GeV-TeV Galactic Cosmic Rays (GCRs)

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101 years since Hess's discovery

Milestones (Galactic CRs):

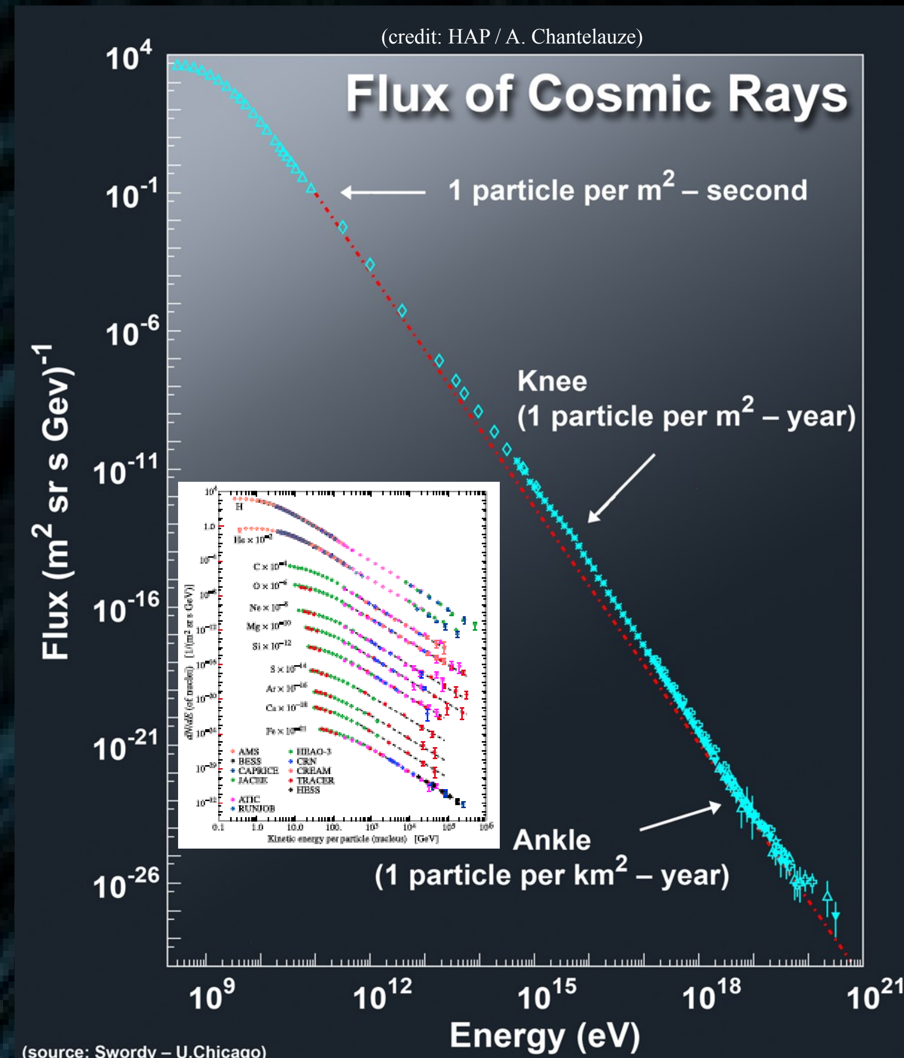
1912: Hess's balloon flights (also Wulf, Pacini)
1932: positron discovery in CR showers (Anderson)
1936: muon (Anderson & Neddermeyer)
1947: pion (Powell), kaon (Rochester & Butler)
1950's: first particle accelerators

1934: Baade & Zwichy propose SNRs as sources
1948: Fermi acceleraction mechanism

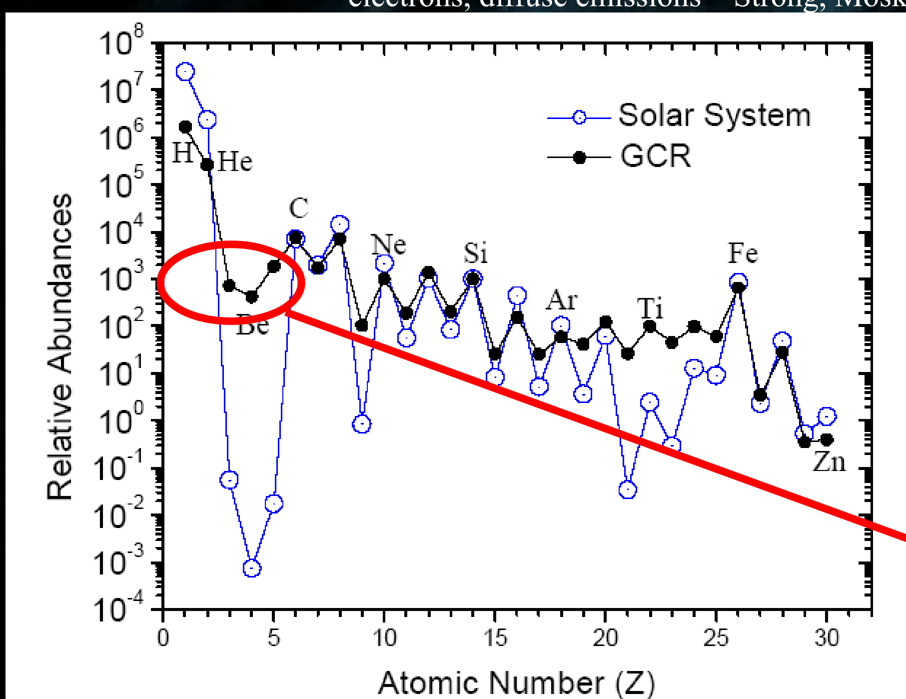
1969: positron fraction spectrum (Fanselow++)
1979: antiproton CRs (…)

1960's: Leaky Box (exponential path length distribution)
1964: Ginzburg & Syrovatskii: Origin of CRs
1970's: validity and limits of LB models

1990's: attempts to build complete models (nuclei, electrons, diffuse emissions – Strong, Moskalenko ++)



Power-law spectra observed for all species.
=> similar acceleration mechanisms efficient in a very large energy range



Some cosmic rays are not produced in stars, eg LiBeB:
=> Secondary CRs, generated from spallation processes
CNO + Interstellar medium (ISM) → LiBeB

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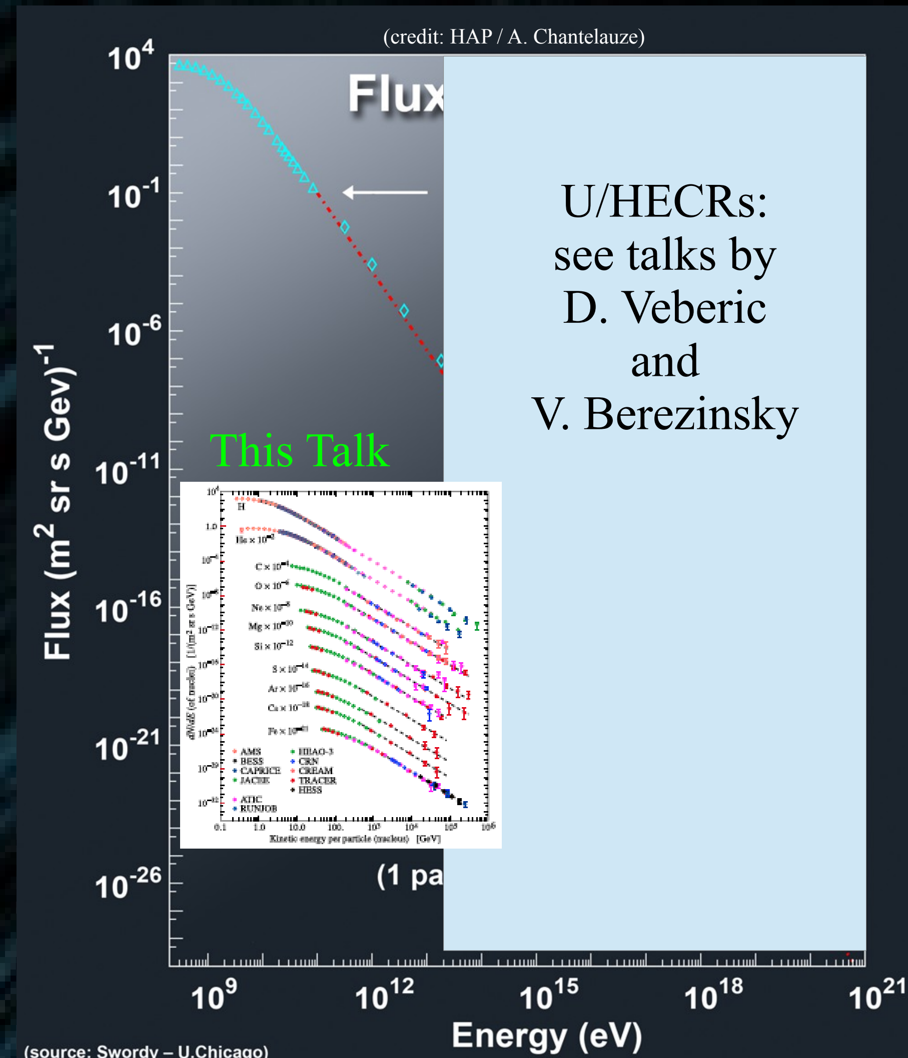

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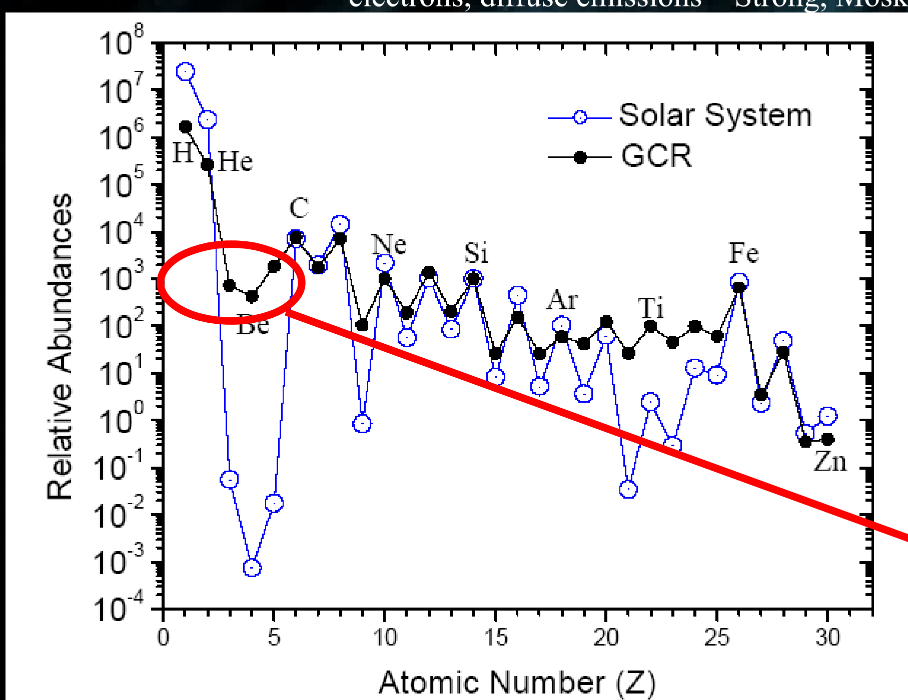

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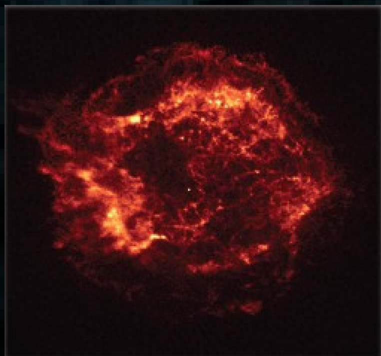
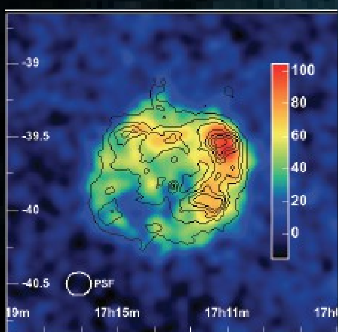
Origin of GeV-TeV GCRs



Cas A (Chandra)



RXJ1713.7-3946 (HESS)

Supernova remnants (SNRs) main origin of all primary CRs: diffusive shock acceleration (DSA – e.g. Malkov & Drury 01).
=> prediction: concave CR spectra, close to power law (~ 1st order Fermi acceleration).
=> roughly consistent with multiwalength observations (radio, X-rays, gamma-rays)
(see HESS talk by G. Vasileidadis)

Potential significant contribution of PWNe for TeV electrons/positrons.

Widely accepted as main CR sources up to 10-100 TeV, then extragalactic sources take over.

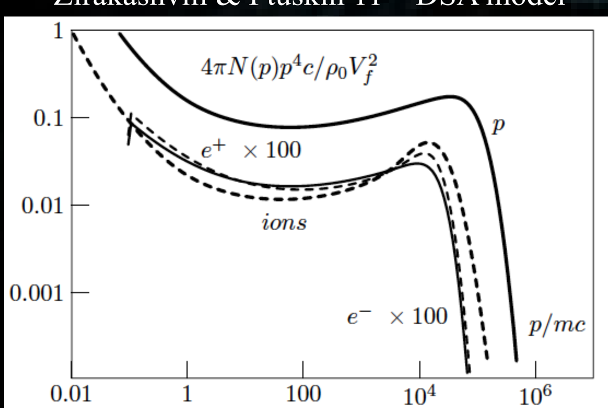
Energetics:

GCR energy density ~ 0.3 eV/cm^3
Volume of confinement zone ~ π . 15^2 . (2 . 5) ~ 7000 kpc^3
Confinement time ~ 20 Myr
=> total energy ~ 5.10^54 erg/Myr
1 SNR => 10^51 erg
3 SNRs / 100 yr => 3.10^55 erg / Myr
=> ~ 1% of SNR energy supply required to explain GCR energy budget

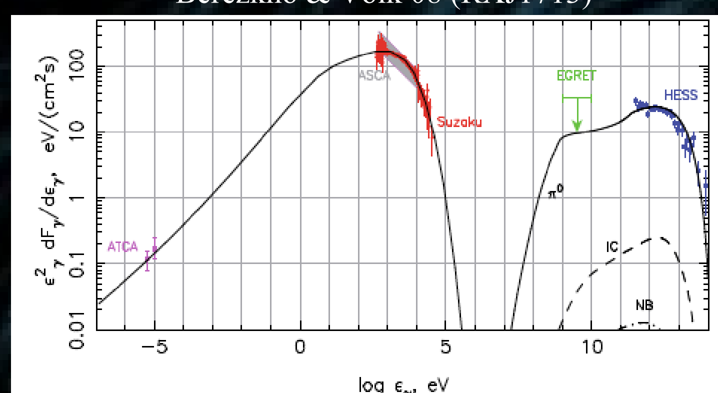
Issues:

* nuclei / electron ratio hard to predict from first principles: leptonic (inverse Compton) or hadronic (pions) gamma-rays?
* full 3D models very difficult to work out self-consistently (numerical simulations, coupled non-linear differential equations)
* escape/release in the ISM not yet completely understood

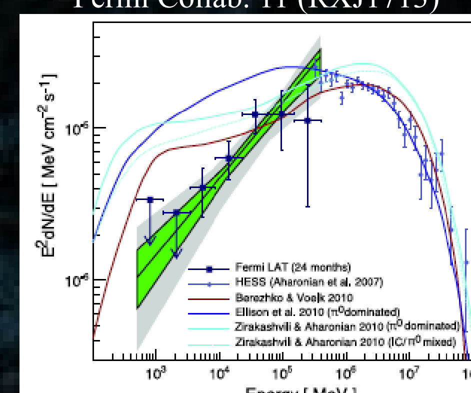
Zirakashvili & Ptuskin 11 – DSA model



Berezhko & Völk 08 (RXJ1713)



Fermi Collab. 11 (RXJ1713)



Outline

* Observations of GCRs

* Transport of CRs in the Galaxy
  - Basic features and strategy(ies) to constrain parameters
  - Where current models succeed

* Selected issues:
  - The positron excess
  - Local sources and anisotropy
  - Limits of current diffusion models

* Perspectives

Observation of GCRs

(see talks by I. Moskalenko, R. Sparvoli, R. Battiston)

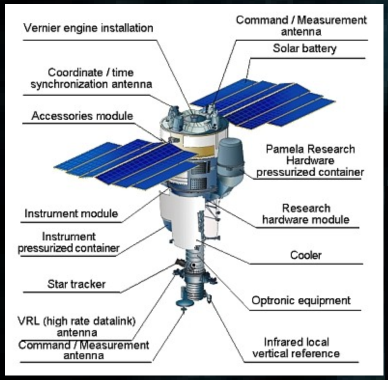
CREAM IV flight

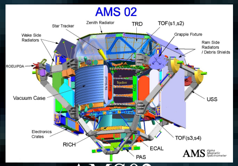
Long balloon flight history (recent e.g. HEAT, BESS, ATIC, CREAM).

Since AMS01: CRs collected in space (PAMELA, AMS02)

Techn: spectrometers, TRD, calorimeter, emulsion.

PAMELA

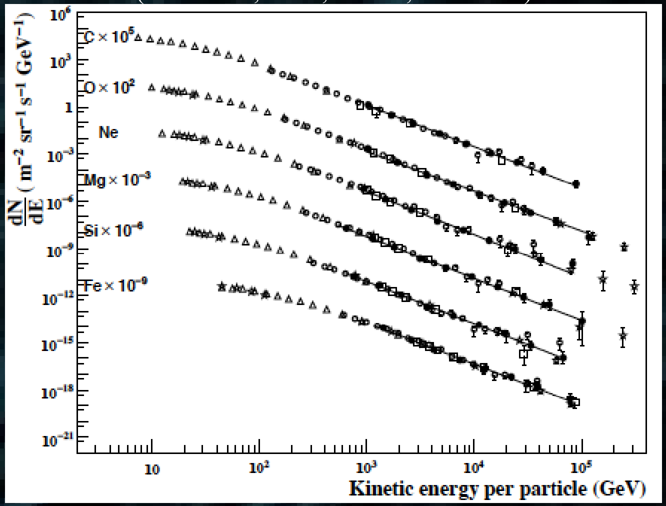




AMS02

Direct GCR measurements
=> very local information
=> translates into constraints on GCR transport models up to 5-10 kpc scale, depending on energy and species.

CREAM II (Ahn++ 09)
(+ HEAO3, CNR, ATIC2, TRACER)



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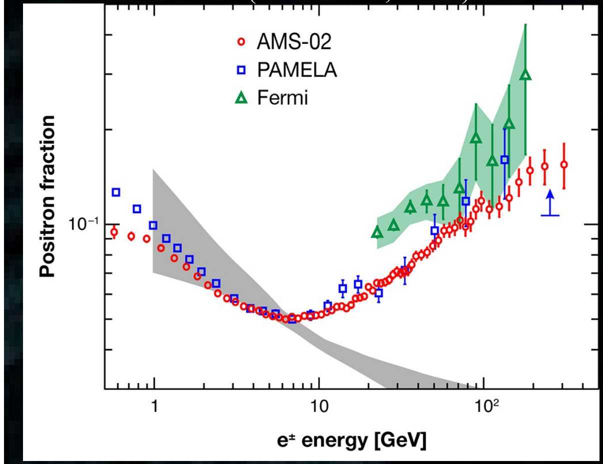
(+ PAMELA, Fermi)



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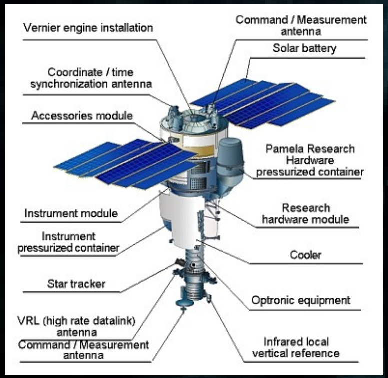

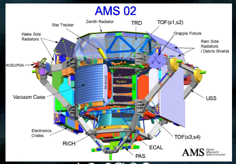

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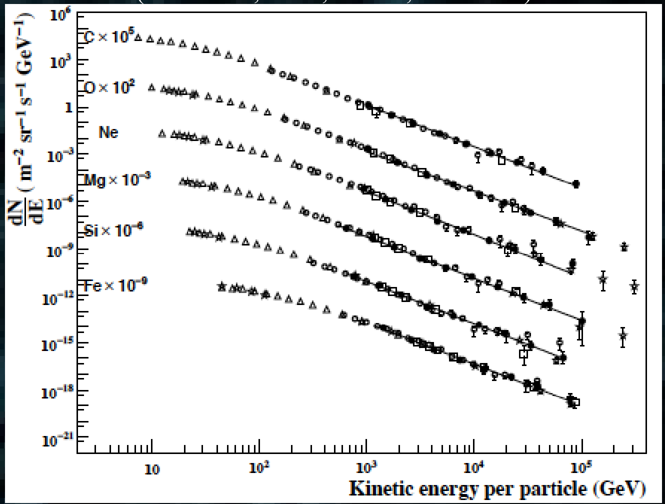

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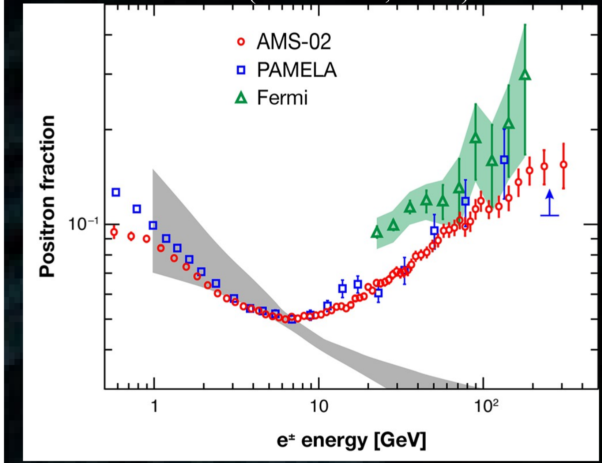


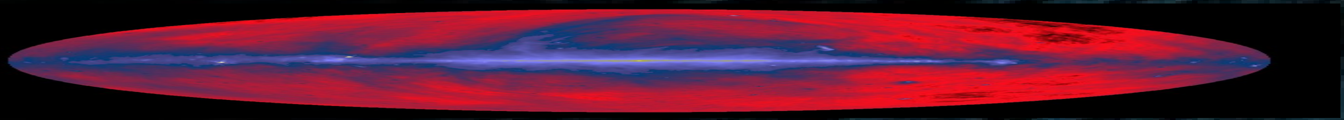
Indirect GCR measurements: diffuse electromagnetic emissions

=> line-of-sight integrated information (beware degeneracies) – Galactic scale probe

Radio: synchrotron from ~10 GeV electrons with B-field (*need 3D map of B-field*)

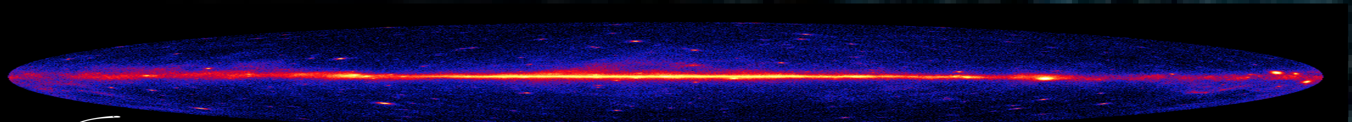
Gamma-rays: mostly p+H and inverse Compton from e- (*need 3D maps of HI, CO, interstellar radiation fields*).

Parkes radio telescope



408 MHz – Haslam++ 82

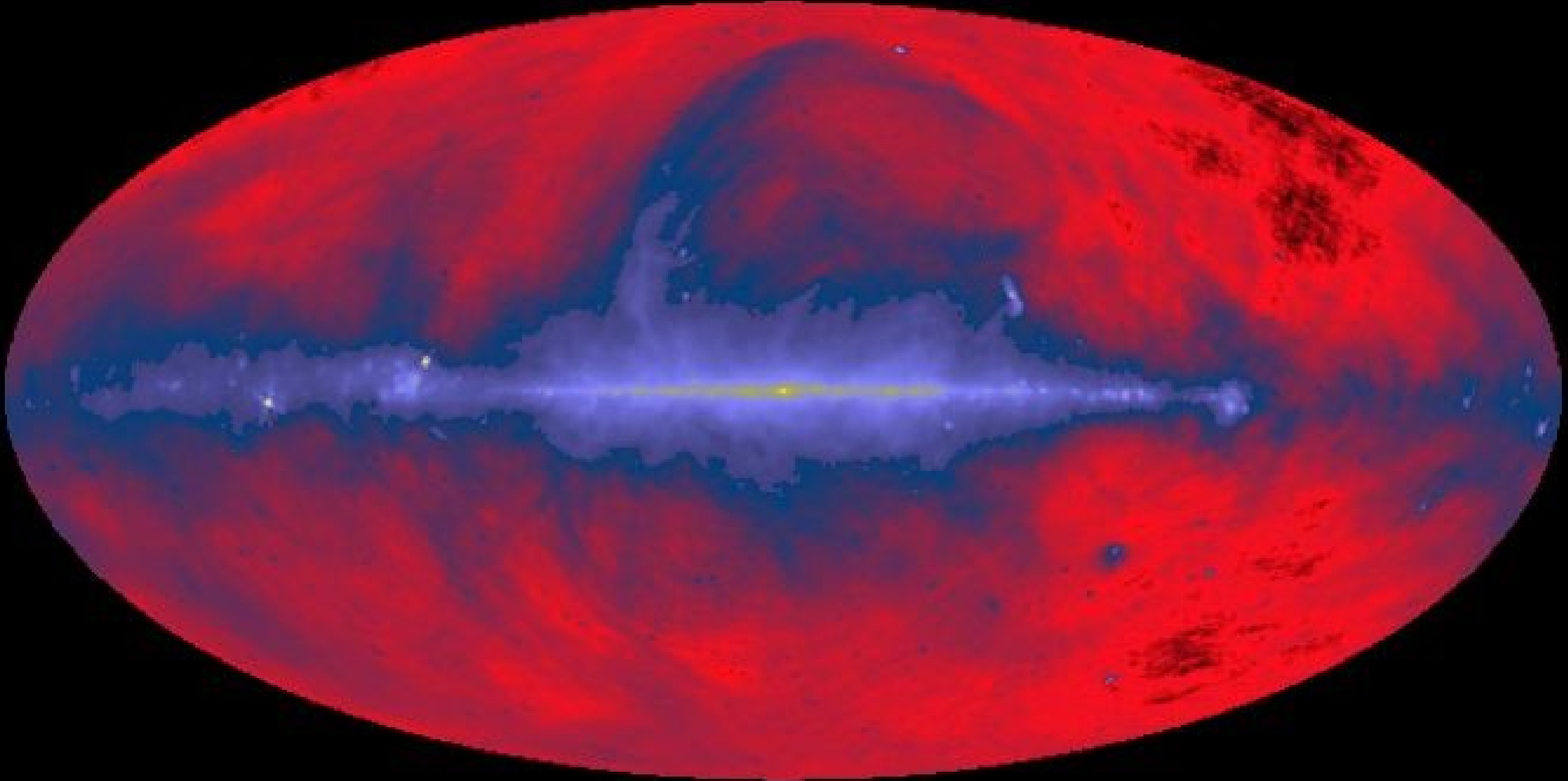
Fermi satellite



Fermi skymap

Transport of Galactic cosmic rays: The standard picture

408 MHz all-sky map



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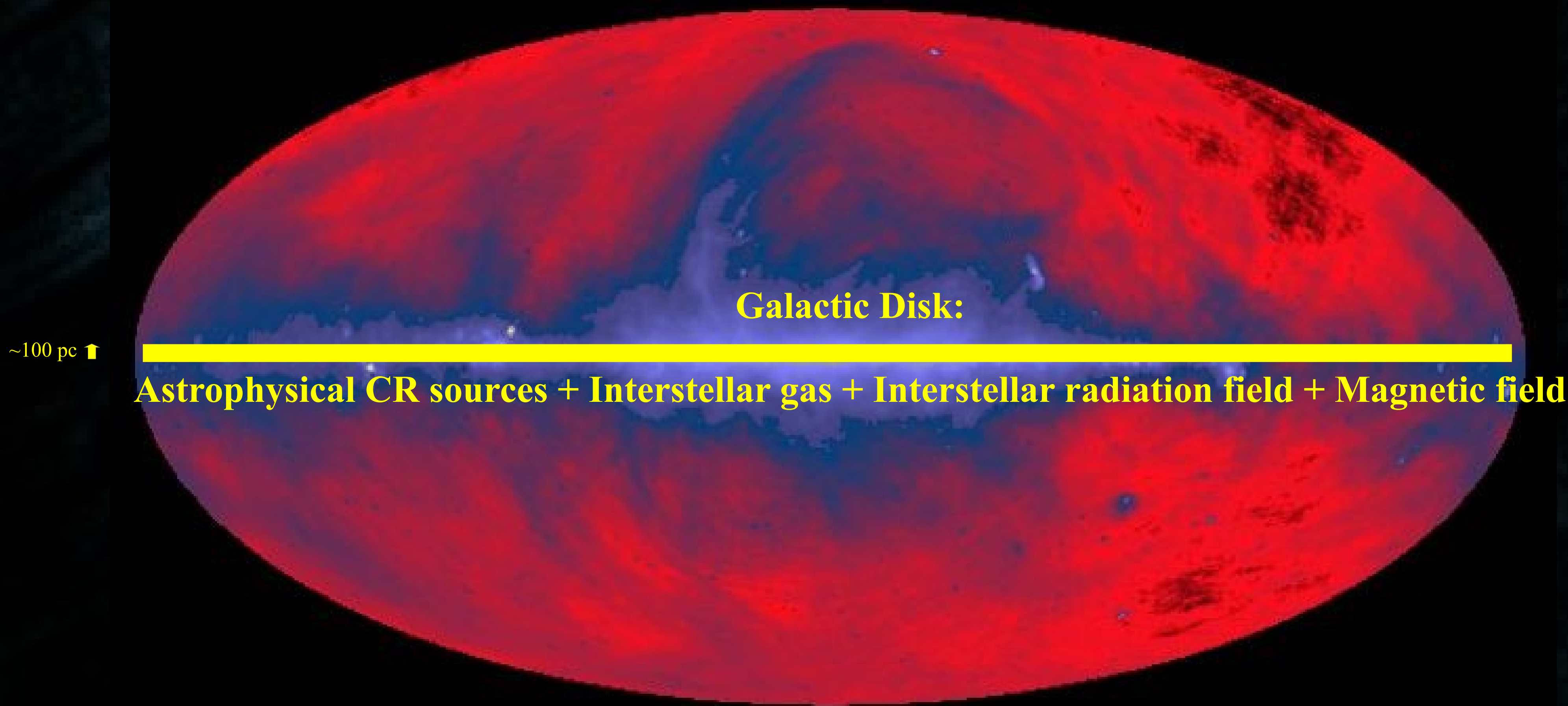

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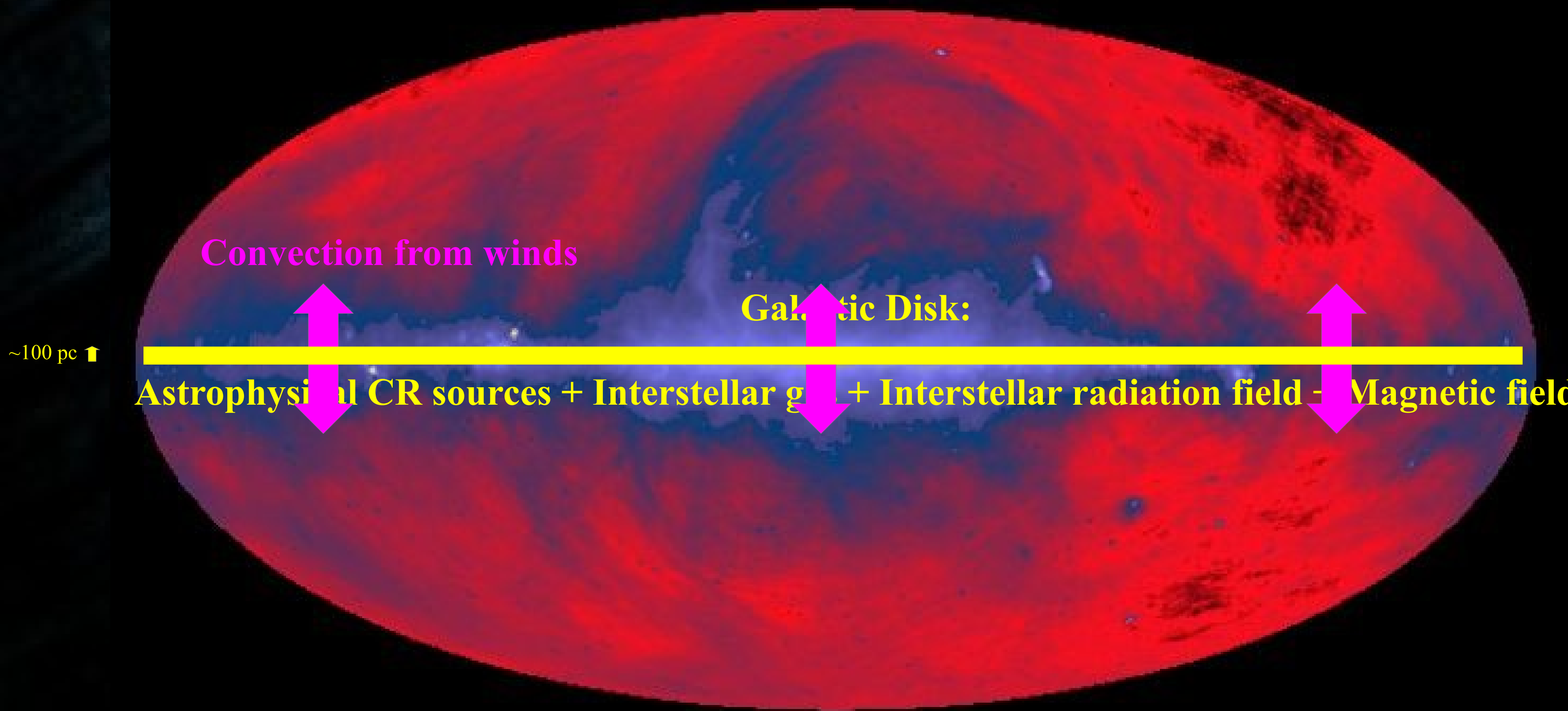

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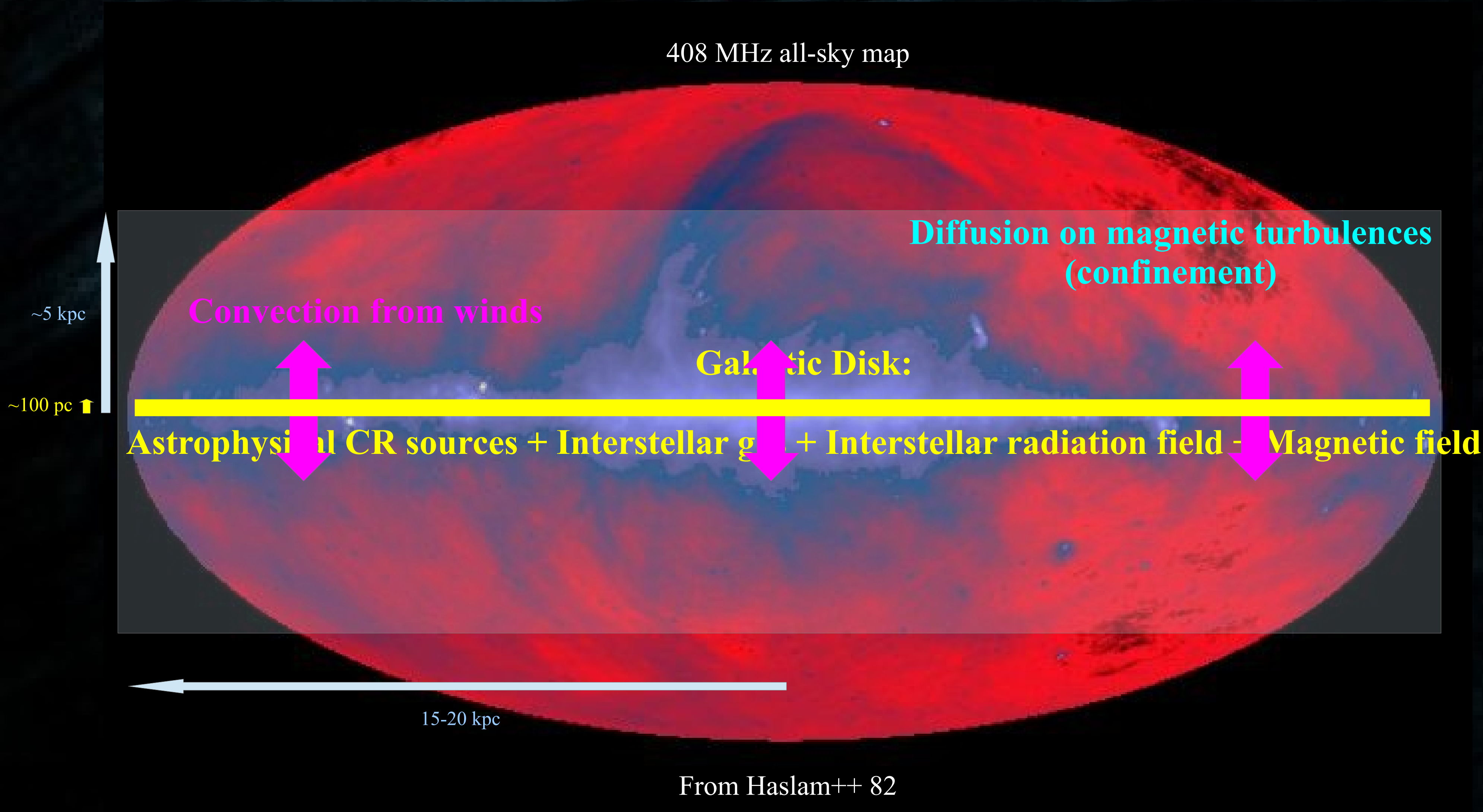

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e.g. Ginzburg & Syrovastkii 64; Berezinsky, Ptuskin++ 90; Longair 92; Schlikeiser 02

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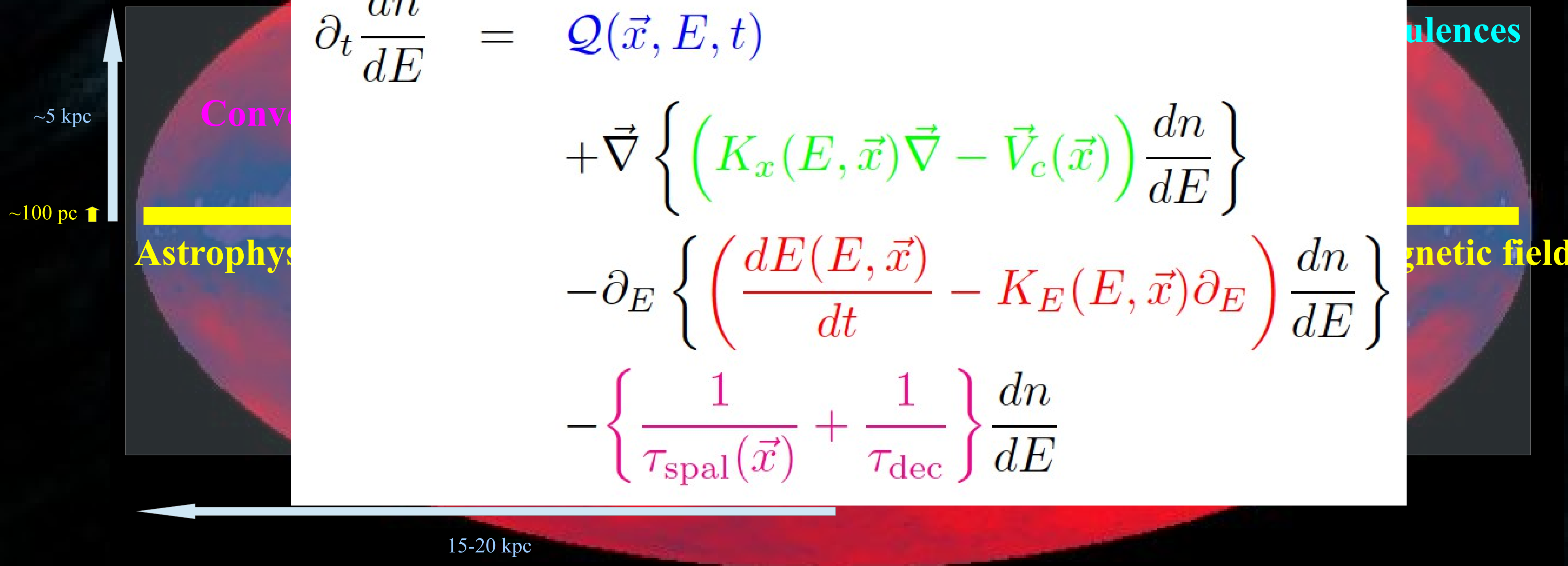

$$
\begin{aligned}
\partial_t \frac{dn}{dE} \; = \; & \mathcal{Q}(\vec{x}, E, t) \\
& + \vec{\nabla} \left\{ \left(K_x(E,\vec{x}) \vec{\nabla} - \vec{V}_c(\vec{x}) \right) \frac{dn}{dE} \right\} \\
& - \partial_E \left\{ \left(\frac{dE(E,\vec{x})}{dt} - K_E(E,\vec{x}) \partial_E \right) \frac{dn}{dE} \right\} \\
& - \left\{ \frac{1}{\tau_{\rm spal}(\vec{x})} + \frac{1}{\tau_{\rm dec}} \right\} \frac{dn}{dE}
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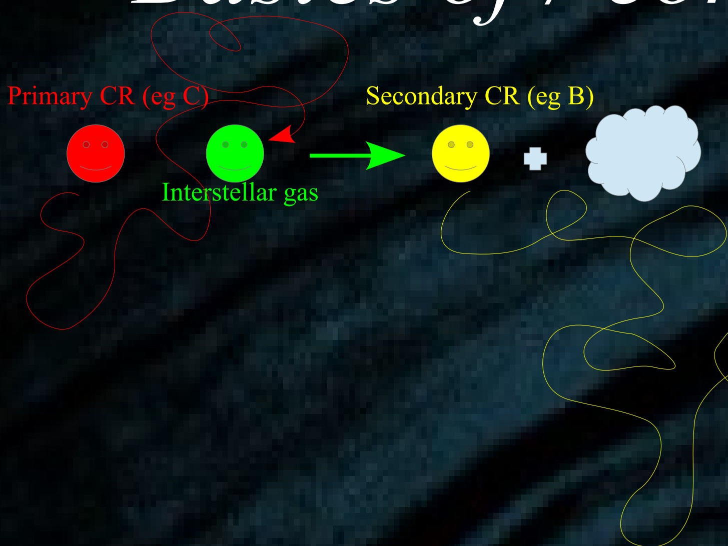
From Haslam++ 82

Basics of / constraints on transport models



Leaky Box (LB) model: the simplest approach.
* Assume steady state, forget about specific diffusion zone.
* Consider 2 timescales: escape from Galaxy + spallation timescale
=> Equilibrium equation (Ni averaged CR density for species labelled i):

$$\frac{\bar{N}_i}{\tau_{\rm esc}} + \frac{\bar{N}_i}{\tau_i} = Q_i + \sum_j \frac{\bar{N}_j}{\tau_{j\to i}}$$

Assume only 1 primary (p) and 1 secondary species (s), write down s/p:

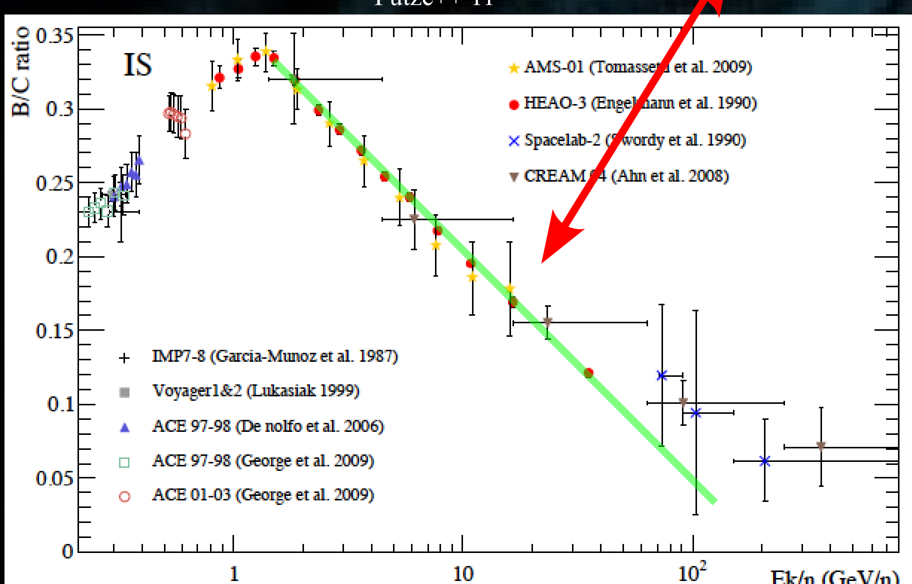
$$\frac{\bar{N}_s}{\bar{N}_p} = \frac{\tau_s\,\tau_{\rm esc}}{\tau_p\,(\tau_{\rm esc}+\tau_s)} \overset{\tau_{\rm esc}\ll\tau_s}{\longrightarrow} \frac{\tau_{\rm esc}(E)}{\tau_p}$$

Compare with data:

$$\tau_{\rm esc}(E) \propto \left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)^{-\delta}$$

~ 20 Myr (1 GeV/n)

Putze++ 11



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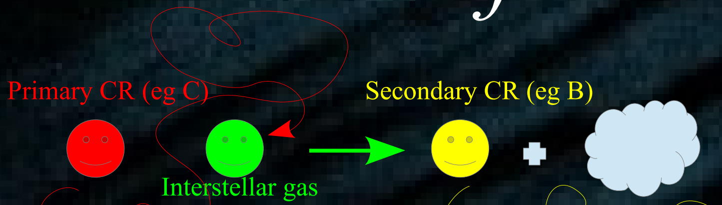

Small-scale example of a potentially leaky box ...

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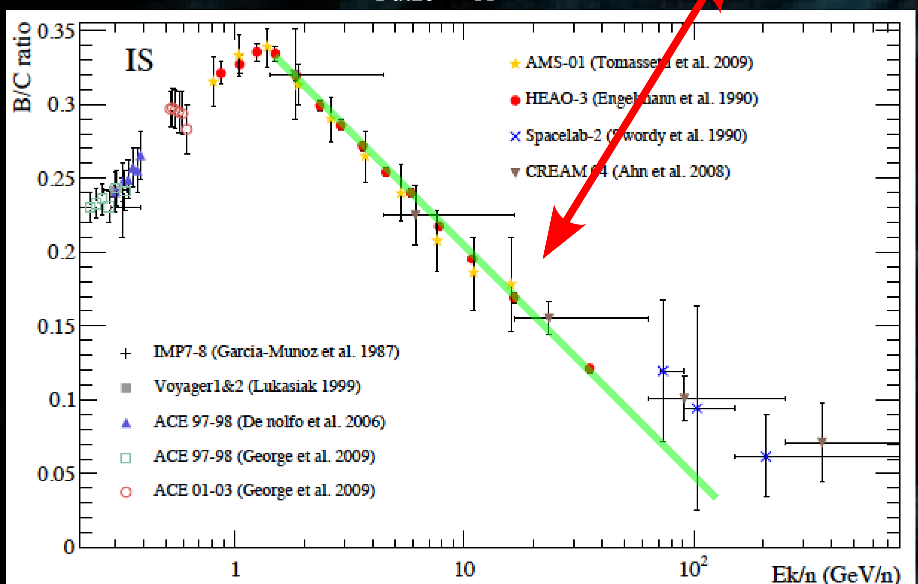

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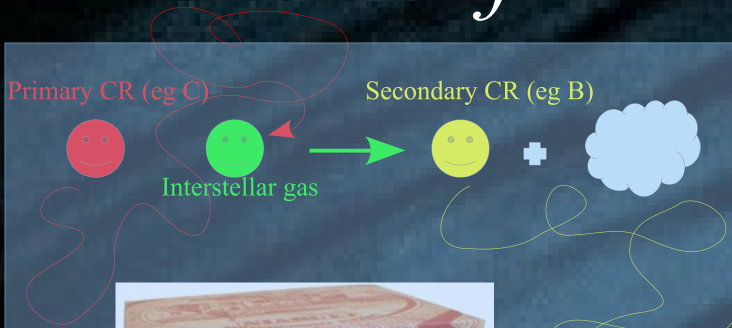

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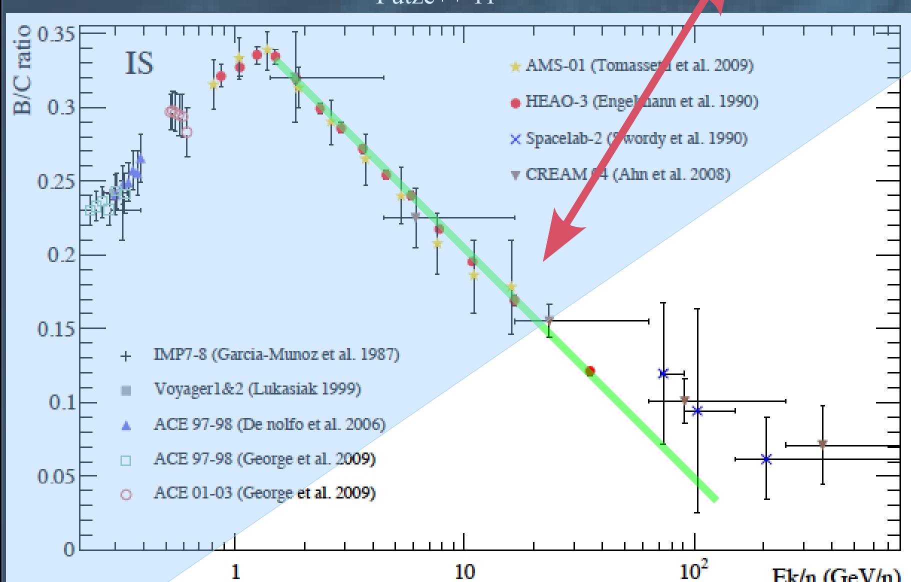
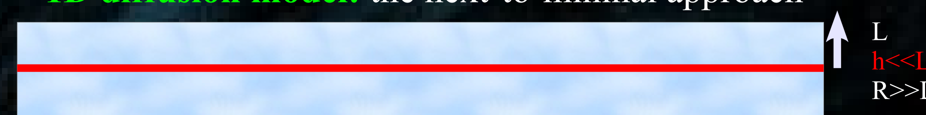


1D diffusion model: the next-to-mininal approach



* Assume steady state, specify diffusion zone (boundary conditions).
* Consider isotropic/homogeneous diffusion + realistic spallation

=> Diffusion equation (for a primary species):

$$-K(E)\frac{d^2\mathcal{N}}{dz^2} + 2\,h\,\delta(z)\,n_{\rm ism}\,v\,\sigma\,\mathcal{N} = 2\,h\,\delta(z)\,q$$

Solve for z≠0, reinject in diff. eq., then integrate over z in vanishing slice ±ε:

$$\begin{cases} \mathcal{N}(z) = \mathcal{N}(0)\,\frac{L-|z|}{L} \\ \frac{K(E)}{h\,L}\,\mathcal{N}(0) + n_{\rm ism}\,v\,\sigma\,\mathcal{N}(0) = q \end{cases}$$

Clear analogy with escape => $\tau_{\rm esc}(E) = \dfrac{h\,L}{K(E)}$

Diffusion coefficient amplitude degenerate with diffusion halo size L!

Breaking degeneracies?

→ Use secondary CR species that do not reach boundaries!
→ Radioactive species as cosmic clocks! (lifetime < residence time ~ 20 Myr)
Diffusion equation for radioactive secondary CRs (neglect spallation):

$$-K(E)\frac{d^2\mathcal{N}_r}{dz^2} + \frac{\mathcal{N}_r}{\tau_{\rm dec}} = 2\,h\,\delta(z)\,n_{\rm ism}\,v\,\sigma\,\mathcal{N}$$

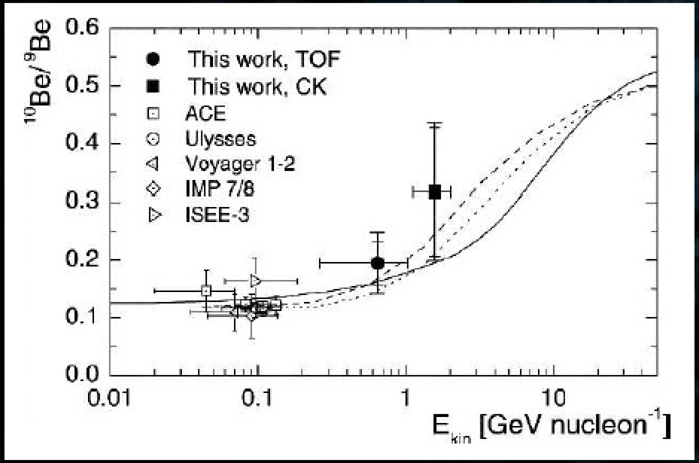
If $\sqrt{K(E)\,\tau_{\rm dec}} \ll L$ then:

$$\begin{cases} \mathcal{N}_r(z) = \mathcal{N}_r(0)\,\exp\left\{-\frac{|z|}{\sqrt{K(E)\tau_{\rm dec}}}\right\} \\ \frac{\mathcal{N}_r(0)}{\mathcal{N}(0)} = \frac{h\,n_{\rm ism}\,\sigma\,v}{\sqrt{K(E)\tau_{\rm dec}}} \end{cases}$$

K(E) / L degeneracy broken!

=> K(E)/L from stable secondaries, then K(E) from radioactive (e.g. Strong++ 07)

Strong++ 07



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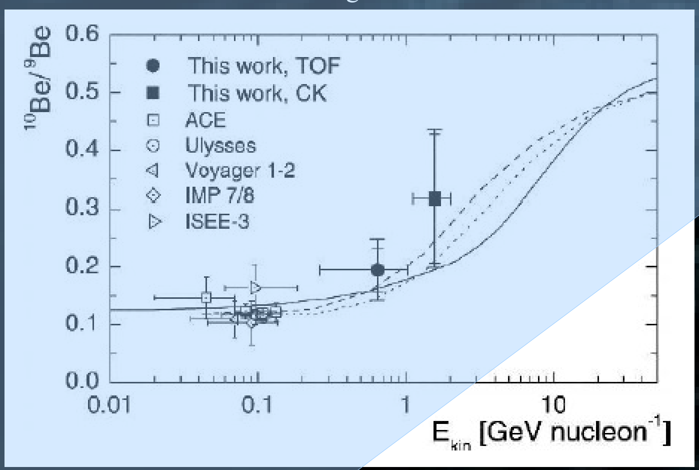
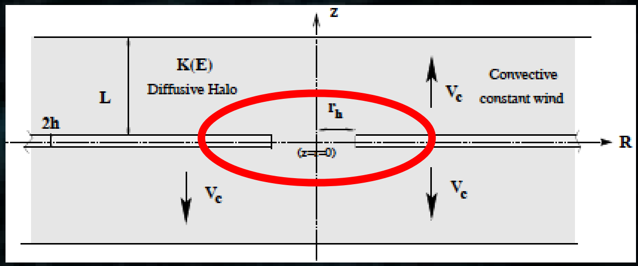


1D model with local bubble (void)
Putze++ 11

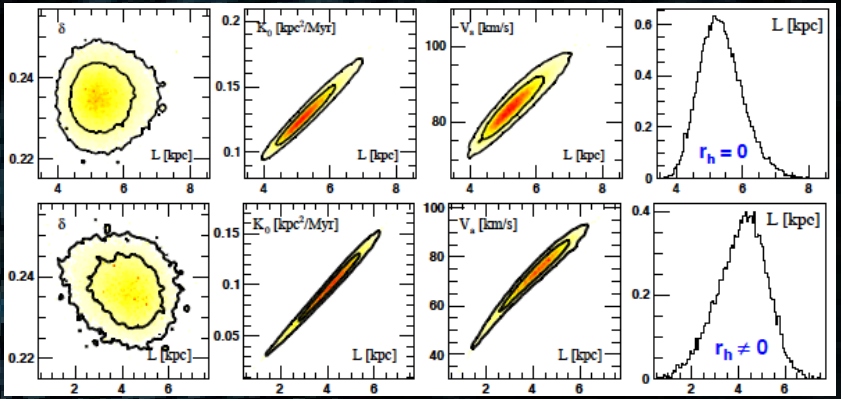


CAVEATS:

* Low quality data (difficult measurements)
* Propagation length scale ~ 100 pc => must account for details of the ISM down to this scale

=> local under-dense region (dubbed "local bubble", e.g. Cox 97)

=> impact on transport parameter estimates (e.g. Donato++ 02; Putze++ 11)



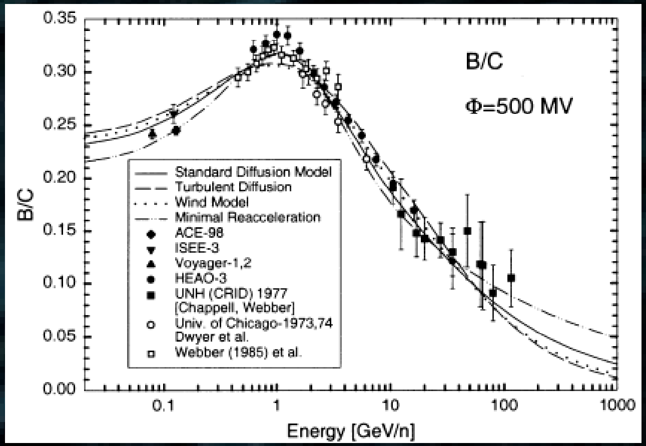
Where current models succeed

Content:
* Diffusion, convection, diffusive reacceleration (with different versions)
* Energy losses (adiabatic, electromagnetic)
* Spallation: nuclear cross sections, from e.g. Ni down to H
* More or less approximate ISM gas distribution (thin disk for semi-analytic models)

Results:
* Good fits to IIaries/Iaries => constrain parameters
* Predictions for other secondaries:
→ antimatter (antiprotons, positrons)
→ diffuse gamma-rays

Usual assumptions / simplifications / arrangements:
* Homogeneous and isotropic spatial diffusion (no strong theoretical support) + cylindrical symmetry
* Power-law dependence in rigidity (theoretically motivated, though ad-hoc low rigidity part, below 1-3 GV)
* Spatially continuous distribution of sources of primary CRs (though discreteness effects important in some cases)
* Empirical recipes at low energy (ad-hoc breaks for spectrum at sources or for K(E))

Jones++ 01: B/C



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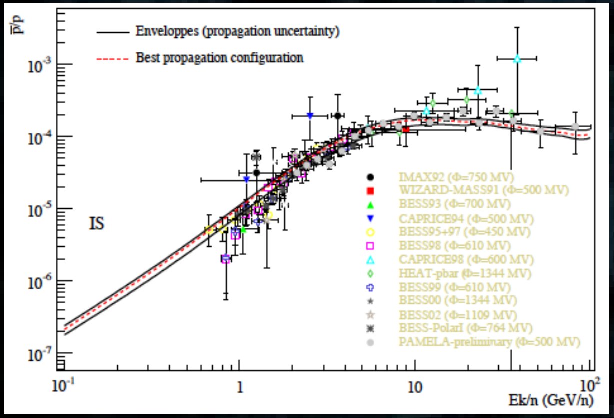
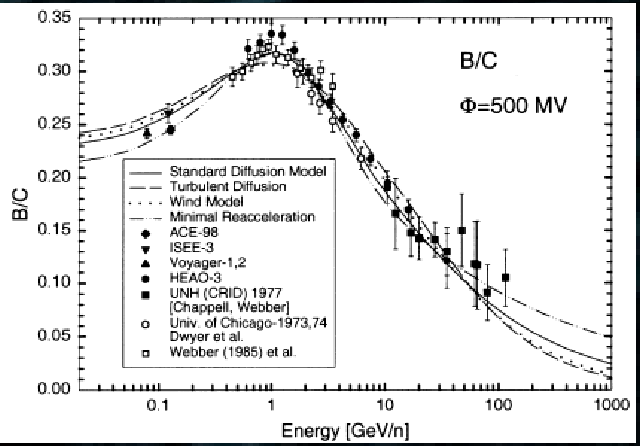
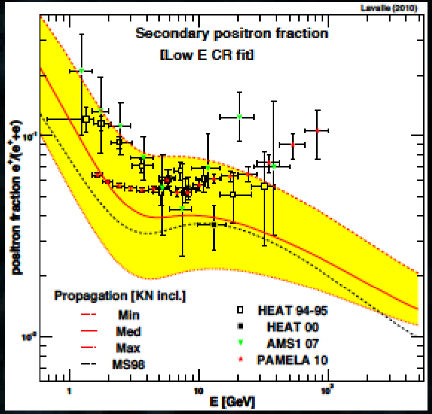
Donato++ 09: antiprotons/protons



Jones++ 01: B/C



Delahaye++ 09, Lavalle 11:
secondary positron fraction



Where current models succeed

Content:
* Diffusion, convection, diffusive reacceleration (with different versions)
* Energy losses (adiabatic, electromagnetic)
* Spallation: nuclear cross sections, from e.g. Ni down to H
* More or less approximate ISM gas distribution (thin disk for semi-analytic models)

Results:
* Good fits to IIaries/Iaries => constrain parameters
* Predictions for other secondaries:
→ antimatter (antiprotons, positrons)
→ diffuse gamma-rays

Usual assumptions / simplifications / arrangements:
* Homogeneous and isotropic spatial diffusion (no strong theoretical support) + cylindrical symmetry
* Power-law dependence in rigidity (theoretically motivated, though ad-hoc low rigidity part, below 1-3 GV)
* Spatially continuous distribution of sources of primary CRs (though discreteness effects important in some cases)
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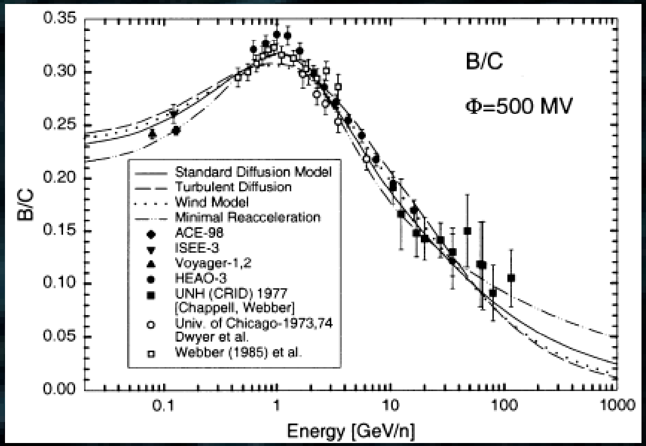
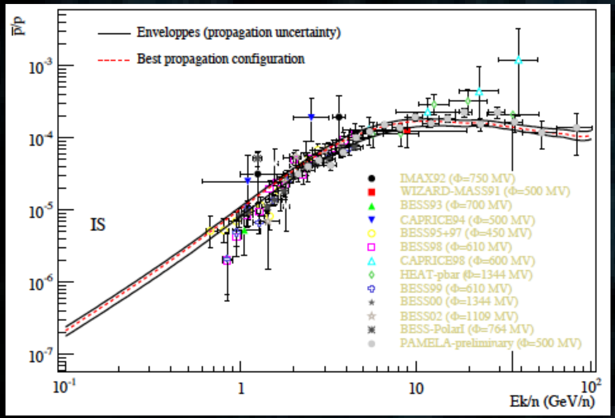
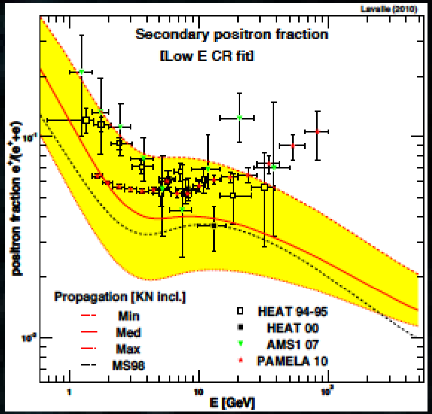
Jones++ 01: B/C

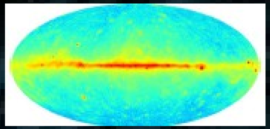


Donato++ 09: antiprotons/protons

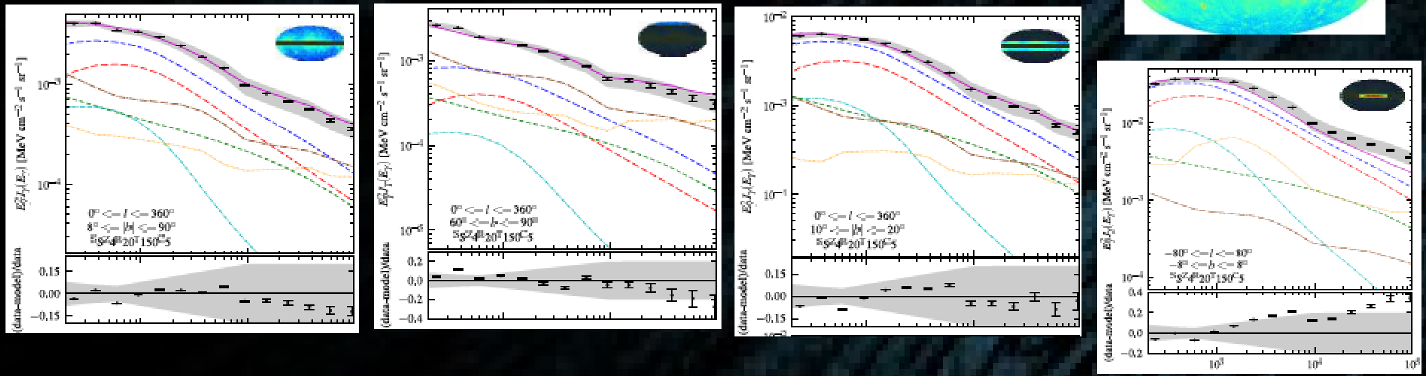


Delahaye++ 09, Lavalle 11: secondary positron fraction





Fermi Collab 12 (Galprop): diffuse gamma-rays



Where current models succeed

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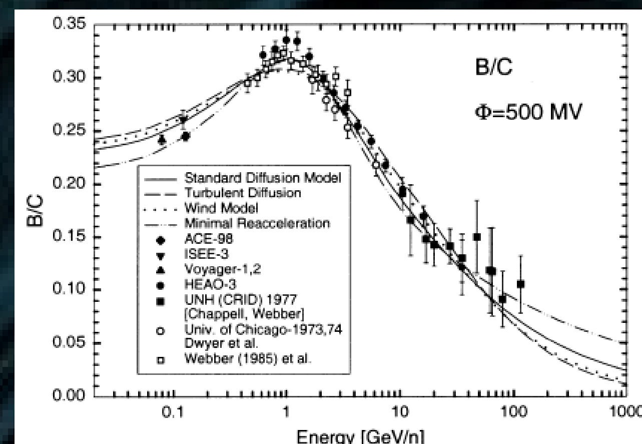
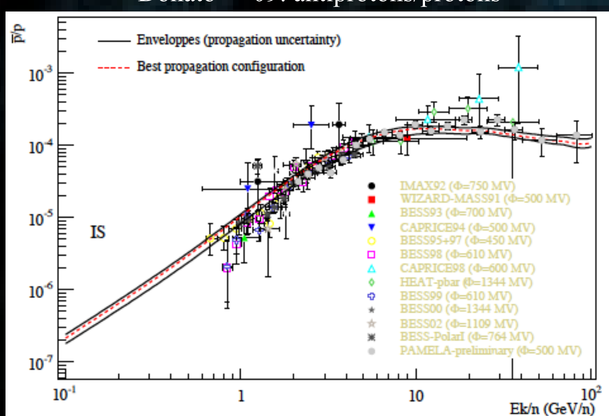
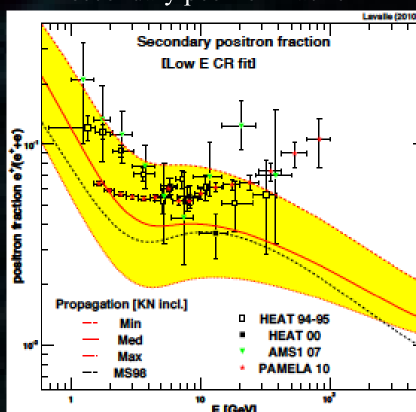


Donato++ 09: antiprotons/protons



Delahaye++ 09, Lavalle 11: secondary positron fraction



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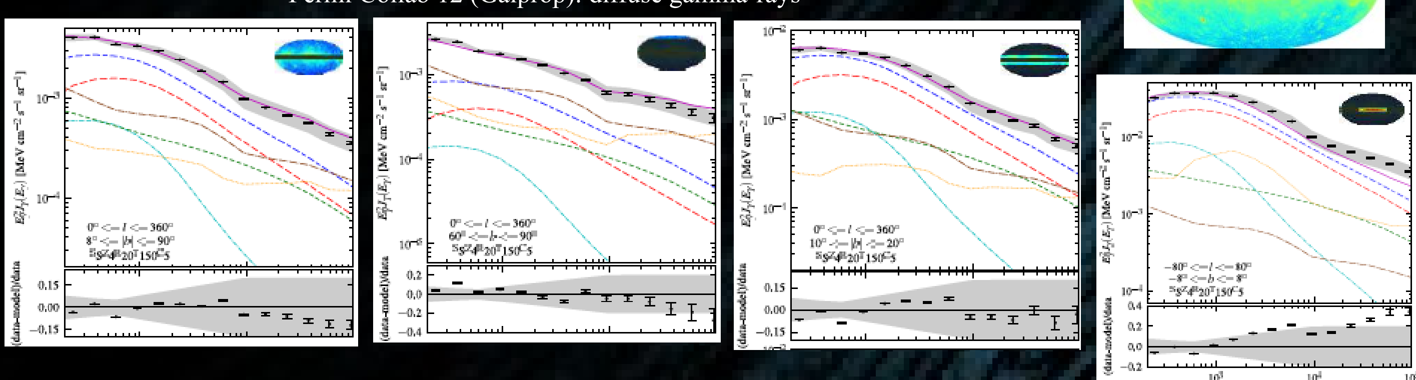
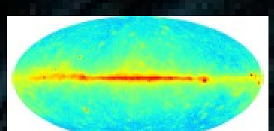
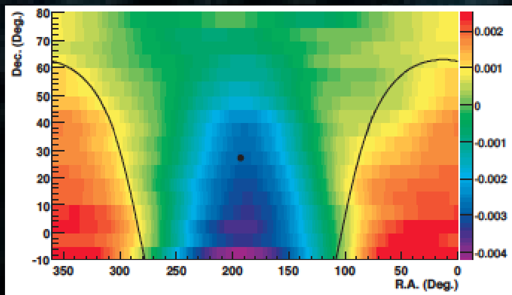




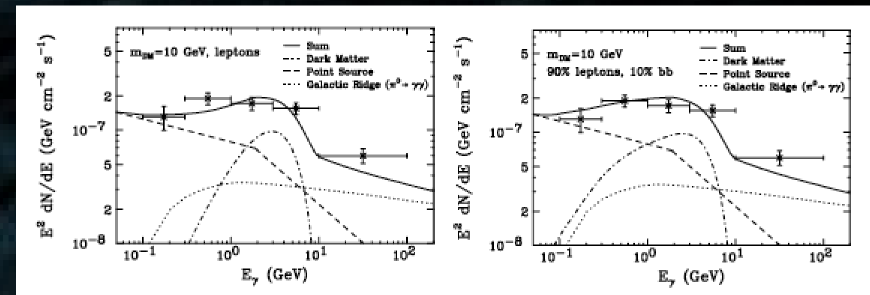
Numerical approaches:
e.g. Galprop (Strong, Moskalenko++), Dragon (Evoli, Maccione++)
→ good for treating complex environments

Semi-analytic approaches:
e.g. Ptuskin++, Maurin++, Shibata++
→ good for addressing theoretical uncertainties

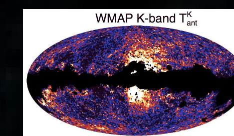
Some issues for which GCRs are concerned

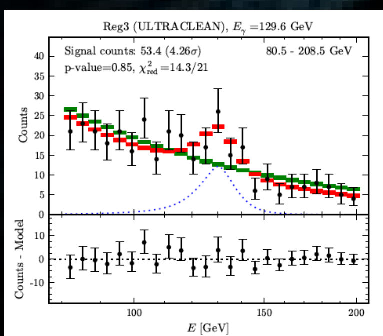


Large scale TeV CR anisotropy:
Tibet, SuperK, Milagro, Icecube
(plot from Milagro Collab. 09)

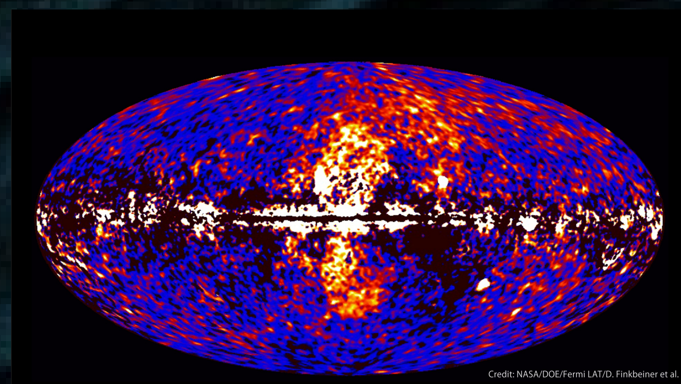


WMAP & Fermi "Hazes" (Finkbeiner++, Hooper++)
(plots from Hooper++ 12)

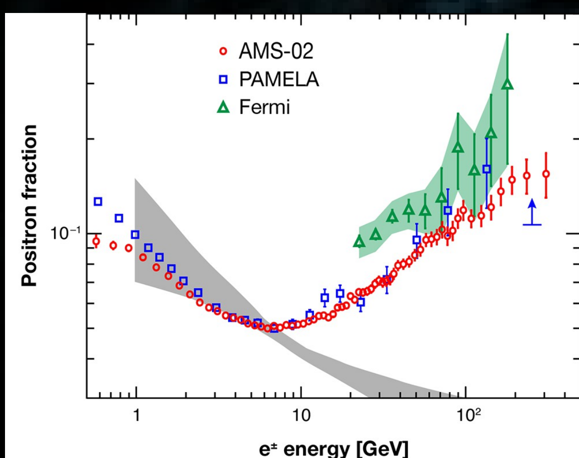




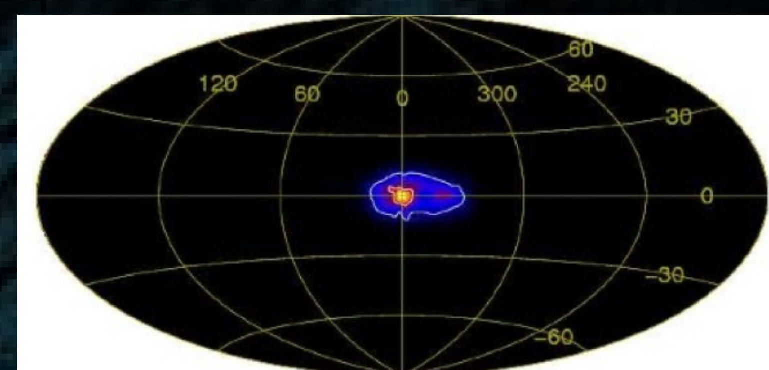
130 GeV Gamma-ray line?
Weniger++, Su++ 12
But see Fermi Collab. 13
(significance reduced to 2 σ)



Origin of Fermi bubbles?
Finkbeiner++ 09, Fermi Collab 10

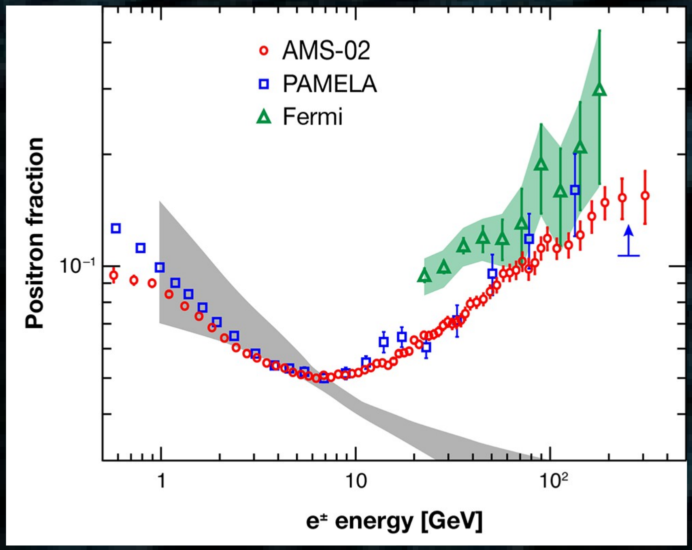


HEAT/PAMELA/Fermi/AMS
positron excess.
Origin?



511 keV, Knödlséder/Weidenspointner++ 05 - 08

On the positron "excess"



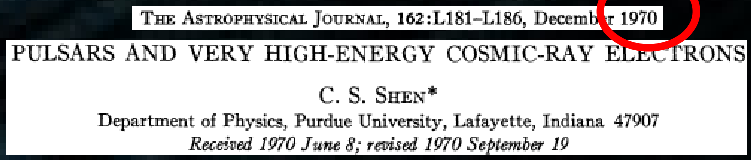
AMS02 Collab (2013)

Pulsars long suspected as local sources of TeV e+e-.

Recent "rediscovery" after PAMELA data release.

Basic spin-down energetics provides correct order of magnitude for local PWNe.

NB: acceleration of secondary e+ at SNR shocks could also make it – e.g. Berezhko++ 03.


THE ASTROPHYSICAL JOURNAL, 162:L181–L186, December 1970

PULSARS AND VERY HIGH-ENERGY COSMIC-RAY ELECTRONS

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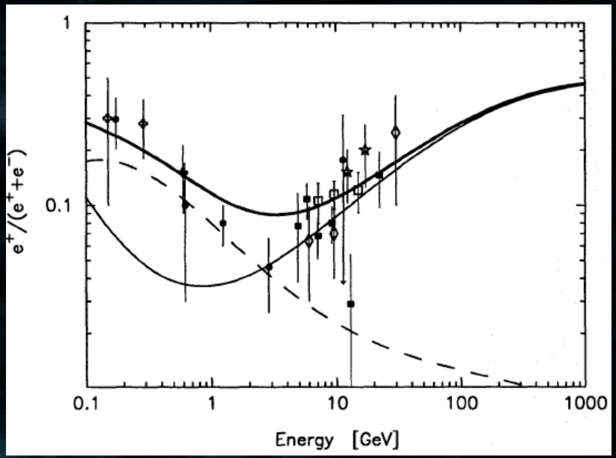
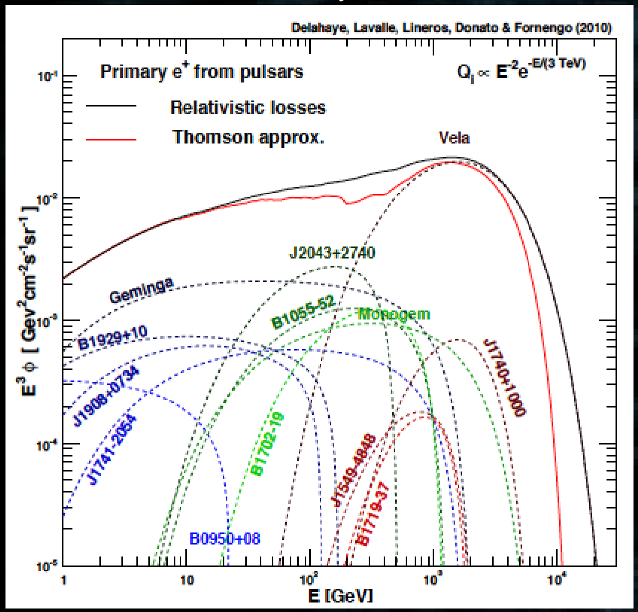
Department of Physics, Purdue University, Lafayette, Indiana 47907

Received 1970 June 8; revised 1970 September 19



Aharonian++ 95

Delahaye++ 10



BUT going to realistic modeling very complicated (e.g. Delahaye++ 10).
=> separate distant/local sources, and accommodate the full data (e-, e+, e+e-, e+/e+e-) – e.g. Kobayashi++ 04.

=> PWNe must be associated with SNRs (core-collapse supernova origin)
=> SNRs as local sources of e-, PWNe as local sources of e+e-
++++ issue of escape of TeV e+e- (SNR crossing) – e.g. Blasi & Amato 10.

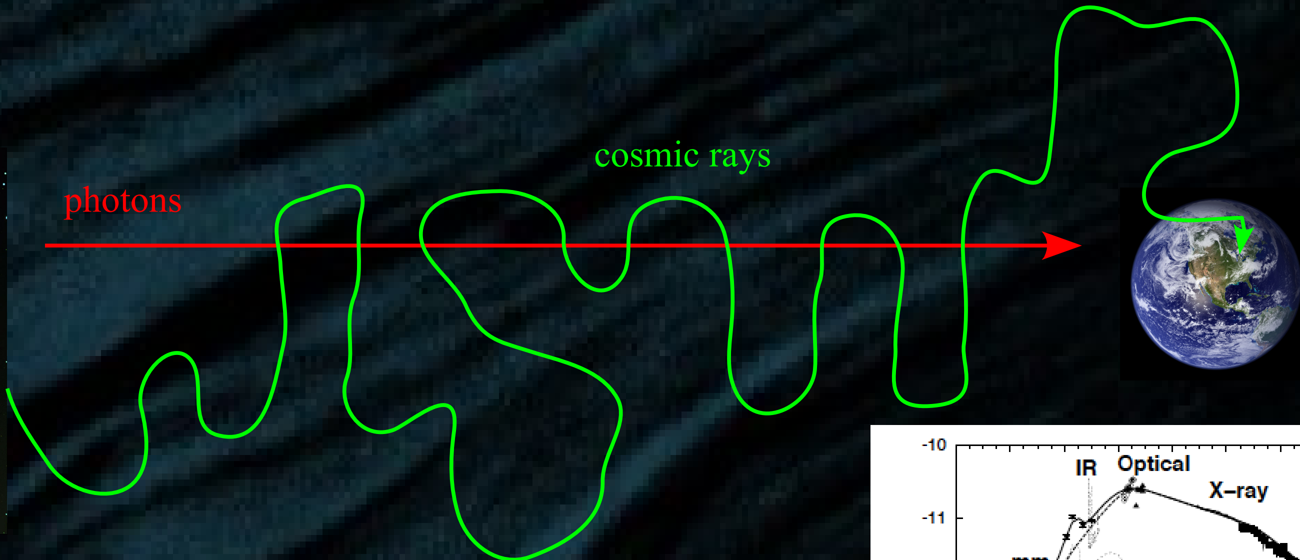
=> tune amplitudes / spectral indices to get good fit … then what?

** Observational constraints!

=> use pulsar timing, multiwavelength data for all observed sources … but … not that simple.

Modeling electron/positron sources?

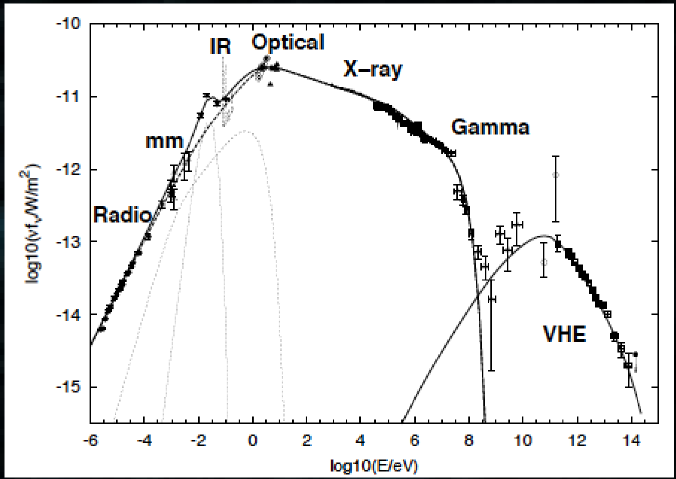
Crab nebula (ESA)
(just for illustration,
not relevant for e+/e-)



$$\text{photon obs. time} = \frac{d}{c} \approx 300\,\text{yr}\left[\frac{d}{100\,\text{pc}}\right]$$

$$\text{transport time} \approx \frac{d^2}{K(E)} \approx 30\,\text{kyr}\left[\frac{E}{1\,\text{TeV}}\right]^{-1/2}\left[\frac{d}{100\,\text{pc}}\right]^2$$

$$\text{E-loss time} = \int_E^{E_s} dE'\, b(E') \approx 300\,\text{kyr @ 1 TeV}$$



Horns & Aharonian 04
Crab SED

Different timescales:

1) E-loss time > source age > transport time
2) transport time >> photon time
   => cannot directly use multiwavelength data
   => requires dynamical models for sources (time evolution)
3) timescales at source (escape issue)

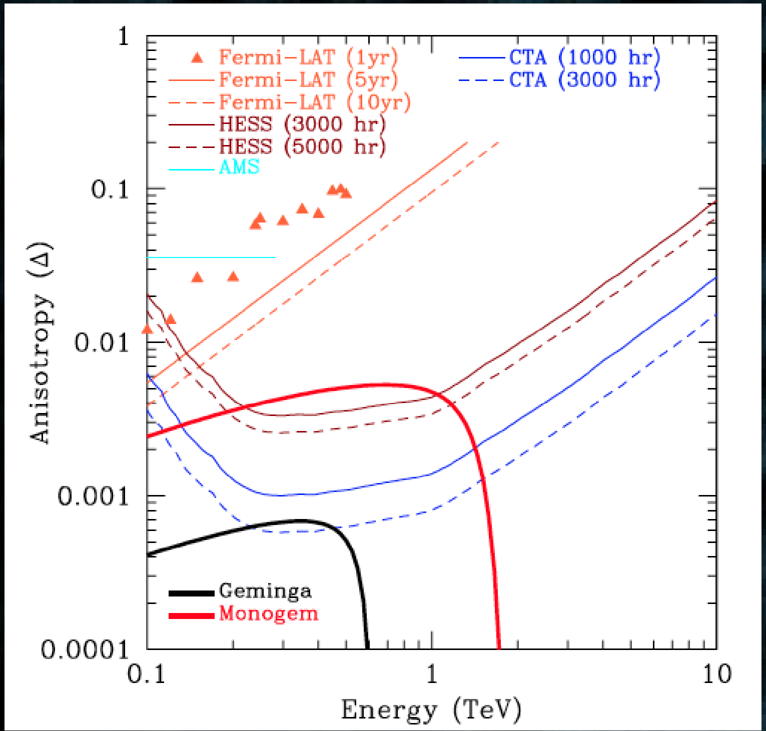
Very complicated problem:

1) photon data: CRs which are mostly still confined in sources (escape issue)
2) coupled evolution of magnetic fields and CR density

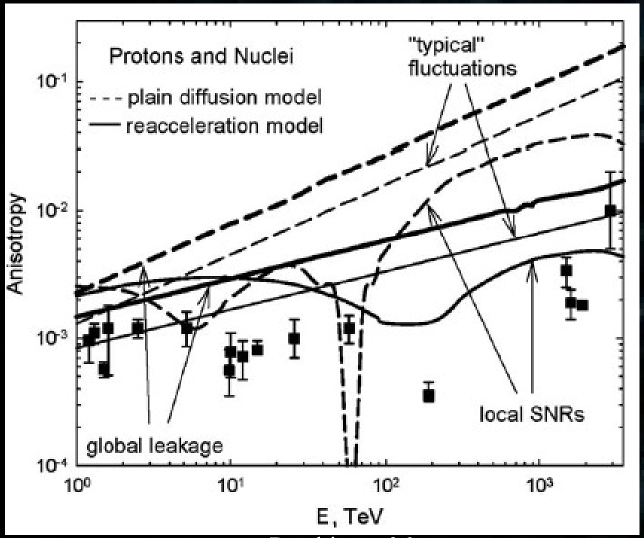
Some attempts at the source level (eg Ohira++ 10-11), but much more work necessary.

Work in prep. with Y. Gallant and A. Marcowith (LUPM).

The anisotropy crisis



Linden & Profumo 13



Ptuskin++ 06

If single source dominates => dipole expected (even in isotropic diffusion)

Intensity proportional to diffusion coefficient, energy dependence driven by diffusion slope.

Caveats:

* model-dependent (diffusion halo size again!)
* contributions of other sources (eg dipole from GC/antiGC asymmetry in the source distribution)
* cancellations might occur in the dipole (sources in opposite directions)

Still:

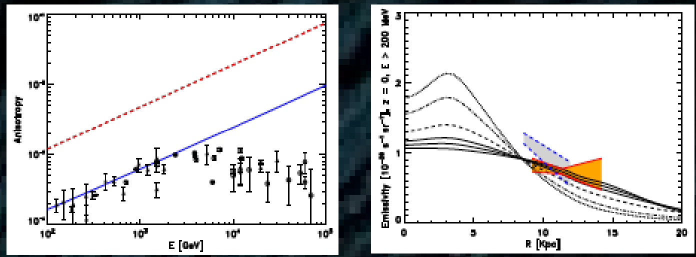
* physically meaningful information => multipole analysis
* should be provided for all CR species separately (eg positrons, antiprotons, etc.)
* will provide constraints to the full transport model
* AMS02 might reach the sensitivity

Problems:

* when applied to protons (local SNRs), anisotropy in excess (e.g. Ptuskin++ 06)
=> indirect constraint on diffusion coefficient
!!!! model-dependent (source + transport)

Possible solutions:

* anisotropic diffusion (parallel ≠ perpendicular transport) – e.g. Evoli++ 12
* change in dynamical properties of magnetic turbulence – e.g. Blasi++ 12


Evoli++ 12

Conclusions and perspectives

Some conclusions:

- Current GCR models allow for a good understanding of (i) the local CR budget and (ii) the diffuse Galactic emission(s)
- NB: there is no "standard model" of GCRs! (many inputs, lucidity is required), but a standard paradigm
- Current models have reached their limits (e.g. discreteness, more realistic diffusion, etc.)

=> prediction power saturates, need to put more physics in ... at the price of increasing theoretical uncertainties (though expected to decrease in the future)

- Far not accurate enough for specific regions (e.g. GC), but still very useful

Some perspectives:

- Better data! (we have entered the precision era with PAMELA and AMS02)
- modeling improvements: include more realistic descriptions of sources, ISM/ISRF, and magnetic fields.
- theoretical improvements: work out more precise relations between magnetic turbulence properties and diffusion.
- theoretical/modeling uncertainties with all new ingredients
- top-down approaches from cosmological simulations of galaxies (DM+gas+stars+baryons+B-field)?

=> toward full 3D models (even without cosmology).

- important for CR physics but also for searches for new physics (e.g. dark matter – see N. Fornengo's talk)

Toward top bottom approaches?

Cosmological simulations:
self-consistent modeling of a galaxy (DM, gas, stars)

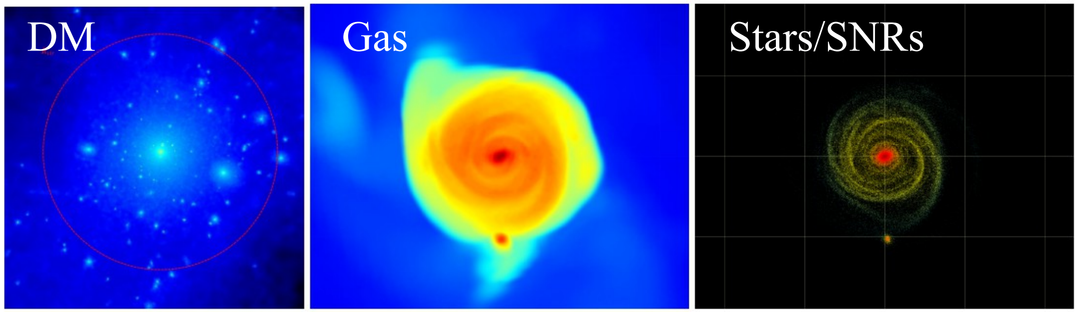
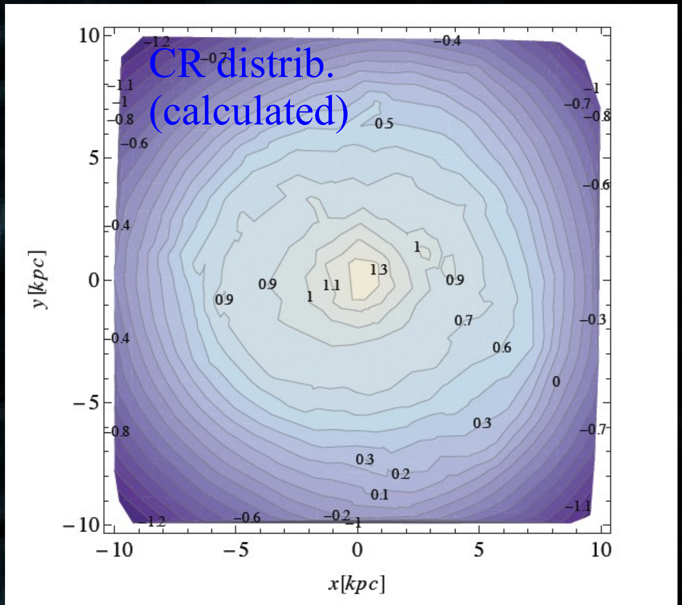
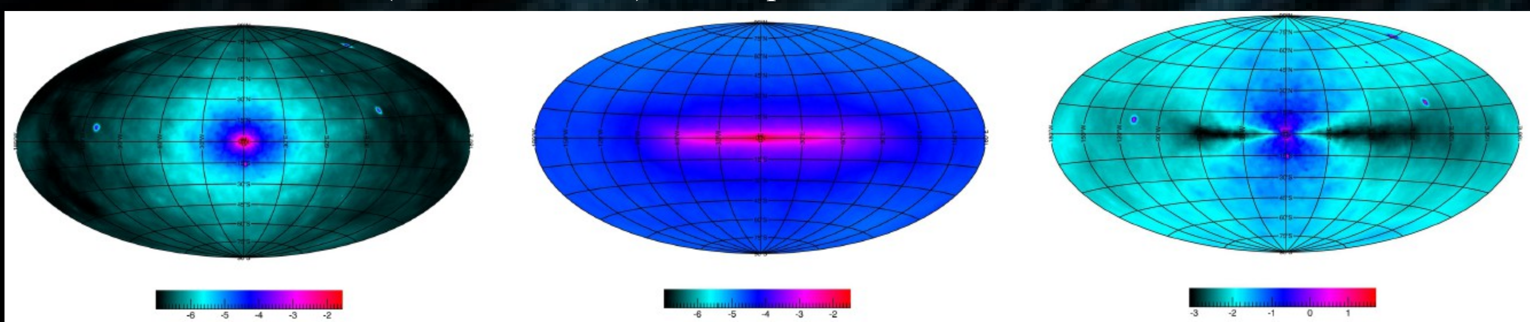


FIG. 1. Left: DM halo and subhalos; the virial radius (264 kpc) appears as a red circle. Middle: top view of the gas content (scaled as in right panel). Right: SN events in the last 500 Myr (10 kpc grid).

arXiv:1204.4121

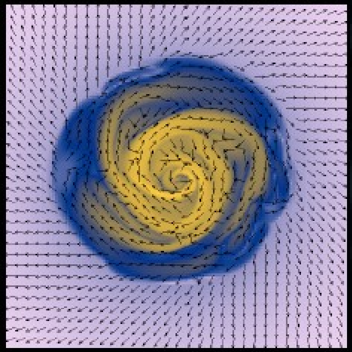


Skymaps:
DM (100 GeV b-bbar) – astro processes – DM/astro



Advantages:
* all ingredients are identified and localized (sources and gas)
* check the relevance of current assumptions
Limits: spatial resolution

=> preliminary results encouraging, work in progress



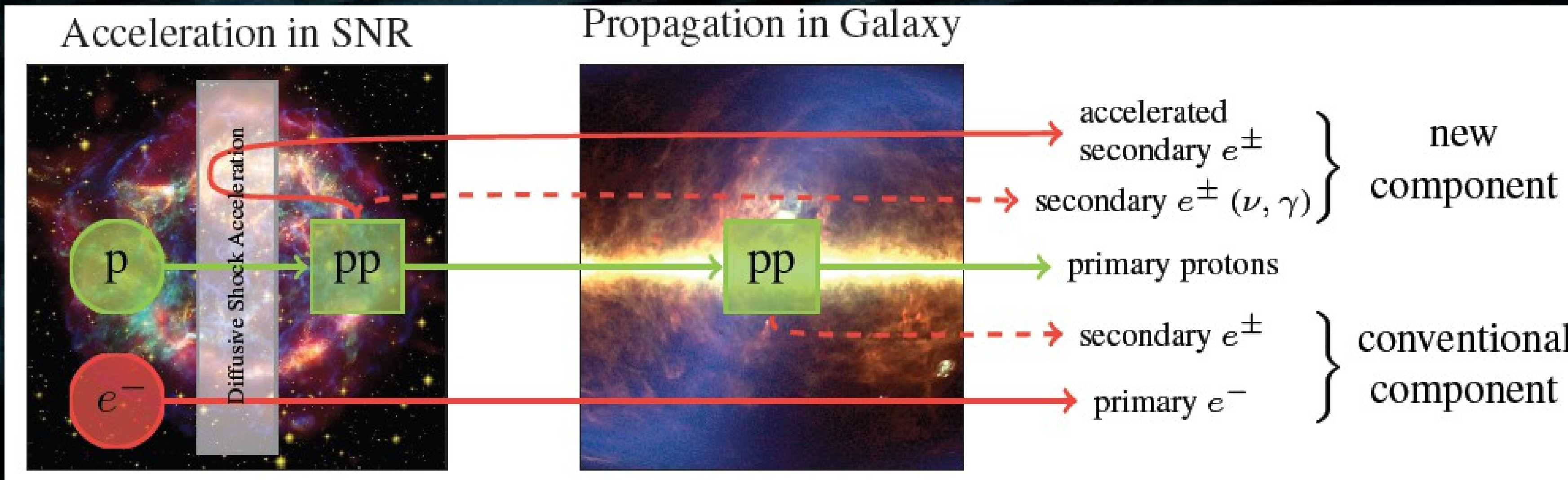
Magnetic fields possible!
(e.g. Dubois & Teyssier 08)

Thanks!

Backup

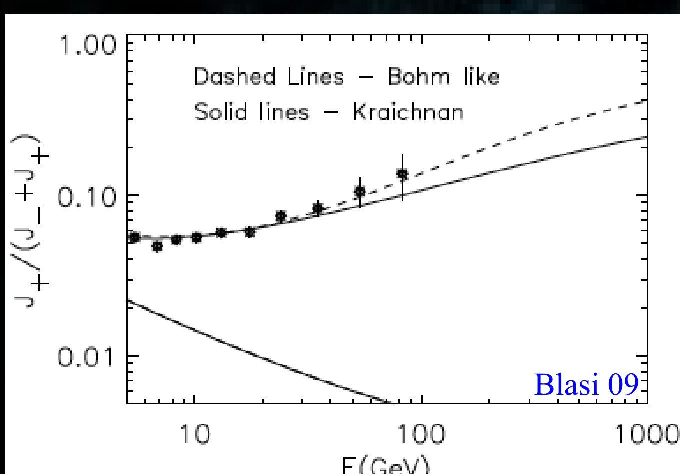
Other astrophysical solution(s)

Secondaries generated in SNRs are accelerated like primaries:
Berezhko++ 03, Blasi 09, Blasi & Serpico 09,
Mertch & Sarkar 09, Ahler++ 09

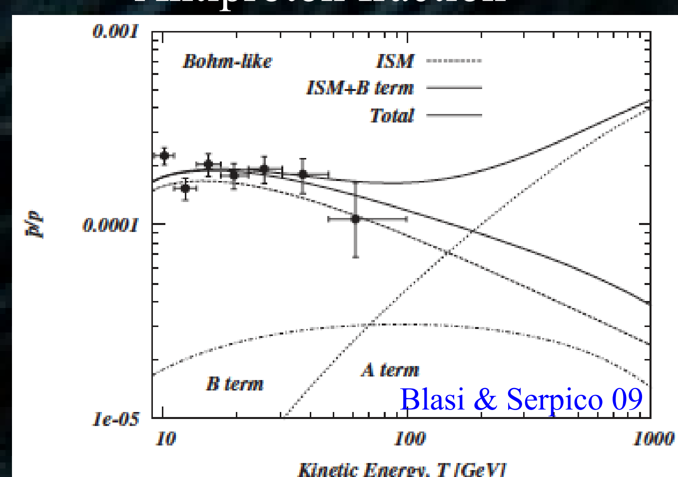


(from Ahler++ 09)

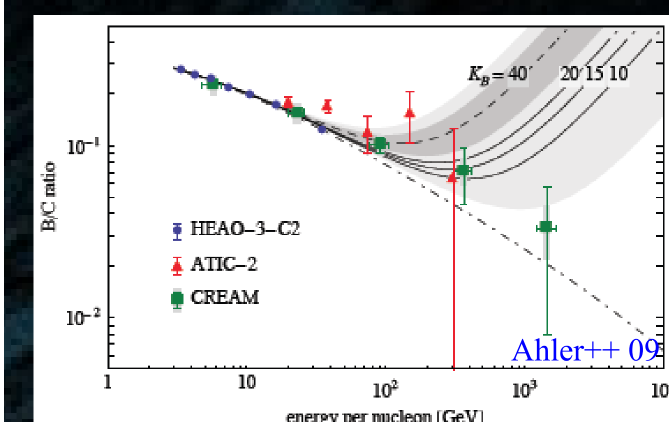
Positron fraction



Antiproton fraction



B/C ratio

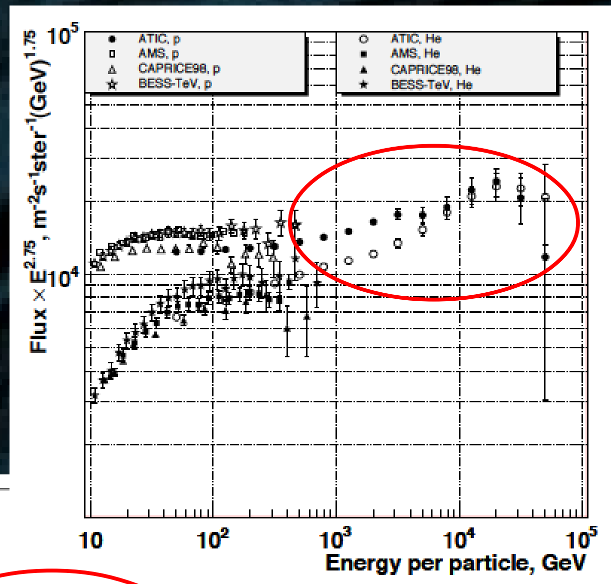


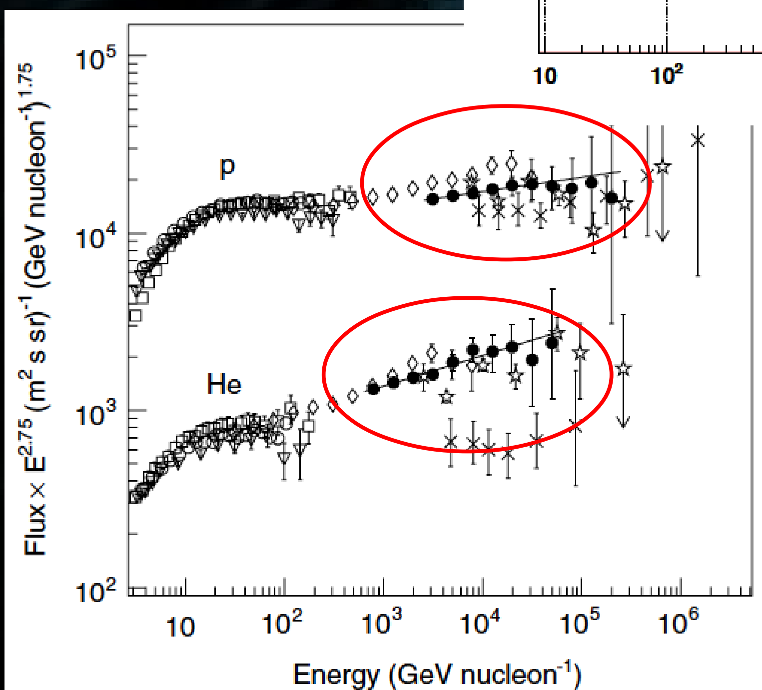
Associated signatures: rising antiproton fraction (like DM) and B/C ratio

What else on K and L?
(on the spectral hardening)

ATIC Collab (2006-2012)

Cream Collab (2010-2011)



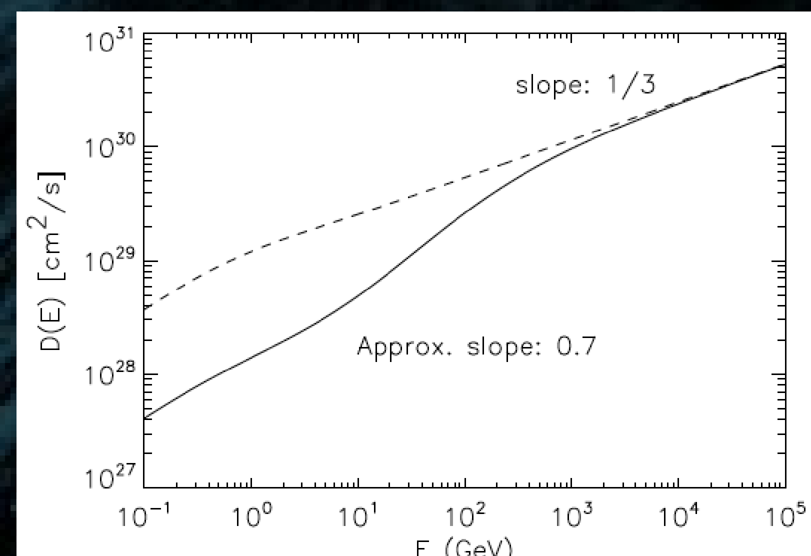


Could be due to a change in diffusion properties (eg Blasi++ 12)

=> K has different slope > 100 GeV (from 0.7 to 0.3)

=> impact on secondary CR production

Blasi++ 12



Julien Lavalle, Lomonosov Conference, Moscow, 24th VIII 2013