Cosmic Rays and the Star-Forming Contribution to the GeV Background

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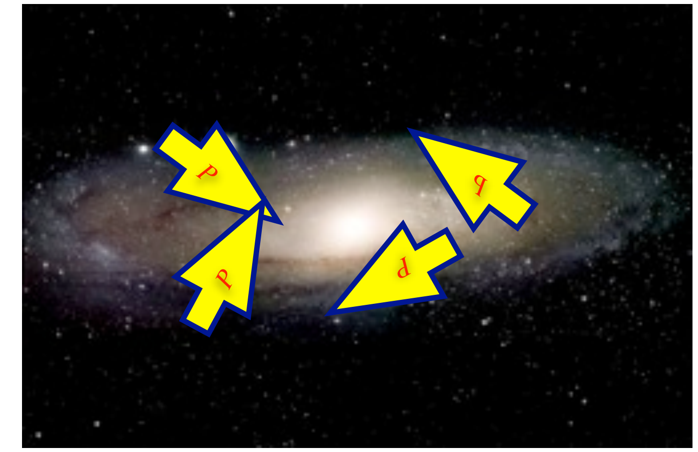
Gamma Rays from Star-Forming Galaxies

Predictions for Normal Galaxies

Pavlidou & BDF 2001



★ **Global Hadronic (Pionic) Luminosity:**

dominated by proton-ISM interactions: $pp \to \pi^0 \to \gamma\gamma$

$$\gamma \text{ emission} = \text{projectiles} \times \text{targets}$$
$$= (\gamma\text{-rays per H atom}) \times (\text{total \# H atoms})$$

★ **projectiles**

$$\gamma\text{-rays per H atom} \sim \text{CR flux} \sim \text{SN rate} \times \tau_{\text{escape}} \sim \text{star-form rate}$$

★ **targets**

$$\text{total \# H atoms} \propto M_{\text{gas,tot}}$$

★ **luminosity**

$$\gamma \text{ emission} \propto \text{star-form rate} \times M_{\text{gas,tot}}$$

Keith?

Resolved Galaxies

LMC and SMC resolved by Fermi

First gamma maps of external galaxies

★ **Expectations**

hotspots at star-forming regions

surface brightness

$$I_\gamma \sim \text{flux} \times \text{targets} \sim N_{\text{H,total}} \Phi_{\text{cr}}$$

gammas should trace total gas column

★ **Reality** Abdo+ 2010

✓ global, integrated flux agrees with CR+ISM model

✓ 30 Doradus bright! star formation makes gamma ray

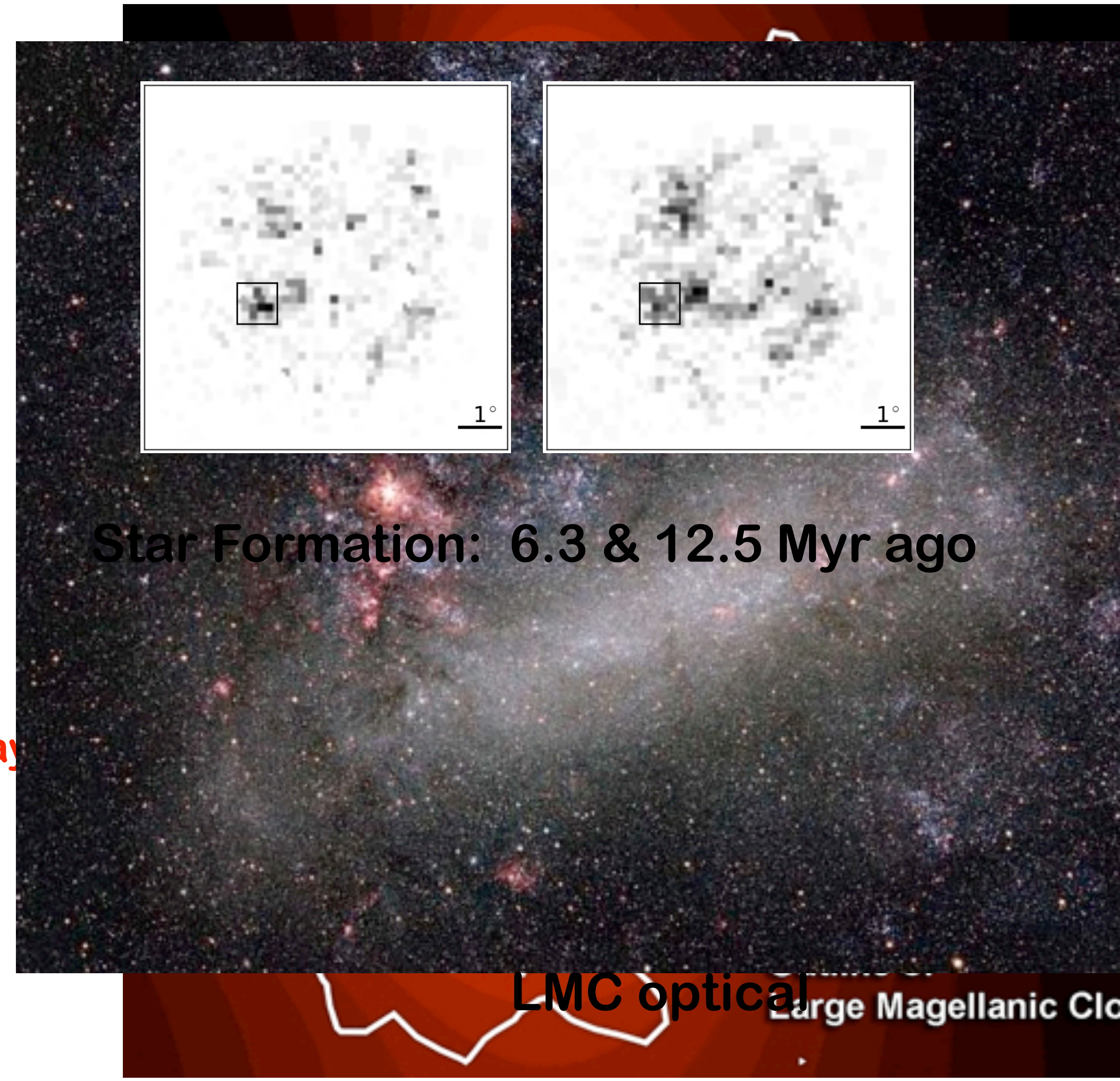
x diffuse emission traces ionized H, not total!?

★ **What's going on?**

cosmic rays diffuse less from sources?

invisible (undetected) gas reservoirs?

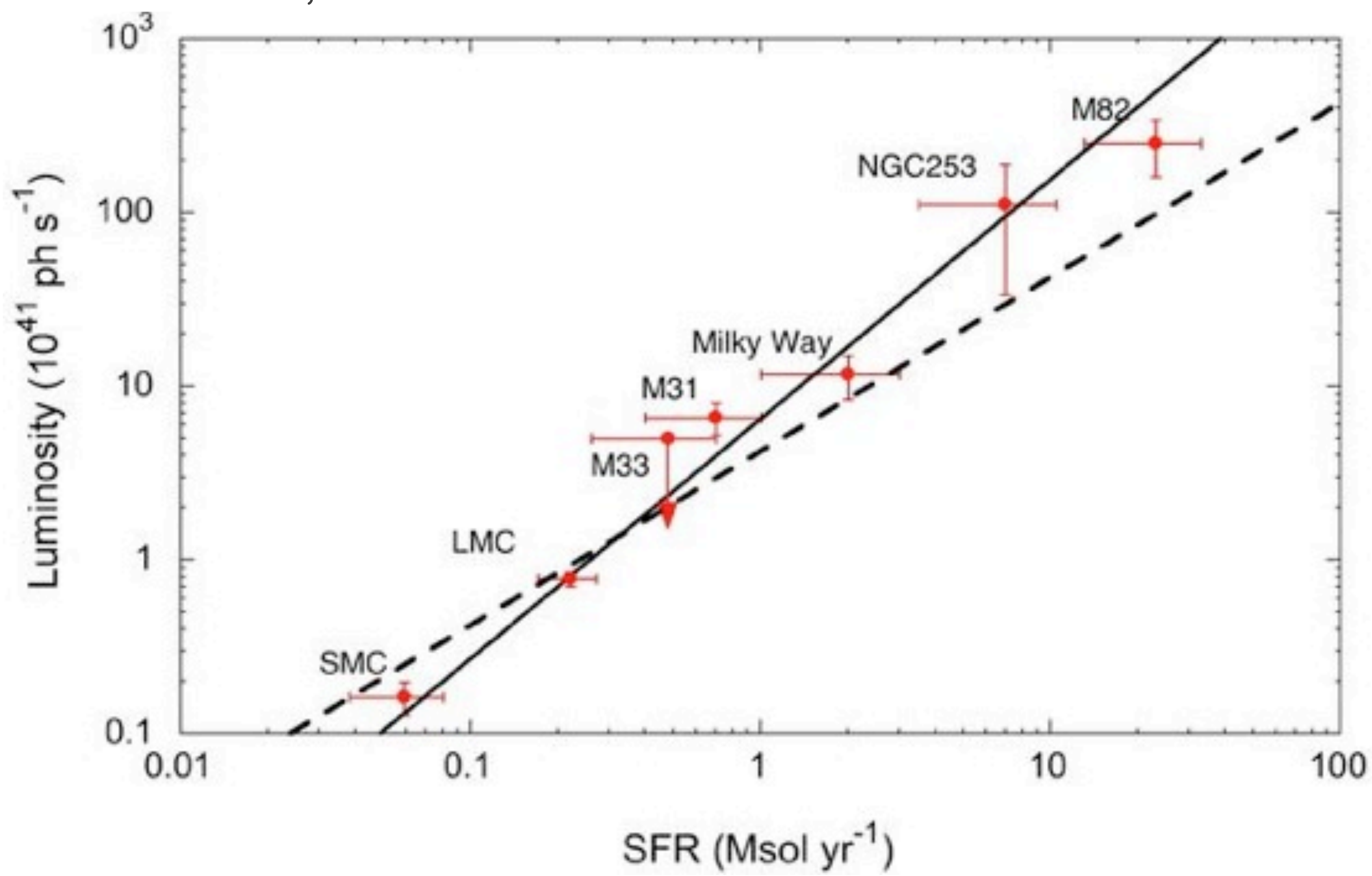
cosmic-ray time dependence important? Foreman+ 2014



LMC Map. color: Fermi
contours: neutral H

How Do Star-Forming Galaxies Make Gamma Rays?

BDF, Pavlidou & Prodanovic 2010; Lacki talk



★ Bulk Galaxy Pionic Emission:

p+ambient matter $L_\gamma \propto \text{SF rate} \cdot M_{\text{gas}}$

but Schmidt-Kennicutt: $\dot{\Sigma}_\star \propto \Sigma_{\text{gas}}^{1.4}$

combine: $L_\gamma \propto (\text{SF rate})^{1.7}$

★ Fermi says...

$$L_\gamma^{\text{obs}} \propto (\text{SF rate})^{1.4\pm0.3}$$

better fit than SF only

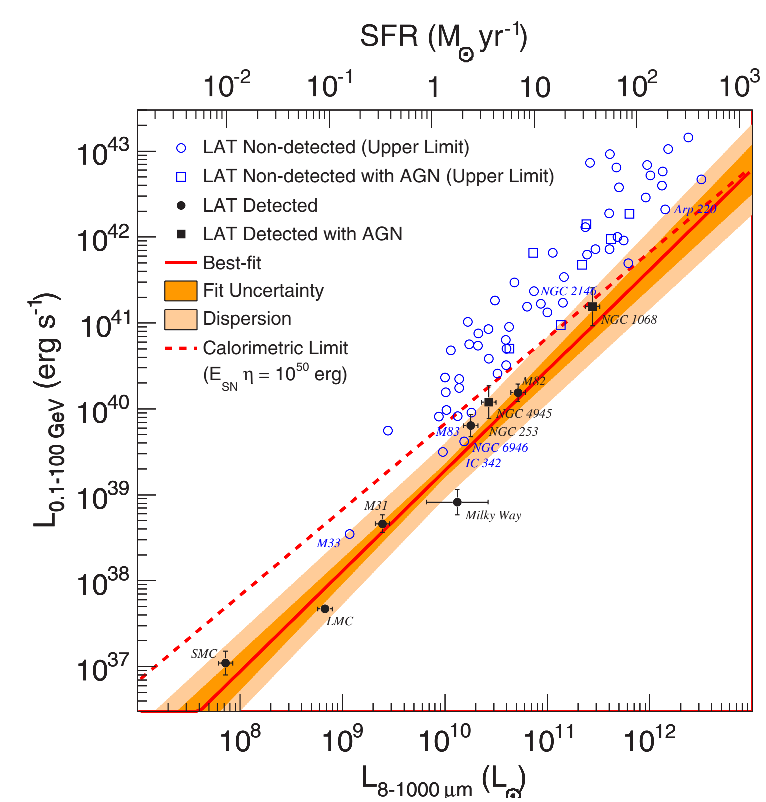
★ Caveats!

wide range of galaxy types, SF modes

resolved LMC map violates global scaling

implicitly assumes universal escaped-dominated cosmic ray propagation

data set small if hard-earned



Ackermann+ 2012

★ Lessons

star form. & cosmic rays strongly linked

simple model unreasonably good

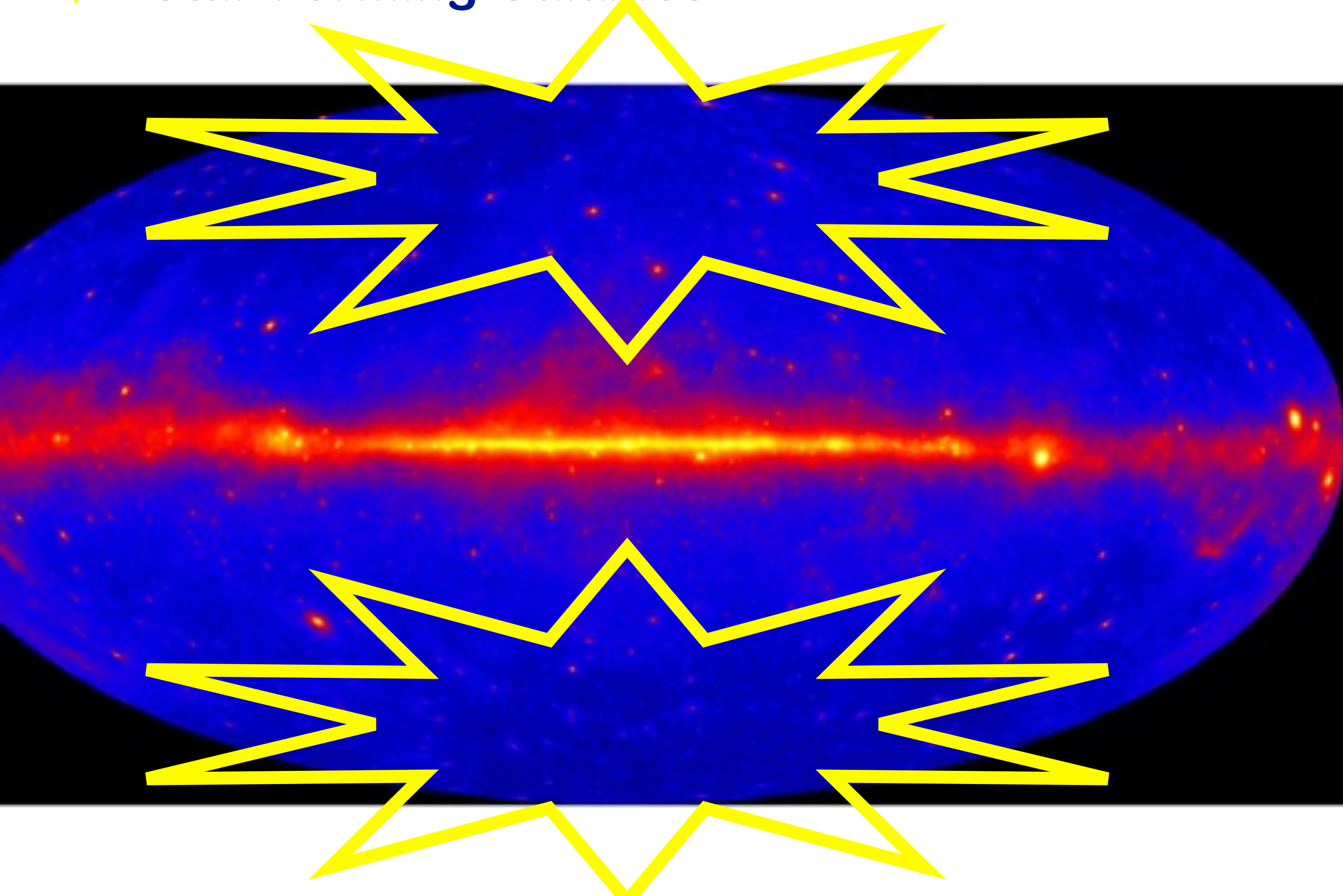
other scalings well-motivated & viable

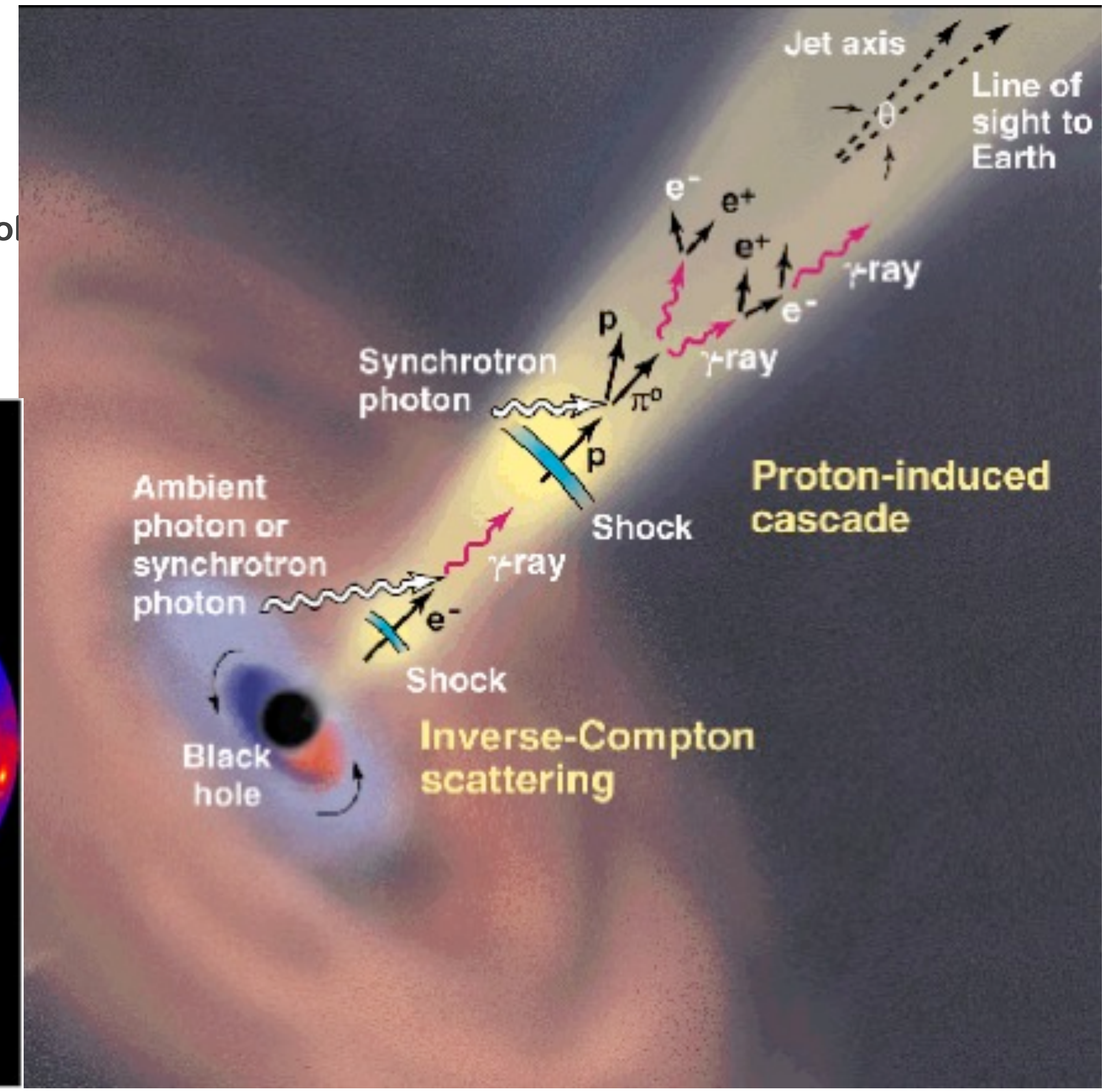
Expectations Pre-Fermi:
Guaranteed Gamma-Ray Background

Guaranteed extragalactic backgrounds

faint, unresolved counterparts to confirmed sources

- ✓ **active galaxies** Stecker & Salamon, Mukherjeee & Chaing, Pol
- ✓ **Star-Forming Galaxies** Pavlidou & BDF 2011

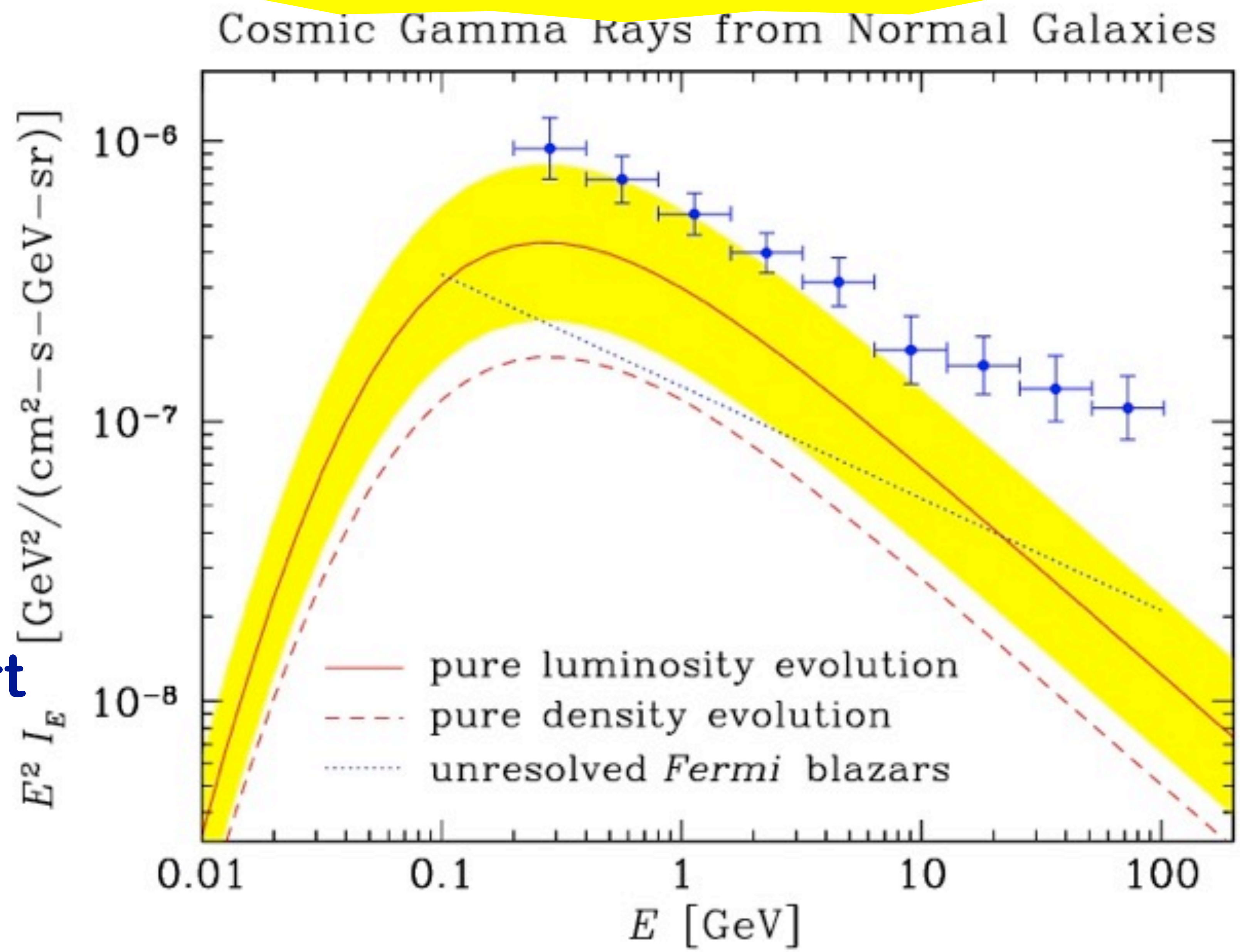




Diffuse Gamma-Ray Background
Unresolved Normal Galaxies?

working hypothesis:
supernovae are engines of cosmic-ray acceleration

Normal Galaxies only--no starbursts
Pure luminosity evolution



star formation → SN → cosmic rays

√ gamma signal:

$$I \sim \int_{\mathrm{los}} (\text{cosmic star form}) \times (\text{ISM targets})$$

√ shape: Galactic/pionic feature redshifted

√ amplitude: substantial part of preliminary Fermi signal

√ observationally calibrated

Fermi MW emissivity, Schmidt-Kennicutt

breaks cosmic SF luminosity-density degeneracy

Curves: BDF, Pavlidou, Prodanovic 2010
Points: Fermi (Abdo et al 2010)

Type Ia Supernovae?

Lien & BDF 2012

Thus far: core-collapse supernovae only

But what about SN Type Ia?

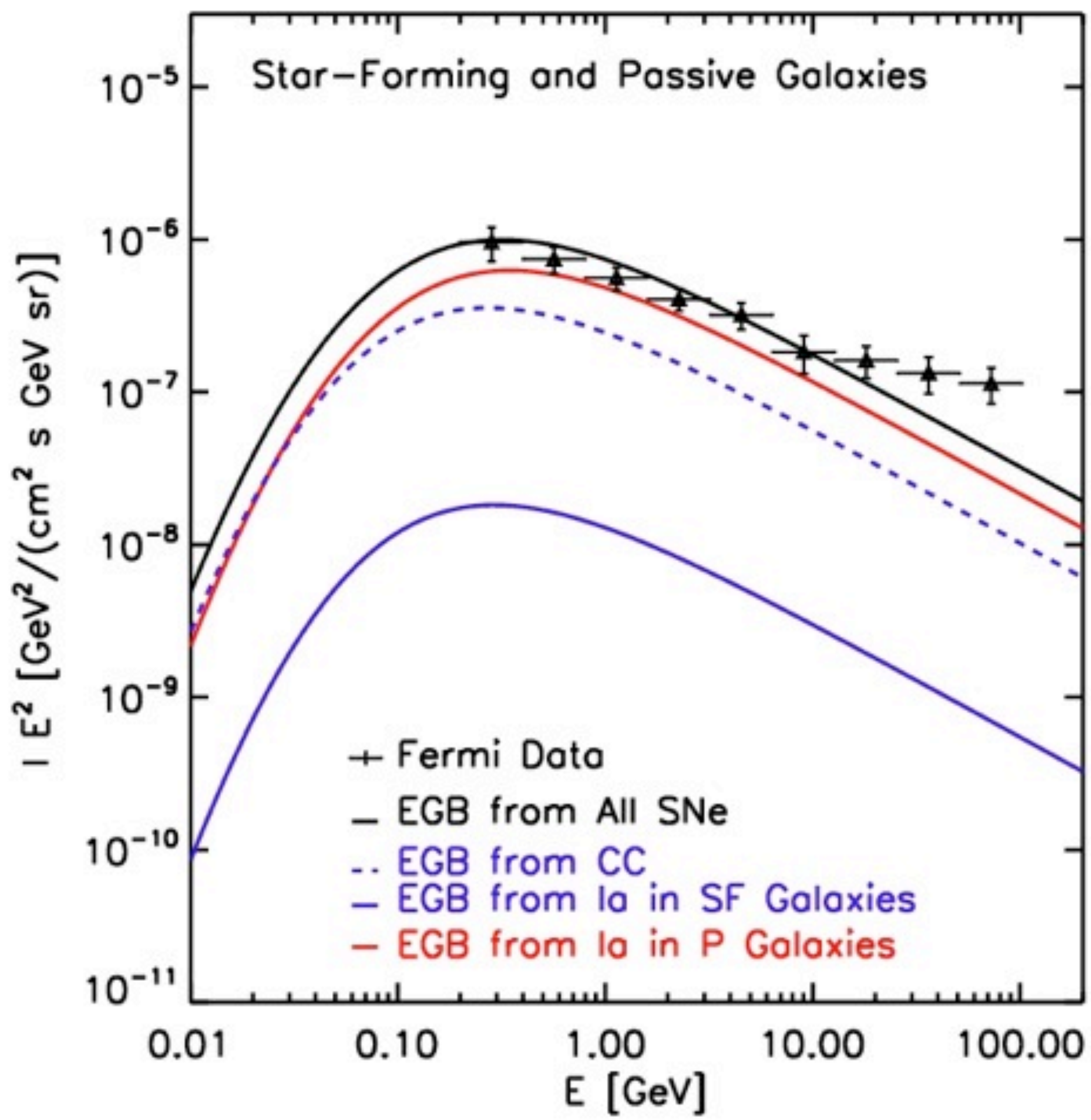
- similar blast energy, shocks
- similar CR acceleration efficiency

Including SN Ia

- add somewhat to total cosmic SN rate:
  rates: Ia/CC ~ 1/4
- but also add to Milky Way CR flux
  which normalizes gamma-ray/SN ratio
- net EGB change is small!

Unless!

- long-lived Ia events occur in elliptical galaxies
- some hints of extended X-ray gas reservoirs
  Humphrey+ 2011; Jiang & Kochanek 07; but David+ 06; Fukuzawa+ 06
- in extreme case, overpredict Fermi signal
- implies limits on hot gas content of ellipticals



Inverse Compton

Chakraborty & BDF 2012

Thus far: only hadronic (pionic) emission

- but CR electrons exist!
- inverse Compton? $e_{\rm cr}\gamma_{\rm interstellar} \rightarrow e\gamma_{\rm fermi}$

In present bulk Milky Way:

- IC subdominant Strong+ 2010

Scaling:

- luminosity: $L_{\rm IC} \propto \Phi_e \; n_{\gamma,\rm isrf}$
- but IC dominates loss:

$$\Phi_e \;\propto\; ({\rm SF\,rate})/\dot{E}_e \;\propto\; ({\rm SF\,rate})/u_{\rm isrf}$$

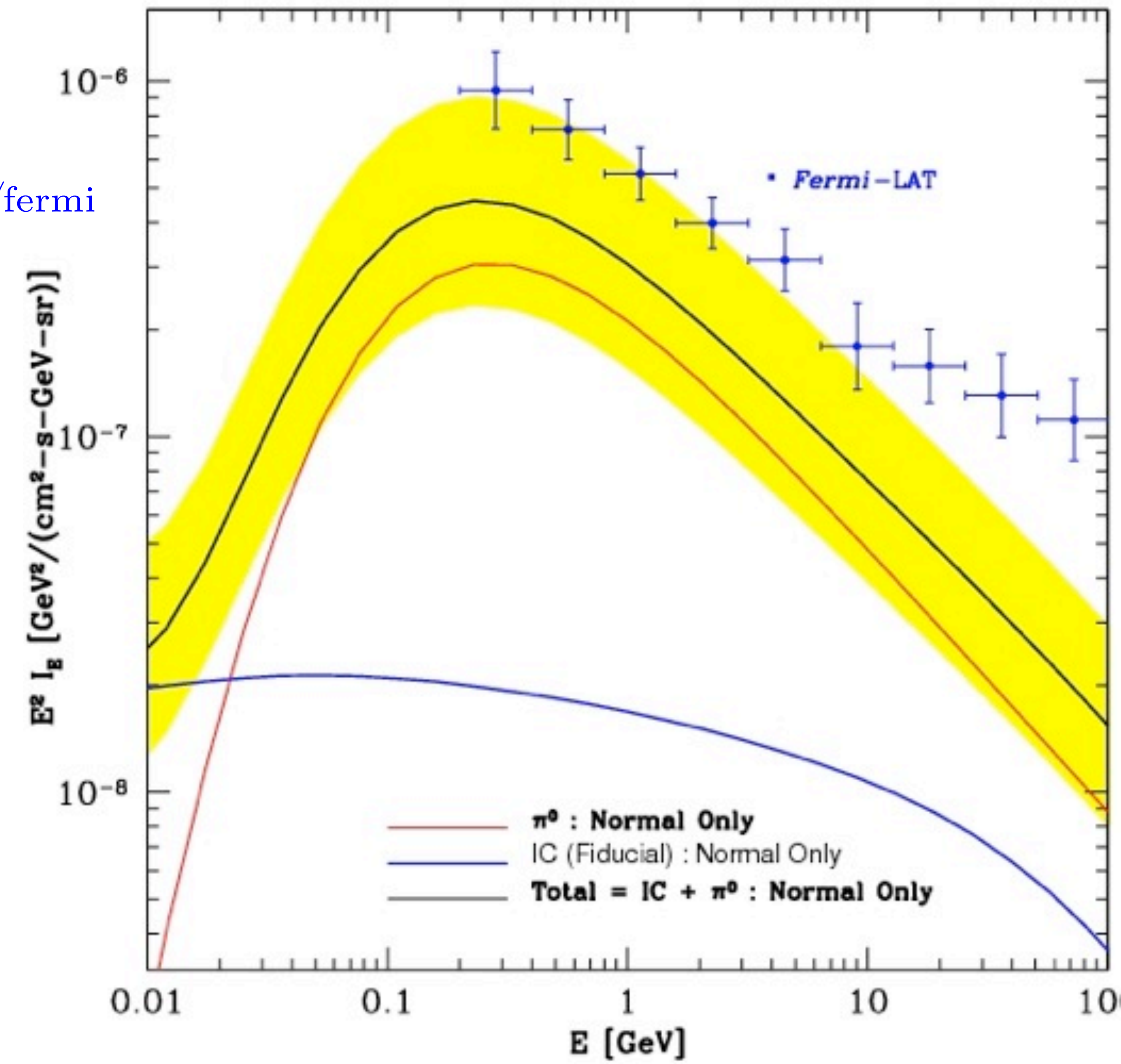
- thus: calorimetry

$$L_{\rm IC} \;\propto\; \frac{\rm SF\,rate}{\langle \epsilon_{\rm isrf} \rangle} \sim {\rm SF\,rate}$$

Hence: cosmic emissivity

$$\mathcal{L}_{\rm IC} \propto \dot{\rho}_\star$$

- note lack of target mass

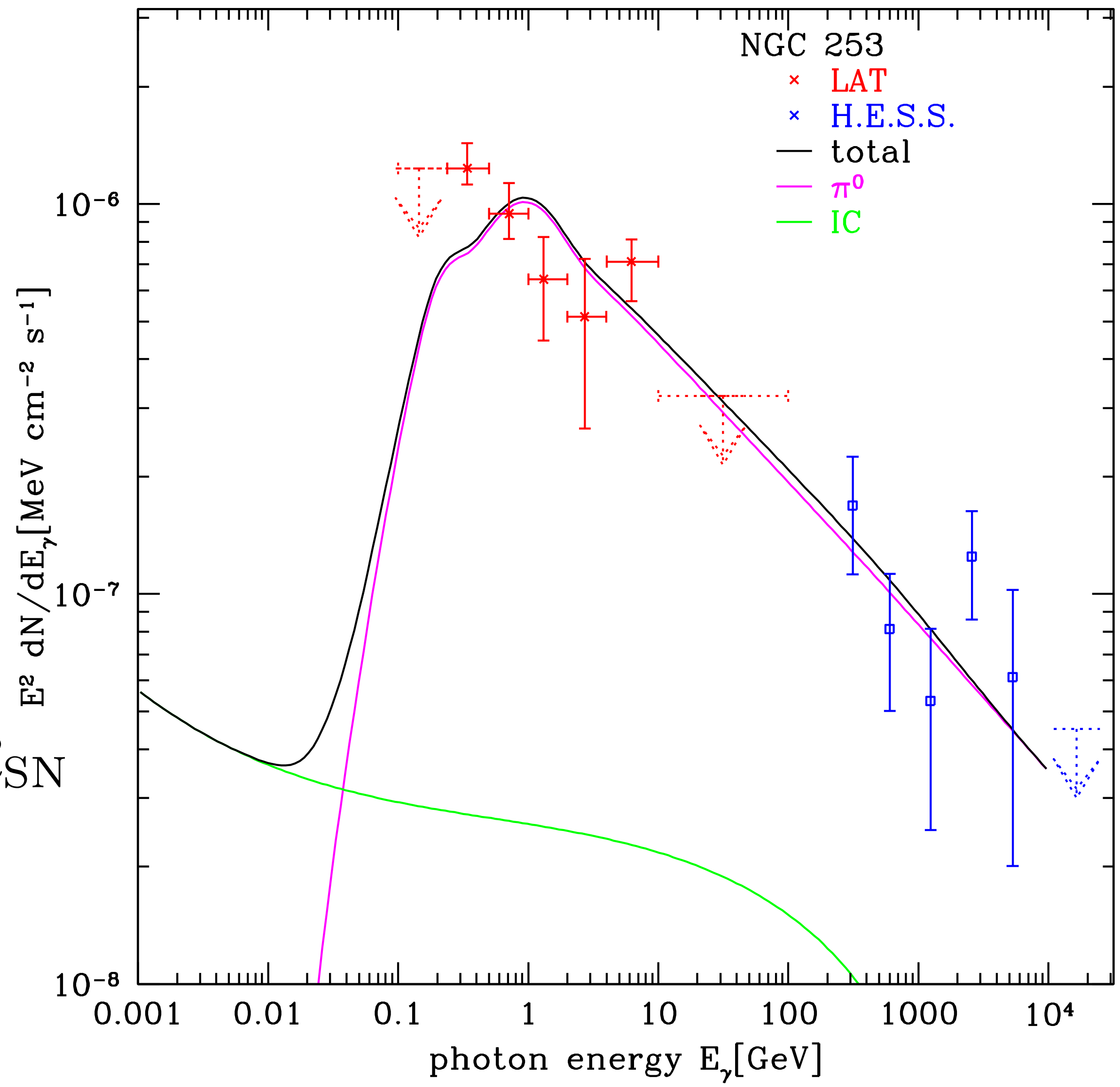


Result:

- IC subdominant in cosmic SF signal
- but becomes important ~ 10 GeV
- increases and hardens SF signal

Cosmic Ray Calorimetry
An Upper Limit to Gamma Rays from Star Formation

Wang & BDF 2014



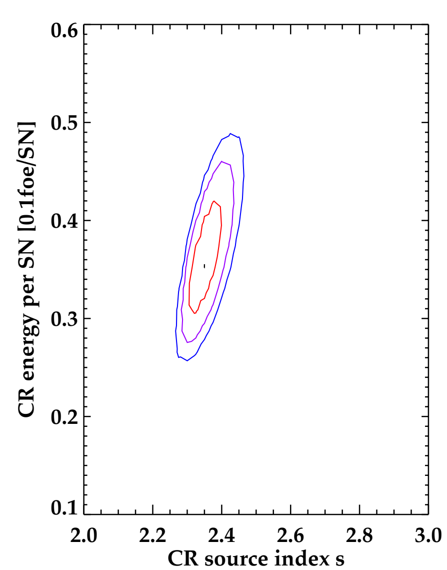
Max star-forming gamma output:

- thick target: all CR collide before escape
- gamma emission set by interaction branching to photons
- simple but self-consistent model: SN hadronic sources + losses: elastic and inelastic

Gamma luminosity $L_\gamma \propto L_{\rm CR} = E_{\rm CR} R_{\rm SN}$

Pionic gamma spectrum set by proton injection spectrum s

- high energies: $s_\gamma \approx s_p$ flatter than in MW-like escape-dominated galaxies
- low energies: pion bump



fit to starbursts: reasonable!

- index consistent with MW SNR
- CR energy/SN ~ 0.03 foe/SN

Calorimetry and Resolved Galaxies

Wang & BDF 2014

Thick target model gives upper limit to gamma emission

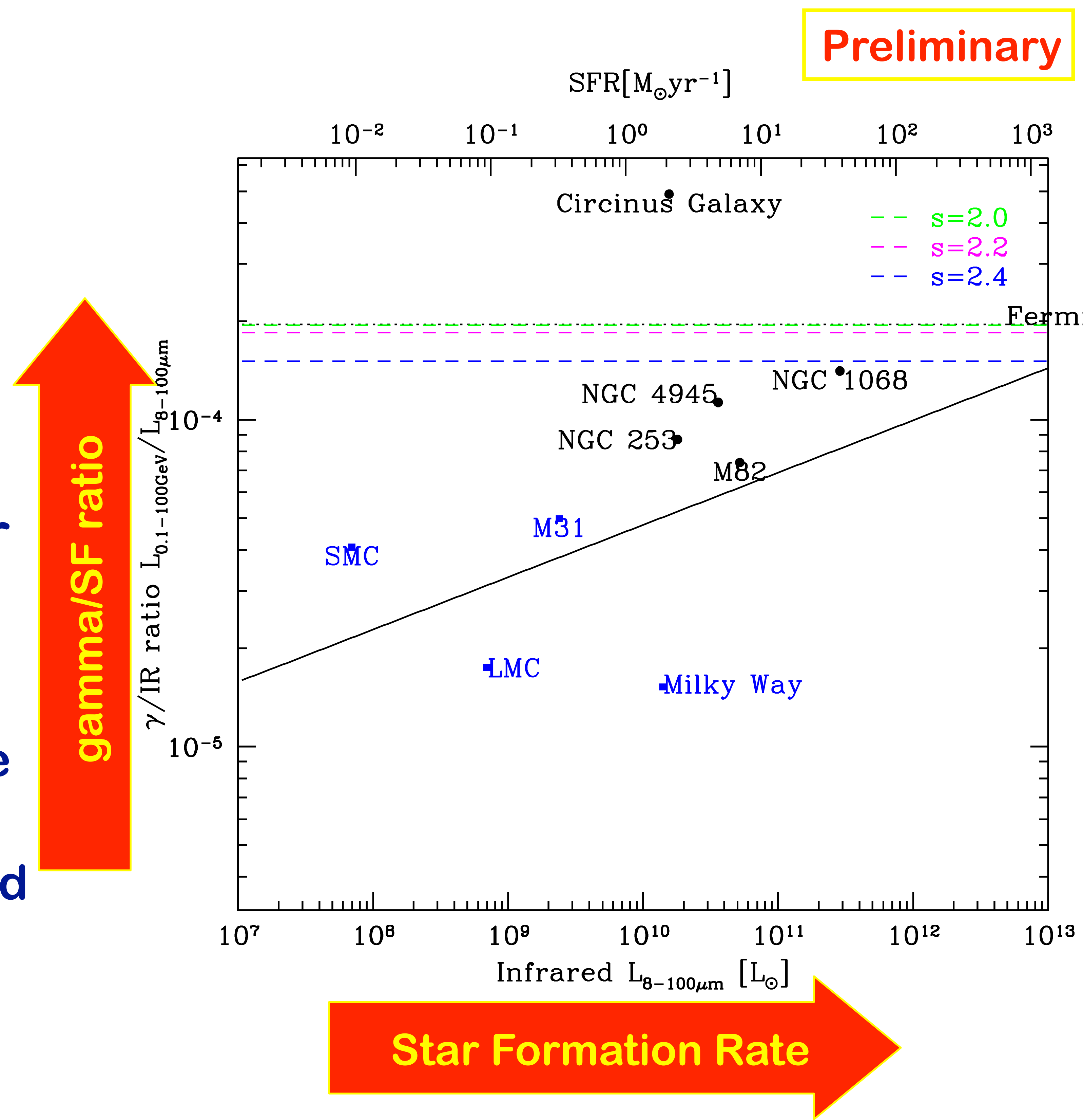
gamma/SFR ratio depends on CR energy losses

- energy dependent
- spectrum dependent

good agreement with other estimates

testing the limit:

- all star-forming galaxies lie below limit
- starbursts just under: good evidence for near calorimetry
- ...except Circinus (AGN?)



Cosmic Ray Calorimetry Limits to the Star-Forming GeV Background

Wang & BDF 2014

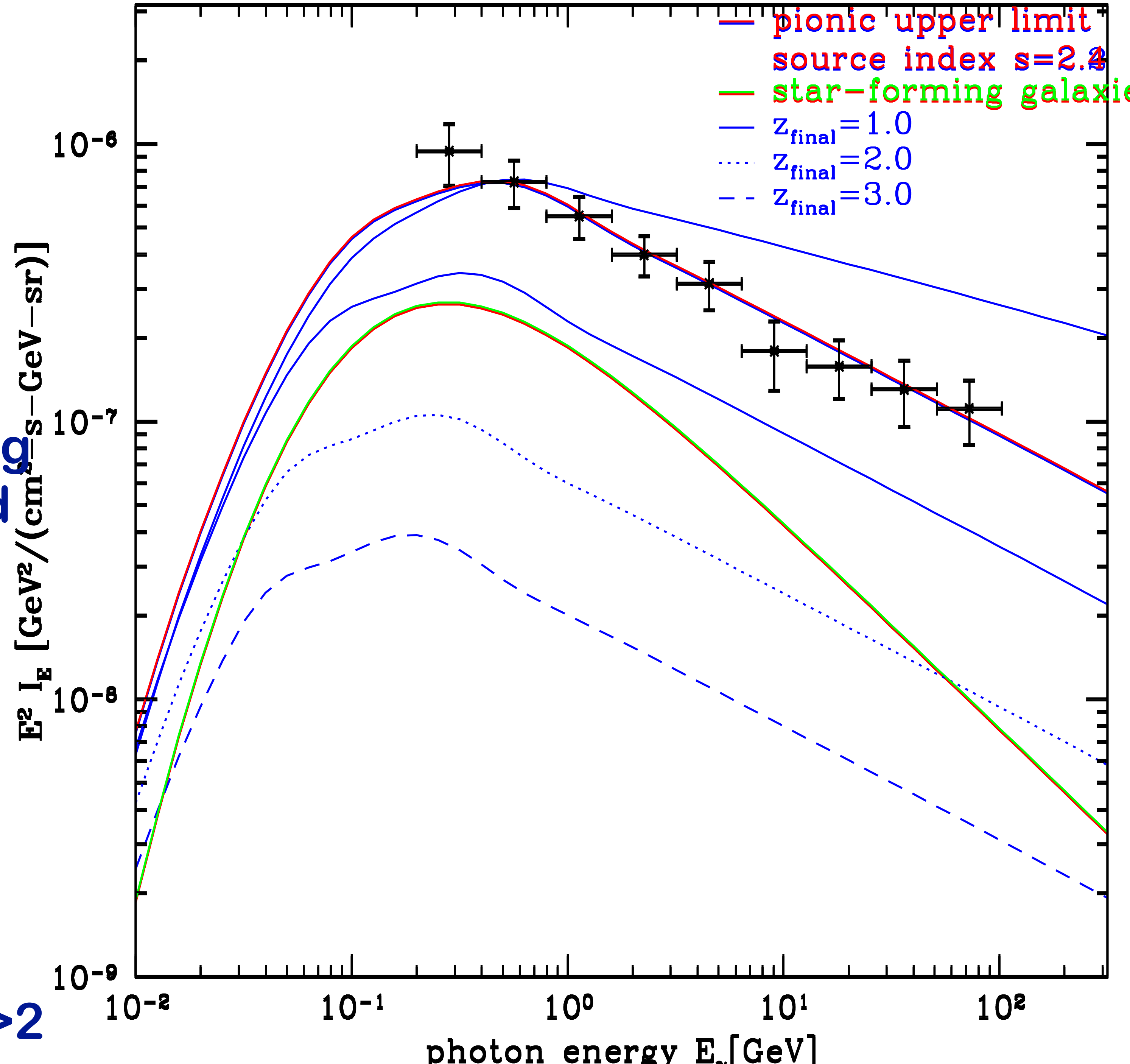
Thick target/starburst model:

fixed gamma/SFR ratio

- max cosmic emissivity $\mathcal{L}_\gamma \propto \dot{\rho}_\star$ cosmic star formation rate
- Index fixed by source CR index

Results:

- if source s=2.4, then star-forming upper limit is unreasonably good fit to data!
- but: worse if flatter s as seen in some SNRs
- and we know some (most) galaxies not calorimetric, so
- EGB cannot be entirely due to star-forming galaxies!
- first galaxies likely starbursts; z>2 signal comparable to normal galaxies at high energy



Preliminary

Cosmic Rays and the Star-Forming Contribution to the GeV Background

star-forming galaxies ⇨ SN ⇨ cosmic rays ⇨ gamma rays

- Fermi era of star-forming galaxies

  Milky Way diffuse, LMC, SMC, M31, starbursts

- star-forming gammas encode cosmic-ray ecology

  global emission fits simple model, but reality more complex

- Guaranteed component of diffuse Fermi background!

  spectral feature: redshifted Galactic (pionic) peak

  signal amplitude: probes cosmic star formation

  hardronic signal significant, spectrum must depart from power law

  cosmic-ray feedback on galaxies and cosmology

  energy/pressure/ionization source, primordial lithium problem

- The Thick Target/Calorimetry Limit

  beauty in simplicity: 2 parameters

  starbursts near calorimetric

  star-forming EGB upper limit near data: EGB not all from star form!

- Open Questions: Cosmic-Ray Archeaology

  CR acceleration efficiency & confinement dependence on galactic environment?

  CR evolution vs metallicity, redshift?

  CR differences: core collapse vs Type Ia?