Turbulence and its impact on particle acceleration/transport and the implications on gamma-ray observations

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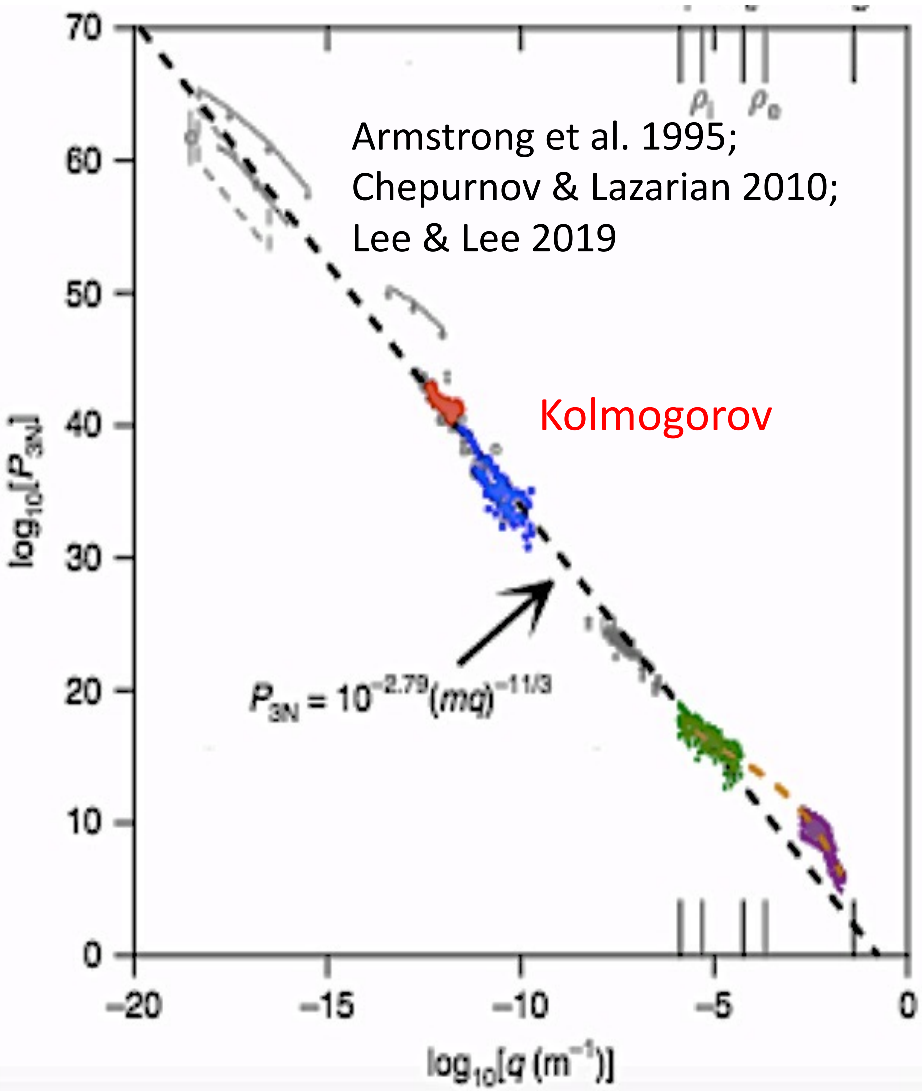
Turbulence and cosmic rays (CRs)

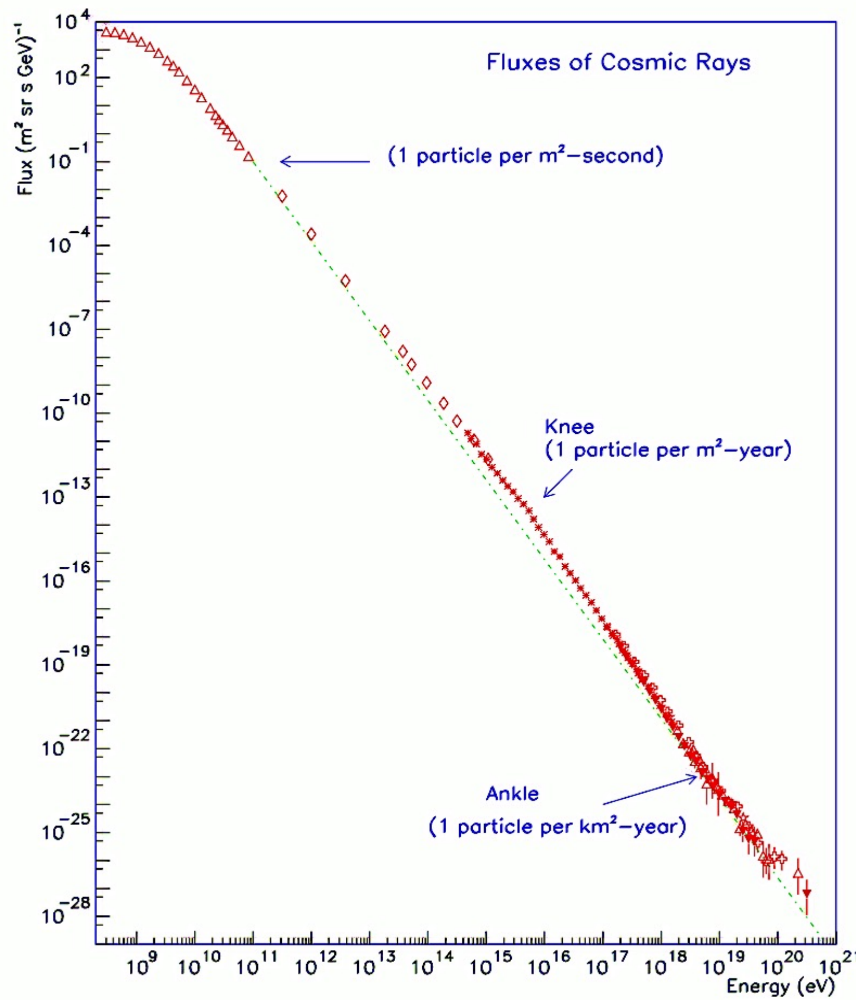
Big Power Law of interstellar turbulence

50 m – 10^{17} m



Cosmic ray energy spectrum

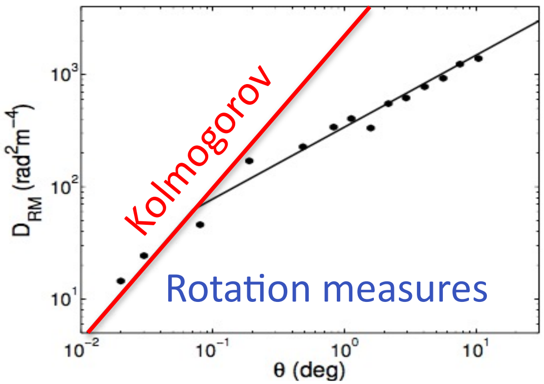
10^9 eV - 10^{20} eV

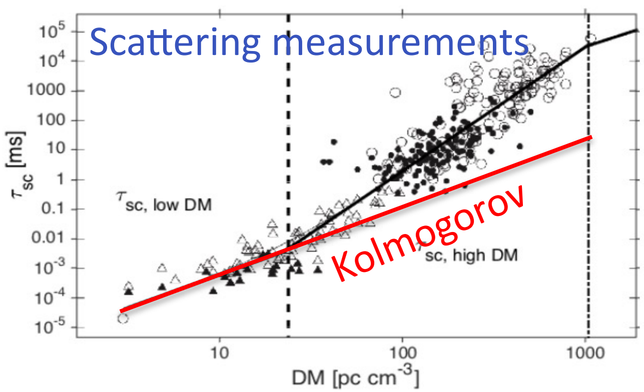


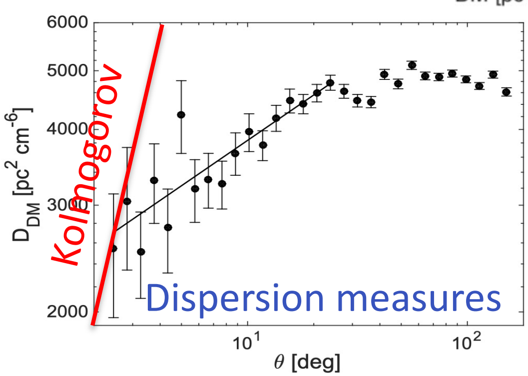
Olinto 2001; compiled by S. Swordy

Turbulence and CRs

Interstellar turbulence spectrum

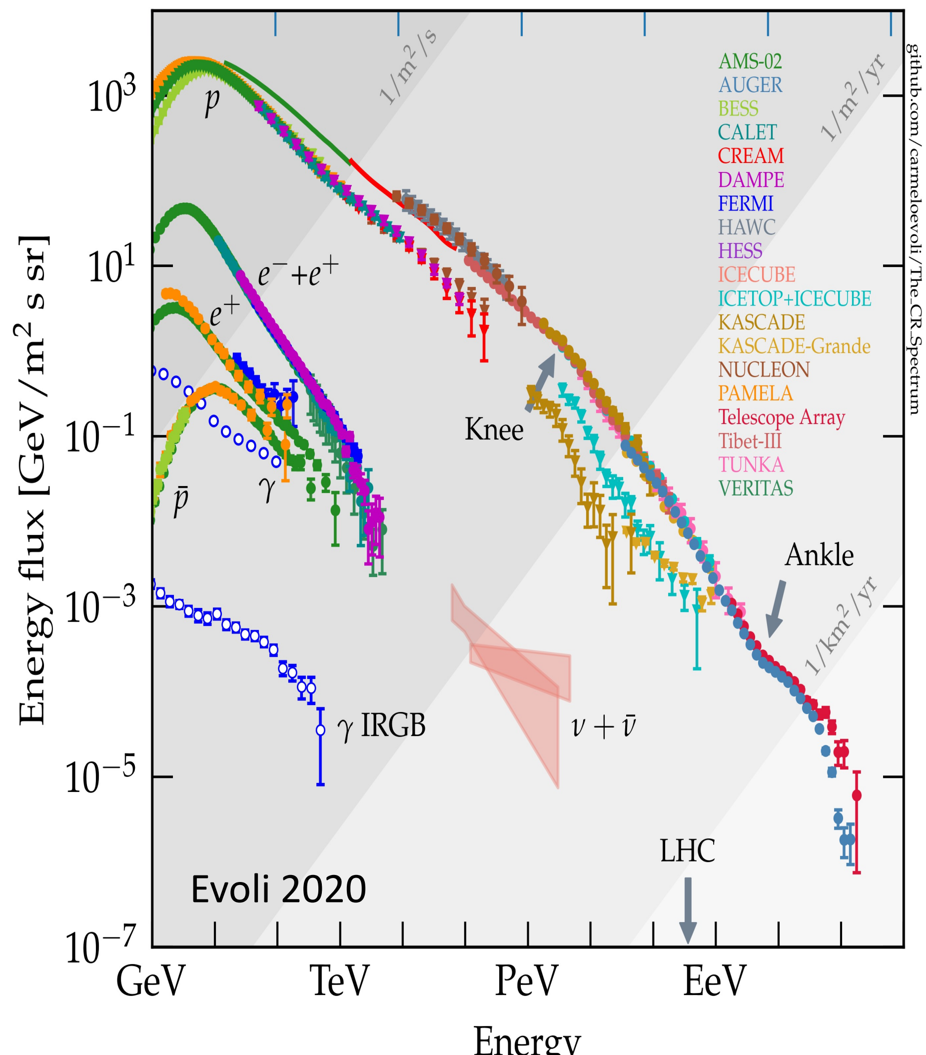






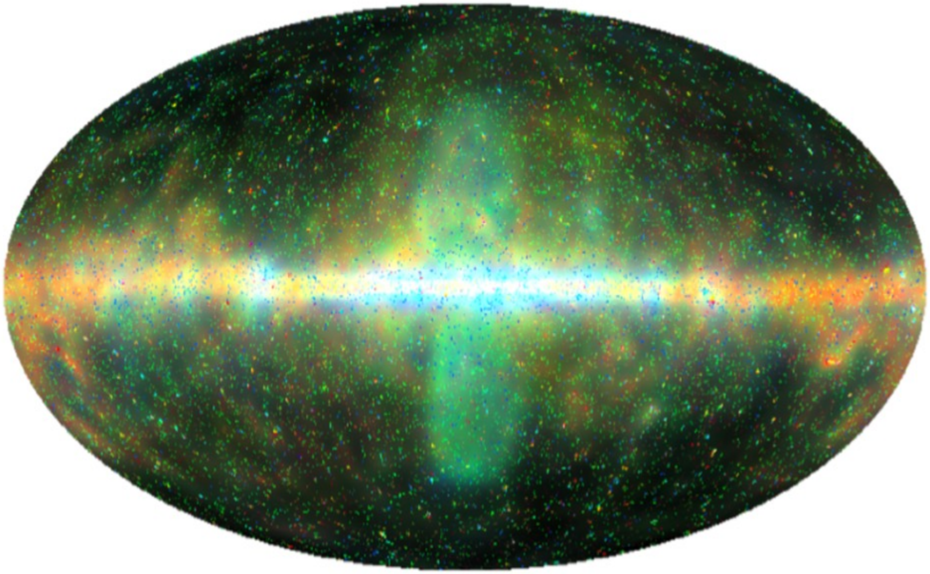
Xu & Zhang 16,17,20;
e.g., Lazarian 2009;
Hennebelle &
Falgarone 2012

CR energy spectrum measured after 2000

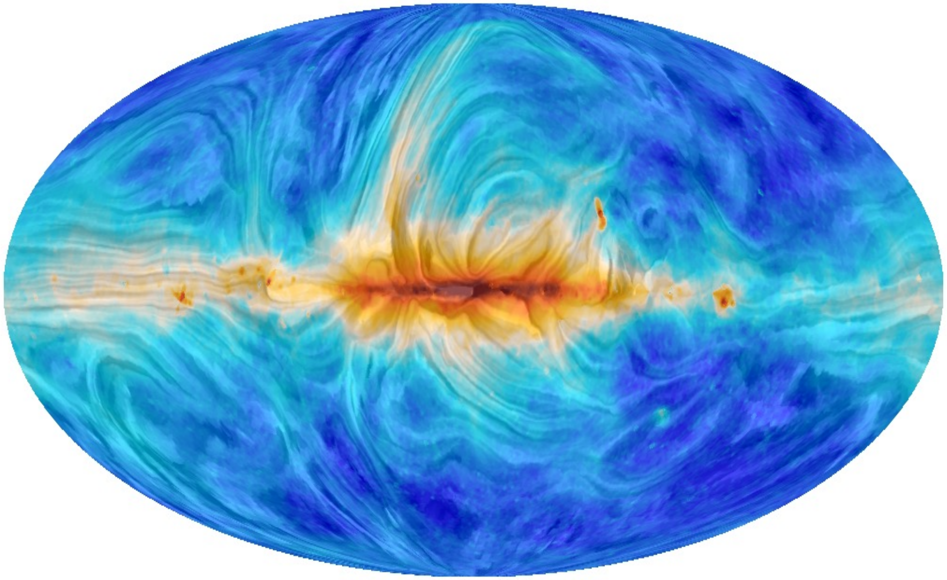


Gamma-ray observations

Gamma-ray sky above 600 MeV



Magnetic field lines traced by synchrotron radiation at 30 GHz

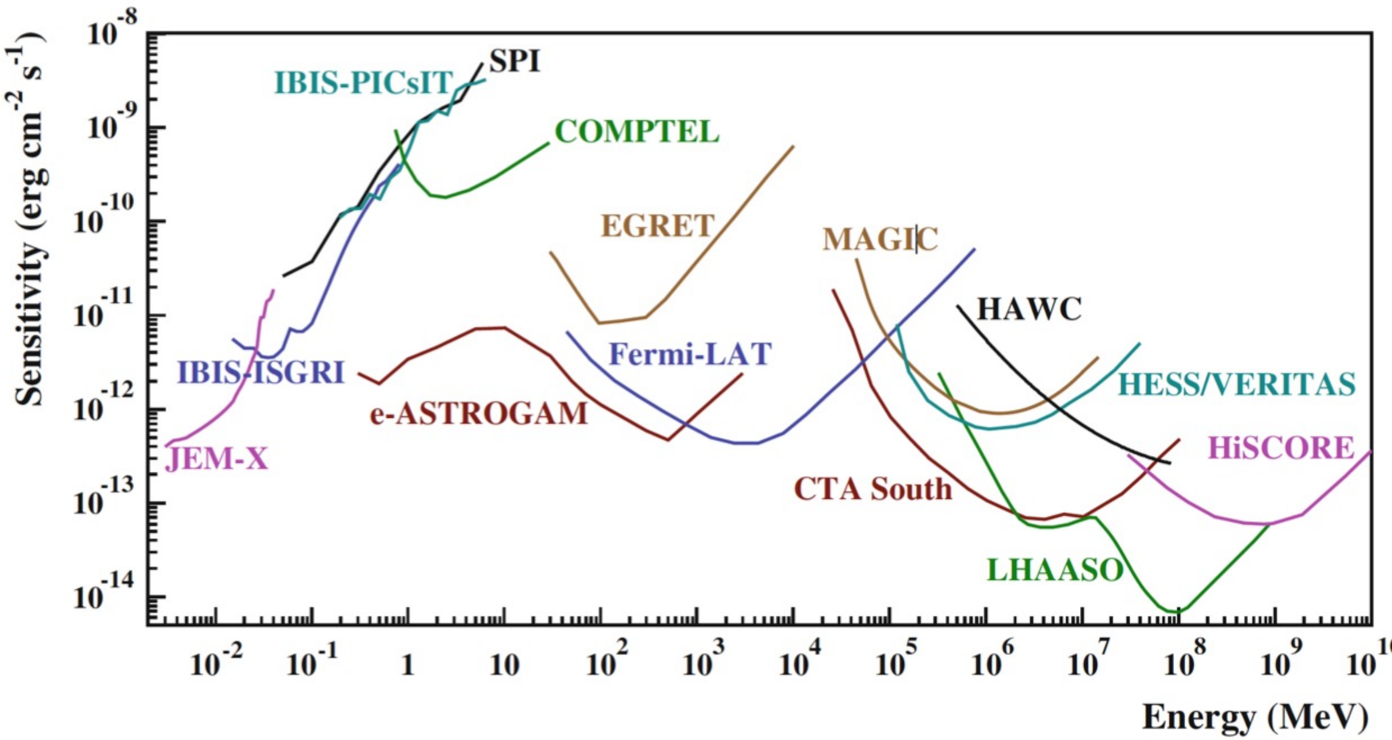


De Angelis & Mallamaci 2018; Di Sciascio 2019

ESA and the Planck Collaboration

Space- and ground-based gamma-ray detectors

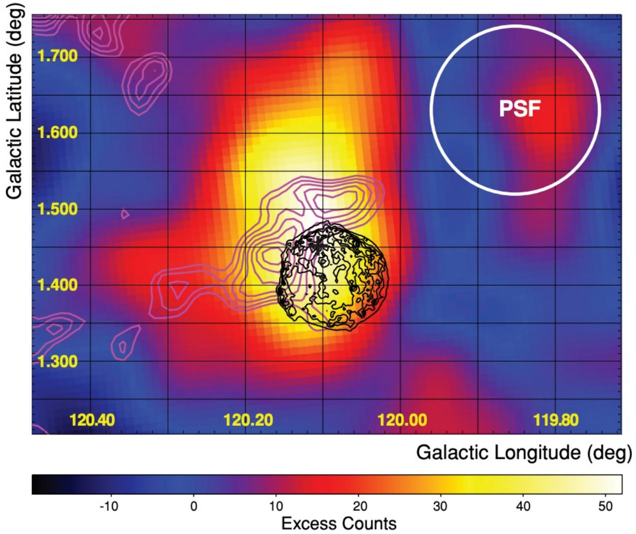
Sensitivity of different X- and gamma-ray instruments



De Angelis & Mallamaci 2018

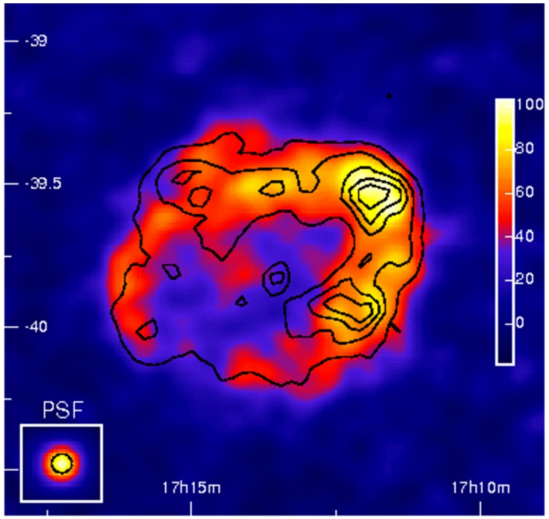
Gamma-ray emission from supernova remnants (SNRs)

VERITAS TeV gamma-ray count map
around Tycho's SNR



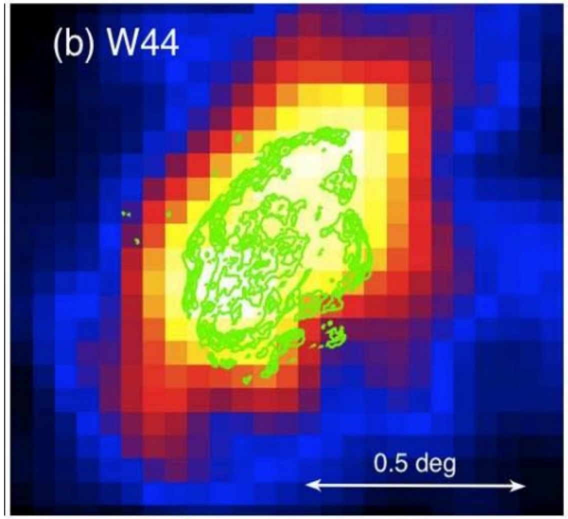
Acciari et al. 2011,
Hwang et al. 2002,
Heyer et al. 1998

H.E.S.S. image of RX 1713.7–3946



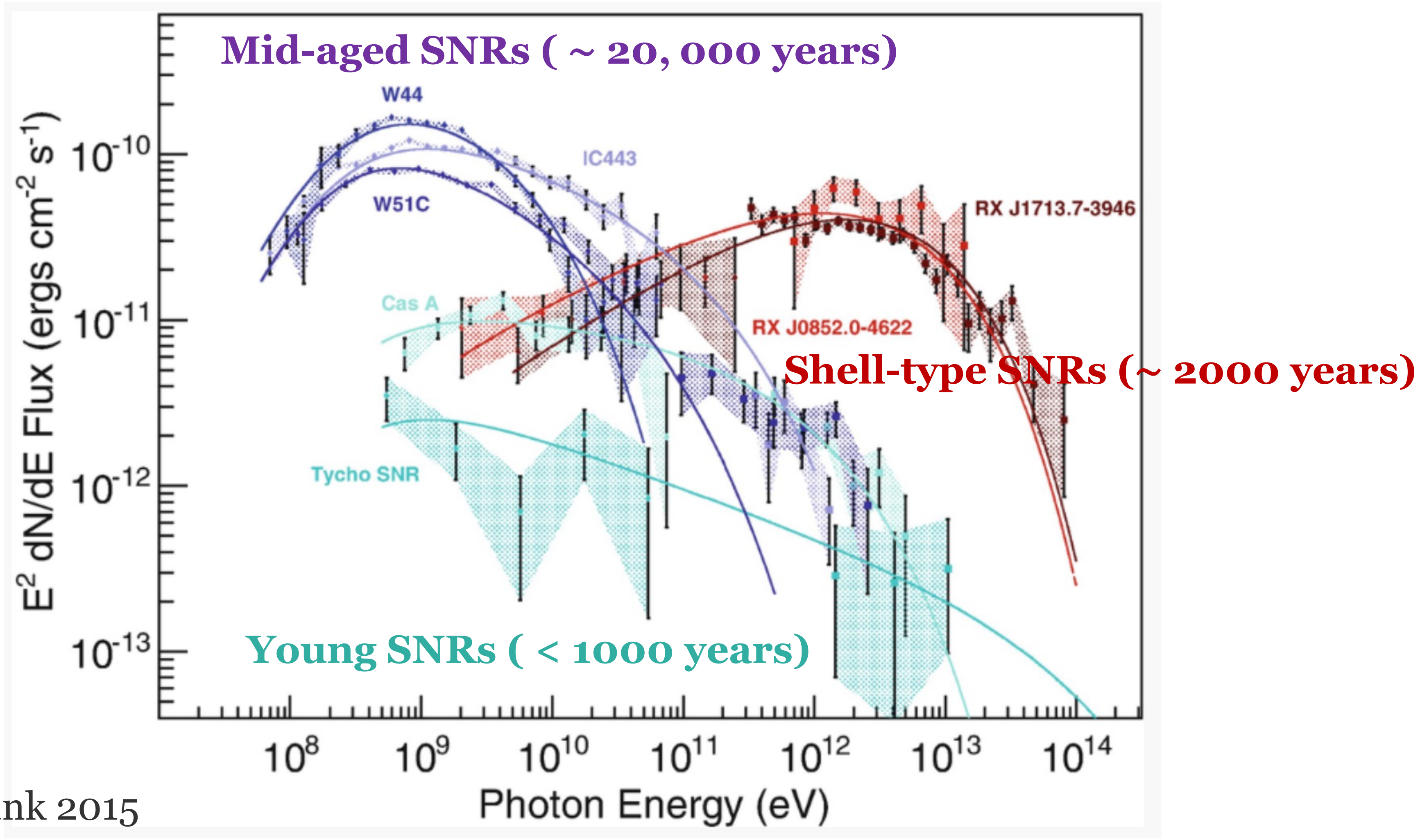
Aharonian et al 2005,
Uchiyama et al. 2002,
Hewitt & Lemoine-Goumard 2015

Fermi LAT count map of W44



Uchiyama &
Fermi LAT Collaboration 2010

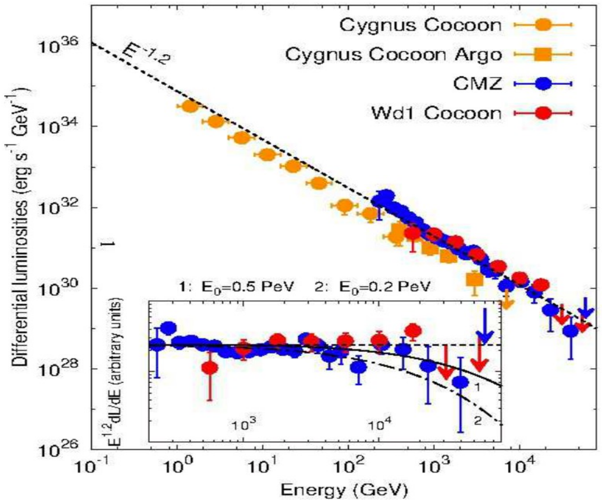
A great variety of gamma ray spectra



Funk 2015

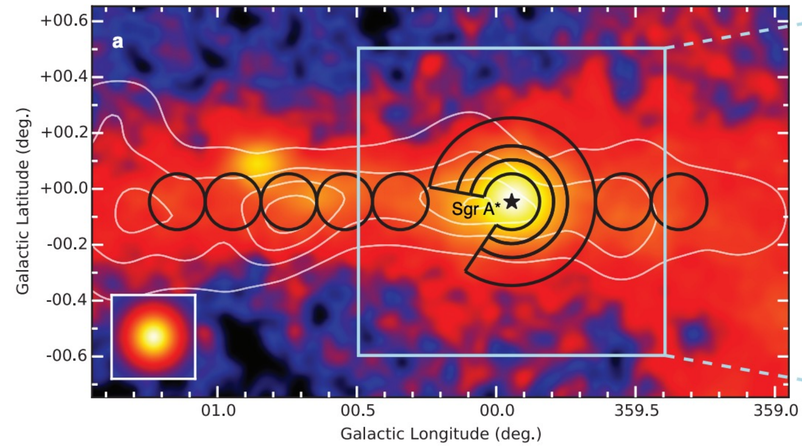
Other candidates of proton PeVatrons

Massive star clusters

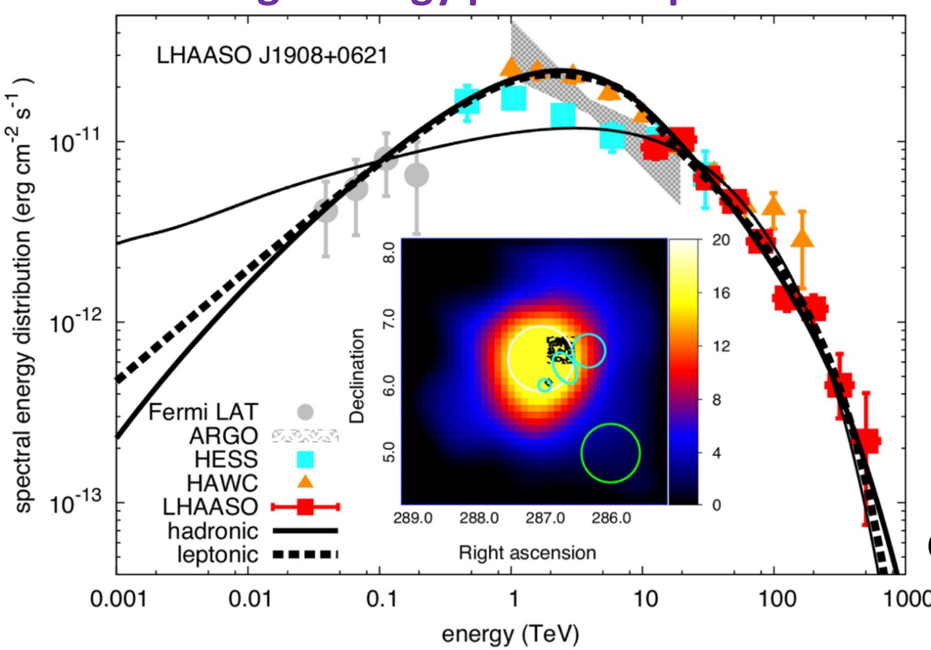


Aharonian et al. 2019

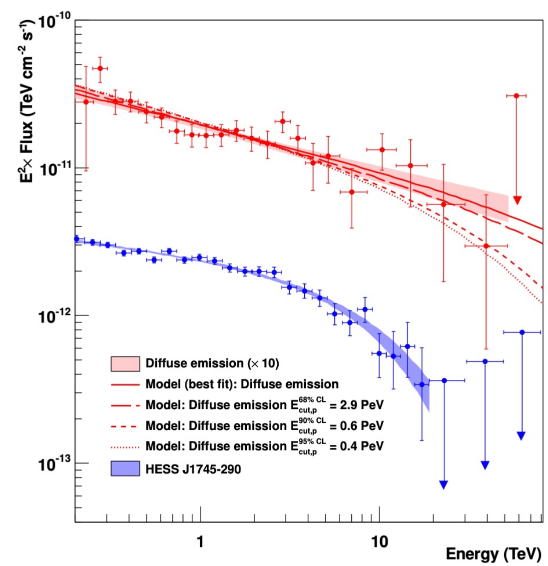
Galactic Centre region



Ultrahigh-energy photons up to 1.4 PeV



Cao et al. 2021



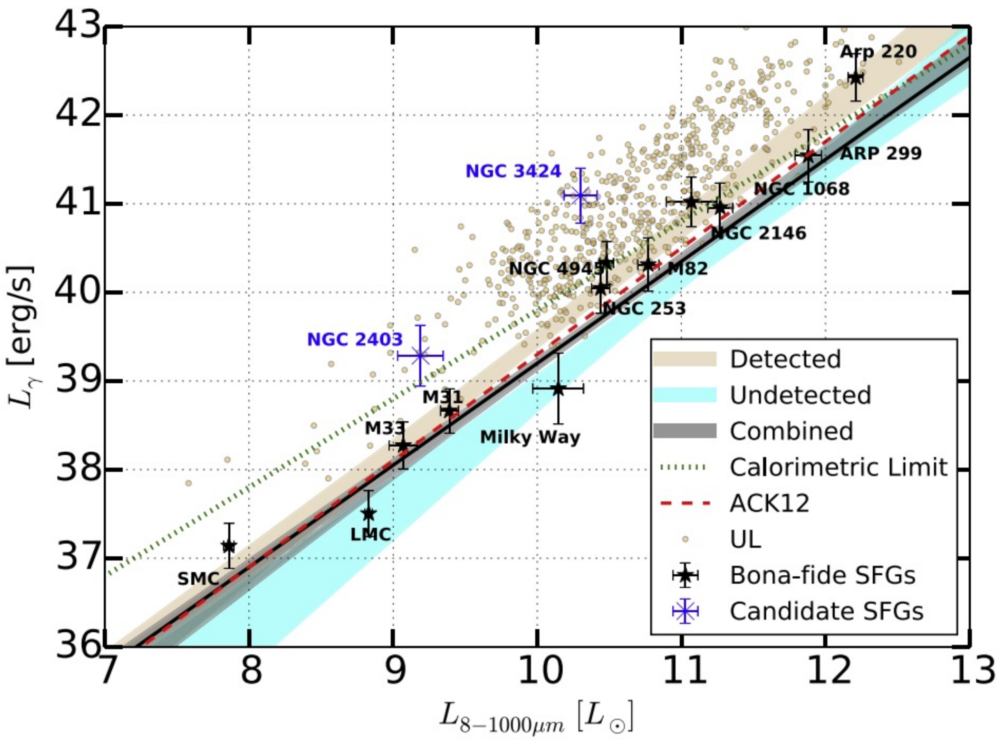
HESS Collaboration 2016

Gamma-ray emission from star-forming galaxies

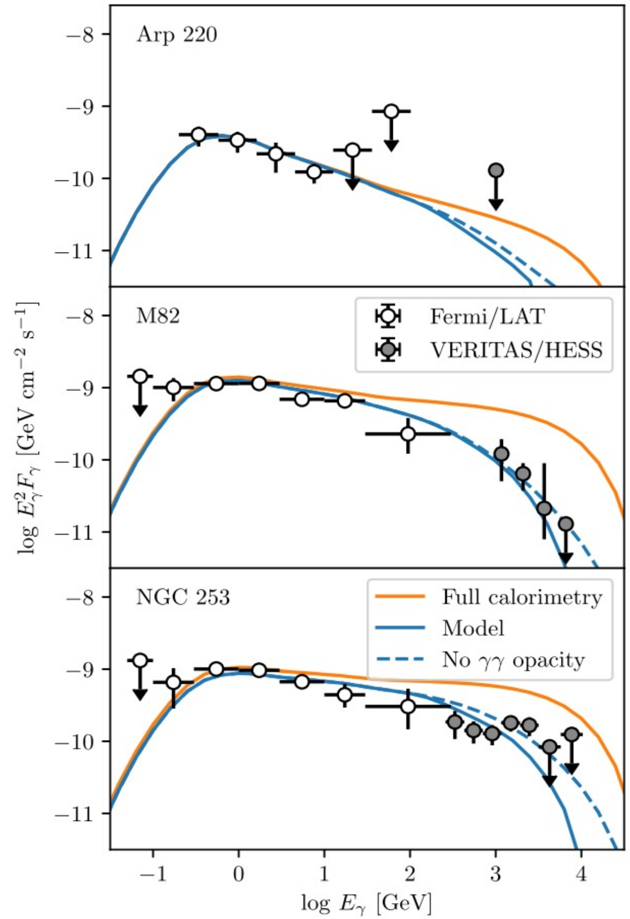
Gamma-ray spectra of starbursts

Diffusion different from MW

Gamma-ray vs. IR luminosities for the SFGs



Ajello et al. 2020,
Griffin et al. 2016



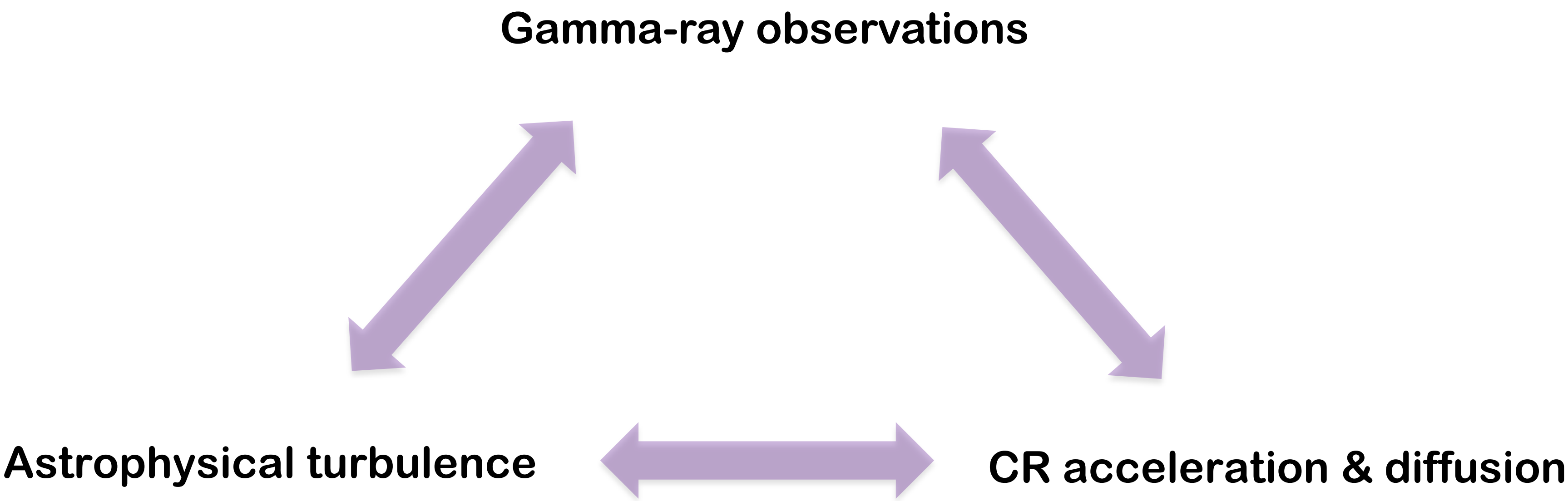
Krumholz, Crocker, Xu, et al. 2020

What we learn from gamma-ray observations, e.g.

- A great variety in luminosities and spectra of SNRs and other CR sources.
- Future gamma-ray observations will reveal a larger variety and statistics of CR sources and more PeVatrons.
- A large energy coverage is important in distinguishing between leptonic and hadronic processes.
- Gamma-ray luminosity vs. radio/infrared luminosity.
- Suppressed diffusion in the vicinity of CR sources, e.g., SNRs, pulsar wind nebulae, star clusters, and in molecular clouds.

We want to know, e.g.

- What are the dominant sources of Galactic CRs, different sources for GeV and PeV?
- The relation between CRs and star formation?
- Does CR acceleration depend on the source & local environment (not considered in the standard DSA model)?
- Does CR diffusion depend on the local environment, near sources and near Earth, Galactic and extragalactic ISM?
- What is the CR injection spectrum at Galactic sources? Any modification due to the diffusion near the sources?


Gamma-ray observations
Astrophysical turbulence
CR acceleration & diffusion

MHD turbulence since 1995

1. Turbulence-wave duality

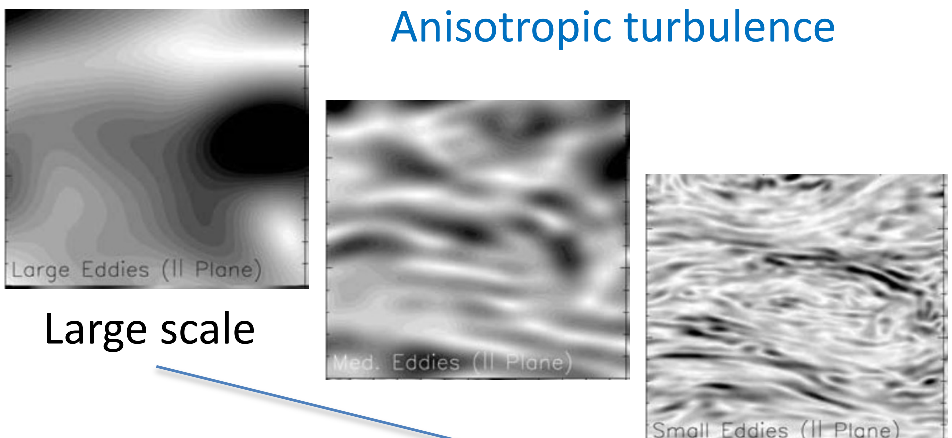
$\perp B_{local}$

Turbulent energy cascade

$\parallel B_{local}$

One-period wave

Anisotropic turbulence



Large scale

Small scale

e.g., Cho & Lazarian 2003; Beresnyak 2014; Guo et al. 2021

Critical balance

$$\frac{l_\perp}{u_l} = \frac{l_\parallel}{V_A}$$

Goldreich & Sridhar 1995;
Lazarian & Vishniac 1999

MHD turbulence since 1995

2. Bi-directional energy flow

Turbulent dynamo

Turbulent reconnection

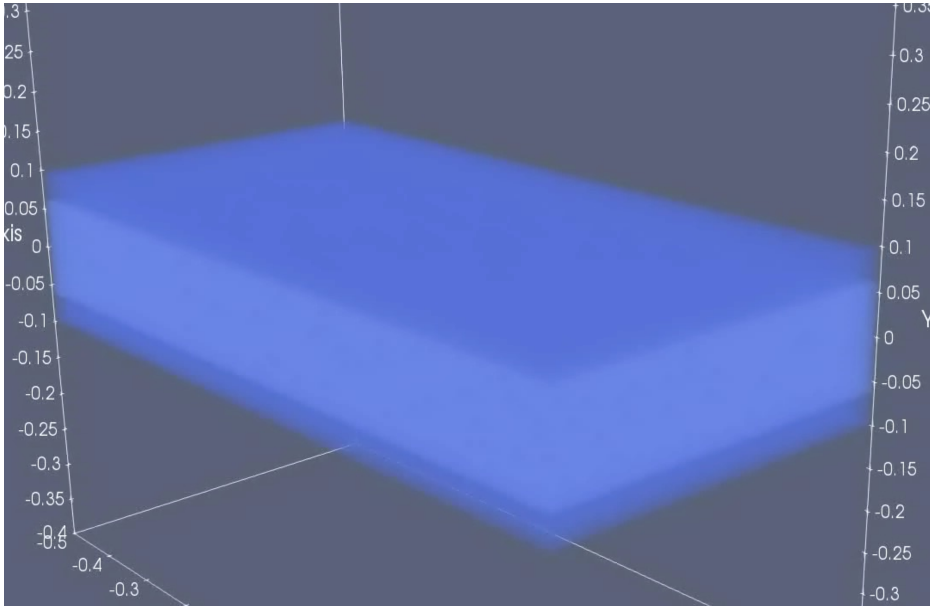
Lazarian & Vishniac 1999

Turbulent kinetic energy ⟷ **Magnetic energy**

on all length scales along the turbulent energy cascade

MHD turbulence since 1995

2. Bi-directional energy flow



Kowal et al.2017, 2019

Turbulent dynamo Turbulent reconnection

Turbulent kinetic energy ⟷ **Magnetic energy**

on all length scales along the turbulent energy cascade

MHD turbulence since 1995

3. Multiple components

Cho & Lazarian 2002, 2003

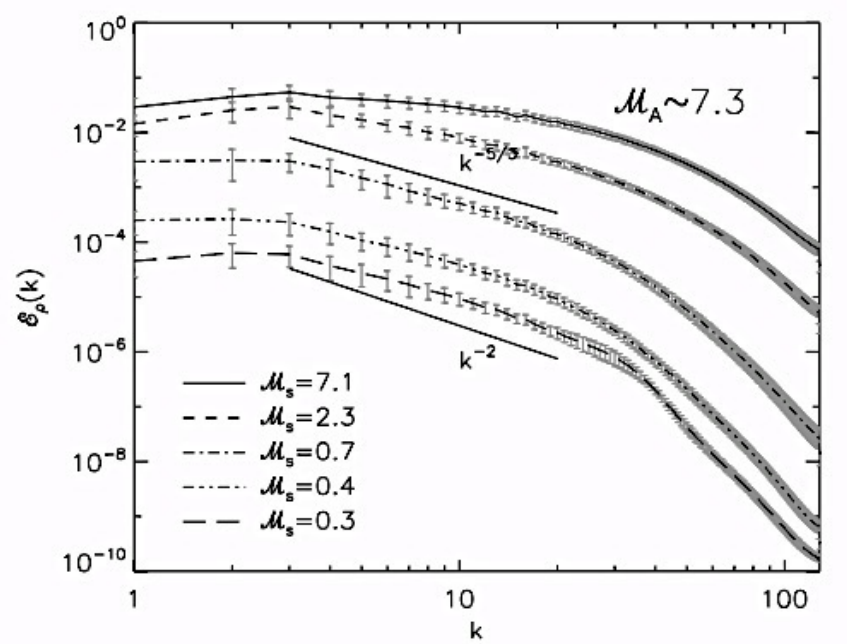
Solenoidal | **Compressive**

Xu, Ji, & Lazarian 2019;

e.g., Federrath & Klessen 2012; Padoan et al. 2016; Kritsuk et al. 2017; Fornieri et al. 2021

Various turbulent spectra

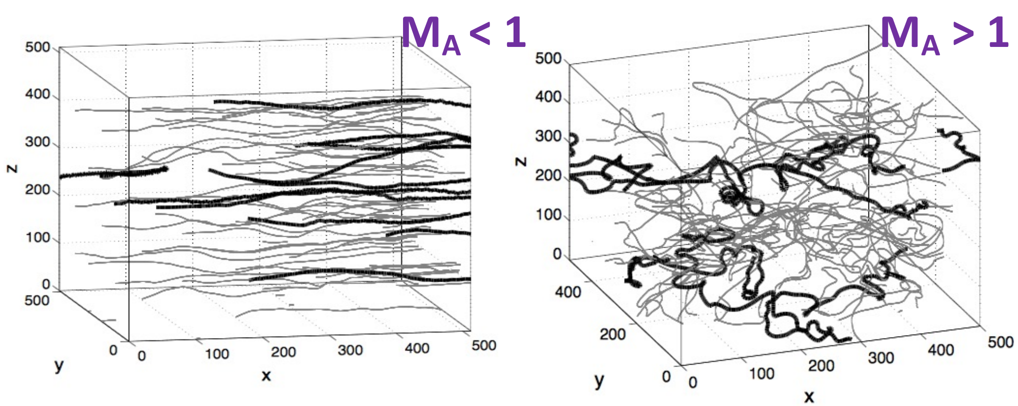
e.g., Kowal et al. 2007; Zhdankin et al. 2017



1. Turbulence-wave duality   2. Bi-directional energy flow   3. Multiple components

Basic parameters for characterizing turbulence:

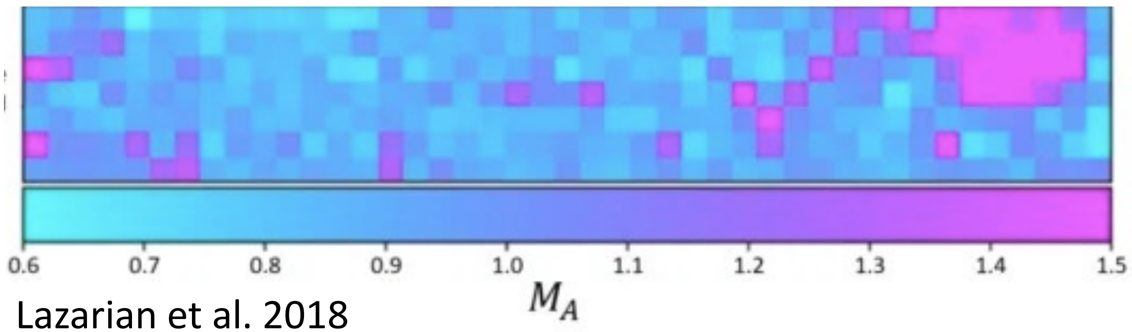
Alfvénic and **Sonic Mach numbers** $\mathbf{M_A}$, $\mathbf{M_S}$



Xu & Yan 2013

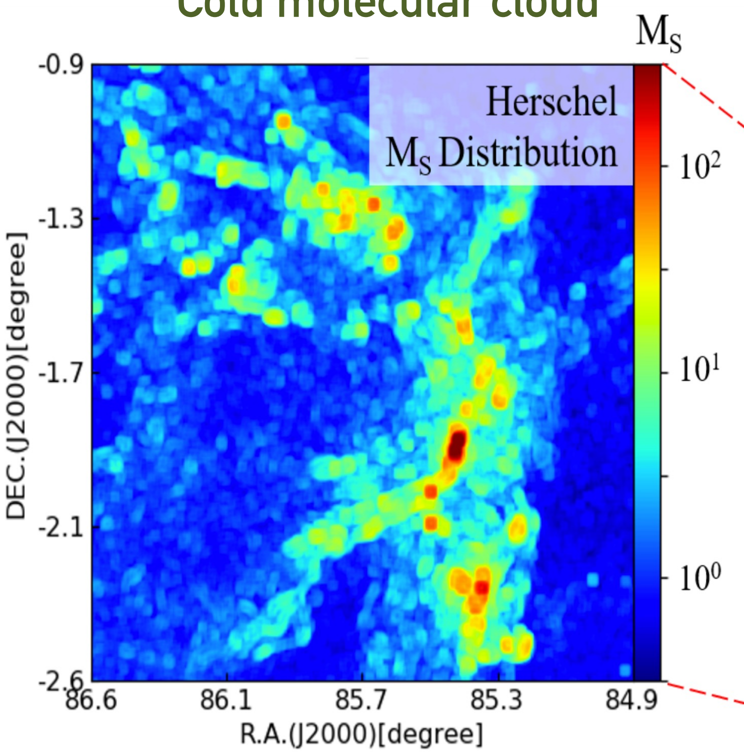
Variety of astrophysical turbulence

HI gas



Lazarian et al. 2018

Cold molecular cloud



Hu et al. in prep

- Rich and diverse variety of turbulence properties in the multi-phase interstellar medium (ISM)

  M_A, M_S

- Turbulence in our local ISM is not representative

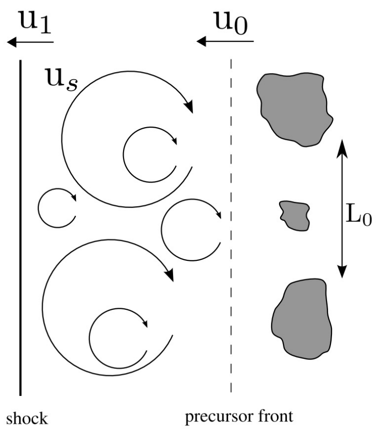
Gradient technique

e.g., Hsieh, et al. 2019; Zhang et al. 2019; Yuen & Lazarian 2020; Xu & Hu 2021; Hu et al. 2021

MHD turbulence and particle acceleration

Shock acceleration

Hydrodynamic energy



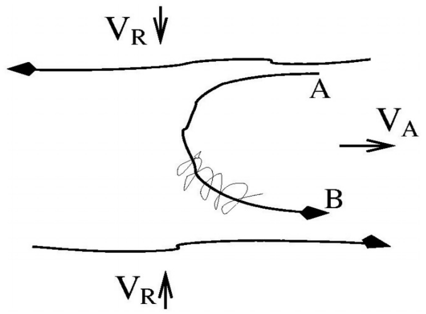
e.g., Beresnyak et al. 2009,
Drury & Downes 2012,
Bruggen 2013

Turbulence

- Decrease acceleration time
- Increase the maximum energy

Turbulent Reconnection acceleration

Magnetic energy



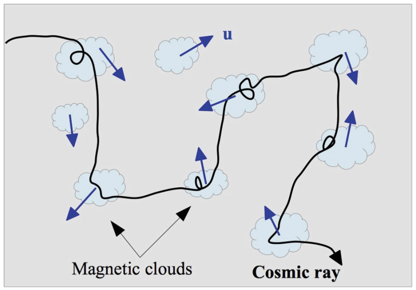
e.g., de Gouveia Dal Pino & Lazarian, 2005;
Kowal et al. 2012; Beresnyak & Li 2016;
Guo et al. 2016; Comisso & Sironi 2019

Turbulence

- Efficient magnetic energy dissipation
- Efficient particle acceleration

MHD turbulence and particle diffusion

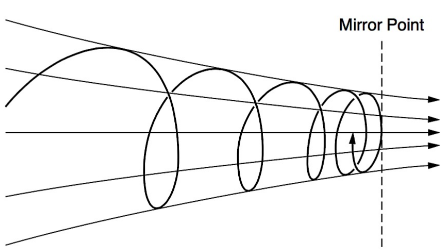
Scattering (// B)



e.g.,
Chandran 2000,
Yan & Lazarian 2002,
Xu & Lazarian 2018,
Fornieri et al. 2021

- **Isotropic** Kolmogorov turbulence: $D_{iso} \propto E^{1/3}$
- **Anisotropic** Kolmogorov turbulence: $D_{ani} \propto E^{-3/2}$
- $D_{ani} >> D_{iso}$

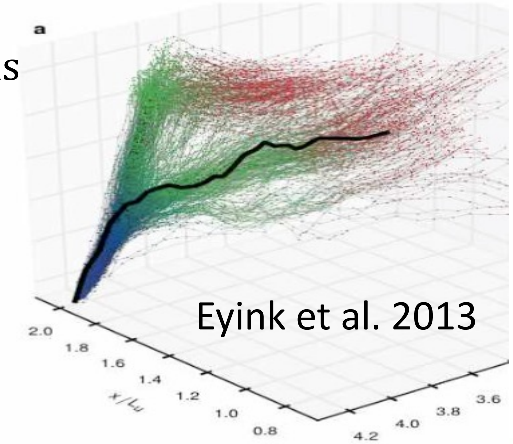
Diffusive mirroring (// B) Compressive



Highly suppressed diffusion e.g., Xu & Lazarian 2020

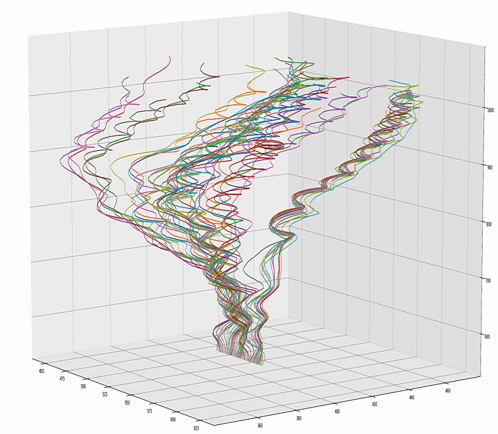
Superdiffusion (⊥ B) Solenoidal

Magnetic fields



Eyink et al. 2013

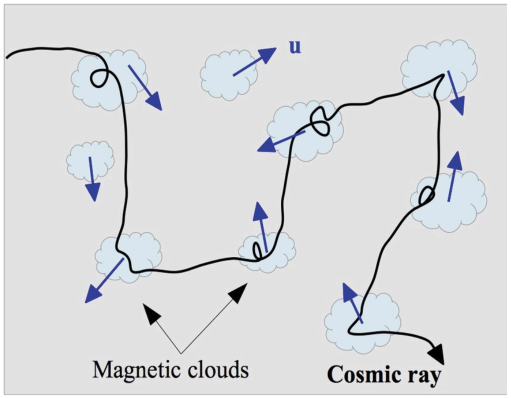
Particles



Hu et al. in prep

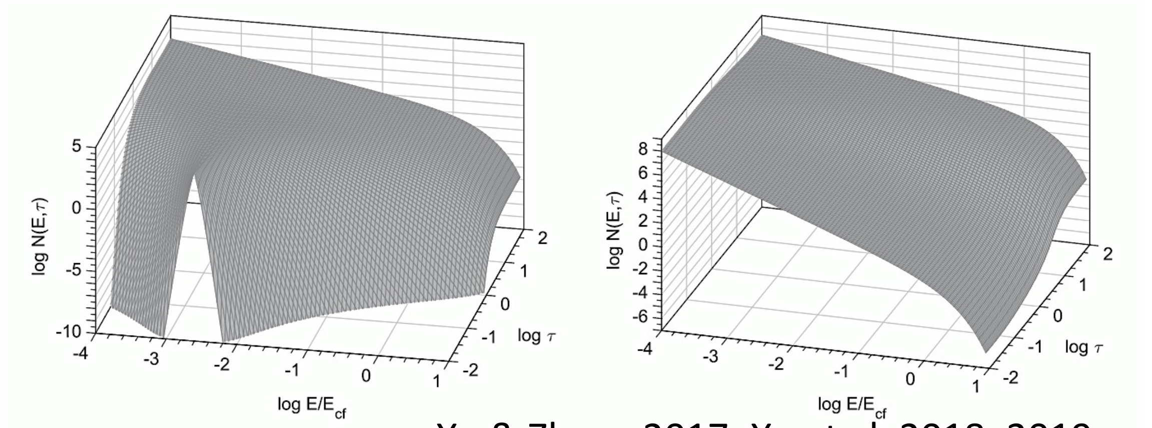
e.g., Lazarian & Yan 2014

MHD turbulence and stochastic acceleration

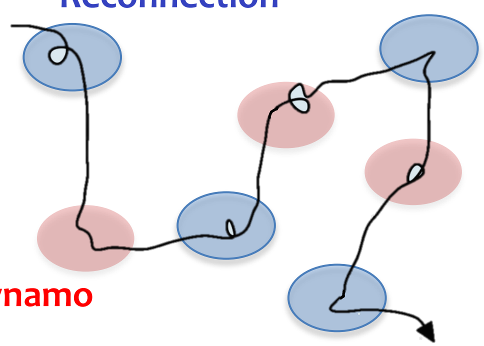


Second-order Fermi acceleration

Broadening and flattening of the injected particle spectrum in e.g., GRBs, PWNe

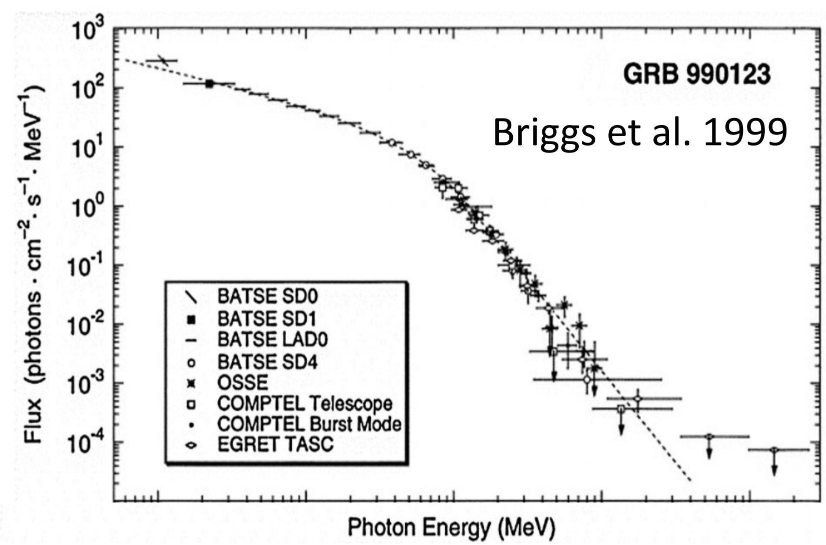


Xu & Zhang 2017; Xu et al. 2018, 2019



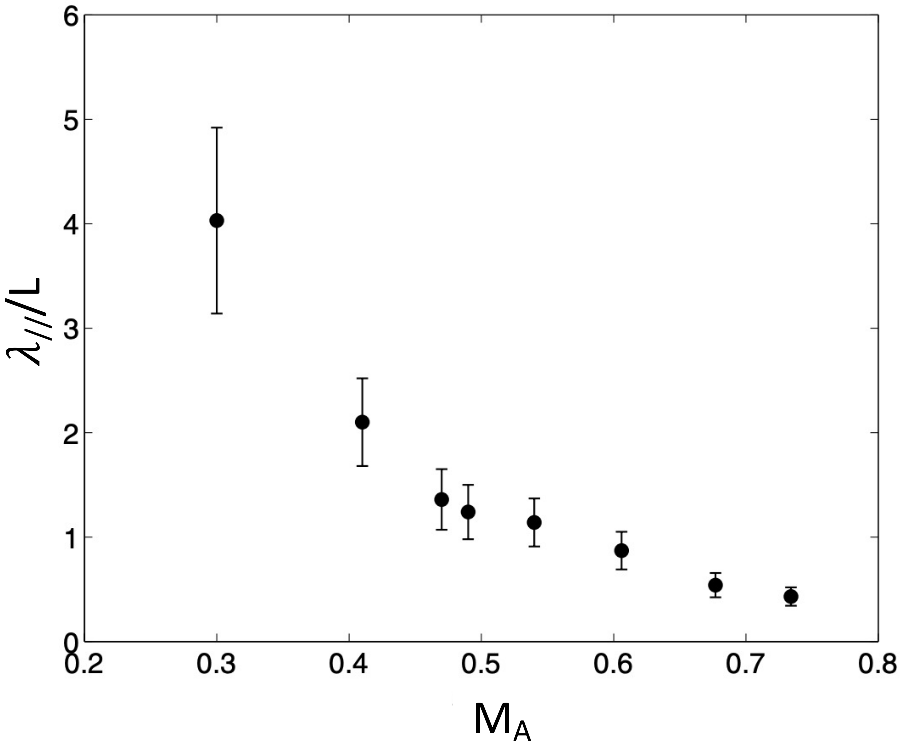
One and half Fermi acceleration

Brunetti & Lazarian 2016; see also e.g., Comisso et al. 2020; Lemoine 2021



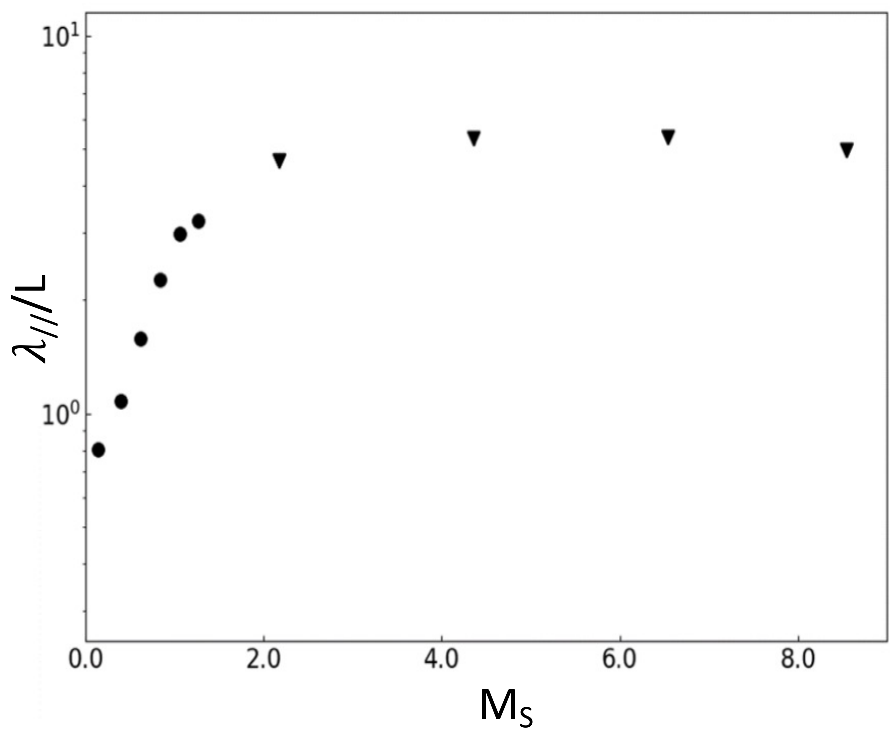
Dependence of CR diffusion on M_A and M_s

Parallel mean free path vs. M_A



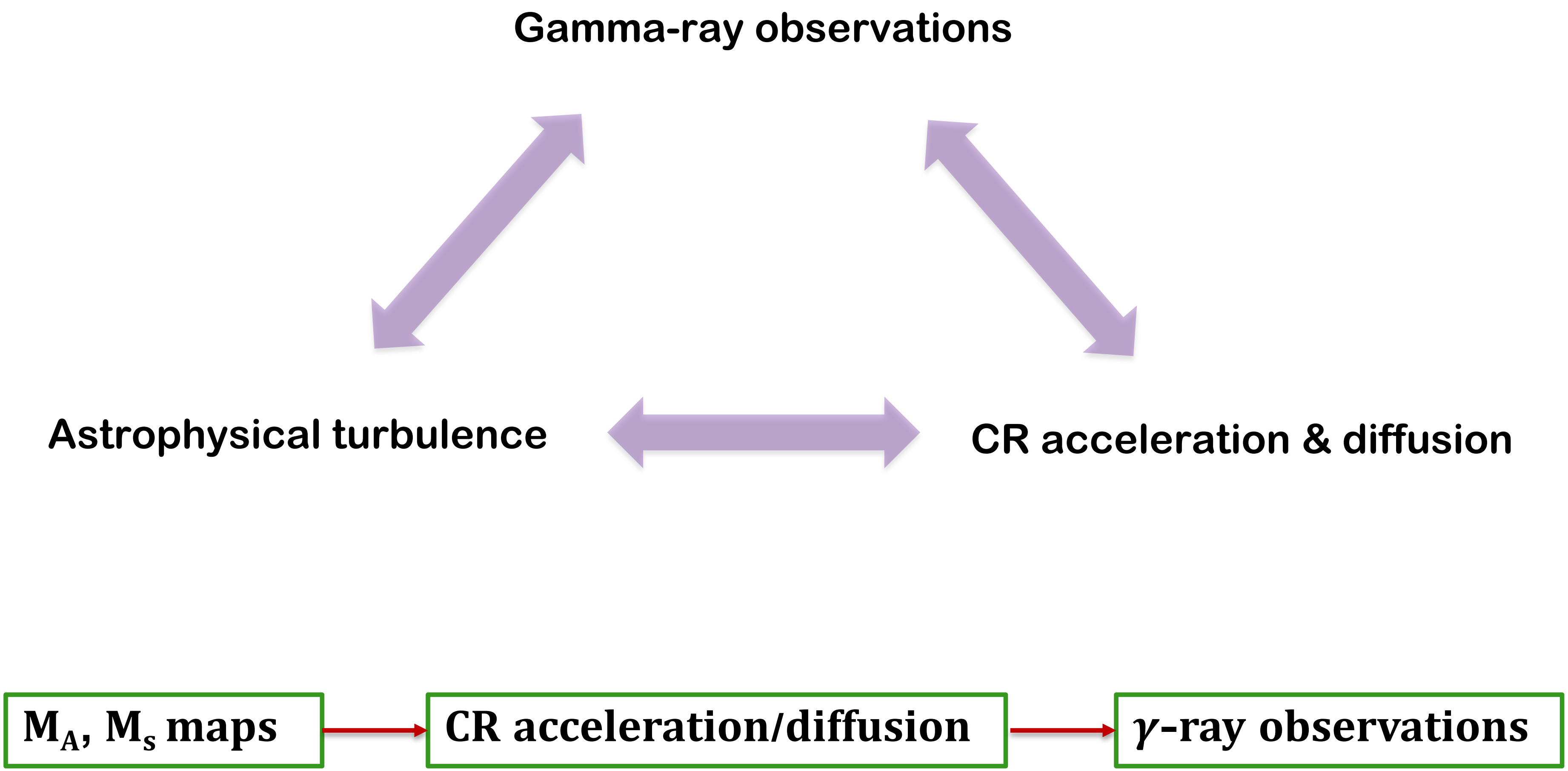
Xu & Yan 2013

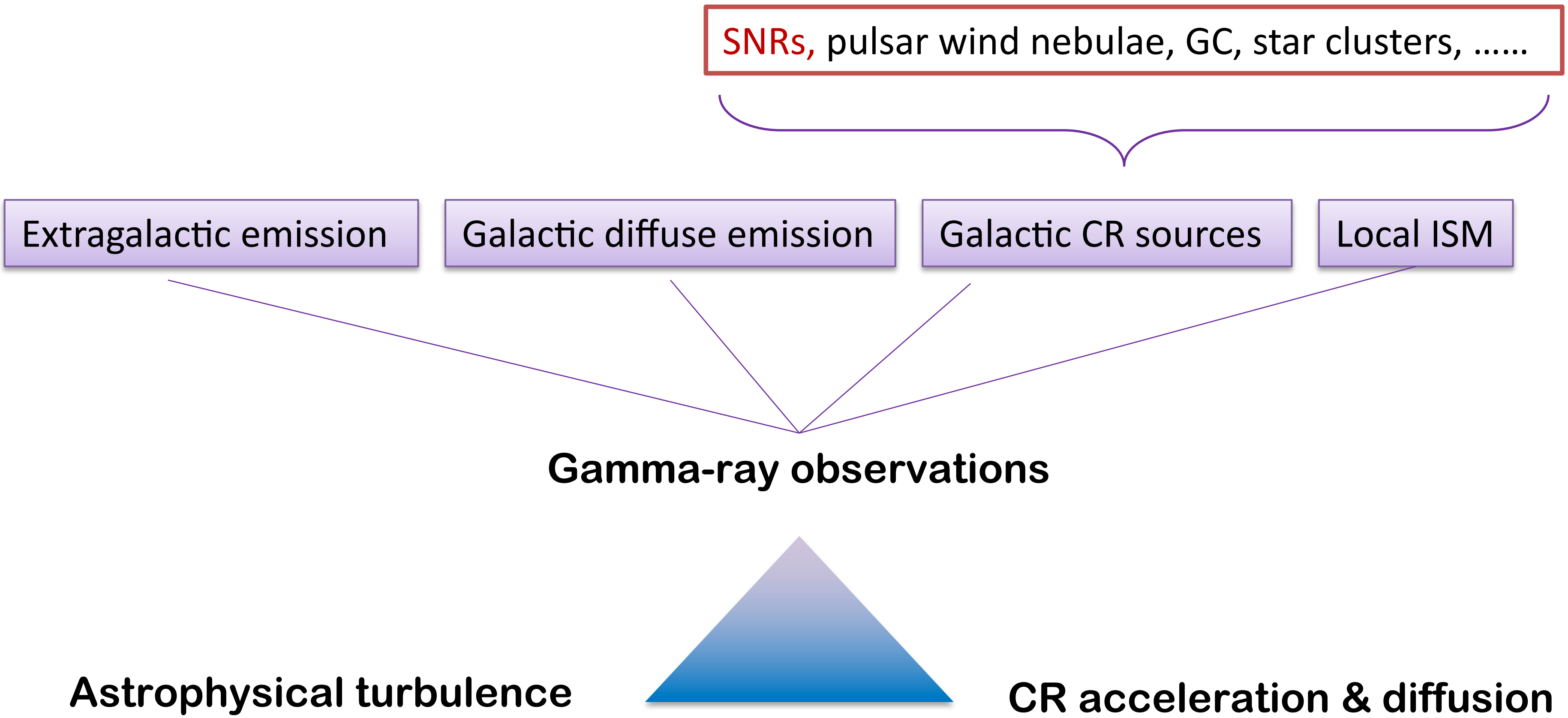
Parallel mean free path vs. M_s



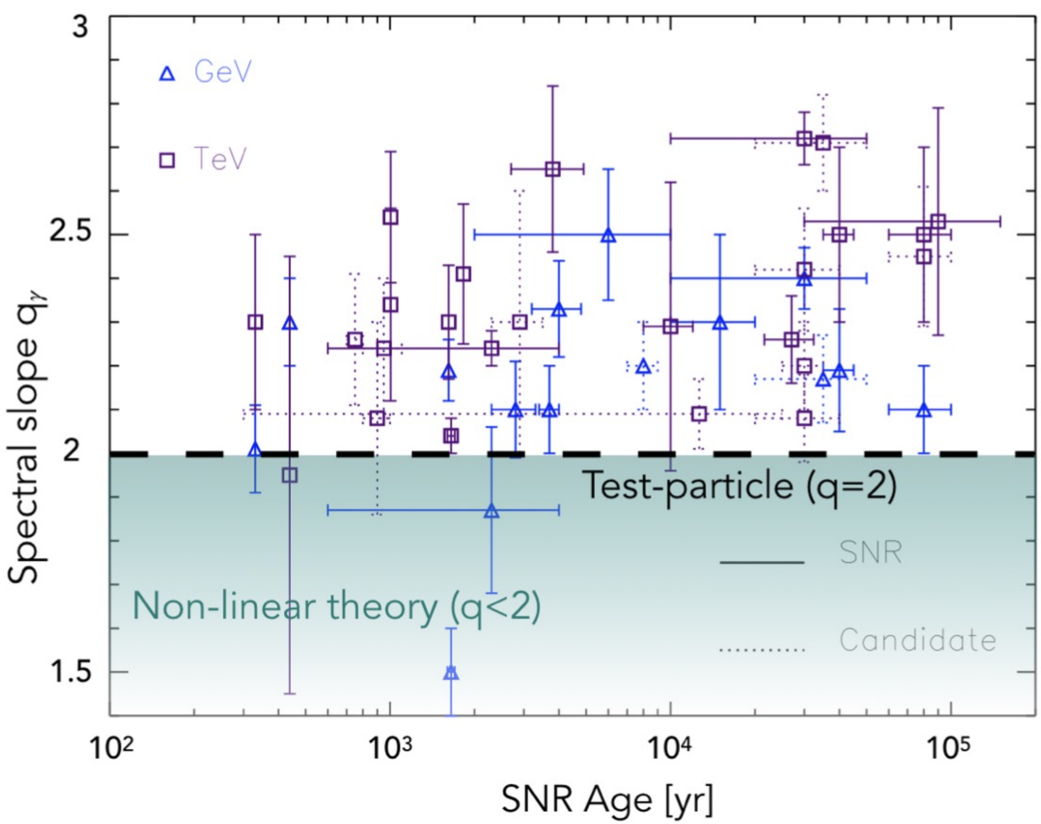
Hu et al. in prep

e.g., Cho & Lazarian 2002, 2003; Lim et al. 2020; Fornieri et al. 2021


Gamma-ray observations
Astrophysical turbulence
CR acceleration & diffusion
M_A, M_s maps
CR acceleration/diffusion
γ-ray observations


SNRs, pulsar wind nebulae, GC, star clusters, ……
Extragalactic emission
Galactic diffuse emission
Galactic CR sources
Local ISM
Gamma-ray observations
Astrophysical turbulence
CR acceleration & diffusion

SNRs: theory vs. observation



Caprioli & Haggerty 2019

Why steepening? e.g.

DSA in a partially ionized medium?

Escaping CRs?

Loss of CR energy to turbulence and magnetic field?

Alfvenic drift?

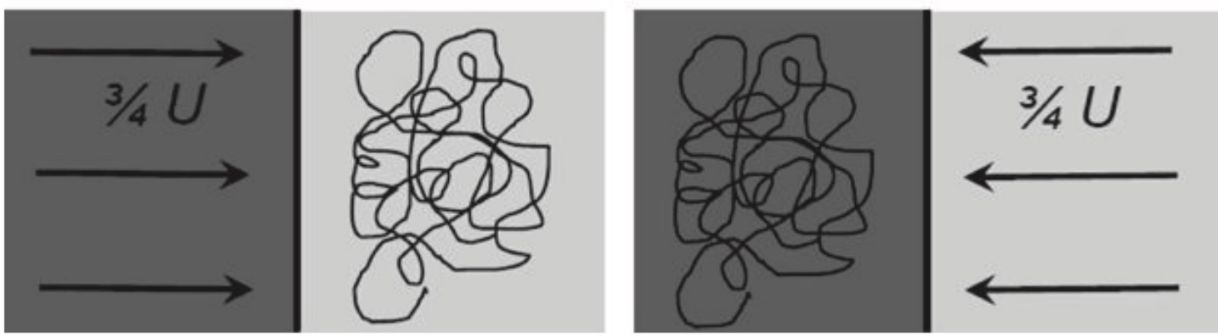
……

e.g., Ptuskin & Zirakashvili 2005, Zirakashvili & Ptuskin 2008, Malkov et al. 2010, Ohira et al. 2010, Ohira & Ioka 2011, Drury 2011, Blasi et al. 2012, Caprioli & Spitkovsky 2014, Osipov et al. 2019, Bell et al. 2019, Malkov & Aharonian 2019, Caprioli et al. 2020……

Diffusive shock acceleration (DSA)

DSA in a strong shock waves

Longair 2011

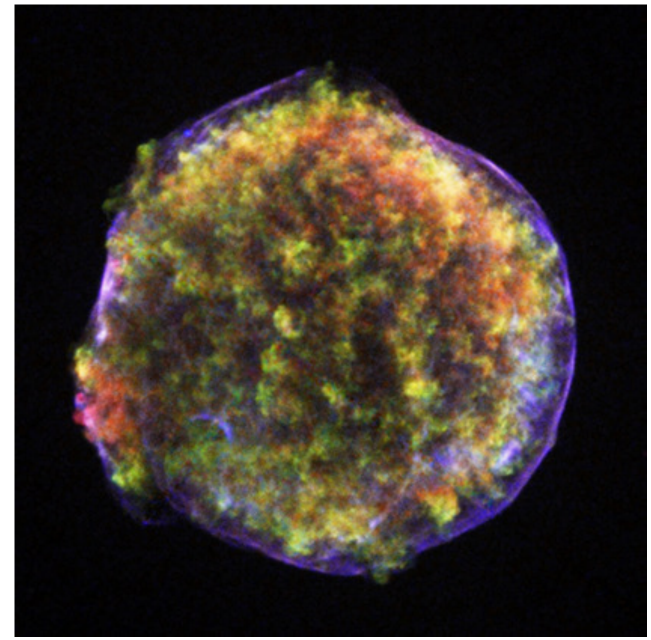


Axford, Leer & Skadron 1977, Krymsky 1977, Bell 1978, Blandford & Ostriker 1978, Drury 1983, Jones & Ellison 1991……

$$N(E)\,\mathrm{d}E \propto E^{-2}\,\mathrm{d}E$$

$E_{\max} \sim 10^{14} Z B_{\mu\mathrm{G}}$ eV Lagage & Cesarsky 1983

X-ray image of Tycho's SNR



NASA/CXC/Rutgers/J.Warren & J.Hughes et al.

Magnetic field amplification

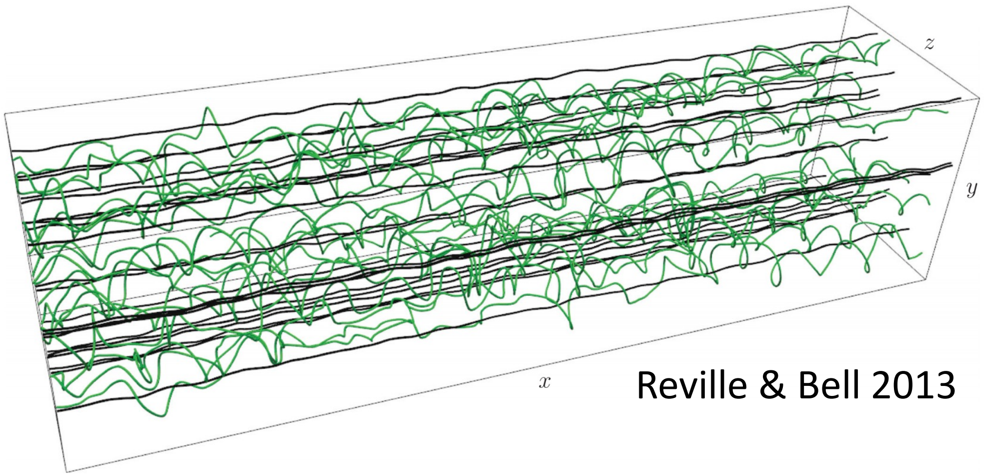
up to ∼300 μG

e.g., Bamba et al. 2005, Völk et al. 2005, Parizot et al. 2006, Morlino & Caprioli 2012, Ressler et al. 2014

Preshock instabilities

CR precursor

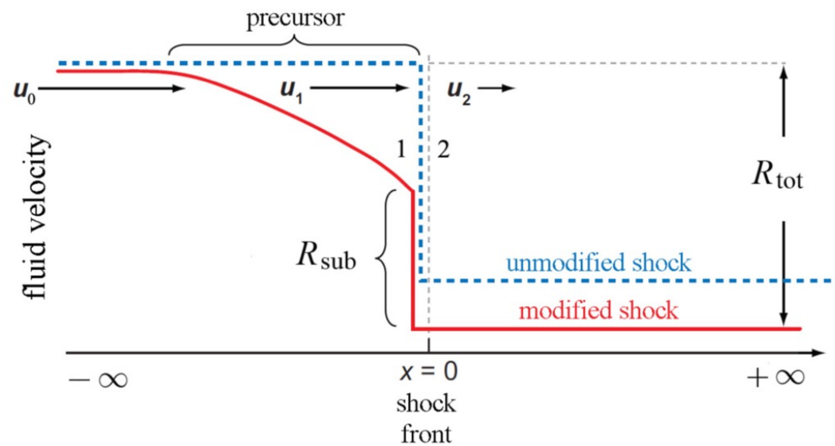
- Amplification of magnetic fields.
- Scattering and diffusion of particles.
- Acceleration of particles.

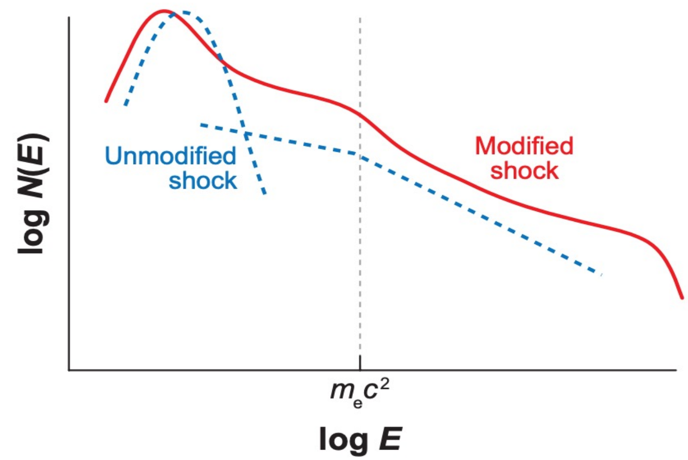


Reville & Bell 2013

e.g., Parker 1958, Skilling 1975, Bell 1978, Dorfi 1991, Gary 1991, Jones & Kang 1992, Bierman 1997, Sturner et al. 1997, Schlickeiser 1999, Baring et al. 1999, Berezhko & Ellison 1999, Malkov & Drury 2001, Blasi 2002,2004, Bell 2004, Berezhko and Völk 2004, Lequeux 2005, Shalchi 2009, Ferrand 2010 , Schure et al. 2012, Vink 2012, Caprioli & Spitkovsky 2014, Bai et al. 2015, Arbutina 2017, Pavlović 2018, Caprioli et al. 2018, Urošević et al. 2019, Zhang & Liu 2020……

Non-linear DSA

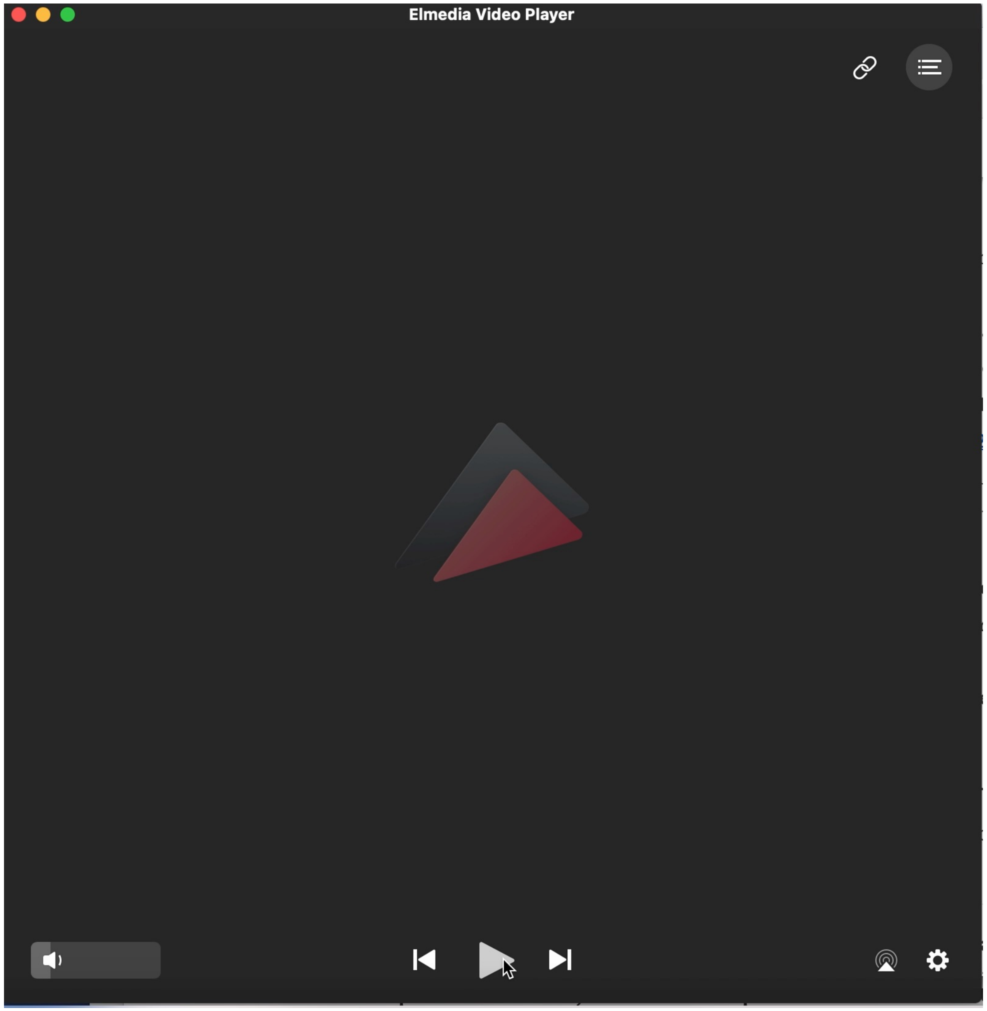




Reynolds 2008

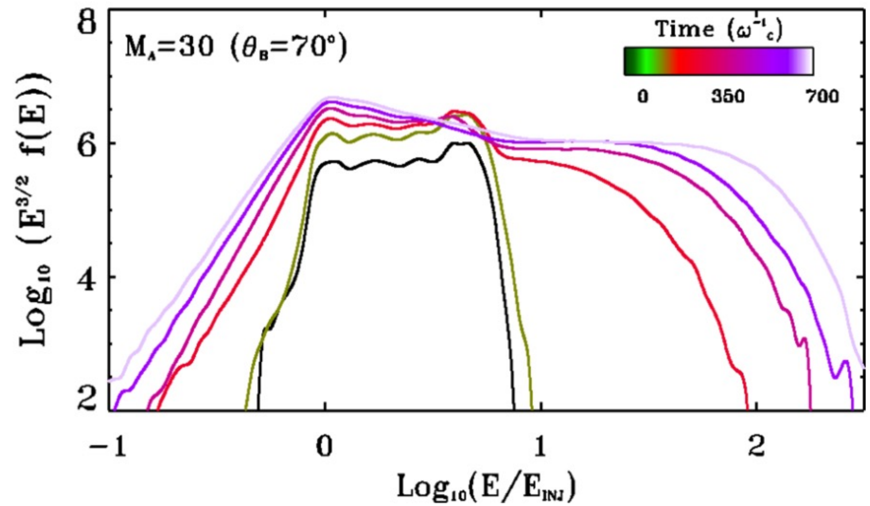
Particles in MHD cells simulations of shock

675 gyrotimes



van Marle, Casse & Marcowith 2018

Energy spectra of non-thermal particles



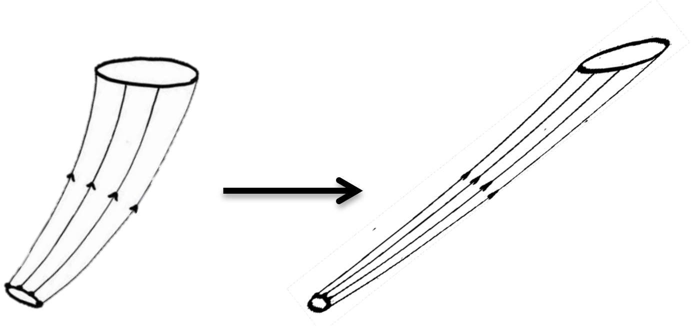
- Oscillations of the shock front and the magnetic field
- Particles initiate NRS instability
- Diffuse particle acceleration
- No clear distinction between parallel and perpendicular shocks

Small-scale turbulence dynamo

Nonlinear turbulent dynamo

e.g. Cho et al. 2009; Beresnyak 2012; Ryu et al. 2008; Mckee et al. 2020; Xu & Lazarian 2017,2020; Gennaro et al. 2020

Turbulent stretching amplifies magnetic fields



$$B \propto \rho l$$

Growth of magnetic energy

$$\mathcal{E} \sim \frac{3}{38}\epsilon t$$

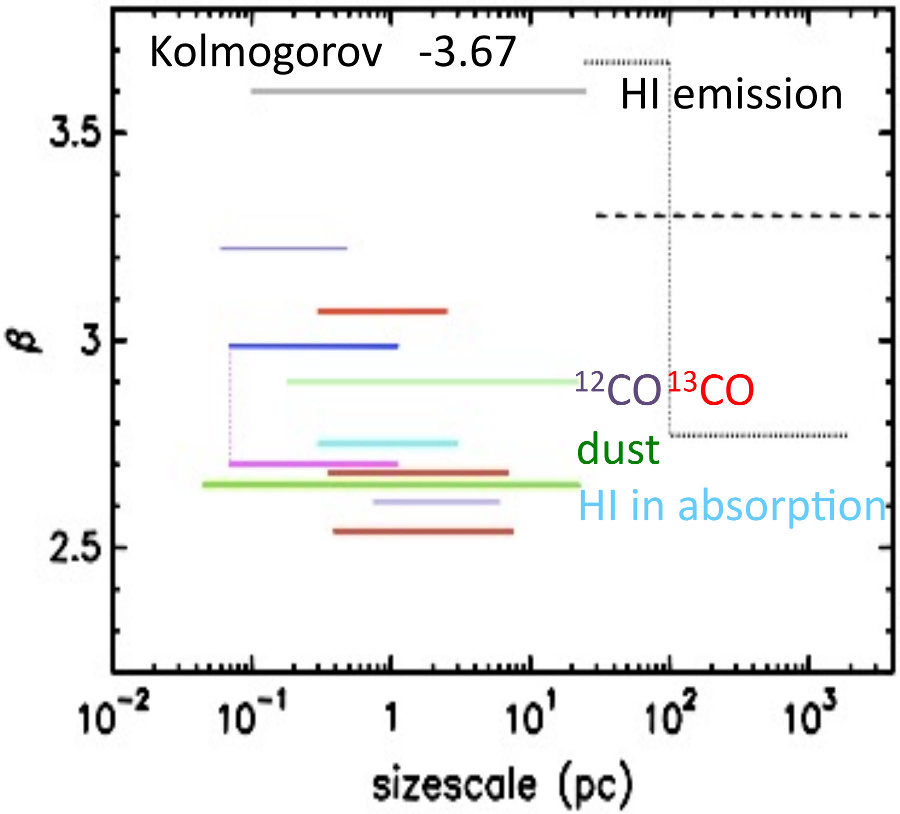
ϵ: turbulent energy cascading rate

Xu & Lazarian 2016

e.g., Kazantsev 1968, Kulsrud & Anderson 1992, Schekochihin et al. 2002, Brandenburg & Subramanian 2005

Preshock turbulent dynamo

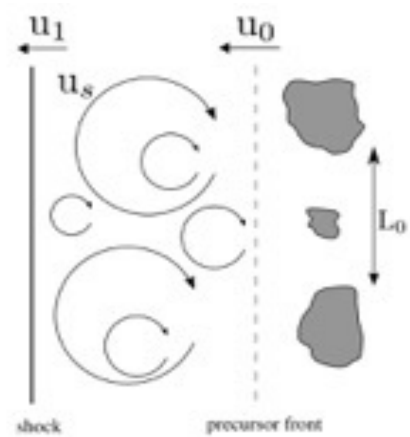
Shallow density spectrum



Hennebelle & Falgarone 12;
e.g., Stutzki et al. 1998; Deshpande et al. 2000; Padoan et al. 2004; Scalo & Elmegreen 2004; Swift 2006; Lazarian 2009

Turbulence-amplified magnetic fields

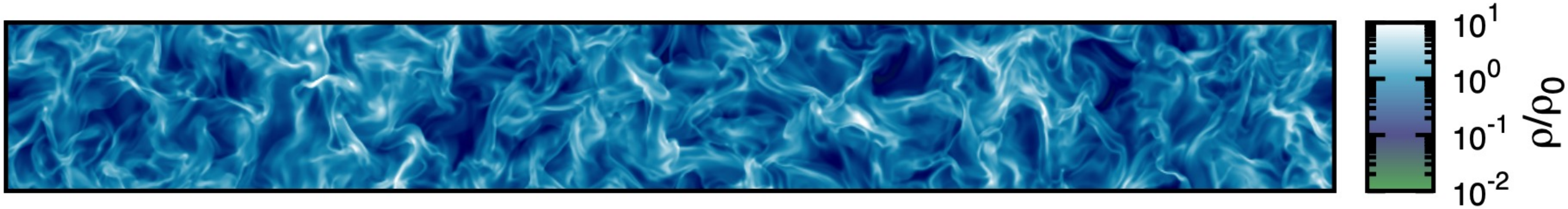
- Density fluctuations + CR precursor → vorticity.
- Vorticity & solenoidal turbulence stretch and amplify magnetic fields
- Independent of detailed plasma physics



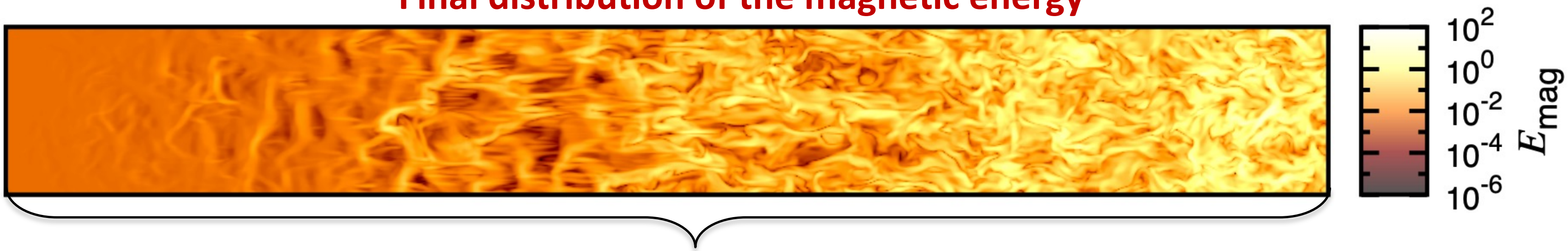
e.g., Beresnyak et al. 2009,
Drury & Downes 2012, Bruggen 2013, Obergaulinger et al. 2014, Walch & Naab 2015, Pais & Pfrommer 2020

Preshock turbulent dynamo

Initial density distribution



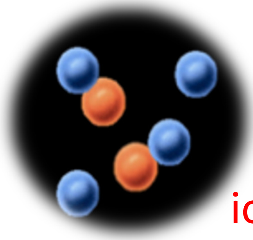
Final distribution of the magnetic energy



Magnetic field amplification depends on interstellar density contrast and size.

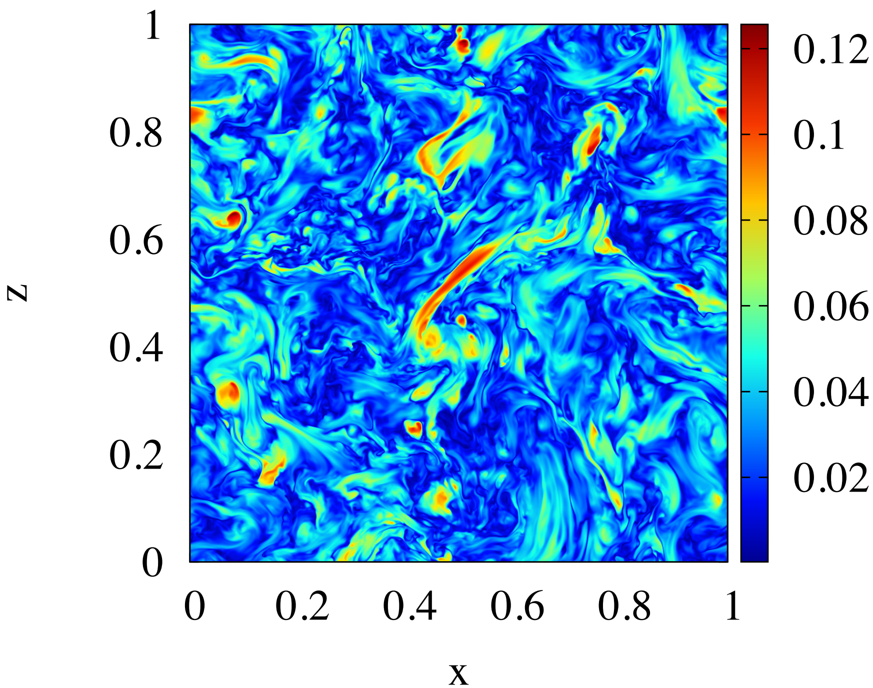
del Valle et al. 2016

Preshock dynamo at a low ionization fraction

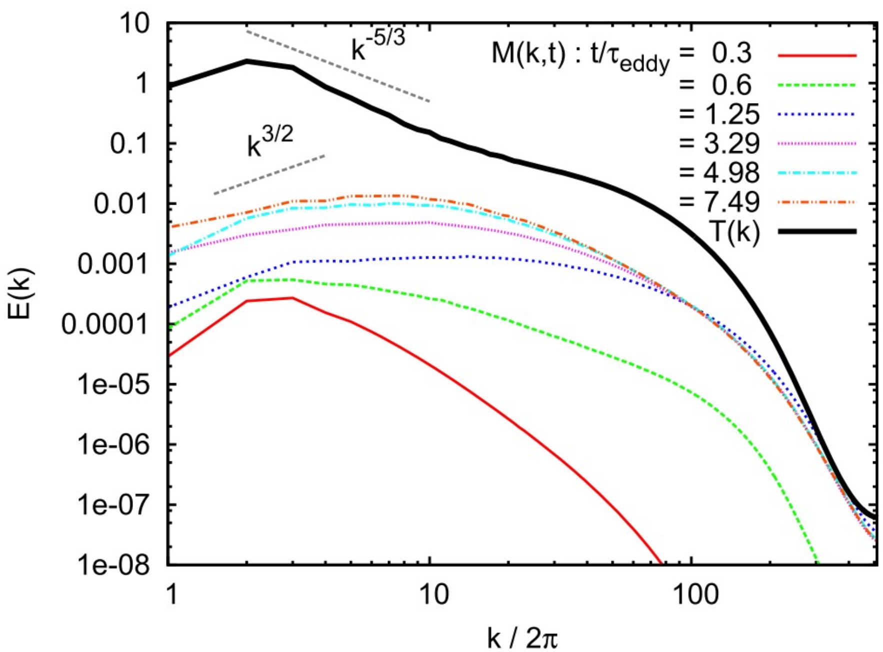


- Weakly ionized upstream ISM
- Two-fluid (neutrals & ions) dynamo

Damped magnetic field fluctuations



Growing magnetic energy spectrum



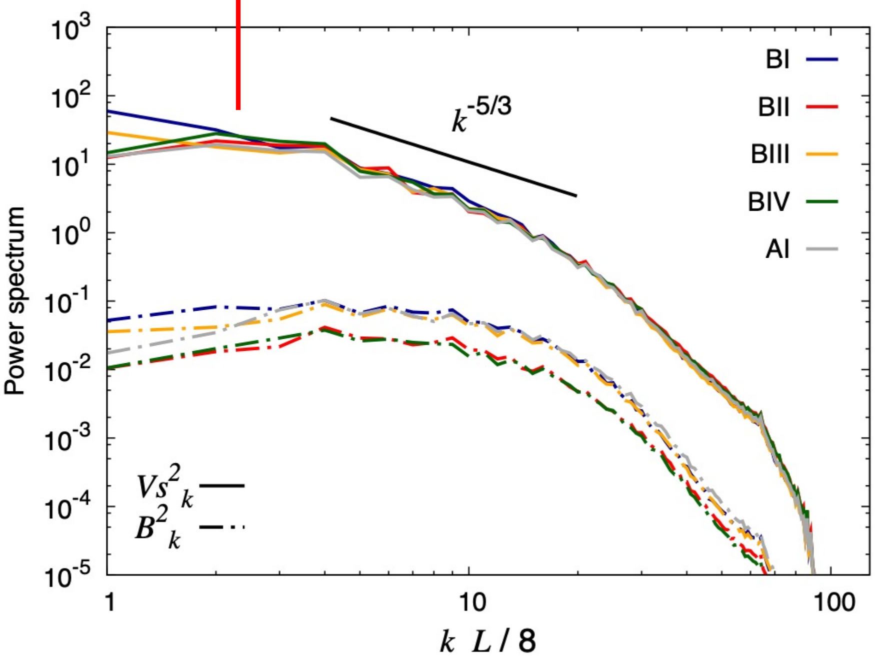
Xu, Garain et al. 2019

Preshock magnetic fluctuations

Turbulence-amplified magnetic fields

MHD 3D

Density structure size t = 3-4 L/$U_{upstream}$

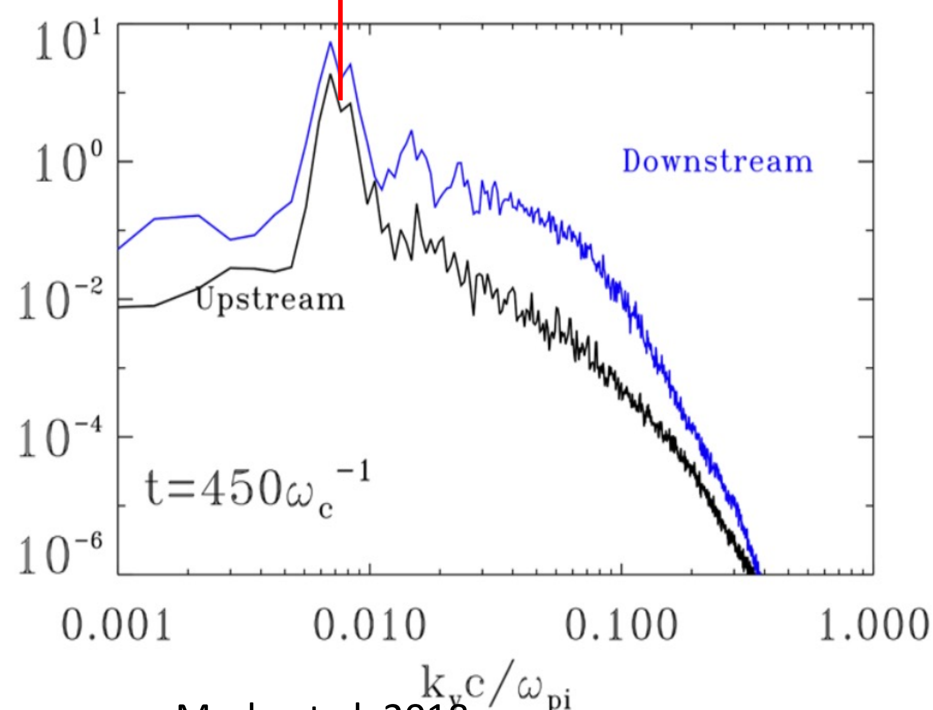


del Valle et al. 2016

CR-driven instabilities

PIC-MHD 2D

100 ion skin depth



van Marle et al. 2018

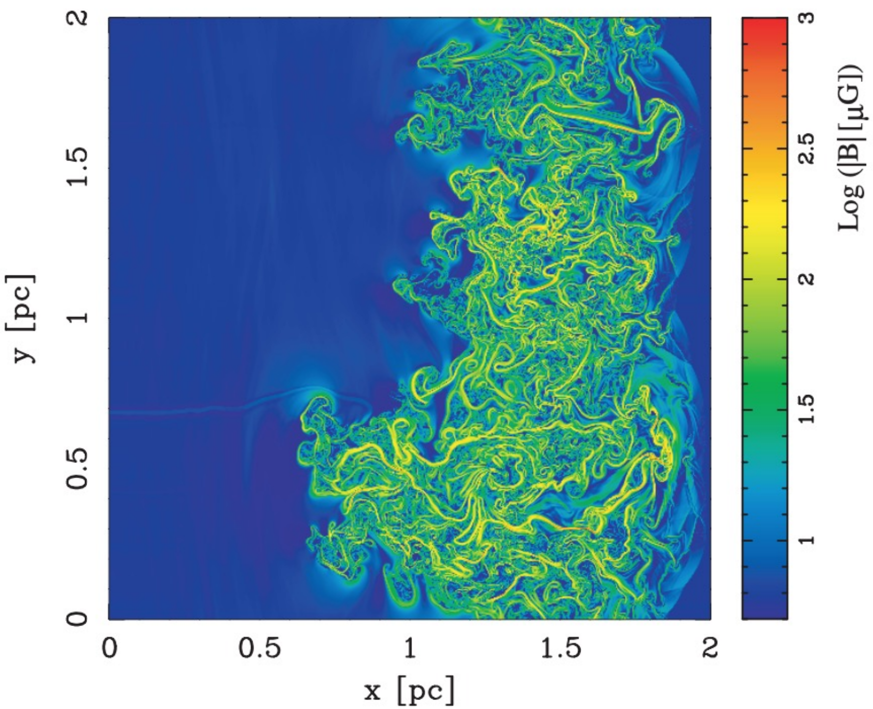
e.g., Marcowith et al. 2020, Pohl et al. 2020; 12 Galactic Particle Acceleration, including PIC | CRI-CRD-MM

Postshock turbulent dynamo

- Upstream density fluctuations in the inhomogeneous ISM
- Generating vorticity and the solenoidal velocity component
- Stretching and amplifying magnetic fields

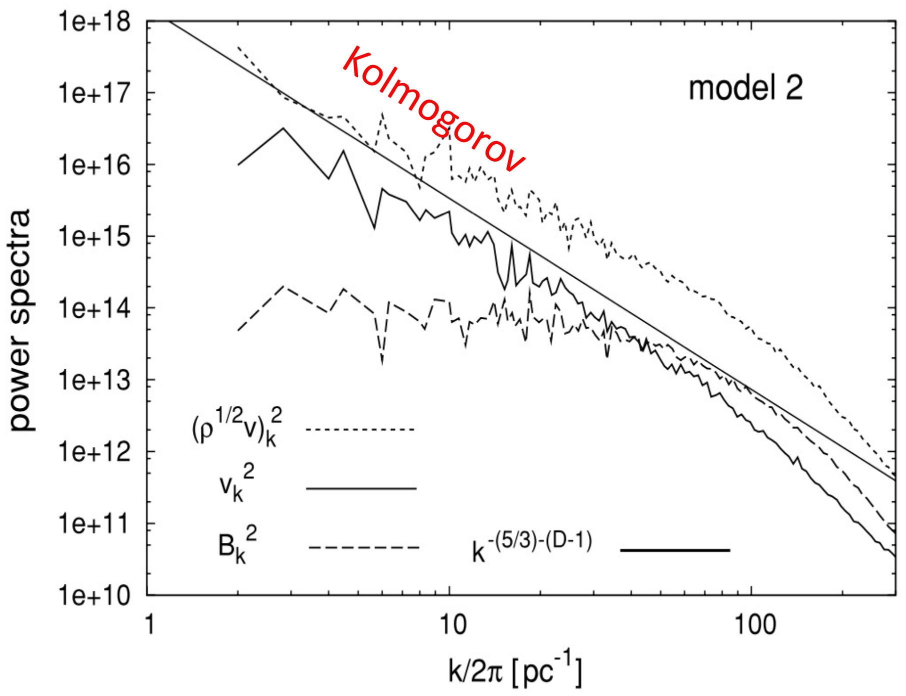
e.g., Dickel et al. 1989, Giacalone & Jokipii 2007, Ji et al. 2016, Winner et al. 2020

Magnetic field fluctuations



Inoue et al. 2009

Magnetic energy spectrum



Postshock turbulent dynamo

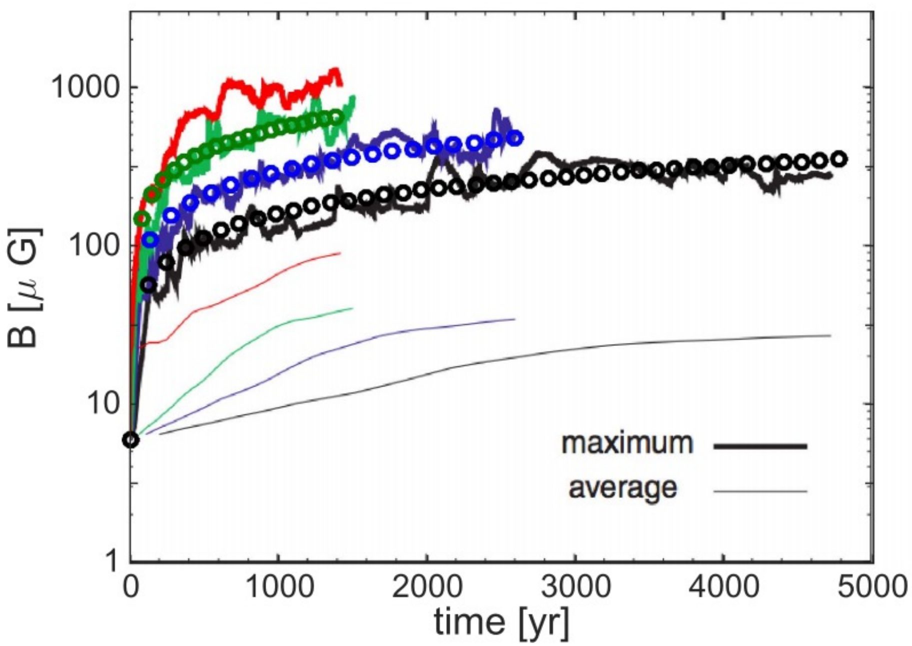
- Nonlinear turbulent dynamo

$$\mathcal{E} \sim \frac{3}{38}\epsilon t$$

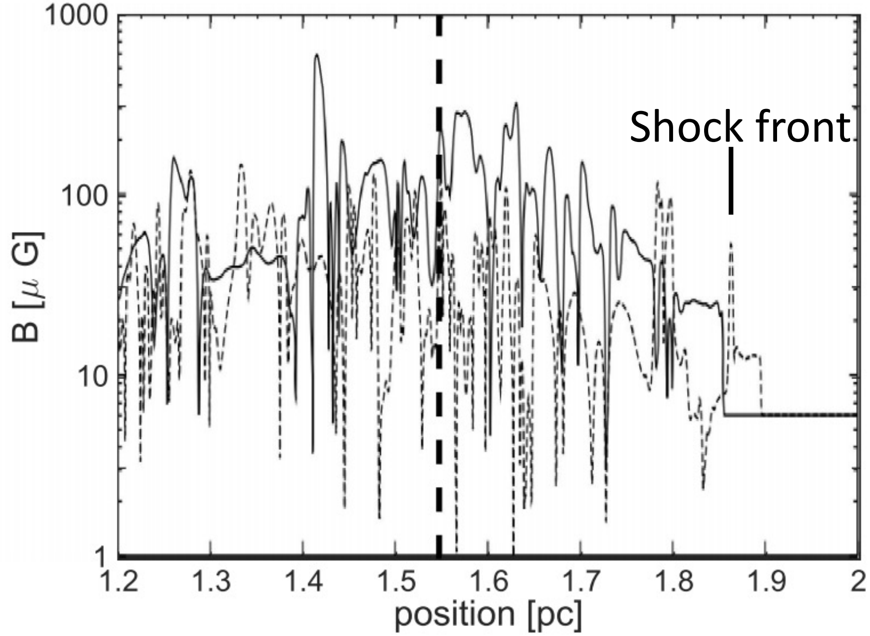
ϵ: turbulent energy cascading rate

Xu & Lazarian 2016

Time evolution of magnetic field



Spatial distribution of magnetic field



Inoue et al. 2009; Xu & Lazarian 2017

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- Nonlinear turbulent dynamo

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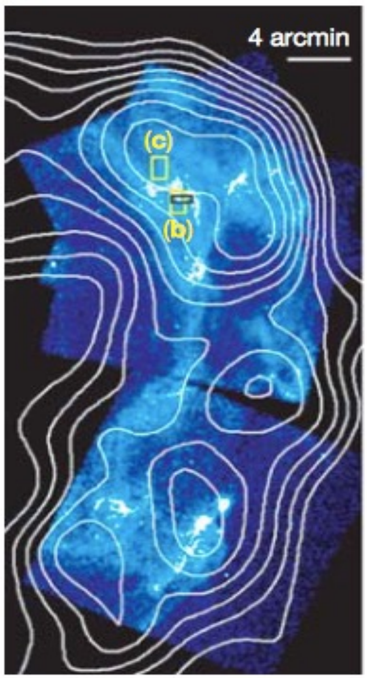
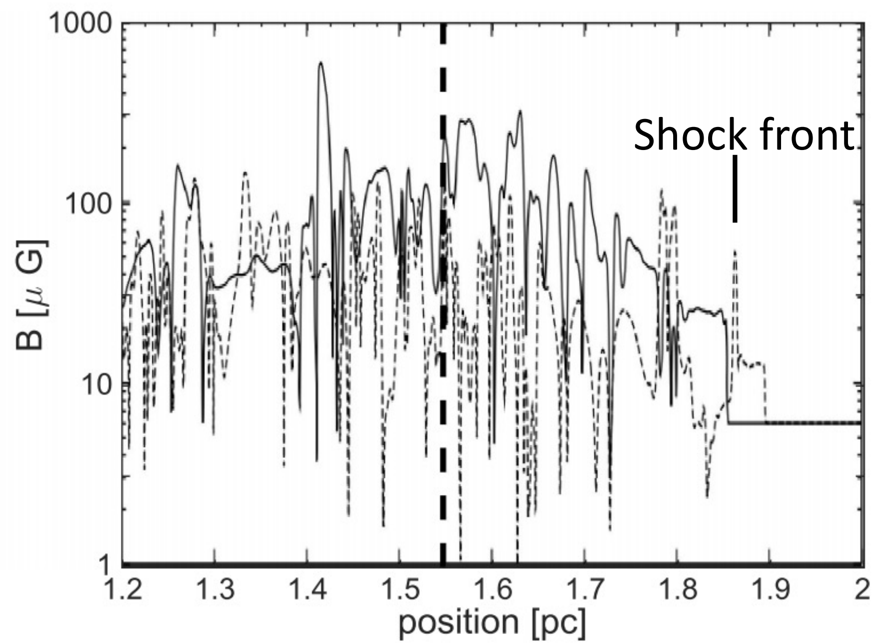


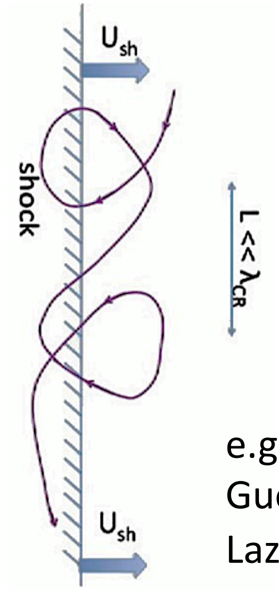
Uchiyama et al. 2007

Spatial distribution of magnetic field



Inoue et al. 2009; Xu & Lazarian 2017

Shock acceleration with turbulent magnetic fields



Turbulence affects

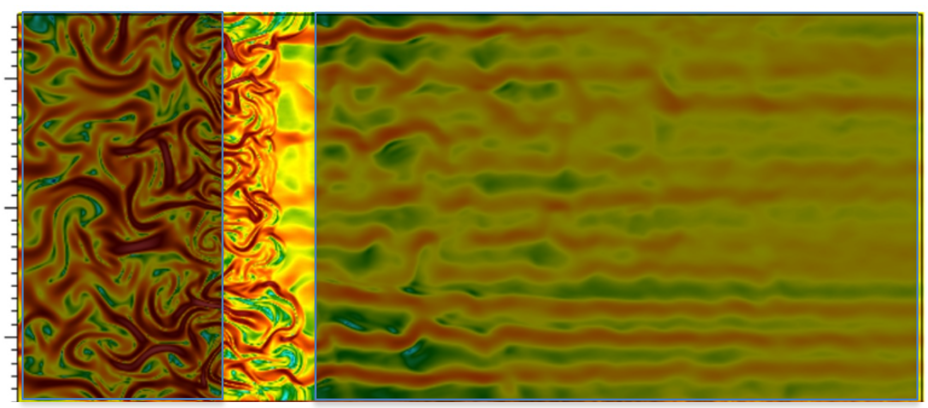
magnetic field amplification and **shock acceleration**

Particles cross the compression without scattering

No clear distinction between parallel and perpendicular shocks

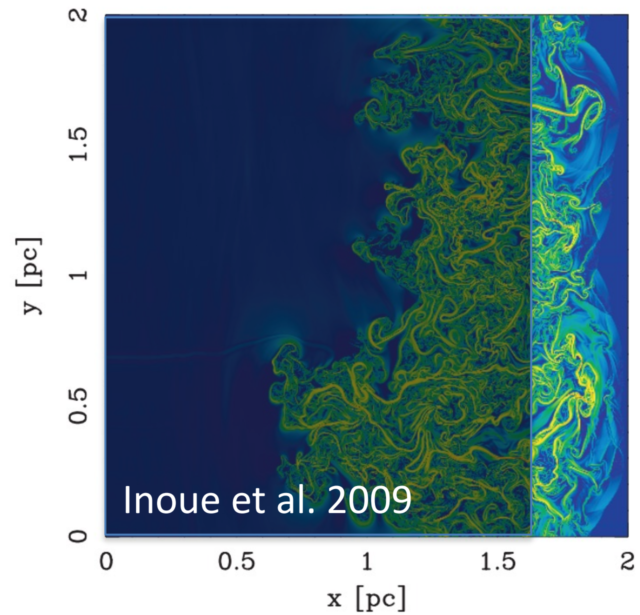
e.g., Jokipii & Giacalone 2007,
Guo & Giacalone 2010,
Lazarian & Yan 2014

PIC-MHD



van Marle et al. 2018

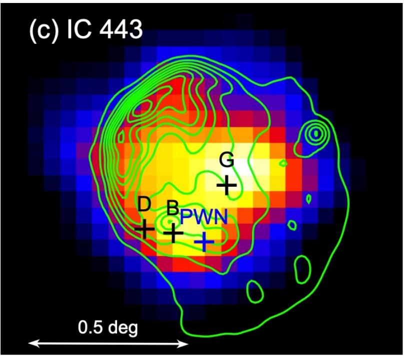
MHD



CR diffusion near SNRs interacting with MCs

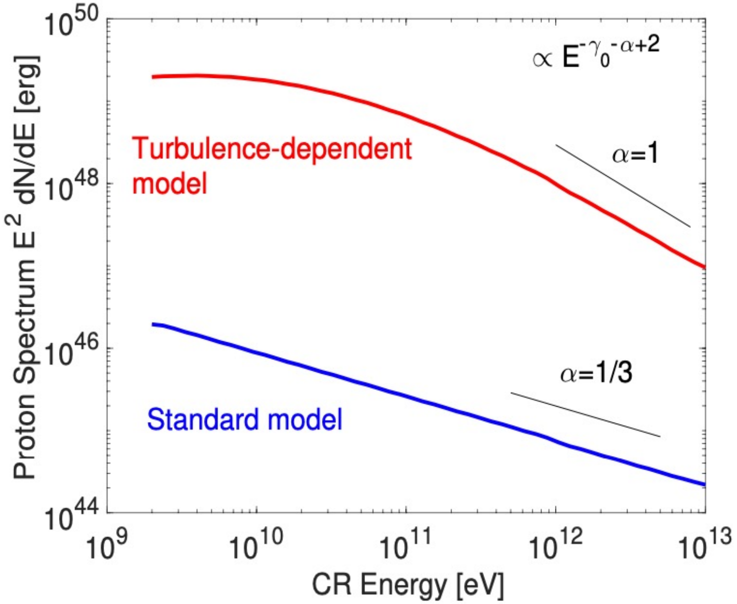
CR diffusion can also explain steep gamma-ray spectra

e.g., Gabici, Aharonian, & Blasi 2007; Li & Chen 2012; Blasi, Amato & Serpico 2012; Evoli & Yan 2014

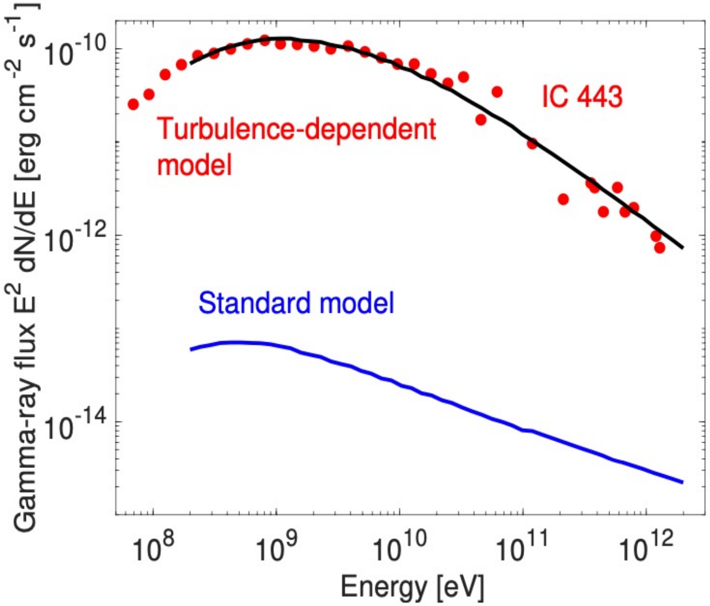


Uchiyama & Fermi LAT Collaboration 2010

CR proton spectrum



Gamma-ray spectrum



Xu submitted

Open questions:

- What are the dominant sources of Galactic CRs, different sources for GeV and PeV?

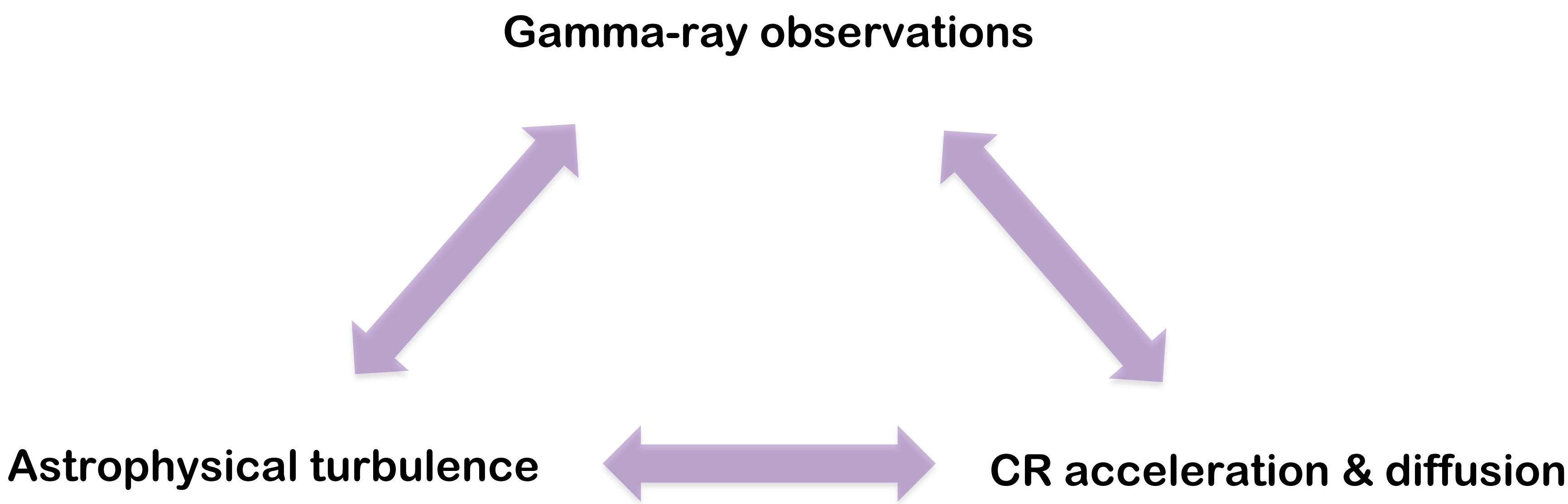
- The relation between CRs and star formation?

- Does CR acceleration depend on the source & local environment (not considered in the standard DSA model)?

- Does CR diffusion depend on the local environment, near sources and near Earth, Galactic and extragalactic ISM?

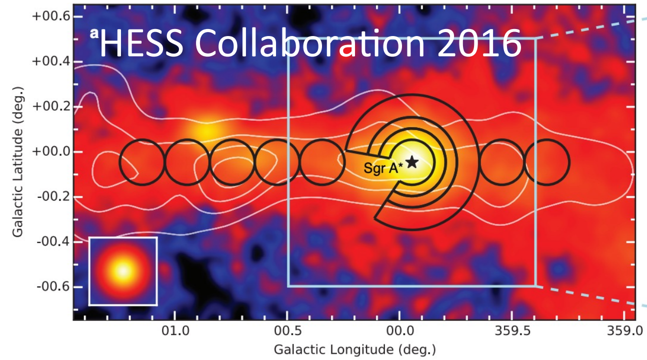
- What is the CR injection spectrum at Galactic sources? Any modification due to the diffusion near the sources?

Class of SNRs and surrounding ISM environment:
broadband γ-ray emission, multi-band observations + turbulence mapping



Acceleration: turbulent dynamo, turbulence/environment dependent
dynamics over the space, time and energy scales in simulations

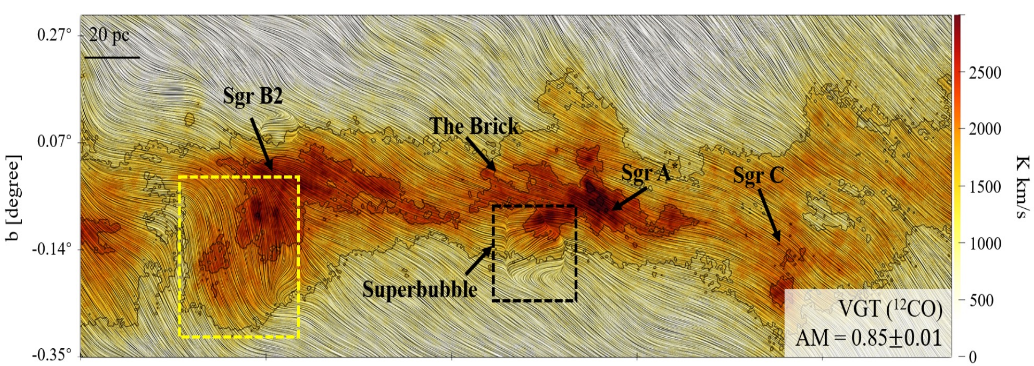
Diffusion: turbulence/environment dependent



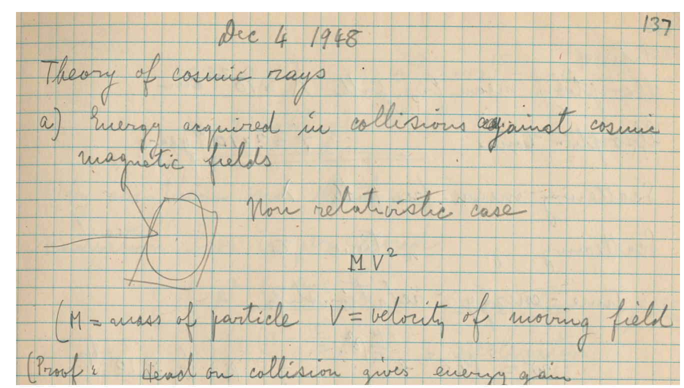
Gamma-ray observations

Astrophysical turbulence

CR acceleration & diffusion



Hu, Lazarian, & Wang 2021



Enrico Fermi's notebook of December 1948