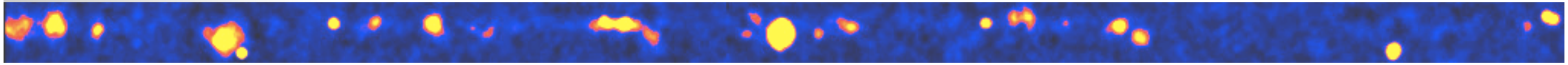
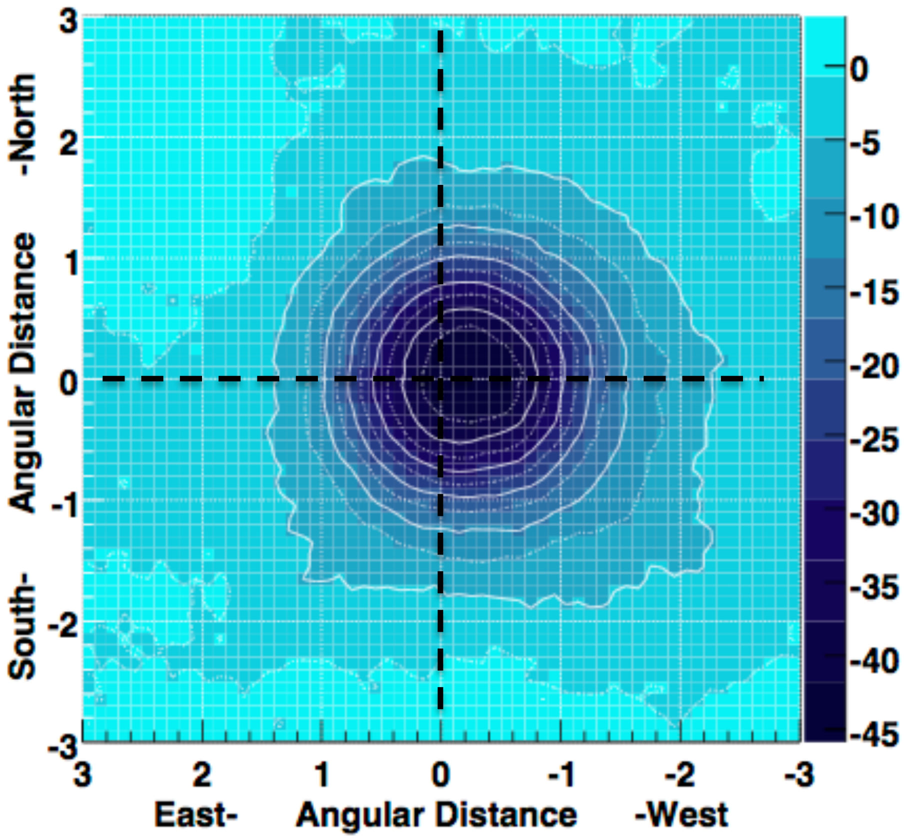
Seeing the moon shadow in CRs

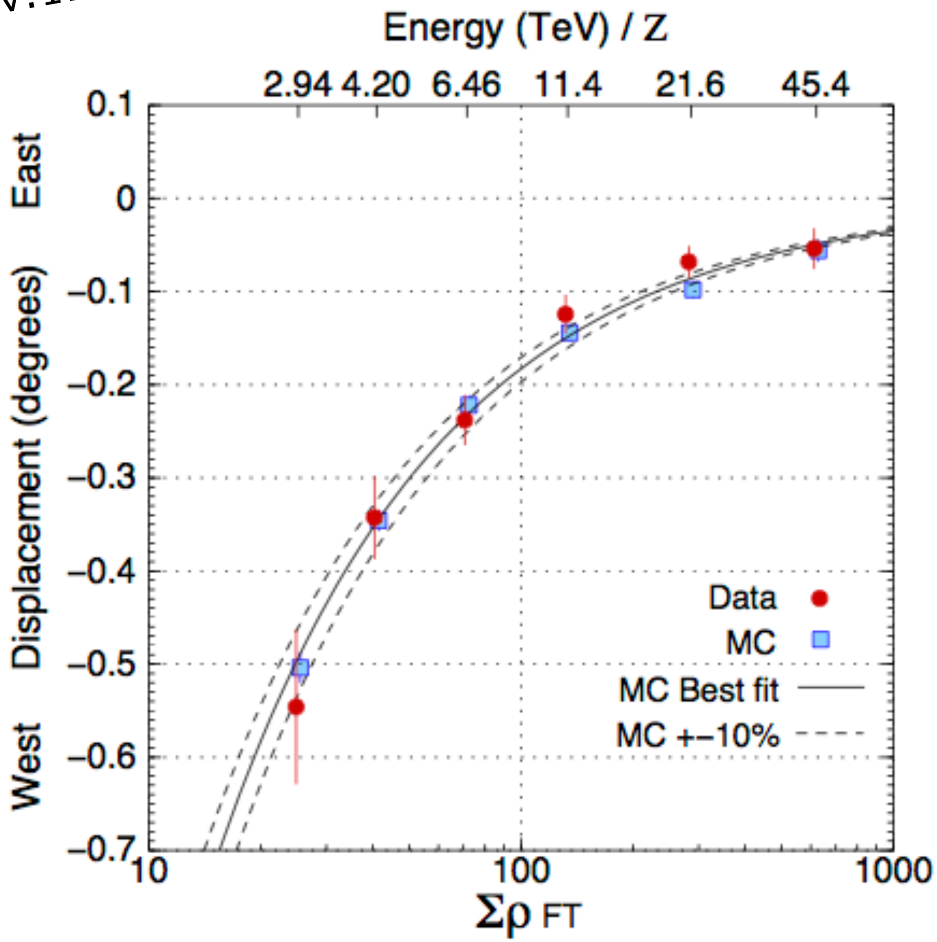


and using the Earth' field as a spectrometer

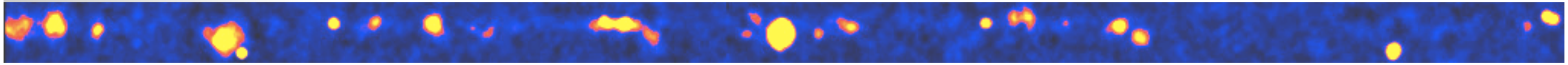
Tibet III
Amenomori et al.
arXiv:0810.3757

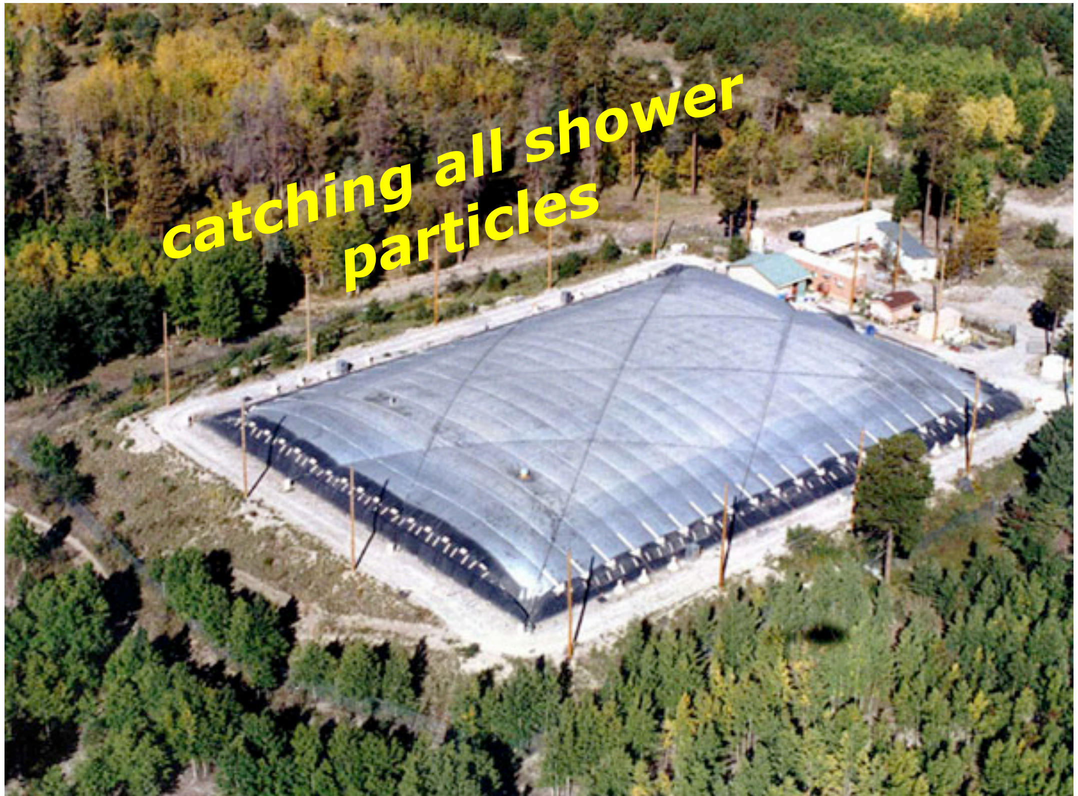
see also ARGO-YBJ results
Bartoli et. al, arXiv:1107.4887





Milargo: 100% coverage



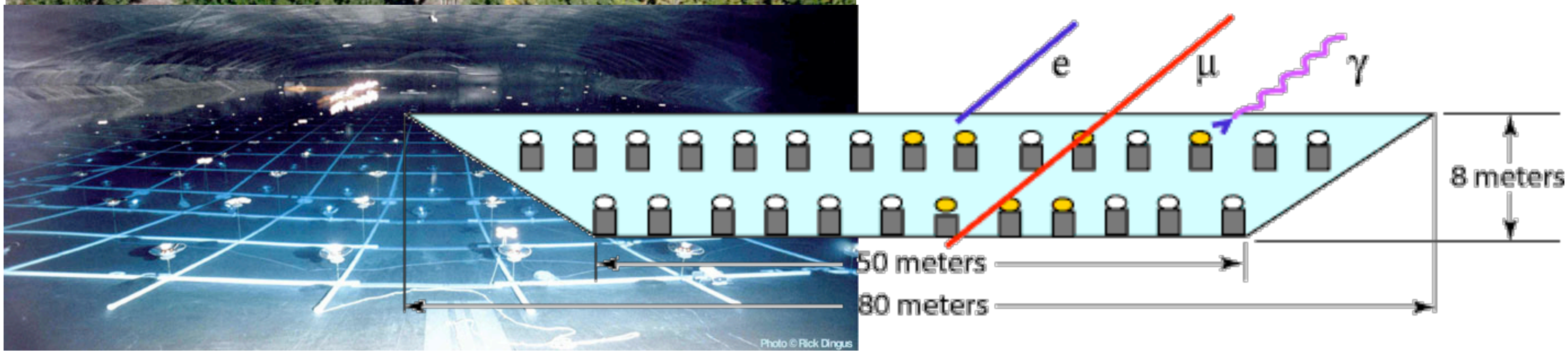


2630 m asl., 36^{o} N

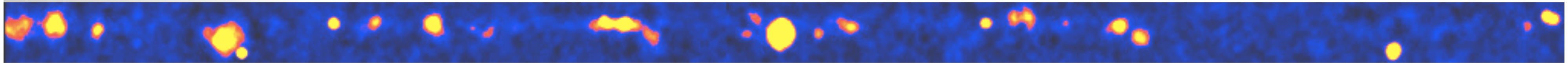
80 m x 60 m x 8 m pond
top layer with 450 PMTs
bottom layer with 273 PMTs

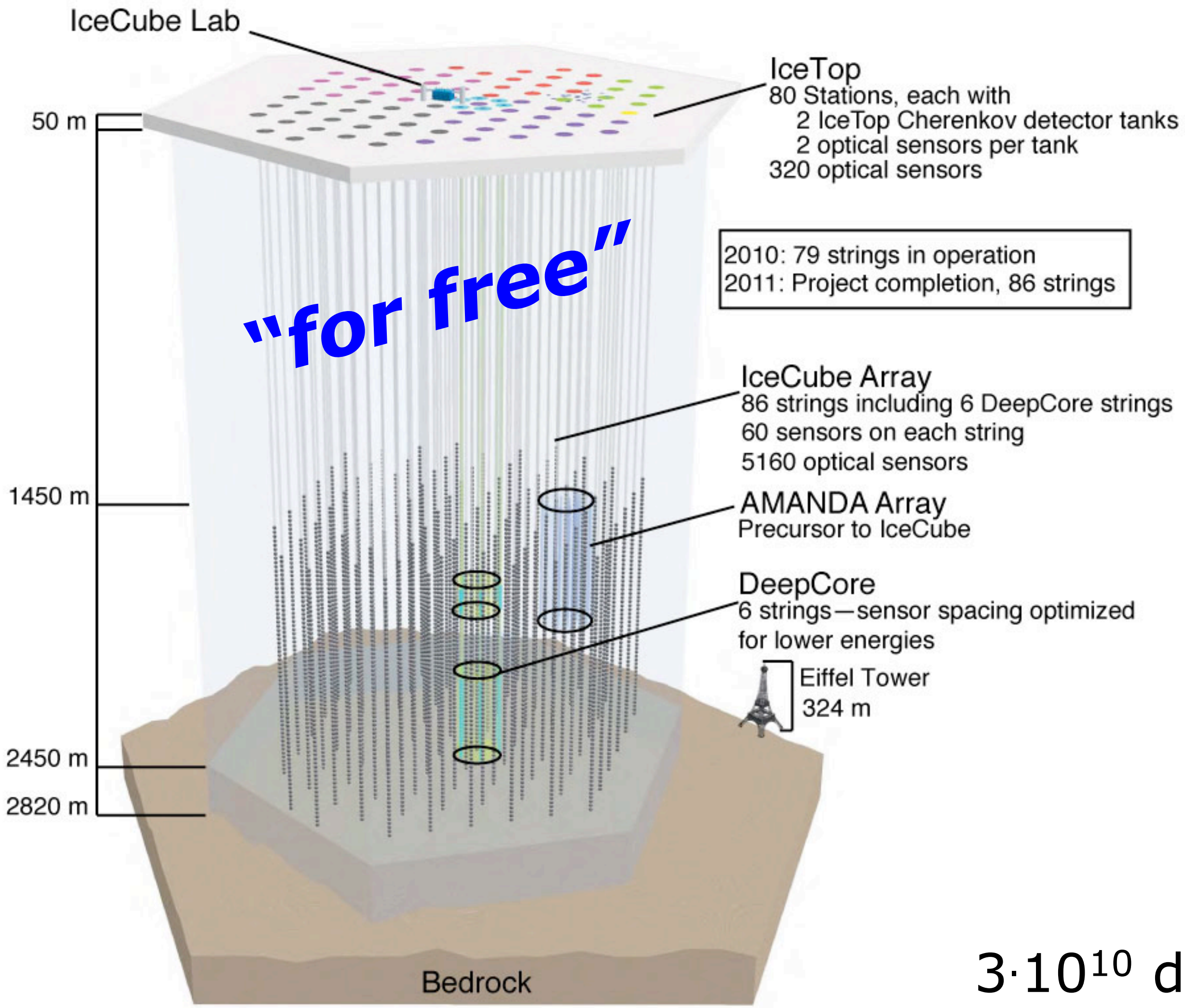
200 m x 200 m x outrigger array

median CR energy after cuts ~6 TeV



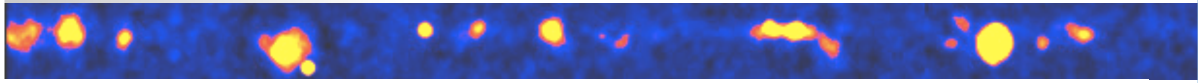
Cosmic ray detection by muons: IceCube

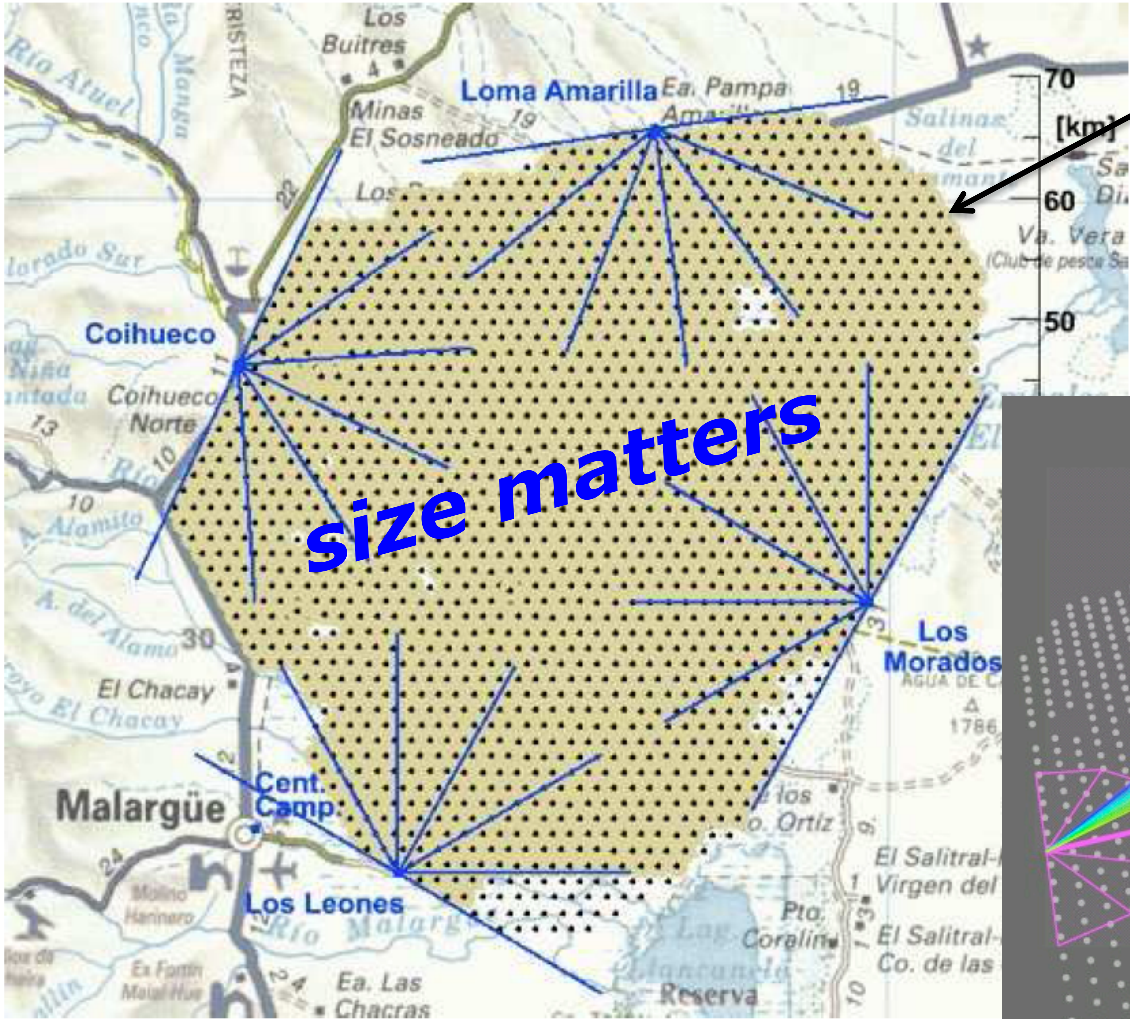




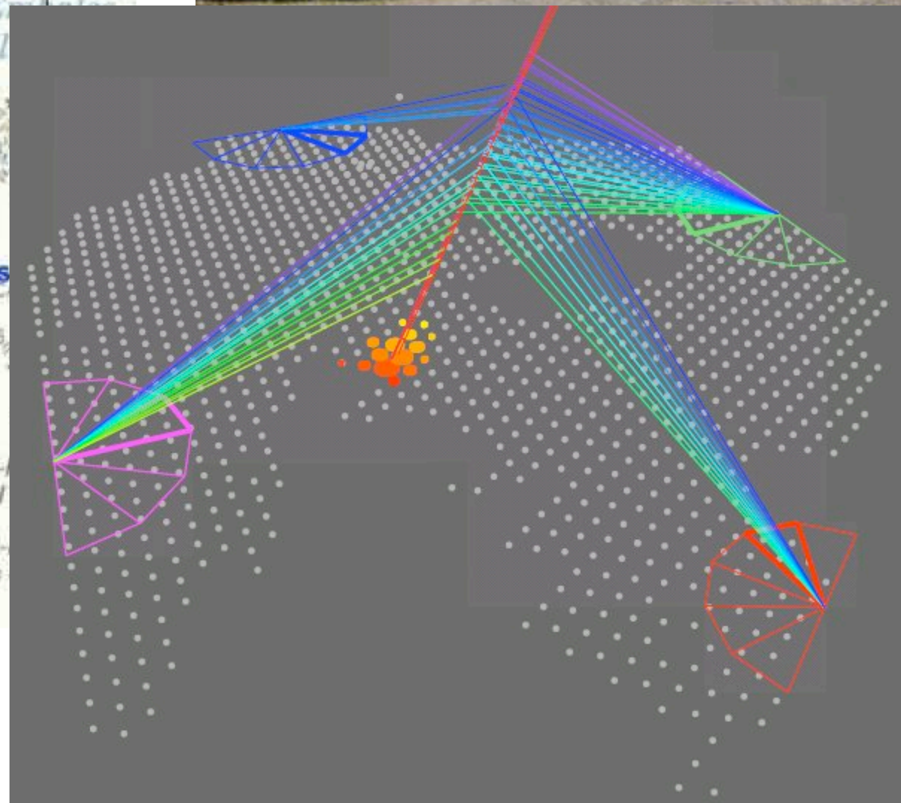
$3 \cdot 10^{10}$ down-going muons
Median shower energy 20 TeV

AUGER: area matters



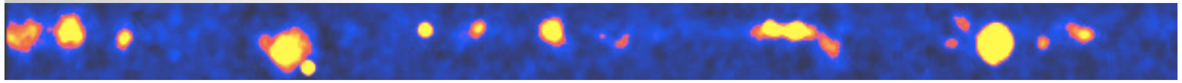


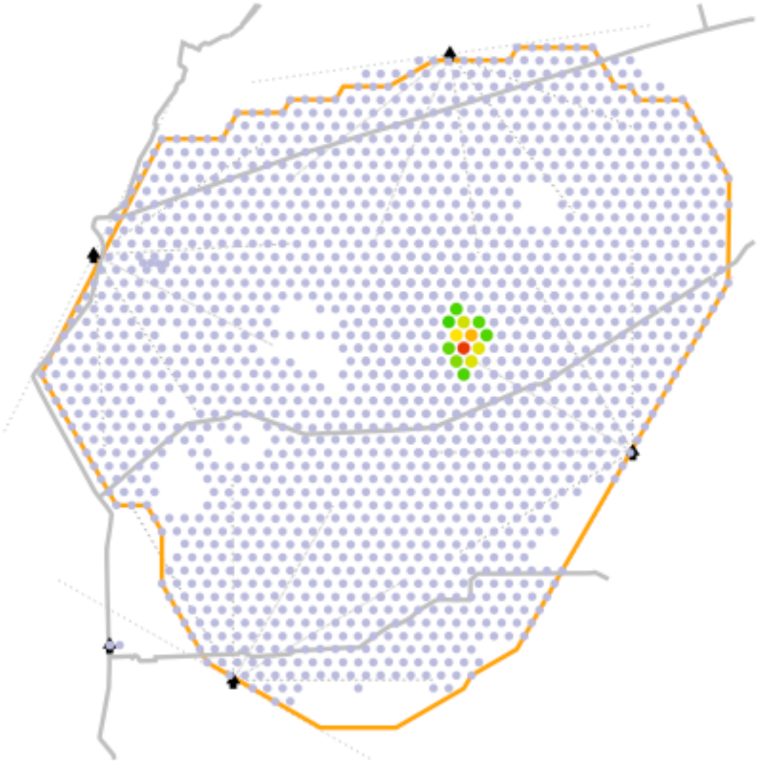
m



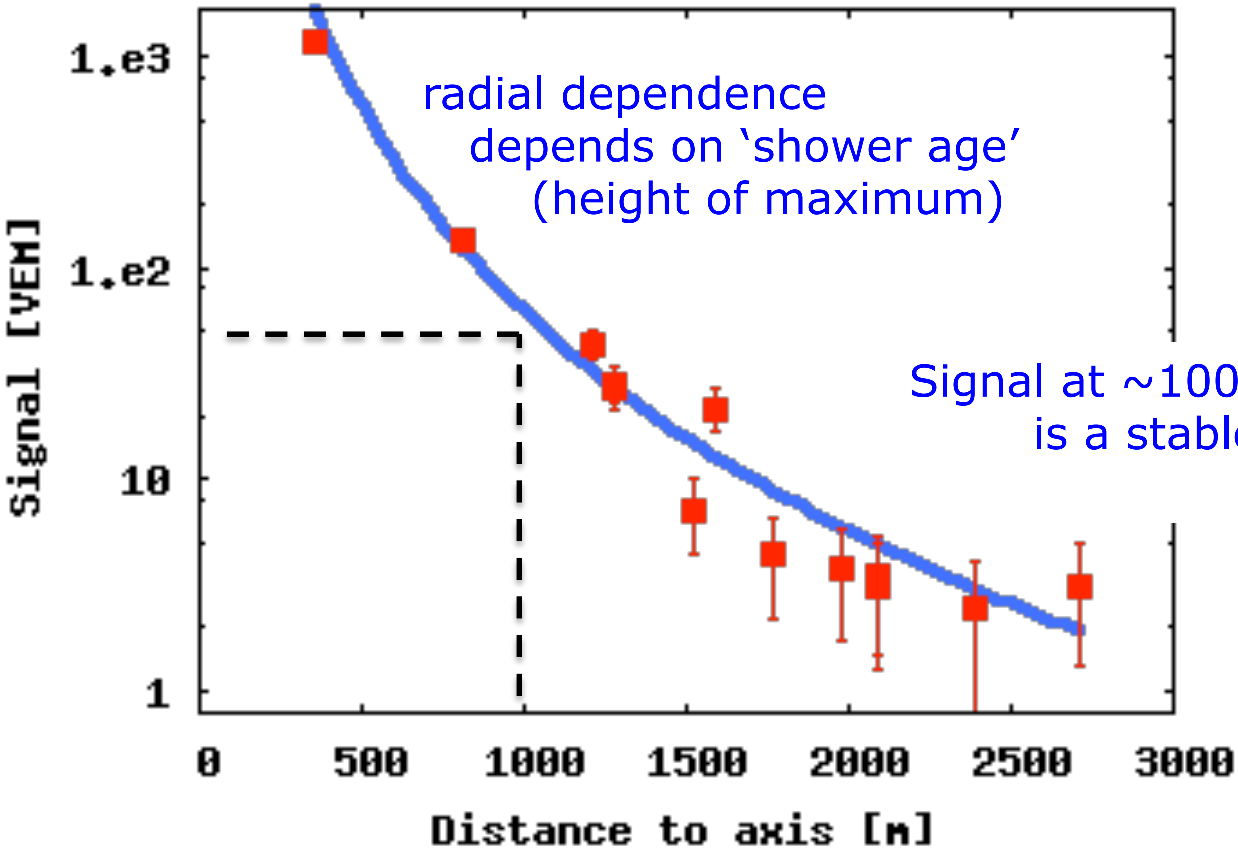
AUGER: 3000 km^2

Energy determination



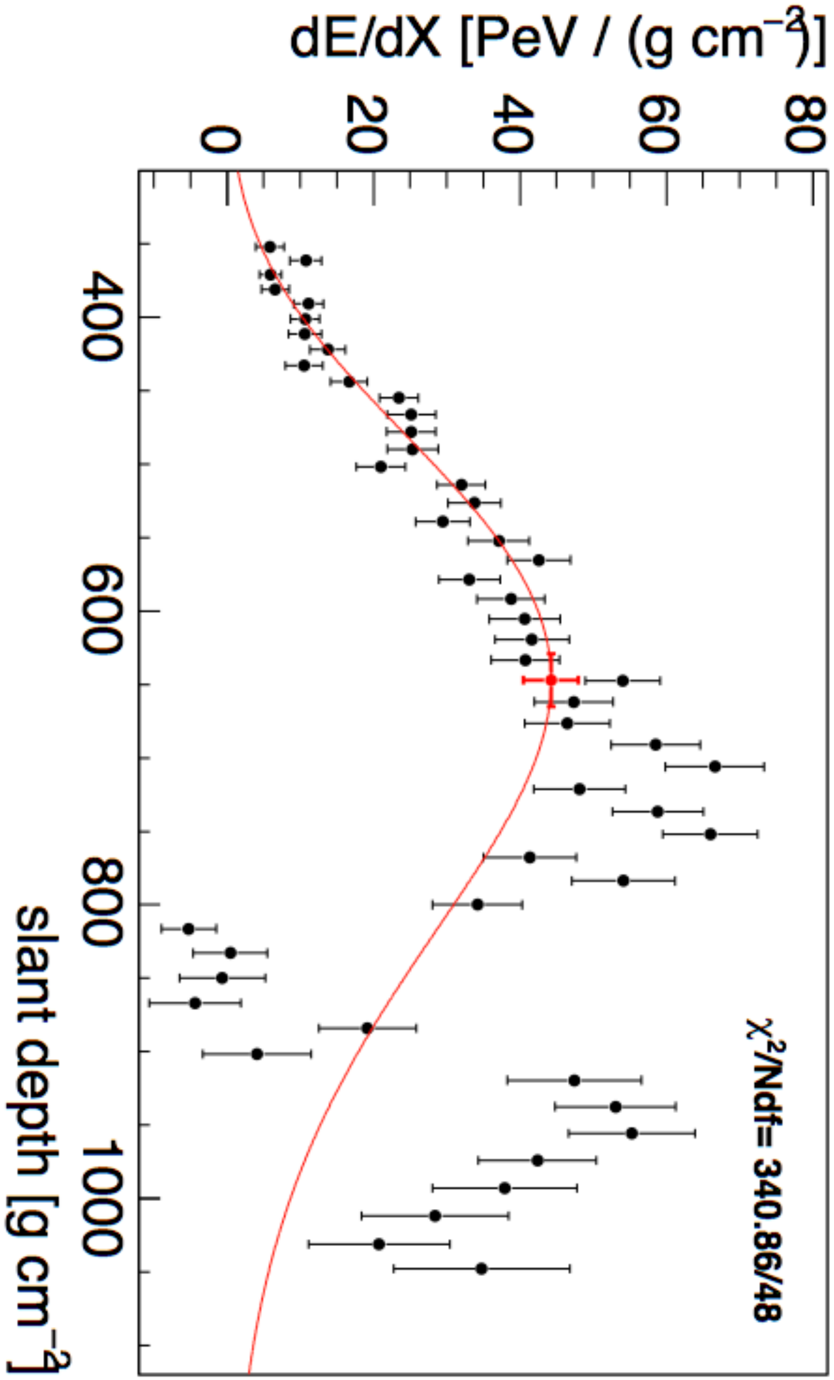


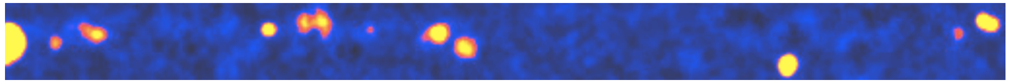
Signal in surface detectors



Signal at ~1000 m core distance
is a stable energy indicator
$\Delta E/E \approx 10\%$

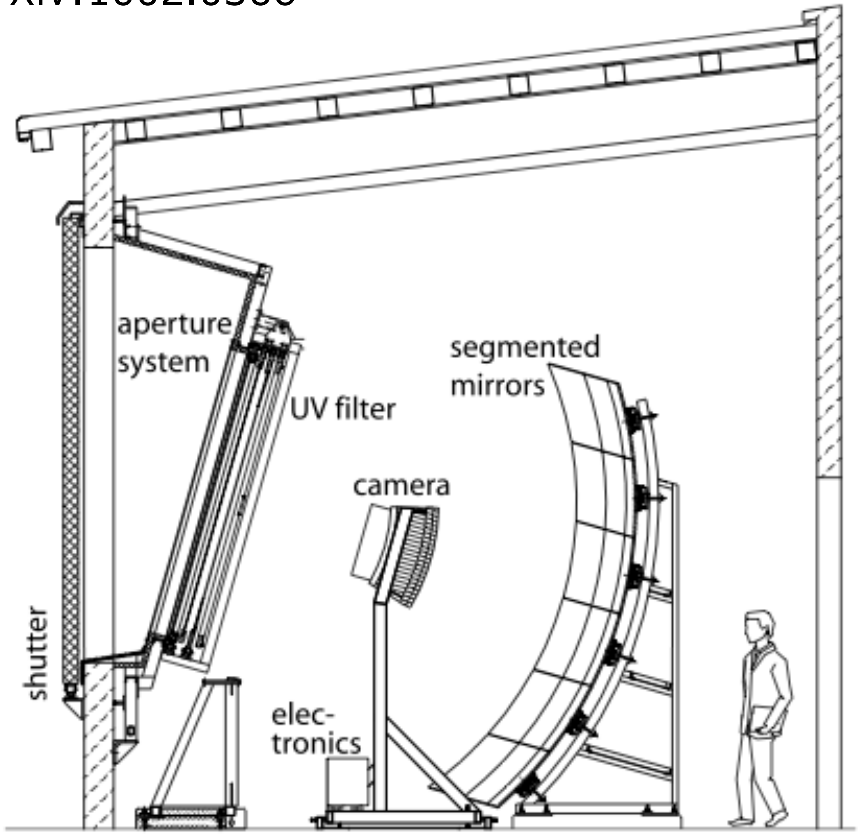
Fluorescence telescopes





provide calorimetric energy measurement

Abraham et al.
arXiv:0907.4282
arXiv:1002.0366



Introduction & overview

Cosmic-ray detectors

- Basics
- Spaced-based instruments
- Ground-based instruments

➢ **Modeling cosmic rays in the Galaxy**

- Processes
- Cosmic-ray diffusion & leaky box models
- Determining model parameters from data
- Analytical vs numerical models

tools to understand data

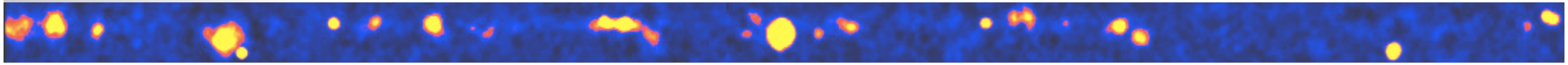
Galactic cosmic rays: local observations

- Composition
- Anisotropy
- Electrons

Probing cosmic rays in the Galaxy: gamma ray astronomy

{Ultra high energy cosmic rays}

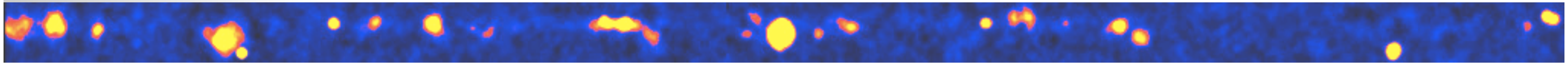
Basics



- Cosmic ray sources (supernovae?) are distributed throughout the disk of the Galaxy
- Cosmic rays wander through the Galaxy, continuously deflected in quasi-random magnetic fields
- Some (very few) of them reach Earth, most escape into extragalactic space

➜ treat cosmic rays as a (relativistic) gas

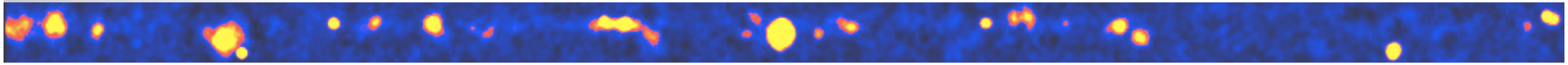
Cosmic ray spectra and composition



Injection/acceleration of CR

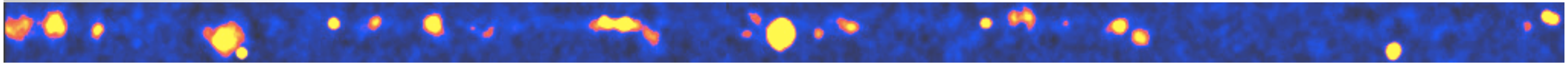
- Distribution of sources
- Reservoir composition of charged particles
- Injection into acceleration process
- Acceleration process and spectra

Cosmic ray spectra and composition



Transport of CR
- in space
  - Spatial diffusion in disk or halo
  - Convection in galactic winds
- in momentum space
  - Energy loss by ionization
  - Re-acceleration (diffusion in momentum space)
- sinks and source terms
  - Escape from Galaxy
  - Nuclear interactions / spallation
  - Radioactive decay

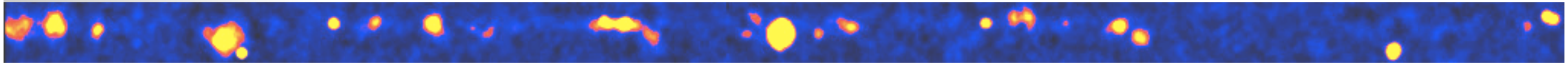
Cosmic ray spectra and composition



Solar modulation / transport in heliosphere

- Diffusion
- Convection
- Adiabatic deceleration

Cosmic ray spectra and composition



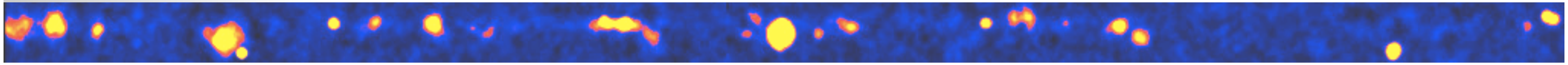
Ginzburg & Ptuskin
Rev. Mod. Phys. 48 (1976) 161

Strong, Moskalenko, Ptuskin
Ann. Rev. Nucl. Part. Sci. 2007, 285

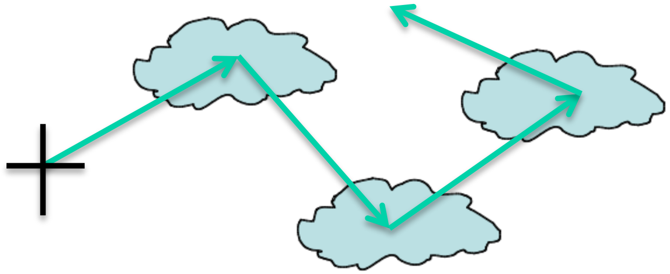
$$\frac{\partial N_i}{\partial t} - \mathrm{div}(D_i \nabla N_i) + \frac{\partial}{\partial E}(b_i N_i) = Q_i - p_i N_i + P_i$$

Diffusion   Energy loss   Sources/Sinks

Diffusion



Simplest model:
$n = t/\tau$ random steps
of size L

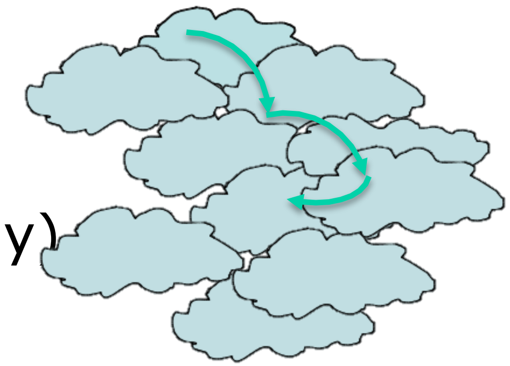


deflection by magnetic fields anchored in gas/clouds

$$\langle \mathbf{r}^2 \rangle = (\mathbf{r}_1 + \mathbf{r}_2 + \ldots + \mathbf{r}_n)^2 = nL^2 = (t/\tau)L^2 = Lct \equiv 2Dt$$

Diffusion coefficient D

Maximum turbulent magnetic field: $L \approx R_{Gyro}$
"Bohm diffusion"



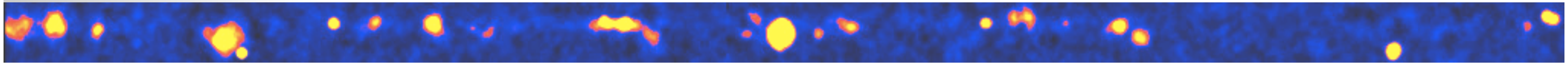
$\rightarrow D = R_{Gyro}c/2$ (or $D = R_{Gyro}c/3$, if done properly)

with $R_{pc} \approx E_{PeV}/B_{\mu G}$,

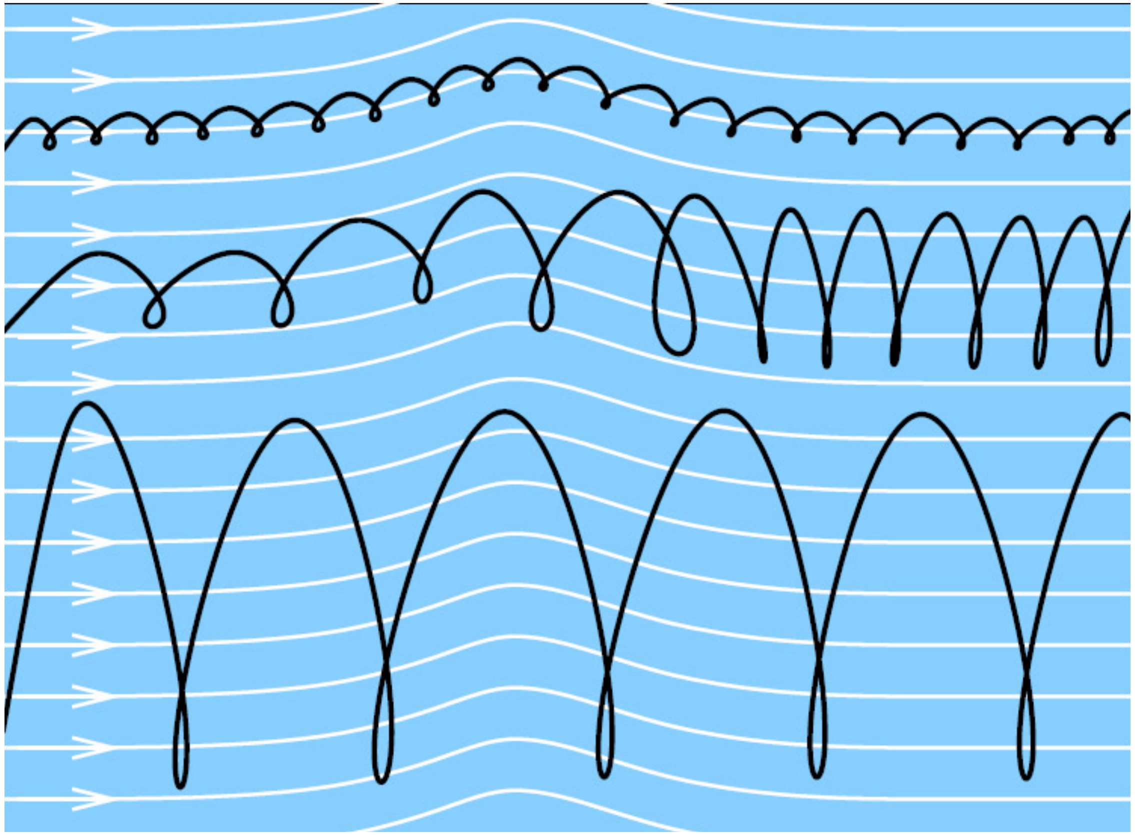
$\langle \mathbf{r}_{pc}{}^2 \rangle^{1/2} \approx 0.3\ (E_{PeV}\, t_{yr}/\ B_{\mu G})^{1/2}$

a few light years in a century !

Diffusion & magnetic fields



Diffusion depends on scale of turbulence of field in relation to gyro radius



Particle follows field line

Pitch angle scattering

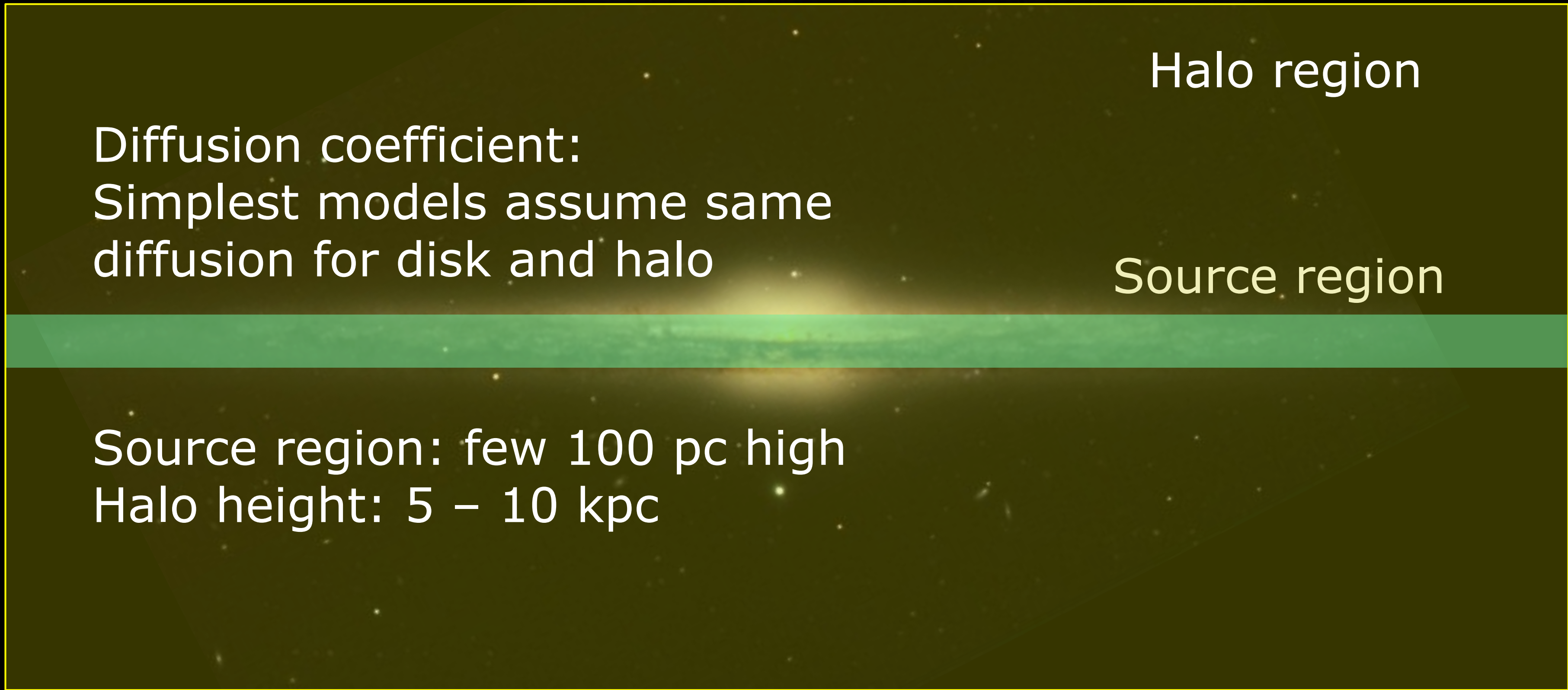
particle ignores turbulence

from R.J. Protheroe, Texas Symp. 2006

Effective diffusion coeff. often much larger than Bohm diffusion

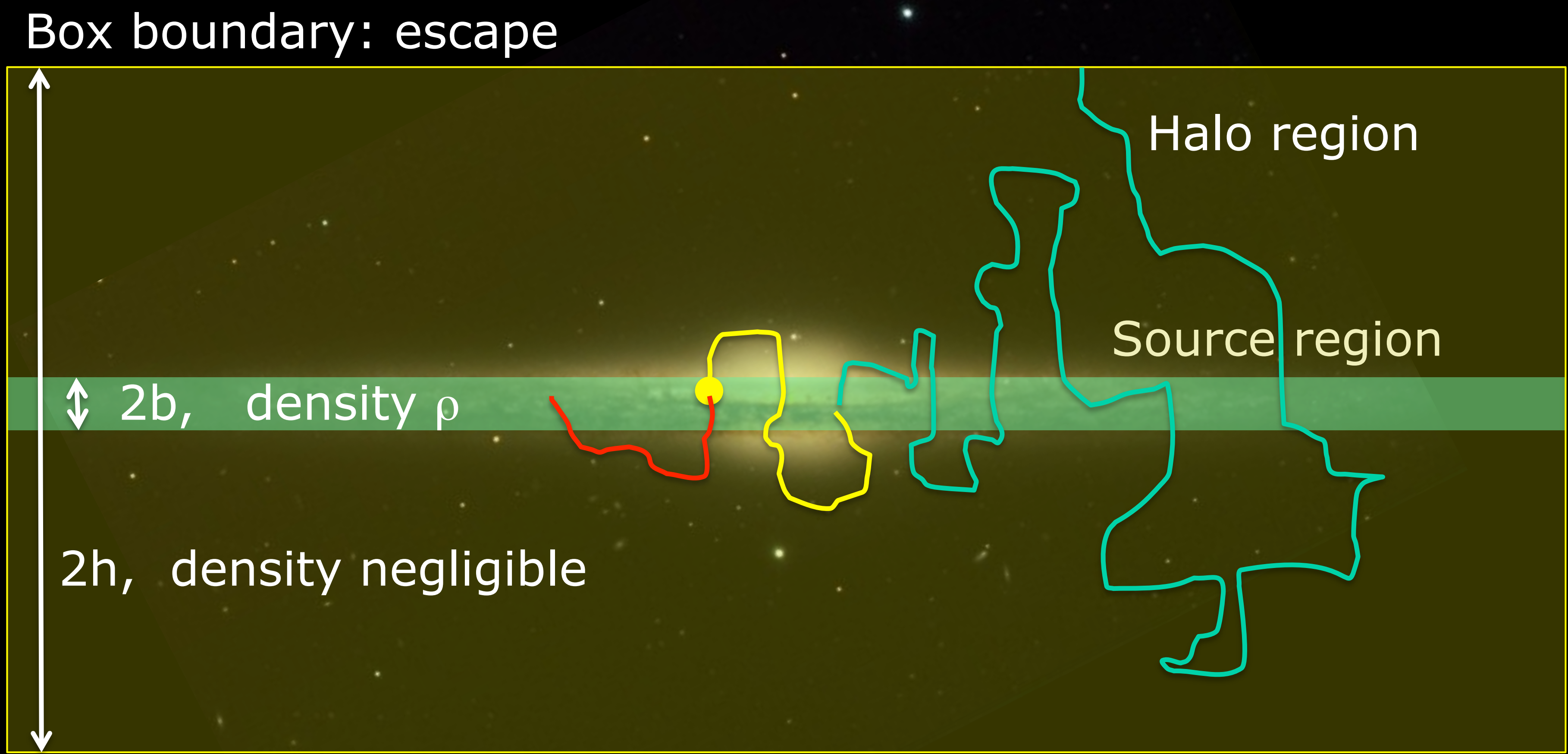
Cosmic ray diffusion models

Box boundary: escape or partly reflecting



Ginzburg & Ptuskin
Rev. Mod. Phys. 48 (1976) 161

Cosmic ray diffusion models

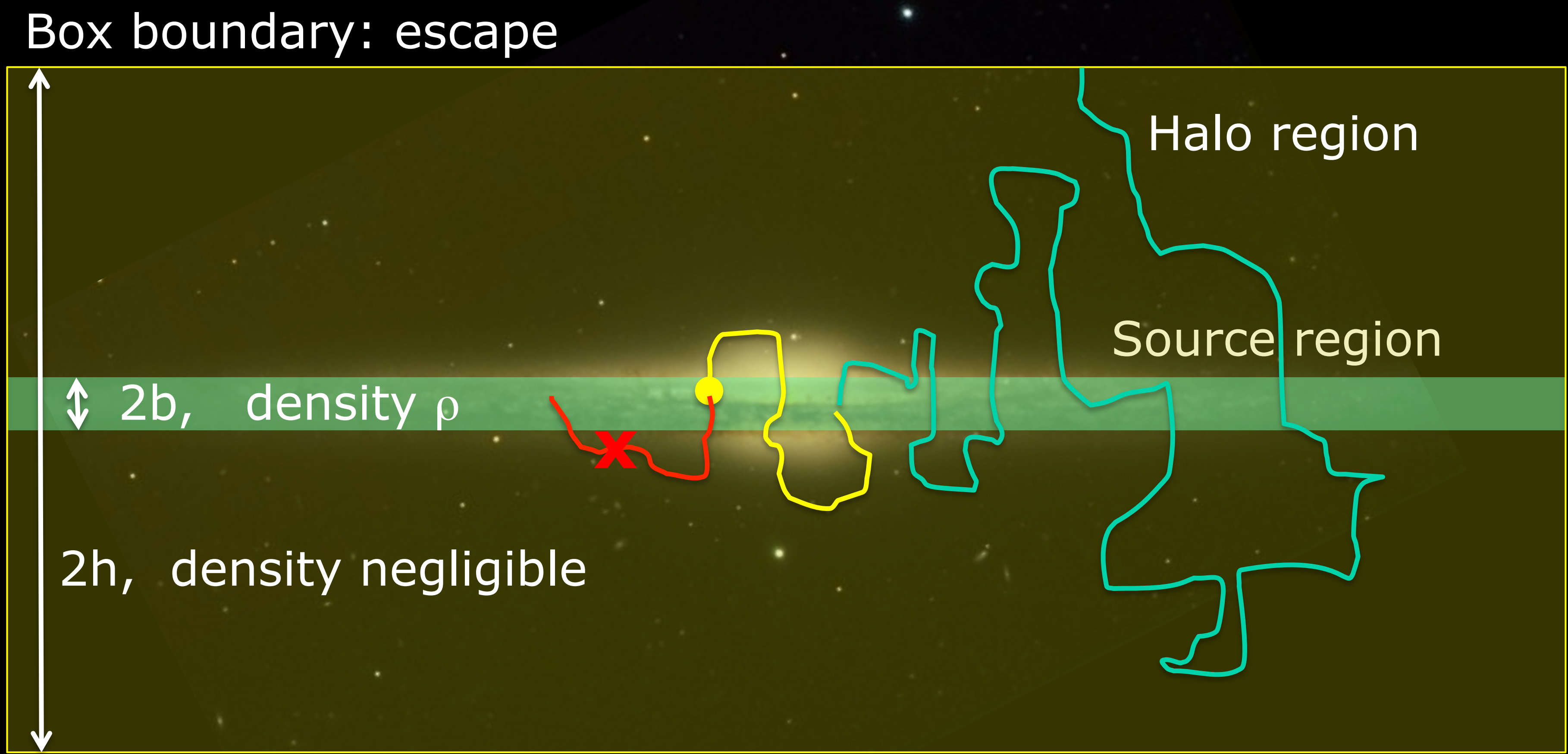


$\langle r^2 \rangle = 2Dt$ ➔ particle escapes after $T \approx h^2/2D$

➔ matter traversed $X \approx c\,T\,\rho\,(b/h) \sim h/D$

measure h/D from yield of reaction products

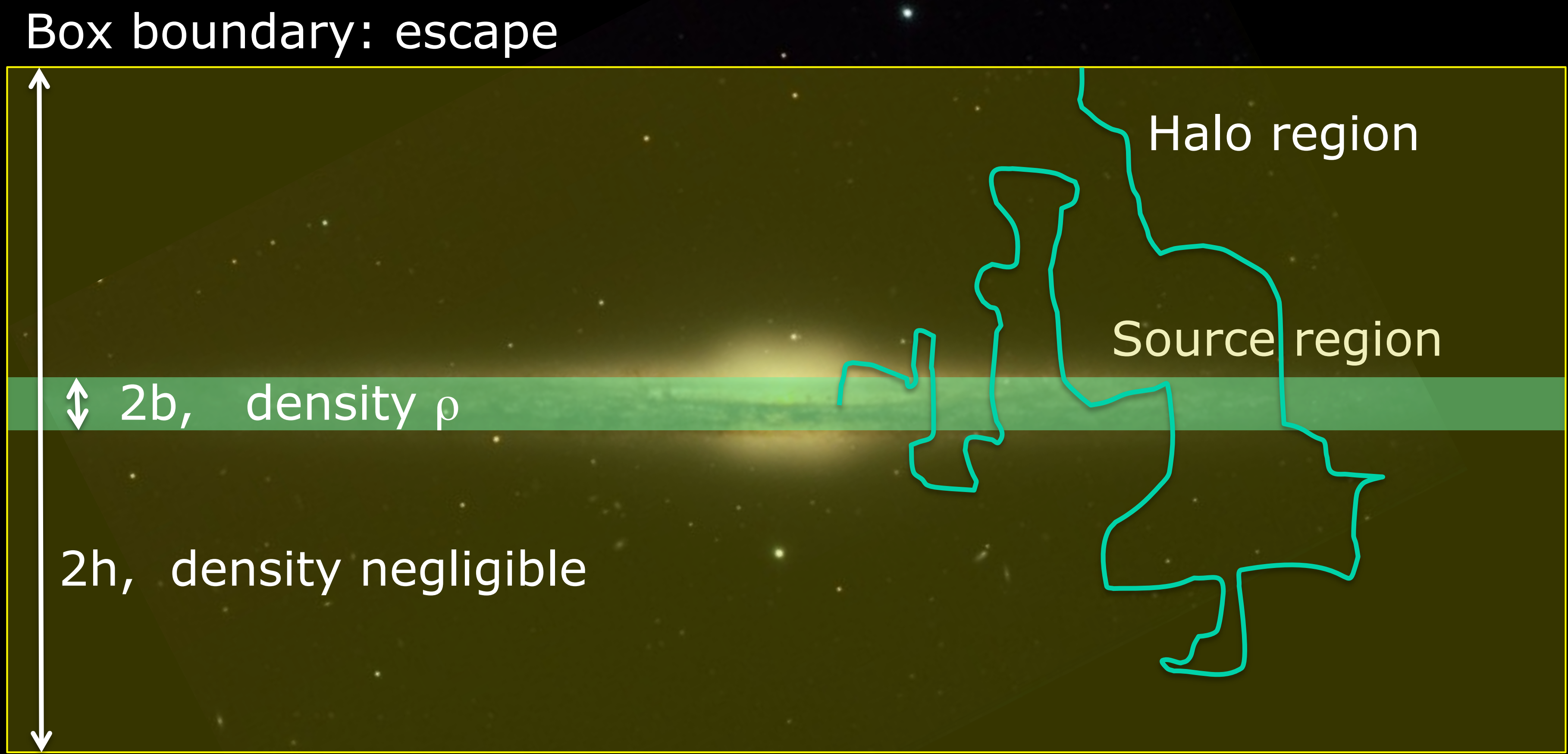
Cosmic ray diffusion models



$\langle r^2 \rangle = 2Dt$ ➔ particle escapes after $T \approx h^2/2D$

measure $T \approx h^2/2D$ using radioactive clocks

Cosmic ray diffusion models

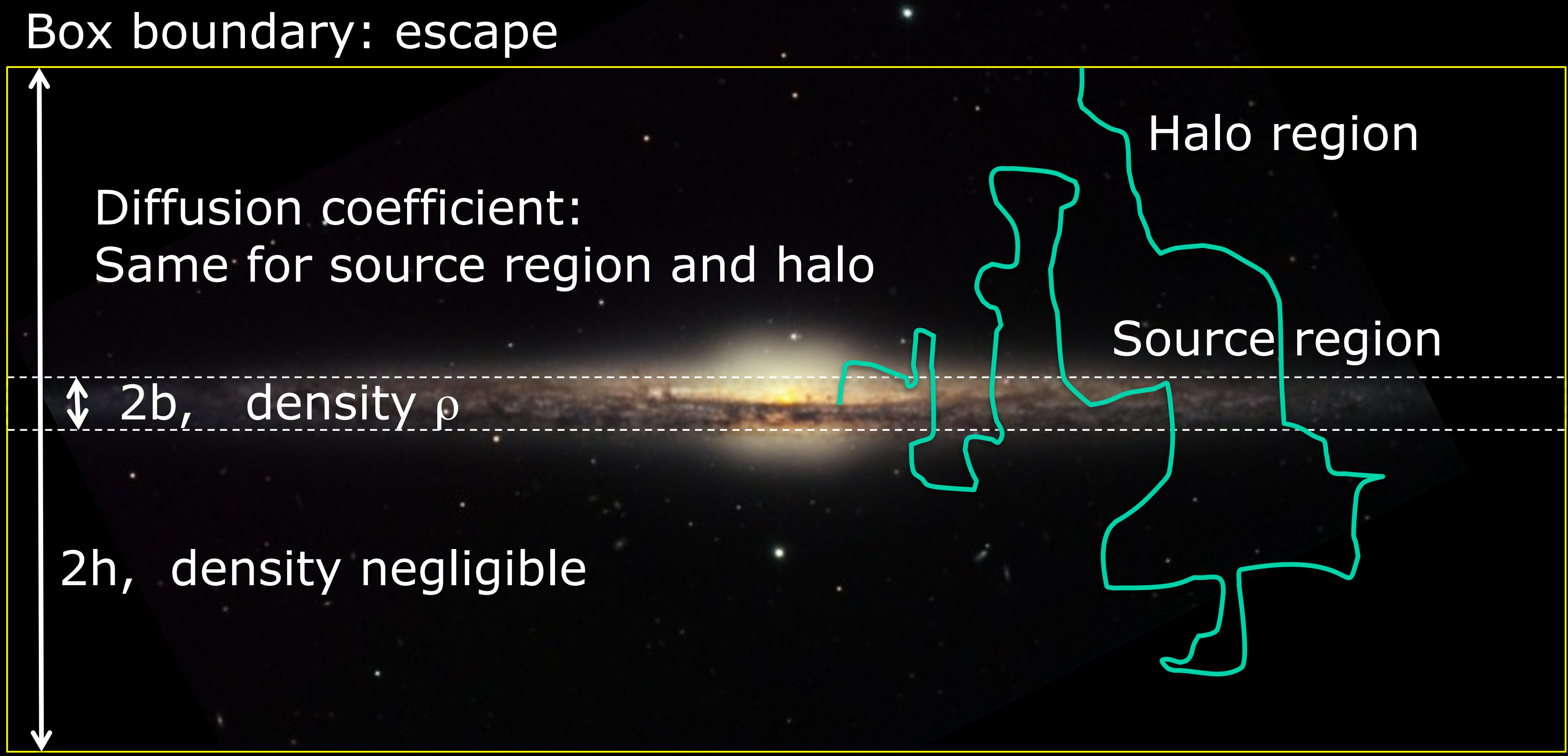


$\langle r^2 \rangle = 2Dt$ ➔ particle escapes after $T \approx h^2/2D$

Energy spectrum: $\Phi \sim \Phi_{source} T(E) \sim \Phi_{source}/D(E)$

steeper than source spectrum

Cosmic ray diffusion models

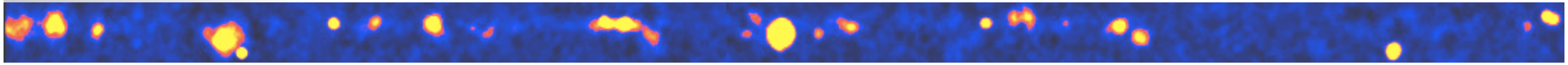


Analytical vs numerical models (GALPROP) galprop.stanford.edu

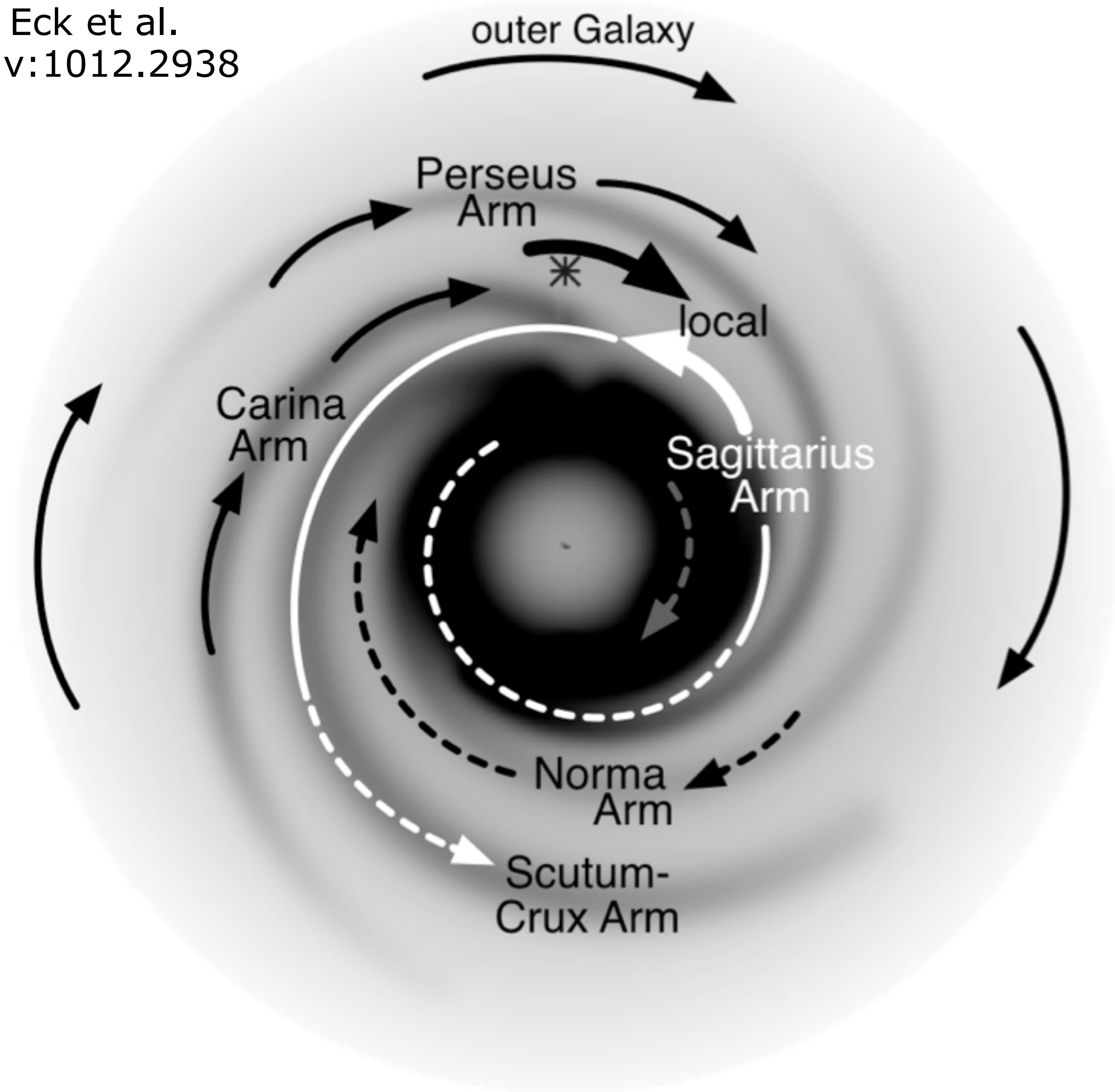
allow real comparison with data

oversimplified, but provide functional relations

Magnetic fields in the Galaxy



van Eck et al.
arXiv:1012.2938



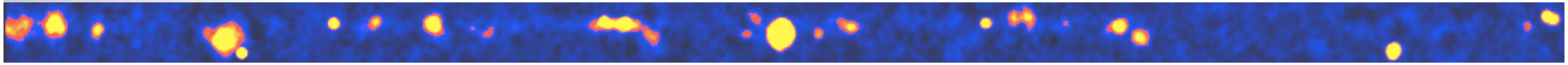
Han et al.
astro-ph/0404221

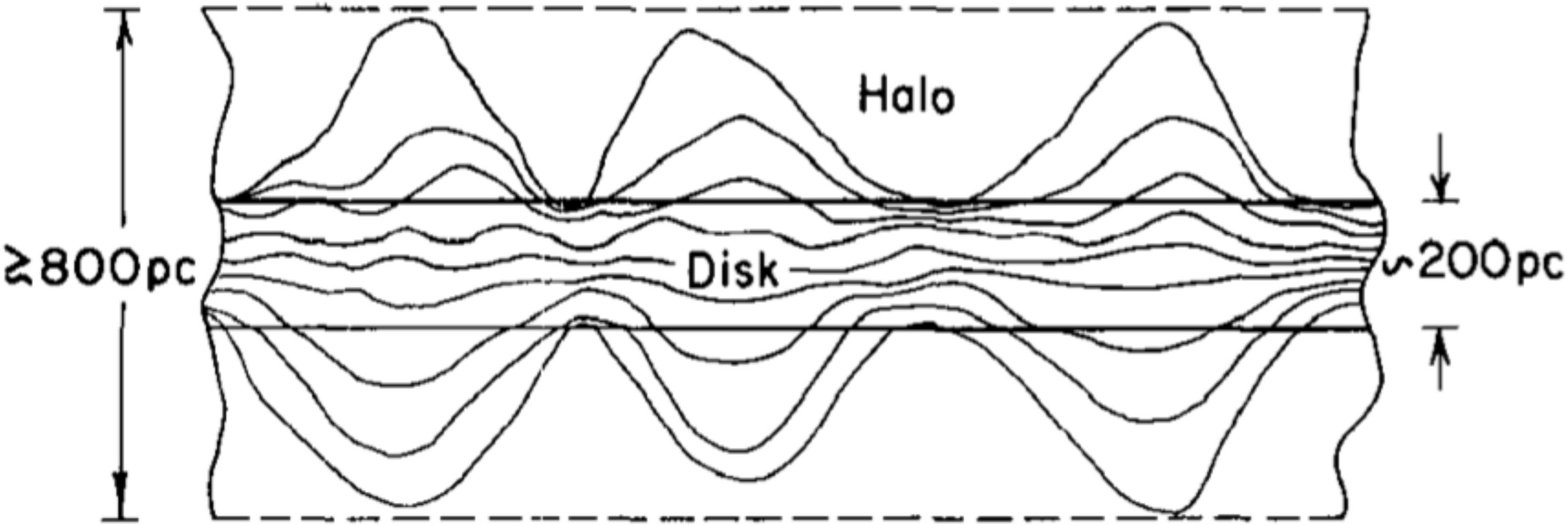
$B_{rms} \approx 6\ \mu G$

$E_B(k) \sim k^{-0.4}$

ordered/random component O(1)

Magnetic fields in the Galaxy

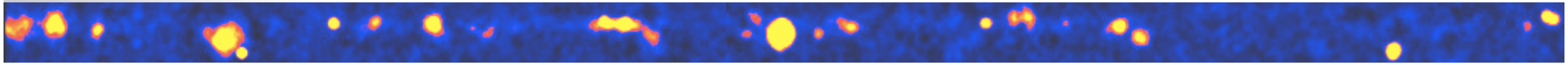




Simpson
Ann. Rev. Nucl Part. Sci. 33 (1983) 323

Halo significantly higher than disk

Measuring & modeling Galactic B-field



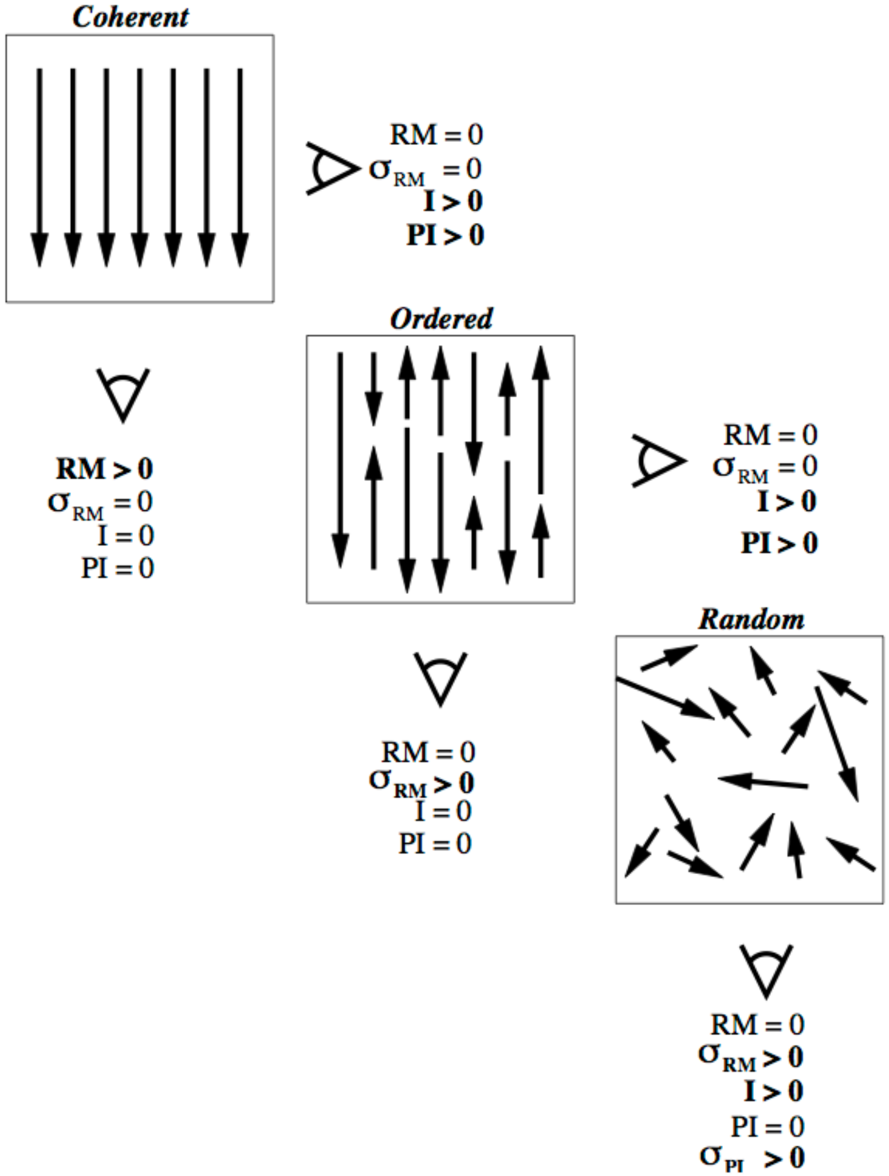
Jaffe et al., arXiv:0907.3994;
1105.5885

Components of field

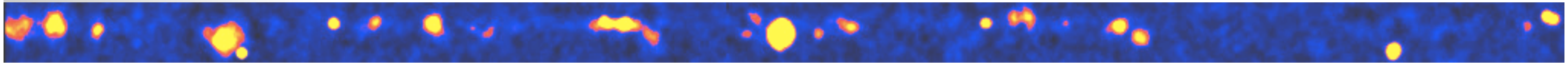
- Coherent
- Ordered
- Random

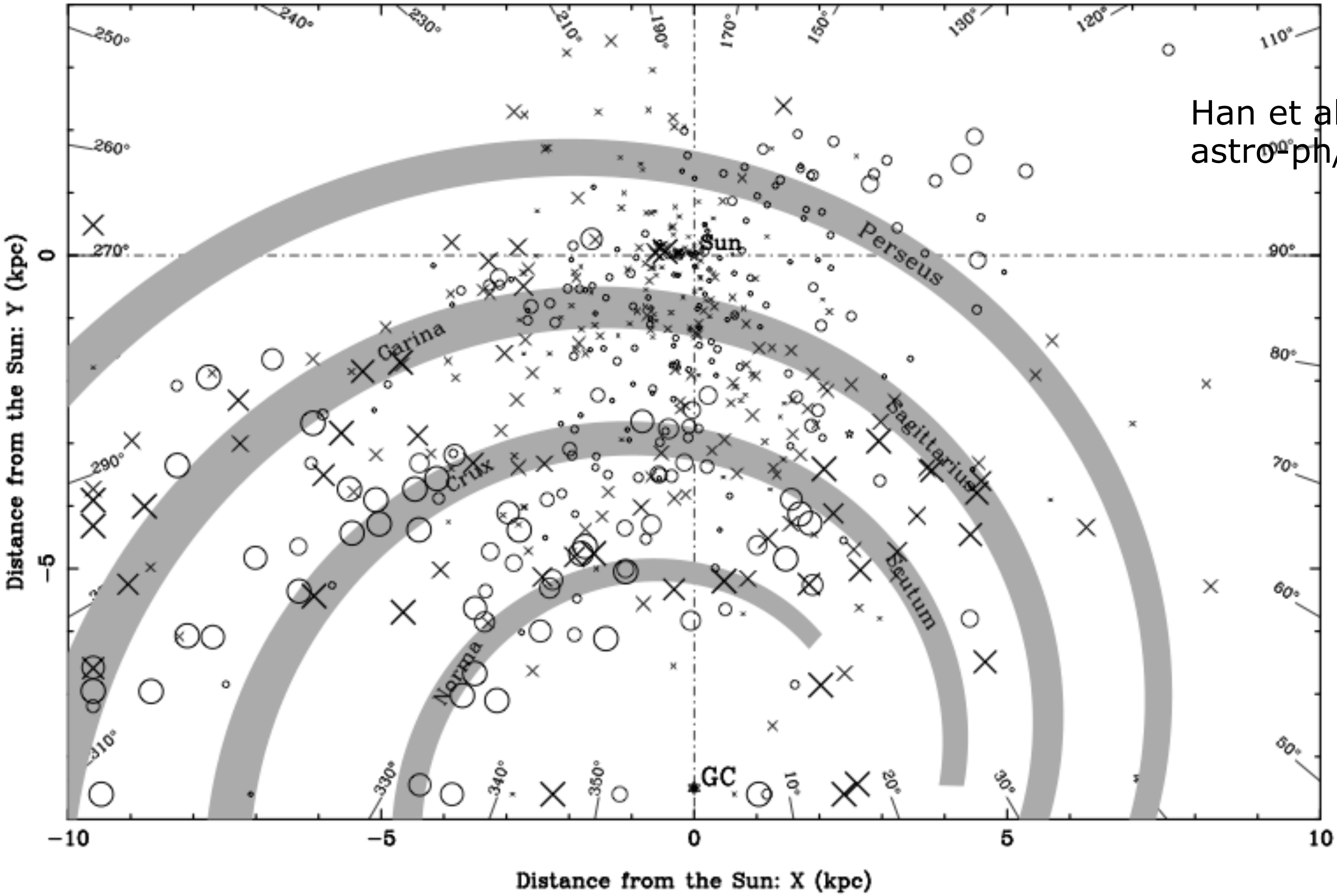
Observables

- CR electron synchrotron rad. intensity
- Synchrotron rad. polarization
- Rotation measure



Pulsar rotation measures





Han et al.
astro-ph/040422

FIG. 1.— Distribution projected on the Galactic plane of the 490 pulsars with well-determined RMs viewed from the North Galactic pole. Pulsars with a positive RM are denoted with crosses, those with a negative RM are denoted with circles, and the symbol area is proportional to the RM. Superimposed onto the pulsar distribution is an approximate outline of the four known spiral arms.

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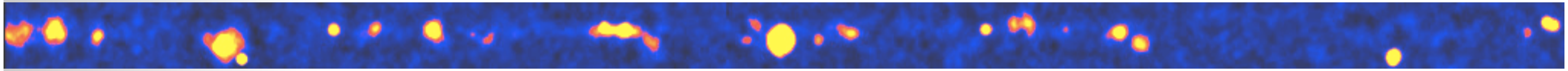
Probing cosmic rays in the Galaxy: gamma ray astronomy

{Ultra high energy cosmic rays}

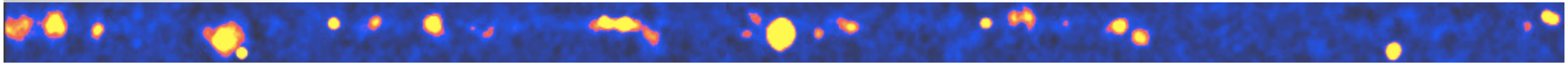
Cosmic ray composition

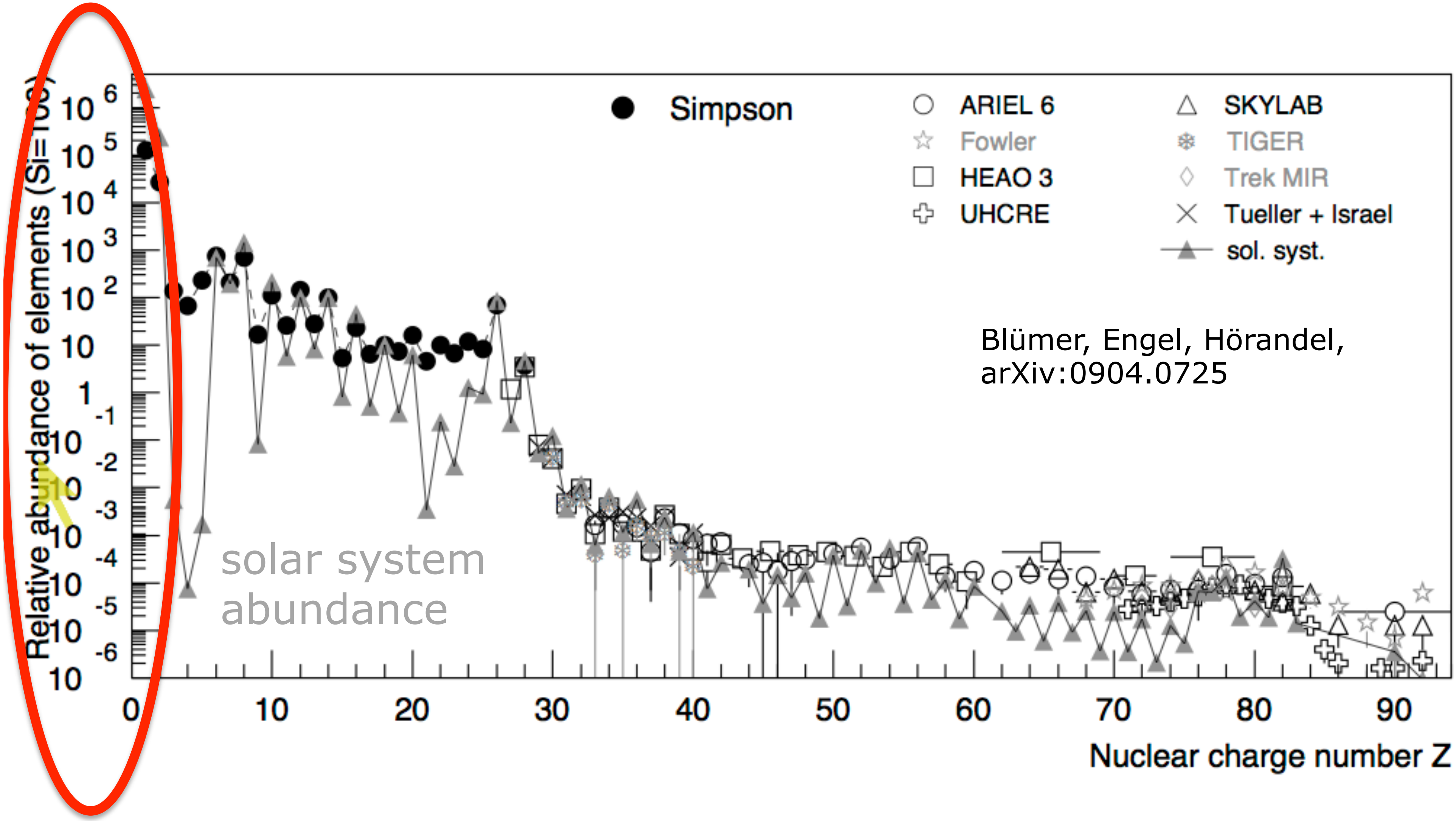


provides a number of useful clues regarding
CR origin and propagation …

by now largely textbook material …

CR composition vs solar abundance





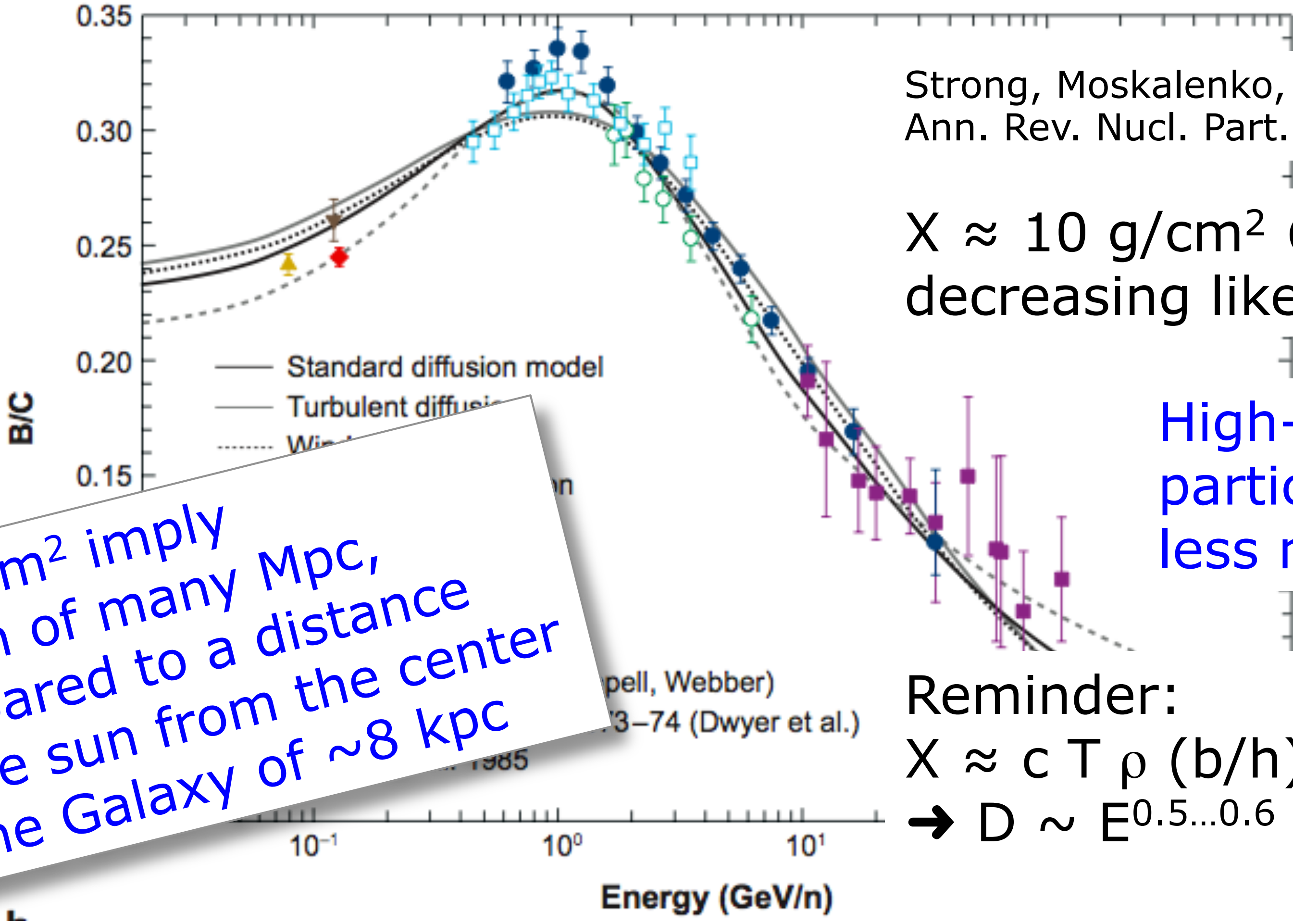
Blümer, Engel, Hörandel, arXiv:0904.0725

Note scale!

Interaction products: spallation nuclei

Some elements (e.g. B) are entirely produced by spallation reactions
Secondary/primary ration measures target “thickness”

Boron
(z=5)
to
Carbon
(z=6)
Ratio



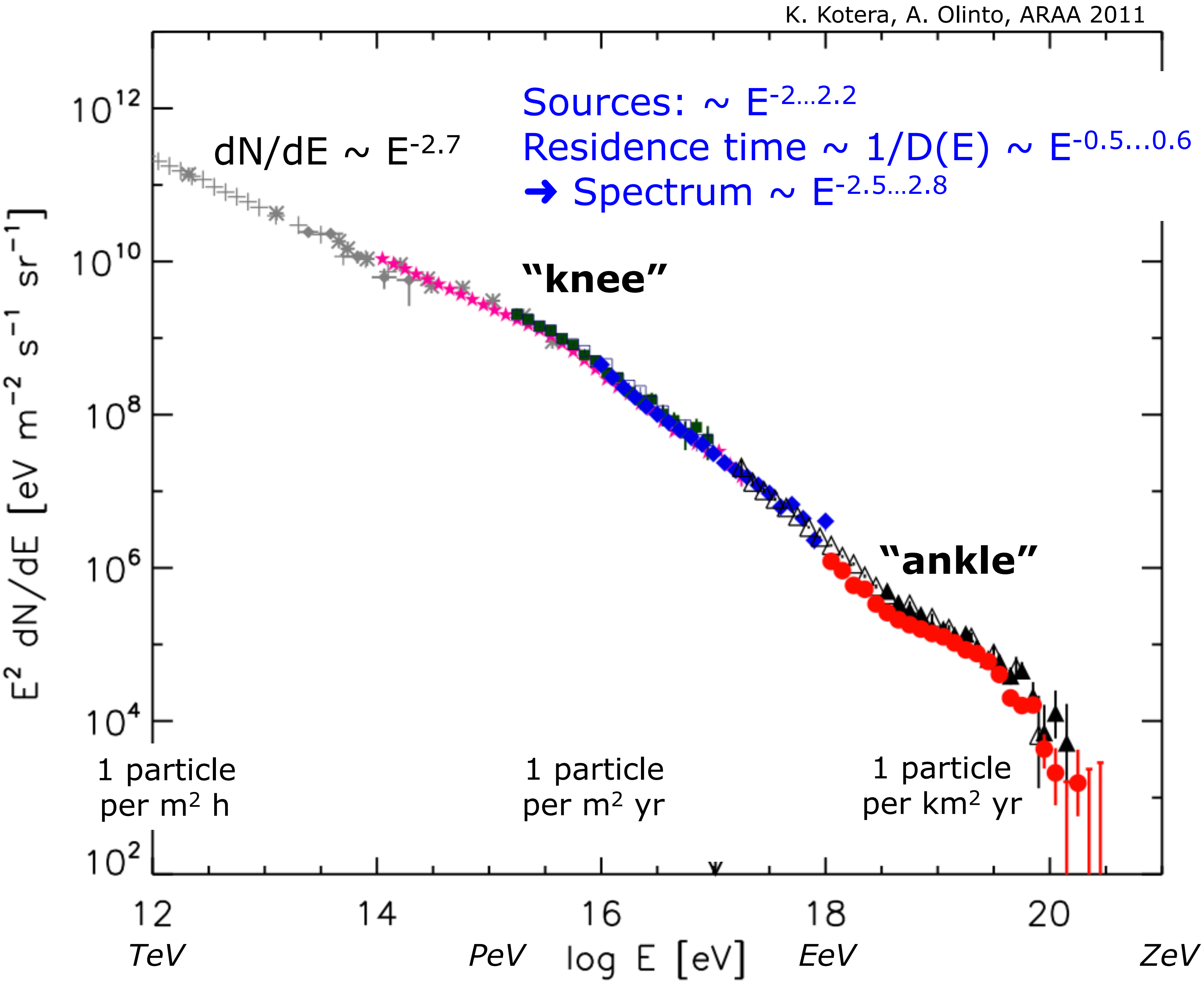
10 g/cm² imply
a path of many Mpc,
compared to a distance
of the sun from the center
of the Galaxy of ~8 kpc

Strong, Moskalenko, Ptuskin
Ann. Rev. Nucl. Part. Sci. 2007

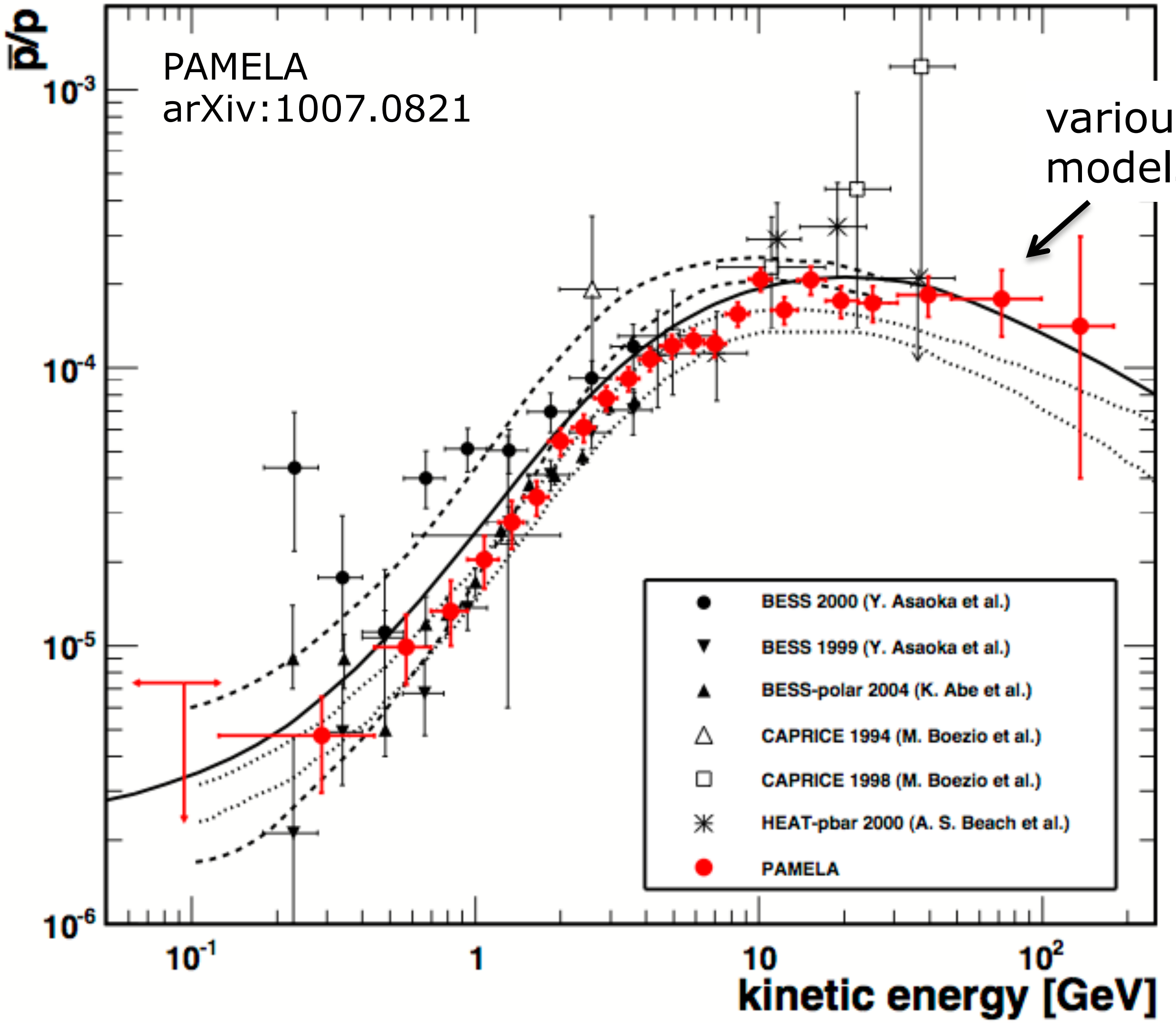
$X \approx 10\ \mathrm{g/cm^2}$ @ 5 GV/c
decreasing like $R^{-0.5\ldots0.6}$

High-energy
particles cross
less material

Reminder:
$X \approx c\,T\,\rho\,(b/h) \sim h/D$
$\rightarrow D \sim E^{0.5\ldots0.6}$

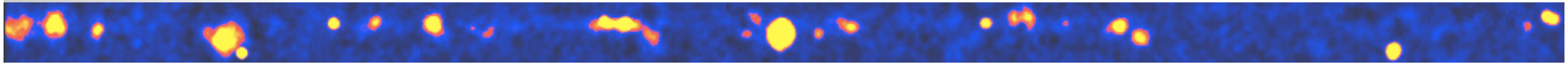

K. Kotera, A. Olinto, ARAA 2011
Sources: ~ E-2…2.2
Residence time ~ 1/D(E) ~ E-0.5…0.6
➜ Spectrum ~ E-2.5…2.8
dN/dE ~ E-2.7
"knee"
"ankle"
1 particle per m2 h
1 particle per m2 yr
1 particle per km2 yr
E2 dN/dE [eV m-2 s-1 sr-1]
10^12
10^10
10^8
10^6
10^4
10^2
12
14
16
18
20
TeV
PeV
EeV
ZeV
log E [eV]

Interaction products: antiprotons

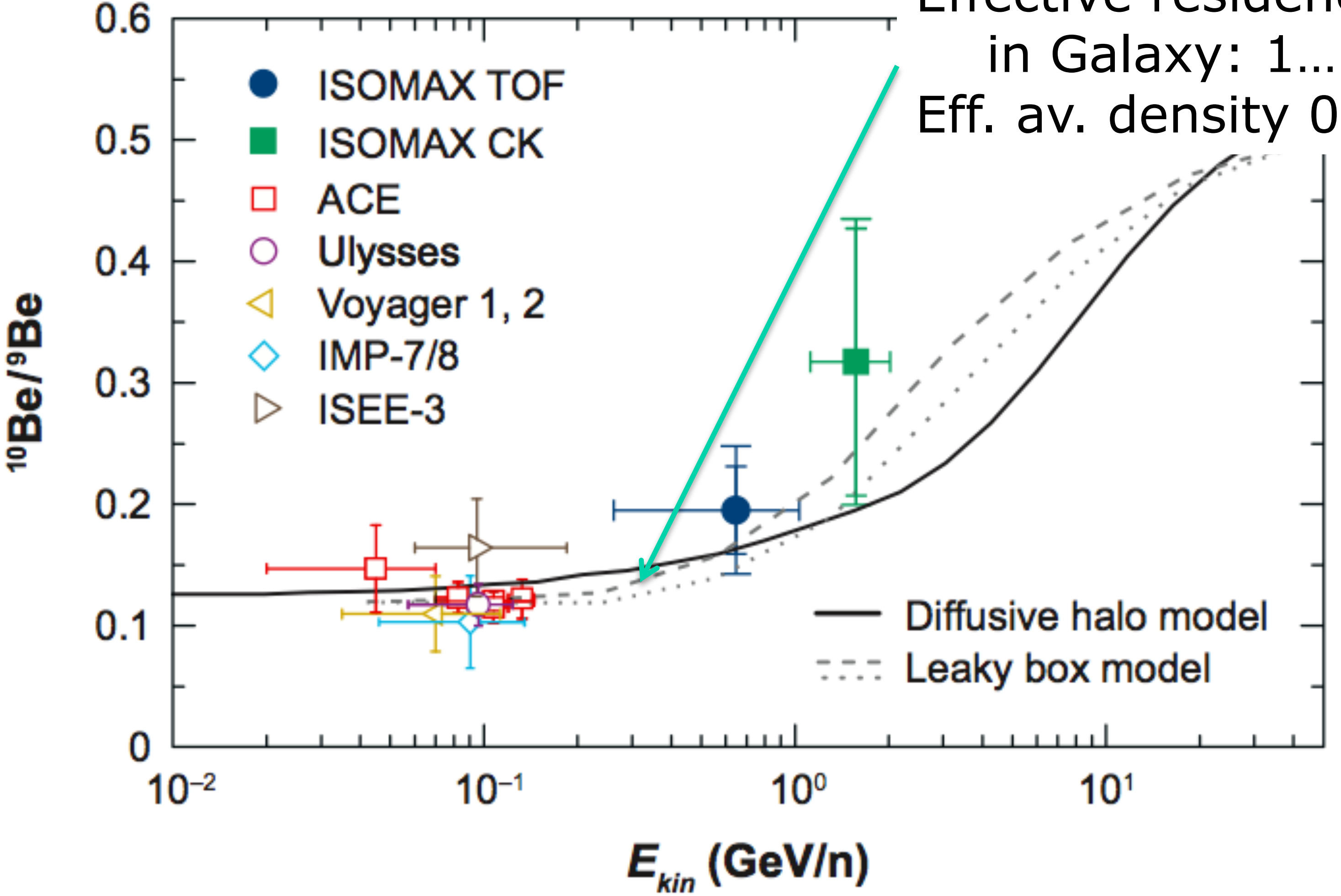


various conventional models

Unstable secondaries as clocks, e.g. ^{10}Be

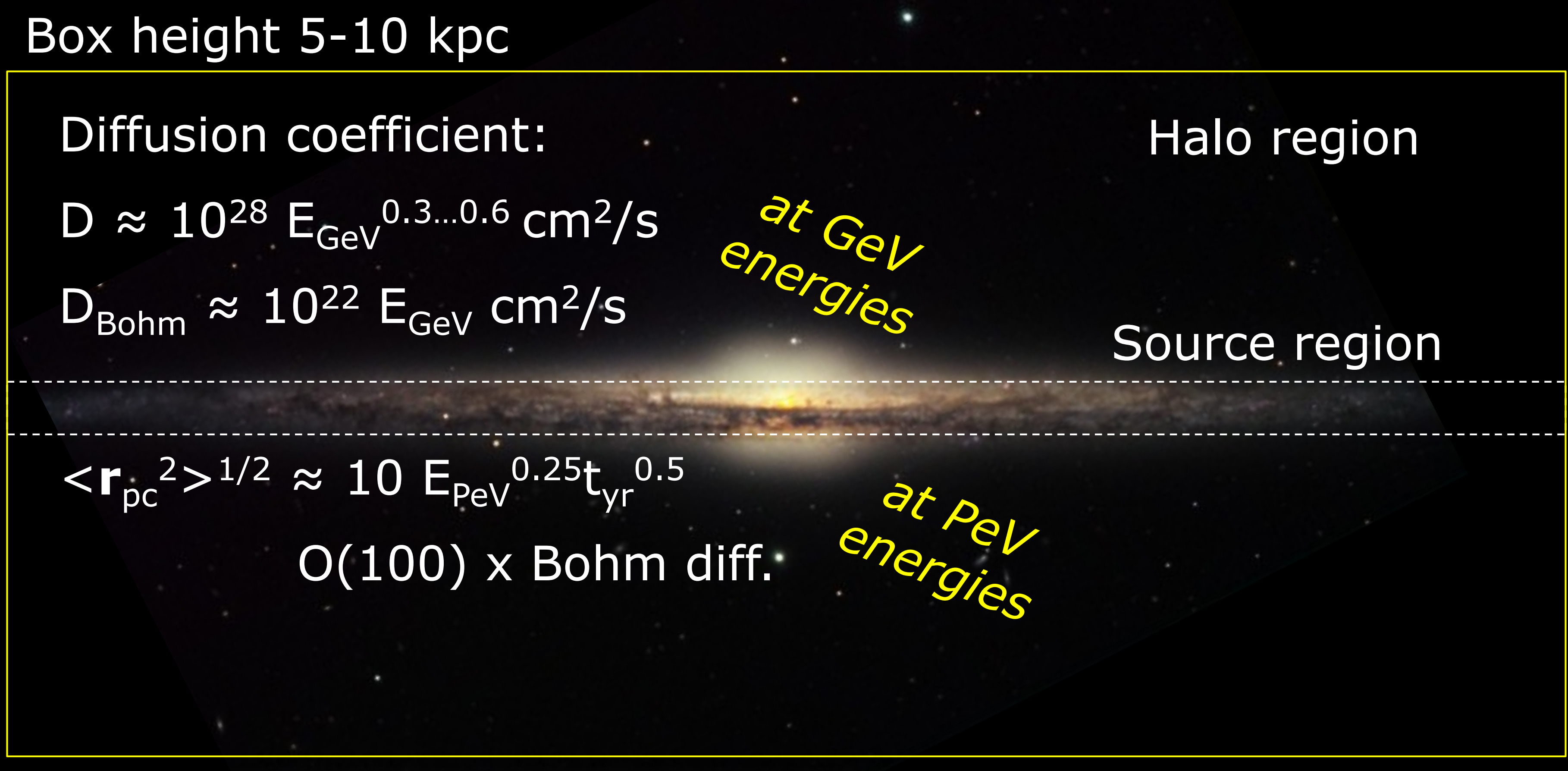


from Strong, Moskalenko, Ptuskin
Ann. Rev. Nucl. Part. Sci. 2007



Half-life of ^{10}Be ≅ 1.5 My
Effective residence time
in Galaxy: 1…2·10^7 y
Eff. av. density 0.2…0.3 g/cm^3

Cosmic ray diffusion models



Cosmic ray energy flow

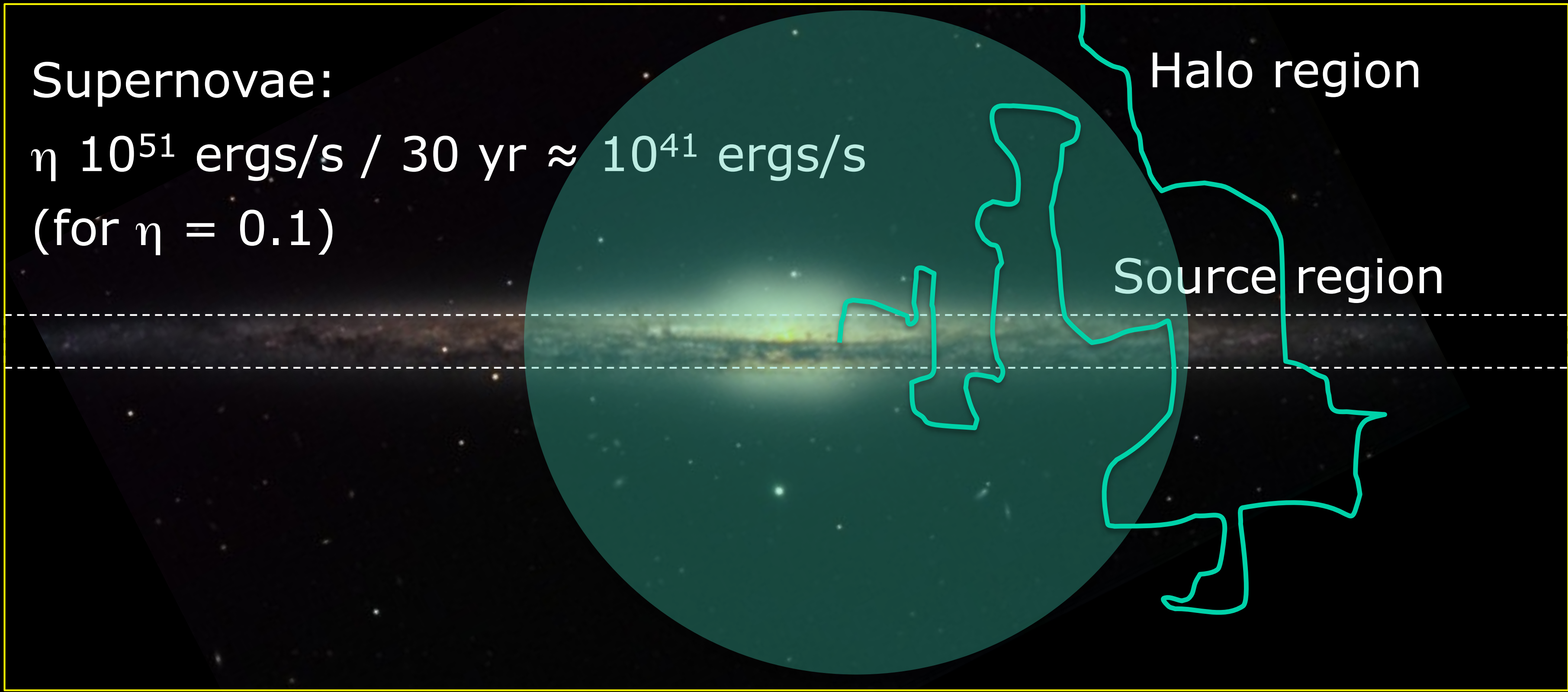
Cosmic ray feed

= Volume x energy density / escape time ≈ 0.3…1 10^{41} ergs/s

Supernovae:

η 10^{51} ergs/s / 30 yr ≈ 10^{41} ergs/s

(for η = 0.1)

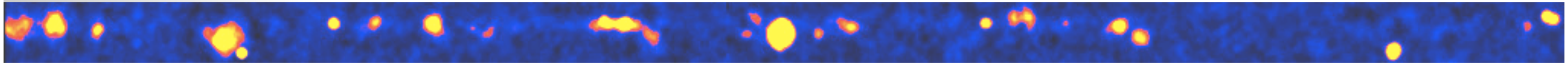


for Myr confinement, CR from $10^{4…5}$ SNR in Galaxy

each "illuminates" a fair fraction of Galaxy

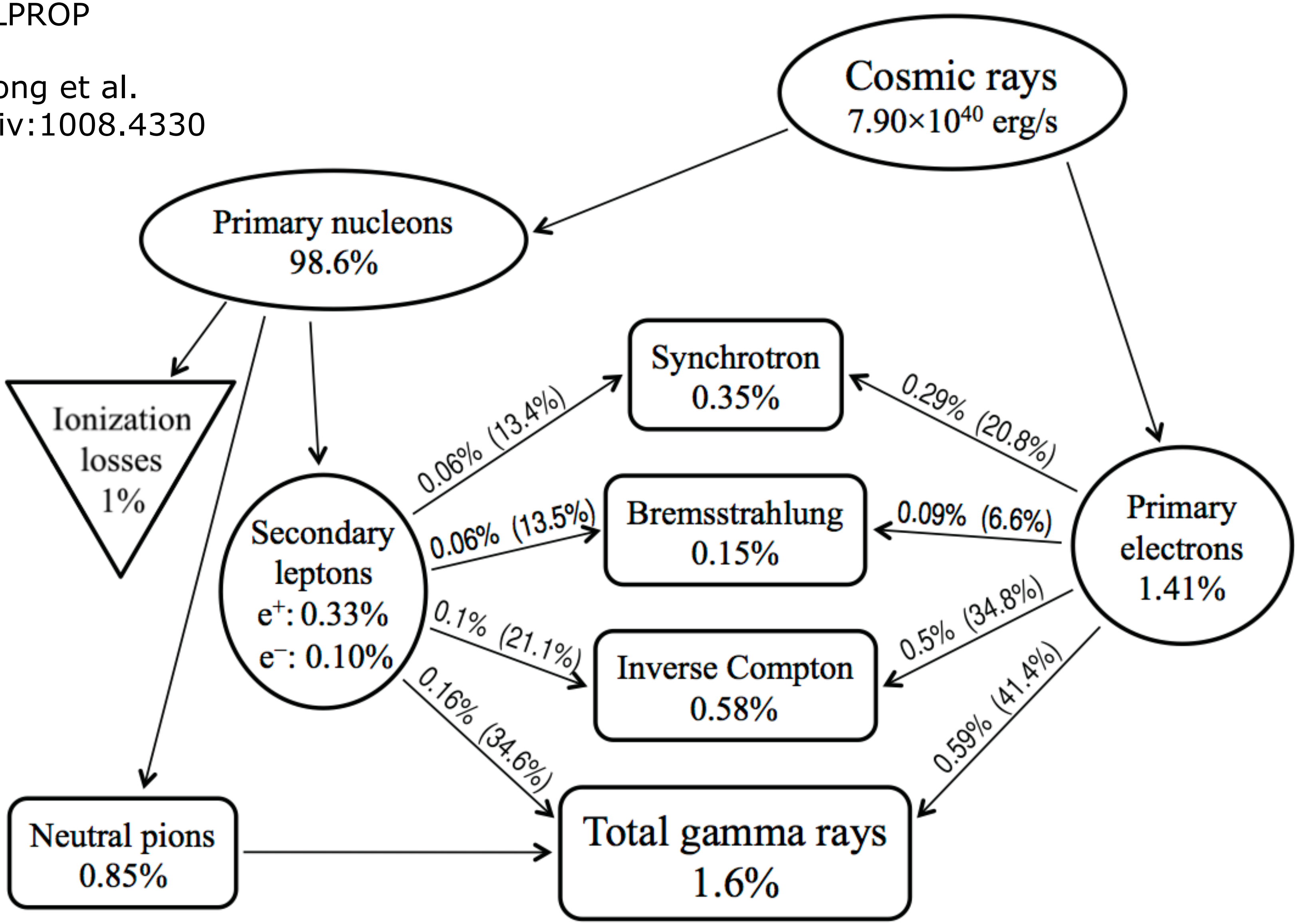
no significant local / temporal variation in CR flux expected

Cosmic ray energy flow



GALPROP

Strong et al.
arXiv:1008.4330

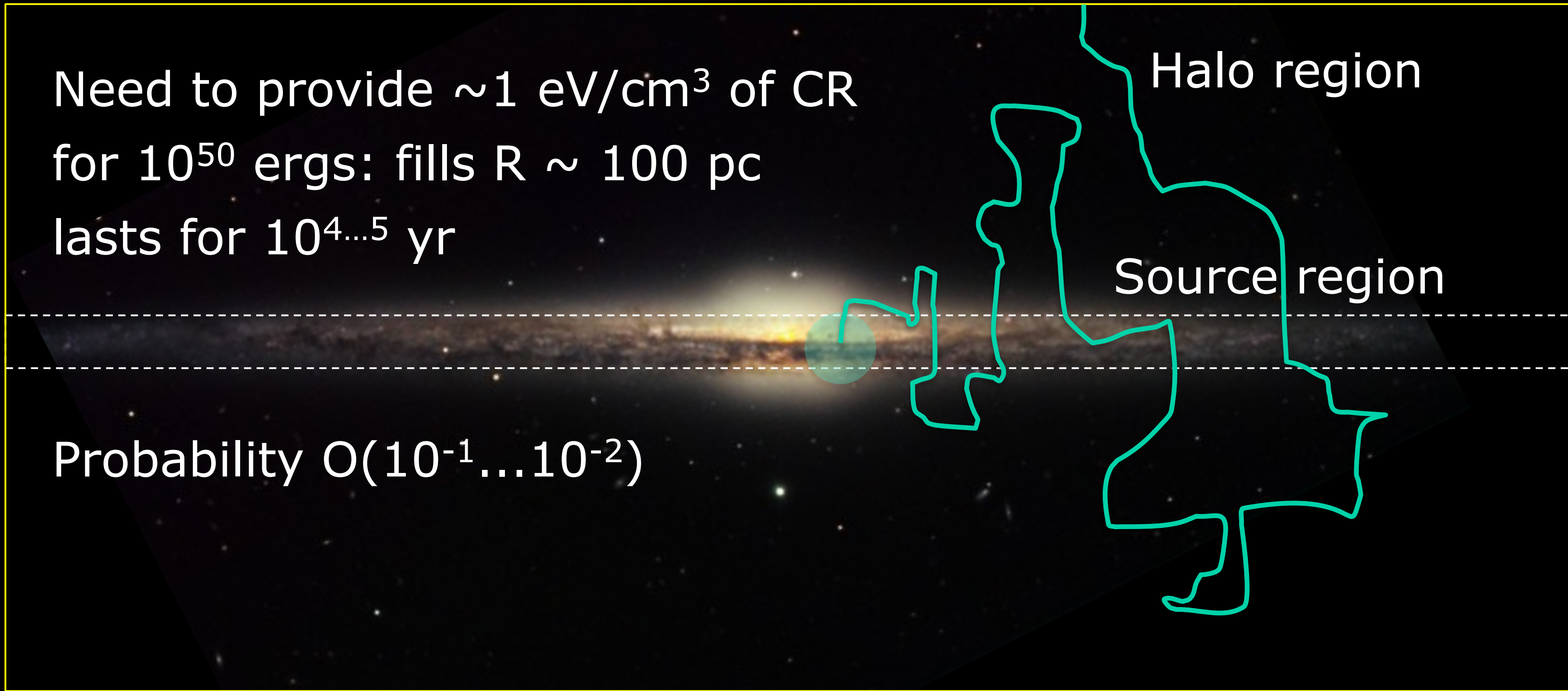


Cosmic ray energy flow

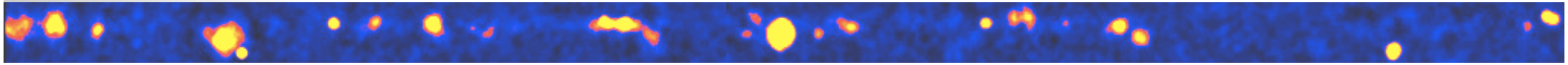
Can a local supernova influence CR spectra ?

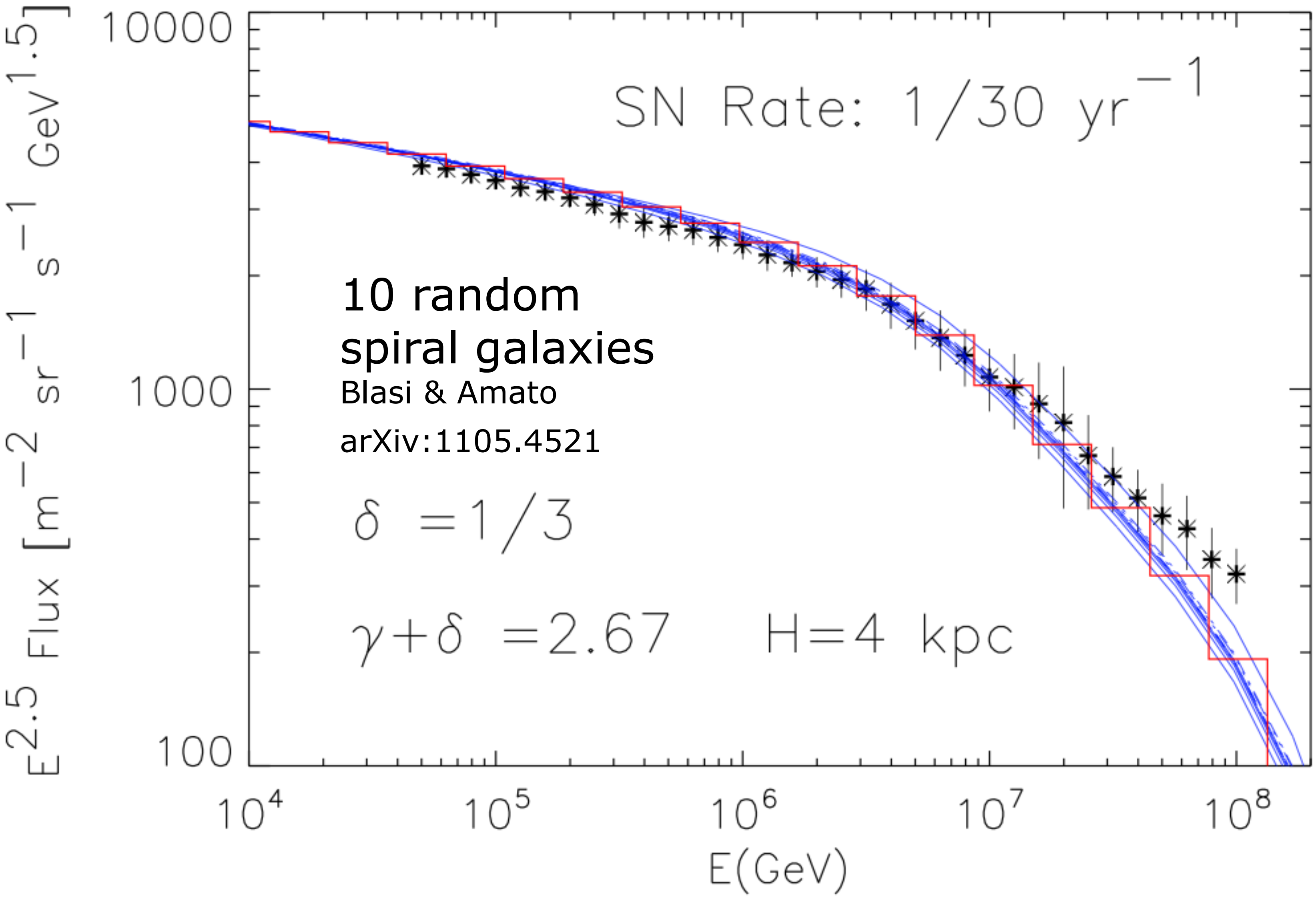
Need to provide ~1 eV/cm^3 of CR
for 10^{50} ergs: fills R ~ 100 pc
lasts for $10^{4...5}$ yr

Probability $O(10^{-1}...10^{-2})$



Modeling CR spectra from SNR





Digression:
Composition details