

Galactic Cosmic Ray Physics with the Ultra-long Wavelength Lunar Farside Observatory

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CR physics: A frontier field deeply connected with other areas of astrophysics

Astro2020 key science area: Unveiling the Hidden Drivers of Galaxy Growth

‘The impact of cosmic rays is one of the largest uncertainties in understanding feedback in galaxy formation’

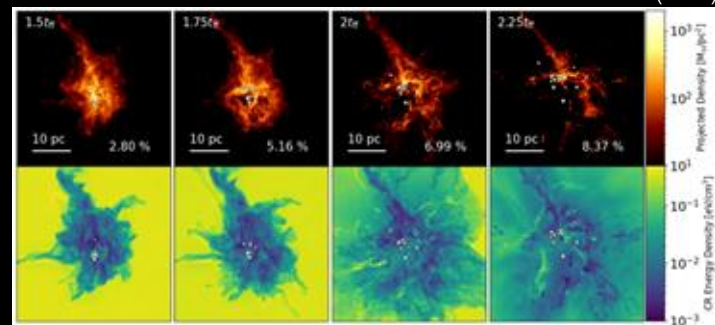
F-Q1: “How do star-forming structures arise from, and interact with, the diffuse interstellar medium?”



- CRs dominate heating in UV-shielded gas, setting the fragmentation mass scale through temperature
- CR ionisation sets the ion fraction, hence how fast collapsing gas passes magnetic field lines
- CR pressure gradients slow collapse and drive winds into the diffuse ISM

Time →

Fitz Axen et al. (2026)



CR physics: A frontier field deeply connected with other areas of astrophysics

CRs provide a key source of pressure in the ISM (observed) and CGM (predicted):

ISM: rough equipartition between CR, thermal, magnetic, and turbulent pressure

CGM: CR pressure dominates over thermal pressure in low- z , L^* haloes

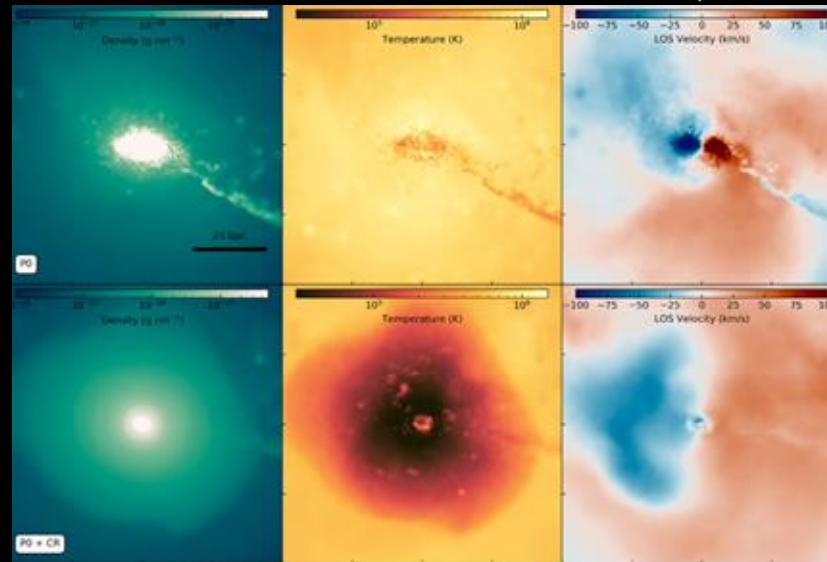
- By preventing cool gas from precipitating onto the disk, CGM CRs may profoundly change galactic star formation histories
- The abundance of CGM CRs strongly depends on transport physics: e.g. energy-dependence of diffusion coefficient κ . **Transport really matters!**
- Inference of CR transport physics requires a statistical comparison between GHz and MHz Galactic radio maps with modern simulations
- Maps also encode CR spectrum, magnetic fields, gas density & temperature

Advances in theory, simulation, and observations inspire **Zweibel's program**, '*Resetting Cosmic Ray Propagation Theory*' — e.g.:

- Push for development of CR hydrodynamics
- Push to expand body of observations of CRs and their sources



Butsky et al. (2022)



Ponnada et al. (2026)

Strong Evidence for Cosmic-Ray-supported $\sim L^*$ Galaxy Halos via X-Ray and tSZ Constraints

Sam B. Ponnada¹, Philip F. Hopkins¹, Yue Samuel Lu², Emily M. Silich¹, Iryna S. Butsky^{3,5}, and Dušan Kereš^{2,4}

Big CR-related science questions: *Ultra-long Wavelength Lunar Farside Observatory*

On cosmic rays themselves:

1. **CRe spectrum:** How do the energy spectrum and abundance of low-energy CRes, which are rigidity-matched to CRps that dominate molecular cloud ionisation at depths where stars form, vary across a galaxy? Is the Voyagers' LIS representative of the Milky Way (and simulated galaxies)?
2. **CR transport:** Which physical paradigm correctly describes the movement of CRs through galaxies? Is diffusivity approximately constant through space and time ('CD'), dependent on local turbulence ('ET'), or dependent on the local CR density gradient and magnetic field strength ('SC')?
3. **IMF universality:** Why does the stellar initial mass function appear universal across the Milky Way, when the CR ionisation rate, which sets the temperature floor in star-forming gas, varies by an order of magnitude between sightlines?

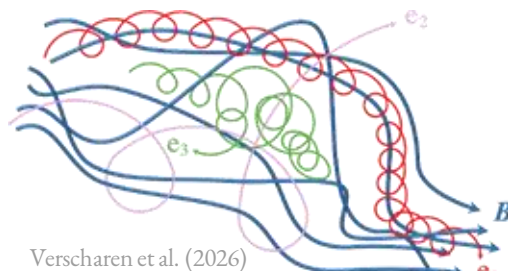
On new probes of magnetic fields and thermal electrons:

4. **GMC magnetic fields:** Can radio–gamma-ray synergy unlock a powerful method to determine magnetic fields within GMCs, based on CR pion decay? What are the magnetic field profiles of Cepheus, Chamaeleon, Orion, and Taurus? Could this method then calibrate the Davis–Chandrasekhar–Fermi (DCF) technique?
5. **ISM magnetic fields:** Can ultra-long wavelength observations unlock the first non-degenerate astronomical measurements of Razin suppression? Can this be turned into an independent method for determining ISM magnetic fields?
6. **FFA and thermal plasma:** Can ultra-long wavelength observations, through EM-derived clumping factors, improve Galactic electron density models (e.g. NE2001 and YMW16)? Could this reduce major systematics in FRB cosmology and pulsar distances?

Charting the lowest-energy CRs accessible to 3D remote sensing

Immediate target: CR electrons with Lorentz factor $\gamma \sim 100\text{--}1000$, kinetic energies $T \sim 50\text{ MeV--}500\text{ MeV}$, rigidities $R \sim 50\text{ MV--}500\text{ MV}$

$$r_g = \frac{R \sin \alpha}{Bc} = 0.02\text{ AU} \cdot \frac{R}{100\text{ MV}} \frac{\sin \alpha}{1} \left(\frac{B}{1\text{ }\mu\text{G}} \right)^{-1}$$



Verscharen et al. (2026)



NASA JPL/Caltech

CR electrons and protons of equal rigidity have identical trajectories (but CR protons traverse them more slowly)
However, energy losses experienced by CR electrons and protons are different!

Implicit target: CR protons with rigidities $R \sim 50\text{ MV--}500\text{ MV}$, kinetic energies $T \sim 1.4\text{ MeV--}130\text{ MeV}$

UltraFar probes the rigidity range of 1.4 MeV–130 MeV protons: the lowest-energy CRs accessible any 3D remote sensing technique, and the ones that dominate CR ionisation of neutral and molecular gas

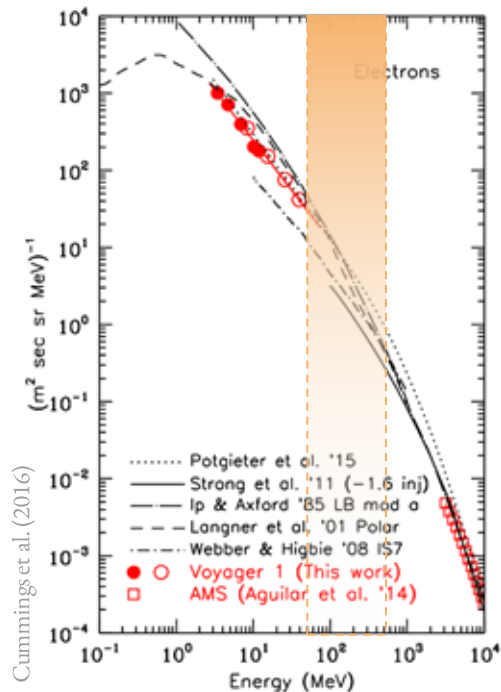
In 2012 and 2018, Voyagers 1 and 2 cross the heliopause and enter interstellar space!

The New York Times

In a Breathtaking First, NASA's Voyager 1 Exits the Solar System

At present, the CRe energy distribution in this Lorentz factor range has only been *partly* probed by the Voyagers in-situ at 'one' epoch and 'one' location: an atypical local cloud... How does this vary throughout the Galaxy?

UltraFar extends LoS and 3D measurements to the entire sky, and goes higher in Lorentz factor

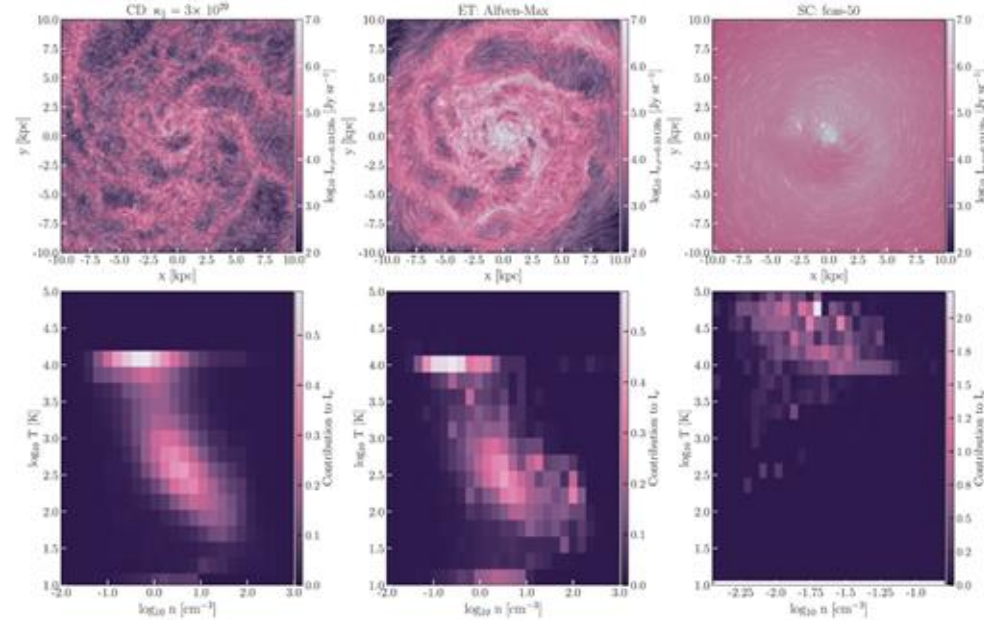


Cummings et al. (2016)

Key galaxy-scale baryon feedback question: How do CRs move through galaxies?

- Supernovae, concentrated in galactic centres, inject $\sim 10\%$ of their energy into CR electrons and protons
- $\gamma = 10^2 - 10^3$ electrons are too few in number to generate self-confinement, so they ride the proton-generated Alfvén waves as **test particles** of the CR transport outwards
- Use Galactic radio maps at a variety of frequencies to reverse-engineer CR transport
- Synchrotron morphology and its frequency-dependence encodes diffusion coefficients, magnetic field structure, ISM phases of origin
- Unique feature of $\gamma = 10^2 - 10^3$ CRes: in contrast to $\gamma = 10^3 - 10^4$ CRes, radiative energy losses (synchrotron and IC CMB) are negligible! Heating and ionisation losses dominate
- **A major lack of theoretical understanding: concordance models are ruled out**

Ponnada et al. (2024)



Synchrotron radiation arises primarily from:

CNM/WNM

CNM/WNM

WNM/WIM

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<https://doi.org/10.1093/mnras/stac2909>

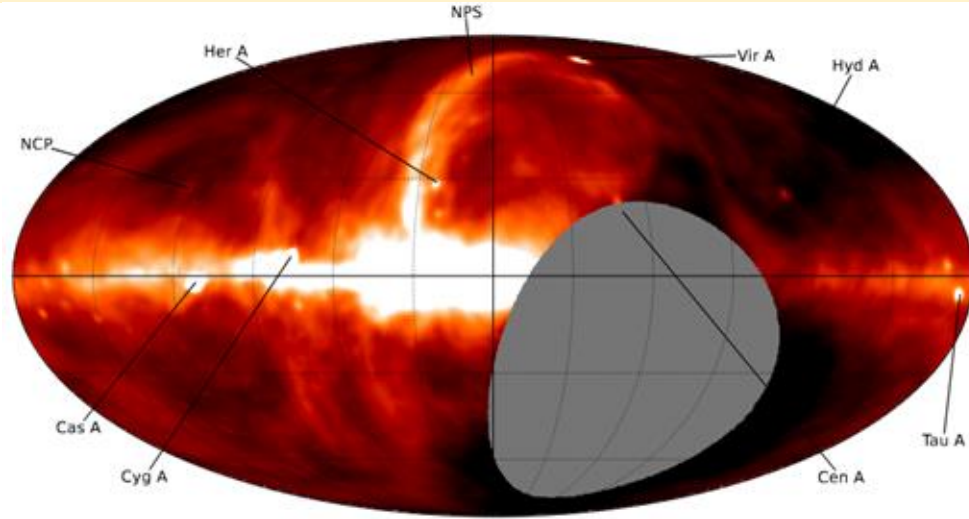
Standard self-confinement and extrinsic turbulence models for cosmic ray transport are fundamentally incompatible with observations

Philip F. Hopkins^{1, *} Jonathan Squire^{2, *} Iryna S. Butsky¹ and Suoqing Ji¹

CR electron energy drives required measurement frequency

Synchrotron critical frequency:

$$\nu_c = \frac{3\gamma^2 e B \langle \sin \alpha \rangle}{4\pi m_e c}$$



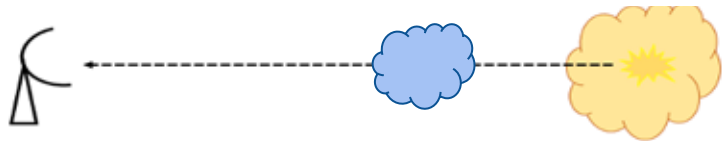
LWA1 74 MHz map Dowel+2017

$$\nu_c \approx 3.3 \text{ Hz} \times \gamma^2 \left(\frac{B}{1 \mu\text{G}} \right) \xrightarrow{B=3 \mu\text{G}} 0.1 \text{ MHz} \left(\frac{\gamma}{100} \right)^2.$$

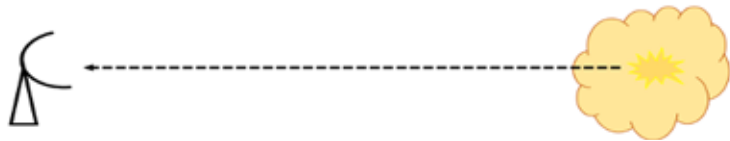
$\gamma = 10^2\text{--}10^3$ electrons require 0.1–10 MHz radio frequencies

Low-frequency spectral turnovers

A. Thermal free–free absorption by foreground



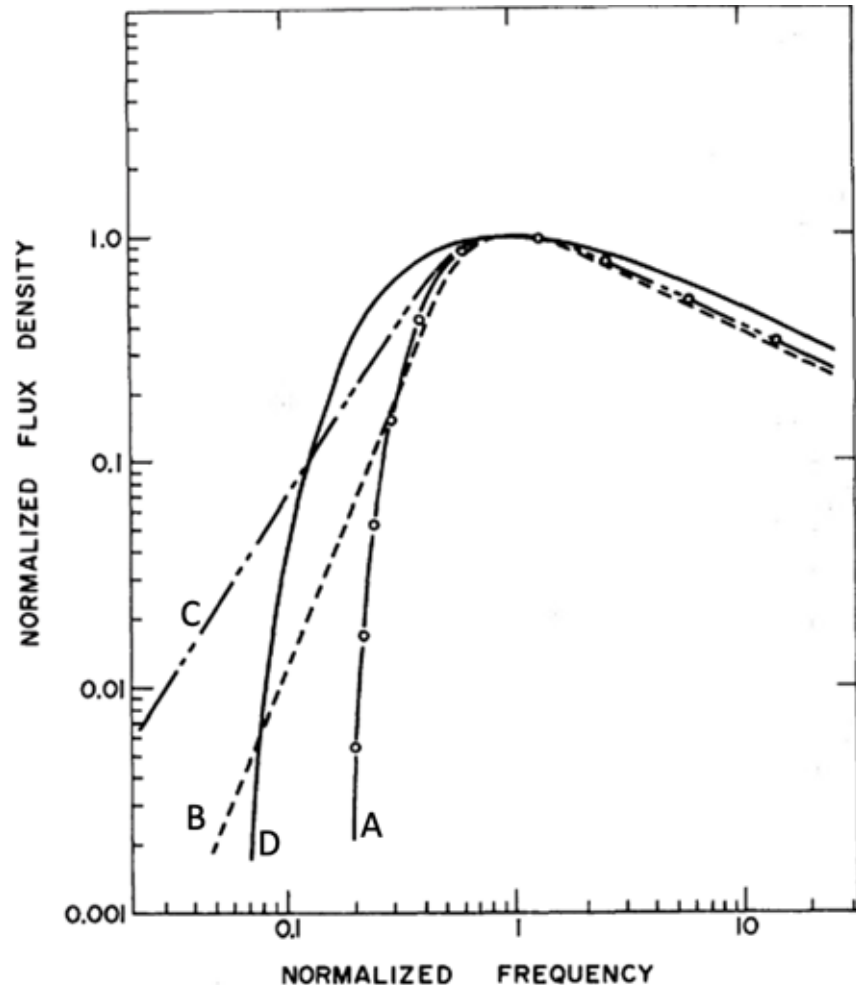
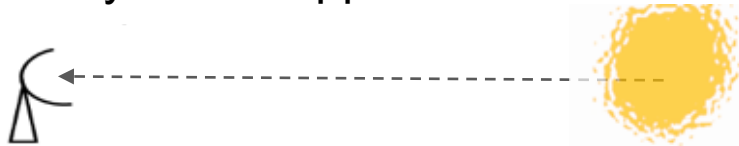
B. Synchrotron self-absorption



C. Thermal absorbers homogeneously mixed



D. Razin–Tsyтовich suppression



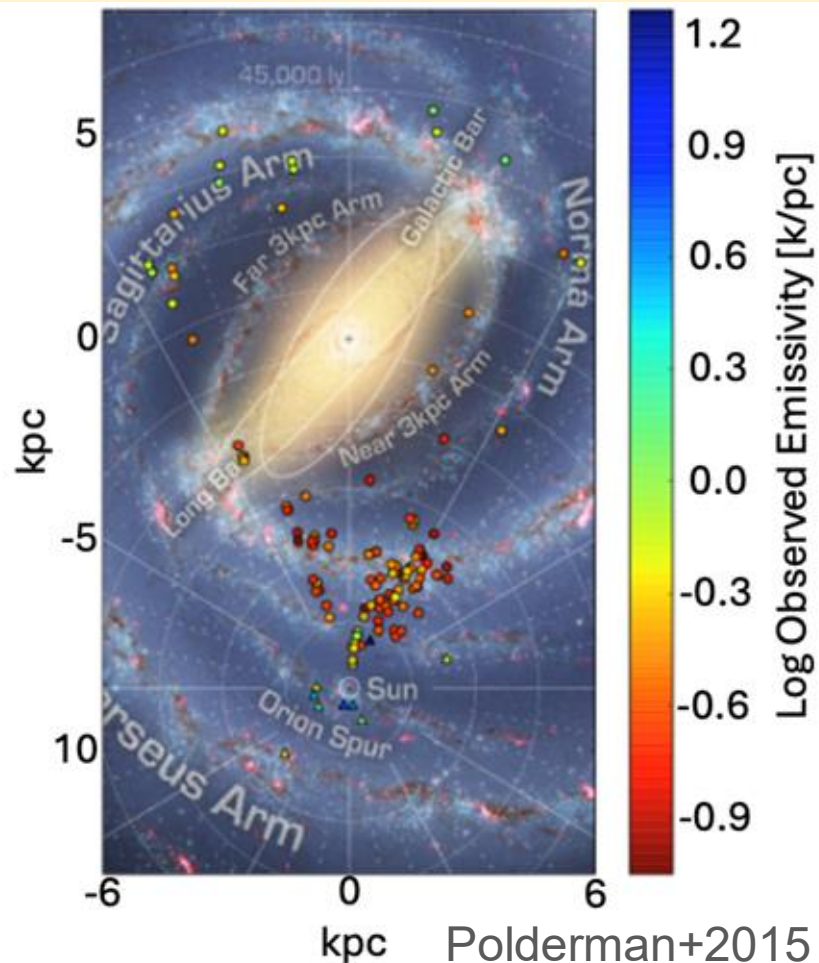
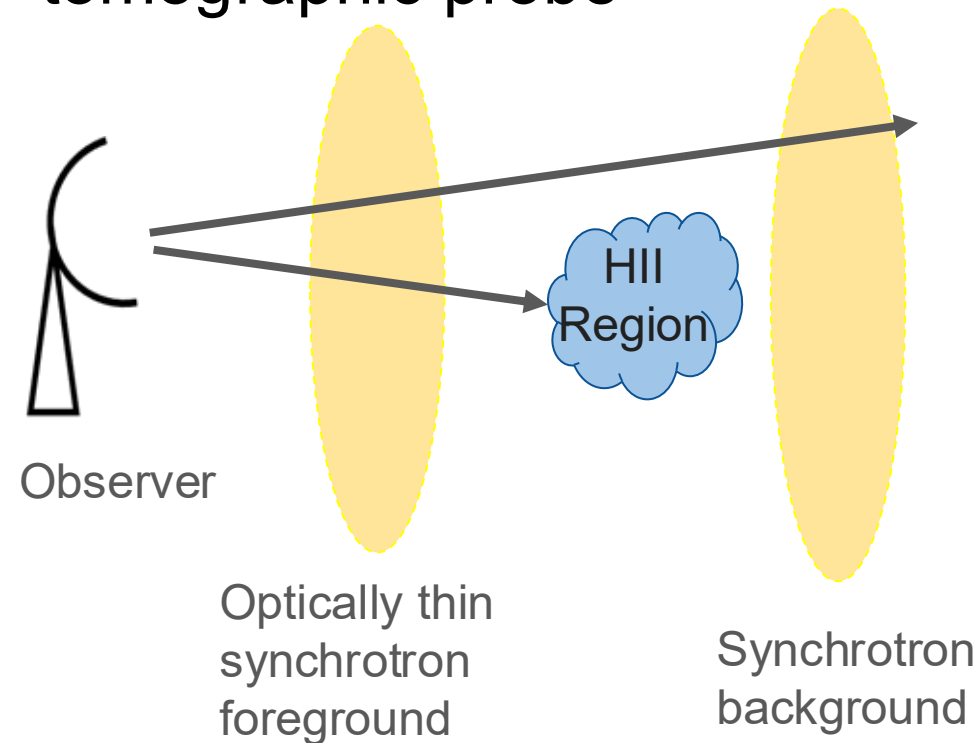
Gregory and Seaquist 1974

Addressing the science questions by observing 0.1–10 MHz spectral features

Science Question (slide 4)	Physical parameter	Observable	Radiative process
1	Spectral index of CRe energy	Optically thin spectral index	Synchrotron emission
2	CRe energy density/(B field strength)	Synchrotron intensity	Synchrotron emission
3, 6	Electron temperature and density	Optical depth	Free–free absorption
3	Electron temperature	Brightness temperature	Optically thick free–free emission
4, 5, 6	(electron density)/(B field strength)	Cutoff frequency	Razin suppression

Mapping cosmic ray electrons in 3D:

Free-free absorption as a
tomographic probe



HII Regions Viewed in Absorption

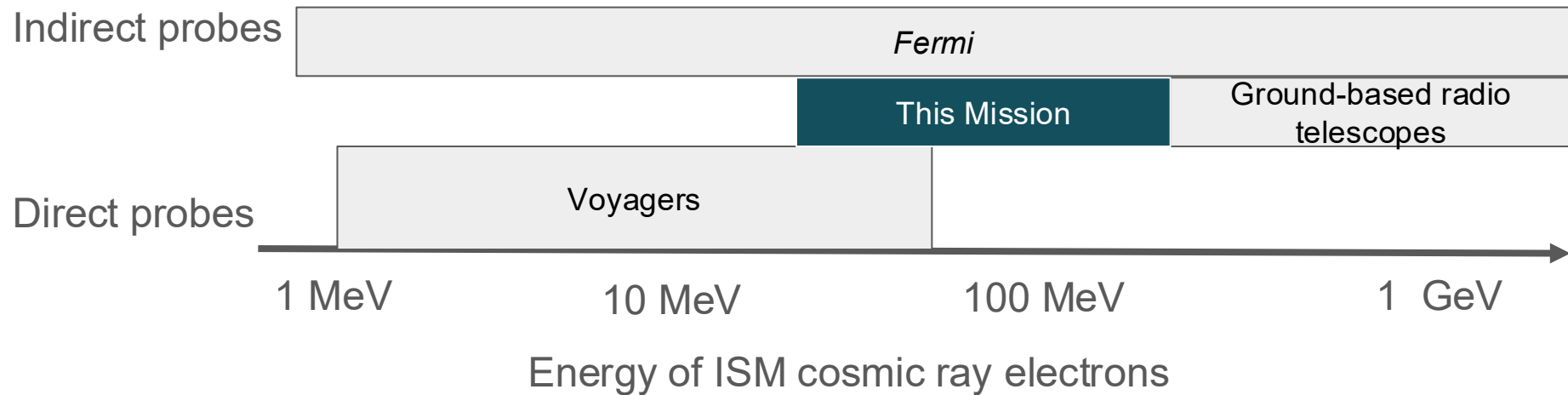
~70–230 MHz MWA GLEAM multi-frequency image of Galactic Plane, Hurley-Walker et al.



Free-free absorption

Lower frequencies → More sight lines probed

Complementary measurements of cosmic ray electrons



Conclusions

- Major questions in a range of astrophysical disciplines, including plasma physics, star formation, ISM structure, galaxy evolution, and cosmology, linked to **the unexplored CRe population with Lorentz factors $\gamma = 10^2 - 10^3$ in microgauss-scale fields**, remain open
- Theoretical tensions and the maturation of astrophysical simulations with CRs suggest **the time is ripe for next-generation observational capability**
- These CRes generate synchrotron emission predominantly in **the 0.1–10 MHz band, one of the last untouched EM windows in astronomy**
- Given Earth's 10 MHz ionospheric cutoff, **we should build a radio interferometer on the RFI-shielded Lunar farside**, that also studies the Dark Ages and magnetised exoplanets!

Magnetic field strengths in giant molecular clouds: UltraFar–*Fermi* synergy

- Although magnetic field strengths B in GMCs are important in star formation, measurements are scarce and method-dependent
- CR proton–ISM proton collisions produce radio synchrotron emission from secondary electrons (through charged pion decay) as well as gamma-rays (through neutral pion decay)
- Thus, by combining UltraFar with (e.g.) *Fermi* and gas column density data, B can be inferred

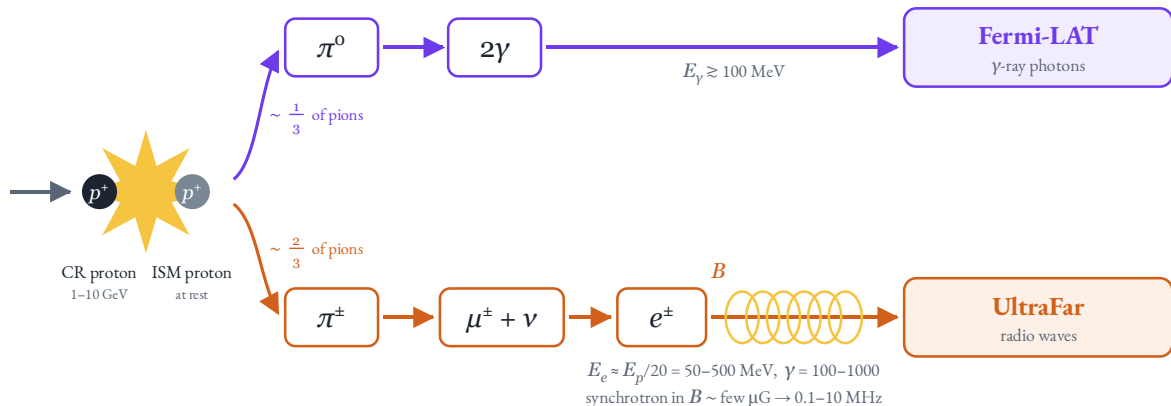


One CR proton population, two EM messengers

Both channels are fed by the same $\sim 1\text{--}10$ GeV proton population.

Each collision yields many pions; isospin symmetry gives $\pi^0 : \pi^+ : \pi^- \sim 1 : 1 : 1$. In addition, given baryon number conservation, two nucleons emerge.

- May work for several individual, nearby GMCs: Cepheus, Chamaeleon, Orion, and Taurus
- *Fermi*-derived CR proton density estimates already exist: half the work's done
- UltraFar's CR proton bands are thus: $1\text{--}100$ MeV (through primary CRes), $1\text{--}10$ GeV (through secondary CRes)



Summary of new capabilities needed:

Recap science objectives and observing capabilities

Frequency range, angular resolution, advantages of large angular scale and absolute calibration

Why observe from space? Must be above ionosphere