The Physics & Astrophysics of Cosmic Rays

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What are Cosmic Rays?

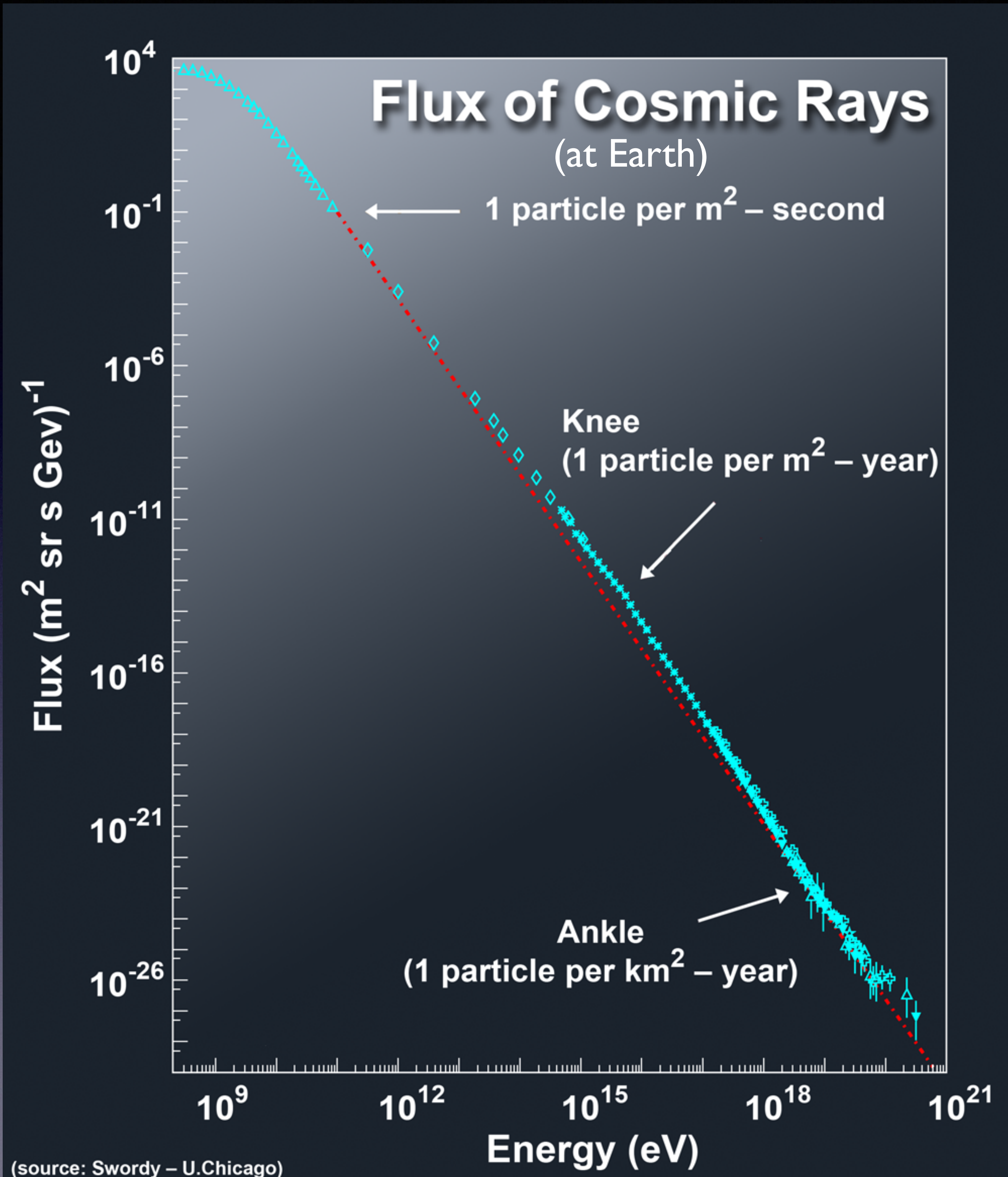
A non-thermal population of relativistic particles that pervade the solar system, galaxies, clusters and intergalactic space

Why you Should Care about Cosmic Rays

- Beautiful physics: nuclear physics, high energy physics, plasma physics …
- An energetically important component of galaxies, clusters, etc.
- Relativistic particles dominate the emission in many wavebands
- Cosmic rays have amazing/surprising/poorly understood properties that can confound attempts at indirect detection of dark matter

Outline

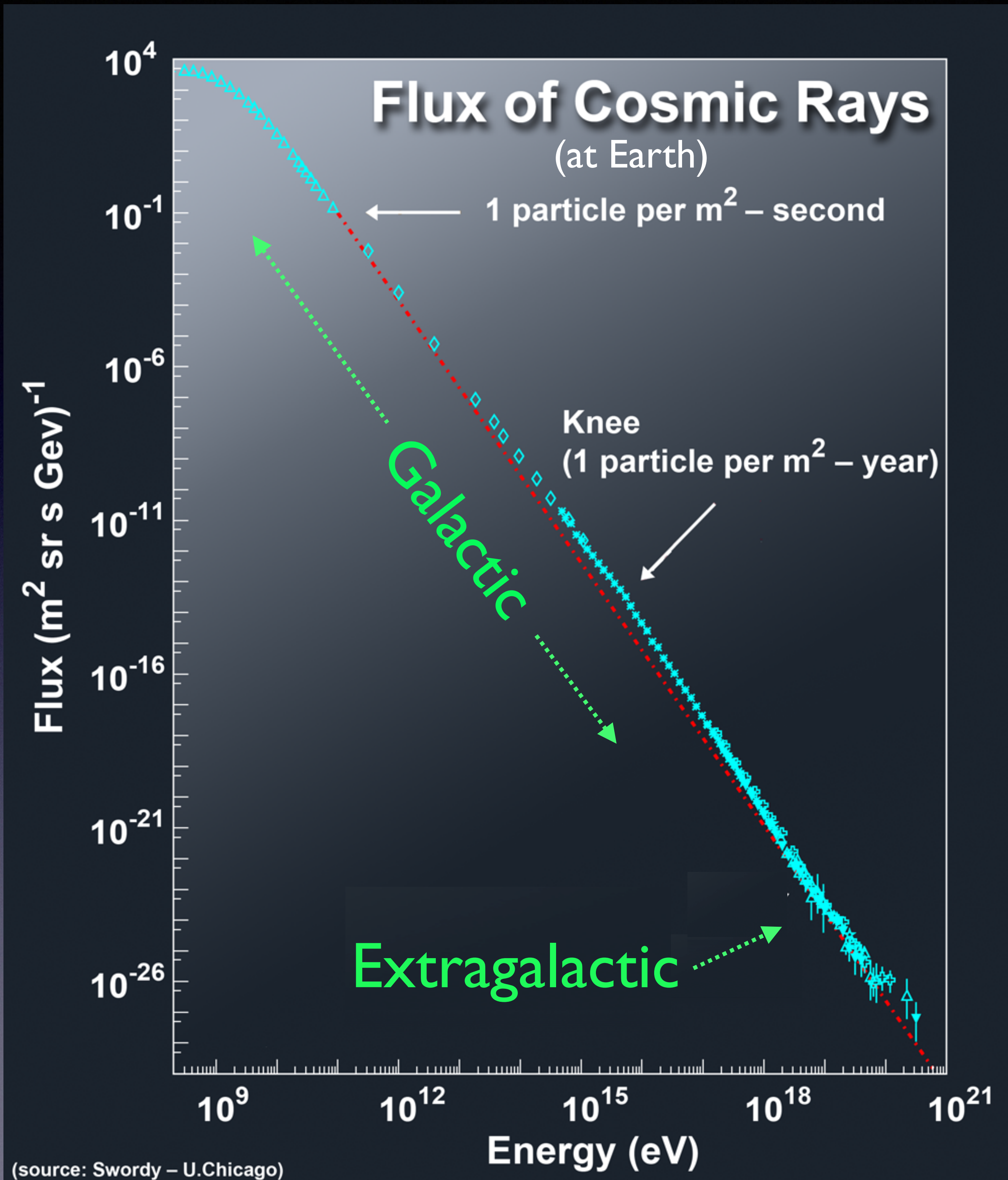
- An Overview of Cosmic Rays in the Galaxy
- The Physical Origin of Cosmic Rays
  - Galactic: Shock Acceleration in Supernovae
- Ultra-High Energy Cosmic Rays: Extragalactic Sources
- The Confinement of Cosmic Rays
- Cosmic Ray (Magneto)Hydrodynamics
- Applications: Galaxies & Clusters
- Open Problems



Composition

mostly protons
at $\lesssim 10^{15}$ eV
(*lots* of detailed composition info)

some indication of heavier nuclei
at $E \gtrsim 10^{18}$ eV



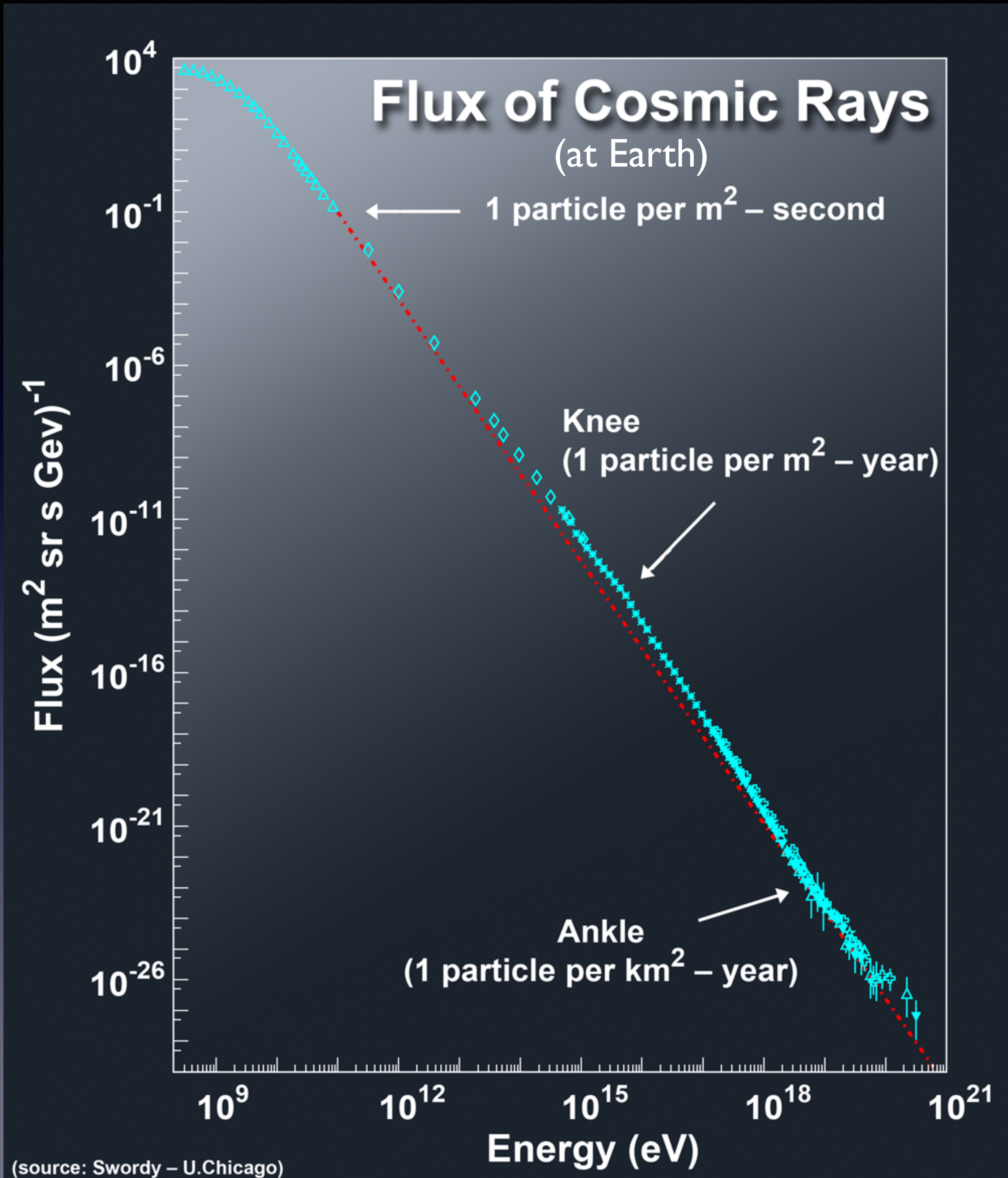
Larmor Radius

$r_L = E/ZeB$

$$r_L \simeq 10\,\mathrm{kpc}\frac{E/(10^{17}\ \mathrm{eV})}{Z(B/1\mu G)}$$

GeV Coulomb mfp
$\sim 10^3\, n^{-1}\, D_{Horizon}$

Interaction with
EM Fluctuations
Govern CR Motion



Ion Spectra & Energetics

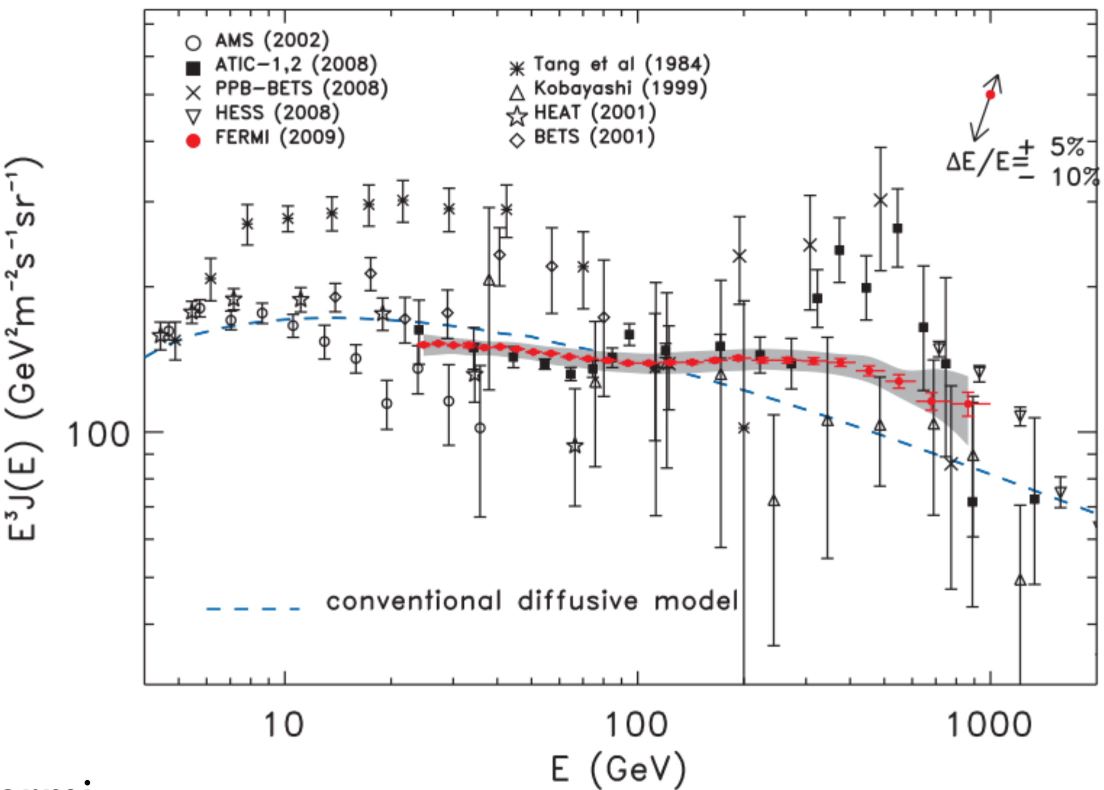
$$\frac{dN}{dE} \propto E^{-2.7}$$

$$\frac{dF_E}{d\ln E} \propto E^{-0.7}$$

most of the energy is
in ~GeV CR protons

energy density
near Earth
$\sim 2\times10^{-12}$ erg cm^{-3}
$\sim$ eV cm^{-3}

Electrons & Positrons



Fermi

e/p ~ 0.02 at ~ GeV

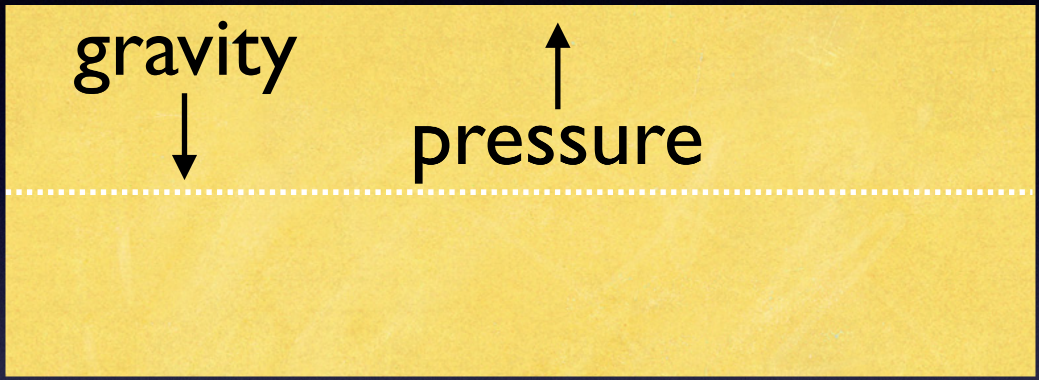
$$\frac{dN}{dE} \propto E^{-3.1}$$

$$\frac{dF_E}{d \ln E} \propto E^{-1.1}$$

e^+/e^- spectrum steeper than protons bec. of radiative losses

(synchrotron & inverse Compton)

Force Balance in Galaxies:
CRs and Magnetic Fields are Important!



Galactic Disk w/ Gas Surface Density Σ_g

Hydrostatic Equil: $P_{midplane} \sim \pi G \Sigma_g^2$
(+ DM, stellar contribution)

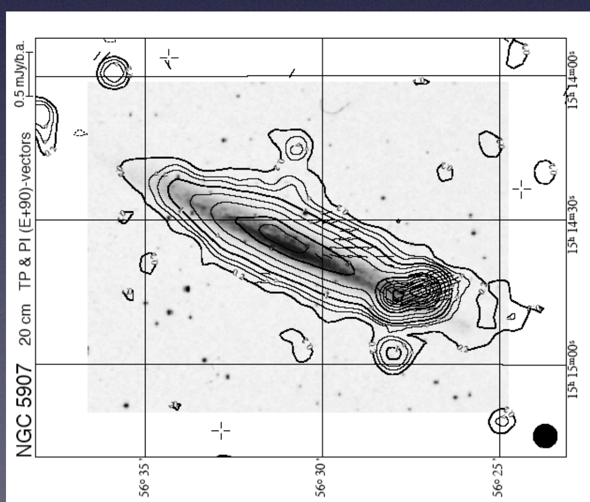
Milky Way: $P_{midplane} \sim 4\ 10^{-12}$ erg cm^{-3}

roughly equal contributions from CRs, B-fields, gas turbulence

(unclear whether this extends to other galaxies, in particular with galactic winds — more later)

Why $P_{CR} \sim P_B \sim P_{Gravity}$?

Rough Idea: B-field & CR Energy Build Up
Until they are Dynamically Important ~ $P_{Gravity}$
Then B-field/CRs are Unstable



Normal Spirals: Synchrotron
(B-field, CR) scale-heights
~kpc > H_{gas} ~ 200 pc

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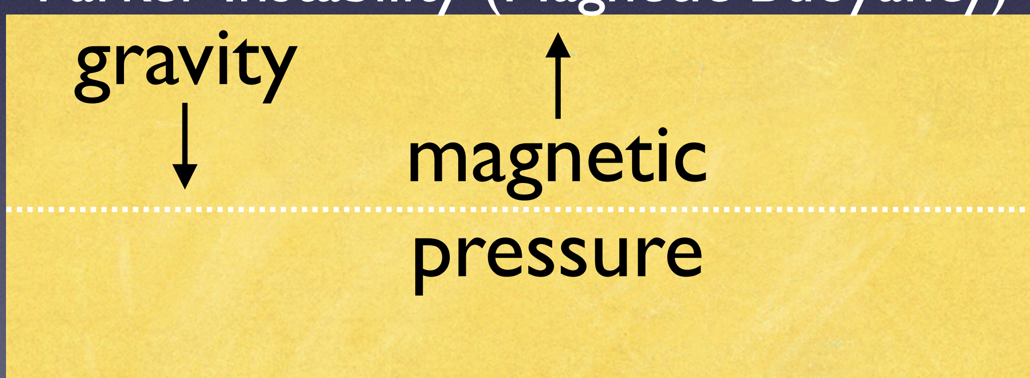
Parker Instability (Magnetic Buoyancy)



Unstable if

$$\frac{d}{dz}\left(\frac{B^2}{\rho^2}\right) < 0$$

(neglects gas/CR pressure)

Confinement Time

(Milky Way CRs Near the Sun)

- ^{10}Be: CR with 1/2 life of 1.6 10^6 yrs. Abundance compared to ^{7}Be & ^{10}Be ⇒

$$\boxed{t_{esc} \simeq 3\,10^7 \;\text{ yrs} \;\left(\frac{E}{3\,\text{GeV}}\right)^{-1/2} \quad \ll \text{kpc}/c \sim 3000\,\text{yrs}}$$

- *If* diffusion: $t_{esc} \sim \dfrac{R^2}{\ell c} \quad \Rightarrow$

$$\boxed{\text{mfp } \ell \sim 0.1\,\text{pc} \;\left(\frac{E}{3\,\text{GeV}}\right)^{1/2}}$$

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- Abundance of spallation products Be, B, Li ⇒
  - CRs traverse a column density $\Sigma_g \cong 5$ g cm^{-2} (E/3 GeV)$^{-1/2}$
  - CRs interact with gas density $\cong \Sigma_g/(c\, t_{esc}\, m_p) \cong 0.1$ cm^{-3}
    - << $n_{avg} \cong 1$ cm^{-3}: inhomogeneous ISM; CR scale-height >> gas scale-height

Inferences from Confinement Time Measurements

- Injection Spectrum ≠ Measured Spectrum

$$\underbrace{\frac{dN}{d\ln E}}_{\text{measured}} \simeq \underbrace{\frac{d\dot{N}}{d\ln E}}_{\text{injected}} t_{esc}(E) \qquad \boxed{\frac{d\dot{N}}{d\ln E} \propto E^{-2.2}}$$

roughly equal energy injected per decade in energy: $\frac{d\dot{F}_E}{d\ln E} \sim \mathrm{const}$

- For e^+/e^- synchrotron/IC cooling dominates

$$t_{\mathrm{synch}} \simeq 3\times10^7\,\mathrm{yrs}\left(\frac{B}{6\mu G}\right)^{-2}\left(\frac{E}{3\,\mathrm{GeV}}\right)^{-1}$$

$$\frac{dN}{d\ln E} \simeq \frac{d\dot{N}}{d\ln E} t_{synch}(E) \qquad \boxed{\frac{d\dot{N}_e}{d\ln E} \propto E^{-2.1}}$$

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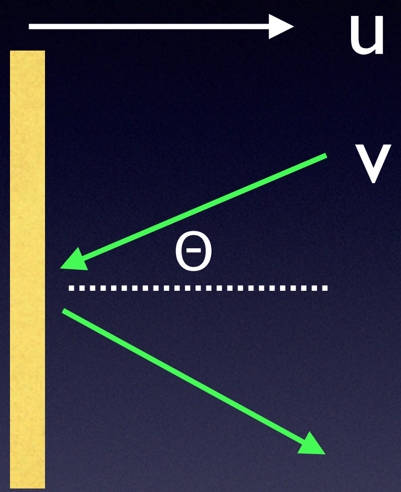
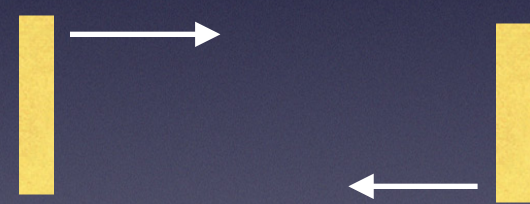
Fermi Acceleration



$$\frac{\Delta E}{E} = 4\frac{u}{v} Cos\theta + 4\frac{u^2}{v^2}$$

(interested in rel. particles with v >> u)



random scatterers:

<CosΘ> = 0

$\Delta E/E \sim u^2/v^2$

(2nd order Fermi accel)

converging flow:

<CosΘ> = 1

$\Delta E/E \sim u/v$

(1st order Fermi accel)

Fermi Acceleration

competition between acceleration (t_{acc}) and escape (t_{esc})

$$\frac{dE}{dt} = \frac{E}{t_{acc}} \qquad \frac{\partial N(E)}{\partial t} + \frac{\partial}{\partial E}\left(N(E)\frac{dE}{dt}\right) = -\frac{N(E)}{t_{esc}}$$

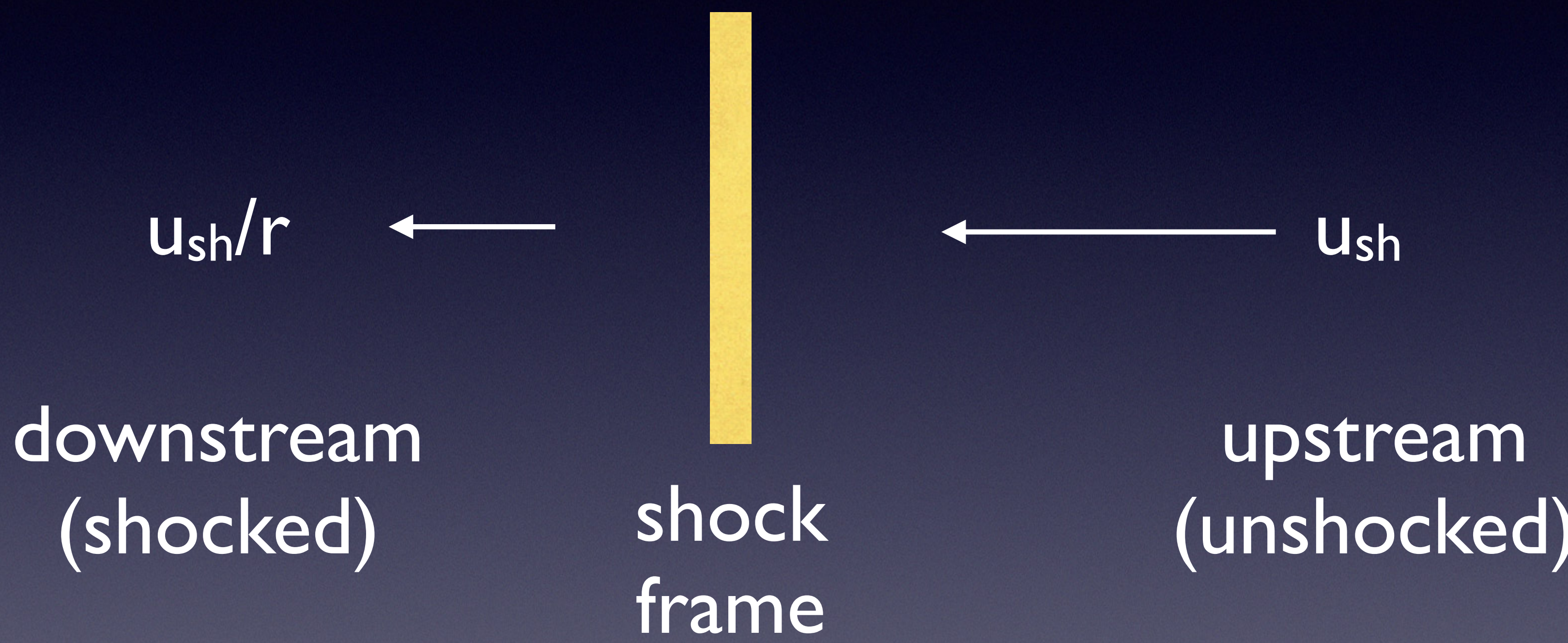
steady state: particles are injected, accelerated, and escape

$$\boxed{N(E) \sim E^{-\alpha} \quad \alpha = 1 + t_{acc}/t_{esc}}$$

✔ power-law   X but need $t_{acc}/t_{esc} \sim 1$ to explain CR spectrum??

Shock Acceleration

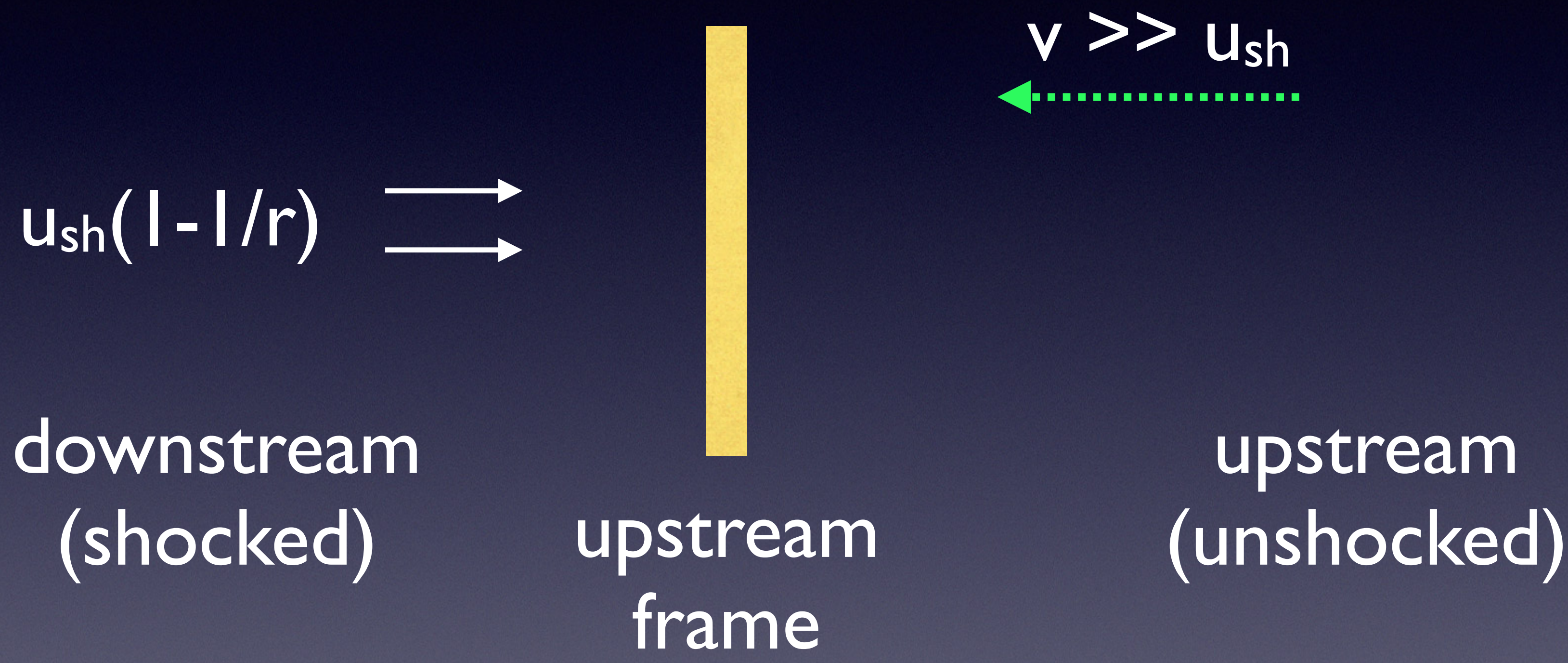
(Bell 1978; Blandford & Ostriker 1978)



$$r = \frac{\rho_{down}}{\rho_{up}} = \frac{v_{up}}{v_{down}} = \frac{\gamma+1}{\gamma-1} \xrightarrow[\gamma=5/3]{} 4$$

Shock Acceleration

(Bell 1978; Blandford & Ostriker 1978)



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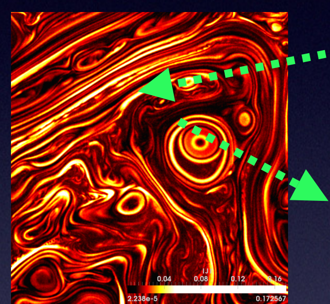


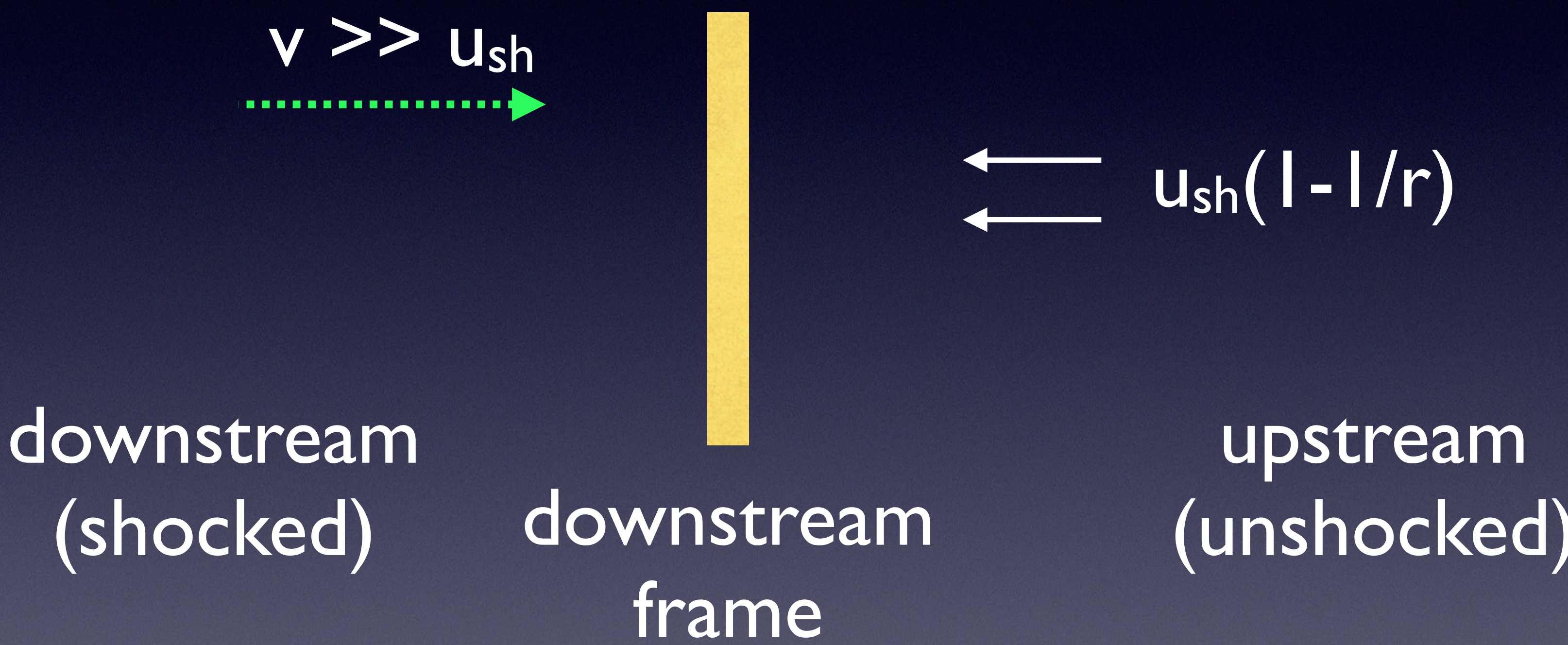
downstream
(shocked)

upstream
frame

upstream
(unshocked)

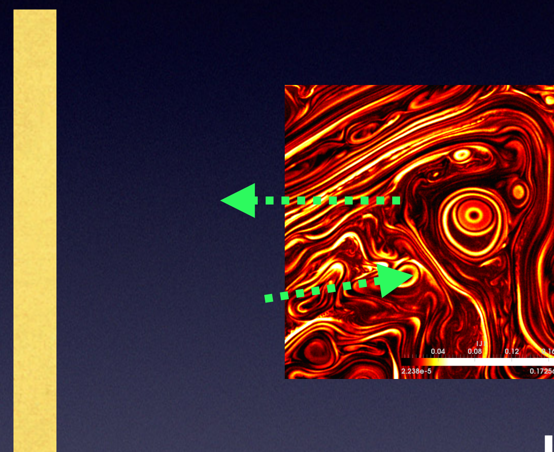
Shock Acceleration

(Bell 1978; Blandford & Ostriker 1978)



Shock Acceleration

(Bell 1978; Blandford & Ostriker 1978)



downstream
(shocked)

downstream
frame

upstream
(unshocked)

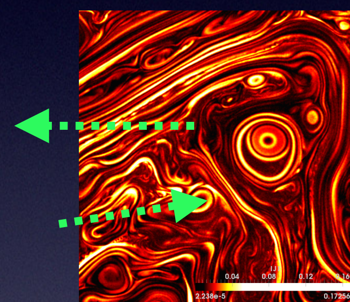
First Order Fermi
Acceleration at Shocks
(given sufficient turbulence to scatter particles)

$$\frac{\Delta E}{E} \simeq \frac{u_{sh}}{c}\left(1 - \frac{1}{r}\right)$$

Shock Acceleration

(Bell 1978; Blandford & Ostriker 1978)

L



downstream (shocked)

downstream frame

upstream (unshocked)

$t_{esc} \sim L/u_{sh}$

$t_{acc} \sim t_{scatter}\ E/\Delta E$

$\sim (L/c)(c/u_{sh}) \sim L/u_{sh}$

$\boxed{N(E) \sim E^{-\alpha} \quad \alpha = 1 + t_{acc}/t_{esc}}$

shocks $\Rightarrow$ $\boxed{\alpha = \dfrac{2+r}{r-1} \rightarrow 2 \text{ for } r = 4}$

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$$t_{\rm synch} \simeq 3 \times 10^7\,{\rm yrs}\left(\frac{B}{6\mu G}\right)^{-2}\left(\frac{E}{3\,{\rm GeV}}\right)^{-1}$$

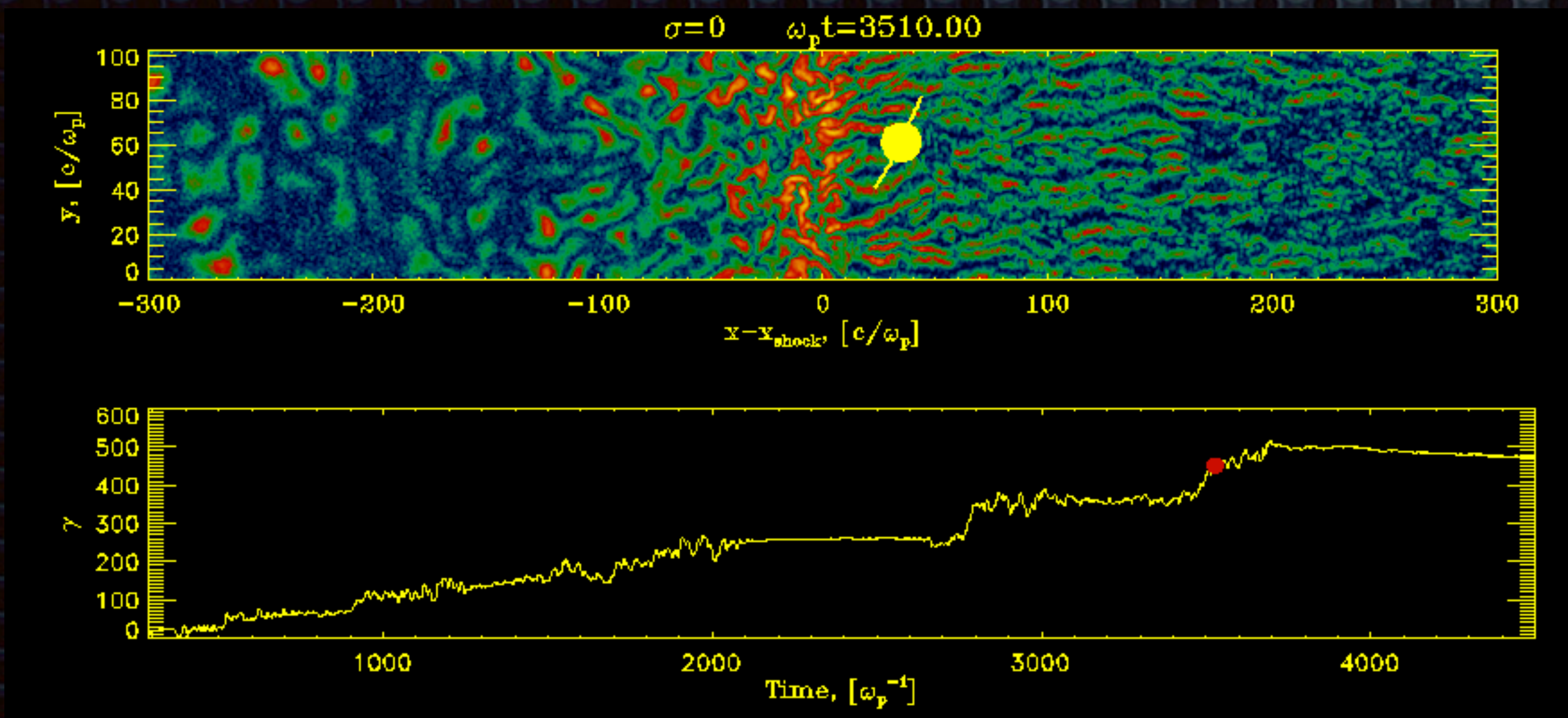
$$\frac{dN_e}{dE} \simeq \frac{d\dot{N}_e}{dE} t_{synch}(E) \qquad \boxed{\frac{d\dot{N}_e}{d\ln E} \propto E^{-2.1}}$$

Shock Acceleration in Particle-in-Cell Plasma Simulations

Self-generated magnetic turbulence scatters particles across the shock; each crossing results in energy gain -- Fermi process

Magnetic filaments

Particle energy

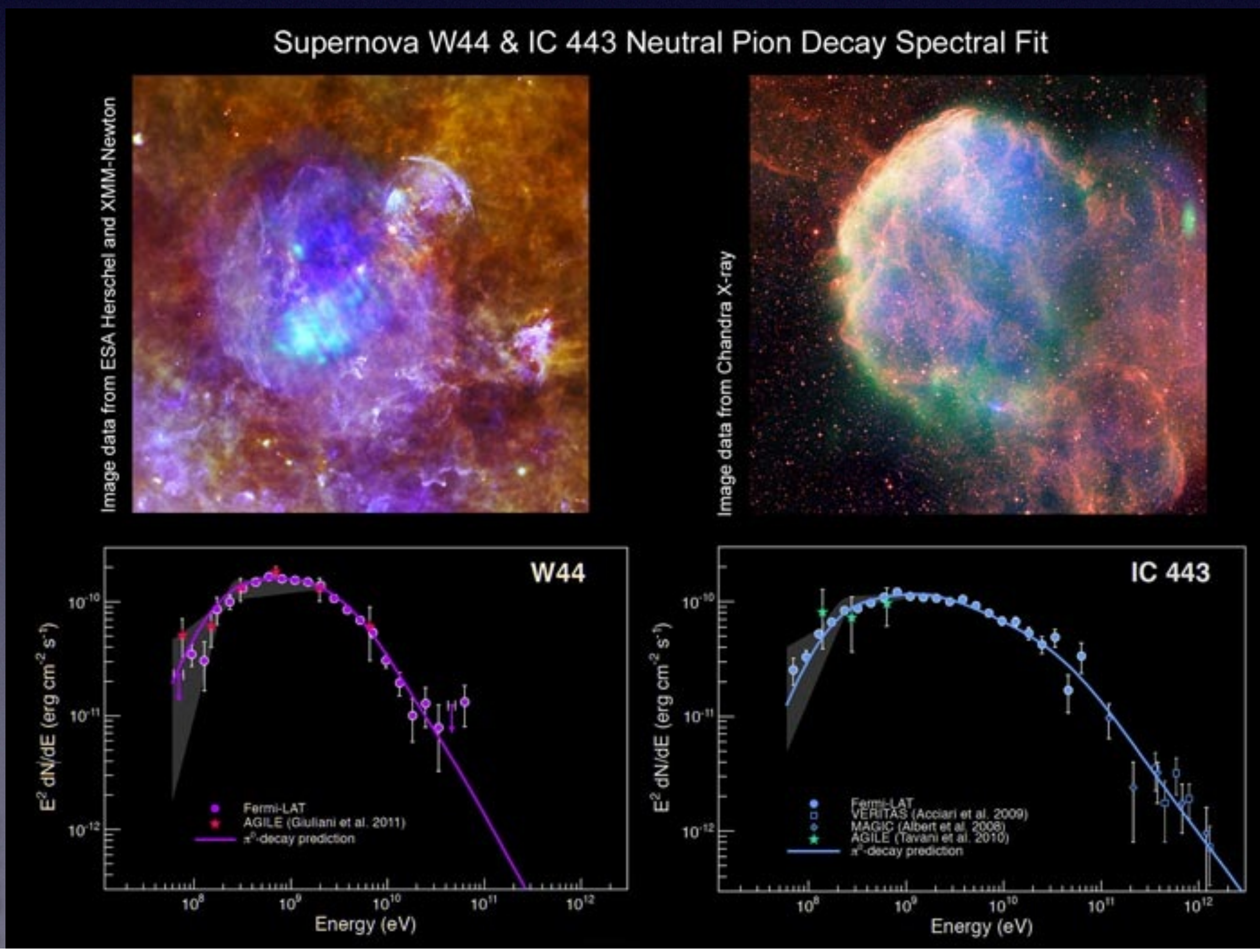


Slide Courtesy of Anatoly Spitkovsky

Galactic Cosmic Rays From Supernova Shocks

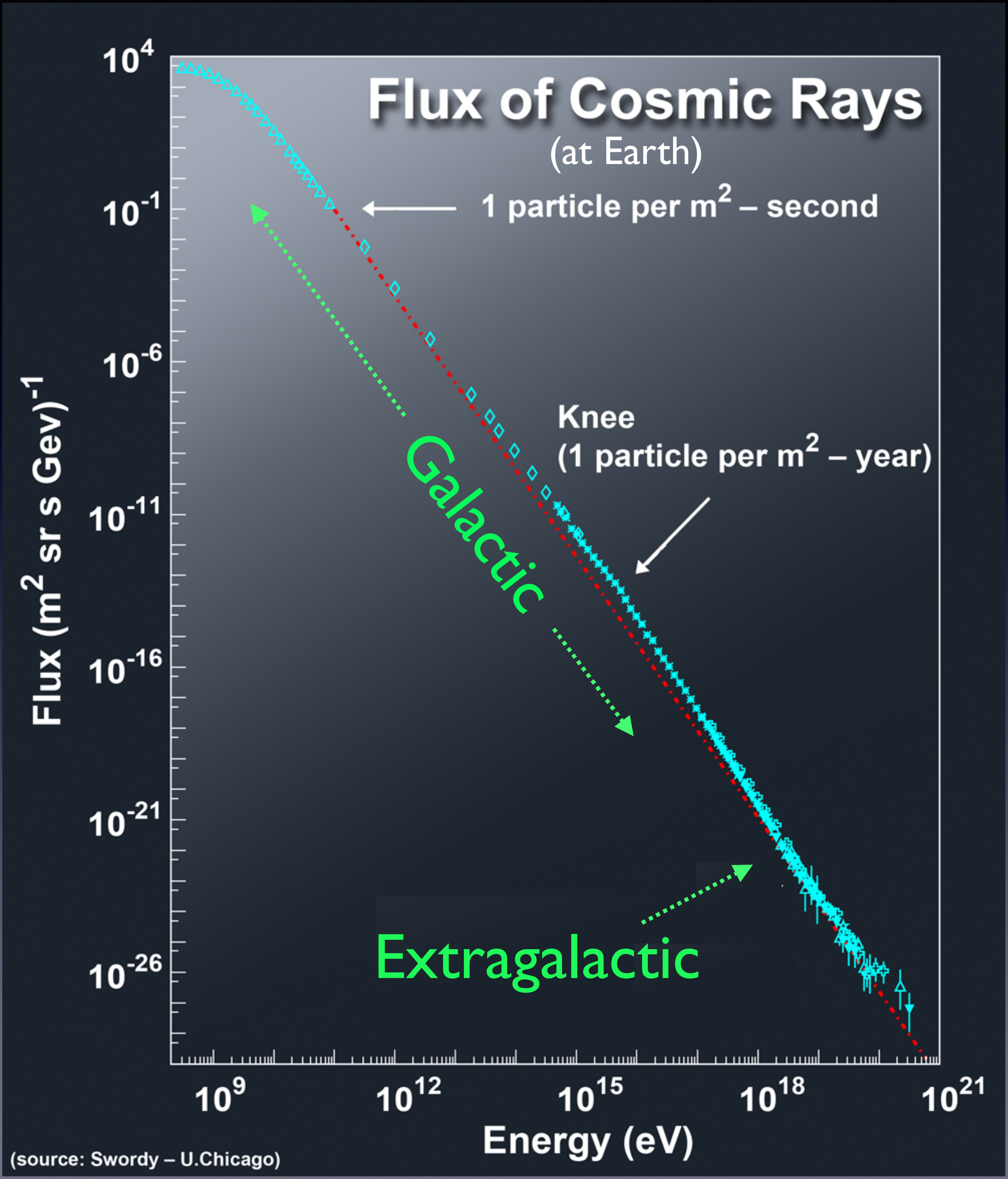
- $\varepsilon_{CR} \sim 2\ 10^{-12}$ erg cm^{-3} $\quad$ $t_{esc} \sim 3\ 10^{7}$ yr $\quad$ $V_{CR} \sim \pi(10\ \mathrm{kpc})^2(2\mathrm{kpc})$

$$\boxed{\dot{E}_{CR} \simeq 10^{41}\ \mathrm{erg\ s^{-1}} \simeq 0.1\ \dot{E}_{SN} \left(\frac{\dot{M}_*}{3\ M_\odot\ yr^{-1}}\right)}$$



Fermi

CR p + p $\rightarrow \pi_0 \rightarrow \gamma$



Larmor Radius

$r_L = E/ZeB$

$$r_L \simeq 1\,\mathrm{pc}\frac{E/(10^{15}\ \mathrm{eV})}{Z(B/100\mu G)}$$

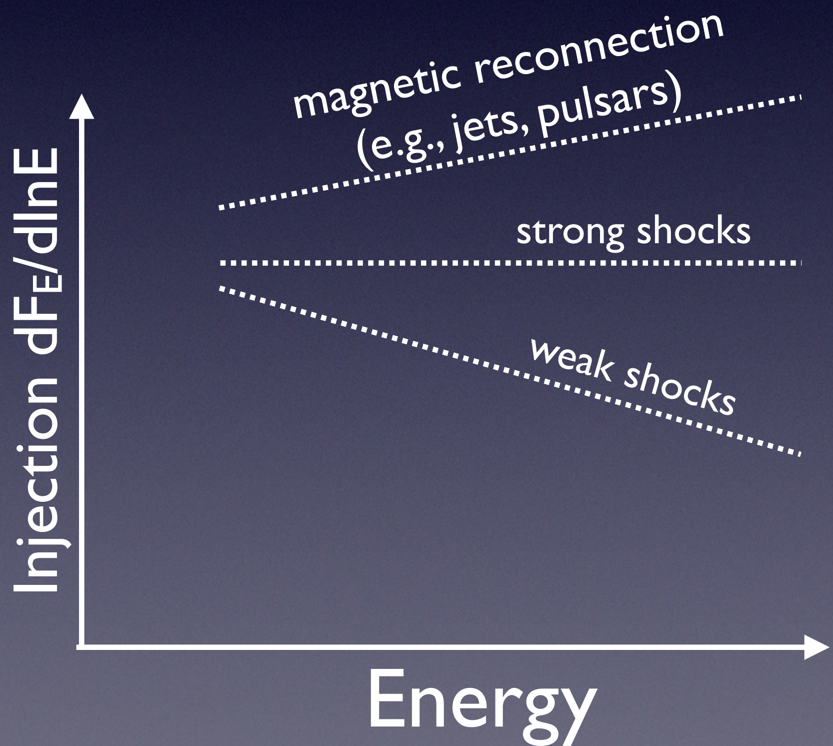
SN shocks cannot accelerate particles with $r_L \gtrsim$ size of remnant ~ few pc

$\rightarrow$

$E_{CR} \lesssim 10^{15}\,Z$ eV

The Range of Injection Energy Spectra

- strong shocks give $dF_E/d\ln E$ ~ const but can get a wider range of spectral slopes from other mechanisms



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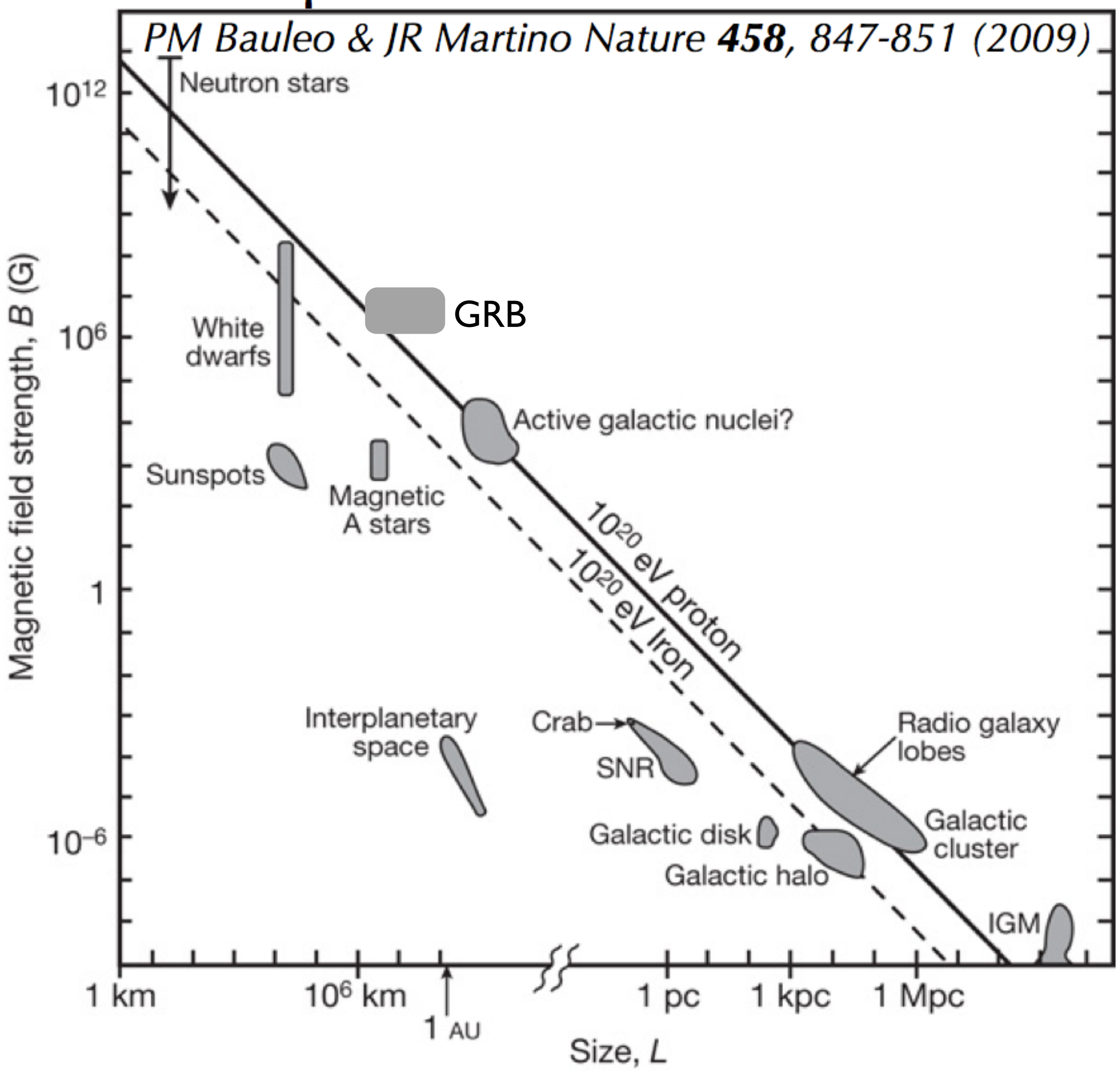
What Sources Satisfy r_L < System Size at ~10^{20} eV?

Hillas plot:



(size of the source)

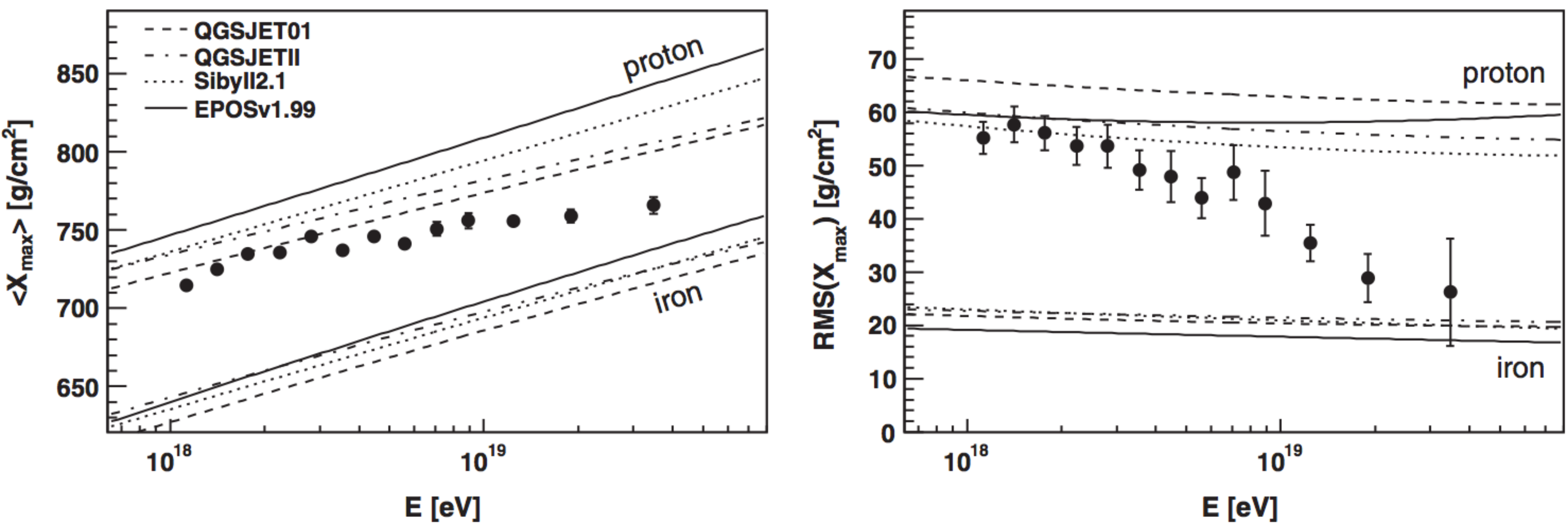
Plausible Sources

AGN (Jets, Lobes)
Cluster Virial Shocks
Gamma-ray Bursts

Above ~$10^{19.5}$ eV sources must be ≲ 50 Mpc due to CMB + CR → π + CR (GZK cutoff)

But anisotropy in UHECR arrival directions with Auger is weak

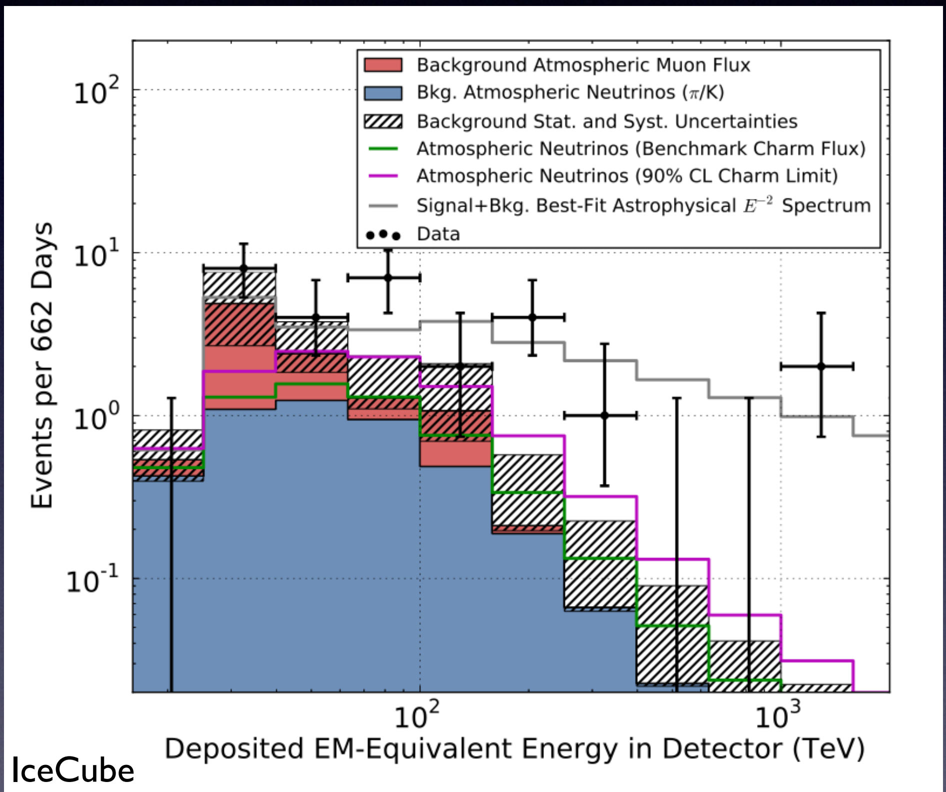
Composition of UHECRs



Auger Collaboration

Composition Dependent Properties of Air Showers From Pierre Auger Observatory Suggest Heavy Nuclei at $\gtrsim 10^{19}$ eV

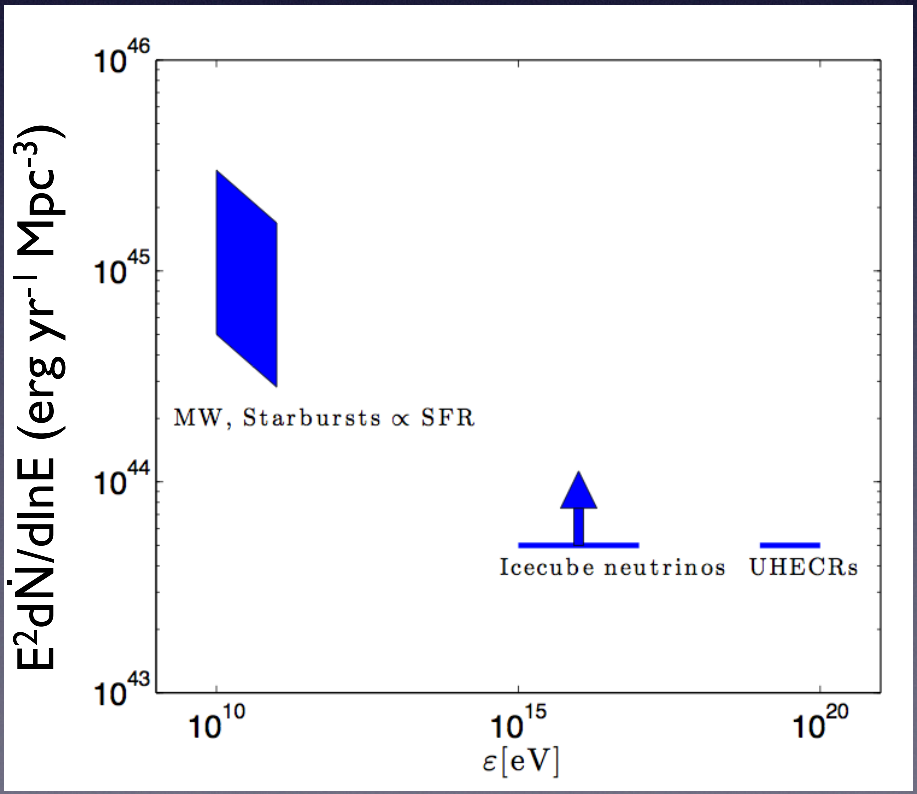
Connection to High Energy Neutrinos From Ice Cube



~28 ~PeV (10^{15} eV) νs

Sources of high energy CR expected to produce νs via p-p and/or photo-meson interaction

CR $p + p \rightarrow \pi_{+/-} \rightarrow e_{+/-} + \nu$



Katz+2013

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Confinement Time

(Milky Way CRs Near the Sun)

- ^{10}Be: CR with 1/2 life of 1.6 10^6 yrs. Abundance compared to ^{7}Be & ^{10}Be ⇒

$$\boxed{t_{esc} \simeq 3\,10^7 \;\; \mathrm{yrs} \;\; \left(\frac{E}{3\,\mathrm{GeV}}\right)^{-1/2} \quad \ll \mathrm{kpc}/c \sim 3000\,\mathrm{yrs}}$$

- *If* diffusion: $t_{esc} \sim \dfrac{R^2}{\ell c} \quad \Rightarrow$

$$\boxed{\mathrm{mfp}\ \ell \sim 0.1\,\mathrm{pc}\ \left(\frac{E}{3\,\mathrm{GeV}}\right)^{1/2}}$$

Why it is Critical to Understand t_{esc}

steady state energy density ~ $\dot{E}\ t_{esc}$

- We don't understand the right **function** to use for t_{esc} in difft environments (high z galaxies, clusters)
  - t_{esc} plausibly depends on E_{CR}, B, n, δv, ionization state, …
- We don't understand whether 'escape' should be modeled as diffusion or advection or …
- Less severe for e- bec. radiative losses often rapid and $\varepsilon_e \sim \dot{E}\ t_{cool}$ (but protons dominate CR energy!)

Physics of CR Confinement

- GeV Coulomb mfp $\sim 10^3 \, n^{-1} \, D_{Horizon} \rightarrow$ Interaction w/ EM Fields Governs CR Motion

- Charged Particle Motion in a Varying B-Field
- Scattering by Cyclotron-Frequency Waves
- Scattering by MHD Turbulence
- Self-Confinement — CRs 'trying' to stream at the speed of light generate instabilities that limit CR streaming to ~ Alfven speed

Charged Particle Motion in a Slowly Varying Magnetic Field

Particle Orbit

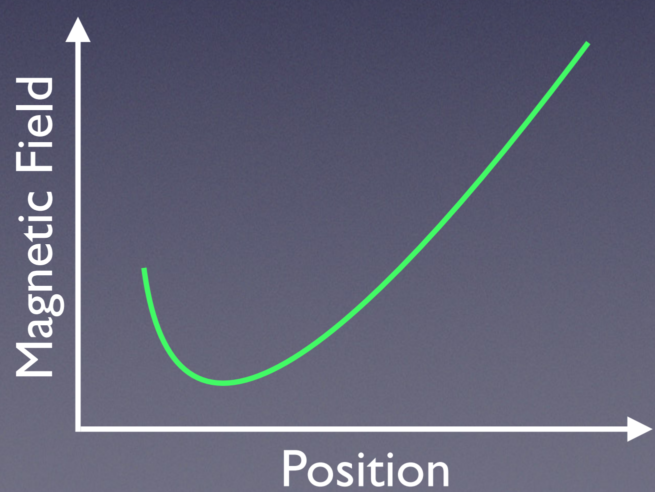
$r_L = c/\Omega$

$\Omega = ZeB/\gamma mc$

If $d\ln B/dt \ll \Omega$ & $d\ln B/dx \ll r_L$

$$\frac{p_\perp^2}{B} = \text{constant}$$

adiabatic invariant



as $B \uparrow$ $p_\perp \uparrow \Rightarrow p_{||} \downarrow$

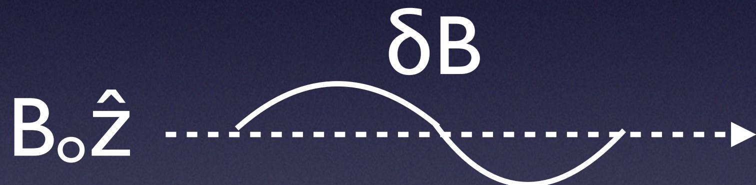
at some pt, $p_{||} \rightarrow 0$

particle is trapped

'magnetic mirror'

Scattering by High Frequency MHD Waves

- High frequency ~ Ω (cyclotron freq) fluctuations in B can scatter particles, converting $p_\perp \Leftrightarrow p_{||}$, much like standard collisions. This sets CR mfp.



$\delta B \sim \delta B \exp[ik_z z - i\omega t]$

if $\omega - k_z v_z = \Omega$ particle is in resonance and sees constant wave amplitude

for rel particles, resonance if $\lambda_{||} \sim 1/k_z \sim r_L$

Scattering by High Frequency MHD Waves

- High frequency ~ Ω (cyclotron freq) fluctuations in B can scatter particles, converting $p_\perp \Leftrightarrow p_{||}$, much like standard collisions. This sets CR mfp.

rate of $p_\perp \Leftrightarrow p_{||}$ scattering for randomly phased resonant waves $\equiv \nu_s \sim \Omega \left(\frac{\delta B}{B_0}\right)^2$

CR mfp $\ell = c/\nu_s$

if diffusion, the inferred CR mfp $\ell \sim 0.1$ pc at ~ GeV

requires $\delta B/B_0 \sim 10^{-3}$ at $\lambda_{||} \sim r_L \sim 10^{12}$ cm

Scattering by MHD Turbulence

- Magnetized Turbulence is Ubiquitous in the ISM with $\delta B/B_0 \sim 1$ at the outer (driving) scale L_{out}
- Let's very naively say $\delta B_0 \sim k^{-1/3}$ as in hydrodynamic turbulence (Kolmogorov)
- $L_{out} \sim 100$ pc $\rightarrow$ $\delta B/B_0 \sim 10^{-3}$ at $\lambda \sim 10^{12}$ cm, comparable to what we inferred is needed
- But reality is more complicated …

Scattering by MHD Turbulence

- MHD Turbulence can be Roughly Decomposed into the 3 MHD Waves: slow, fast, Alfven
- Alfven, slow turbulence anisotropic wrt B-field

'eddies' elongated along mean B-field: $\lambda_\perp << \lambda_{||}$

when $\lambda_{||} \sim r_L$ of CR, $\lambda_\perp << r_L$;

strongly suppresses CR scattering bec of averaging over many eddies

→ Alfven/slow modes are an inefficient source of scattering

Scattering by MHD Turbulence

- MHD Turbulence can be Roughly Decomposed into the 3 MHD Waves: slow, fast, Alfven
- fast mode (~sound wave w/ B-field compressions) turbulence isotropic wrt B-field

$\delta B \sim k^{-1/4}$ waves with $\lambda \sim r_L \rightarrow$

CR mfp $\sim c\, L_{out}^{1/2}\, \Omega^{1/2}$

$\sim E^{1/2}$ as observed

fast modes are strongly damped but nonetheless may be the dominant source of CR scattering by ambient turbulence

(e.g., Yan & Lazarian 2004)

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What do we know about Magnetic Fields and CRs in Galaxies from their Non-thermal Emission?

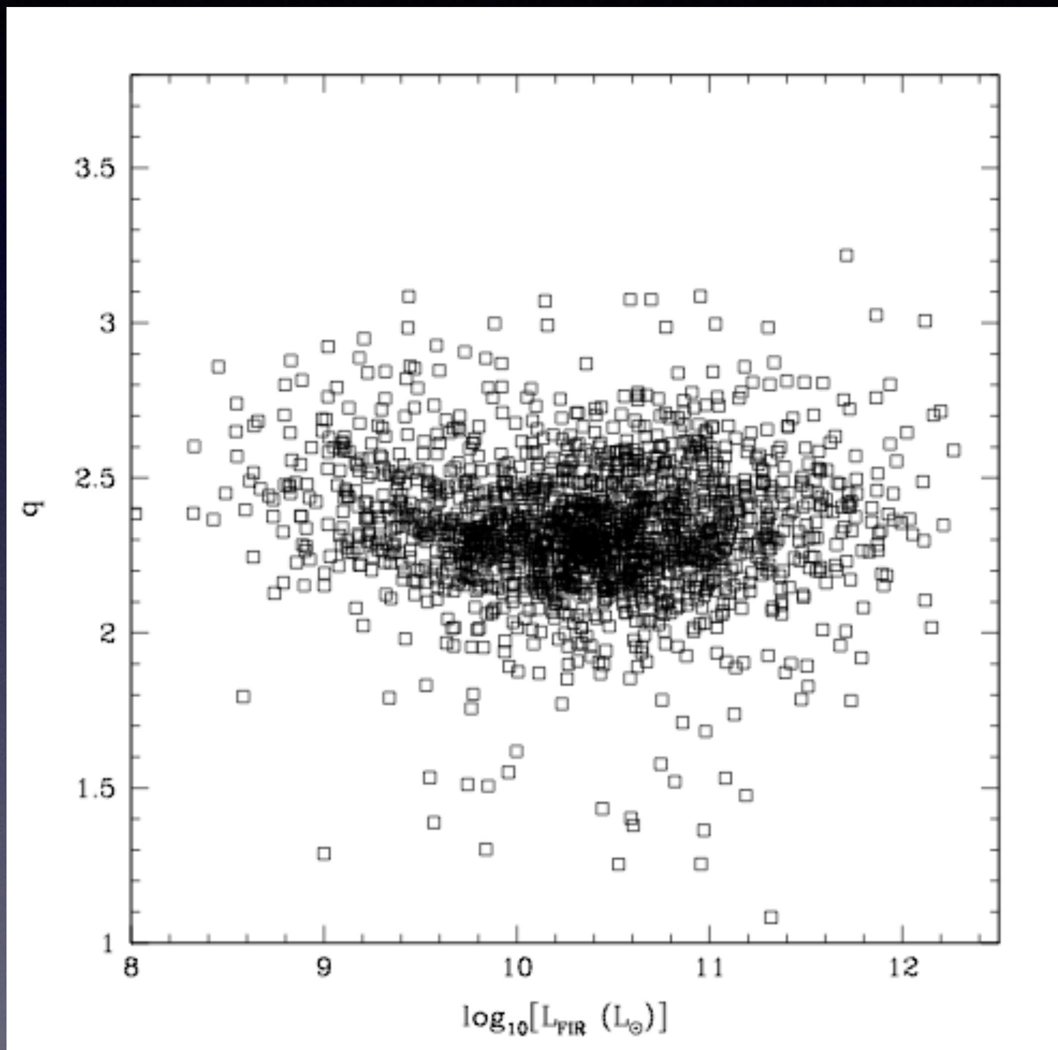
(based on Thompson+ 2006, 2007; Lacki+ 2010, 2011)

- Constraints primarily for star-forming galaxies in which core-collapse supernova rate is large (>> Ia rate)

- Synchrotron (radio) emission from star-forming galaxies
  - Implications for B-fields in star-forming galaxies
  - The Far-infrared-radio (FIR) correlation of star-forming galaxies

- Gamma-ray emission from starbursts
  - Suggests CR pressure is sub-dominant in prototypical starbursts M82, NGC 253

The FIR-Radio Correlation



Yun et al. 2001

$\mathrm{Log}_{10}[L_{FIR}/L_{radio}]$

$\mathrm{Log}_{10}[L_{FIR}]$

$\nu L_\nu \approx$ **2 x 10^{-6} L$_{FIR}$**

(at ~ few GHz, where the radio emission is nonthermal)

UV → **FIR** (dust)

Massive Stars

supernovae

cosmic rays

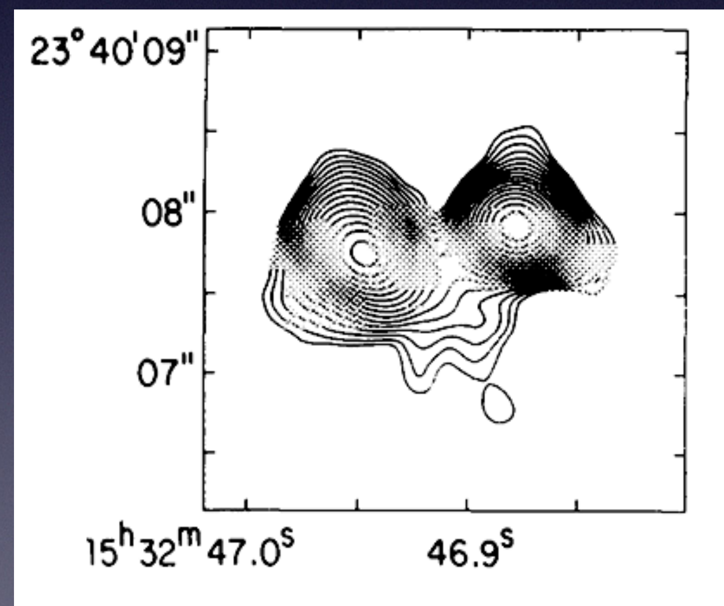
+ B-fields

Radio (synchrotron)

Estimating B-Field Strengths in Other Galaxies

- Very few Zeeman detections in other galaxies
- Use observed radio emission (synchrotron) to estimate B
- Two Observables: L_{rad} & R
  (+ radio spectrum)
  - e.g., Arp 220 ($L_{FIR} \sim 10^{12}\, L_{\odot}$):

    $L_{rad} \sim 10^{40}$ ergs/s & R ~ 100 pc



The Minimum Energy Estimate

$$\mathbf{P} \propto \gamma^2 \mathbf{B}^2 \quad \mathbf{t_{syn}} \sim \mathbf{10^9 B_{\mu G}^{-3/2}} \nu_{\mathbf{GHz}}^{-1/2} \text{ yr} \quad \gamma \sim \mathbf{10^4} \nu_{\mathbf{GHz}}^{1/2} \mathbf{B}_{\mu\mathbf{G}}^{-1/2}$$

$$\nu L_\nu \sim \frac{\epsilon_e V}{t_{syn}} \propto \epsilon_e V B^{3/2}$$

$$assume\ \epsilon_{tot} = \delta \epsilon_e \sim \frac{B^2}{8\pi} \quad (\delta \equiv \text{p/e CR energy} \sim 10 - 100)$$

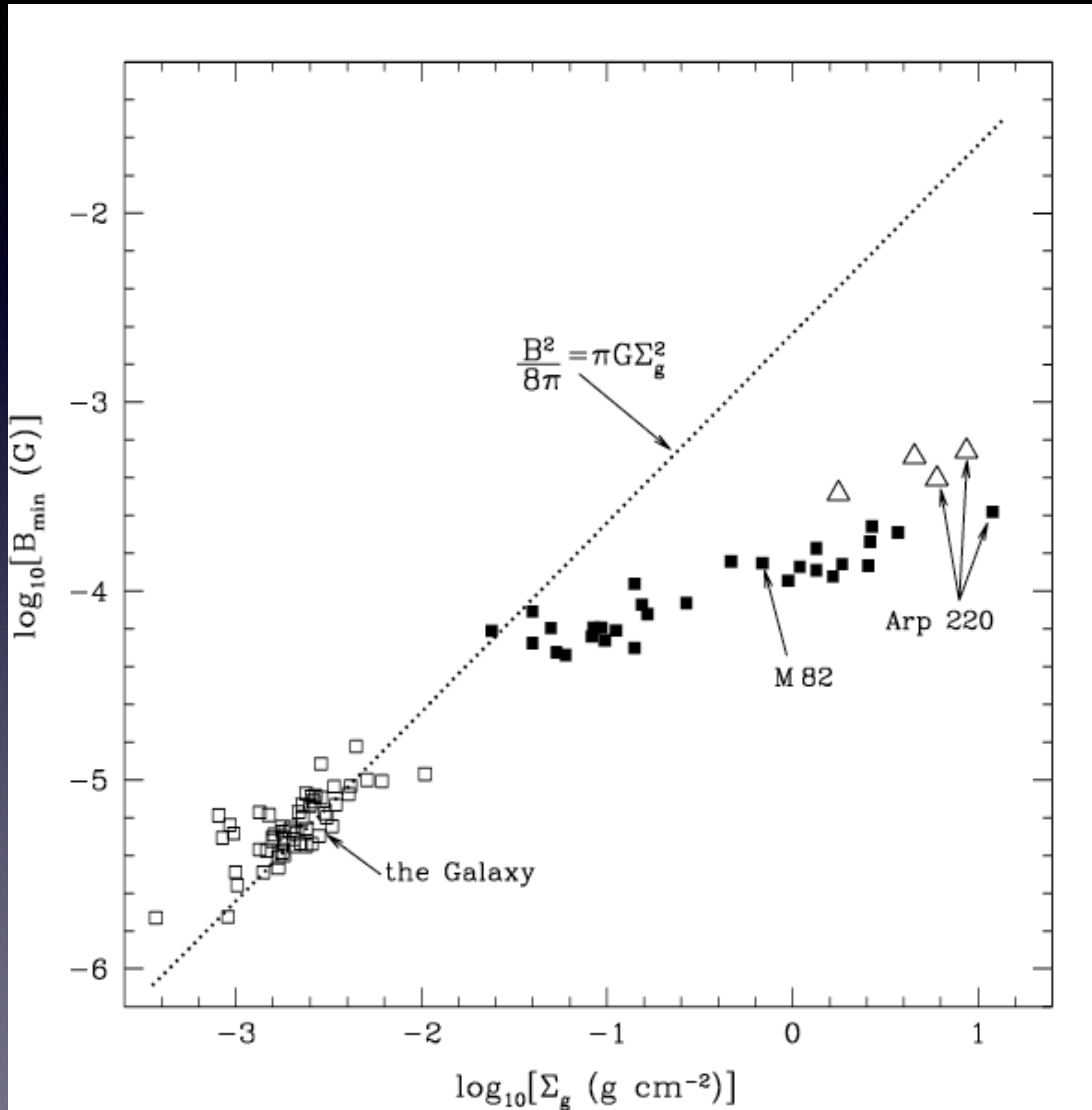
$$\rightarrow \nu L_\nu \propto \delta^{-1} B^{7/2} V \qquad \boxed{\rightarrow \mathbf{B} \equiv \mathbf{B}_{\text{min}} \propto \delta^{\mathbf{2/7}} \left(\frac{\mathbf{L}_\nu}{\mathbf{V}} \right)^{\mathbf{2/7}}}$$

$$(\text{minimum energy bec. } \epsilon_{tot} + B^2/8\pi \text{ minimized by } \epsilon_{tot} \sim B^2/8\pi)$$

Milky Way: B_{min} ~ 5 μG, consistent with Faraday Rot.

$\epsilon_{tot} \sim B^2/8\pi$ confirmed by γ-ray observations (pion decay from p-p interactions)

The Minimum Energy Magnetic Field From Local Spirals to Luminous Starbursts



if B_{min} is correct, B-fields are dynamically weak compared to gravity in starbursts

(and thus likely unimpt. in regulating star formation, transporting angular momentum, …)

Thompson+2006

The Failure of the Min. Energy Estimate

- $\epsilon_e << B^2/8\pi$ if **$t_{cool} << t_{esc}$**

time for rel. e⁻ to radiate away its energy (synch & IC)

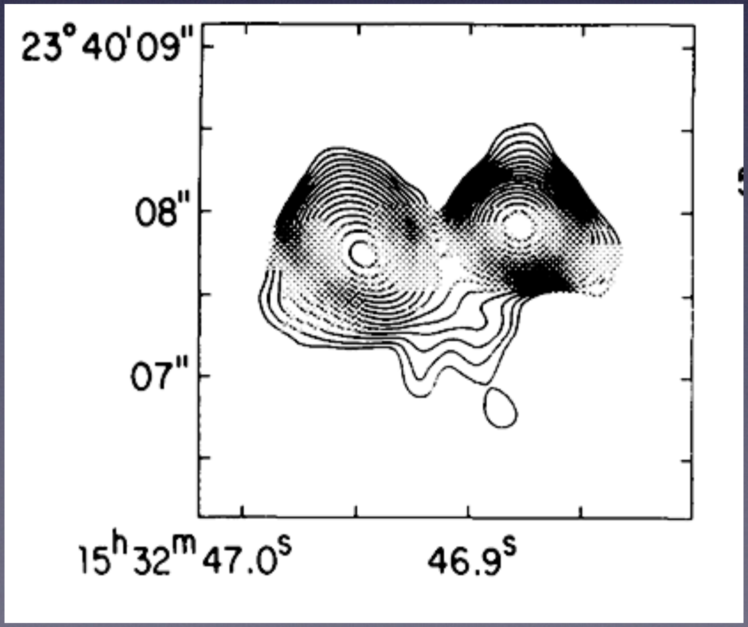
time for rel e⁻ to escape the galactic disk

- if $\mathbf{t_{cool} << t_{esc}}$, **$B >> B_{min}$**
  - $L_{radio} \sim \epsilon_e B^{3/2}$: $\epsilon_e \downarrow \Rightarrow B \uparrow$
- MW: $t_{syn} \sim t_{IC} \sim t_{esc} \sim 10^{7.5}$ yr
- Arp 220: $t_{syn} \sim$? (B ~ ?)

  $t_{IC} \sim 5000$ yr

  $t_{esc} \sim$?; $t_{esc} > R/v_w \sim 3\ 10^5$ yr

  $t_{IC} << t_{esc}$



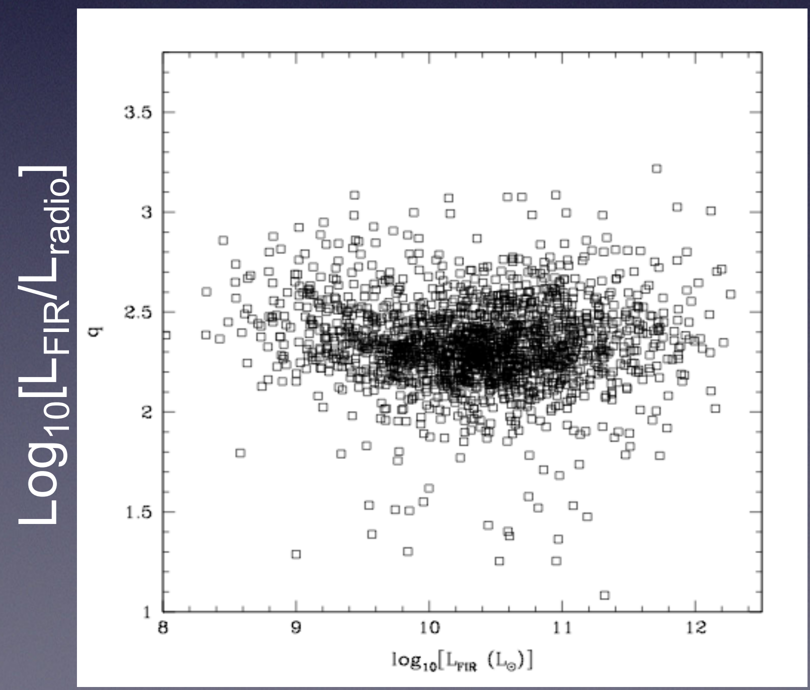
Implications of $t_{syn} < t_{esc}$

- $t_{syn} < t_{esc}$: e's radiate all the energy supplied by SN shocks

$$\boxed{\nu \mathbf{L}_\nu \sim \dot{\mathbf{E}}_\mathbf{e} \propto \mathrm{SN\ Rate} \propto \mathbf{L}_{\mathbf{FIR}}}$$

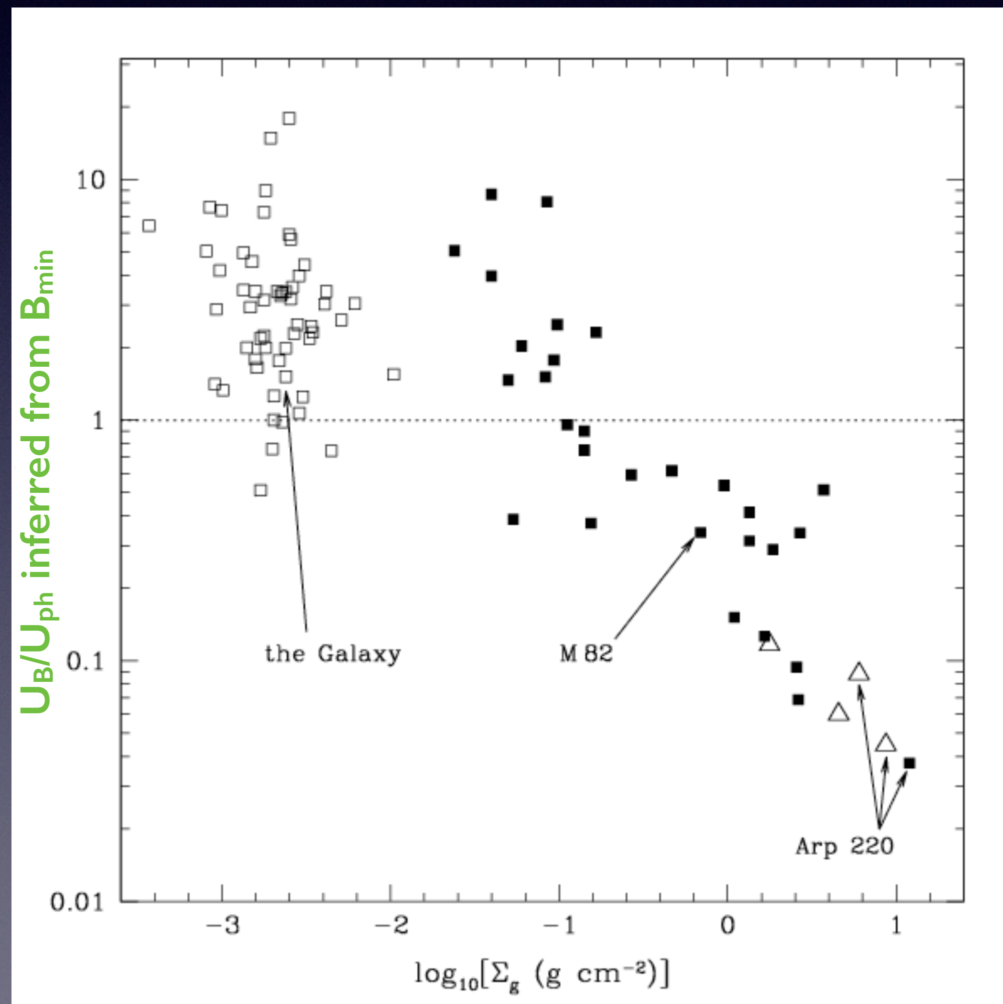
normalization of FIR-Radio → ≅1% of SN energy supplied to CR e's

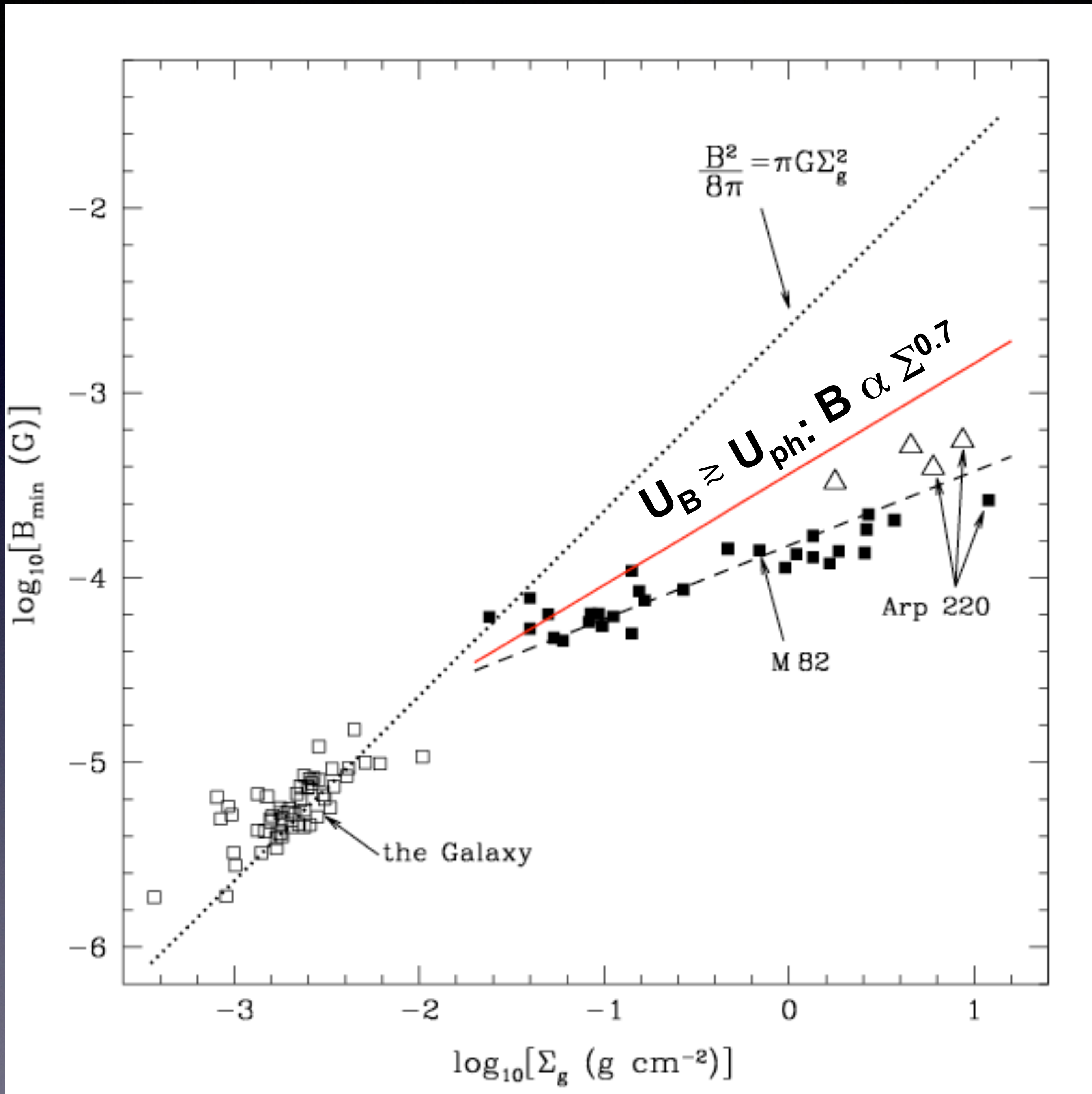
- Clean explanation for **linear** FIR-Radio Correlation
  - "calorimeter theory" (Volk 1989; Thompson+2006)
  - $t_{esc} < t_{syn}$ requires tremendous fine tuning and even more energy → e- in SN shocks



Synchrotron vs. IC cooling

- Conditions in Starbursts & FIR-Radio favor $t_{cool} < t_{esc}$
  - B_{min} is an underestimate
- FIR-Radio also Requires $t_{syn} < t_{IC}$, i.e., **$U_B > U_{ph}$**





Thompson+2006

What do we know about Magnetic Fields and CRs in Galaxies from their Non-thermal Emission?

(based on Thompson+ 2006, 2007; Lacki+ 2010, 2011)

- Constraints primarily for star-forming galaxies in which core-collapse supernova rate >> Ia rate
- Synchrotron (radio) emission from star-forming galaxies
  - Implications for B-fields in star-forming galaxies
  - The Far-infrared-radio (FIR) correlation of star-forming galaxies
- **Gamma-ray emission from starbursts**
  - **Suggests CR pressure is sub-dominant in prototypical starbursts M82, NGC 253**

Gamma-ray Emission from Starbursts

- Largest flux $\gtrsim$ GeV via neutral pion decay ($m_\pi c^2 \sim 140$ MeV)
  - e- IC, bremsstrahlung can also contribute (but ps have more energy)

$$\text{CR } p + p \rightarrow \pi_0 \rightarrow \gamma$$

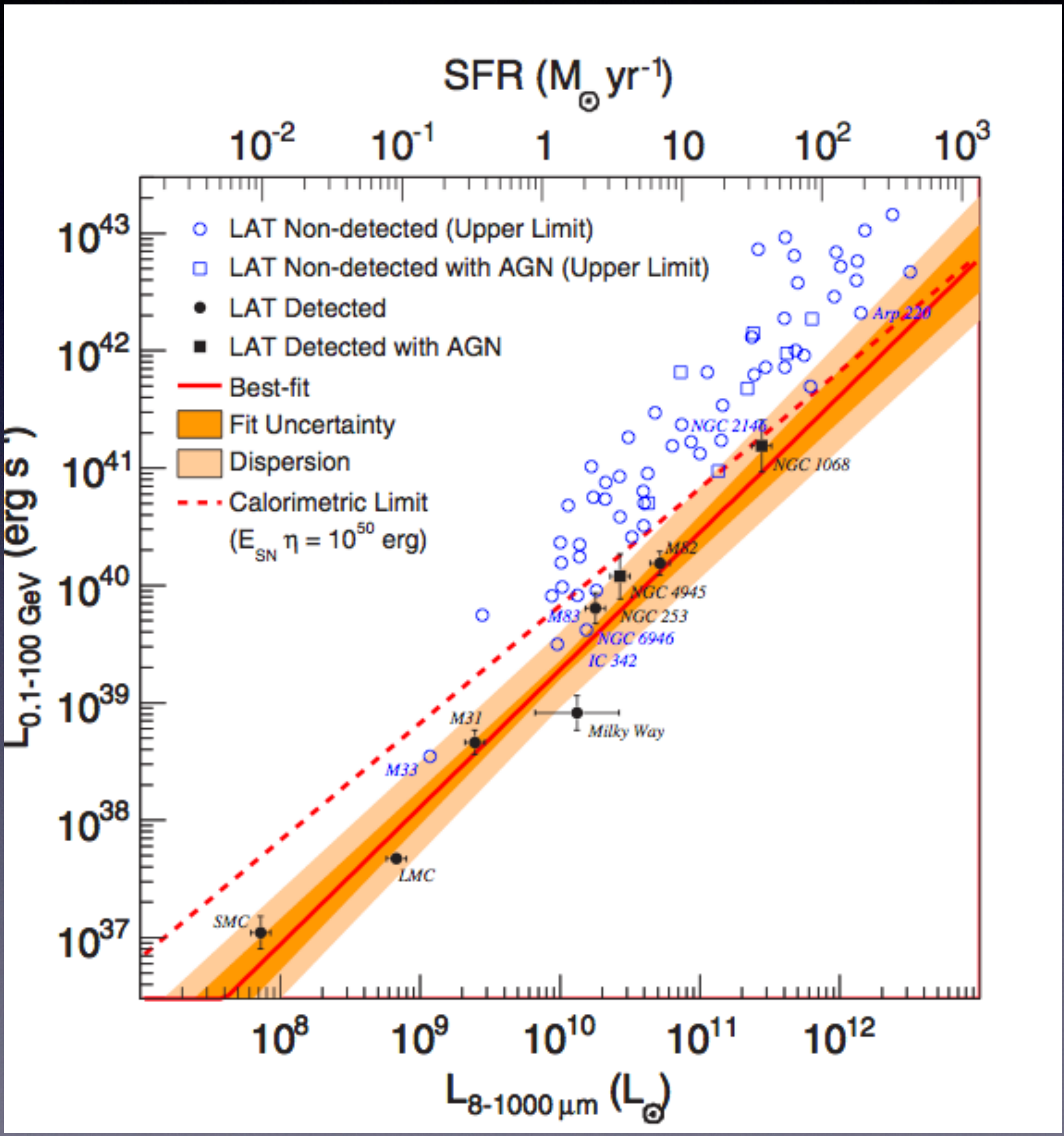
$$t_{\rm pion} \simeq 10^5 \,\mathrm{yrs}\, \left(\frac{n}{10^3\,\mathrm{cm}^{-3}}\right)^{-1}$$

- $t_{\rm pion}$ <(?) $t_{\rm esc}$ in dense starbursts → 'proton calorimeter'

a GeV-FIR correlation: $\boxed{L(\gtrsim \mathrm{GeV}) \simeq 2\times10^{-4}\left(\frac{\eta_p}{0.1}\right) L_{\rm FIR}}$

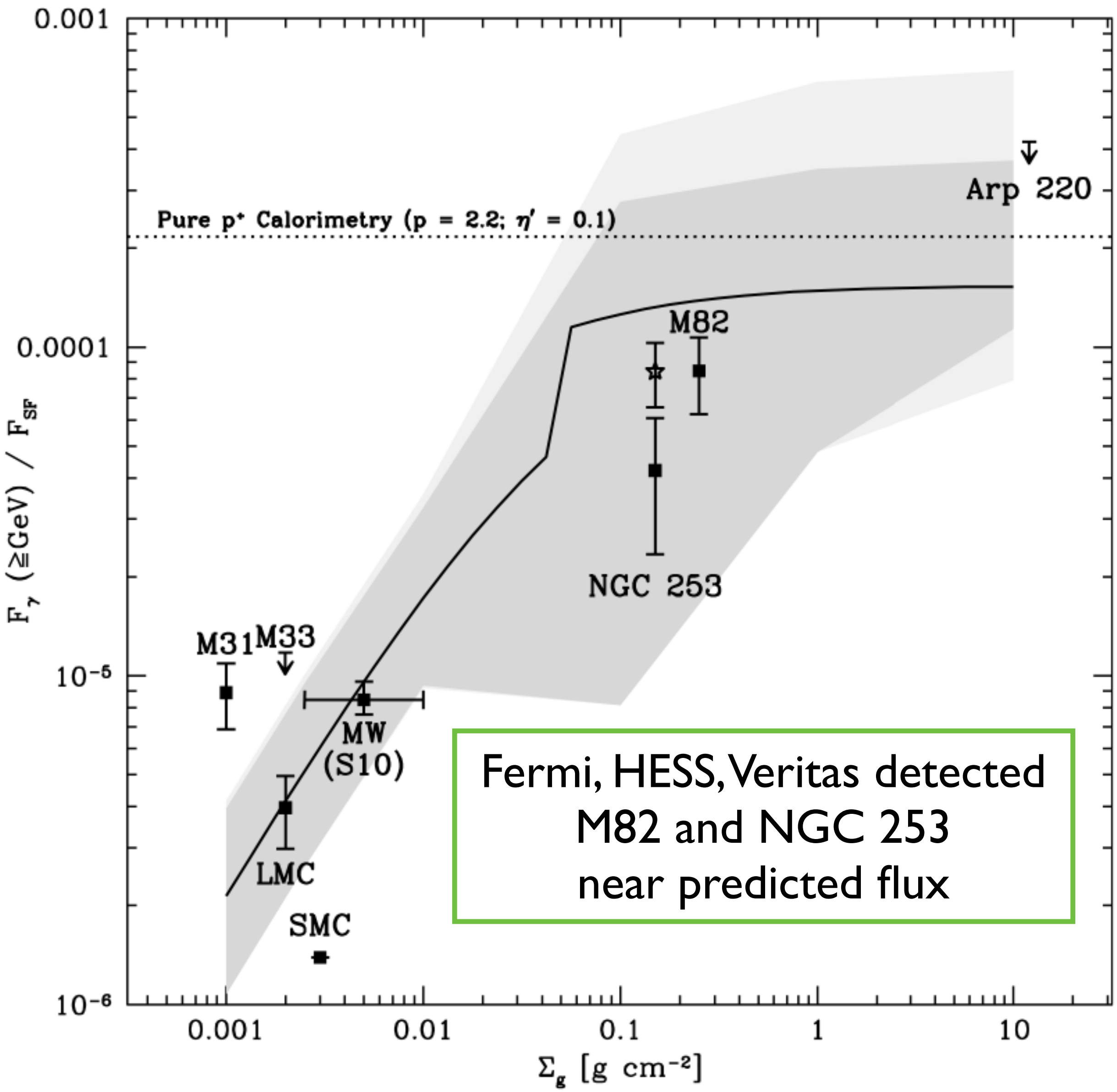
(prediction by TQW 2007, prior to launch of Fermi)

Gamma-ray Emission from Starbursts



Ackermann+2012

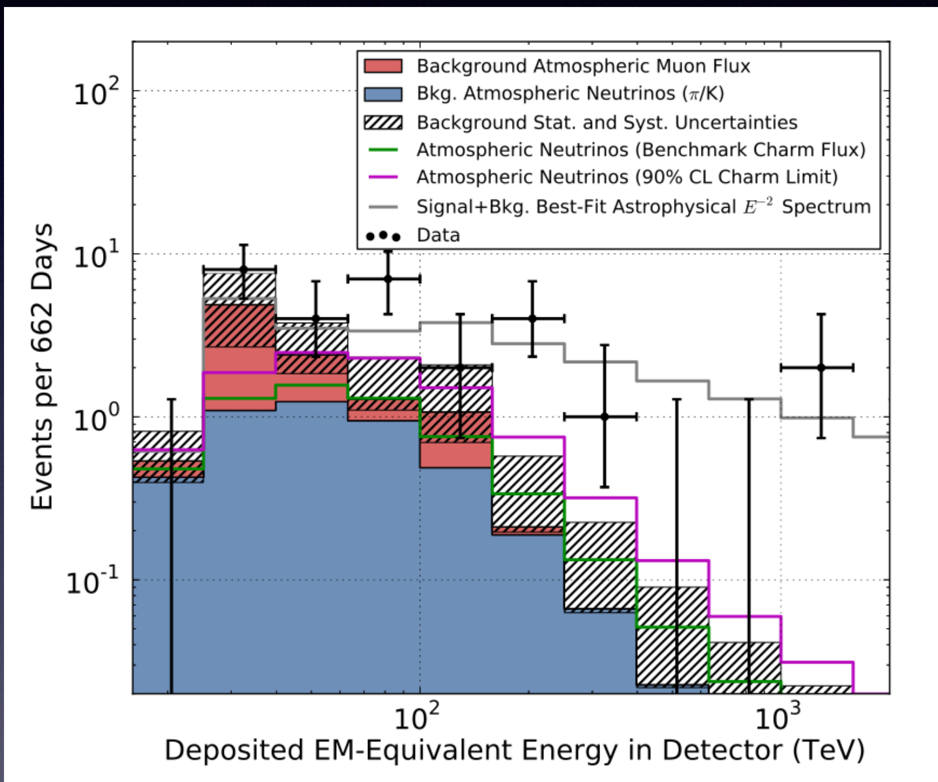
Gamma-ray Emission from Starbursts



Fermi, HESS, Veritas detected
M82 and NGC 253
near predicted flux

Lacki+2011

High Density Star Forming Galaxies are a Significant Contributor to the Extragalactic Gamma-ray and Neutrino Backgrounds

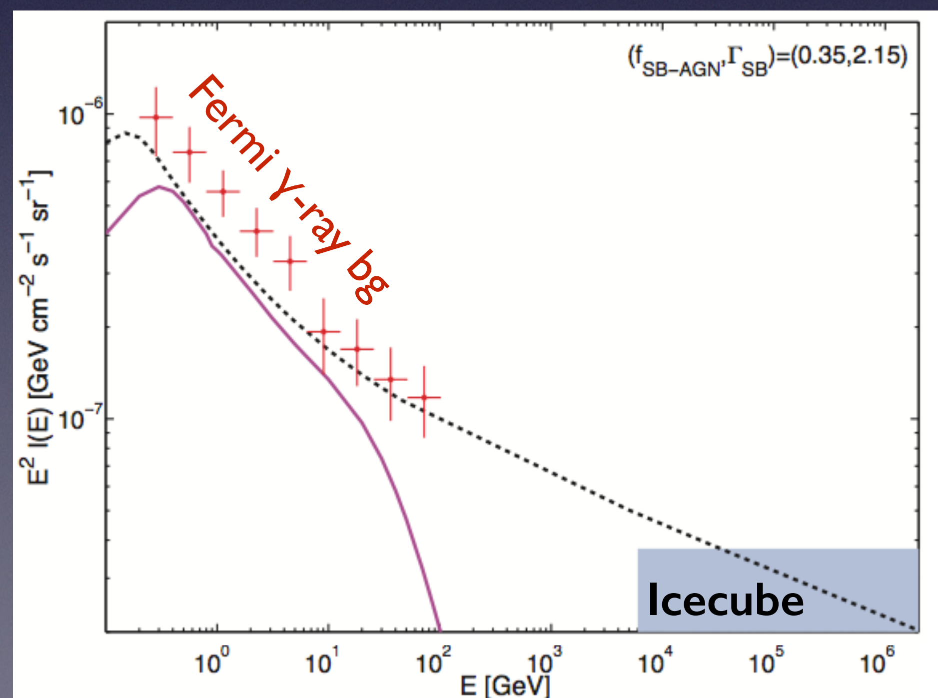


~28 ~PeV (10^{15} eV) νs

Sources of high energy CR expected to produce νs and γ via p-p interaction

$$\mathrm{CR}\ p + p \rightarrow \pi_0 \rightarrow \gamma$$

$$\mathrm{CR}\ p + p \rightarrow \pi_{+/-} \rightarrow e_{+/-} + \nu$$



Tamborra+2014

Implications for CR Pressure & Galactic Winds

- Given large ≳ GeV fluxes, need to account for pion losses in determining steady state CR energy ε_{CR}

$$\epsilon_{CR} \sim \dot{\epsilon}_{CR}\,\mathrm{Min}(\mathrm{t_{pion}}, \mathrm{t_{esc}}) \lesssim \dot{\epsilon}_{CR}\, t_{\rm pion}$$

- Best applied in prototypical starbursts M82 & NGC 253
  - Assume CRs interact with gas at $n_{eff} \sim \langle n \rangle \sim 300\ \mathrm{cm^{-3}}$
    - → $P_{CR} \sim 0.05\ P_{Hydro}$ ($P_{Hydro} = \pi G \Sigma_g^2$) → CRs subdominant
  - Estimate n_{eff} such that $P_{CR} \sim P_{Hydro}$ → $n_{eff} \sim 10\ \mathrm{cm^{-3}}$

$$t_{\rm pion} \sim 10^7 {\rm yrs} \gg \frac{R}{v_{\rm wind}} \sim 10^6\ {\rm yrs} \left(\frac{R}{300\,{\rm pc}}\right)\left(\frac{300\,{\rm km\,s^{-1}}}{v_{\rm wind}}\right)$$

ruled out by large GeV flux

Suggests that CRs are not driving the winds in NGC 253 and M82

(Lacki+2011)