Non-thermal Emission of Star-Forming Galaxies

Status and Outlook from keV to TeV Energies

Keith Bechtol

on behalf of the *Fermi* -LAT Collaboration

4th International Fermi Symposium

1 November 2012

Fermi Gamma-ray Space Telescope

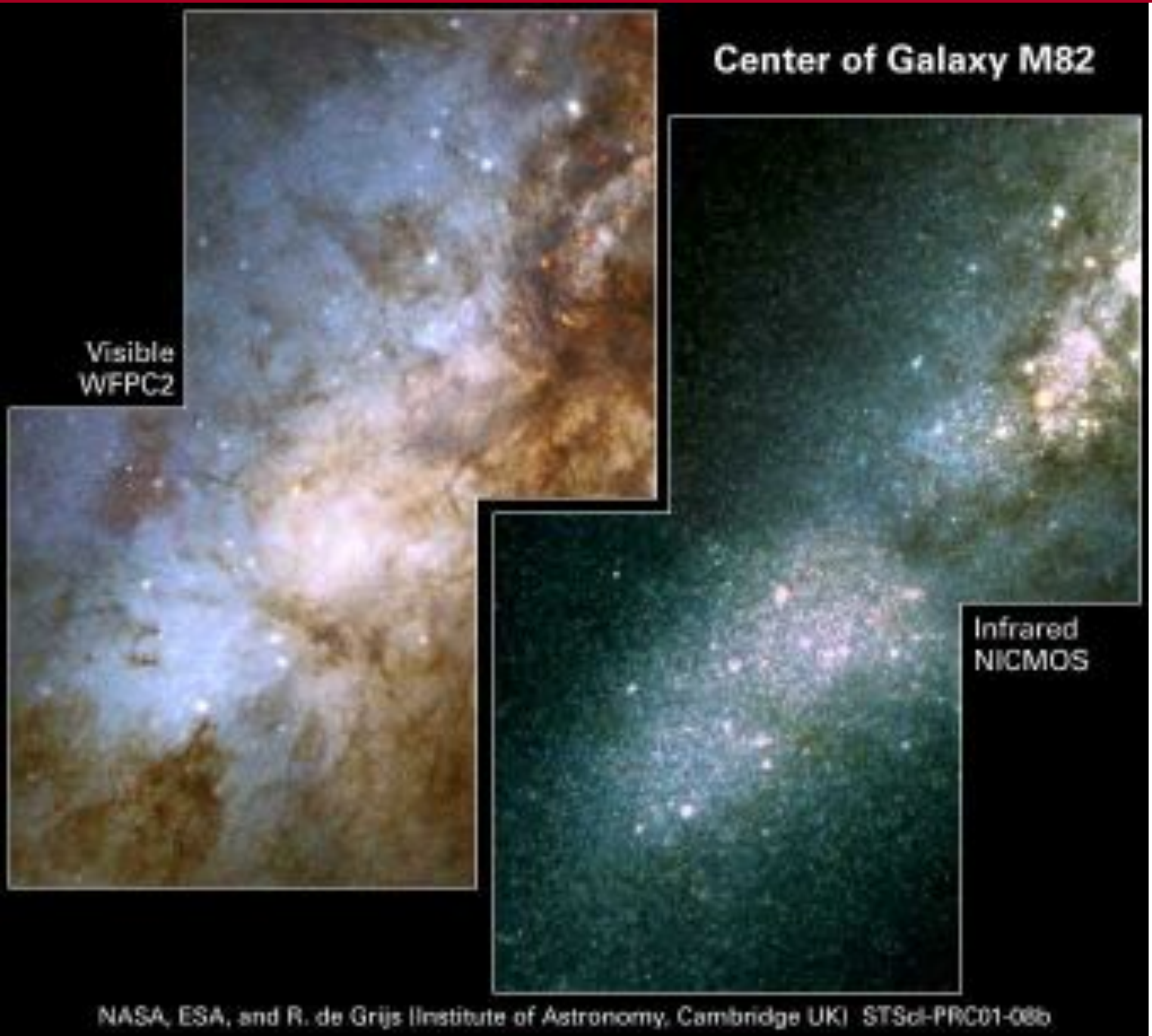
KICP Kavli Institute for Cosmological Physics AT THE UNIVERSITY OF CHICAGO

Related Posters

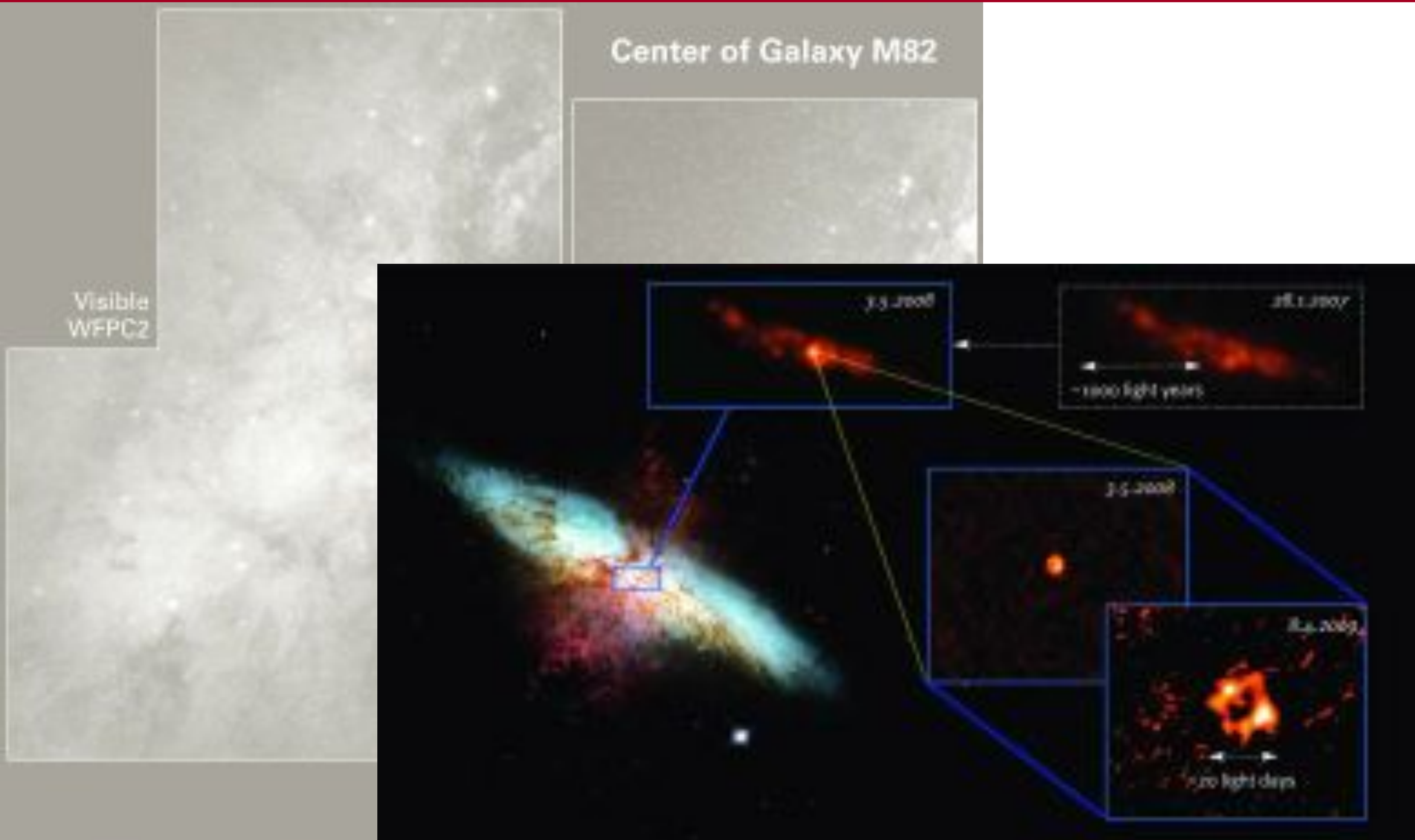
Nachiketa Chakraborty *"The Cosmic Star-Forming, Diffuse Gamma-ray Background"*

Emma Storm *"Gamma Rays from Star Formation in Galaxy Clusters"*

Star-forming Galaxies

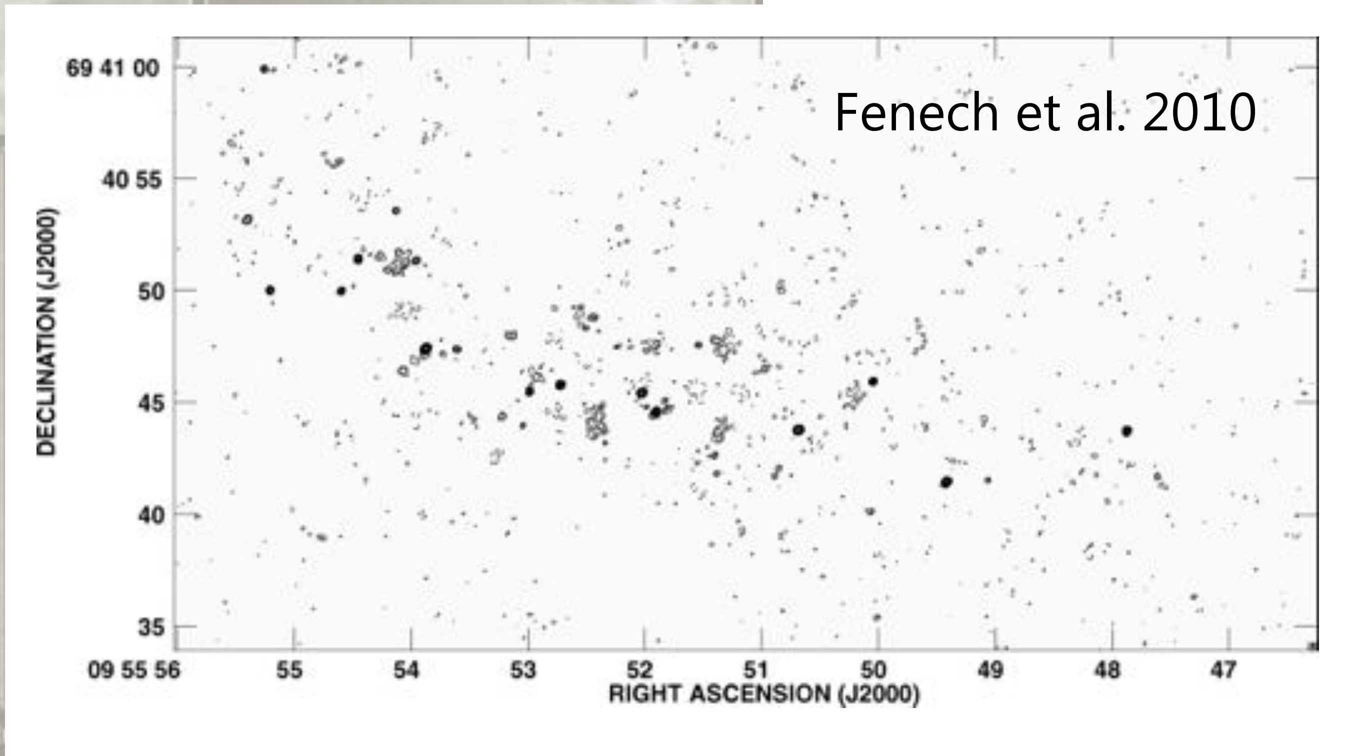


Star-forming Galaxies



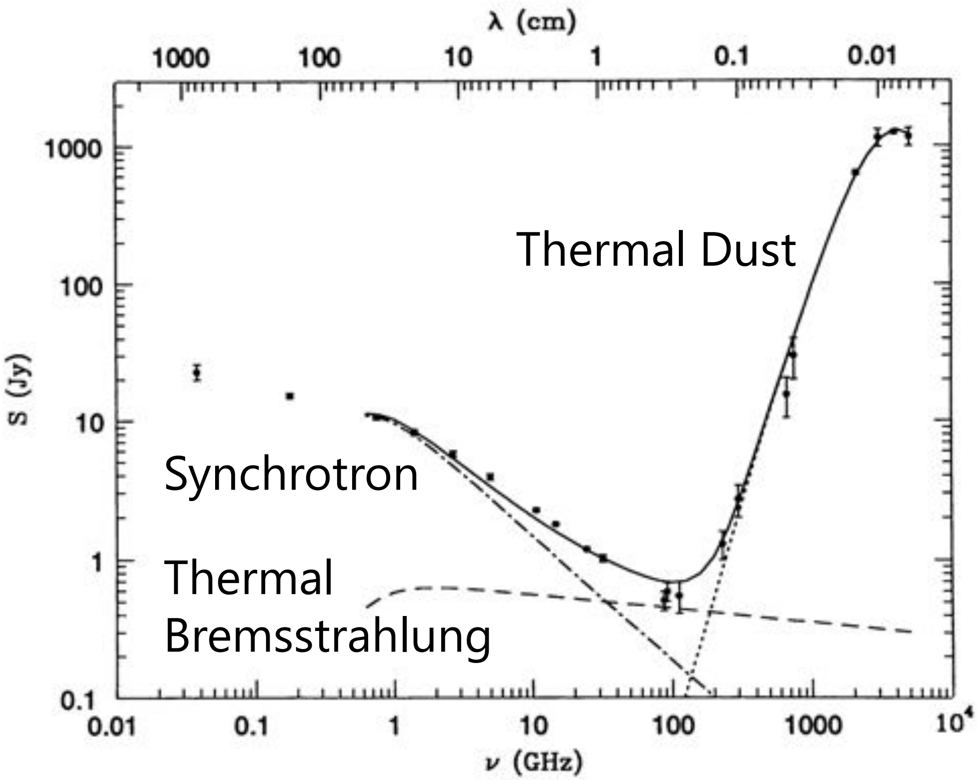
Radio Images: A. Brunthaler, MPIfR

Star-forming Galaxies



Global Emissions

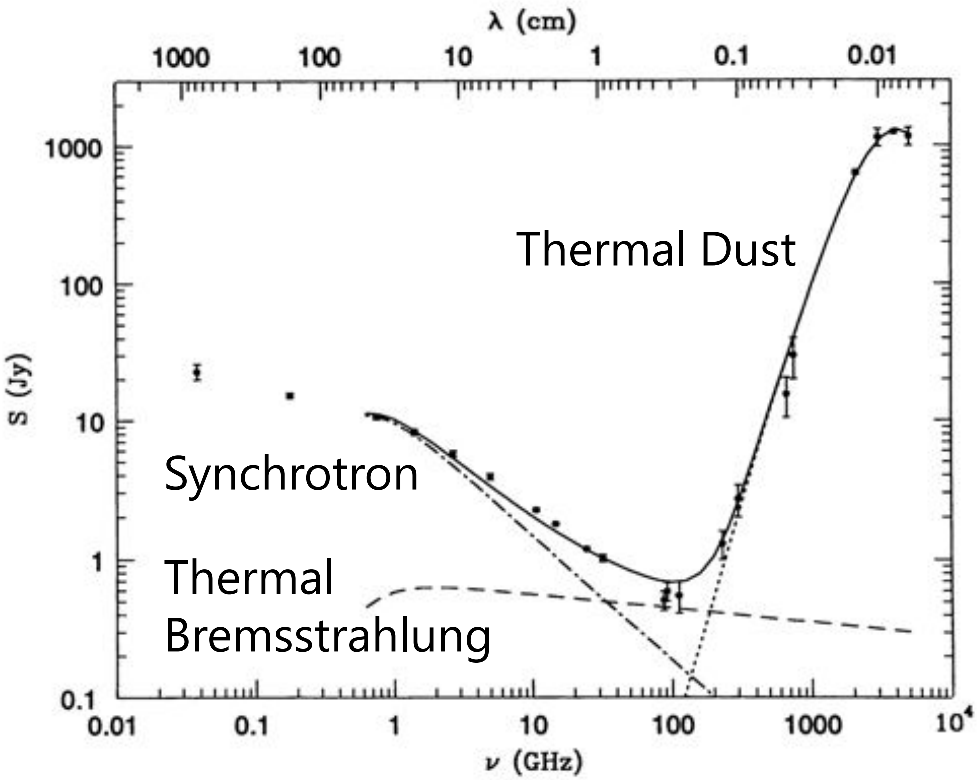
Radio and Far-IR SED for M82



Reviewed by Condon (1992). Data from Klein et al. (1988), Carlstrom & Kronberg (1991)

Global Emissions

Radio and Far-IR SED for M82



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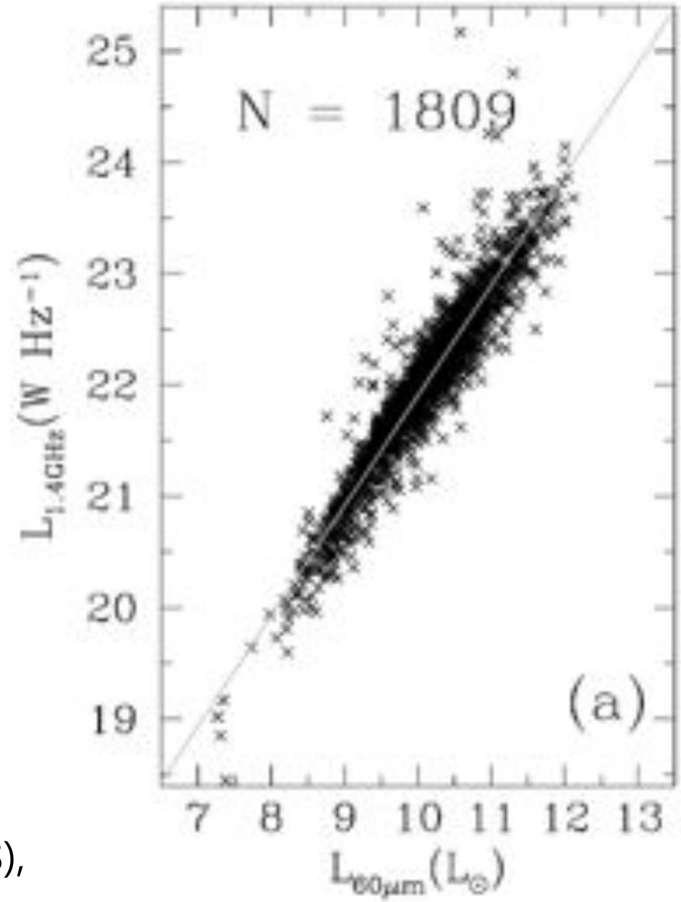
Empirical Radio Far-IR Correlation



Yun et al. (2001)

OUTLINE

New science enabled by *Fermi* during the past 4 years?

Combined GeV and TeV spectral analysis, spatially resolved LMC, population studies, estimating the IGRB contribution of galaxies

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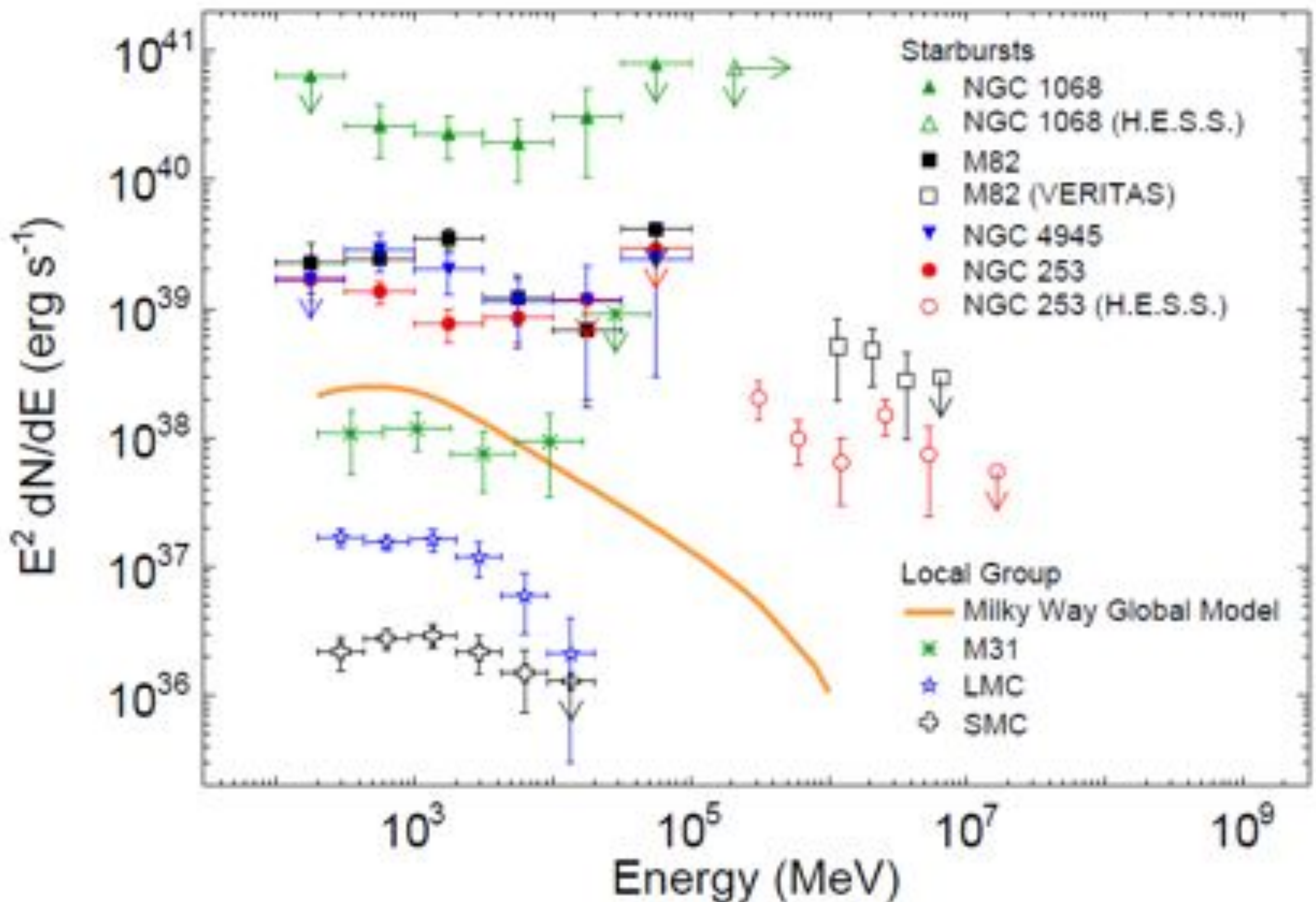
spatially resolved LMC, population studies,
estimating the IGRB contribution of galaxies

Outlook at keV, GeV, and TeV energies

LAT prospects for ULIRGs,
predicted gamma-ray flux distributions,
opportunities with *NuSTAR* and CTA

GeV and TeV Detections

Gamma-ray detected galaxies now span 3+ orders of magnitude in total gamma-ray luminosity

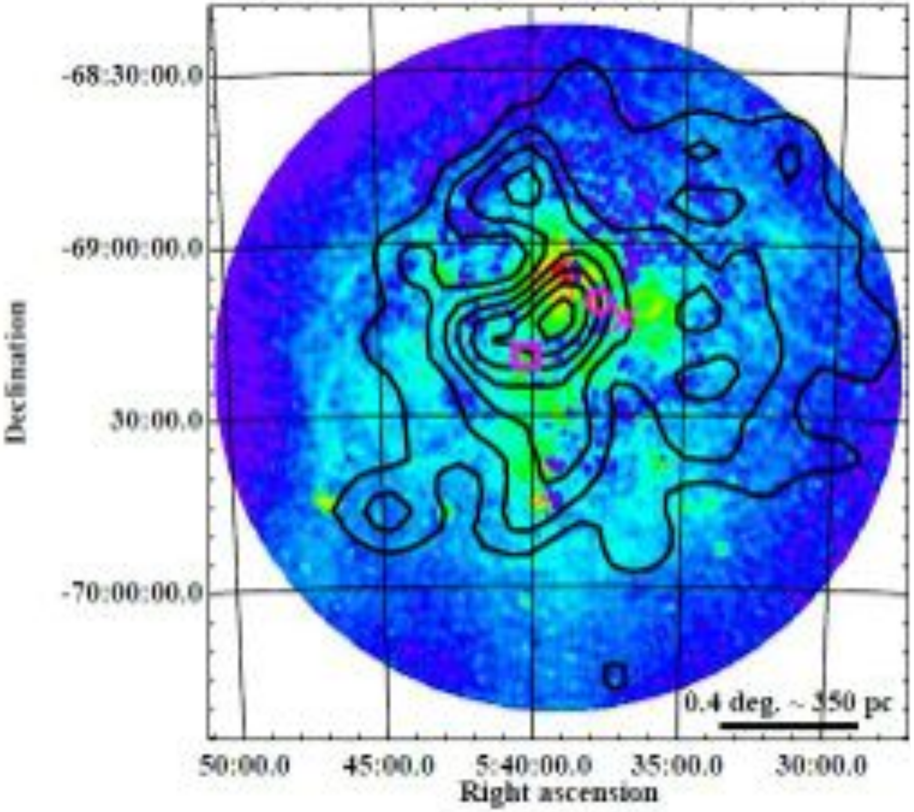


Milky Way model from Strong et al. 2010

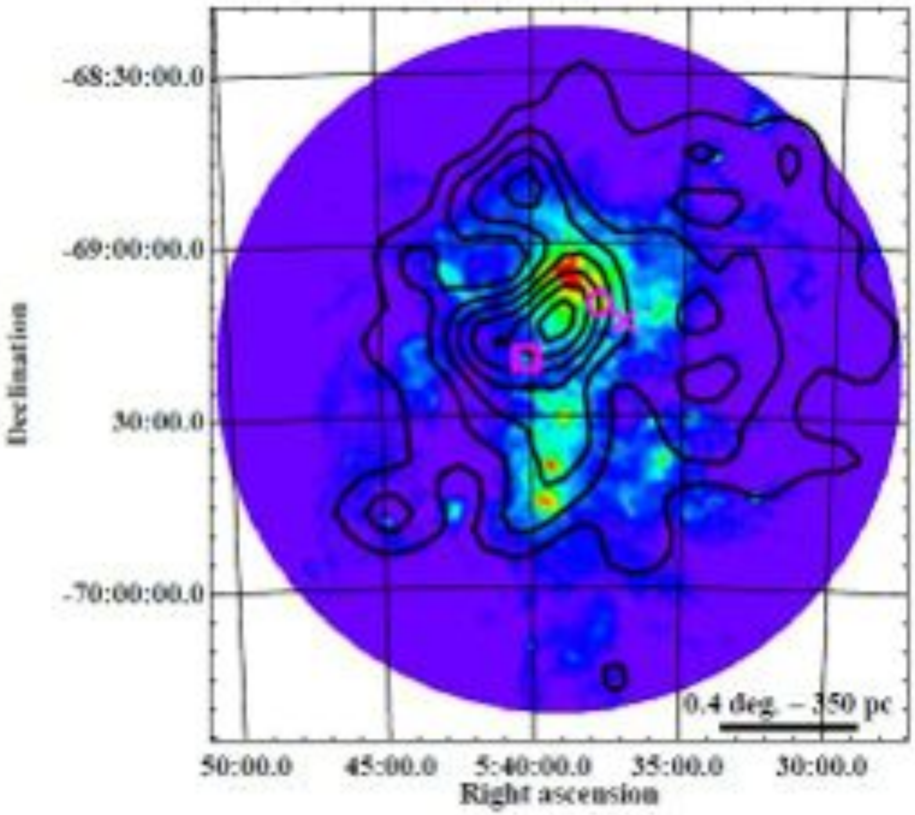
Ackermann et al. 2012, ApJ, 755, 164

Spatially Resolved LMC

1.4 GHz (Color), 1-3 GeV (Contours)



24 μm (Color), 1-3 GeV (Contours)



Propagation lengths for CR electrons (100-140 pc at ~3 GeV) and nuclei (200-320 pc at ~20 GeV) assuming they are accelerated in the star-forming region 30 Doradus (Murphy et al. 2012)

Population Studies

Galaxies whose gamma-ray emission is powered by CR interactions are an emerging source class in the *Fermi* -LAT sky survey

First "population studies" now possible

5 Local Group galaxies
+ 64 starbursts selected for IR flux
and high molecular gas content
Ackermann et al. 2012, ApJ, 755, 164

see also Lenain & Walter 2011

Cosmic-Ray Energetics

Gamma-ray Luminosity ≈ CR luminosity
× Interaction Efficiency

Distinct for leptons and nuclei

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In SNR paradigm of CR origin…

CR luminosity = SN Rate (Related to SFR)
× SN Energy
× Acceleration Efficiency

Universal on average?

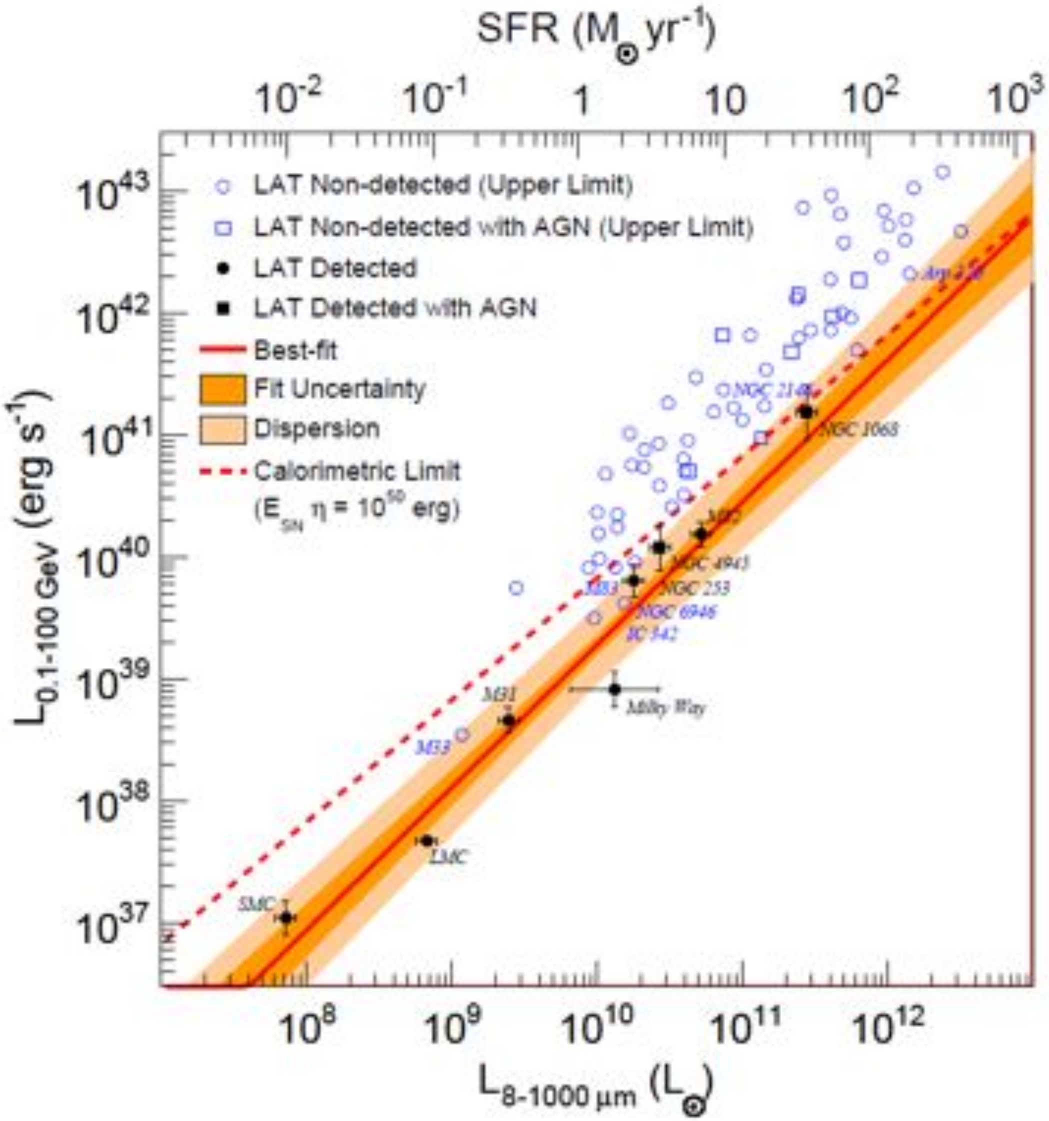
Luminosity Scaling Relations

Gamma-ray vs. IR Luminosity

Power law slope = 1.17 ± 0.07
Sqrt(variance) = 0.24

Upper limits included in fit

Correlation significance accounting for selection effects and distance uncertainties
P < 0.005
(*P* < 0.02 excluding galaxies hosting *Swift* -BAT AGN)



Ackermann et al. 2012, ApJ, 755, 164

Luminosity Scaling Relations

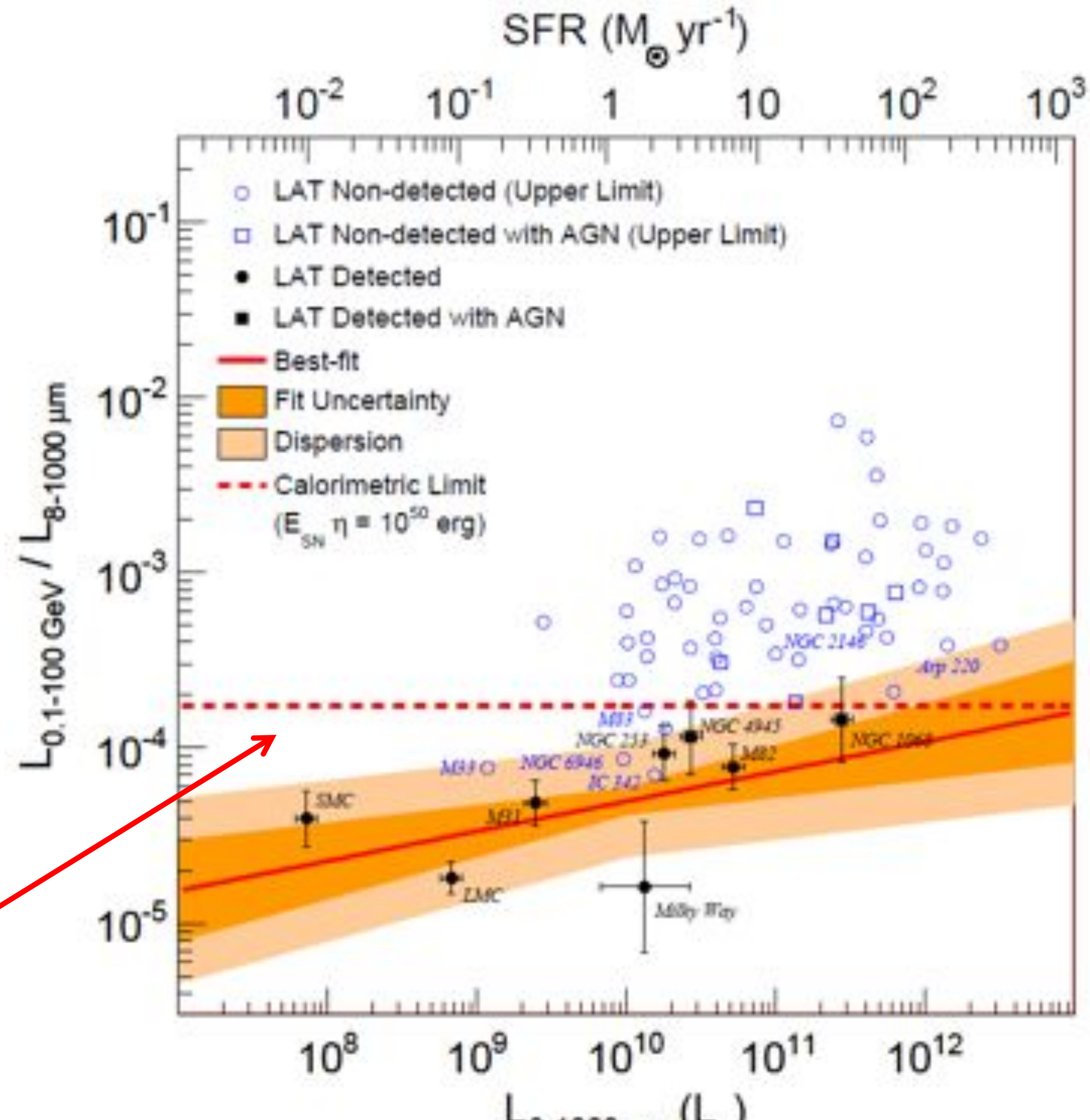
Gamma-ray vs. IR Luminosity

Power law slope = 1.17 ± 0.07
Sqrt(variance) = 0.24

Luminosity ratio is measure of gamma-ray yield per unit star-formation

In "calorimetric limit", inelastic collisions dominate CR energy losses

(here, assume each SNR injects 10^{50} erg of CR nuclei)



Ackermann et al. 2012, ApJ, 755, 164

Cosmic-Ray Energetics

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In SNR paradigm of CR origin…

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× SN Energy
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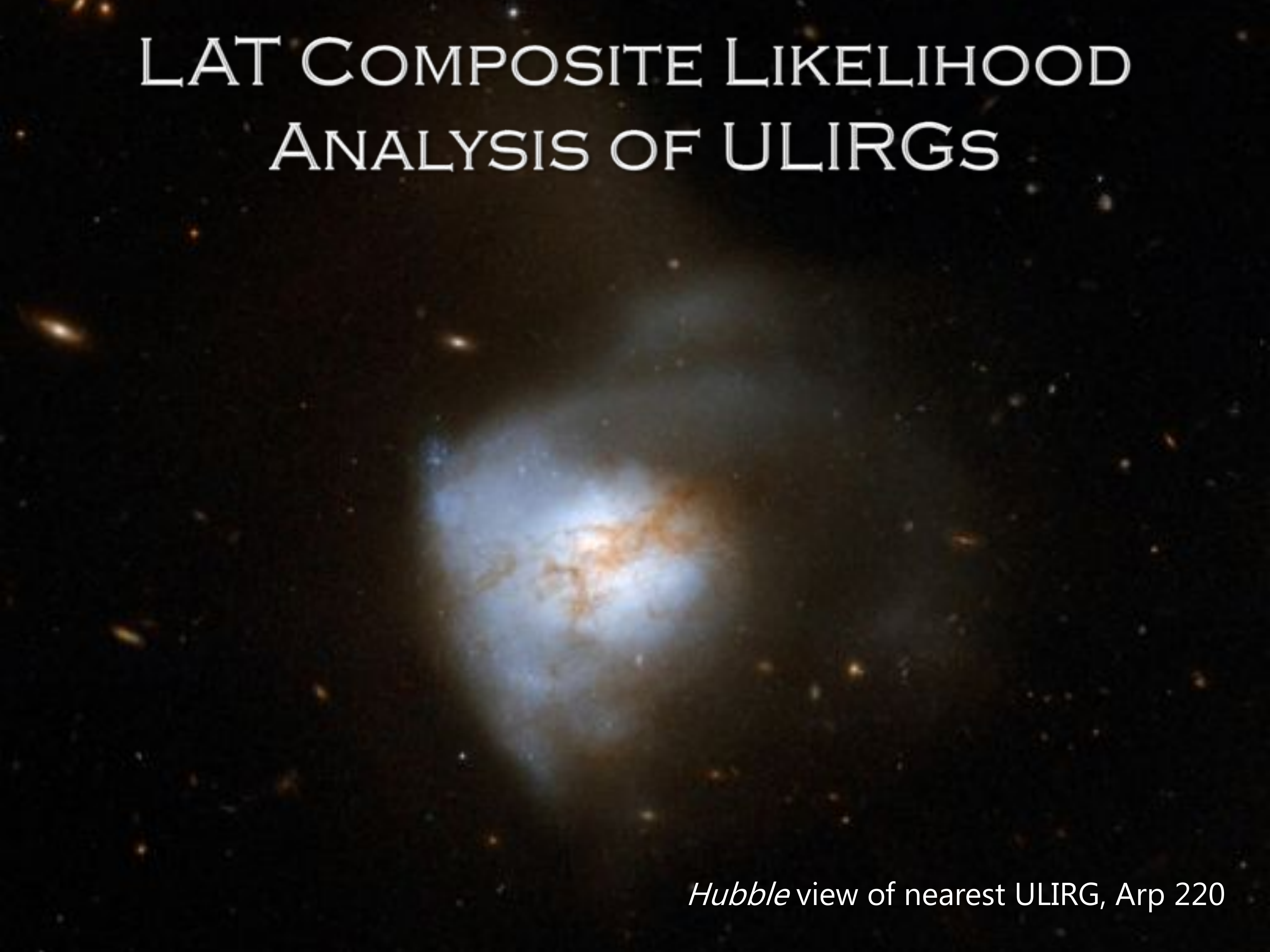
Universal on average?

Scaling relation between gamma-ray luminosity and SFR consistent with prediction of SNR paradigm

Infer "calorimetric efficiencies" of 10-30% for CR nuclei in starbursts

See, e.g., Lacki et al. 2012, Persic & Rephaeli 2012,
Abramowski et al. 2012 (H.E.S.S.), Ackermann et al. 2012, ApJ, 755, 164 (LAT)

LAT Composite Likelihood Analysis of ULIRGs



Hubble view of nearest ULIRG, Arp 220

ULIRG Sample Selection

Ultra Luminous Infrared Galaxies (ULIRGs)

$L_{8\text{-}1000\mu m} > 10^{12}\ L_{Sol}$

No ULIRGs have yet been individually detected by the LAT so search for a **cumulative** signal

Rank ULIRG candidates according to ratio of predicted gamma-ray flux (using gamma-IR scaling relation) to LAT sensitivity at candidate location

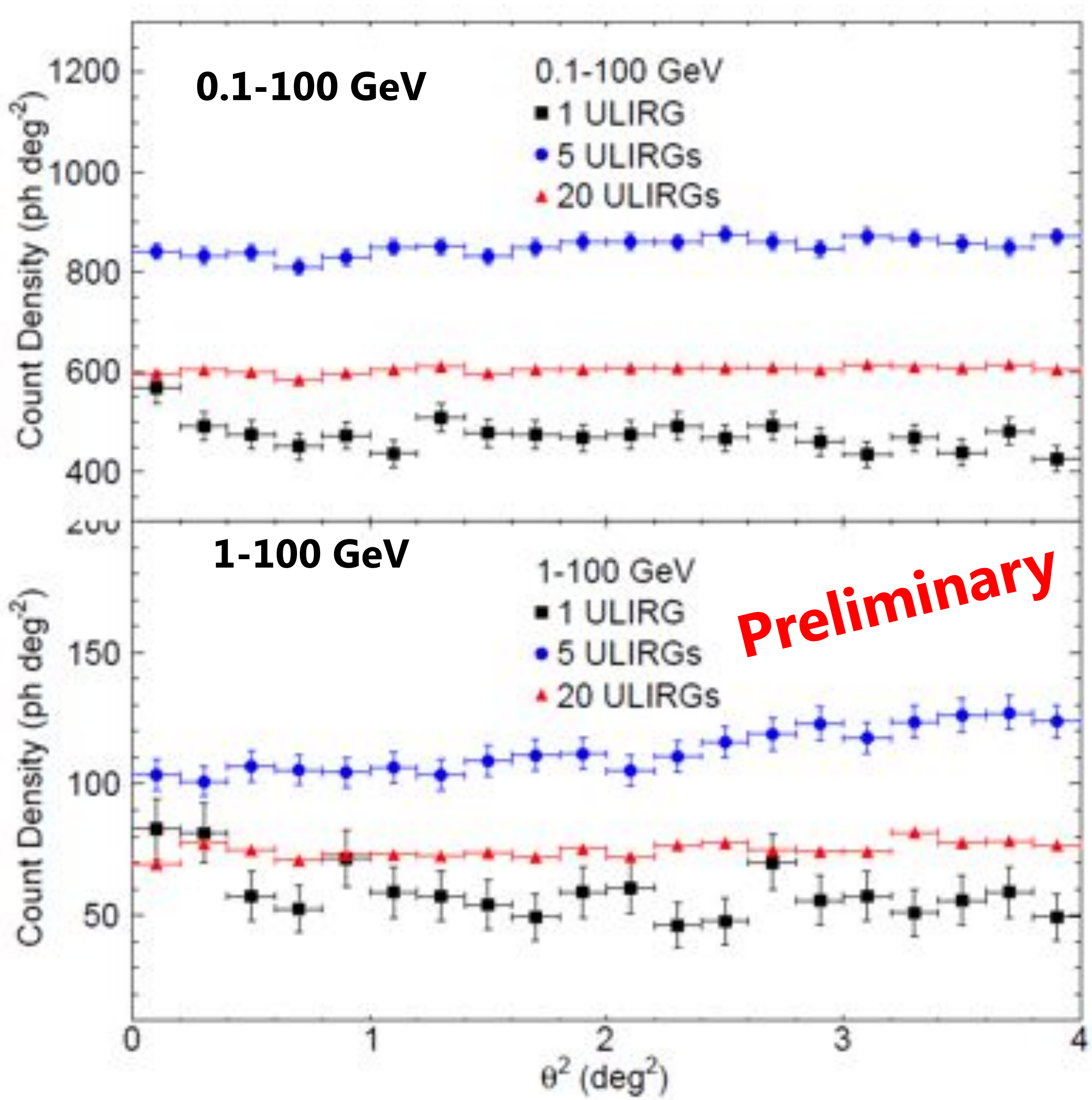
Account for AGN contribution to IR luminosity using mid-IR *Spitzer* observations (Nardini et al. 2010)

ULIRG Radial Count Densities

"Stacked" Radial Count Density Distributions

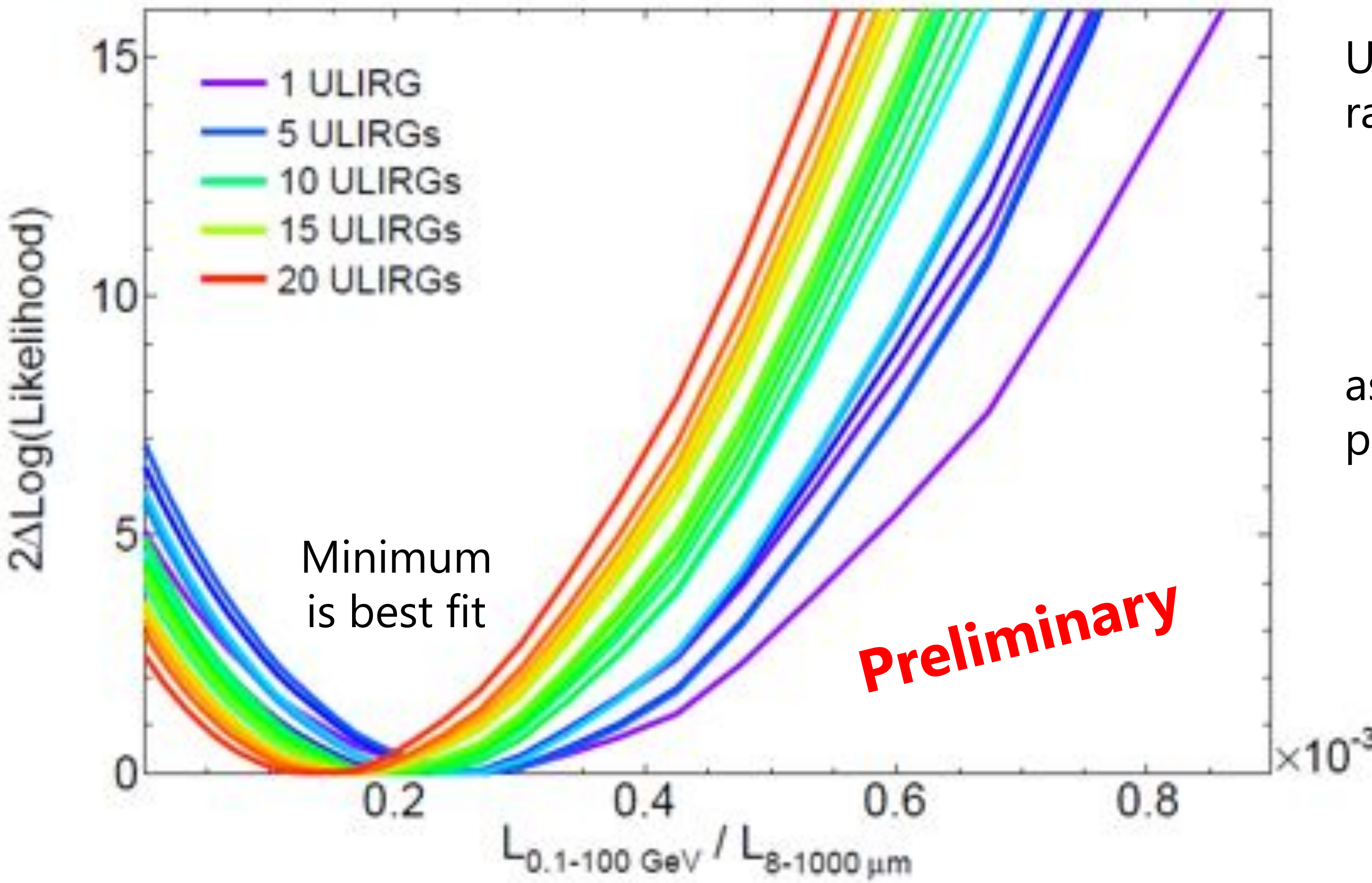
Simple search for cumulative signal

No significant excess in at low angular separations from ULIRGs



ULIRG Composite Likelihood

Likelihood Curves



Use the luminosity ratio

$$\frac{L_{0.1-100\mathrm{GeV}}}{L_{8-1000\mu m}}$$

as **global** fit parameter for ULIRGs

Incorporate conservative 0.18 dex uncertainty in AGN fractional contribution to total IR luminosity for each ULIRG in the fit

ULIRG Composite Likelihood

Significance Trending

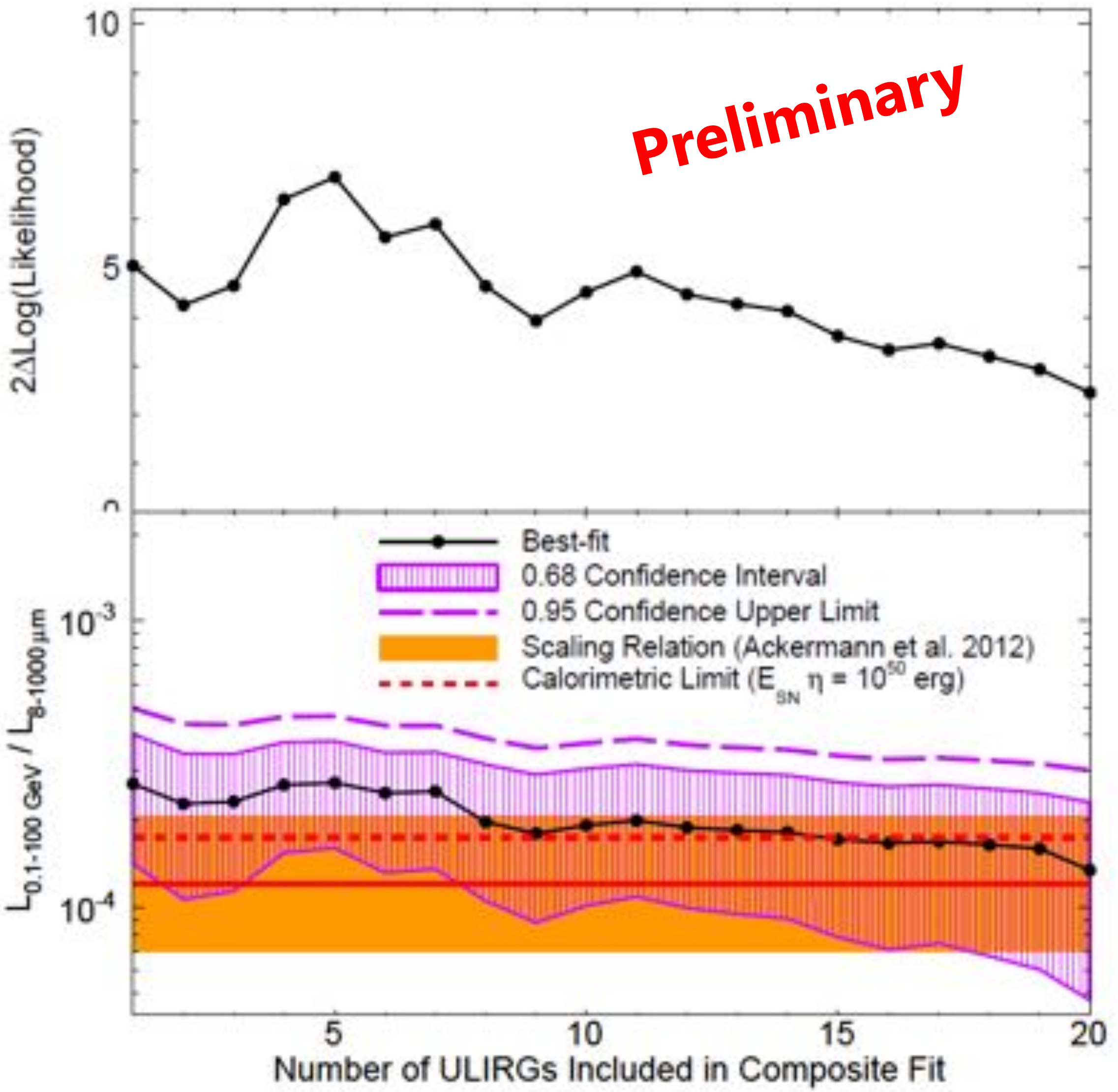
Peak significance with 5 ULIRGs (TS~7) declines when adding more objects

Arp 220 dominates significance (TS ~ 5)

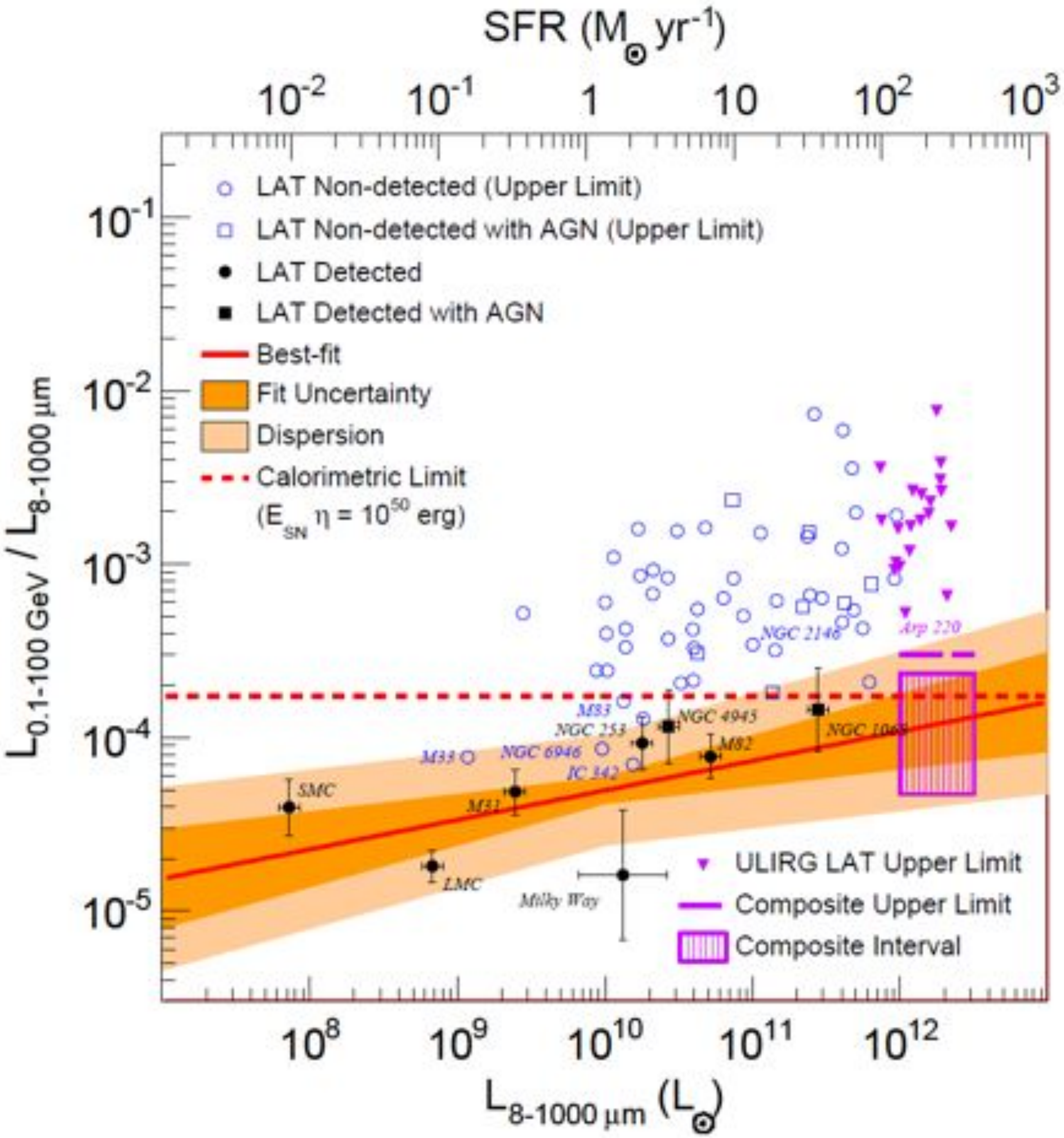
Fit Trending

68% confidence interval consistent with the scaling relation obtained from mostly lower luminosity galaxies

95% confidence level above nominal "calorimetric" limit for CR nuclei



ULIRGs In Context



New ULIRG Constraints

Composite limits most sensitive yet in the regime of extreme star formation at GeV energies

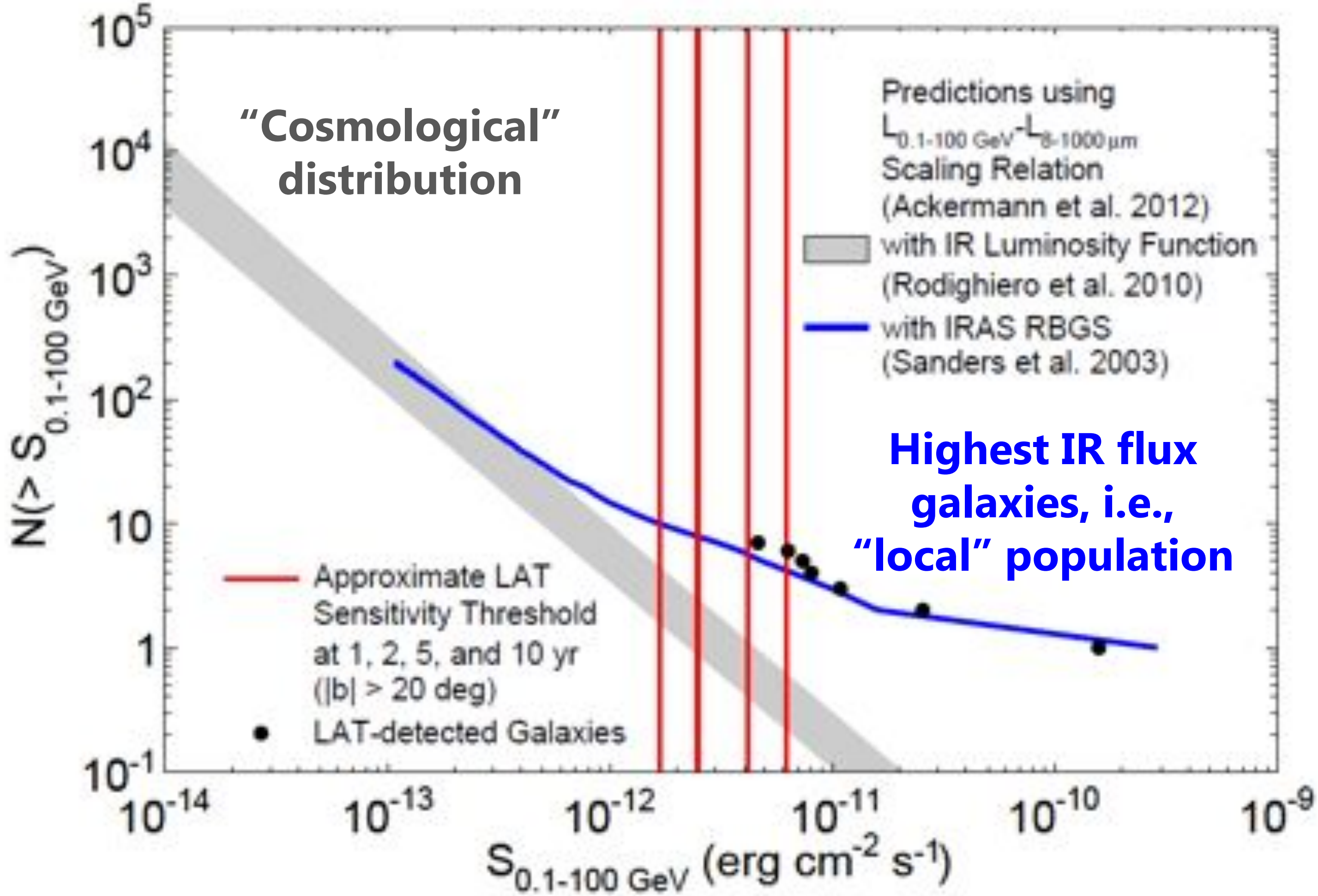
But not yet able to make a conclusive statement regarding gamma-ray emission ULIRGs due to marginal significance of signal

GeV Flux Distribution and IGRB Contribution

"Lockman Hole"
~15 deg^2
Herschel SPIRE
250, 350, 500 μm

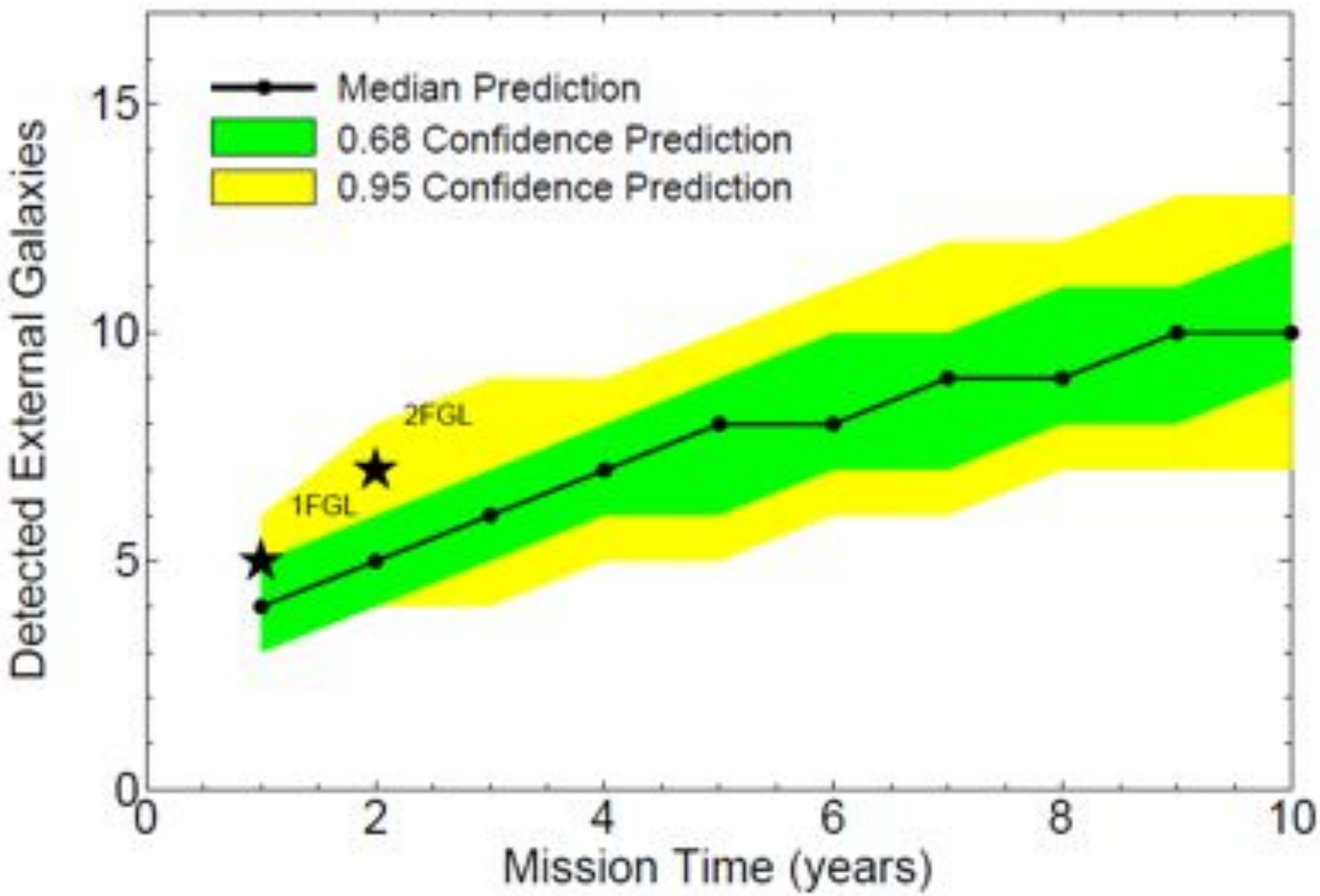
Local Flux Distribution

Enhancement to predicted number of LAT-detectable Galaxies due to our nearest neighbors within Mpc-scale distances



LAT Detection Outlook

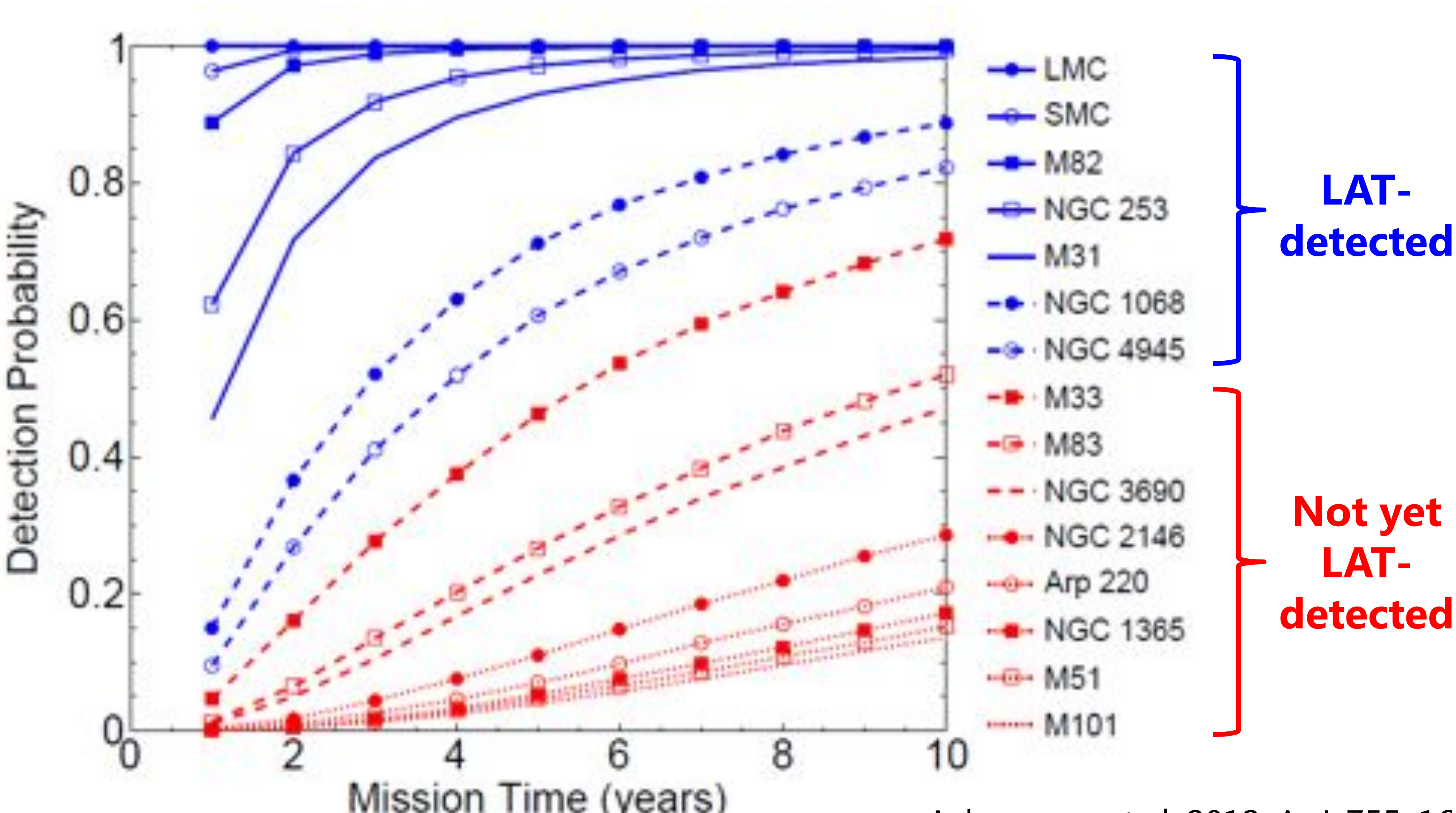
Predicted Cumulative LAT Detection Totals



Ackermann et al. 2012, ApJ, 755, 164

LAT Detection Outlook

Detection Probabilities for Individual Galaxies



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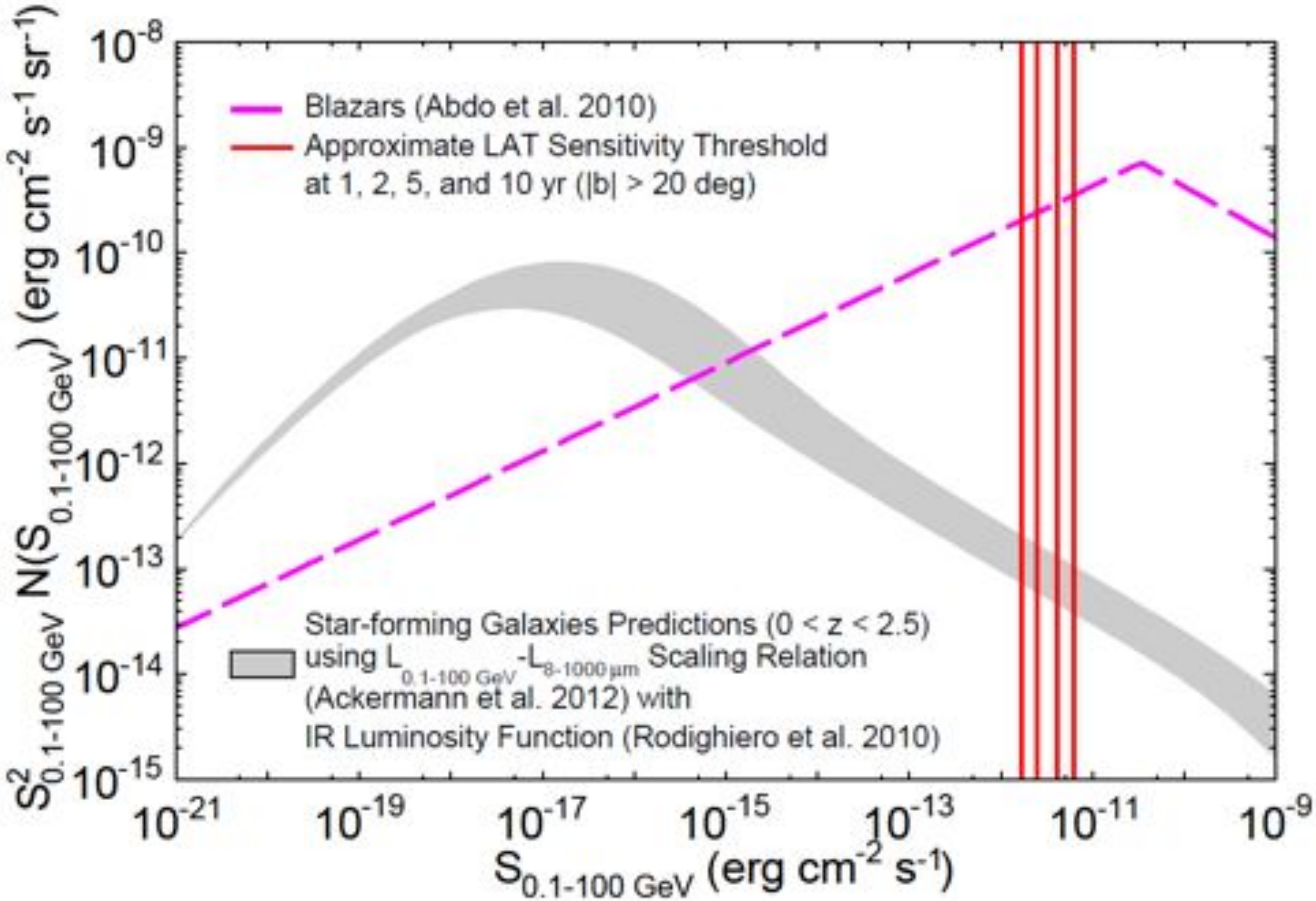
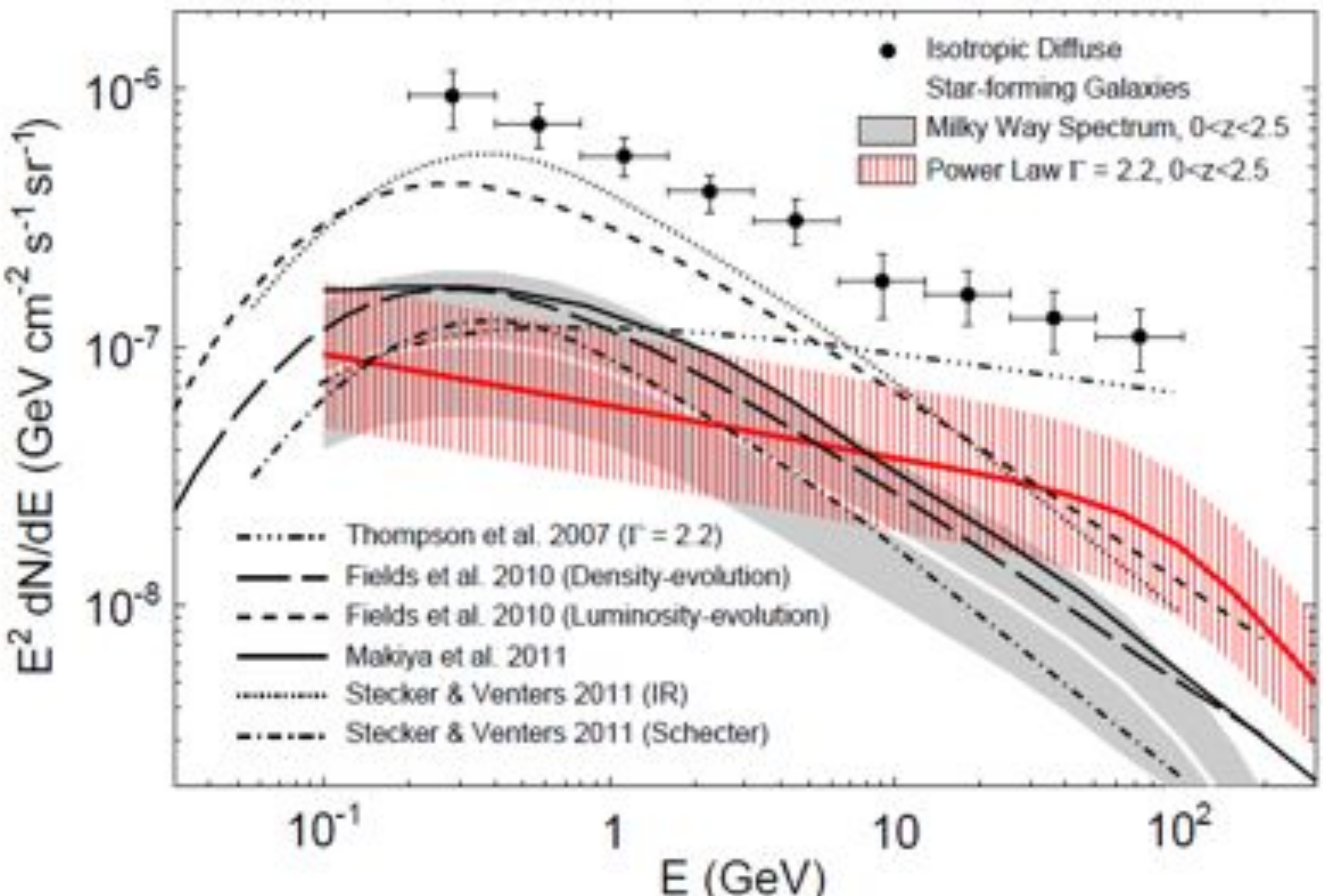
Flux Distribution Comparison

Most of the cumulative intensity of star-forming galaxies is not resolved by the LAT into individual objects, in contrast with blazars



IGRB Contribution

Contribution by unresolved star-forming galaxies is comparable to that of blazars
4-23% of LAT-measured isotropic diffuse intensity >0.1 GeV



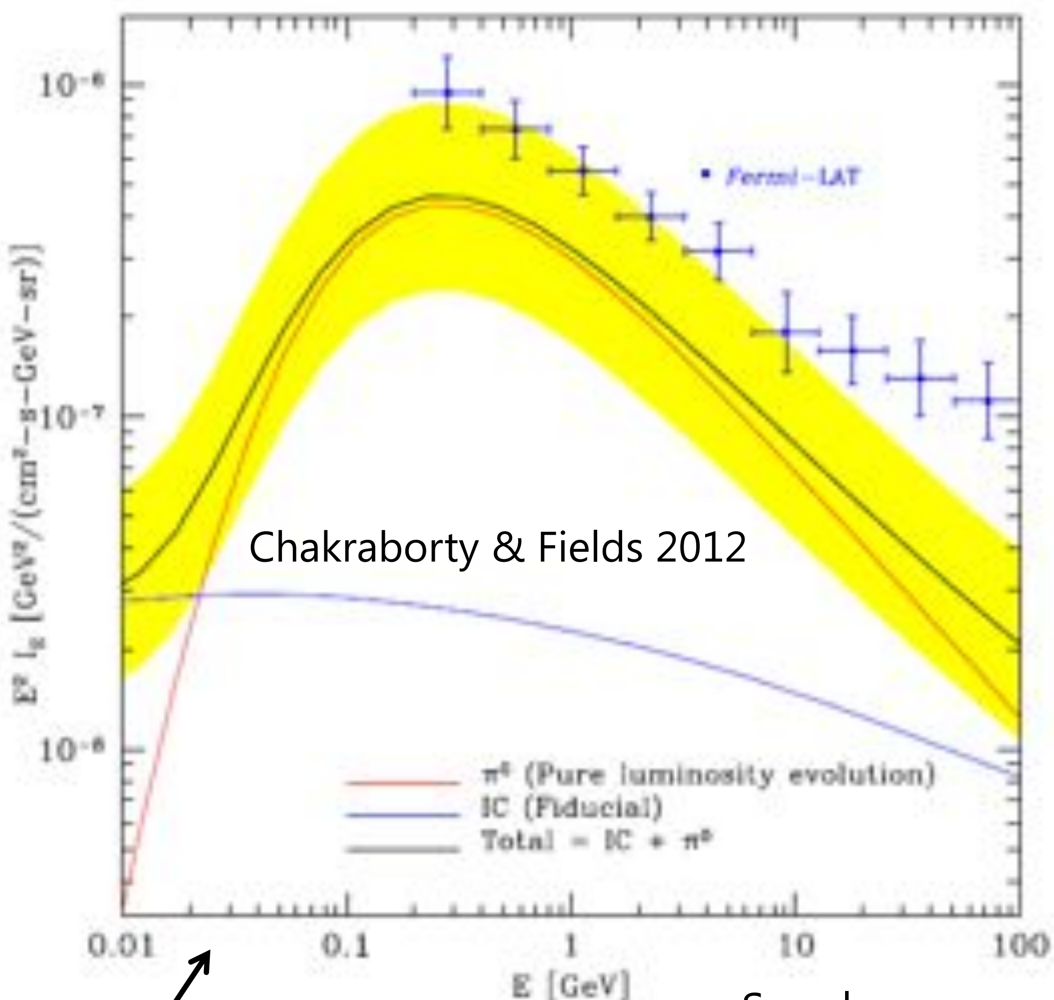
Ackermann et al. 2012, ApJ, 755, 164

Pionic IGRB Spectral Feature

Redshifted pionic spectral cutoff expected < 0.2 GeV for star-forming galaxies

Spectral measurement at these energies may clarify contribution of hadronic processes to IGRB intensity

See **Markus Ackermann's** talk for an updated IGRB analysis 0.2-410 GeV. Extension to energies < 0.2 GeV is work in progress…



See poster by **Nachiketa Chakraborti**

See also
Stecker & Venters 2011
Lacki Thompson 2012

Science Opportunities at keV and TeV Energies

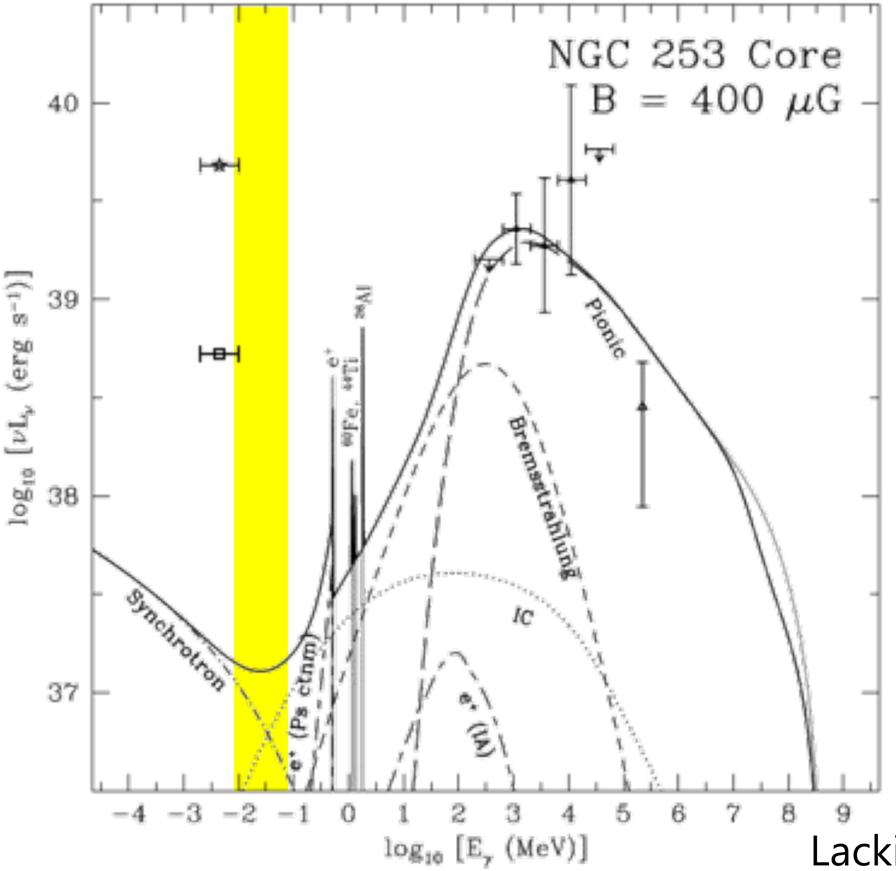
NuSTAR **launched 13 June 2012**
http://www.nustar.caltech.edu/home

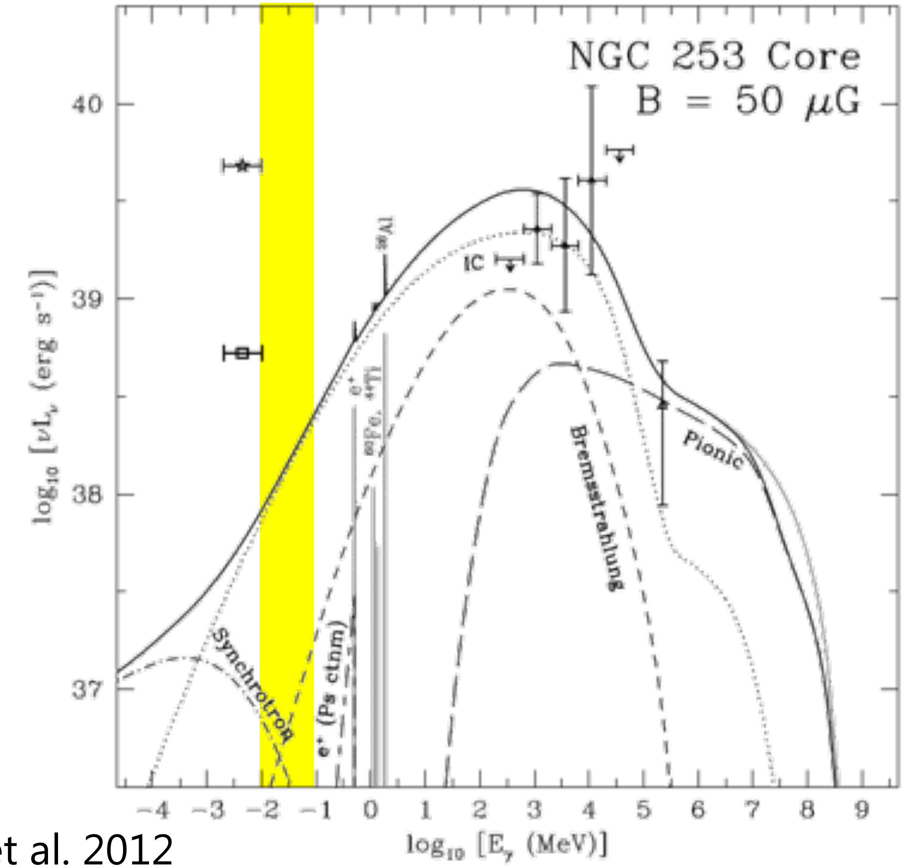
CTA
Design Concept
http://www.cta-observatory.org/

Interpreting GeV Emission

"Hadronic" Scenario

"Leptonic" Scenario



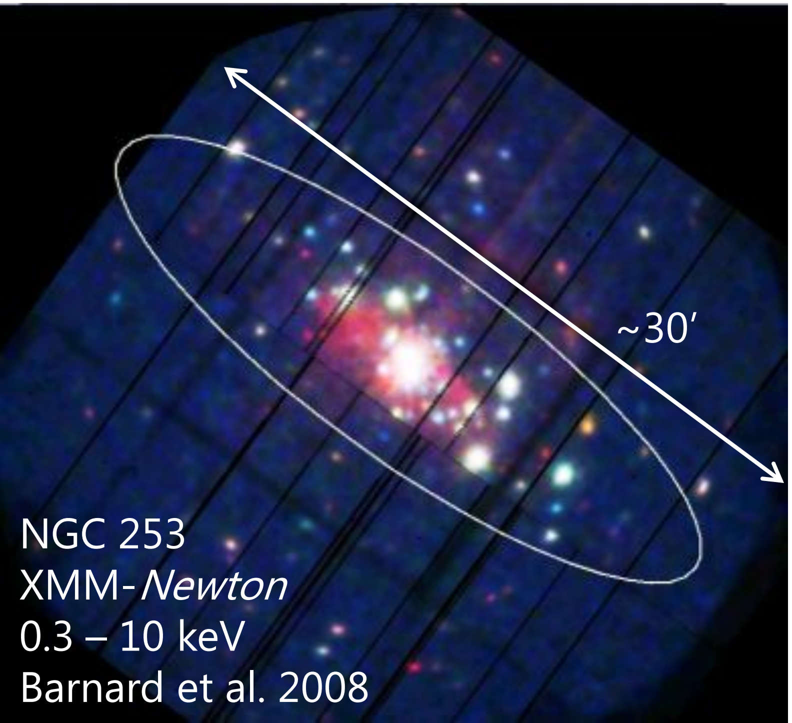


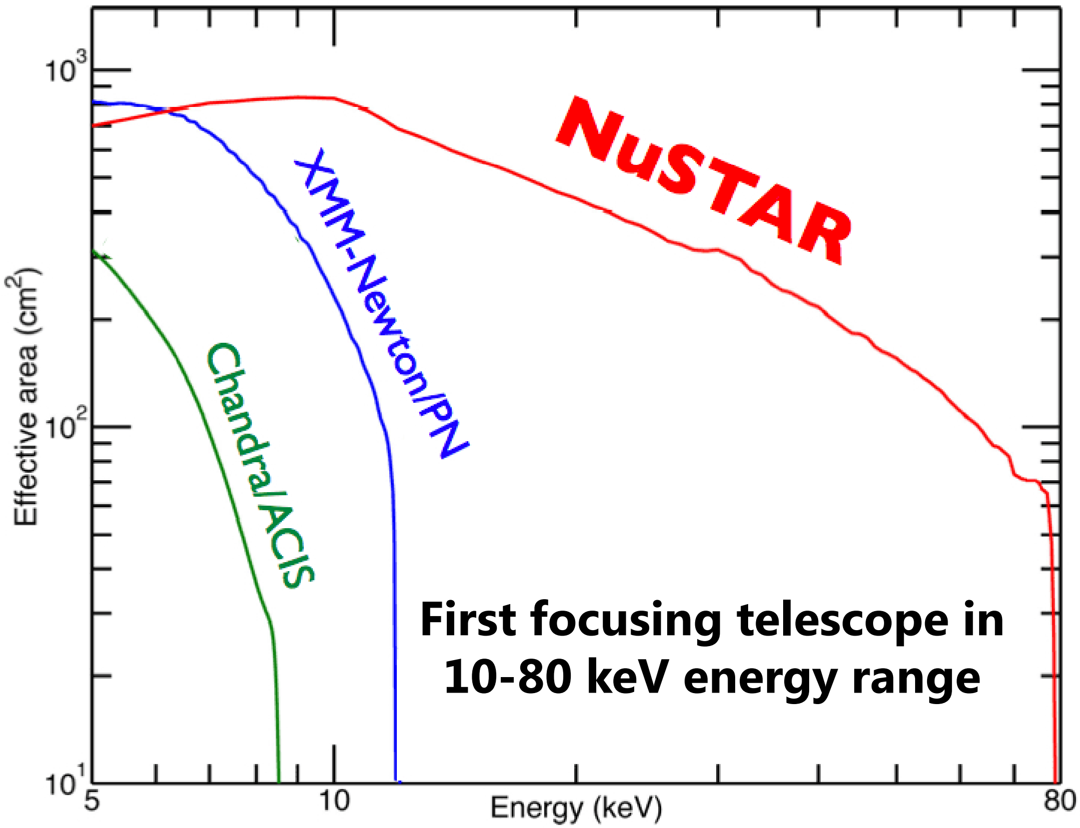
Lacki et al. 2012

NuSTAR band can help isolate inverse Compton component / constrain magnetic field in conjunction with radio synchrotron measurements

UNIQUE *NuSTAR* CAPABILITIES

Observation program includes NGC 253 and several other low-redshift starburst galaxies



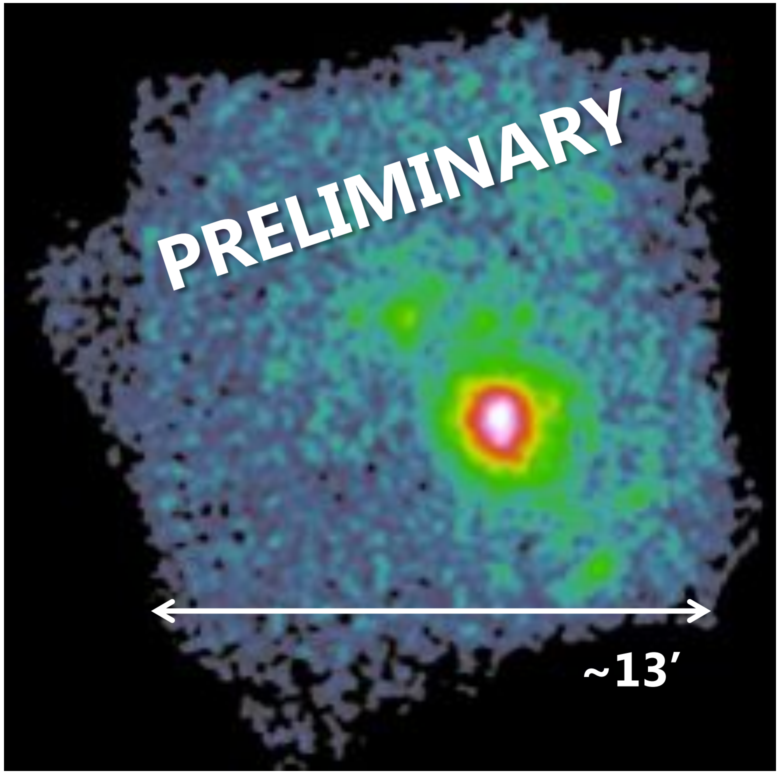


NuSTAR's unprecedented angular resolution >10 keV (17″ FWHM, 57″ HPD) essential for best constraints on diffuse non-thermal emission – need to subtract X-ray binaries and thermal gas in starbursts

First Look

NuSTAR observations of NGC 253 are currently underway!

Smoothed background-subtracted counts map 7-15 keV

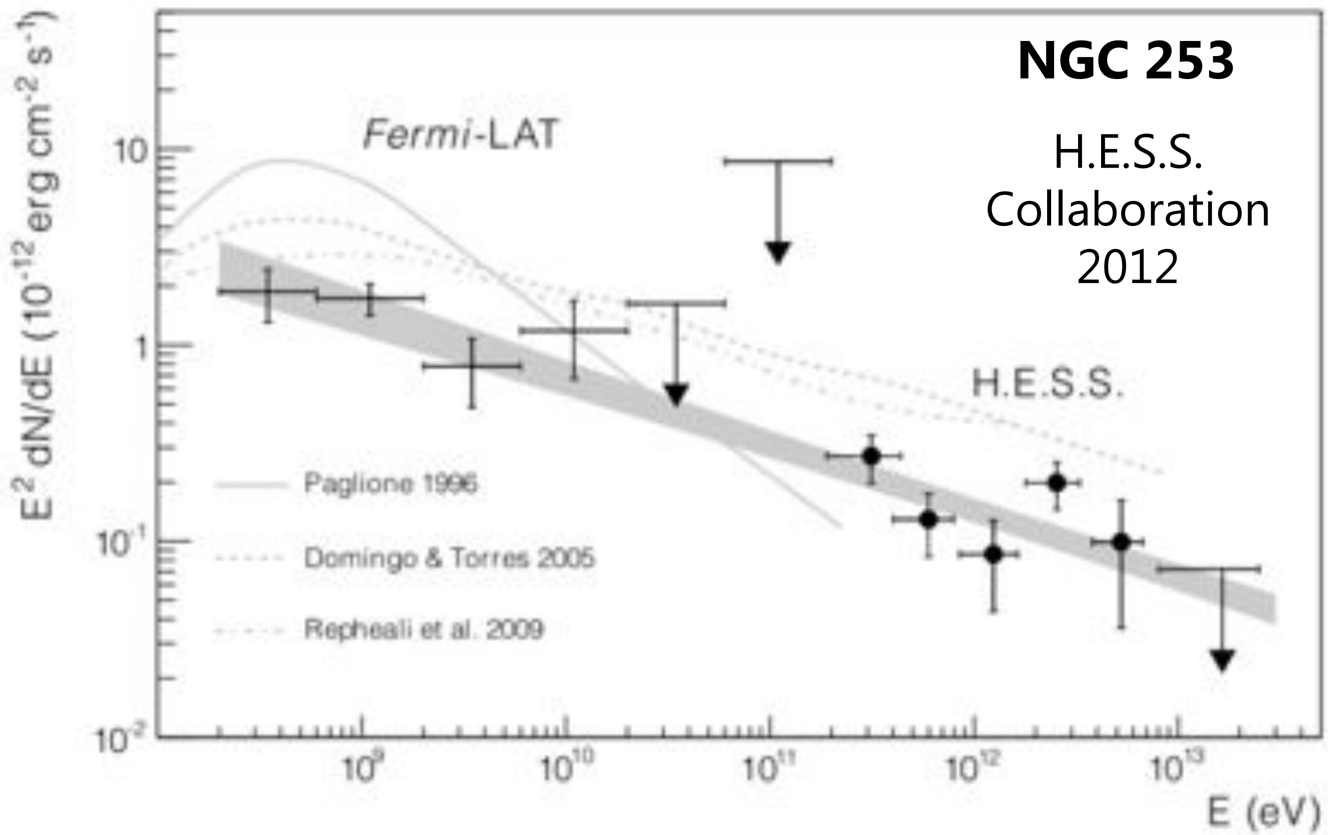


Coordinated *Chandra* and VLBA monitoring of X-ray binaries

Dan Wik, Andrew Ptak, Ann Hornschemeier, Bret Lehmer, Andreas Zezas, Megan Argo, Keith Bechtol, Brian Grefenstette, Fiona Harrison, Jean-Christophe Leyder, Tom Maccarone, Kristin Madsen, Daniel Stern, Tonia Venters, Will Zhang, Steve Boggs, Finn Christensen, Bill Craig, Chuck Hailey, and the *NuSTAR* team

Fermi-LAT and CTA Synergy

Gamma-ray spectra of M82 and NGC 253 are well described by unbroken power laws given current statistical precision

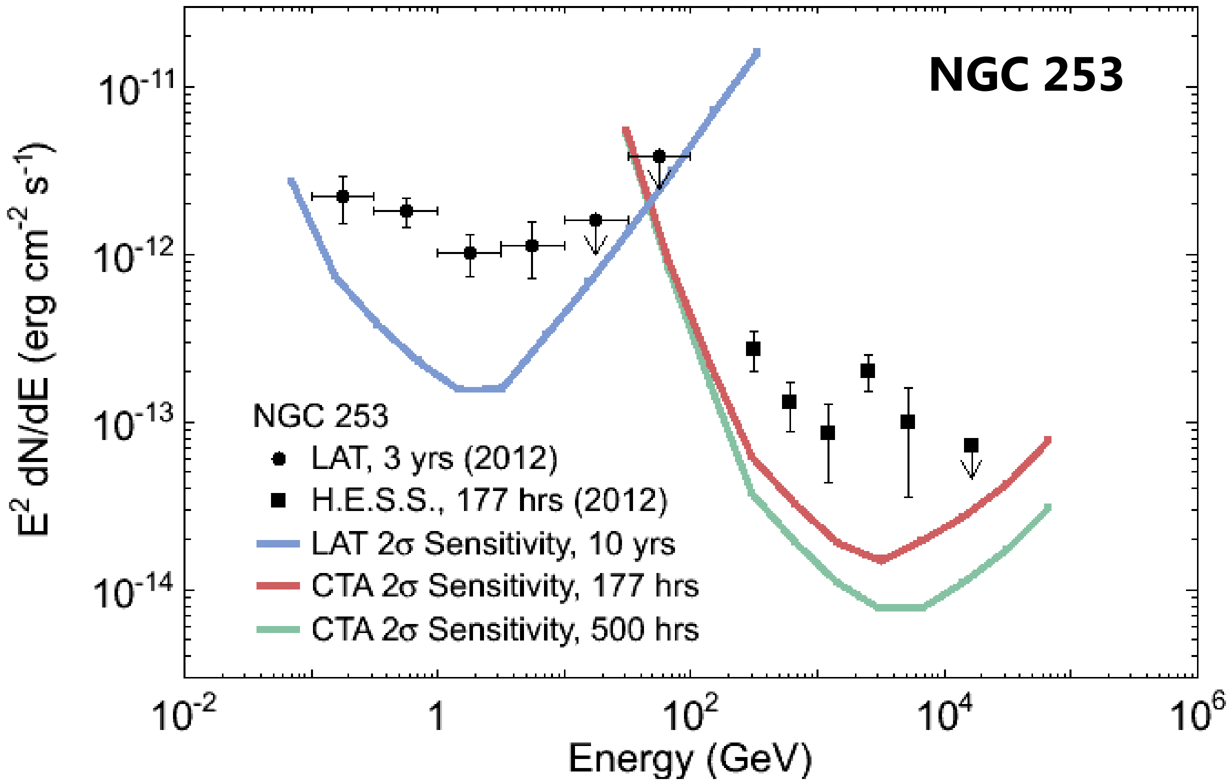


All-sky coverage provided by *Fermi* –LAT survey can provide guidance (with additional theoretical input) for CTA target selection

CTA Science Opportunities

Gamma-ray detections of NGC 253 with future differential sensitivity curves overlaid

defined as 2σ detections in bins of 1/3 decade in energy (courtesy Stefan Funk, see also arXiv:1205.0832)



Example CTA Research Areas

Are gamma-ray spectra of starbursts more complex than simple power laws?
Spectral transition from "soft" quiescent galaxies to "hard" starbursts?
Highest energy CRs in starburst systems?
Can the starburst / disk be separated with CTA imaging?

Realism and Optimism

Realism

- ✗ Limited number of additional LAT-detectable galaxies
- ✗ Expected fluxes of ULIRGs just beyond LAT reach
- ✗ Is it possible to empirically constrain contribution of high-redshift star-forming galaxies to the IGRB?

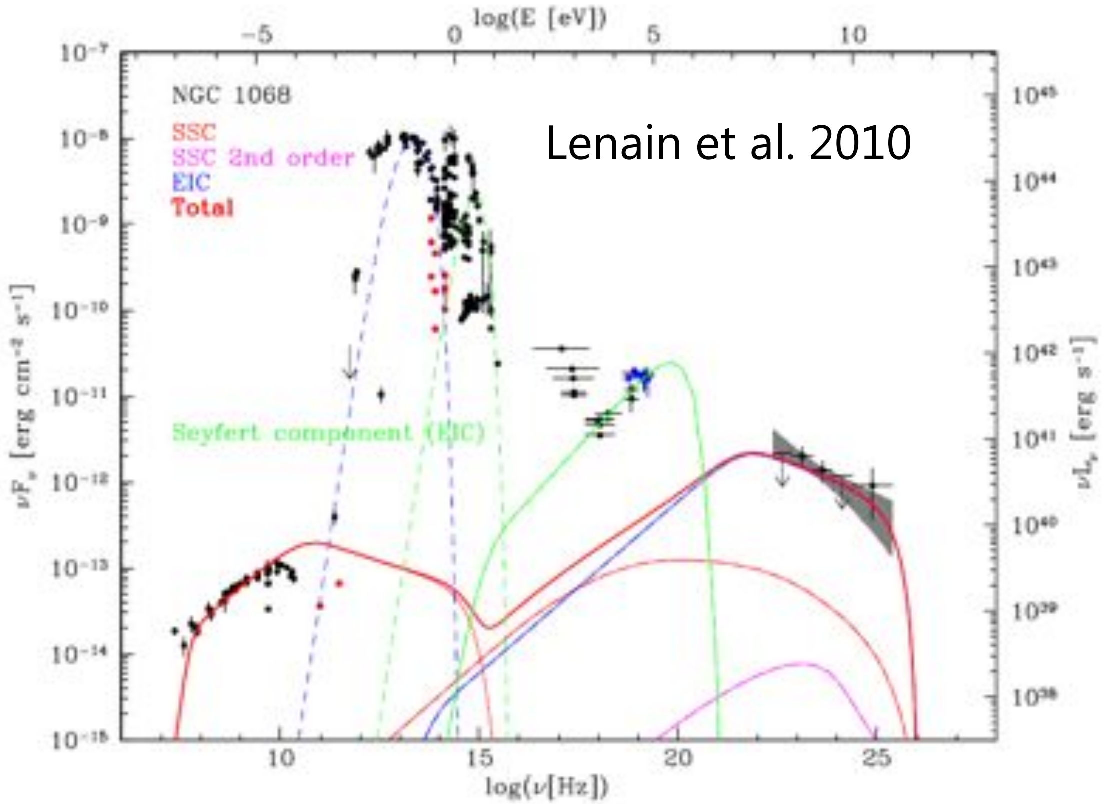
Optimism

- ✓ A few excellent candidates still out there, e.g., M33
- ✓ Potential extension of IGRB spectrum to lower energies to constrain role of hadronic processes
- ✓ *NuSTAR* provides an alternative way to constrain leptonic component of nearby starbursts
- ✓ *Fermi* -LAT survey can help guide CTA target selection
- ✓ Compelling CR physics opportunities enabled with combined LAT-CTA spectral measurements

Back-ups

AGN Contributions?

Broadband SED Modeling of NGC 1068



NGC 1068 is composite starburst / Seyfert 2 system

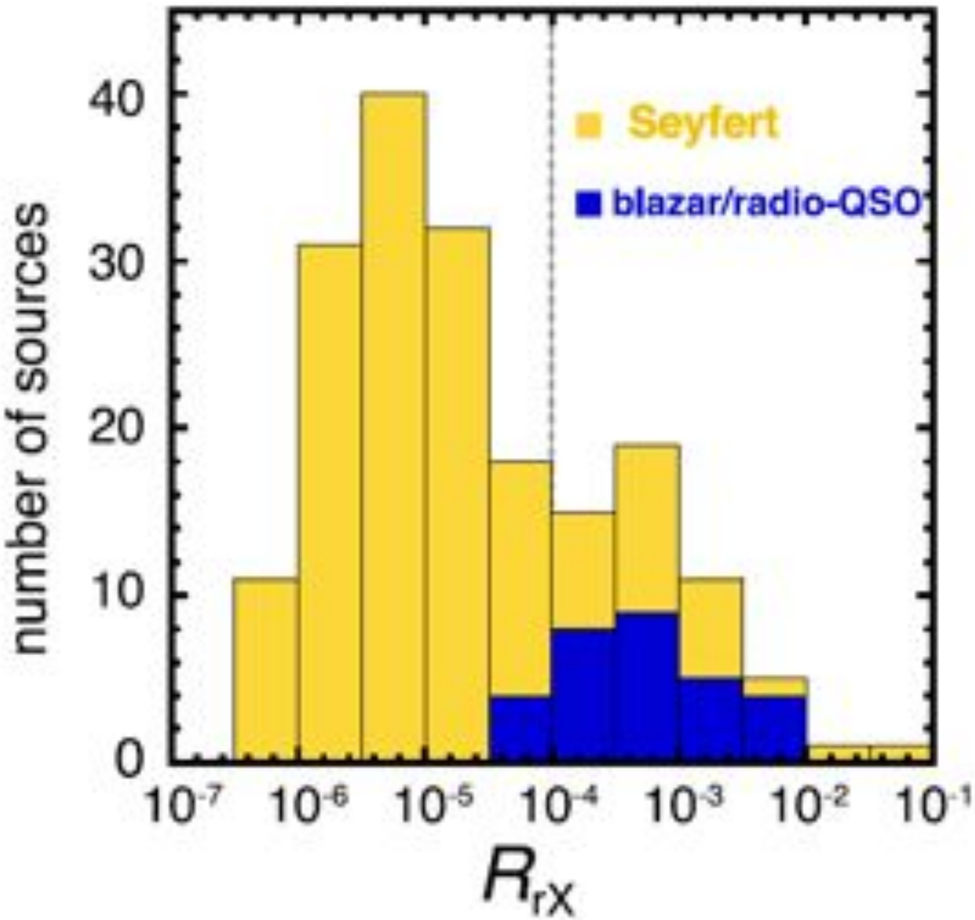
Attribution of GeV gamma rays to AGN vs. CR interactions not entirely clear…

AGN Contributions?

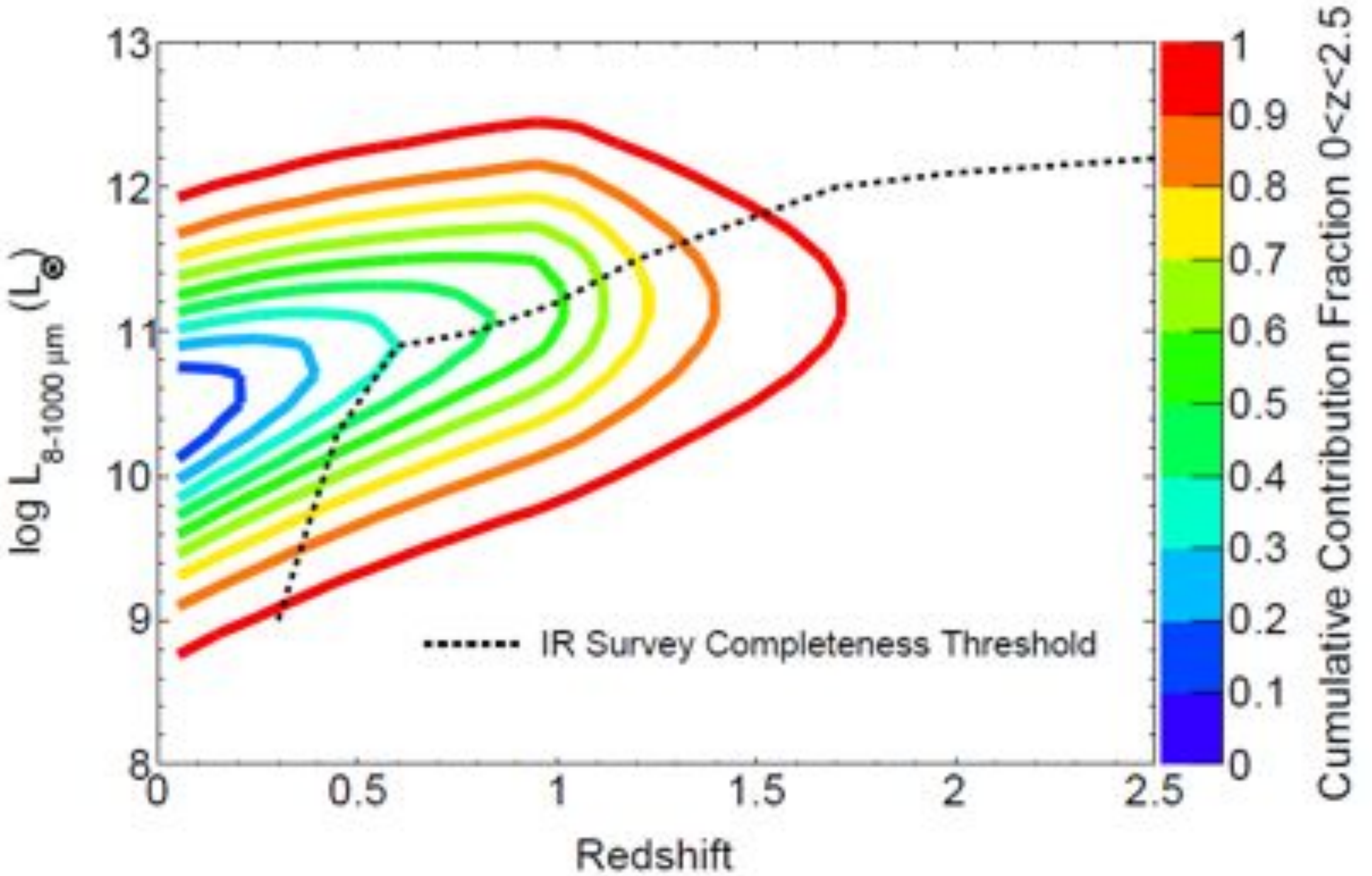
Gamma-ray limits for other Seyfert galaxies

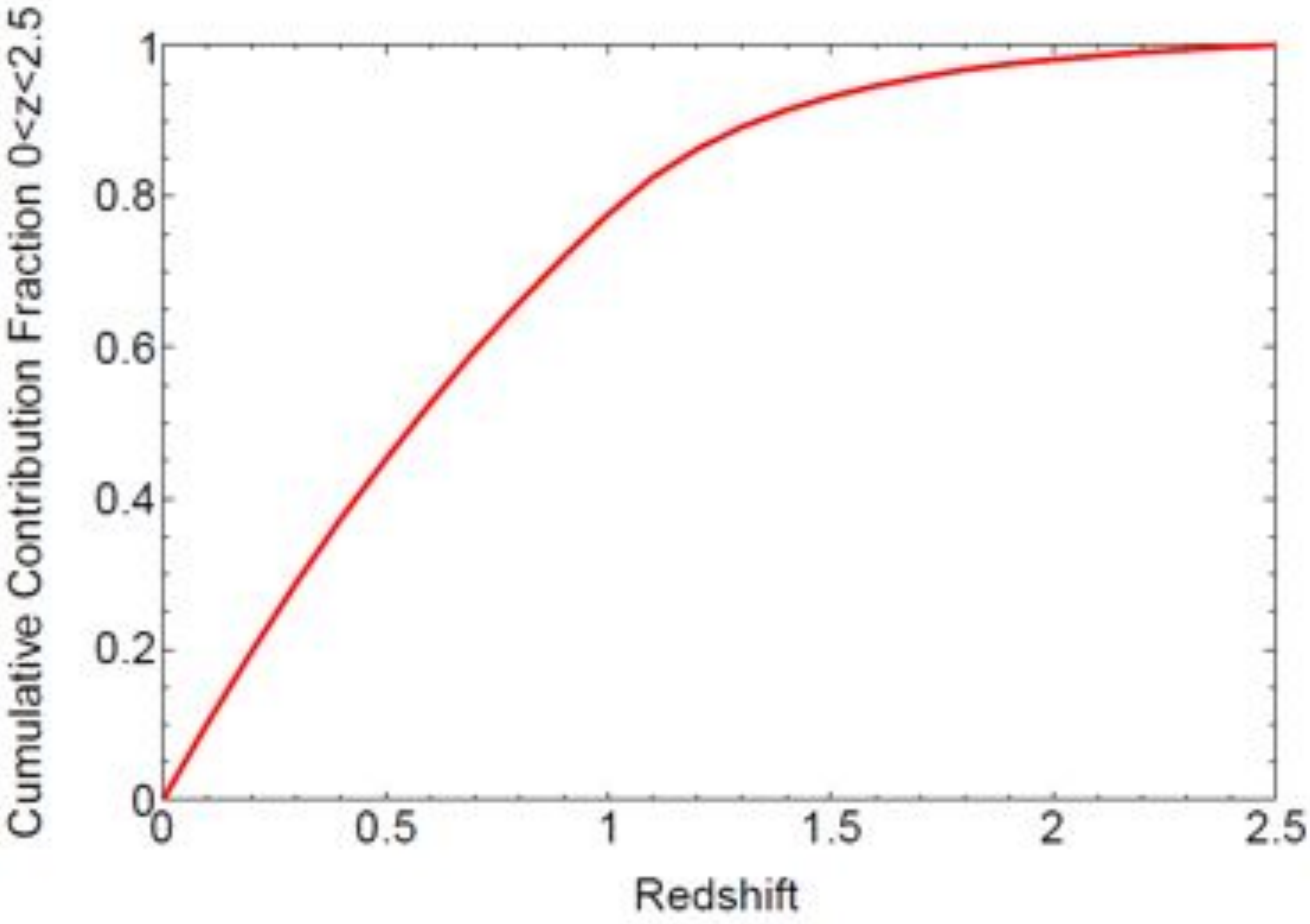
No other hard X-ray selected "radio-quiet" Seyferts from *Swift*-BAT catalog conclusively detected by the LAT

For details, see Teng et al. 2011 and Ackermann et al. 2012, ApJ, 747, 104



Hard X-ray radio loudness parameters distribution for *Swift* -BAT AGN


13
12
11
10
9
8
0
0.5
1
1.5
2
2.5
log L8-1000 μm (L⊙)
Redshift
IR Survey Completeness Threshold
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Cumulative Contribution Fraction 0<z<2.5


Cumulative Contribution Fraction 0<z<2.5
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0.8
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0
0.5
1
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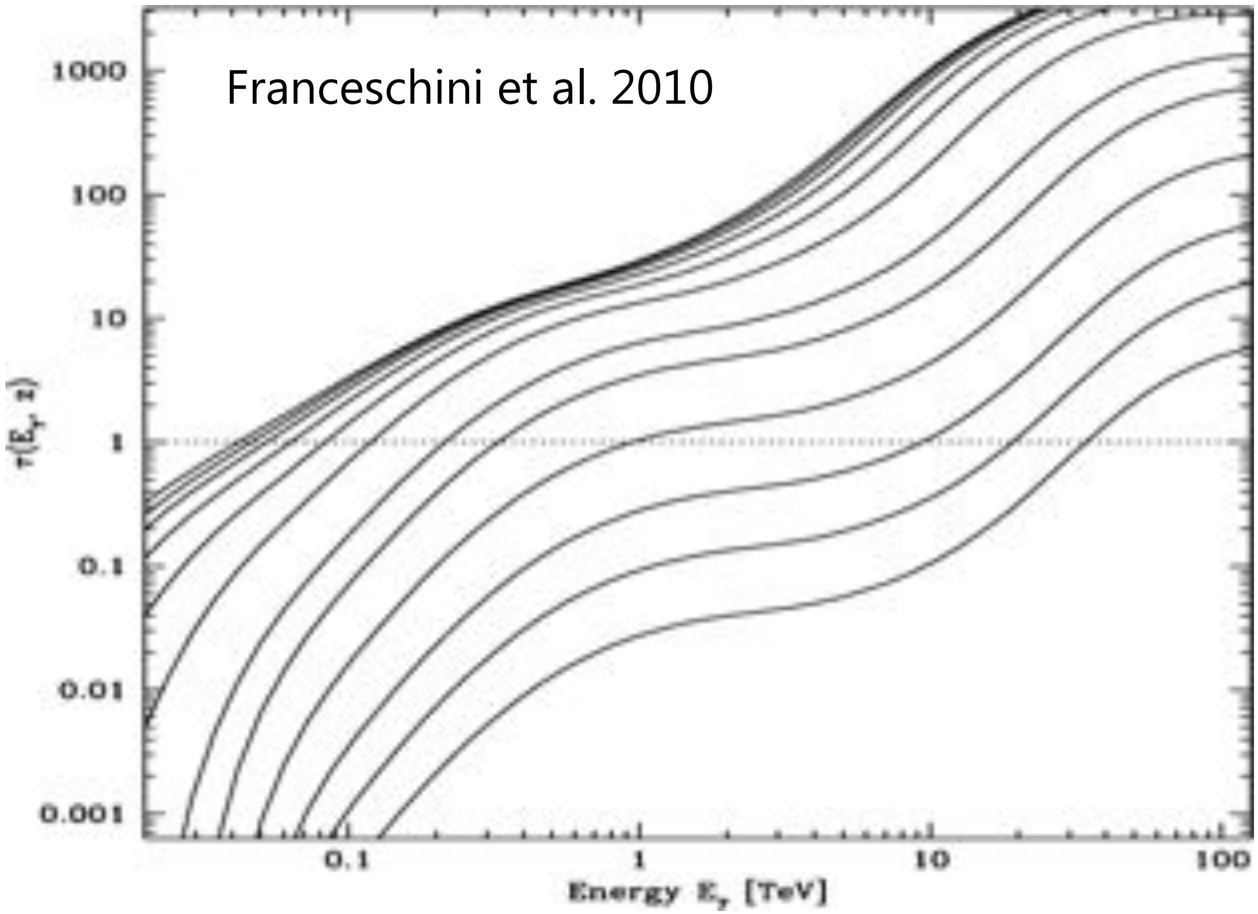
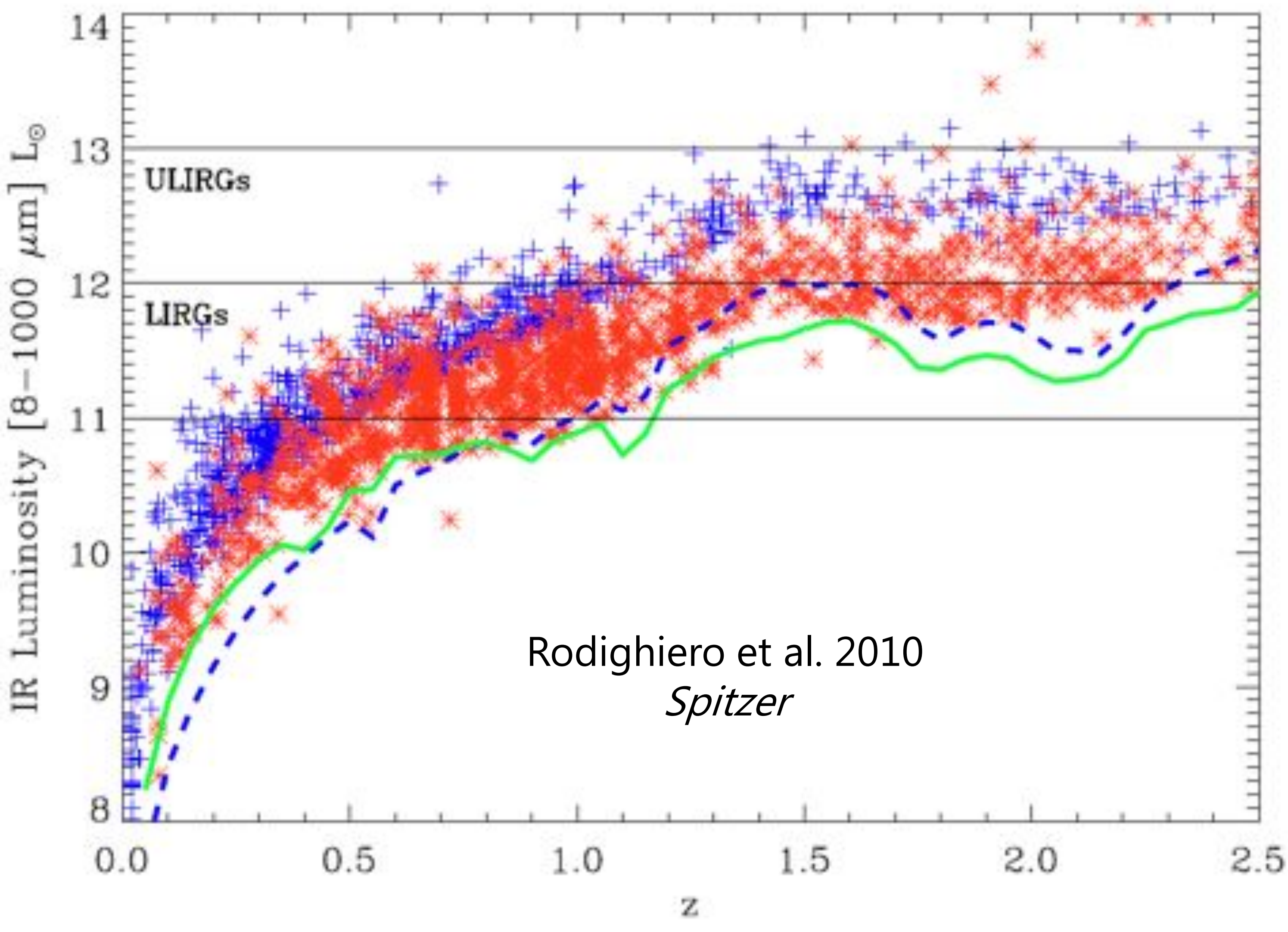
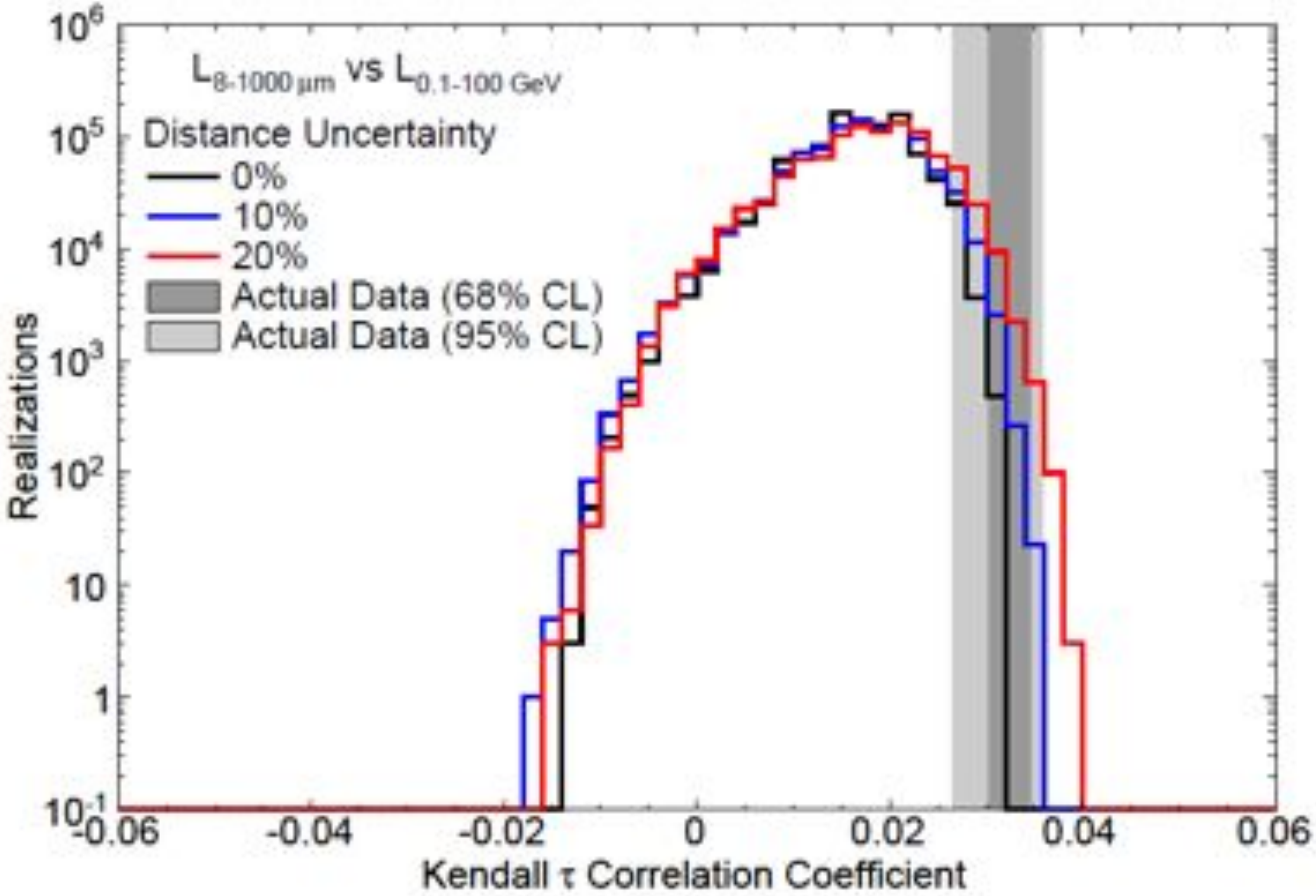
2
2.5
Redshift



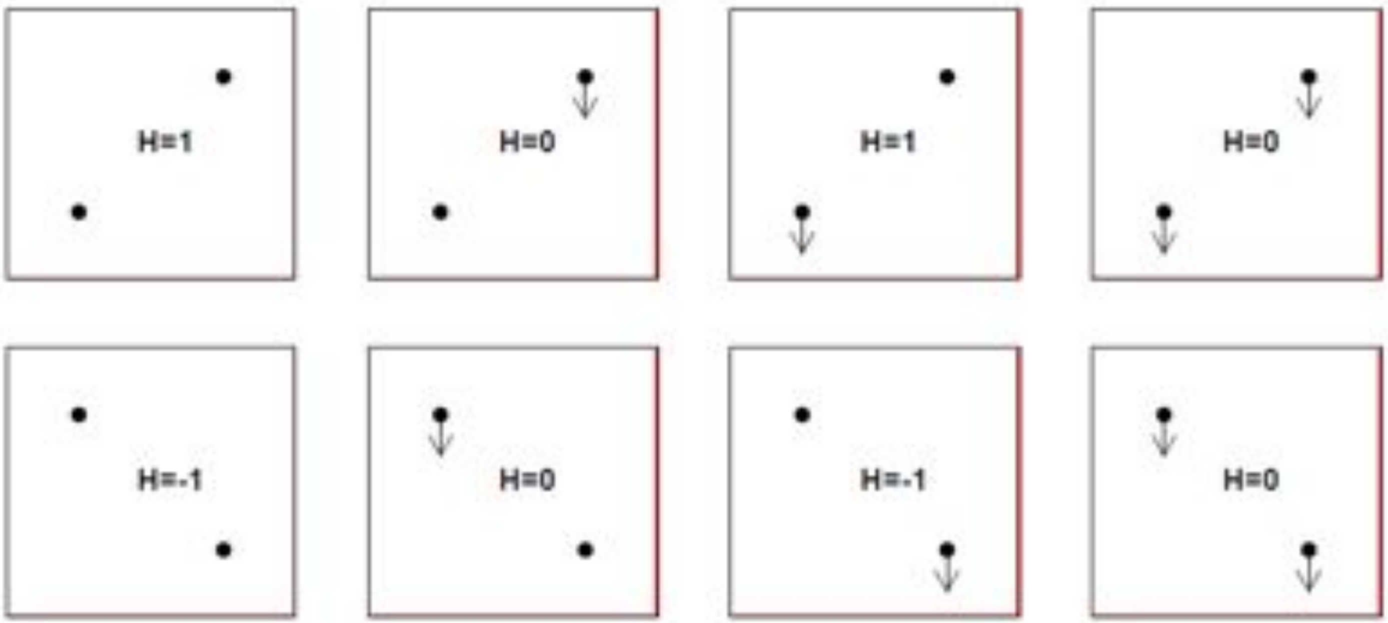
Contours indicate increasing source redshift from bottom to top
z = 0.003, 0.01, 0.03, 0.1, 0.3, 0.5, 1, 1.5, 2, 2.5, 3, 4



Rodighiero et al. 2010
Spitzer



$L_{8\text{-}1000\,\mu m}$ vs $L_{0.1\text{-}100\,GeV}$
Distance Uncertainty
0%
10%
20%
Actual Data (68% CL)
Actual Data (95% CL)
Realizations
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
Kendall τ Correlation Coefficient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H=0
H=1
H=0
H=-1
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H=-1
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