4th EuCAPT Annual Symposium

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INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

Cosmic Ray Propagation

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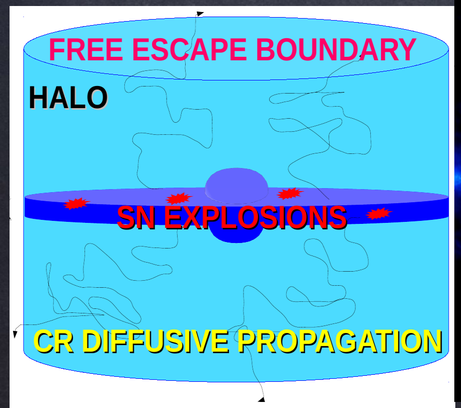
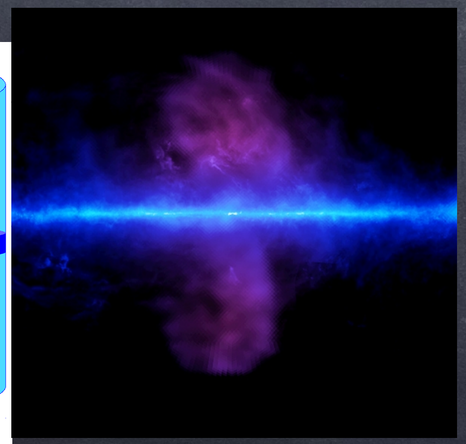
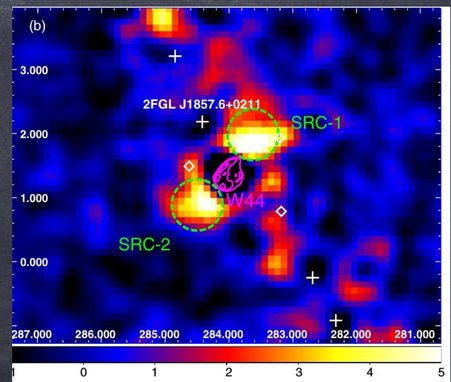
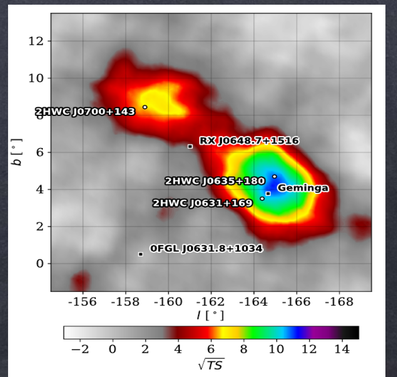






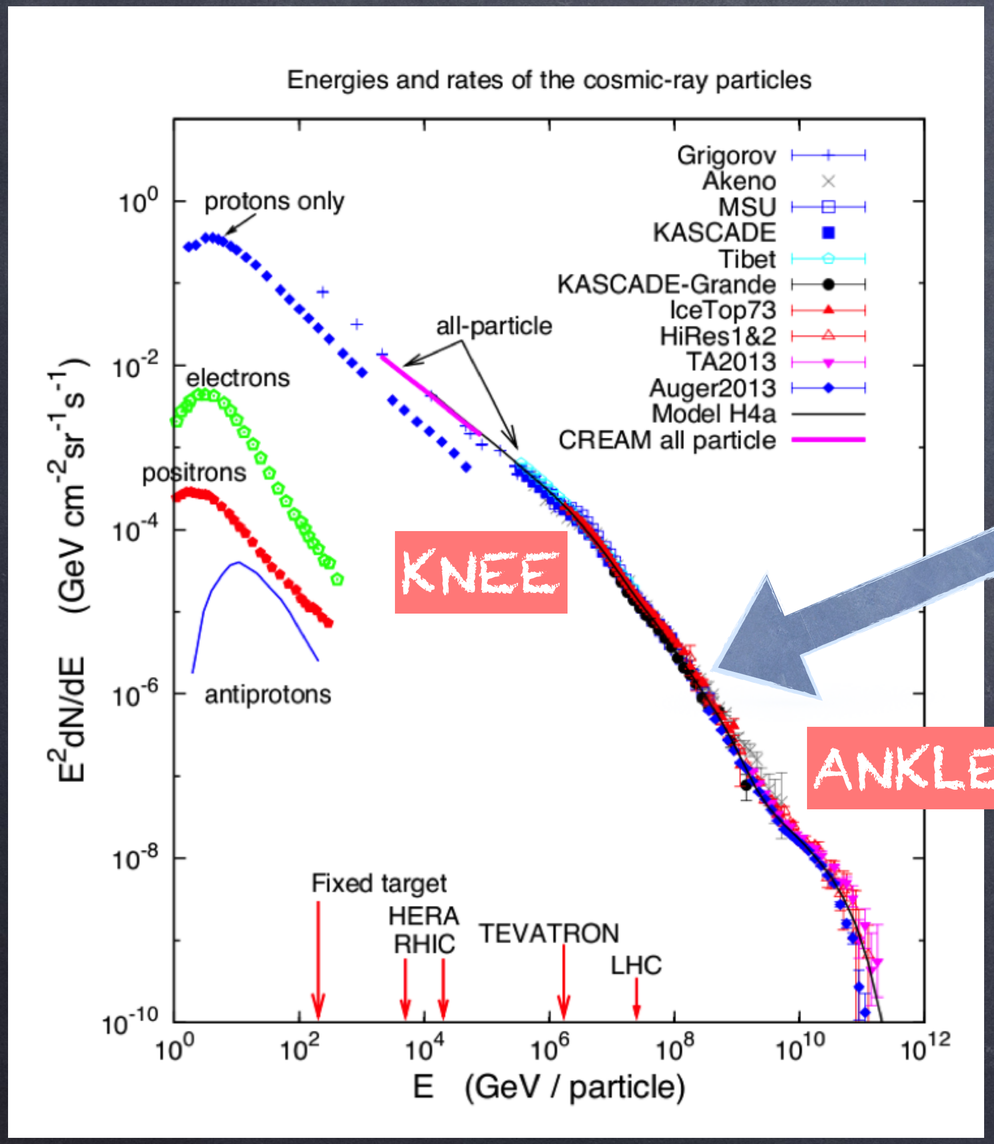


Overview - CR propagation

- what data and observations tell us
- microphysics of transport
- active role played by CRs
- summary

... from data & observations

CR spectrum & magnetic confinement



Galactic magnetic field

$$r_L \approx 10^{-6}\,\mathrm{pc}\;\mathrm{E_{GeV}/B_{\mu G}}$$

Galactic VS extraGalactic

power-law spectrum $\propto E^{-2.7}$

$$W_{CR} \approx W_{th} \approx W_B \sim 1\,\mathrm{eV/cm^{-3}}$$

Blasi 2013 - review CRs

Gabici et al. 2019 - review CRs

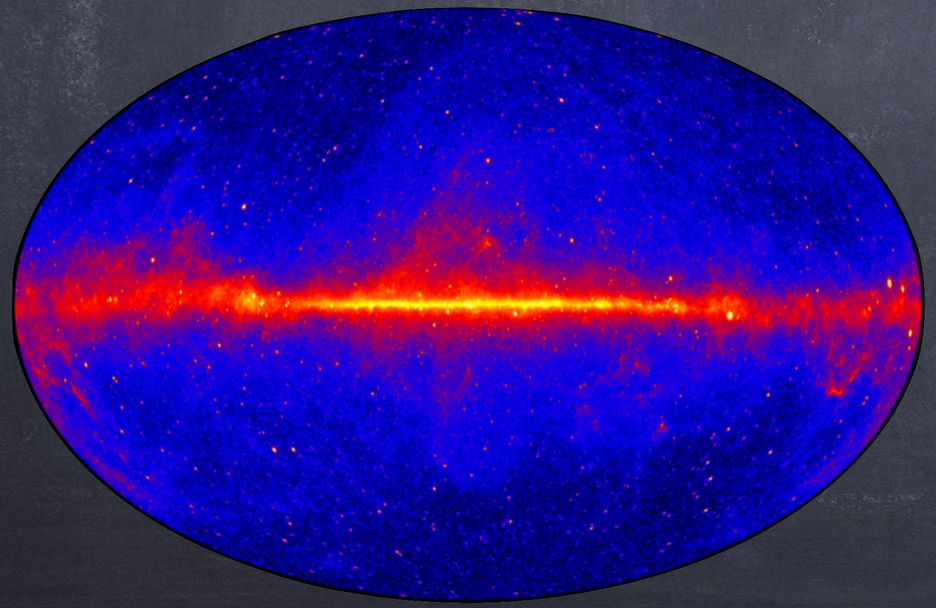
CR energetics

- Galactic disk shine in gamma rays
- CRs roughly uniform in disk
- CR sources in disk

$$E_{\mathrm{CR,disk}} \sim W_{\mathrm{CR}} \times V_{\mathrm{disk}} \approx 10^{55}\mathrm{erg}$$

$$L_{\mathrm{CR,disk}} \sim E_{\mathrm{CR}}/\tau_d \approx 10^{41}\mathrm{erg/s}$$

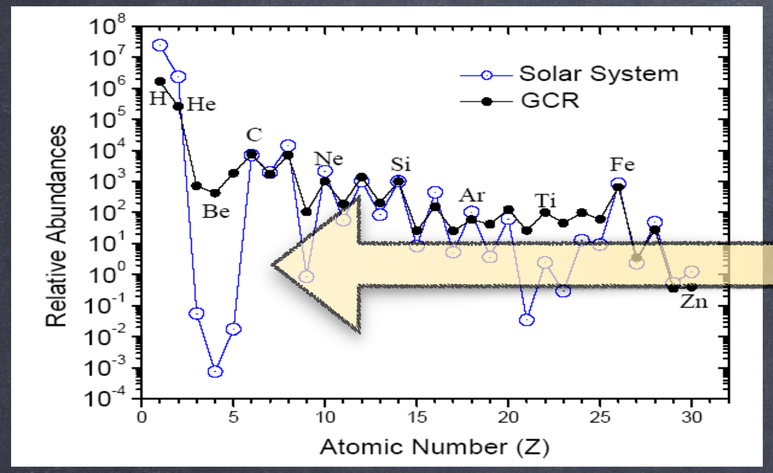
~ 10% of SNR power



CR composition - residence time

primary CRs (p, He, CNO, ...) —> accelerated from ISM

secondary CRs (LiBeB, $\bar{p}$, ...) —> primary + ISM (spallation)



rare nuclei in ISM are

much more abundant in CRs

secondary/primary

- $n_s/n_p \propto \sigma_s X/\mu m_p$
- $X = \mu m_p c\, n_d\, \tau_{\rm disk}$ [grammage - traversed matter]
- $\tau_{\rm disk}({\rm GeV}) \approx$ few Myr

unstable isotopes

- $\tau(^{10}{\rm Be}) \sim 1.4\,{\rm Myr}$
- $^{10}{\rm Be/be} \sim \tau(^{10}{\rm Be})/\tau_{\rm gal}$
- $\tau_{\rm gal}({\rm GeV}) \approx$ tens Myr

CR composition - diffusion

$\tau_{disk}(\mathrm{GeV}) \approx$ few Myr

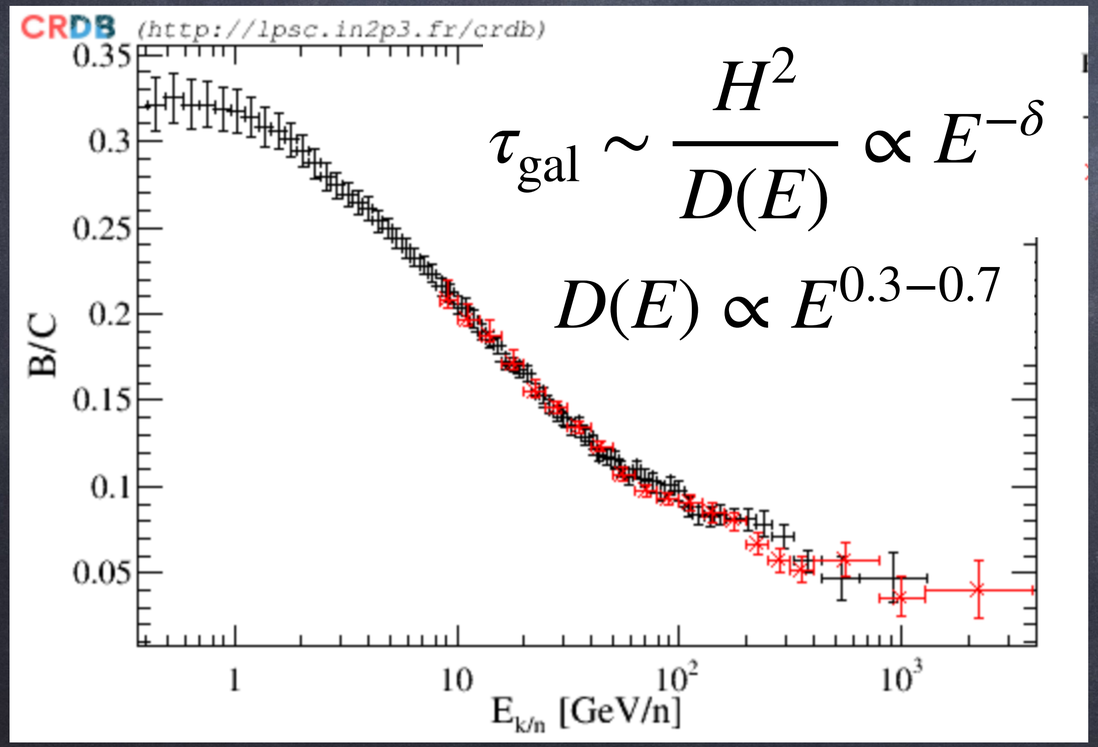
$\tau_{gal}(\mathrm{GeV}) \approx$ tens Myr

>> τ_{ball} diffusive transport

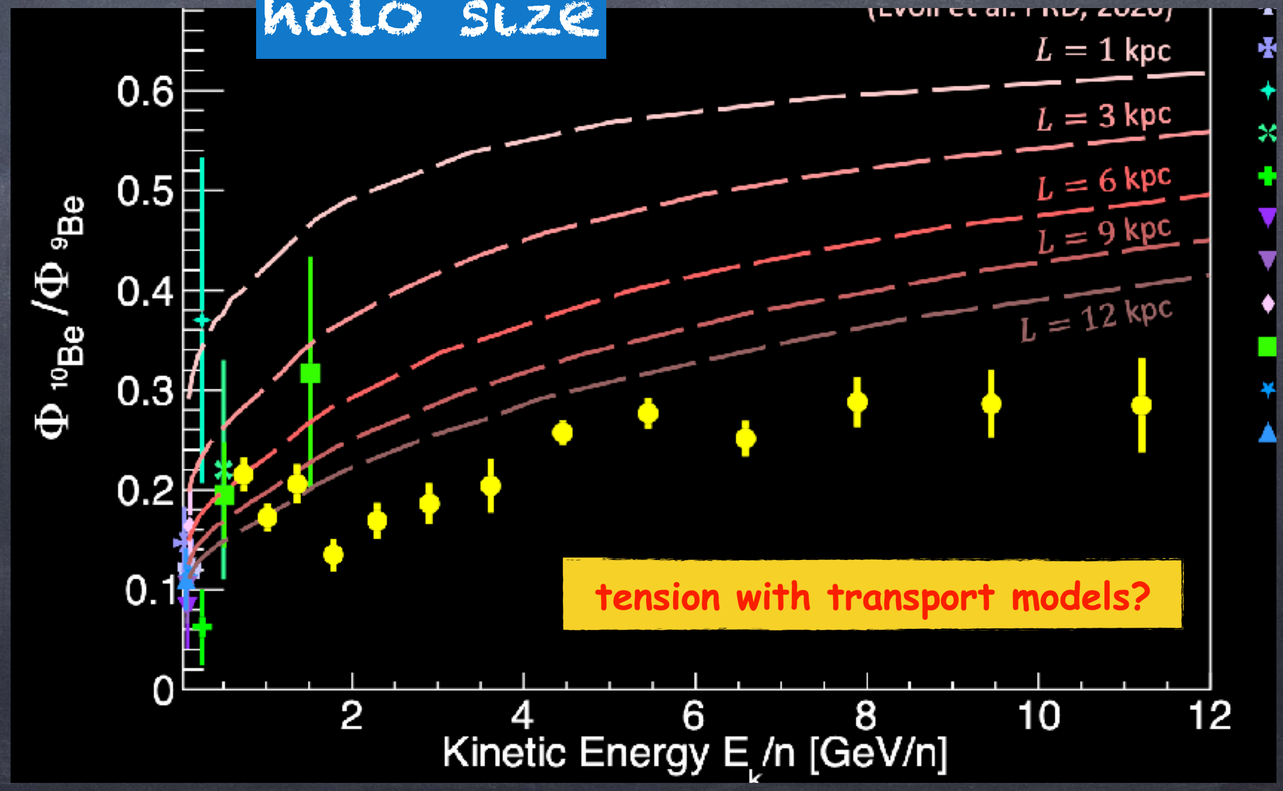
diffusive halo >> disk

h ~ 150 pc H~4 kpc

E-dependent escape



halo size

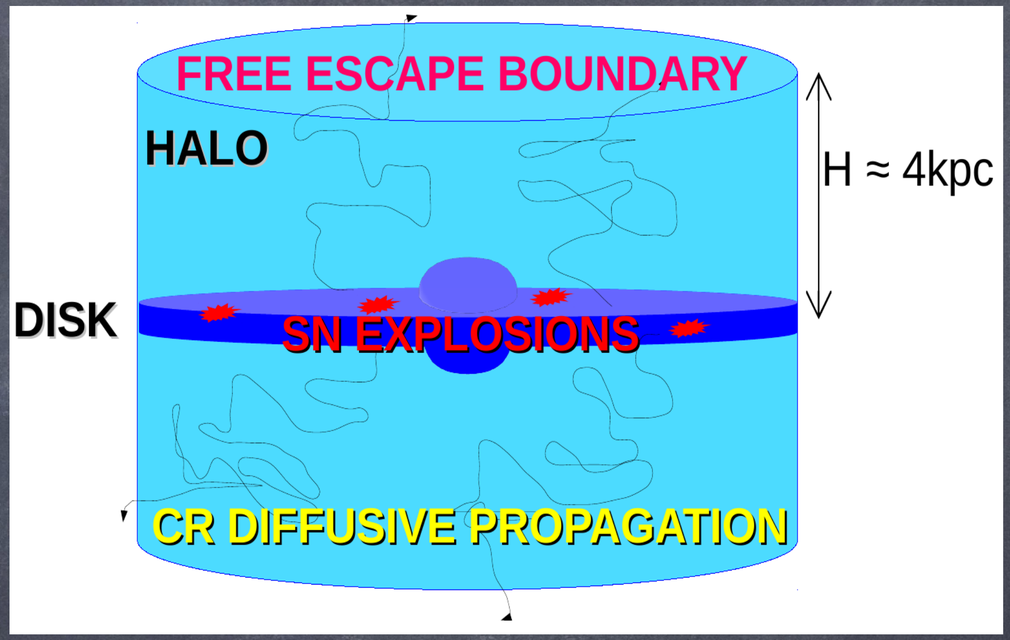


CRs in a nutshell - SNR paradigm

~ 10% of SNR power

diffusive shock acceleration

- power-law spectrum $Q_{\rm CR} \propto E^{-2}$
- rigidity dependent $R \propto p/Z$
- protons to the knee? $\approx 3\,{\rm PeV}$



Galactic propagation

- H ~ few kpc
- $D(E) \propto E^{0.3-0.7}$
- equilibrium $N_{\rm CR} \propto Q_{\rm CR}/D \propto E^{-2.7}$

CR propagation - gamma rays

HADRONIC

- protons + ISM gas —> π_0
- π_0 —> gamma rays
- $E_\gamma \approx E_p/10$

LEPTONIC

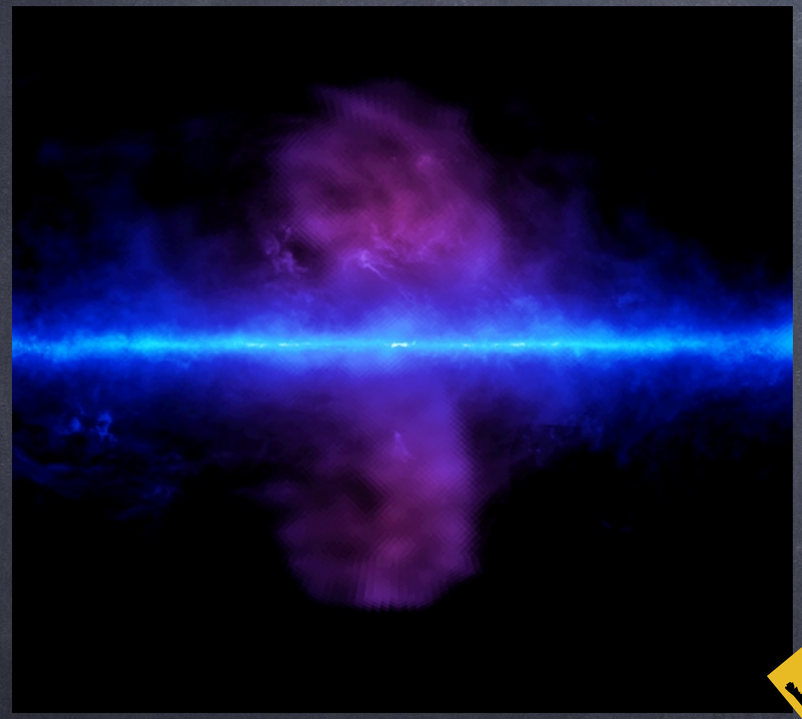
- $e^\pm$ + B —> synchrotron [radio, X]
- $e^\pm$ + ISRF —> gamma rays

need target gas

CMB is everywhere

CR propagation - gamma rays

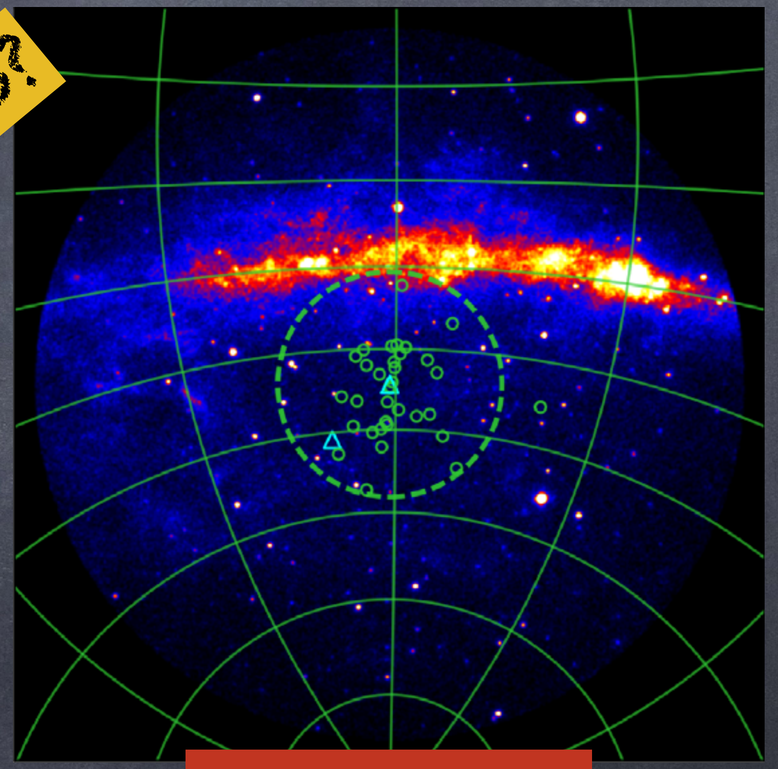
Fermi Bubbles



$\gtrsim 10$ kpc

how large is diffusive halo?

Andromeda halo

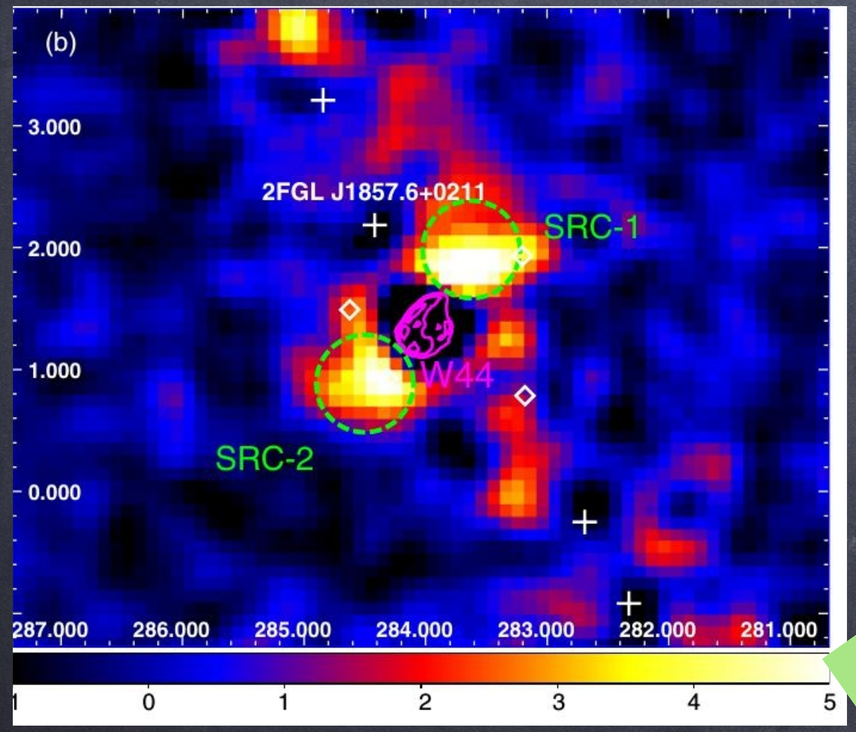


≈ 100 kpc

Karwin et al. 2019 - analysis M31

CR propagation - gamma rays

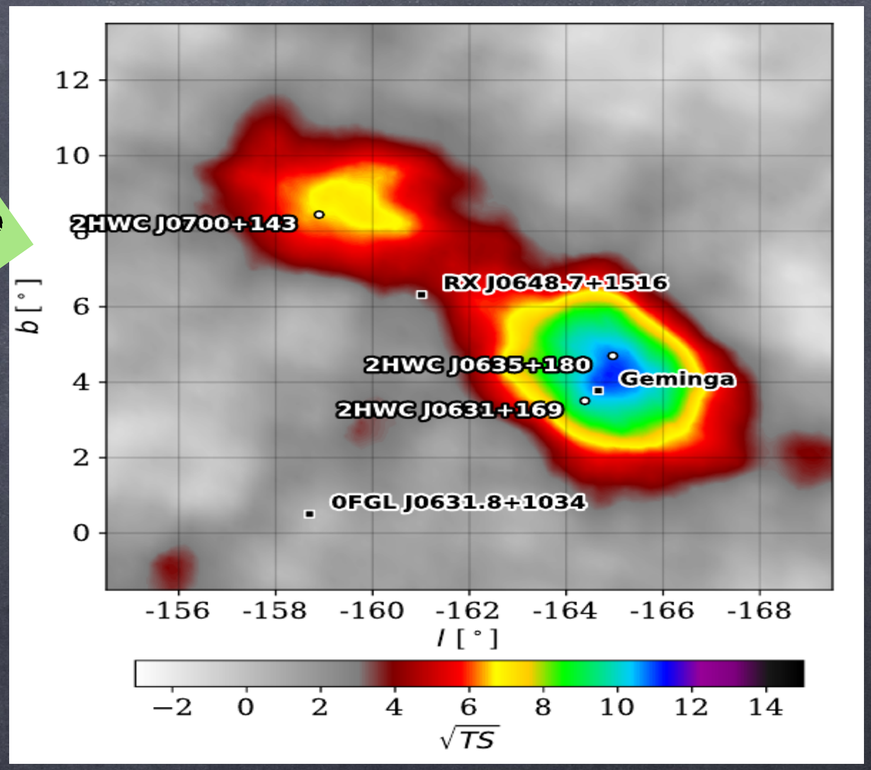
Molecular clouds around SNRs



SNR W44

probe $\lesssim$10s pc scales

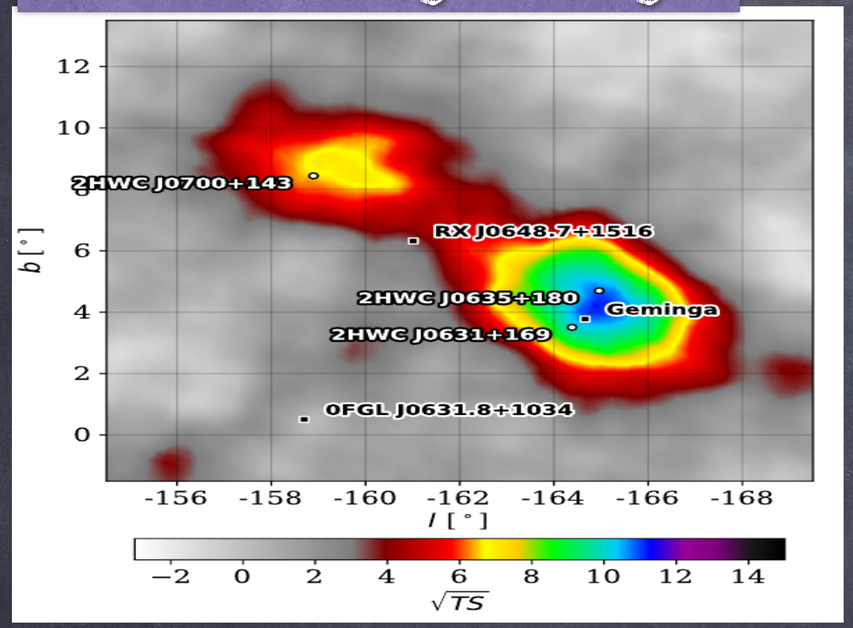
TeV halos pulsars



HAWC - Geminga & Monogem

CR propagation - TeV halos

HAWC: Geminga-Monogem



- 10-200 TeV $e^{\pm}$, ICS on CMB
- $E_e \sim 100\,\mathrm{TeV}$, $E_\gamma \sim 20\,\mathrm{TeV}$
- 10s pc extension

- 3D isotropic diffusion & small D
- energy losses CMB/B
  $\tau_{\mathrm{CMB}} \approx 10\,\mathrm{kyr}$

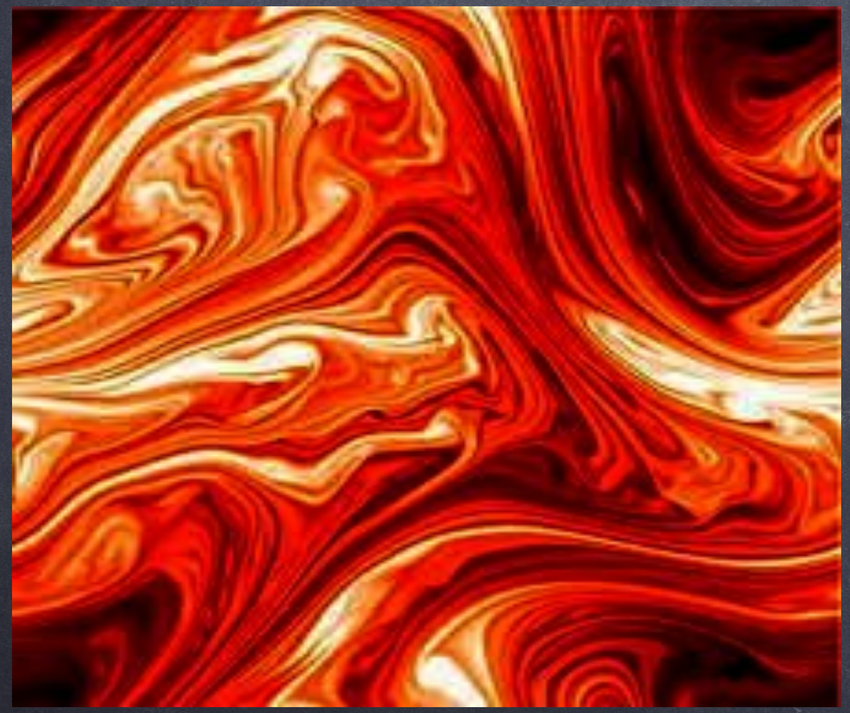
$$R_{\mathrm{halo}} \sim \sqrt{4D\tau_{\mathrm{CMB}}} \sim 30\mathrm{pc}\sqrt{D_{27}\tau_4}$$

$D_{\mathrm{ISM}}(100\mathrm{TeV}) \approx 10^{30}\ \mathrm{cm}^2/\mathrm{s}$ → ? → $D_{\mathrm{halo}}(100\mathrm{TeV}) \approx 10^{27}\ \mathrm{cm}^2/\mathrm{s}$

... microphysics

CR transport - microphysics

MHD TURBULENCE



- ISM is magnetized
- ISM is turbulent

CRs interact with turbulence

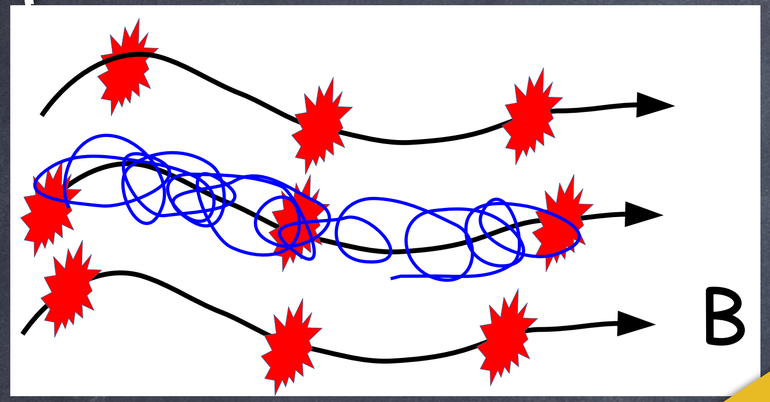
- Injected by sources [10s pc]
  - Cascade (type, anisotropy)
  - Power spectrum
  - Intermittency ...
- Produced by CRs

Fornieri et al. 2021

Lazarian 2023

CR transport - microphysics

parallel diffusion

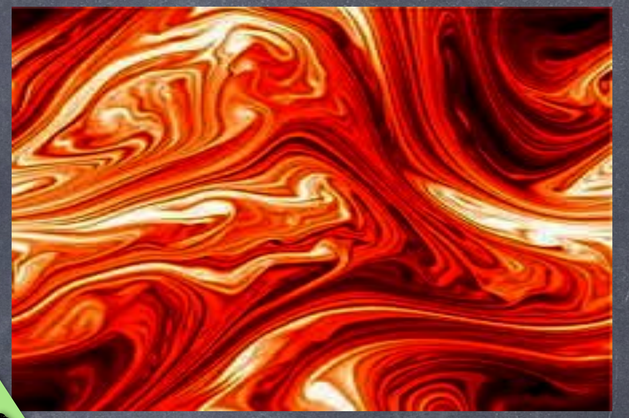


(parallel) diffusion coefficient

$$D_{\parallel}(E) \propto \lambda_{\mathrm{mfp}}$$

Diffusive mean free path

MHD turbulence



- CR gyromotion
- scattering off waves
- $k \sim 1/r_L$ (resonance)

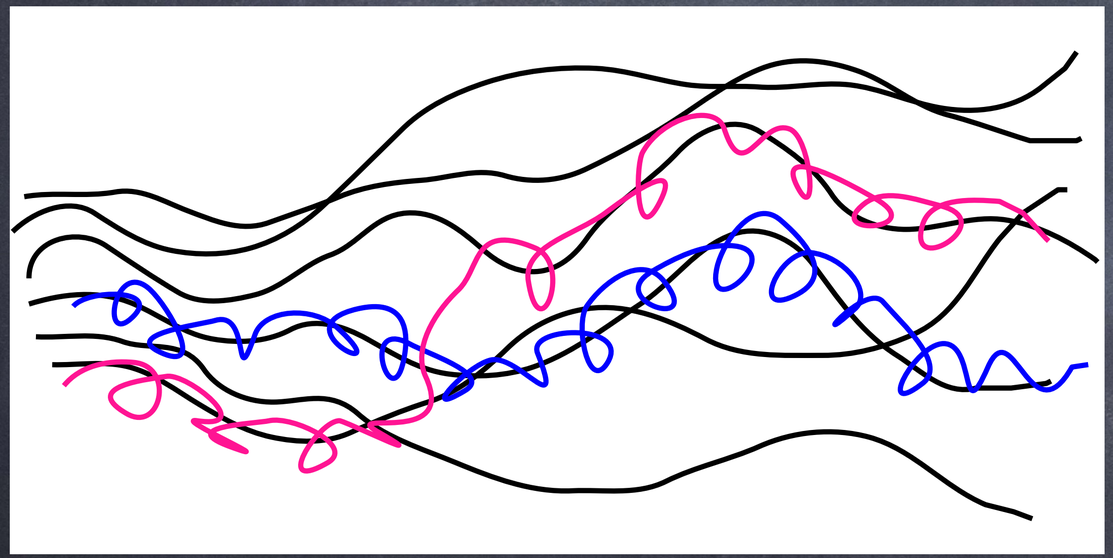
- source injection (10s pc)
- cascade to $k \sim 1/r_L$?
- damping?

Mertsch 2020 - review turbulence & transport

CR transport - microphysics

Shalchi 2020 - review perp. Transport

Perpendicular transport



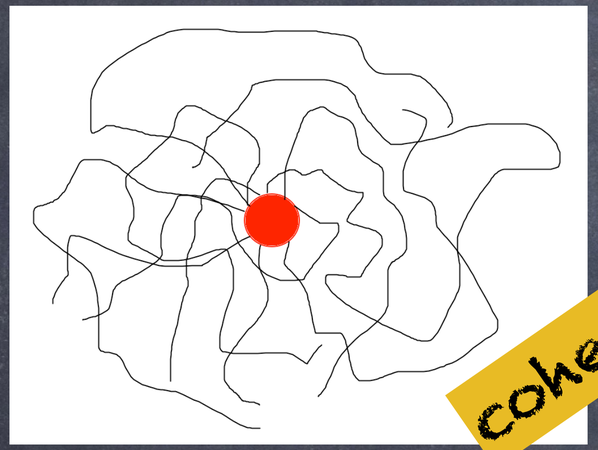
- field line walk (FLRW)
  - turbulent motion of field lines
  - large-scale ($\gg r_L$) turbulence
- Small-scale perp. diffusion
  - CRs jump between field lines
  - scattering, drifts...

—> LARGE-SCALE PERPENDICULAR DIFFUSION

$$D_\perp(E) \lesssim D_\parallel(E)$$

CR transport around sources

highly turbulent ISM

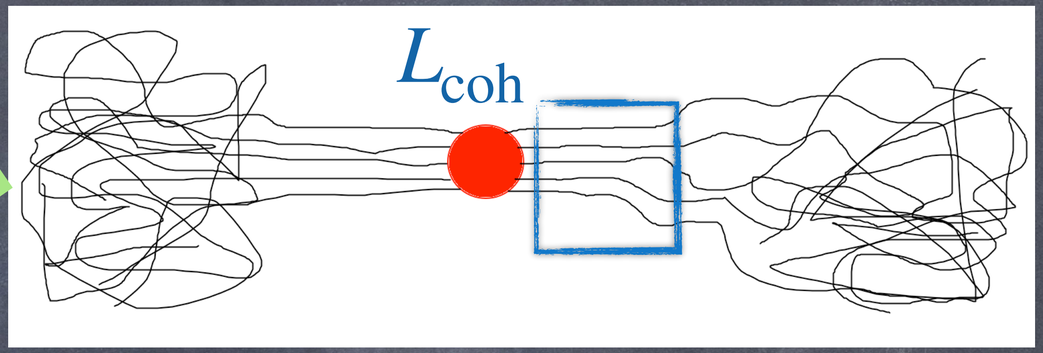


- small $L_{\rm coh}$ << size
- 3D isotropic diffusion
- Small D
- spherical morphology

coherence length - turbulence

"local" probe

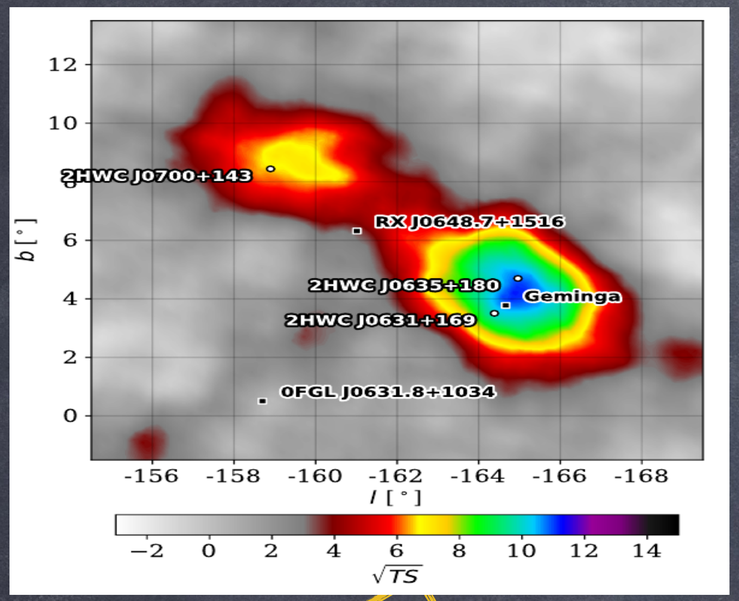
anisotropic transport



- $L_{\rm coh} \gtrsim$ size
- typical $D_{\parallel}$, $D_{\perp} \ll D_{\parallel}$
- emission morphology depends on flux-tube orientation
- elongated structures

Nava & Gabici 2013 - 3D VS anisotropic prop.

CR transport - TeV halos



$D_{ISM}(100TeV) \approx 10^{30}\ cm^2/s$

$D_{halo}(100TeV) \approx 10^{27}\ cm^2/s$

- highly turbulent region around some PSR
  - filling factor? extension?
  - how many halos?
- anisotropic diffusion
  - need small ψ_{incl} for spherical halo
  - chance? morphology?
  - look for features?
- self-generated turbulence?

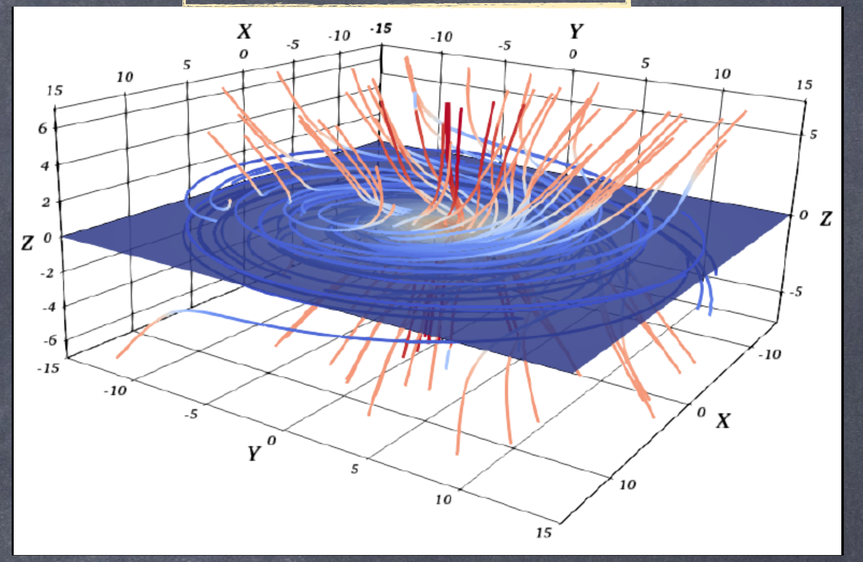
Martin et al. 2022

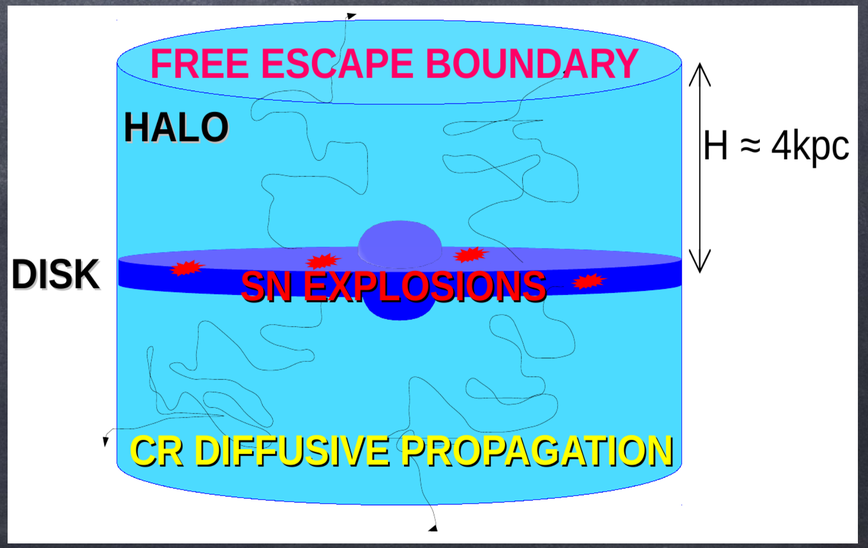
CR transport on Galactic scales

- large-scale Galactic B field
- propagation on scales >> $L_{\rm coh}$ [10s pc?]
- effective global diffusion? (B/C, ...)
- some effect of anisotropic diffusion?
- Non-uniform transport in the Galaxy?
- Up to which distance from disk?

"global" probe

Cerri et al. 2017



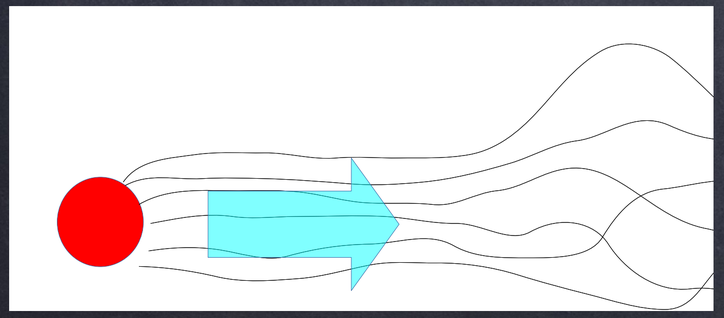


... CR driving

CR-induced turbulence

CR GRADIENT

- transfer momentum to waves
- generate resonant Alfvén waves ($k \sim r_L$)
- resonant streaming instability

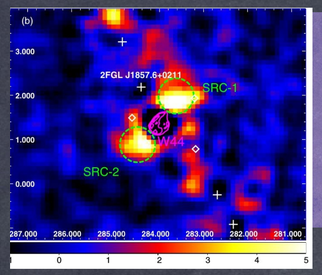


CR CURRENT

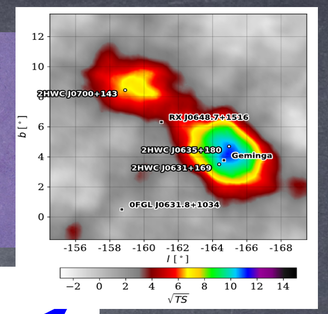
- Waves on scales $\ll r_L$
- grow to $k \sim r_L$
- non-resonant streaming instability
- important for acceleration

more waves - more scattering

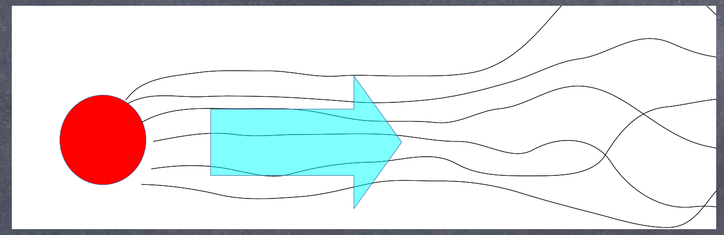
suppressed diffusion

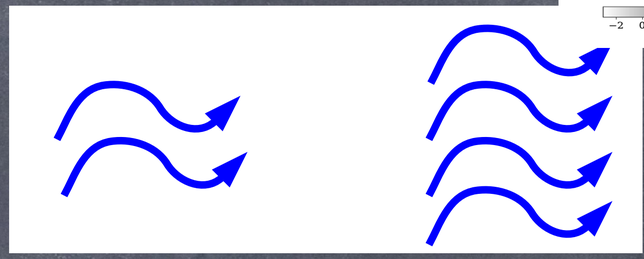


CR-induced turbulence

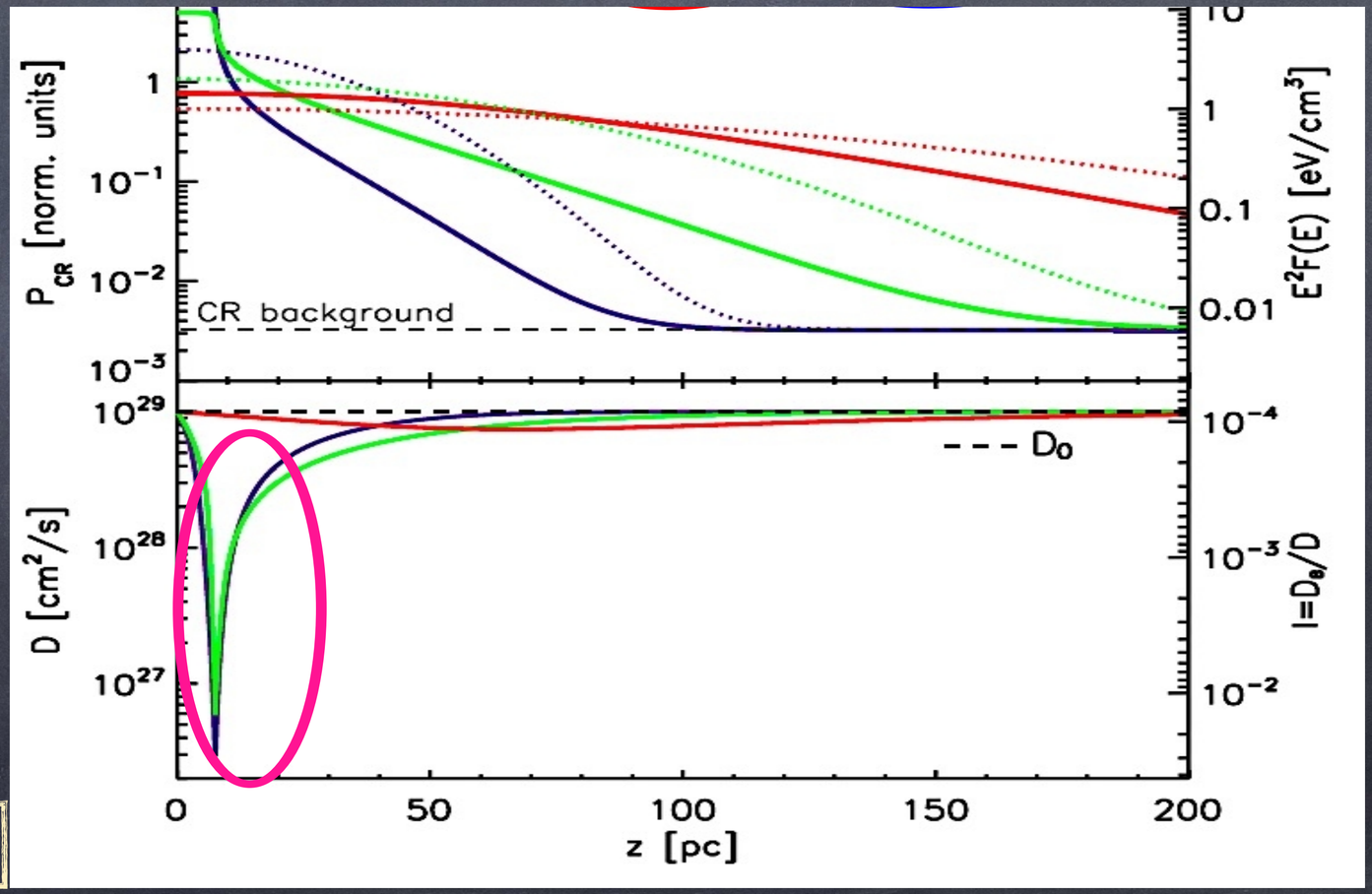


... around sources





- self-confinement around sources (SNR, ...PSRs?)
- suppressed diffusion
- longer residence time
- enhanced gamma-ray signals
- energy-dependent effect - spectra



Nava et al. 2016, 2019 | D'Angelo et al. 2016

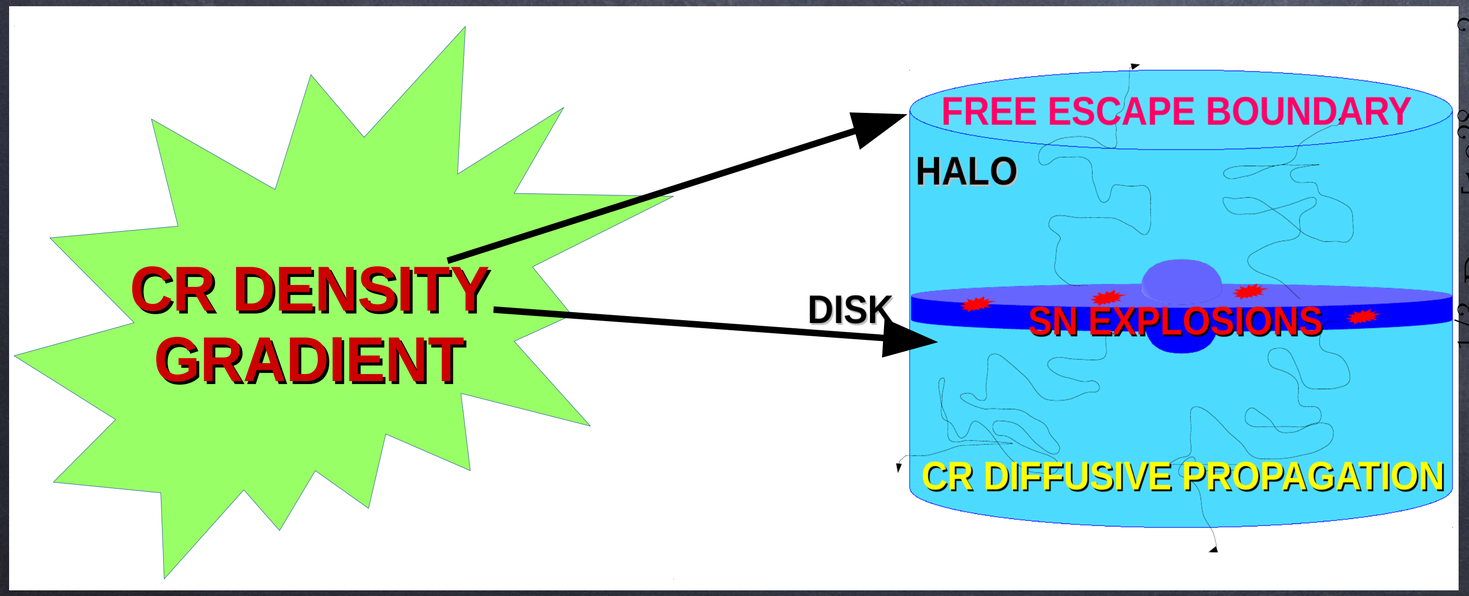
CR-induced turbulence

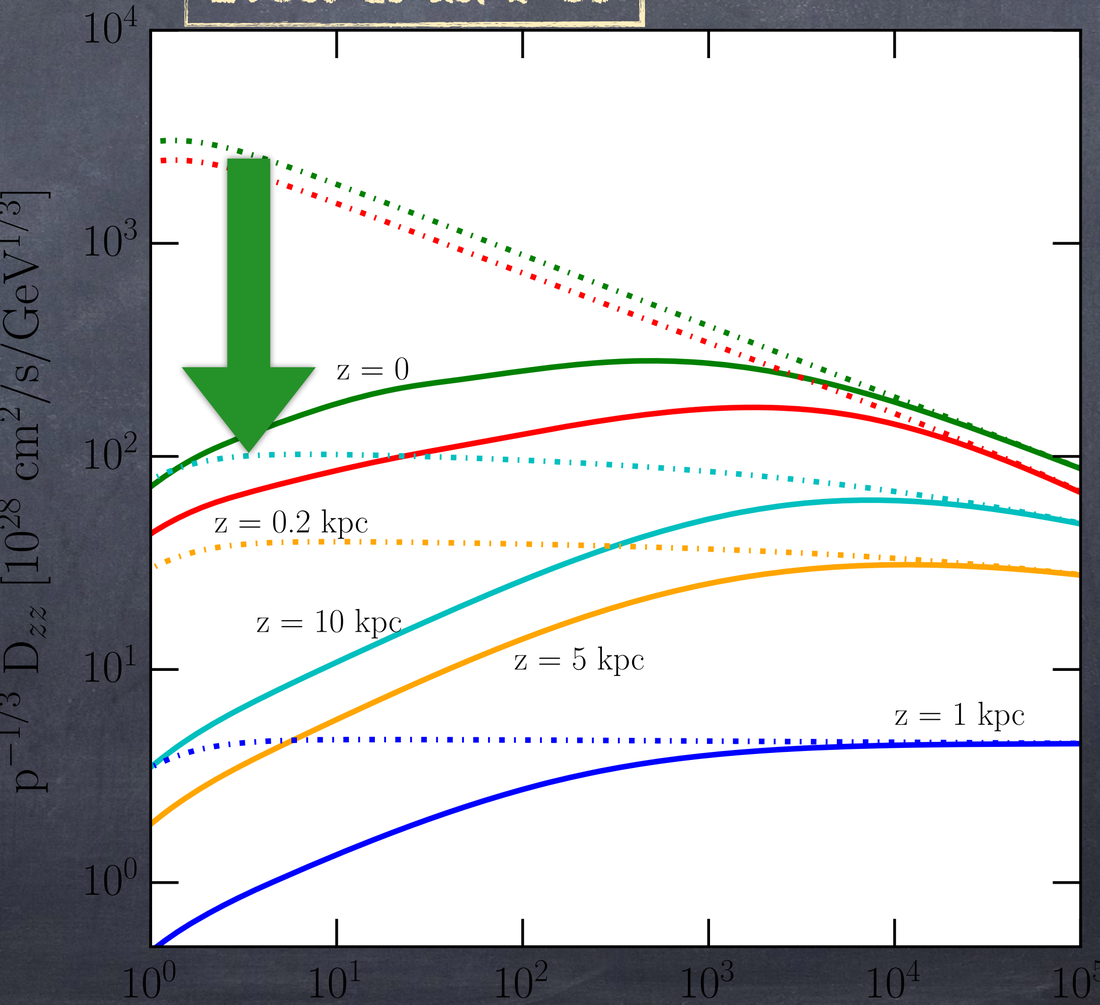
... Galaxy

- Self-generated diffusion
  - may shape D(E)
  - likely dominant up to 100s GeV

Aloisio et al. 2015

Evoli et al. 2018





CR-induced turbulence

... Galaxy

- self-generated diffusion
  - coupling CRs-ISM
  - $W_{CR} \approx W_{th} \approx W_B \sim 1\,\mathrm{eV/cm^{-3}}$
  - dynamical impact
  - large-scale outflows - winds

Breischwerdt et al. 1991

Recchia et al. 2016, 2017

CR-induced turbulence

CRs can largely affect their own transport

- self-generated diffusion
- self-generated advection
- confinement around sources

propagation is non-linear

need to take such effects into account in order to understand data and observations...

... summary

summary

... CR propagation

- turbulence, turbulence, turbulence
  - very difficult
  - modeling/simulation
  - probe in solar system
  - ... extend to ISM ...
- B field, structures
  - anisotropic transport
  - global VS local probes
  - ... be careful to the information they carry ...
- CR driving
  - non-linearities
  - both local & global scales