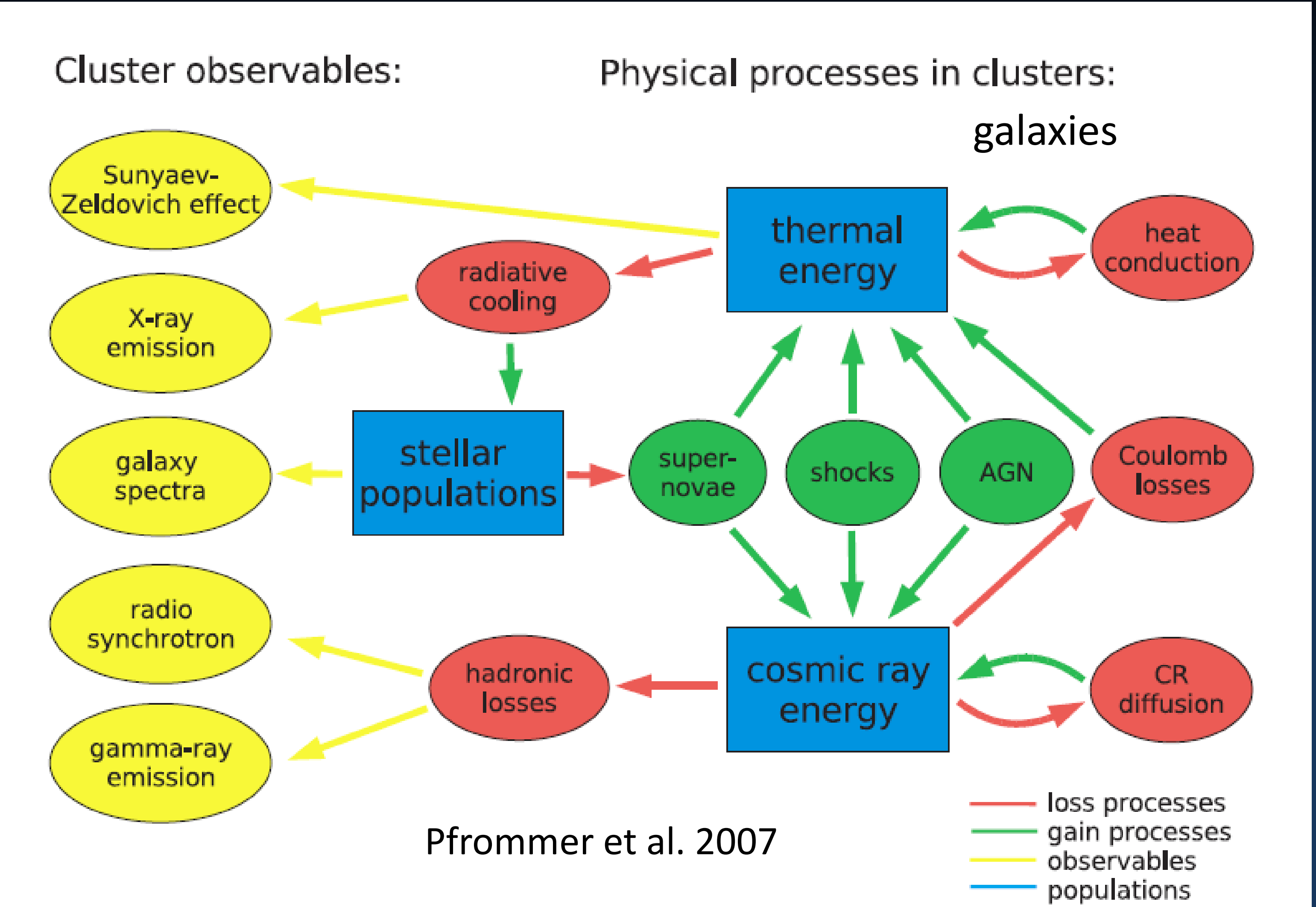
Cosmic-ray Connections between the Interstellar and Intergalactic Medium

Can star-forming galaxies inject significant amounts of non-thermal energy into the intergalactic medium in the form of relativistic nuclei?

Keith Bechtol
with several results from *Fermi* LAT Collaboration
Clusters of Galaxies as Cosmic Laboratories
Stockholm
12 September 2011
bechtol@stanford.edu

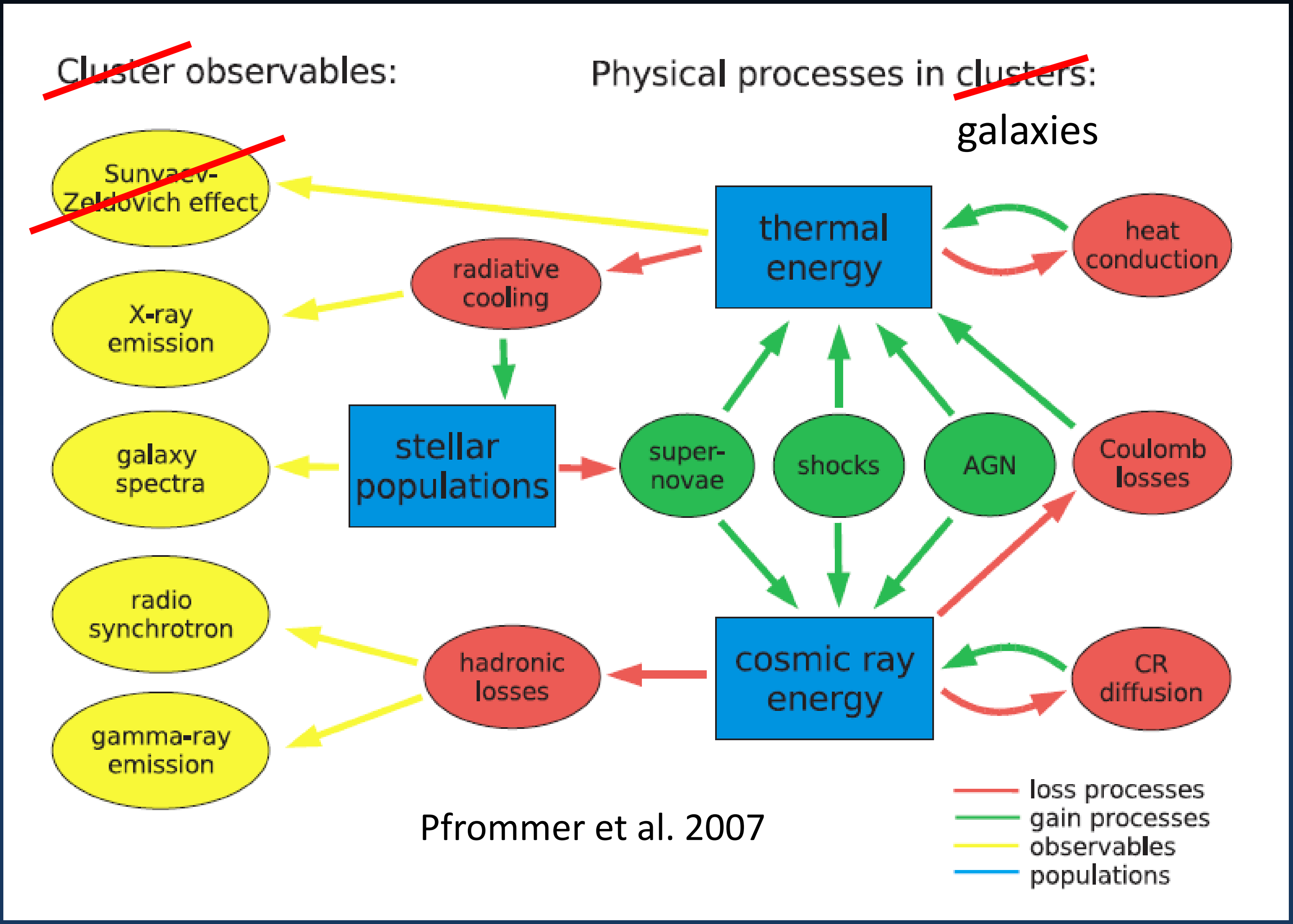
KIPAC
SLAC NATIONAL ACCELERATOR LABORATORY
STANFORD UNIVERSITY

Galaxy Cluster Physical Context



Pfrommer et al. 2007

Galaxy ~~Cluster~~ Physical Context



Underlying cosmic-ray physics is similar for interstellar medium and intergalactic medium

Energy Budget Near the Solar System

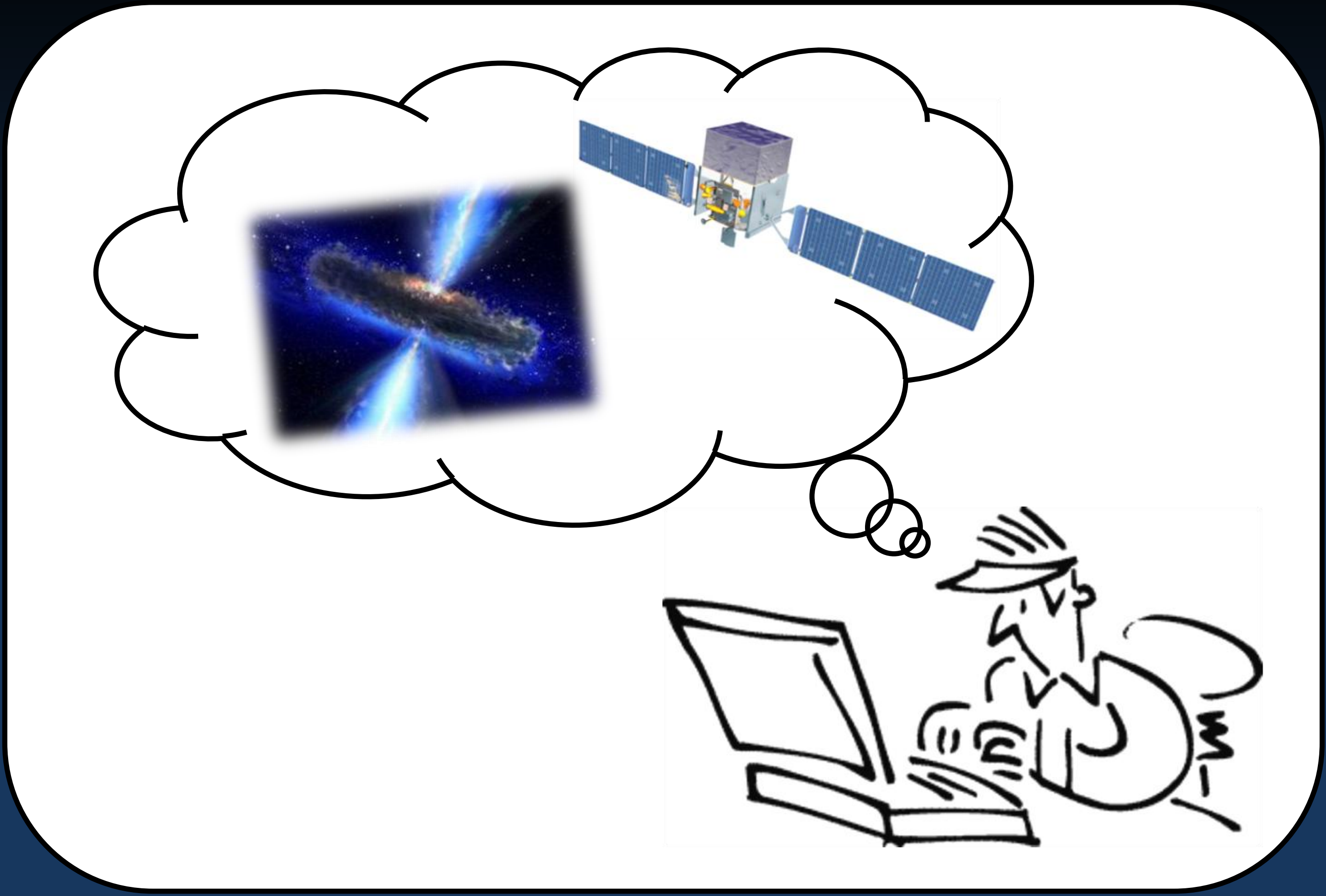
Table 1.5 Energy Densities in the Local ISM

Component		$u(\mathrm{eV\,cm^{-3}})$	Note
Cosmic microwave background	$(T_{\mathrm{CMB}} = 2.725\,\mathrm{K})$	0.265	*a*
Far-infrared radiation from dust		0.31	*b*
Starlight ($h\nu < 13.6\,\mathrm{eV}$)		0.54	*c*
Thermal kinetic energy $(3/2)nkT$		0.49	*d*
Turbulent kinetic energy $(1/2)\rho v^2$		0.22	*e*
Magnetic energy $B^2/8\pi$		0.89	*f*
Cosmic rays		1.39	*g*

a Fixsen & Mather (2002).
b Chapter 12.
c Chapter 12.
d For $nT = 3800\,\mathrm{cm^{-3}\,K}$ (see §17.7).
e For $n_{\mathrm{H}} = 30\,\mathrm{cm^{-3}}$, $v = 1\,\mathrm{km\,s^{-1}}$, or $\langle n_{\mathrm{H}}\rangle = 1\,\mathrm{cm^{-3}}$, $\langle v^2\rangle^{1/2} = 5.5\,\mathrm{km\,s^{-1}}$.
f For median $B_{\mathrm{tot}} \approx 6.0\,\mu\mathrm{G}$ (Heiles & Crutcher 2005).
g For cosmic ray spectrum X3 in Fig. 13.5.

From Drain
"Physics of the Interstellar and Intergalactic Medium"
Chapter 1

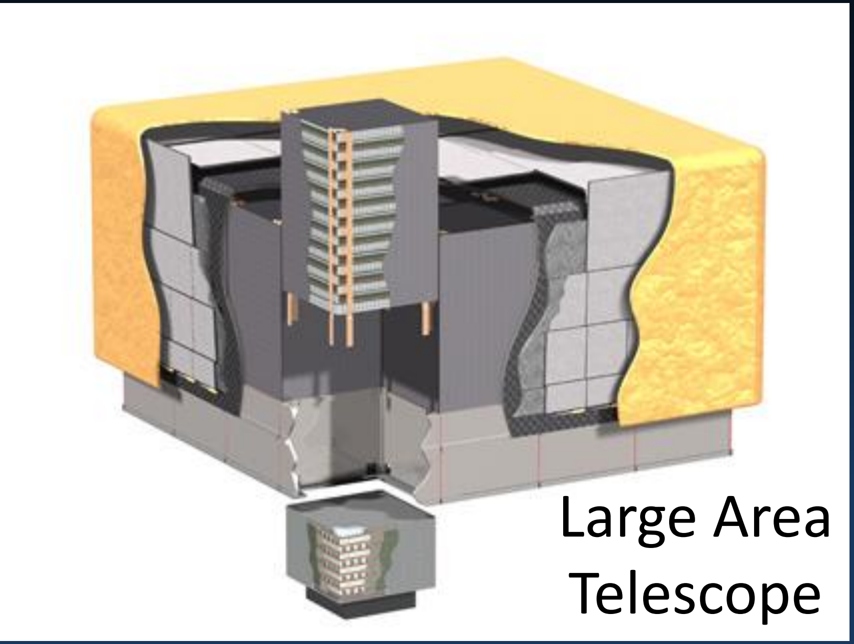
Non-thermal energy dominates in the local interstellar medium



Part 1

GAMMA-RAY OBSERVER'S PERSPECTIVE

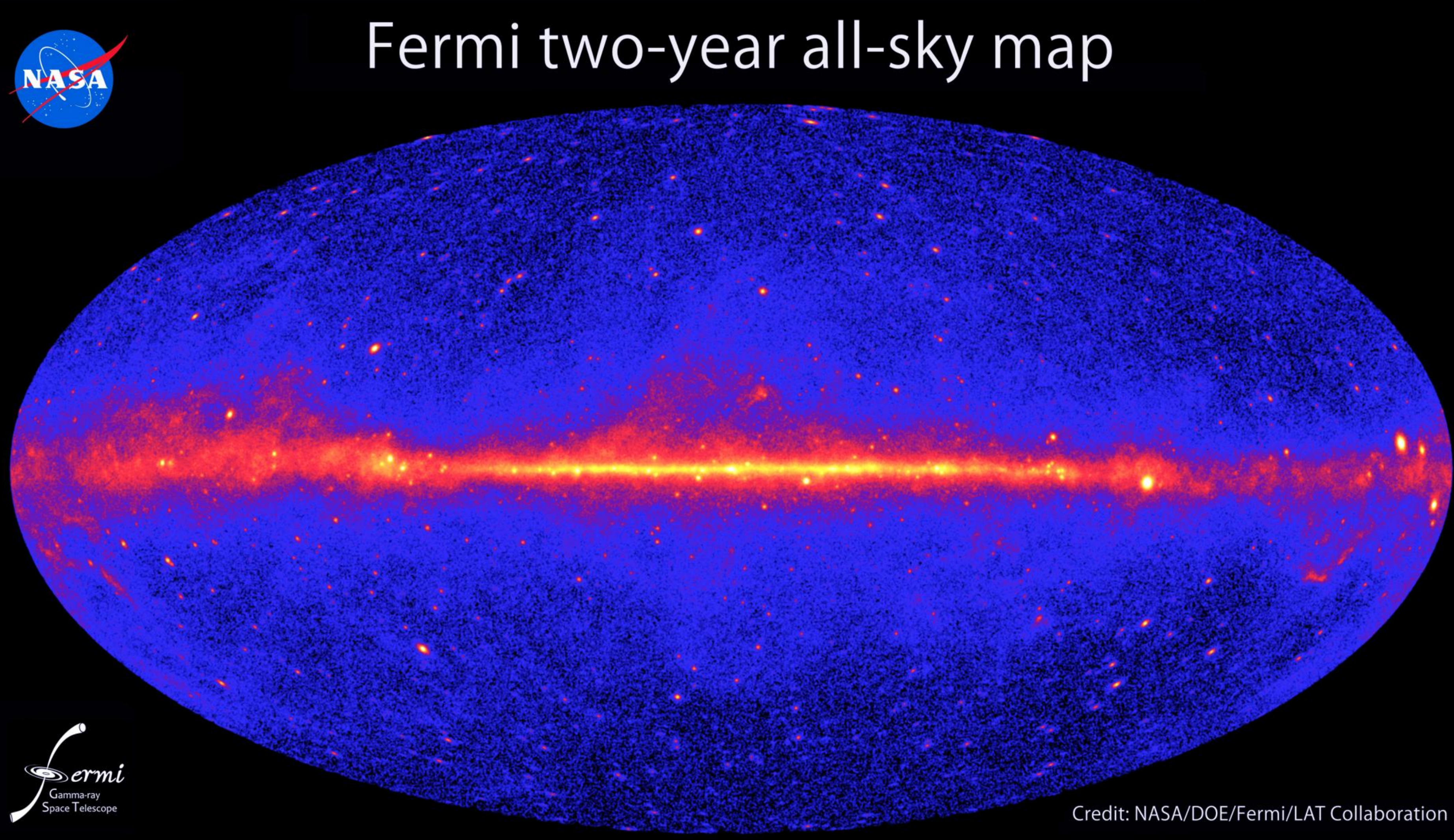
Flashback to Summer 2008



Advances in
effective area (~8000 cm^2 at 1 GeV),
angular resolution (~3.5 - 0.1 deg),
energy range (20 MeV - > 300 GeV), and
instantaneous field of view (2.4sr)
and sky-survey operation strategy

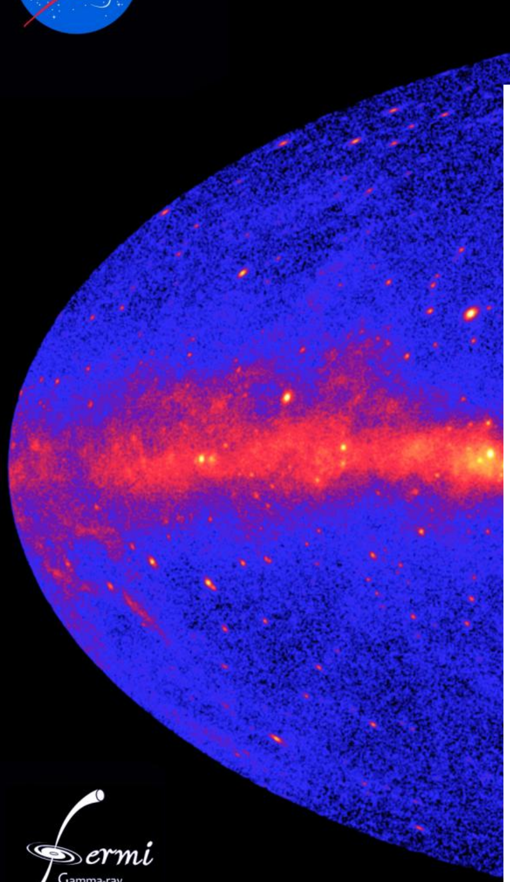
Exciting opportunities ahead!

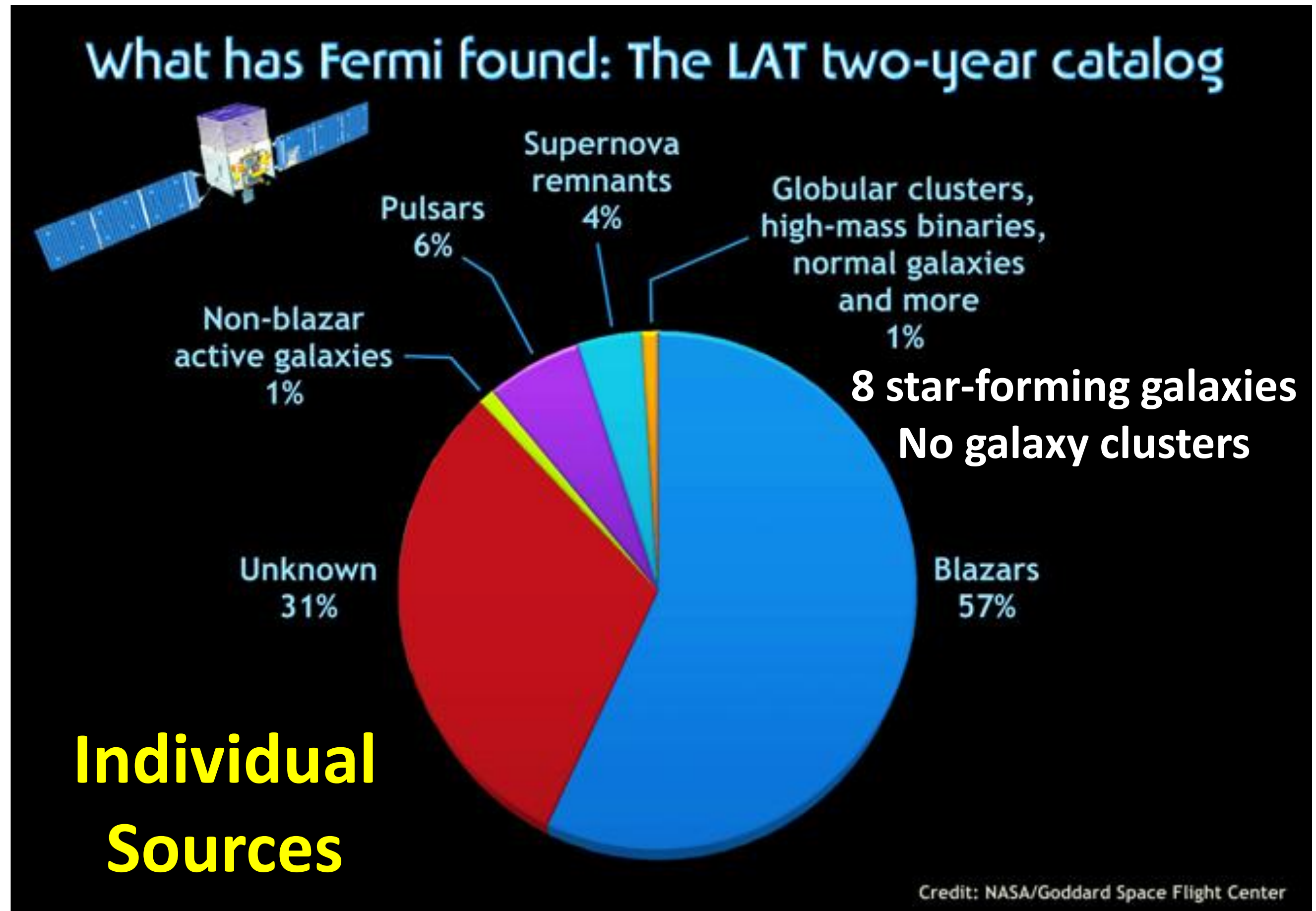
Tour of the GeV Gamma-ray Sky



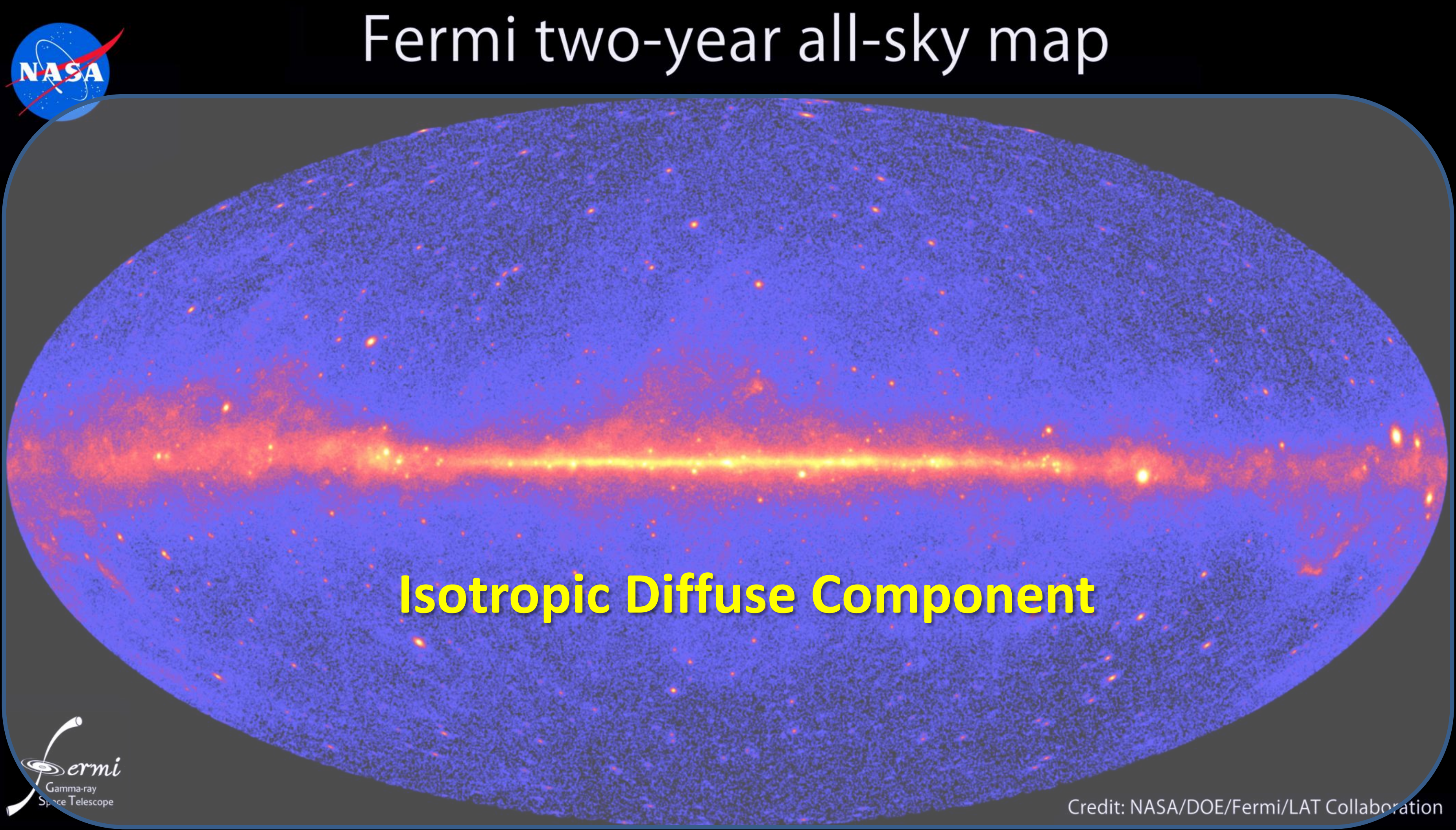
Tour of the GeV Gamma-ray Sky

Fermi two-year all-sky map



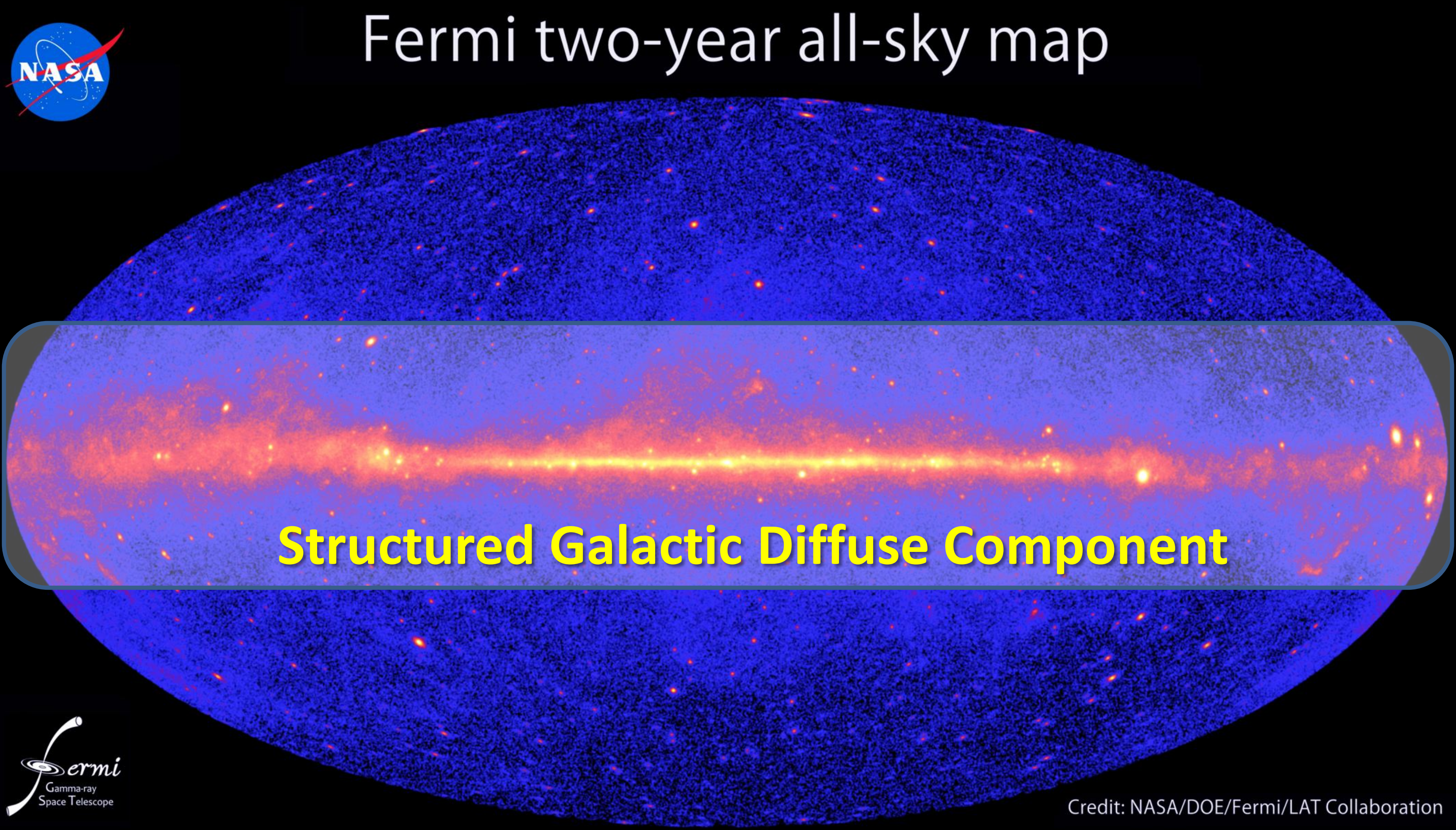


Tour of the GeV Gamma-ray Sky

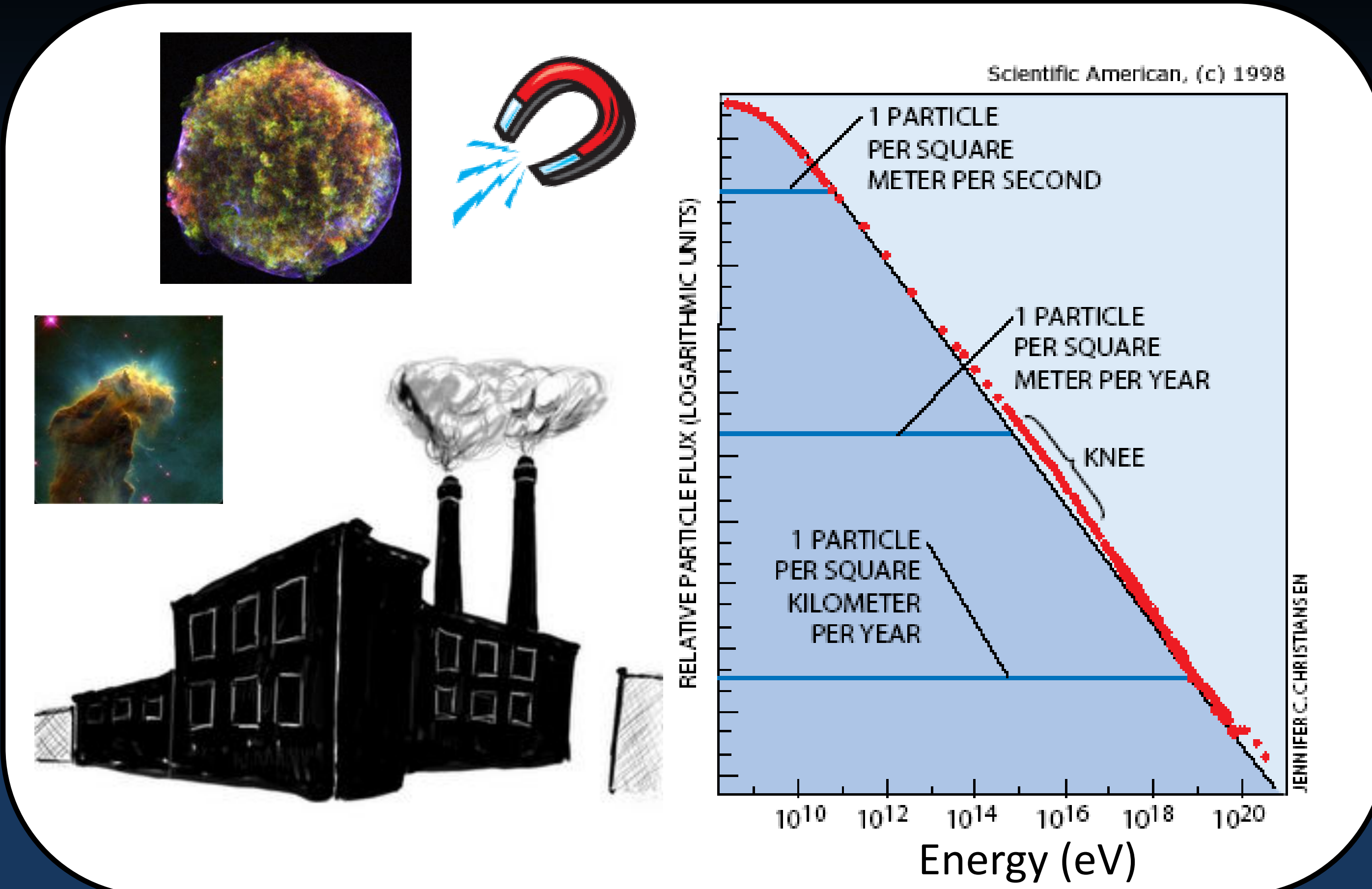


Collective emission of unresolved (extragalactic) sources, genuine diffuse processes??

Tour of the GeV Gamma-ray Sky



Relativistic nuclei and electrons interacting with ambient gas and radiation fields



Part 2

MILKY WAY AS COSMIC-RAY FACTORY

Following the Cosmic-ray Nuclei

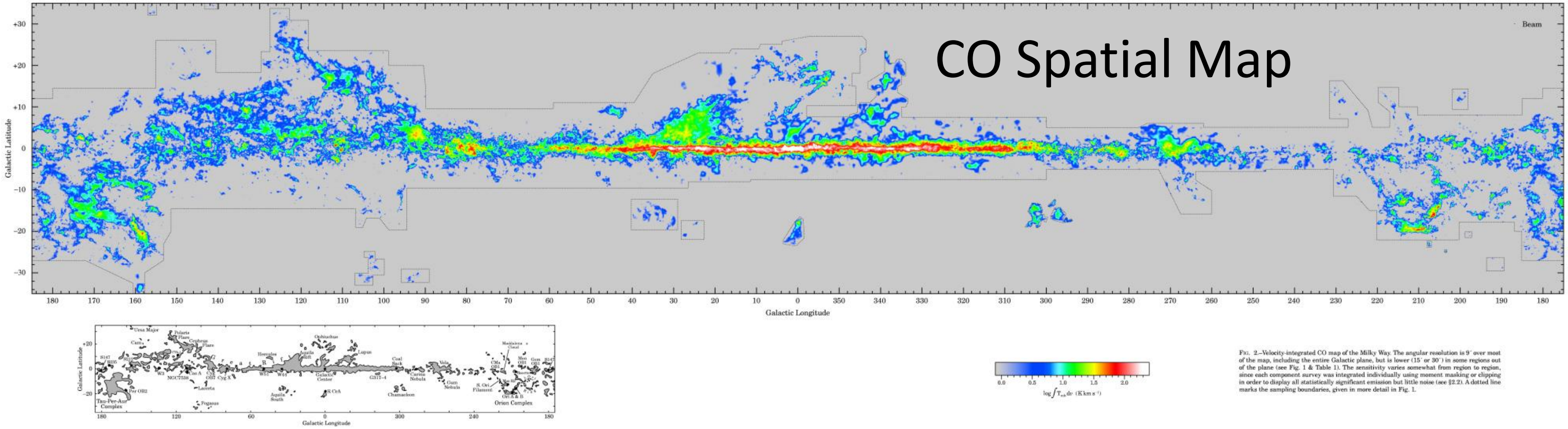
- Ambient gas serves as target material for inelastic collisions by cosmic-ray nuclei

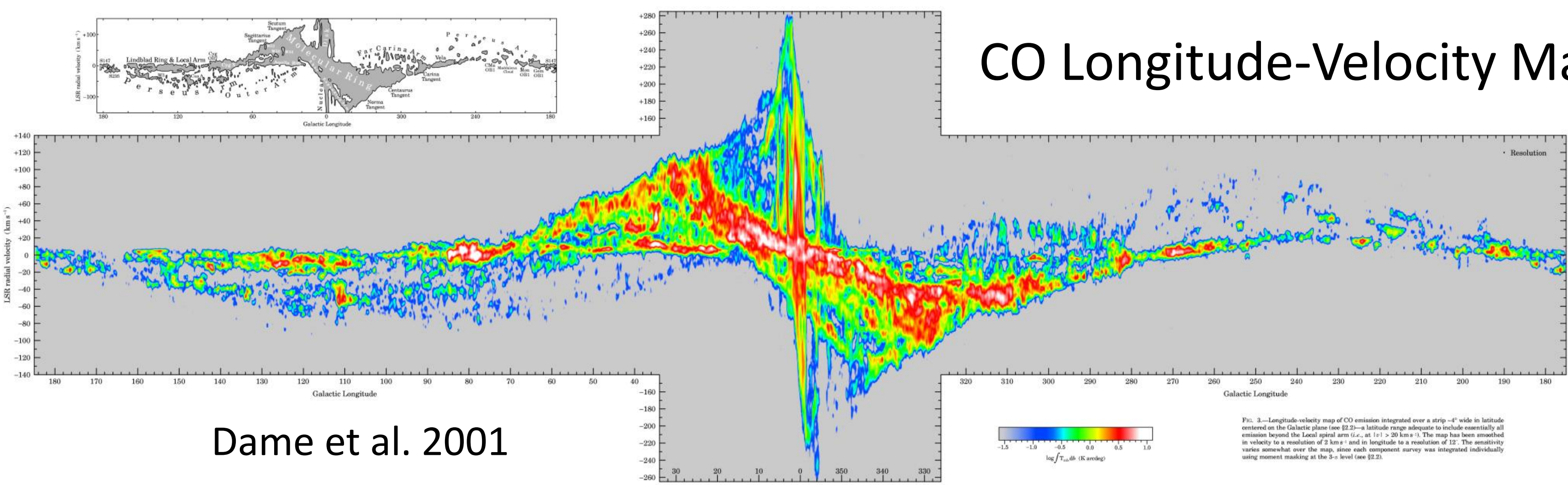
$$p + p \rightarrow \begin{cases} \pi^{\pm} \rightarrow e^{\pm} + \text{neutrinos} \\ \pi^{0} \rightarrow 2\gamma \end{cases}$$

Gamma-ray emissivity (e.g. ph H-atom^{-1} s^{-1}) provides unique information regarding the acceleration and transport of cosmic-ray nuclei

- Gas components
  - Atomic hydrogen (HI, 21cm surveys)
  - Molecular hydrogen (H_2, CO 1-0 surveys as proxy)
  - ‘Dark gas’ (look for dust reddening)

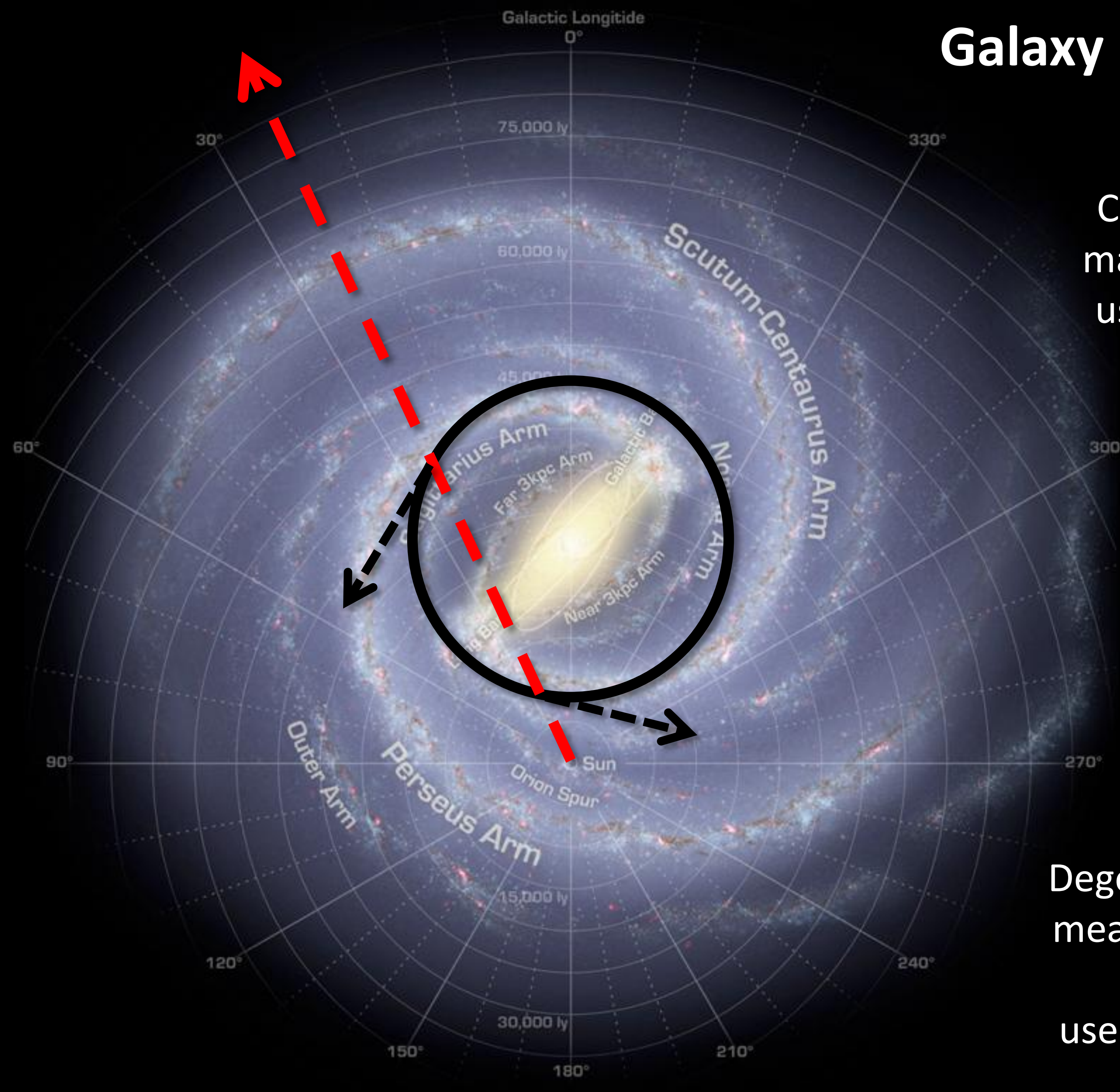
Gas Content of Milky Way: Molecular Gas Example





Dame et al. 2001

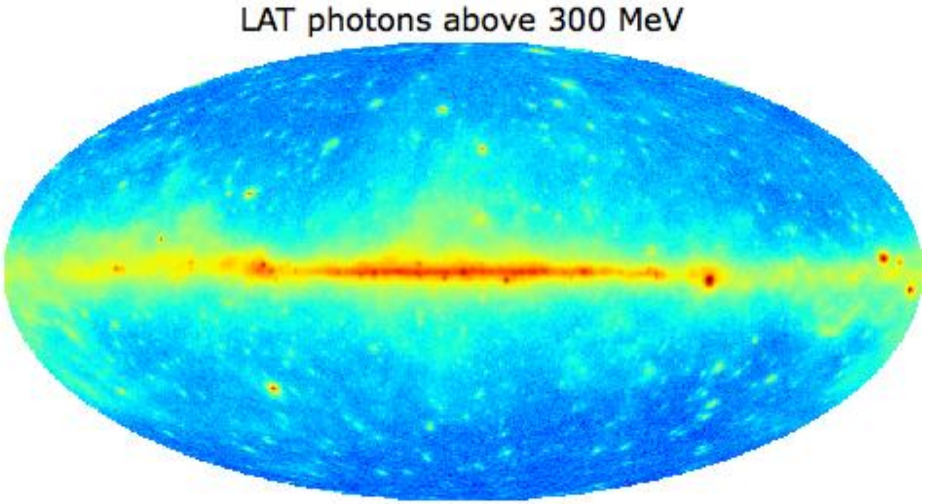
Galaxy Rotation

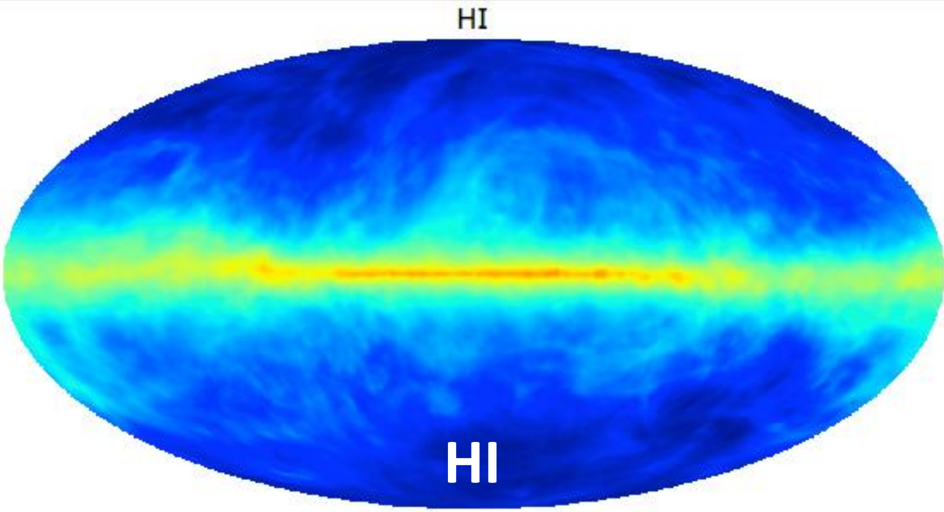


Create 3-dimensional map of gas distribution using Doppler-shifted lines

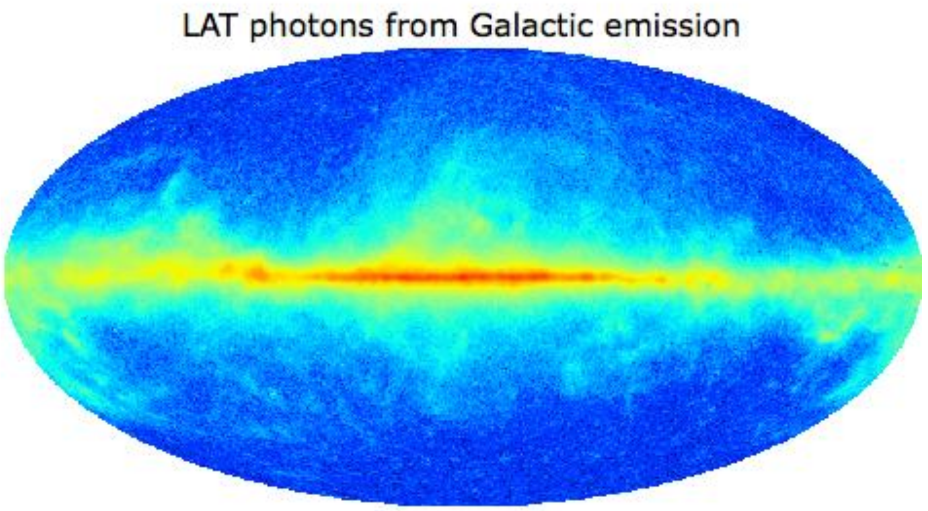
Degeneracy for distance measurements towards inner Galaxy, use concentric rings for gas templates

Data / Gas Templates Comparison

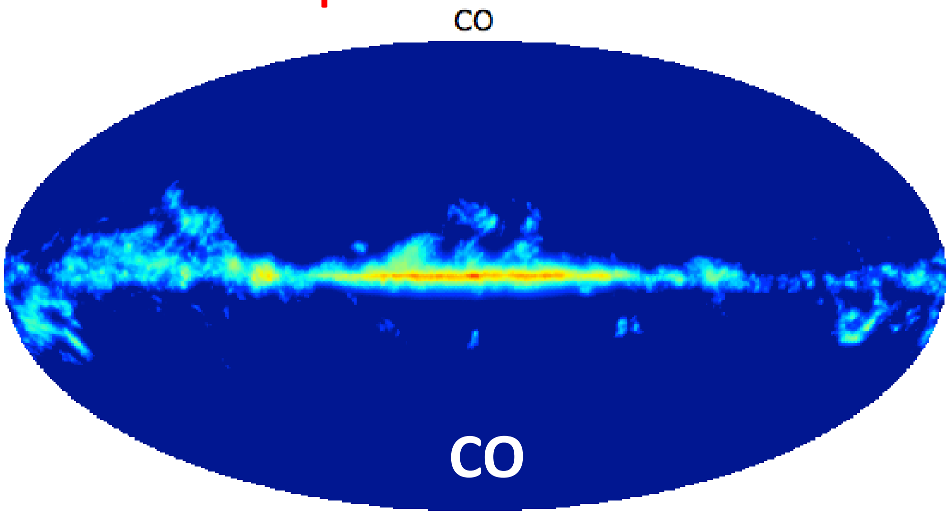




Column densities convolved with LAT PSF and exposure-corrected

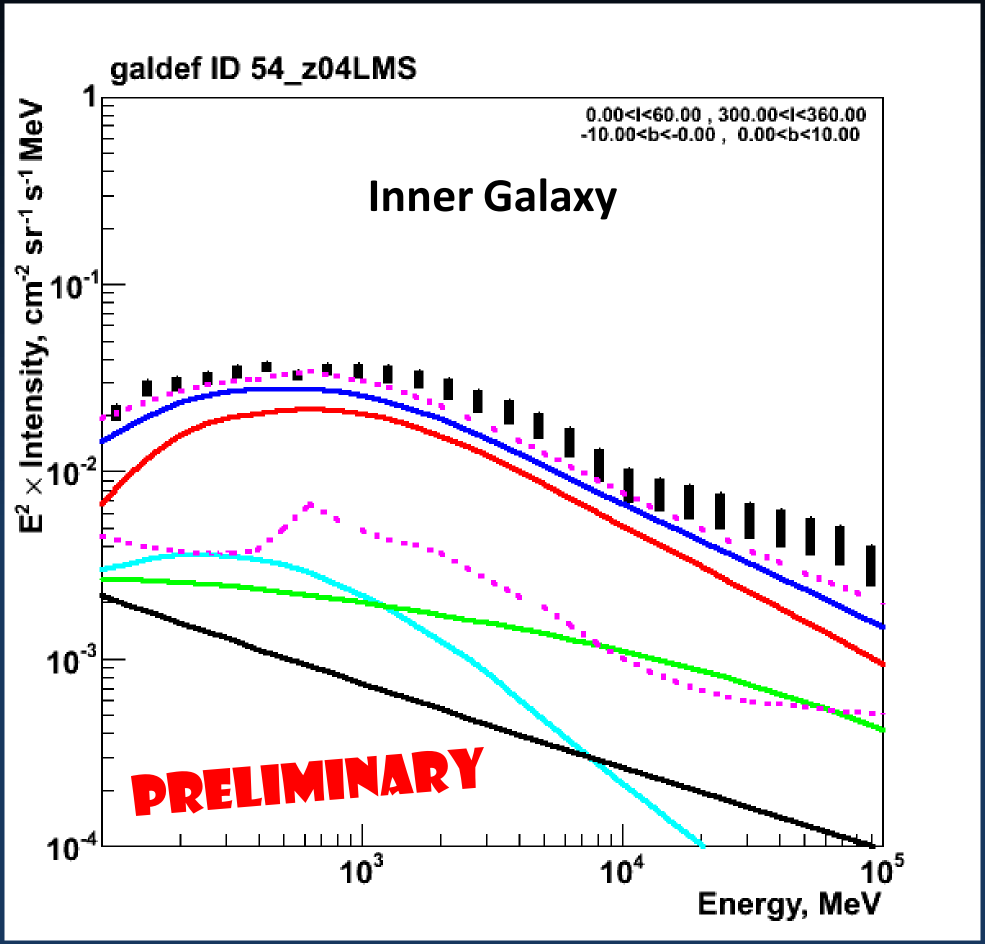


Subtract point sources and isotropic diffuse



Column densities convolved with LAT PSF and exposure-corrected

Diffusion and Galactic 'Sea' of Cosmic Rays

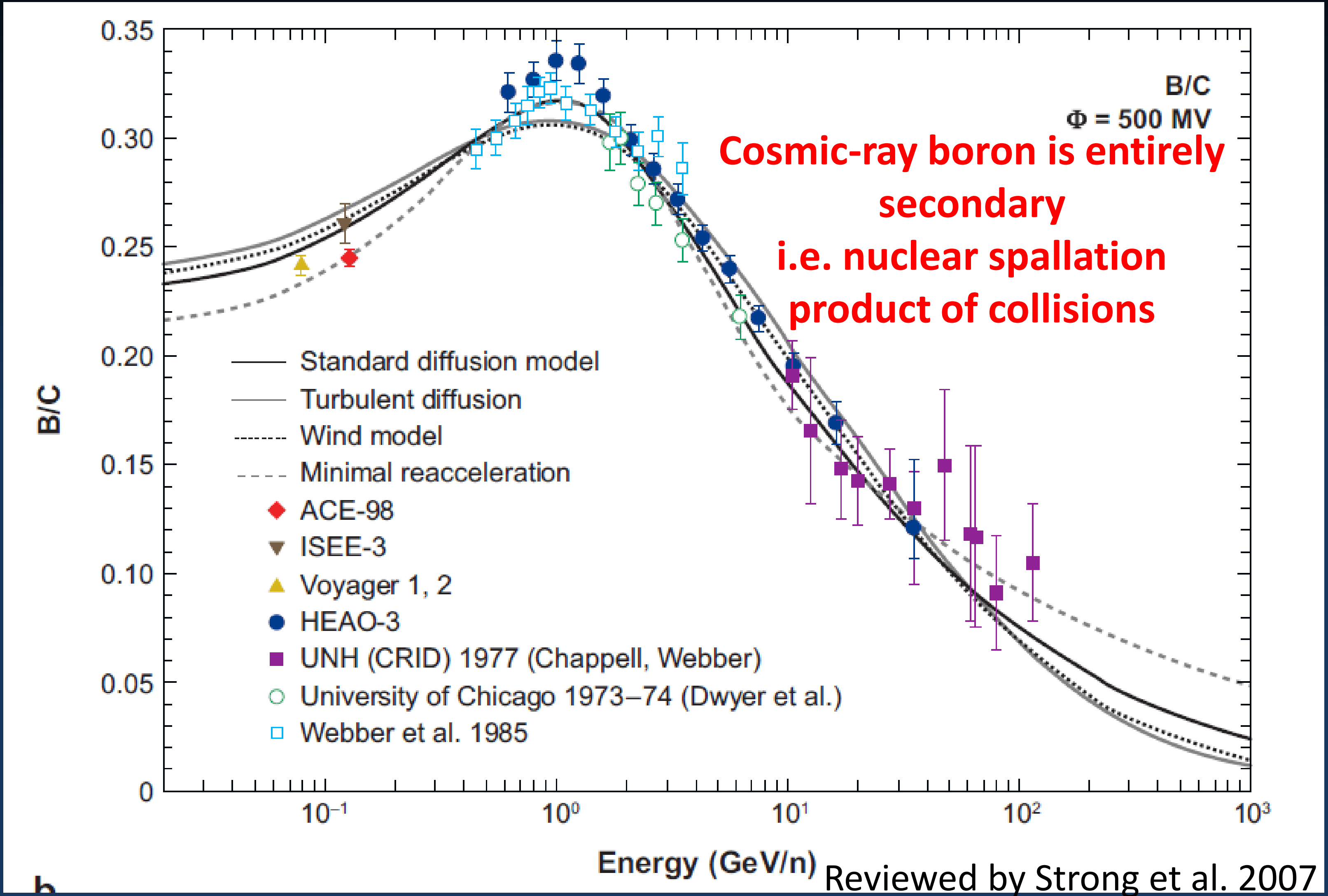


Black = LAT data
Red = pion decay
Green = inverse Compton
Cyan = bremsstrahlung
Blue = total without sources

Magenta = sources and inclusive total

- Diffusion is energy-dependent process; inelastic collision cross section for cosmic-ray protons is nearly energy-independent
- Diffuse hadronic gamma-ray spectrum above pion production threshold matches locally measured cosmic-ray spectrum (spectral index ~ 2.7)

Interaction Length of Cosmic-ray Nuclei



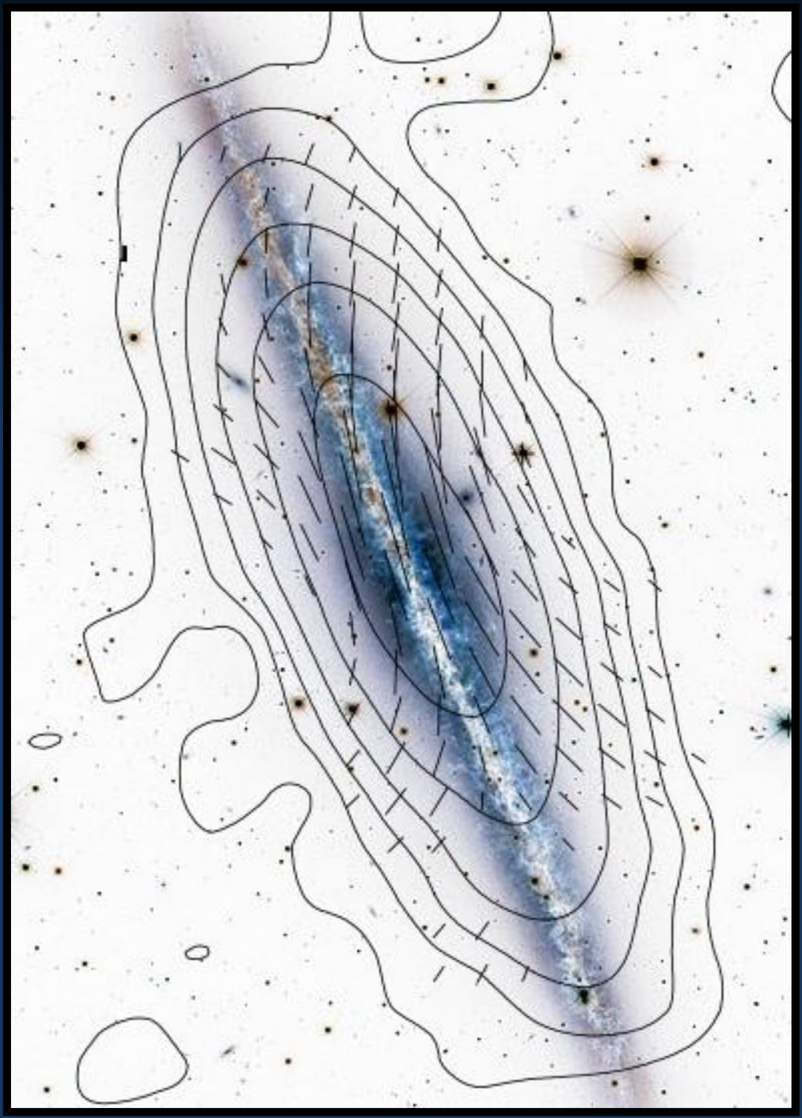
Reviewed by Strong et al. 2007

Secondary to primary ratio allows estimation of total column density of matter traversed by cosmic-ray nuclei

Kiloparsec-scale Cosmic-ray Halo

Radioisotope measurements suggest that cosmic-ray nuclei spend a large fraction of time in low-density environs

Also, extended radio synchrotron halos are detected around other galaxies

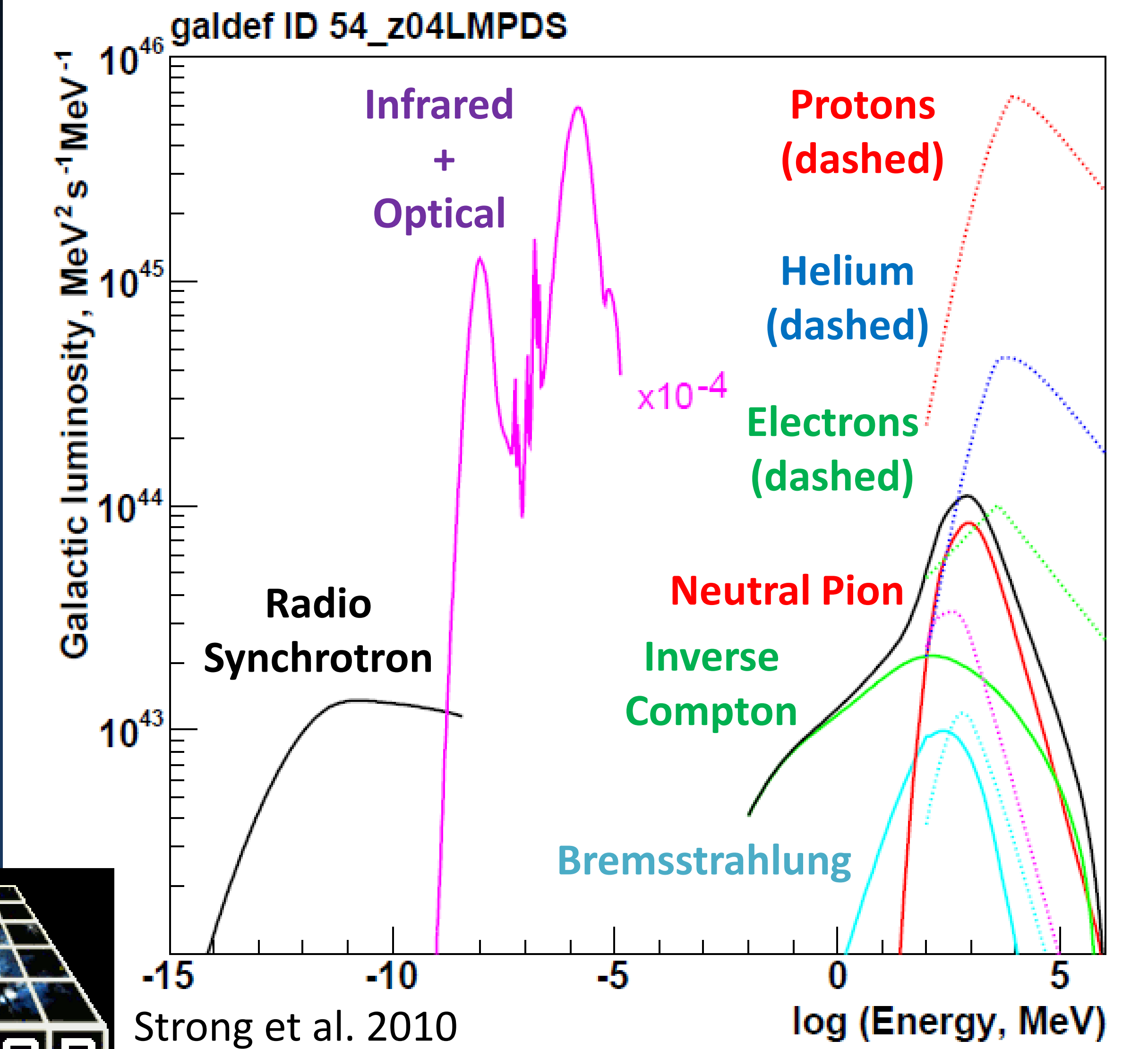


Edge on spiral galaxy NGC 891 observed with Effelsberg Telescope - 8.4 GHz contours overlaid on optical image (CFHT)

Milky Way Global Cosmic-ray Related Luminosity

Numerical model incorporating:

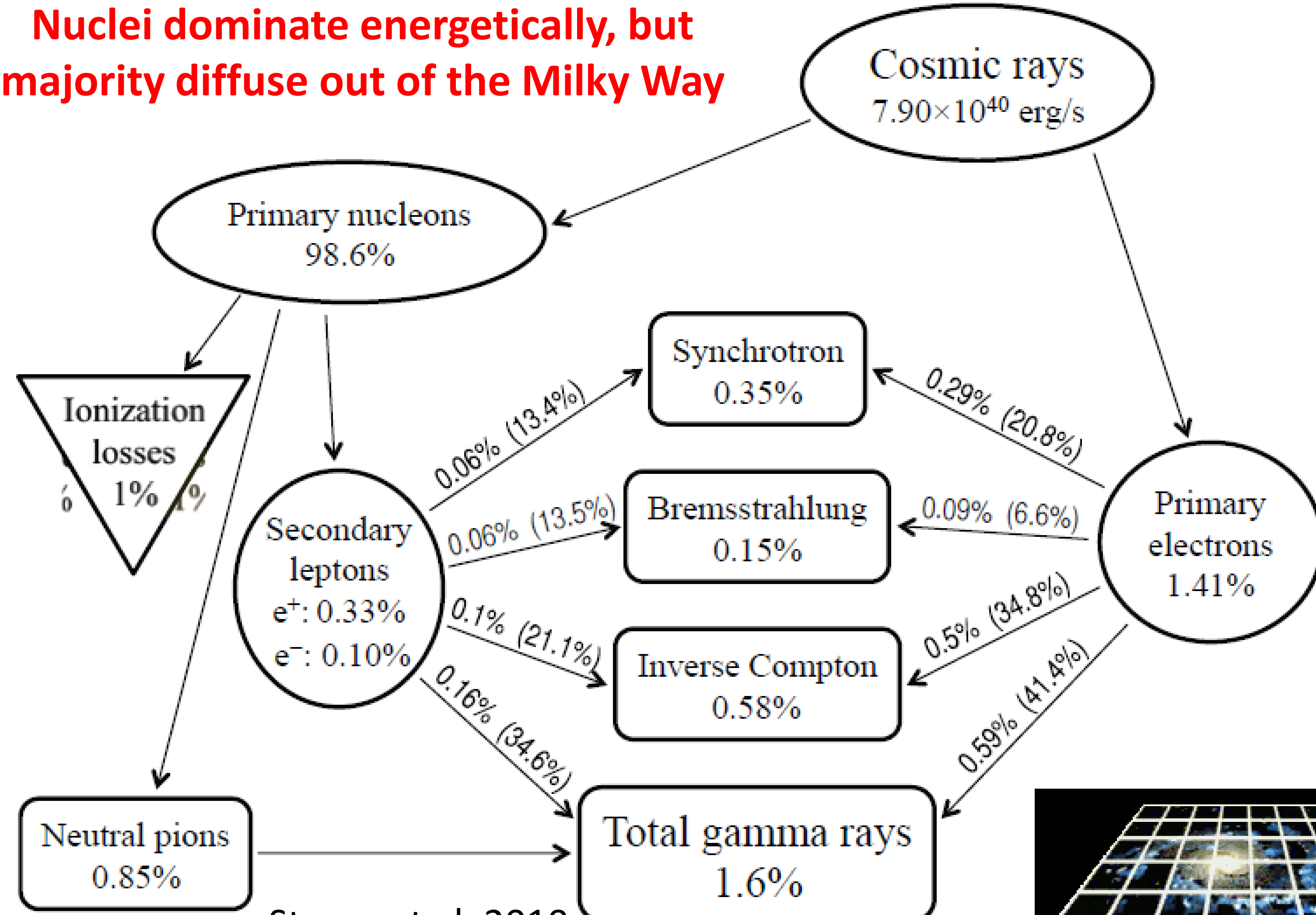
- 3-dimensional gas distribution
- Radio and gamma-ray data
- Measurements of cosmic rays near the Earth, including elemental and isotopic composition



Strong et al. 2010

Energy Budget of Galactic Cosmic Rays

Nuclei dominate energetically, but majority diffuse out of the Milky Way



Strong et al. 2010

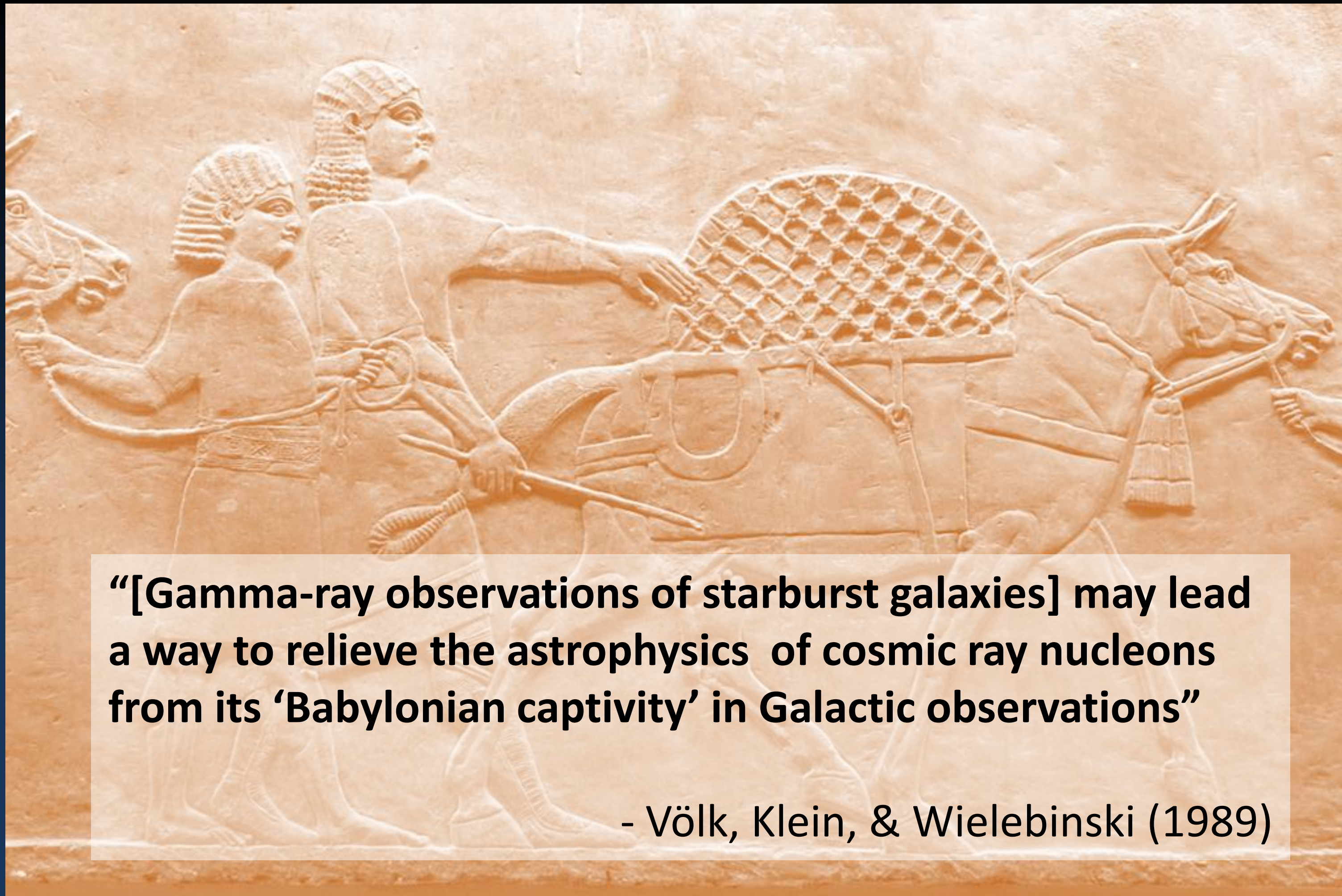
Summary: Milky Way Cosmic-ray Luminosity

- Local cosmic-ray energy density, gas mass estimates from radio surveys, ‘leaky-box’ model (e.g. Berezinskii et al. 1990)
  - Grammage from secondary to primary ratios (B/C)
  - Estimate: **10^{41} erg s^{-1}**

- Gamma-ray luminosity (Dogiel et al. 2002)
  - Estimated gamma-ray luminosity of Milky Way
  - Secondary to primary ratios (B/C)
  - Estimate: **5×10^{40} erg s^{-1}**

- Detailed numerical modeling (Strong et al. 2010)
  - GALPROP
  - Estimate: **7×10^{40} erg s^{-1}**

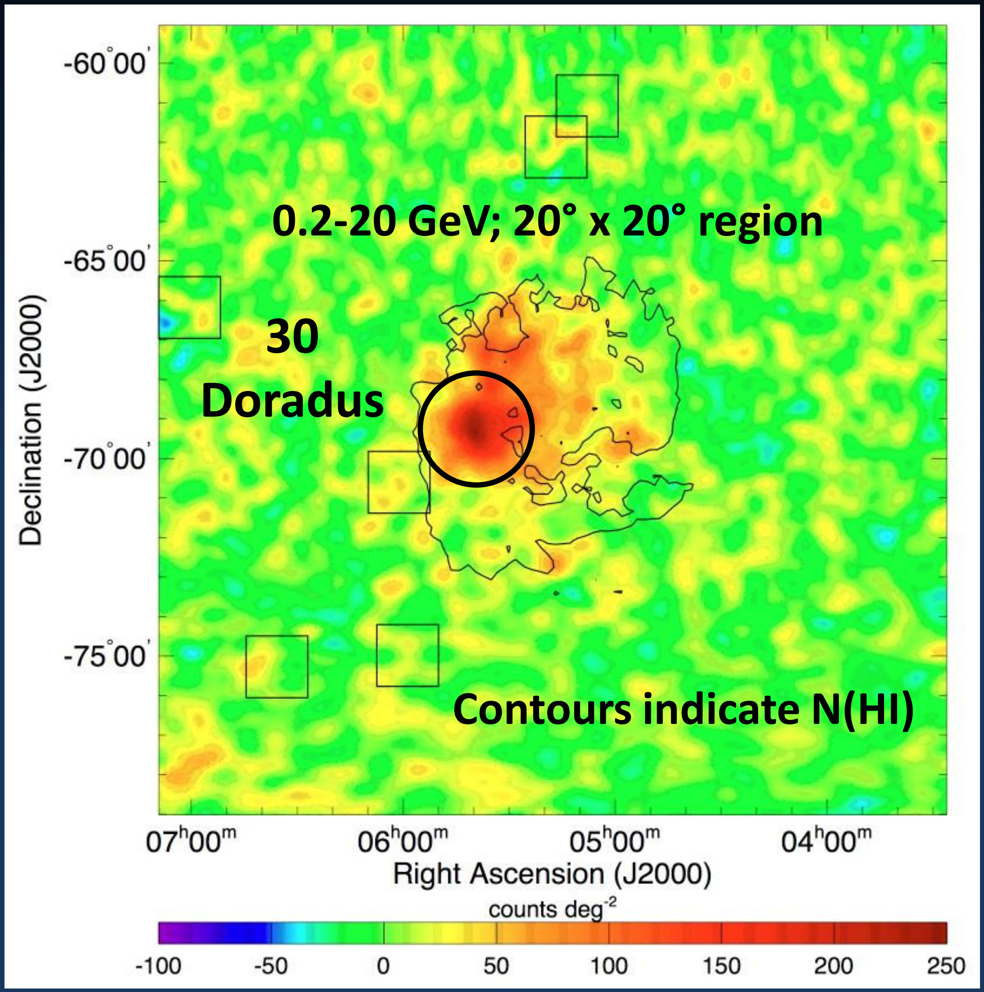
Consensus among methods!



Part 3

COSMIC RAYS IN EXTERNAL GALAXIES

LMC Spatially Resolved by *Fermi* LAT



Background-subtracted smoothed residual counts map of the LMC region

- **Diffuse emission peaking in massive star-forming region 30 Doradus**
- Gamma-ray emission correlates with ***ionized*** gas (1% by mass) rather than with ***total*** gas density
- Cosmic-ray diffusion length small compared to size of LMC

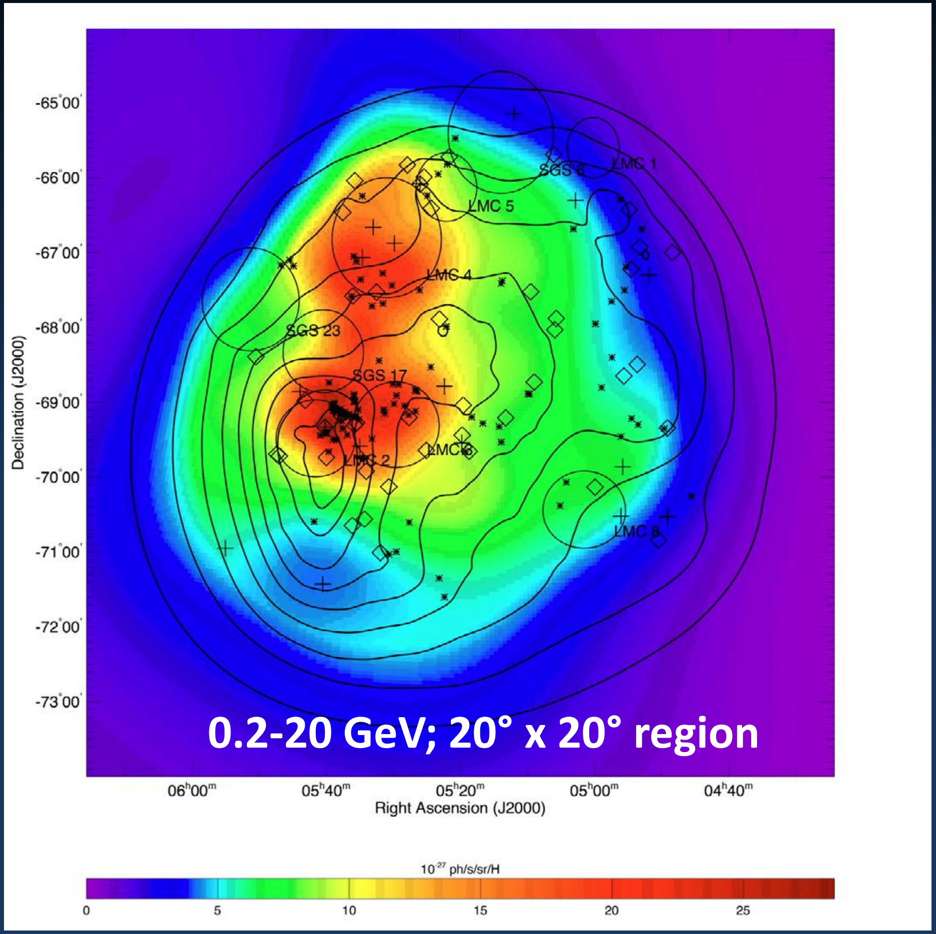
Abdo, A. A. et al. 2010, A&A, 512, A7

Connection with Star Formation within a Galaxy

Gamma-ray Emissivity >0.1 GeV
(ph s^{-1} sr^{-1} H-atom^{-1})
Adaptively smoothed

Contours: N(H) column densities

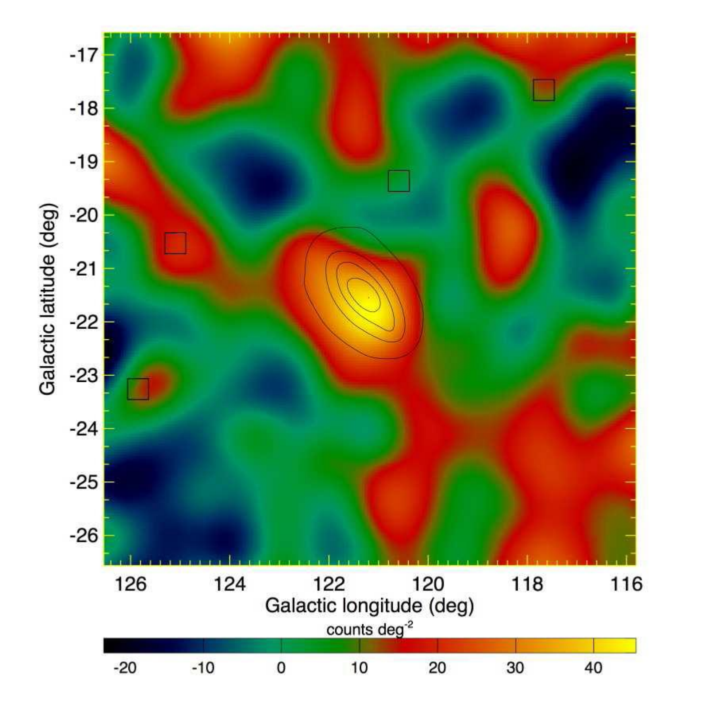
Pulsars (+)
Wolf-Rayet stars (★)
SNRs (◊)
Supergiant shells (circles)



Cosmic-ray intensity correlated with massive star-forming regions as identified by Wolf-Rayet stars, supergiant bubbles, SNRs, & pulsars

Abdo, A. A. et al. 2010, A&A, 512, A7

Our Sister Galaxy: Andromeda/M31



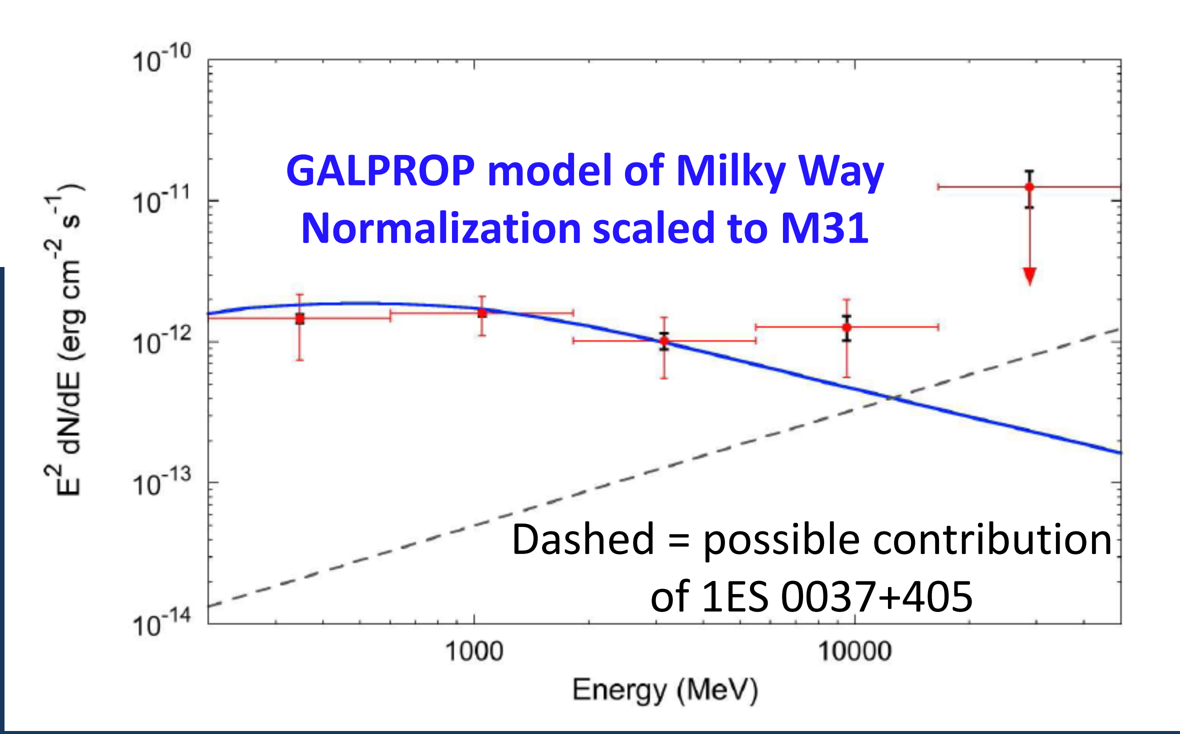
Smoothed residual counts map

0.2-20 GeV; 10° x 10° region

IRIS 100μm contours

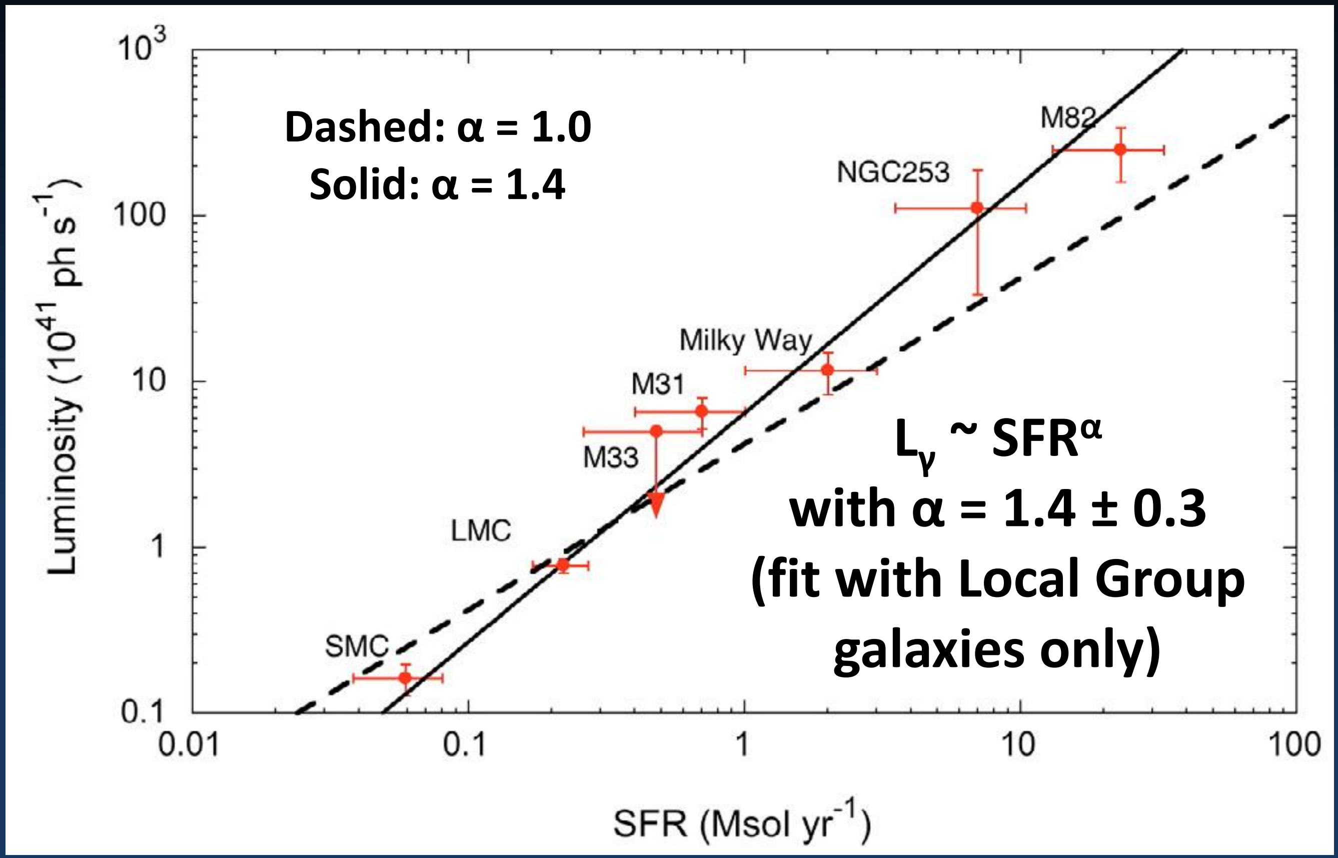
Not yet spatially resolved by the LAT

Spectrum consistent with Milky Way, but roughly half as luminous



Abdo, A. A. et al. 2010, A&A, 523, L2

Connection with Star-formation on Galaxy Scales



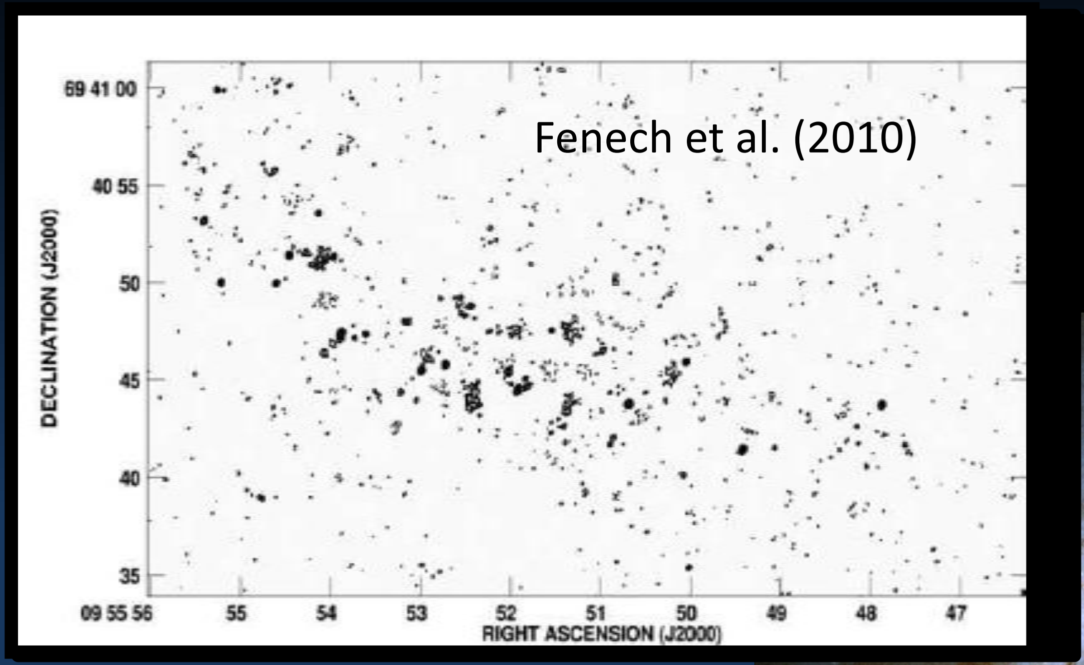
Globsl Gamma-ray Luminosity >0.1 GeV

Local Group galaxies suggest relationship between gamma-ray luminosity and SFR

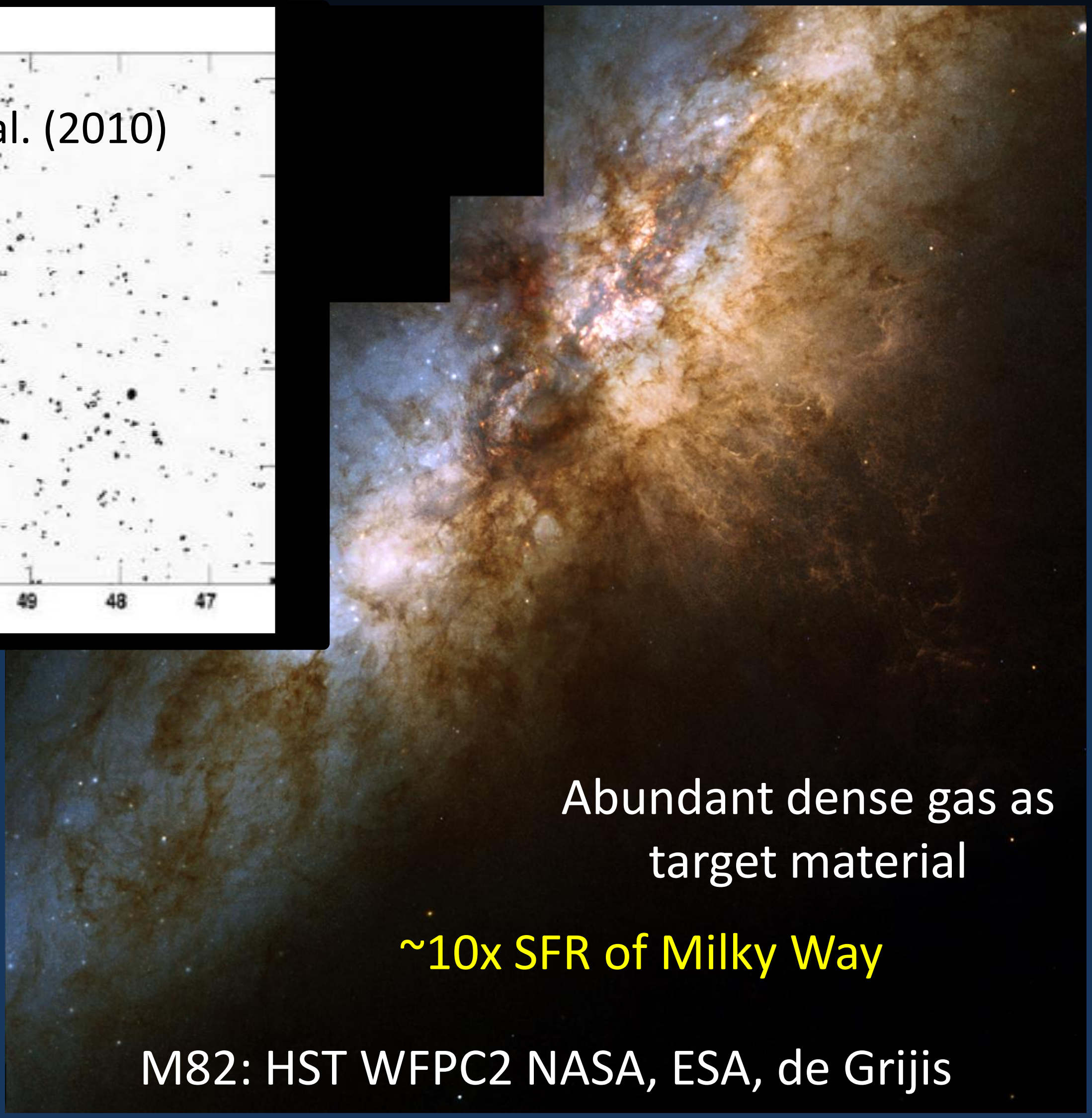
Starbursts M82 and NGC 253 consistent with trend

Abdo, A. A. et al. 2010, A&A, 523, L2

Fermi LAT Search for Starbursts



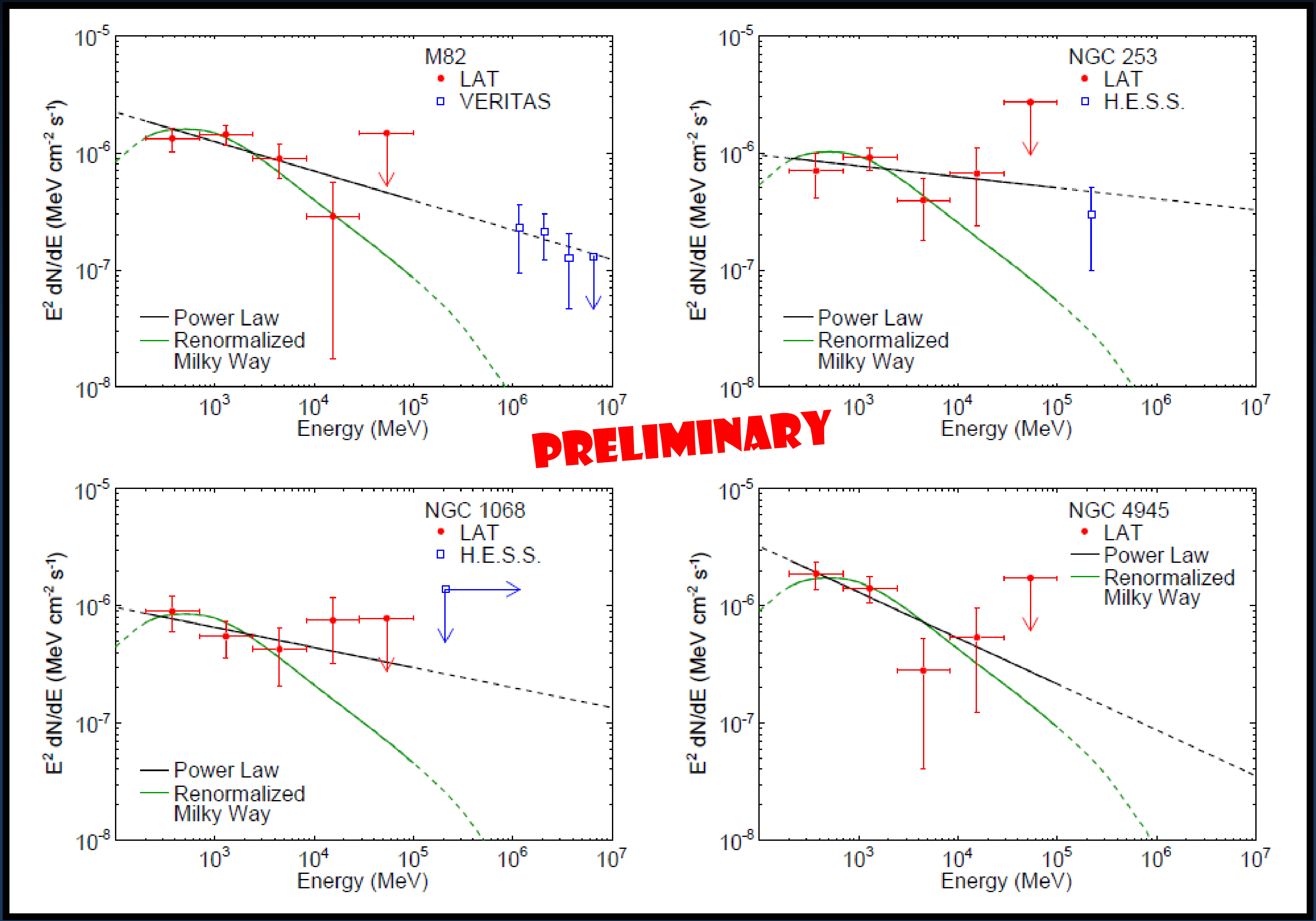
Monitoring radio sources in M82 (including 32 SNRs) with VLBI and MERLIN



Now 4 starburst galaxies are detected in high energy gamma-rays

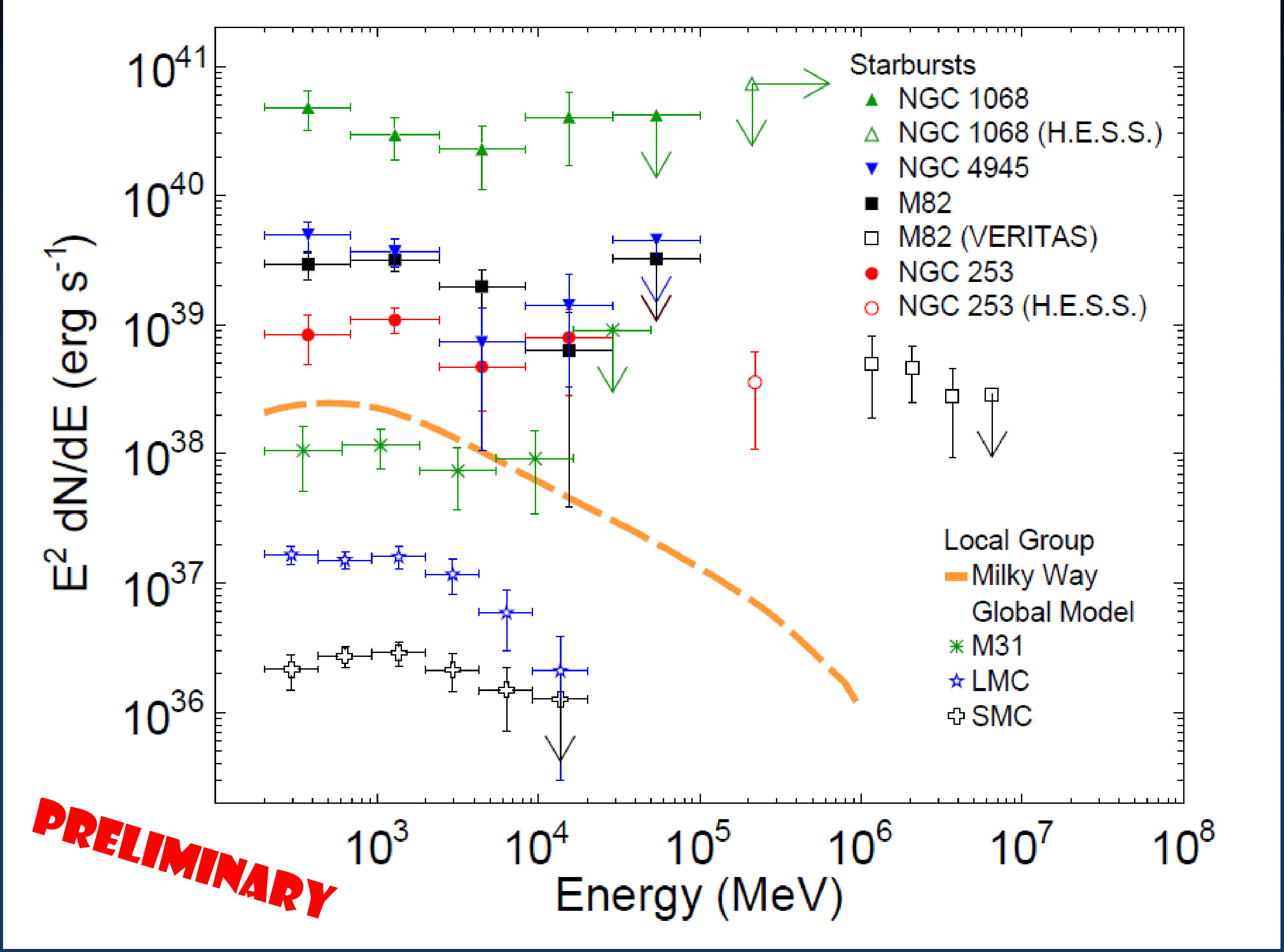
Spectral Energy Distributions of Starbursts

Combination of GeV and TeV flux measurements evidence harder spectrum than Milky Way



***New results from H.E.S.S. Collaboration on NGC 253 consistent with photon index 2.3**

Spectral Energy Distribution Comparison



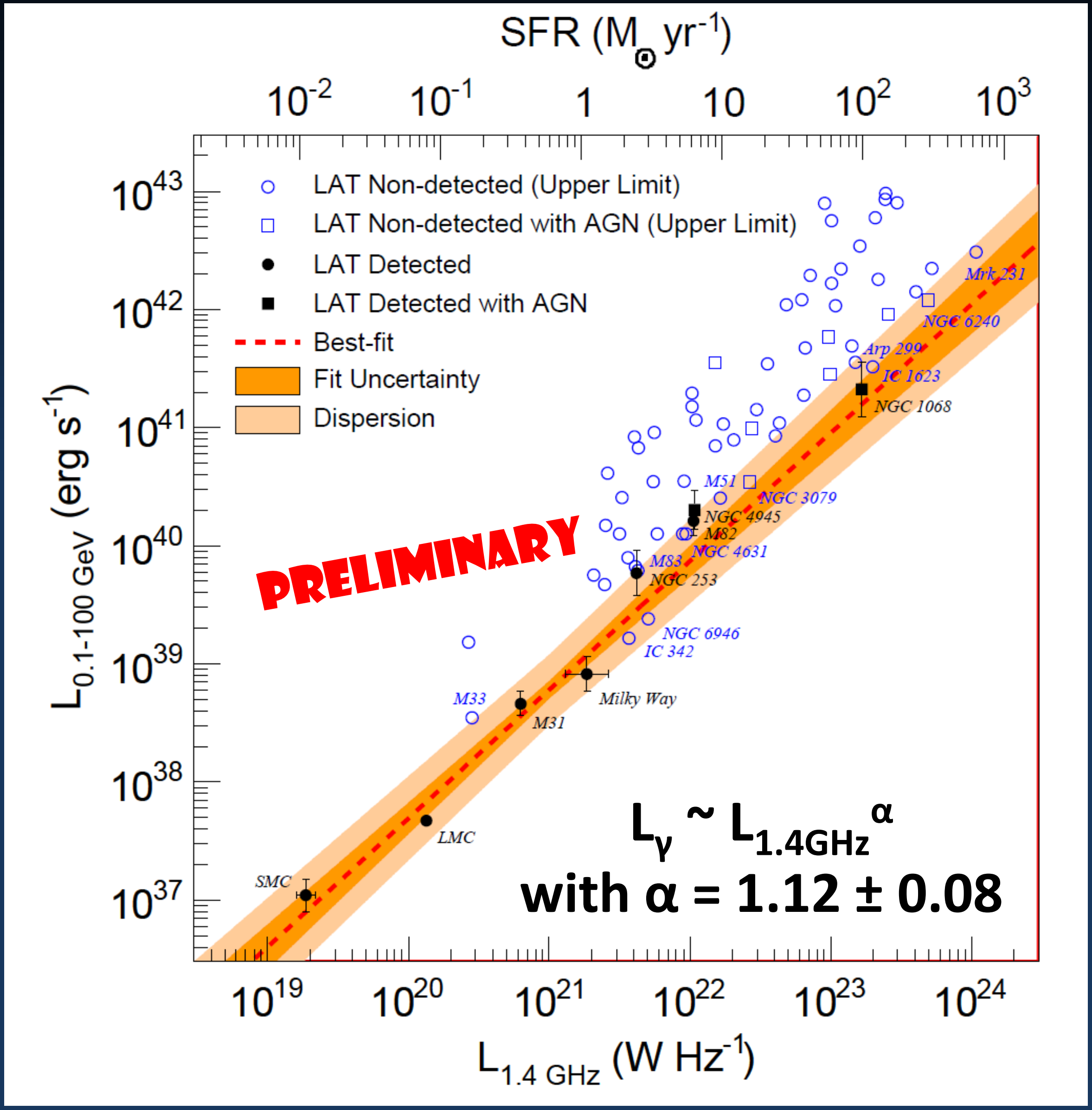
Spectra of quiescent galaxies likely to be strongly affected by energy-dependent diffusion of cosmic-ray nuclei

Radio Continuum-Gamma Luminosity Plane

Use 1.4 GHz continuum luminosity as tracer of star-formation rate

Radio-synchrotron-emitting electrons thought to be accelerated by core collapse supernova remnants – traces massive stars

Nearly linear scaling relationship found using statistical methods which include detections and upper limits
(EM algorim, Buckley James)

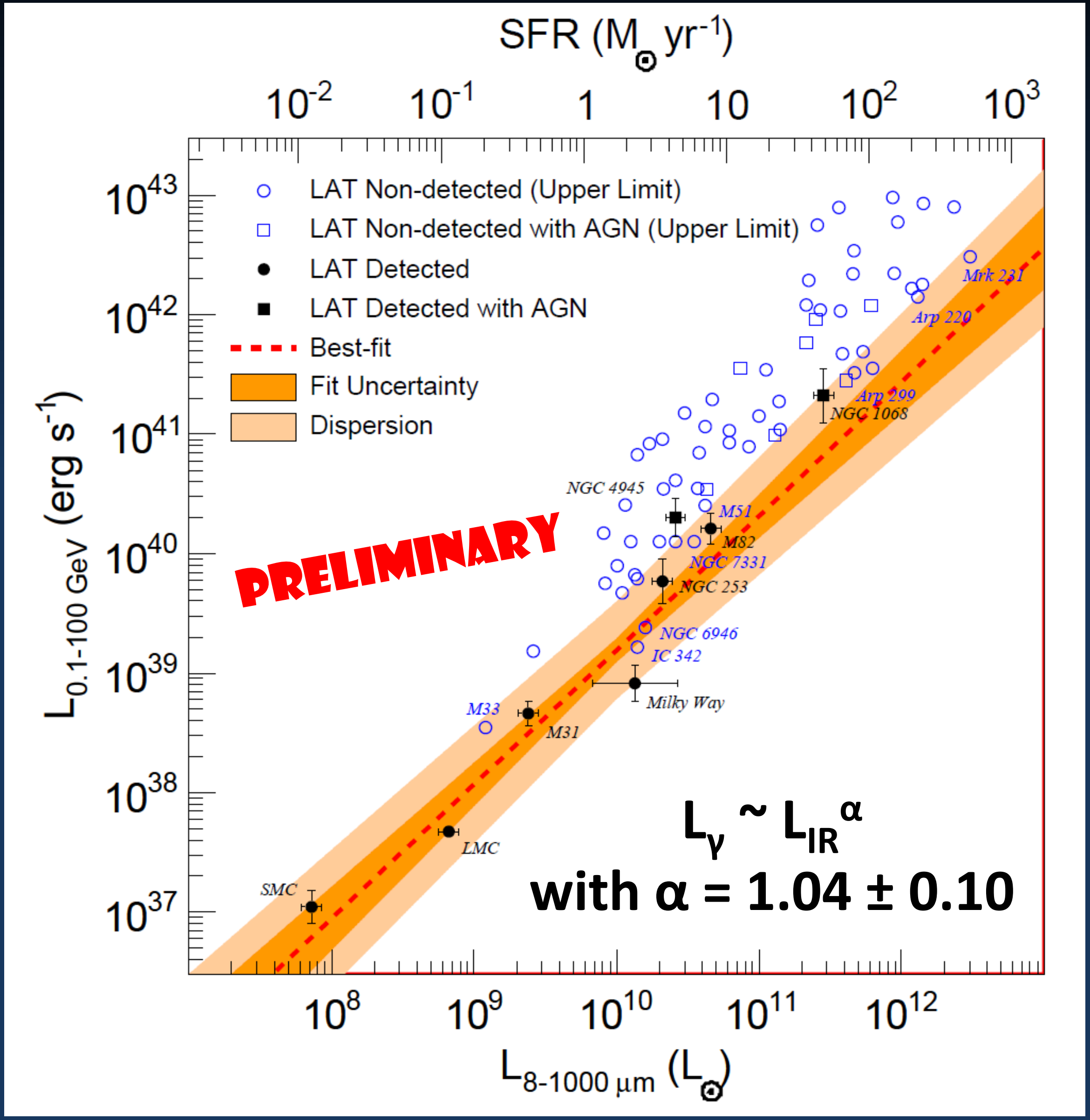


Total Infrared-Gamma Luminosity Plane

IR luminosity from dust warmed by UV radiation of massive stars

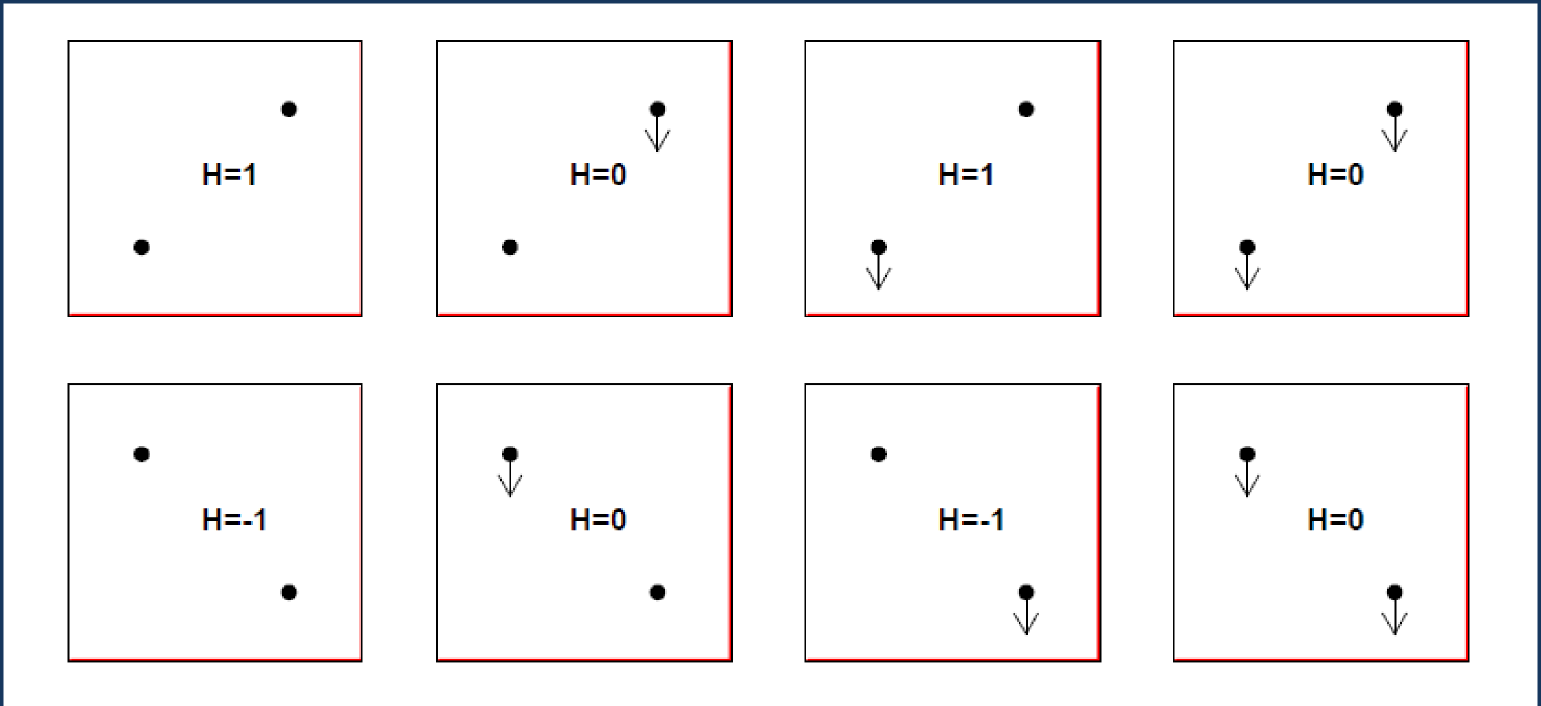
Scaling relationship consistent with linear found between wavebands

Agreement between SFR tracers not surprising given well-known infrared-radio correlation for star-forming galaxies



Correlation Significance Test

- Kendall tau correlation coefficient
  - Non-parametric, rank correlation test (i.e. how monotonic are data?)
  - May be generalized to include upper limits
- Tau coefficient is sum of rank values, H, over all pairs of points
  - Normalized so that tau=1 corresponds to perfectly monotonically increasing data with no upper limits



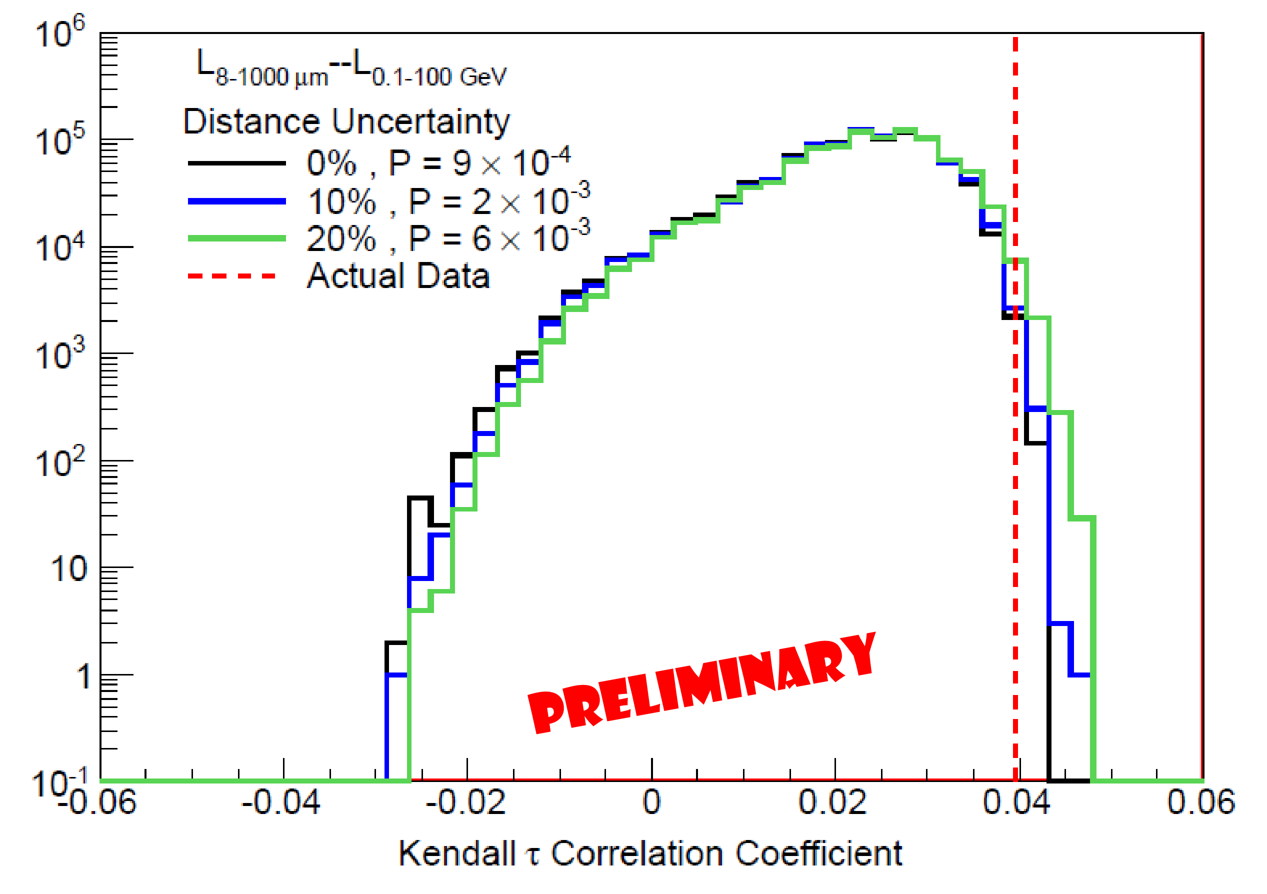
Correlation Significance Test

Perform scramble test on data, ***but keep only the observable permutations*** given LAT sensitivity (must be particularly careful when working with flux-limited samples, see works by Petrosian and Efron). Take both LAT sensitivity and distance measurement uncertainty into account.

Notice log scale

Scrambled null hypothesis datasets tend towards positive correlation mostly due to LAT sensitivity effects

Correlation significant
***p*-values < 0.01**
Suggestive, but not yet conclusive
A working hypothesis



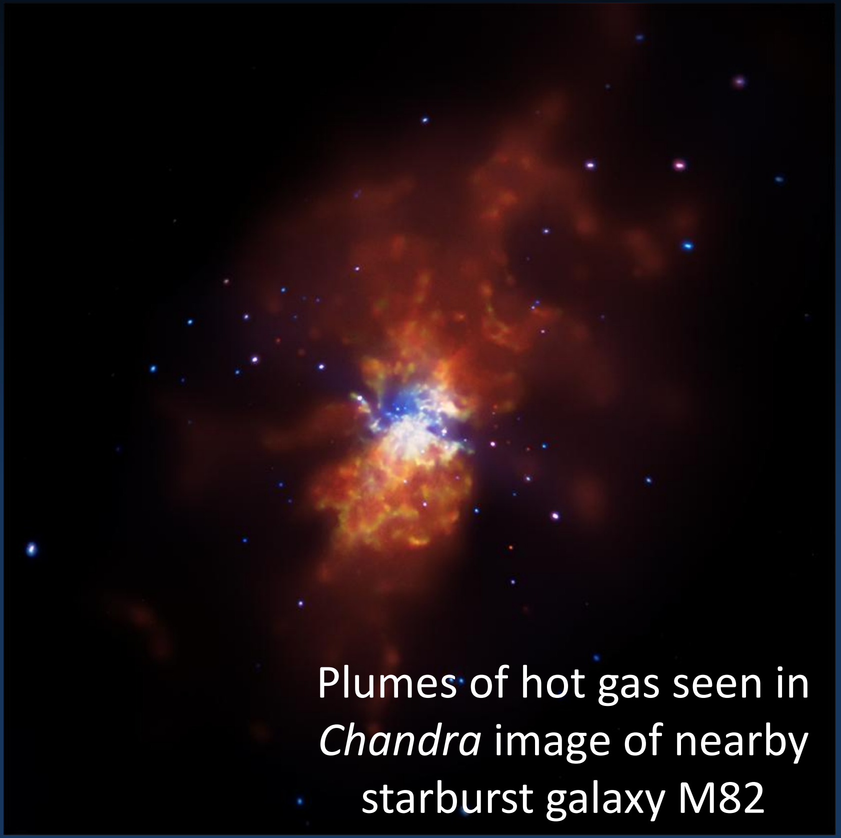
Physics of Cosmic-ray Nuclei in Starbursts

- Majority of models predict that gamma-ray spectra of starburst galaxies are dominated by hadronic processes
  - Primaries: expect similar proton/electron ratio as for Milky Way
  - Secondaries: more energy into gamma-rays than secondary leptons
  - Cannot yet completely exclude inverse Compton interpretation

- Harder gamma-ray spectra of starbursts relative to Milky Way suggest energy-independent transport/loss mechanisms
  - Closer to theoretically expected injection spectrum from diffuse shock acceleration
  - Proton ‘calorimetry’ (many nuclei interact before diffusively escaping)
  - Advection by galactic winds

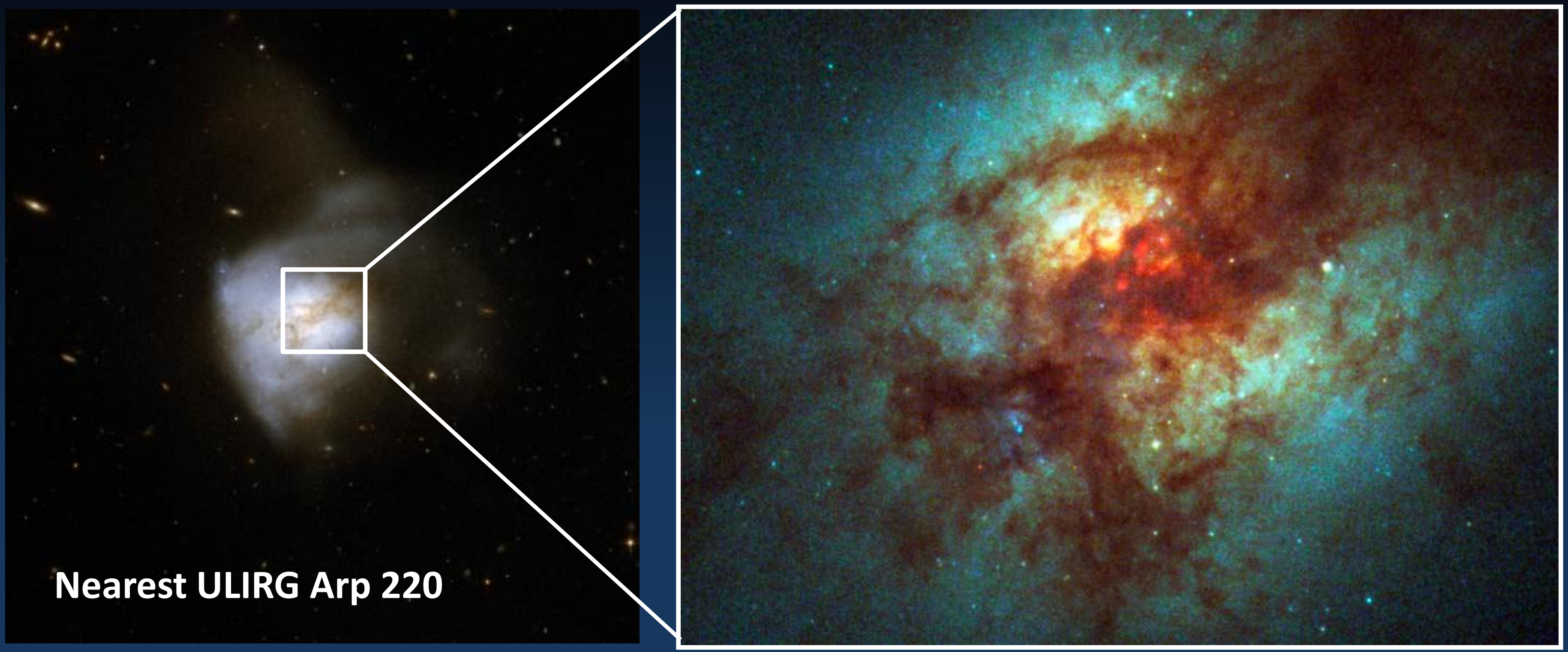
Galactic Winds

- ‘Superwinds’ observed for many low-redshift starbursts (Lehnert & Heckman 1996)
- Mechanical energy from overlapping supernovae shells / O, B associations
- A natural feedback mechanism for cosmic rays?
- Cosmic rays may be subject to adiabatic losses once outside the galaxy



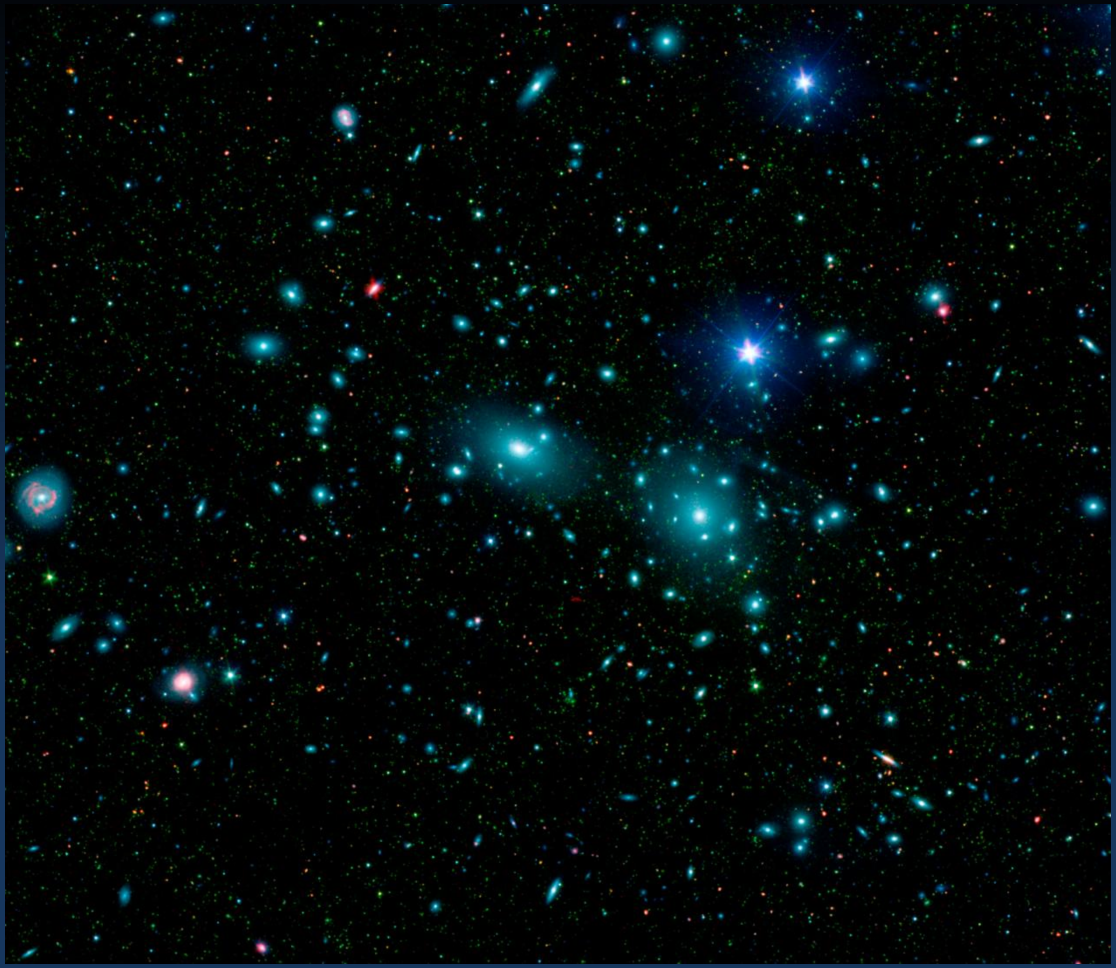
Plumes of hot gas seen in *Chandra* image of nearby starburst galaxy M82

Fermi LAT Non-detection of ULIRGs



If cosmic-ray luminosity is indeed proportional to SFR, gamma-ray non-detection of Arp 220 and other ULIRGs suggests ULIRGs are not much more calorimetrically efficient than the Milky Way, despite their large quantities of dense ambient gas

A test of the simple power-law form proposed scaling relationships (waiting for more galaxies to be detected/constraining limits from *Fermi* LAT)



Part 4

APPLICATION TO GALAXY CLUSTERS

Fermi LAT Search for Galaxy Clusters

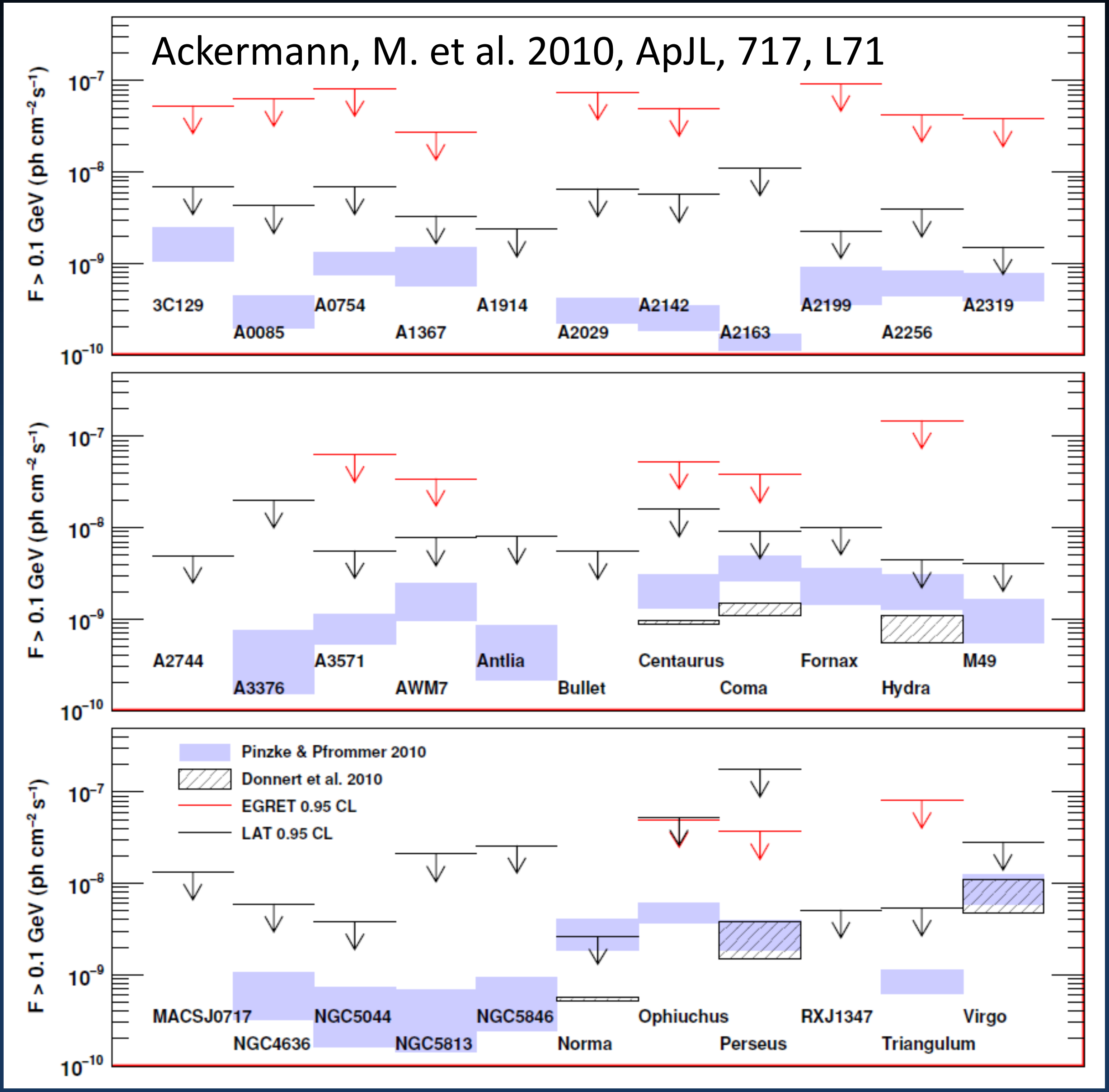
18 months of data

Typical flux upper limits >0.1 GeV
$0.5\text{-}1.0 \times 10^{-8}$ ph cm^{-2} s^{-1}

Used both point-like and extended spatial King models

Limits combined with simple models suggest cosmic-ray energy densities < few percent of thermal gas
(see also Pinzke, Pfrommer, Bergstrom 2011 arXiv:1105.3240)

For dark matter see arXiv:1002.2239



Cosmic-ray Nuclei in Intracluster Medium

- Intracluster medium as reservoir of cosmic-ray nuclei over cosmological times
  - See early works by Volk, Aharonian, Breitschwerdt 1996, Berezinsky, Blasi, Ptuskin 1997
  - Losses by inelastic collisions or ionization negligible due to low gas density
  - Confined by magnetic fields, large volume

- Sources of cosmic rays
  - Star-forming galaxies (almost guaranteed)
  - AGN (hadronic component of jets uncertain)
  - Large scale shocks, accretion and mergers (strong evidence for electron acceleration from synchrotron radio relics)

Cosmic Rays Injected by Star-forming Galaxies

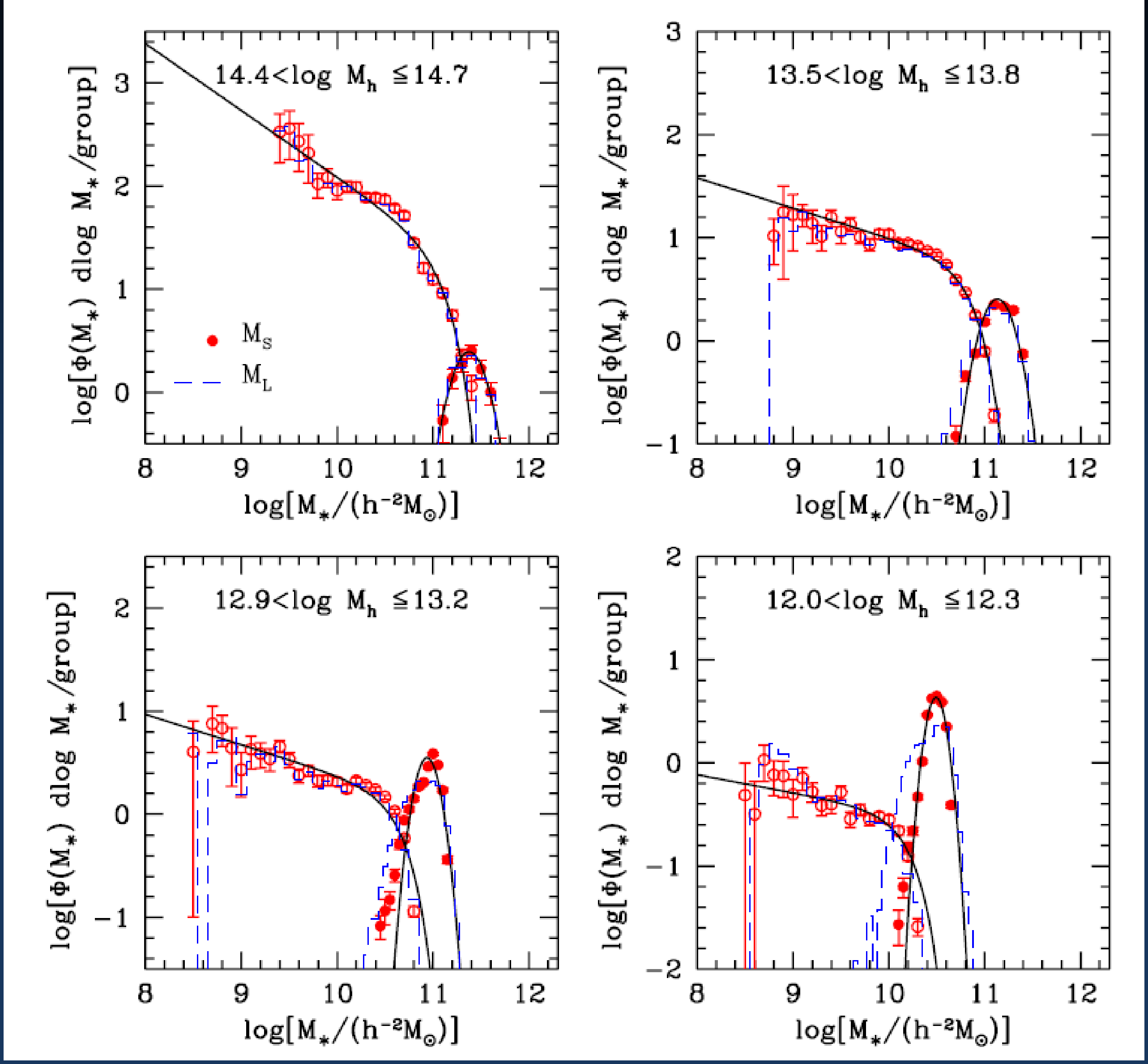
Cosmology ingredients for a rough estimate

1. **Stellar mass function of galaxies in clusters**
2. **Fraction of galaxies which are actively forming stars in clusters as a function of stellar mass**
3. **SFR of star-forming galaxies as a function of stellar mass**
4. **History of clusters in terms of galaxy formation and infall, and ability to confine cosmic rays**

(prescription suggested informally by Andrew Wetzel)

$$L_{\mathrm{CRp}} = \int dm_* \underbrace{\Phi(m_{\mathrm{halo}}, m_*)}_{1}\underbrace{(1\text{-}f_{\mathrm{quenched}}(m_{\mathrm{halo}}, m_*))}_{2}\, \underbrace{L_{\mathrm{CRp}}(\mathrm{SFR}(m_*))}_{3}$$

1. Stellar Mass Function



Yang, Mo, Van Den Bosch 2007

SDSS Data

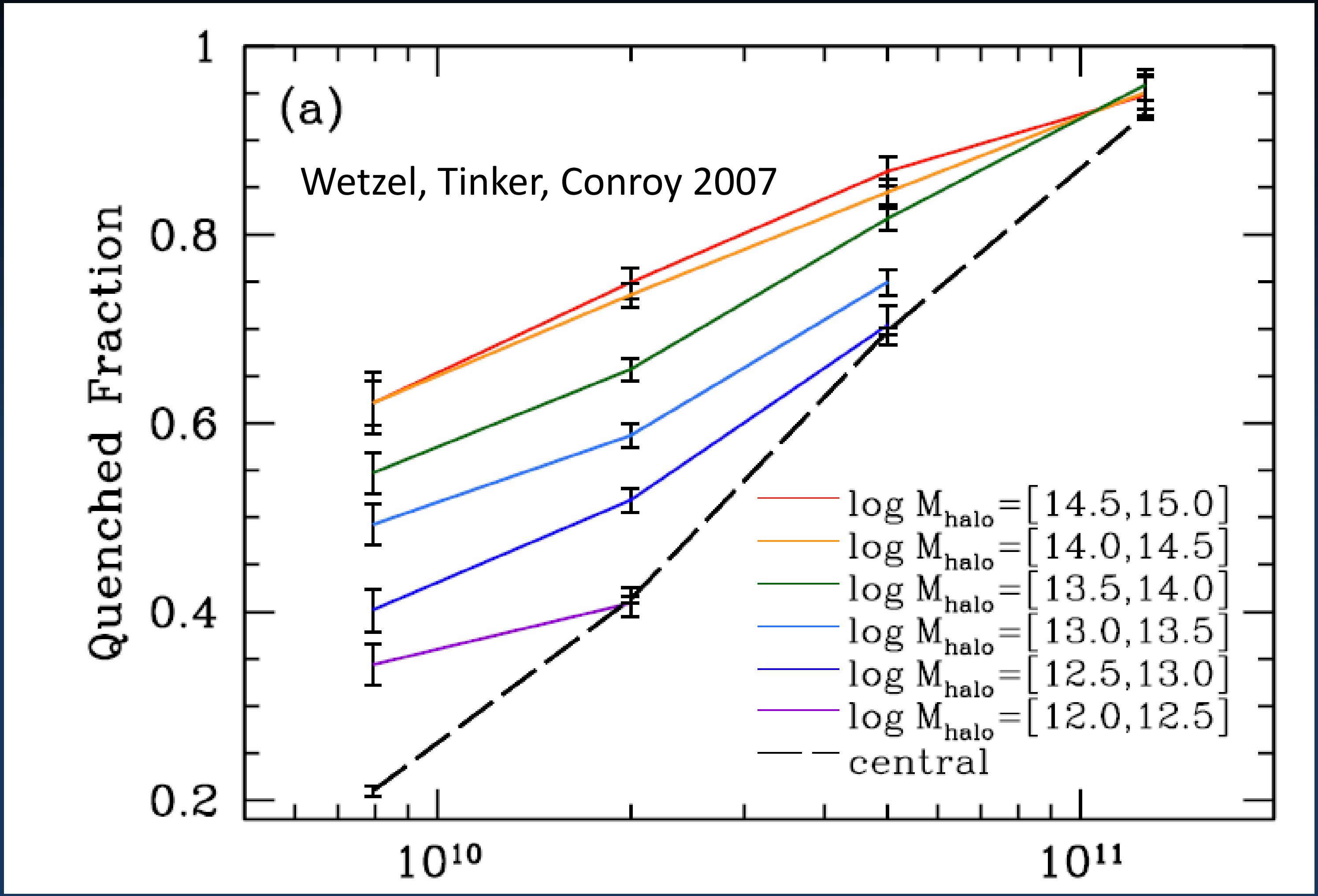
Red and blue for different methods of calculating total (dark) halo mass

Satellite and central galaxy mass functions shown separately

Solid black curves represent parameterizations

Large number of satellite galaxies in massive halos

2. Quenched Fraction of Galaxies



Using SDSS data

Satellite galaxies are increasingly likely to have quenched star formation in massive halos

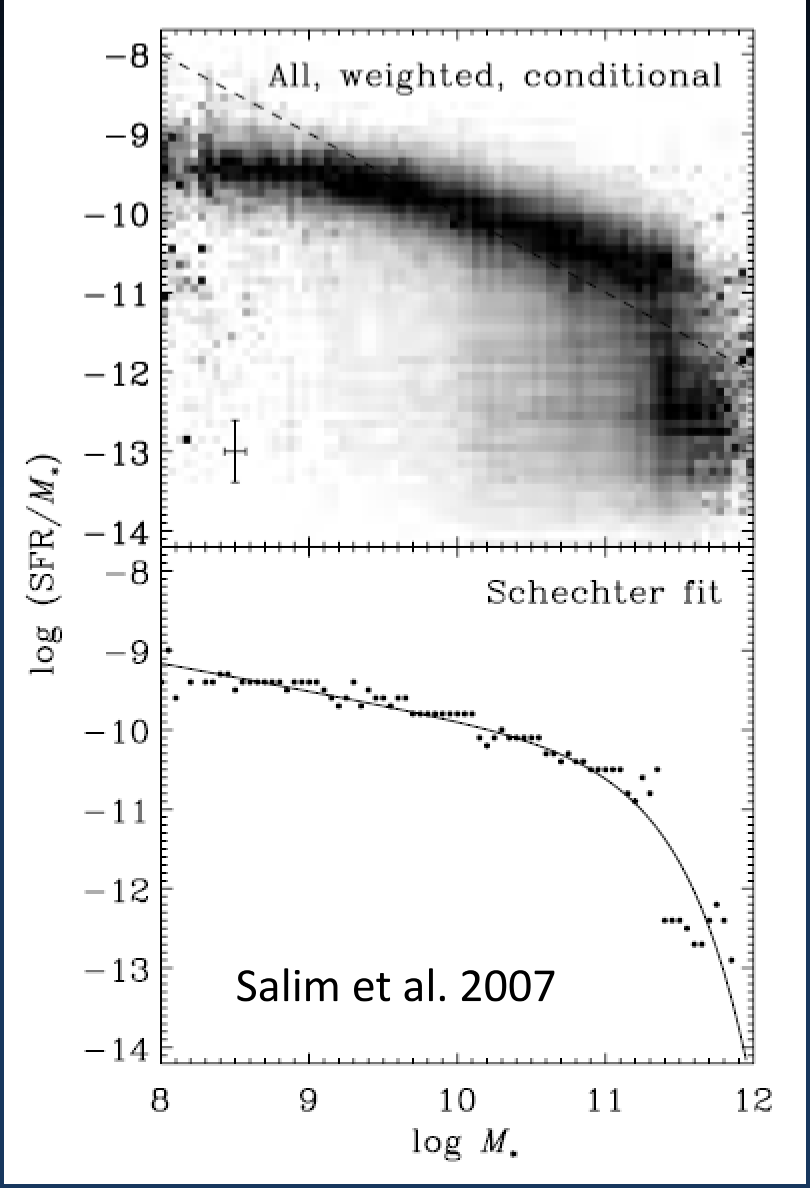
3. Specific Star Formation Rates

Overlapping samples of SDSS and *GALEX* galaxies

SSFR = SFR / m_*

Top plot normalized separately for each stellar mass range for visibility

Galaxies with high stellar mass typically have lower specific star formation rates



4. Time in Cluster

- Use 3-6 Gyr as baseline estimate

- A proper model would keep track of the galaxy histories as the cluster is assembled
  - What were star-formation rates in past compared to today?
  - Where are the galaxies with respect to center?

Example 'Back of the Envelope' Estimates

- Thermal kinetic energy = 3/2 nKT
  - Assume gas temperate of 5 keV
  - Use f_{gas} = 0.113

- Scenario in which most cosmic-ray nuclei escape into intergalactic medium (i.e. galaxies not hadron calorimeters)

- No adiabatic cooling yet

M_{Halo} (M_{Sol})	L_{CRp} (erg s^{-1})	L_{CRp} x 3 Gyr (erg)	$E_{Thermal}$ (erg)	E_{CRp} / $E_{Thermal}$
3 x 10^{14}	1.3 x 10^{43}	1 x 10^{60}	5 x 10^{62}	0.005
1 x 10^{14}	1.5 x10^{42}	1 x 10^{59}	2 x10^{62}	0.005
3 x 10^{13}	7.X 10^{41}	6 x 10^{58}	5 x10^{61}	0.001

Suggested Improvements to Approach

- Include galaxy cluster time evolution/assembly
  - N-body simulations with halo abundance matching
  - Merger histories for galaxies
  - Follow locations of galaxies in cluster halo (e.g. star formation more likely to be quenched in central regions)

- Consider importance of adiabatic loses in case that cosmic-ray protons are transported out of the galaxies by winds
  - Do galactic winds behave the same way in the cluster environment?

- Recent work
  - See discussion in *MAGIC* Collaboration paper on Perseus Cluster Observations: Aleksic et al. 2010, ApJ, 710, 634

Conclusions

- Gamma-ray observations provide unique opportunities to study the acceleration and transport of cosmic-ray nuclei in the interstellar and intergalactic medium
  - Now able to better estimate cosmic-ray luminosities and calorimetric efficiency of Milky Way and other galaxies
- Role of star-forming galaxies could be important to interpret (hoped for) future detections of galaxy clusters by gamma-ray telescopes
  - Observations by *Fermi* and current ground-based instruments constrain energy ratio of cosmic rays to thermal gas at percent level
  - Details likely depend of star-formation histories of galaxies in cluster
- Connection between high energy astrophysics and cosmology