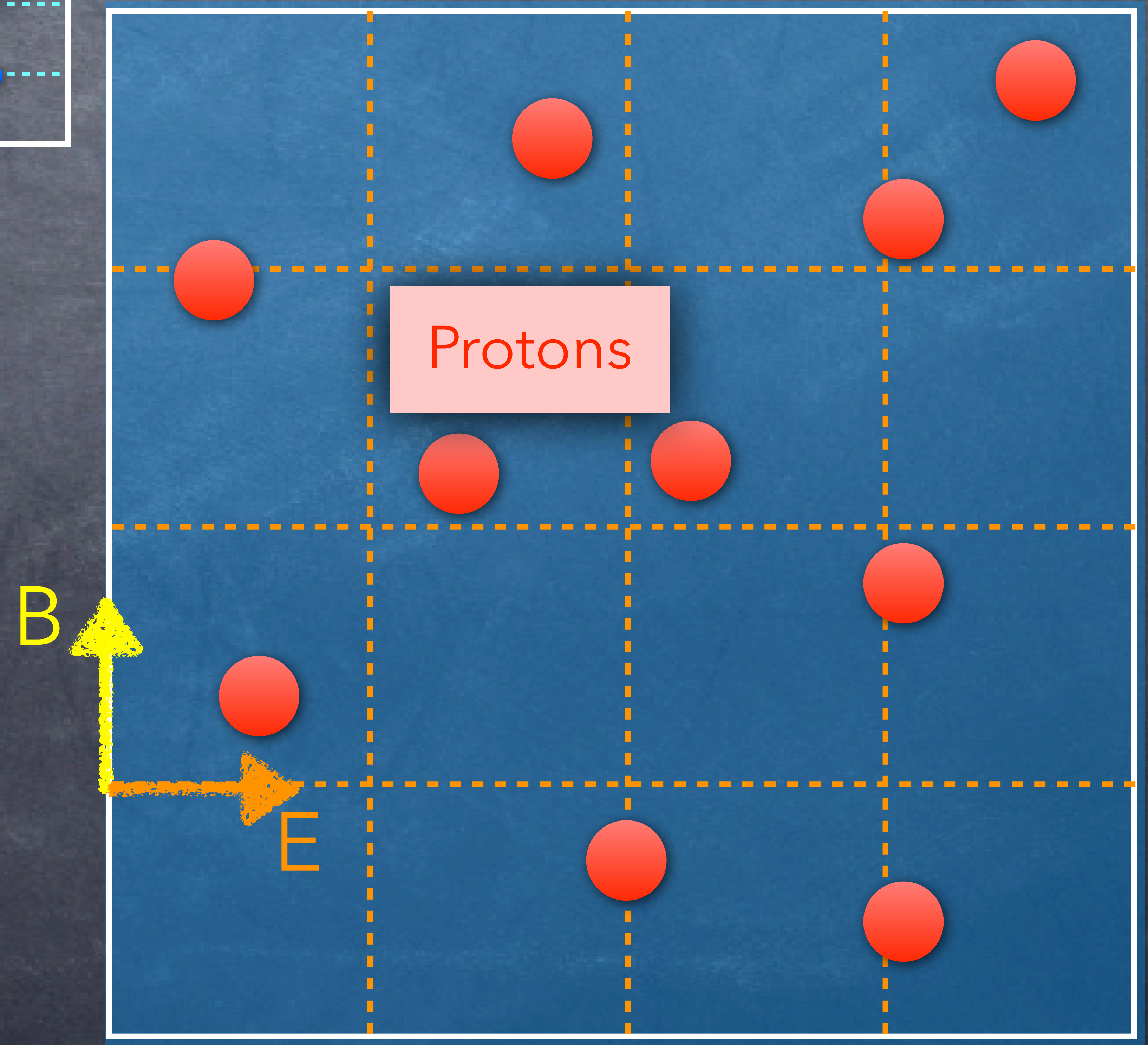
- Full-PIC approach
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



- Hybrid approach: Fluid electrons - Kinetic protons

(Winske & Omidi; Burgess et al., Lipatov 2002; Giacalone et al. 1993,1997,2004-2013; DC & Spitkovsky 2013-2015, Haggerty & DC 2019-2022)

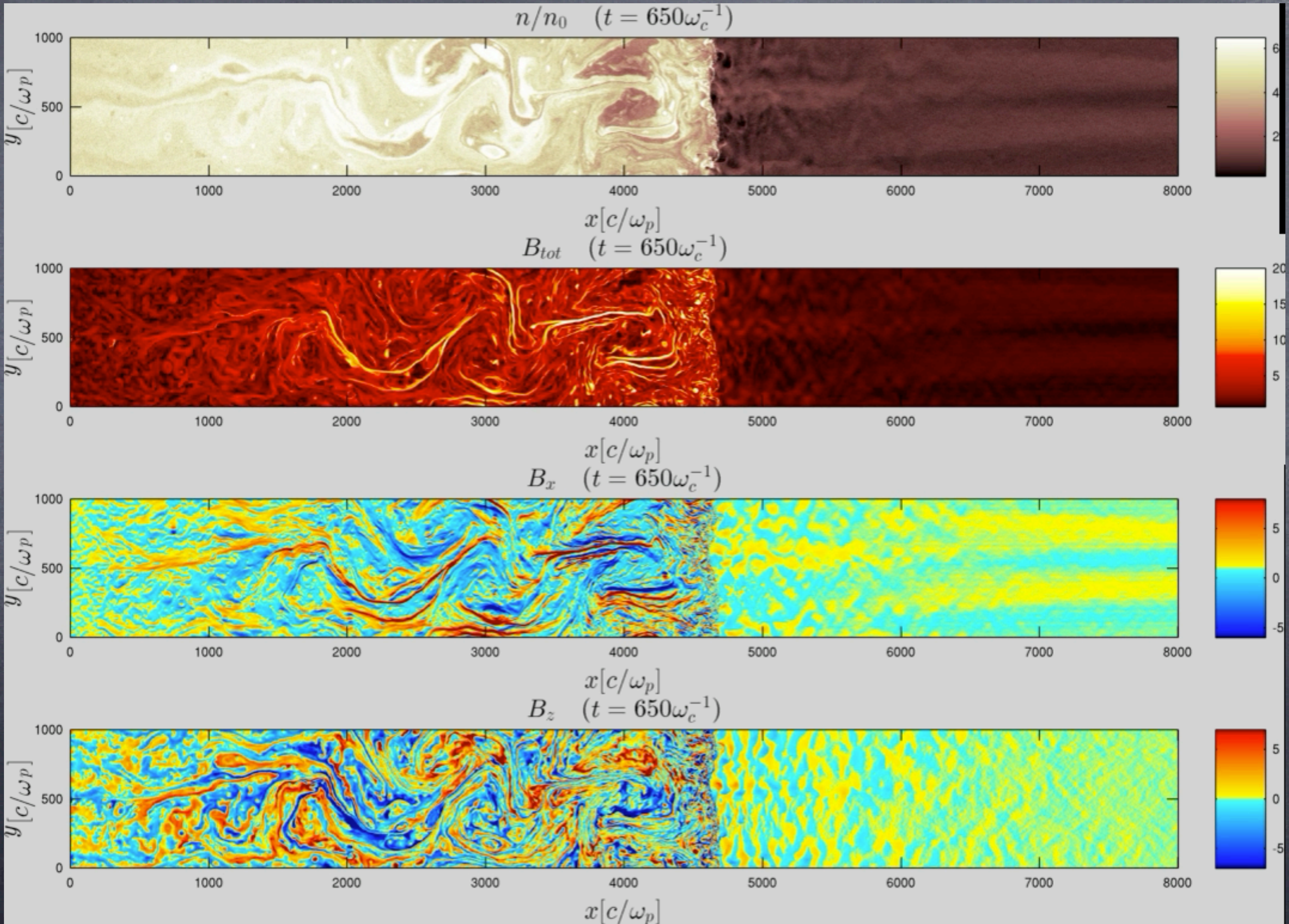
  - massless electrons for more macroscopical time/length scales



Magnetic-Field Amplification in Shocks

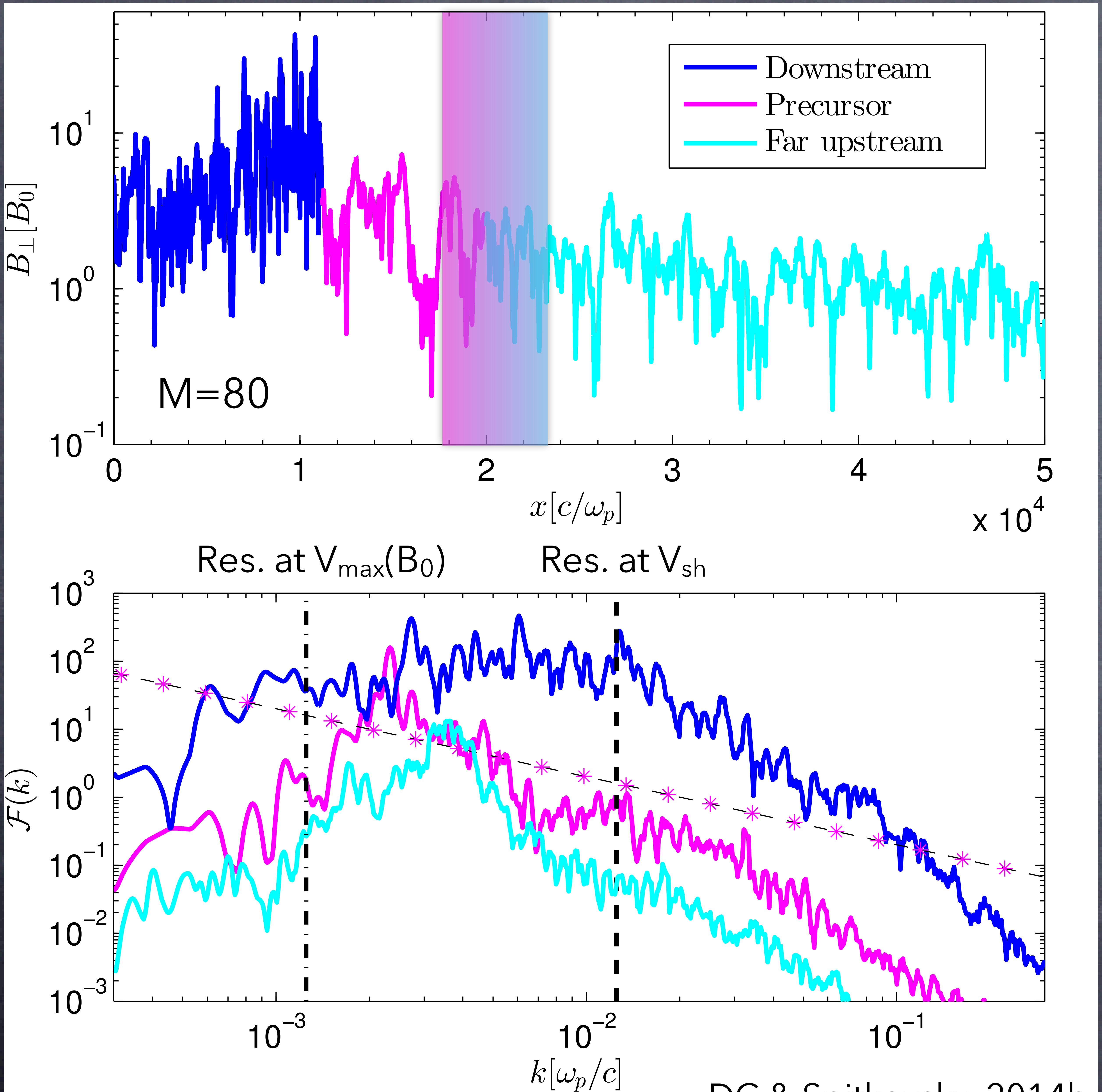
Initial B field

$M_s = M_A = 30$



DC & Spitkovsky, 2014

Which Instability is at Work?



DC & Spitkovsky, 2014b

B energy density per unit logarithmic band-width, F(k)

$$\frac{B_\perp^2}{8\pi} = \frac{B_0^2}{8\pi}\int_{k_{min}}^{k_{max}} \frac{dk}{k}\mathcal{F}(k)$$

- Far upstream: *Escaping* CRs at p_{max}

Free escape boundary

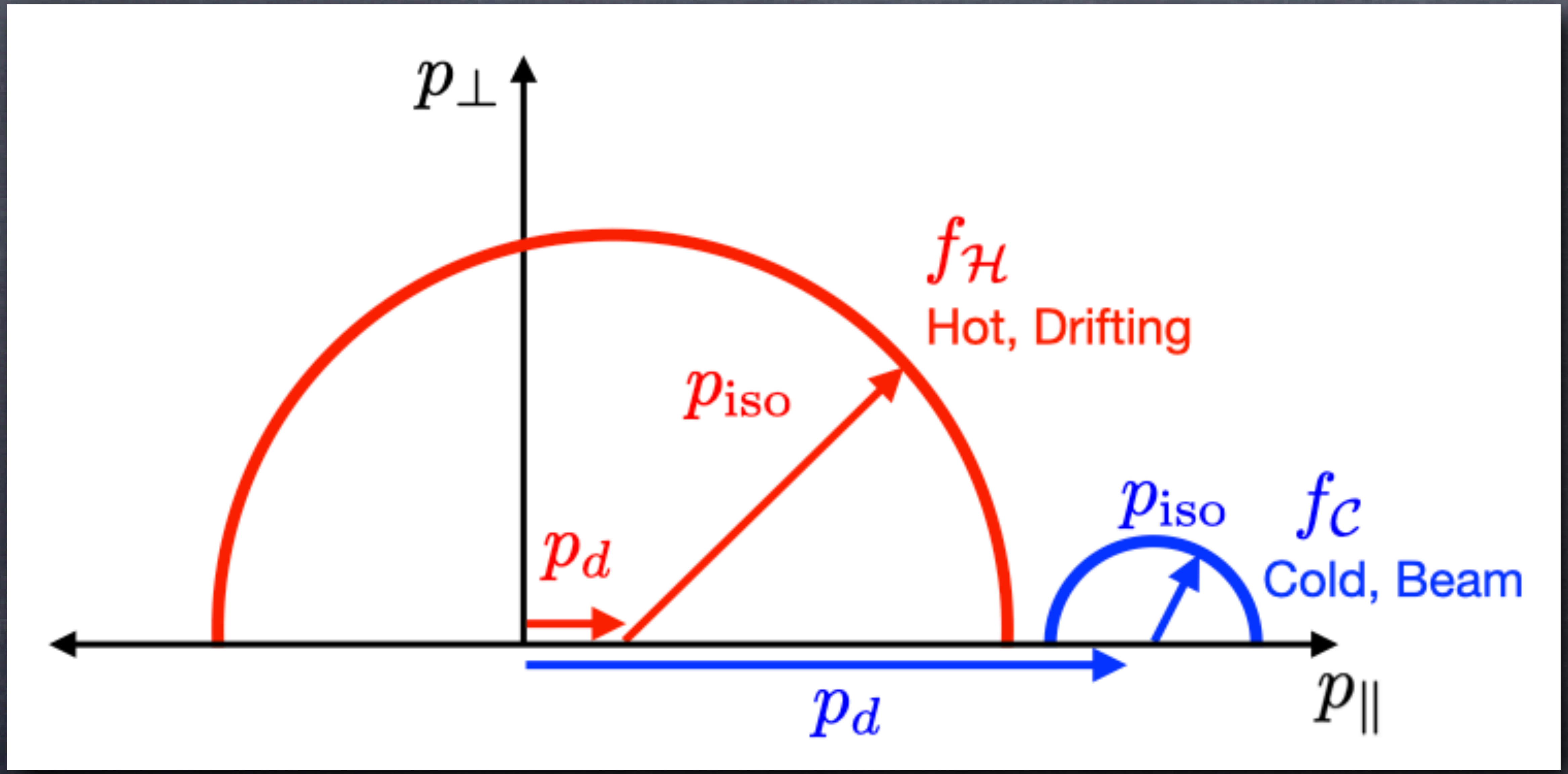
- Precursor: Current in *diffusing* CRs
- E_{max} in a SNR depends on
  - Current in escaping particles
  - B-field at saturation
- Bell+13: Time needed for saturation may become comparable to the SNR age

$$E_{max} = 230\ \eta_{0.03} n_e^{1/2} u_7^2 R_{pc}\ \text{TeV}$$

- Hard time reaching the CR knee ~ PeV!

A Simple Question

- "*Thermodynamical*" argument: if $P_{\rm cr} > P_{\rm B}$, CRs must amplify the field.
- Given a generic distribution, e.g., $n_{\rm cr}$ CRs of isotropic momentum $p_{\rm iso}$ drifting with momentum $p_{\rm d}$, how much B-field can be produced?



CR current and energy density:

$$J_{\rm cr} = e n_{\rm cr} v_d$$

$$\varepsilon_{\rm cr} \simeq n_{\rm cr} c \max\{p_{\rm iso}, p_{\rm d}\}$$

What is the value of $\delta B / B_0(J_{\rm cr}, \varepsilon_{\rm cr})$ at saturation?

Maybe a *Not-so-simple* Question?

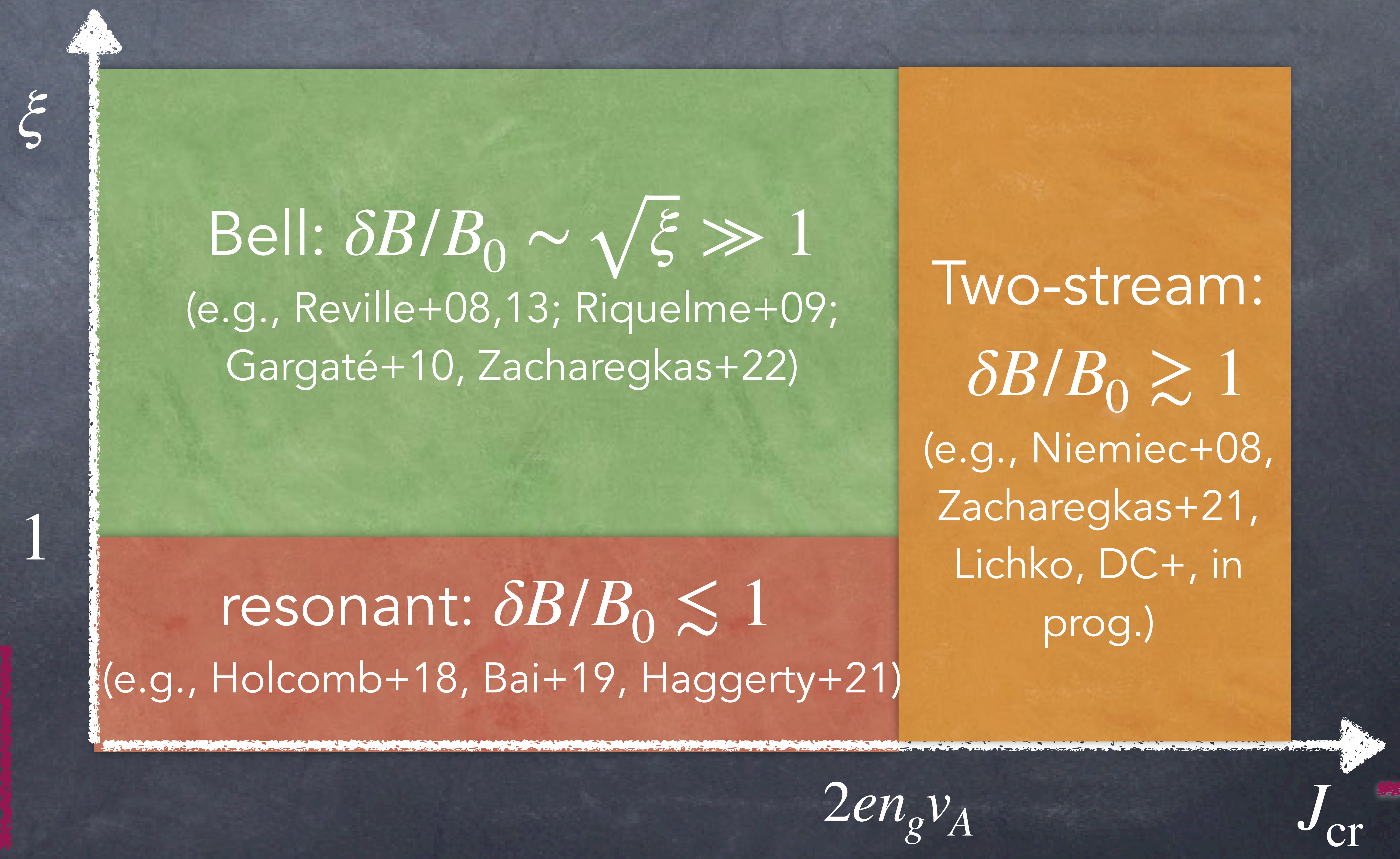
- Depending on the CR parameters, the: filamentation, Weibel, (modified) two-stream, Buneman, resonant, "interm-scale", Bell, … instability may grow the fastest (e.g., Bret 2009)
  - *Caveat*: *fastest* growing doesn't imply *most important* for saturation!
- Most important regime for CR acceleration (e.g., SNRs): Bell instability (Bell04, Amato+09)
  - Introducing the parameter

$$\xi \equiv \frac{1}{2}\frac{\varepsilon_{\rm cr}}{\varepsilon_{\rm B}}\frac{v_{\rm d}}{c}$$

Bell dominates if $\xi \gg 1$ and:

$$k_{\rm max} r_L \simeq \xi; \qquad \gamma_{\rm max} = \frac{1}{2}\frac{J_{\rm cr}}{e n_g v_A}\Omega_c$$

Bell's *ansatz*: $[k_{\rm max} r_L]_{\delta B} \sim 1 \rightarrow \frac{\delta B}{B_0} \sim \sqrt{\xi}$

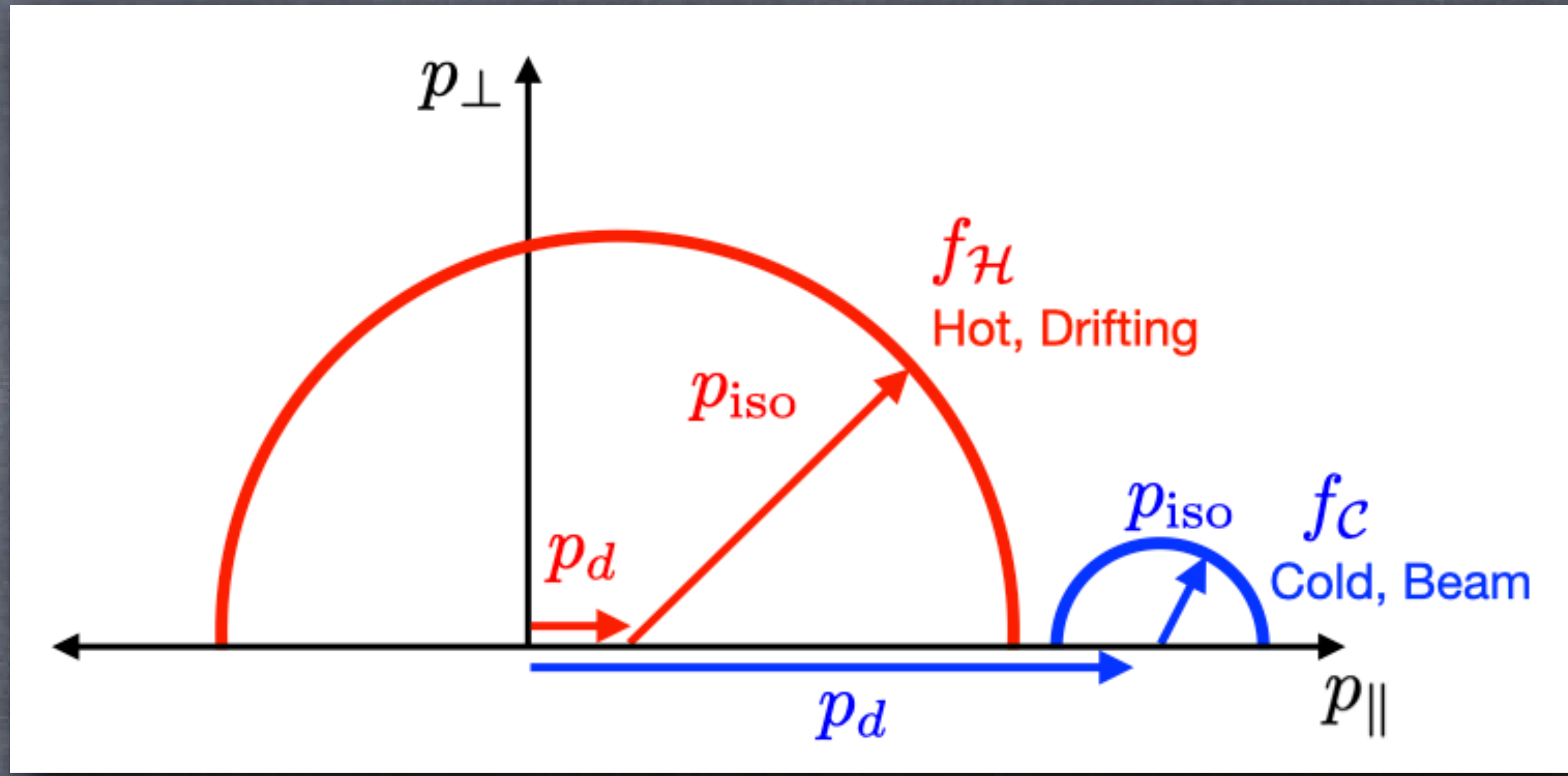


The Saturation of the Bell Instability

Probing the *Ansatz*

- Bell's *ansatz* (also see Blasi+15), has never been validated by self-consistent kinetic simulations (though see, e.g., Bell 05, Zirakashvili+07, Niemiec+08, Ohira+09, Riquelme+09, Gargaté+10, Reville+13, Kobzar+17, Haggerty+19, Marret+21, Gupta+21, Zacharegkas+19,21…)

- What is the physical meaning of $\xi \equiv \frac{1}{2}\frac{\varepsilon_{\rm cr}}{\varepsilon_{\rm B}}\frac{v_{\rm d}}{c}$?
  - Only *similar* to a ratio of CR to magnetic energy fluxes!
  - Derived for a *hot* distribution of *relativistic* CRs
  - What is its general formula?



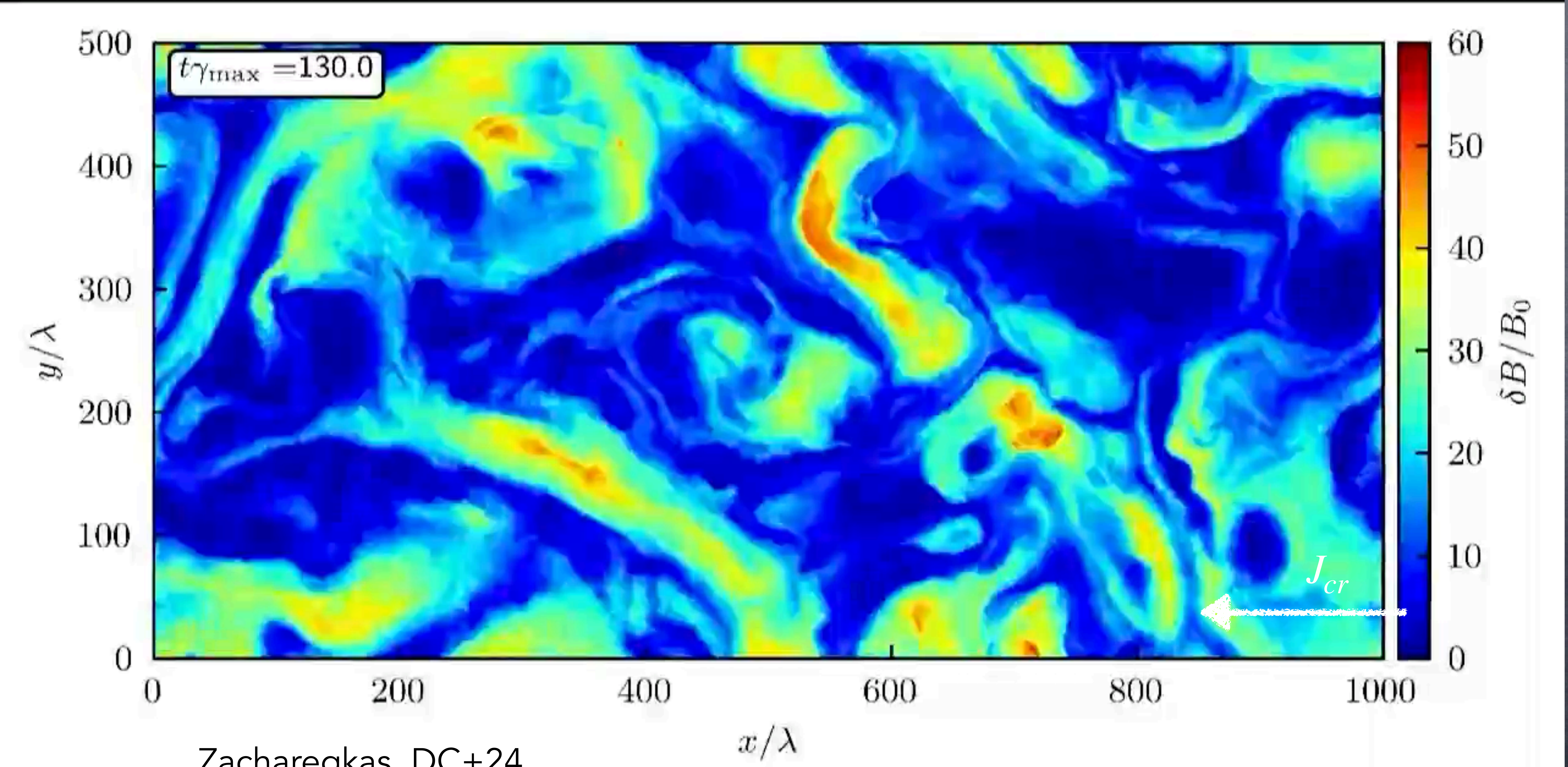
- Need to introduce the relativistic stress tensor $T^{\mu\nu} = (e_{\rm cr} + p_{\rm cr})u_d^\mu u_d^\nu + p\eta^{\mu\nu}$
  - CRs have a given energy density/pressure in their rest frame ($e_{\rm cr}$ and $p_{\rm cr}$, defined by $n_{\rm cr}$ and $p_{\rm iso}$), and then boosted with a drift four-velocity $u_d = (\gamma_{\rm d} c, p_d/m)$

The *Magic* of B Saturation

https://www.xkcd.com/2904/

Controlled Simulations of CR-driven Instabilities

- Hybrid sims in periodic boxes in the Bell regime (e.g., Haggerty, Zweibel & Caprioli 2019)

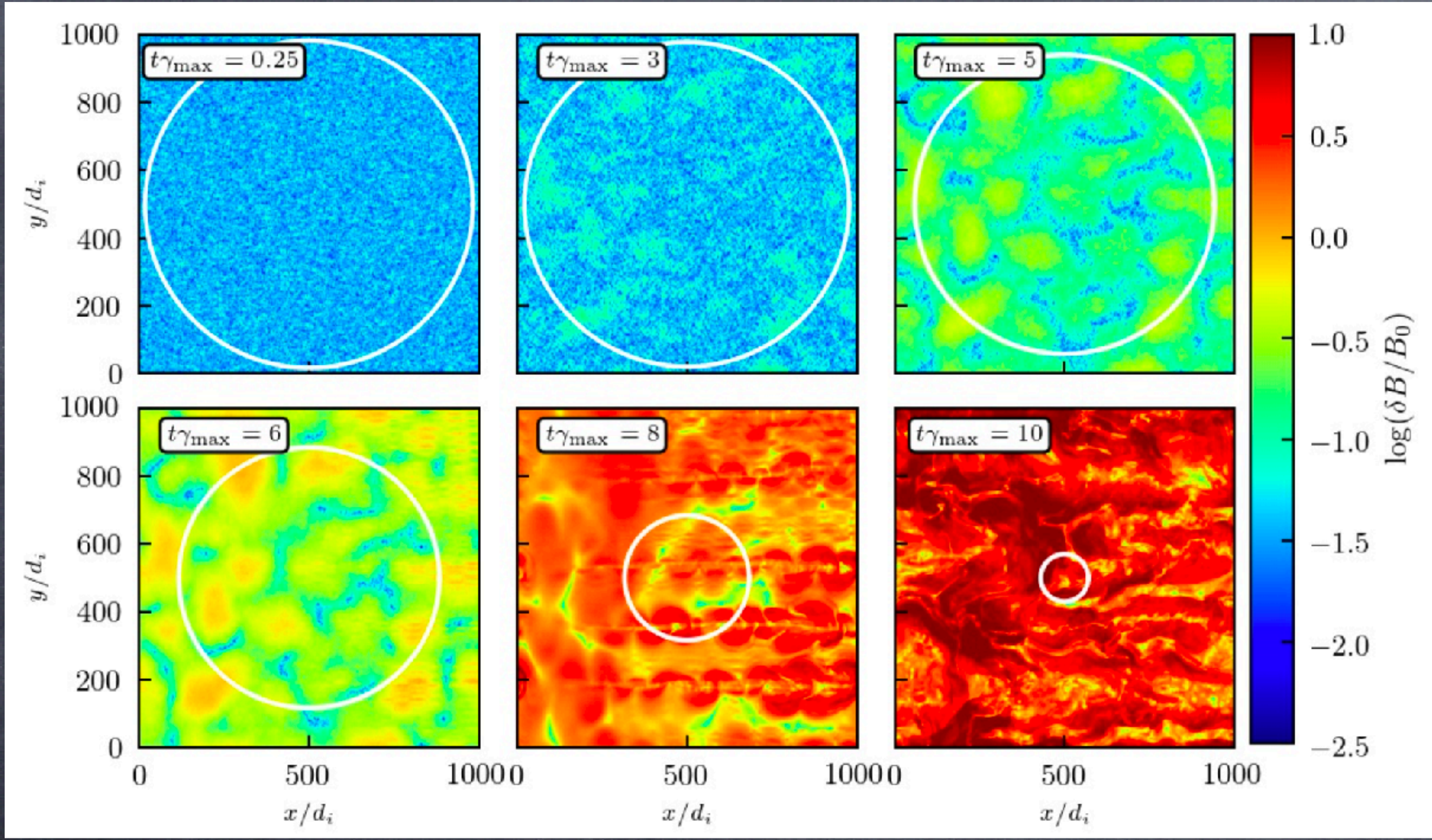


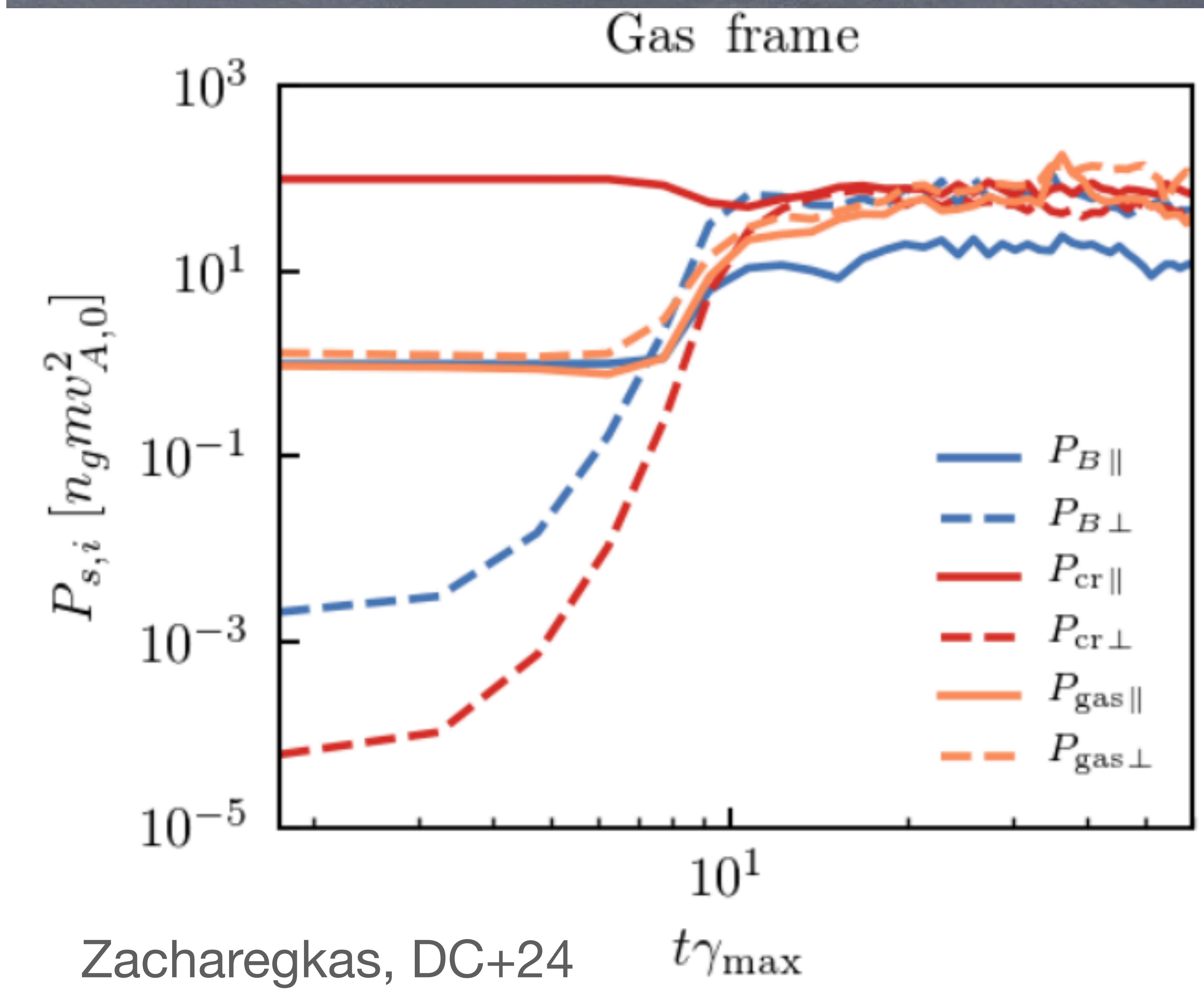
Zacharegkas, DC+24

Note the large $\delta B/B_0$ at saturation

Can also be driven by leptons! (Gupta, DC & Haggerty 2021)

The Saturation of the Bell Instability



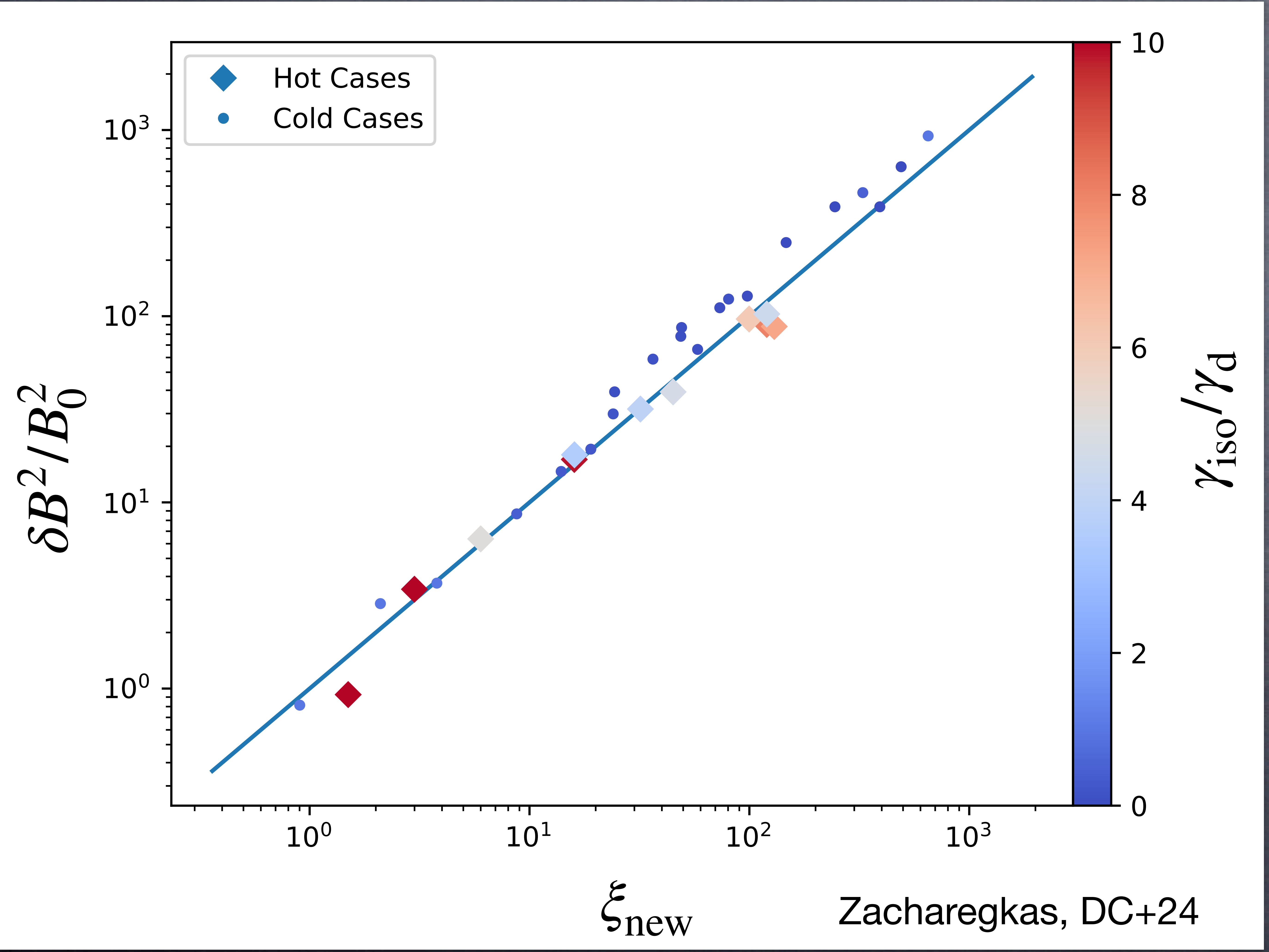


Zacharegkas, DC+24

- After the linear stage, power moves at larger and larger scales
- At saturation $\delta B/B_0 \gg 1$: magnetic pressure ~ gas pressure ~ initial CR pressure

An Extensive Survey

- Tens of (un-)driven runs exploring hot/cold cases, (non-)relativistic, values of ξ, …
  - The quantity that best expresses *B* at saturation is:



$$\xi_{\rm new} = \frac{T^{00} - \gamma_{\rm iso}\rho_{\rm cr}c^2/\gamma_{\rm d}}{P_B} = \frac{T^{0x}}{P_B}\frac{v_{\rm d}}{c} = \frac{T^{xx} - P_{\rm cr}}{P_B}$$

$$\xi_{\rm new} = 2\gamma_{\rm iso}\frac{n_{\rm cr}}{n_g}\frac{c^2}{v_A^2}\left(\gamma_d - 1 + \frac{\gamma_d}{3}\frac{v_d^2}{c^2}\frac{v_{\rm iso}^2}{c^2}\right)$$

$\xi_{\rm new}$ = *kinetic* energy density, or *anisotropic* momentum flux, normalized to the initial B pressure

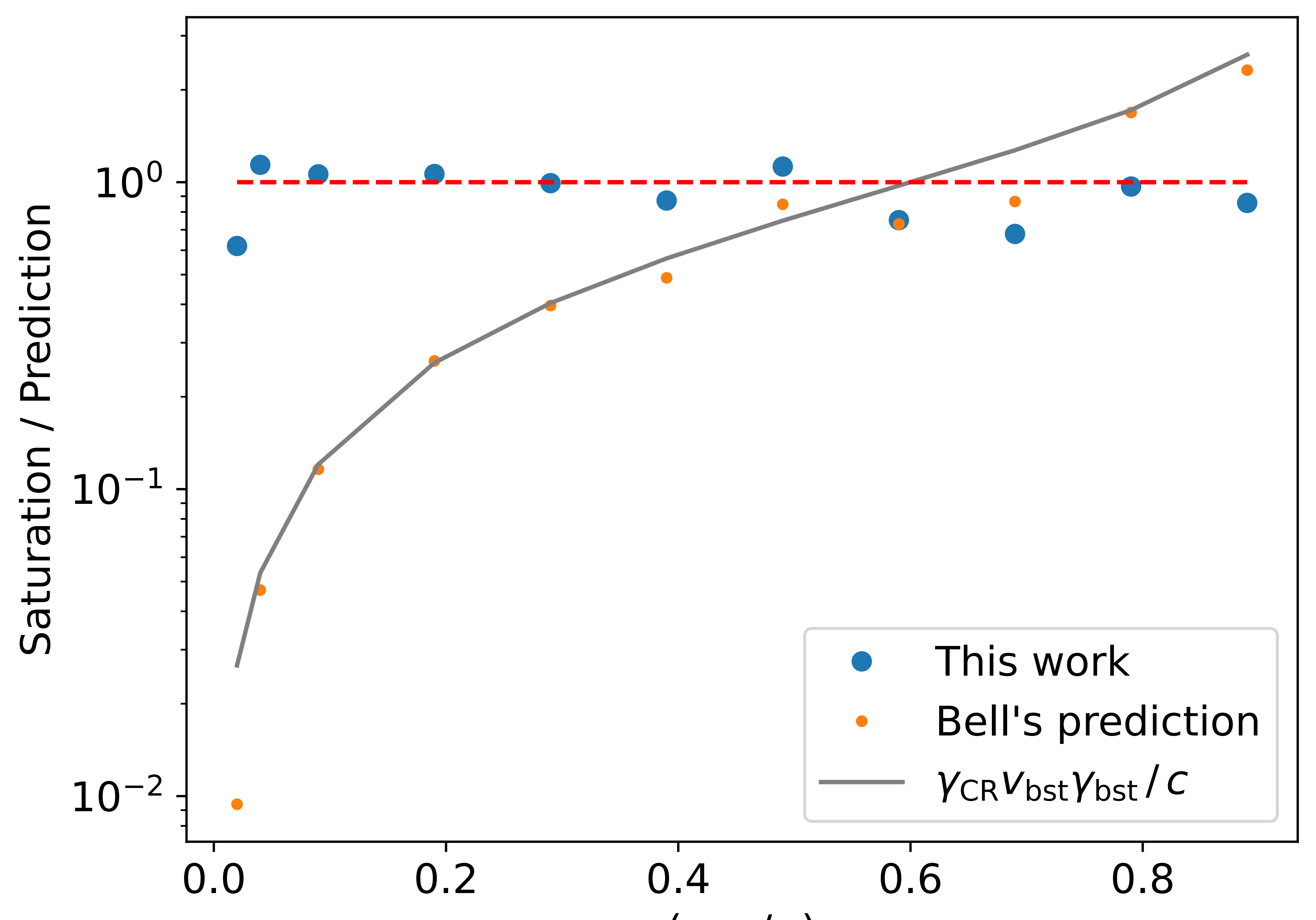
At saturation, $\dfrac{\delta B}{B_0} \simeq \dfrac{\sqrt{\xi}}{2}$

Comparison with Bell's ansatz

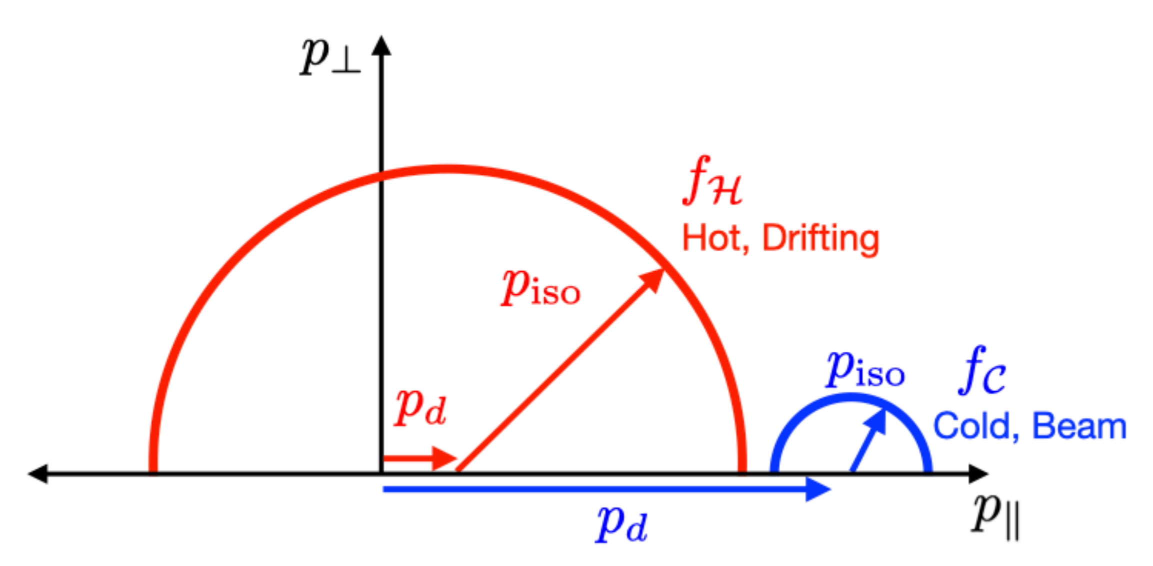
- Simulations suggest that saturation may be *smaller* than the one predicted by Bell, since

$$\frac{\xi_{\rm new}}{\xi_{\rm Bell}} \simeq 2\frac{v_d}{c}$$

- Though dynamo effects in the precursor may be important: Beresnyak+09, Drury & Downes 12, Downes & Drury 2014
- Does this make it harder for SNRs ($v_d \sim v_{sh}$) to reach the knee? (Bell+13, Cardillo+15, Cristofari+20,22,…)
  - In shocks, amplification happens
    - far upstream: because of escaping CRs (*cold beam*, $v_d \sim c$)
    - in the precursor: because of diffusing CRs (hot distribution)
- *Most of the amplification must be driven by escaping CRs!*



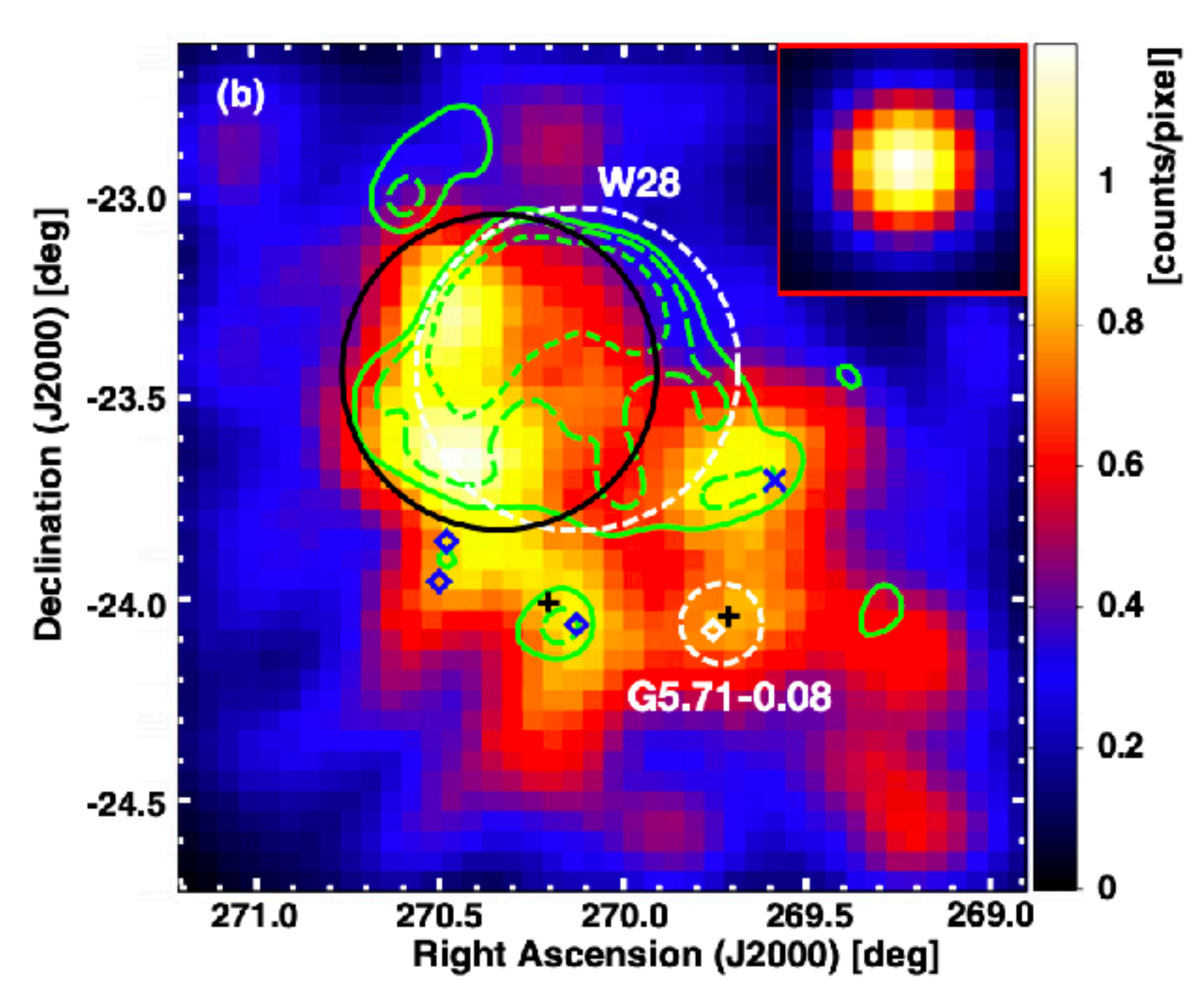
Zacharegkas+24



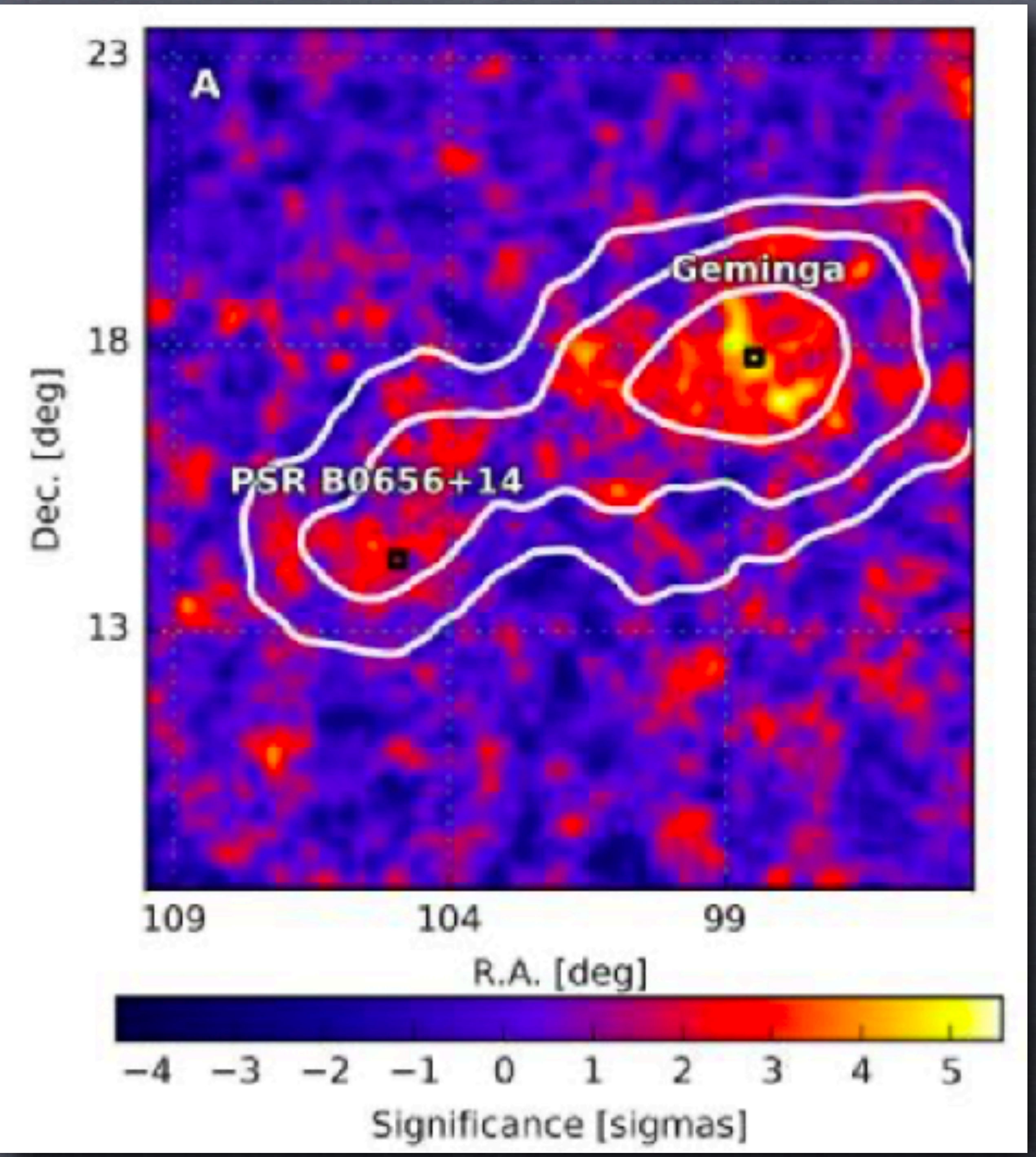
Bell Instability and CR Transport

Evidence of CR "*Spheres of Influence*"

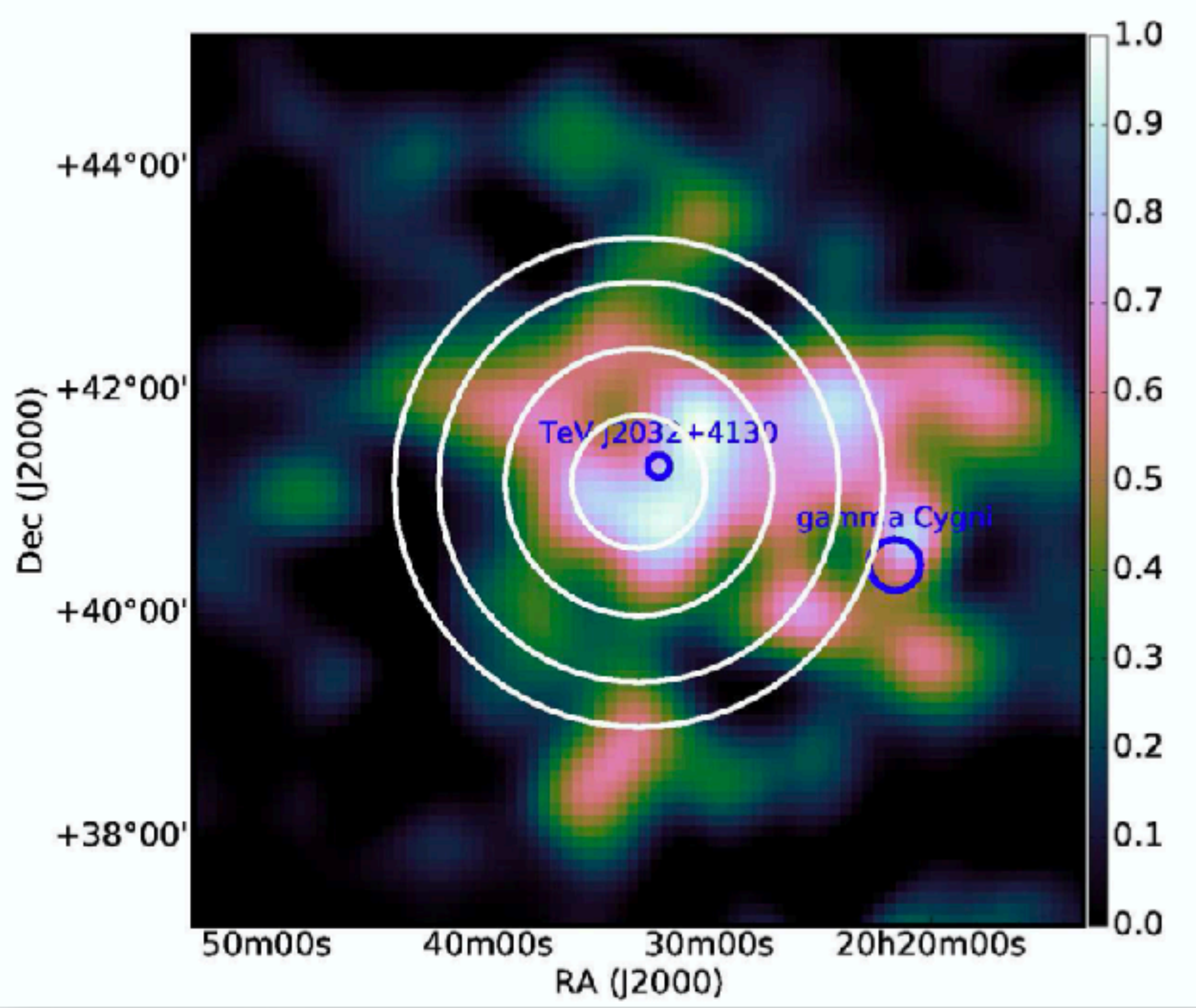
Supernova Remnants (SNRs)	Pulsar Wind Nebulae (PWNe)	Stellar Clusters
Casanova+10, Hanabata+14,…	HAWC 18, …	Ohm+13, Aharonian+19, …



W28



Geminga

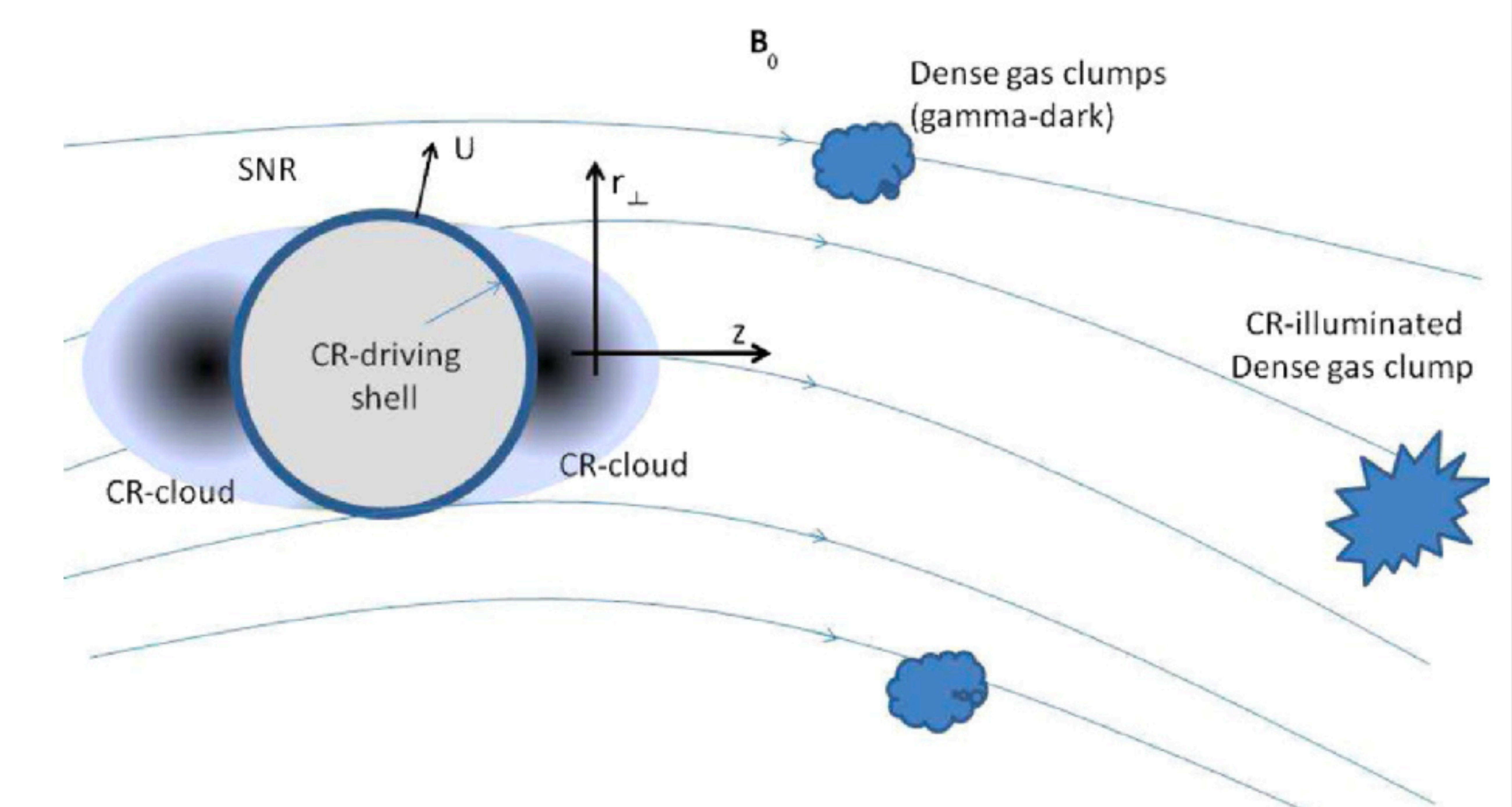


Cygnus Loop

- TeV haloes 50-100 pc wide are ubiquitous around CR sources. *Why*?
  - They require a diffusion coefficient ~100x smaller than the Galactic one

CR Self-confinement

- Gradients in CR distributions generate currents, and hence B amplification
  - Analytical calculations (e.g., Gabici+09,Fujita+11,Malkov+13, Nava+16,19, etc…)
    - Assume: *resonant streaming instability* (Kulsrud+69, Zweibel79) balanced by some *damping* (e.g., Brunetti+07,Wiener+13), and 1D escape along a *flux tube*



from Malkov+13

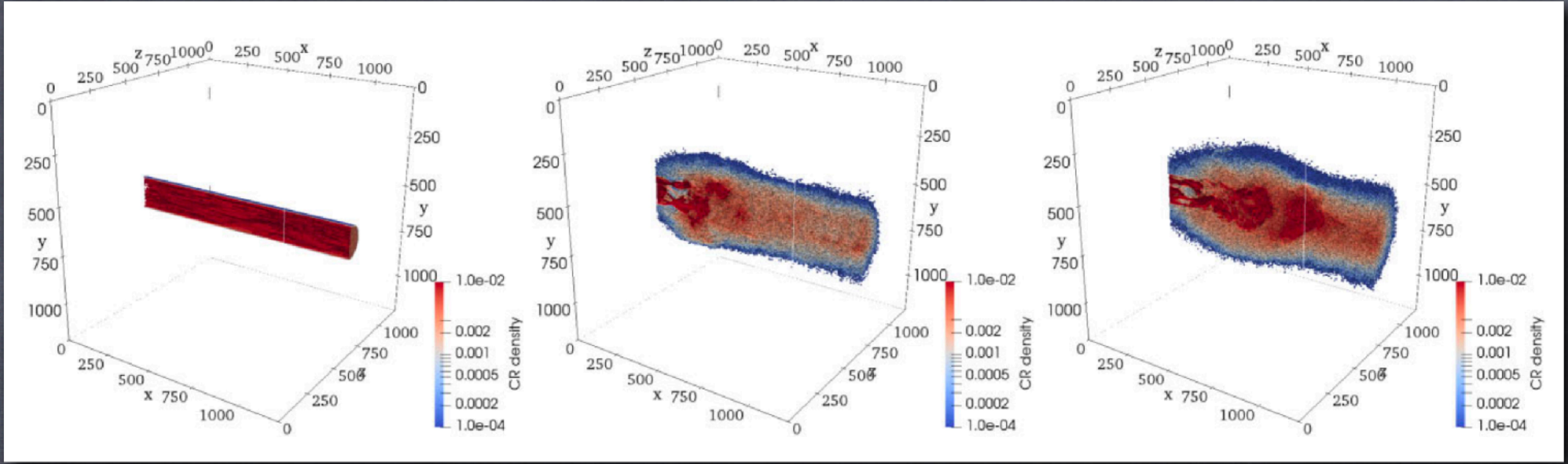
- These *assumptions* may be *violated*
- When $P_{cr} > P_B$ amplification occurs via Bell (Bell04, Amato-Blasi09)
- The flux tube may expand sideways due to the CR overpressure: bubbles?

Global Hybrid Simulations of CR Escape

Schroer, DC+2021

Implications

- Size of "spheres of influence" ~50-100pc (Schroer, DC+2021, 2022)



- CR diffusion is reduced in such bubbles
  - A factor of ~100 is reasonable and consistent with TeV haloes
  - Possible modifications to secondary/primary yield and spectra (e.g., B/C, $\bar{p}/p$,…)
- The dynamical role of CRs in galaxy evolution needs to be re-evaluated

How to Model Astro Sources

CRAFT: a Cosmic-Ray Fast Analytic Tool

(Malkov01; Blasi02,04; Amato & Blasi05,06; Caprioli+09-12-,… Diesing & Caprioli 2021, 2023)

- Iterative analytical solution of the CR transport (Parker) equation:

$$\tilde{u}(x)\frac{\partial f(x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(x,p)}{\partial x}\right] + \frac{p}{3}\frac{\mathrm{d}\tilde{u}(x)}{\mathrm{d}x}\frac{\partial f(x,p)}{\partial p} + Q(x,p),$$

Advection | Diffusion | Energy change | Injection

- Very fast: a few seconds on a laptop (vs days on clusters: Caprioli+2010)
- Can embed microphysics from kinetic simulations into (M)HD

$$f(x,p) = f_2(p)\exp\left[-\int_x^0 dx'\frac{\tilde{u}(x')}{D(x',p)}\right]\left[1-\frac{W(x,p)}{W_0(p)}\right];$$

$$\Phi_{esc}(p) = -D(x_0,p)\left.\frac{\partial f}{\partial x}\right|_{x_0} = -\frac{u_0 f_2(p)}{W_0(p)};$$

$$W(x,p) = \int_x^0 dx'\frac{u_0}{D(x',p)}\exp\left[\int_{x'}^0 dx''\frac{\tilde{u}(x'')}{D(x'',p)}\right].$$

$$f_2(p) = \frac{\eta n_0 q_p(p)}{4\pi p_{inj}^3}\exp\left\{-\int_{p_{inj}}^p \frac{dp'}{p'}q_p(p')\left[U_p(p')+\frac{1}{W_0(p')}\right]\right\}$$

$$U_p(p) = \frac{\tilde{u}_1}{u_0} - \int_{x_0}^0 \frac{dx}{u_0}\left\{\frac{\partial\tilde{u}(x)}{\partial x}\exp\left[-\int_x^0 dx'\frac{\tilde{u}(x')}{D(x',p)}\right]\left[1-\frac{W(x,p)}{W_0(p)}\right]\right\}$$

CR distribution function

u

P_{cr}

Mass+momentum conservation eqs.

$$\frac{p(x)}{\rho(x)^\gamma} = \frac{p_0}{\rho_0^\gamma};$$

$$\rho(x)u(x) = \rho_0 u_0$$

$$\rho(x)u(x)^2 + p(x) + p_{cr}(x) + p_B(x) = \rho_0 u_0^2 + p_{g,0} + p_{B,0}$$

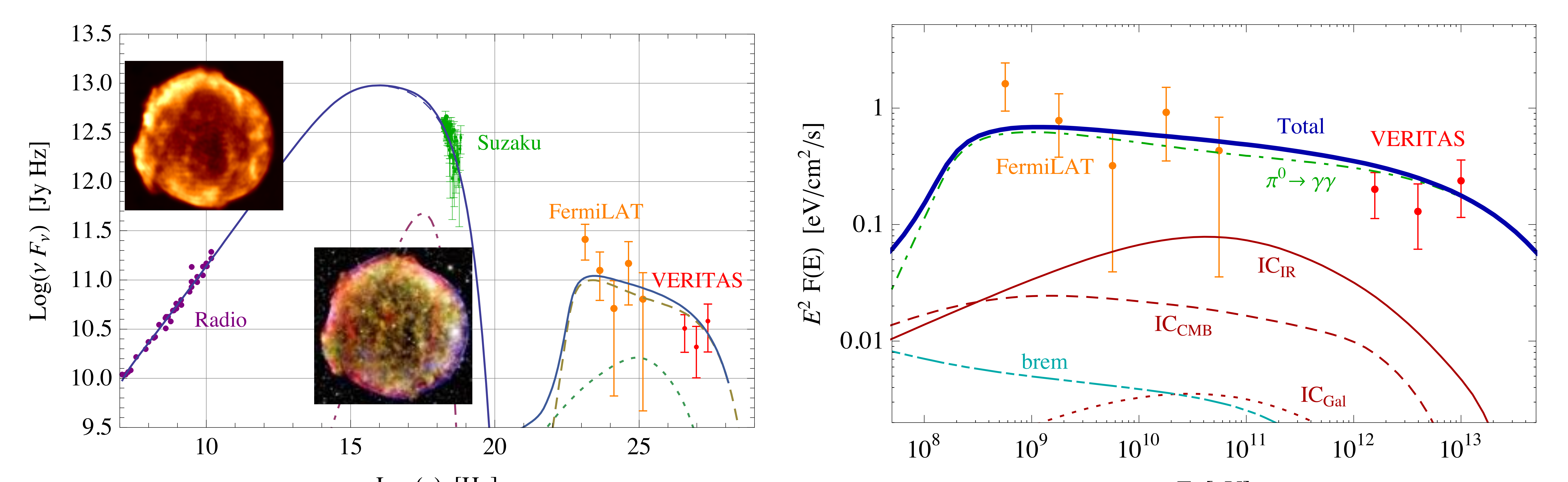
$P_B + P_{cr}$

$$2\tilde{u}(x)\frac{dp_B(x)}{dx} = v_A(x)\frac{dp_{cr}(x)}{dx} - 3p_B(x)\frac{d\tilde{u}(x)}{dx}$$

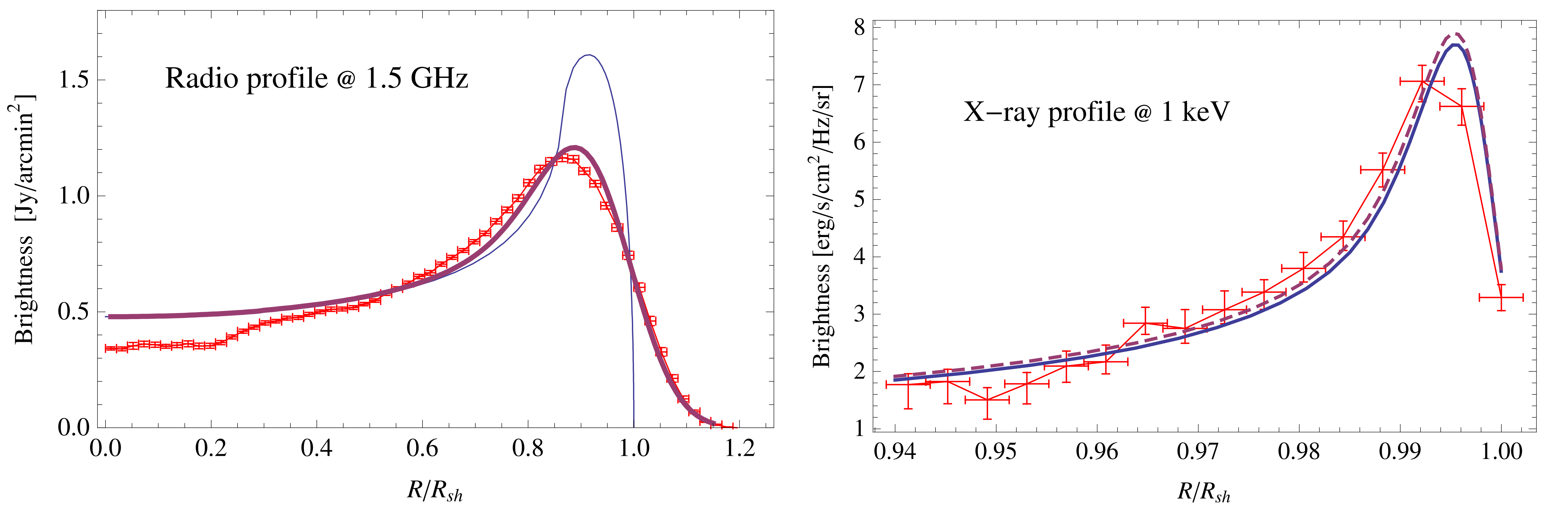
Magnetic turbulence transport equation

Example 1: Tycho SNR

Type Ia SN
Age=452yr
Distance~3kpc



Morlino & Caprioli 2012



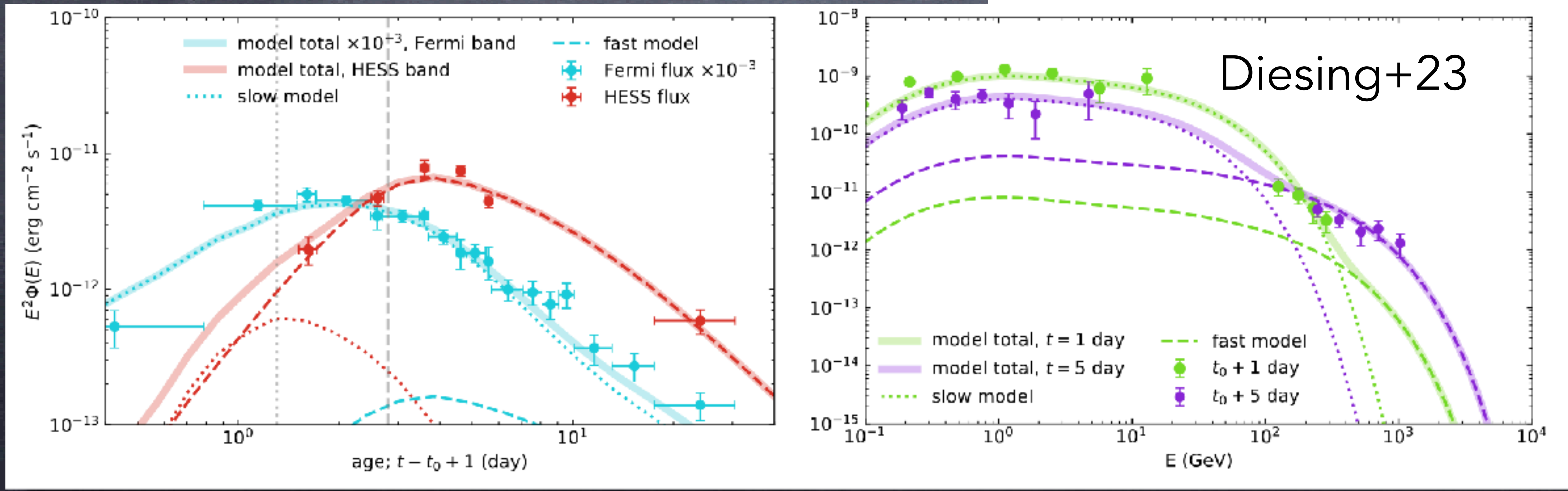
- Acceleration efficiency. ~10%
- Protons up to ~0.5 PeV

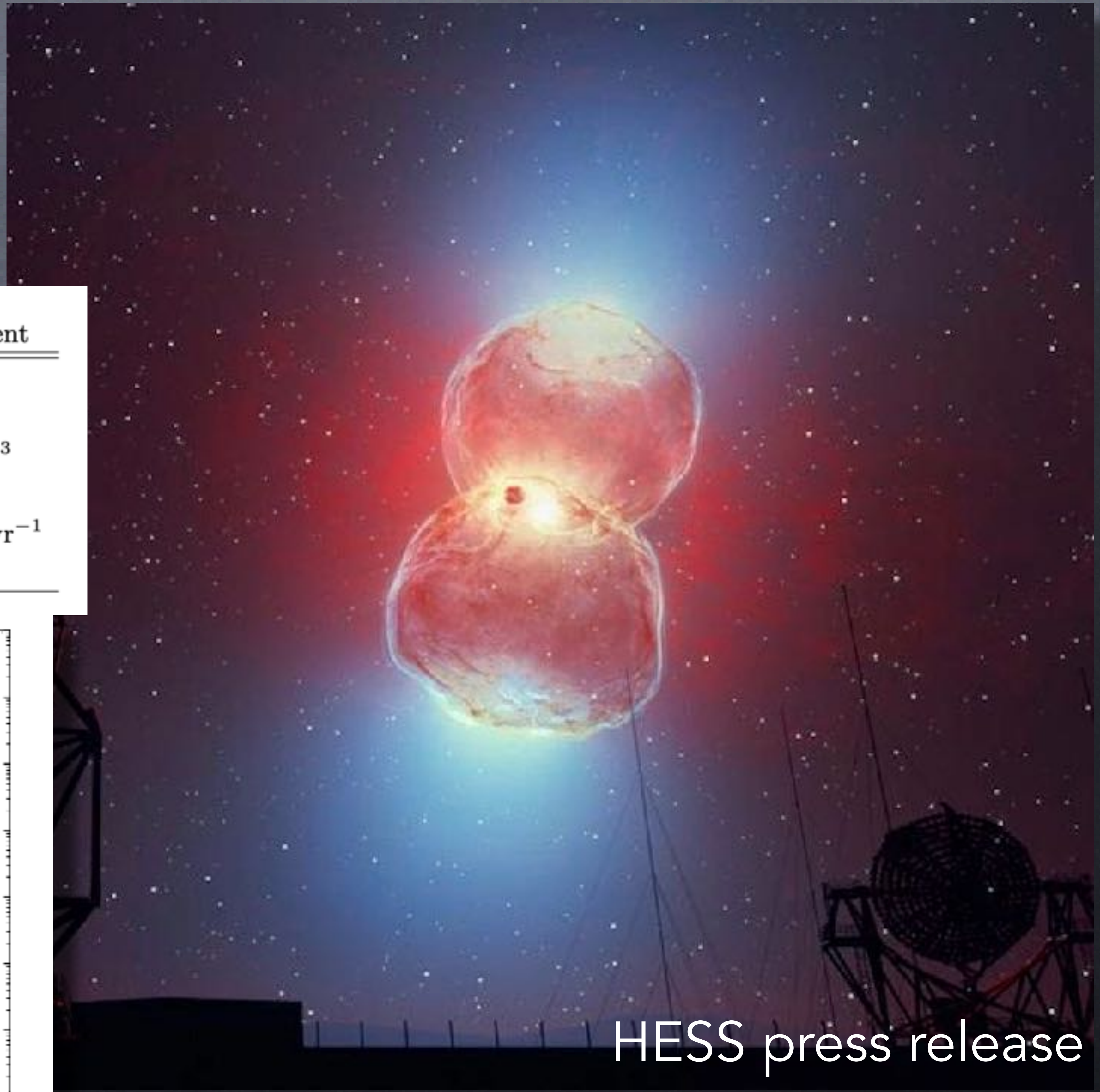
- Only two free parameters: electron/proton ratio and injection (now constrained with PIC!)

Example 2: Nova RS-Ophiuchi

- CRAFT: GeV/TeV peaks achieved at Sedov transition (Diesing, DC+23)
  - Incompatible with a single-shock scenario
- Fast/poloidal + slow/equatorial shocks
  - TeV (GeV) from fast (slow) shock
  - Also in radio (Munari+22, de Ruiter+23)

Parameter	Slow Component	Fast Component
M_{ej}	$1 \times 10^{-7} M_\odot$	$1 \times 10^{-7} M_\odot$
$v_{sh,init}$	1300 km s^{-1}	4500 km s^{-1}
$n_{0,init}$	1.2×10^{10} cm^{-3}	5.0×10^{7} cm^{-3}
r_{crit}	1.0 AU	6.0 AU
$\dot{M}_{wind}$	$5 \times 10^{-7} M_\odot$ yr^{-1}	$5 \times 10^{-7} M_\odot$ yr^{-1}
v_{wind}	30 km s^{-1}	30 km s^{-1}

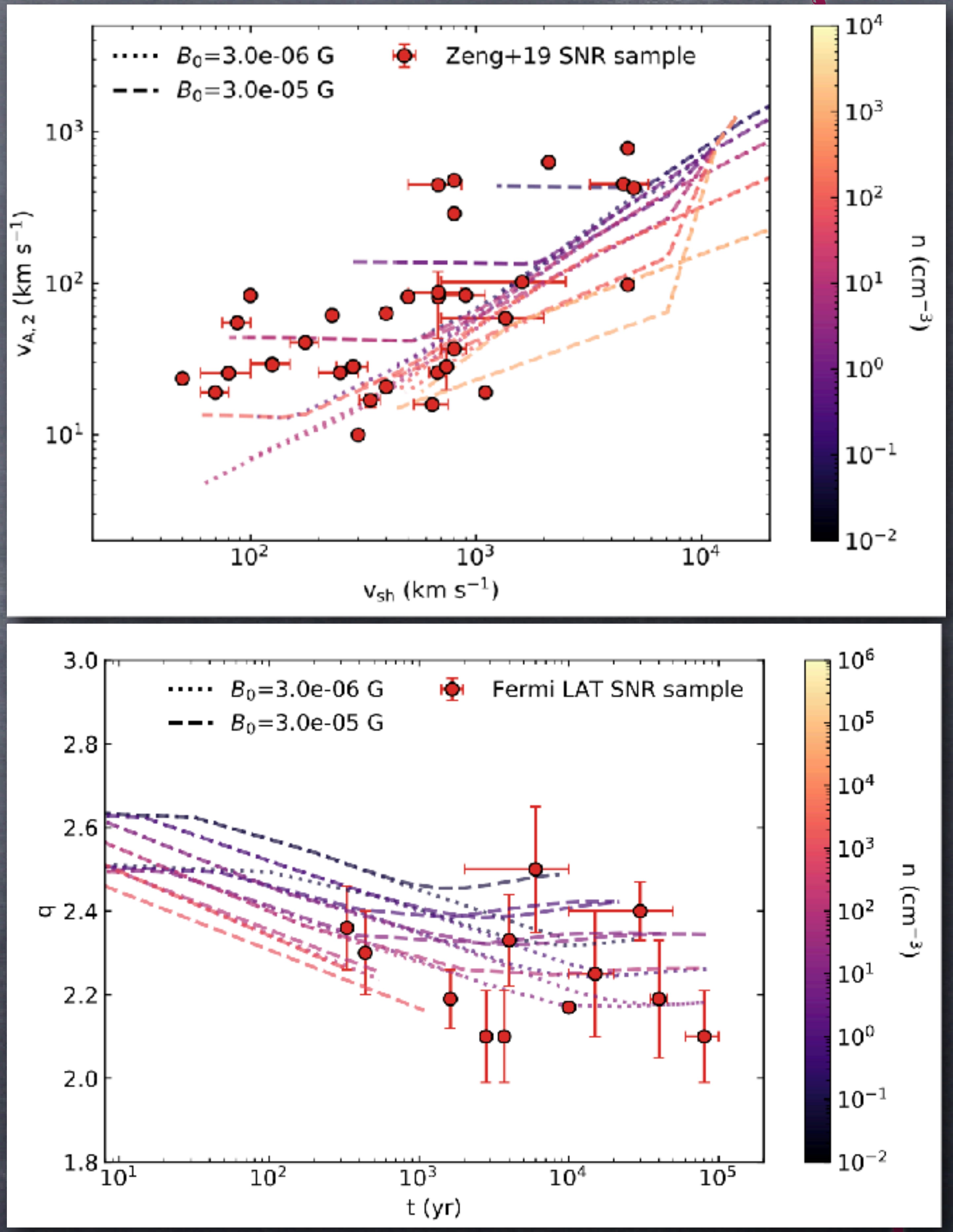




This is likely a generic feature of *nova* eruptions and maybe even SN explosions!

Example 3: Spectral Indexes in SNRs and Radio SNe

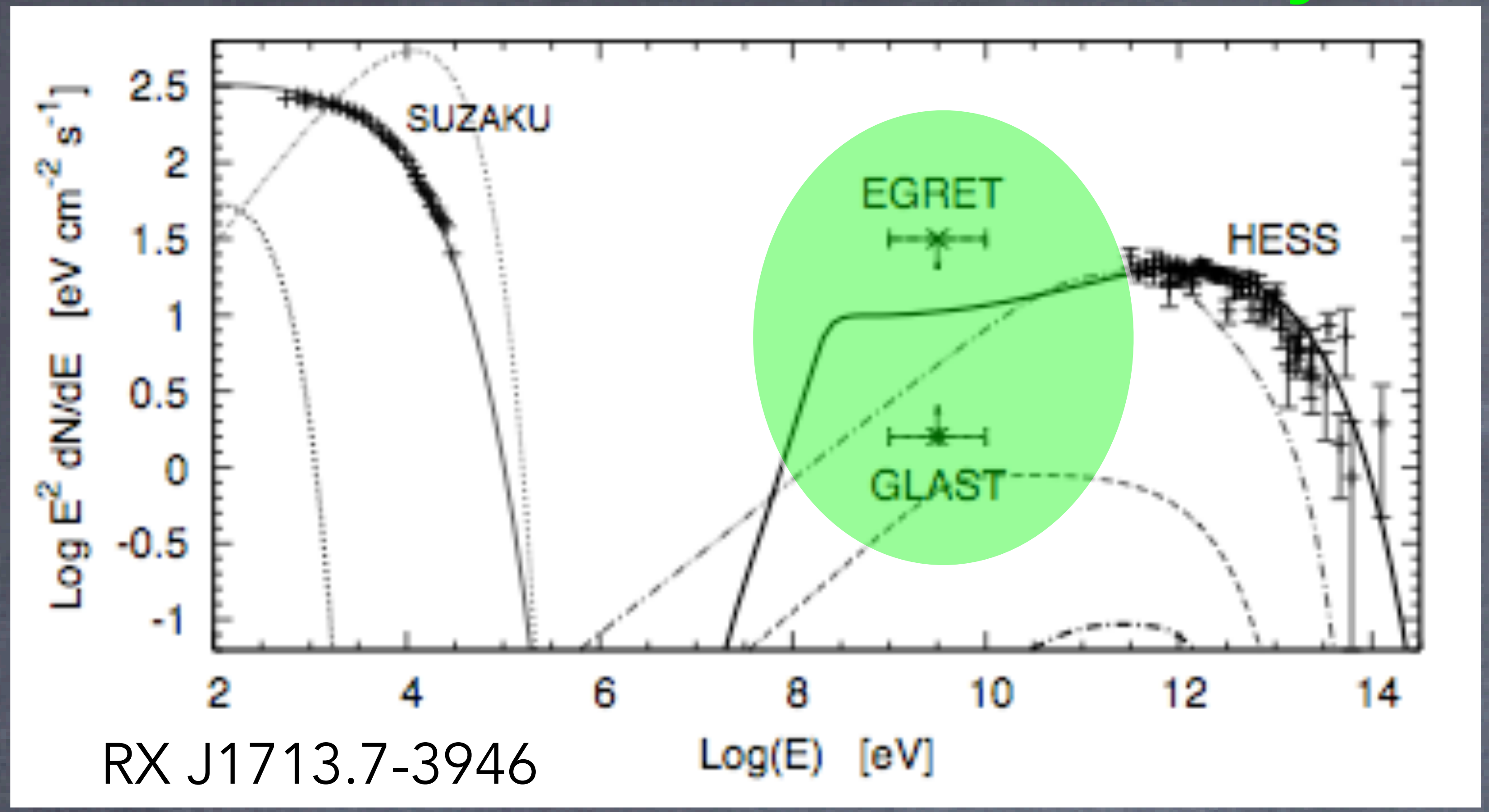
- B amplification controls the CR spectrum, making it steeper (Caprioli+21)
  - Young SNe ($v_{sh} \sim 10^4$ km/s): $f(E) \propto E^{-3}$
  - SNRs ($v_{sh} \sim 10^3$ km/s): $f(E) \propto E^{-2.3} - E^{-2.7}$
- The saturation of the Bell instability *naturally* explains both regimes!
  - see also Cristofari, Blasi & Caprioli 2022
- Modeling of shock-powered transients, including synchrotron absorption (Diesing+ in prep)
  - Radio SNe, kilonovae, COWs/FBOTs, …



Diesing & Caprioli 2021

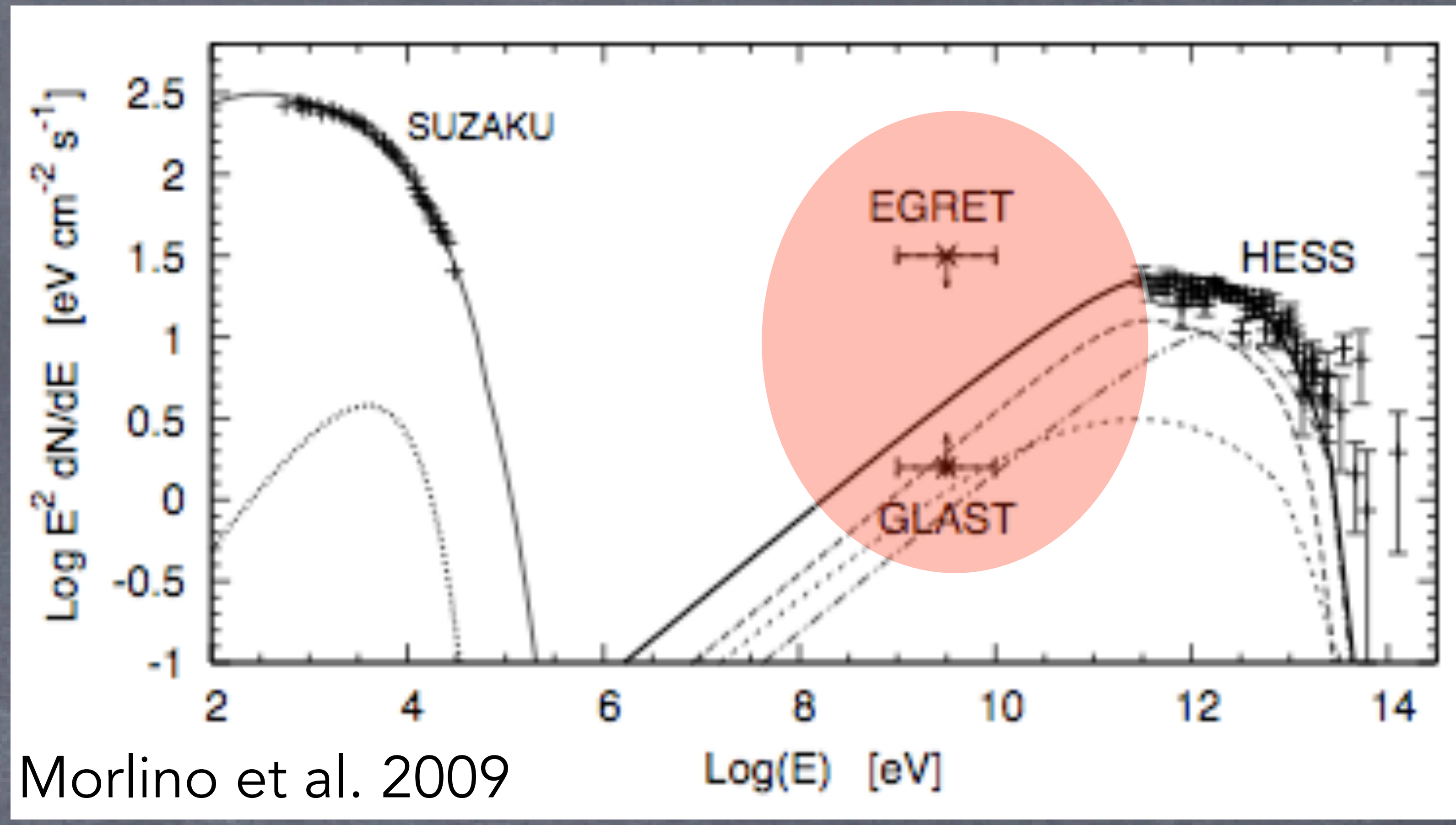
Hadronic vs Leptonic Scenarios

HADRONIC (π_0 decay)



γ-ray spectrum parallel to the proton one (~E^{-2})

LEPTONIC (Inverse Compton)



γ-ray spectrum flatter than the proton (electron) one (~E$^{-1.5}$)

- Shock-accelerated spectra are steeper than E^{-2} when acceleration is efficient
  - Studied self-consistently in PIC simulations (Haggerty+20, Caprioli+20)
  - Slope depends on B-field amplification (Zacharegkas, Caprioli, Haggerty+23)
  - Solves tension between theory and observations of SNRs, radio SNe, Galactic CRs (Caprioli11)

Example 4: SNR *Hadronicity*

- CRAFT: time-resolved, synthetic spectra for different SNR environments (Corso, Diesing, DC 23)
  - The *γ-ray nature depends only on the SNR environment!*
    - Crucial to account for B amplification
    - Useful for predicting neutrino fluxes (Simon, Diesing, DC, in prog.)

Hadronicity:

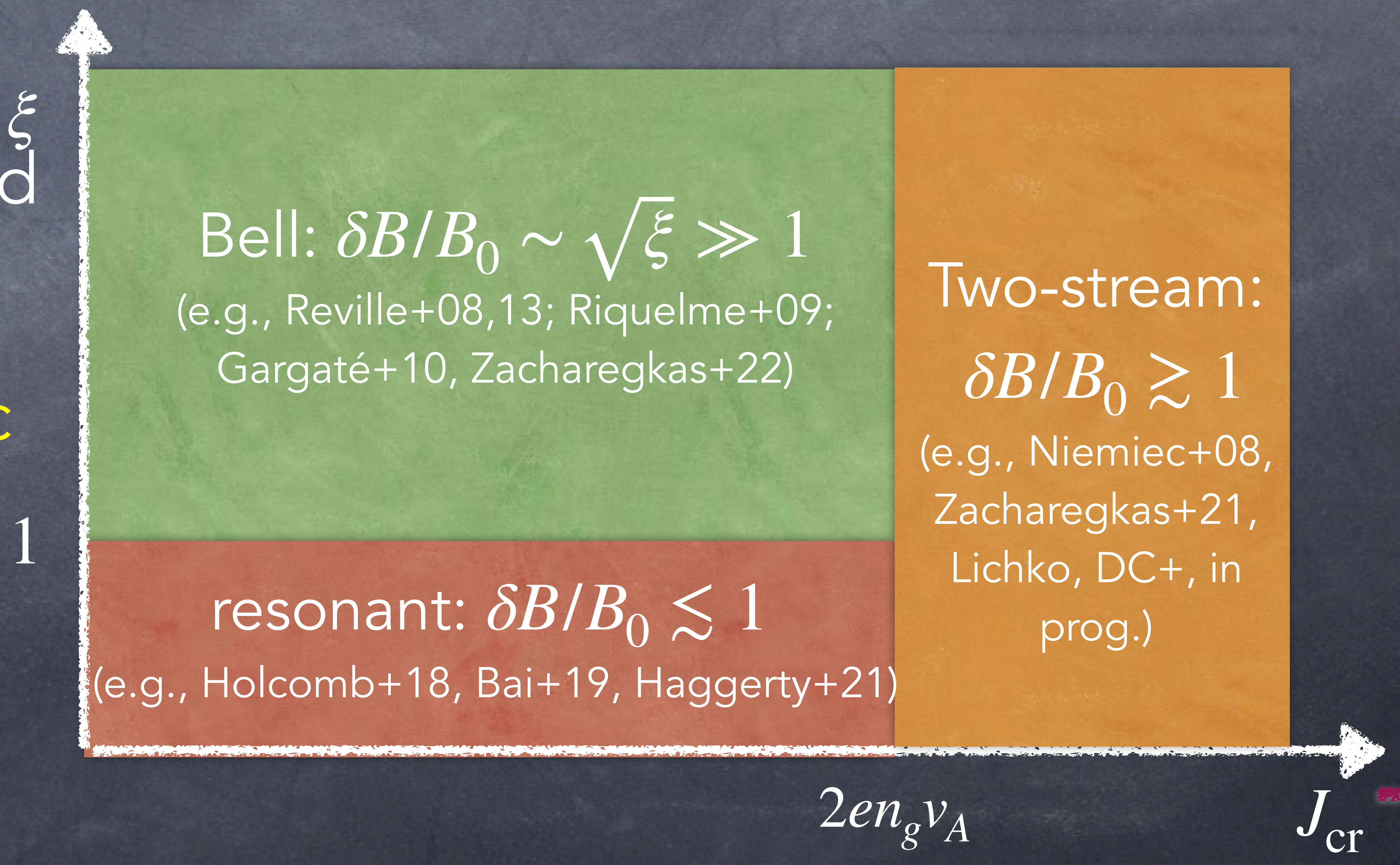
$$H = \frac{2}{\pi} \arctan\left[\log\left(\frac{L_{\rm had}}{L_{\rm lep}}\right)\right]$$

Resonant Streaming Instability

Maybe a *Not-so-simple* Question?

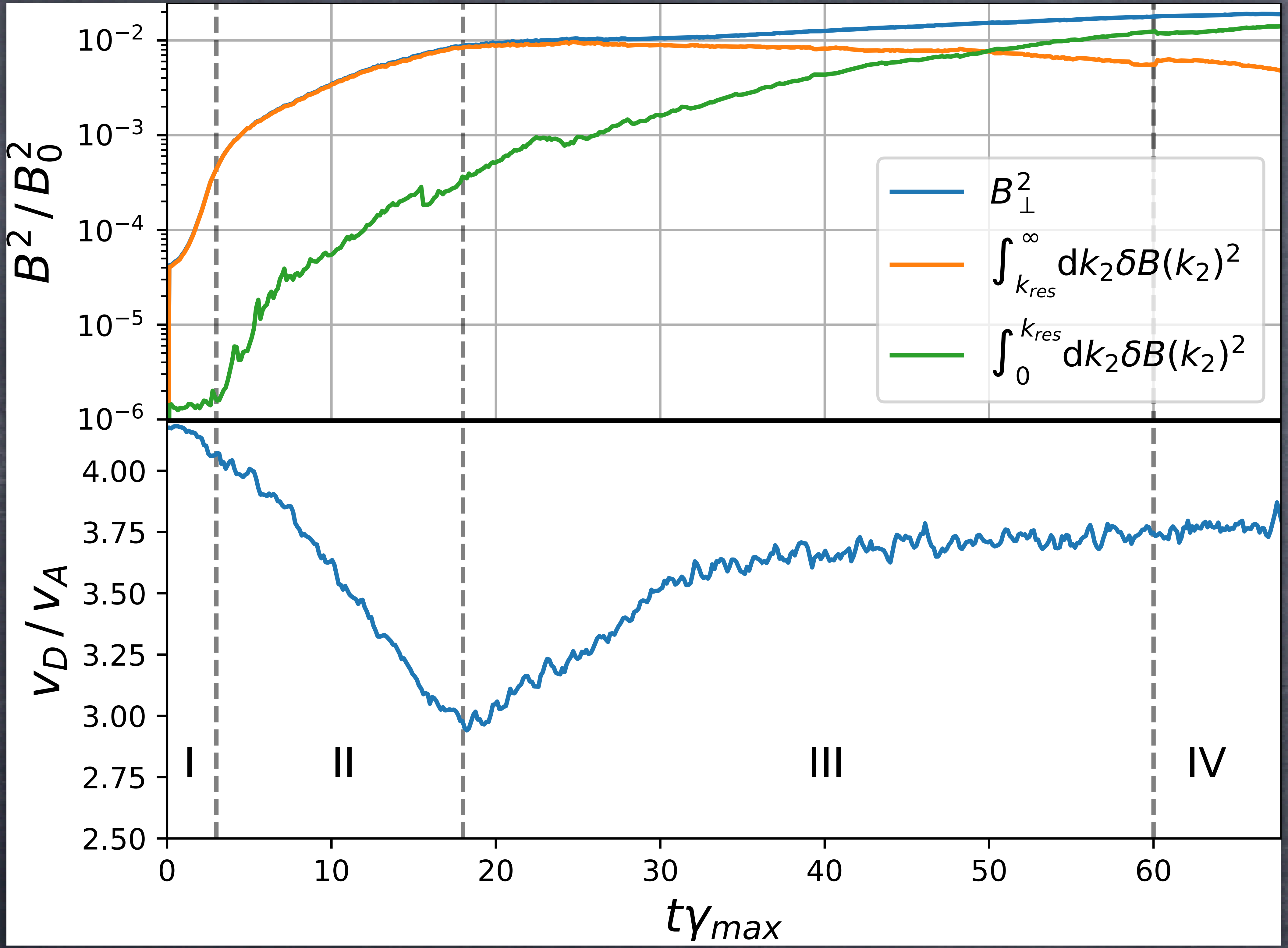
- Depending on the CR parameters, the: filamentation, Weibel, (modified) two-stream, Buneman, resonant, "interm-scale", Bell, … instability may grow the fastest (e.g., Bret 2009)
  - *Caveat*: *fastest* growing doesn't imply *most important* for saturation!
- Most important regime for CR transport in the Galaxy: resonant instability

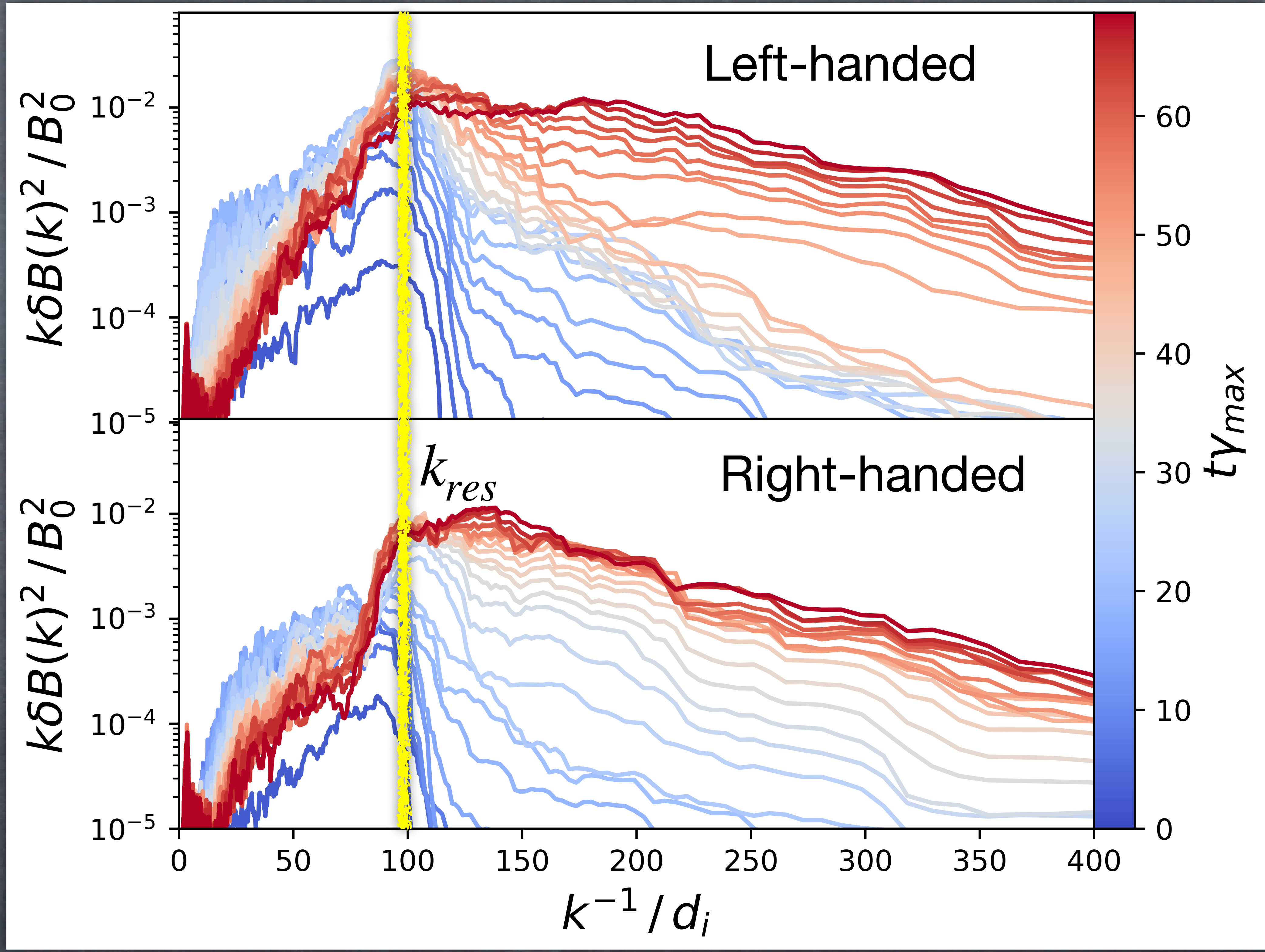
- Likely balance between growth and some damping
- Transition from intrinsic to extrinsic turbulence?
  - Need to explain, e.g., B/C, Be…



Towards Understanding Diffusion in the Galaxy

- Does SI always trap CRs? No: diffusion requires a relic drift speed $v_d(p) \sim \frac{D(p)}{f(p)} \frac{df(p)}{dz}$
- Need to balance SI with: ion-neutral,… non-linear Landau damping (NLLD)
- 1D hybrid simulations of resonant SI, for Galactic-like conditions (Schroer, DC, Blasi 2024)





- Checks all the *signatures* of NLLD (Lee-Völk 73: modification of Maxwellian, *inverse energy cascade*)
- First evidence of a *relic drift energy*: self-generated diffusion

Summary

- **Non-resonant (Bell) Instability**
  - A *simulation-validated* prediction for saturation (Zacharegkas+2024)
  - Controls shock dynamics and CR acceleration (Haggerty & DC20, DC+21, Diesing & DC 2023)
  - CR propagation around sources (Schroer+2021, 2022)
  - Relevant at scales probed by current galaxy simulations (Semenov+2021)
- **CRAFT: CR Analytical Fast Tool,**
  - Fast tool for calculating CR spectra, including important plasma physics
  - Applied to SNRs, SNe, novae, expected hadronicity (Morlino+12, Diesing+21,23; Corso+23, Simon+ in prog.)
- **Resonant Streaming Instability**
  - Saturation unknown; depends on balance with non-linear Landau damping (Schroer+24)
  - Responsible for the formation of the galactic halo (Schroer+ in prog)
  - May control CR propagation in the Galaxy and CR feedback

End