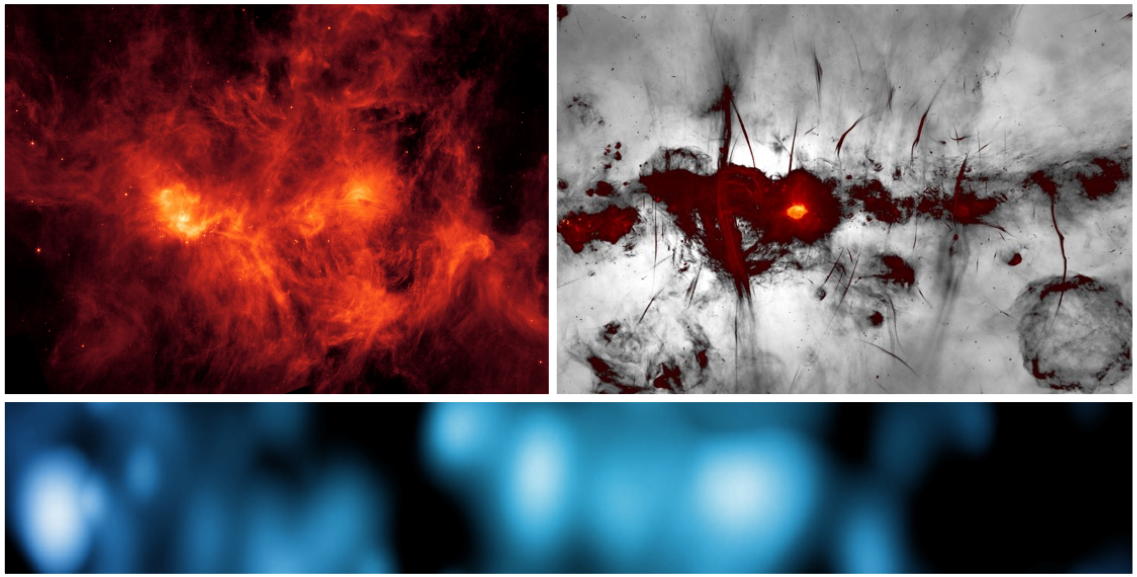
The Galactic Center and Multiphase ISM as Multimessenger Laboratories

Prospects for Astronomical Diagnostics and Tests of Cosmic-Ray Propagation

17th December, 2025 – MeV-PeV Frontiers – IPMU, Kashiwa, Japan



Credit: Perseus Molecular Cloud, NASA/JPL-Caltech (2019); Galactic Center with MeerKAT, I. Heywood, SARAO (2022); Neutrinos from the Galactic Plane; IceCube Collab. (2023)

Ellis R Owen

SPDR Fellow

Astrophysical Big Bang Laboratory, RIKEN Pioneering Research Institute, Japan

ellis.owen@riken.jp www.ellisowen.org

OUTLINE

- Introduction to cosmic ray processes and multimessenger astronomy in interstellar environments
  - Part I: Using neutrinos as an astronomical tool

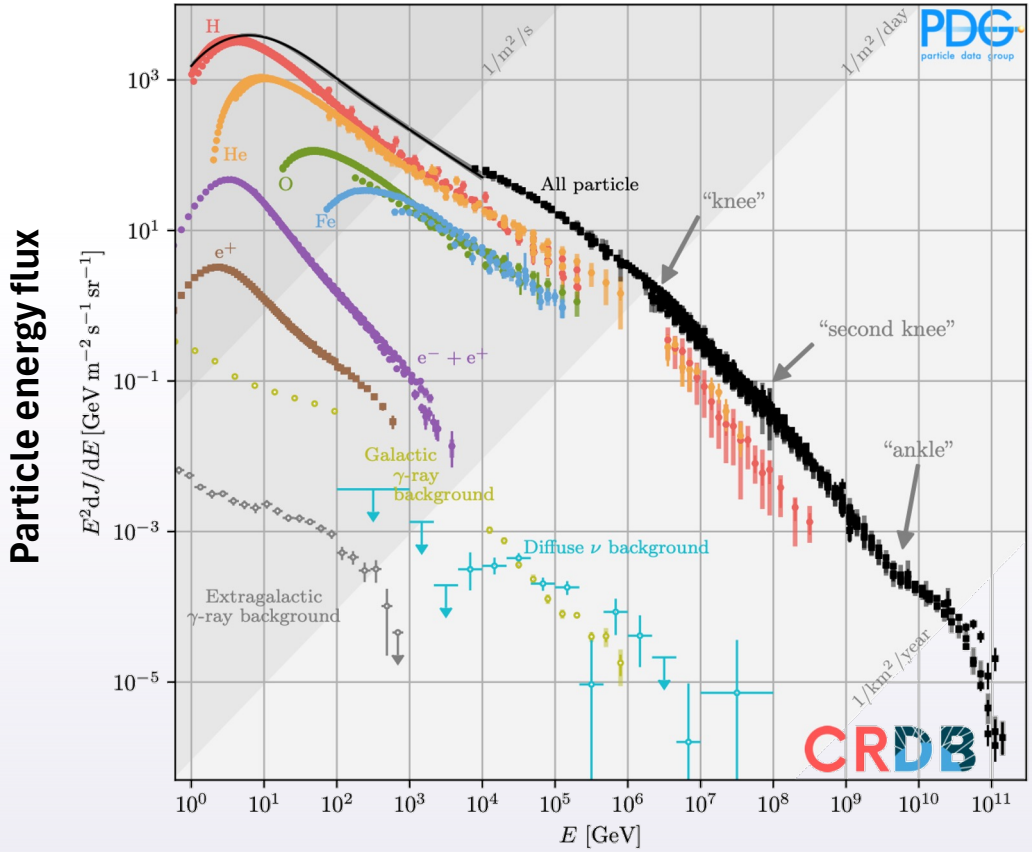
    Papers: *Lai et al. (inc. Owen) 2503.11625, Crudele, Owen et al. (in prep)*
  - Part II: Using high-energy radiation to test cosmic-ray propagation in the multiphase ISM

    Papers: *Ng, Owen et al. (in prep.)*
- Summary

COSMIC RAY SPECTRUM AND ORIGINS

- Cosmic rays are nucleons (mainly protons, He, O…) and electrons

Cosmic ray spectrum measured around Earth

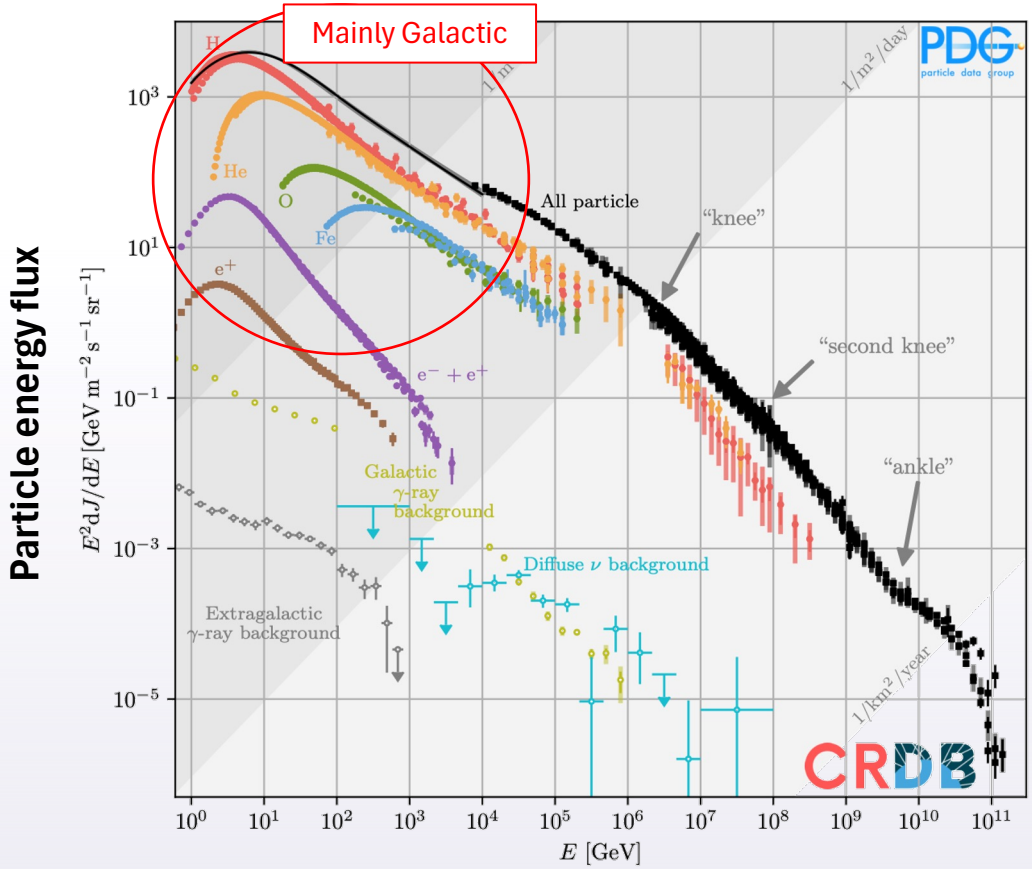


Navas et al., Particle Data Group (2024)

COSMIC RAY SPECTRUM AND ORIGINS

- Cosmic rays are nucleons (mainly protons, He, O…) and electrons

Cosmic ray spectrum measured around Earth

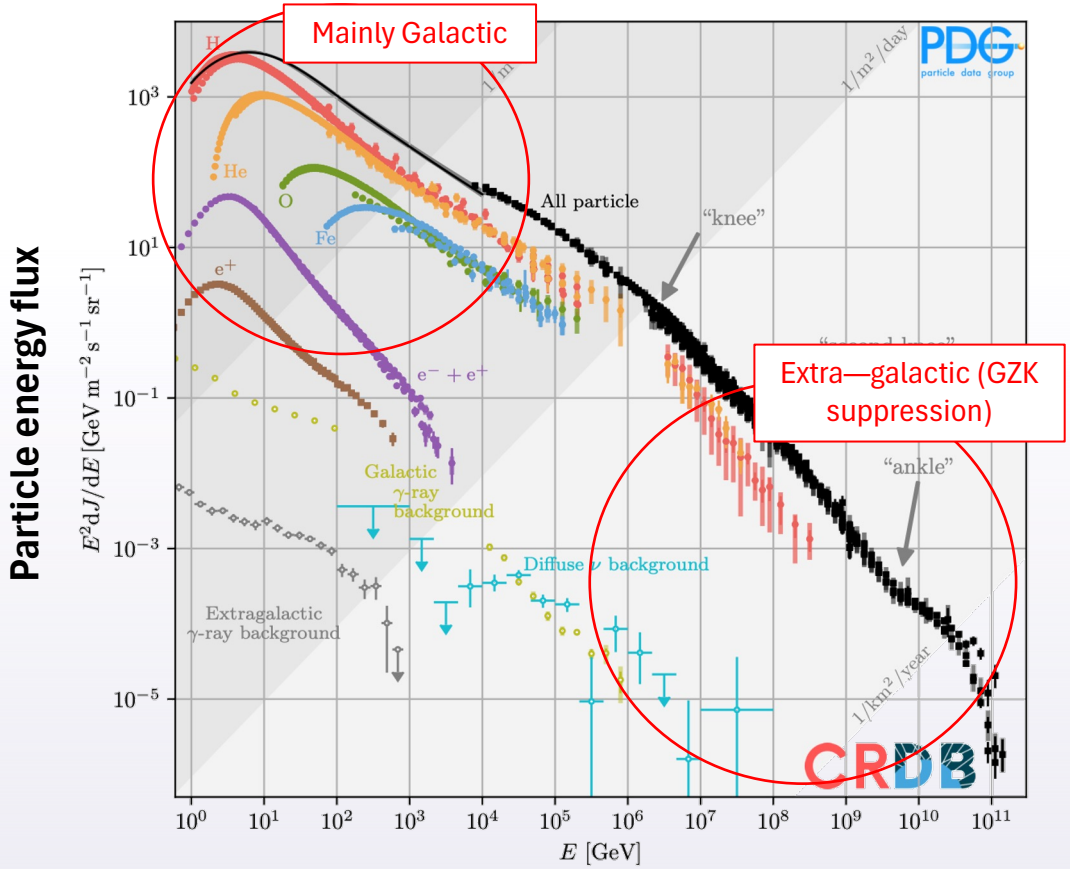


Navas et al., Particle Data Group (2024)

COSMIC RAY SPECTRUM AND ORIGINS

- Cosmic rays are nucleons (mainly protons, He, O…) and electrons

Cosmic ray spectrum measured around Earth

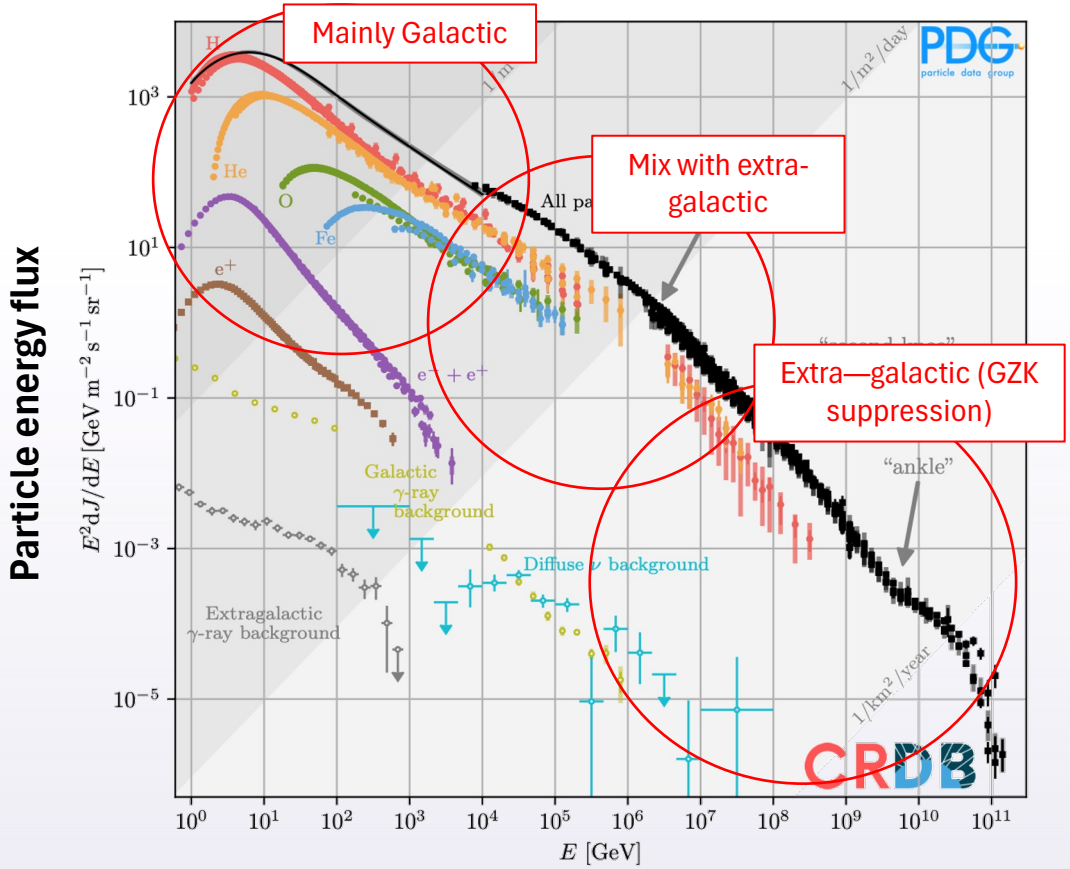


Navas et al., Particle Data Group (2024)

COSMIC RAY SPECTRUM AND ORIGINS

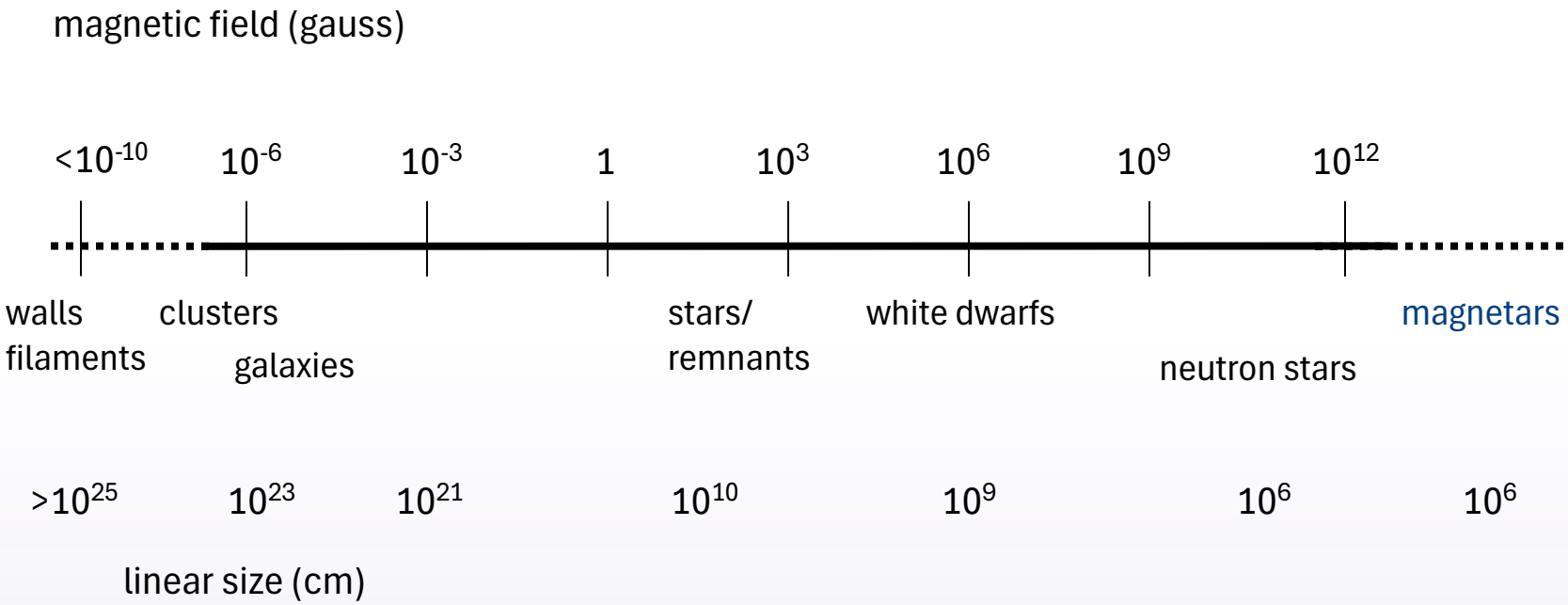
- Cosmic rays are nucleons (mainly protons, He, O…) and electrons

Cosmic ray spectrum measured around Earth



Navas et al., Particle Data Group (2024)

MAGNETIC FIELDS AND COSMIC RAY CONFINEMENT



MAGNETIC FIELDS AND COSMIC RAY CONFINEMENT

magnetic field (gauss)

$<10^{-10}$	10^{-6}	10^{-3}	1	10^{3}	10^{6}	10^{9}	10^{12}
walls filaments	clusters galaxies			stars/ remnants	white dwarfs	neutron stars	magnetars
$>10^{25}$	10^{23}	10^{21}		10^{10}	10^{9}	10^{6}	10^{6}

linear size (cm)

$>10^{21}$	10^{19}	10^{18}	10^{10}	10^{7}	10^{4}	10^{-1}

PeV gyro-scale (cm)

MAGNETIC FIELDS AND COSMIC RAY CONFINEMENT

magnetic field (gauss)

$<10^{-10}$	10^{-6}	10^{-3}	1	10^{3}	10^{6}	10^{9}	10^{12}
walls filaments	clusters galaxies			stars/ remnants	white dwarfs	neutron stars	magnetars
$>10^{25}$	10^{23}	10^{21}		10^{10}	10^{9}	10^{6}	10^{6}

linear size (cm)

$>10^{21}$	10^{19}	10^{18}	10^{10}	10^{7}	10^{4}	10^{-1}

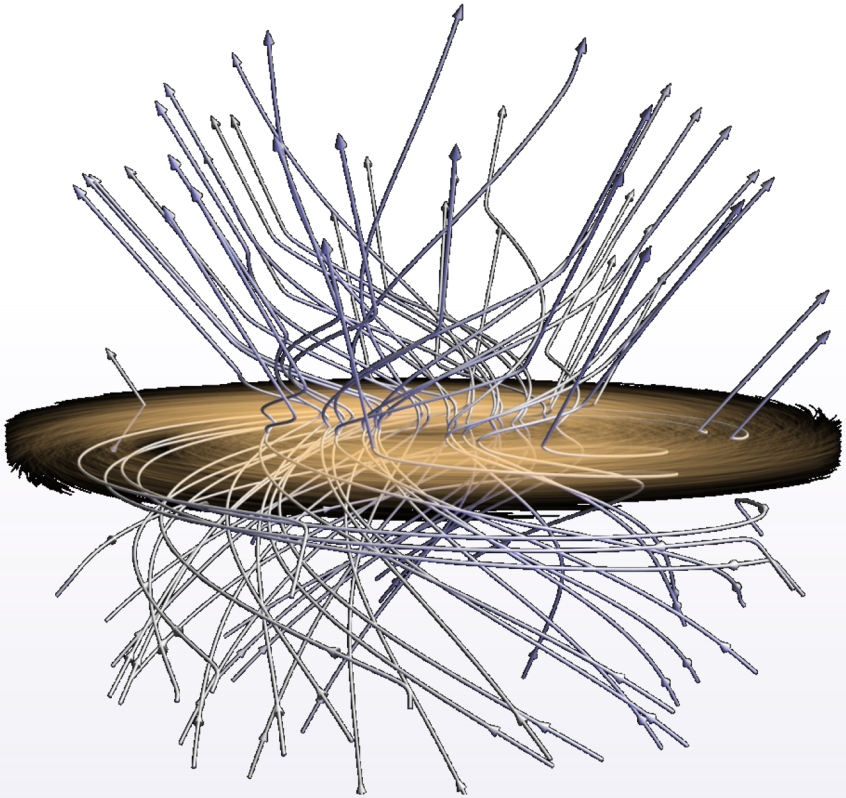
PeV gyro-scale (cm)

$\sim10^{25}$	10^{22}	10^{21}	10^{13}	10^{10}	10^{7}	10^{2}

EeV gyro-scale (cm)

COSMIC RAYS IN GALAXIES

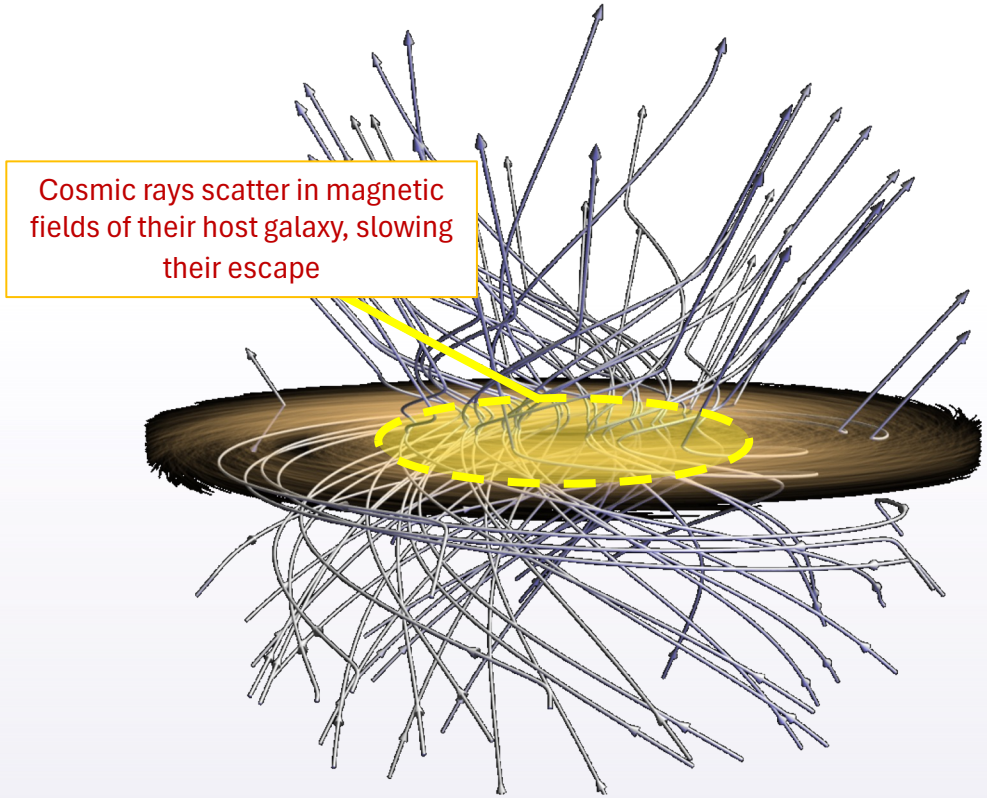
Cosmic ray magnetic containment



Adapted from Farrar et al. (2016)

COSMIC RAYS IN GALAXIES

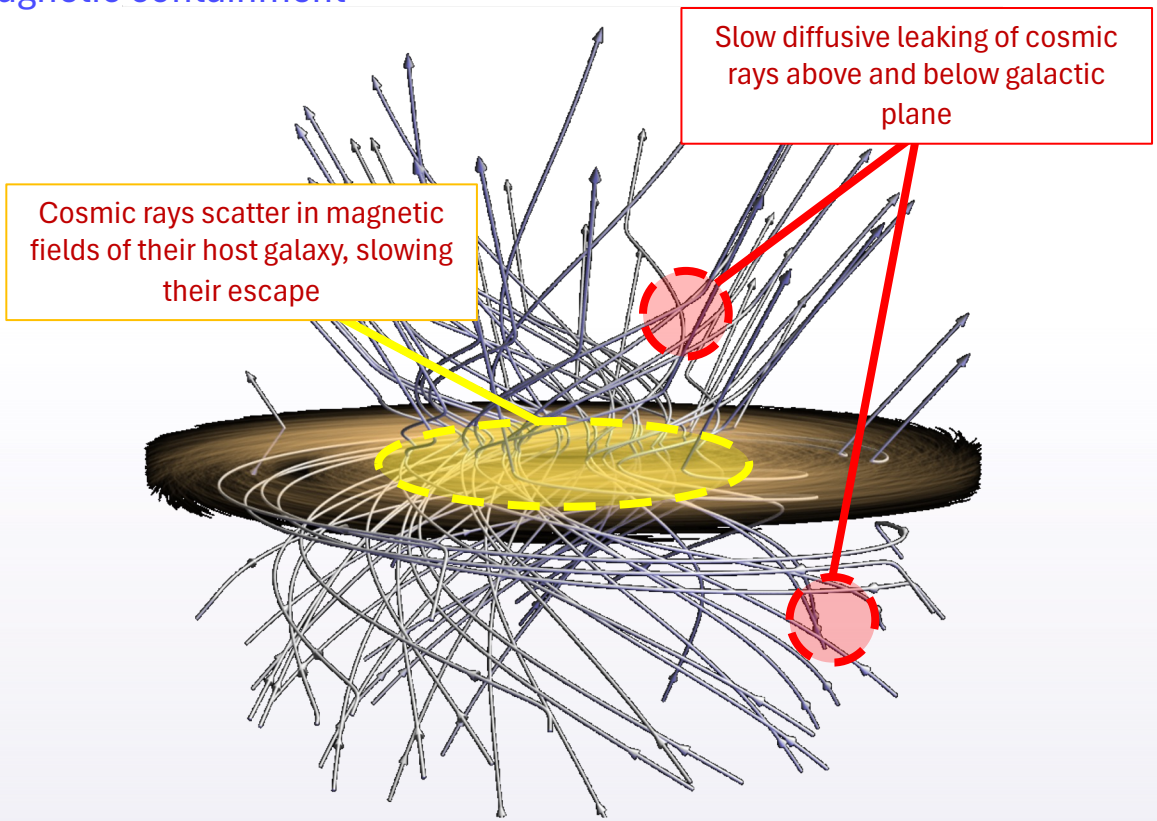
Cosmic ray magnetic containment



Adapted from Farrar et al. (2016)

COSMIC RAYS IN GALAXIES

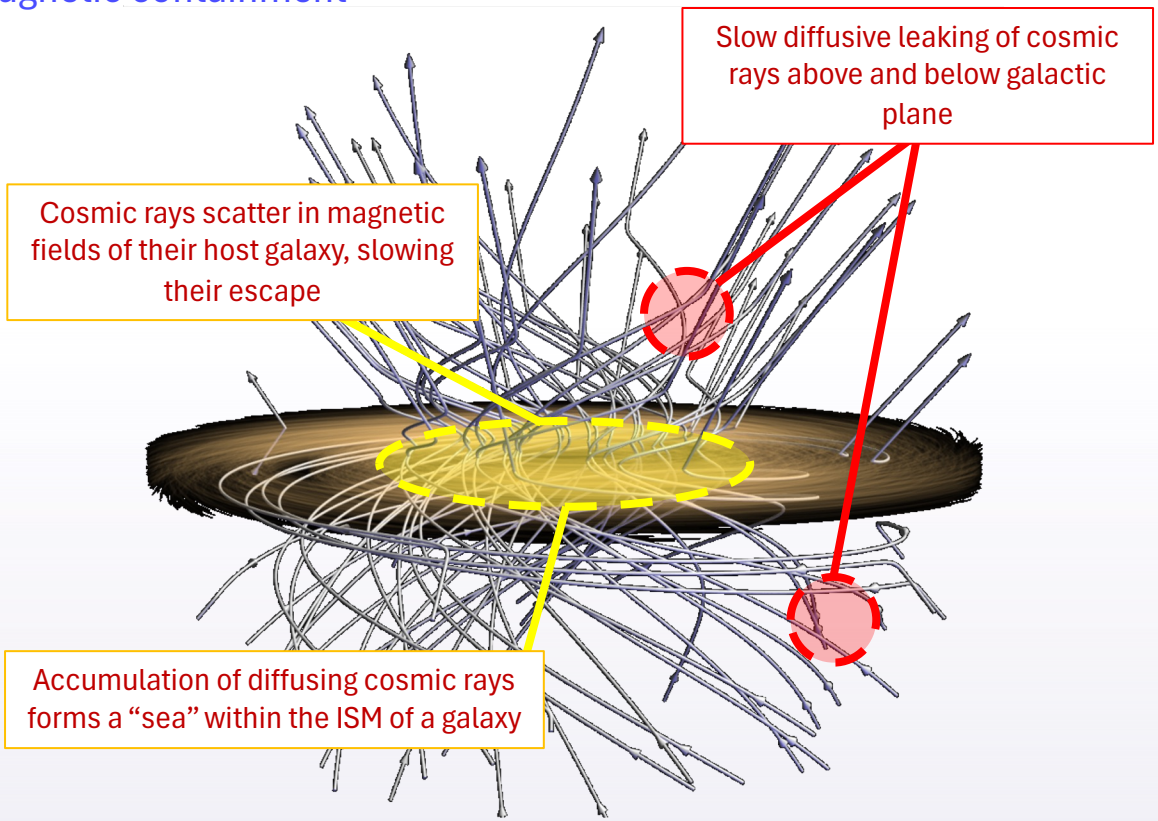
Cosmic ray magnetic containment



Adapted from Farrar et al. (2016)

COSMIC RAYS IN GALAXIES

Cosmic ray magnetic containment



Adapted from Farrar et al. (2016)

COLLISIONAL COSMIC RAY PROCESSES

Cosmic rays can interact with radiation and matter fields

COLLISIONAL COSMIC RAY PROCESSES

Cosmic rays can interact with radiation and matter fields

Figures adapted from Owen 2023 (A&G)

pp-pion production

$$\mathrm{p} + \mathrm{p} \rightarrow \begin{matrix} \mathrm{p} + \cdots \\ \mathrm{n} + \cdots \end{matrix} + \zeta_0 \left(\pi^0 \right) + \zeta_\pm \left(\pi^+ \quad \pi^- \right)$$

Pion multiplicities

COLLISIONAL COSMIC RAY PROCESSES

Cosmic rays can interact with radiation and matter fields

Figures adapted from Owen 2023 (A&G)

pp-pion production

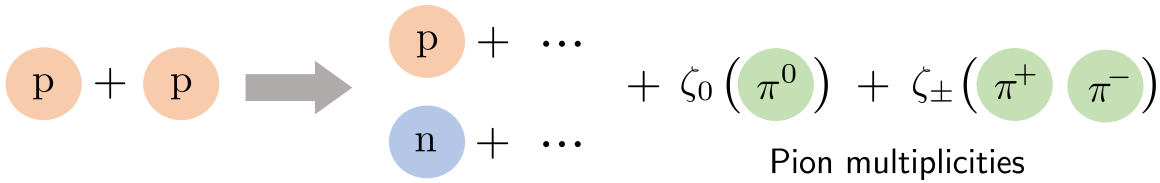
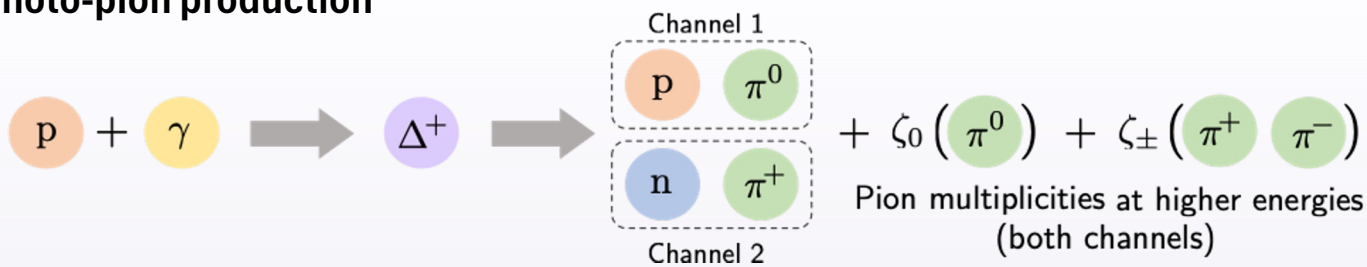


Photo-pion production



COLLISIONAL COSMIC RAY PROCESSES

Cosmic rays can interact with radiation and matter fields

Figures adapted from Owen 2023 (A&G)

pp-pion production

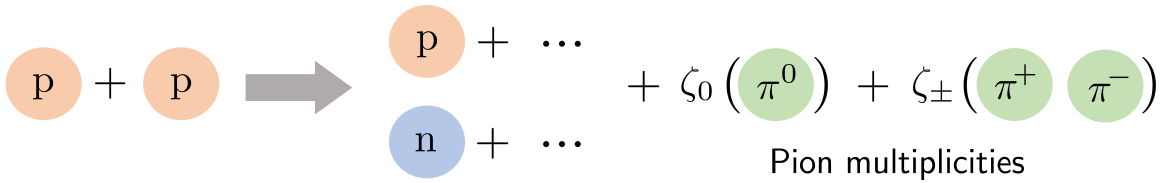
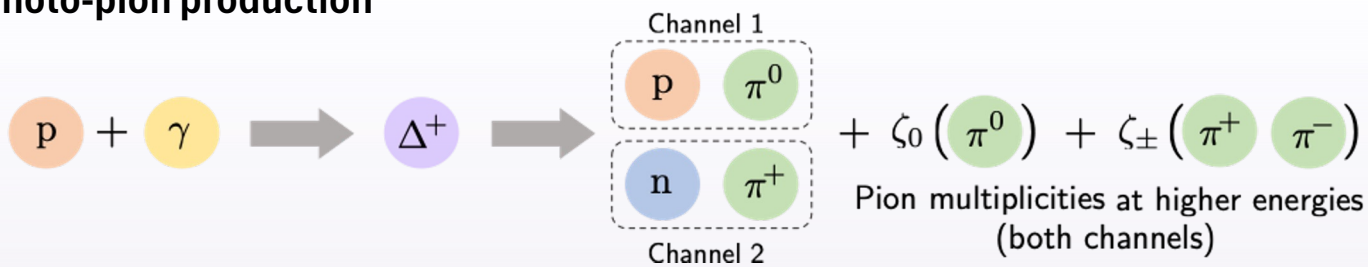


Photo-pion production

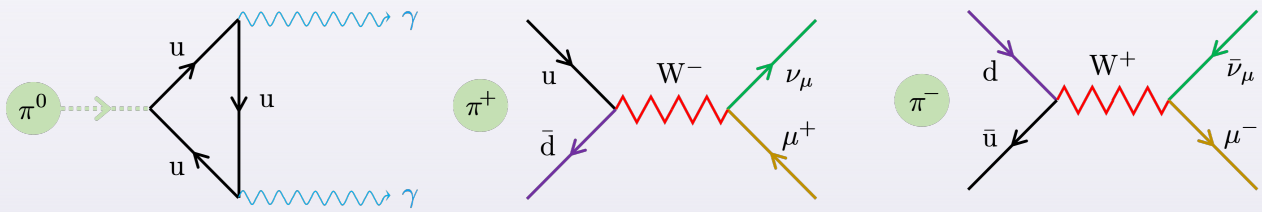


Multi-messengers

A by-product of UHE CR propagation:

- Gamma-rays
- Neutrinos

Pion decays

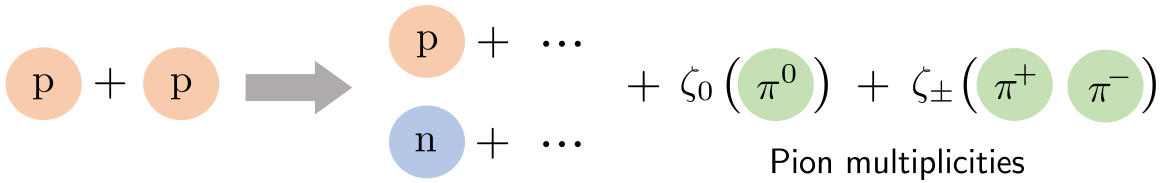


COLLISIONAL COSMIC RAY PROCESSES

Cosmic rays can interact with radiation and matter fields

Figures adapted from Owen 2023 (A&G)

pp-pion production



Bethe-Heitler cooling

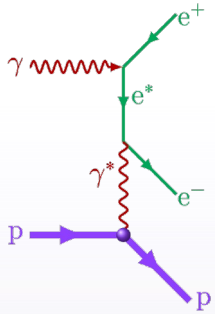
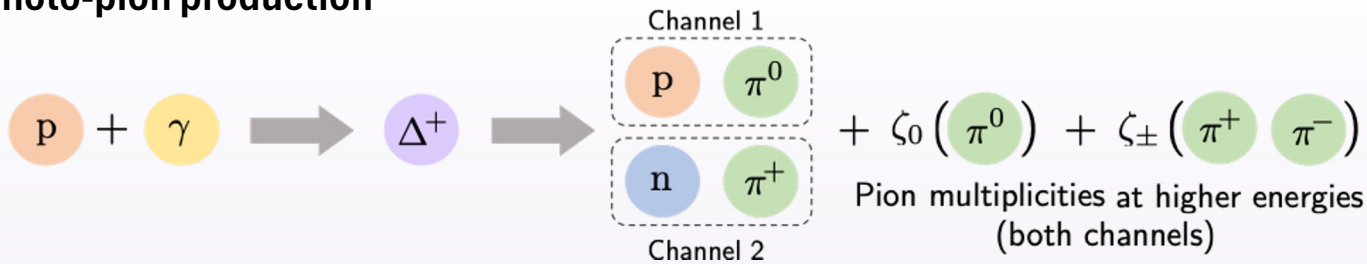


Photo-pion production

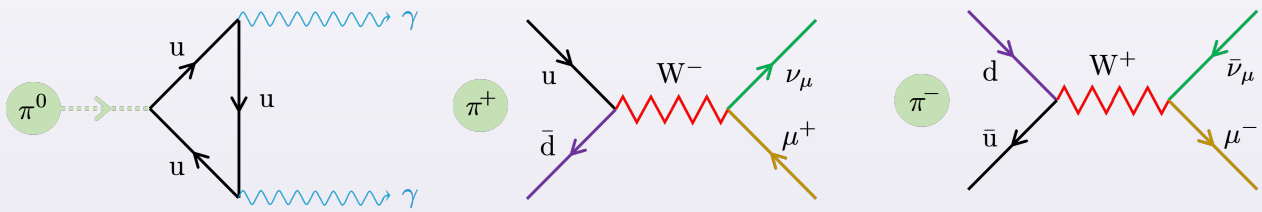


Multi-messengers

A by-product of UHE CR propagation:

- Gamma-rays
- Neutrinos

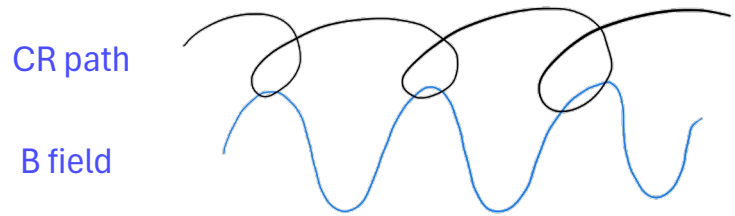
Pion decays



COLLISIONLESS COSMIC RAY PROCESSES

Classical cosmic ray hydrodynamics

Cosmic rays **excite MHD waves** and then scatter off them



- In the strong coupling limit, **CRs stream down pressure gradient** at v_A
- Waves thermalize by damping
- Transfer momentum and energy to ambient gas
- Net effect: momentum + energy transfer to the thermal gas (i.e. CRs can do work / heat without collisions)

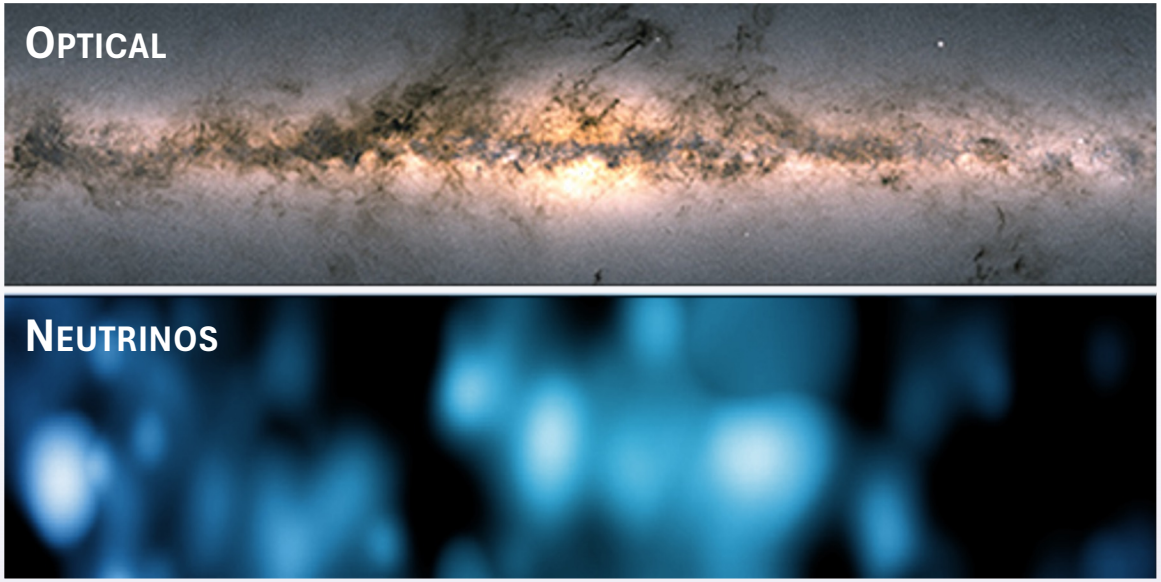
Momentum $$\frac{\partial(\rho\vec{u})}{\partial t} = [\cdots] - \nabla P_{\rm CR}$$

Energy $$H_{\rm CR} = -v_{\rm A} \cdot \nabla P_{\rm CR}$$

- Wave growth vs damping is **environment-dependent**, e.g. **neutral–ion damping** can suppress turbulence and weaken CR coupling

Part I | Using neutrinos as an astronomical tool

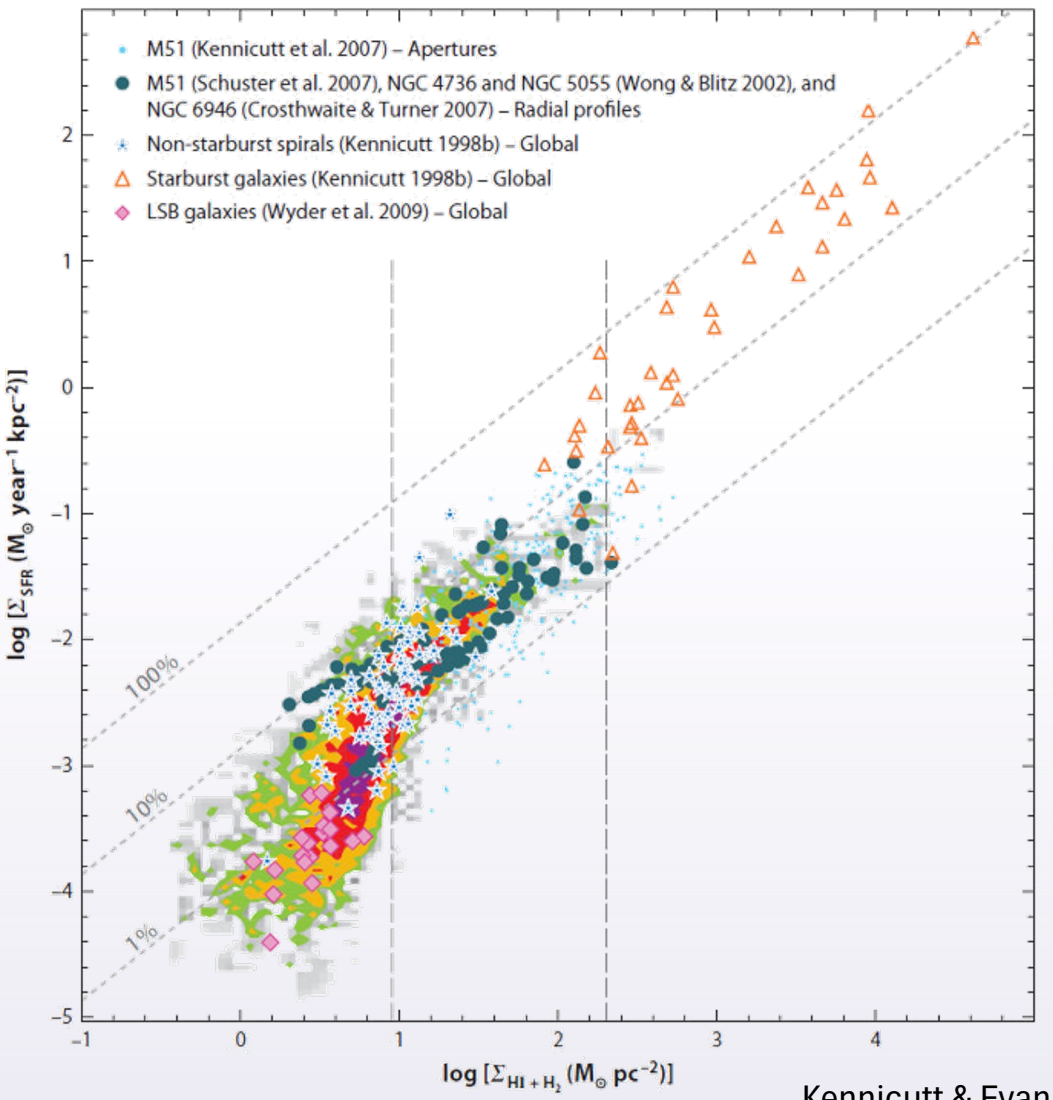
Collaborators: Paul C. W. Lai (UCL-MSSL), Matteo Agostini (UCL), Kinwah Wu (UCL-MSSL), Beatrice Crudele (UCL), Hayden Ng (UCL/ECAP)



Neutrinos from the Galactic Plane; IceCube Collab. (2023)

Papers: Lai et al. (inc. Owen), 2503.11625; Crudele Owen et al. (in prep)

GAS DENSITY MEASUREMENT IN ASTRONOMY



Kennicutt & Evans (2012)

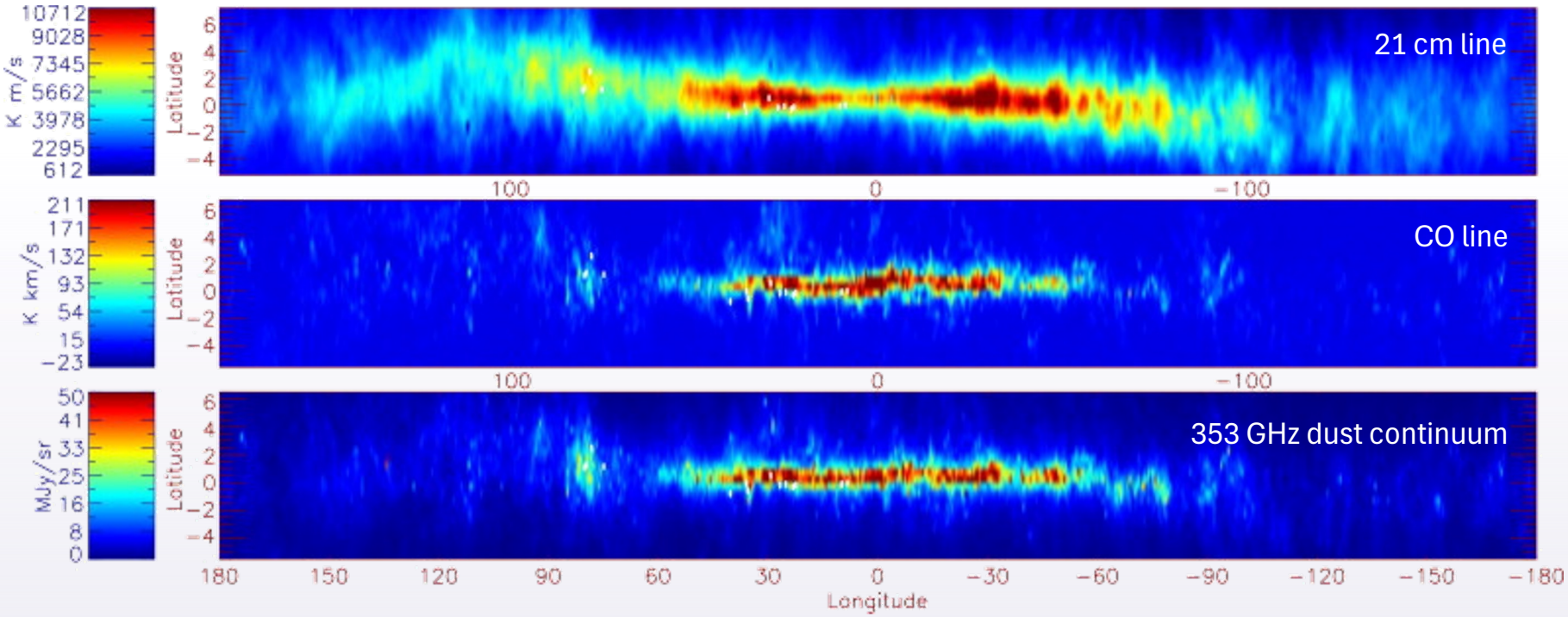
Improving our confidence in gas density and distribution measurement tools is critical for advancing galaxy formation/evolution

E.g. deviations from the KS relation in galaxy types/regions

But relies on a robust determination of gas mass/surface density

GAS DENSITY MEASUREMENT IN ASTRONOMY

- Determinations of gas density within galaxies relies on tracers
- Can be inconsistent



Pedaletti et al. (2015)

COLLISIONAL COSMIC RAY PROCESSES

- Cosmic rays are a key **driver** of multimessenger astrophysics

Figures adapted from Owen 2023 (A&G)

pp-pion production

$$\mathrm{p} + \mathrm{p} \rightarrow \begin{matrix} \mathrm{p} + \cdots \\ \mathrm{n} + \cdots \end{matrix} + \zeta_0 \left(\pi^0 \right) + \zeta_\pm \left(\pi^+ \quad \pi^- \right)$$

Pion multiplicities

Bethe-Heitler cooling

Photo-pion production

$$\mathrm{p} + \gamma \rightarrow \Delta^+ \rightarrow \begin{matrix} \text{Channel 1} \\ \mathrm{p} \quad \pi^0 \\ \mathrm{n} \quad \pi^+ \\ \text{Channel 2} \end{matrix} + \zeta_0 \left(\pi^0 \right) + \zeta_\pm \left(\pi^+ \quad \pi^- \right)$$

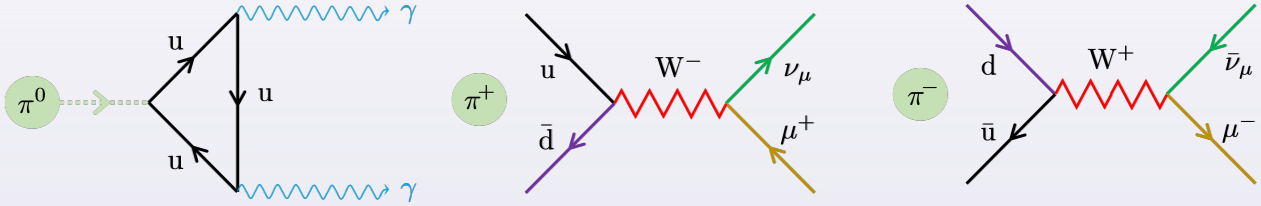
Pion multiplicities at higher energies (both channels)

Cosmogenic multi-messengers

A by-product of UHE CR propagation:

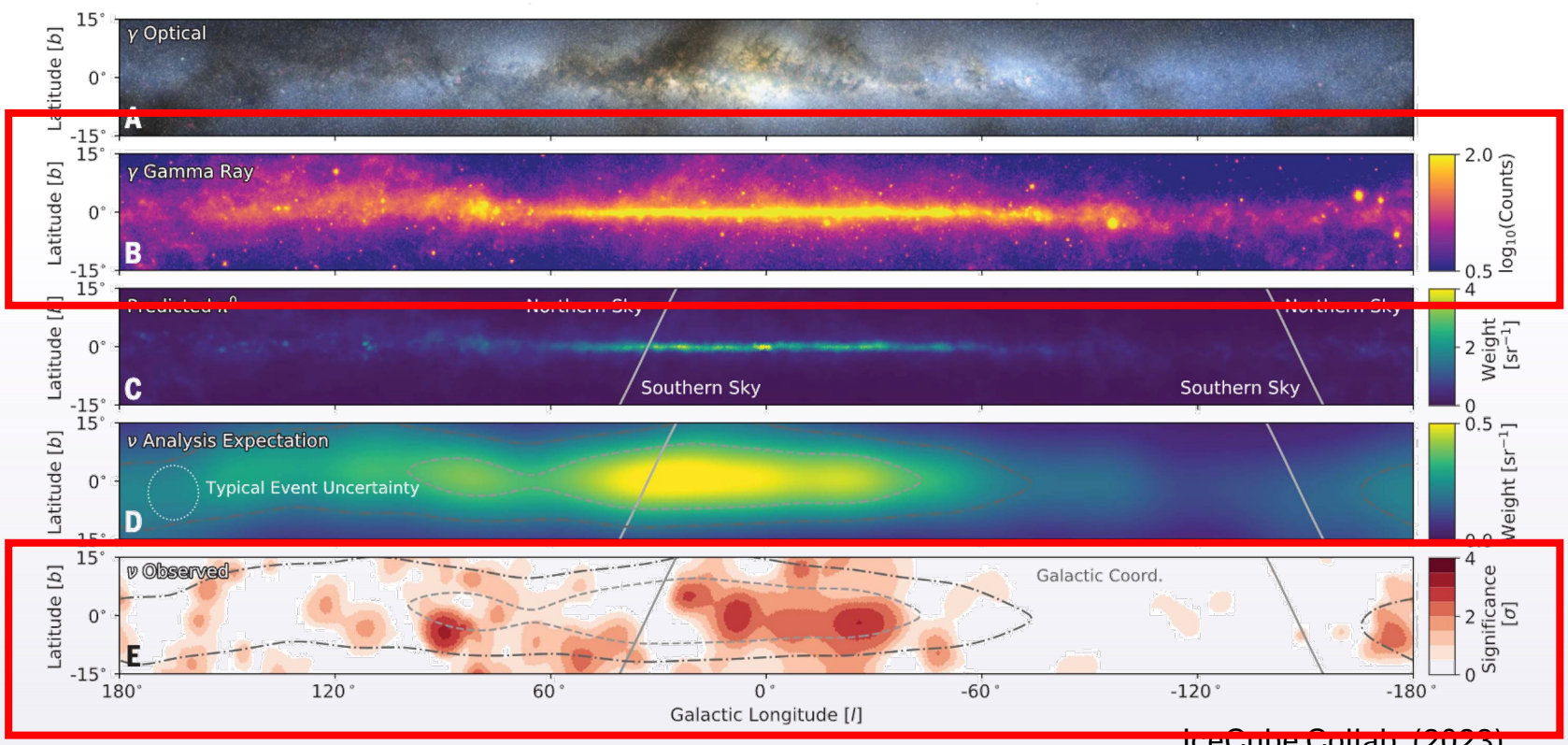
- Gamma-rays
- Neutrinos

Pion decays



NEUTRINOS FROM THE GALAXY

Confirmation of the Milky Way as a neutrino source (pp interactions)



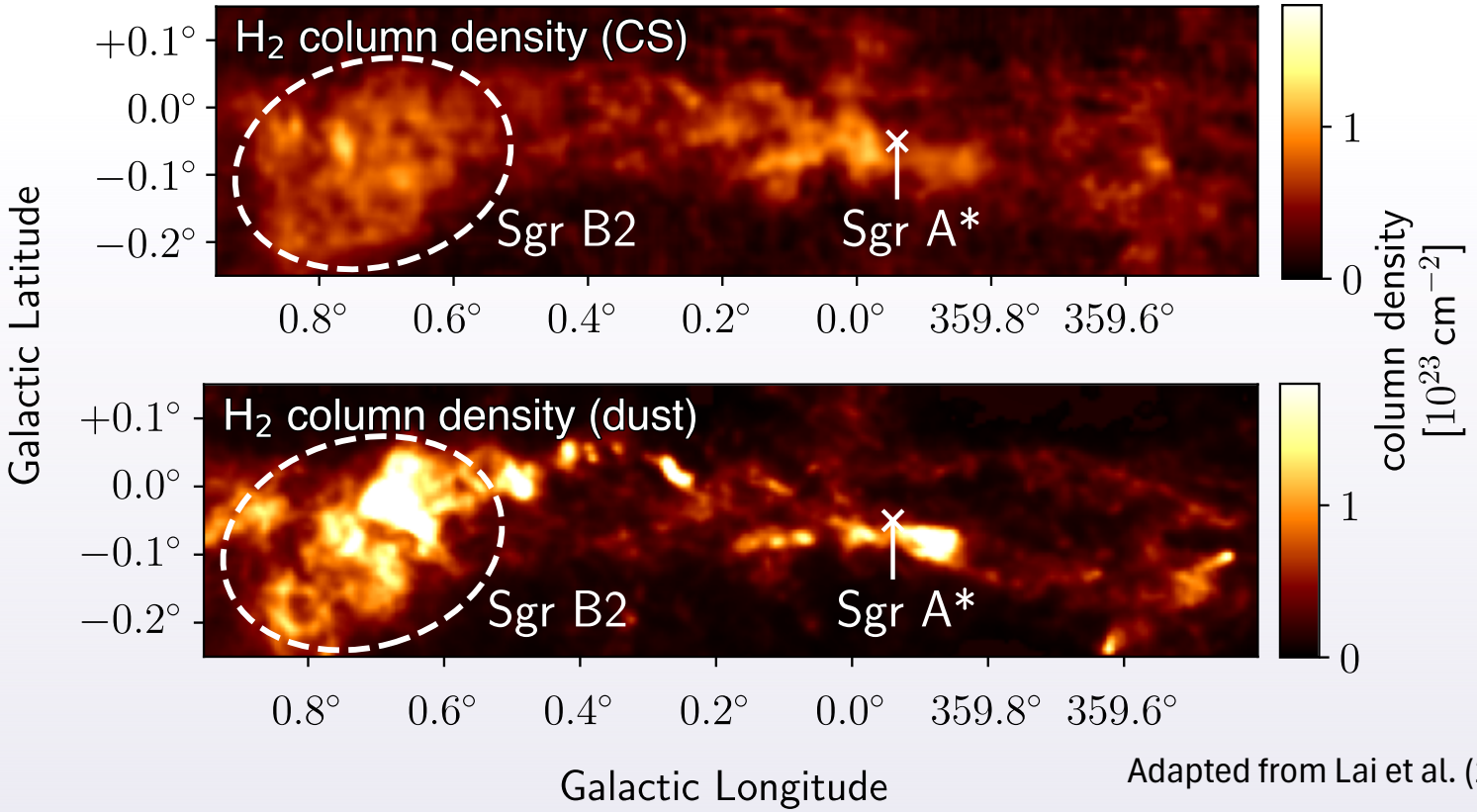
IceCube Collab. (2023)

THE GALACTIC CENTRAL MOLECULAR ZONE

- Typical tracers yield very different views of the of the region around the GC

THE GALACTIC CENTRAL MOLECULAR ZONE

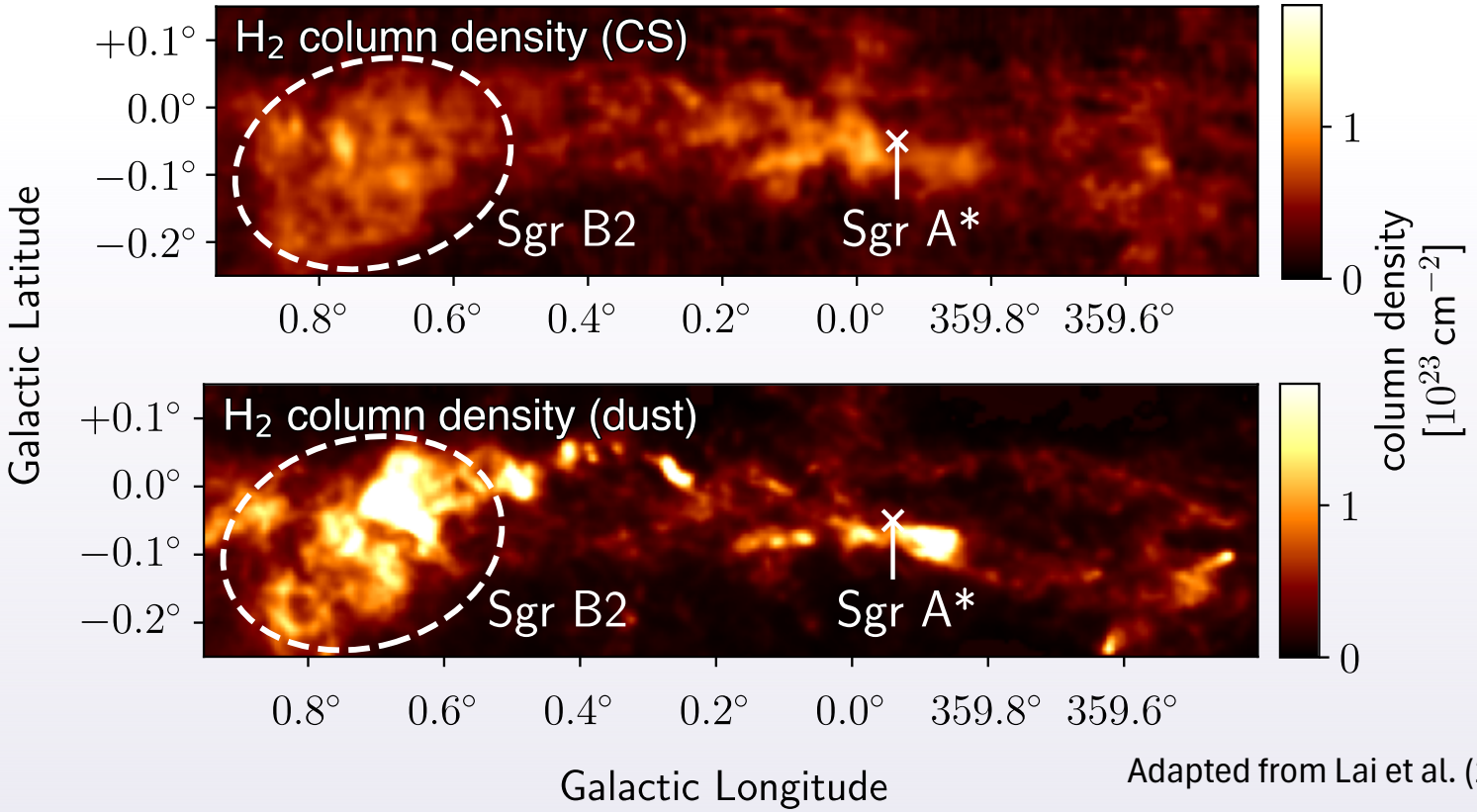
- Typical tracers yield very different views of the of the region around the GC



Adapted from Lai et al. (2025)

THE GALACTIC CENTRAL MOLECULAR ZONE

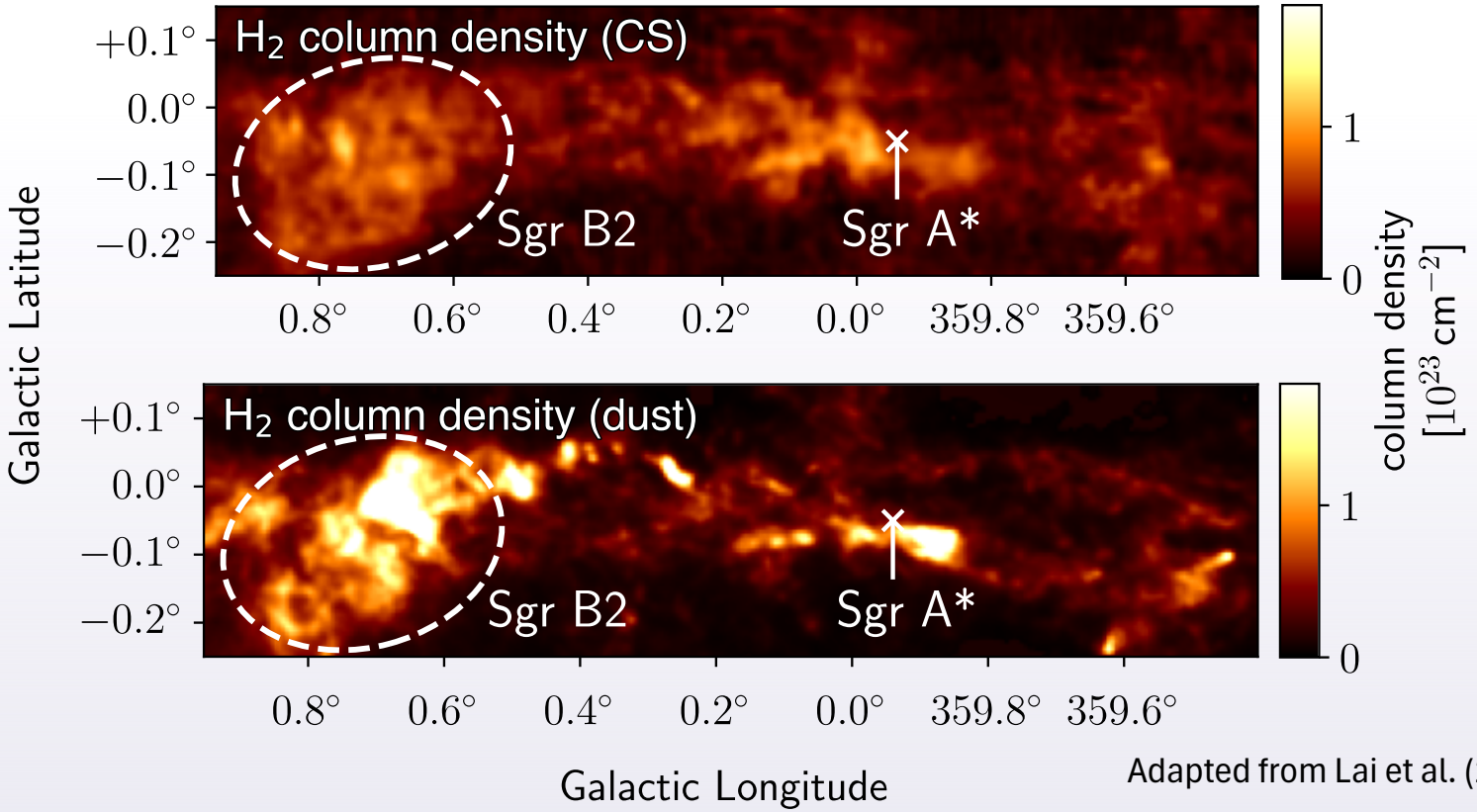
- Typical tracers yield very different views of the of the region around the GC
- Which is the most "correct"?



Adapted from Lai et al. (2025)

THE GALACTIC CENTRAL MOLECULAR ZONE

- Typical tracers yield very different views of the of the region around the GC
- Which is the most "correct"?
- As neutrinos have been detected, can use them to calibrate



Adapted from Lai et al. (2025)

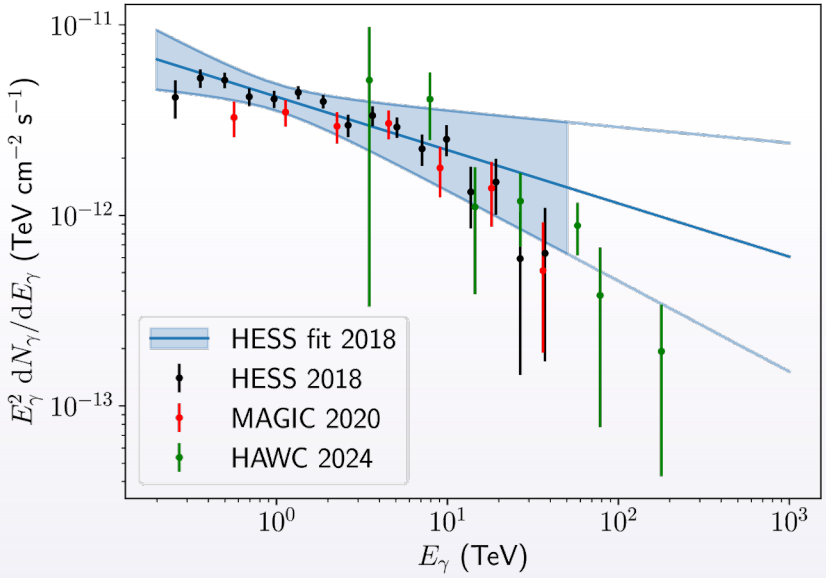
GALACTIC CENTER NEUTRINOS AS AN ASTRONOMICAL TOOL

Proof of concept

GALACTIC CENTER NEUTRINOS AS AN ASTRONOMICAL TOOL

Proof of concept

Infer CR spectrum from gamma-ray observations (sources subtracted)



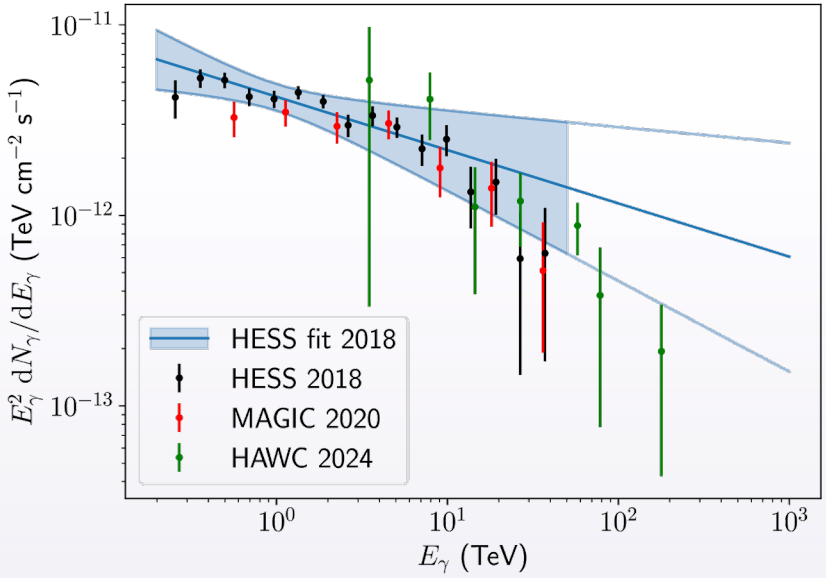
Best fit from HESS data, blue shaded areas 1-sigma probability intervals

GALACTIC CENTER NEUTRINOS AS AN ASTRONOMICAL TOOL

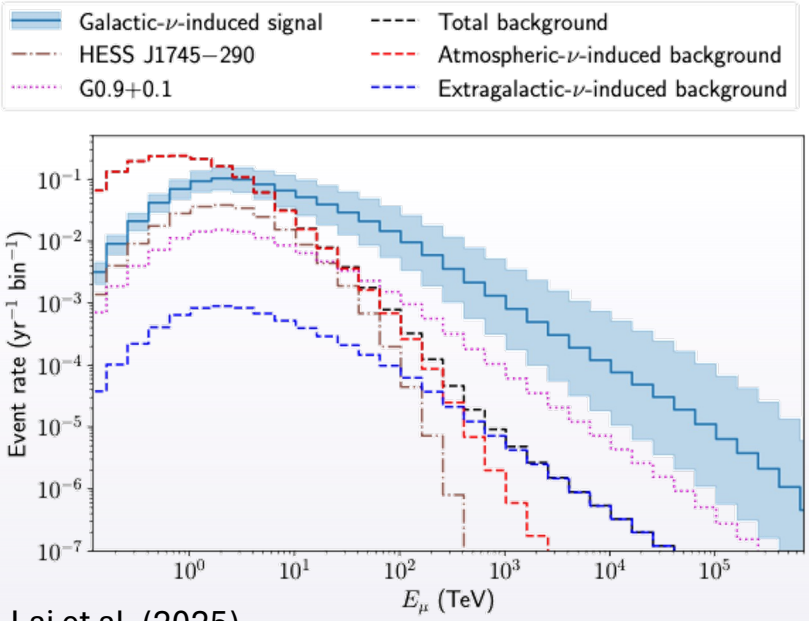
Proof of concept

Infer CR spectrum from gamma-ray observations (sources subtracted)

Predict muon neutrino flux (and normalization) assuming hadronic origin



Best fit from HESS data, blue shaded areas 1-sigma probability intervals



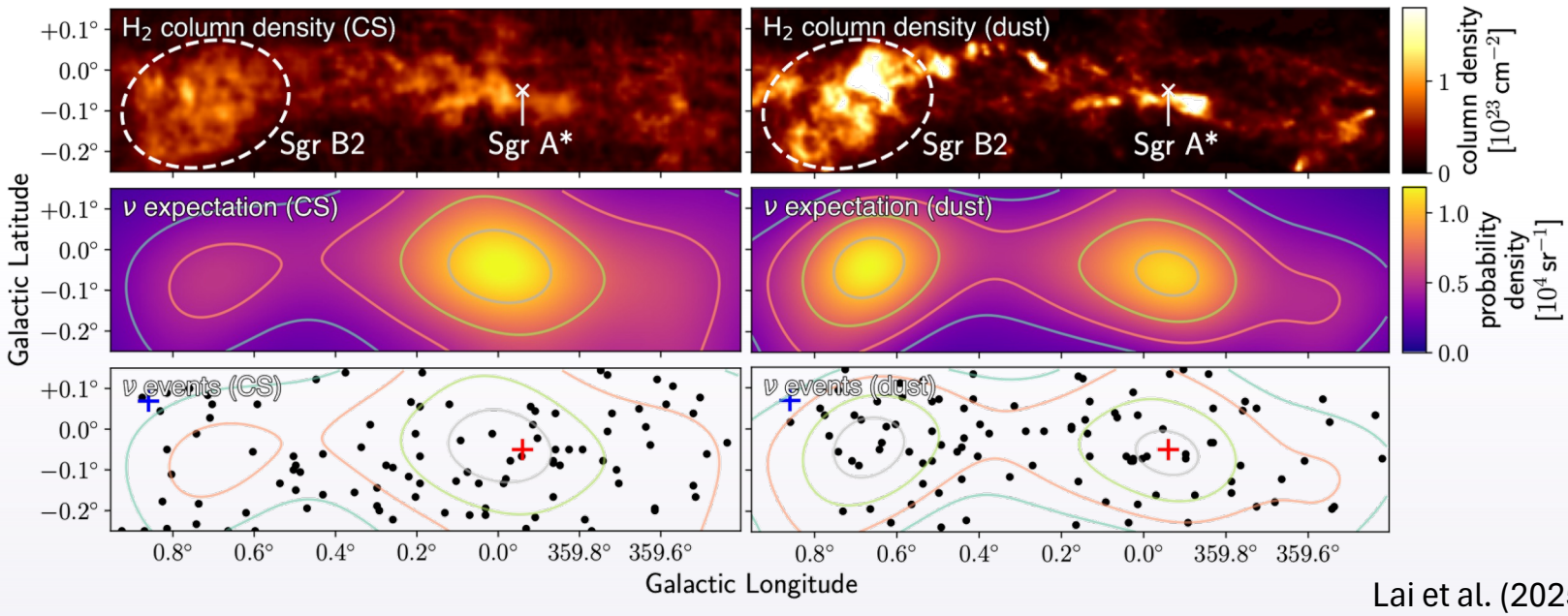
Lai et al. (2025)

Predicted muon neutrinos detected by an IceCube in North (at KM3NeT location)

GALACTIC CENTER NEUTRINOS AS AN ASTRONOMICAL TOOL

Different gas maps - expected neutrino picture of the Milky Way's GC region

Same total flux assumed in both cases



Lai et al. (2025)

Middle: probability of neutrino emission, based on the corresponding gas maps and smoothed with a Gaussian kernel to emulate an angular resolution of next-gen instruments (0.09 degrees)

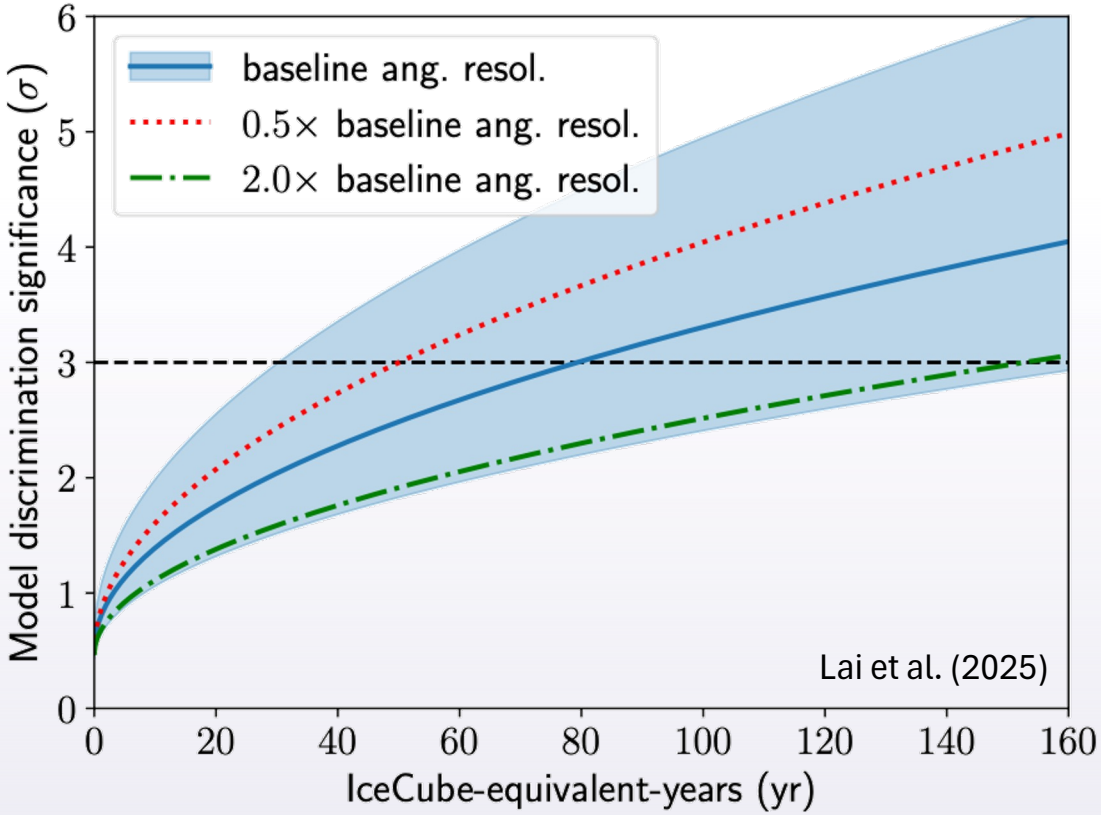
Bottom: Picture of 100 neutrinos (future neutrino telescope with 10x IceCube exposure). Red circles can't be used for analysis, as they are nearby sources

CALIBRATION TIMESCALE FOR GAS TRACERS

Projected maps are clearly different, allowing tracers to be discriminated as integration time increases, and clear gas tracer calibration to be obtained

CALIBRATION TIMESCALE FOR GAS TRACERS

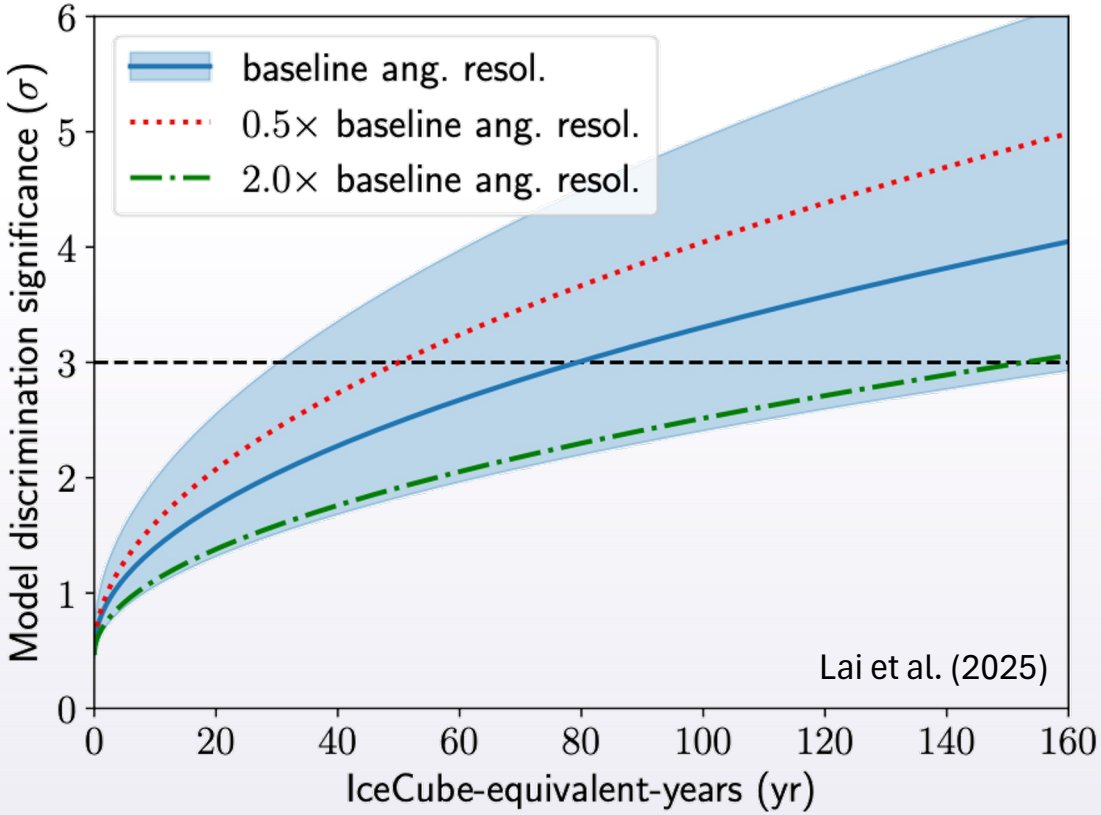
Projected maps are clearly different, allowing tracers to be discriminated as integration time increases, and clear gas tracer calibration to be obtained



Considering only muon neutrinos (track-like events); angular resolution average around 0.09 deg (varies with energy)

CALIBRATION TIMESCALE FOR GAS TRACERS

Projected maps are clearly different, allowing tracers to be discriminated as integration time increases, and clear gas tracer calibration to be obtained

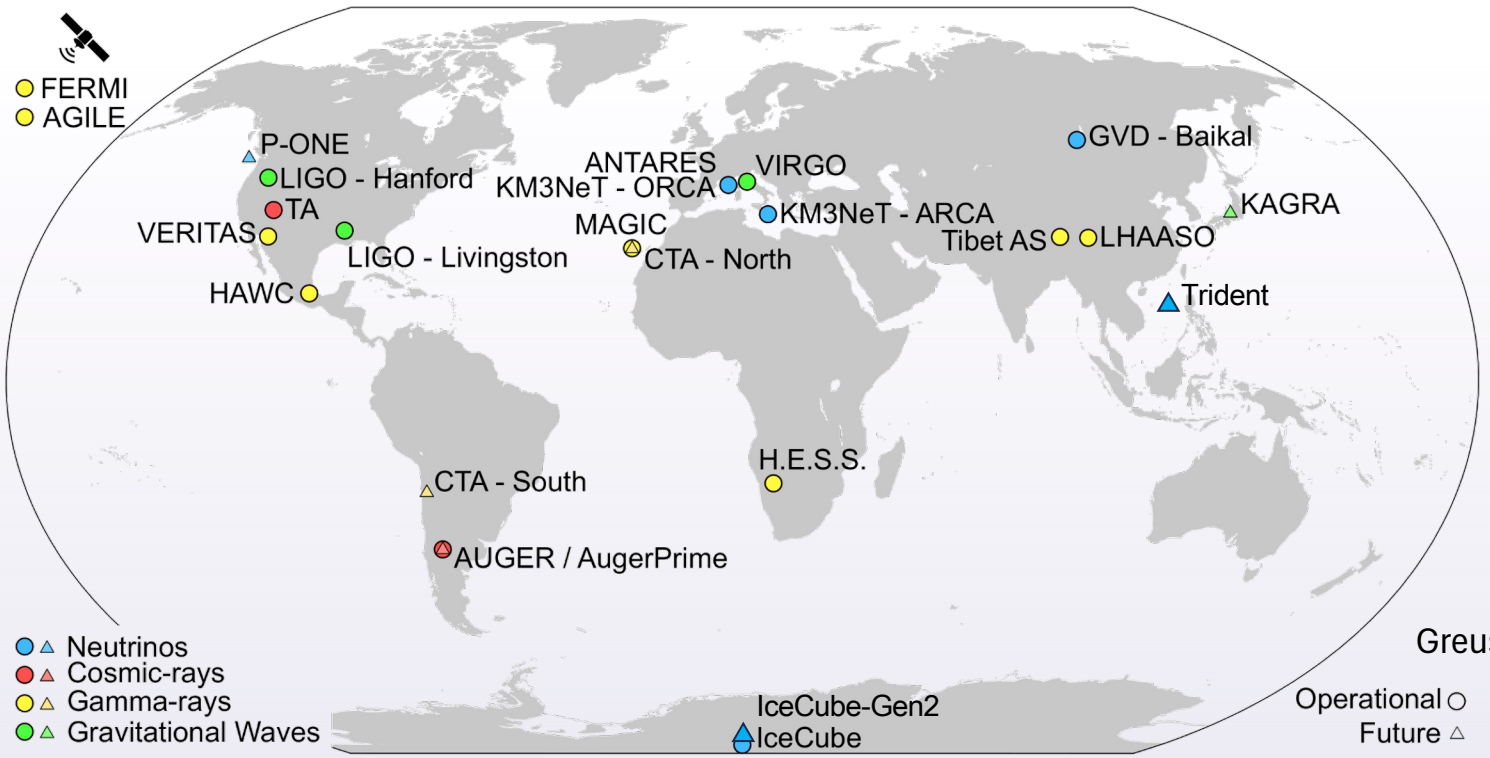


Considering only muon neutrinos (track-like events); angular resolution average around 0.09 deg (varies with energy)

Requires about 80 IceCube years with current instruments

HIGH ENERGY MULTI-MESSENGER OUTLOOK

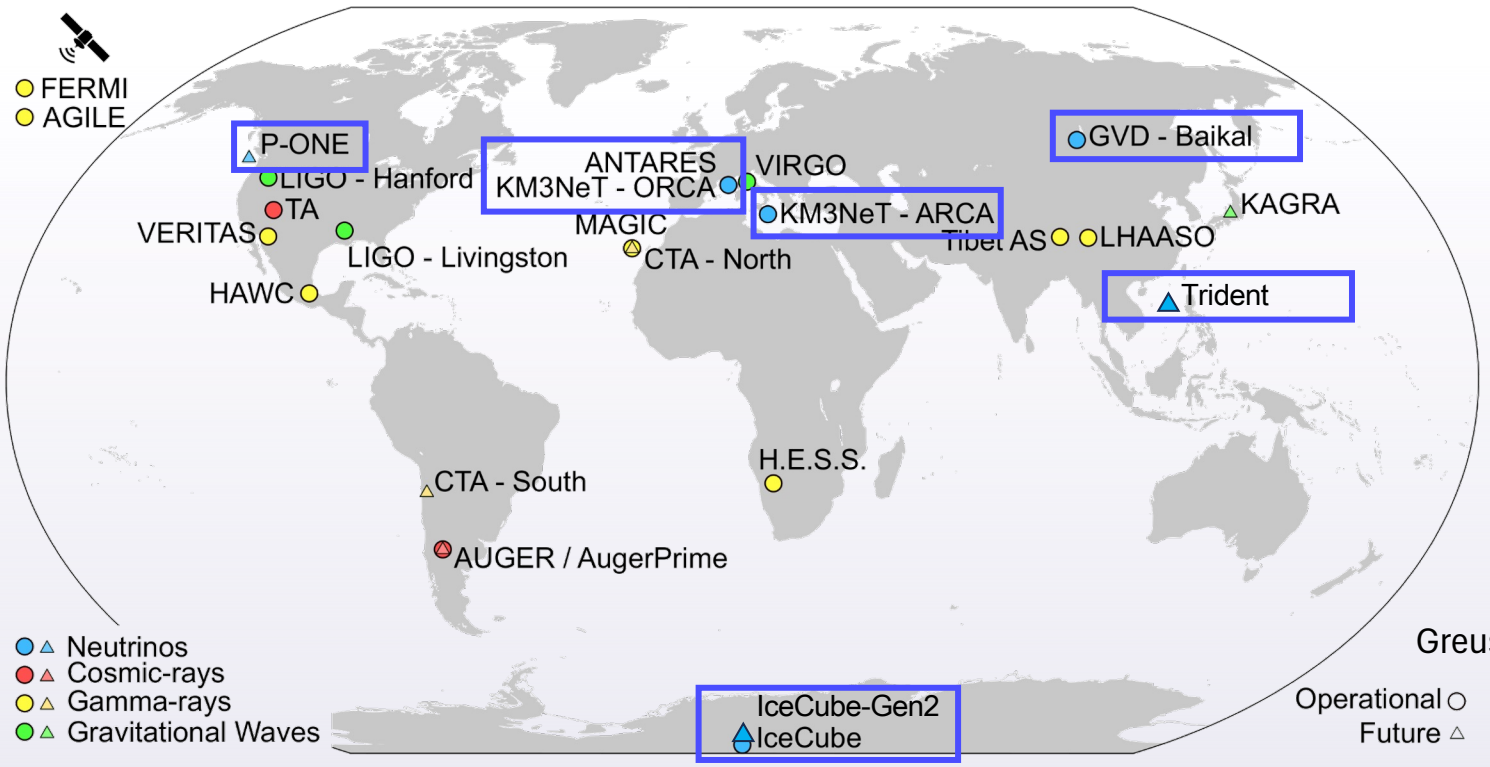
- UHE CRs: TAx4 (upgrade of TA to 3000 km^2), AugerPrime (upgrade of Auger)
- Gamma-rays: *Fermi*-LAT, LHAASO, CTAO (Northern and Southern), SWGO
- Neutrinos: IceCube-Gen2, KM3NeT, GRAND (>EeV), P-ONE, PUEO (>EeV), Trinity (PeV-EeV)
- GW astronomy, and advancements in traditional astronomy



Adapted from Greus & Losa (2021)

HIGH ENERGY MULTI-MESSENGER OUTLOOK

- UHE CRs: TAx4 (upgrade of TA to 3000 km^2), AugerPrime (upgrade of Auger)
- Gamma-rays: *Fermi*-LAT, LHAASO, CTAO (Northern and Southern), SWGO
- Neutrinos: IceCube-Gen2, KM3NeT, GRAND (>EeV), P-ONE, PUEO (>EeV), Trinity (PeV-EeV)
- GW astronomy, and advancements in traditional astronomy

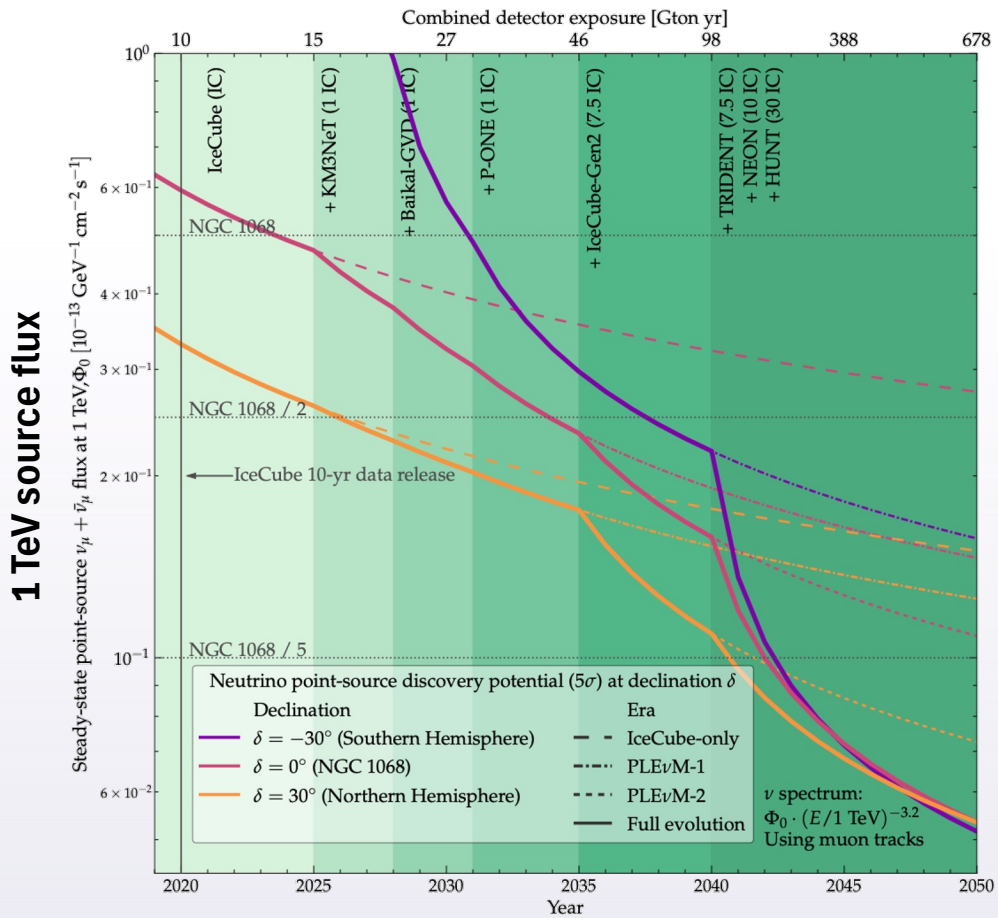


Adapted from Greus & Losa (2021)

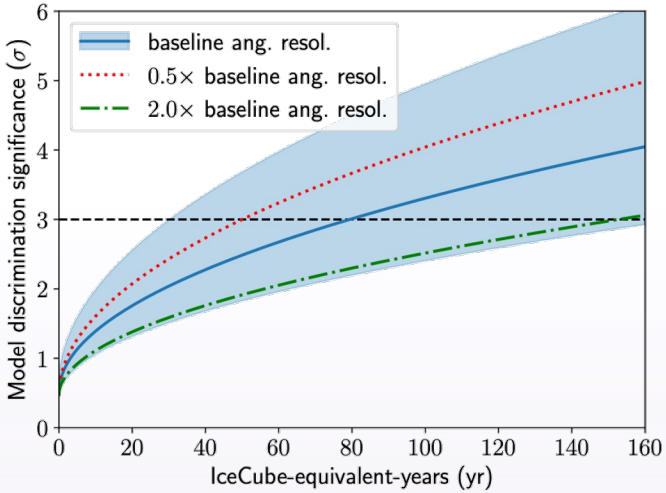
FUTURE NEUTRINO OBSERVATORIES ROADMAP

Gas tracers could be calibrated at 3-sigma significance within 25 IceCube years

Combined detector exposure



1 TeV source flux

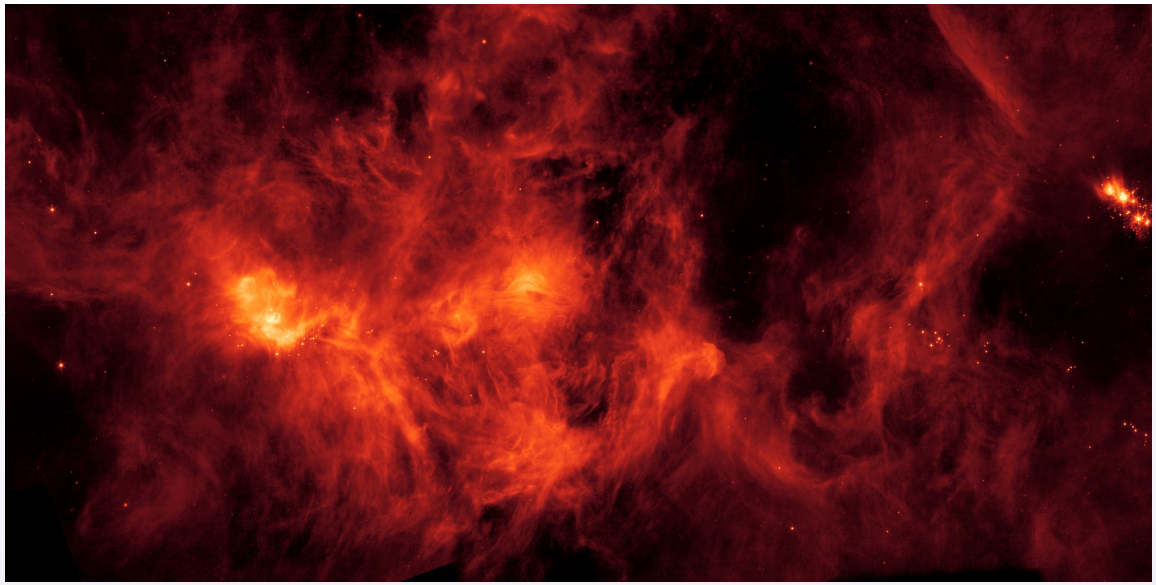


80 IceCube yrs = 10-30 years, depending on tracers

Schumacher et al. (2025)

Part II | Using gamma-rays to test CR propagation in the multiphase ISM

Collaborators: Hayden P. H. Ng (UCL/ECAP), Szu-Ting Chen (ECAP/NTHU)



Perseus Molecular Cloud observed in Infrared with Spitzer
Credit: NASA/JPL-Caltech (2019)

Papers: Ng, Owen et al. (in prep)

COLLISIONLESS COSMIC RAY PROCESSES

Classical cosmic ray hydrodynamics

Cosmic rays excite MHD waves and then scatter off them

- In the strong coupling limit, CRs stream down pressure gradient at v_A
- Waves thermalize by damping
- Transfer momentum and energy to thermal gas
- Net effect: momentum + energy transfer to the thermal gas (i.e. CRs can do work / heat without collisions)

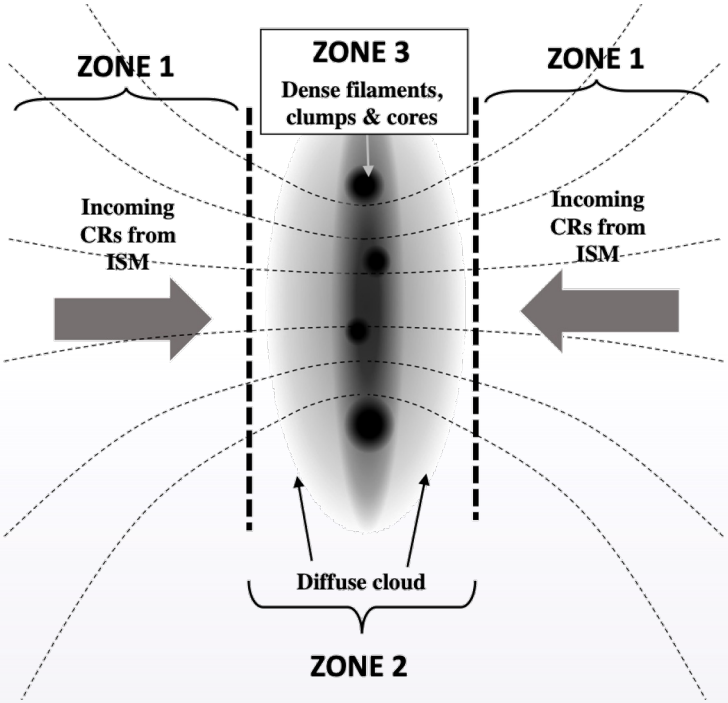
Momentum $$\frac{\partial(\rho\vec{u})}{\partial t} = [\cdots] - \nabla P_{\rm CR}$$

Energy $$H_{\rm CR} = -v_{\rm A} \cdot \nabla P_{\rm CR}$$

- Wave growth vs damping is environment-dependent, e.g. neutral–ion damping can suppress turbulence and weaken CR coupling

WHAT ABOUT DENSE GAS?

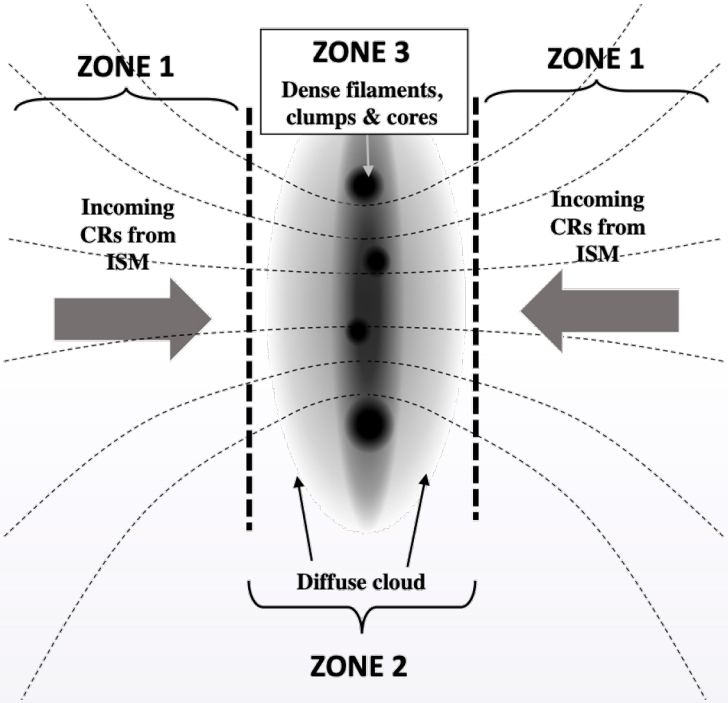
The “standard” picture: **CRs weakly couple with dense gas**



Owen et al. (2021)

WHAT ABOUT DENSE GAS?

The "standard" picture: **CRs weakly couple with dense gas**

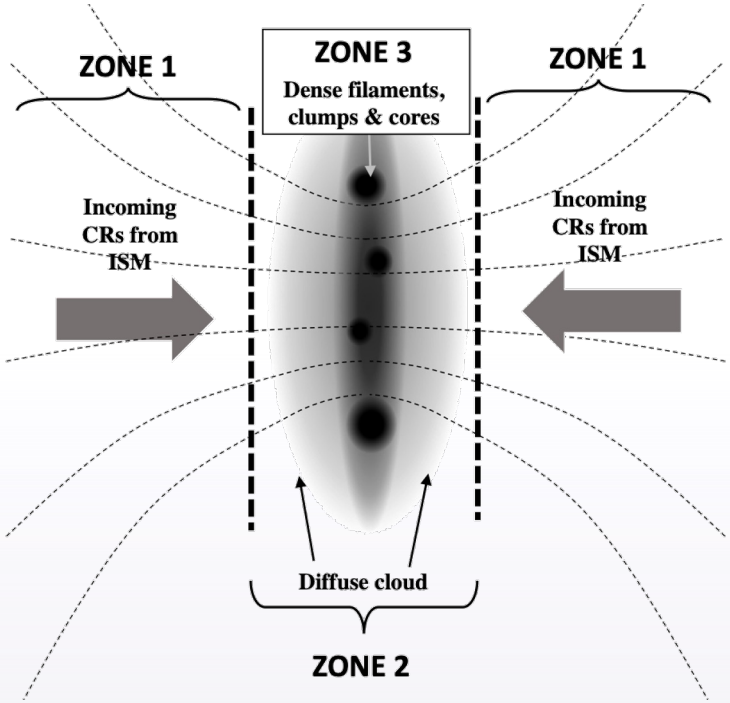


Owen et al. (2021)

- "Decoupling" in the clumps/cores – low ionization fraction; neutral-ion damping **suppresses turbulence**

WHAT ABOUT DENSE GAS?

The "standard" picture: **CRs weakly couple with dense gas**

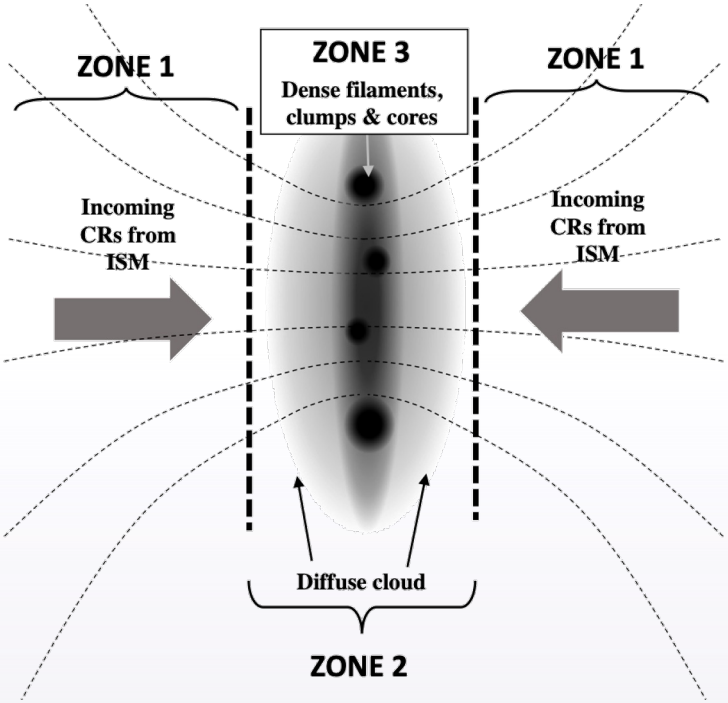


Owen et al. (2021)

- "Decoupling" in the clumps/cores – low ionization fraction; neutral-ion damping **suppresses turbulence**
- Streaming reduces energy density; **spectral shape preserved**

WHAT ABOUT DENSE GAS?

The "standard" picture: **CRs weakly couple with dense gas**

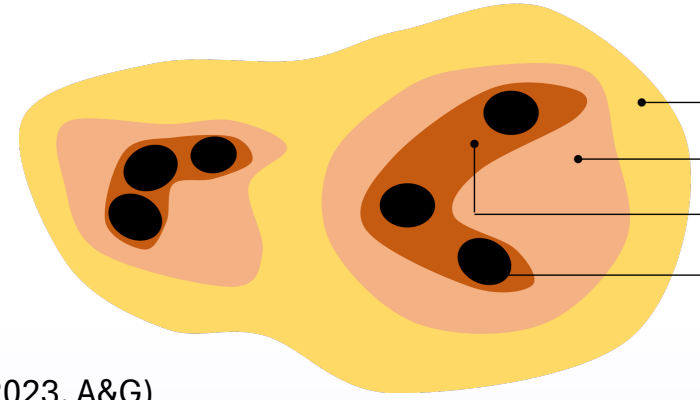


Owen et al. (2021)

- "Decoupling" in the clumps/cores – low ionization fraction; neutral-ion damping **suppresses turbulence**
- Streaming reduces energy density; **spectral shape preserved**
- Cosmic ray effects in all clouds should be **similar throughout the galaxy**

COSMIC RAY PROPAGATION IN THE MULTIPHASE ISM

Hierarchical ISM structure → hierarchical consideration of CR physics

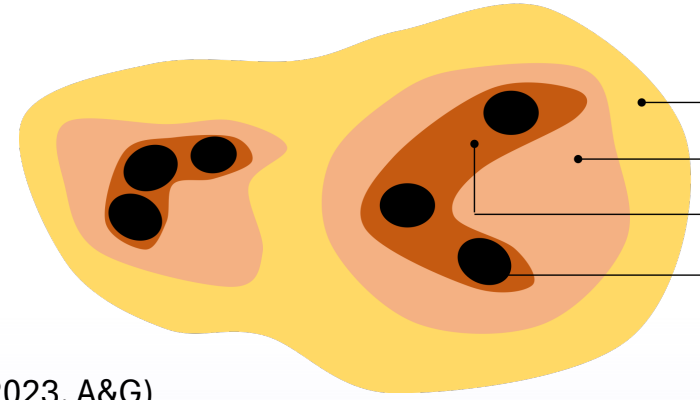


	Size / pc	Denisty / cm^{-3}
Cloud	~1-10	~ 50-500
Clump	~1	10^3-10^4
Filament	~0.1 (wide)	10^4-10^5
Core	~0.05-0.1	>10^5

(Owen 2023, A&G)

COSMIC RAY PROPAGATION IN THE MULTIPHASE ISM

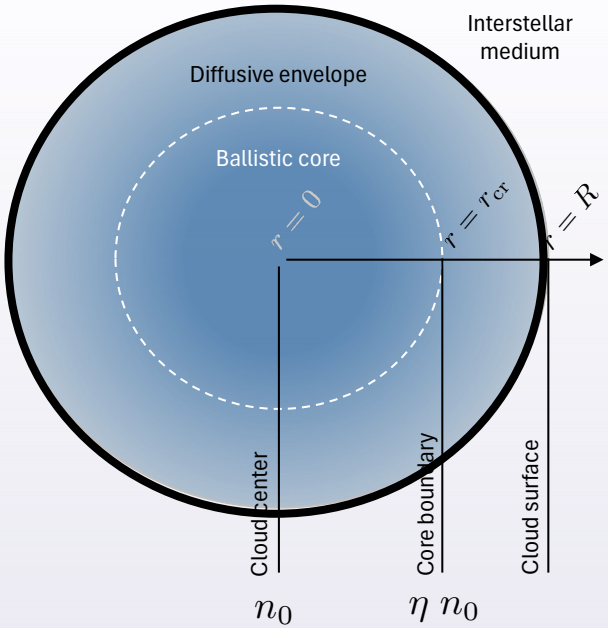
Hierarchical ISM structure → hierarchical consideration of CR physics



	Size / pc	Denisty / cm^{-3}
Cloud	~1-10	~ 50-500
Clump	~1	10^3-10^4
Filament	~0.1 (wide)	10^4-10^5
Core	~0.05-0.1	>10^5

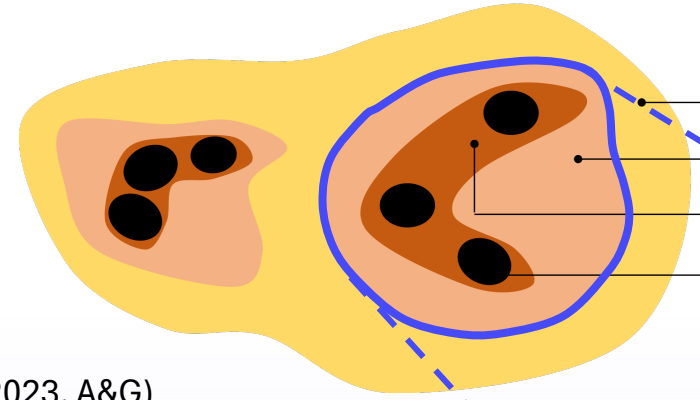
(Owen 2023, A&G)

"Spherical cow" model



COSMIC RAY PROPAGATION IN THE MULTIPHASE ISM

Hierarchical ISM structure → hierarchical consideration of CR physics

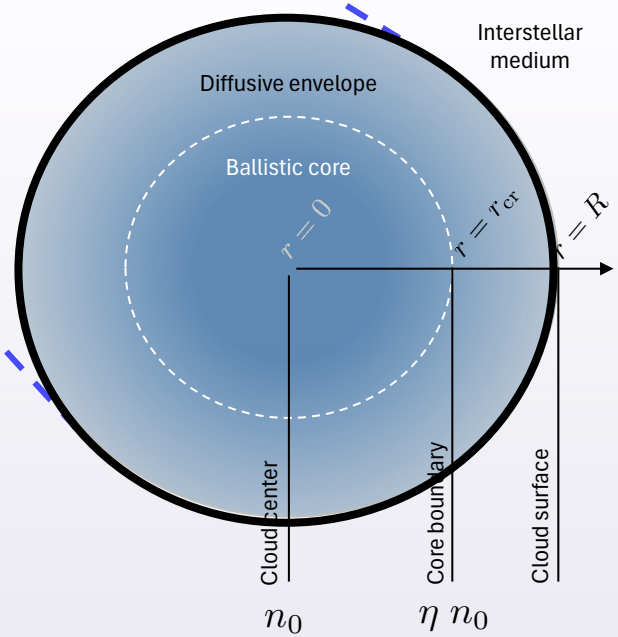


	Size / pc	Denisty / cm^{-3}
Cloud	~1-10	~ 50-500
Clump	~1	10^3-10^4
Filament	~0.1 (wide)	10^4-10^5
Core	~0.05-0.1	>10^5

(Owen 2023, A&G)

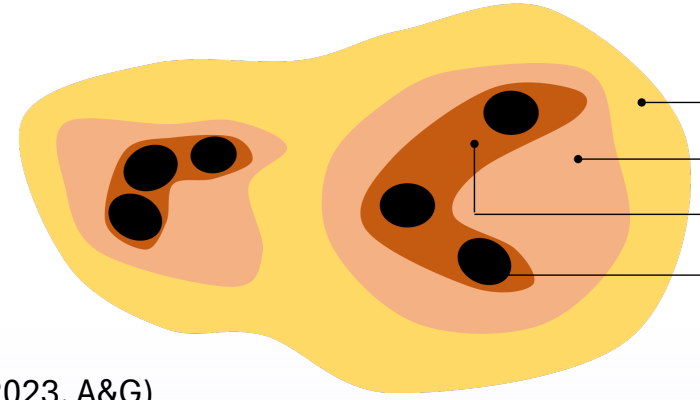
"Spherical cow" model

Clump



COSMIC RAY PROPAGATION IN THE MULTIPHASE ISM

Hierarchical ISM structure → hierarchical consideration of CR physics

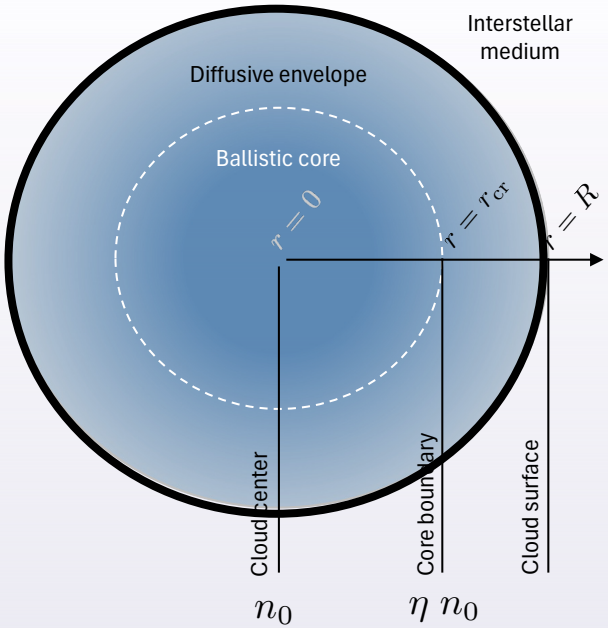


	Size / pc	Denisty / cm^{-3}
Cloud	~1-10	~ 50-500
Clump	~1	10^3-10^4
Filament	~0.1 (wide)	10^4-10^5
Core	~0.05-0.1	>10^5

(Owen 2023, A&G)

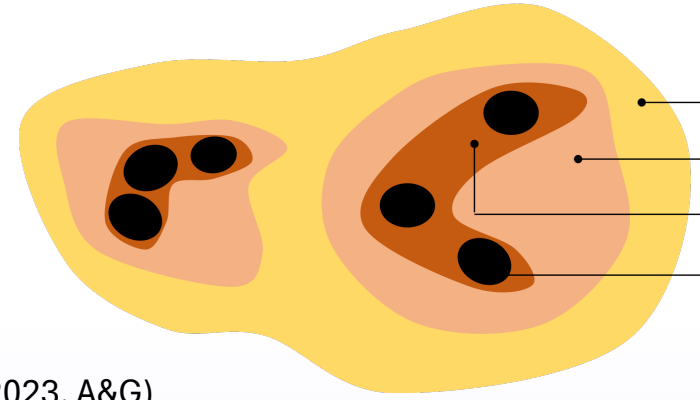
"Spherical cow" model

Consider two-zone transport configuration



COSMIC RAY PROPAGATION IN THE MULTIPHASE ISM

Hierarchical ISM structure → hierarchical consideration of CR physics



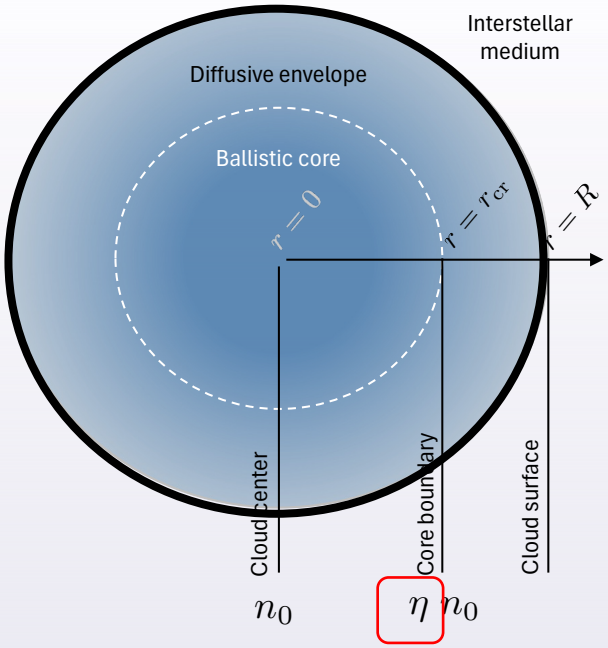
	Size / pc	Denisty / cm^{-3}
Cloud	~1-10	~ 50-500
Clump	~1	10^3-10^4
Filament	~0.1 (wide)	10^4-10^5
Core	~0.05-0.1	>10^5

(Owen 2023, A&G)

"Spherical cow" model

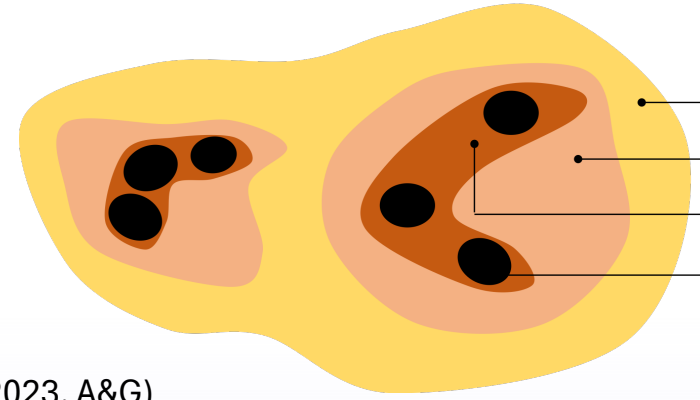
Consider two-zone transport configuration

η = density of transition



COSMIC RAY PROPAGATION IN THE MULTIPHASE ISM

Hierarchical ISM structure → hierarchical consideration of CR physics



	Size / pc	Denisty / cm^{-3}
Cloud	~1-10	~ 50-500
Clump	~1	10^3-10^4
Filament	~0.1 (wide)	10^4-10^5
Core	~0.05-0.1	>10^5

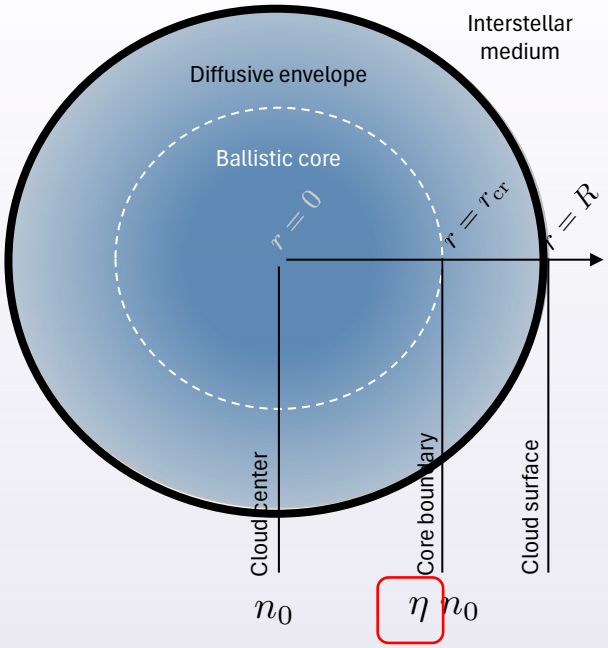
(Owen 2023, A&G)

"Spherical cow" model

Consider two-zone transport configuration

η = density of transition

$\eta = 1$: entirely diffusive
$\eta = 0$: entirely ballistic ["standard picture"]



TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\frac{\partial n_i}{\partial t} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \ ,$$

TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \ ,$$

Steady state

TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \boxed{\nabla \cdot [D(E_i, r) \nabla n_i]} + c \nabla \cdot n_i - \frac{\partial}{\partial \gamma} [b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \ ,$$

Steady state

Diffusion

TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \boxed{\nabla \cdot [D(E_i, r)\nabla n_i]} + \boxed{c\nabla \cdot n_i} - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \ ,$$

Steady state

Diffusion

Ballistic

TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \boxed{\nabla \cdot [D(E_i, r)\nabla n_i]} + \boxed{c\nabla \cdot n_i} - \boxed{\frac{\partial}{\partial \gamma}[b(E_i)\, n_i]} = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \ ,$$

Steady state

Diffusion

Ballistic

Cooling

TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \boxed{\nabla \cdot [D(E_i, r)\nabla n_i]} + \boxed{c\nabla \cdot n_i} - \boxed{\frac{\partial}{\partial \gamma}[b(E_i)\, n_i]} = \boxed{\Gamma_i(E_i)} - \Lambda_i(E_i) n_i \ ,$$

Steady state Diffusion Ballistic Cooling Injection

TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r) \nabla n_i] + c \nabla \cdot n_i - \frac{\partial}{\partial \gamma} [b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

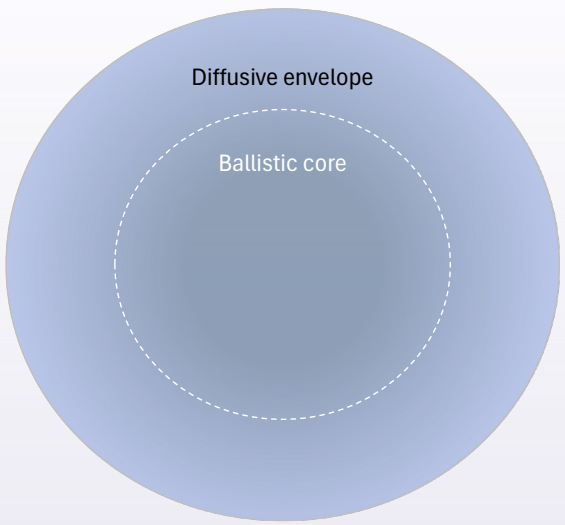
TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

Transport terms



Solve from surface to core (inward direction)

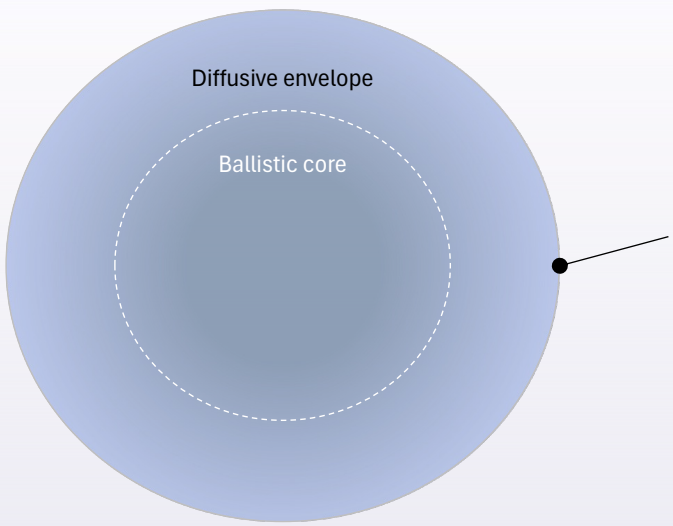
TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

Transport terms



Solve from surface to core (inward direction)

Outer boundary set by ISM CR flux and density (GALPROP)

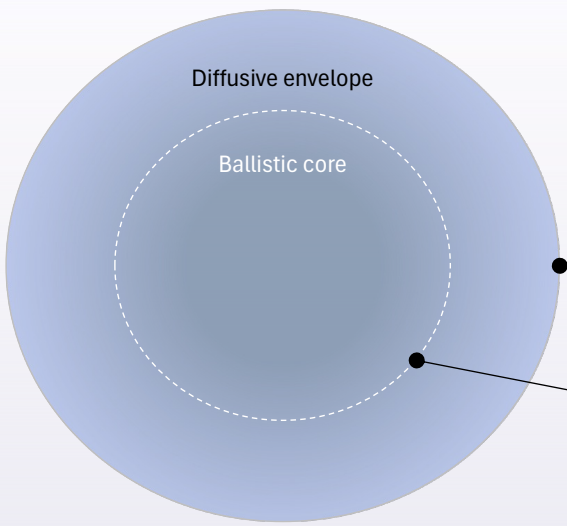
TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

Transport terms



Solve from surface to core (inward direction)

Outer boundary set by ISM CR flux and density (GALPROP)

Interface: switch propagation term

TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

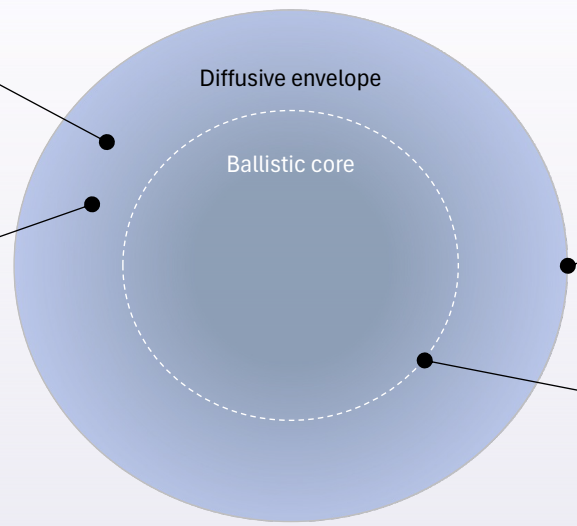
Transport terms

Ballistic term = 0

Diffusion term

B field follows density (Crutcher 2010)

Kraichnan turbulence



Solve from surface to core (inward direction)

Outer boundary set by ISM CR flux and density (GALPROP)

Interface: switch propagation term

TWO-ZONE TRANSPORT MODEL (I)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

Transport terms

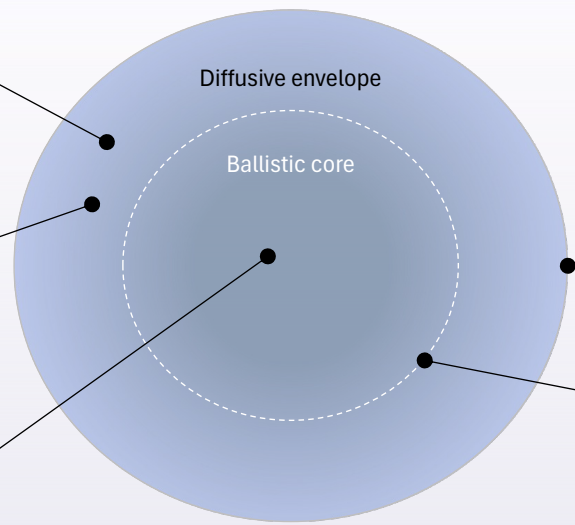
Ballistic term = 0

Diffusion term

B field follows density (Crutcher 2010)

Kraichnan turbulence

Diffusion term = 0



Solve from surface to core (inward direction)

Outer boundary set by ISM CR flux and density (GALPROP)

Interface: switch propagation term

TWO-ZONE TRANSPORT MODEL (II)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

TWO-ZONE TRANSPORT MODEL (II)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

CR microphysics terms differ depending on species

TWO-ZONE TRANSPORT MODEL (II)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

CR microphysics terms differ depending on species

Cooling

Injection

Absorption

TWO-ZONE TRANSPORT MODEL (II)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

CR microphysics terms differ depending on species

	CR Protons	CR Electrons
Cooling		
Injection		
Absorption		

TWO-ZONE TRANSPORT MODEL (II)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

CR microphysics terms differ depending on species

	CR Protons	CR Electrons
Cooling	Streaming cooling; ionization losses	
Injection	None	
Absorption	pp interactions	

TWO-ZONE TRANSPORT MODEL (II)

The transport equation

$$\cancel{\frac{\partial n_i}{\partial t}} - \nabla \cdot [D(E_i, r)\nabla n_i] + c\nabla \cdot n_i - \frac{\partial}{\partial \gamma}[b(E_i)\, n_i] = \Gamma_i(E_i) - \Lambda_i(E_i) n_i \,,$$

Steady state | Diffusion | Ballistic | Cooling | Injection | Absorption

CR microphysics terms differ depending on species

	CR Protons	**CR Electrons**
Cooling	Streaming cooling; ionization losses	Synchrotron, ionization losses
Injection	None	Secondary production from pp interactions (Aafrag + Kamae)
Absorption	pp interactions	None

IDENTIFYING NATURAL LABORATORIES

Selection based on mass and distance (brightest in gamma-rays)

Name	Average distance d/pc	Mass/$M_\odot$	Effective size/ pc	$M/d^2/M_\odot\,\mathrm{pc}^{-2}$
		Molecular clumps		
Perseus-c5	290	2.3×10^3	0.89	0.03
Taurus-c1	140	2.8×10^3	1.1	0.14
Taurus-c2	150	4.2×10^2	0.59	0.02
Taurus-c3	140	1.9×10^3	1.1	0.10
Taurus-c4	140	2.4×10^3	1.4	0.12

Ng, Owen et al. (2025, *in prep*)
Same sample selection as Yang et al. (2023)

IDENTIFYING NATURAL LABORATORIES

Selection based on mass and distance (brightest in gamma-rays)

proxy for gamma-ray flux

Name	Average distance d/pc	Mass/$M_\odot$	Effective size/ pc	$M/d^2/M_\odot\,\mathrm{pc}^{-2}$
		Molecular clumps		
Perseus-c5	290	2.3×10^3	0.89	0.03
Taurus-c1	140	2.8×10^3	1.1	0.14
Taurus-c2	150	4.2×10^2	0.59	0.02
Taurus-c3	140	1.9×10^3	1.1	0.10
Taurus-c4	140	2.4×10^3	1.4	0.12

Ng, Owen et al. (2025, *in prep*)
Same sample selection as Yang et al. (2023)

IDENTIFYING NATURAL LABORATORIES

Selection based on mass and distance (brightest in gamma-rays)

proxy for gamma-ray flux

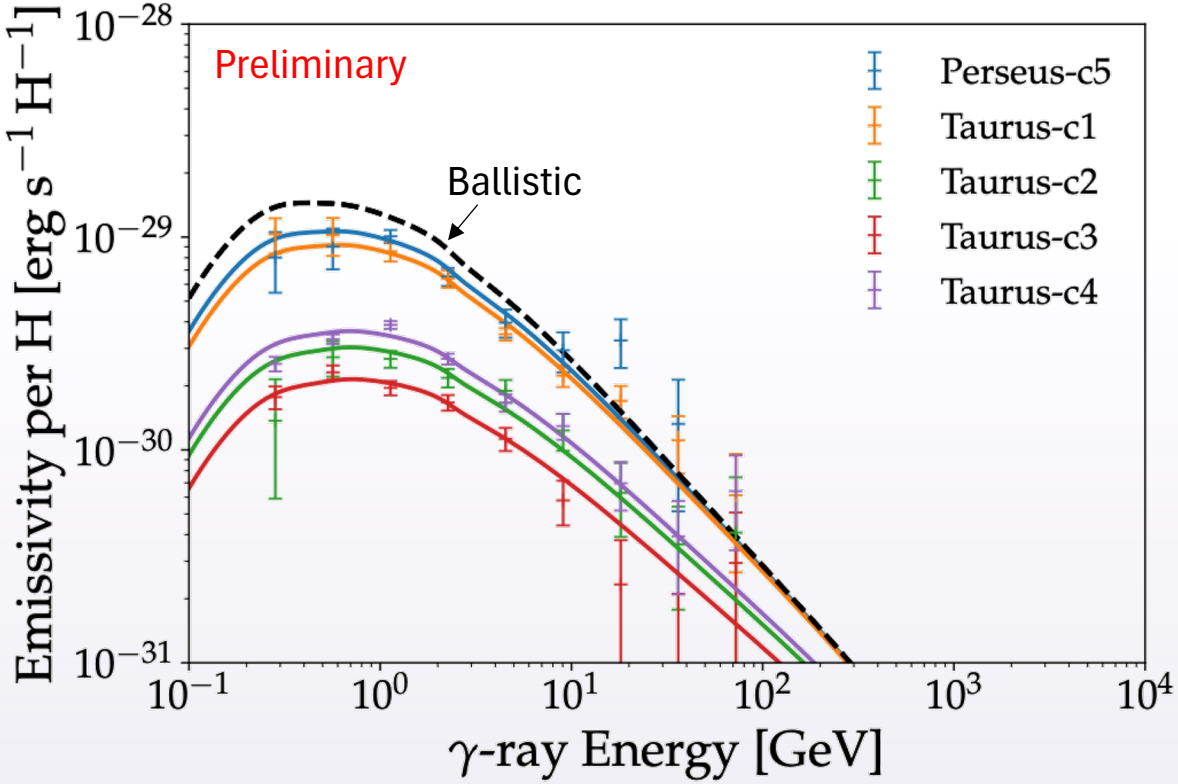
Name	Average distance d/pc	Mass/$M_\odot$	Effective size/ pc	$M/d^2/M_\odot\,\mathrm{pc}^{-2}$
		Molecular clumps		
Perseus-c5	290	2.3×10^3	0.89	0.03
Taurus-c1	140	2.8×10^3	1.1	0.14
Taurus-c2	150	4.2×10^2	0.59	0.02
Taurus-c3	140	1.9×10^3	1.1	0.10
Taurus-c4	140	2.4×10^3	1.4	0.12

best chance to see gamma-ray suppression

Ng, Owen et al. (2025, *in prep*)
Same sample selection as Yang et al. (2023)

TESTING COSMIC RAY TRANSPORT

Suppression feature first reported in these clumps by Yang et al. 2023
Confirm their result, and find **suppression of diffusion coefficient** (>100)



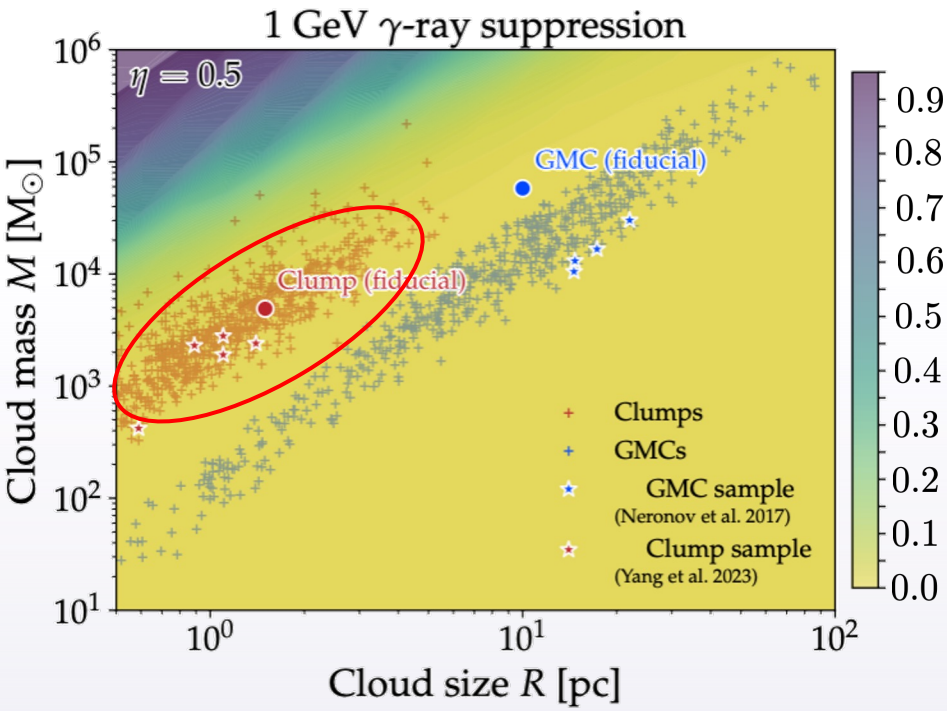
Magnitude of D range
[8.2e24, 3.8e26] cm^2 s^{-1}

Ng, Owen et al. (2025, *in prep*)

Data provided by R. Z. Yang; see Yang et al. (2023)

HOW BIG IS THE COSMIC RAY "KILLING" ZONE?

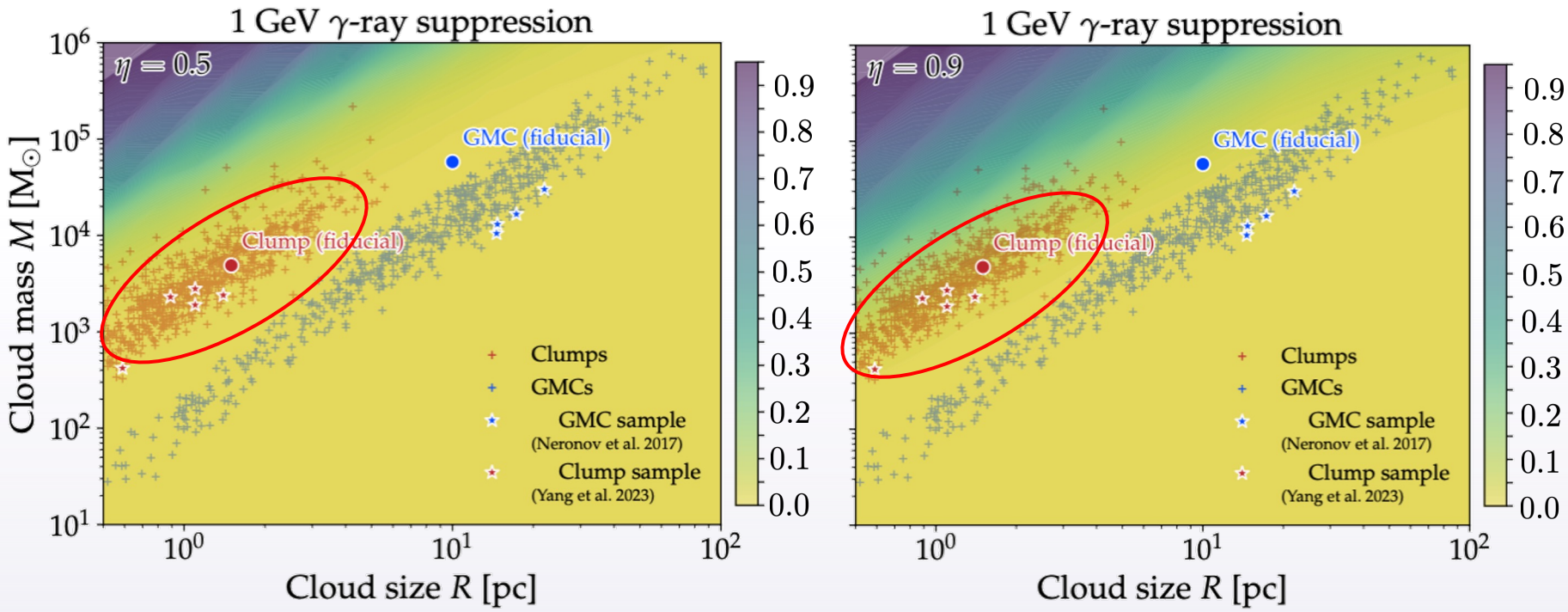
Adopting average propagation physics for the 5 Taurus and Perseus clumps



Ng, Owen et al. (2025, *in prep*)

HOW BIG IS THE COSMIC RAY "KILLING" ZONE?

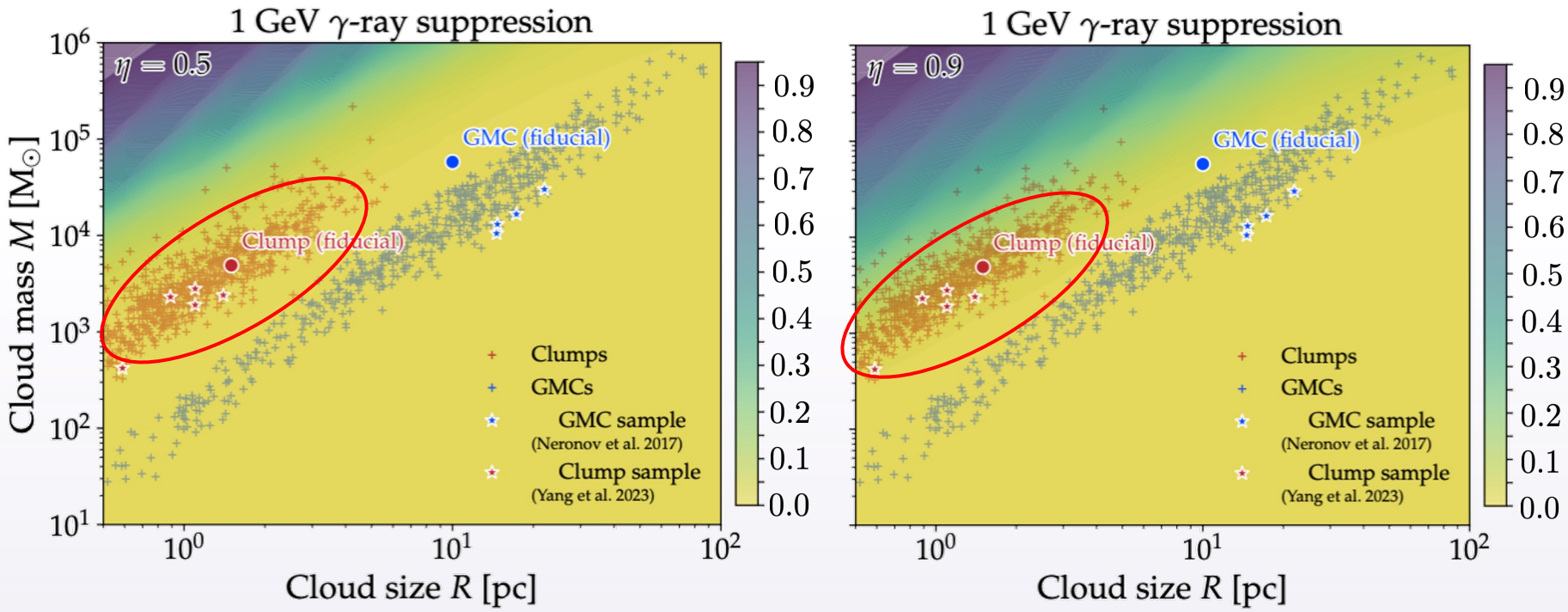
Adopting average propagation physics for the 5 Taurus and Perseus clumps



Ng, Owen et al. (2025, *in prep*)

HOW BIG IS THE COSMIC RAY "KILLING" ZONE?

Adopting average propagation physics for the 5 Taurus and Perseus clumps

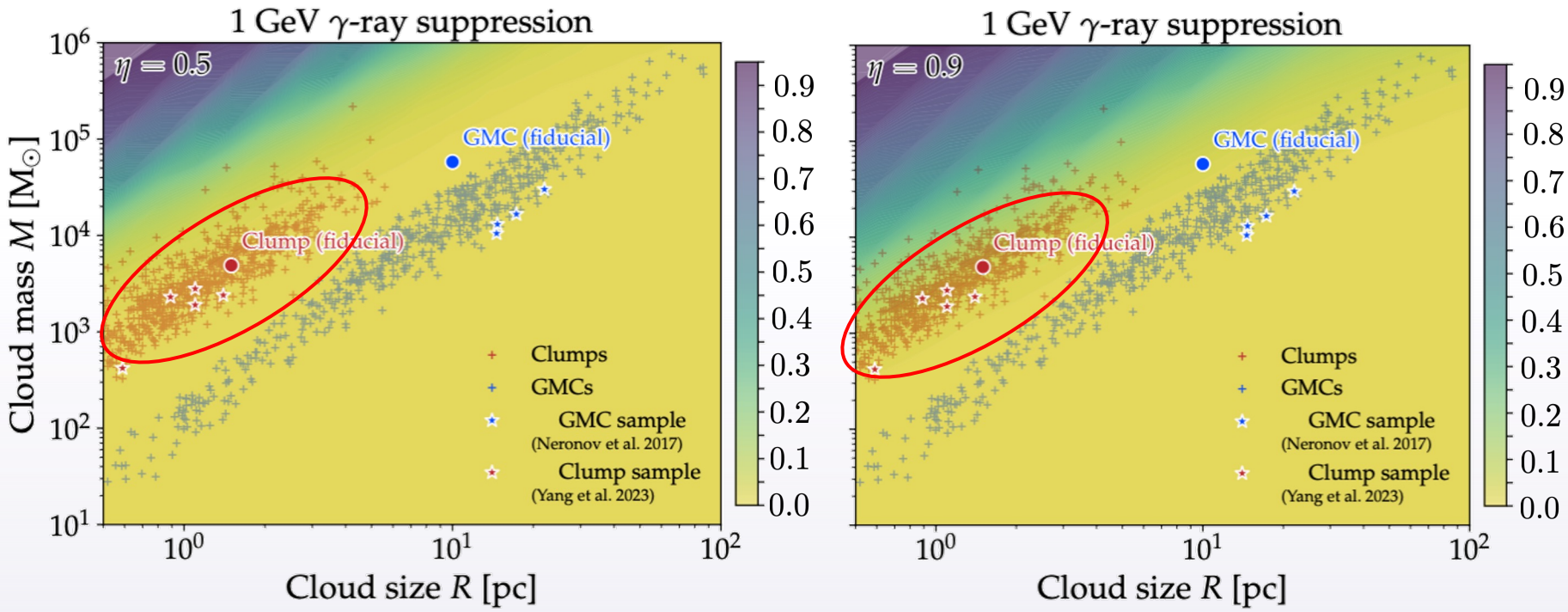


Ng, Owen et al. (2025, *in prep*)

Fitting to the Perseus and Taurus clumps indicates all of them have $\eta > 0.9$

HOW BIG IS THE COSMIC RAY "KILLING" ZONE?

Adopting average propagation physics for the 5 Taurus and Perseus clumps



Ng, Owen et al. (2025, *in prep*)

Fitting to the Perseus and Taurus clumps indicates all of them have $\eta > 0.9$

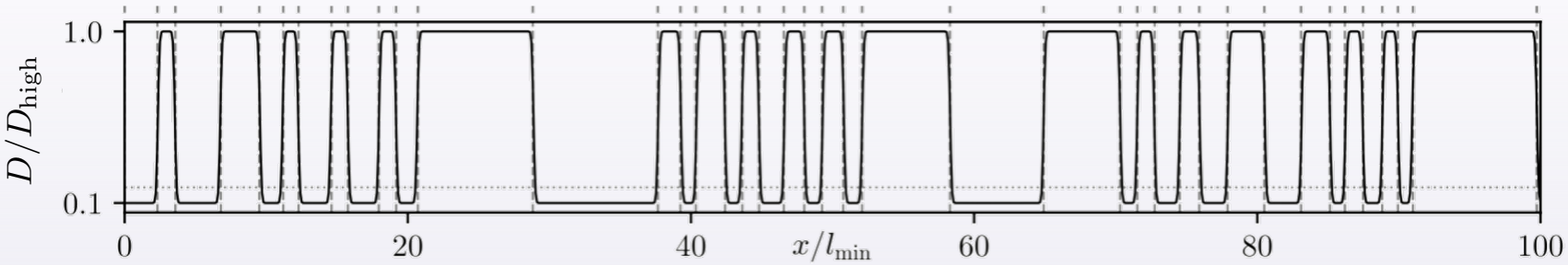
- **What causes this seemingly strong coupling with dense gas?**

ONE POSSIBILITY – INTERMITTENT STRUCTURES

Localized pockets of intermittent magnetic structures

ONE POSSIBILITY – INTERMITTENT STRUCTURES

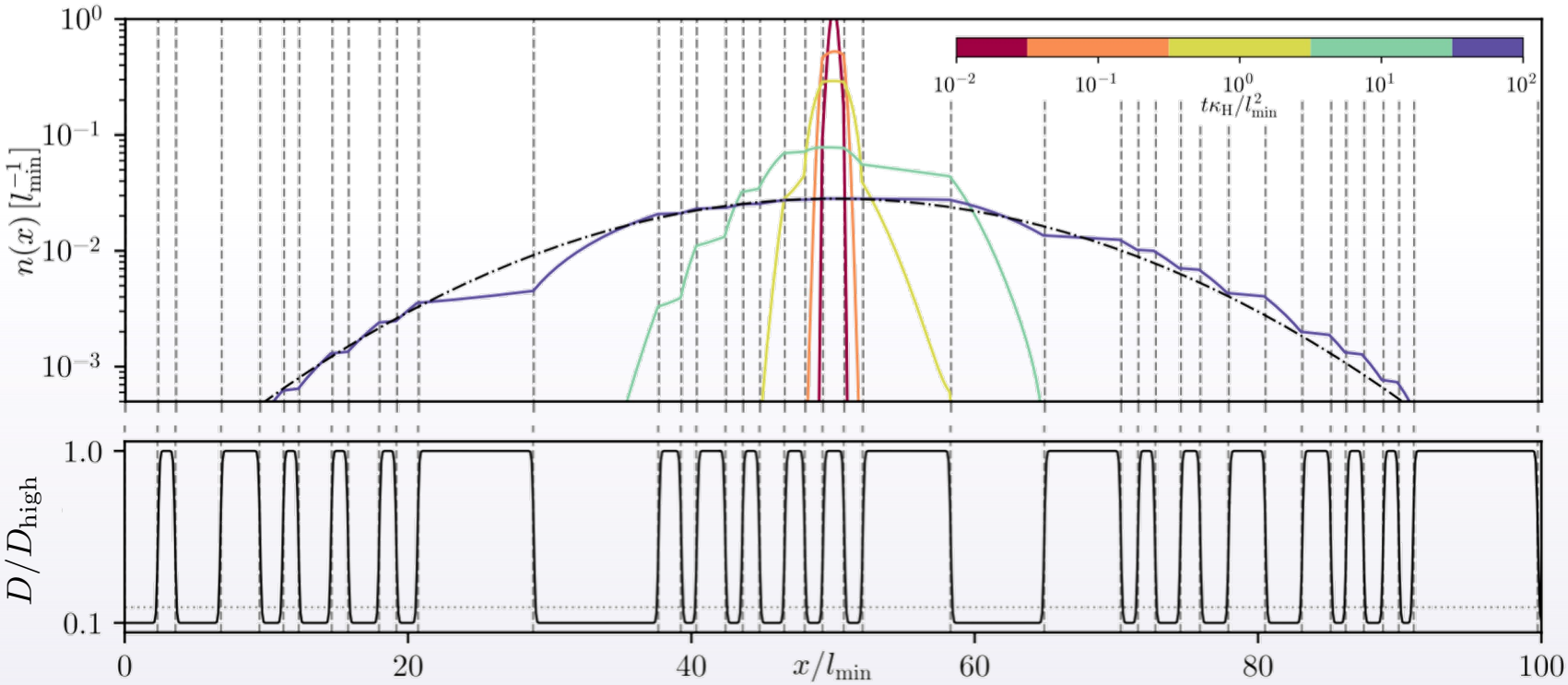
Localized pockets of intermittent magnetic structures



ONE POSSIBILITY – INTERMITTENT STRUCTURES

Localized pockets of intermittent magnetic structures

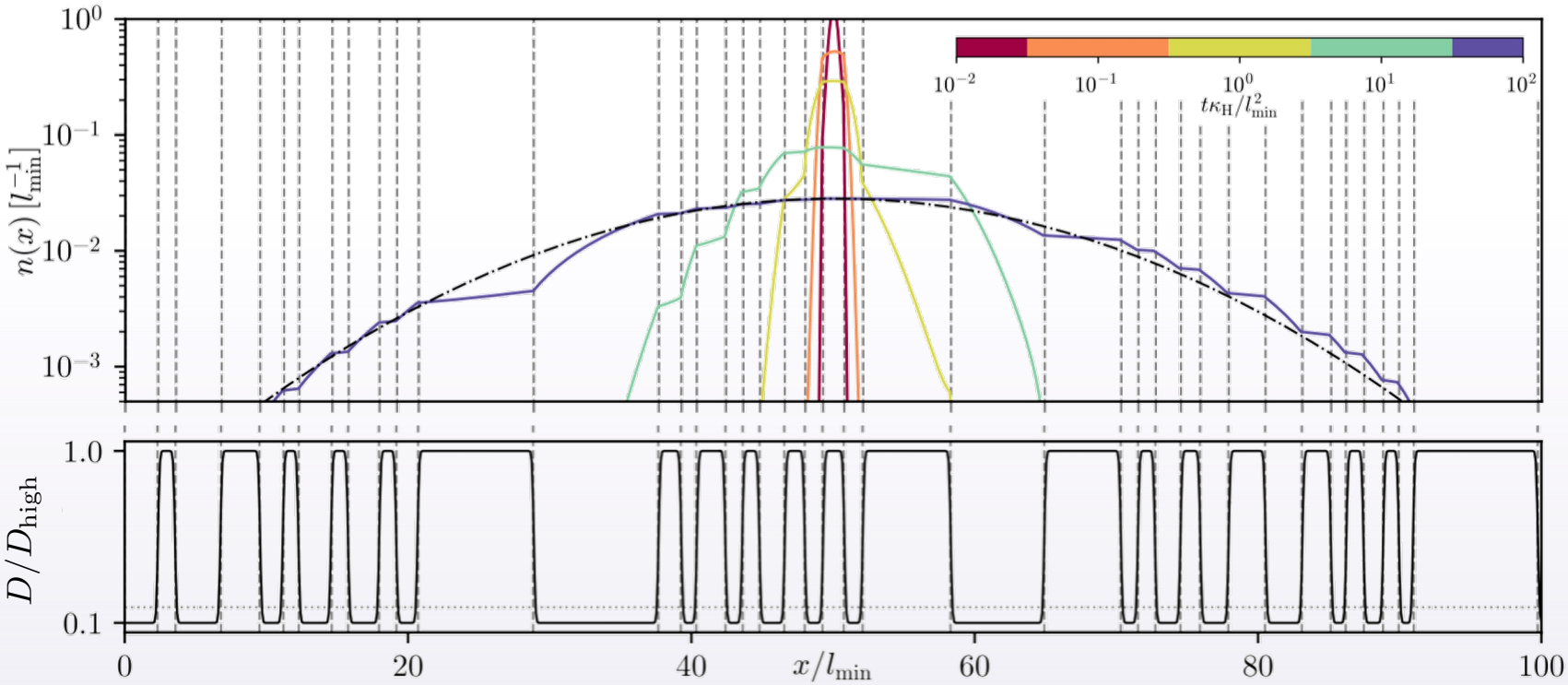
Ewhart et al. (2025)



ONE POSSIBILITY – INTERMITTENT STRUCTURES

Localized pockets of intermittent magnetic structures

Ewhart et al. (2025)

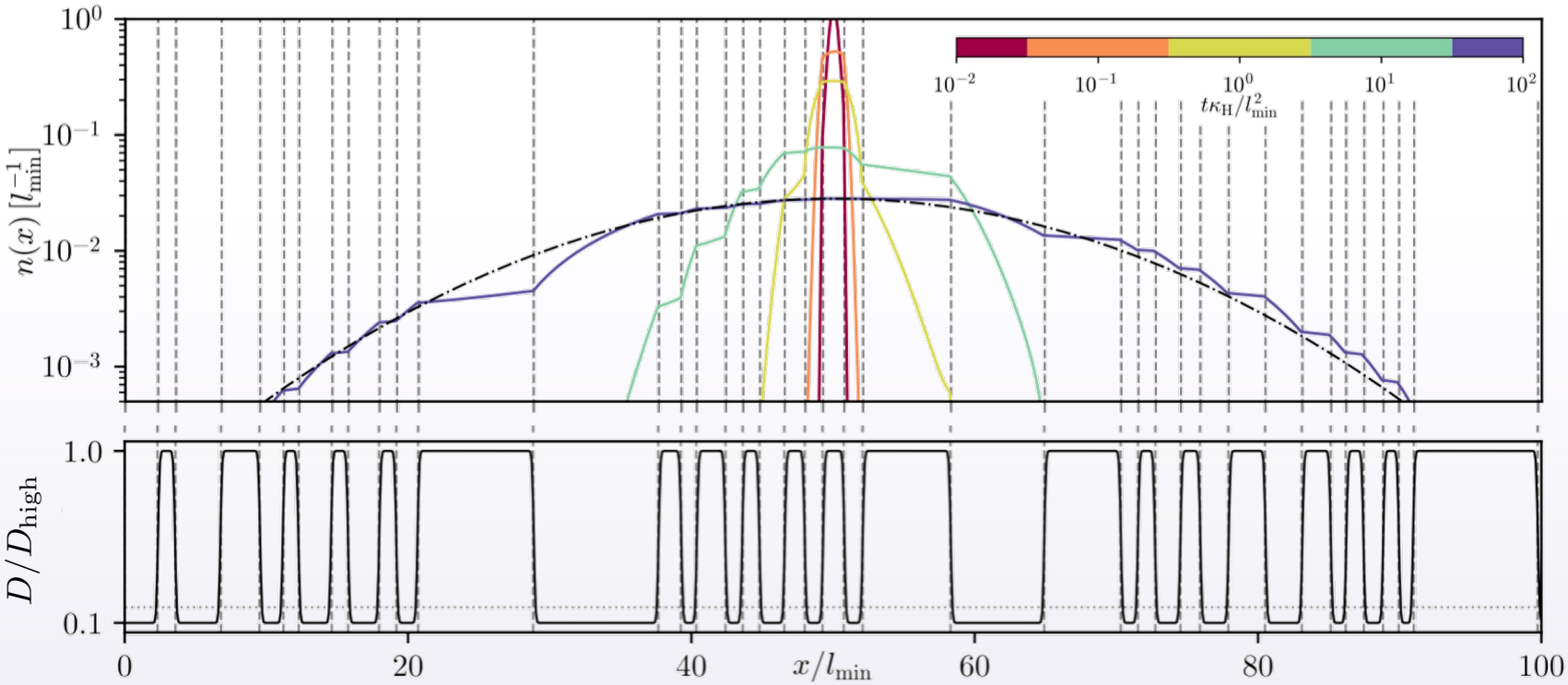


$$D_{\rm eff} = \left[\frac{f}{D_{\rm low}} + \frac{1-f}{D_{\rm high}}\right]^{-1} \approx \frac{D_{\rm low}}{f}$$

ONE POSSIBILITY – INTERMITTENT STRUCTURES

Localized pockets of intermittent magnetic structures

Ewhart et al. (2025)

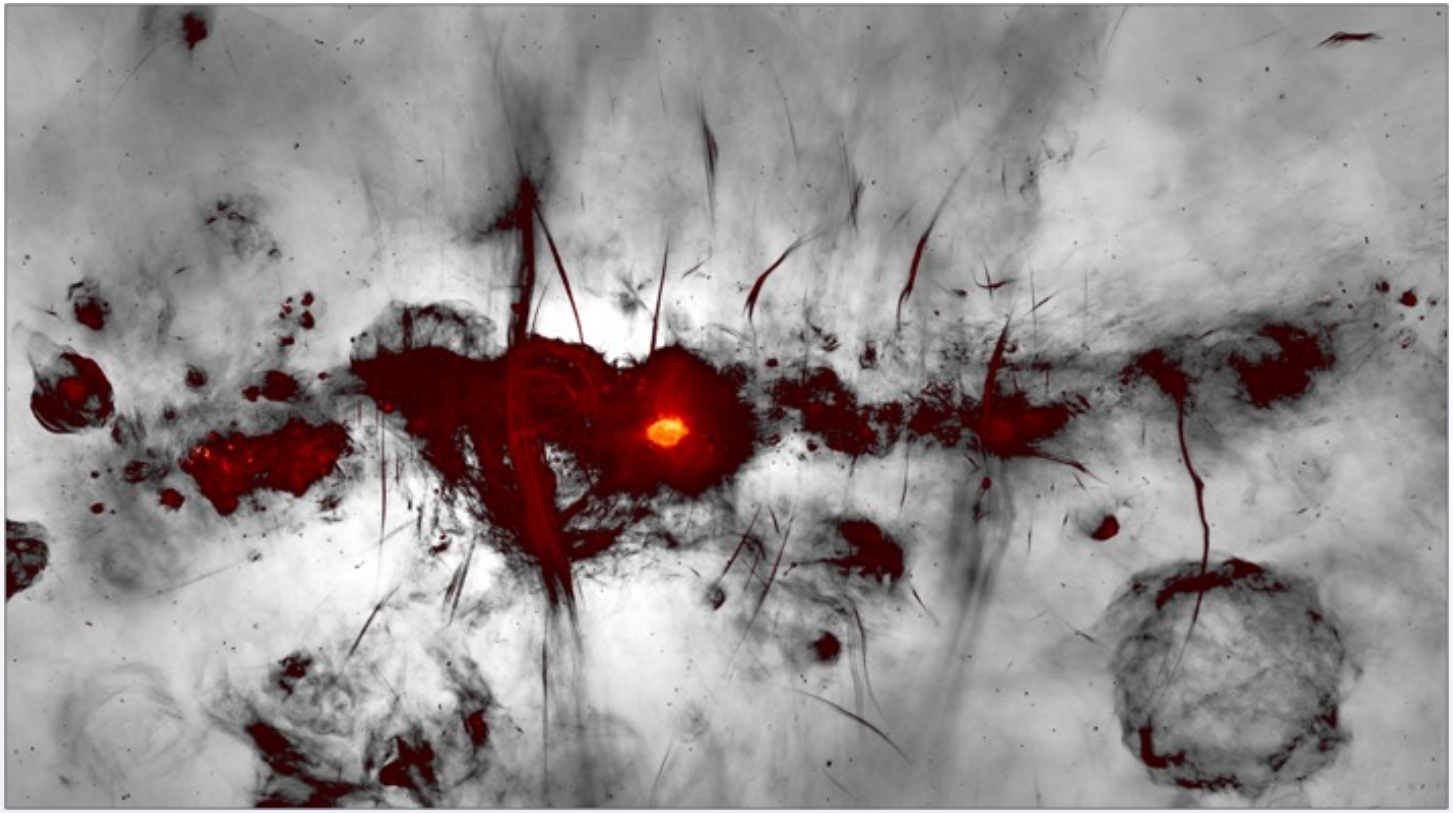


$$D_{\rm eff} = \left[\frac{f}{D_{\rm low}} + \frac{1-f}{D_{\rm high}}\right]^{-1} \approx \frac{D_{\rm low}}{f}$$

"Looks" like a single diffusion coefficient over large scales – e.g. in gamma-ray observations

ANOTHER EXAMPLE – BACK TO THE GALACTIC CENTER

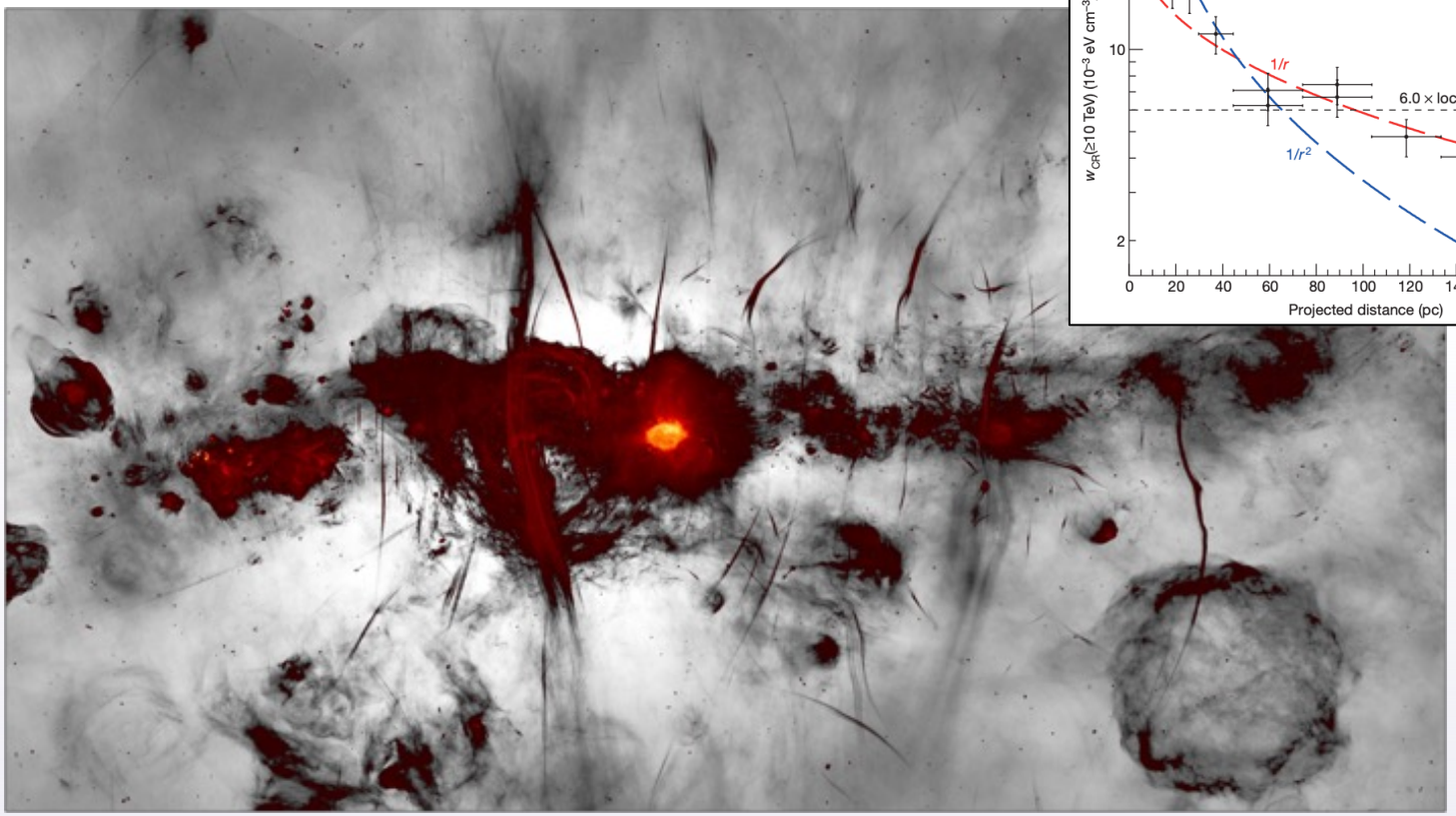
Should we apply the same interpretation here?

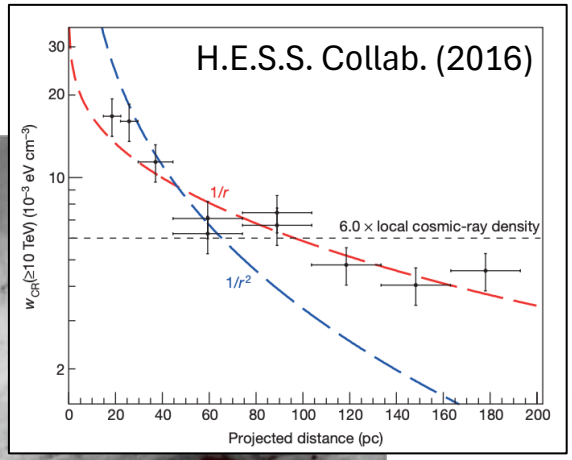


Credit: I. Heywood, SARAO (2022)

ANOTHER EXAMPLE – BACK TO THE GALACTIC CENTER

Should we apply the same interpretation here?

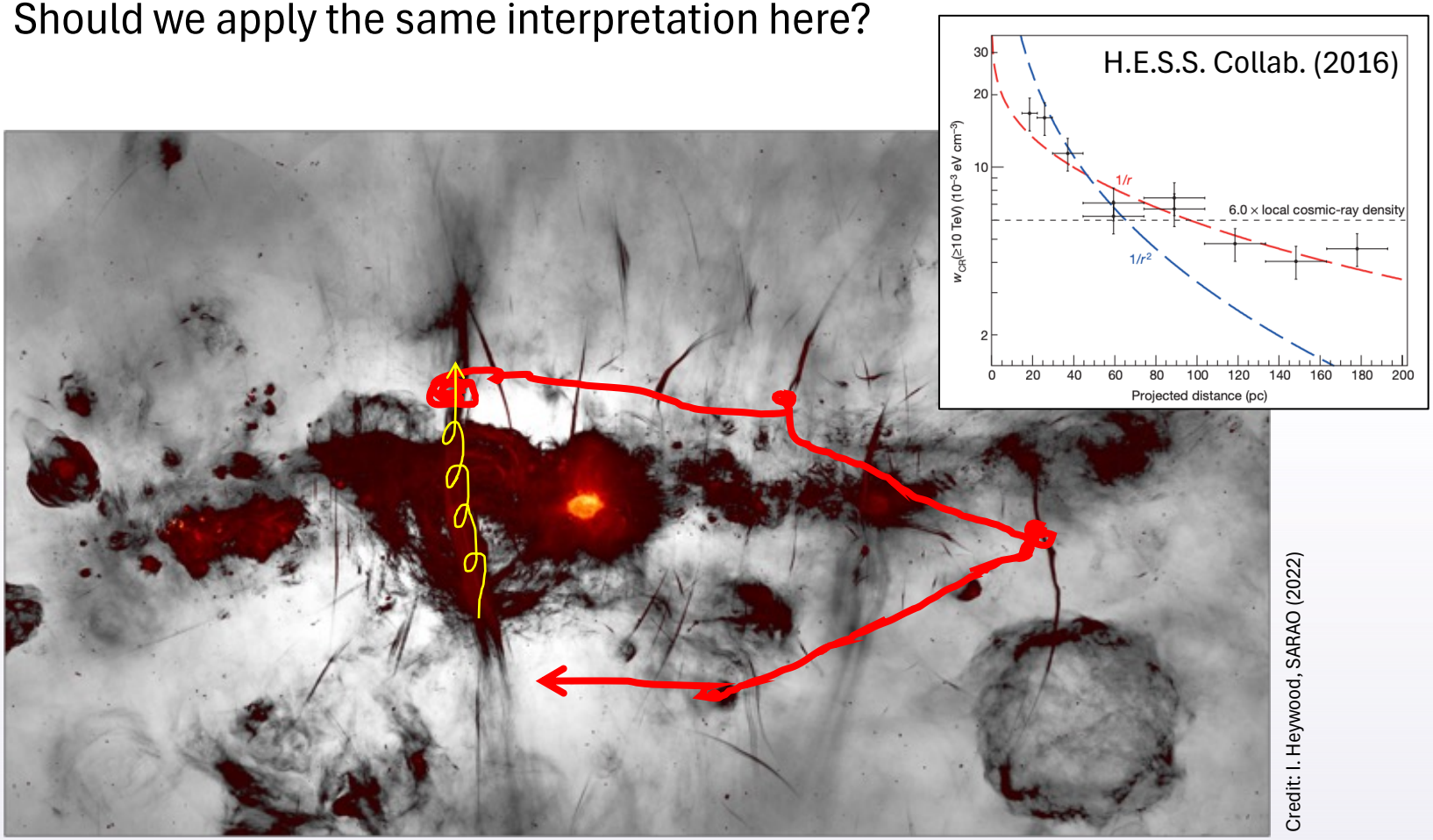




Credit: I. Heywood, SARAO (2022)

ANOTHER EXAMPLE – BACK TO THE GALACTIC CENTER

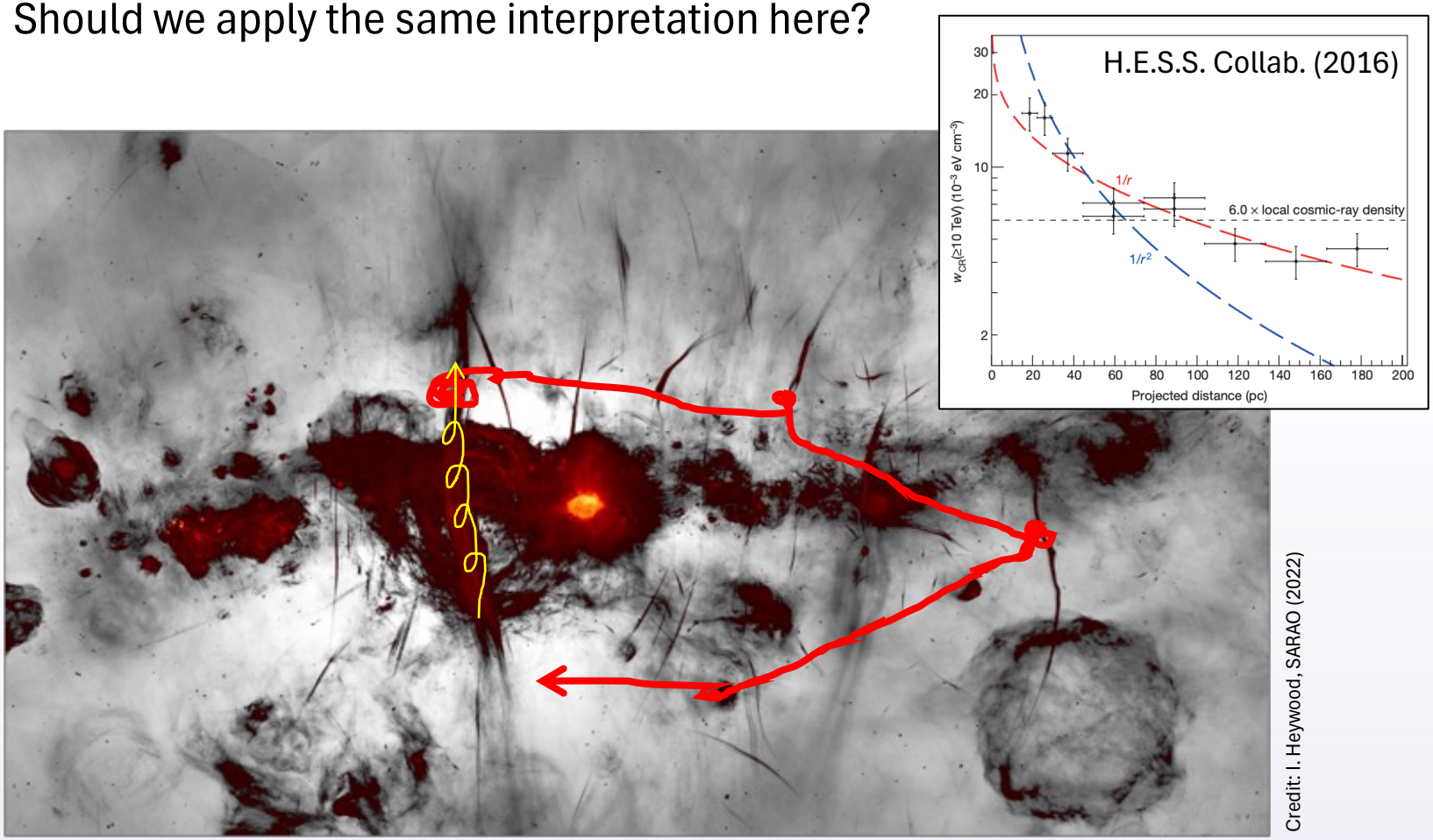
Should we apply the same interpretation here?



Credit: I. Heywood, SARAO (2022)

ANOTHER EXAMPLE – BACK TO THE GALACTIC CENTER

Should we apply the same interpretation here?



Credit: I. Heywood, SARAO (2022)

And what about more phase-complex field configurations?

NON-BROWNIAN PROPAGATION IN MAGNTO-COMPLEX MEDIA

More general framework for non-Brownian propagation

Levy framework (Mathematic Biology)

Basic governing equation to modify – a more generalized diffusion equation

$$\frac{\partial \varphi(x,t)}{\partial t} = -\frac{\partial}{\partial x} f(x,t)\varphi(x,t) + \gamma \frac{\partial^\alpha \varphi(x,t)}{\partial |x|^\alpha}$$

NON-BROWNIAN PROPAGATION IN MAGNTO-COMPLEX MEDIA

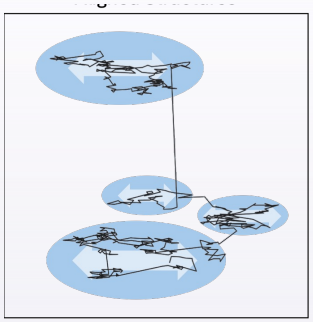
More general framework for non-Brownian propagation

Levy framework (Mathematic Biology)

Basic governing equation to modify – a more generalized diffusion equation

$$\frac{\partial \varphi(x,t)}{\partial t} = -\frac{\partial}{\partial x} \boxed{f(x,t)} \varphi(x,t) + \gamma \frac{\partial^\alpha \varphi(x,t)}{\partial |x|^\alpha}$$

Potential (external forces)



NON-BROWNIAN PROPAGATION IN MAGNTO-COMPLEX MEDIA

More general framework for non-Brownian propagation

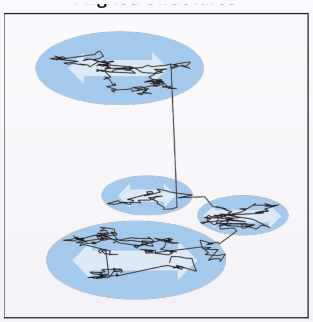
Levy framework (Mathematic Biology)

Basic governing equation to modify – a more generalized diffusion equation

$$\frac{\partial \varphi(x,t)}{\partial t} = -\frac{\partial}{\partial x} f(x,t)\varphi(x,t) + \gamma \frac{\partial^{\alpha} \varphi(x,t)}{\partial |x|^{\alpha}}$$

Potential (external forces)

Stability parameter
Smaller values = heavier tail in the step distribution



NON-BROWNIAN PROPAGATION IN MAGNTO-COMPLEX MEDIA

More general framework for non-Brownian propagation

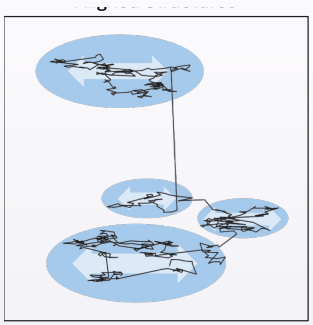
Levy framework (Mathematic Biology)

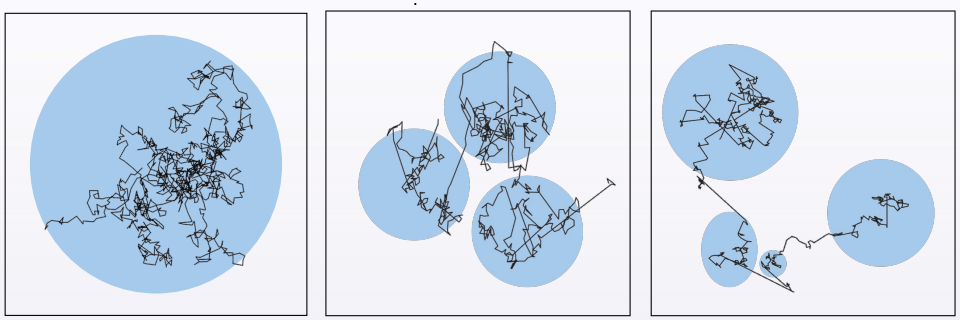
Basic governing equation to modify – a more generalized diffusion equation

$$\frac{\partial \varphi(x,t)}{\partial t} = -\frac{\partial}{\partial x} f(x,t)\varphi(x,t) + \gamma \frac{\partial^{\alpha} \varphi(x,t)}{\partial |x|^{\alpha}}$$

Potential (external forces)

Stability parameter
Smaller values = heavier tail in the step distribution





$\alpha = 2$ $\alpha < 2$ $\alpha \ll 2$

NON-BROWNIAN PROPAGATION IN MAGNTO-COMPLEX MEDIA

More general framework for non-Brownian propagation

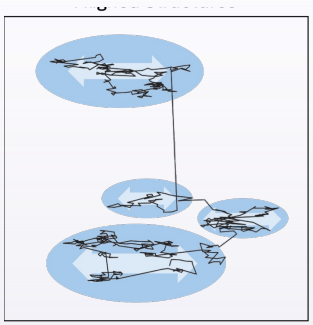
Levy framework (Mathematic Biology)

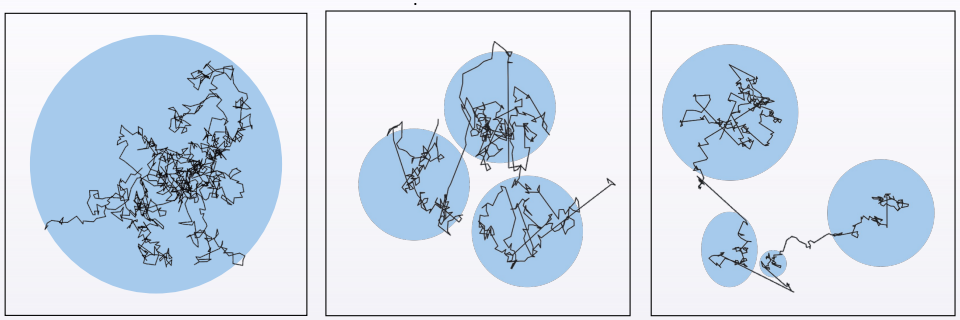
Basic governing equation to modify – a more generalized diffusion equation

$$\frac{\partial \varphi(x,t)}{\partial t} = -\frac{\partial}{\partial x} f(x,t)\varphi(x,t) + \gamma \frac{\partial^{\alpha} \varphi(x,t)}{\partial |x|^{\alpha}}$$

Potential (external forces)

Stability parameter
Smaller values = heavier tail in the step distribution





$\alpha = 2$ $\alpha < 2$ $\alpha \ll 2$

Promising environments for testing: suppressed D in gamma-ray emitting regions

- GC; Molecular clouds; TeV Halos; PWN, etc…

SUMMARY

SUMMARY

- We can use the **galactic center** and **multiphase ISM** to measure gas density tracers and test cosmic-ray propagation physics

SUMMARY

- We can use the **galactic center** and **multiphase ISM** to measure gas density tracers and test cosmic-ray propagation physics

- GC neutrinos enable **calibration of competing gas tracers**; next-gen exposure makes this a realistic 10–30 yr program

SUMMARY

- We can use the **galactic center** and **multiphase ISM** to measure gas density tracers and test cosmic-ray propagation physics
- GC neutrinos enable **calibration of competing gas tracers**; next-gen exposure makes this a realistic 10–30 yr program
- Gamma-ray-emitting dense clumps show **strong diffusion suppression**

SUMMARY

- We can use the **galactic center** and **multiphase ISM** to measure gas density tracers and test cosmic-ray propagation physics
- GC neutrinos enable **calibration of competing gas tracers**; next-gen exposure makes this a realistic 10–30 yr program
- Gamma-ray-emitting dense clumps show **strong diffusion suppression**
- Intermittent magnetic structures (and potentially **non-Brownian / Lévy-type transport**) may reconcile “local suppression” with large-scale effective diffusion