Interstellar gamma-ray emission from cosmic rays in star-forming galaxies

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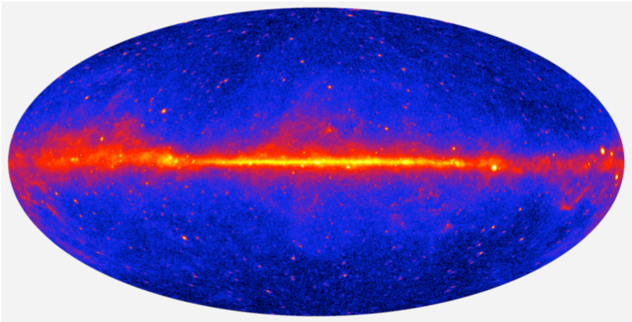
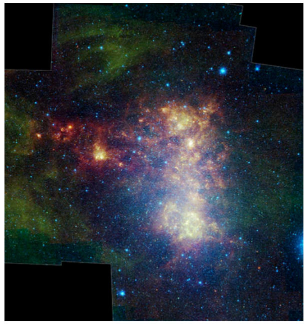
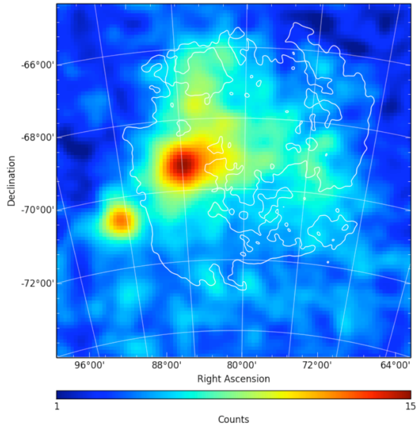
A&A, Vol. 564, A61 (http://arxiv.org/abs/1402.0383)

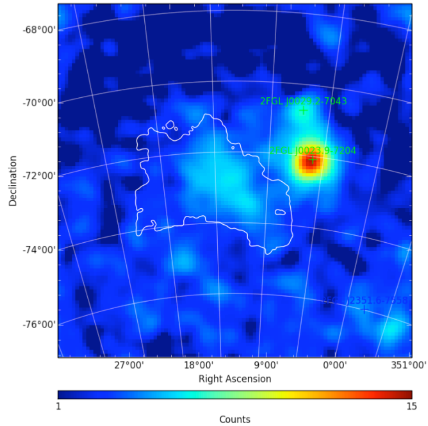
A new class of γ-ray sources I : star-forming galaxies !

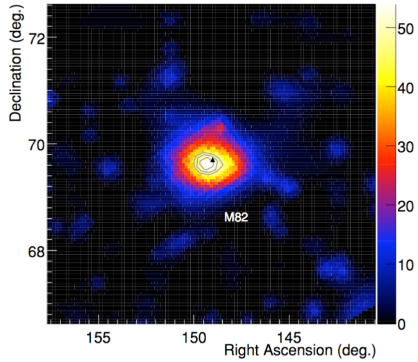


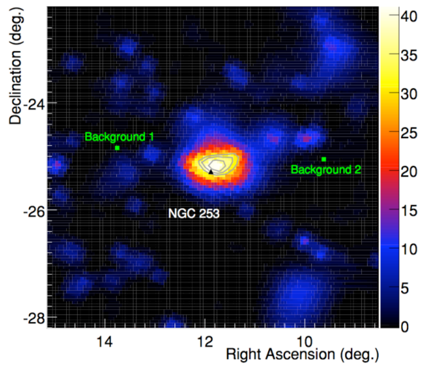
Observing interstellar emission from other systems than the Milky Way: SMC, LMC, M31, NGC253, M82





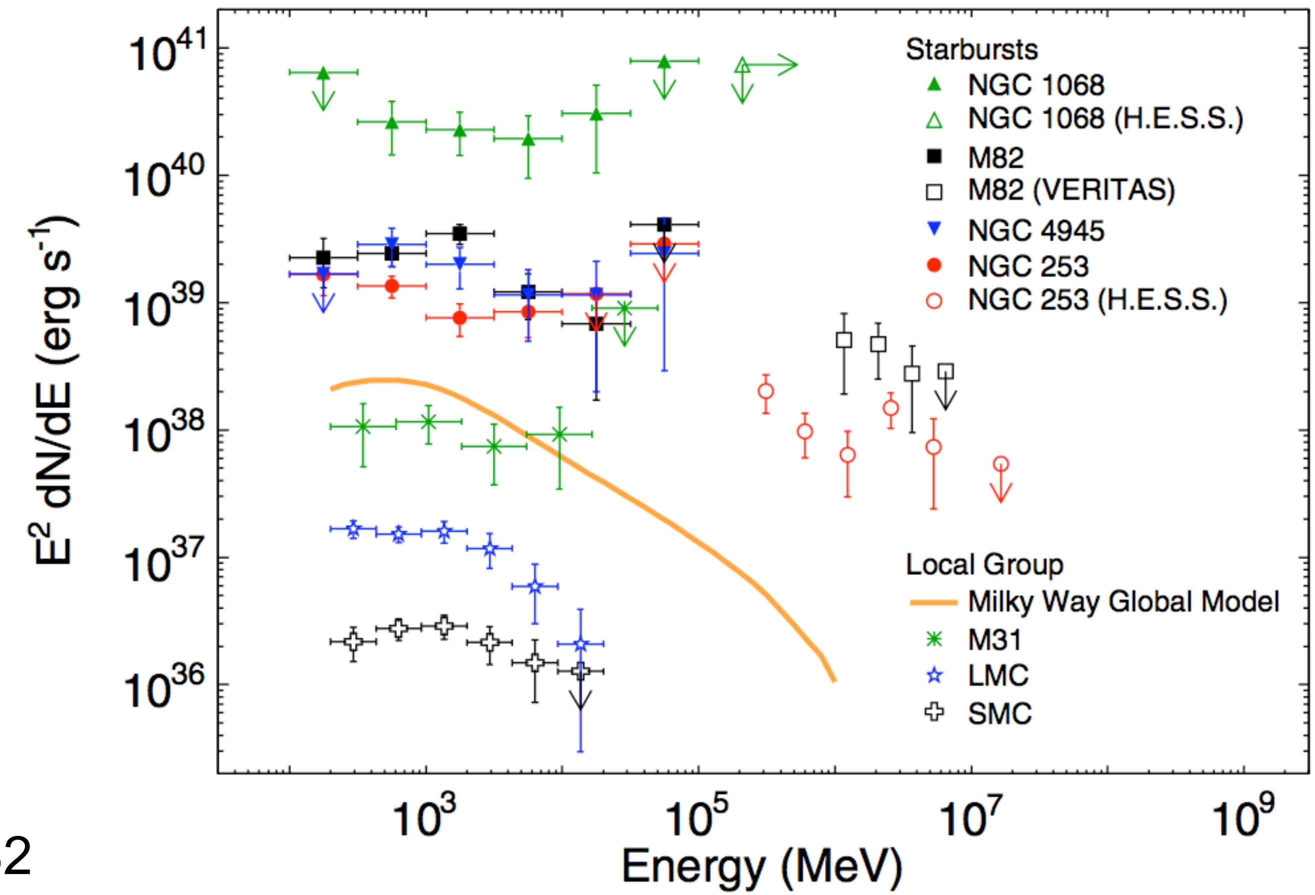






Different realizations of a CR population under different global conditions

A new class of γ-ray sources II : different spectra ?



Flatter spectra for starburst systems M82 and NGC253

2.2-2.3 ±0.1

Milky Way has 2.6-2.7

Different galactic CR populations
Different transport conditions (rather than source)
Test CR propagation knowledge

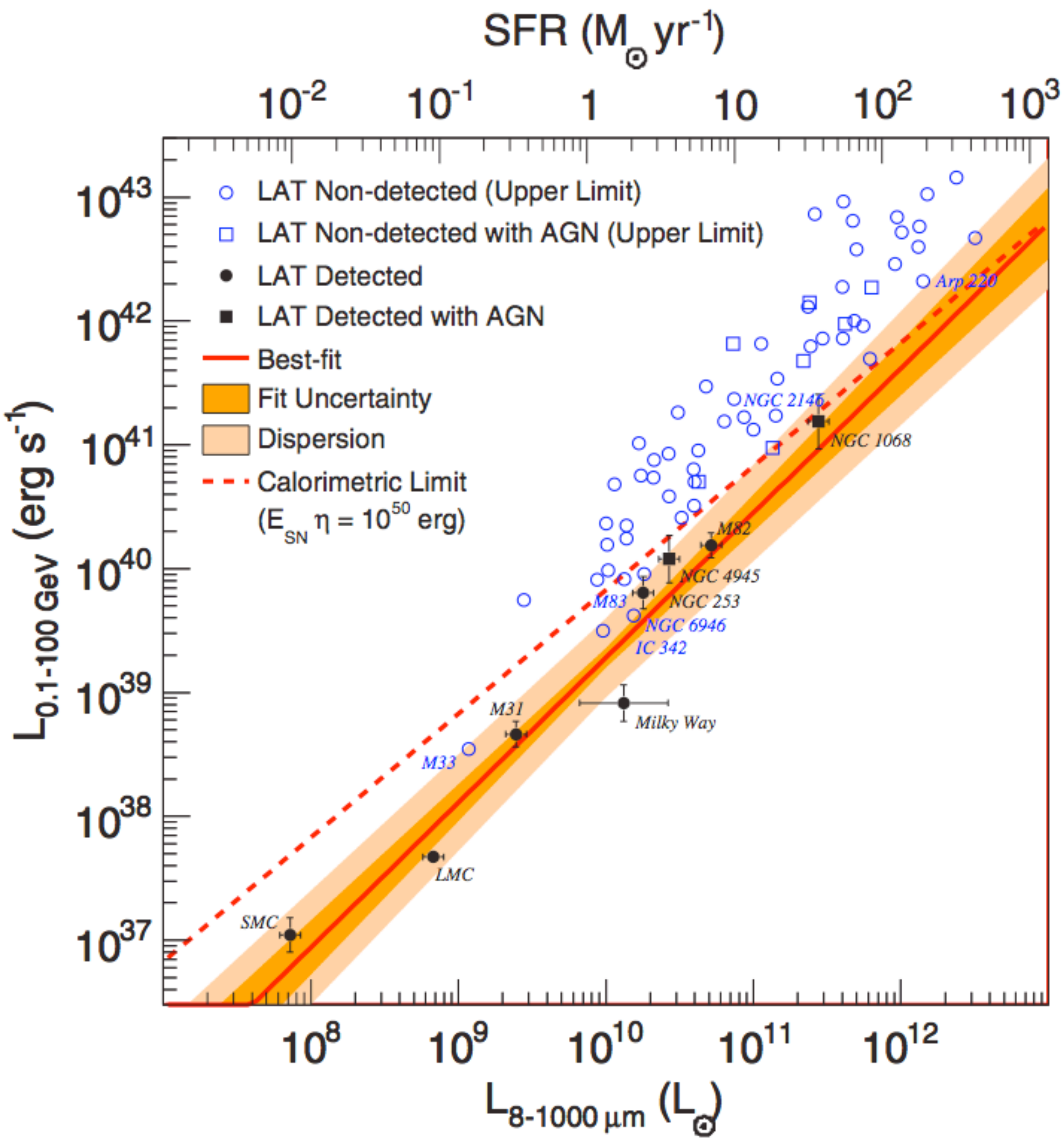
A new class of γ-ray sources III : correlation L_γ-L_{IR} ?

Fermi/LAT observations of 64 IR-bright galaxies

Upper limits

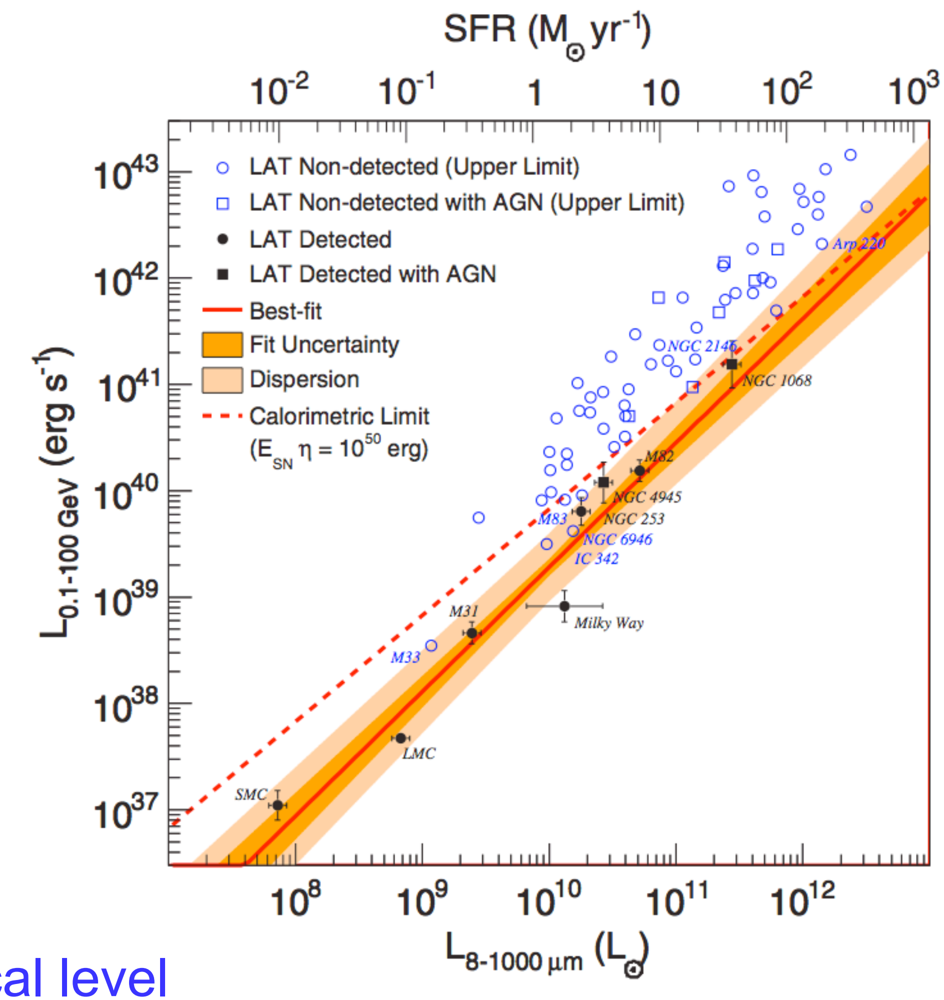
Almost linear correlation over broad range

Power-law index 1.1 ±0.1 (with P-values ≤0.05 and sensitivity to SMC/LMC)



A new class of γ-ray sources III : correlation L_γ-L_{IR} ?

Possible physical connection:
- Star formation → massive stars
- … UV/O radiation heats dust
- … reradiates in IR → L_{IR}
- Star formation → massive stars
- … powerful outflows and shocks
- … particle acceleration, CRs
- … interact with ISM → L_γ



Investigate scenario at theoretical level

What scaling laws can be expected ?

Can we gain knowledge on galactic cosmic rays ?

This work in context

Models of individual objects

- M82 and NGC253
- Too many parameters for a few spectral points (CR injection index, diffusion coefficient, mass, SFR,…)
- Determining global galactic properties is a challenge in itself (SFR, mass, Xco…)

More generic models

- One-zone, leaky box
- Order of magnitude estimates

This work

- Define a generic model for star-forming spiral galaxies (SFG)
- Sizes from 4 to 40kpc, SFR from 10^{-2} to 10^{4} $M_{\odot}$/yr… ~90 synthetic galaxies
- Use CR source and transport parameters obtained from Milky Way studies
- CR input power $\propto$ star formation rate (SFR)
- 2D diffusion code

Model I

Components

- Exponential disk of atomic gas
- Uniform ring or core of molecular gas
- Magnetic field (no topology): $B=B_0(\Sigma_{gas}/\Sigma_0)^a \times \exp(-|z|/z_B)$
- Interstellar radiation field (ISRF)

  CMB, T=2.7K

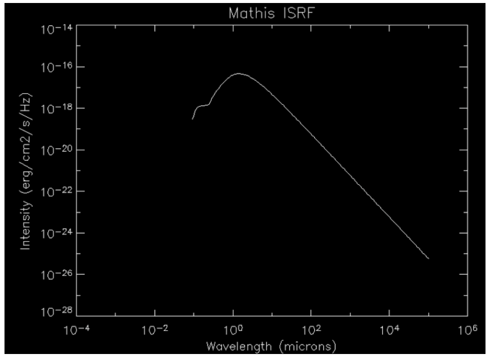
  stellar and infrared, dust emission model (Draine 2007, Draine&Li 2007)

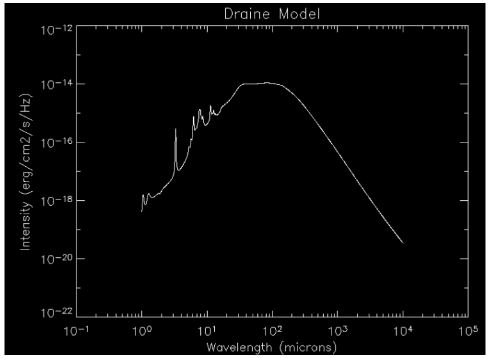
$$U_{IR}(R,z) \propto \Sigma_{SFR}(R) \times \exp(-|z|/z_{IR})$$

$$U_{UVO}(R,z) \propto \langle U\rangle \times \exp(-|z|/z_{UVO})$$

Molecular core

Molecular ring





$$\frac{dM_{\rm dust}}{dU} = (1-\gamma)M_{\rm dust}\delta(U-U_{\rm min}) + \gamma M_{\rm dust}\frac{(\alpha-1)}{U_{\rm min}^{1-\alpha} - U_{\rm max}^{1-\alpha}}U^{-\alpha}$$

- Starlight intensity is U x local ISRF (Mathis-1983)
- Fraction of dust heated by diffuse intensity U_{min}
- Rest heated by distribution of intensities up to U_{max}
- Resulting I_{dust} from Draine model for given dust composition

Model II

Cosmic-ray related parameters from GALPROP Milky Way studies

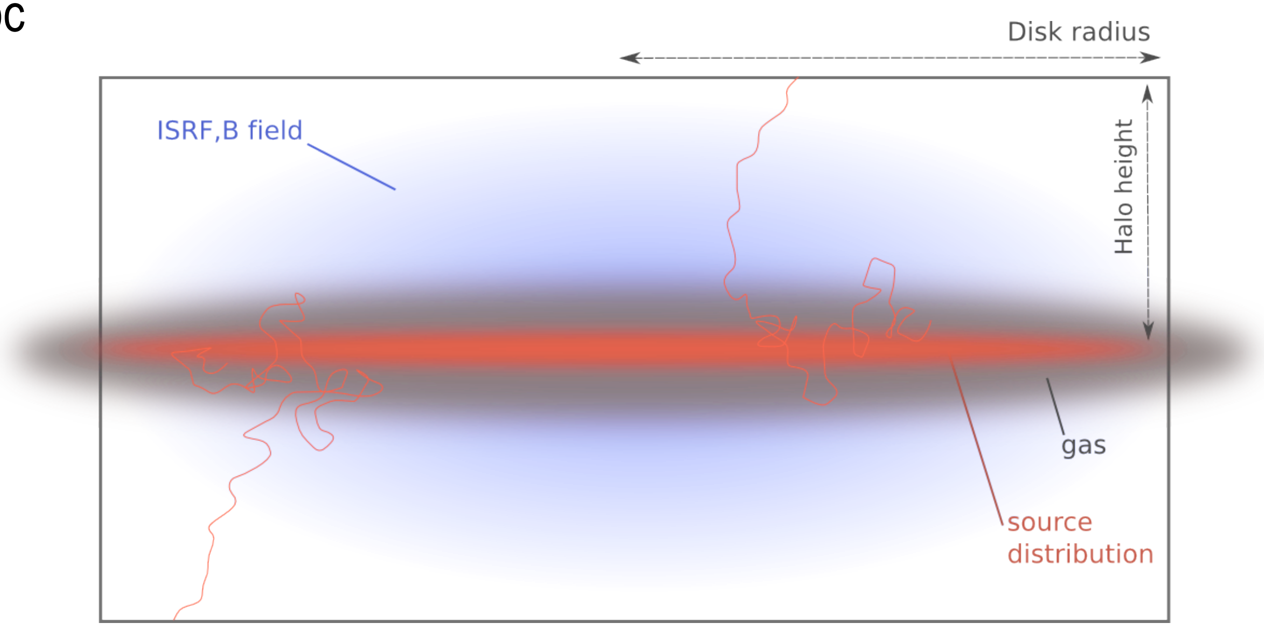
- Source spectra for p+He and e
- Ratio L_{CR}/SFR
- Plain diffusion model with $D_{xx} = 3.4 \times 10^{28} \beta \left(\frac{R}{4\,\mathrm{GV}}\right)^{0.5} \mathrm{cm^2\,s^{-1}} \quad \text{for} \quad R \geq 4\,\mathrm{GV}$

$$D_{xx} = 3.4\,10^{28}\,\mathrm{cm^2\,s^{-1}} \quad \text{for} \quad R < 4\,\mathrm{GV},$$

Others

- CR source distribution $\propto \Sigma_{SFR}$
- Galactic halo height 2 or 4kpc

GALPROP-based
2D cylindrical
Spatial resolution 50-100pc
Steady-state



$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

Model III

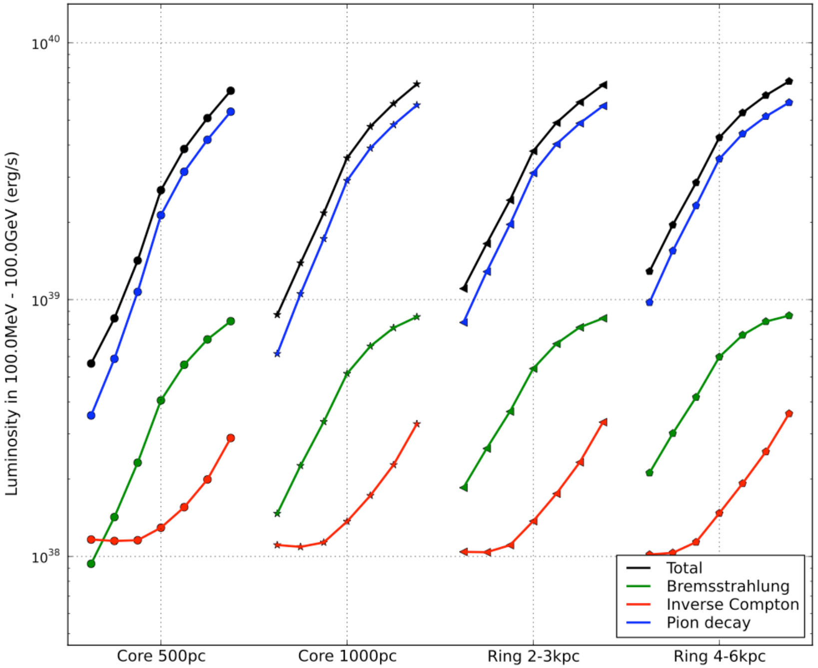
Comparison with the original GALPROP calculation

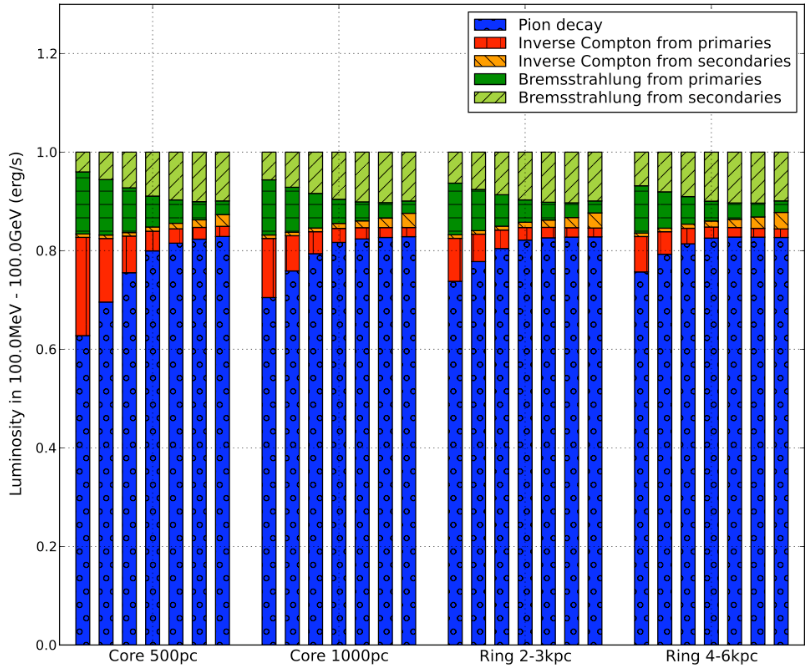
- Used to fix four parameters: (B_0,Σ_0), z_{IR}, z_{UVO}
- Source- and volume-averaged ISRF/B energy densities differ by 30/10%
- Output γ-ray and radio spectra differ by 5% maximum

Results: luminosity evolution

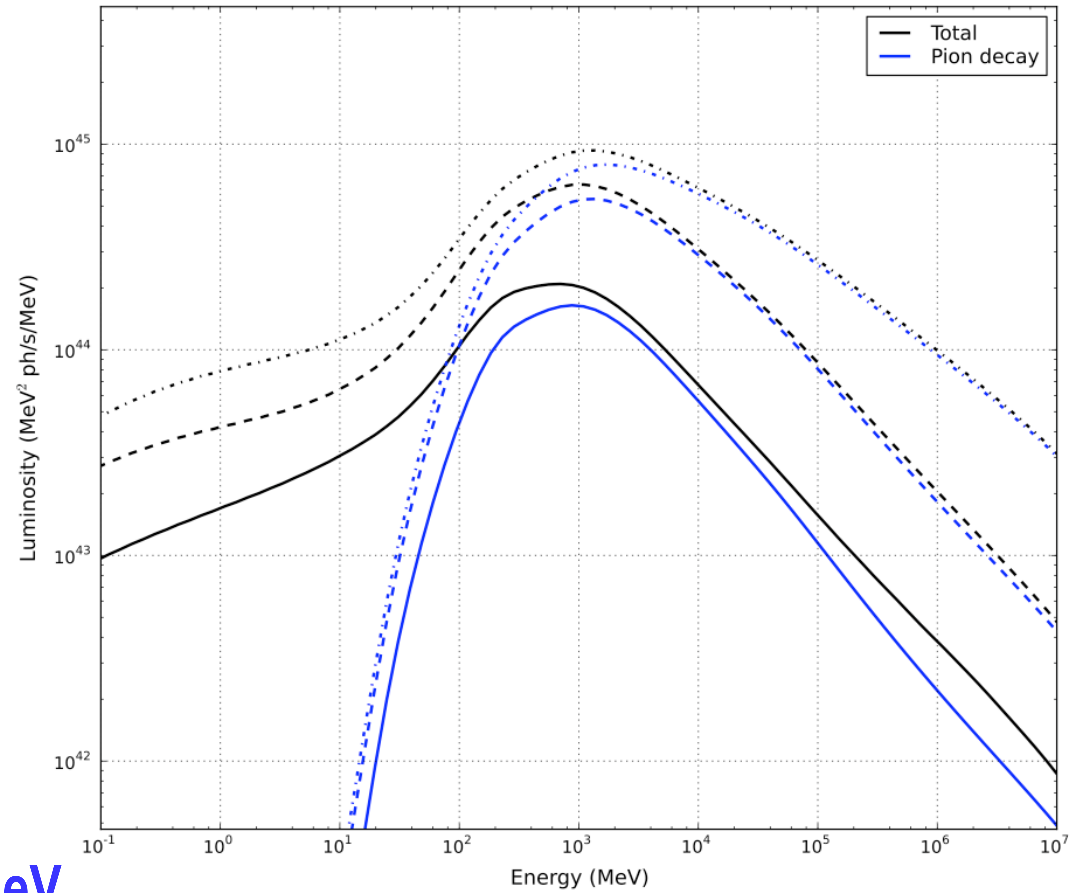
High-energy γ-rays 100MeV-100GeV

- For 1 galaxy size, 4 gas distributions, 7 gas densities 5…500 H_2/cm^3 (the independent variable)
- Same CR input power (to allow comparison)
- Composite emission, mainly pion decay
- Increases not as much as gas density and flattens
  … transition/shift from diffusion-dominated to loss-dominated regime





Results: spectral evolution



High-energy γ-rays 100MeV-100GeV

- For 1 galaxy model, 1 gas distribution, 3 gas densities (5,50,500 H_2/cm^3)
- Emission increases more at ~1TeV than at ~1GeV: spectrum flattens

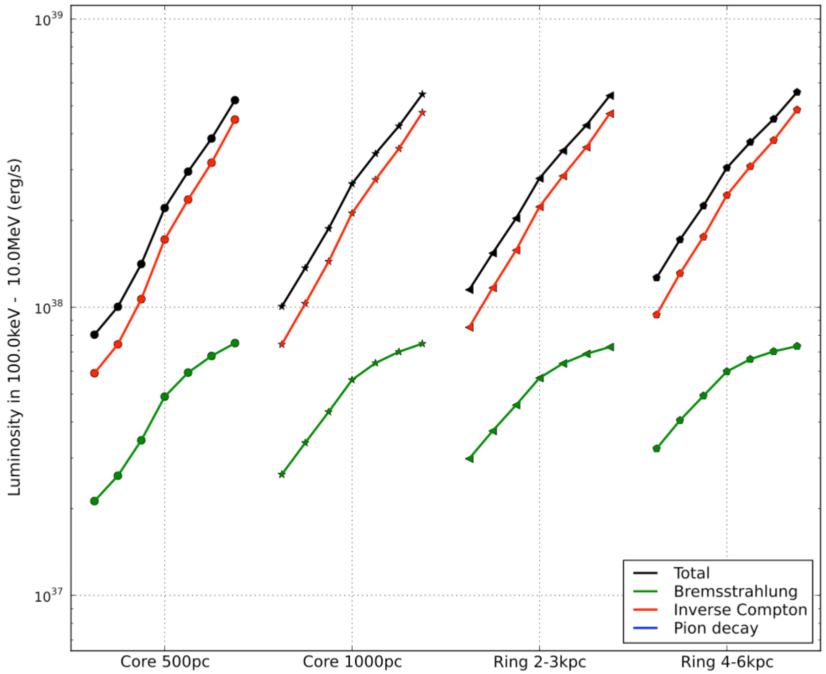
… higher-energy particles are closer to diffusion-dominated

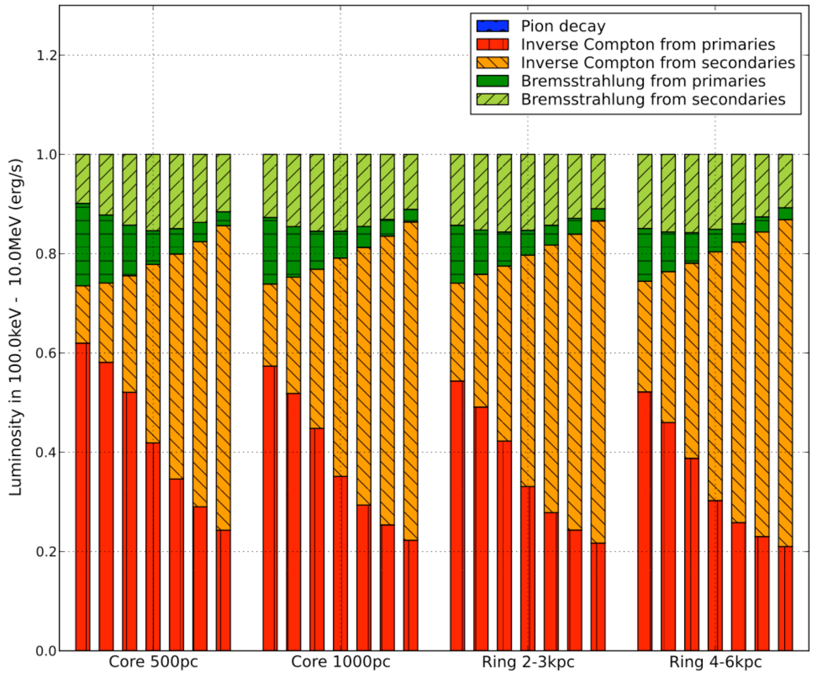
- Can get flat/flatter spectrum just from diffusion (no calorimetry here)

Results: luminosity evolution

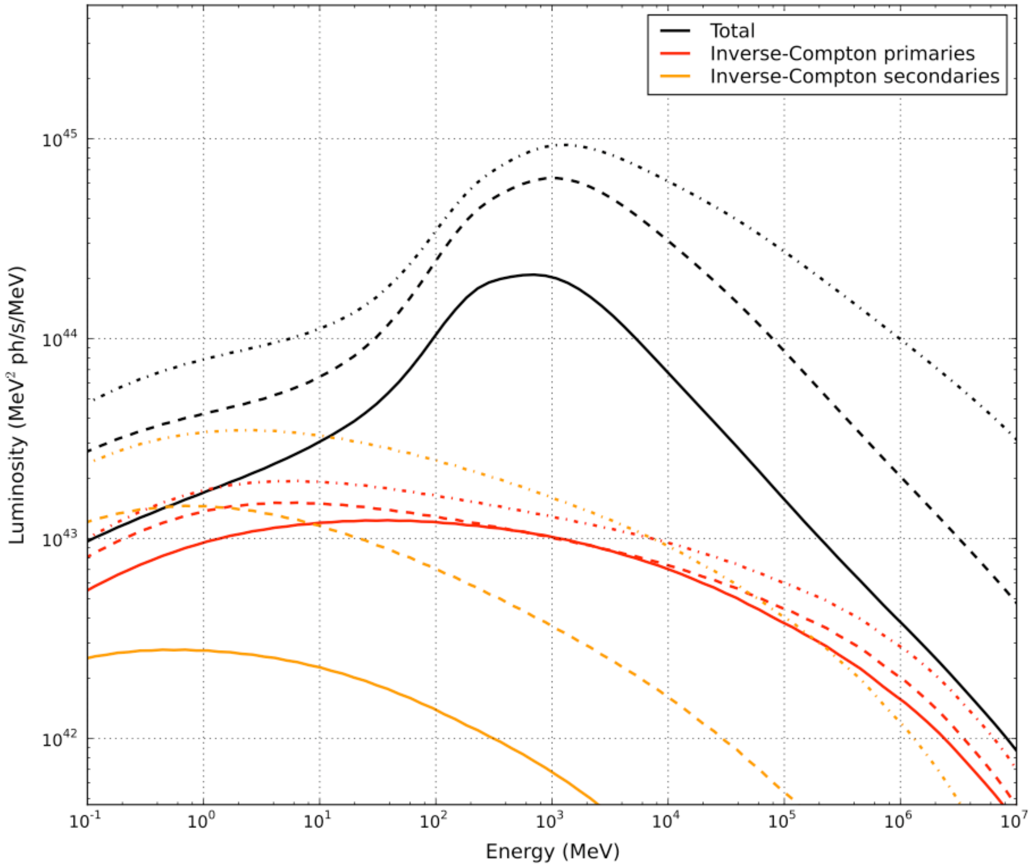
Soft γ-rays 100keV-10MeV

- For 1 galaxy model, 4 gas distributions, 7 gas densities
- Same CR input power
- Leptonic emission, mainly inverse-Compton
- At high gas densities, secondaries dominate (70-80%)





Results: spectral evolution



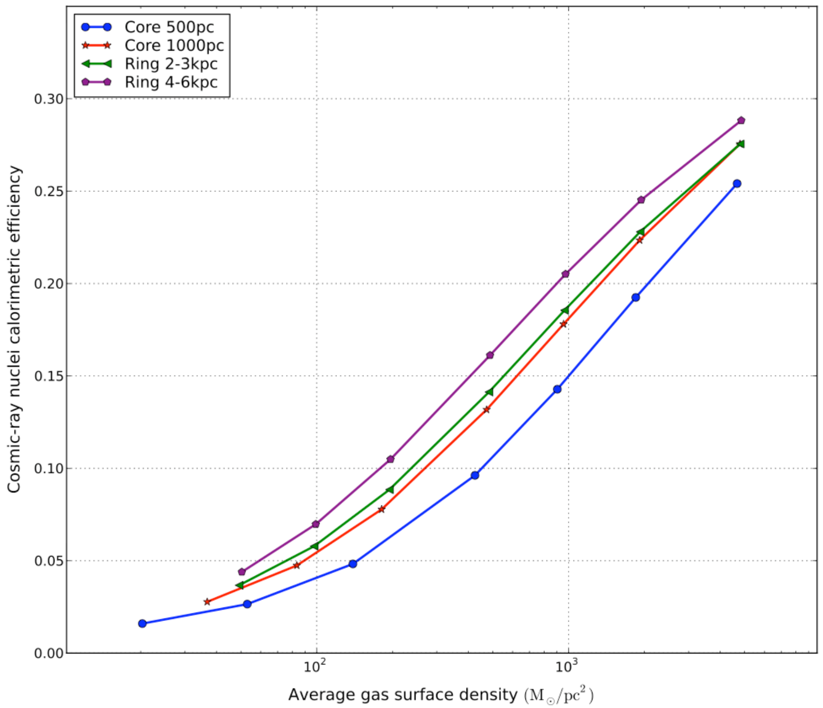
Soft γ-rays 100keV-10MeV

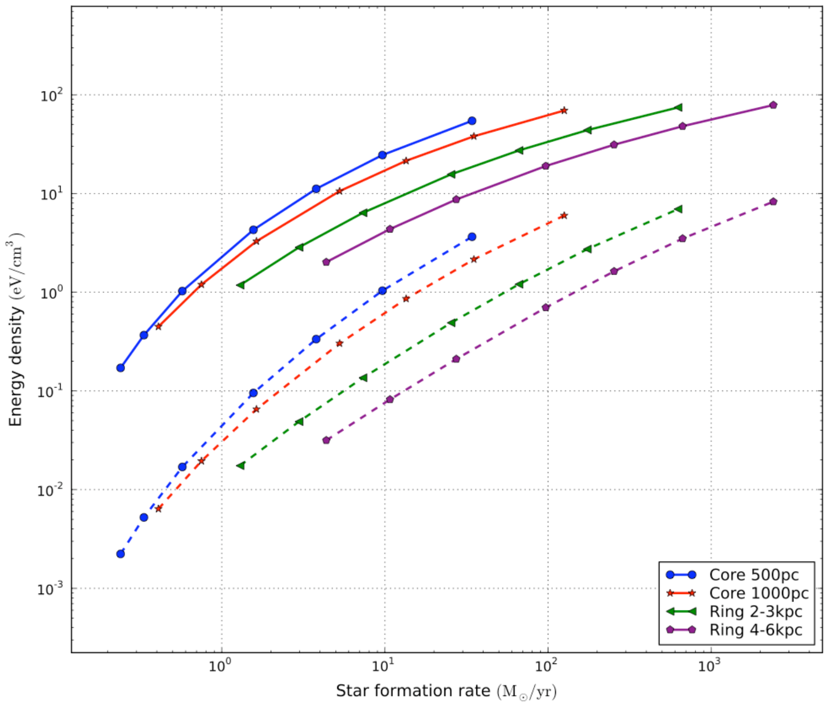
- For 1 galaxy model, 1 gas distribution, 3 gas densities (5,50,500 H_2/cm^3)
- Primaries emission stable: they are loss-dominated
  … increase in IR photon density compensated by decrease in CR electron density
- Secondaries emission increases by 10: more secondaries produced by CR protons
  … increases not as much as gas density
  … because CR protons move from diffusion-dominated to loss-dominated

Results: the galactic CR population

Calorimetry and CR energy densities

- Calorimetric efficiency: fraction of CR power lost in the galaxy
  … increases from ~1% to 30%
- CR energy density increases from ~1eV/cm^3 to ~100eV/cm^3
  … larger jump for >1TeV CRs
- Comparison: IR and B field rises up to 3300eV/cm^3

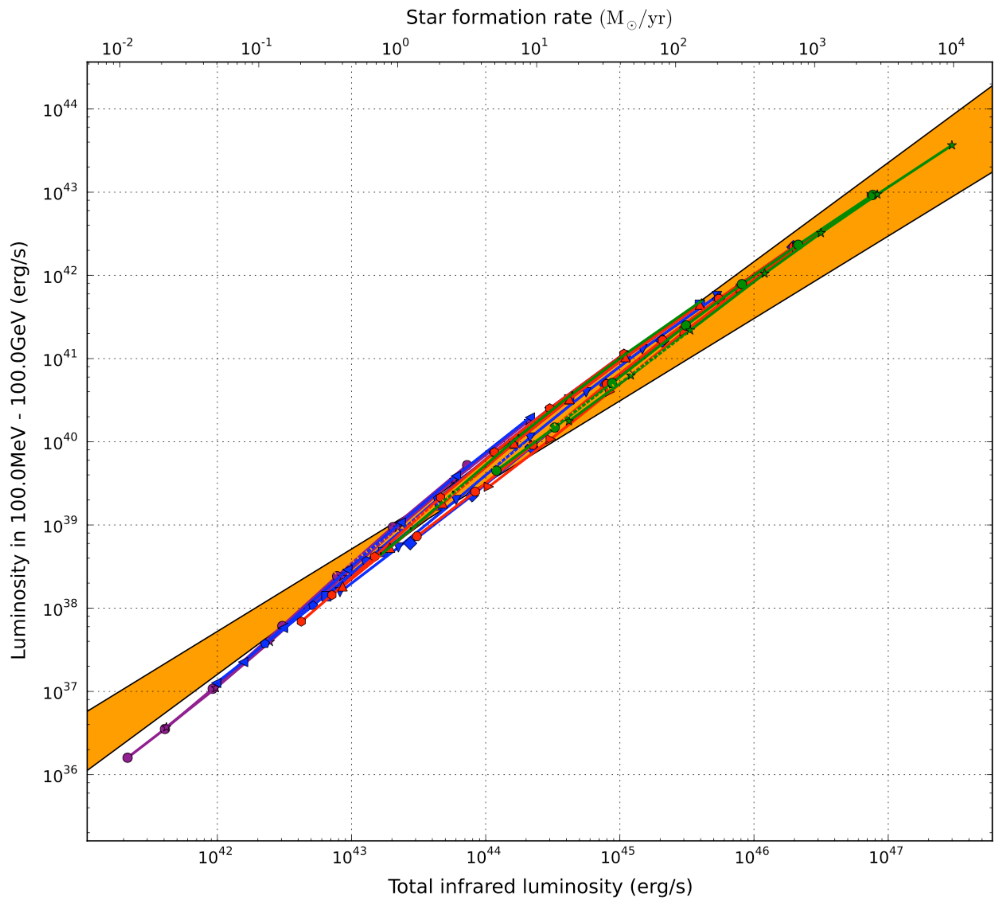




Results: the Fermi/LAT correlation I

100MeV-100GeV

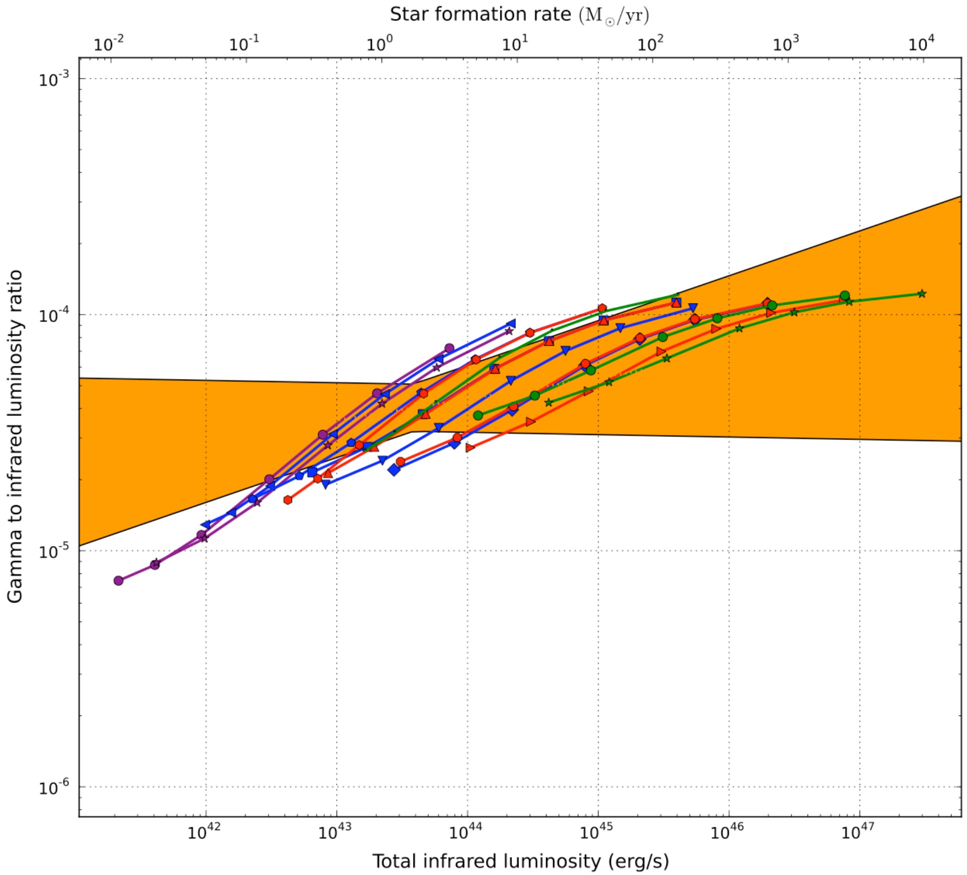
- 4 galaxy sizes, 6 gas distributions, 7 molecular gas densities: 88 models
- Not so bad: formally, no parameter tuned to match it
- … but beware of the log !



Results: the Fermi/LAT correlation II

100MeV-100GeV

- Good overlap at SFR~1-10 M_{sun}/yr
- Observed trend at higher SFRs
- Downturn at lower SFRs
  … lower CR→γ conversion efficiency
  … because of smaller halo
  … and lower average gas density



Caveats

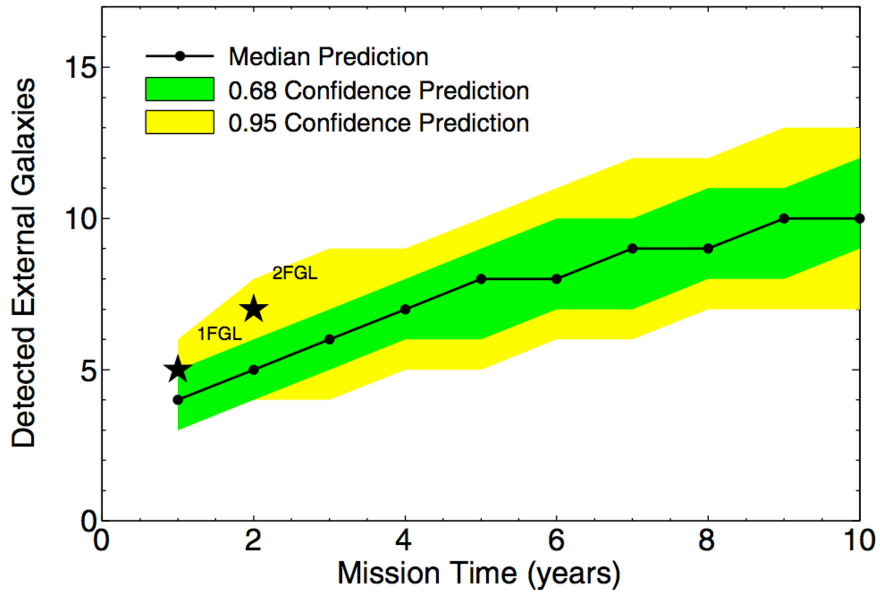
- Model: interstellar CR-ISM emission
- Obs: all gamma-ray sources
- In SMC/LMC, origin of emission unclear

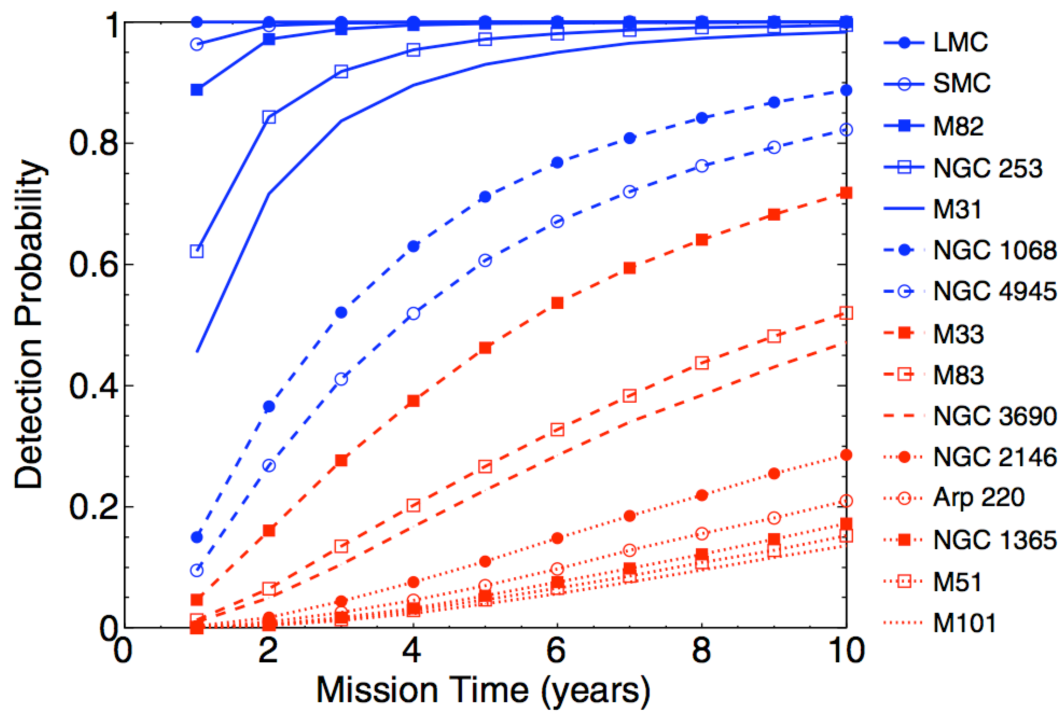
Does not call for major modifications of the Milky Way transport scheme
Plain diffusion, CRs experience large-scale volume-averaged ISM conditions
No universal L_γ-SFR relationship

Prospects for high energies

Future detections using Fermi/LAT

- From inferred L_{IR}-L_{γ} scaling relation
- 10 objects after 10 years (7 objects now)
- M33, M83, NGC3690

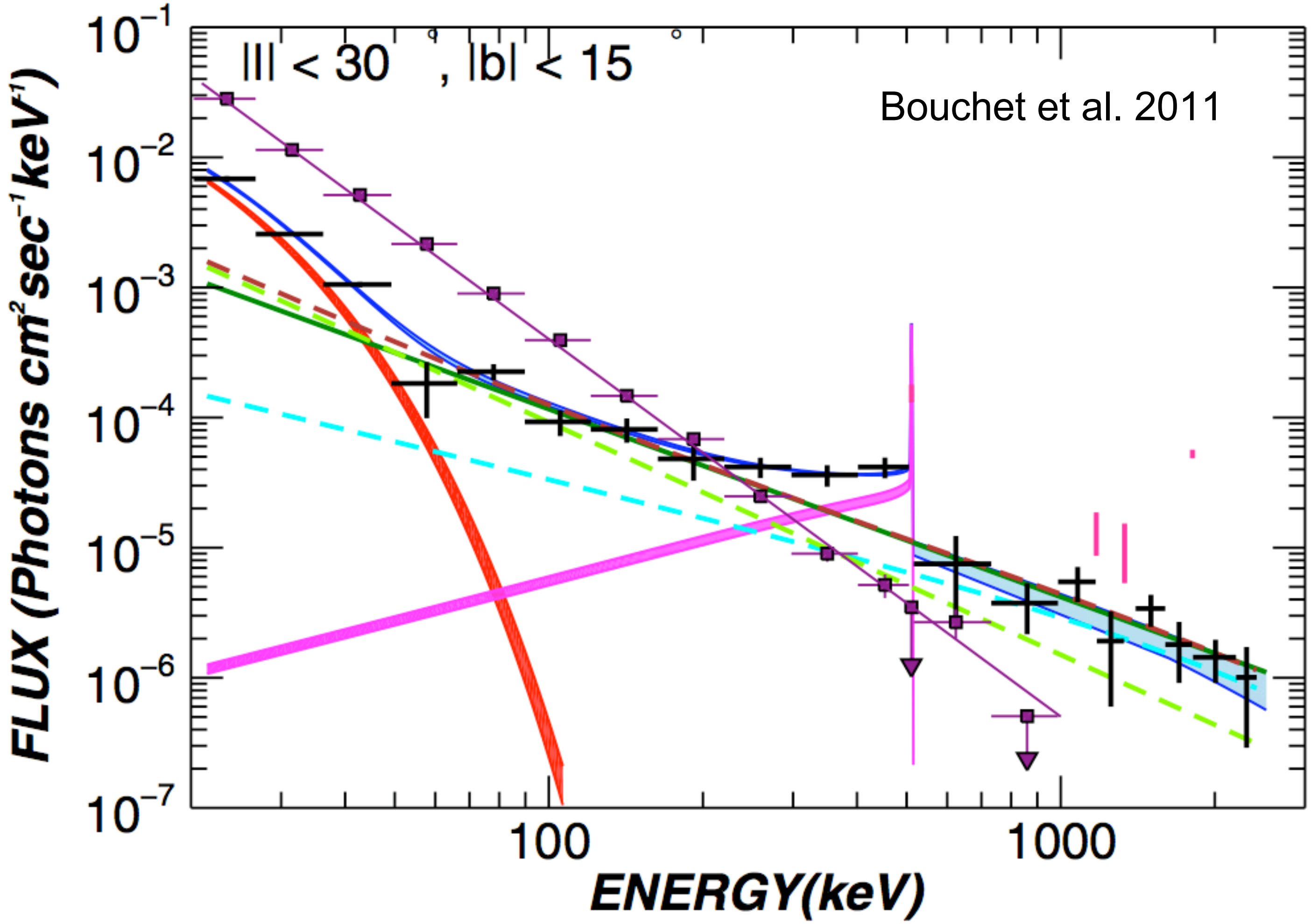




Prospects for soft gamma-rays

From INTEGRAL/SPI Milky Way study: not so good

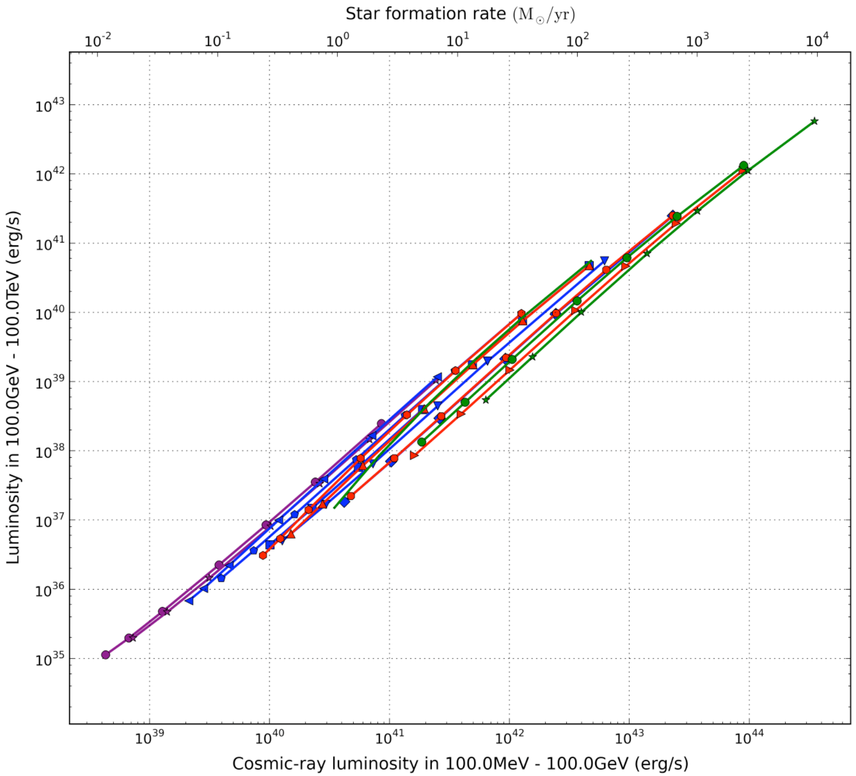
- Signal dominated up to 511keV by population of sources and positron annihilation
- No mission planned for 1-10MeV (but candidates for M4)

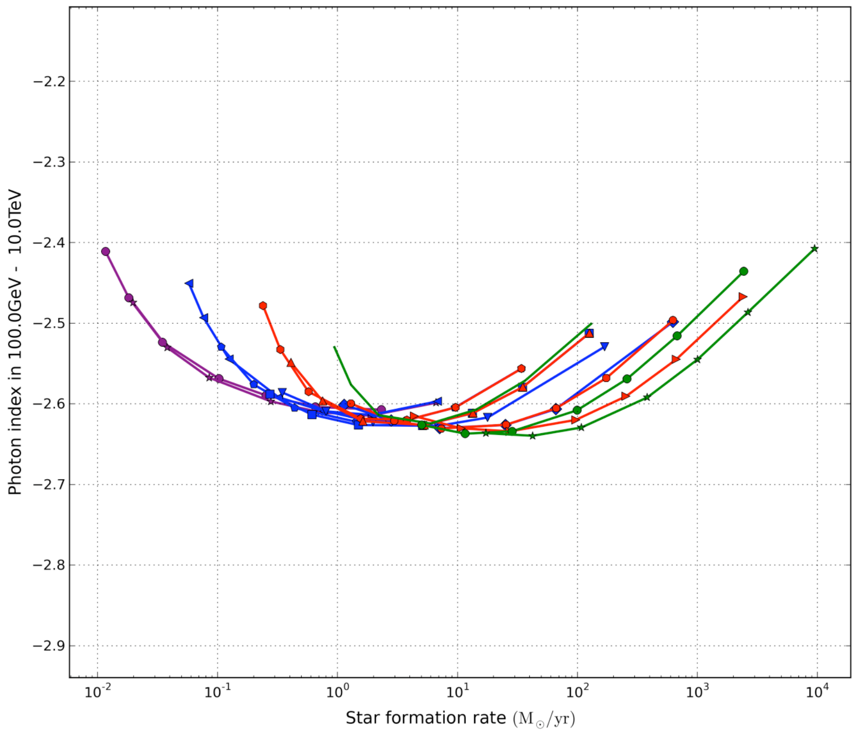


Prospects for very high energies I

100GeV-100TeV

- Stronger non-linearity in L_γ-SFR (index 1.5-2.0)
- Photon indices trace evolution with increasing density: strong inverse-Compton→ ~diffusion-dominated π^0 → ~loss-dominated π^0

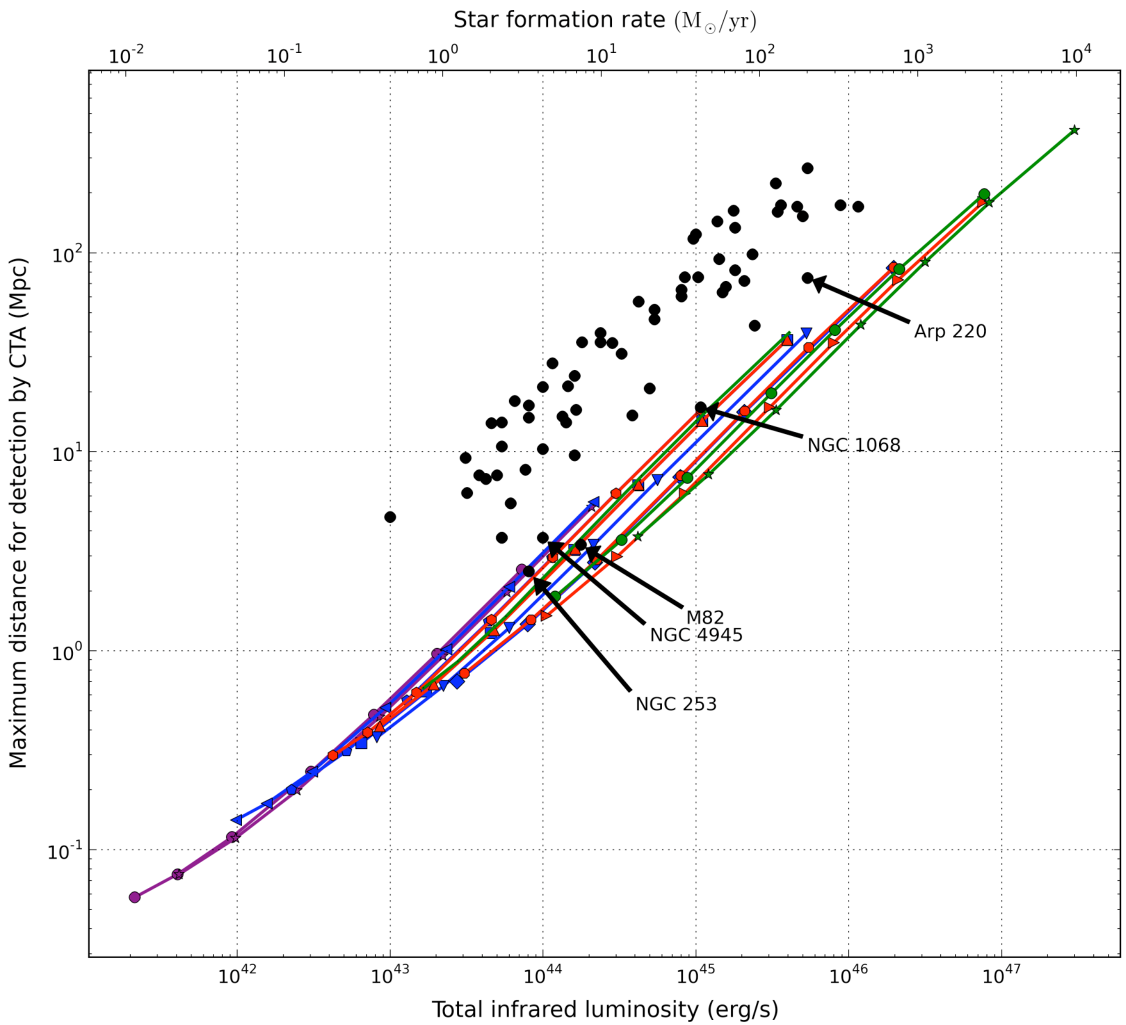




Prospects for very high energies II

100GeV-100TeV

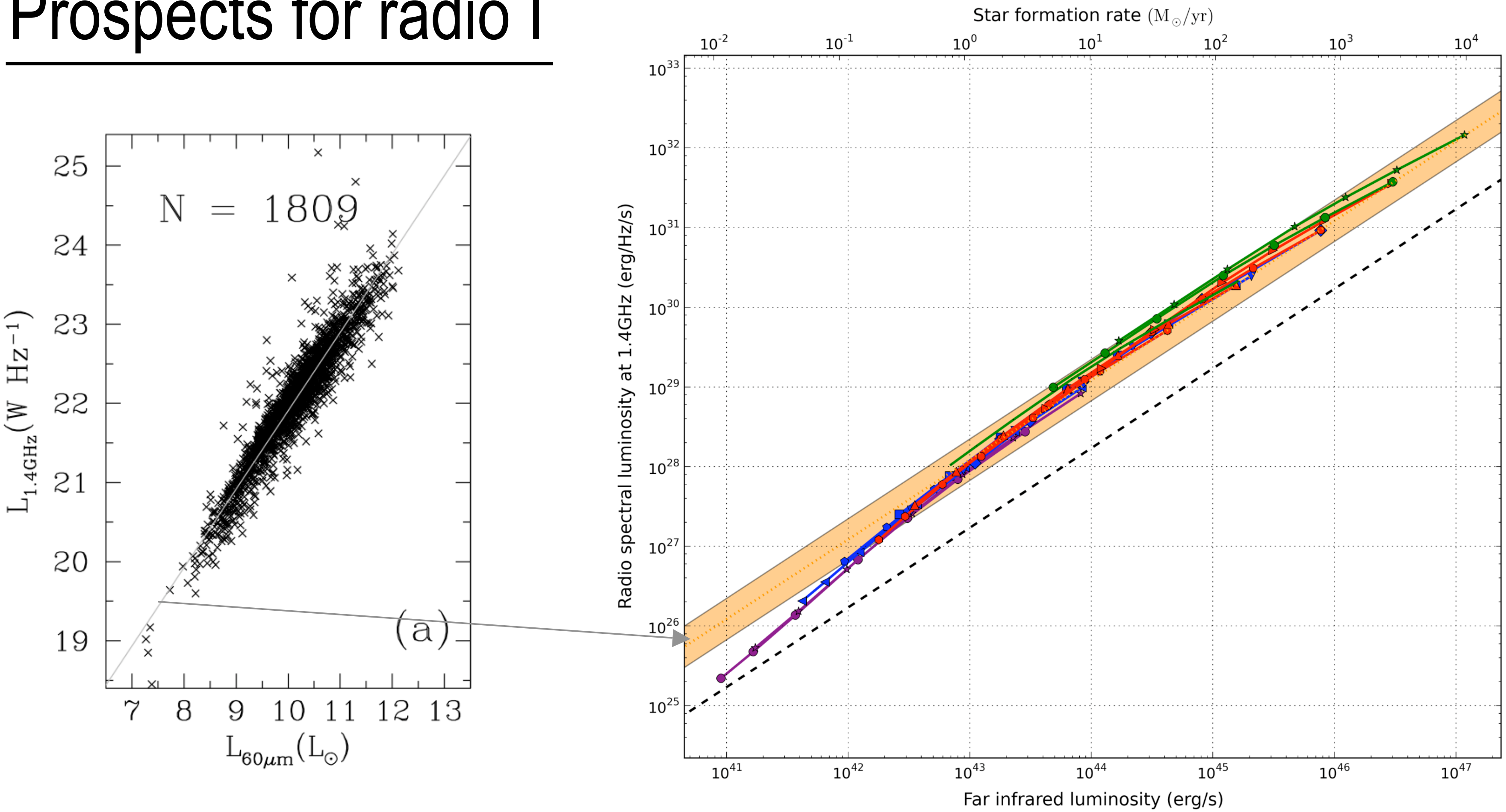
- From modelled L_{IR}-L_γ relation and spectra
- Maximum distance, to get 1mCrab @ 1 TeV (detectable by CTA in 50-100h)
- Compare with Fermi/LAT sample (black dots)



Only a handful of objects accessible with CTA ?

- Modelled spectra too soft compared to observations
  - PWNe contribution not accounted for

Prospects for radio I



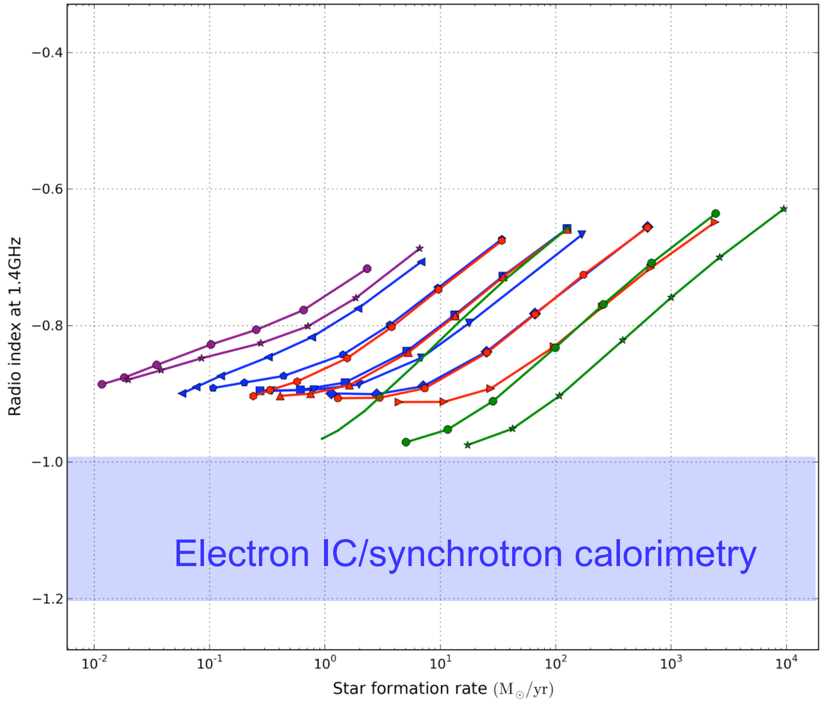
Far infrared - radio continuum correlation

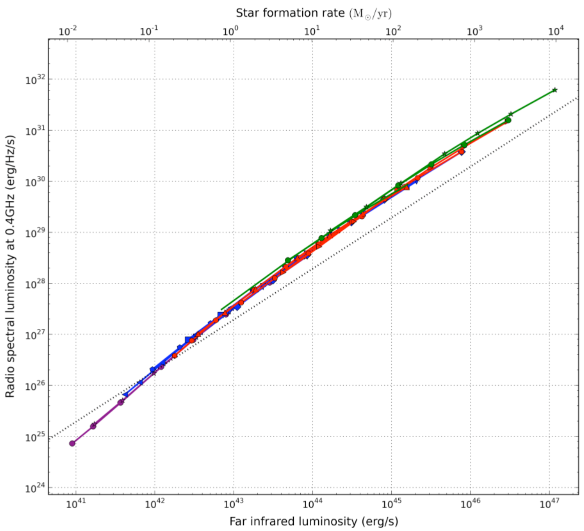
- Formally one degree of freedom in model (B field index)
- Downturn at low SFRs (also in Yun-2001):
- …free-free compensates ? consistent with SMC/LMC observations of high thermal fraction ?
- Amazingly small scatter

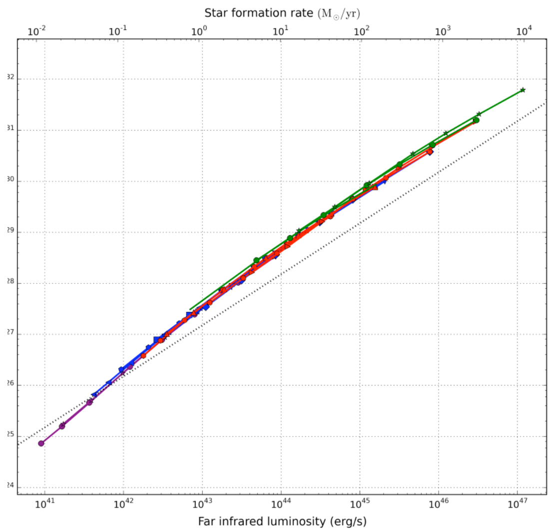
Prospects for radio II

On-going study…

- Spectral indices seem OK
- Test correlation at other frequencies
- Halo vs disk contribution
- Prospects for LOFAR and SKA ?







Martin-2014
in preparation