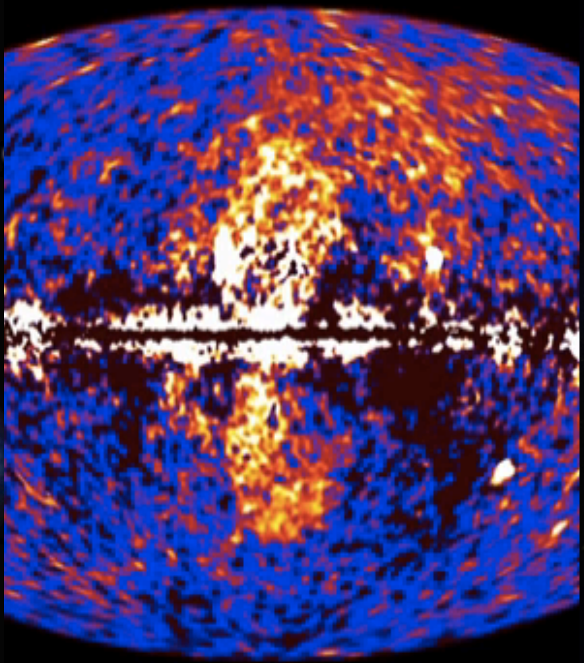
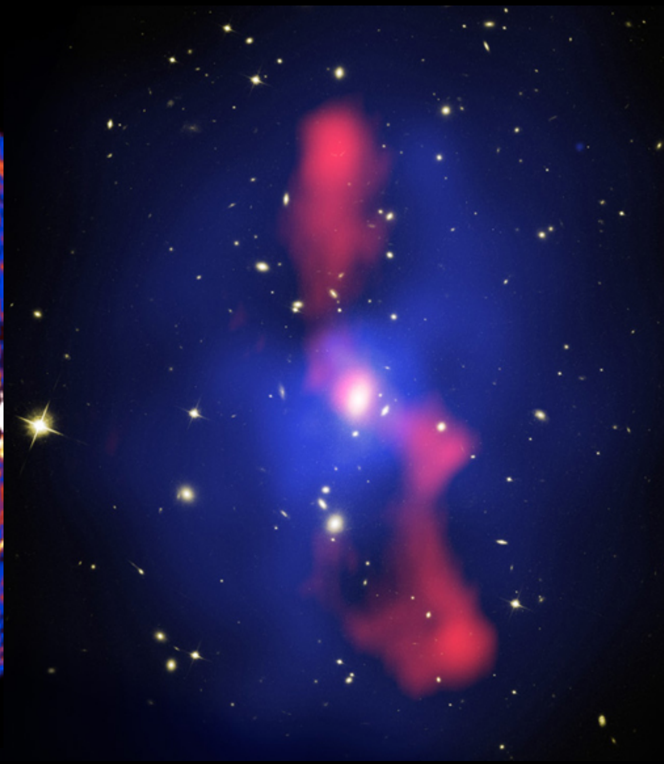
Modeling Cosmic Rays in Galaxies and Clusters





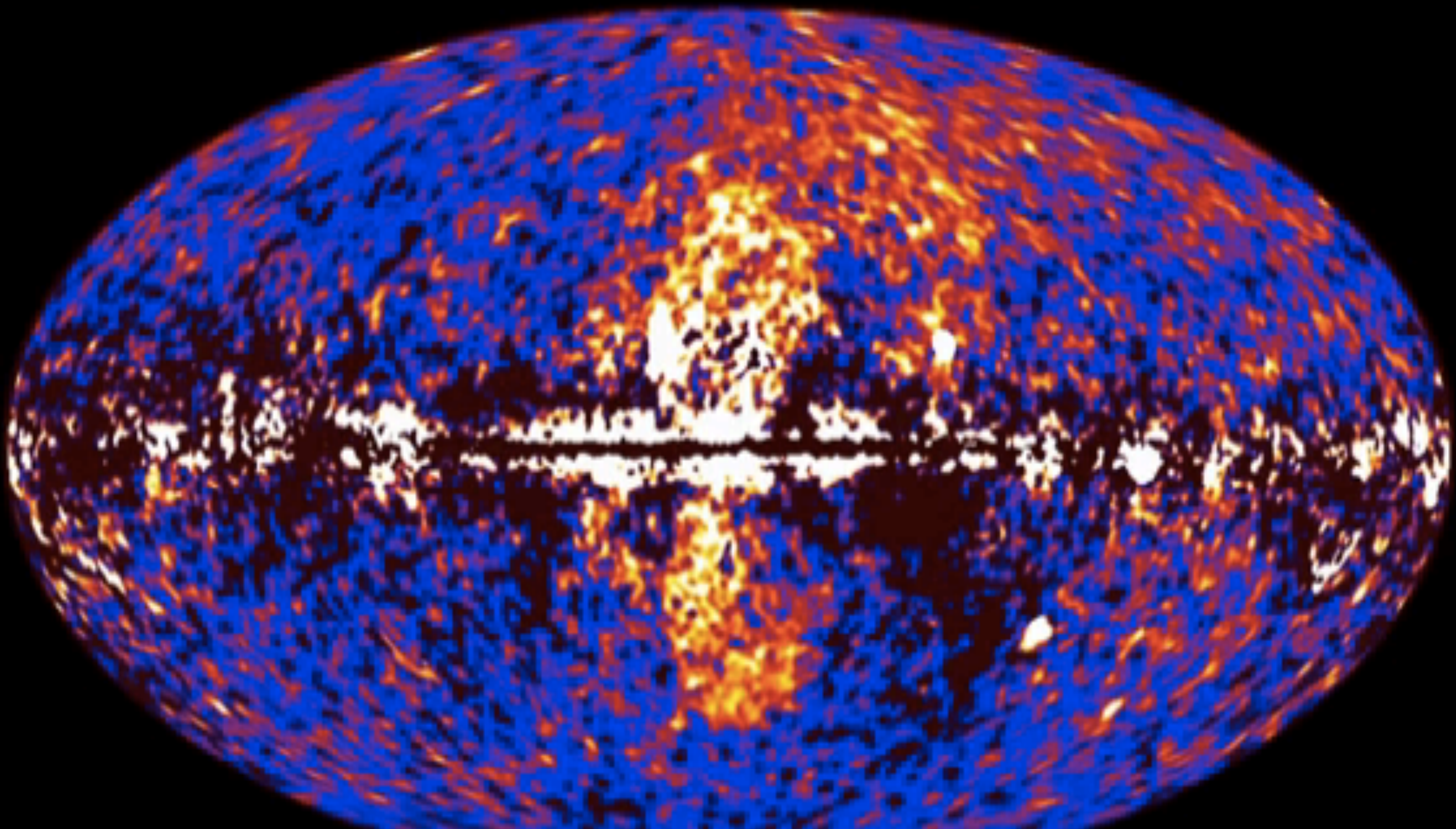
Hsiang-Yi Karen Yang

National Tsing Hua University, Institute of Astronomy

Jan. 18, 2021 Astronomy Winter School: High-energy Astrophysics Hsinchu, Taiwan

Starburst wind feedback in M82

Shull 2009
NOAO/AURA/NSF/WIYN



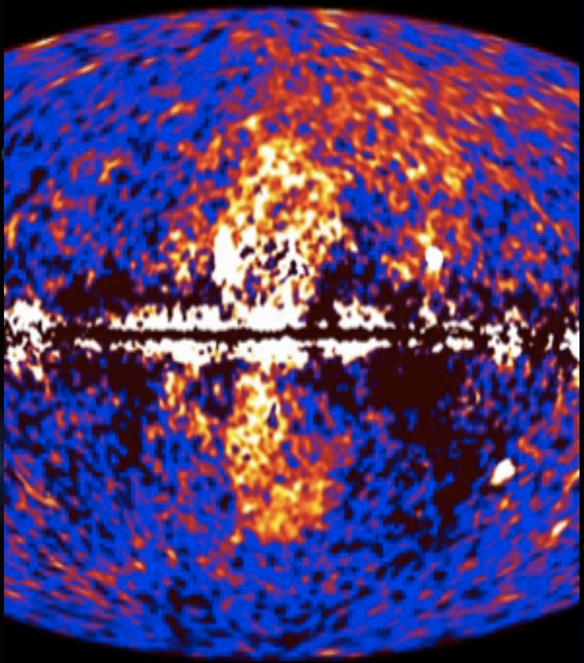
Fermi bubbles in the Milky Way Galaxy

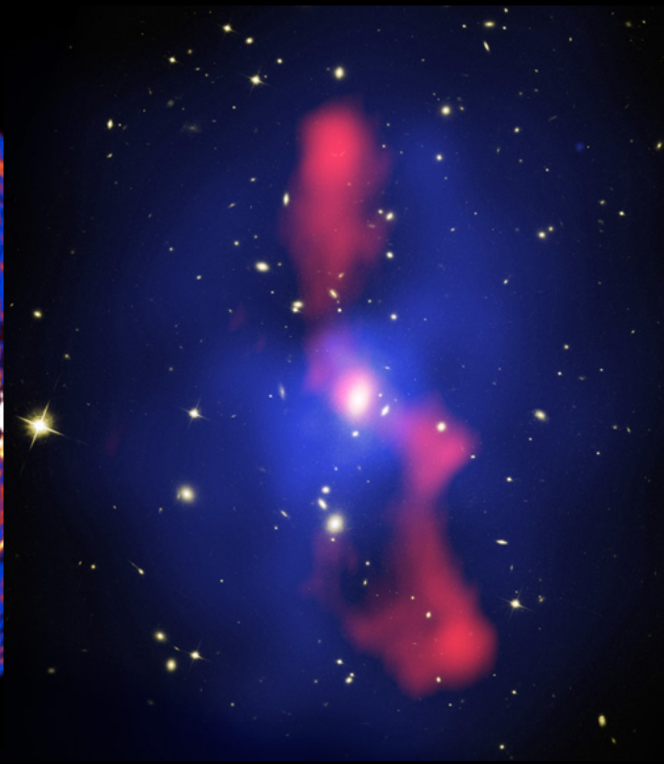
NASA/DOE/Fermi LAT/Su et al. 2010

AGN feedback in MS0735.6+7421

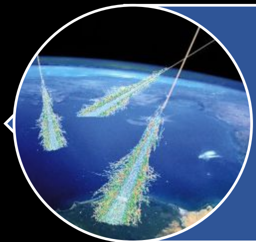
Chandra/HST/VLA

Energetic feedback in the universe



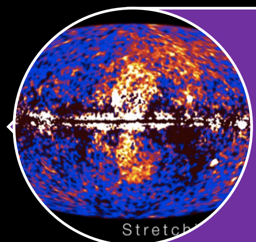


Cosmic rays (CRs) are crucial!!!



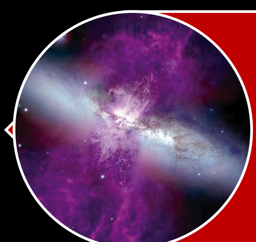
Lecture 1 (today):

Modeling CRs in Galaxies and Clusters



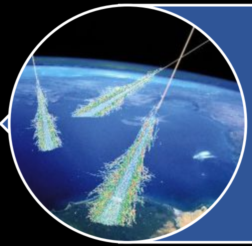
Lecture 2 (1/19 11:30am):

Physical Origin of the Fermi Bubbles



Lecture 3 (1/21 1:30pm):

CR Feedback in Galaxies and Clusters



Lecture 1 (today):
Modeling CRs in Galaxies and Clusters

- Properties of CRs in the Milky Way Galaxy
- How to model CRs in galaxy simulations
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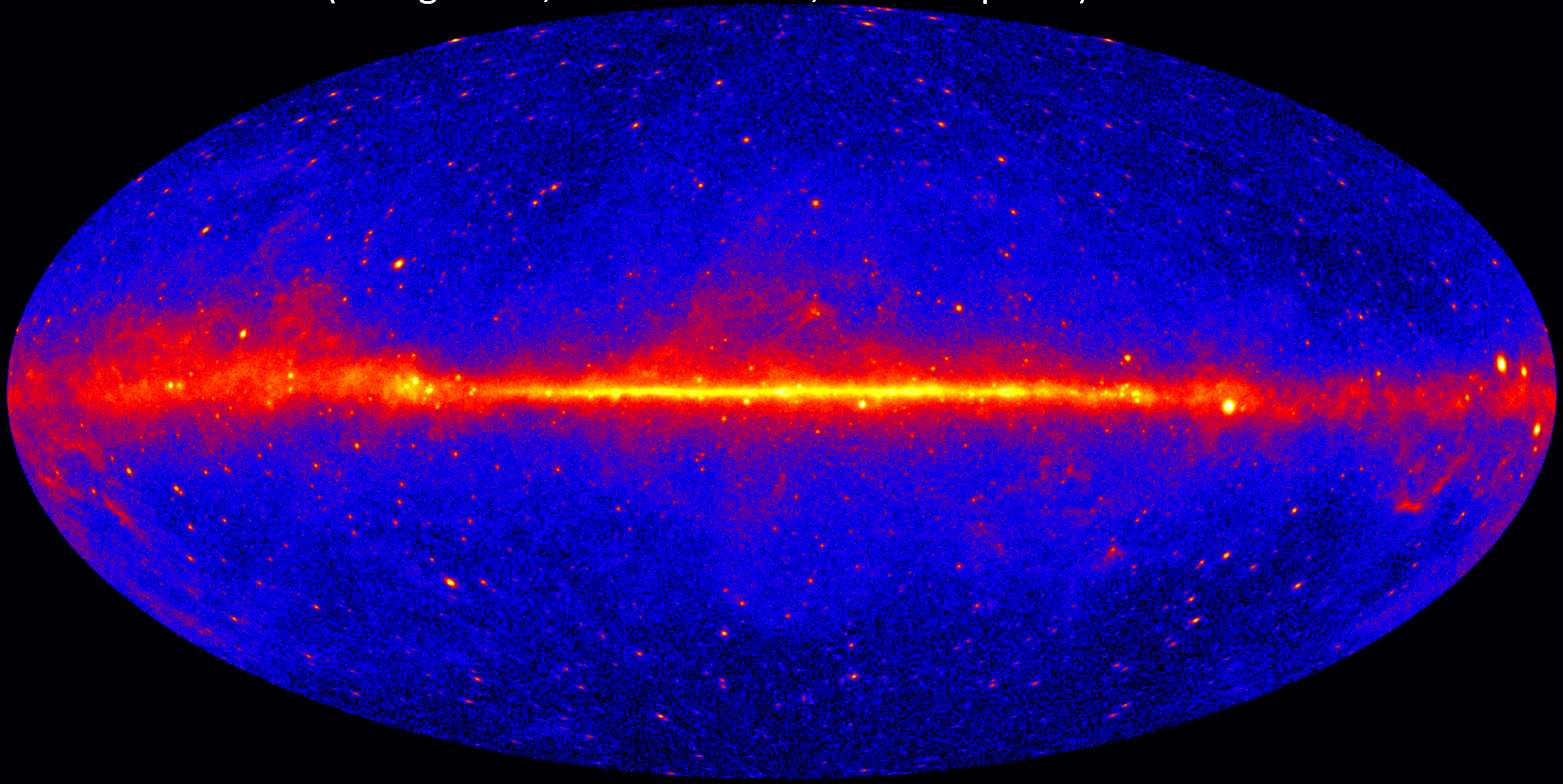
Gamma-ray all-sky map by Fermi

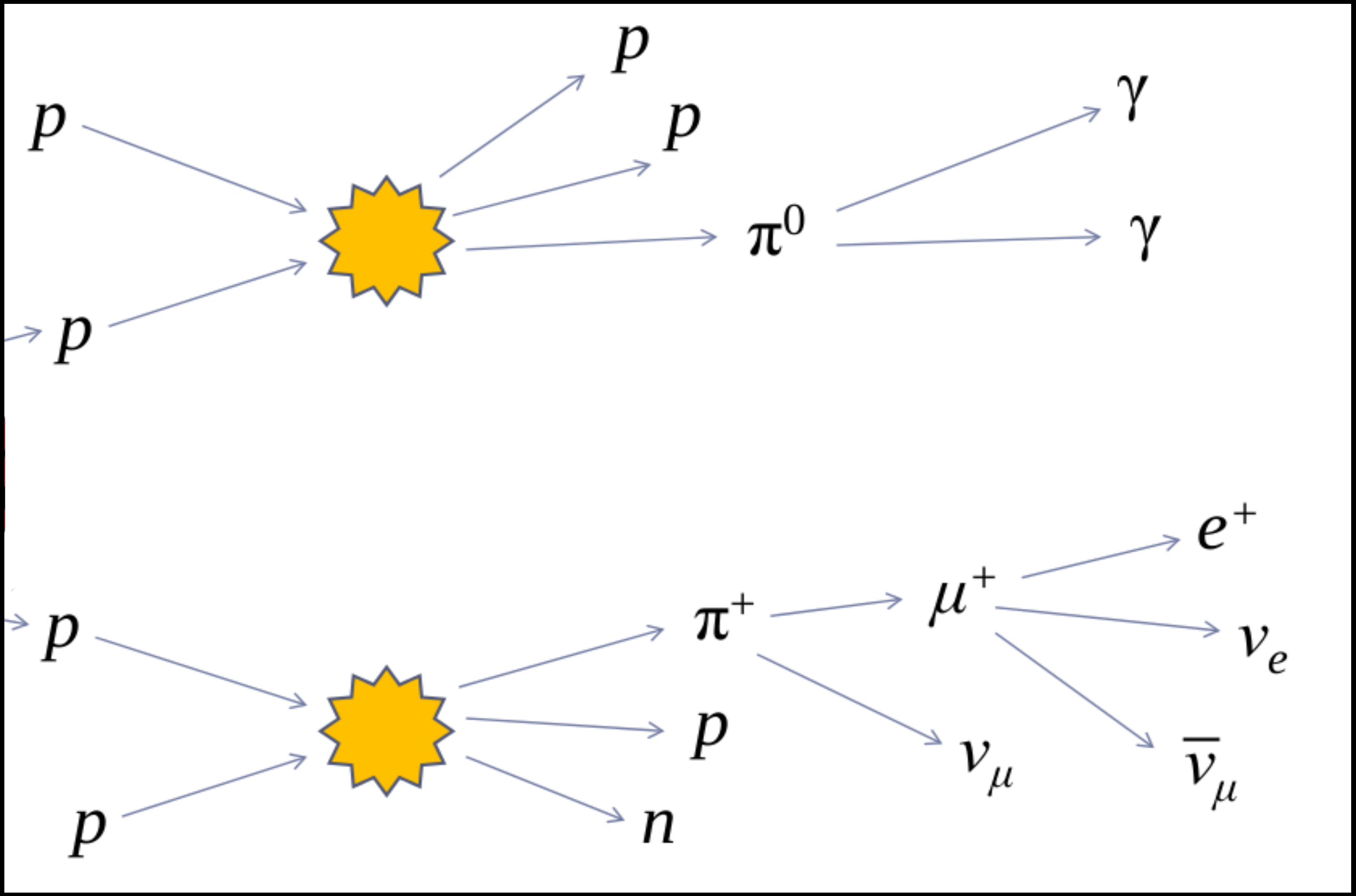
Point sources (blazars/AGNs, pulsars)
Extended sources (supernova remnants, galaxies)
Diffuse emission (background, Fermi bubbles, Galactic plane)



Credit: NASA/DOE/Fermi LAT Collaboration

Gamma-ray production by CRs

- Hadronic process – inelastic collisions between CRp and thermal nuclei in the ISM



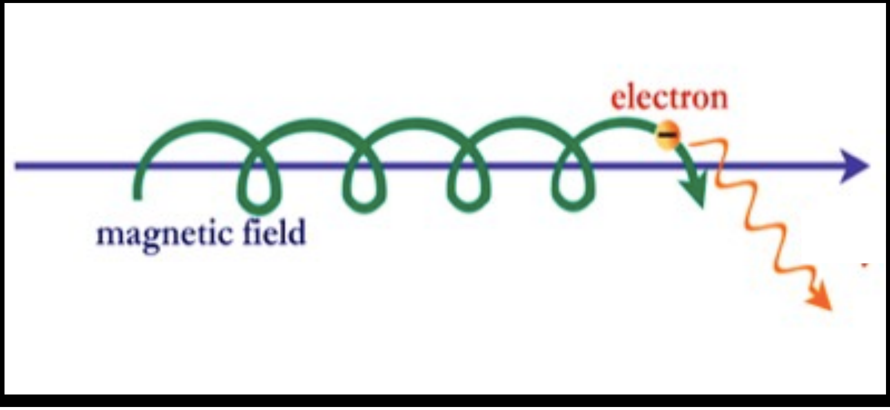
Gamma-ray production by CRs

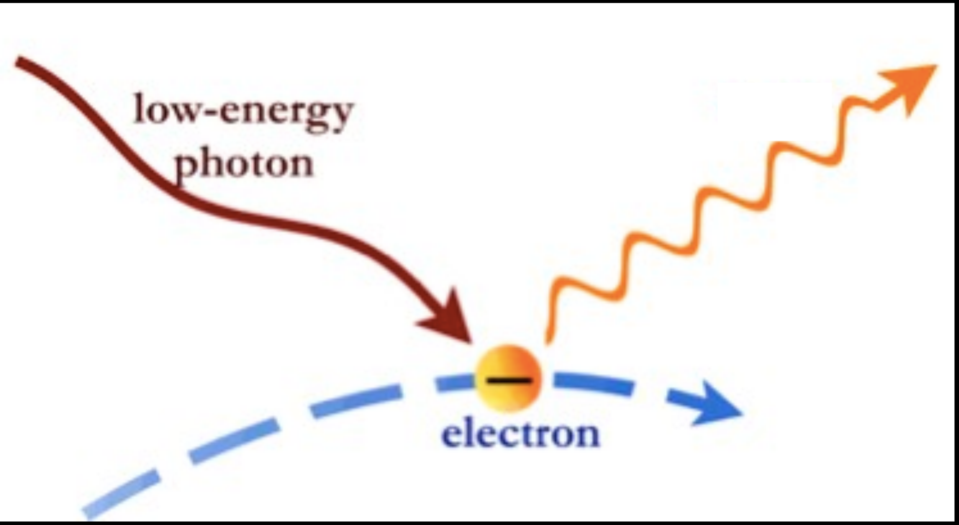
- Leptonic processes by CRe:

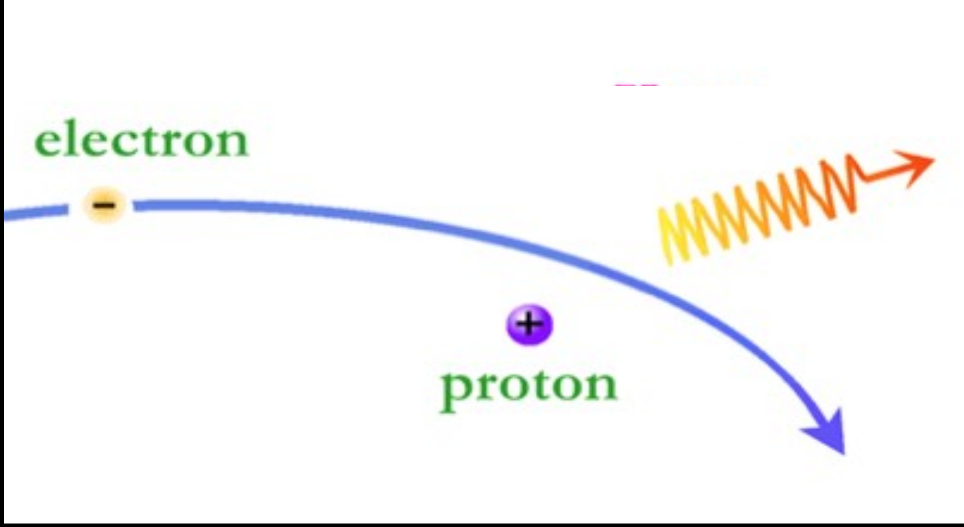
-- inverse Compton

-- synchrotron

-- bremsstrahlung







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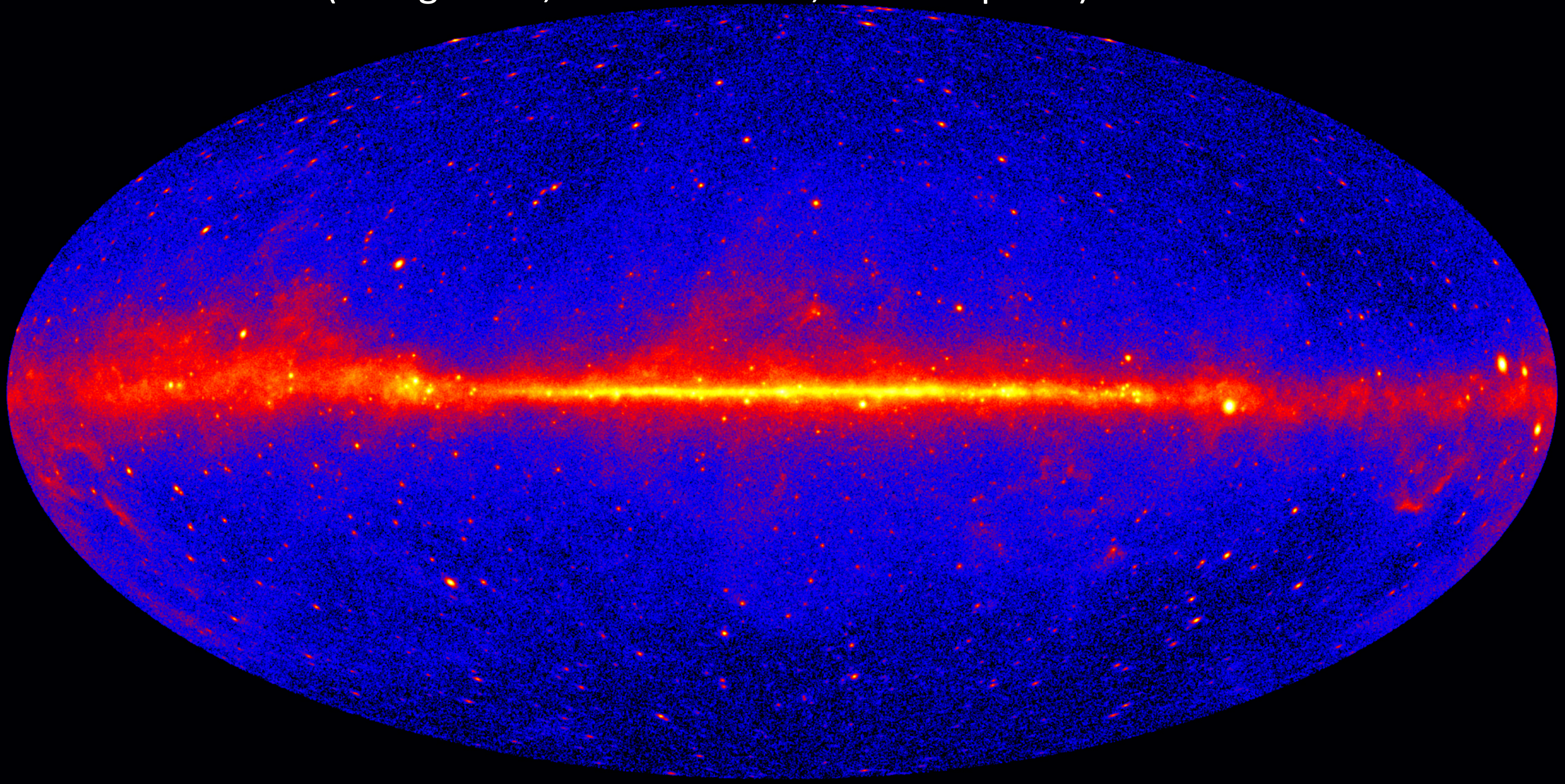
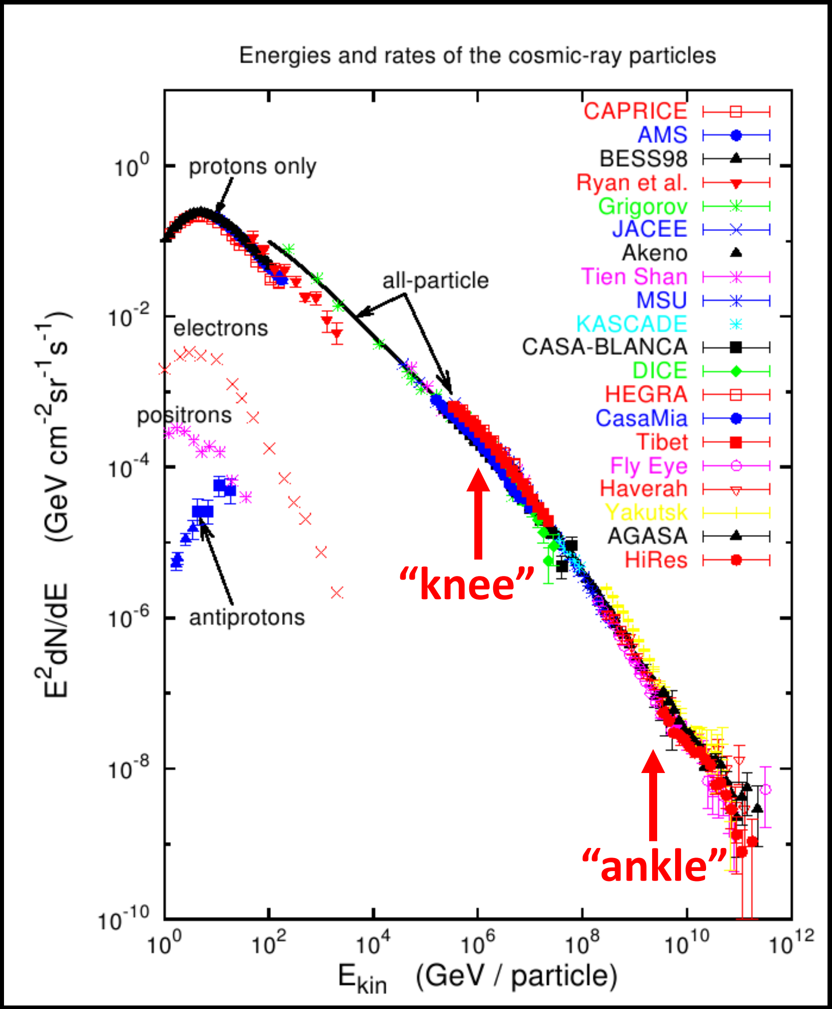


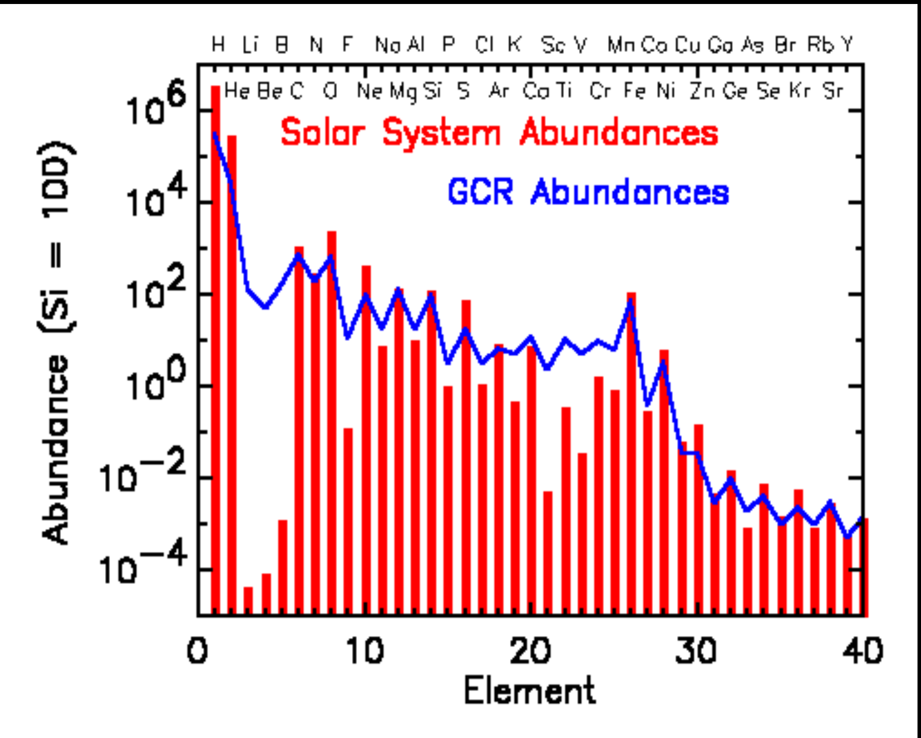
Credit: NASA/DOE/Fermi LAT Collaboration

Properties of CRs observed on Earth



- Mostly protons (n_i/n_e ~ 50-100)
- U_{CR} ~ 1eV cm^{-3} ~ U_B ~ U_{rad} ~ U_{th}
- Require ~10% of mechanical E_{SN}
- <E> ~ 3GeV

Composition => CRs are confined



Overabundance of Li, Be, B interpreted as spallation of CNO nuclei

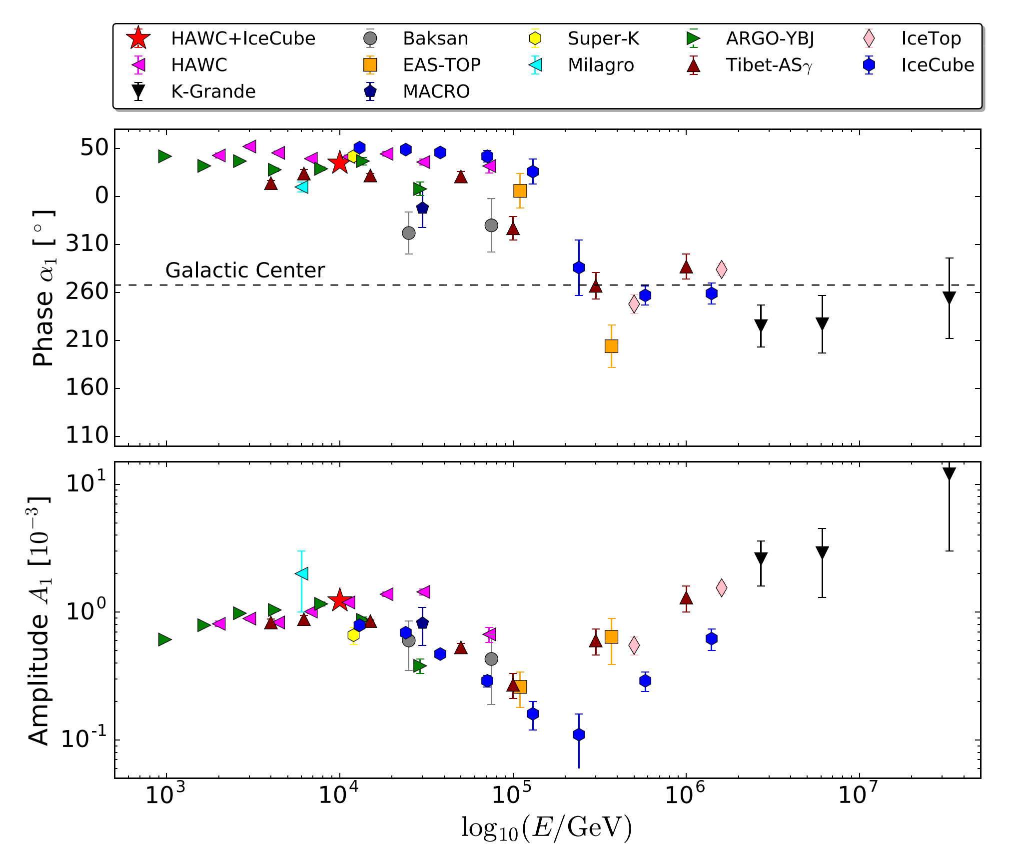
$\Rightarrow$ Grammage ~ 3-5 g/cm^2 from source to detection

$$X_s \equiv \int_{CR\ path} \rho dl = \int_{CR\ path} \rho c dt$$

$\Rightarrow$ Residence time ~20 Myr

$$\Delta t_{res} = \int_{CR\ path} dt = X_s / (\langle n \rangle m_p c)$$

Isotropy => CRs are well scattered



Anisotropy of CRs

- Increases with energy
- Amplitude ~ 10^{-3} for TeV CRs

Abeysekara+2019

CR propagation in the Milky Way

Galactic magnetic field
Star formation
CR acceleration by SNR

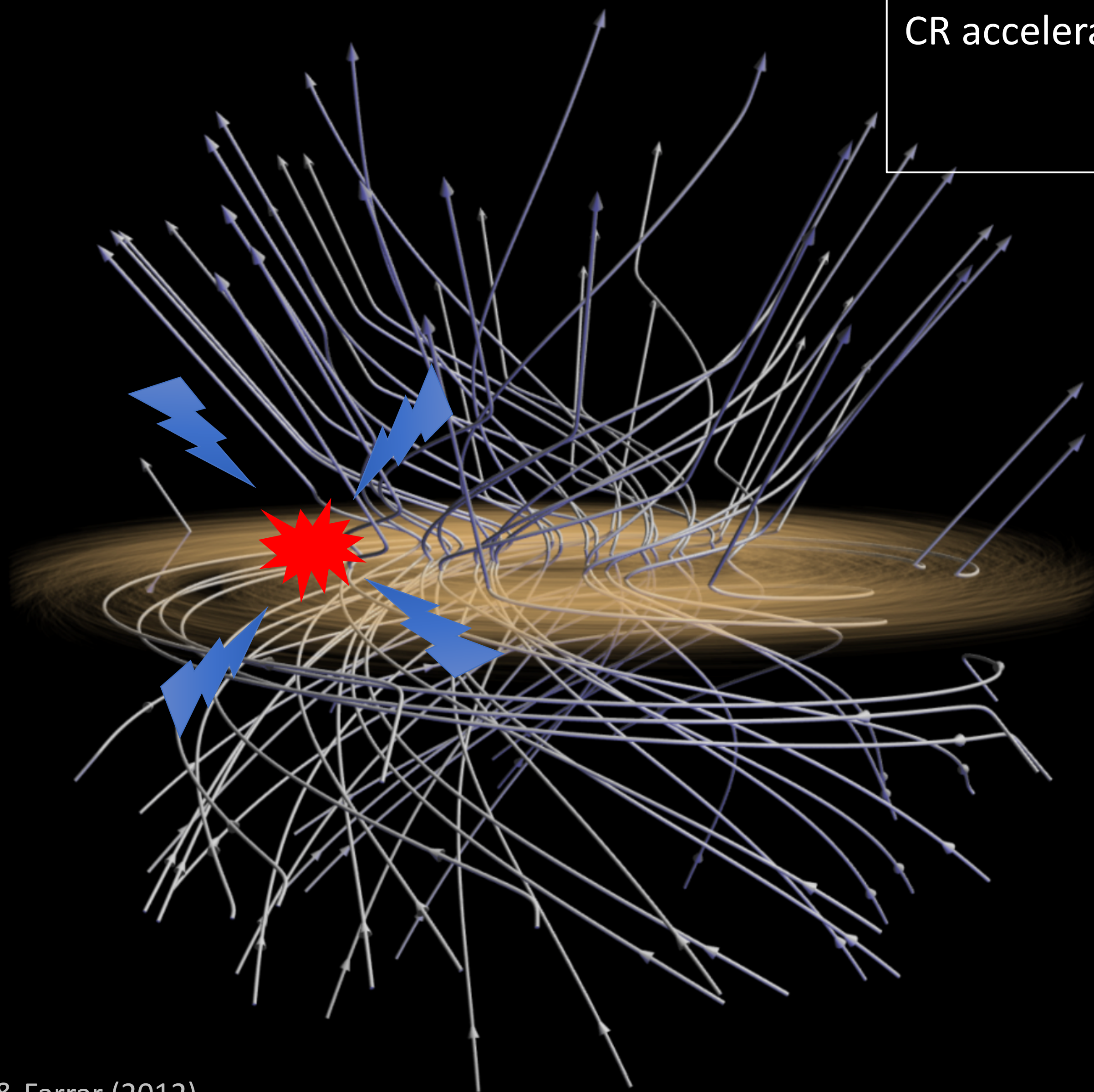


image credit: Jasson & Farrar (2012)

CR propagation in the Milky Way

- Galactic magnetic field
- Star formation
- CR acceleration by SNR
- Diffusion-like propagation
- Escape, emission, etc

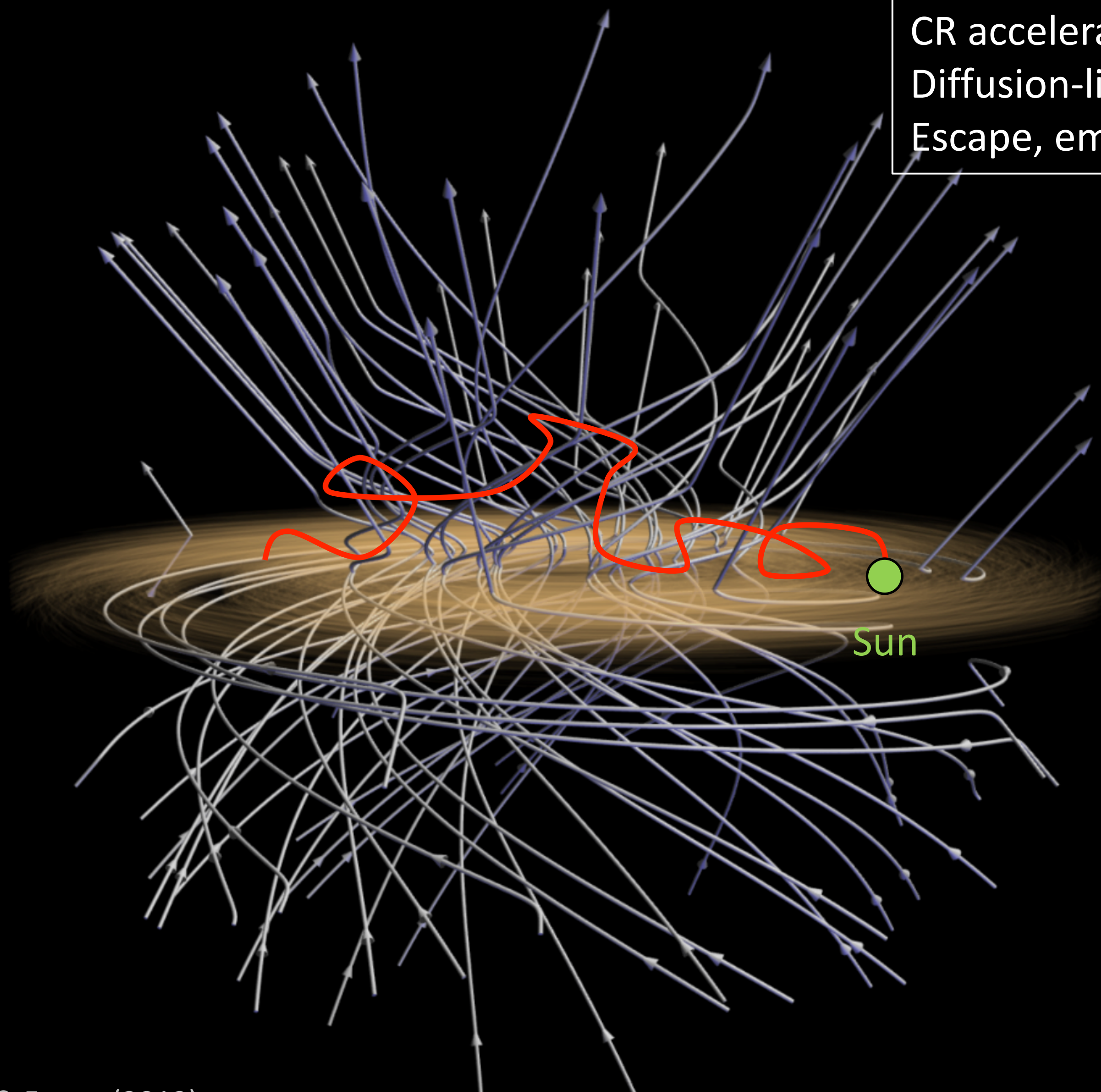
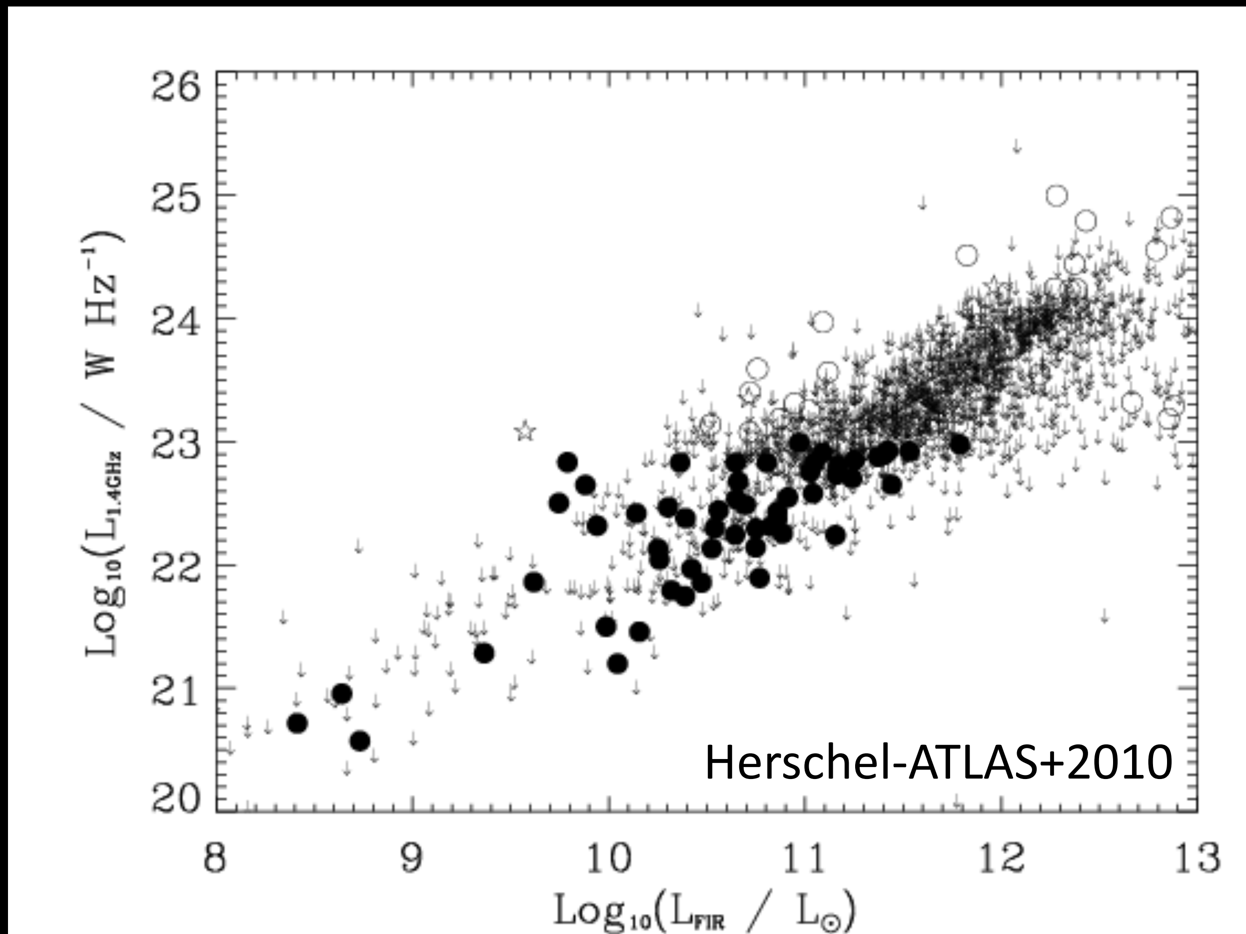


image credit: Jasson & Farrar (2012)

The FIR – Radio relation hints a universal process

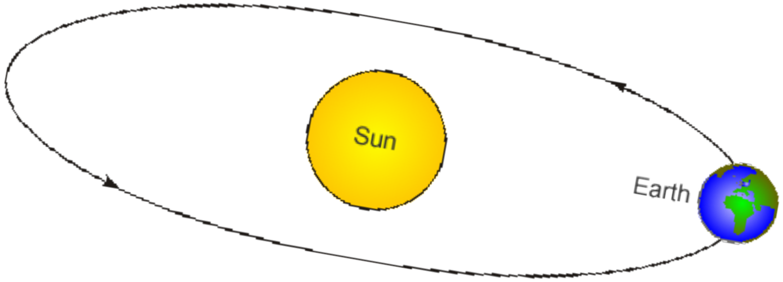
Proportional to CR energy density



Proportional to SFR

How to model CRs in the galaxies?

It is an extreme multi-scale problem



Milky Way-like galaxy:

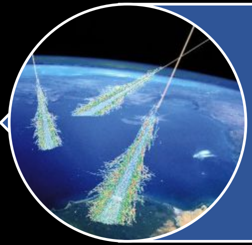
$$r_{\text{gal}} \sim 10^4 \text{ pc}$$

gyro-orbit of GeV cosmic ray:

$$r_{\text{cr}} = \frac{p_\perp}{e\,B_{\mu\text{G}}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

Goal -- develop a fluid theory for a collisionless, non-Maxwellian component!

Courtesy of C. Pfrommer



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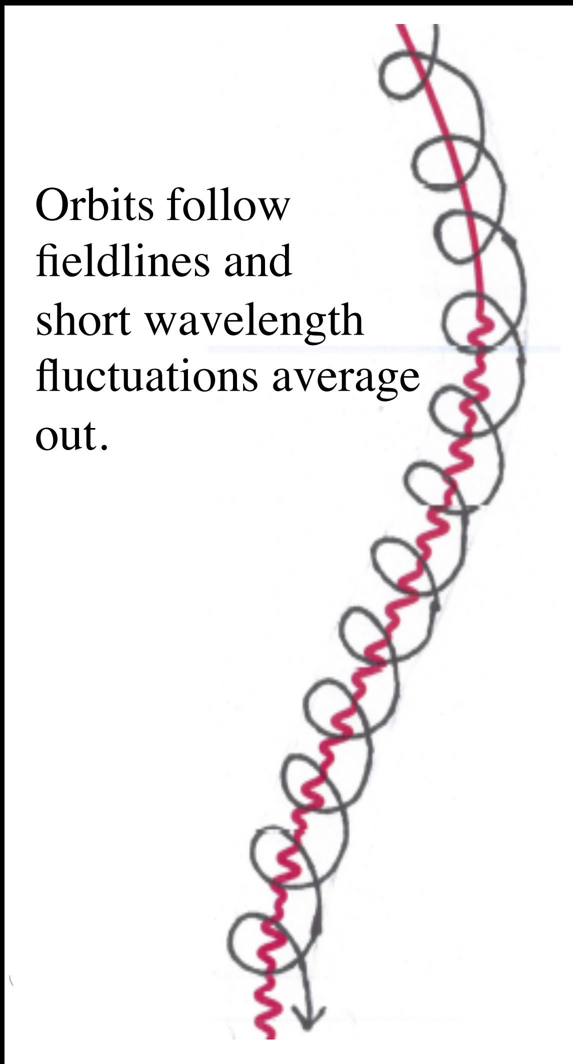
CRs interact collisionlessly with the thermal gas through gyro-scale plasma waves, exchanging momentum and energy

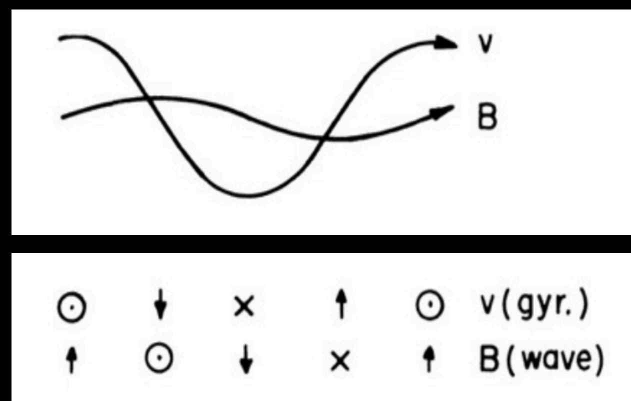
Gyro-resonance scattering



Pitch angle: $\mu = \cos\vartheta$

Gyro frequency: $\omega_c = \dfrac{ZeB}{\gamma mc}$

Resonance condition: $\omega - kv\mu = \pm\omega_c$



Systematic non-zero Lorentz force F = v x B

=> Scattering rate or rate of diffusion in μ:

$$\nu = \frac{\langle(\Delta\mu)^2\rangle}{\Delta t} \sim \frac{\pi}{2}\omega_c(1-\mu^2)\left(\frac{\delta B}{B}\right)^2$$

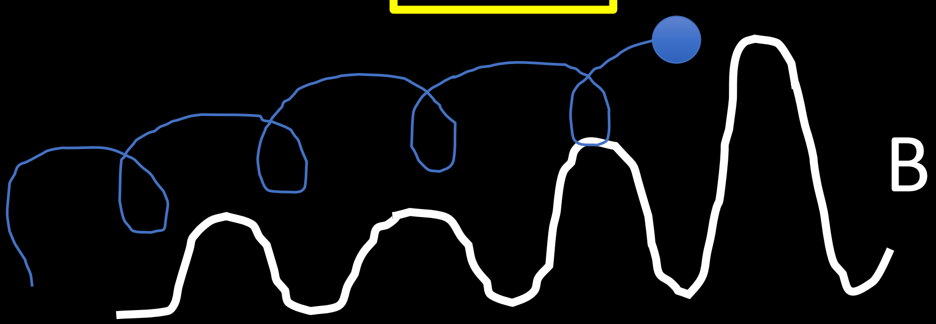
Gyro-resonance amplification of Alfven waves

- Streaming instability (Wentzel 1968, Kulsrud & Pearce 1969):
  Anisotropy => wave growth => enhanced scattering

Wave growth rate

$$\Gamma_{\rm CR}(k_\parallel) \sim \Omega_0 \frac{n_{\rm CR}(>\gamma)}{n_{\rm i}} \left(\frac{v_{\rm D}}{v_{\rm A}} - 1\right)$$

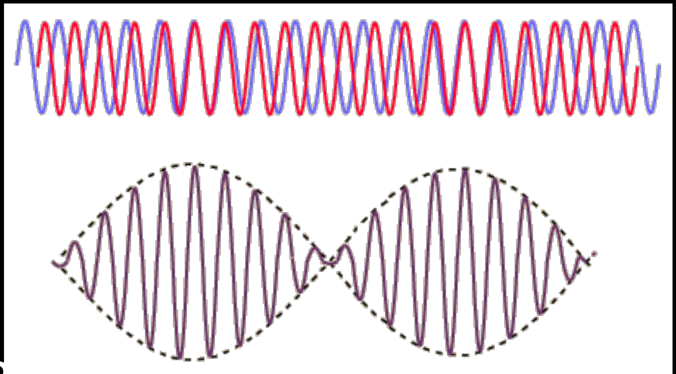
$v_D > v_A$



- Marginal stability: $v_D \sim v_A$
  (Alfvenic streaming)

When waves are damped

- Damping mechanisms
  - -- ion-neutral friction (HI, H_2)
  - -- nonlinear Landau damping (hot gas)
  - -- turbulent damping



- Damping rate = growth rate => v_D, ν, $\delta B/B$

$$v_{\rm beat} = \frac{\omega_1 - \omega_2}{k_1 - k_2}$$

$$v_{\rm beat} - v_{\rm th} = 0.$$

- Transport speed could be ***super-Alfvenic: $v_D > v_A$***

Refs: Thomas & Pfrommer (2018) for a recent summary of damping mechanisms

When waves are damped

$v_D \sim v_A$

streaming inhibited
(by perturbations)

$v_D > v_A$

fast streaming
(perturbations smoothed out)

Fokker-Planck (F-P) equation (Skilling 1975)

Describes back reaction of waves (subscript 1) on zero-order CR distribution function f_0:

$$\frac{df_0}{dt} = -\left\langle \frac{q}{m}\left(\boldsymbol{E}_1 + \frac{v \times \boldsymbol{B}_1}{c}\right) \cdot \boldsymbol{\nabla}_p f_1 \right\rangle$$
$$= \boldsymbol{\nabla}_p \cdot \boldsymbol{D} \cdot \boldsymbol{\nabla}_p f_0.$$

(averaged over wave periods and phases)

$$D_{\mu\mu} = \frac{\nu(1-\mu^2)}{2}$$

Pitch-angle scattering dominates => spatial diffusion

$D_{\mu p} = D_{p\mu}$ are order (v_A/c)

D_{pp} is order $(v_A/c)^2$ => leads to 2nd-order Fermi acceleration when waves travel in both directions

By a little algebra…

(see Zweibel 2017 for a review)

$\Rightarrow$ Making the frequent scattering approximation

$\Rightarrow$ Assume v/c~1

$\Rightarrow$ Dropping higher-order terms in v_A/c

$\Rightarrow$ Averaging over pitch angles

$\Rightarrow$ Multiply by momentum and energy and integrate over momentum space

Classical CR hydrodynamics

(*Self-confinement model*: assumes CRs scatter on self-excited waves)

CRs stream down pressure gradient with v_A:

$$\boldsymbol{v}_s = -\mathrm{sgn}(\hat{\boldsymbol{b}} \cdot \nabla e_{\mathrm{CR}})\boldsymbol{v}_{\mathrm{A}}$$

$$\frac{\partial(\varrho \boldsymbol{u})}{\partial t} = [\ldots] - \nabla P_{\mathrm{CR}}$$

Momemtum transfer via pressure gradient

$$\frac{\partial e_{CR}}{\partial t} + \nabla \cdot (e_{\mathrm{CR}} \boldsymbol{v}) = -P_{\mathrm{CR}} \nabla \cdot \boldsymbol{v} - \nabla \cdot \boldsymbol{F} + \nabla \cdot (\boldsymbol{\kappa} \cdot \nabla e_{\mathrm{CR}}) - H_{\mathrm{CR}}$$

Advection

Adiabatic

Streaming and diffusion

Heating via waves

$$\boldsymbol{F} = (e_{\mathrm{CR}} + P_{\mathrm{cr}})\boldsymbol{v}_{\mathrm{A}}, \ \ \kappa_{\parallel} \sim v^2/\nu$$

$$H_{CR} = -v_A \cdot \nabla P_{CR}$$

Refs: Wentzel 1974, Drury & Volk 1981, Breitschwerdt+1991

Other processes that need to be included

CR energy losses due to collisions and radiation

CRp:

-- ionization

-- Coulomb

-- Hadronic

CRe:

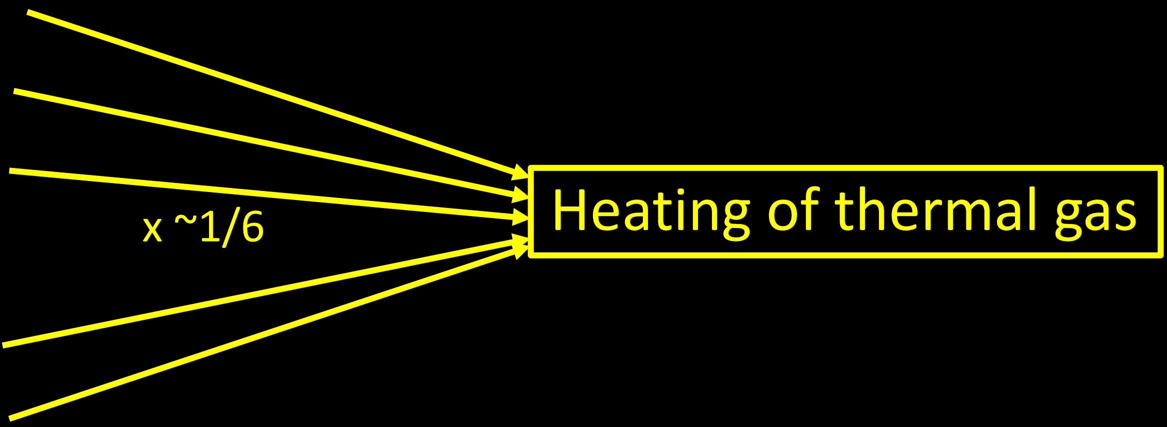
-- ionization

-- Coulomb

-- bremsstrahlung

-- inverse Compton

-- Synchrotron



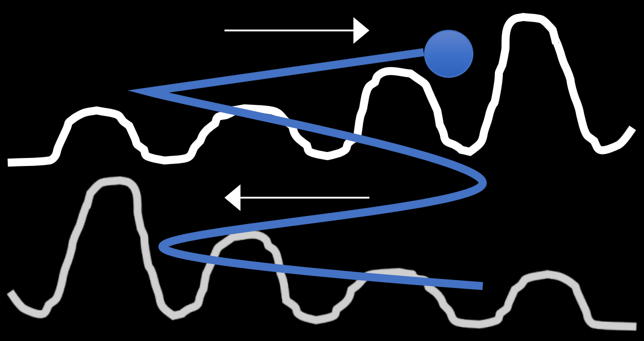
Refs: Yoast-Hull+2012

Generalized CR hydrodynamics

(***Extrinsic turbulence model***: assumes CRs scatter on waves as part of turbulent cascade)

$$\boldsymbol{v}_\mathrm{D} = \left(\frac{\nu_+ - \nu_-}{\nu_+ + \nu_-}\right)\boldsymbol{v}_\mathrm{A} \equiv f\boldsymbol{v}_\mathrm{A}, \text{where } f < 1$$

$$H_\mathrm{CR} = -f\boldsymbol{v}_\mathrm{A} \cdot \nabla P_\mathrm{CR}$$



For balanced turbulence, f=0

-- CRs ***advect*** with gas, ***no wave heating***

-- ***Diffusion*** from B wandering or unresolved B

Refs: Zweibel (2017)

Self confinement or extrinsic turbulence?

- On the scale of particle gyroradii, whether CR-induced turbulence (W_{CR}) or externally injected turbulence (W_{ext}) is dominant?
  - W_{CR}: Growth rate = Damping rate
  - W_{ext}: Assume Kolmogorov turbulence
- $W_{ext}(\lambda_{tr}) = W_{ext}(\lambda_{tr})$

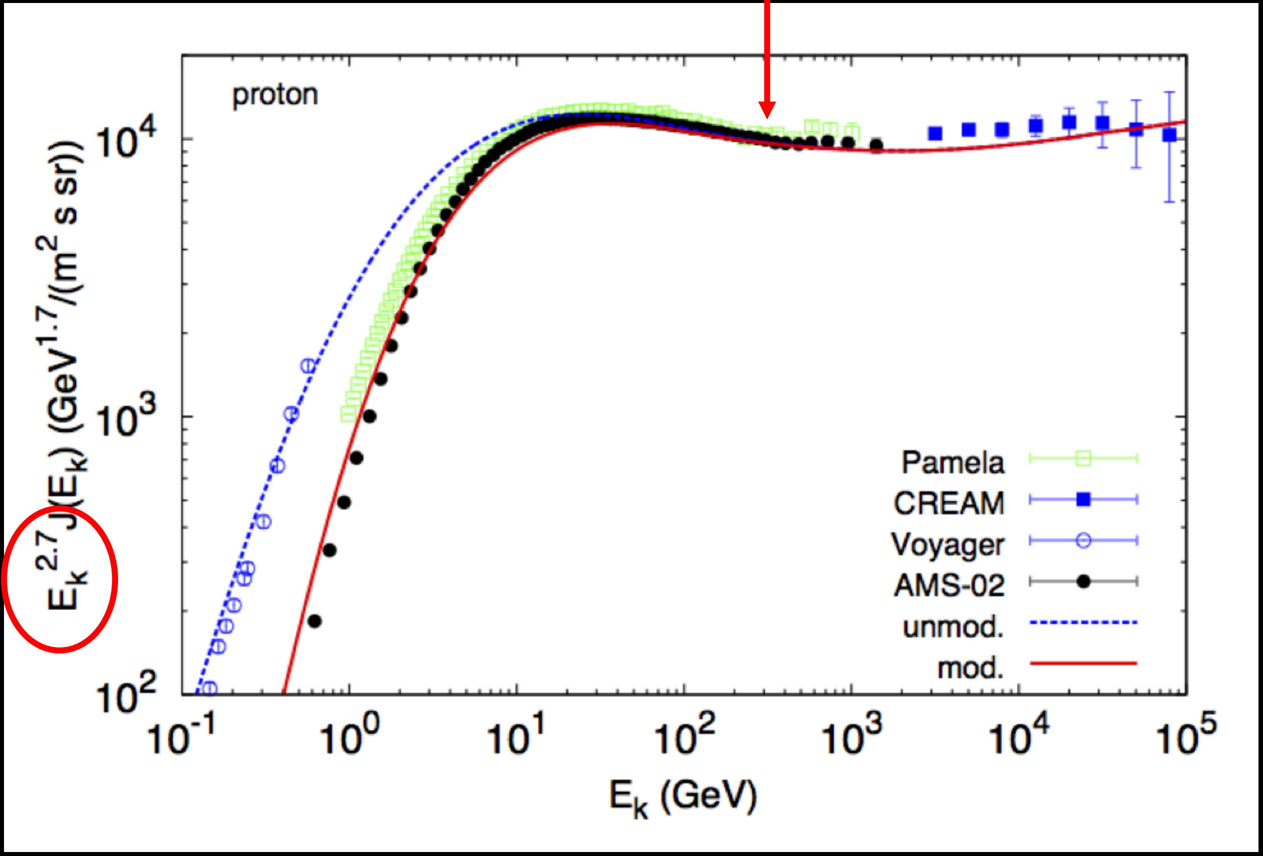
  => $\lambda_{tr} \sim 10^{15}$ cm, $E_{tr} \sim 230$ GeV
- For CRs with $E < E_{tr}$, confined by self-excited waves

  For CRs with $E > E_{tr}$, confined by external turbulence

Refs: Amato & Blasi (2018)

Self confinement or extrinsic turbulence?

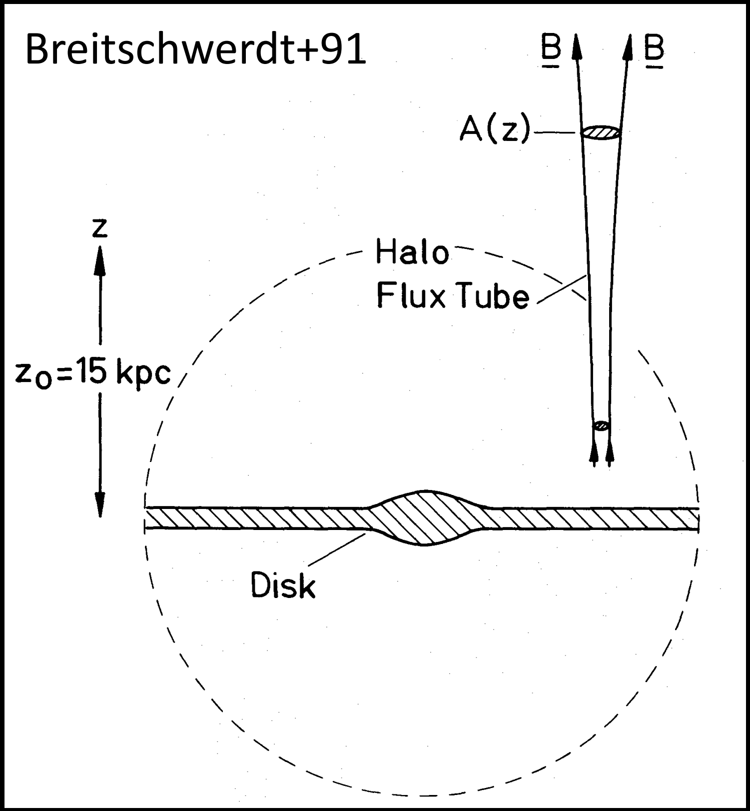
This change in spectral shape could be due to E_{tr}



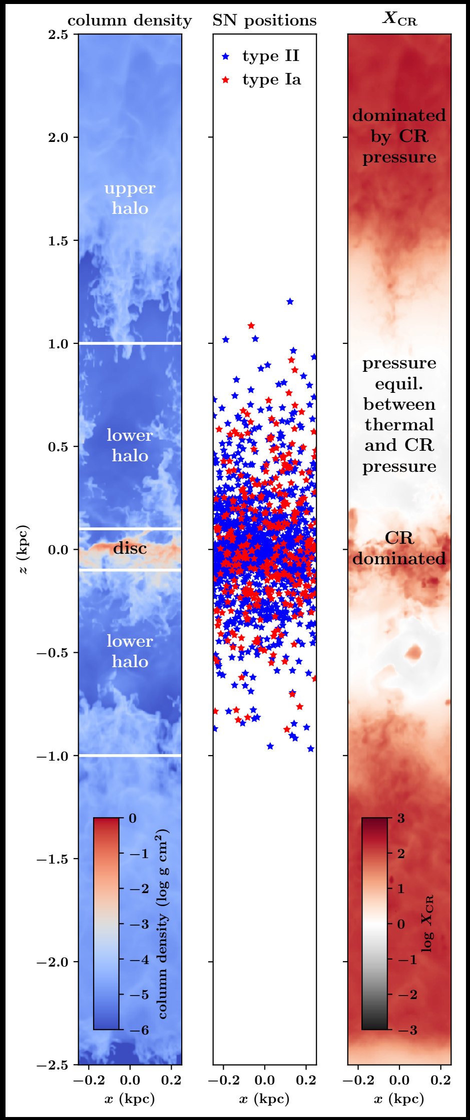
Aloisio+2015

Numerical approaches

1D flux-tubes → 3D galaxy patches



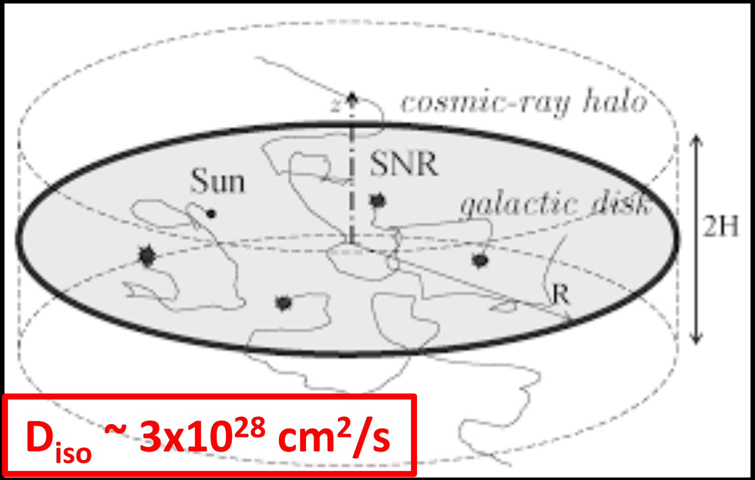
Ipavich 75, Zirakashvili+96, Everett+08, Dorfi+12, Recchia+17, Samui+18, Mao+18, Owen+19…



Girichidis+18
Farber+17
Holguin+18

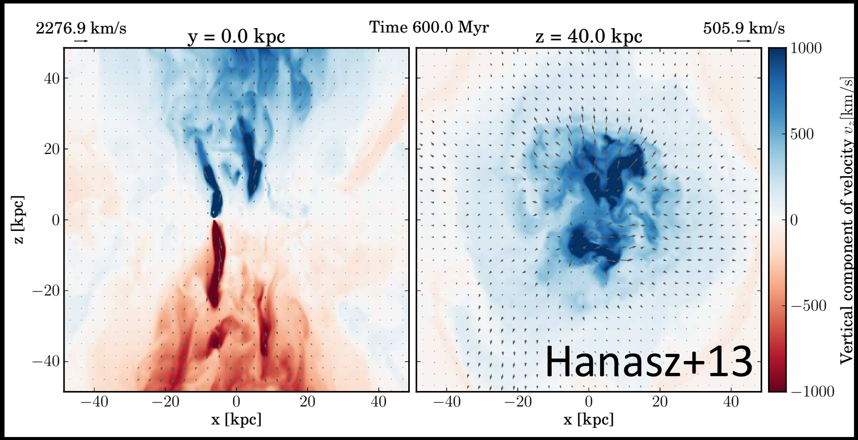
3D transport models → 3D HD/MHD simulations

"Leaky box" or "flat halo diffusion" models:
-- Assume free escape of CRs at z>|H|
-- Sophisticated treatments for CR composition
-- Milky Way's radiation field and B field
-- Constant CR diffusion coefficient



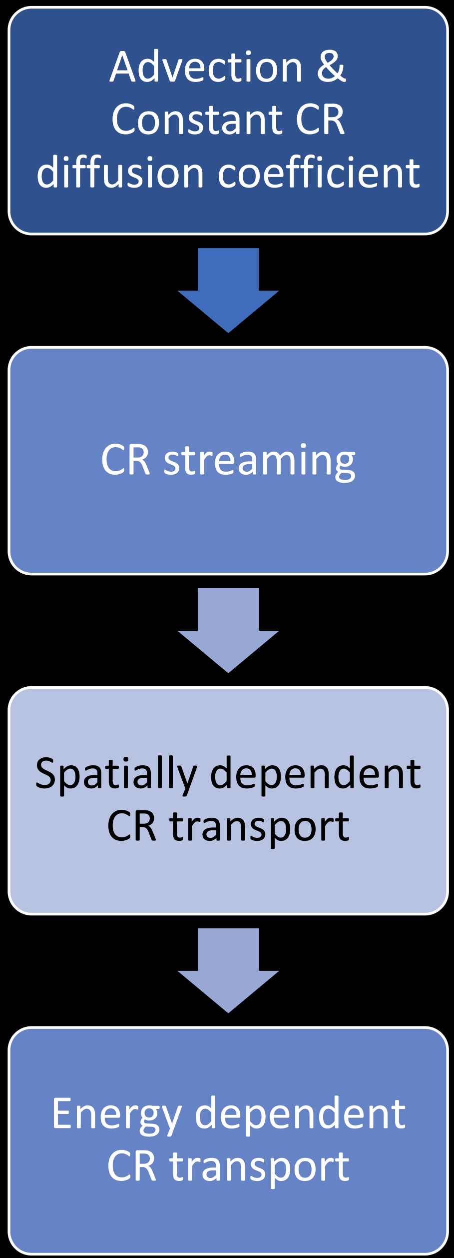
$D_{iso} \sim 3x10^{28}$ cm^2/s

GALPROP (Strong & Moskalenko 98)
DRAGON (Evoli+08)
PICARD (Kissmann 14)
Usine (Maurin+01)



Isolated galaxies:
Uhlig+12, Booth+13, Salem+14, Simpson+16, Ruszkowski+17, Wiener+17, Pfrommer+17, Jacob+18…
Cosmological simulations:
Jubelgas+08, Wadepuhl+11, Salem+14, 16, Liang+16, Chan+18, Buck+19, Ji+19, Hopkins+20ab…

Image source: http://www.issibern.ch



$$\Delta t \propto (\Delta x)^2$$

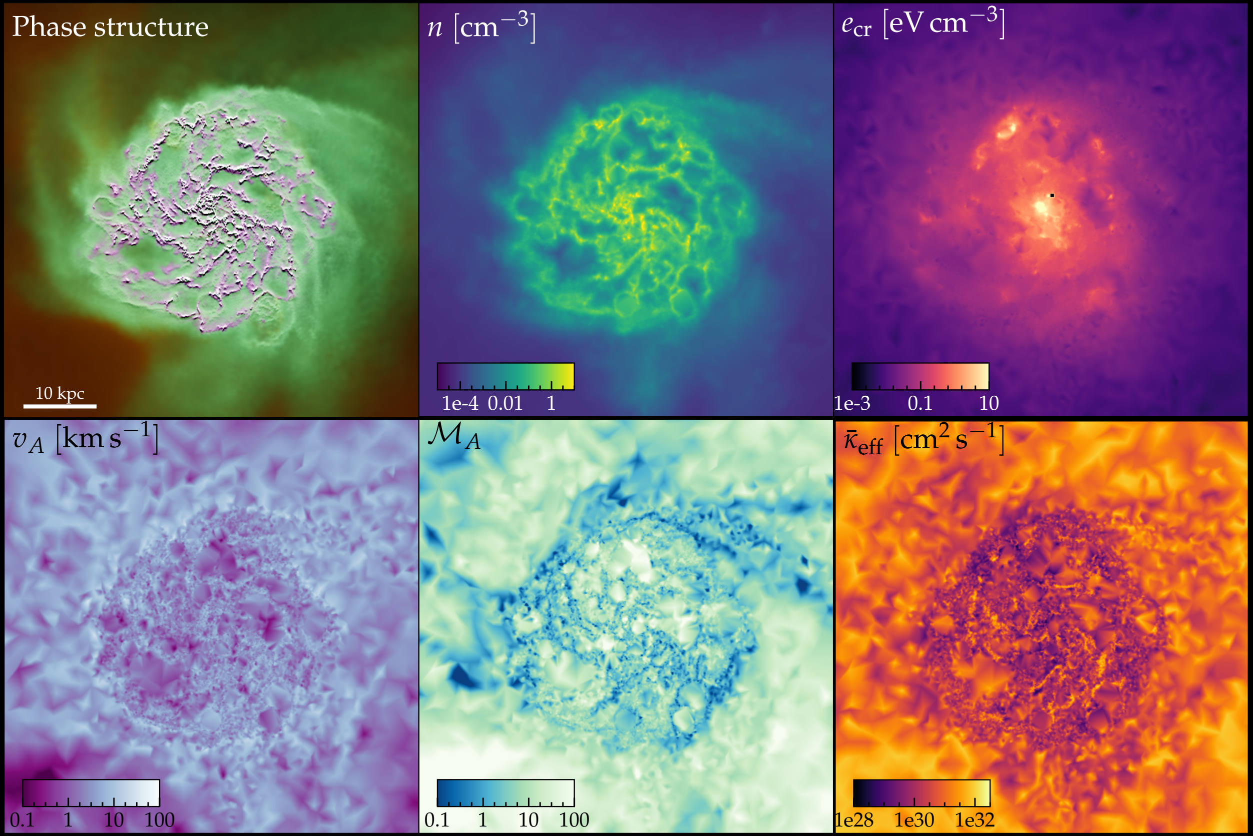
$$\Delta t \propto (\Delta x)^3$$

Regularization (Sharma+09)
Two-moment method (Jiang & Oh 18, Hopkins+20)
Wave equations (Thomas & Pfrommer 18)

Current status and open questions

Putting everything we know into the simulation…

- FIRE: 3D MHD cosmological galaxy simulations
- Testing all possible choices of different CR transport physics
- Observational constraints: Lγ, grammage, residence time, CR energy densities



Refs: Hopkins+2020, astro-ph://2002.06211

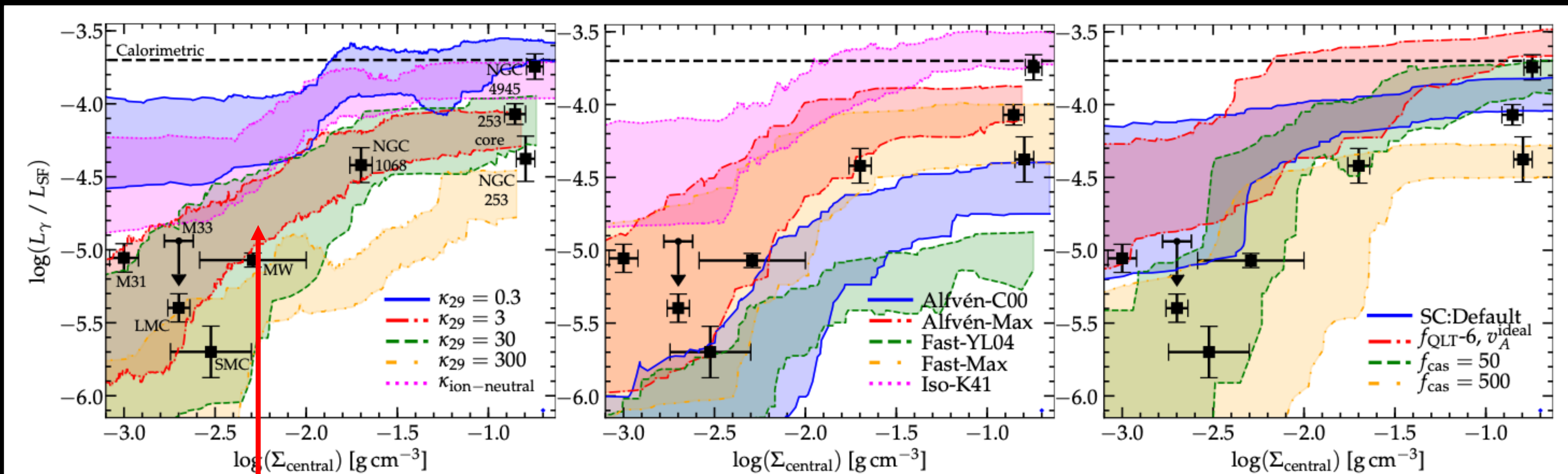
Pu

Name	Description	Ref.	$\langle \kappa_{\rm eff}^{\rm iso} \rangle^{\nu}_{29}$	L_γ, X_s?	$\langle e_{\rm cr} \rangle$
CD:	**Constant-Diffusivity Models (§ 3.1; Eq. 3)**: $\kappa_\parallel = \kappa_{29}\,10^{29}\,{\rm cm^2\,s^{-1}}$, varied $v_{\rm st} \sim v_A$				
$\kappa_{29} = 0$	$\kappa_{29} = 0$, $v_{\rm st} = (0, 1, 3, 4, 1+\beta^{1/2}, 3[1+\beta^{1/2}])\,v_A$ (§ 3.1.2)	a	$\lesssim$0.01	× (high)	40
$\kappa_{29} = 0.03$	$\kappa_{29} = 0.03$, $v_{\rm st} = (1,3)\,v_A$	a	0.015	× (high)	50
$\kappa_{29} = 0.3$	$\kappa_{29} = 0.3$, $v_{\rm st} = (0,1,3)\,v_A$	a	0.1	× (high)	8
$\kappa_{29} = 3$	$\kappa_{29} = 3$, $v_{\rm st} = (0,1,3)\,v_A$ (favored models in Papers I & II)	a	1	✓	1
$\kappa_{29} = 30$	$\kappa_{29} = 30$, $v_{\rm st} = v_A$	a	10	✓	0.4
$\kappa_{29} = 300$	$\kappa_{29} = 300$, $v_{\rm st} = v_A$	a	100	○ (low)	0.04
$\kappa_{\rm ion-neutral}$	$\kappa_{29} = 3$ in neutral gas, $= 0.1$ in ionized gas (§ 3.1.1; Eq. 4)	b	0.05	× (high)	20
ET:	**Extrinsic Turbulence Models (§ 3.2, Eq. 5)**: $\kappa_\parallel = \mathcal{M}_A^{-2}\,c\,\ell_{\rm turb}\,f_{\rm turb}$, varied $f_{\rm turb}$				
Alfvén-C00	$f_{\rm turb} = 0.14\,(c_s/v_A)/\ln(\ell_{\rm turb}/r_{\rm L})$: anisotropic GS95 spectrum of Alfvén modes	c	1500	○ (low)	0.2
Alfvén-C00-Vs	as Alfvén-C00, adding additional "streaming" $v_{\rm st} = v_A$ or $v_A^{\rm ion}$	–	1500	○ (low)	0.2
Alfvén-YL02	$f_{\rm turb} = 70\,(c/v_A)^{5/11}\,(\ell_{\rm turb}/r_{\rm L})^{9/11}$: modified non-resonant Alfvén scattering	d	$>10^4$	○ (low)	0.001
Alfvén-Hi	$f_{\rm turb} = 1000$: arbitrarily changed $f_{\rm turb}$	–	400	○ (low)	0.02
Alfvén-Max	$f_{\rm turb} = 1$: GS95 Alfvén scattering ignoring gyro-averaging/anisotropy	–	1	✓	2
Fast-YL04	$f_{\rm turb} = f(\lambda_{\rm damp})$: non-resonant fast-modes, damped below $\lambda_{\rm damp}$	e	80	○ (low)	0.006
Fast-Max	as YL04, neglect ion-neutral and $\beta > 1$ viscous damping	e	6	✓	1
Fast-Mod	$f_{\rm turb} \sim 1000\times$ the "Fast-Max" value (different spectrum, broadening)	–	700	○ (low)	0.04
Fast-NoDamp	$f_{\rm turb} = (r_{\rm L}/\ell_{\rm turb})^{1/2}$: Fast-YL04, ignoring any fast-mode damping	–	0.003	× (high)	3
Fast-NoCDamp	$f_{\rm turb}$ given by Fast-Max with viscous damping only	–	0.03	× (high)	5
Iso-K41	$f_{\rm turb} = (r_{\rm L}/\ell_{\rm turb})^{1/3}$: isotropic, undamped K41 cascade down to $< r_{\rm L}$	f	0.004	× (high)	0.4
Fast-Max+Vs	as Fast-YL04, adding additional "streaming" $v_{\rm st} = v_A$ or $v_A^{\rm ion}$	–	7	✓	1
SC:	**Self-Confinement Models (§ 3.3, Eq. 6)**: $\kappa_\parallel \propto \Gamma$ (damping), $v_{\rm st} = v_A^{\rm ion}$, varied Γ				
Default	default scalings for $\Gamma = \Gamma_{\rm in} + \Gamma_{\rm turb} + \Gamma_{\rm LL} + \Gamma_{\rm NLL}$, Appendix A	–	0.02	× (high)	10
Non-Eqm	replace $\kappa_\parallel$, $v_{\rm st}$ with evolved gyro-resonant $\delta{\bf B}[r_{\rm L}]$ (§ 3.3.2)	–	0.03	× (high)	4
10 GeV	adopt $\gamma_{\rm L} = 10$ instead of $= 1$ (typical $E_{\rm cr}/Z \sim 10\,$GeV; § 3.3.3)	–	0.03	× (high)	15
$v_A^{\rm ideal}$	adopt $v_A = v_A^{\rm ideal}$ instead of $v_A^{\rm ion}$ in Eq. 6 (§ 3.3.1)	–	0.007	× (high)	15
$f_{\rm QLT}$-6	multiply $\kappa_\parallel$ in Eq. 6 by $f_{\rm QLT}$ (weaker growth or stronger damping; § 3.3.4)	–	0.05	× (high)	10
$f_{\rm QLT}$-6, 10 GeV	combines "$f_{\rm QLT}$-6" and "10 GeV" models	–	0.1	× (high)	8
$f_{\rm QLT}$-6, $v_A^{\rm ideal}$	combines "$f_{\rm QLT}$-6" and "$v_A^{\rm ideal}$" models	–	0.04	× (high)	10
$f_{\rm QLT}$-100	multiply $\kappa_\parallel$ in Eq. 6 by $f_{\rm QLT} = 100$	–	5	✓	0.3
$f_{\rm cas}$-5	$f_{\rm cas} = 5$ in $\Gamma_{\rm turb}$ & $\Gamma_{\rm LL}$	–	0.06	× (high)	8
$f_{\rm cas}$-50	$f_{\rm cas} = 50$ in $\Gamma_{\rm turb}$ & $\Gamma_{\rm LL}$	–	2	✓	0.3
$f_{\rm cas}$-500	$f_{\rm cas} = 500$	–	10	✓	0.4
$f_{\rm cas}$-DA	$f_{\rm cas} = (\ell_{\rm turb}/r_{\rm L})^{1/10}$, for a "dynamically aligned" perpendicular spectrum ($\sim k_\perp^{-3/2}$)	–	0.02	× (high)	10
$f_{\rm cas}$-B73	$f_{\rm cas} = {\rm MIN}(1, \mathcal{M}_A^{-1/2})$, for a B73 spectrum above ℓ_A	–	0.005	× (high)	20
$f_{\rm cas}$-L16	$f_{\rm cas}$ follows a multi-component cascade model from L16	g	0.004	× (high)	15
$f_{\rm cas}$-K41	$f_{\rm cas} = \mathcal{M}_A^{-1/2}\,(\ell_{\rm turb}/r_{\rm L})^{1/6}$ for an isotropic, undamped K41 cascade	–	15	✓	0.3
NE, $f_{\rm cas}$-L16	as "Non-Eqm" but with $f_{\rm cas}$ following $f_{\rm cas}$-L16 model	–	0.01	× (high)	4
NE, $f_{\rm QLT}$-100	as "Non-Eqm" but with $f_{\rm QLT} = 100$	–	7	✓	0.3
ET+SC:	**Combined Extrinsic-Turbulence & Self-Confinement (§ 3.4)**: $\nu_{\rm total} = \sum \nu_i$ (sum ET+SC terms), $v_{\rm st} = v_A^{\rm ion}$				
A+F+SC100	ET:Alfvén-C00 + ET:Fast-Max + SC:$f_{\rm turb} = 100$	–	2	✓	1
A+SC100	ET:Alfvén-C00 + SC:$f_{\rm turb} = 100$	–	5	✓	0.3

Refs: Hop

Putting everything we know into the simulation…

Constant diffusion | Extrinsic turbulence | Self confinement

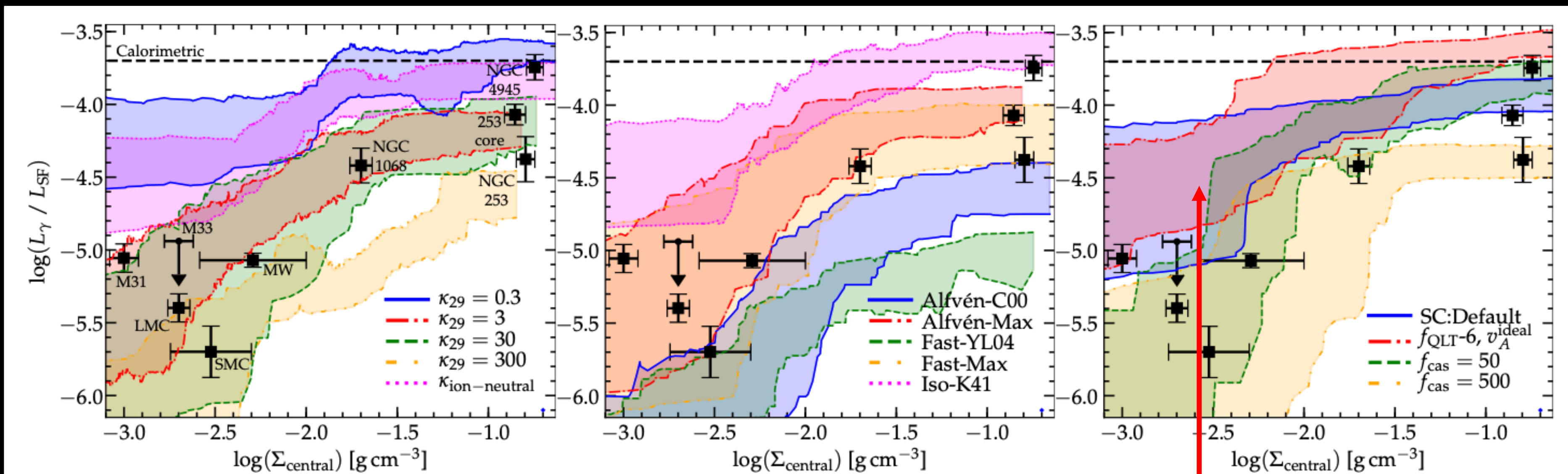


A larger CR diffusion coefficient (3-30)x10^{29} cm^2/s is required
(could be still consistent due to anisotropic transport and height of leaky boxes)

Refs: Hopkins+2020, astro-ph://2002.06211

Putting everything we know into the simulation…

Constant diffusion | Extrinsic turbulence | Self confinement



The standard self-confinement model over-predicts Lγ, implying too much confinement by a factor of 100!!

Refs: Hopkins+2020, astro-ph://2002.06211

Some open questions

- Whether the standard self-confinement model is consistent with observational constraints? Are significant modifications needed?

- How are CRs above ~200-300 GeV confined? By Alfvenic turbulence or fast MHD waves?

- How are these processes modified in high-β environments (i.e., galaxy clusters)?

- How do CRs affect feedback from stars and SMBHs?

(see Karen's lecture on 1/21)

Summary

- CRs are key agents in our understanding of our Milky-Way Galaxy as well as feedback processes in galaxies and clusters
- CRs exchange momentum and energy with thermal gas via plasma waves, which is the core of classical/generalized CR hydrodynamics
- CR physics in galaxies is complex and extreme multi-scale, which poses great challenges to our understanding of plasma physics and galaxy formation

References

- Acceleration of CRs (see F. Rieger's lectures)
- Non-resonant/Bell streaming instability
  - Bell, 2004, MNRAS, 353, 550
- Review articles
  - Zweibel, 2013, PhPl, 20, 055501
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  - Amato & Blasi, 2018, Advance in Space Research, 62, 2731