Galactic cosmic rays: acceleration and transport

Recent progresses and some perspectives

A.Marcowith (L.U.P.M.)

The standard model of galactic cosmic ray

Drury et al 2001 SSR vol 99 329

Cosmic-Ray sources

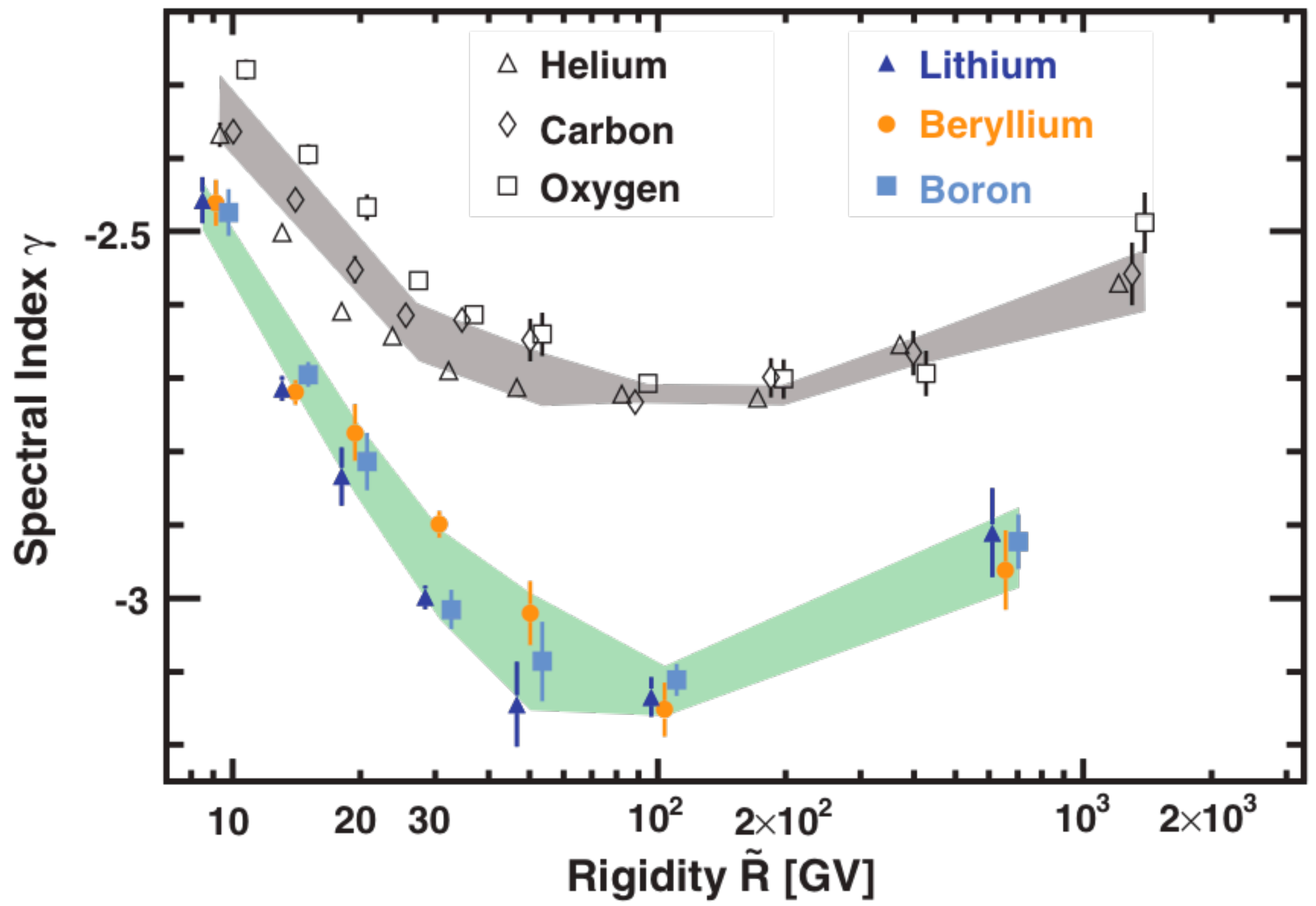
- Cosmic Rays up to at least the knee are accelerated at high Mach supernova remnant shocks by the diffusive acceleration process (DSA).
- The maximum CR energy is reached at the start of the Sedov phase.
- The accelerated matter has a similar composition to solar system matter.

Cosmic-Ray transport

- CR propagate in the interstellar medium (ISM) diffusively.
- CR secondaries produced by spallation reaction explain some elements overabundances (eg Li-Be-B)
- The diffusive transport explains the high angular spectrum isotropy.

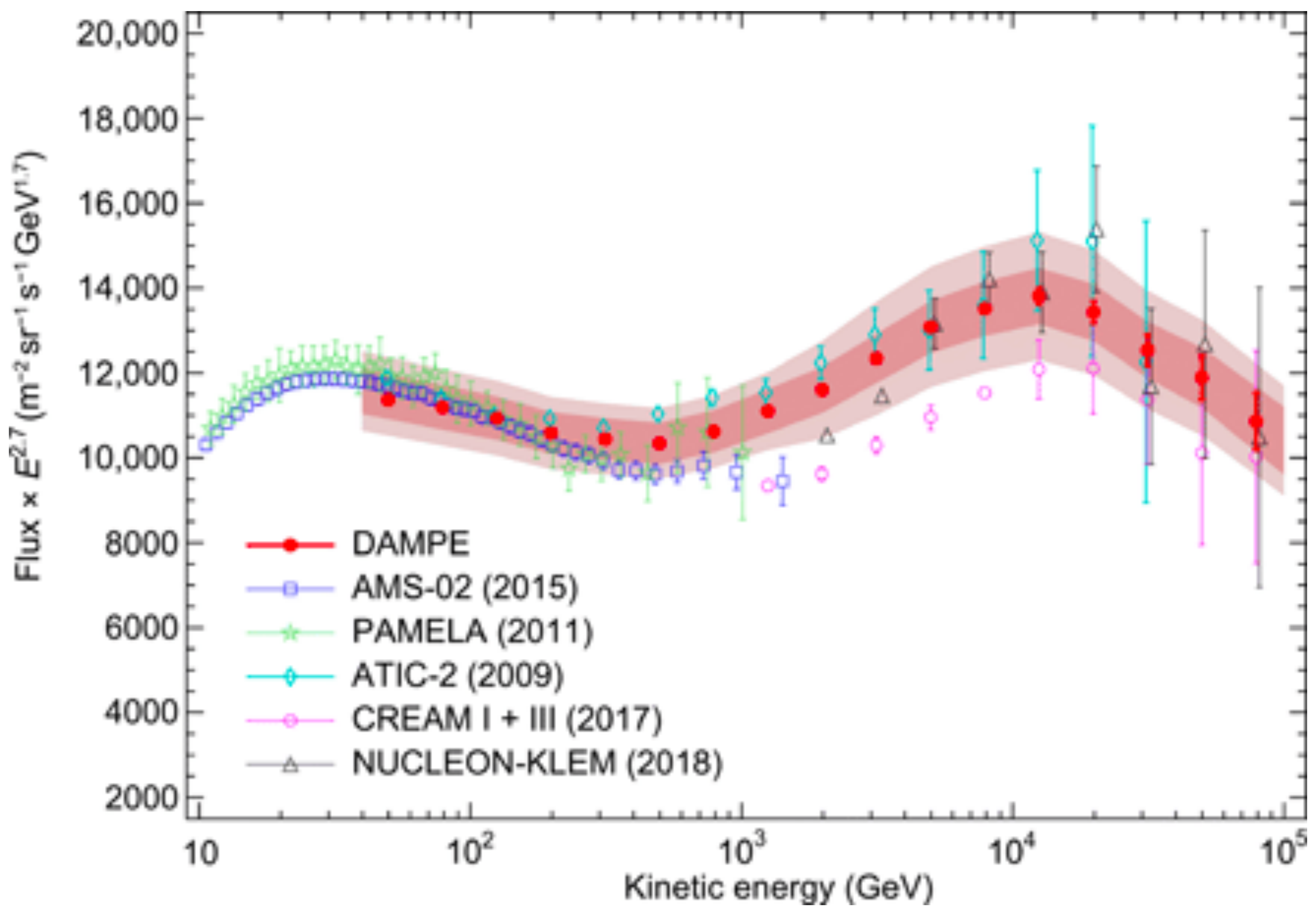
Some (not exhaustive) new features

Spectral hardening around 200 GeV/N



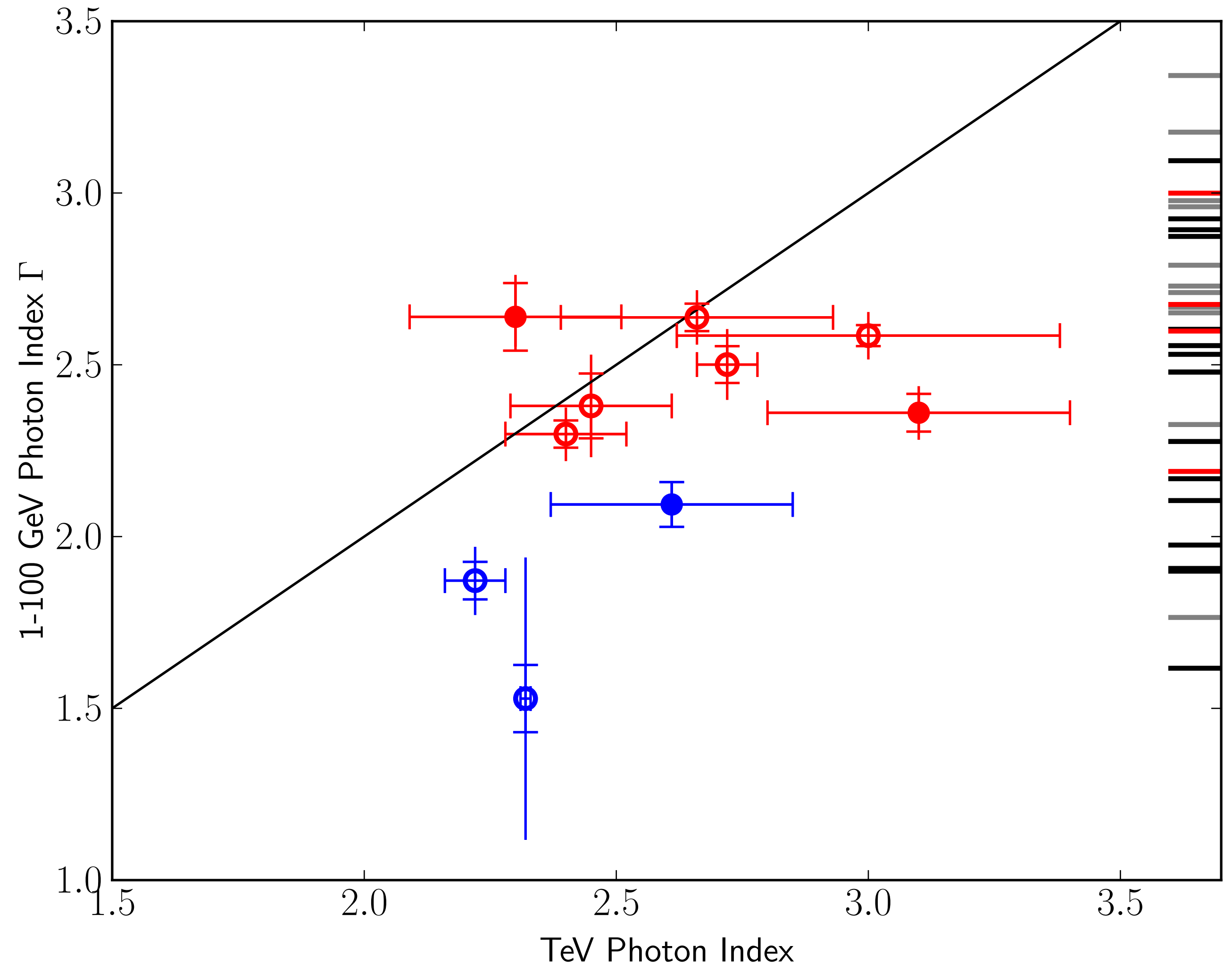
AMS collaboration PRL 2018 120 021101

Spectral bump around 1 TeV



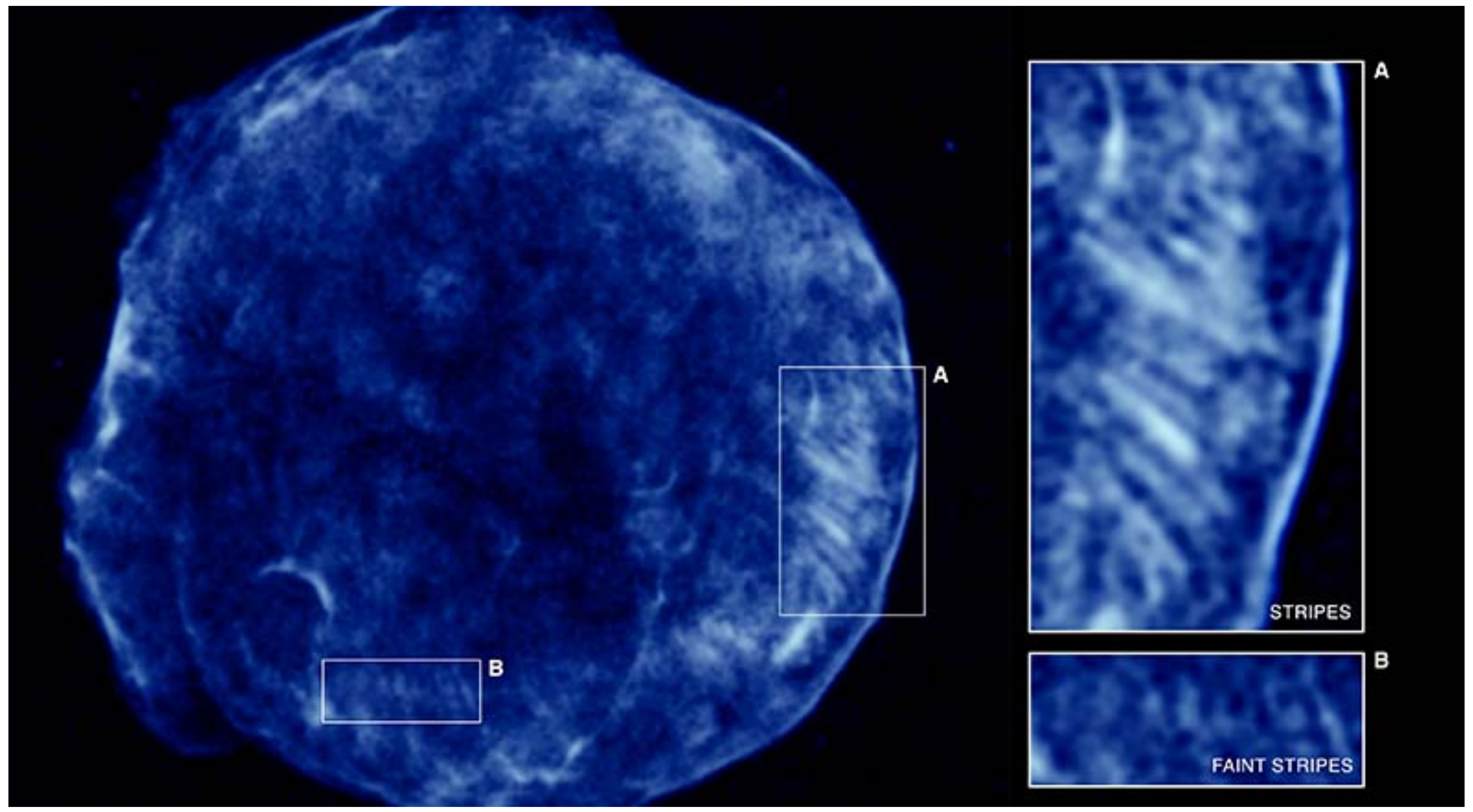
DAMPE collaboration Science adv 2018 5 3793

SNR Gamma-ray spectral index GeV-TeV



Acero et al (Fermi) ApJS 2016 224 8

Tycho X-ray stripes and filaments



Eriksen et al 2011 ApJ 728 L28

New observational results from direct or indirect measurements => standard paradigm has to include cosmic rays and magnetic fields feed backs in sources and transport problems.

Some hot topics

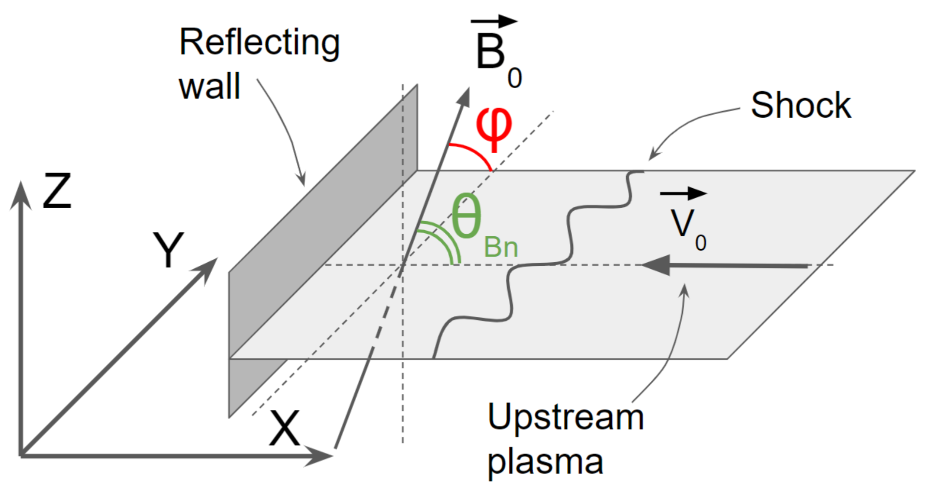
Look for alternative sources **(as)** (superbubbles, early supernova expansion , galactic centre), better understanding of ISM properties **(ism),** CR-turbulence microphysics **(mi). All these may question the standard model.**

- Source spectrum: (as, mi)
  - How to explain softer source spectra $E^{-2.2/-2.4}$?
  - What is the nature of CR self-generated turbulence in sources ?
  - Where are the Pevatrons ?
- Direct measurements: (as, ism, mi)
  - How to explain new CR features in the CR spectrum ?
  - How to explain anisotropy amplitude and phase properly ?
- Indirect measurements: (ism, mi)
  - How to explain the gamma-ray gradient problem ?
- Elemental anomalies: (as)
  - How to explain CR anomalies ? ^{22}Ne, …

Any of these items do have a definite explanation yet

Cosmic Ray acceleration at shocks

- CR at shocks have strong non-linear feed backs:
  - CR carry a lot of current and pressure density, hence they trigger some instabilities and turbulence (X-ray stripes).
  - Shock acceleration is a *multi-scale* phenomenon (space plasma shocks have less dynamics) : this makes simulations very difficult.
  - However a series of problems have been addressed recently with some success using a panel of kinetic and or fluid simulations:
    - Particle injection
    - Instability driving and magnetic field amplification

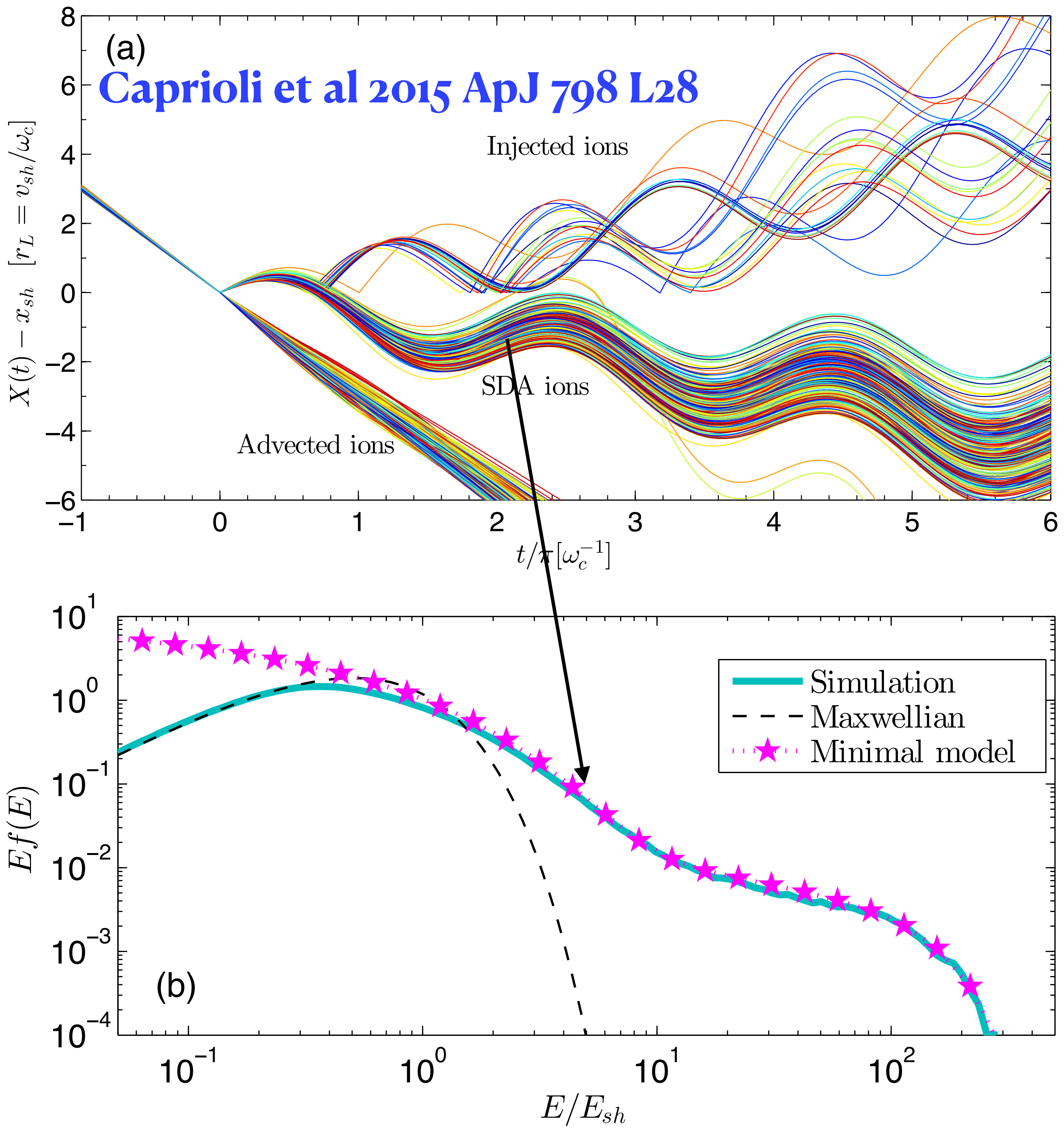


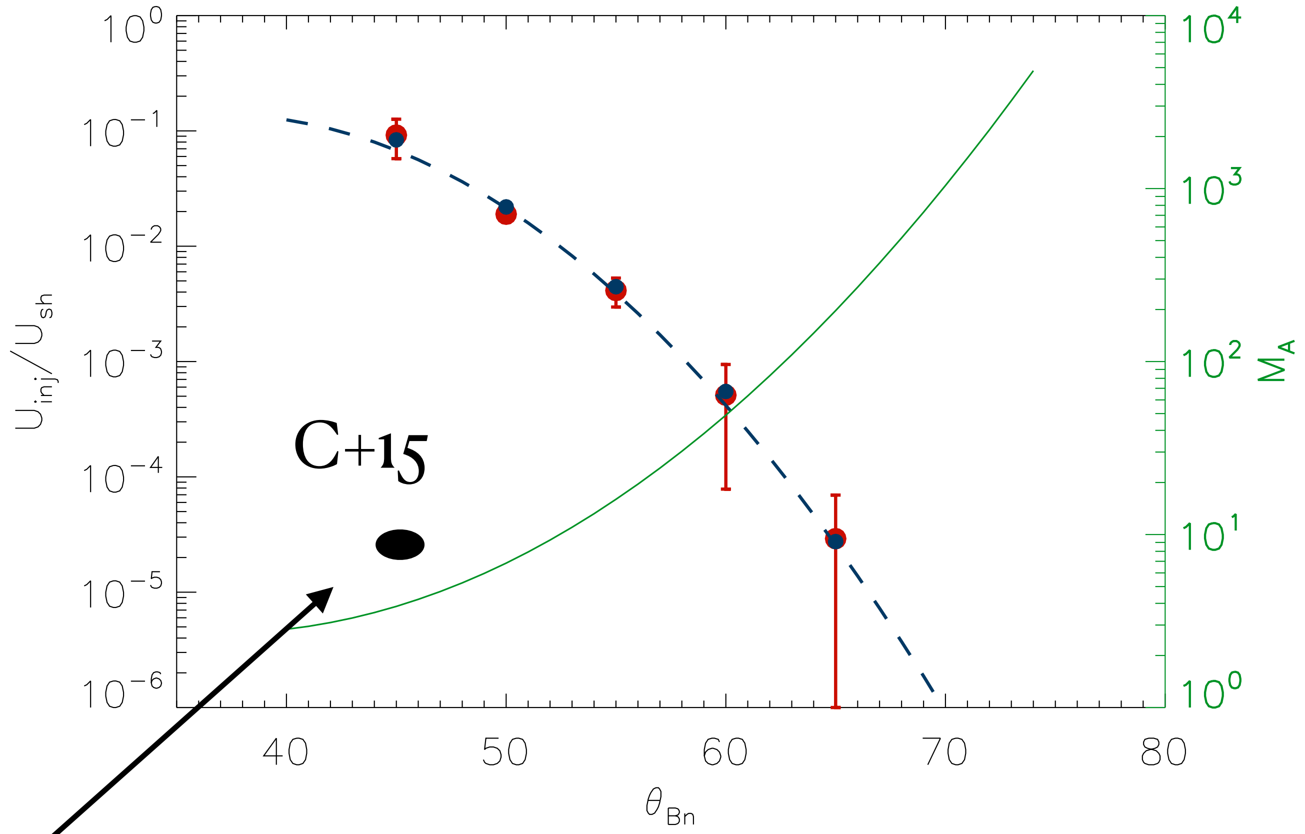
Particle injection : obliquity effects

Particle-in-cell / hybrid simulations

- Ion injection: strong effect of magnetic field obliquity, injection drops above 60°

Ion injection for a Mach 10 shock, and obliquity angle 45°

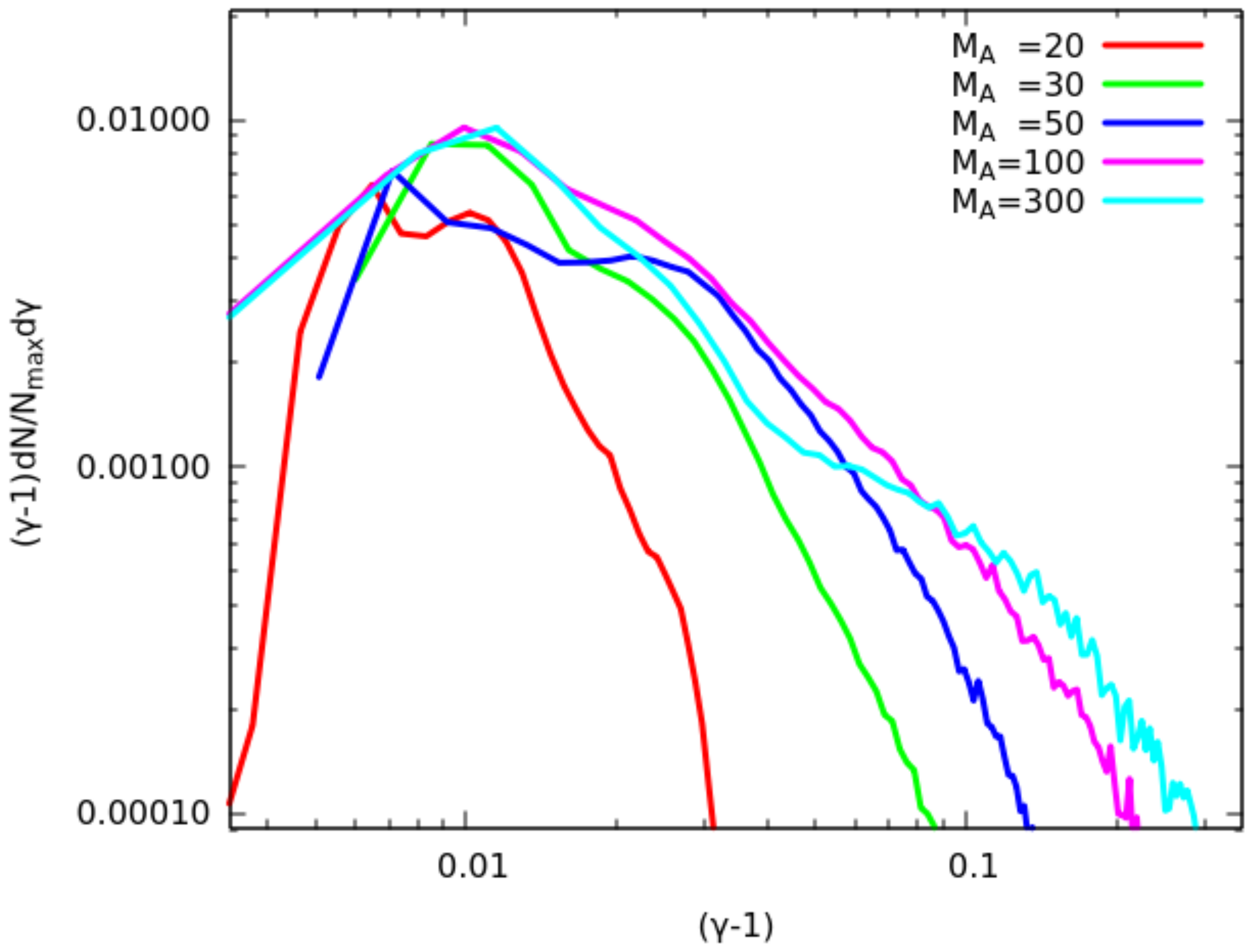




Black: energy density in injected ions / kinetic shock energy density as function of MF obliquity for M=20.

Green: critical Alfvenic Mach necessary for ions to start DSA as function of magnetic obliquity

AJ van Marle et al in prep



Spectral energy distribution at the shock front for an obliquity of 60°
DSA occurs above M~50 **(combining PIC and MHD)** but based on injection rates provided by PIC simulations.

electron injection (see back up)

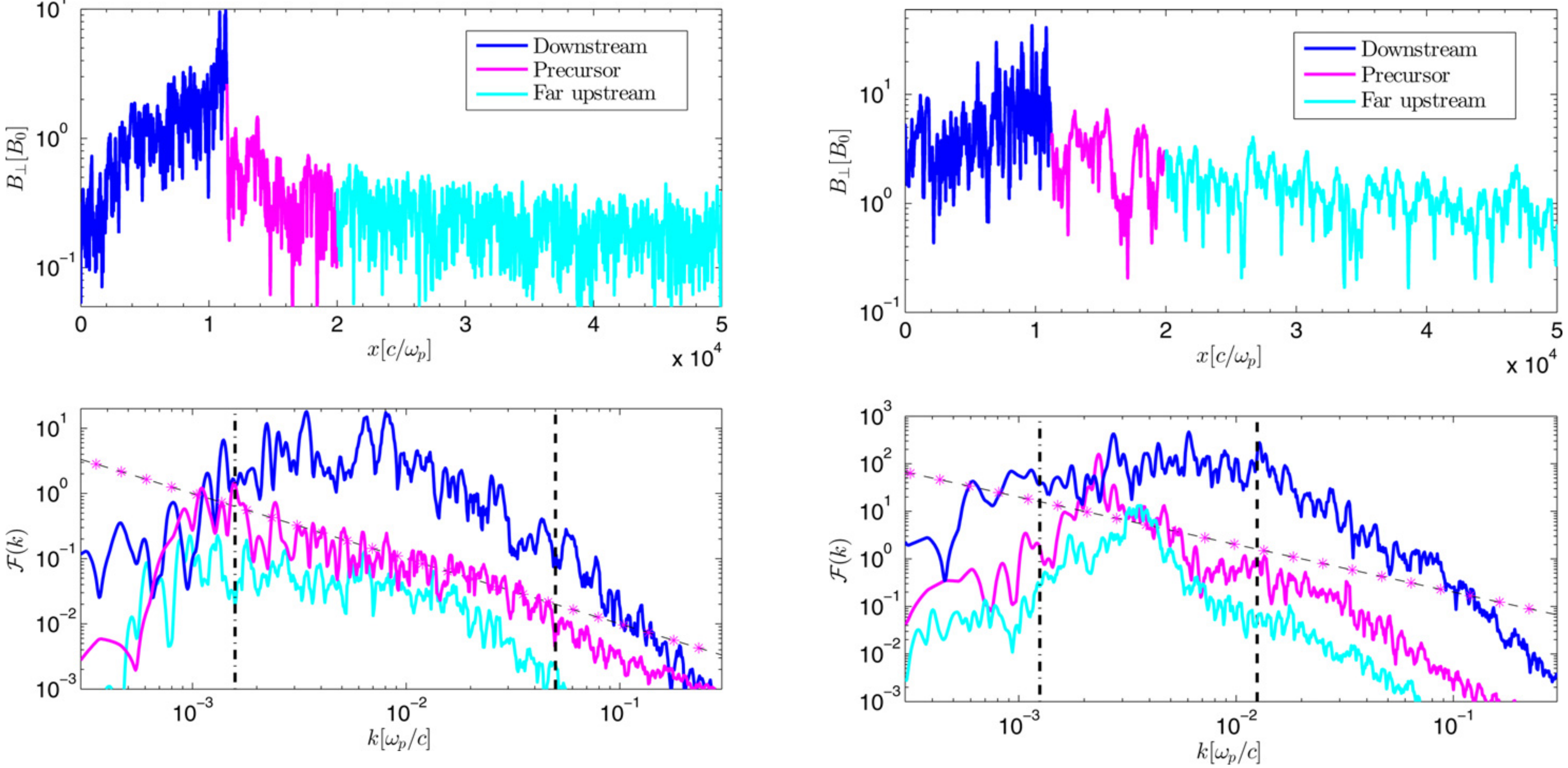
Magnetic field amplification

Particle-in-cell/hybrid/magnetohydrodynamics

- The dominant instability depends on the shock Alfvenic Mach number

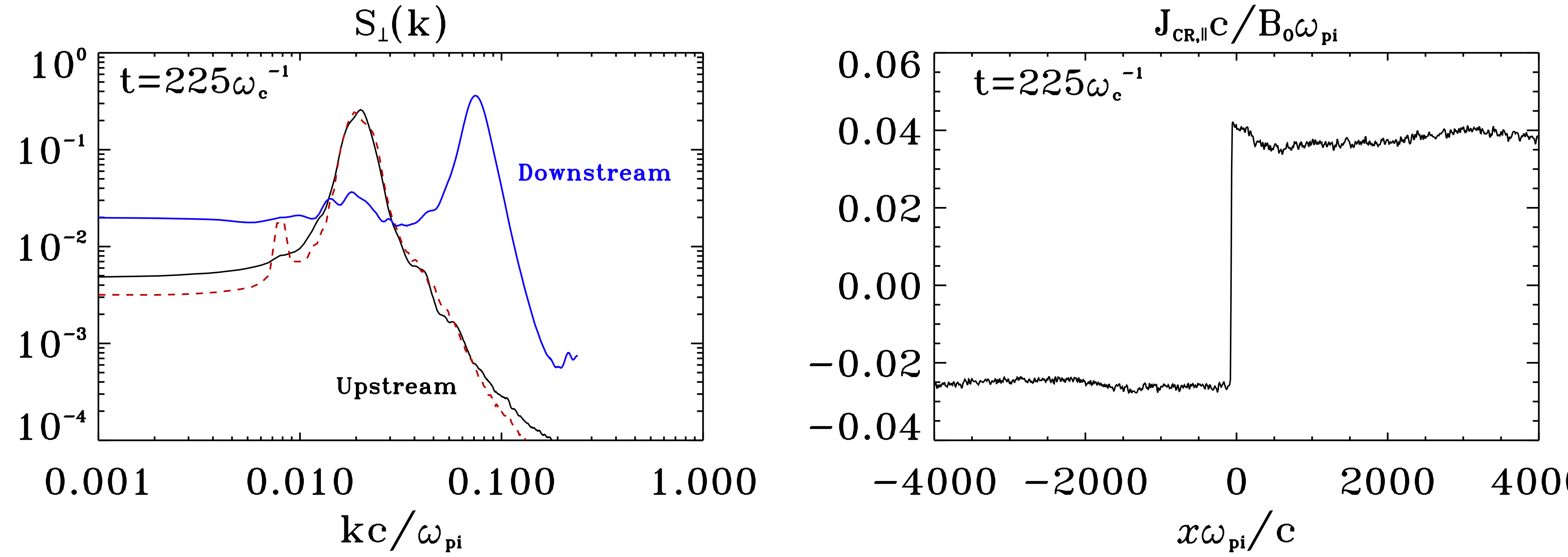
Low Mach shocks : resonant streaming (see A.Marret's talk) instability ($F(k) \sim k^{-1}$)

M=20 M=80



Caprioli & Spitkovsky 2014 ApJ 794 46 **(hybrid method)**

High Mach shocks : non-resonant streaming instability, magnetic field amplitude is higher



van Marle et al 2018 MNRAS 473 3394 **(combining MHD and PIC)**

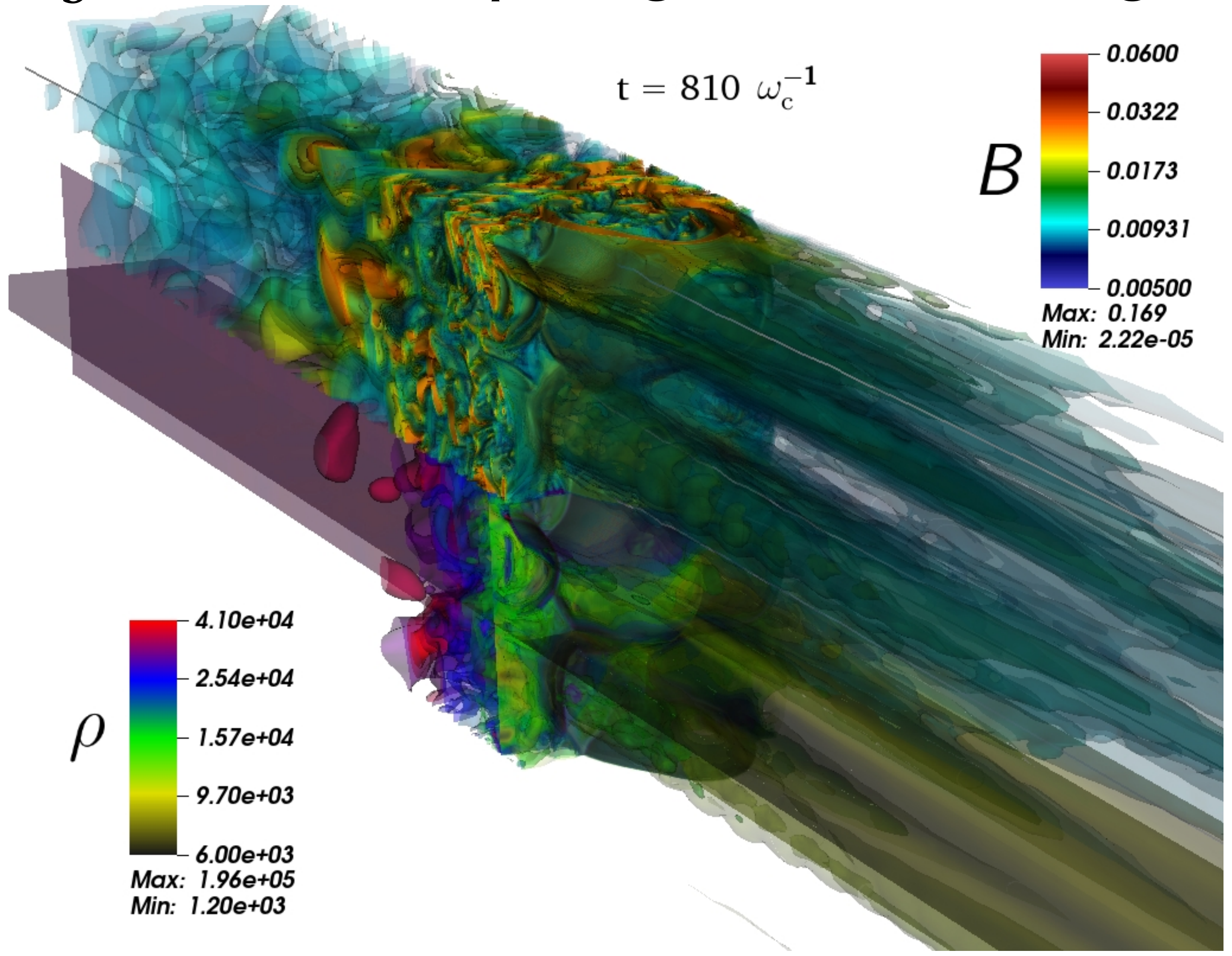
<u>Saturation levels</u>: Magnetic energy density.

$$\left(\frac{\delta B_{\rm sat}}{B_{\rm back}}\right)^2 \simeq 3\left(\frac{P_{\rm CR}}{\rho u_{\rm sh}^2}\right) M_{\rm A}\ ,\ M_{\rm A} = u_{\rm sh}/V_{\rm A}$$

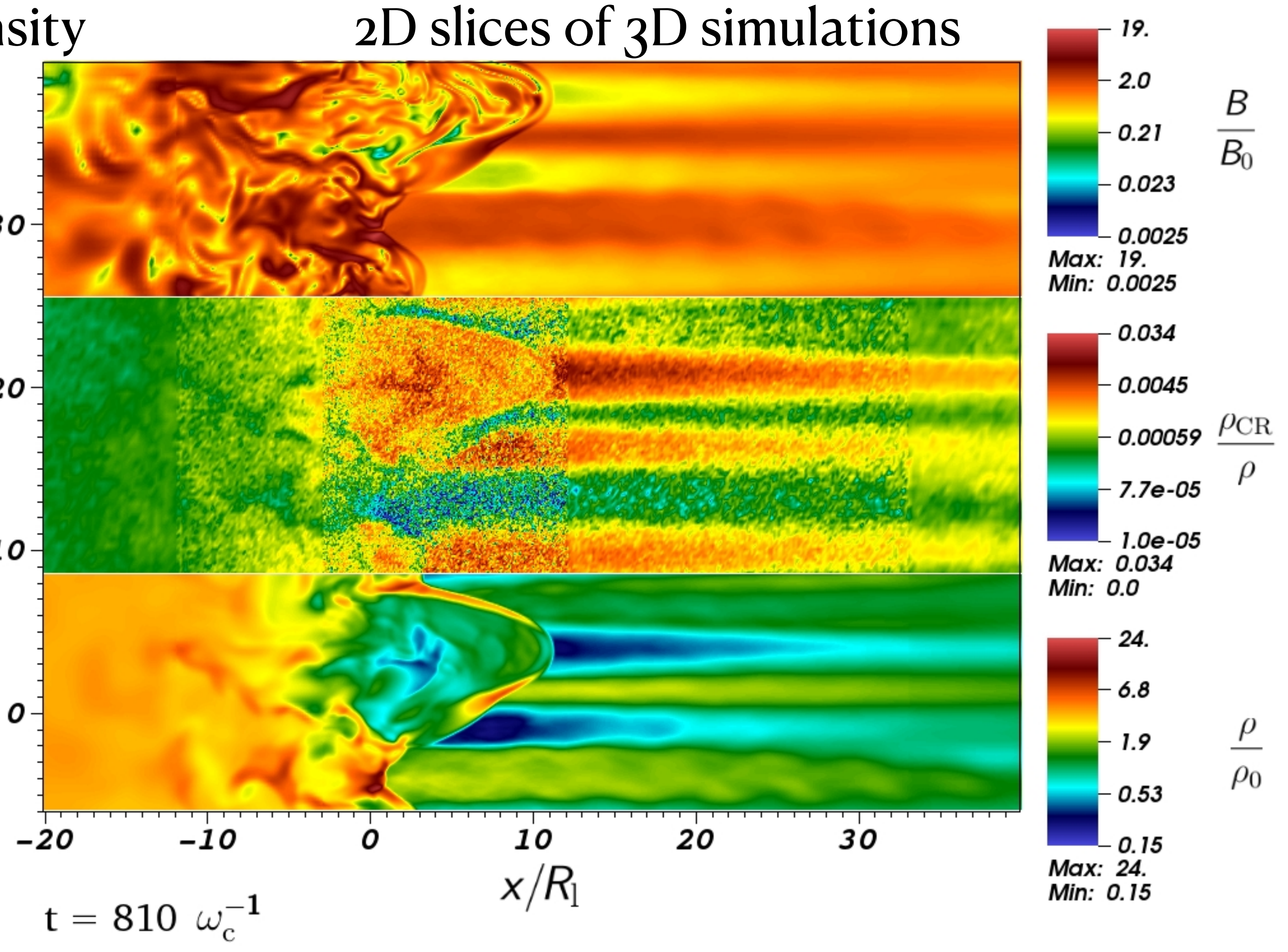
CR sources : Still some numerical challenges

- A great challenge is to address the feed back of high energy particles over the shock structure in multi-D simulations.
  - shock corrugation effects by CR-driven turbulence : obliquity and injection rates are space and time-dependent.

3D simulations (up): magnetic field (down) gas density



2D slices of 3D simulations



- One difficulty is to re-evaluate the injection including now large scale (HE CR Larmor radii) turbulent perturbations in 2D-3D configurations.
- Then, derive a self-similar CR spectrum building, and maximum energy increases with time.
- We also need to properly account for HE CR escape upstream.

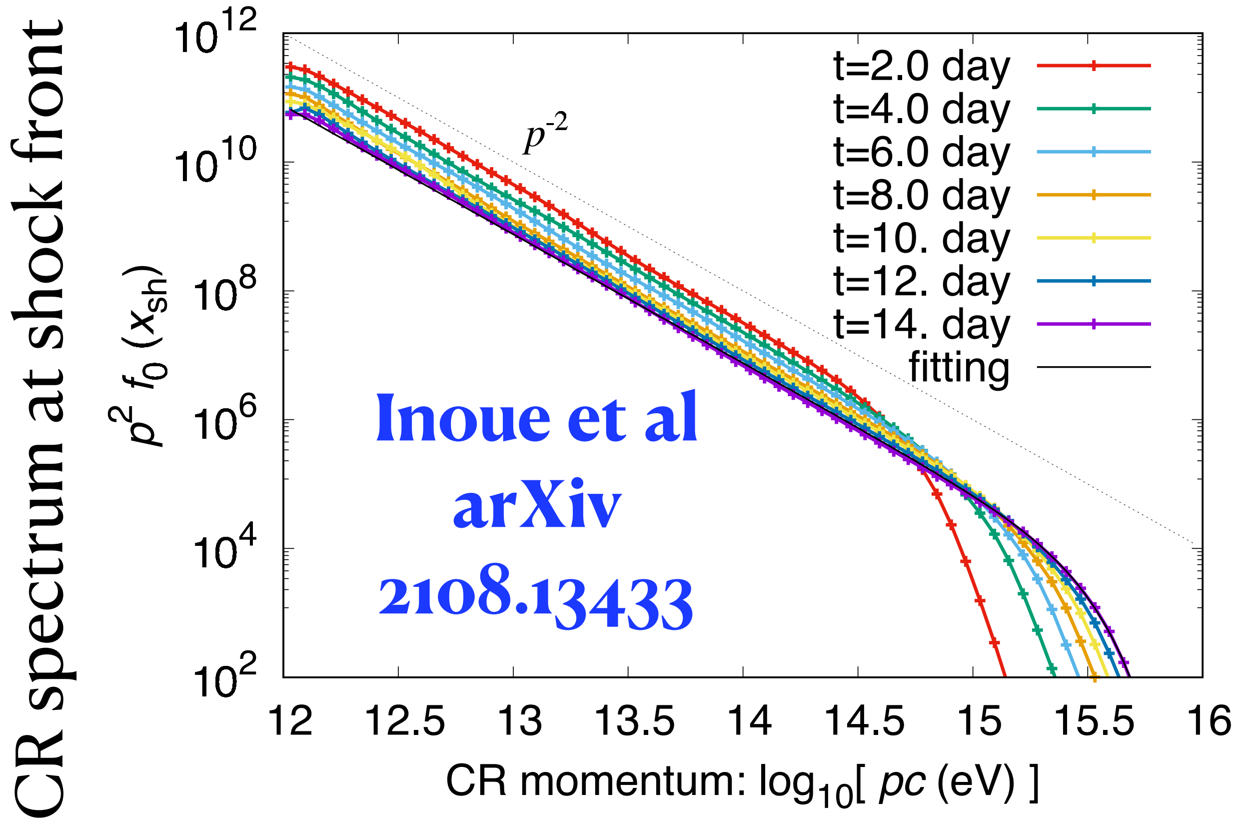
AJ van Marle et al MNRAS 2019 490 1156

Solutions to derive E_{max}?

E_{max} still out of reach using first principles simulations. We have to rely on other methods combining MHD and kinetic Eqs.

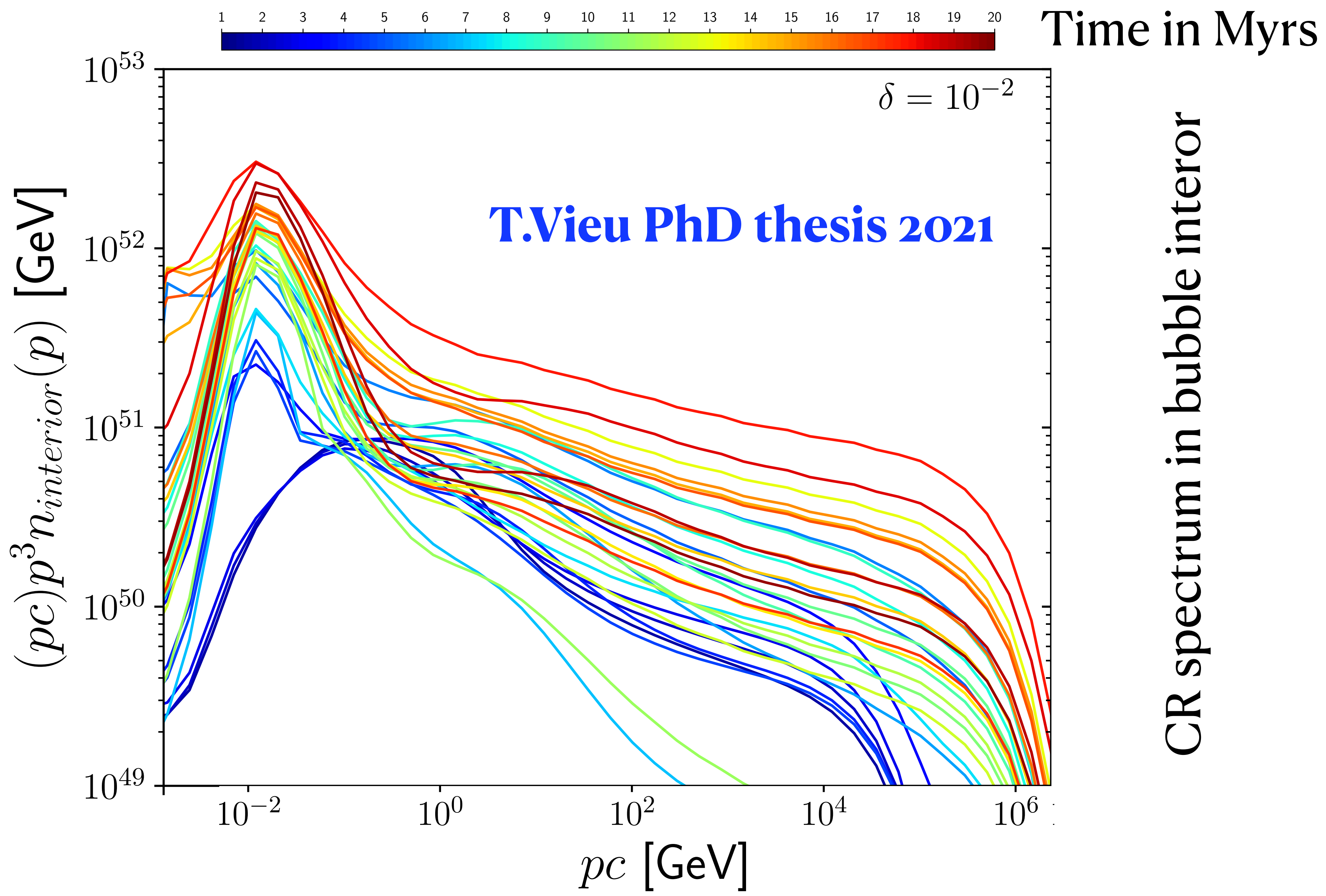
Examples of alternative CR sources.

- <u>Young supernova remnants and supernovae</u> [MHD+solving 1D Fokker-Planck Eq in spherical geometry]
  - Faster shocks (10 000 km/s) moving in dense circum-stellar winds (instability growth time reduced)



Case of core-collapse SN in a red super-giant wind:

> PeV (CR knee) energies can be reached after one week, needs enhanced mass loss rates (10^{-3} sol mass/year) prior to the explosion.



- <u>Massive star clusters (MSC)</u>

[semi-analytical solutions of diffusion-convection Eqs]

  - Higher energies (up to 100 PeV): Hillas criterium including magnetic turbulence generation in the MSC **(Bykov et al 2001 SSR 99 317)**
  - The CR spectrum shows a strong intermittency depending on: time, stellar content.

Cosmic Ray sources : perspectives for the next decade

- Continue on the development of simulation ressources (exascale initiative).
- CR dynamics at sources : needs for new numerical schemes (combining PIC and MHD on a grid ?).
- Strengthen the links with space plasmas (PNST) and laser plasmas communities (code techniques sharing, laboratory tests of particle acceleration with accurate diagnostics). (support, common meetings @ SF2A)
- Multi-wavelength/messengers: constrain microphysics parameters.

Transport in the interstellar medium

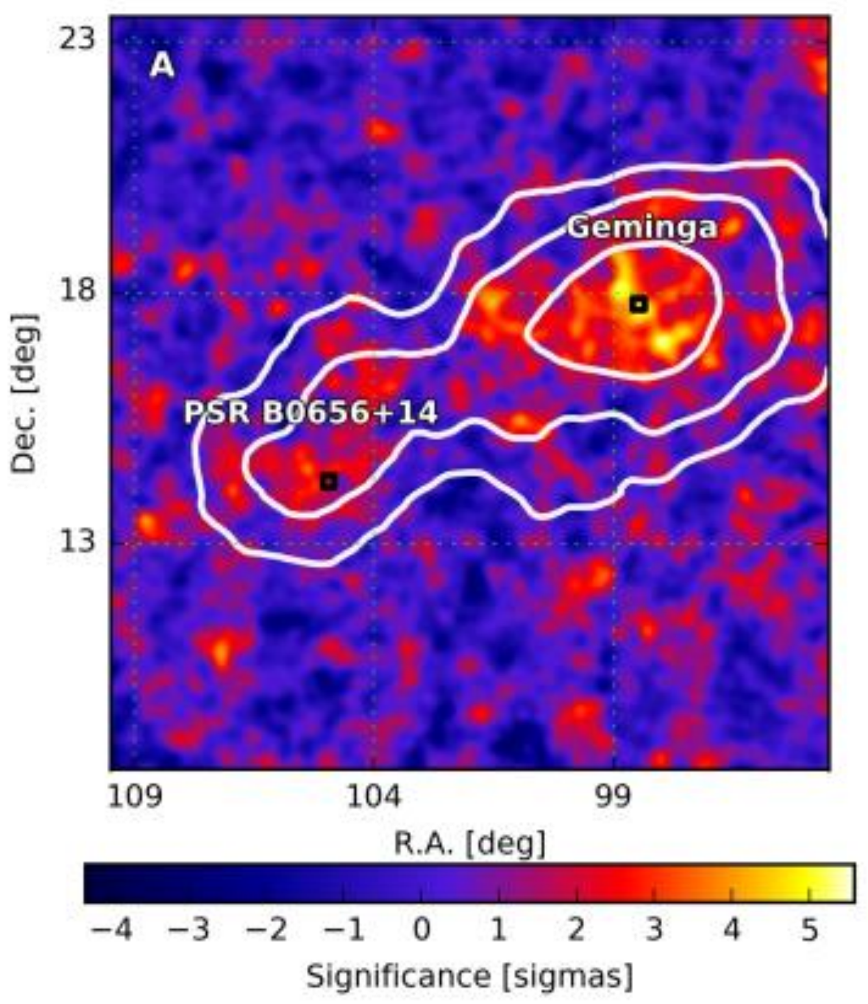
- CR feed back through self-generated turbulence occurs at different scales.
  - in sources (see before)
  - « close » to sources
  - at galactic scales
  - as ionizing particles
- Impact over CR phenomenology (see back up)

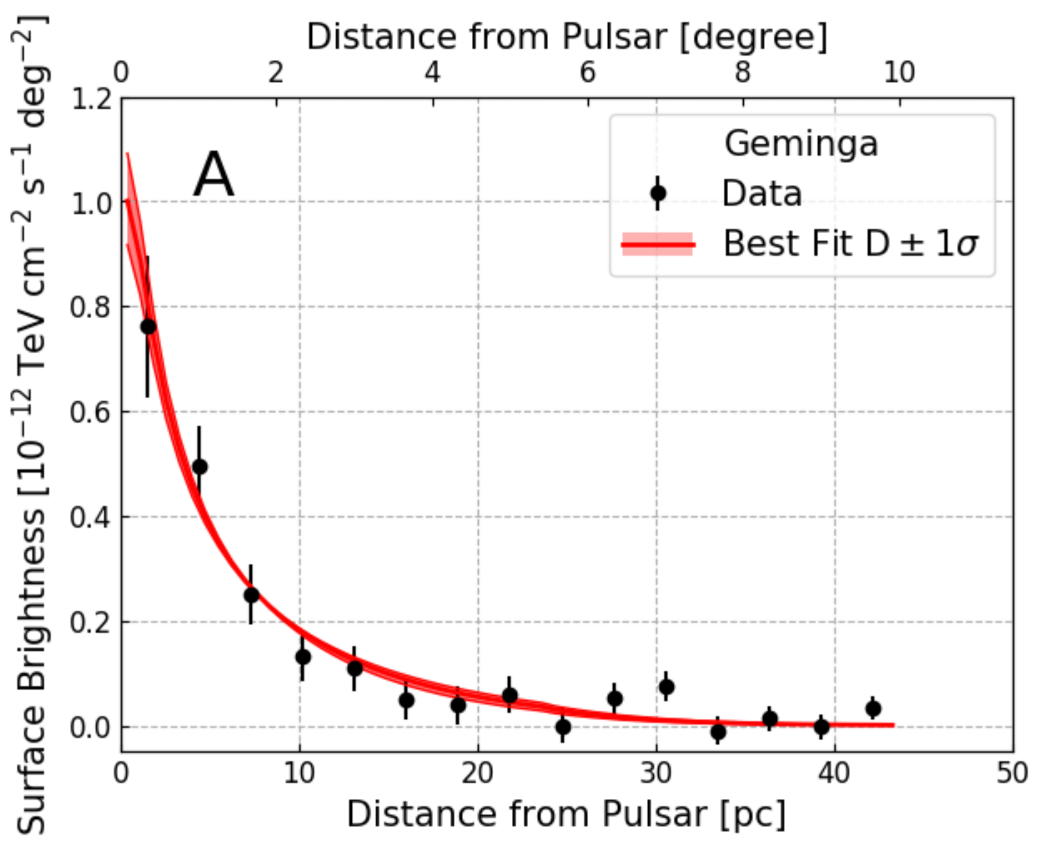
Propagation close to sources

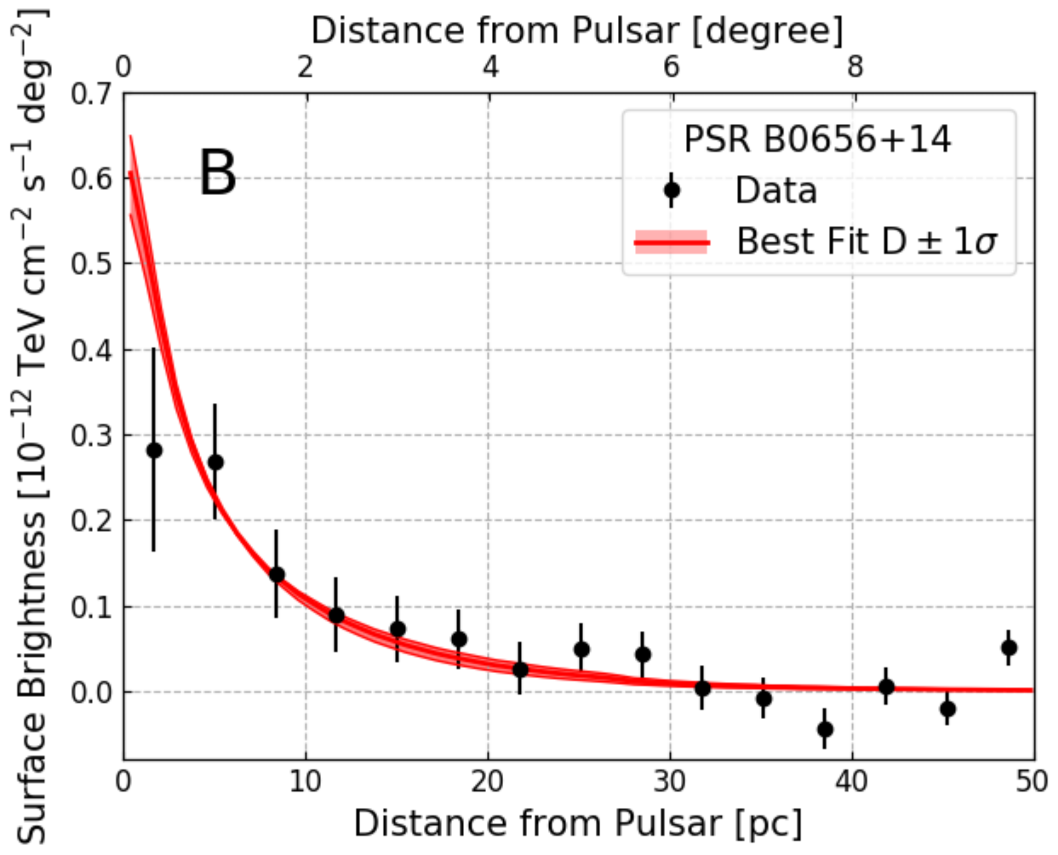
A reduced diffusivity to account to fit phenomenological models (CR intermittency).

- Gamma-ray halos around pulsars
- CR halos around SNR or massive star clusters (see back up).

Gamma-ray halos around pulsars



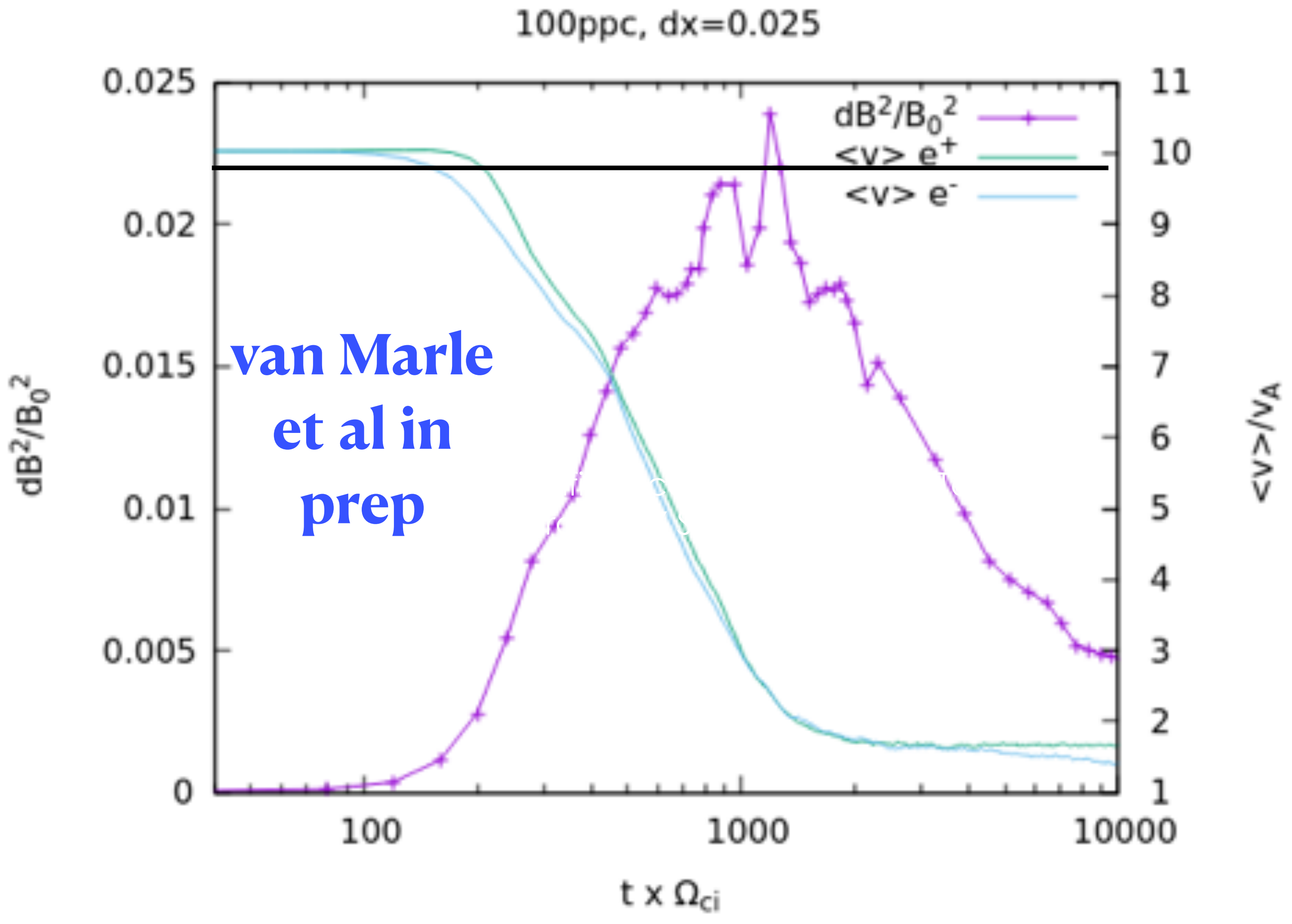




Gamma-ray profiles fit well with a random walk with diffusion coefficients reduced by a factor ~ 100.

Abeysekara et al 2017 Science 358 911

<u>One possible explanation</u> : streaming instability triggered by an electron-positron (e-e) beam **(Evoli et al 2018 PRD 98 3017)**



<u>PIC-MHD set-up</u>: e-e beam moving in electron-proton (e-p) background with n_{ee}/n_{ep}=0.01 and drift speed 0.1 c and 10 $v_{A.}$ e-e distribution Maxwell-Jüttner with T = 10 mc².

> e-e driven resonant streaming instability

> Magnetic field consistent with theoretical expectations (solid black line)

> need a proper rescaling to derive effective diffusion coefficients

> other streaming instability regimes can be induced: dissymmetries in electron/positron abundances, proton component **(Guépin et al 2020 A&A 635 A138)**

Cosmic Ray feed back studies

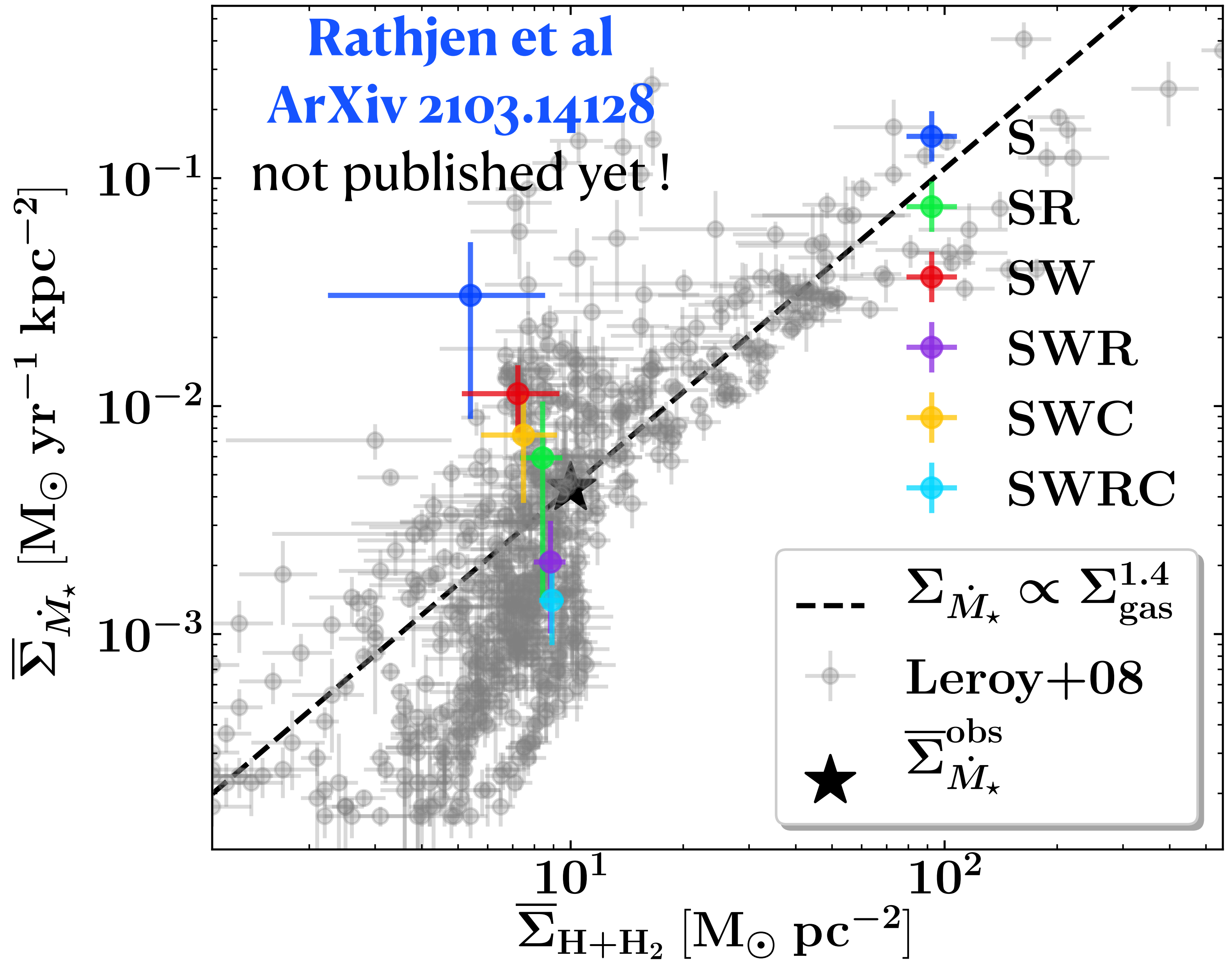
- Huge amount of works this last decade <=> impact of CRs over star formation
  - at large galactic scales : CR wind driven
  - at small scales: in-situ CR injection sources (SNRs, Stellar winds, Young Stellar Objects, reconnection in molecular clouds).

Cosmic Ray Magneto-hydrodynamics

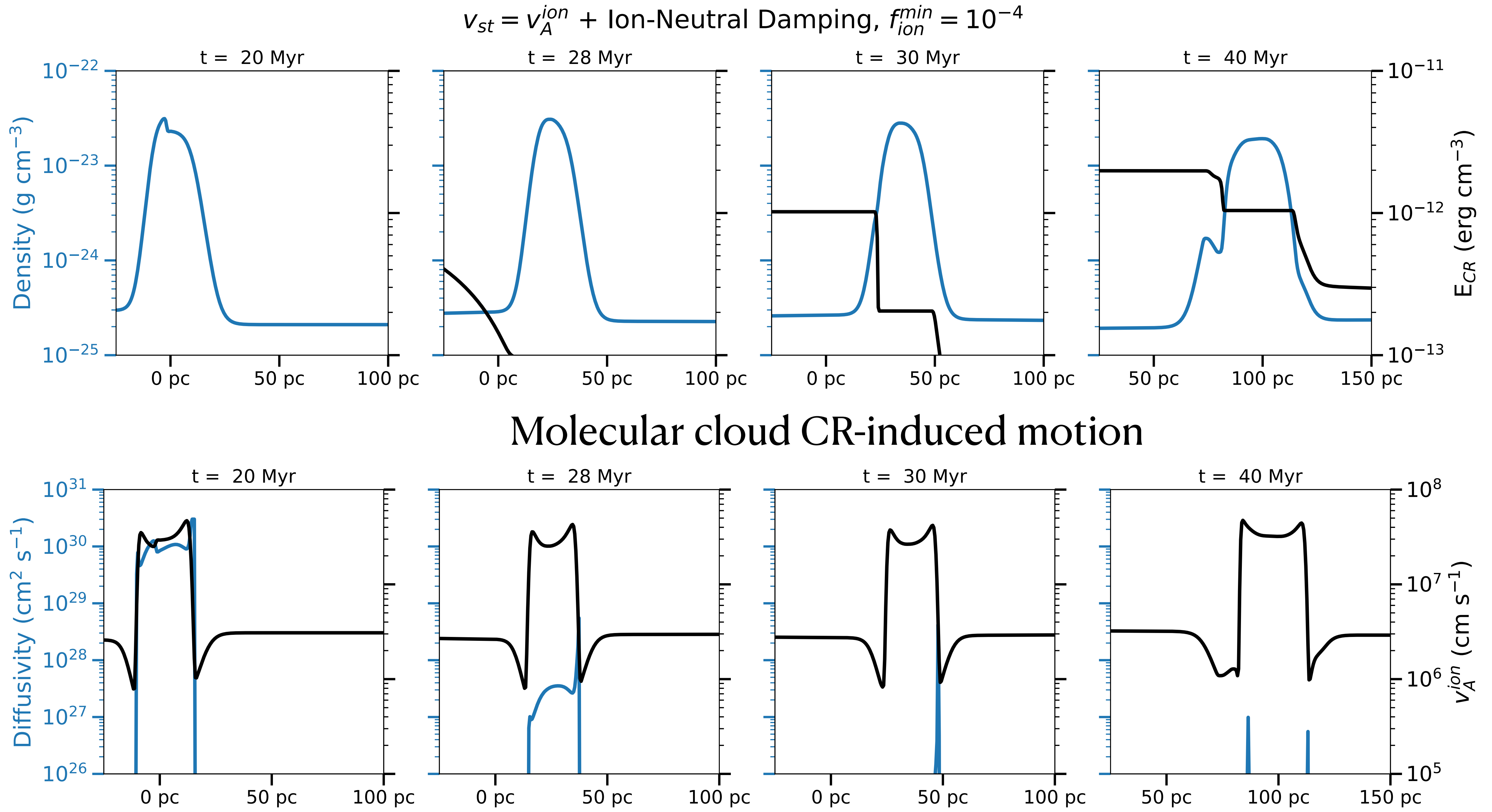
the impact over star formation rate

- Concerns 1-10 GeV CRs (they carry most of the pressure).
- Fast (numerical/conceptual) developments: multi-fluid approach **Hopkins et al 2021 MNRAS 501 4184, Thomas & Pfrommer 2019 MNRAS 485 2977, Dubois et al 2019 A&A 631 A121** (CRAMP PNHE-PCMI-PNCG project)
  - Effect of CR self-generated turbulence in MHD codes, including diffusion and advection and sometimes losses (multi CR components).
  - Simulations of large galactic scales and molecular cloud scales: CR induce gas motion due to their parallel gradient.

Surface density star forming rates vs surface gas densities, CR = SWRC



CR as they bring some more pressure smooth the gas in the halo and reduce the SFR



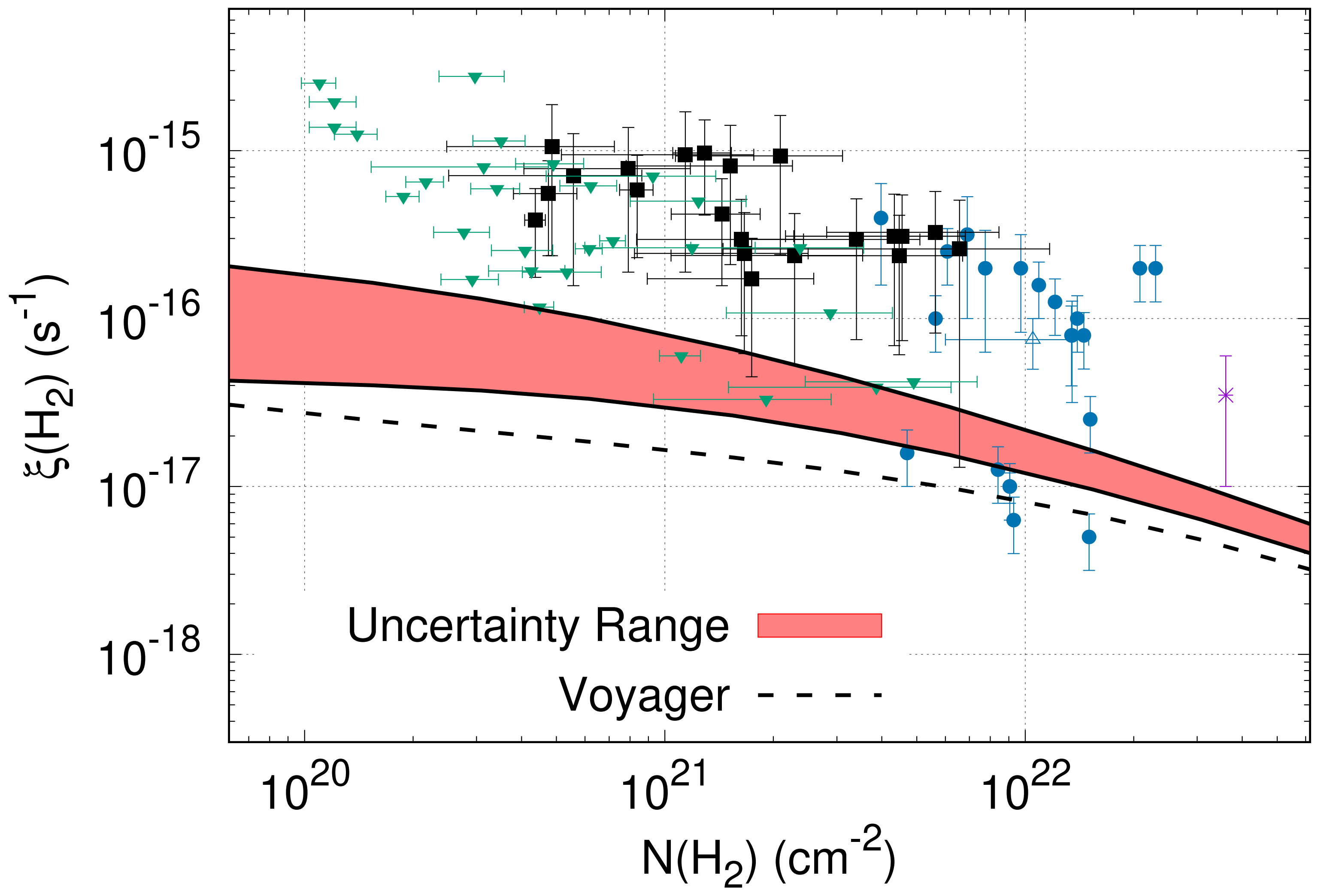
Molecular cloud CR-induced motion

Bustard & Zweibel 2021 ApJ 916 106

Ionization by Cosmic Rays

- Concerns MeV nuclei and keV electrons
- Add a constrain from H2 ionization rates with direct data (eg S/P ratios). Voyager spectra are unable to explain this trend, strong source stochasticity ?
- Revise injection rate by SNR, other sources like Young Stellar Objects **Padovani et al 2016 A&A 590 A8** ? or other way to inject in-situ CRs (via reconnection) in starless cores **Gaches et al 2021 ApJ 917 L39** ...

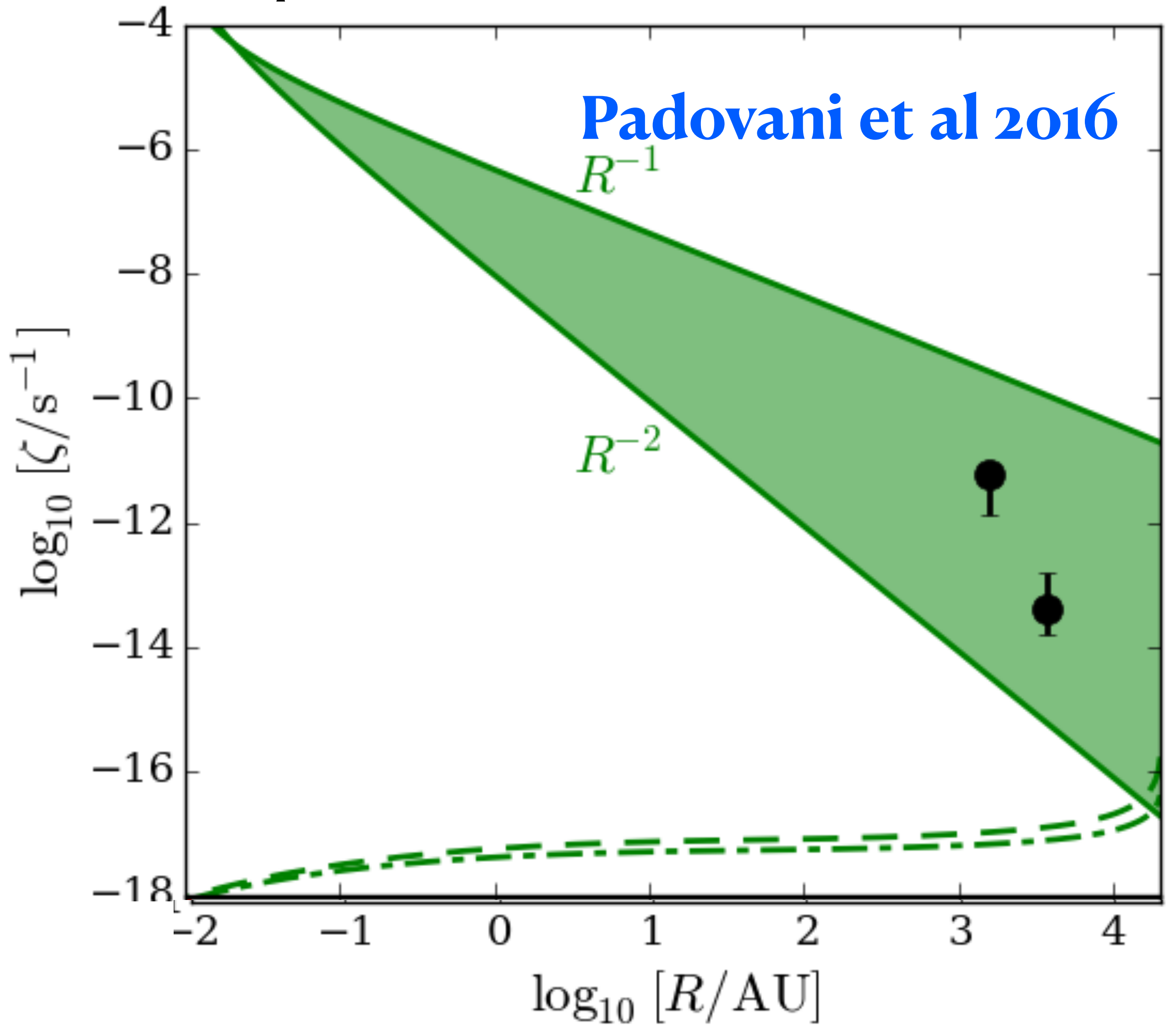
H2 ionization rates as function of H2 column density



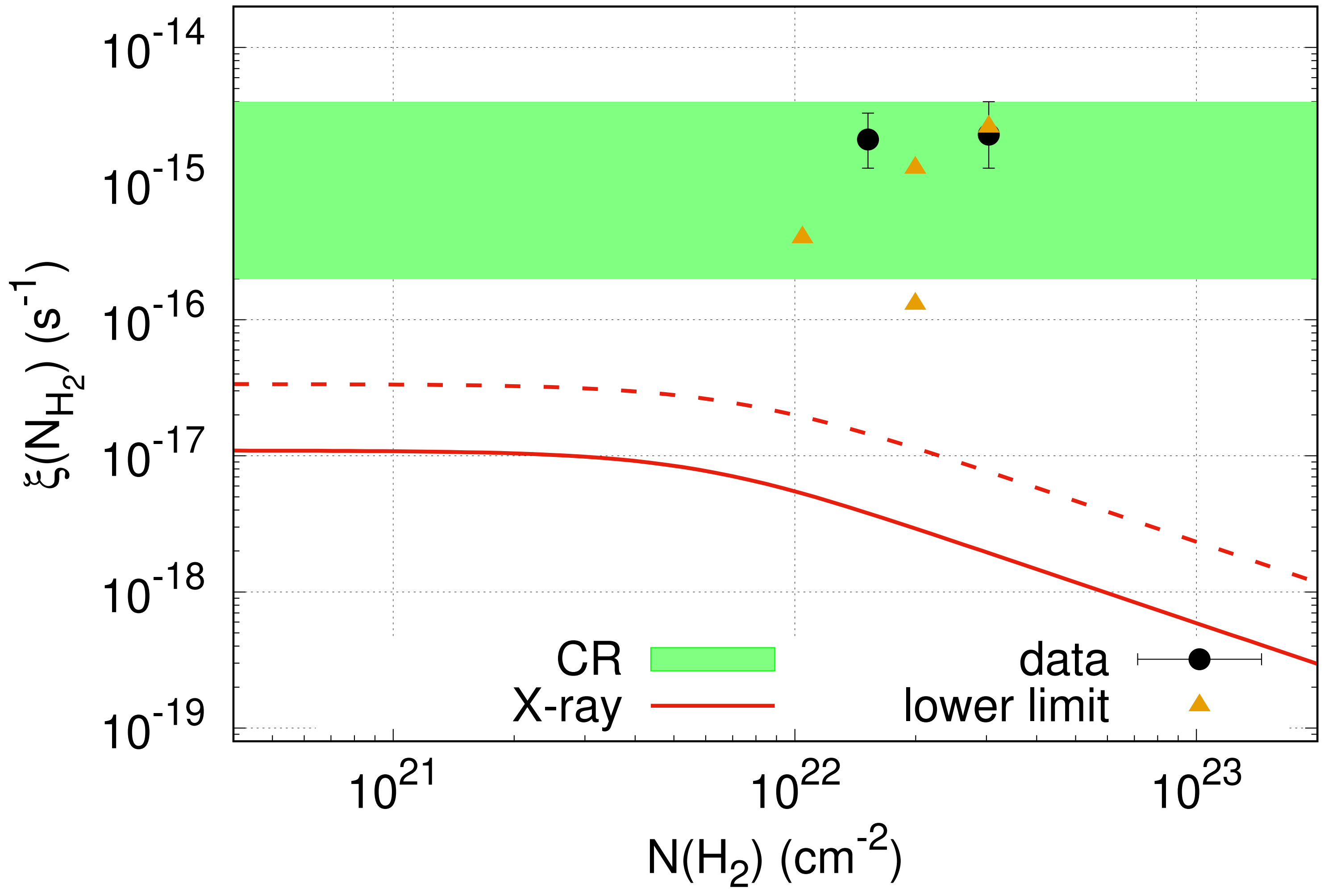
Phan V-M. thesis 2020

SNR may inject enough CRs to explain local ionization rates enhanced, but diffuse ionization rate far more difficult to explain

Ionization rates in the envelope of OMC-FIR4: in-situ CR produced at accretion shocks in YSO



Ionization rates of clouds nearby SNR W28



Phan V-M. thesis 2020

CR transport: perspectives for the next decade

It requires some update of PNHE main (sub)themes, mostly trans-disciplinary.

- Same numerical developments as in source studies.
- My personal opinion on CR propagation: the basic block of CR propagation wave/turbulence-particle not understood yet (see discussion in **Lemoine Arxiv2104.08199**)

  > Need for more contacts: PNST, laser plasma community, Inertial Confinement plasma community. Thematic schools also could help.
- Nearby sources emission: CTA, SWGO (unfortunately France is not part of LHAASO), Meerkat, SKA.
- GeV CRs: feed back terms in the star formation process: strengthen links with PCMI (our Galaxy), PNCG (CR feed back and cosmology): support common meetings @ SF2A …
- MeV CRs: strengthen links with PCMI (molecular cloud scales), PNPS (young stars, stellar discs), PNP (planets atmosphere). (support, and convince these 2 last PNs about non-thermal Astrophysics impacts).
- Continue on cross section measurements (spallation) : links with IN2P3 activities (see Vincent's talk)

Summary

- Recent progresses driven by first (or almost) principles but still long way to describe CR spectral evolution and maximum energies.
- Maximum energy (PeV) is a real challenge for the standard CR model: alternative sources ? (cc-SNe, massive star clusters and super bubbles) : gamma-ray (and CTA) should help.

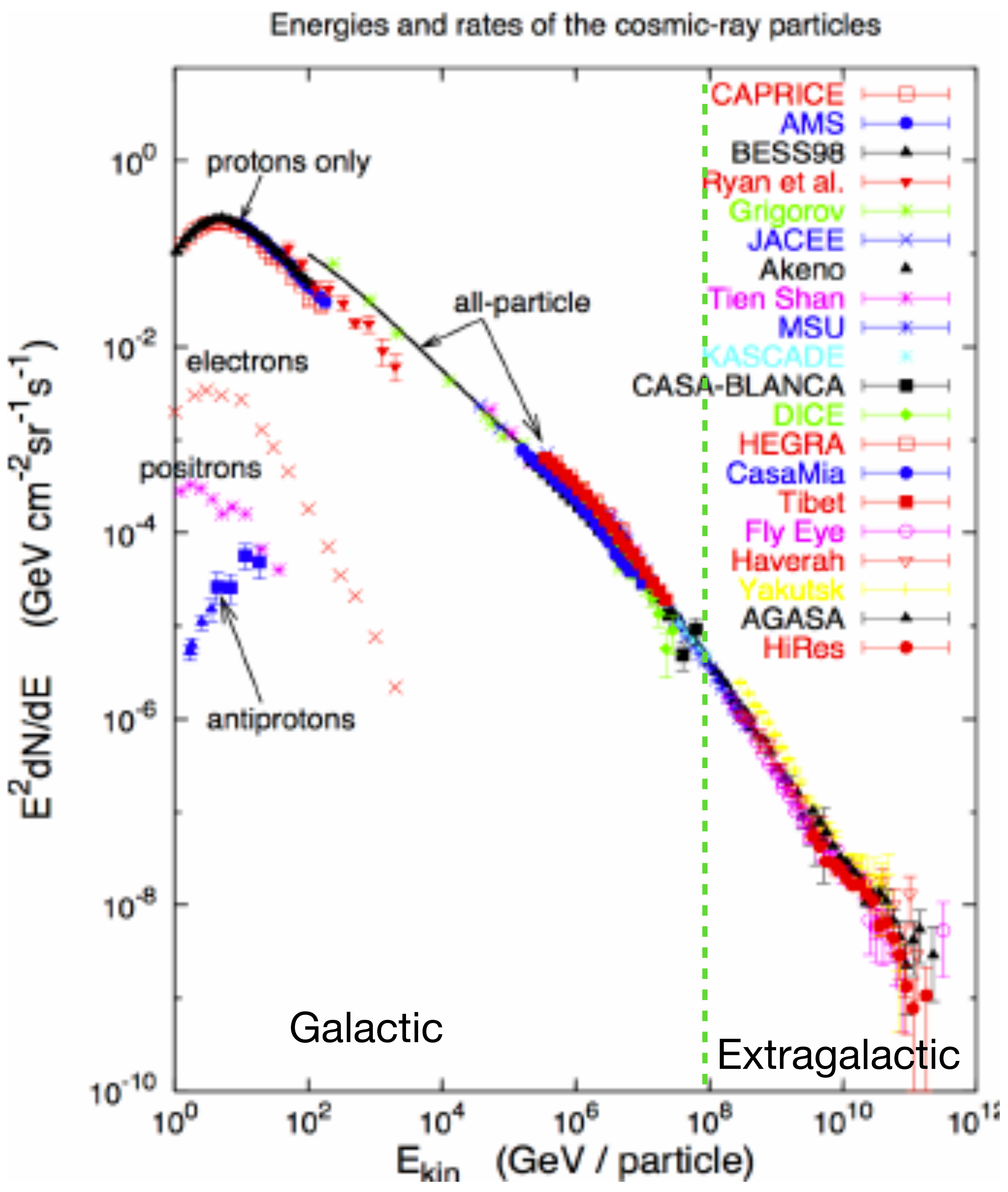
- CR transport is not smooth in the ISM, intermittency due to reduced diffusivity around sources (again probed by CTA), especially in the GeV-TeV domain (impact over CR hardening ?)
- GeV CRs contribute to star formation feed back (winds and/or local injection, see above source intermittency).
- MeV CRs (keV electrons) contribute to star formation feed back (ionization).

- Advocate for a special support for theory, eg INTERCOS project supported by IN2P3, we have several senior and young theorists and expert in numerics very high in the A.T.P. ranking.
- Need for breakthrough ideas (eg **Lemoine PRD 2019 99 3006**, on generalized Fermi acceleration) > also need for informal, brain storming meetings (aside ERC, ANR projects of course) — cheap/innovative/friendly—

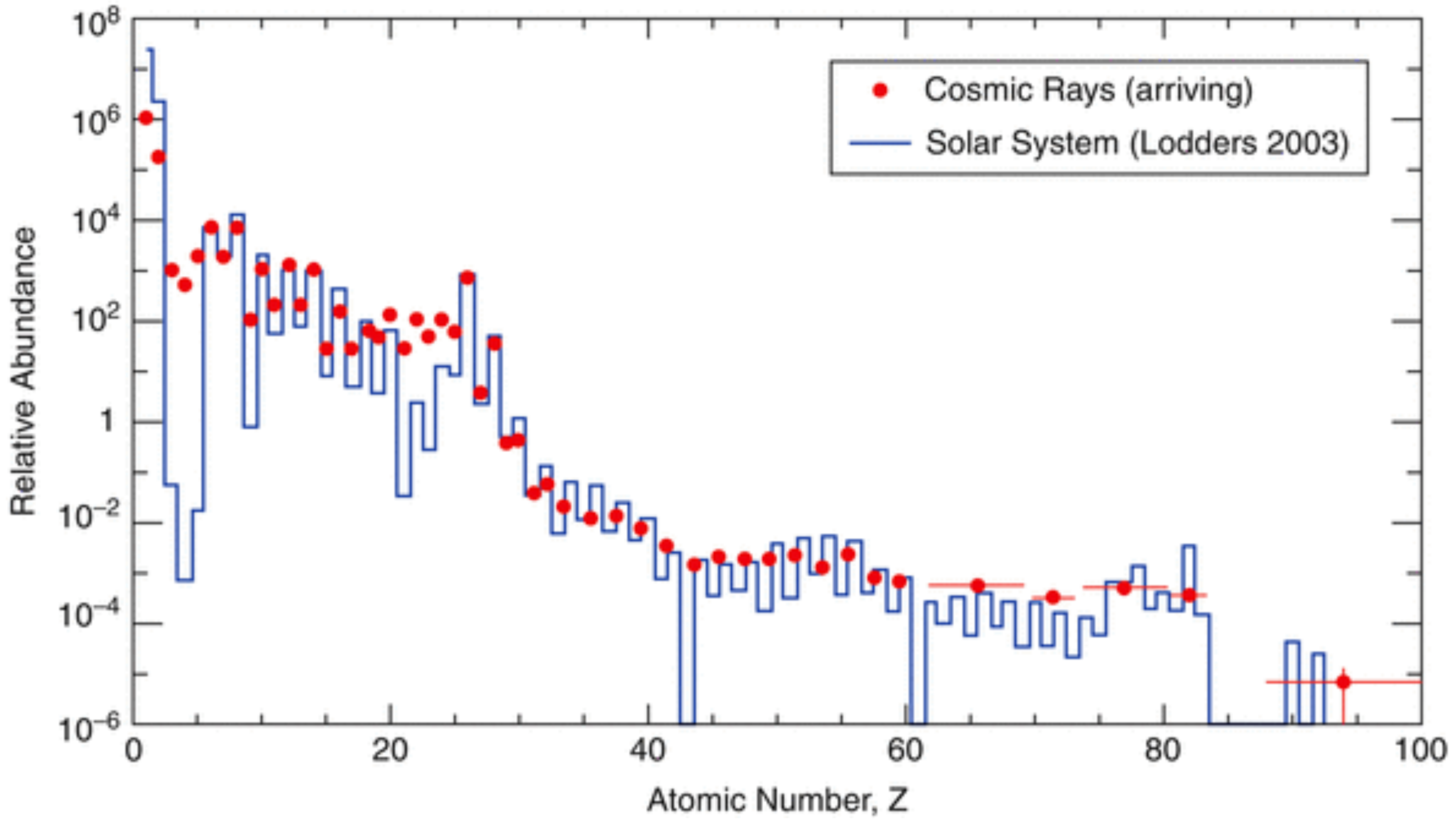
Back up

The three Cosmic Ray spectra

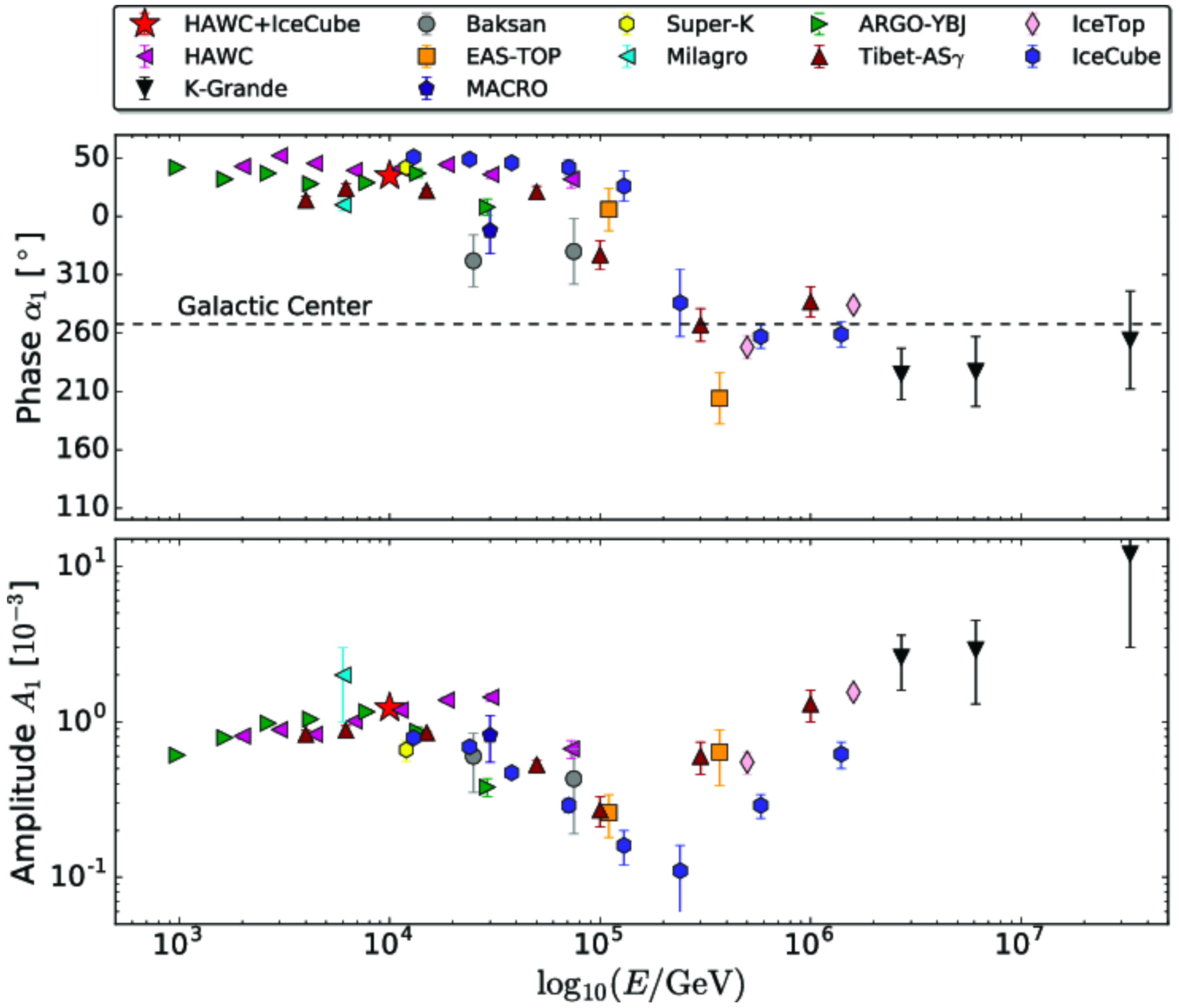
Energy spectrum / Composition spectrum / Angular spectrum



From MeV to almost ZeV or 10^{21} eV
galactic origin up to 10^{17}eV



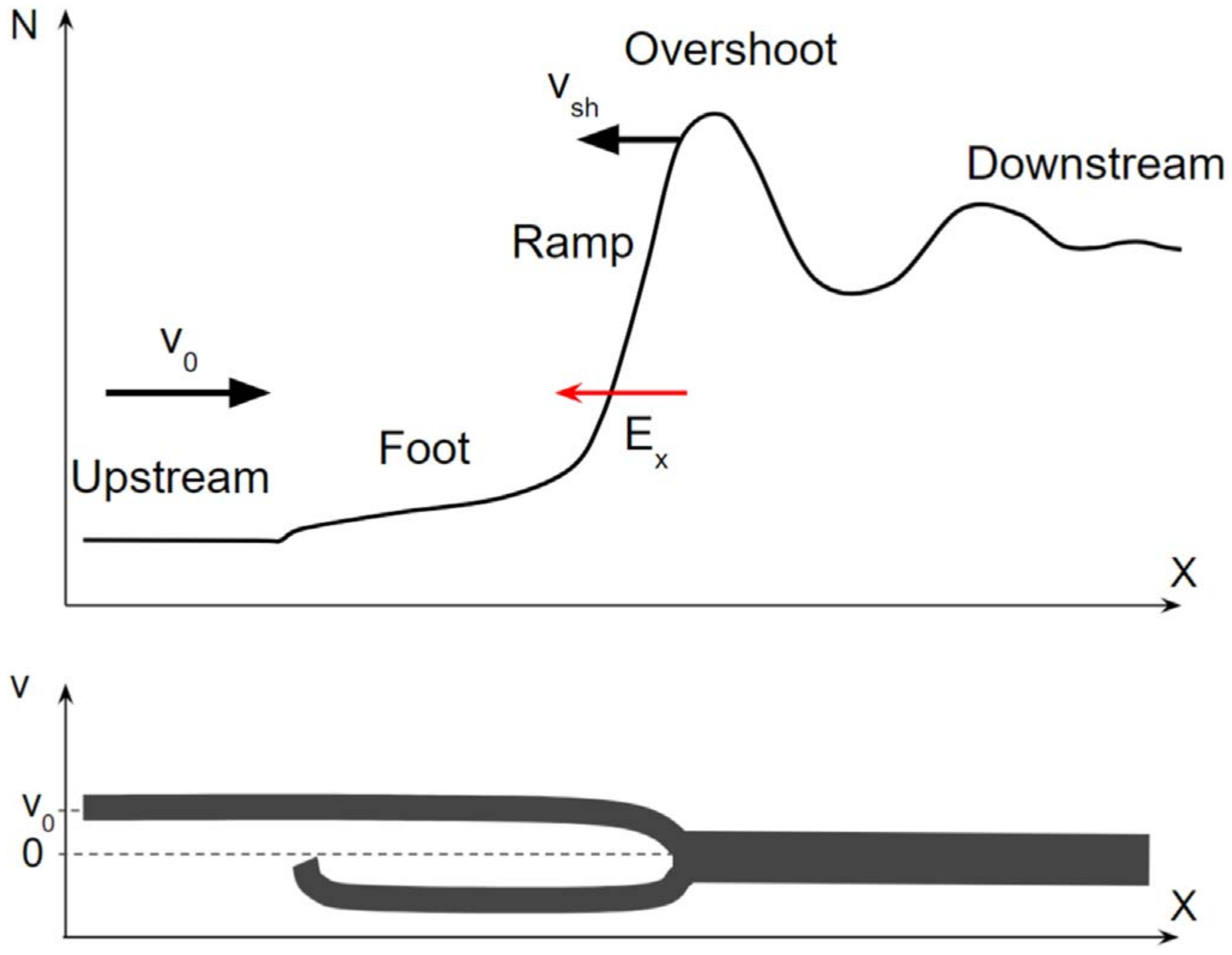
Light element production by spallation
(here composition @ a few GeV/N)



High level of isotropy
(anisotropy increases at the highest energies)

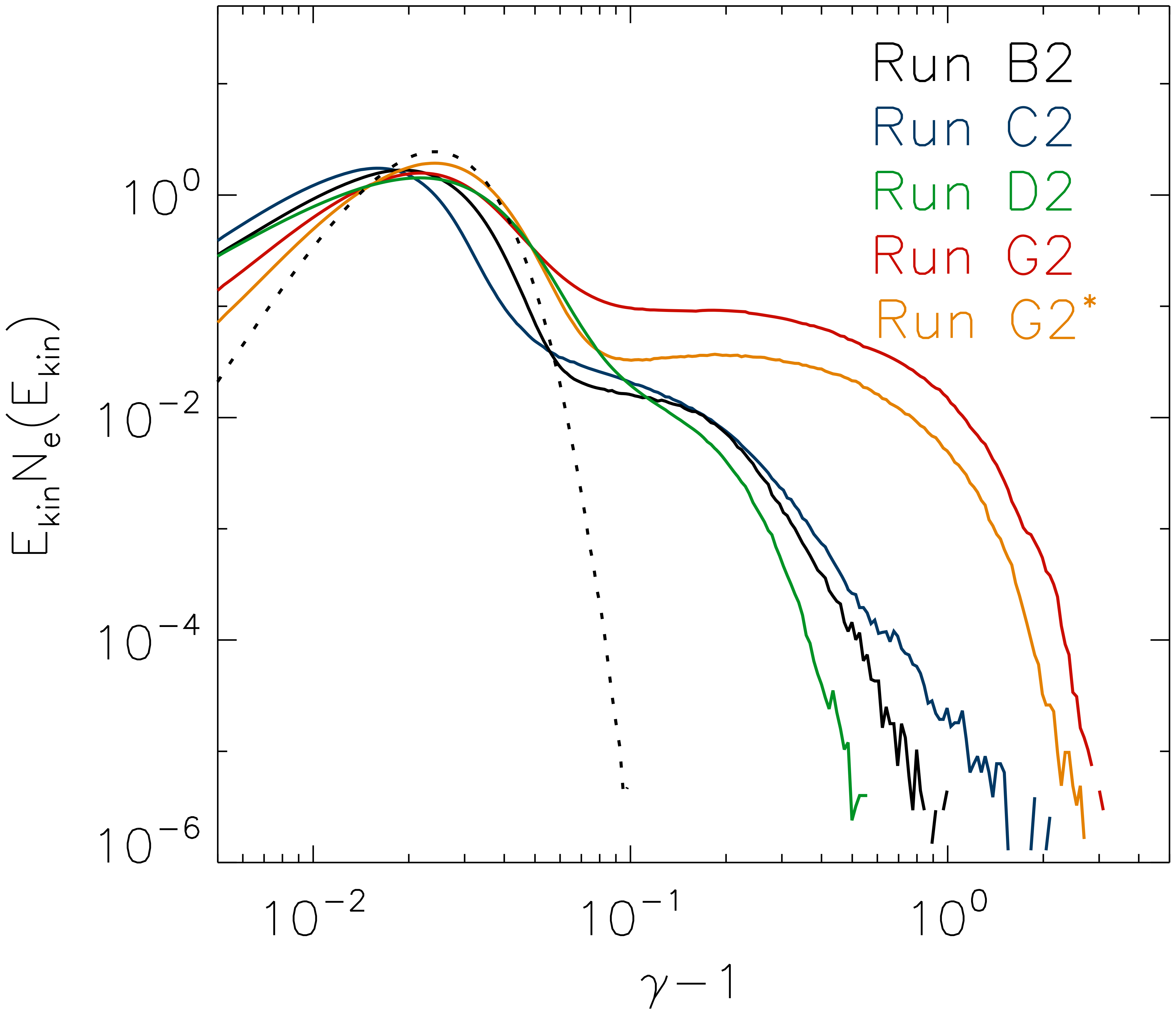
Electron injection

- Electron injection and acceleration at quasi-perpendicular shocks



Acceleration by shock surfing process (foot) and magnetic reconnection (ramp, overshoot)

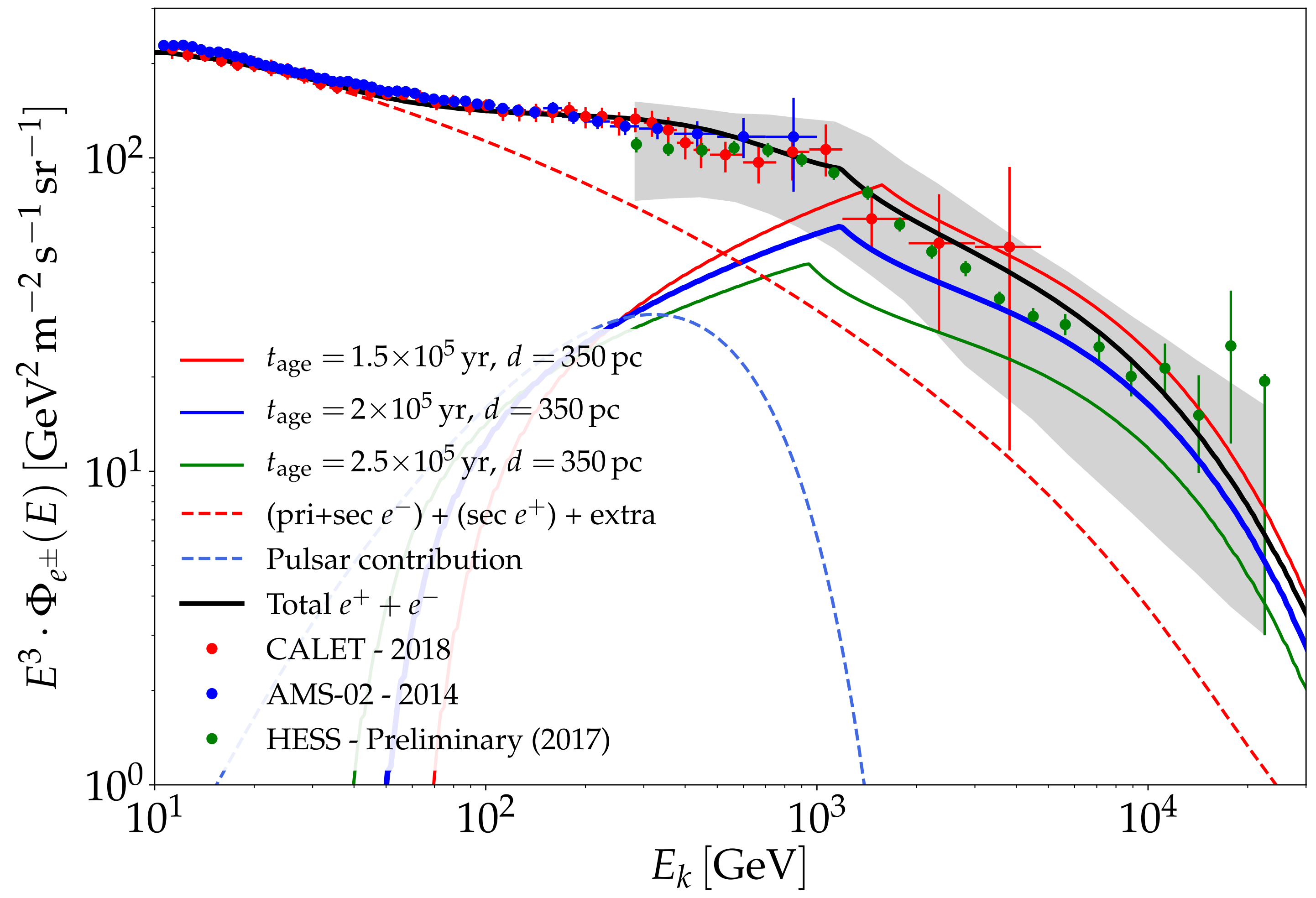
Bohdan et al 2019
ApJ 878 5



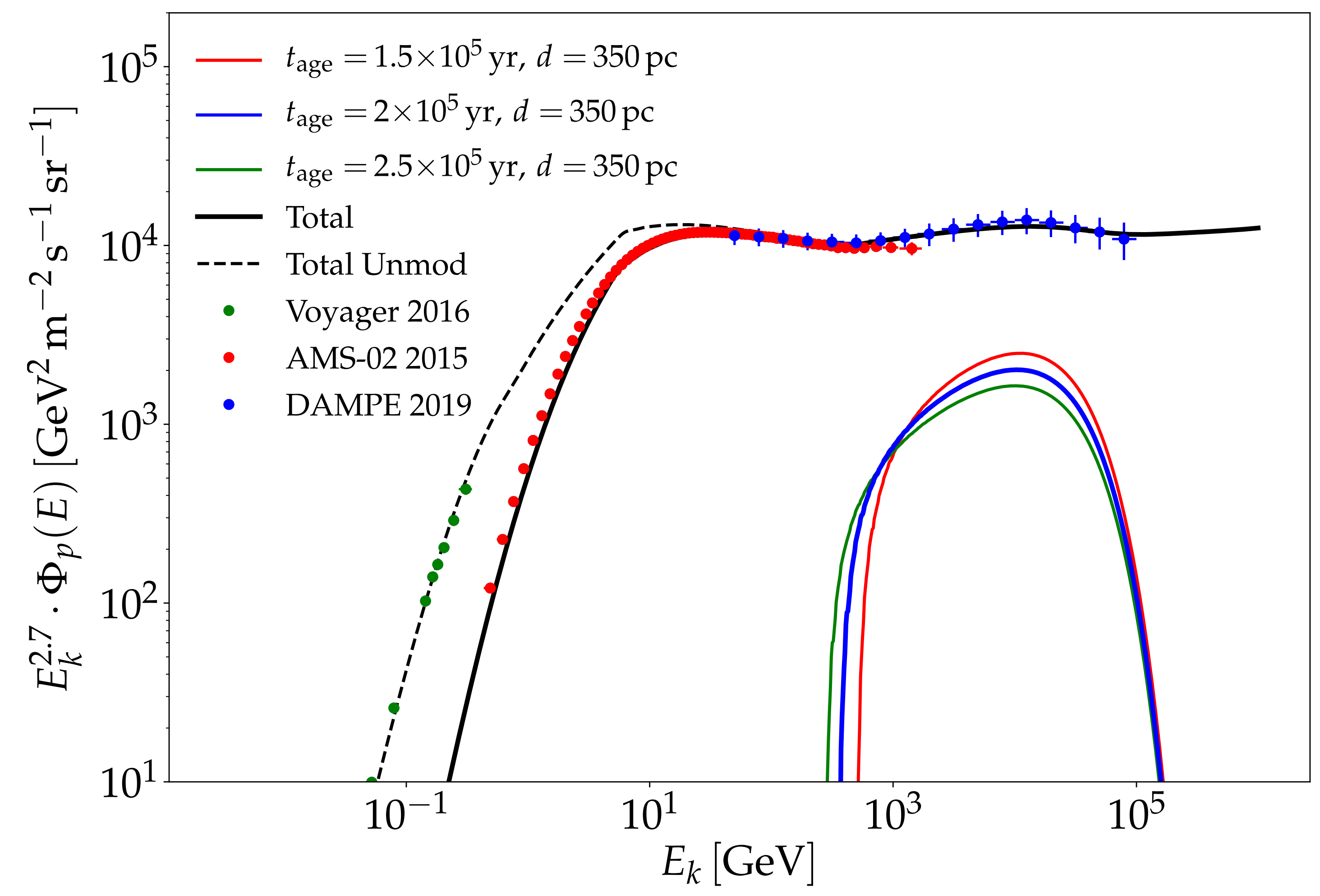
Phenomenology

- Try to fit nuclei, lepton, anti-nuclei, anisotropy with one source and propagation model

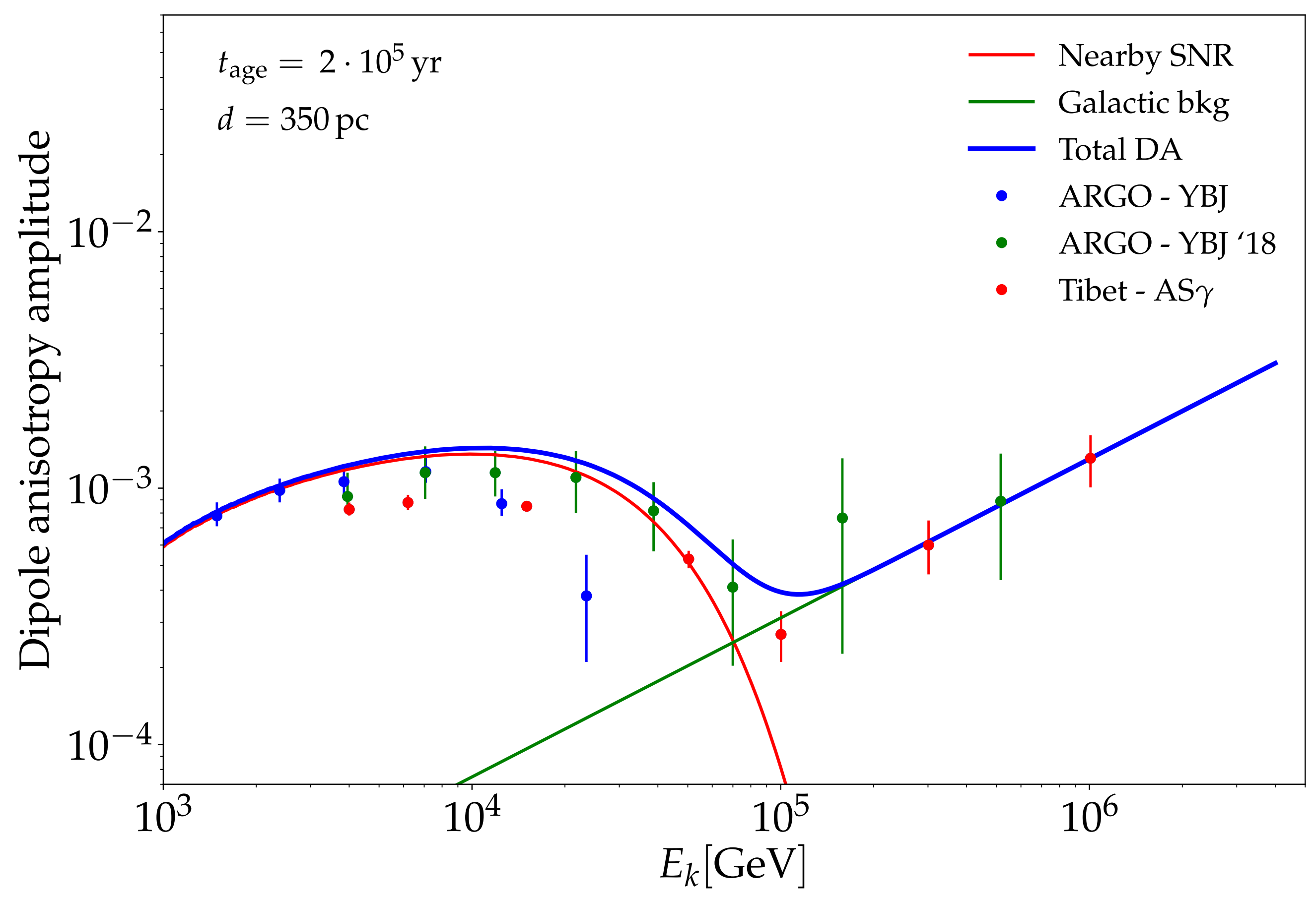
Electron spectrum



Proton spectrum



Dipole anisotropy



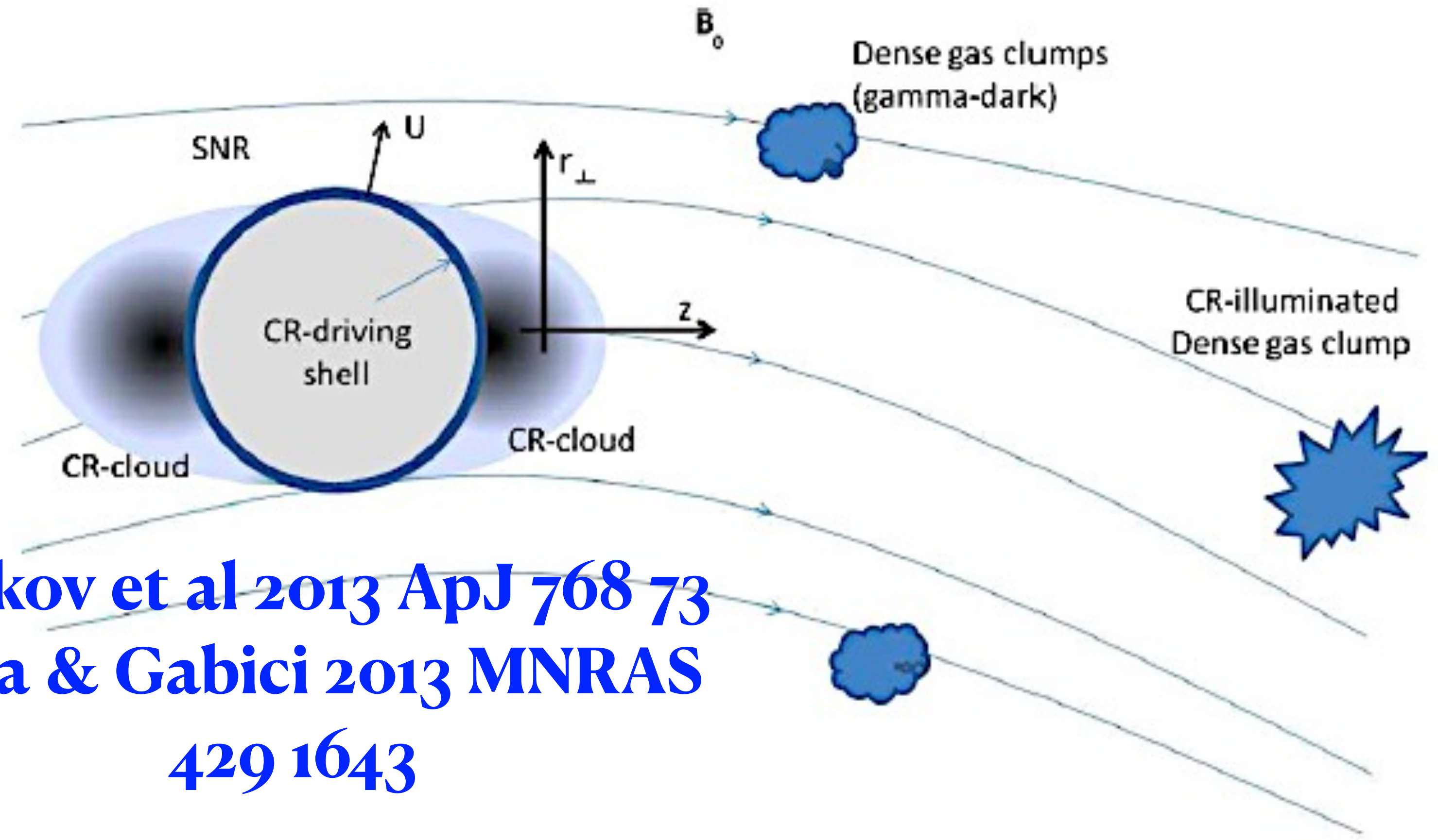
Fornieri arXiv2007.15321

Tentative to explain the DAMPE bump by the action of a hidden SNR

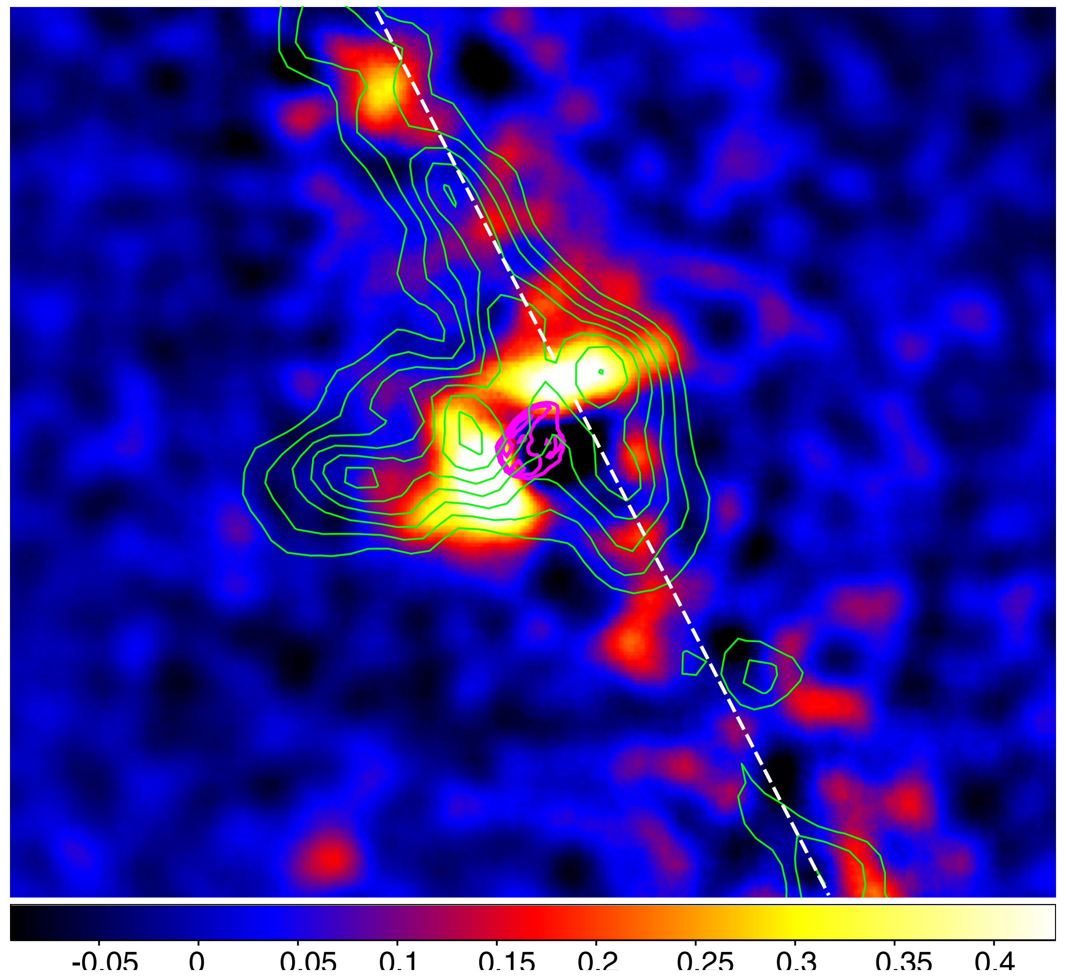
- Source time-dependent injection model
- Diffusion coefficients accounting for spectral hardening
- Also B/C, anti-proton, phase anisotropy has to be fitted....

Cosmic ray propagation around supernova remnants

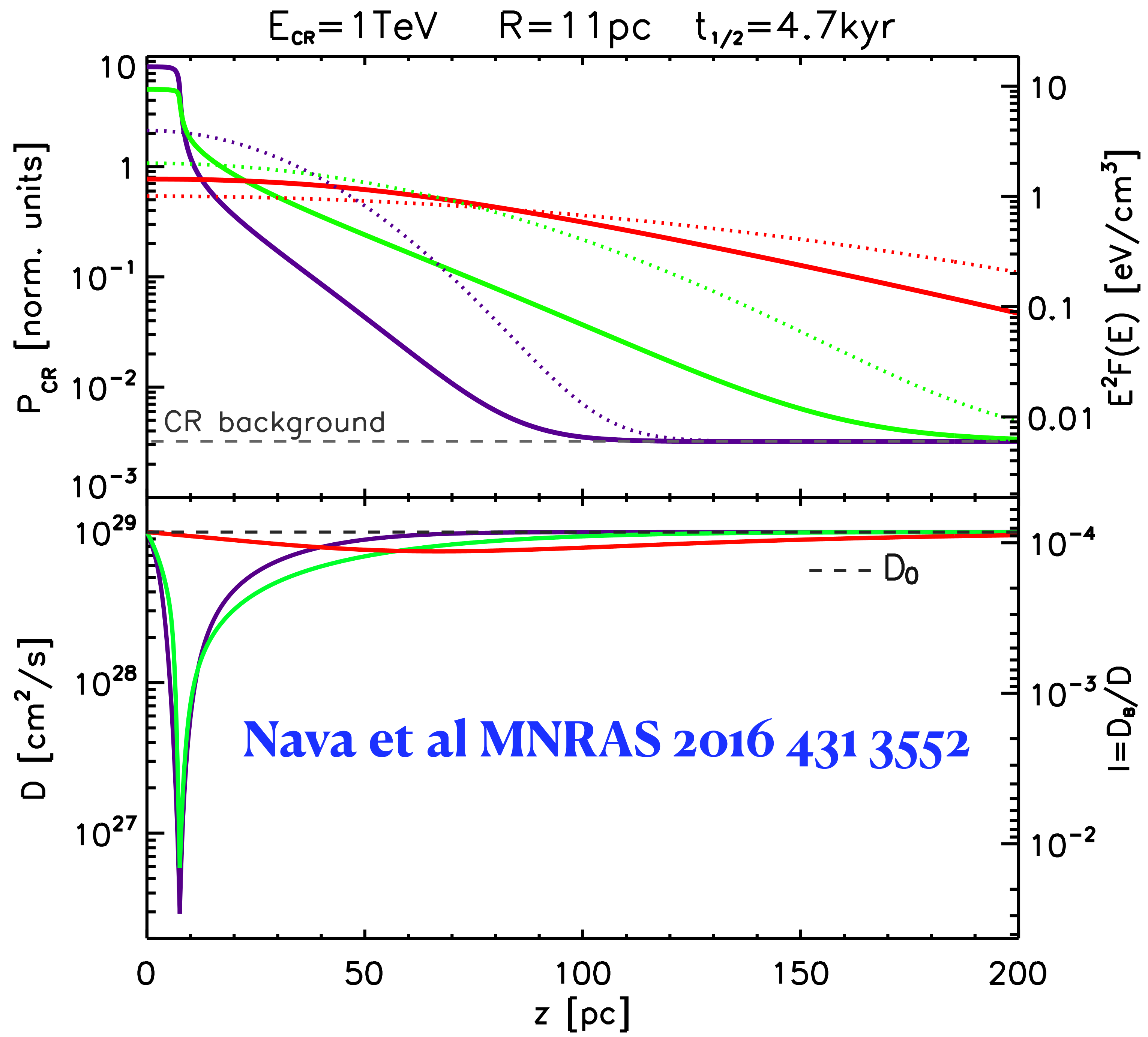
- No fully reliable models of CR escape do exist yet.
- One way : consider CR cloud decoupled from acceleration and 1D propagation along magnetic flux tubes.
- Draw-backs : 1D (flux tube approximation has to apply), homogeneous ISM, quasi-linear theory.



Malkov et al 2013 ApJ 768 73
Nava & Gabici 2013 MNRAS 429 1643



W44 SNR : Fermi residual map, contours CO map, magenta radio SNR, dashed galactic plane (gamma-ray more extended) **Uchiyama et al ApJ 749 L35**



Nava et al MNRAS 2016 431 3552

This setup is started to be investigated eg using PIC simulations (see **Schroer et al 2021 ApJ 914 L13:** possible triggering of the non-resonant streaming instability => peaking of the flux tube approximation)

Results of the CR cloud model: Diffusion (here at 1 TeV)is reduced over 5-10 kyrs (here in a warm neutral medium), equivalent effects in atomic and diffuse molecular phases (**Brahimi et al 2020 A&A 633 A72**).