Galactic Cosmic-Ray (GCR) propagation

Today: 1 lecture
→ Overview of GCR transport and recent results

Tomorrow: 2 hands-on sessions
→ Calculations + notebook (timescales, simplified solutions, fit biases)

Recent reviews

The Nine Lives of Cosmic Rays in Galaxies – Grenier et al., ARAA 53, 199 (2015)
Origin of small-scale anisotropies in GCRs – Ahlers & Mertsch, PrPNP 94, 184 (2017)
The origin of GCRs: challenges to the standard paradigm – Gabici et al., Frontiers (arXiv:1903.11584)
Cosmic-ray models (transition Galactic/extra-galactic) – Kachelrieβ & Semikoz, PrPNP 109, 103710 (2019)

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Physics and astrophysics of cosmic rays
OHP, 25 Nov. 2019

I. Introduction
- I.1. Milestones
- I.2. GCR observables and questions

II. GCR transport in the Galaxy
- II.1. Ingredients and processes
- II.2. Transport calibration and dark matter

III. Transport equation and codes
- III.1. How to solve?
- III.2. From interstellar fluxes to CR data

IV. Interpretation of recent data
- IV.1. Selected results and interpretation
- IV.2. A precision era: things to care about!

VI. Simplex, complex, multiplex
- V.1. ‘Non-standard’ (but likely) processes
- V.2. Selected puzzling data

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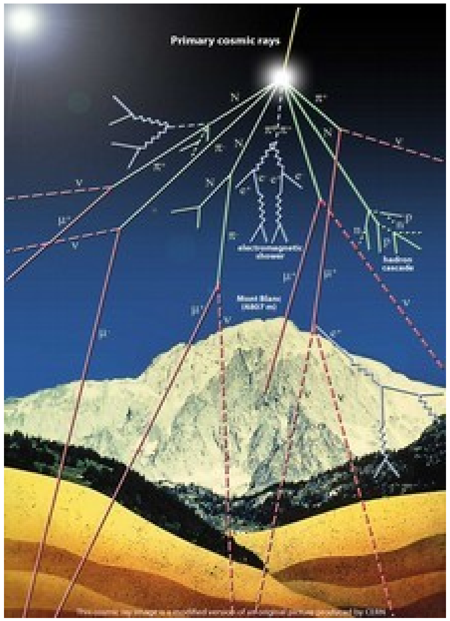
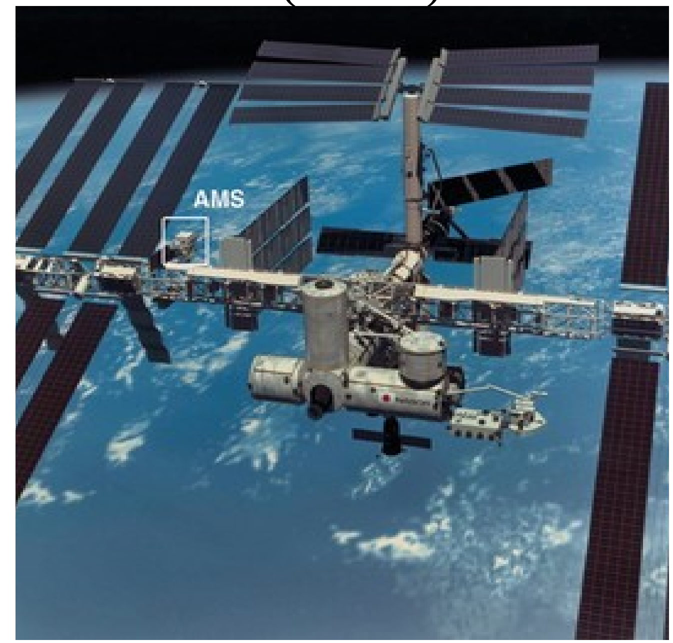
Experimental milestones

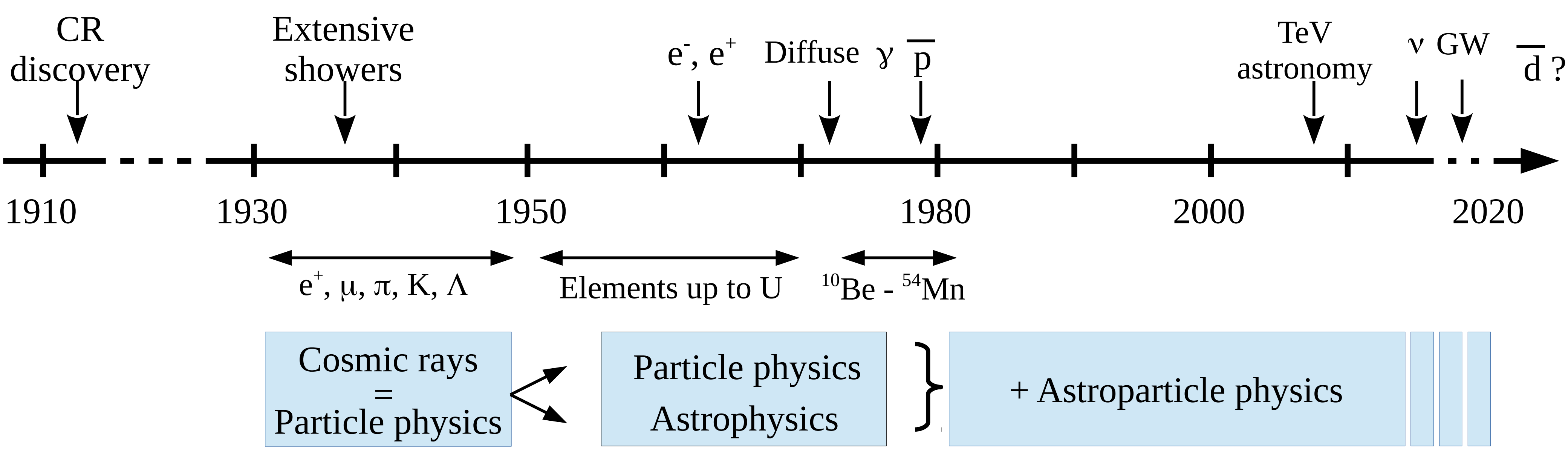
Mountain altitude < 5 km



CREAM balloon ~ 40 km

AMS-02 (on ISS) ~ 300 km

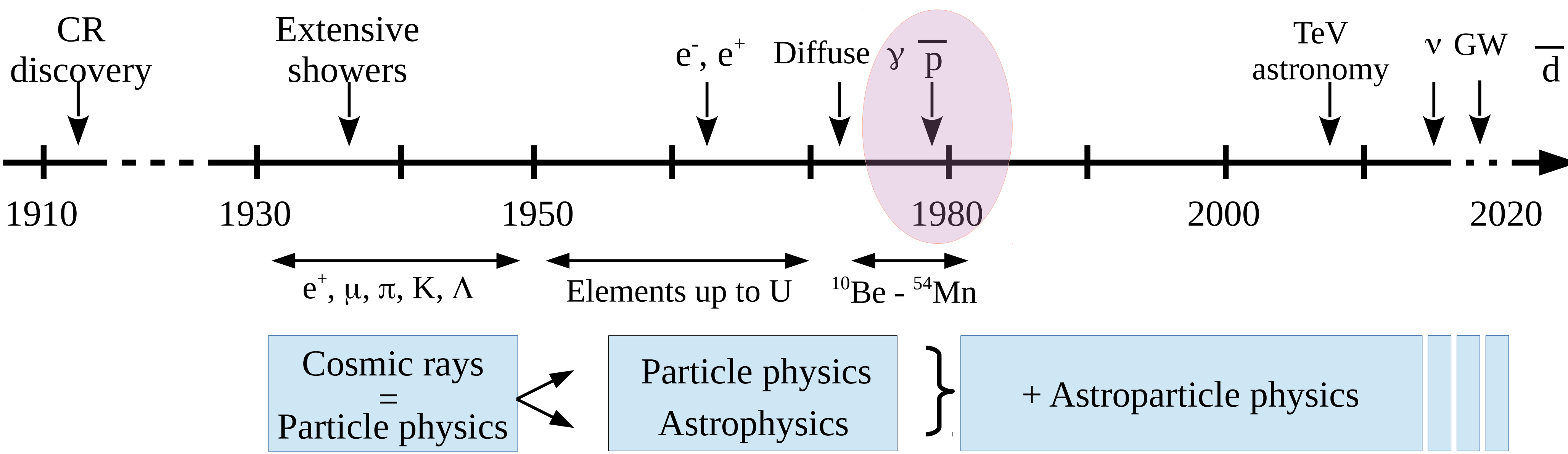




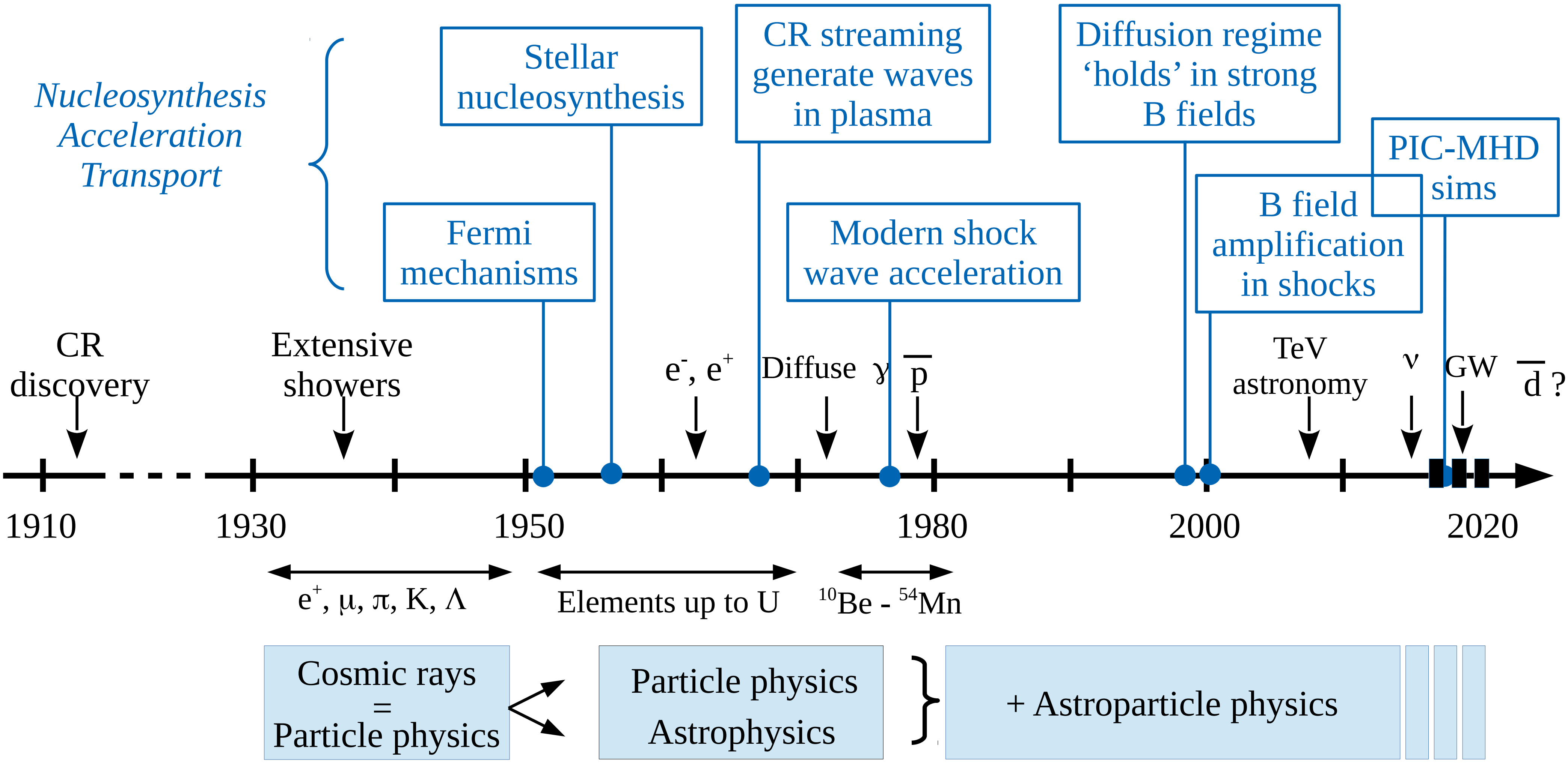
“Phenomenology” milestone

2019 Cosmology Gruber prize (N. Kaiser and J. Silk)

“[…] for their seminal contributions to the theory of cosmological structure formation and probes of dark matter.
[…] while Silk recognized dark matter's indirect signatures such as antiprotons in cosmic rays and high energy neutrinos from the Sun

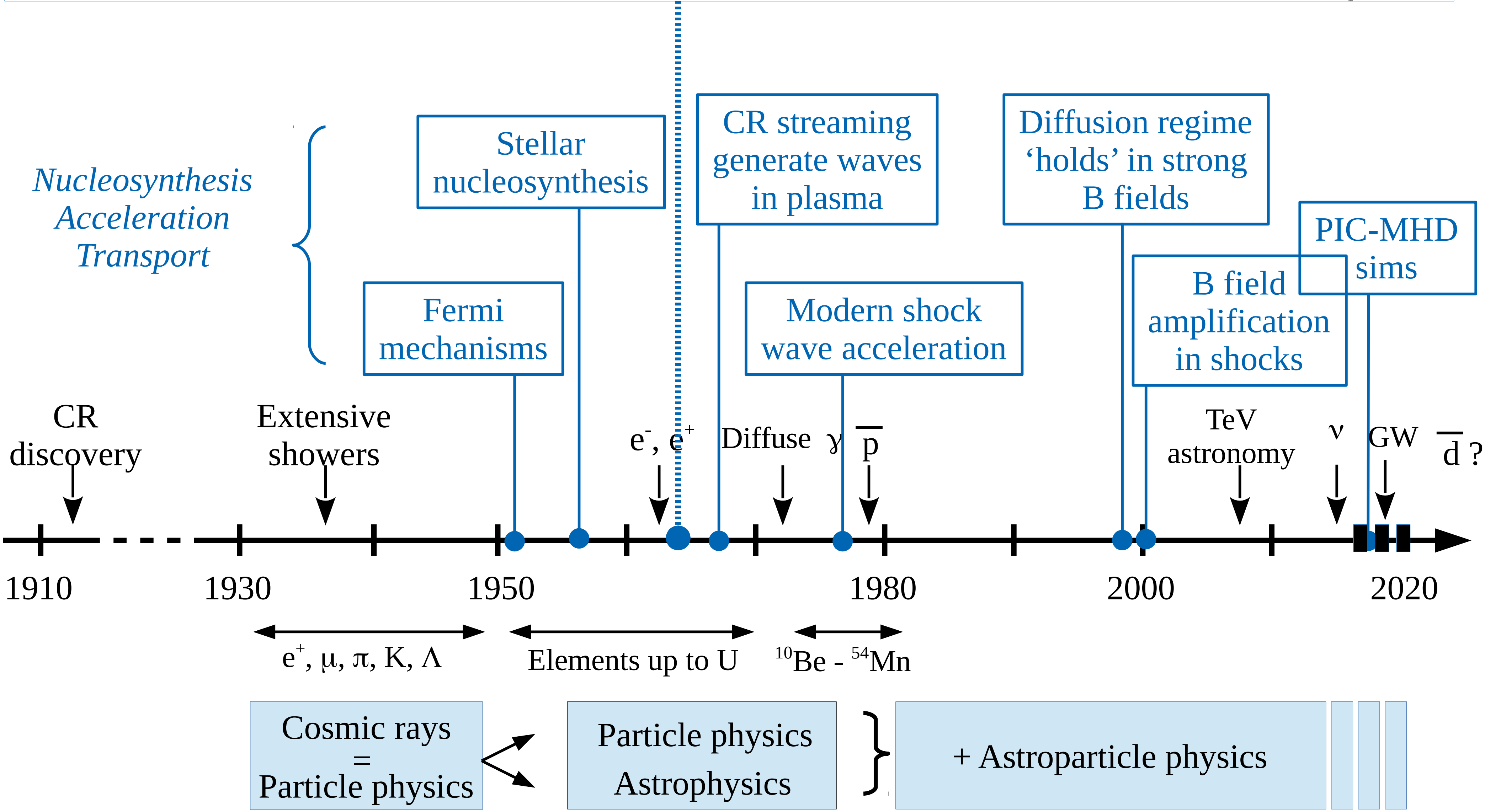


Theoretical milestones



Diffusion equation

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right) + \vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\left(\Gamma_{\rm rad} + \Gamma_{\rm inel}\right)}^{\text{Catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j \frac{\partial N^j}{\partial E}\right)}^{\text{E gains/losses}} = \overbrace{Q^j(E,\vec{r}) \quad + \sum_{m_i > m_j} \Gamma^{i\to j} N^i}^{\text{Source term: prim.+sec.}}$$



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Charged vs neutral cosmic rays

Two categories

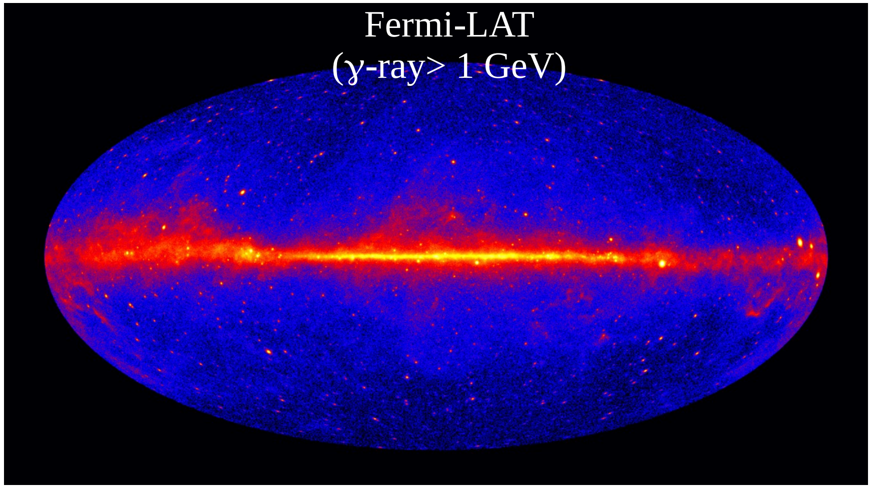
- *Neutral species*
  - ✓ Gamma-rays
  - ✓ Neutrinos

Multi-messenger approaches
Multi-wavelength observations

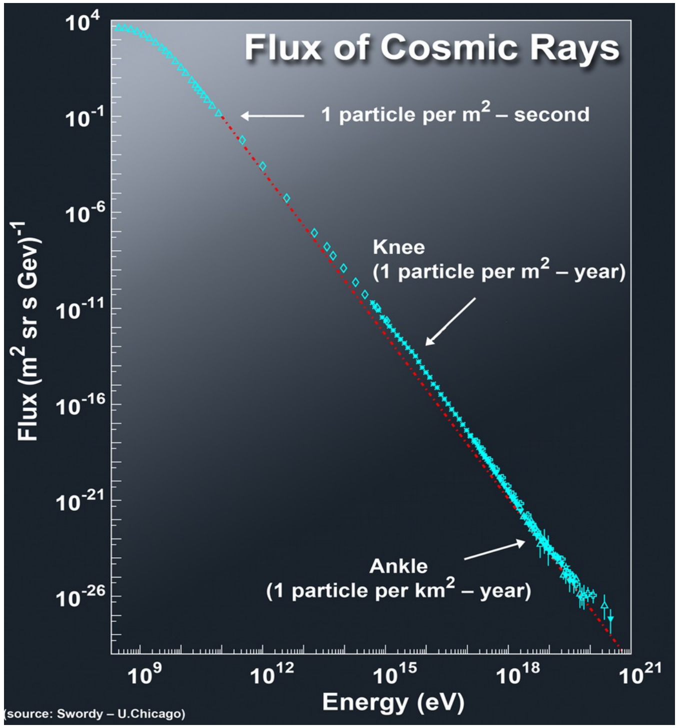
- *Charged species*
  - ✓ Leptons
  - ✓ Nuclei

Observation types

→ *Astronomy*
point-like, extended, diffuse emissions



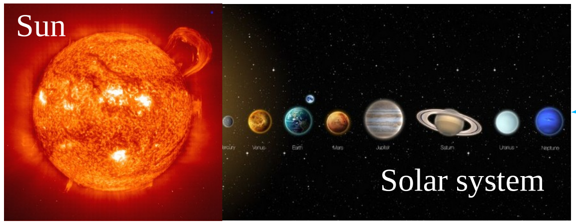
→ *Spectra & anisotropy maps*
(diffusion/deflection in B)

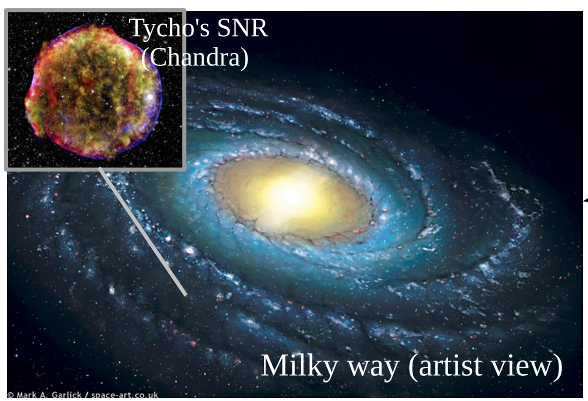


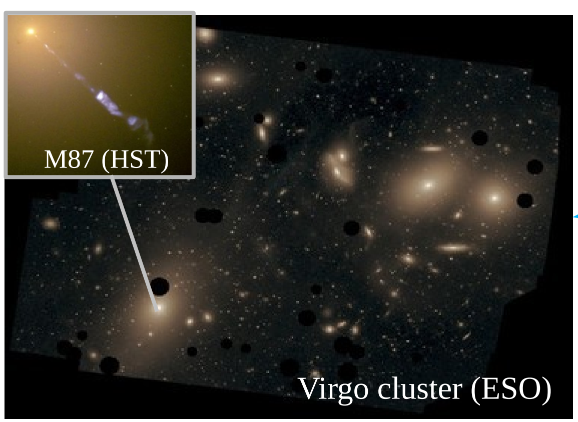
30 orders of magnitude

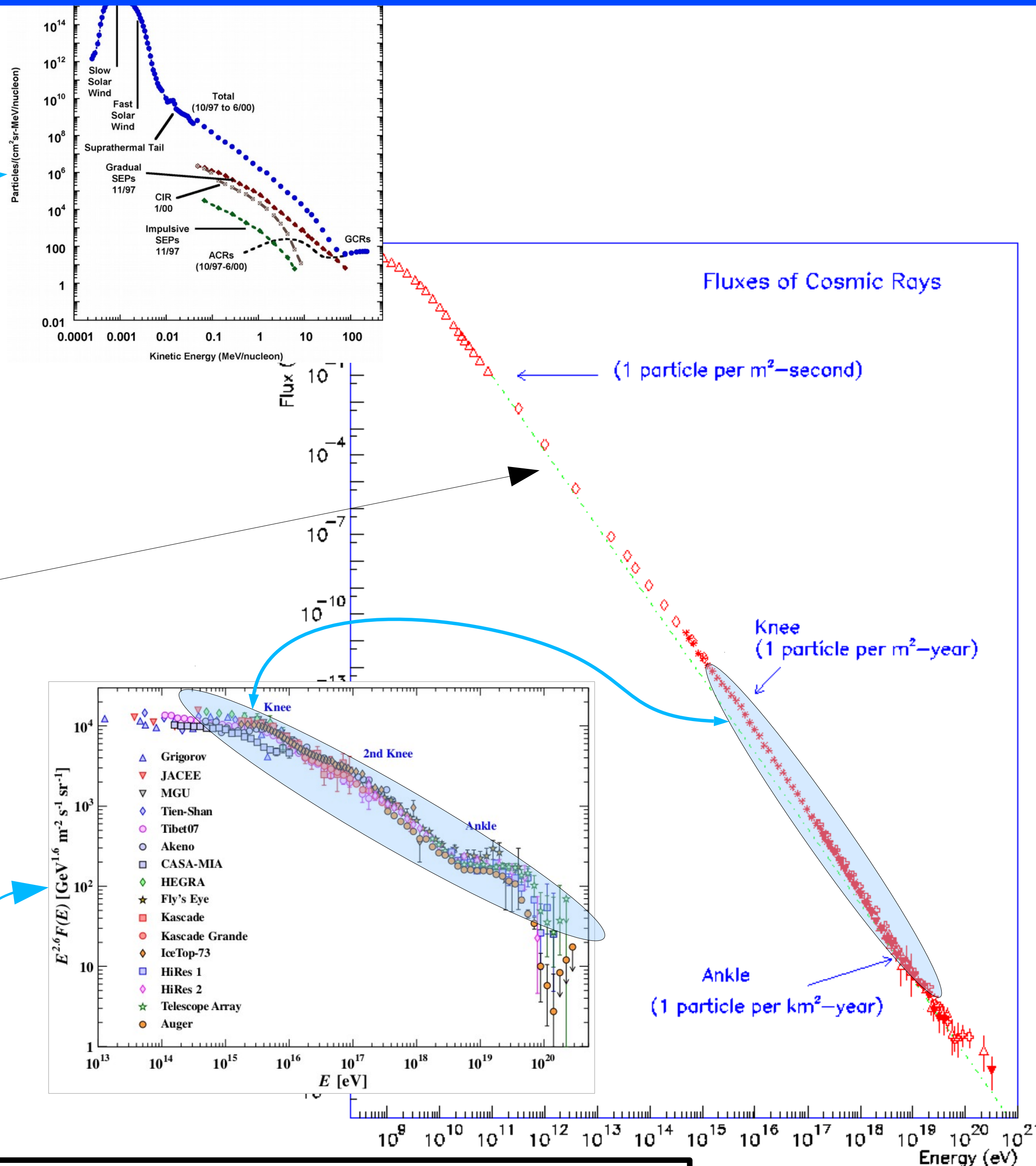
12 orders of magnitude

All-CR spectrum and putative sources









Transition galactic vs extragalactic
→ CR sources and transport?
→ Origin of spectral features, anisotropy?

Detection: direct vs indirect

"Direct" CR detection (< 10^{15} eV ~ PeV)

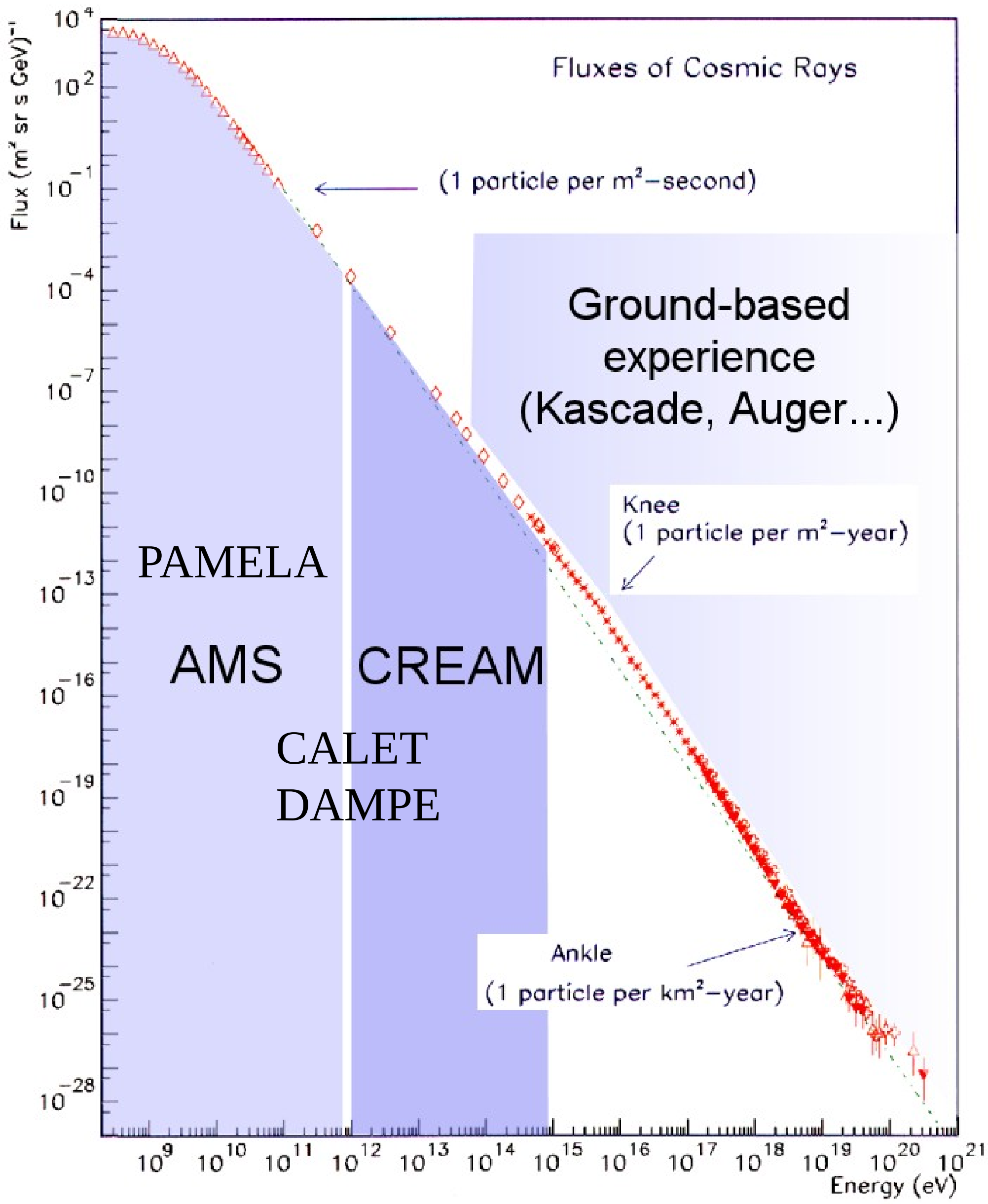
- Detectors "above" atmosphere (balloon or space)
- "Particle physics"-like detectors

→ Identification of CR nature and energy

"Indirect" CR detection (> 10^{15} eV)

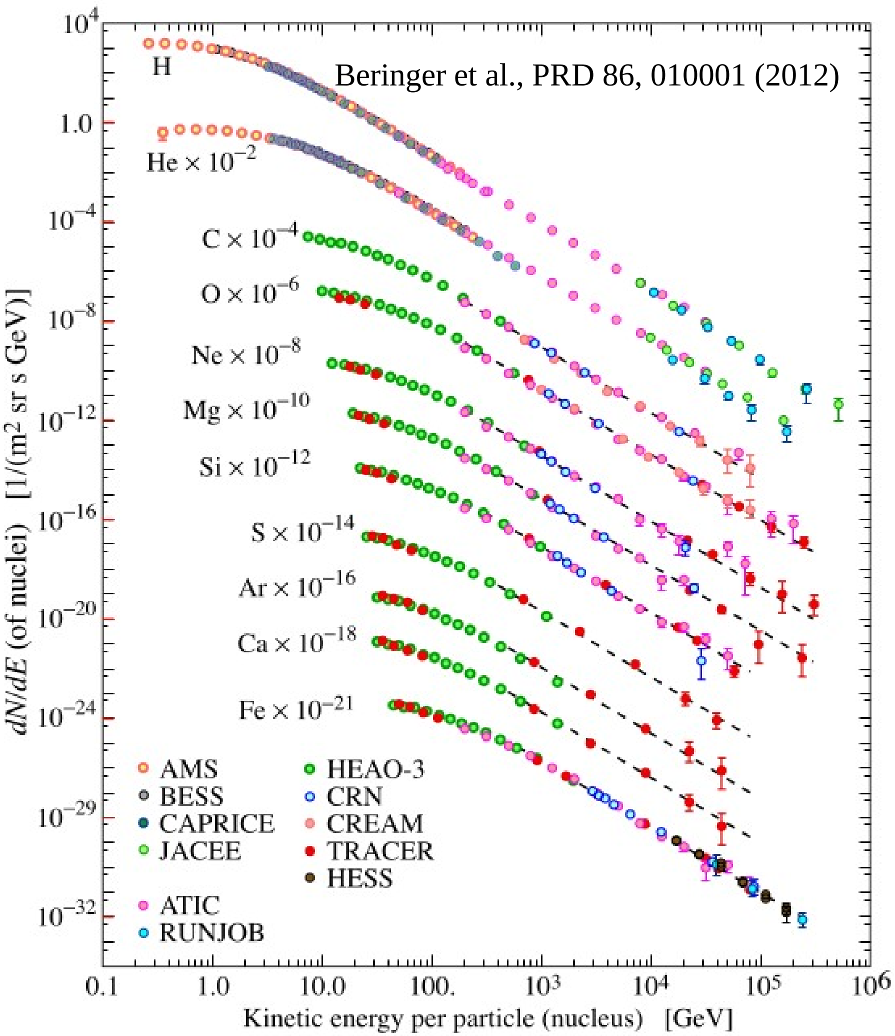
- Ground-based detectors
- Use atmosphere as "calorimeter"
- Measure shower properties

→ Reconstruct CR most likely nature and energy



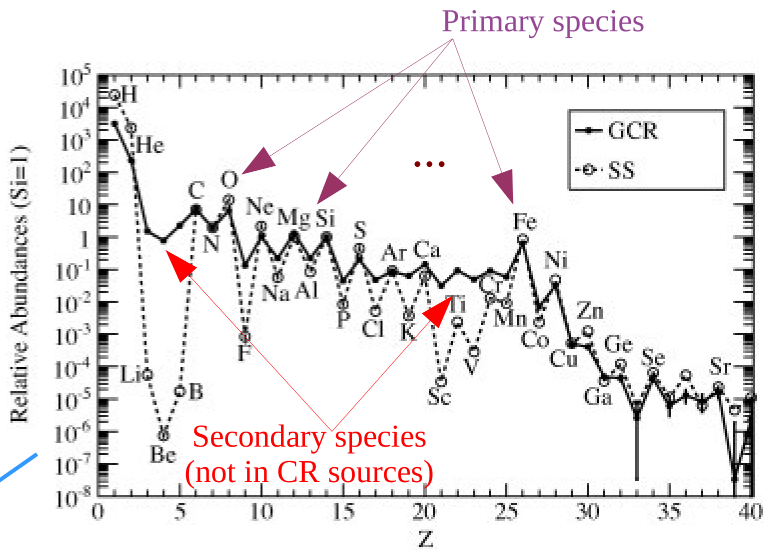
Galactic CR data (E~10^8-10^{15} eV)

Elemental spectra



Energy units

E type	Expression	Unit	*Natural for*
Rigidity	$R = \frac{pc}{Ze} = \frac{p}{Z} = r_l B$	[GV]	*Magnet (AMS)*
Total E	$E^2 = p^2 + m^2$	[GeV]	*Calorimeter (CREAM)*
Ek per nucleon	$E_{k/n} (= T) = \frac{E_k}{A}$	[GeV/n]	*Nuclear reaction*



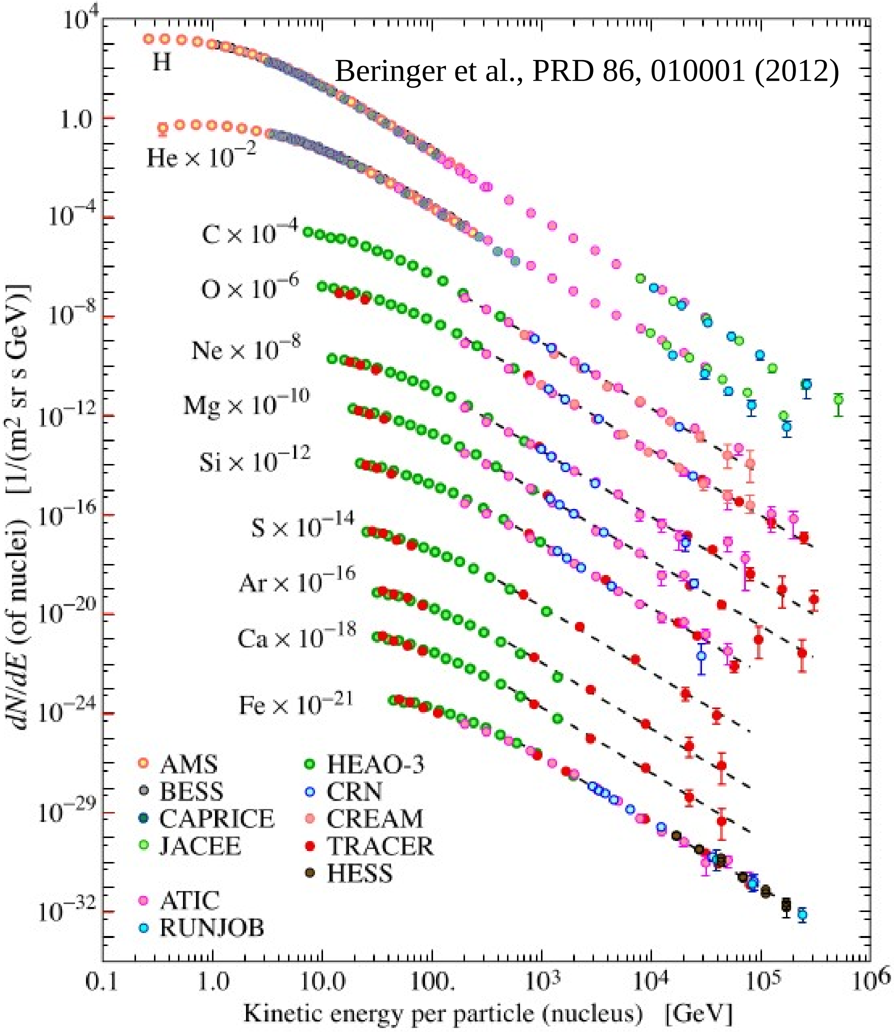
Bauch et al., AdSR 53 (2014)

→ Origin of quasi-universal power law ($E^{-2.8}$)?
→ Maximum energy of Galactic sources?
→ Abundances of elements and isotopes?

Antiprotons, e+, e-, gamma: primary or secondary?

Galactic CR data ($E \sim 10^{8}$-10^{15} eV)

Elemental spectra



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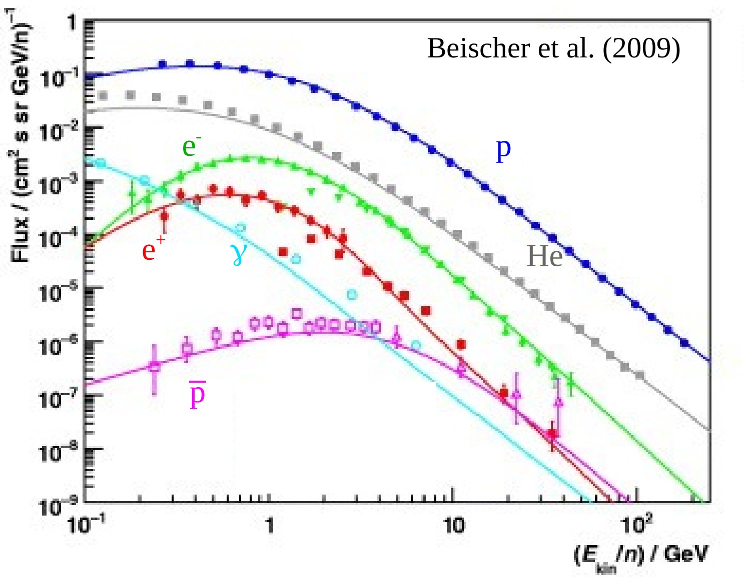
Protons and He
vs
diffuse γ-rays, pbar, e^- and e^+

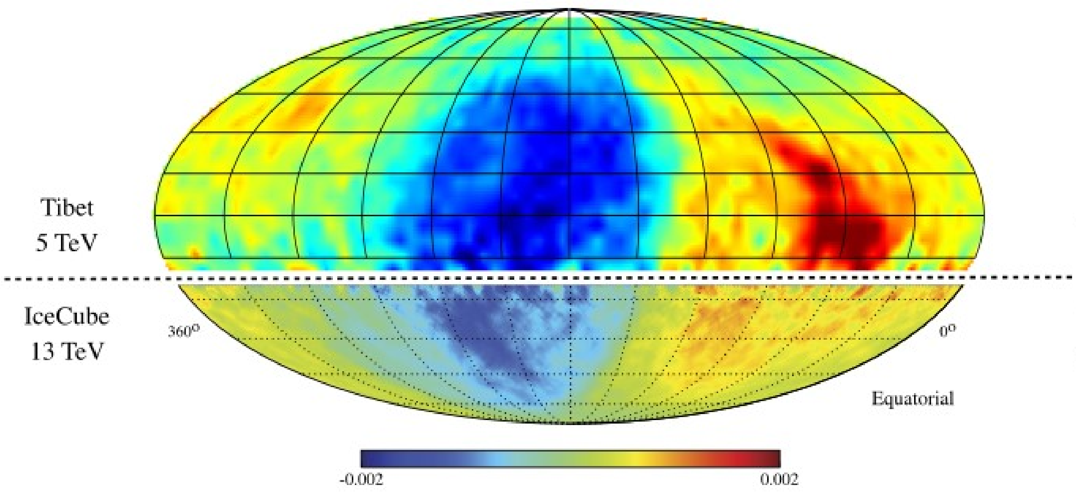


N.B.: rare CRs produced by H,He + ISM
→ How well do we know the astro. production?
→ Are there primary sources?
→ Is it a good place to look for dark matter?

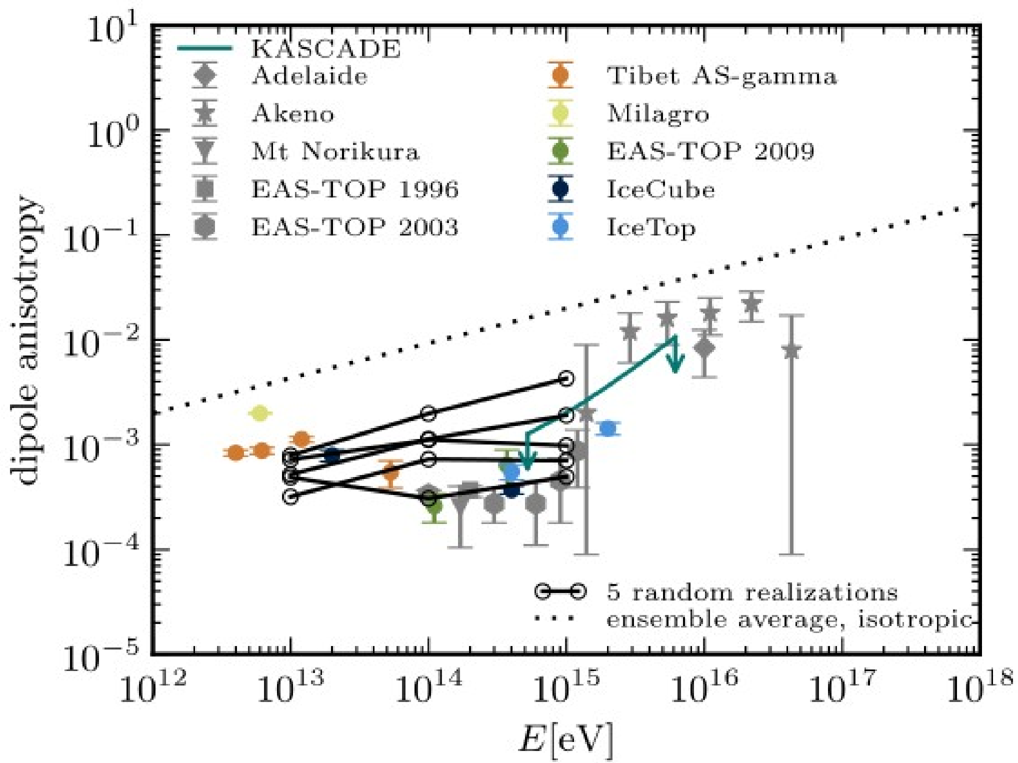
Galactic CR anisotropy (~10^{-3})

Ahlers & Mertsch, PrPNP 94, 184 (2017)

"Large scale" anisotropy



Dipole anisotropy



Patterns in small-scale anisotropies ($\delta<10^{-3}$)

→ Heliosphere?
→ Small-scale 'random' magnetic field?
→ Non-uniform or non-diffusive transport?

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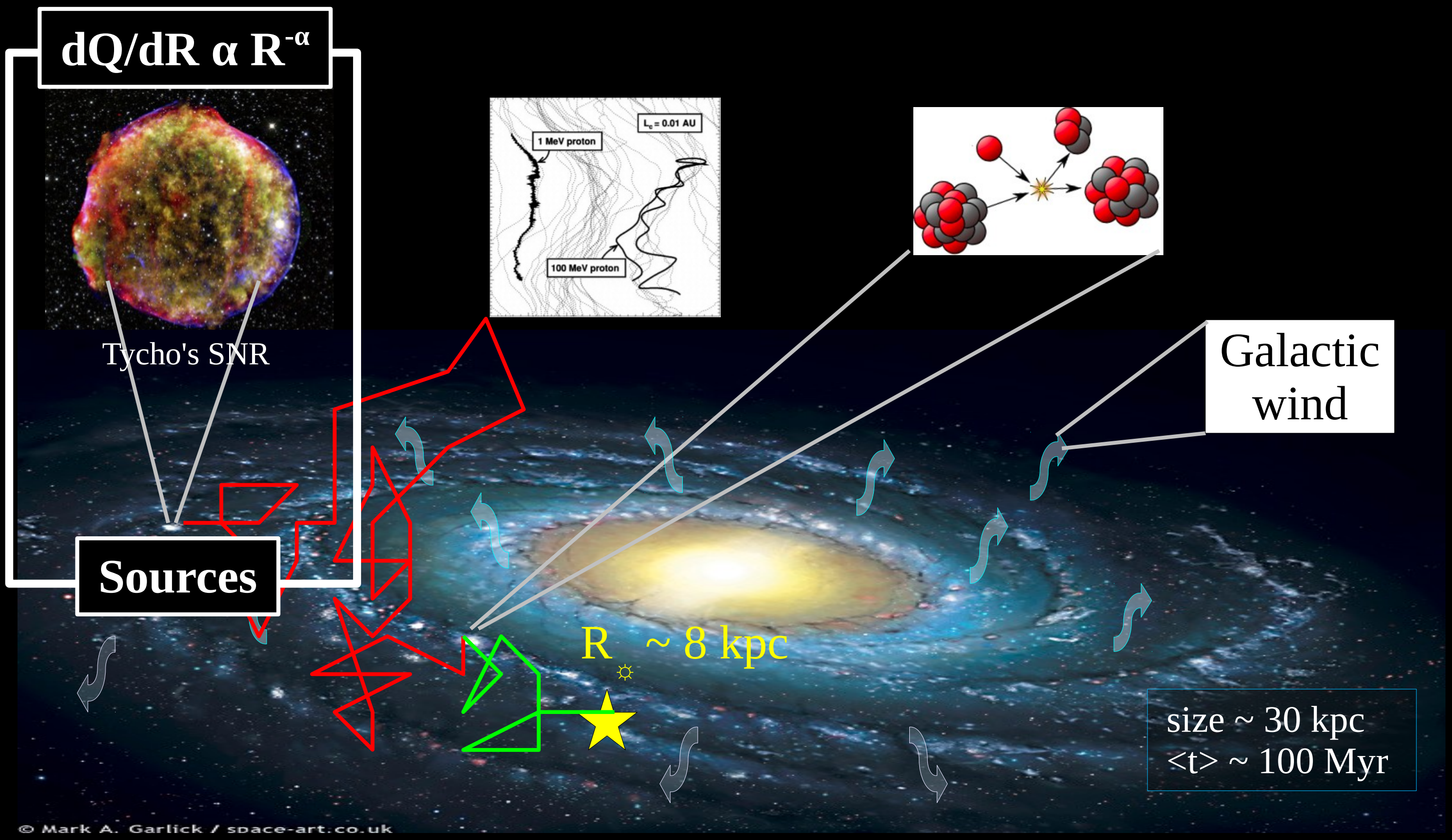
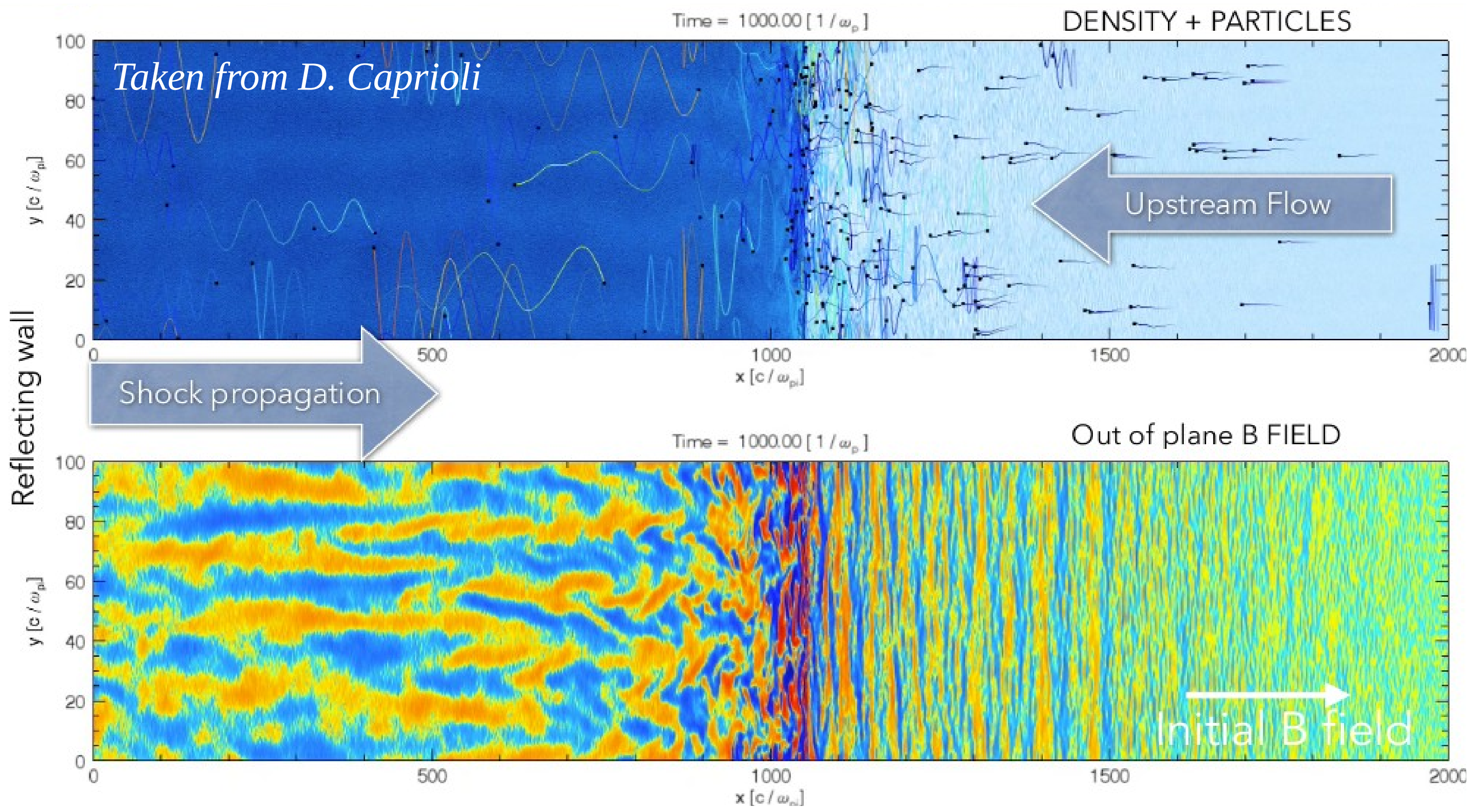
Source spectrum



Source spectrum

Hybrid simulations (fluid e-, kinetic p) of collisionless shocks

Dhybrid code: Gargaté et al. (2007), Caprioli & Spitkovsky (2014)



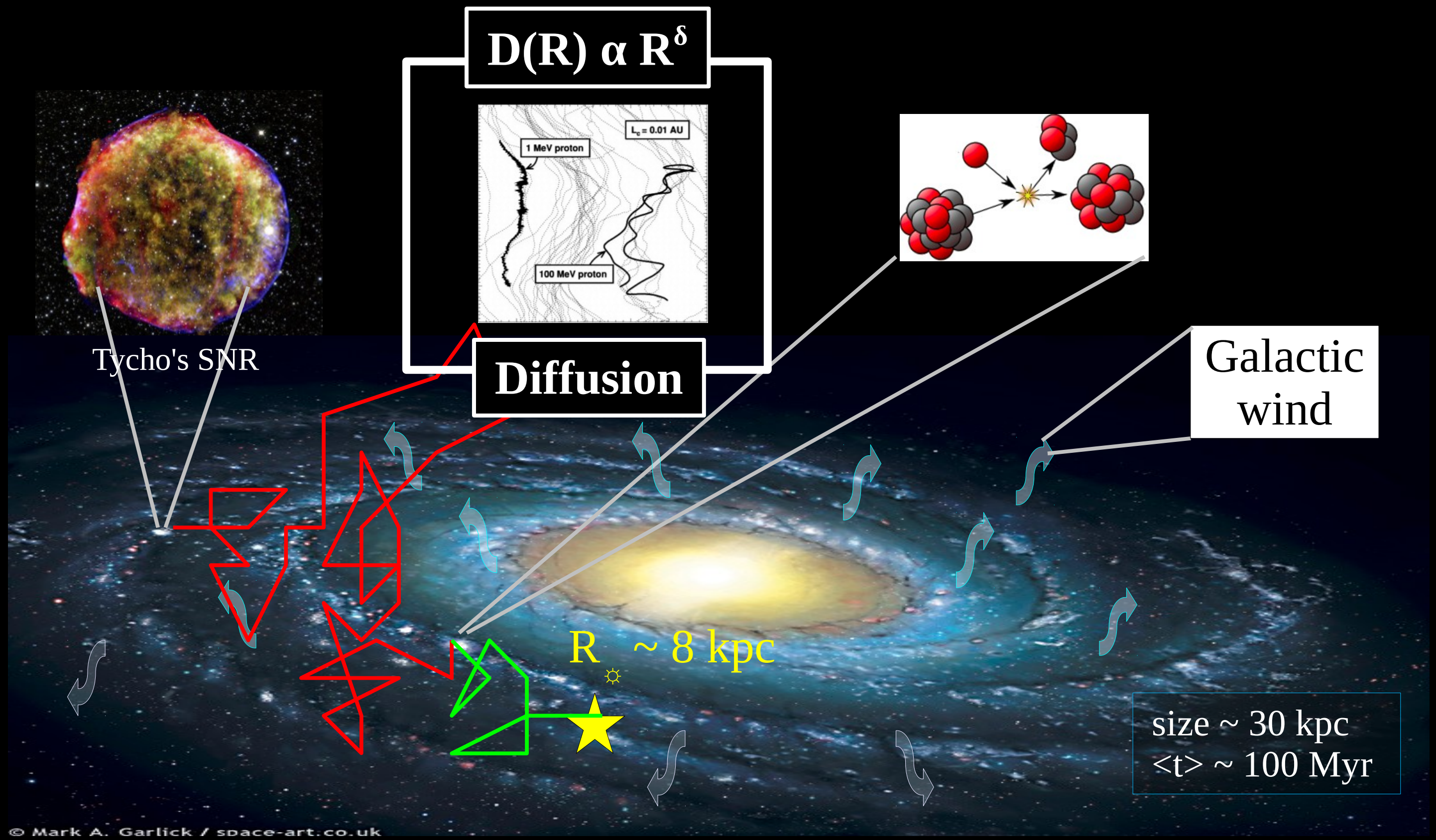
B amplification, compression ratios… (concave spectra, γ-ray emission… ?)

Amato, IJMD 23, 130013 (2013)

But in almost all propagation models

- Power-law or broken power-law (with cut-off at high energy)
- No time-dependence in fluxes (except for highest energies)

Transport



D(R) α R^δ
Diffusion
Tycho's SNR
Galactic wind
R☼ ~ 8 kpc
size ~ 30 kpc
<t> ~ 100 Myr
© Mark A. Garlick / space-art.co.uk

Transport: from microphysics to diffusion

Adapted from R. Tautz

- **Physics problem:** motion in a turbulent field
- **Ansatz:** diffusion equation $\frac{\partial f}{\partial t} - S = \nabla \cdot \left(\kappa_{nj} \cdot \nabla f - \boldsymbol{v} f \right) + \frac{\partial}{\partial \boldsymbol{p}} \left(p^2 D_p \frac{\partial}{\partial \boldsymbol{p}} \frac{f}{p^2} - \dot{\boldsymbol{p}} f \right) + \ldots$

$$\boldsymbol{\kappa} = \begin{pmatrix} \kappa_\perp & \kappa_A & 0 \\ -\kappa_A & \kappa_\perp & 0 \\ 0 & 0 & \kappa_{||} \end{pmatrix}$$

$\kappa_{||}$: Diffusion *along*[2] $\boldsymbol{B}$
$\kappa_\perp$: Diffusion *across*[3] $\boldsymbol{B}$
κ_A: Drift effects[4]

Analytical calculation

- Mean free path $\lambda_{||} \propto \kappa_{||} \propto \int_{-1}^{1} \mathrm{d}\mu \, \frac{(1-\mu^2)^2}{D_{\mu\mu}(\mu)}$

  Pitch angle $\mu = \cos(\widehat{\boldsymbol{v},\boldsymbol{B}_0})$
- Fokker-Planck coefficient $D_{\mu\mu} = \int_0^{\infty} \mathrm{d}t \, \langle \dot{\mu}(t) \, \dot{\mu}^*(0) \rangle$

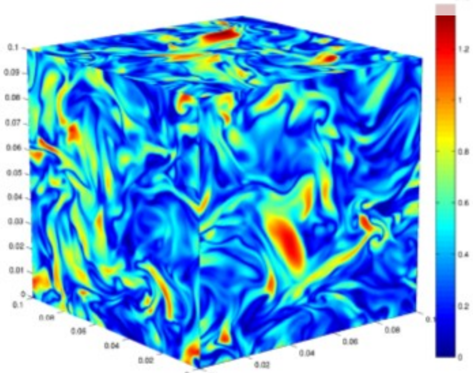
  Taylor-Green-Kubo formula
- Equation of motion (Lorentz) $\dot{\mu} = \frac{\partial}{\partial t}\left(\frac{v_{||}}{v}\right) \overset{\text{static}}{=} \frac{\dot{v}_{||}}{v} = \frac{\Omega}{v}\left(v_x \frac{\delta B_y}{B_0} - v_y \frac{\delta B_x}{B_0}\right)$

  Unknown $v_{x,y}$, unknown position in $\delta B_{x,y}$

→ Can only be solved in ideal situations
- Quasi-Linear Theory ($\delta B \ll B$): QLT
- 2[nd] order QLT: SOQLT
- Non-linear guiding centre: NLGC

Numerical simulations

Reality: resonant wave-particle interaction with stochastic motion... turbulence model requires:
- E spectrum (different. eq. for wave): $W \propto k^{-s}$
- Geometry
- Dynamical behaviour
  - Instabilities
  - Damped waved
  - Intermittency



Diffusion in MHD turbulence

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κ_A: Drift effects[4]

Analytical calculation

- Mean free path $\lambda_{||} \propto \kappa$...

*Pitch angle μ=cos(**v**,**B**$_0$)*

- Fokker-Planck coefficie...

Taylor-Green-Kubo for...

- Equation of motion (Lo...

Unknown $v_{x,y}$, unknown position in $\delta B_{x,y}$

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- 2nd order QLT: SOQLT
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Numerical simulations

...ave-particle interaction with turbulence model requires: ...ifferent. eq. for wave): $W \propto k^{-s}$

...haviour

...ved

See Mertsch, arXiv:1910.01172 for a review

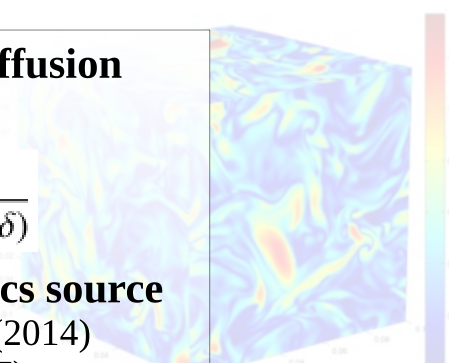
→ **For data interpretation, phenomenological approach of diffusion**

Moreover, until recently, in all propagation models
- Isotropic diffusion (no tensor, $K_{//} = K_\perp$)
- Simple rigidity power-law (α K_0 R^δ)

Diffusion in space ↔ momentum diffusion
(e.g., Seo & Ptuskin, 1994)

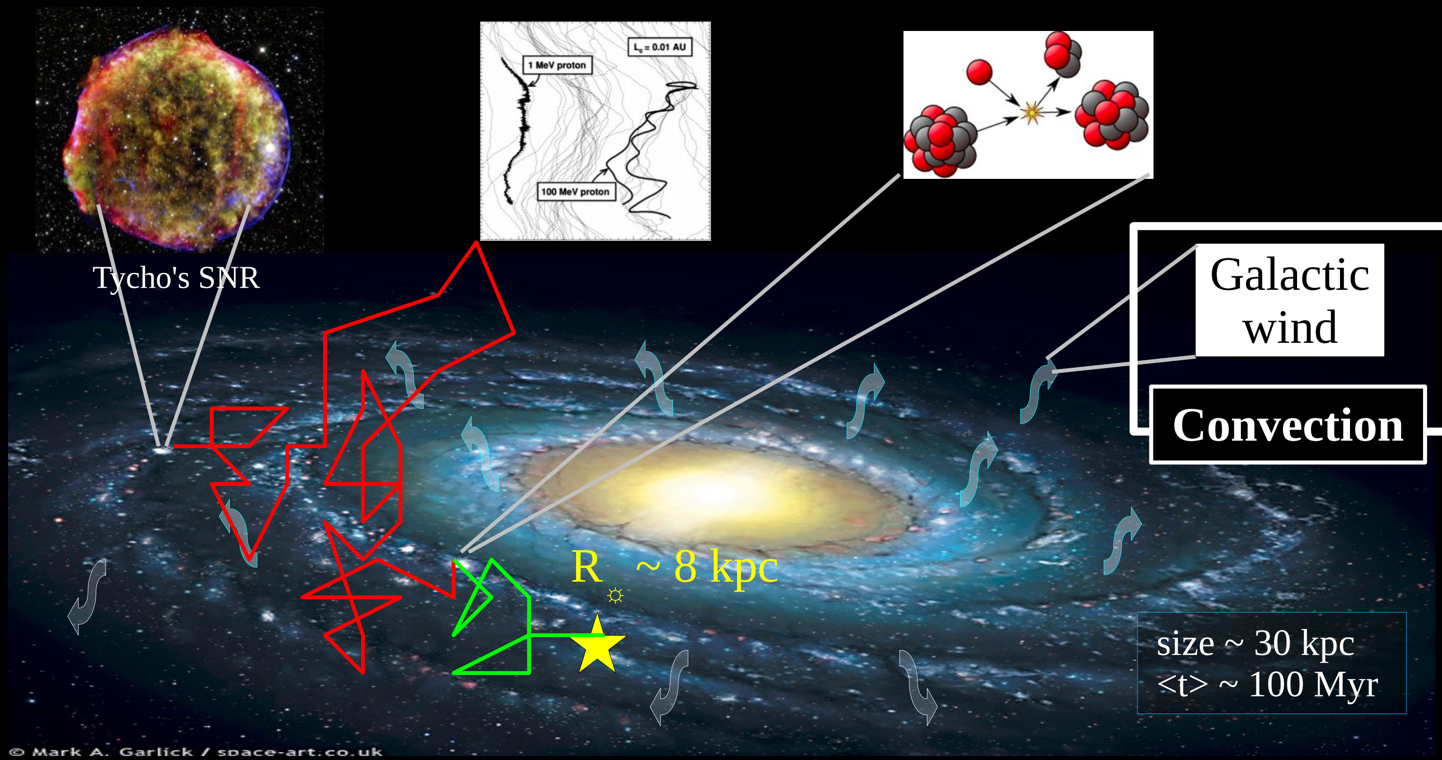
$$K_{pp}(R) \times K(R) = \frac{4\,(V_a \beta E)^2}{3\delta(4-\delta^2)(4-\delta)}$$

Energetics of reacceleration < energetics source
Thornbury & Drury, MNRAS 442, 3010 (2014)
Drury & Strong, A&A 597, 117 (2017)



Diffusion in MHD turbulence

Transport



Tycho's SNR
1 MeV proton
L = 0.01 AU
100 MeV proton
Galactic wind
Convection
R☼ ~ 8 kpc
size ~ 30 kpc
<t> ~ 100 Myr
© Mark A. Garlick / space-art.co.uk

Convections: CR-driven winds?

Firstly introduced

- Pressure-driven galactic winds (Jonhson & Axford, 1971)
- CR-driven galactic winds (Ipavitch, 1975)

Further refinements on CR-driven winds (semi-analytical or numerical hydrodynamics)

- Breitschwerdt et al. (1991, 1993)
- Zirakashvili et al. (1996)

Recent advances (moving-mesh code AREPO)

Pakmor et al., ApJL 824, 30 (2016)

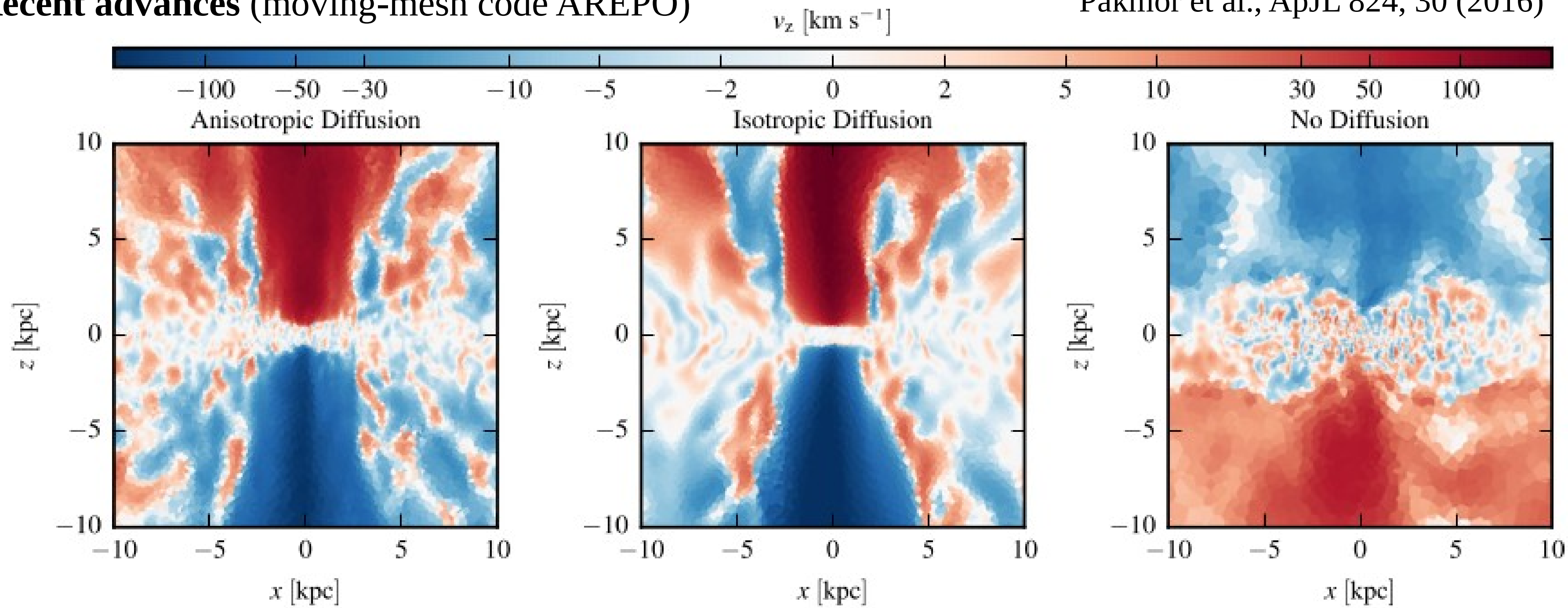
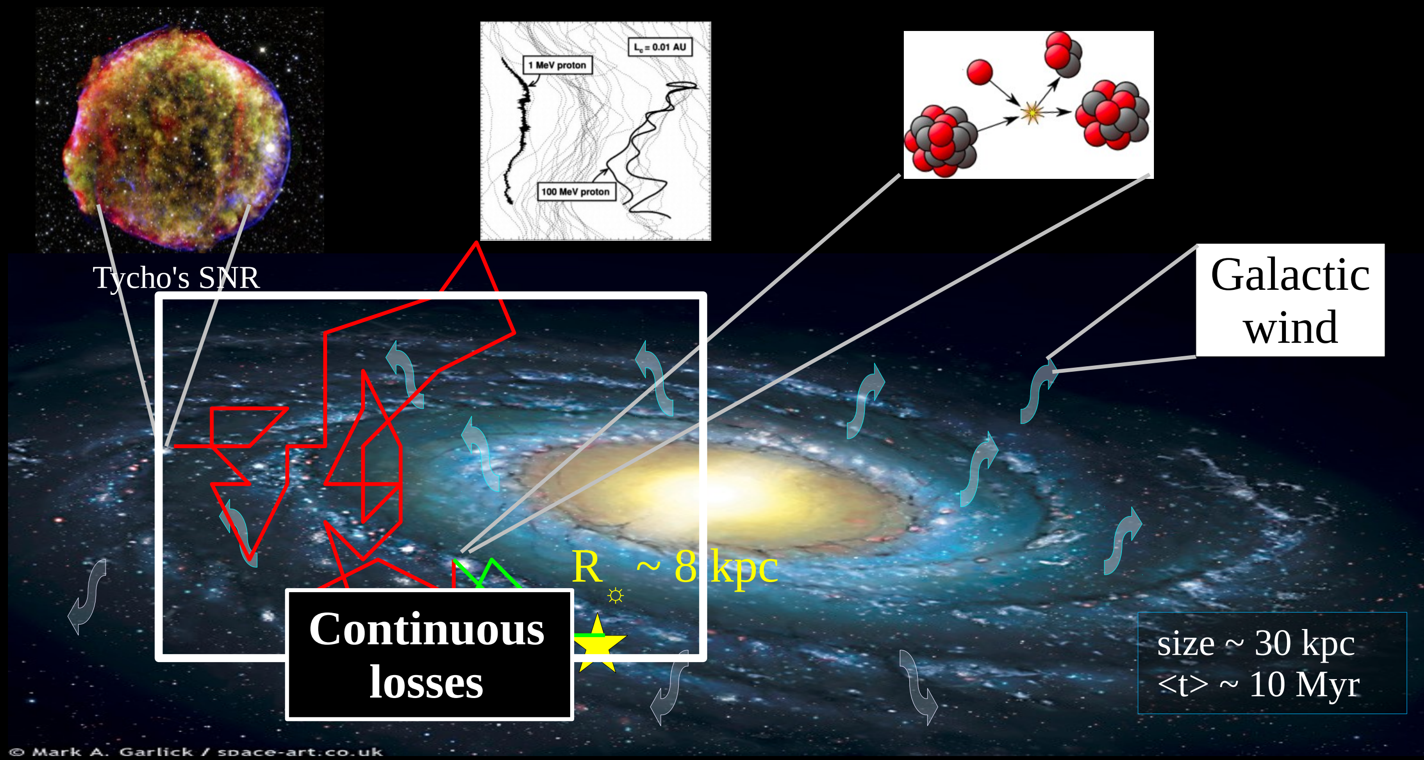


Figure 3. Slices in the x−z plane through the center of the disk of the, showing the z-velocity component after 1.5 Gyr. The columns from left to right correspond to the simulations with anisotropic CR diffusion, isotropic CR diffusion, and without CR diffusion, respectively.

Advection + self-generated waves → Galactic halo

Evoli et al., PRL 121, 021102 (2018)

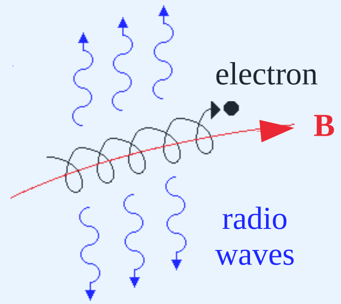
Energy losses



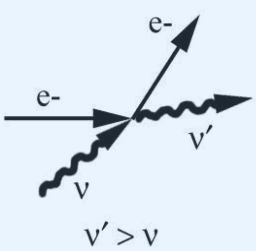
GCR journey

Leptons

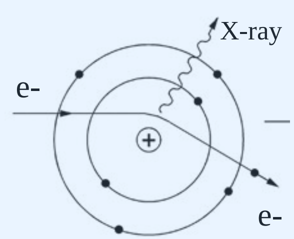
Synchrotron
- Power emitted ∥ and · to B (polarised emission)
- $\nu(P_{max})$ ~ 300 MHz (for 100 MeV e^-)



Inverse Compton
- Fold to cross section and density of photons

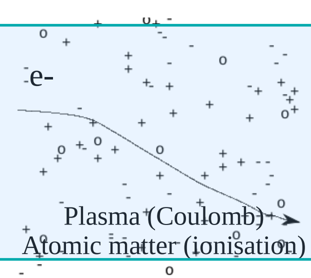


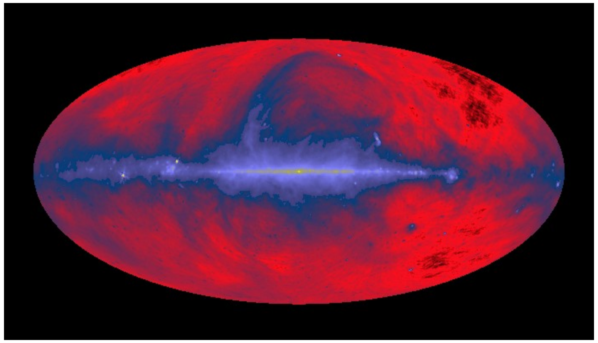
Bremsstrahlung (or free-free)
- In plasma or atomic hydrogen
- In the ISM: H (neutral+molecular) and He dominant



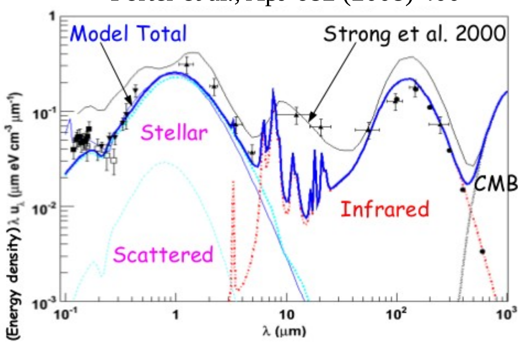
Nuclei

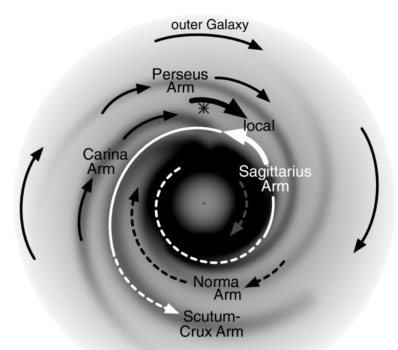
Ionisation and Coulomb
- Ionisation: interaction in neutral matter
- Coulomb: scattering off free electrons





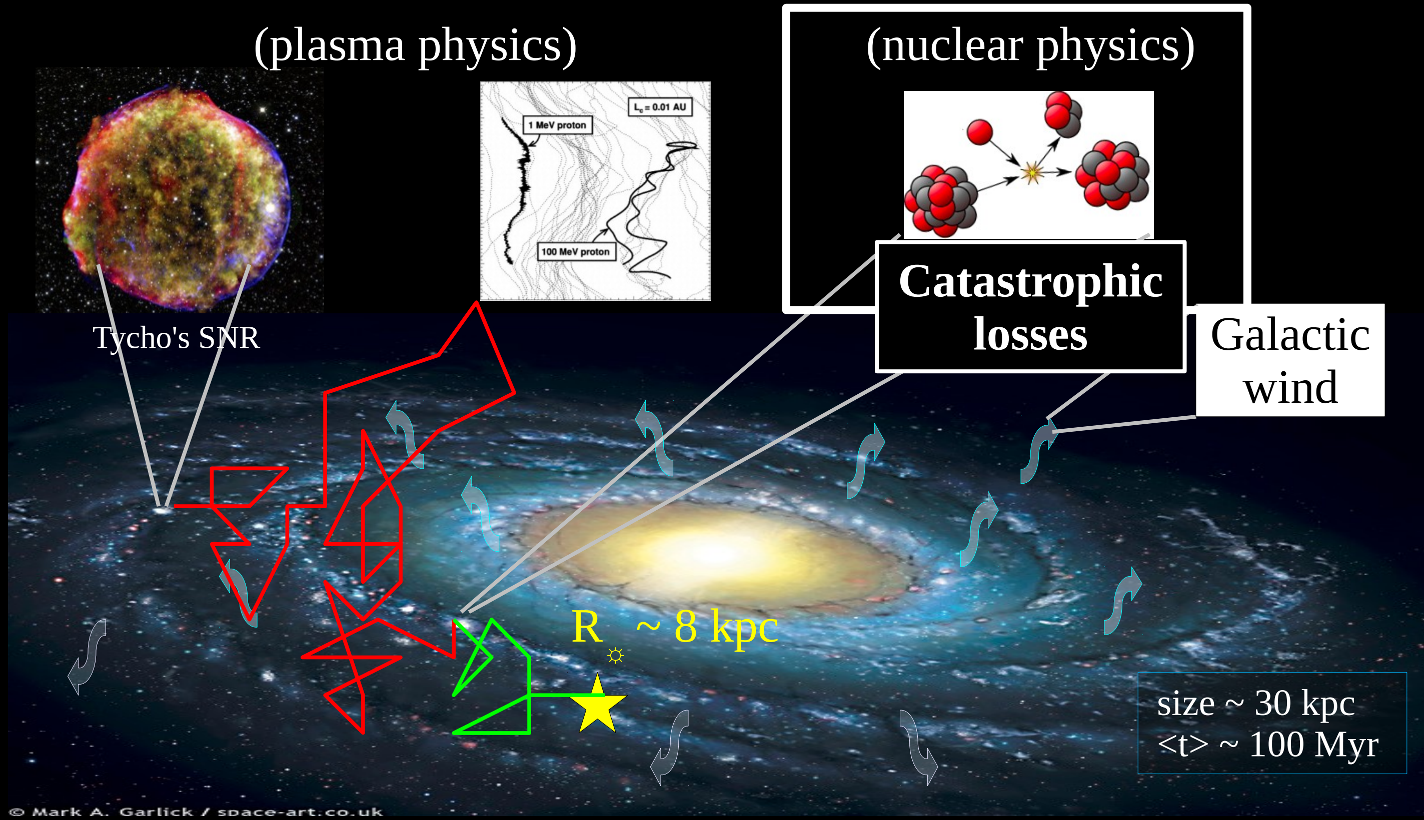
Porter et al., ApJ 682 (2008) 400





Van Eck et al. ApJ 728 (2011) 97

Nuclear interactions



(astrophysics + particle physics)

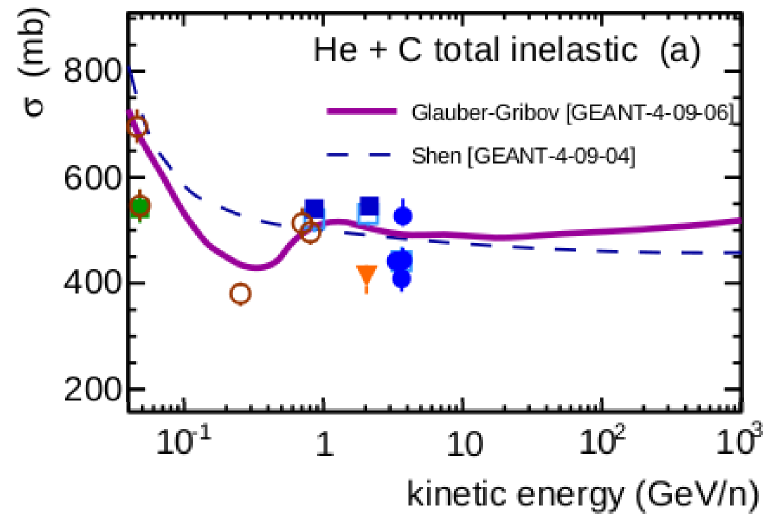
Nuclear interactions

CR modelling requires

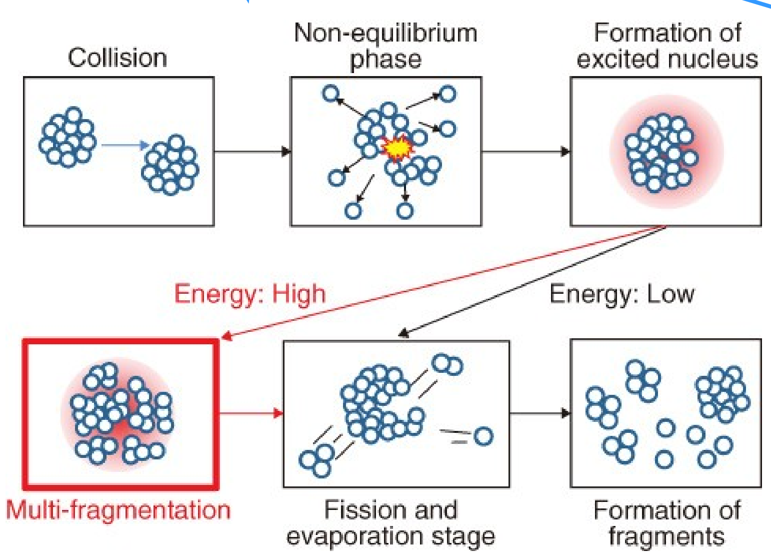
- Inelastic cross sections (CR destruction)
- Production cross sections (secondary species)

on ISM
(~ 90% H, 10% He)

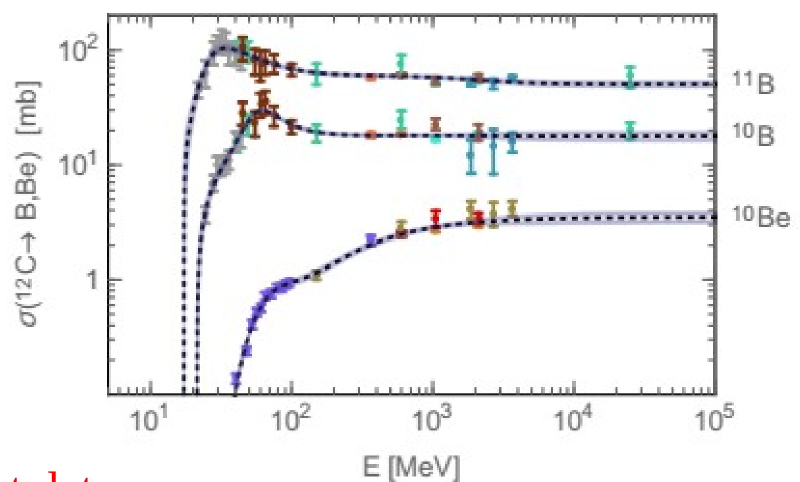
Tomassetti, PRD 93, 3005 (2017)



Ogawa et al., NIMPRA 723, 36 (2013)



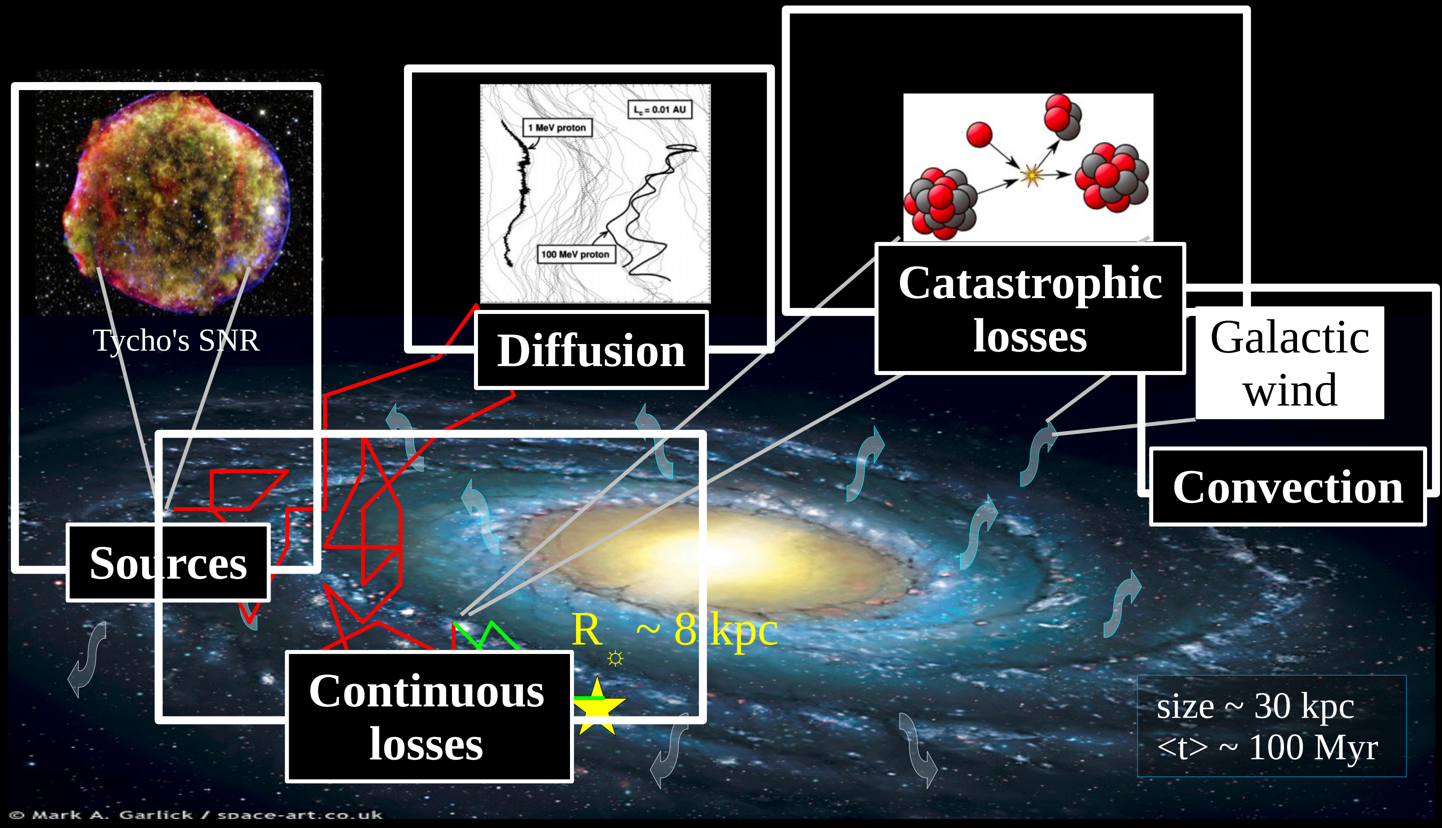
Reinert & Winkler, JCAP 01, 055 (2018)



Various approaches
→ Microscopic
→ Semi-empirical
→ Parametric

→ Scarce or inconsistent data
[see Génolini et al, PRC 98, 034611 (2018)]

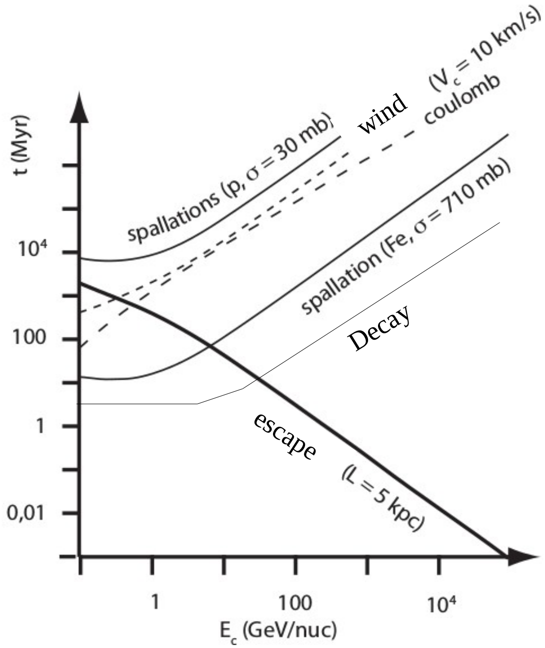
GCR journey



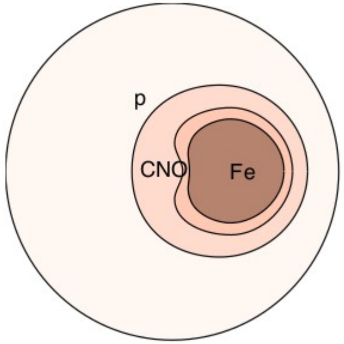
→ In any system, to learn something, always look at the characteristic times!

Timescales and consequences

Nuclear component



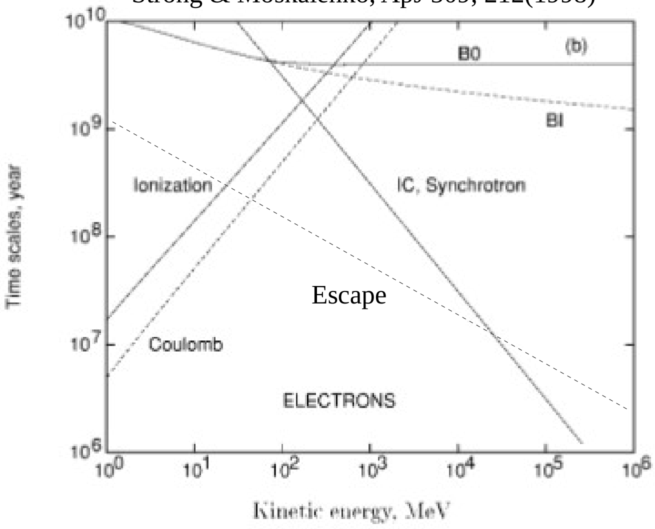
→ CR nuclei originate from a large volume (for sources)
→ Below a few GeV/n, heavy CRs depleted/closer w.r.t. light ones
→ Radioactive nuclei only feel the "local" diffusion coefficient



Taillet & Maurin, A&A 402, 971 (2003)
Maurin & Taillet, A&A 404, 949 (2003)

Leptons

Strong & Moskalenko, ApJ 509, 212(1998)



→ CR leptons at high energy are very local (few hundreds of pc)
→ Time-dependent/single source effects expected
→ Local/recent sources considered in time-dependent framework

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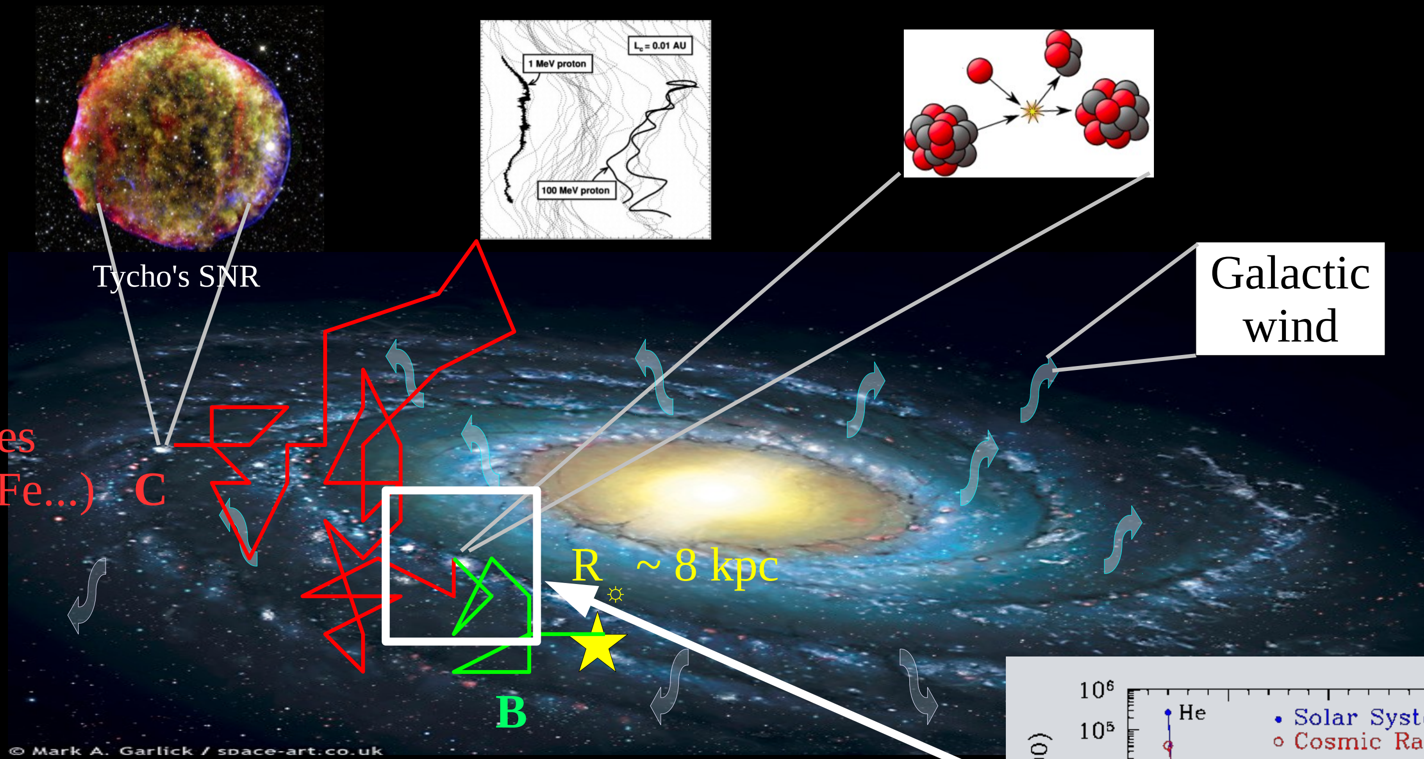
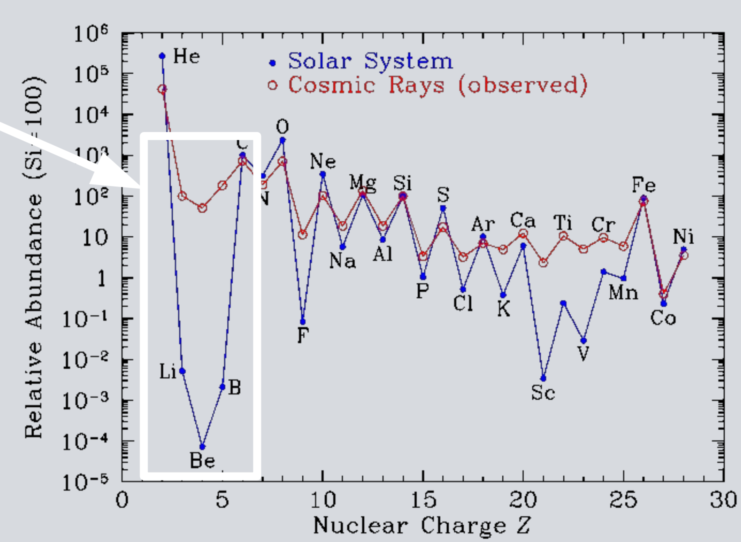
Primary vs secondary species

Primary species
(p, He, C, O, Si, Fe...)

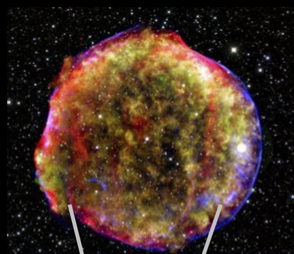




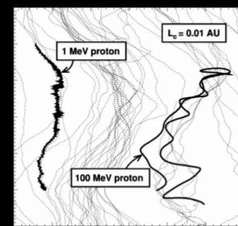
Secondary species
(^{2}H, ^{3}He, Li-Be-B, sub-Fe)

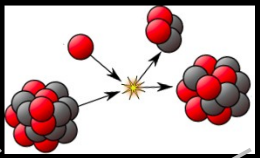
Secondary-to-primary ratio to calibrate transport

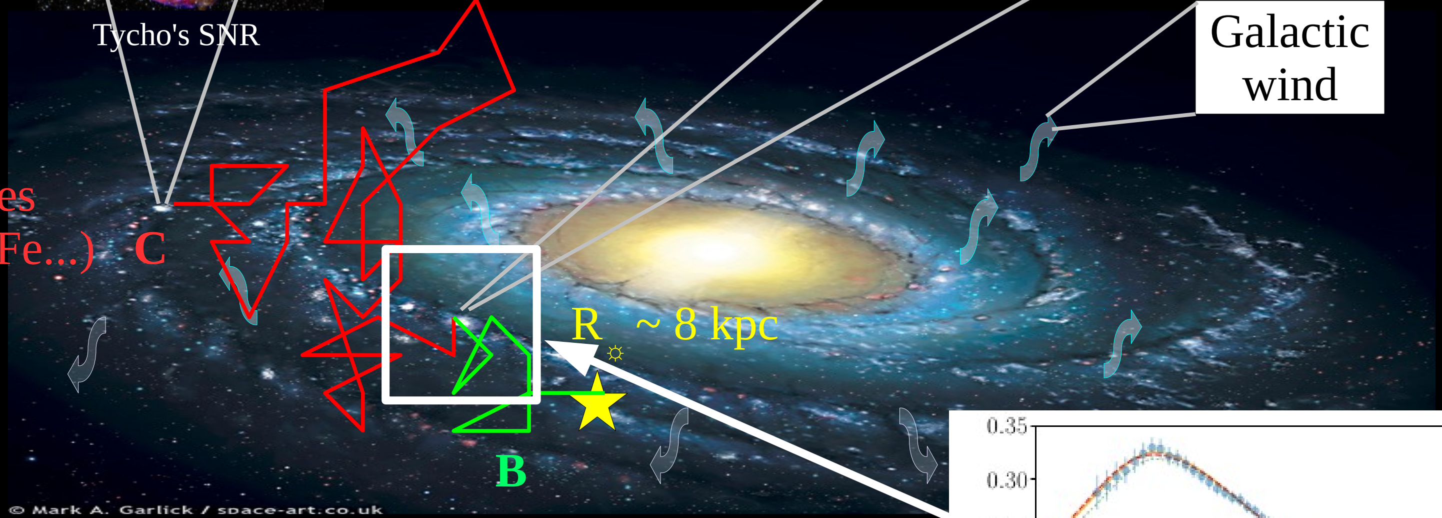
$R^{-\alpha}$



$D_0 R^{\delta}$

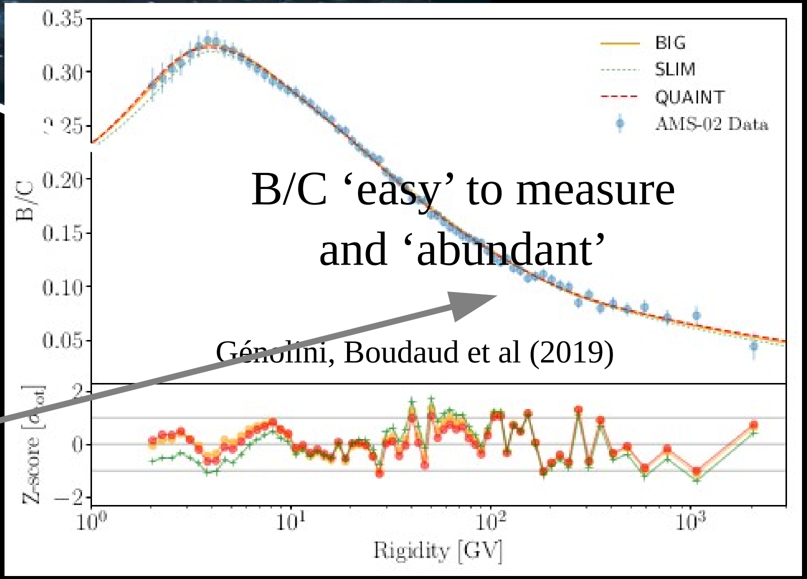






Primary species
(p, He, C, O, Si, Fe...)

Secondary species
(^{2}H, ^{3}He, Li-Be-B, sub-Fe)

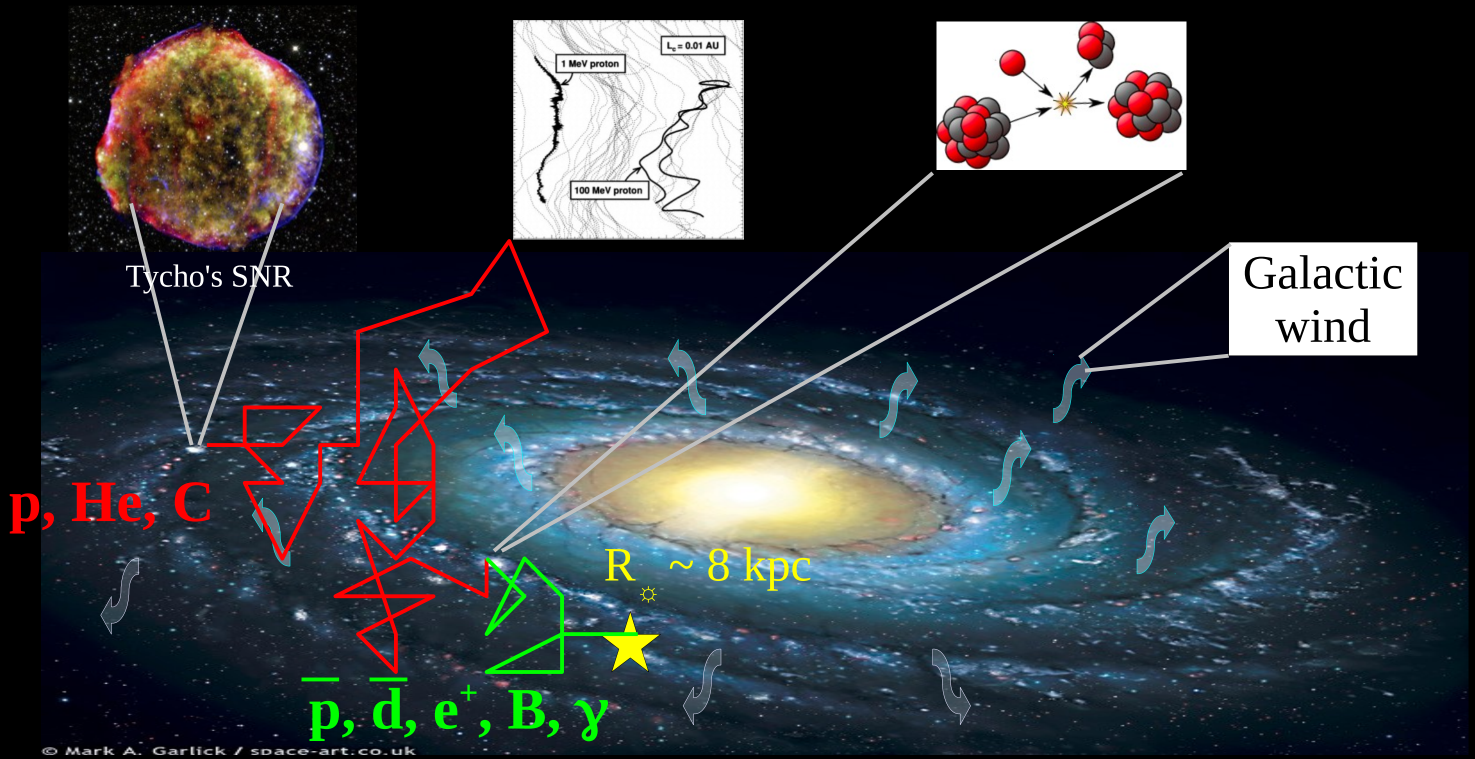


B/C 'easy' to measure
and 'abundant'

Génolini, Boudaud et al (2019)

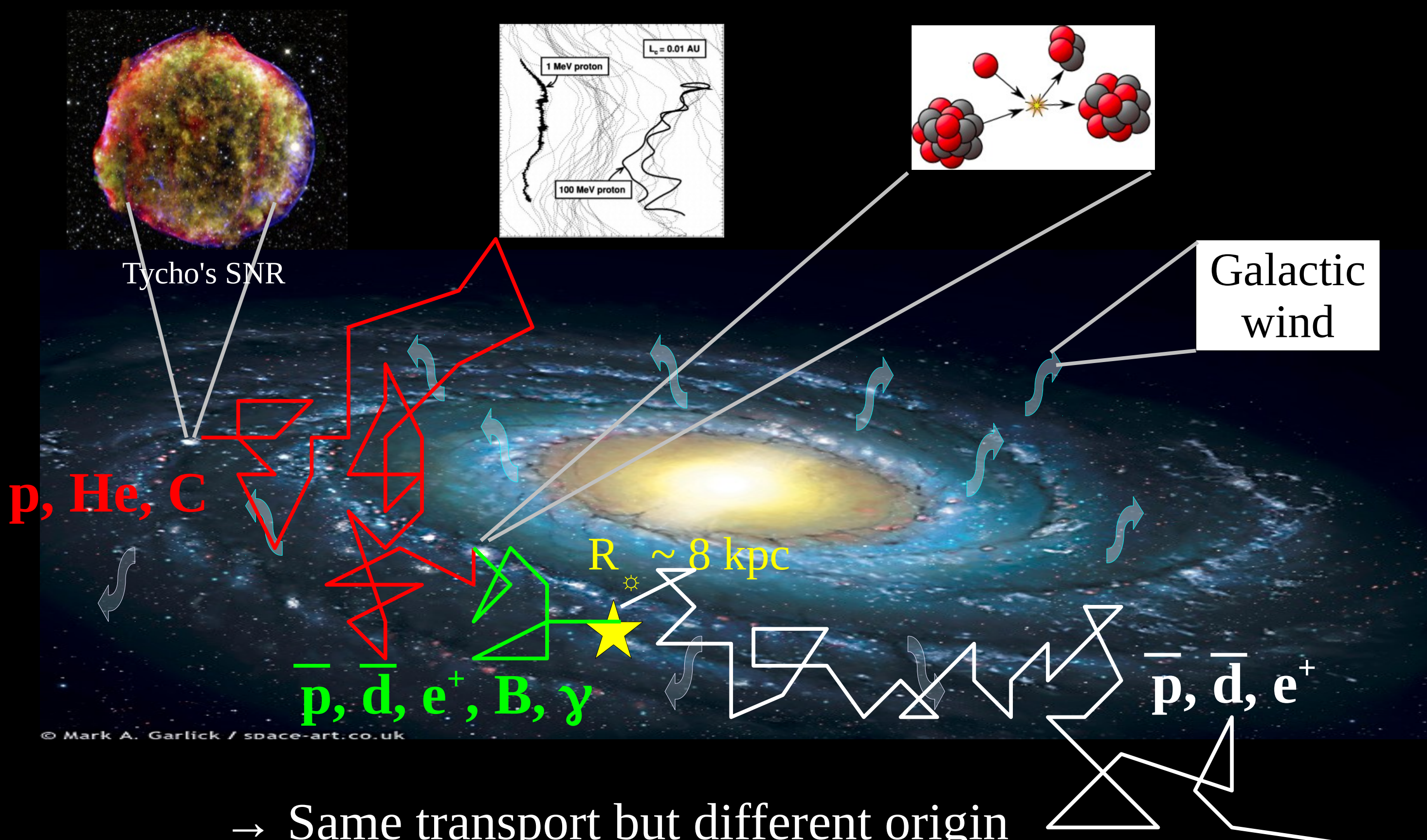
Primary species P: source/diffusion ~ $R^{-(\alpha+\delta)}$
Secondary species S: $(\sigma^{P\rightarrow S} \cdot P)$/diffusion ~ $R^{-(\alpha+2\delta)}$
→ Secondary to primary ratio ~ $\sigma^{P\rightarrow S} \cdot R^{-\delta}$

“Background” calculation for rare channels



→ Same propagation history for B/C, or pbar/p
(apply previously derived parameters)

Look for dark matter “signal”



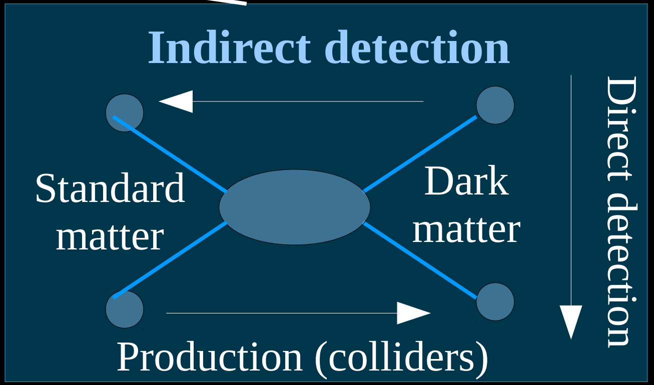
→ Same transport but different origin (from DM halo)

Universe (after Planck)
- 68.3 % dark energy
- 26.8 % dark matter
- 4.9 % ordinary matter

→

Milky-Way dark matter halo
- ~ spherical halo
- radius ~300 kpc

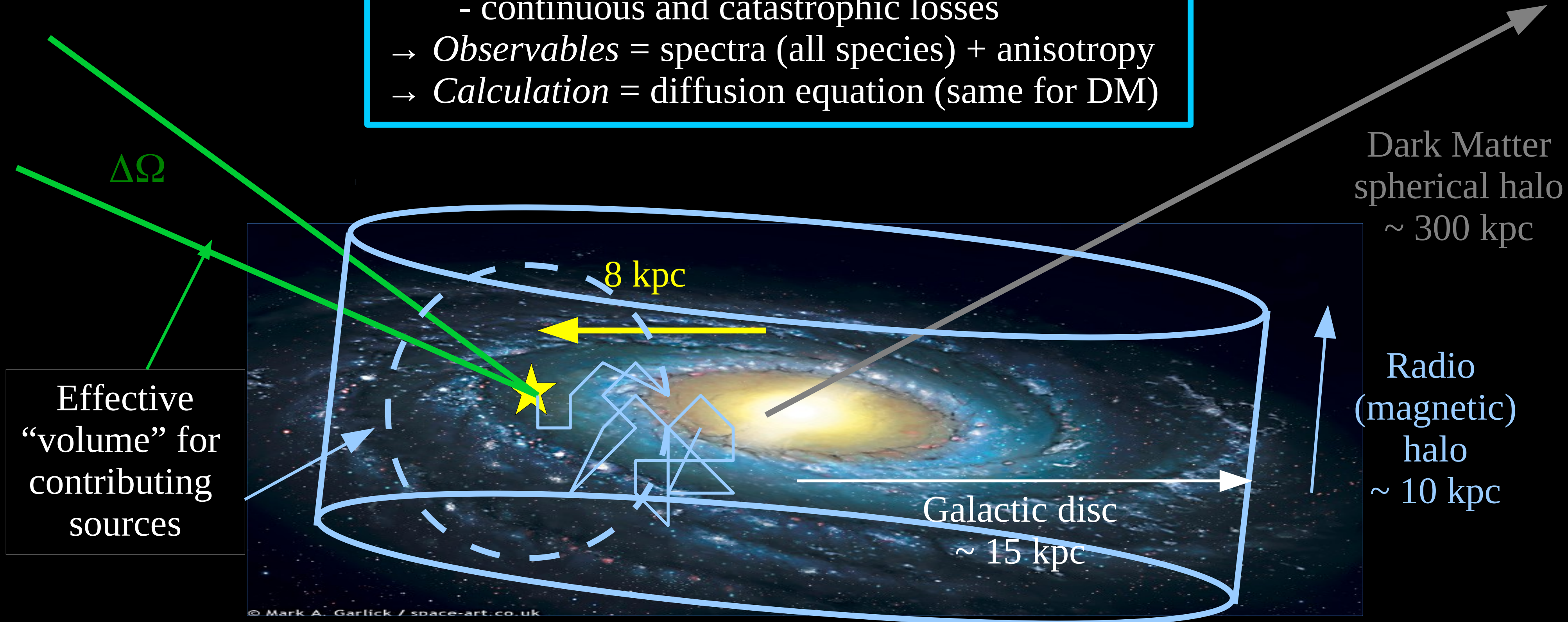
→



Indirect DM search: gamma-ray astronomy

Charge particles
- diffusion in turbulent B
- continuous and catastrophic losses

→ *Observables* = spectra (all species) + anisotropy
→ *Calculation* = diffusion equation (same for DM)



Neutral particles
- propagate in straight line
- absorption ~ negligible at GeV-TeV in the Galaxy

→ *Observables* = skymaps + spectra
→ *Calculation* = line-of-sight integration on ΔΩ

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Diffusion equation

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{(\Gamma_{\rm rad}+\Gamma_{\rm inel})}^{\text{Catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j \frac{\partial N^j}{\partial E}\right)}^{\text{E gains/losses}} = \overbrace{Q^j(E,\vec{r}) \quad + \sum_{m_i>m_j} \Gamma^{i\to j} N^i}^{\text{Source term: prim.+sec.}}$$

N.B.: in practice, to solve for ~100 isotopes

Solving the diffusion equation: toolbox

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{(\Gamma_{\rm rad}+\Gamma_{\rm inel})}^{\text{Catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j\frac{\partial N^j}{\partial E}\right)}^{\text{E gains/losses}} = \overbrace{Q^j(E,\vec{r}) \quad + \sum_{m_i>m_j}\Gamma^{i\to j}N^i}^{\text{Source term: prim.+sec.}}$$

N.B.: in practice, to solve for ~100 isotopes

	Weighted-slab/LB
Approach	Separate fragmentation: • Grammage dist. (PLD) • Integrate on grammage LB → PLD(X) = $e^{(-X/\lambda esc)}$
Tools	• 1D numerical integr.
Pros	• Simple
cons	• Leakage approx. fails (leptons and decay)
Codes and/or references	Davis (1960) – Leaky box Ginzburg & Syrovatskii (1969) Jones/Ptuskin/Webber (70-01) Jones *et al.* (2001)

↓ 0D

Solving the diffusion equation: toolbox

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\left(\Gamma_{\rm rad}+\Gamma_{\rm inel}\right)}^{\text{Catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j \frac{\partial N^j}{\partial E}\right)}^{\text{E gains/losses}} = \overbrace{Q^j(E,\vec{r}) \quad + \sum_{m_i>m_j} \Gamma^{i\rightarrow j} N^i}^{\text{Source term: prim.+sec.}}$$

N.B.: in practice, to solve for ~100 isotopes

	Weighted-slab/LB	*(Semi-)analytical*
Approach	Separate fragmentation: • Grammage dist. (PLD) • Integrate on grammage LB → PLD(X) = $e^{(-X/\lambda esc)}$	Simplify problem: • dominant effects • simple geometry
Tools	• 1D numerical integr.	• Green functions • Fourier/Bessel • Diff. equations
Pros	• Simple	• Direct dep. in sol. • Fast (e.g. w/ MCMC)
cons	• Leakage approx. fails (leptons and decay)	• “Effective” models • New eq. per model
Codes and/ or references	Davis (1960) – Leaky box Ginzburg & Syrovatskii (1969) Jones/Ptuskin/Webber (70-01) Jones *et al.* (2001)	Ptuskin (1980+) Schlickeiser (1990+) USINE (2000+)

↓ 0D ↓ 1D, 2D

Solving the diffusion equation: toolbox

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\left(\Gamma_{\rm rad}+\Gamma_{\rm inel}\right)}^{\text{Catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j \frac{\partial N^j}{\partial E}\right)}^{\text{E gains/losses}} = \overbrace{Q^j(E,\vec{r}) \quad + \sum_{m_i>m_j} \Gamma^{i\to j} N^i}^{\text{Source term: prim.+sec.}}$$

N.B.: in practice, to solve for ~100 isotopes

	Weighted-slab/LB	*(Semi-)analytical*	*Finite difference scheme*
Approach	Separate fragmentation: • Grammage dist. (PLD) • Integrate on grammage LB → PLD(X) = $e^{(-X/\lambda esc)}$	Simplify problem: • dominant effects • simple geometry	Discretize equation: • Numerical scheme (e.g., Crank-Nicholson) → Matrix inversion
Tools	• 1D numerical integr.	• Green functions • Fourier/Bessel • Diff. equations	• Num. recipes/solvers (NAG, GSL libraries)
Pros	• Simple	• Direct dep. in sol. • Fast (e.g. w/ MCMC)	• Simple algebra • Universal (any model)
cons	• Leakage approx. fails (leptons and decay)	• "Effective" models • New eq. per model	• Slower / instabilities • RAM for high.res.
Codes and/ or references	Davis (1960) – Leaky box Ginzburg & Syrovatskii (1969) Jones/Ptuskin/Webber (70-01) Jones *et al.* (2001)	Ptuskin (1980+) Schlickeiser (1990+) USINE (2000+)	GALPROP (Strong *et al.*, 1998) DRAGON (Evoli *et al.*, 2008) PICARD (Kissmann *et al.*, 2013)
	↓ 0D	↓ 1D, 2D	↓ 3D, 3D+1

Solving the diffusion equation: toolbox

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right) + \vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\left(\Gamma_{\rm rad}+\Gamma_{\rm inel}\right)}^{\text{Catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j\frac{\partial N^j}{\partial E}\right)}^{\text{E gains/losses}} = \overbrace{Q^j(E,\vec{r}) \quad + \sum_{m_i>m_j}\Gamma^{i\to j}N^i}^{\text{Source term: prim.+sec.}}$$

N.B.: in practice, to solve for ~100 isotopes

	Weighted-slab/LB	*(Semi-)analytical*	*Finite difference scheme*	*Monte Carlo*
Approach	Separate fragmentation: • Grammage dist. (PLD) • Integrate on grammage LB → PLD(X) = $e^{(-X/\lambda esc)}$	Simplify problem: • dominant effects • simple geometry	Discretize equation: • Numerical scheme (e.g., Crank-Nicholson) → Matrix inversion	Follow each particle: • N particles at t=0 • evolve each @ t+1 1D : $\Delta z = \pm\sqrt{2D\Delta t}$
Tools	• 1D numerical integr.	• Green functions • Fourier/Bessel • Diff. equations	• Num. recipes/solvers (NAG, GSL libraries)	• Stochastic diff. equations Markov process + MPI
Pros	• Simple	• Direct dep. in sol. • Fast (e.g. w/ MCMC)	• Simple algebra • Universal (any model)	• Stat. properties (along path) • t step (for/back)-ward
cons	• Leakage approx. fails (leptons and decay)	• "Effective" models • New eq. per model	• Slower / instabilities • RAM for high.res.	• N large (statistical errors) • Massively parallel
Codes and/or references	Davis (1960) – Leaky box Ginzburg & Syrovatskii (1969) Jones/Ptuskin/Webber (70-01) Jones *et al.* (2001)	Ptuskin (1980+) Schlickeiser (1990+) USINE (2000+)	GALPROP (Strong *et al.*, 1998) DRAGON (Evoli *et al.*, 2008) PICARD (Kissmann *et al.*, 2013)	Webber & Rockstroh (1997) Farahat *et al.* (2008) Kopp, Büshing *et al.* (2012) CRPROPA3.1 (Merten *et al.*, 2017)
	↓ 0D	↓ 1D, 2D	↓ 3D, 3D+1	↓ 3D, 3D+1

USINE code

https://lpsc.in2p3.fr/usine

D.M., arXiv:1807.02968 (CPC, in press)

USINE

version 3.5

Search docs

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4. Inside USINE (c++)
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6. Parameter value syntax (init. file)
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Edit on GitLab

USINE documentation

Welcome to USINE, a library with several semi-analytical Galactic cosmic-ray (GCR) propagation models (PDF version of documentation here).

We hope you will enjoy using USINE whether you want to:

- **learn and know more about CR propagation phenomenology**, taking advantage of the simple command-line interface and graphical pop-ups to quickly see and compare the importance of various ingredients on the resulting fluxes;
- **perform state-of-the art analyses of new CR data**, taking advantage of the very flexible ASCII parameter file to select your model, configuration, etc., to fit your data with any number of free parameter (transport, source, geometry...) and nuisance parameters (cross sections, data systematic uncertainties...);
- **develop and use you own semi-analytical model** without having to spend years setting all inputs and outputs right, taking advantage of the modularity and flexibility of the USINE C++ library.

If you use USINE, please cite Maurin (2018)

For any question, contact D. Maurin (LPSC).

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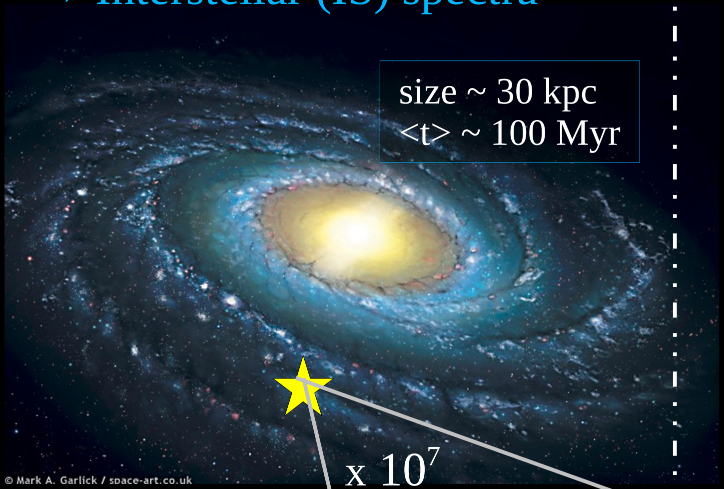
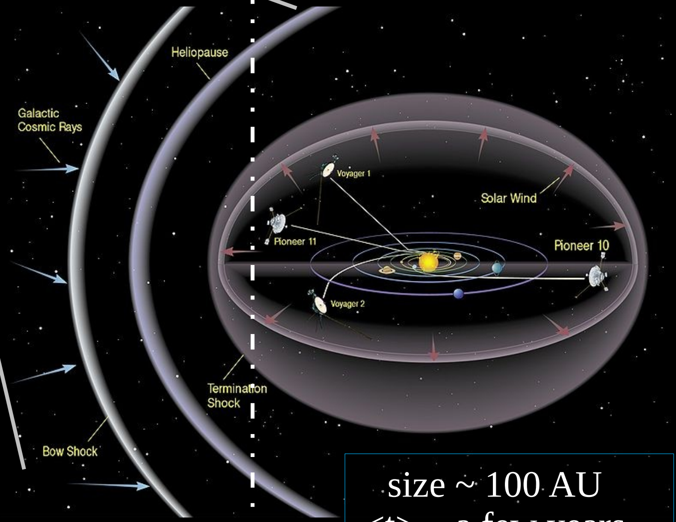
Last steps before detection… Solar modulation

1. Transport in the Galaxy
→ Interstellar (IS) spectra

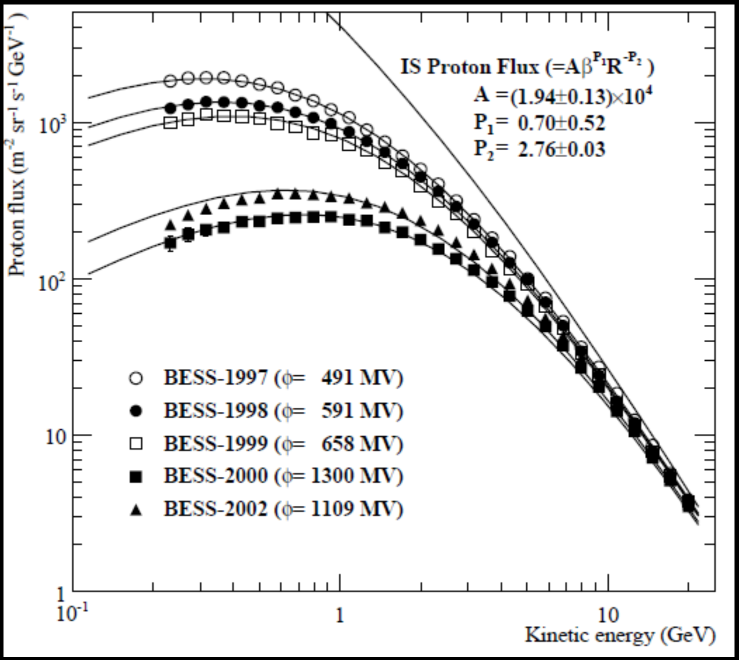


size ~ 30 kpc
<t> ~ 100 Myr

x 10^7



size ~ 100 AU
<t> ~ a few years

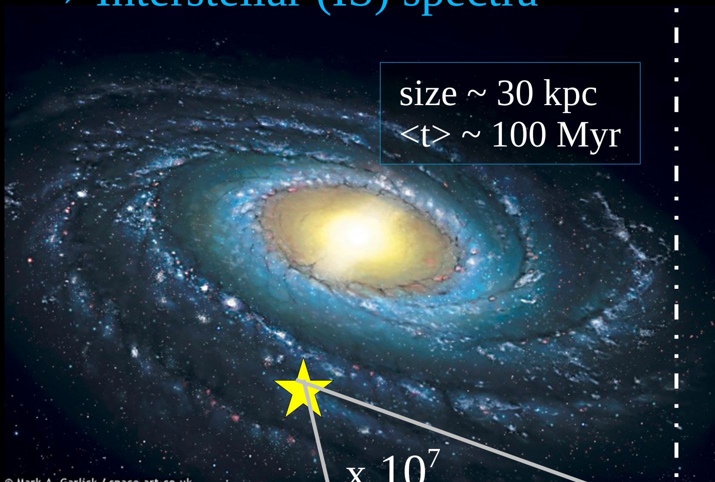


2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)

[time-independent] **[time-dependent]**

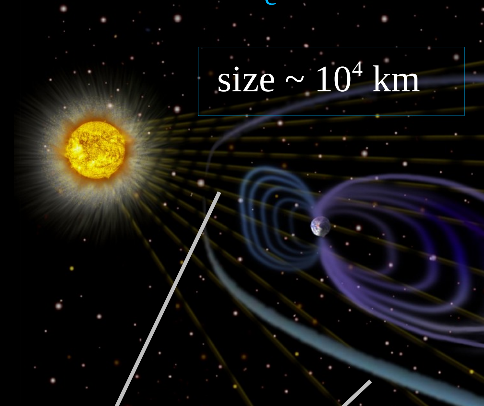
Last steps before detection… R cutoff

1. Transport in the Galaxy
→ Interstellar (IS) spectra

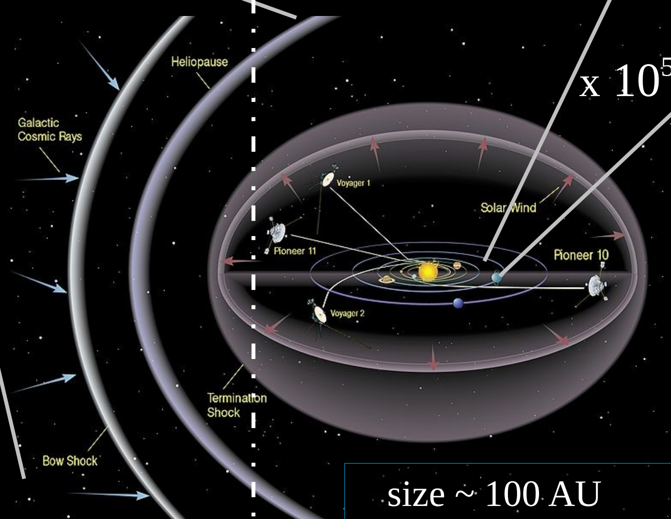


x 10^7

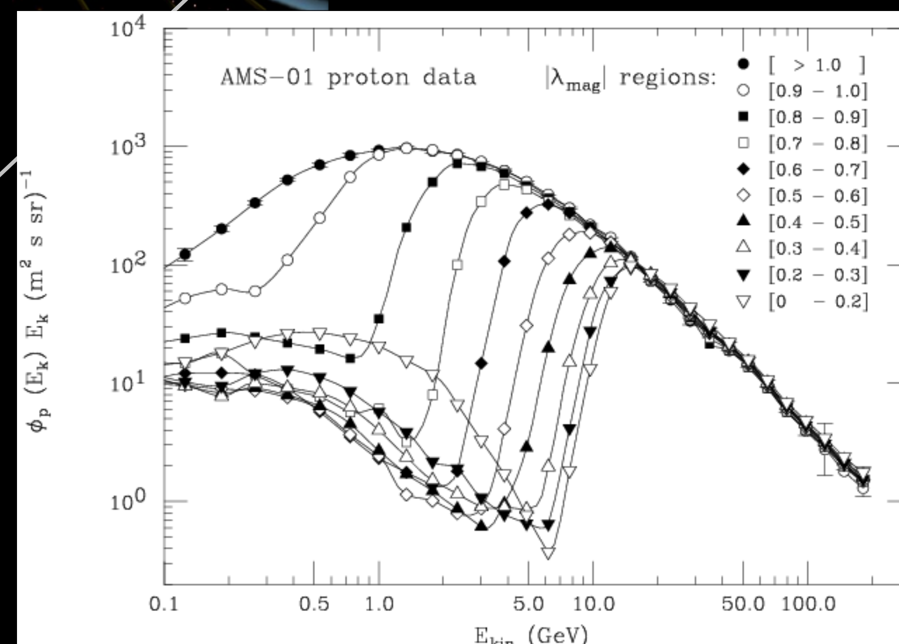
3. Earth magnetic shield
→ Cut-off rigidity R_c (at Earth)



x 10^5



size ~ 100 AU
<t> ~ a few years

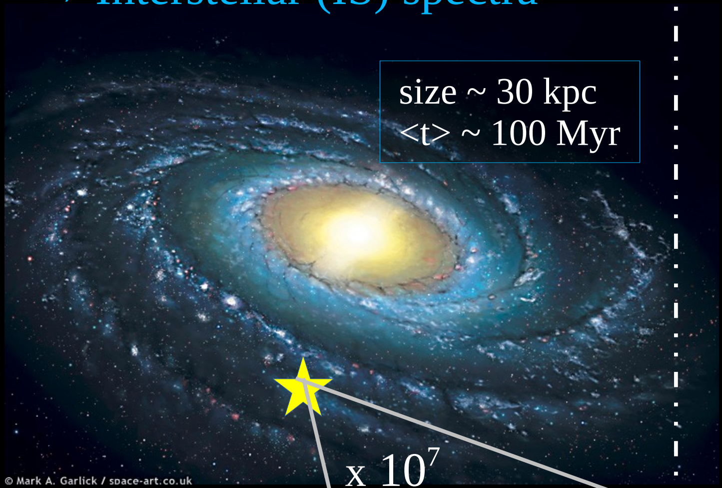


2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)

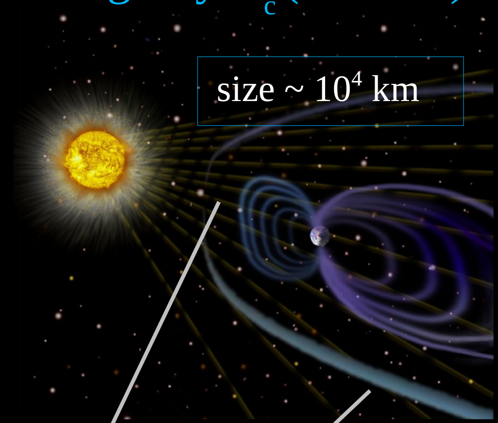
[time-independent] **[time-dependent]**

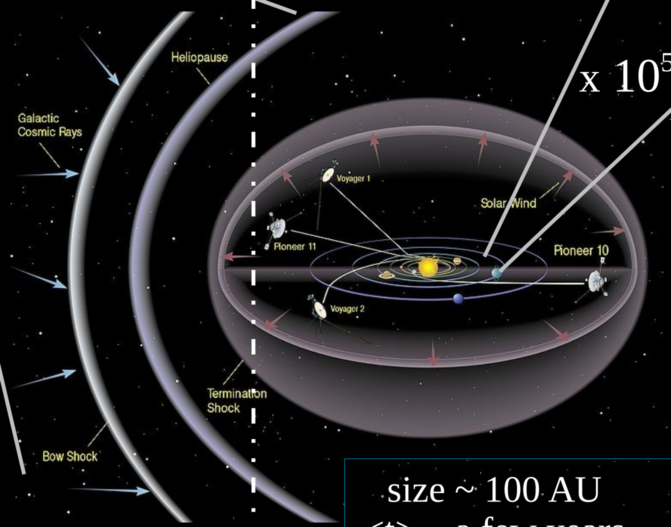
Last steps before detection… atmosphere

1. Transport in the Galaxy
→ Interstellar (IS) spectra

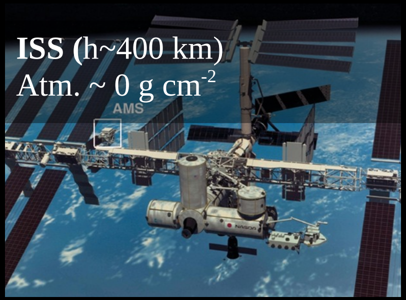


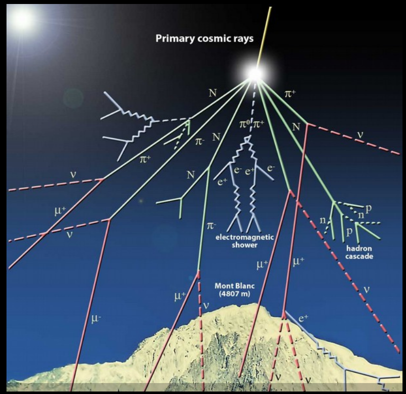
3. Earth magnetic shield
→ Cut-off rigidity R_c (at Earth)





2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)





4. Atmosphere
→ CR showers

[time-independent] **[time-dependent]**

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Installed on ISS in May 2011

→ Circular orbit, 400 km, 51.6°

→ Continuous operation 24/7

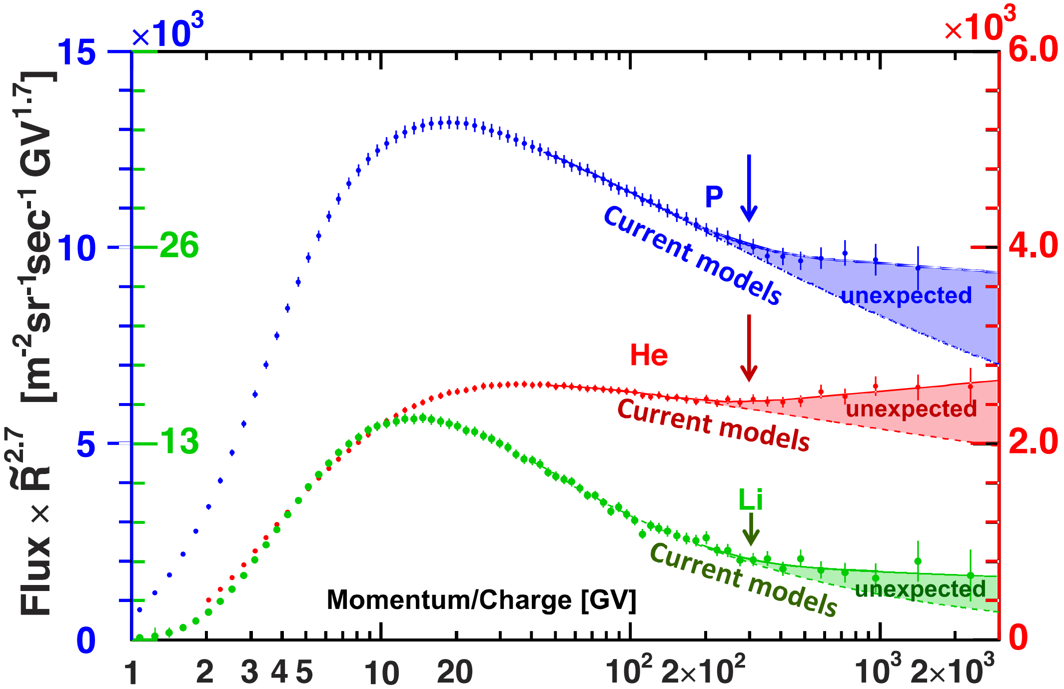
→ Average rate ~700 Hz (60 millions particles/day)

More than 140 billion events so far!

High rigidity break and species-dependent slopes

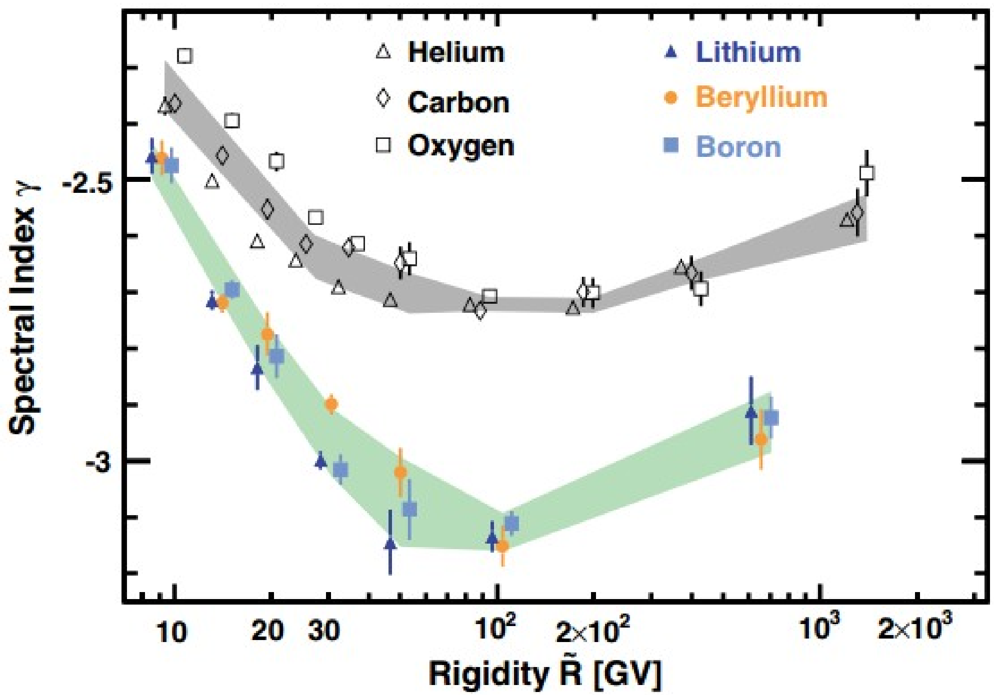
→ Spectral break at ~ 300 GV
→ Different slope H and He

(see also PAMELA ad CREAM)



→ Break seen in all data (primary and seconday species)

Aguilar *et al.*, PRL 120, 021101 (2018)



Origin of difference in slopes?
→ Acceleration, spatial segregation, different kind of sources...

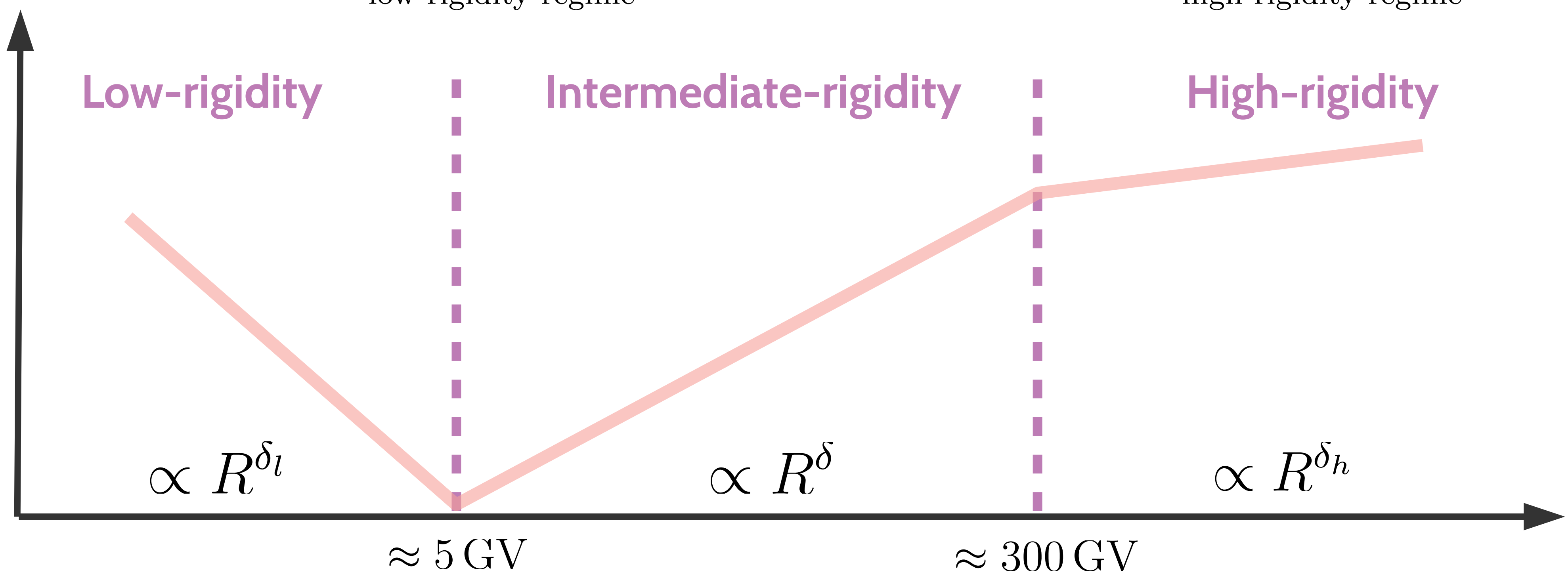
Origin of spectral break?
→ spatial dependence of diffusion coefficient, time-dependent propagation, break in diffusion coefficient (coupling CR/waves)

B/C analysis: 3 regimes for the diffusion coefficient

Génolini, Boudaud et al., PRD 99, 123028 (2019)

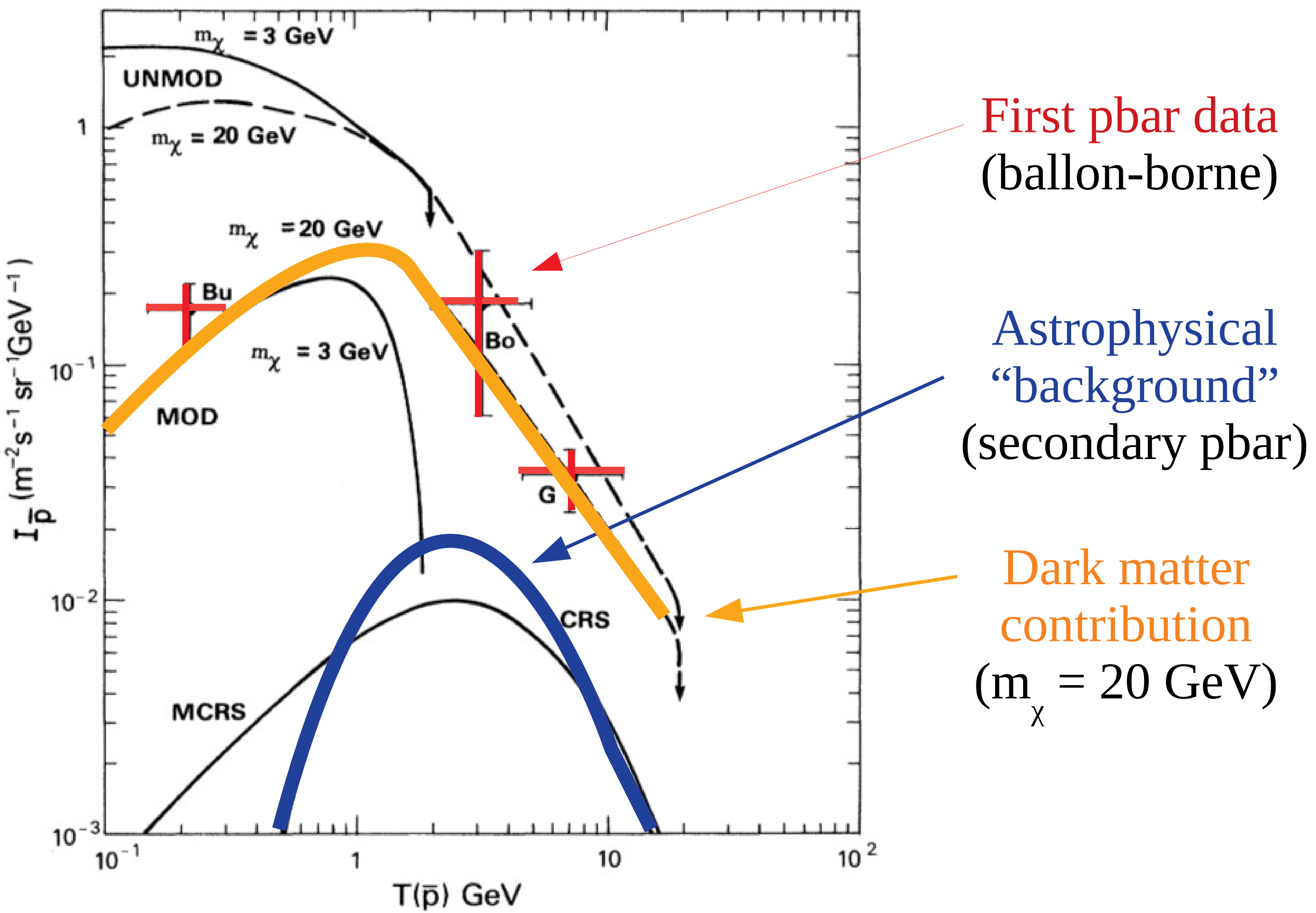
[steady-state +homogeneous and isotropic diffusion + homogeneous sources/gas]
→ several breaks in the diffusion coefficient

$$K(R) = \beta^\eta K_{10} \underbrace{\left\{1+\left(\frac{R}{R_\mathrm{l}}\right)^{\frac{\delta_\mathrm{l}-\delta}{s_\mathrm{l}}}\right\}^{s_\mathrm{l}}}_{\text{low-rigidity regime}} \underbrace{\left\{\frac{R}{(R_{10}\equiv 10\,\mathrm{GV})}\right\}^{\delta}}_{\text{intermediate regime}} \underbrace{\left\{1+\left(\frac{R}{R_\mathrm{h}}\right)^{\frac{\delta-\delta_\mathrm{h}}{s_\mathrm{h}}}\right\}^{-s_\mathrm{h}}}_{\text{high-rigidity regime}}.$$



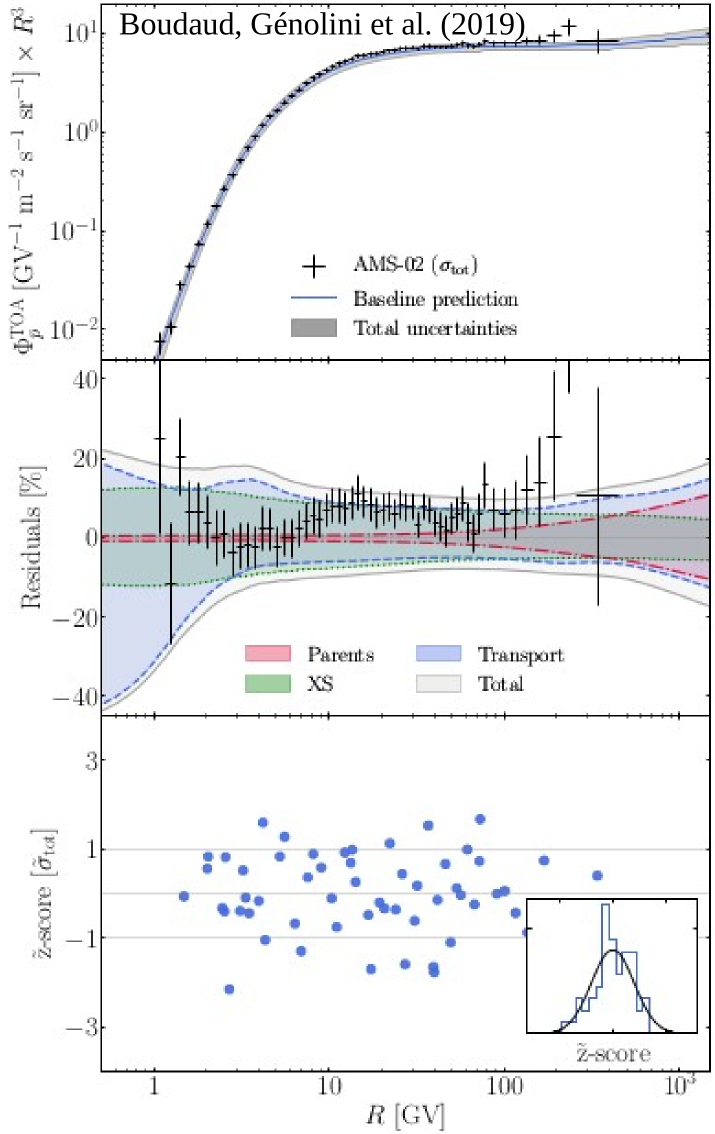
Dark matter detection in CRs?

Stecker, Rudaz & Walsh, PRL **55**, 2622 (1985)



Give me 3 possible conclusions
from this plot?

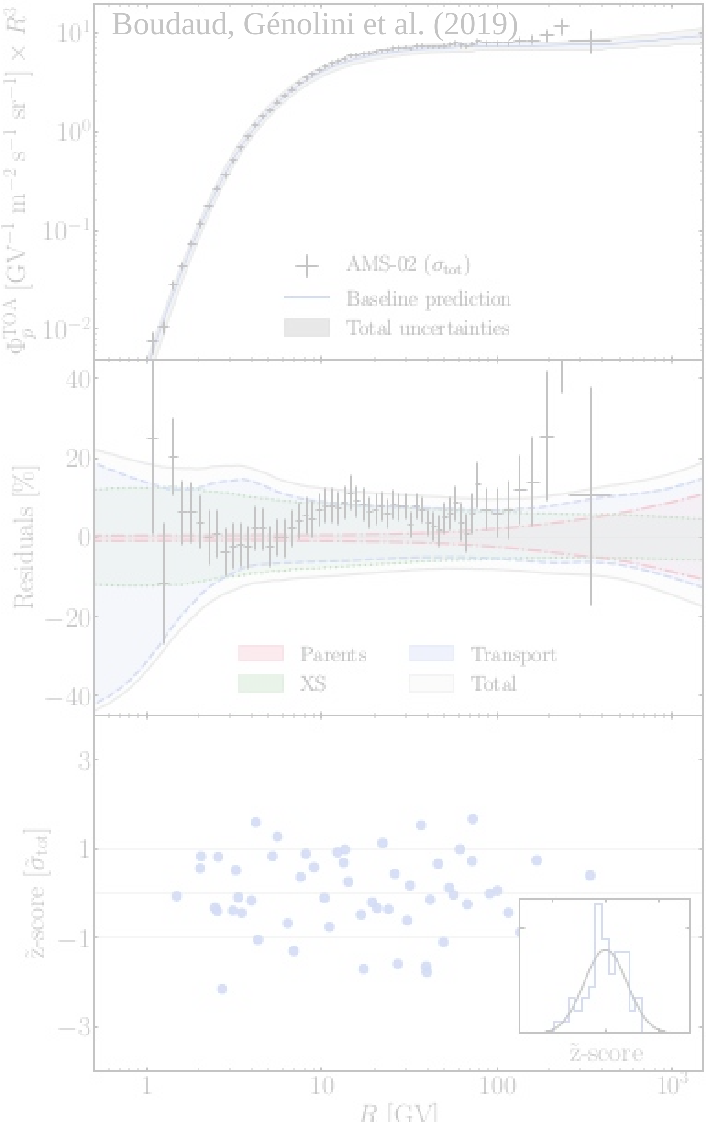
Dark matter detection with AMS-02?

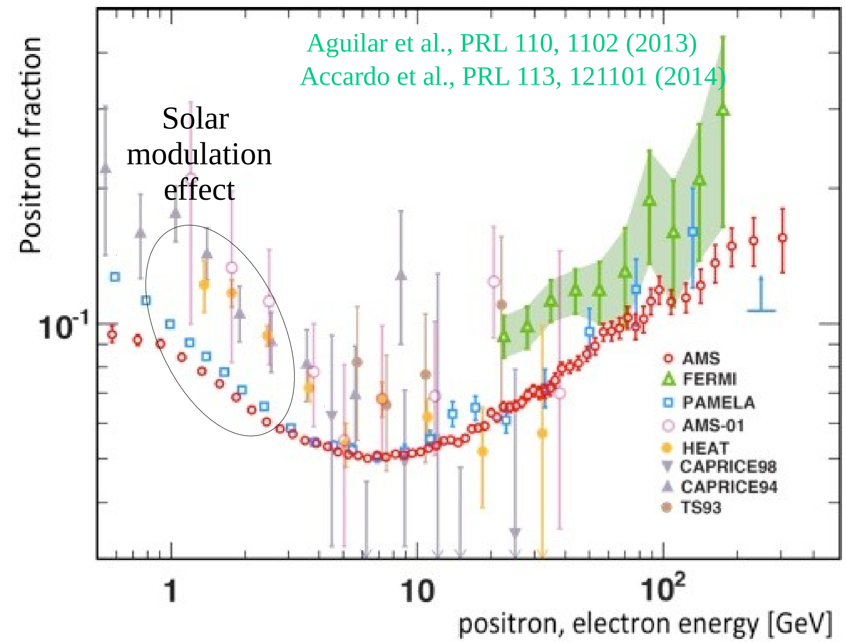


Antiprotons

→ Seems consistent with astrophysics only
→ Several groups working on X-sections

Dark matter detection with AMS-02?





Positron fraction, e^-, e^+ and e^-+e^+ spectra used to test astrophysical and/or dark matter hypothesis

- Contribution from local SNRs/pulsars?
  → e.g., Delahaye et al., A&A 524, A51 (2010)
- Dark matter hypothesis?
  → e.g., Boudaud et al., A&A 575, 67 (2015)
  [N.B.: no boost, Lavalle et al., A&A 479, 427 (2008)]

N.B.: see also e- and e+ in Aguilar et al., PRL 113, 121102 (2014)

Antiprotons

→ Seems consistent with astrophysics only
→ Several groups working on X-sections

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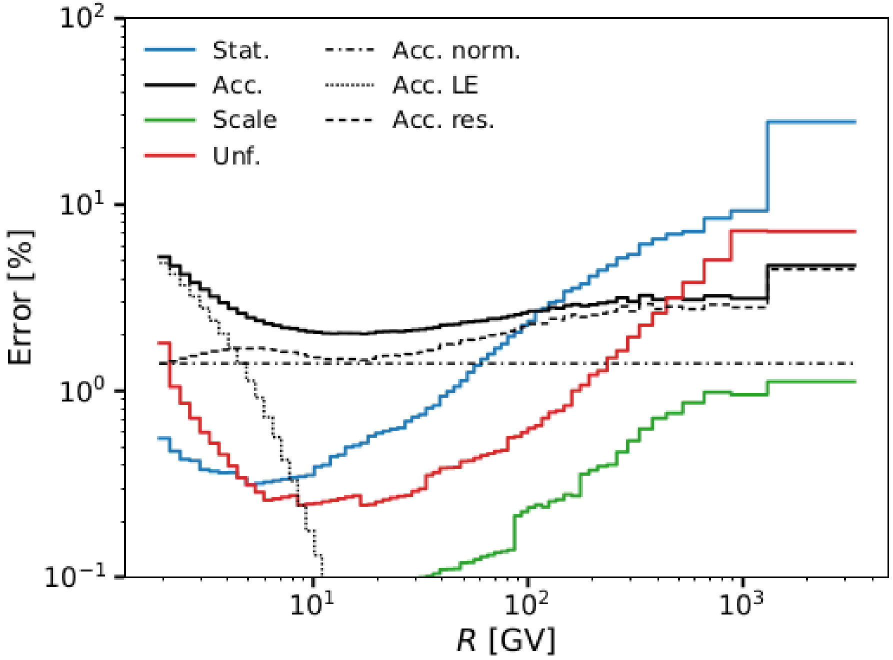
How to analyse high-precision data?

New generation of experiments (e.g., AMS-02)
→ percent-level precision + systematic-dominated



Methods used to constrain models with these data should be updated
→ improved model precision: boundary condition, numerical stability, etc.
→ critical ingredients: cross sections, data systematic uncertainties, solar modulation

$$\chi^2 = \sum_{i,j=1}^{n_E,n_E} (\text{data}_i - \text{model}_i)\,(C^{-1})_{ij}\,(\text{data}_j - \text{model}_j) + \sum_t \mathcal{N}^t + \mathcal{N}$$

Account for
correlated uncertainties
→ *requires covariance matrix!*

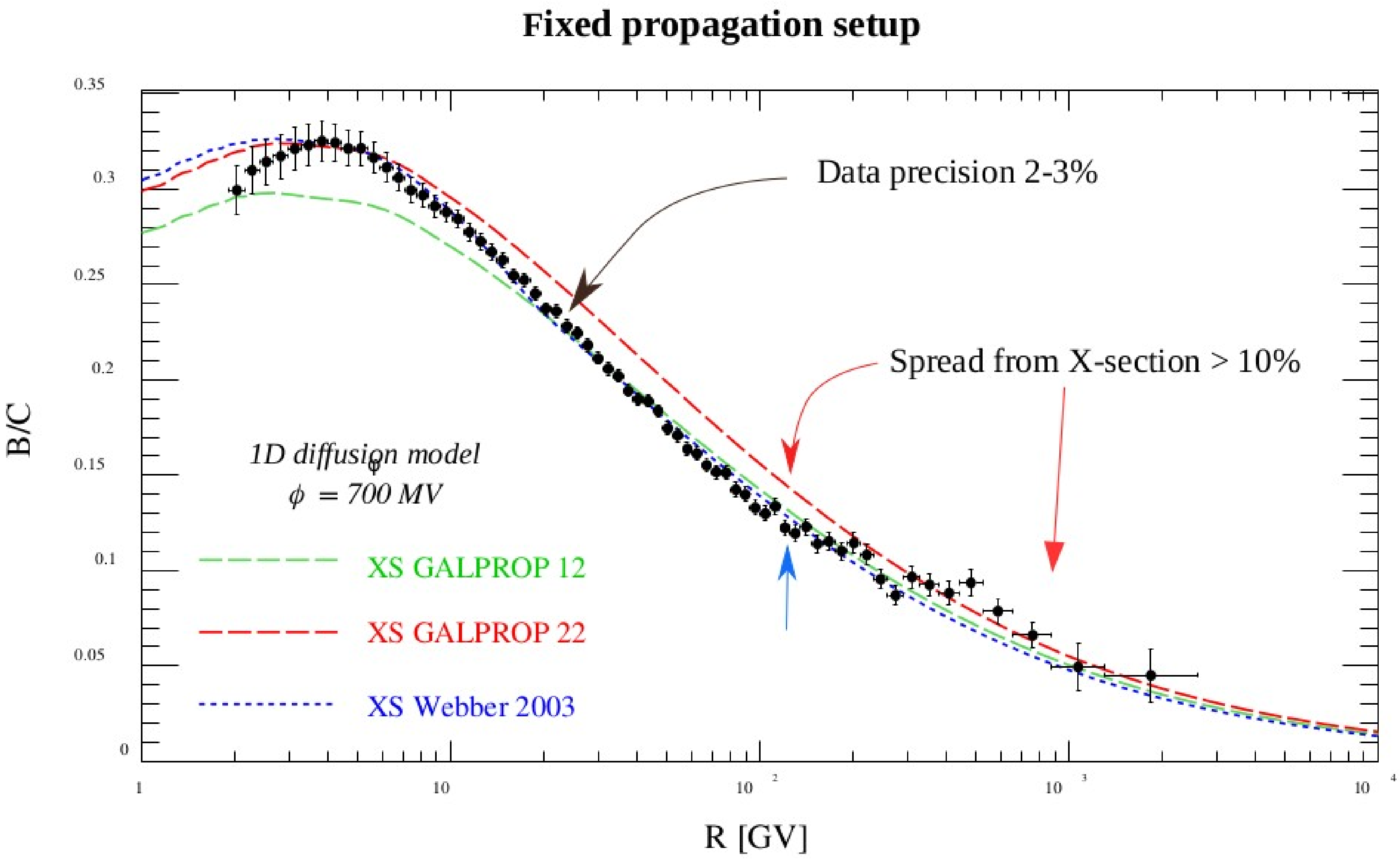
Penalty for nuisance parameters
(solar modulation level, cross sections)
→ *requires prescriptions*

$$\mathcal{N} = \frac{(y-\bar{y})^2}{\sigma_y^2}$$

Impact of XS uncertainties

Systematics from XS dominate over data CR uncertainties

(e.g., Maurin, Putze, and Derome, A&A 516, 67 (2010))



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Break 1: production in source (nested leaky box)?

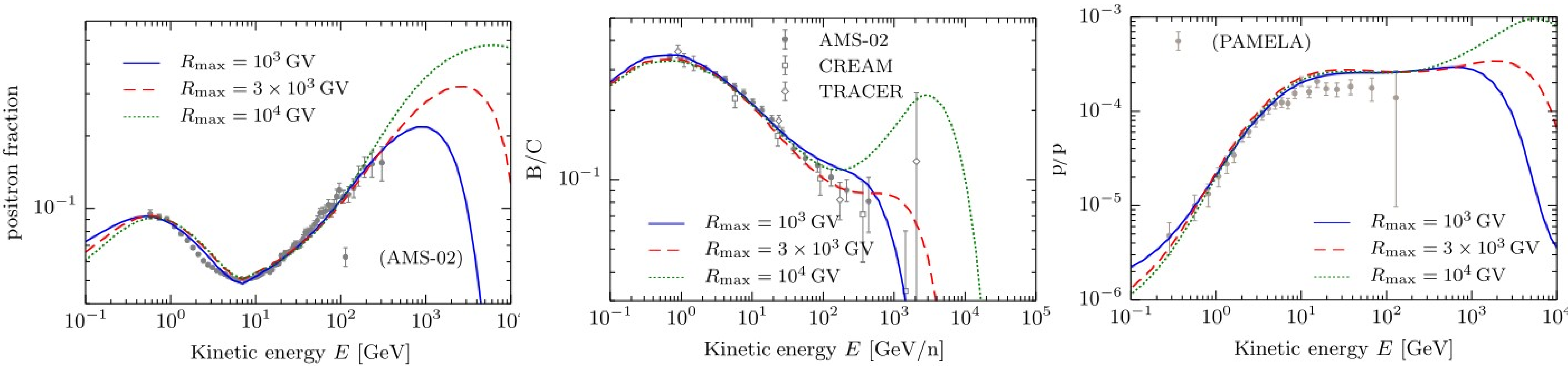
N.B.: modern version of nested leaky box developed in the 70's (residual grammage)
[e.g., Coswik, ARNPS 66, 297 (2016) for an historical review of his work..]

- Primary species $\propto$ $R^{-(\alpha+\delta)}$
- Secondary species $\propto$ $R^{-(\alpha+2\delta)}$

\+ secondary produced in source $\propto$ $R^{-(\alpha+\delta)}$

- Berezhko *et al.*, A&A **410**, 189 (2003)
- Blasi, PRL 103, 051104 (2009); Blasi & Serpico, PRL 103, 1103 (2009)
- Ahlers, Mertsch, Sarkar, PRD 80, 123017 (2009); Mertsch & Sarkar, PRL 103, 081104 (2009), PRD 90, 061301 (2014)
- Cholis & Hooper, PRD 89, 043013 (2014)
- Tomassetti & Donato, A&A 544, 16 (2012), ApJ 803, L15 (2015); Tomassetti, PRD 92, 063001 (2015)
- ...

Mertsch & Sarkar, PRD 90, 061301 (2014)



There is most certainly production at source at some stage...
→ which level (and relative level of species), which energy range?
[debated whether only part or all of the positron fraction rise can be explained]

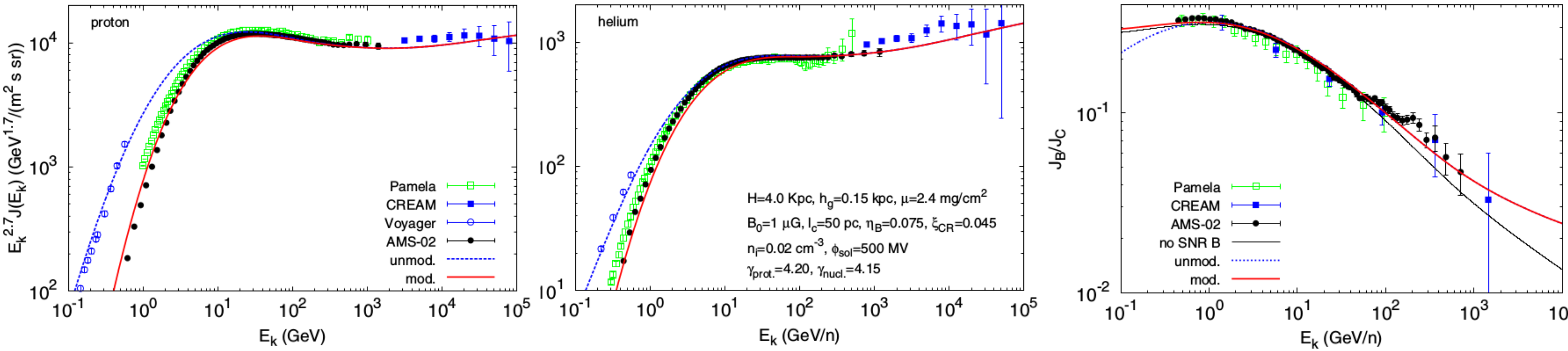
Break 2: spatial-dependent diffusion coefficient?

N.B.: Different diffusion coefficient in the disk and halo
[self-generated turbulence vs pre-existing turbulence,
or different damping mechanisms in different medium?]

$K_{disc} \propto R^{\delta 1}$
$K_{halo} \propto R^{\delta 2}$

- Blasi et al., PRL 109, 61101 (2012); Aloisio & Blasi, JCAP 07, 001 (2013); Aloisio et al., A&A 583, A95 (2015)
- Evoli & Yan, ApJ 782, 36 (2014)
- Tomassetti, ApJ, 715, L13 (2012); PRD 92, 1301 (2015); Feng et al., PRD accepted (2016)
- Guo, Tian, Jin, ApJ 819, 54 (2016)

Aloisio et al., A&A 583, A95 (2015)



- <u>p and He ‘break’</u>: region where self-generation of waves < pre-existing turbulence (similar spectral break expected for C, O...)

- <u>Difference in spectral slope</u>: attributed to differences in acceleration/injection

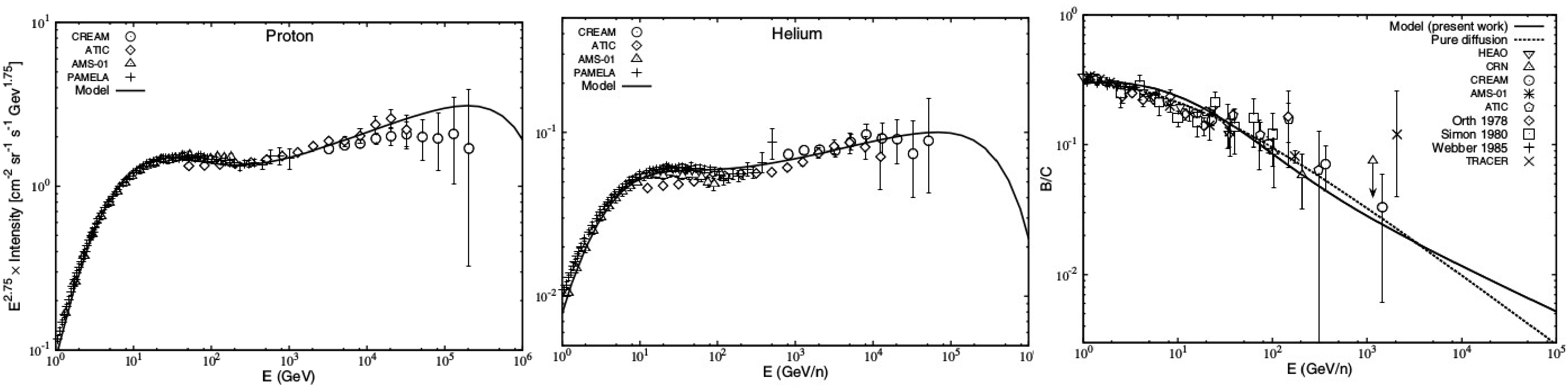
[but disputed by other others, e.g. Yan (advocate medium-dependant damping)]

Break 3: other ideas?

N.B.: Reacceleration, local sources, multiple spectra...

- Local sources: Thoudam & Hörandel (2012, 2013); Bernard et al., A&A 555, 48 (2013), ...
- Multi-sources: Biermann et al., ApJ 725, 184 (2010); Ohira & Ioka, ApJ 729, 13 (2011)...
- Source spectrum: Malkov et al., Phys.Plas 19, 082901 (2012), Ptuskin et al., ApJ 763, 47 (2013); Bell, MNRAS 447 (2224 (2015)...
- Reacceleration: Wandel et al., ApJ 316, 676 (1987); Thoudam and Hörandel, A&A 567, A33 (2014)
- ...

Thoudam and Hörandel, A&A 567, A33 (2014)



→ Many other possibilities…
(some less 'natural' than others)

Spatial and temporal discreteness of sources

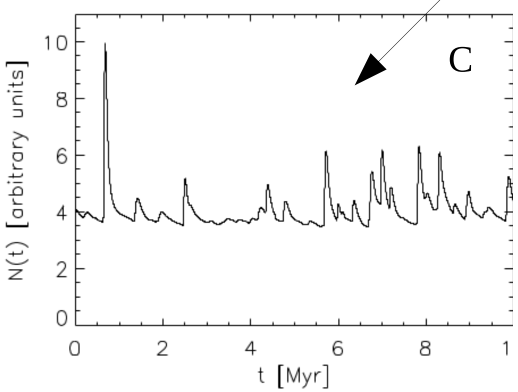
N.B.: spatial and temporal discreteness

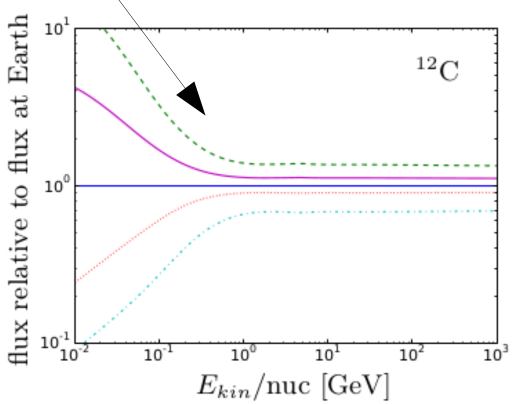
[variability of position/time/spectrum per CR source → break-down of average calculation]

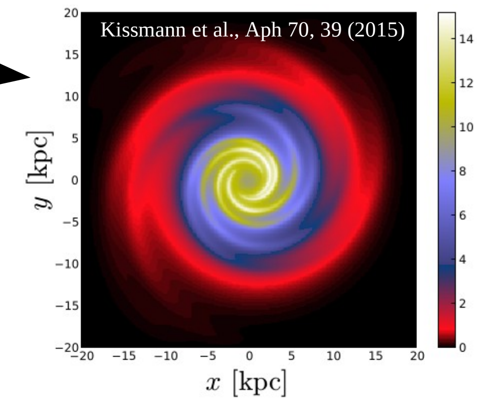
<u>Influence of spiral arm structure</u>: Büshing et al., ApJ 619, 314 (2005); Effenberger et al., A&A 547, 120 (2012); Gagerro et al., PRL 111, 1102 (2013); Kopp et al., NewA 30, 32 (2014); Benyamin, ApJ 782, 34 (2014), ApJ 826, 47 (2014); Gaggero et al., PRD 89, 083007 (2014); Kissmann et al., Aph 70, 39 (2015), Werner et al., APh 64, 18 (2015)...

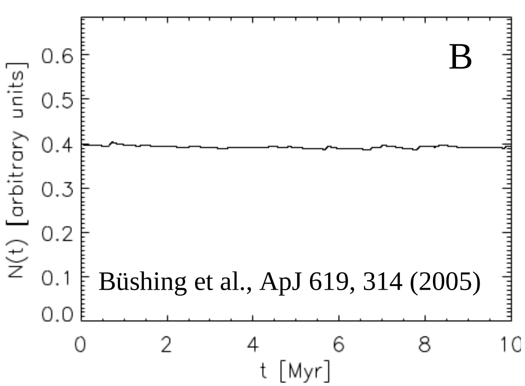
<u>Effect of stochastic sources</u>: Lee, ApJ 229, 424 (1979), Higdon & Lingenfelter, ApJ 582, 330 (2003), Taillet et al., ApJ 609, 173 (2004), Mertsh JCAP 02, 031 (2010), Thoudam & Hörandel, MNRAS 421, 624+1209 (2012); Bernard et al., A&A 544, 92 (2012), Génolini et al., A&A 600, 68 (2017)...

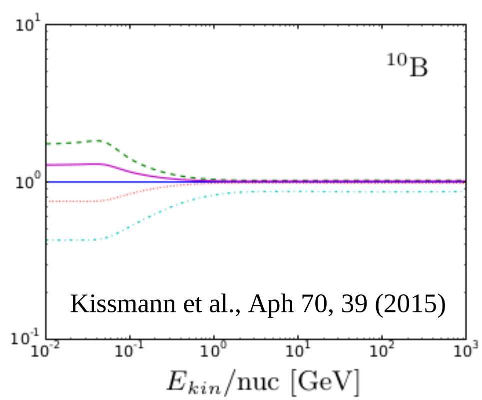
<u>Single source</u>: Erlykin & Wolfendale (1997…); Kachelrieß et al., PRL 115, 181103 (2015); Tomassetti et al. ApJL 815, 1 (2015)...











→ Local spectra may be different everywhere else in the Galaxy (important for γ-rays)

5. Departure from ‘standard’: discreteness of sources

N.B.: spatial and temporal discreteness

[variability of position/time/spectrum per CR source → break-down of average calculation]

Influence of spiral arm structure: Büshing et al., ApJ 619, 314 (2005); Effenberger et al., A&A 547, 120 (2012); Gagerro et al., PRL 111, 1102 (2013); Kopp et al., NewA 30, 32 (2014); Benyamin, ApJ 782, 34 (2014), ApJ 826, 47 (2014); Gaggero et al., PRD 89, 083007 (2014); Kissmann et al., Aph 70, 39 (2015), Werner et al., APh 64, 18 (2015)...

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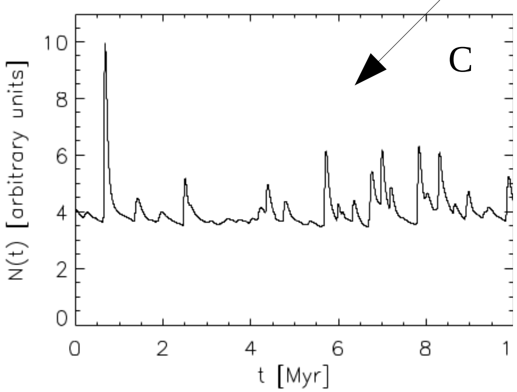
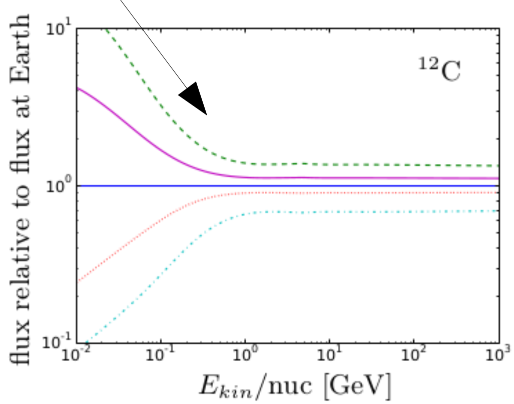
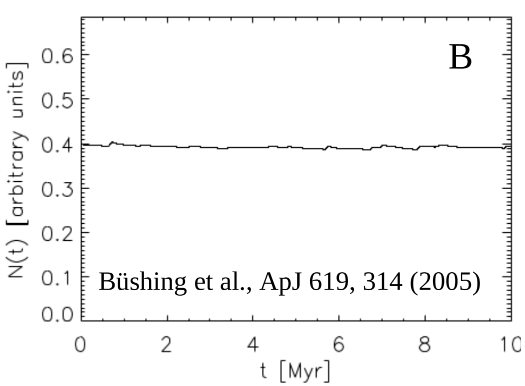
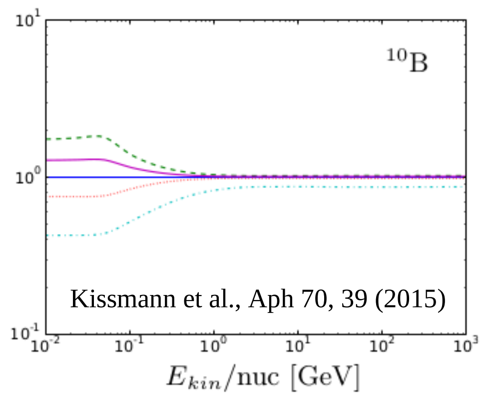
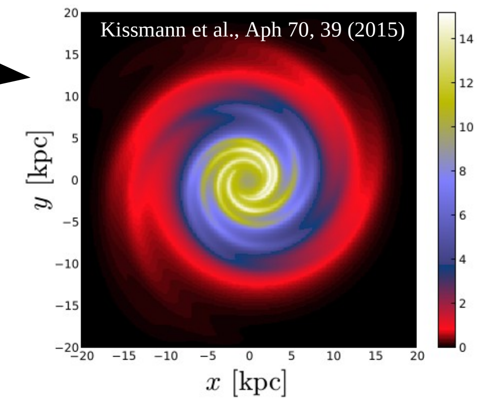


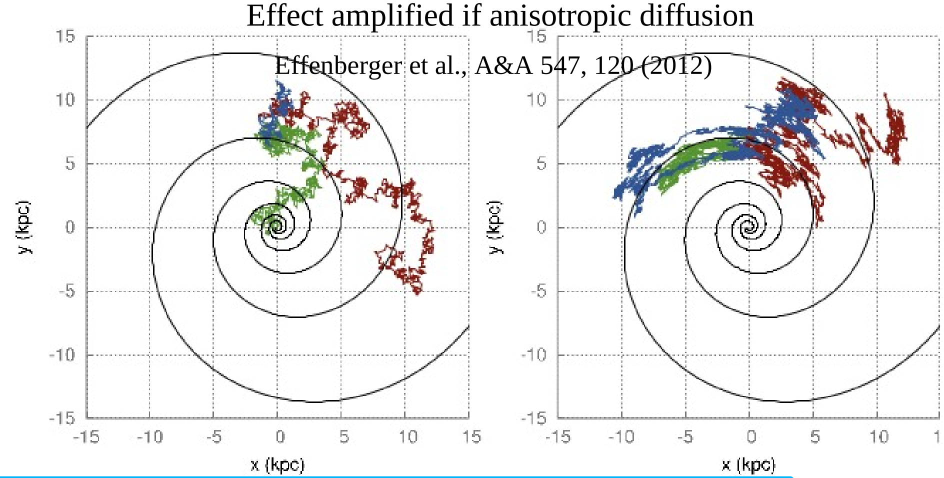








Effect amplified if anisotropic diffusion



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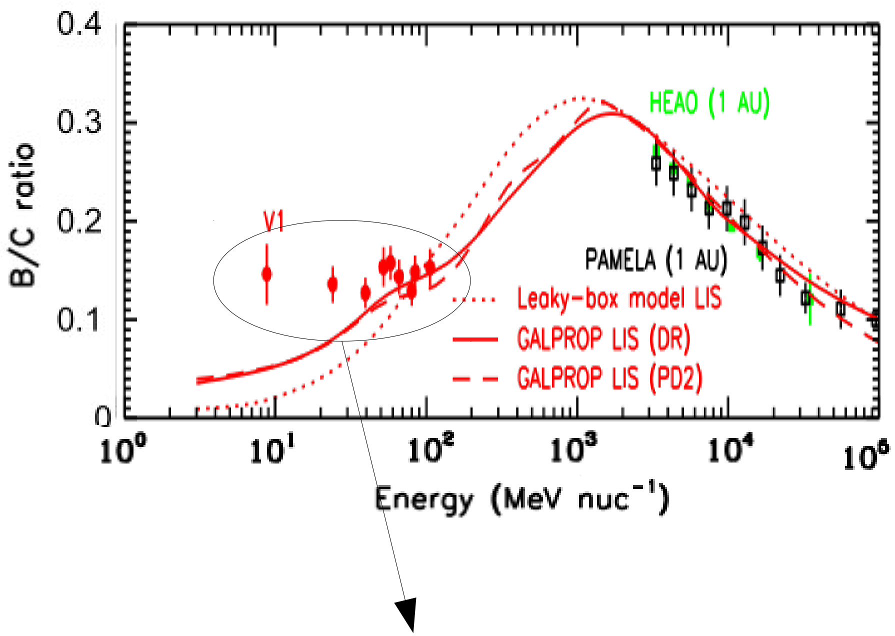
Low-energy data

Voyager IS data

Stone et al., Science 341, 150 (2013)
Cummings et al., ApJ 831, 18 (2016)

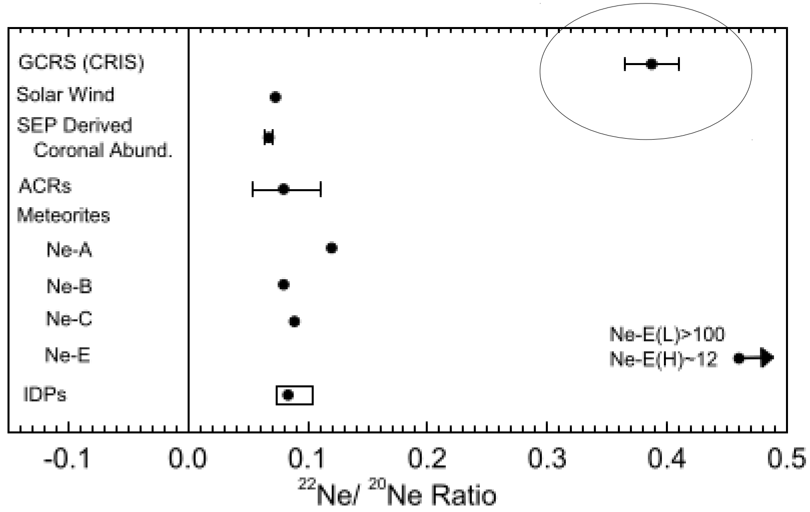


B/C not compatible with current models

→ light isotopes soon from Voyager (and Voyager 1)

→ Anomalies in isotopic abundances

Binns et al., ApJ 634, 361 (2005)



Excess ~ 5 times Solar System abundances

[Wolf-Rayet stars (evolutionary products of OB stars) in OB associations that form superbubbles]

→ Part of CRs from superbubbles?

The local interstellar medium (LISM) puzzle

→ Nearby SN events

Fields et al., Astro2020 Science White Paper

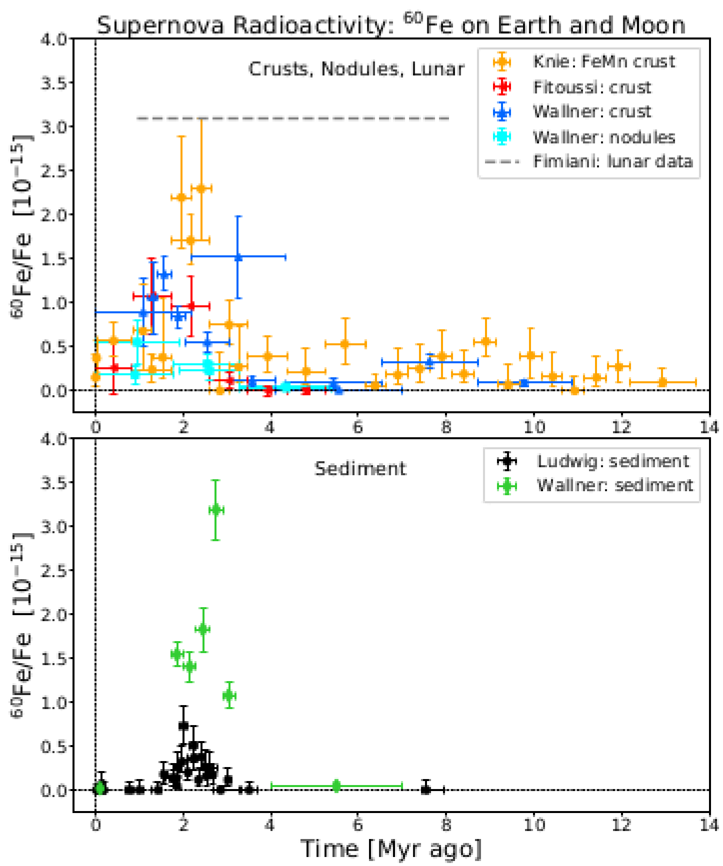
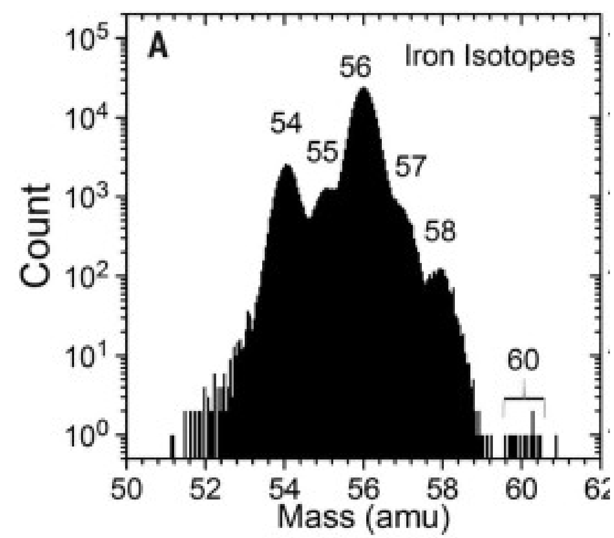


Figure 1: Global and lunar detections of ^{60}Fe, not corrected for decay. All data show a signal around ∼2–3 Myr. Amplitude differences may reflect iron uptake variations, or latitude variations in iron fall-out. *Upper panel:* ^{60}Fe/Fe ratios in deep-ocean Fe-Mn crusts. *Lower panel:* ^{60}Fe/Fe in deep-ocean sediments, showing signal duration $\gtrsim$ 1 Myr. Data: refs. [40, 23, 70, 22, 46].

→ ^{60}Fe also in CRs

Binns et al., Science 352, 677 (2016)



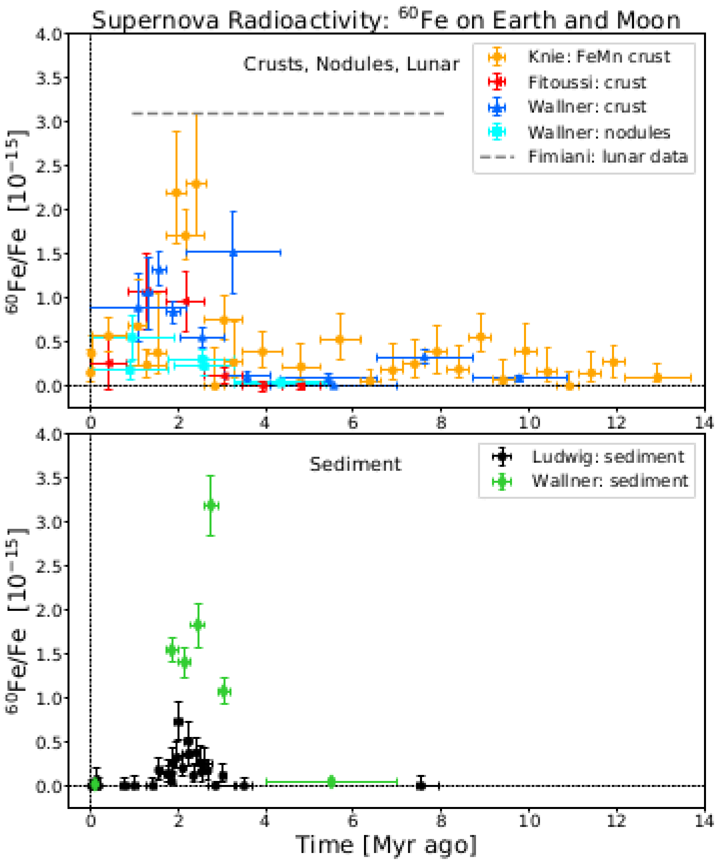
→ time for acceleration and transport to Earth does not greatly exceed the 2.6 Myr (^{60}Fe half-life)

→ source distance does not greatly exceed ≲1 kpc

The local interstellar medium (LISM) puzzle

→ Nearby SN events

Fields et al., Astro2020 Science White Paper



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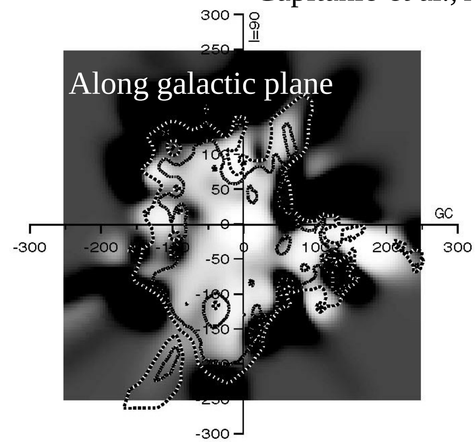
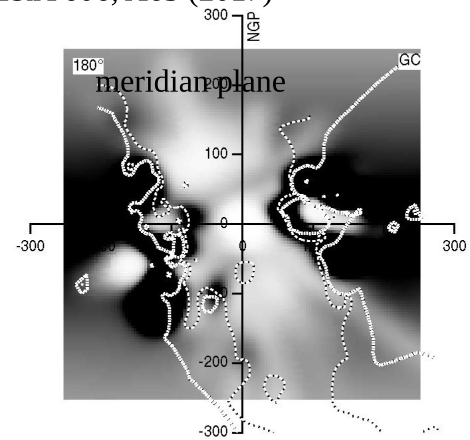
→ LISM origin...

NaI absorption measurements (5890 Å)
Lallement et al., A&A 411, 447 (2003)
Welsh et al., A&A 510, A54 (2010)
Capitanio et al., A&A 606, A65 (2017)





→ 20 SN explosions during the past 10-20 Myr (age of the local bubble)

→ 1 more SN ~ 1 Myr ago?
(as close as ~ 40 pc, related to Pliocene-Pleistocen extinction?)

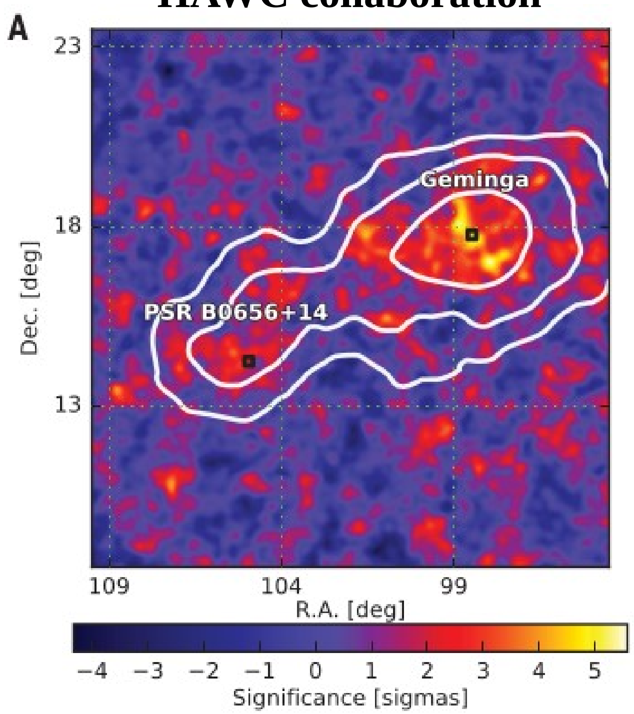
Maíz-Apellániz, ApJ **560**, L83 (2001)
Berghöfer & Breitschwerdt, A&A **390**, 299 (2002)
Benítez et al., PRL **88**, 081101 (2002)

→ Impact on CR fluxes?

HAWC, local diffusion, and back to leptons...

→ Extended γ-ray emission around pulsars

Abeysekara et al., Science 358, 911 (2017)
HAWC collaboration



Di Mauro, Manconi, Donato, arXiv:190305647
Fermi-LAT data

→ 7.8 − 11.8σ significance around Geminga
→ Geminga pulsar proper motion detected

→ Pockets of "inefficient" diffusion ($D_{pocket} << D_{halo}$)

Hooper & Linden, PRD 98, 083009 (2018)
Profumo et al., PRD 97, 123008 (2018)

"Lessons from HAWC pulsar wind nebulae observations: The diffusion constant is not a constant; pulsars remain the likeliest sources of the anomalous positron fraction; cosmic rays are trapped for long periods of time in pockets of inefficient diffusion"

→ May further "decouples" predictions from nuclei and leptons...

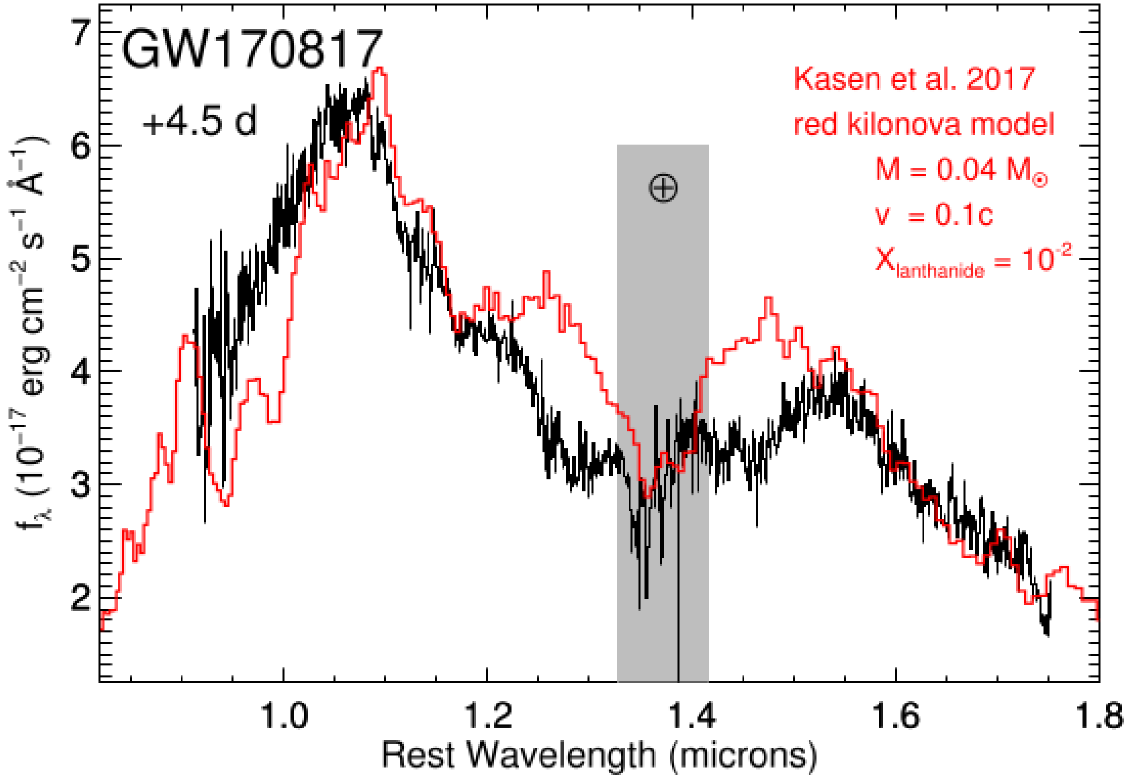
Super-heavy CRs and gravitational waves

Light curve properties and time evolution of binary neutron star merger

→ Early emission (blue KN, ~0.3 $M_\odot$ ejecta @ 0.3c,): lanthanide<10^{-4}% → light r-process (A<140)
[Nicholl et al., ApJL 848, 18 (2017)]

→ Late emission >2.5 d (‘red KN’, 0.04 $M_\odot$ ejecta @ 0.1c, lanthanide~10^{-2} % → heavy r-process
[Chornock et al., ApJL 848, 19 (2017)]

→ Favours NS merger as major contributors to r-process nucleosynthesis!



The Emergence of a Lanthanide-rich Kilonova Following the Merger of Two Neutron Stars

Conclusions

→ Lot of recent advances (experiments, simulations, theory)

→ We are getting closer to a more detailed understanding of GCRs

… but lots of plausible subtleties (inhomogeneity, space-time granularity, …)
and many complications in modelling and interpretation of high-precision data!