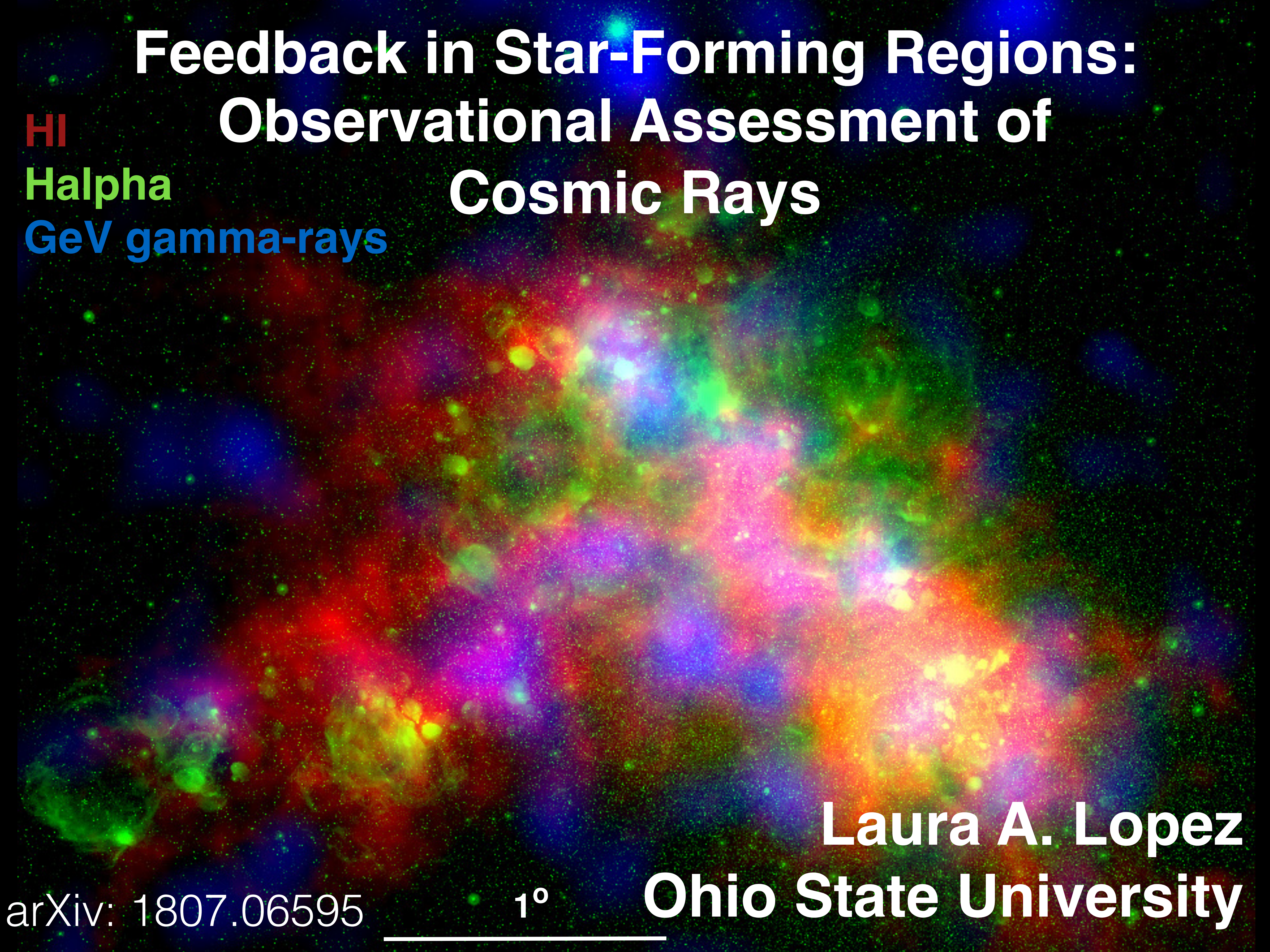
Feedback in Star-Forming Regions: Observational Assessment of Cosmic Rays



Laura A. Lopez
Ohio State University

arXiv: 1807.06595

In the Feedback Loop - Small Scales

Stellar feedback: the injection of energy & momentum by stars

Radiation Pressure (direct and dust-processed)

Jijina+96, Krumholz+09, Fall+10, Krumholz+10, Draine+11, Murray+11, Skinner+15, Gupta+16, Kim+16, Raskutti+16, Rodriguez-Ramirez+16, Rahner+17, Raskutti+17, Ali+18, Kim+18, Tsang+18

Photoionization Heating

Whitworth79, Dale+05, Dale+14, Geen+16, Gavagnin+17, Ali+18, Haid+18, Kim+18, Kuiper+18, Shima+18

Stellar Winds

Yorke+89, Harper-Clark+09, Rogers+13, Dale+14, Goldsmith+17, Rahner+17, Haid+18, Naiman+18, Wareing+18

Supernovae

Rogers+13, Kim+15, Martizzi+15, Walch+15, Geen+16, Haid+16, Kortgen+16, Gentry+17, Zhang+18

Cosmic Rays

Protostellar Jets

Quillen+05, Cunningham+06, Li+06, Matzner07, Nakamura+08, Cunningham+09, Wang+10, Offner+14, Matzner+15, Bally16

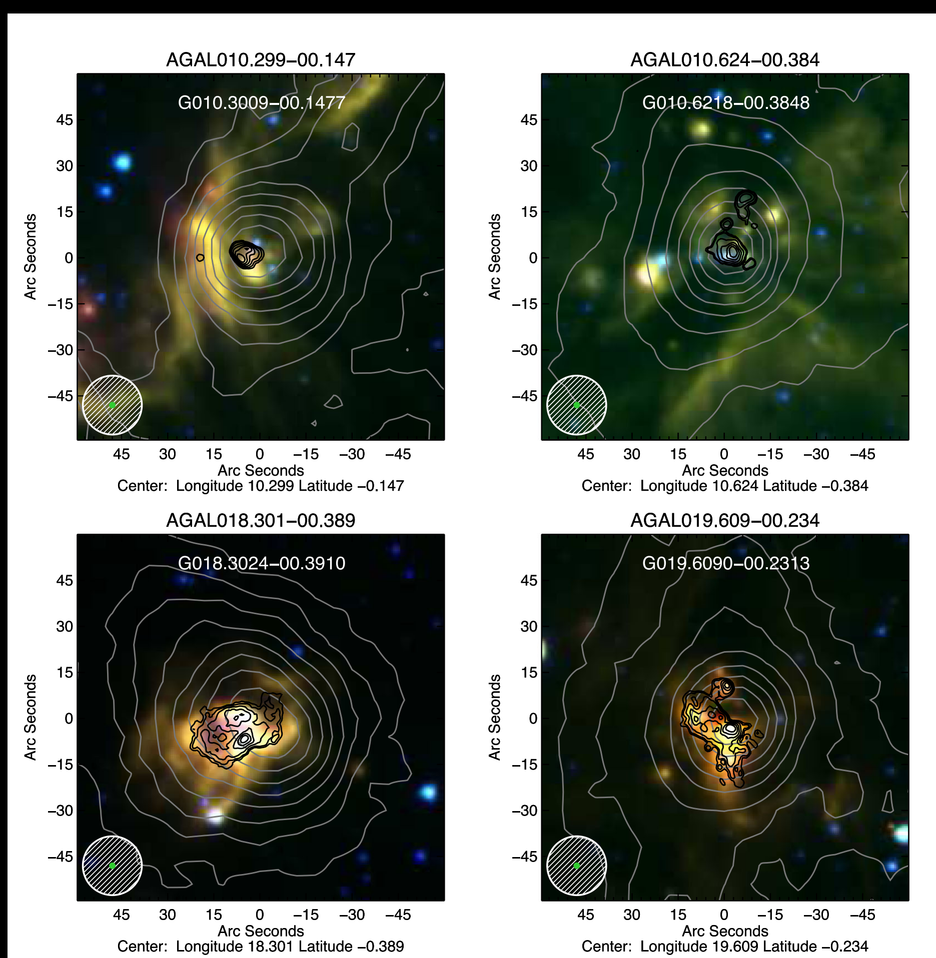
OSU Grad Student,
Grace Olivier

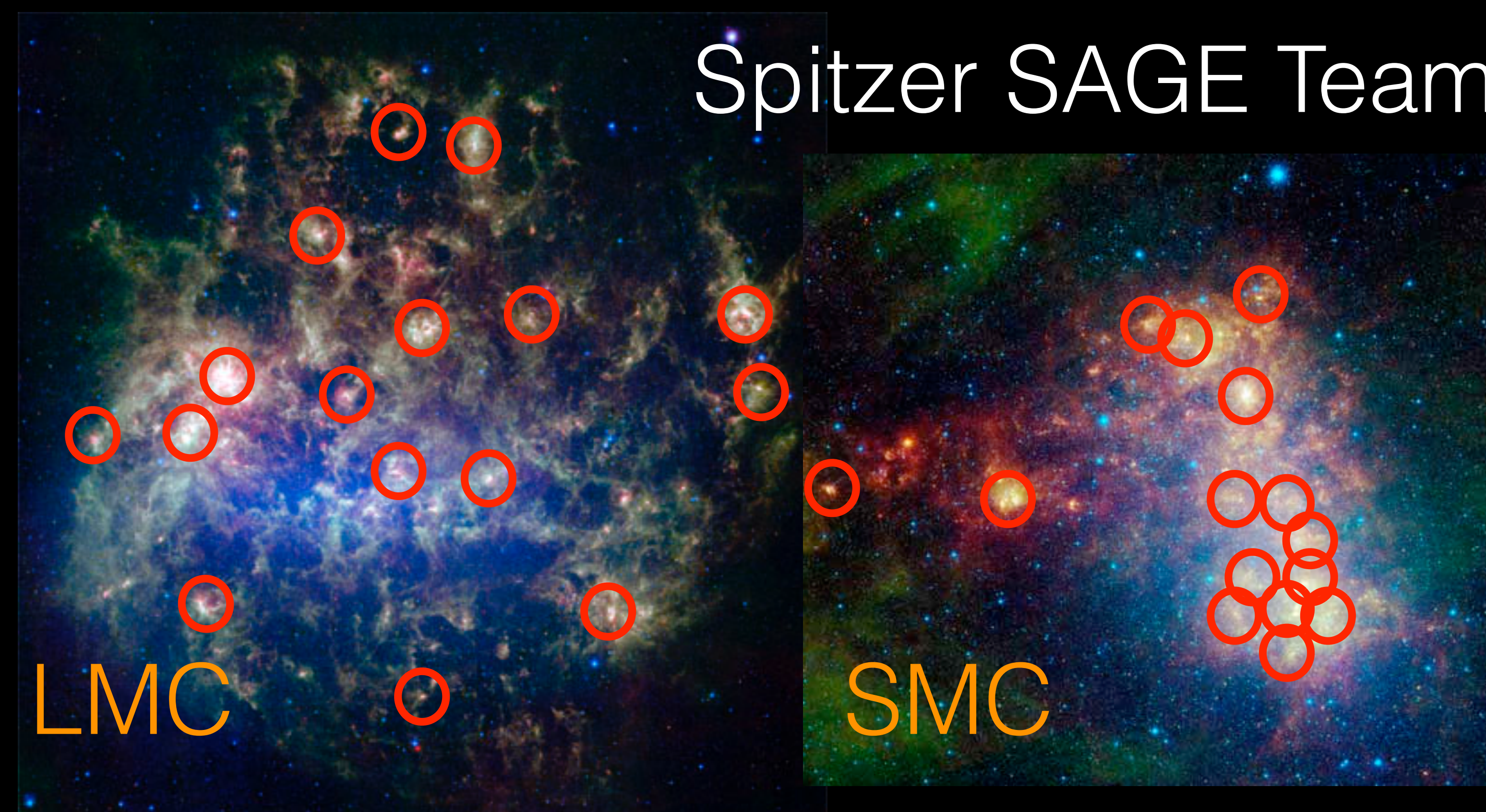
Sample

Ultra-compact HII Regions in the Milky Way

Large HII Regions in the Magellanic Clouds

Urquhart+13





LL+14

R < 0.1 pc
$n > 10^4$ cm^{-3}

R ~ 3-200 pc
$n \sim 1$ cm^{-3}

Measuring Feedback Observationally

Pressure Source	Direct Radiation from stars	Dust-Processed Radiation	Warm HII Gas	Hot Shocked Gas
Relation	$P_{dir} = u_{\nu} = \frac{L_{bol}}{4\pi r^2 c}$	$P_{IR} = \frac{\tau_{IR} L}{4\pi r^2 c}$	$P_{HII} = 2\, n_e\, kT_{HII}$	$P_x = 2\, n_x\, kT_x$
Methods	UBV photometry or radio free-free emission $\rightarrow L_{bol}$	IR SED modeling $\rightarrow \tau_{IR}$	Obtain n_e using flux density of free-free emission	X-ray spectral modeling of bremsstrahlung
Data	Optical or Radio	Infrared	Radio	X-ray

Importance of Cosmic Rays

From Karen Yang's talk:

1. CRs can drive galactic winds

    -No transport, no wind
    -Mass loading depends on transport

2. CRs can suppress star formation

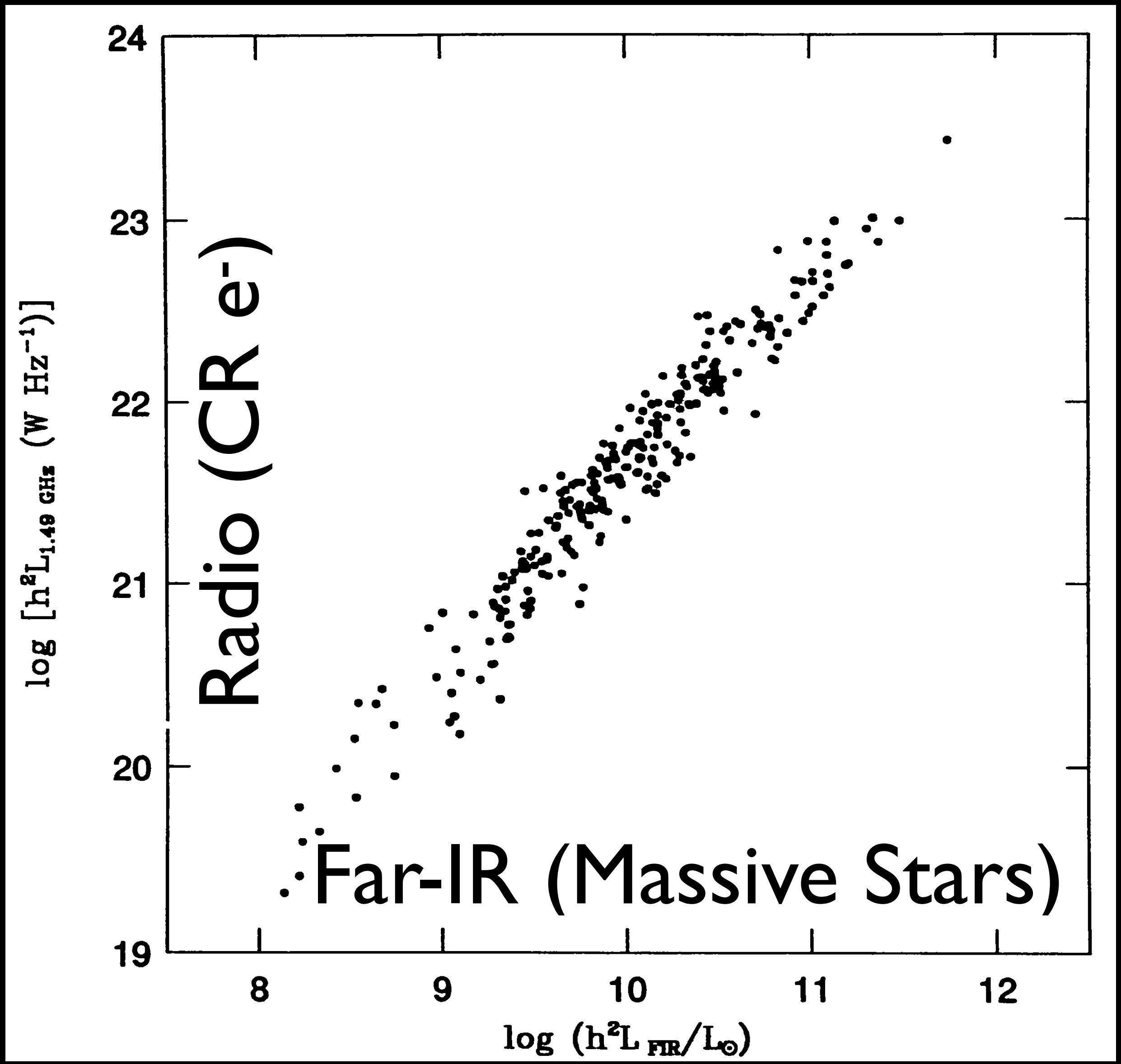
3. CRs can affect wind properties: CR winds are cooler, multiphase, accelerated more gently

4. CRs can affect CGM properties: CGM is cooler and metal-enriched

References: Ipavich75, Breitschwerdt+91, Zirakashvili+96, Ptuskin+97, Everett+08, Jubelgas+08, Socrates+08, Everett+10, Samui+10, Wadepuhl+11, Dorfi+12, Uhlig+12, Booth+13, Hanasz+13, Salem+14, Girichidis+16, Liang+16, Pakmor+16, Ruszkowski+16, Simpson+16, Pfrommer+17a,b, Recchia+17, Ruszkowski+17, Wiener+17, Butsky+18, Farber+18, Girichidis+18, Heintz+18, Holguin+18, Jacob+18, Mao+18, Samui+18

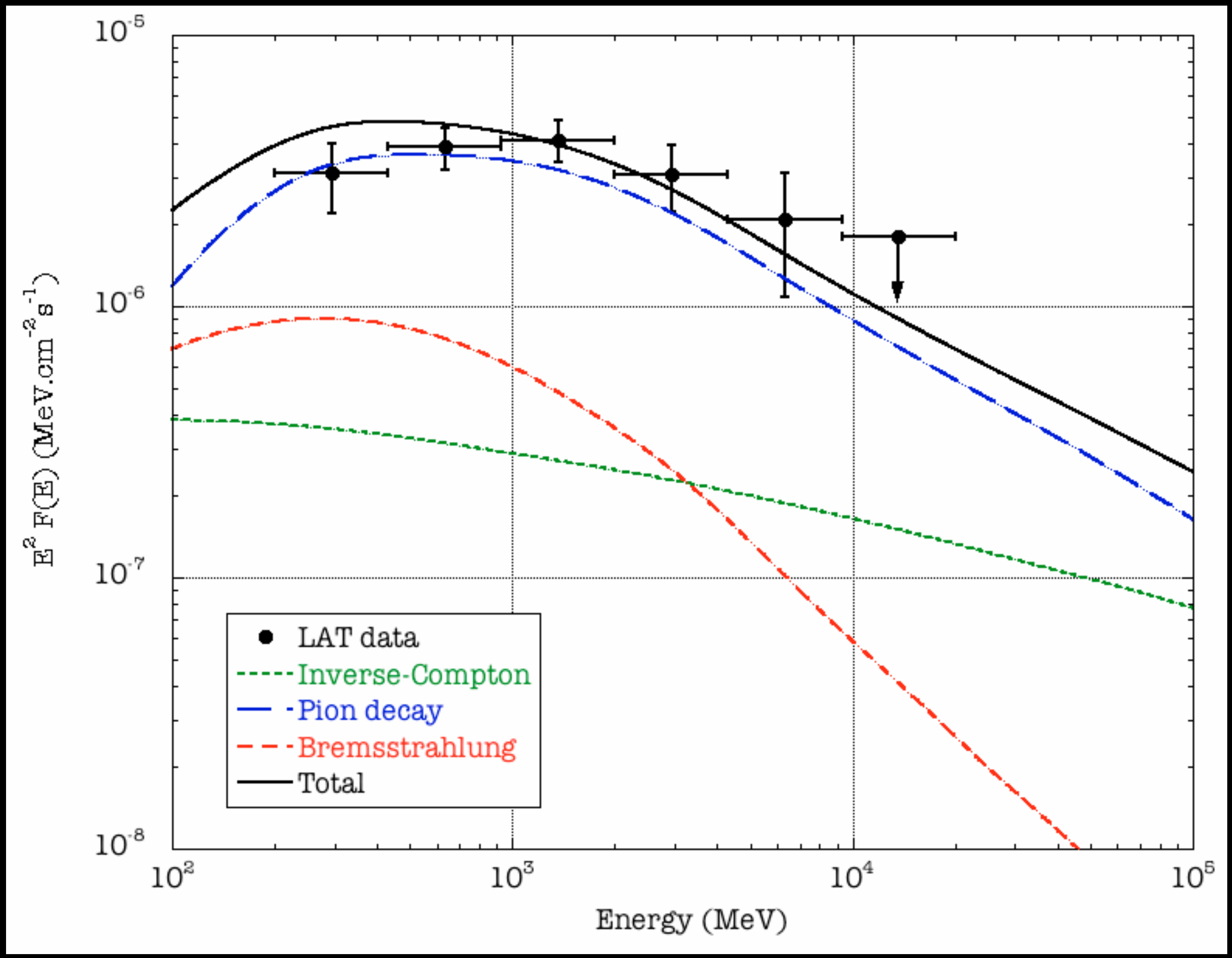
Observing Cosmic Rays

<u>CR Electrons</u>:
Radio, X-rays, Gamma-rays



Condon+92

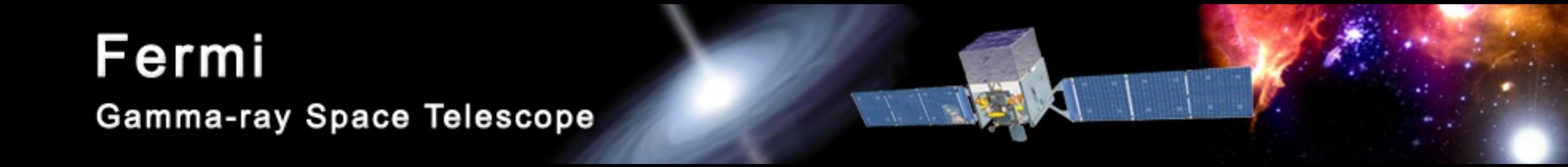
<u>CR Protons</u>:
Gamma-rays



Abdo+10

Note 1: Most extragalactic CR constraints come from radio

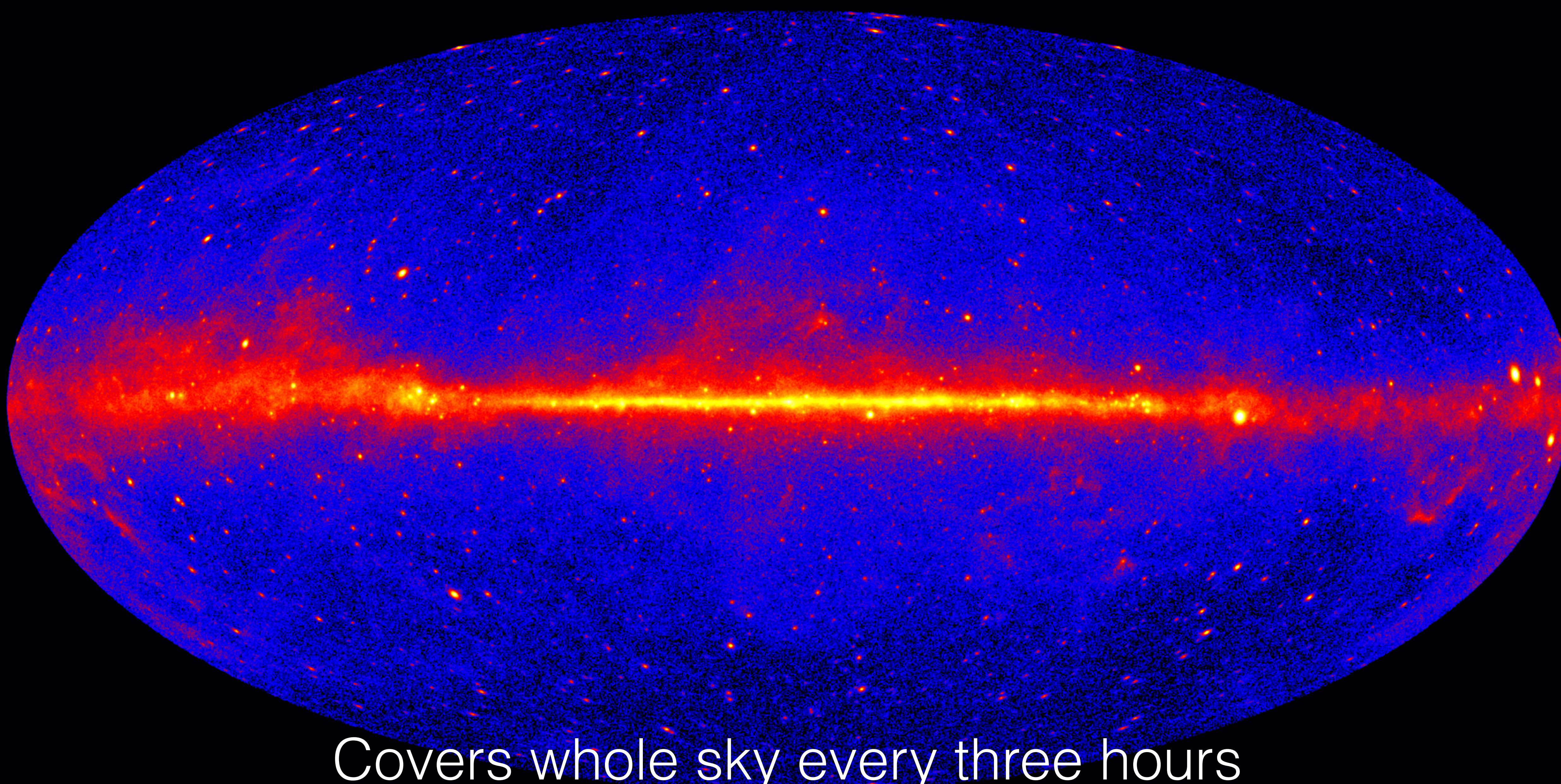
Note 2: CR protons are 99% of CR population



Launched June 11, 2008

Two instruments:

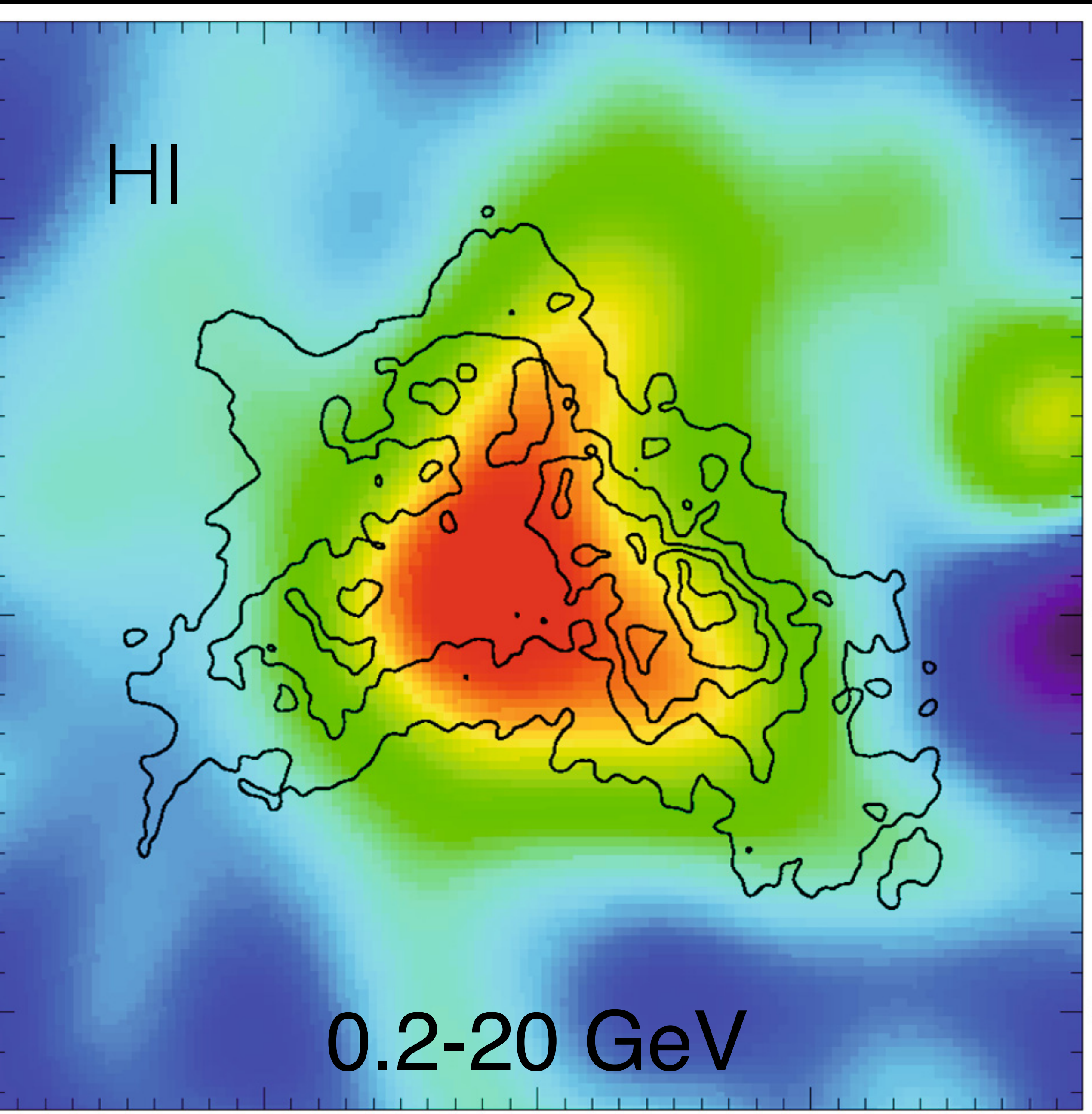
- Large Area Telescope (LAT): 20 MeV-300 GeV
- Gamma-ray Burst Monitor (GBM): 10 keV-25 MeV



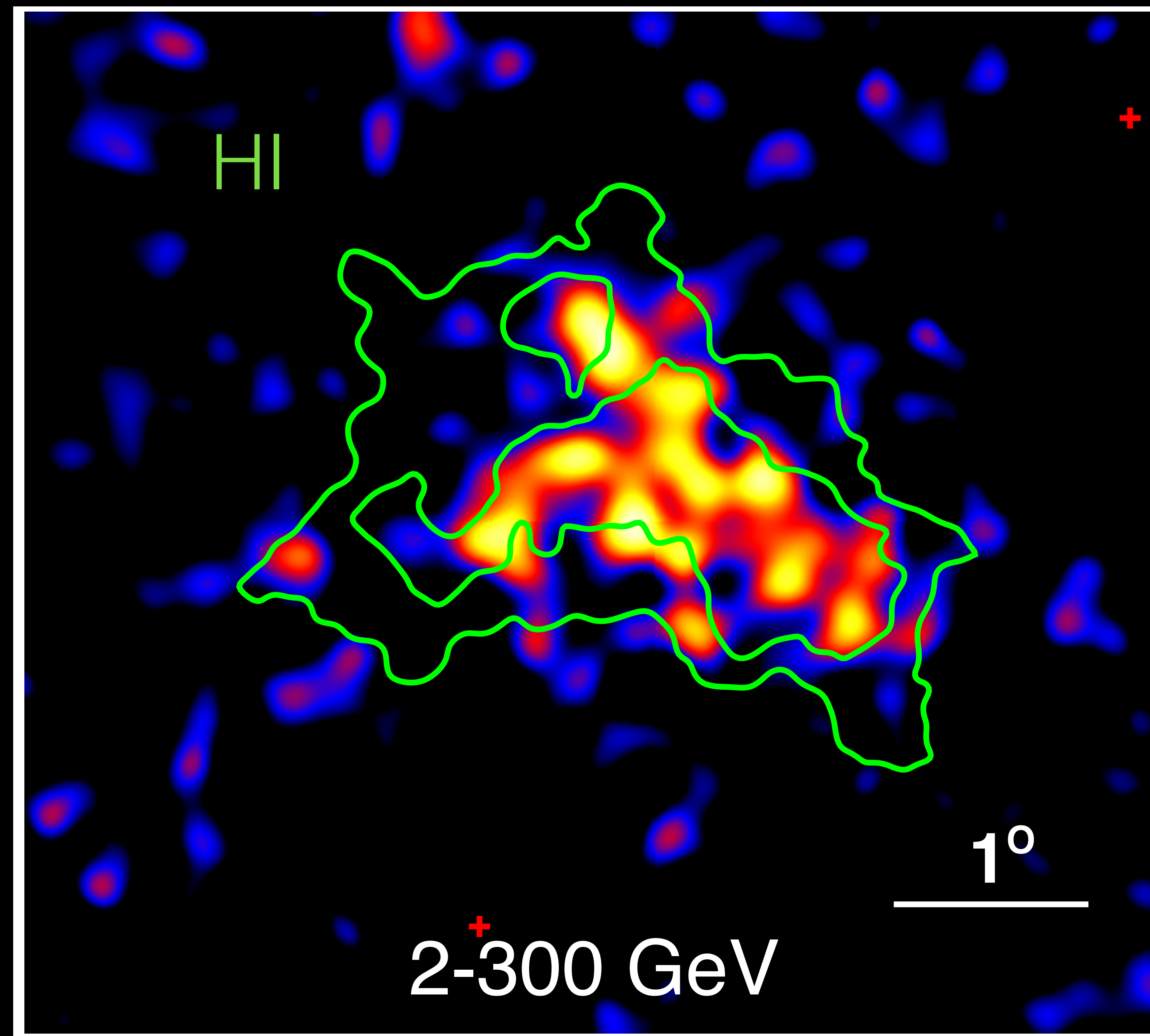
Covers whole sky every three hours

Localizing Gamma-Rays in SMC

17 months of data



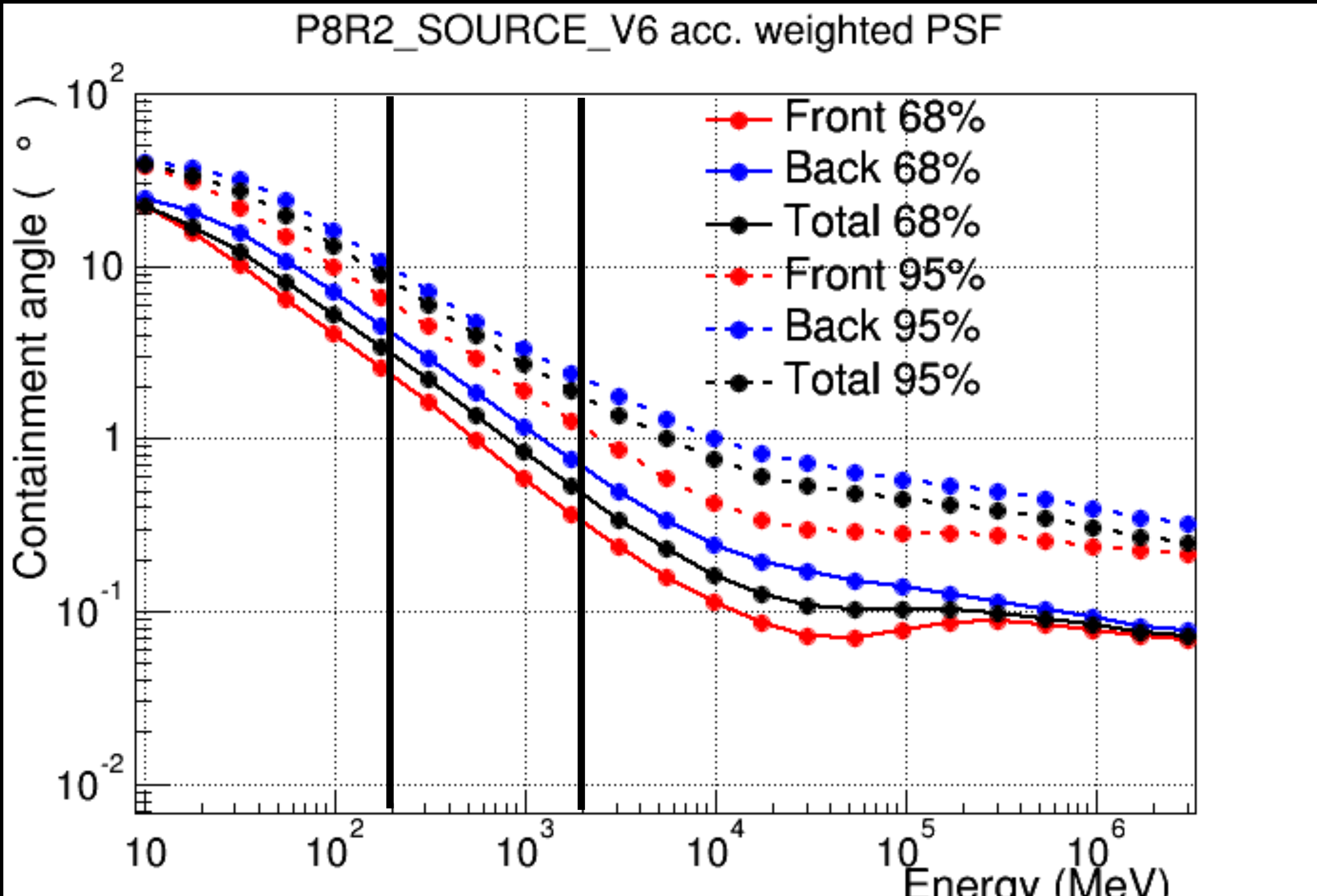
105 months of data



Abdo+10a

LL+18a

Better maps because 1) use more data and 2) use only >2 GeV gamma-rays (10x better spatial resolution)

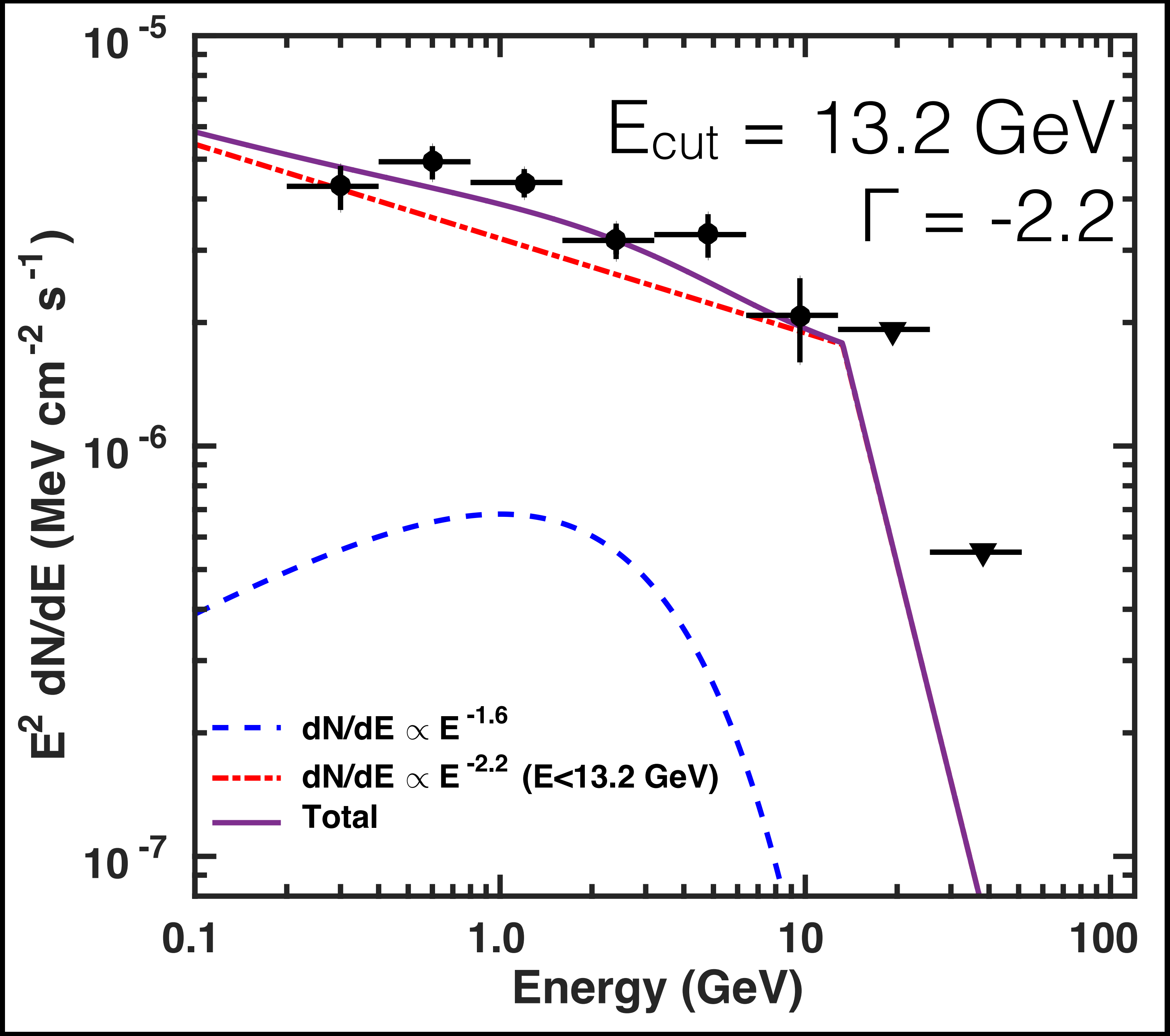


https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

GeV Gamma-Ray Spectrum of the SMC

Gamma-ray emissivity is ~5x less than Milky Way, implying 5x lower density of CR nuclei.

Could result from either a lower CR injection rate per unit star-forming volume or from a smaller CR confinement length.



LL+18a

See also: Maria Haupt’s poster

SMC is Far Below the Calorimetric Limit

Starbursting galaxies are CR proton "calorimeters": all CR protons experience pion losses (Thompson+07; Socrates+08; Lacki+11; Ackermann+12, Pfrommer+17)

$$f_{cal} = L_\gamma / L_\gamma^{max}$$

$$L_\gamma^{max} = 1/3\, \dot{E}_{CR} = 1/3\, \eta\, E_{SN}\, \Gamma_{SN}$$

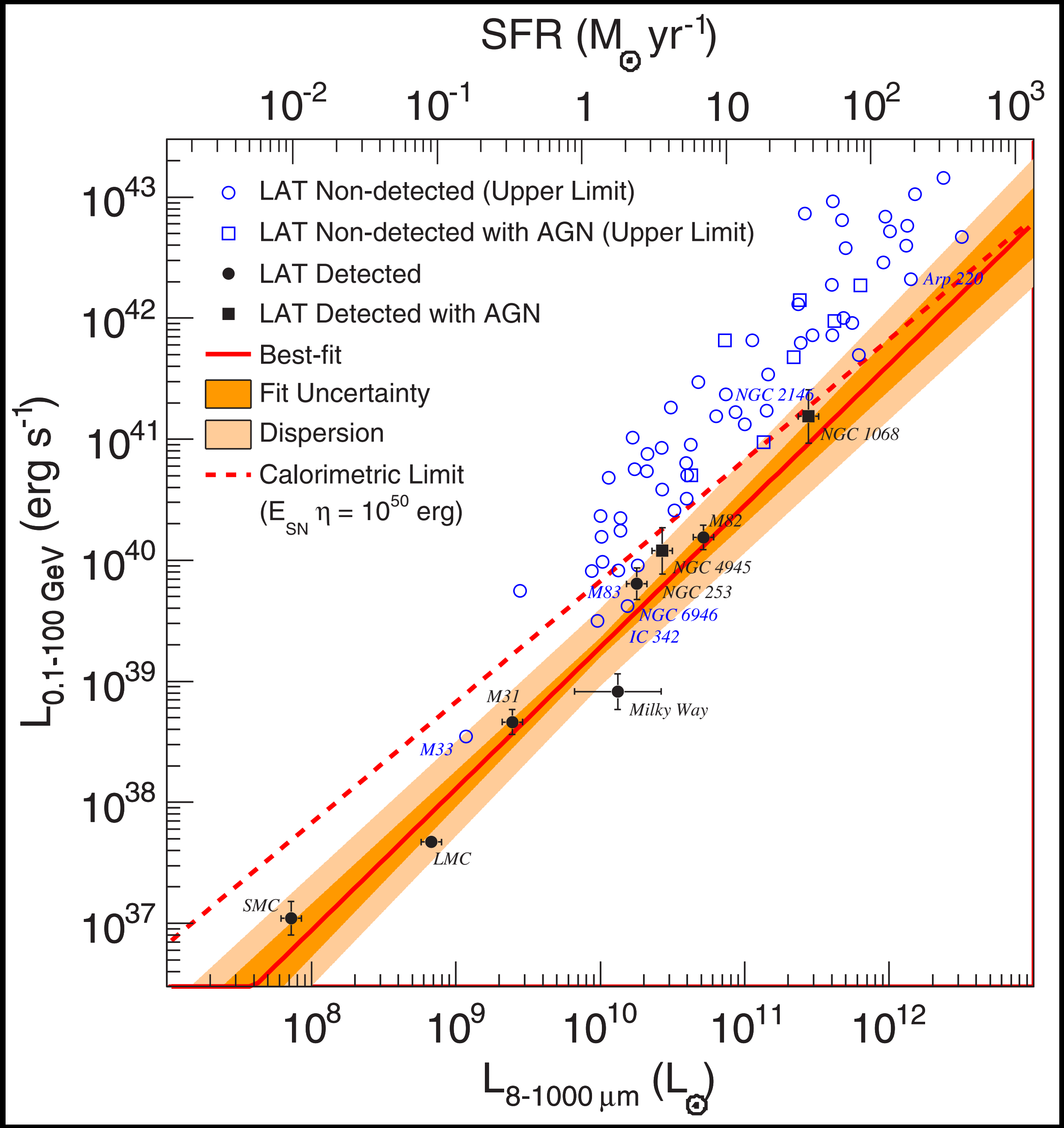
η : fraction of SN kinetic energy into CRs

E_{SN} : SN kinetic energy

Γ_{SN} : SN rate

SMC is are far below calorimetric limit (Lopez+18a):

- Milky Way: 3.3%
- SMC: 0.7%
- LMC: 1.5%



Ackermann+12

Constraints on CR Transport from Gamma-Rays

CR injection produces a power-law distribution: $\Gamma \sim -2$ to -2.4

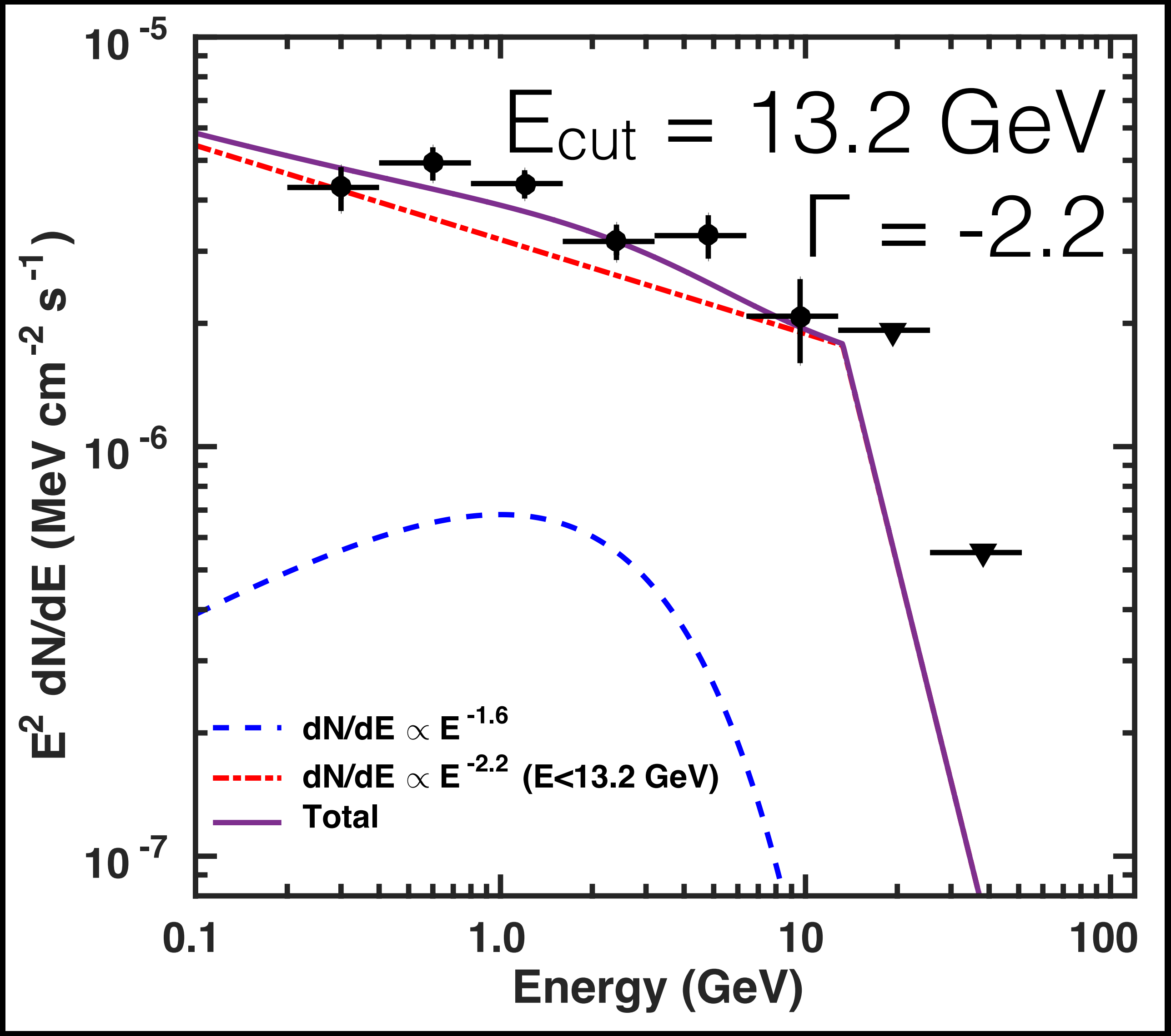
CR Proton Loss/Escape Process	Gamma-ray spectral index Γ	Gamma-ray luminosity L_γ
Pionic losses	-2 to -2.4	$\sim L_\gamma^{max}$
Advection	-2 to -2.4	$< L_\gamma^{max}$
Diffusion	-2.5 to -2.9	$<< L_\gamma^{max}$

Below 13 GeV

Above 13 GeV

Constraints on CR Transport from Gamma-Rays

E_{cut} gives constraint on confinement length or diffusion coefficient, since $t_{diff} \sim l_{conf}^2 / D_0 \sim 45\ (E_{CR}/1\ \mathrm{GeV})^{-1/2}$ Myr



E.g., adopting E_{CR} = 130 GeV and assuming $D_0 = 5\times10^{28}$ cm^2 s^{-1}, $l_{conf} \sim 800$ pc

Setting $t_{diff} \sim t_{adv} \sim 10\ (h/1\ \mathrm{kpc})\ (v_{wind}/100\ \mathrm{km\ s^{-1}})^{-1}$ Myr gives constraint on wind velocity:

For h = 1 kpc, $v_{wind} \sim 250$ km s^{-1}

For h = 0.5 kpc, $v_{wind} \sim 125$ km s^{-1}

CR Proton Lifetimes

What produces the cutoff in the GeV spectrum of the SMC?…

A different way to put it: what sets the residence time of CR protons?

It is the shortest of three timescales:

Pion loss timescale: $t_\pi \approx 100(\frac{n_{\rm eff}}{0.5\ {\rm cm}^{-3}})^{-1}\ {\rm Myr}$

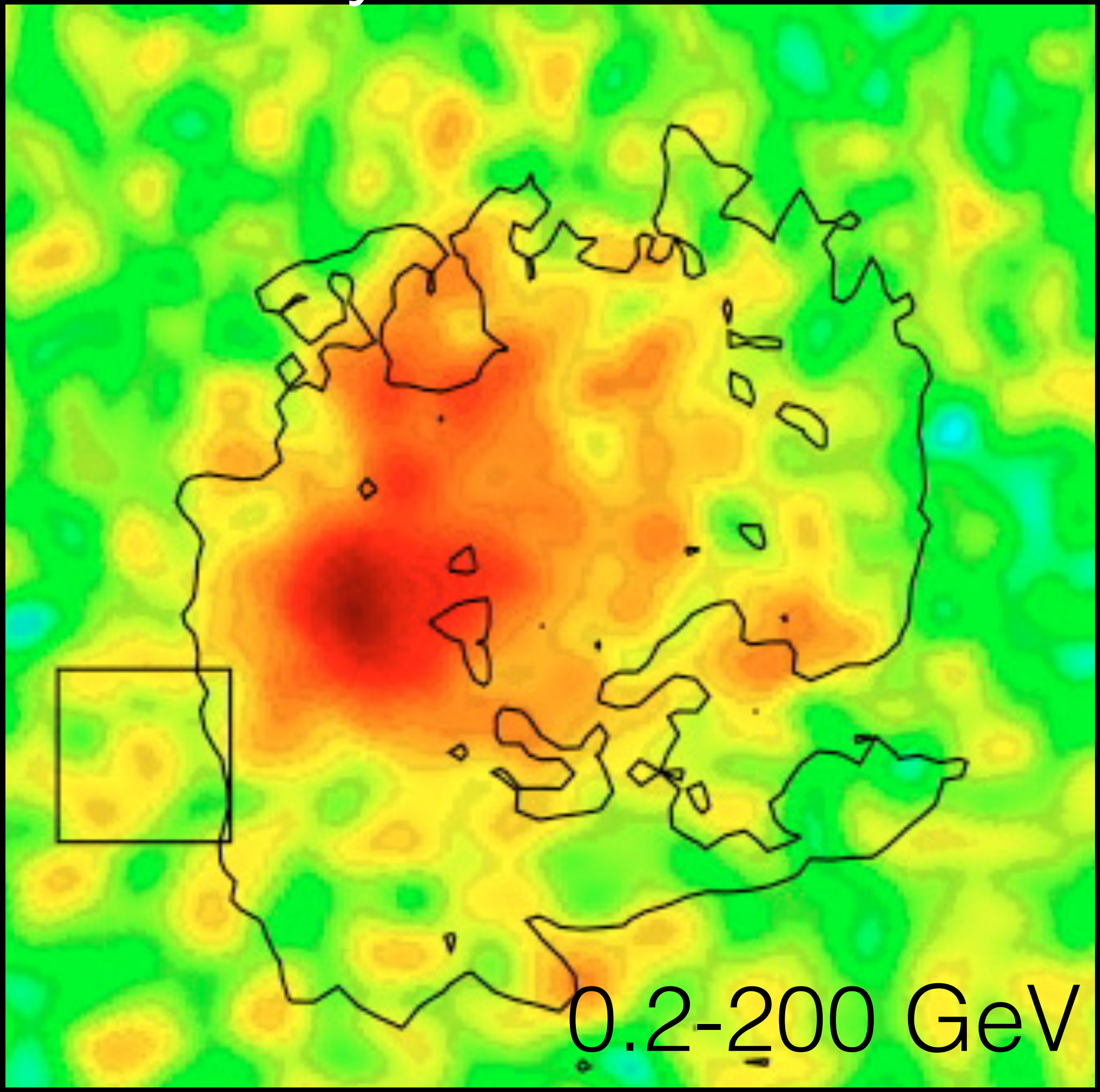
Diffusion timescale: $t_{\rm diff} \approx 45(\frac{E_{\rm CR}}{1\ {\rm GeV}})^{-1/2}\ {\rm Myr}$

Advection timescale:

$$t_{\rm adv} = h/v_{\rm wind} \approx 10(\frac{h}{1\ {\rm kpc}})(\frac{v_{\rm wind}}{100\ {\rm km\ s}^{-1}})^{-1}\ {\rm Myr}$$

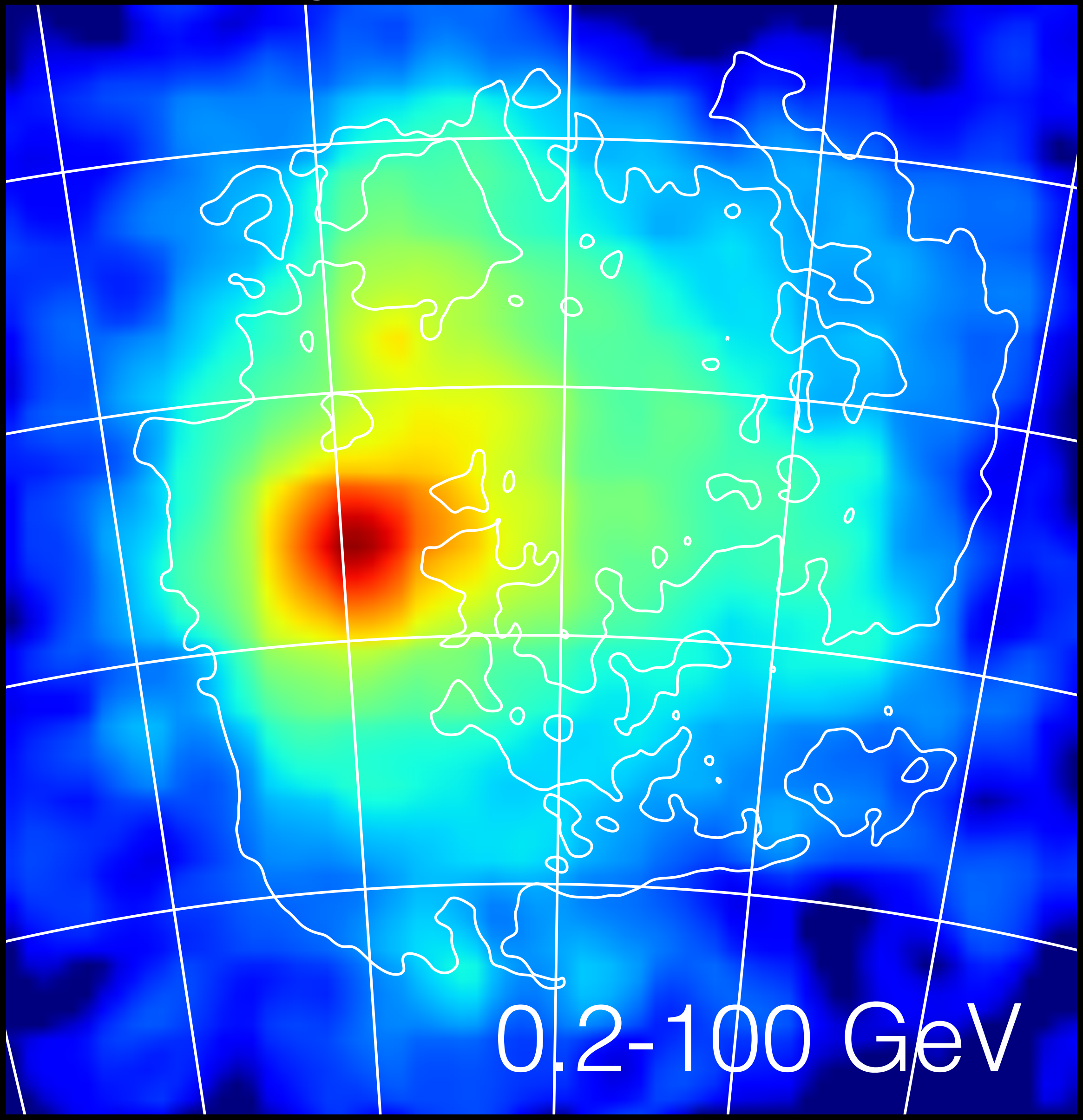
Localizing Gamma-Rays in LMC

1 year of data



Abdo et al. 2010b

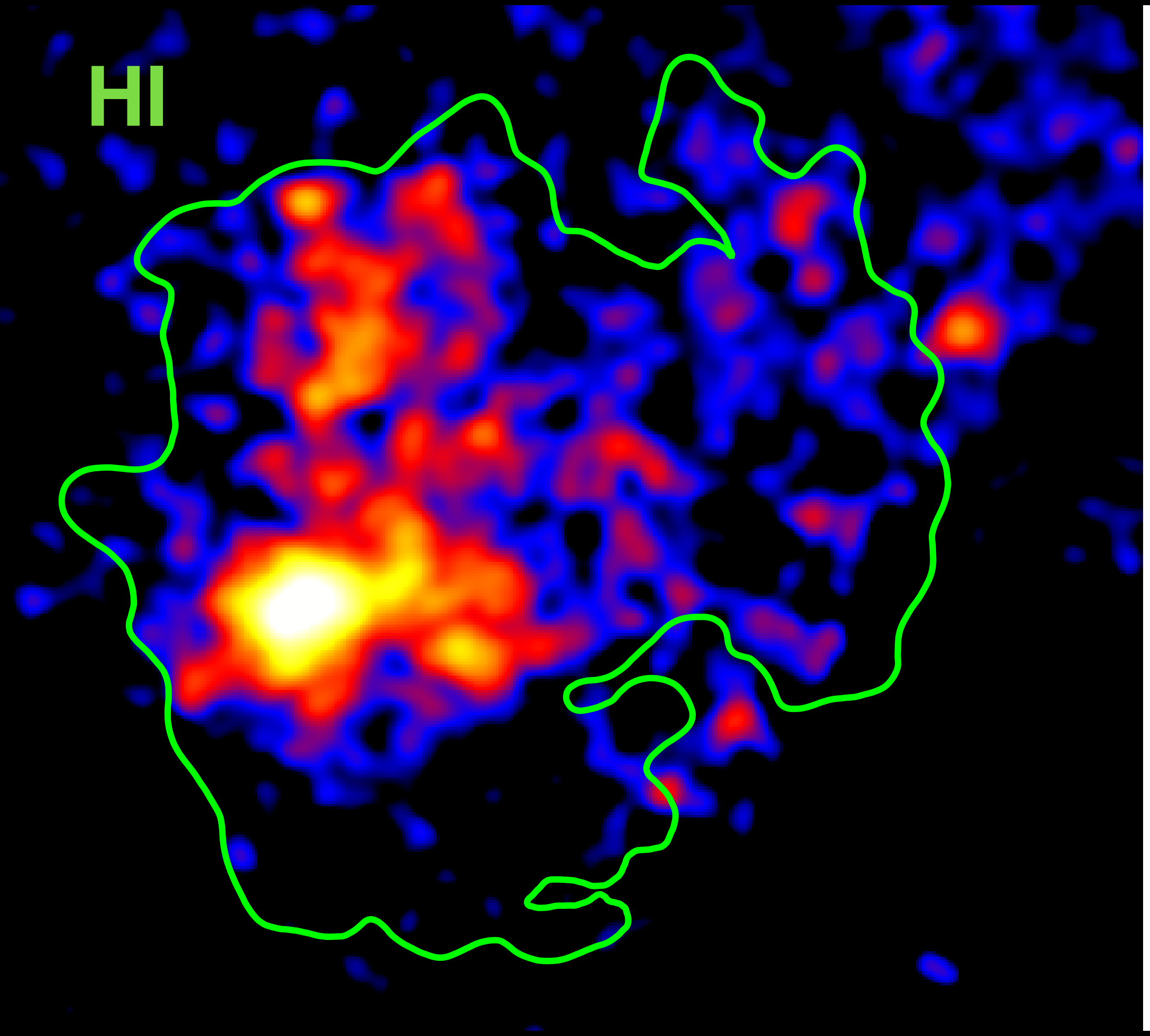
6 years of data

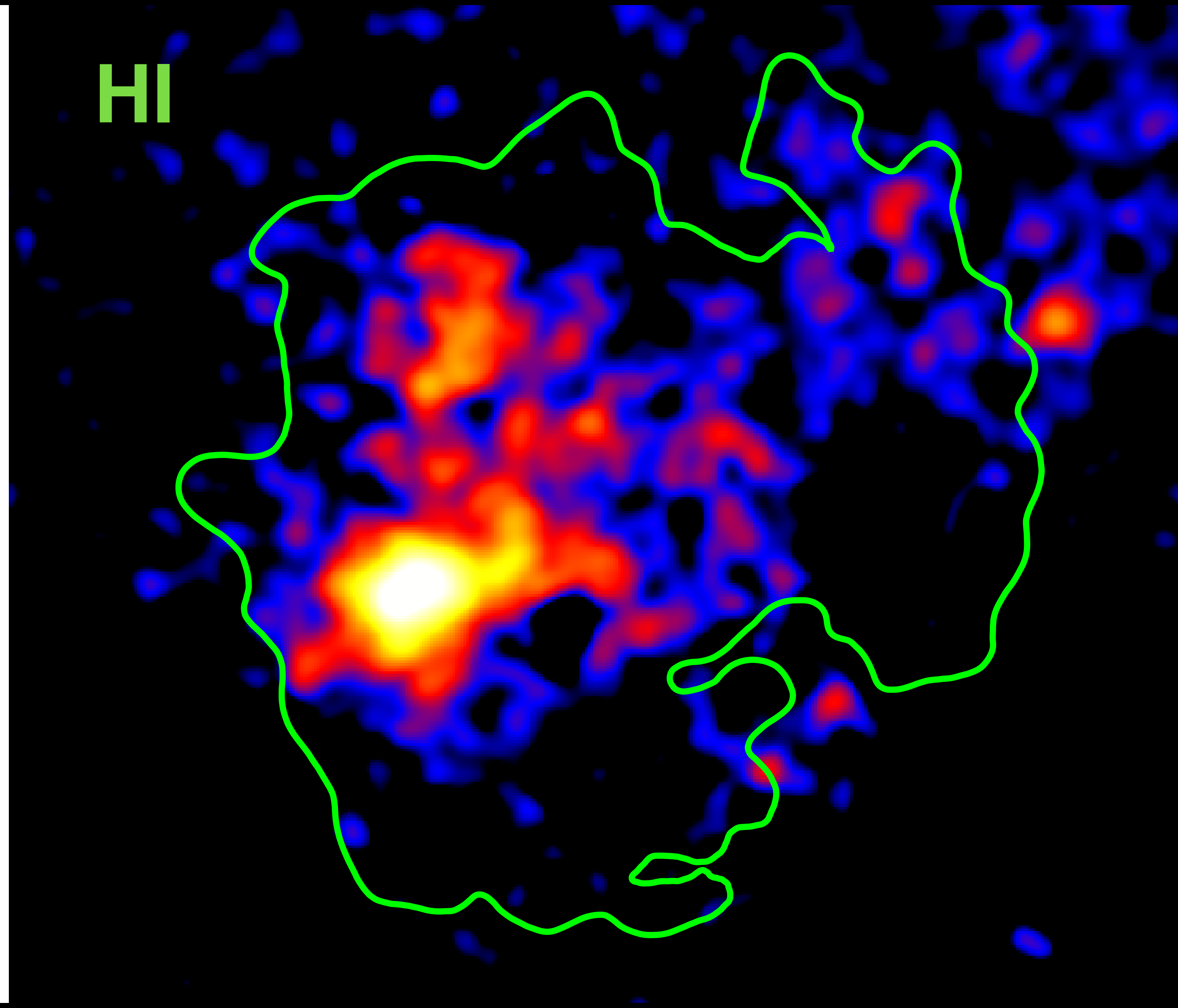


Ackermann et al. 2016

Localizing Gamma-Rays in LMC

10 years of data



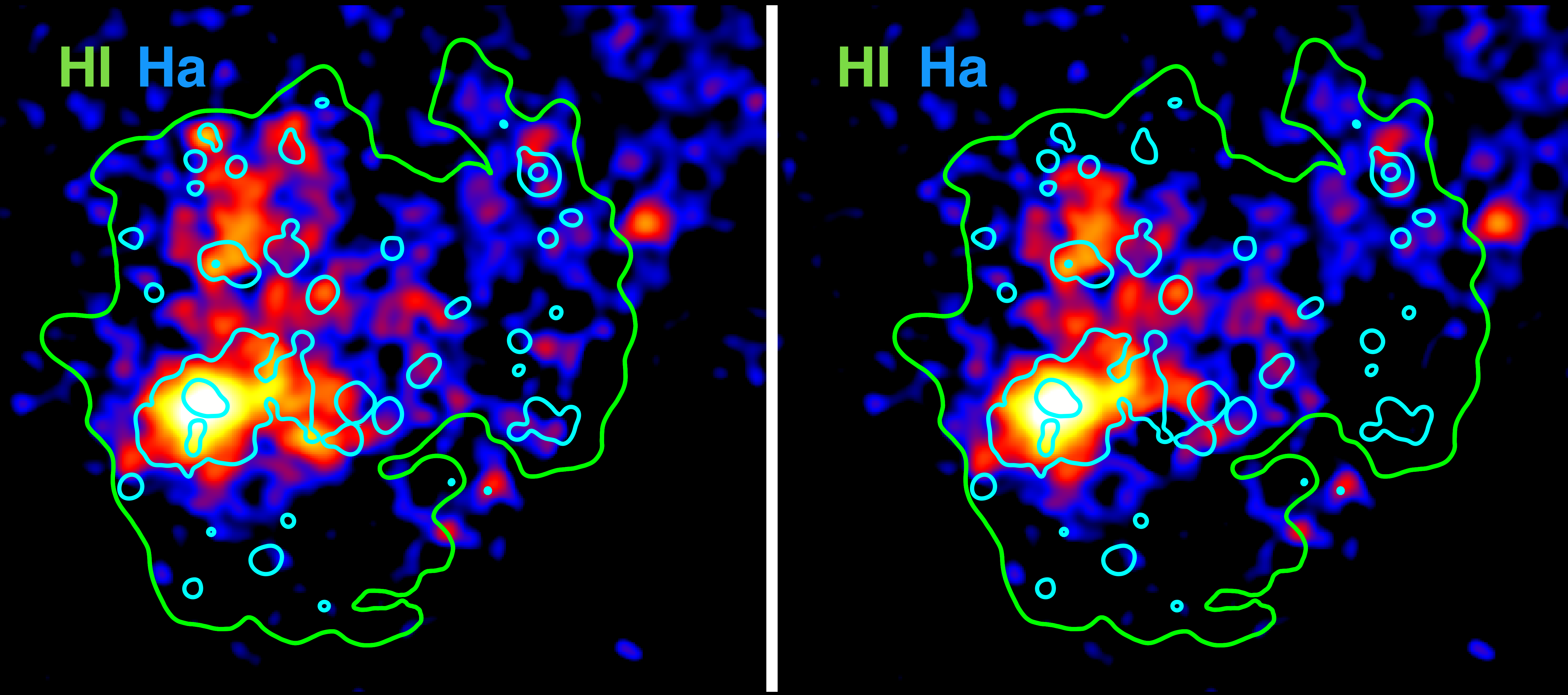


With point sources

Without point sources

Localizing Gamma-Rays in LMC

10 years of data



With point sources

Without point sources

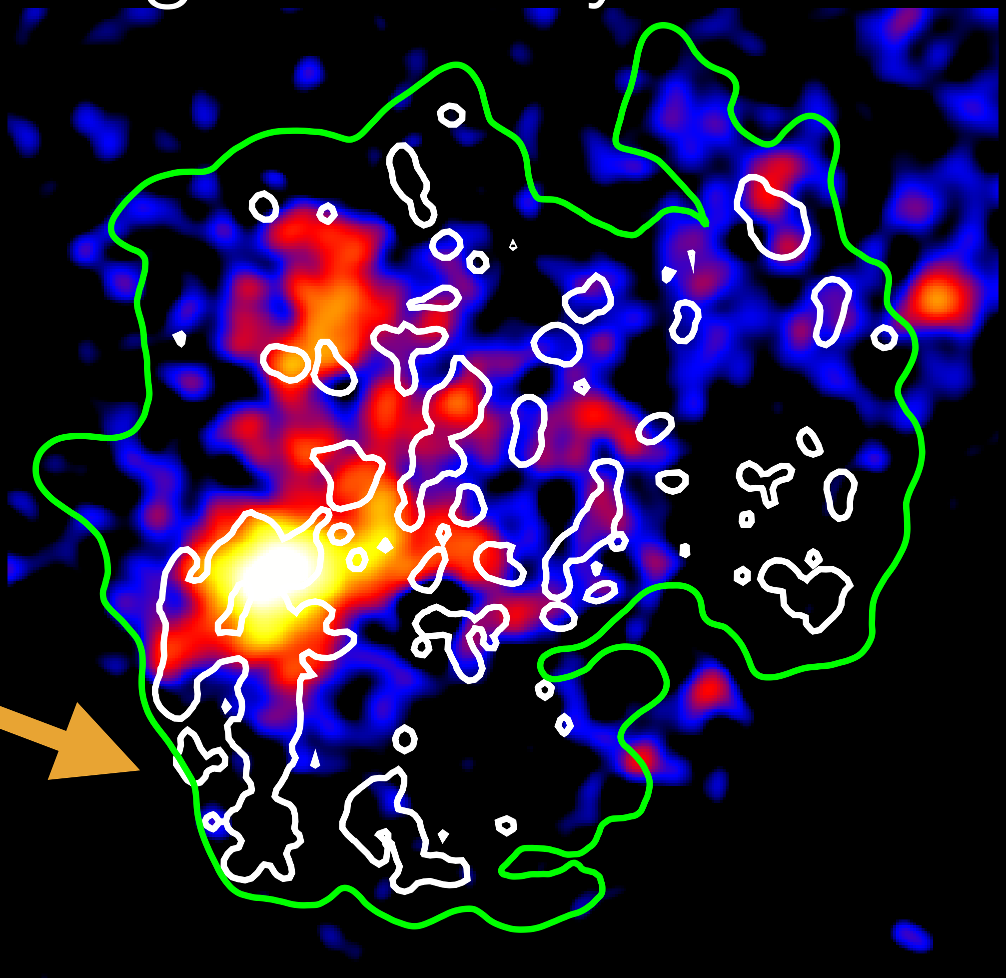
Why are some Massive-Star Regions Not Gamma-ray Bright?

Age?

Maybe massive-star regions are only gamma-ray bright for a limited amount of time.

Cosmic-rays aren't encountering dense gas necessary to produce gamma-rays?

South of 30 Dor has lots of dense gas, yet it is not gamma-ray bright there.



H_2 from Mexiner+10

Why are some Massive-Star Regions Not Gamma-ray Bright?

Age?

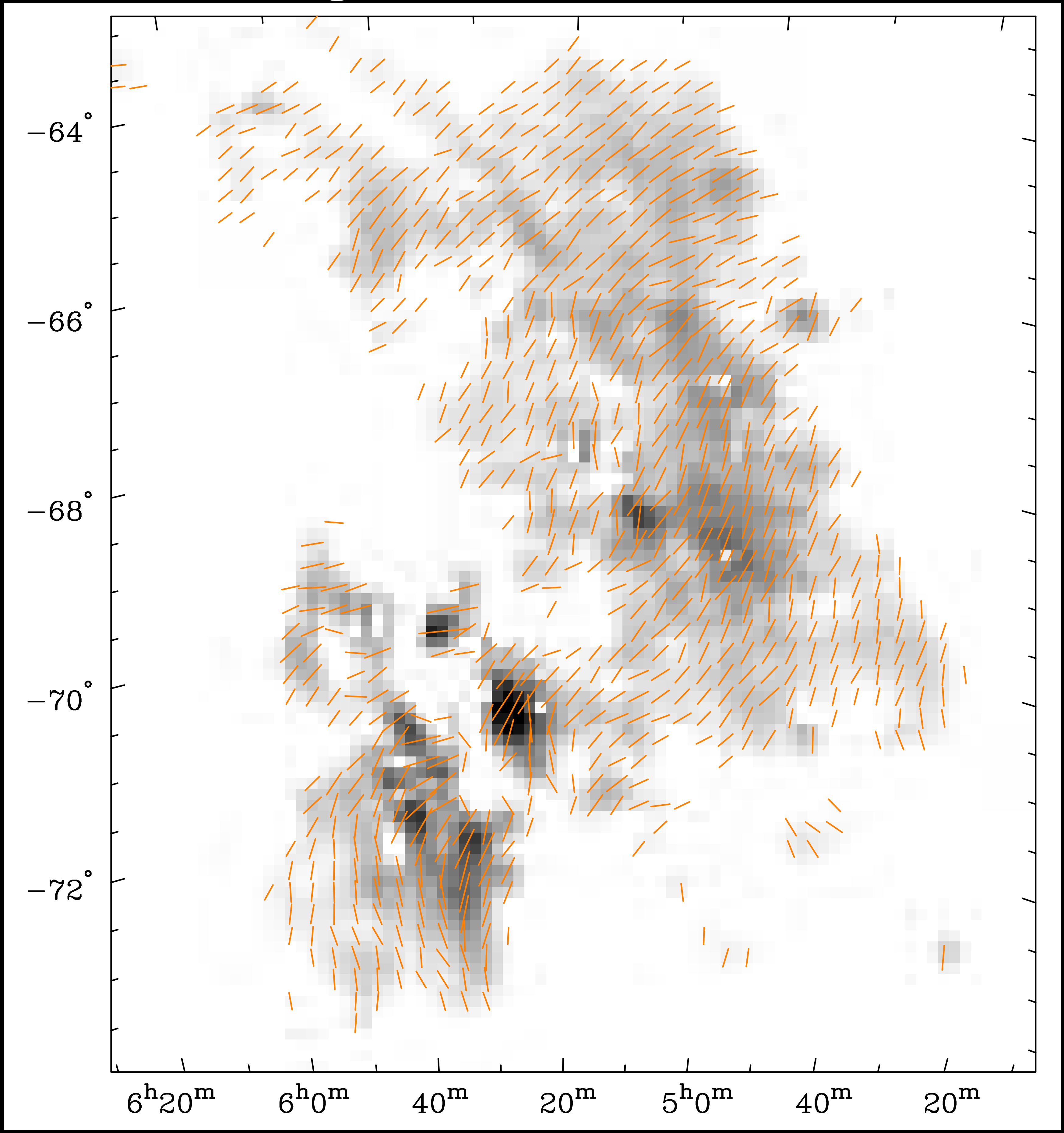
Maybe massive-star regions are only gamma-ray bright for a limited amount of time.

Cosmic-rays aren't encountering dense gas necessary to produce gamma-rays?

This explanation is not completely consistent with dense gas maps of the LMC.

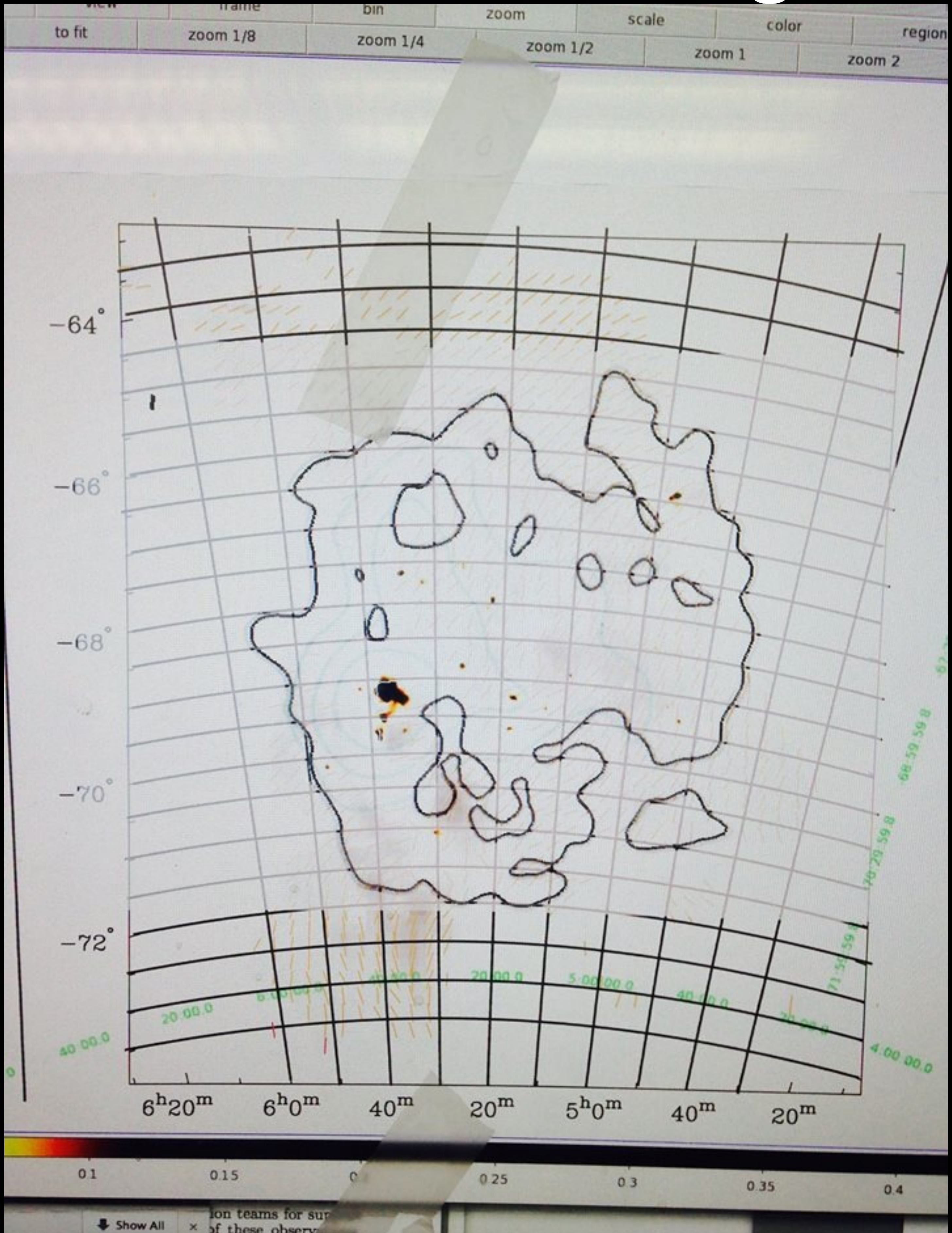
Magnetic fields…?

Magnetic Fields...?

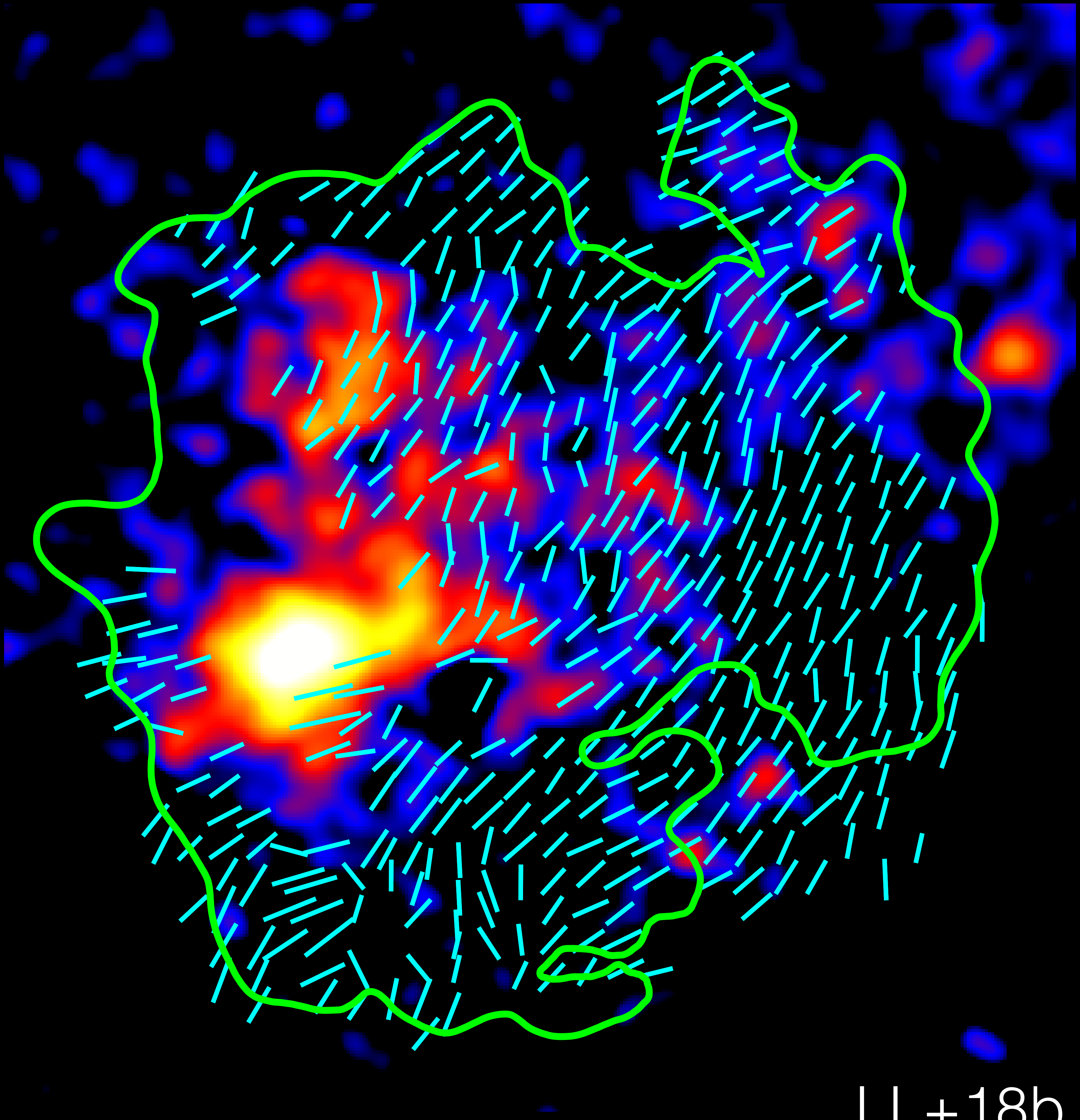


Mao+12

The Science is Getting Done.



Magnetic Fields…!?



LL+18b

Lots More To Do

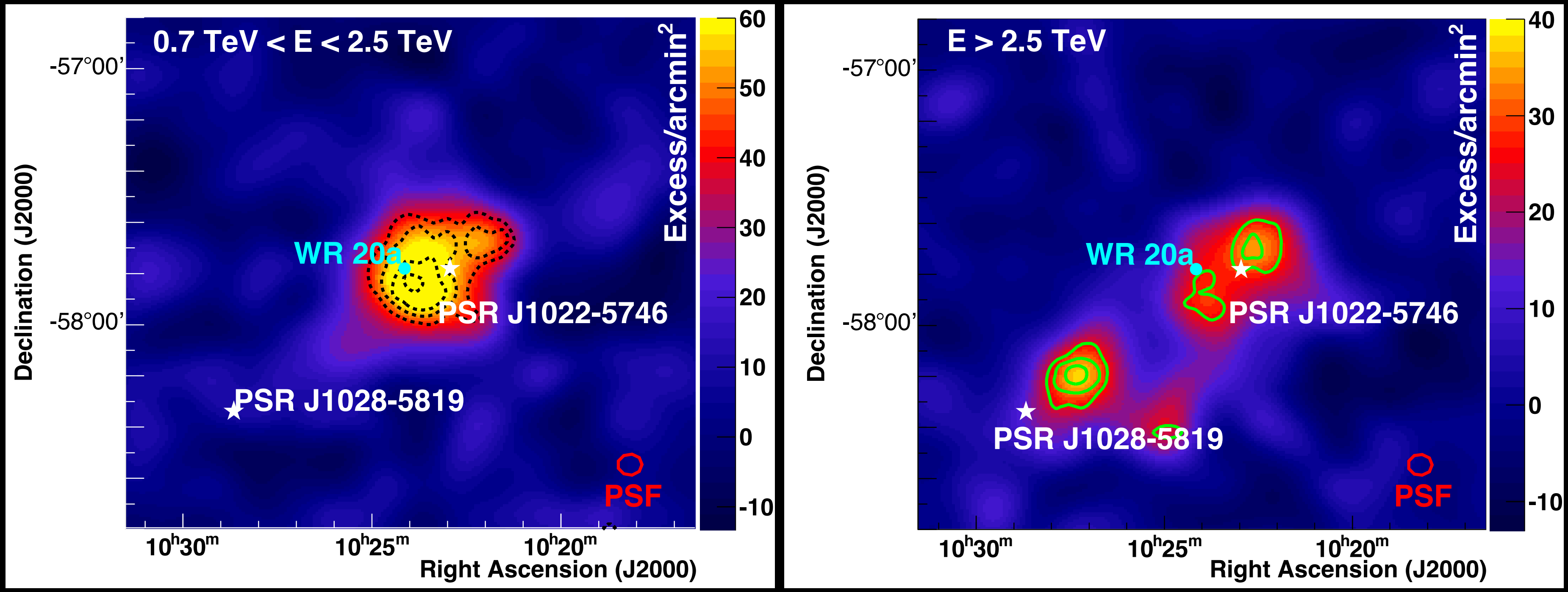
Spatially-resolved gamma-ray spectral analysis of LMC

Does far-IR/gamma-ray correlation break down at small scales?

Analyze more nearby galaxies (e.g., M33) with *Fermi*

Probe CR feedback from star clusters without SNe (e.g., Westerlund 2)

HESS+ 11



What other constraints do you/we want on CR feedback from gamma-ray observations?

Summary

arXiv: 1807.06595

Measurement of relative role of feedback modes in ultra-compact HII regions show indirect radiation pressure dominates and pressure terms evolve with HII region size.

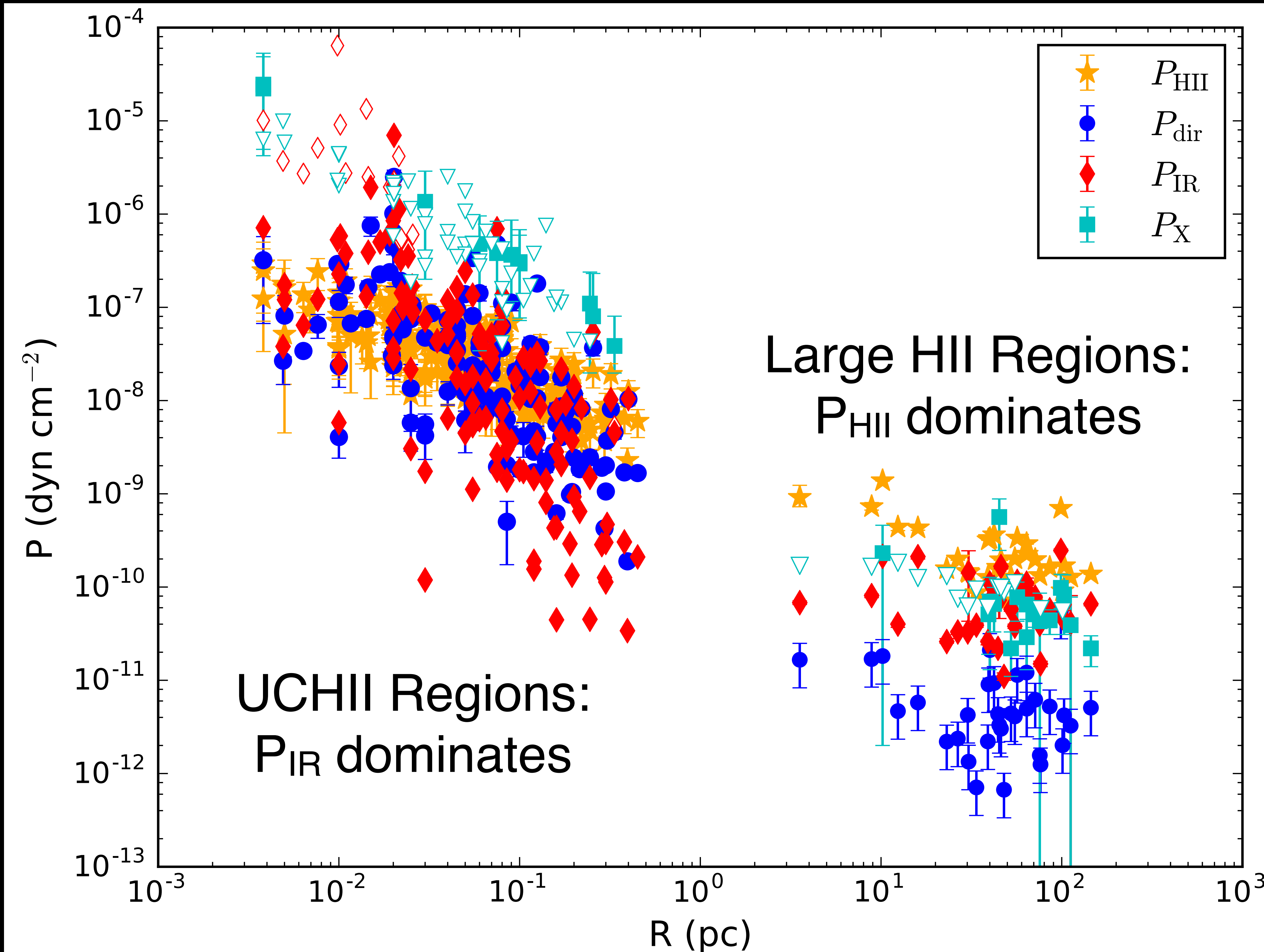
Gamma-ray observations are key to probe CR protons, which are the bulk of the CR population.

Analysis of 9 years of Fermi data toward the SMC shows substructure along the star-forming Bar and Wing.

Gamma-ray spectrum shows a power-law slope with an exponential cutoff. Based on the sub-calorimetric luminosity and the spectral shape, CR protons are likely escaping the SMC via advection and diffusion.

LMC also shows substantial substructure that correlates with star-forming regions but may also depend on cluster age and B-field orientation (suggestive of anisotropic diffusion).

Feedback Trends



Olivier, LL+ in prep