Are Star-forming and Starburst Galaxies actually Cosmic-rays calorimeters?

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In collaboration with

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Starburst Galaxies: Phenomenological View


The Starburst Galaxy M82

Credit:
NASA, ESA and the Hubble Heritage Team (STScI/AURA).
Acknowledgment: J. Gallagher (University of Wisconsin),
M. Mountain (STScI) and P. Puxley (NSF).

- Galaxies with high star-formation rate (~100 M⊙/yr, to be compared with ~1 M⊙/yr in the Milky Way)
- Intense Star forming activity mainly concentrated in the core (nucleus), which lasts for $\sim 10^{7-8}\,\mathrm{yr}$
- High dense interstellar gas ($n_{\mathrm{ISM}} \simeq 10^2\,\mathrm{cm}^{-3}$)
- High degree of magnetic turbulence which traps high-energy protons for a long time $\sim 10^5\,\mathrm{yr}$: **Cosmic Reservoirs**

Expected copious hadronic production:

Interstellar gas as the target

$$p + p \rightarrow \pi^+ \, \pi^- \, \pi^0 \ldots$$

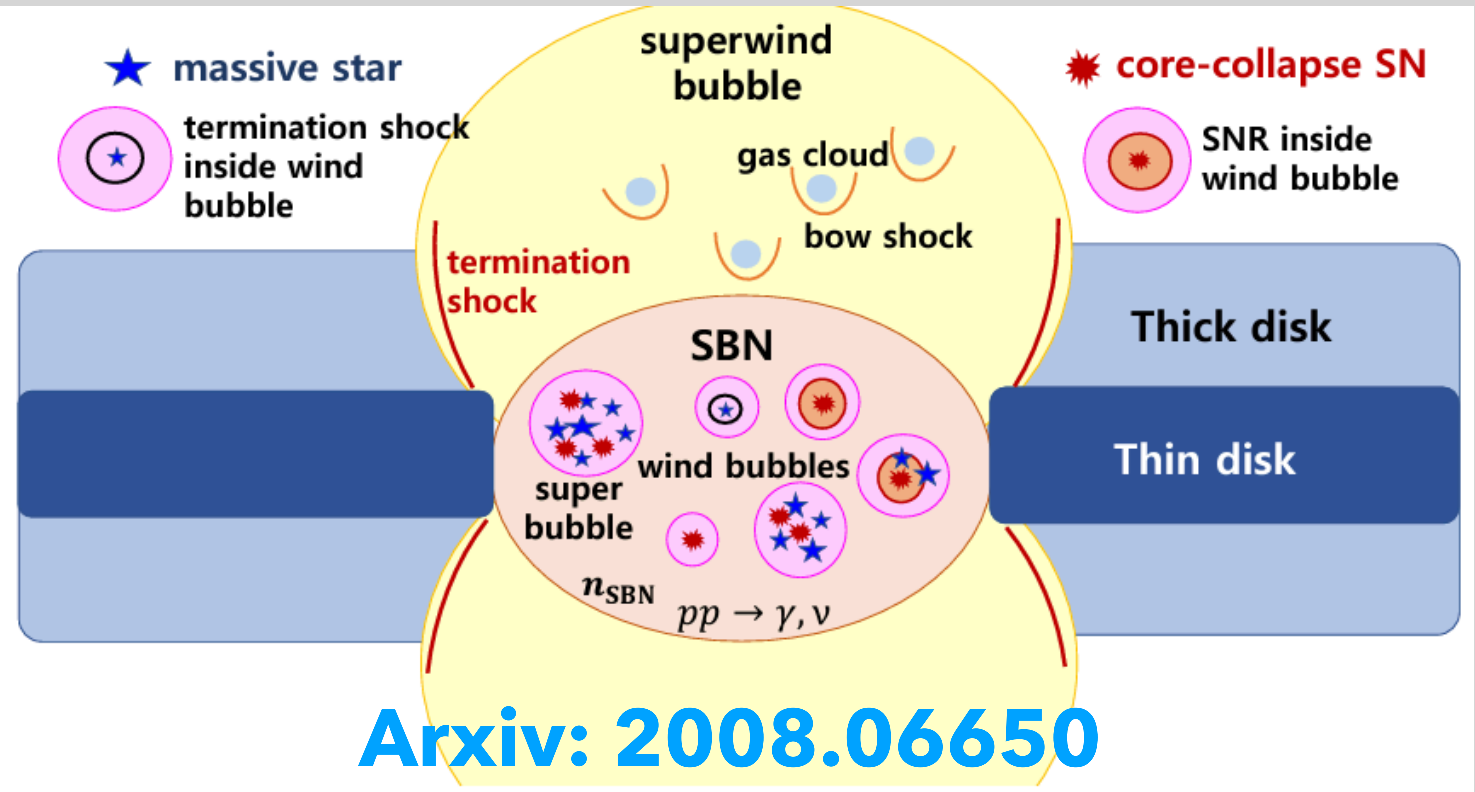
- **Neutrinos** and **γ-rays** from pions decays: $\pi^\pm \rightarrow e^\pm \, \nu_e \, \nu_\mu \, \overline{\nu}_\mu$ $\pi^0 \rightarrow \gamma \, \gamma$

Starburst Galaxies: Theoretical View

Leaky-box-like model for CR transport

$$f(p)\left(\frac{1}{\tau_{\rm loss}(p)}+\frac{1}{\tau_{\rm adv}(p)}+\frac{1}{\tau_{\rm diff}(p)}\right)=Q(p)$$

injected CR from SN explosion $Q(p)\propto\left(\frac{p}{m_p}\right)^{-\alpha}\cdot e^{-p/p_{\rm max}}$



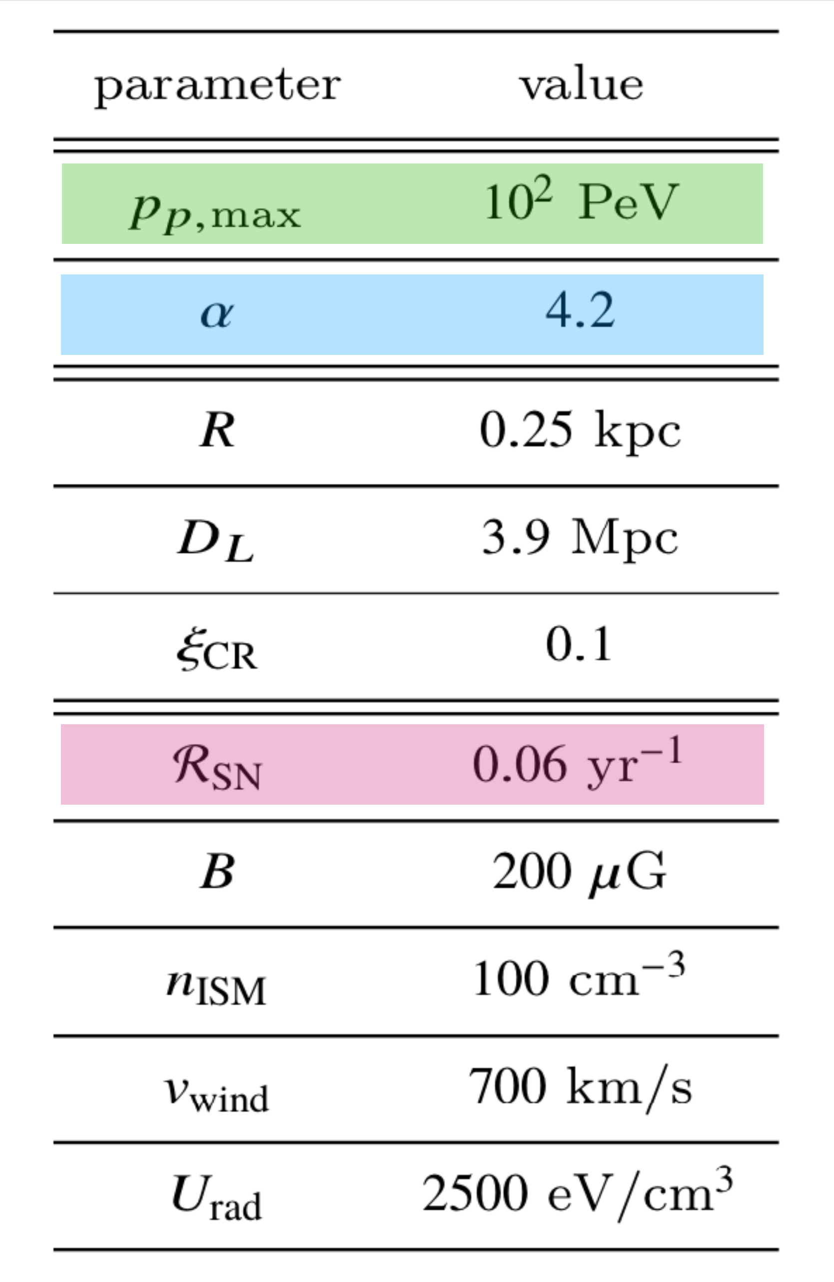
Arxiv: 2008.06650

✦ $\tau_{\rm loss}\simeq\tau_{pp}\propto\frac{1}{n_{\rm ISM}}$ The denser the SBN, the more the energy losses affects the CR transport

✦ $\tau_{\rm adv}=R/v_{\rm wind}$

✦ $\tau_{\rm diff}=R^2/D$

*Peretti et al., **arXiv:1812.01996, arXiv:1911.06163***



parameter	value
$p_{p,\rm max}$	10^2 PeV
α	4.2
R	0.25 kpc
D_L	3.9 Mpc
$\xi_{\rm CR}$	0.1
$\mathcal{R}_{\rm SN}$	$0.06\ \rm yr^{-1}$
B	$200\ \mu$G
$n_{\rm ISM}$	$100\ \rm cm^{-3}$
$v_{\rm wind}$	700 km/s
$U_{\rm rad}$	$2500\ \rm eV/cm^3$

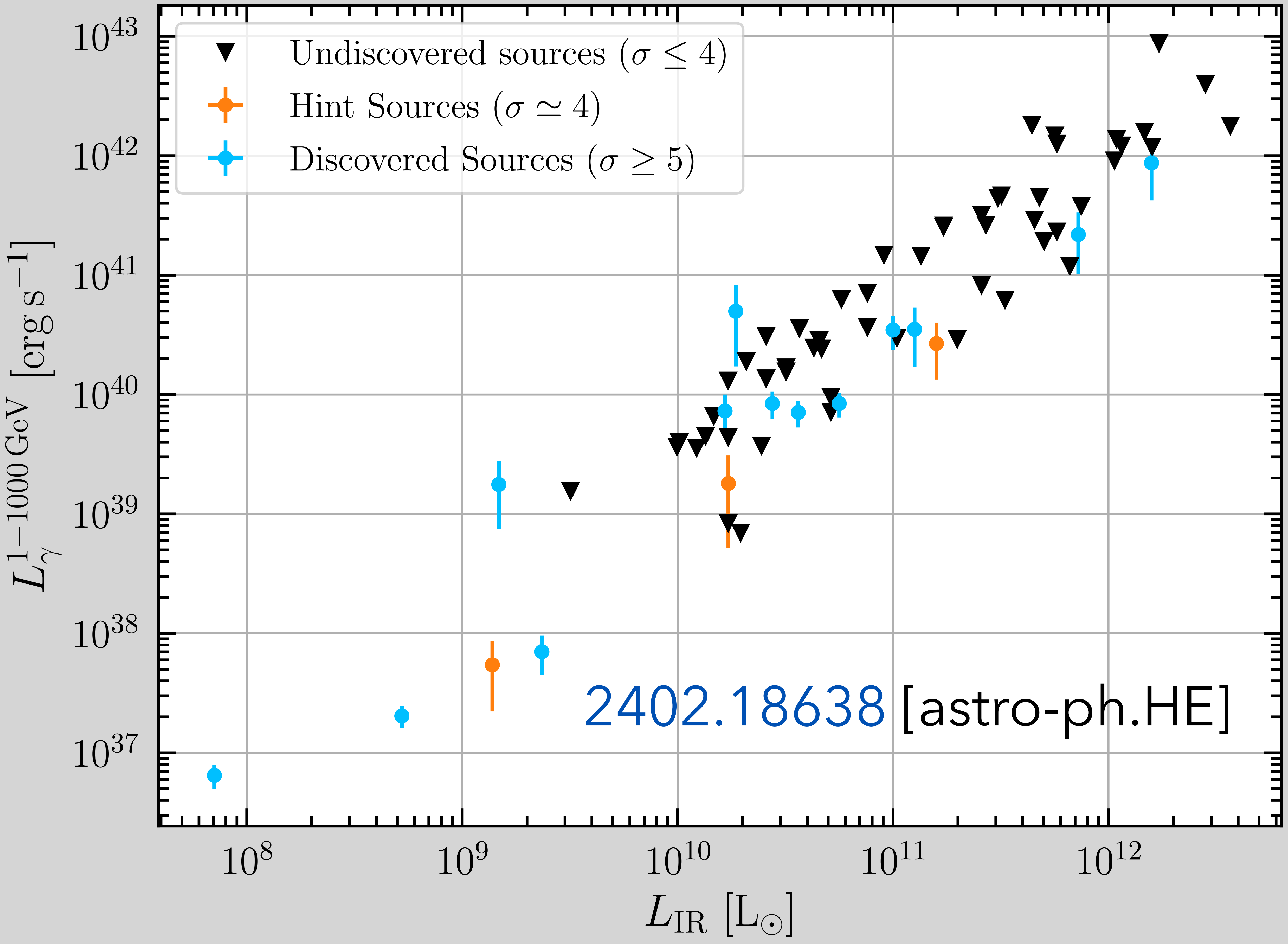
Main Parameters for SBGs

- Cut-off energy
- Spectral index
- Rate of SuperNovae explosions

Star-formation and γ-rays

There is a tight correlation between the γ-ray luminosity and the Infrared (IR) Luminosity

Analysing a catalogue of 70 sources with 15 years of Fermi-LAT data



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The IR Luminosity is strictly connected to the Star Formation Rate (SFR)

$$\mathrm{SFR} = 1.36 \cdot 10^{-10} \left(\frac{\mathrm{L_{IR}}}{\mathrm{L_{\odot}}}\right)\left(1 + \sqrt{\frac{10^{9}\mathrm{L_{\odot}}}{\mathrm{L_{IR}}}}\right)\ [\mathrm{M_{\odot}\,yr^{-1}}]$$

✦The higher the SFR, the more CRs get injected in SBG disk

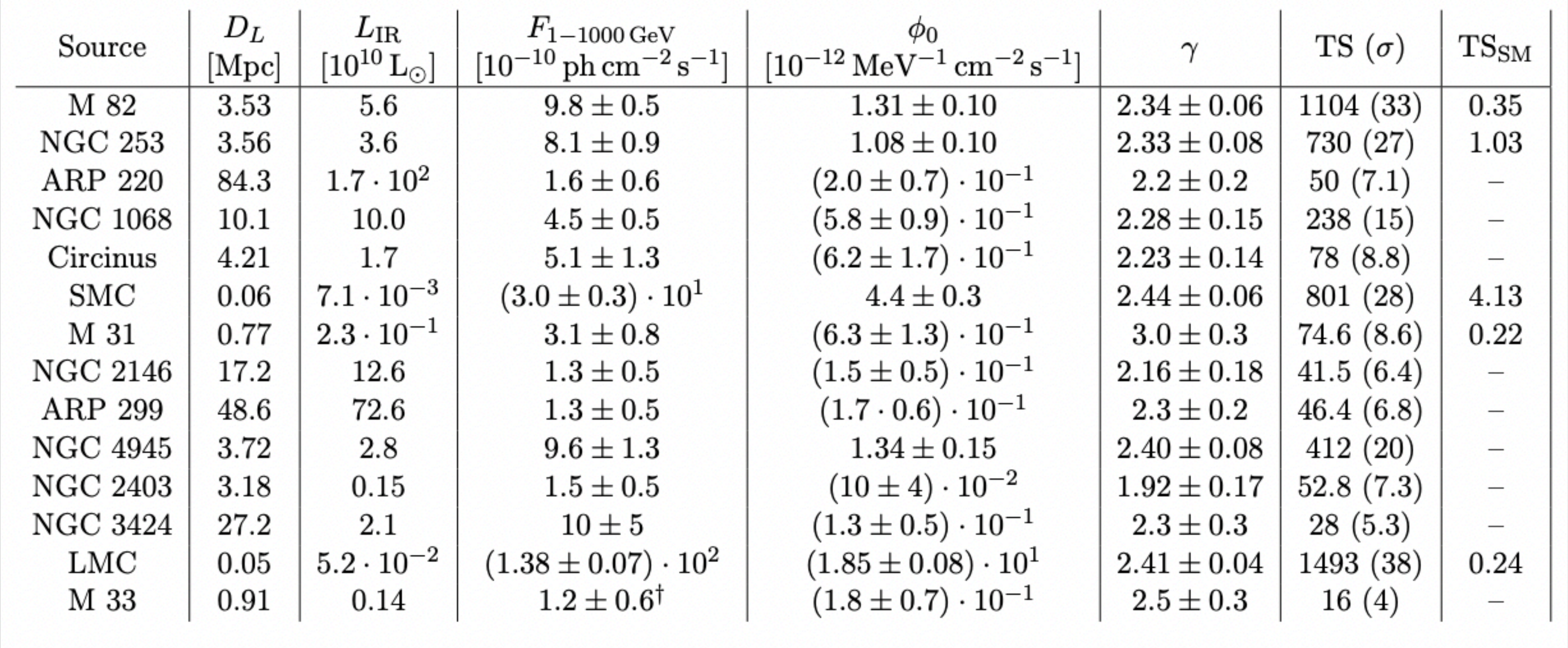
✦The higher the SFR, the more dense the system is and the CRs are trapped into the system **(Complete CR calorimetry)**

Properties of Discovered Sources

14 sources are discovered with more than $5\sigma\,(\mathrm{TS} > 25)$

$E_\gamma \in [1 - 1000]\,\mathrm{GeV}$

Take a look at 2402.18638 [astro-ph.HE]

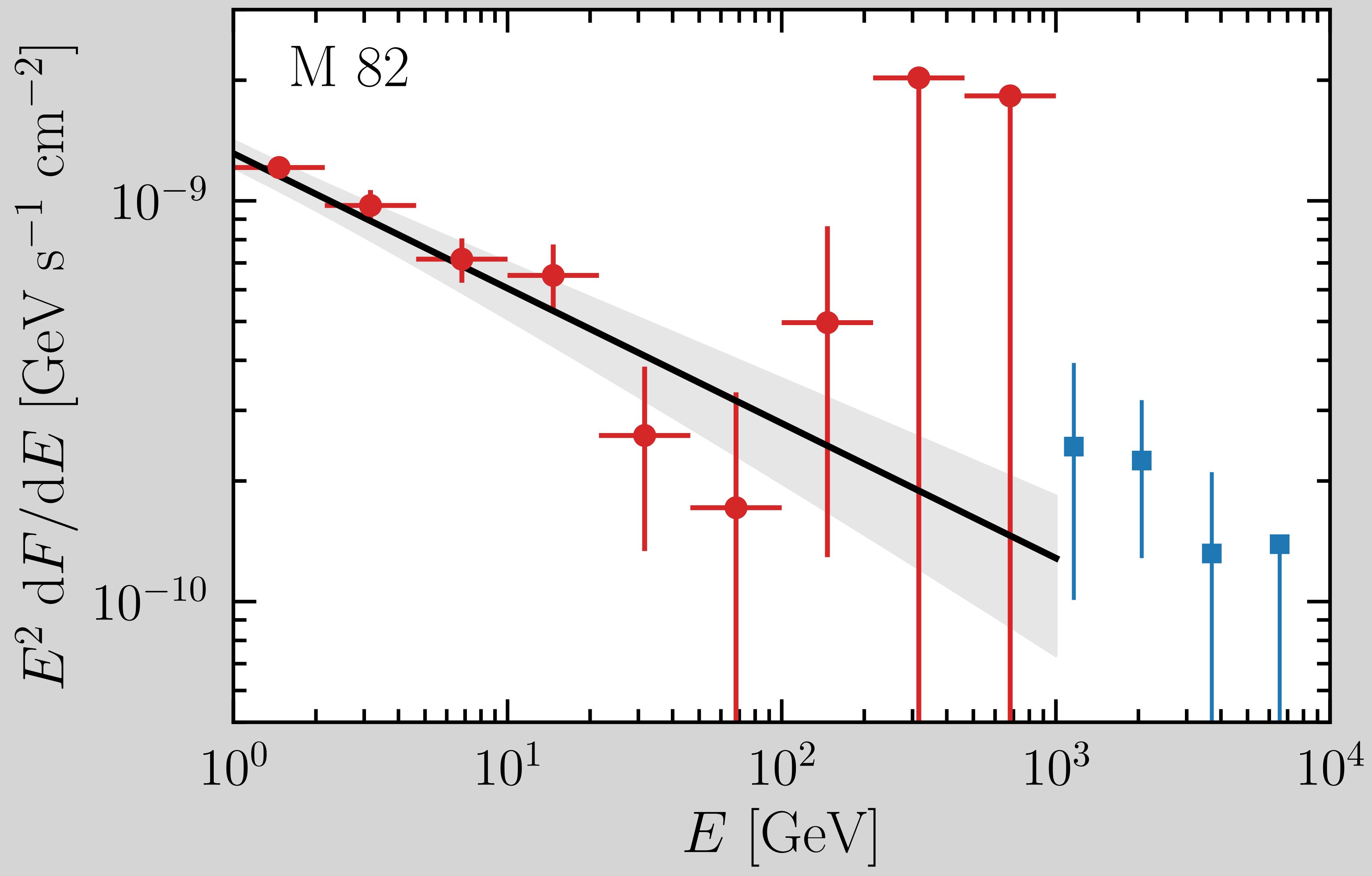


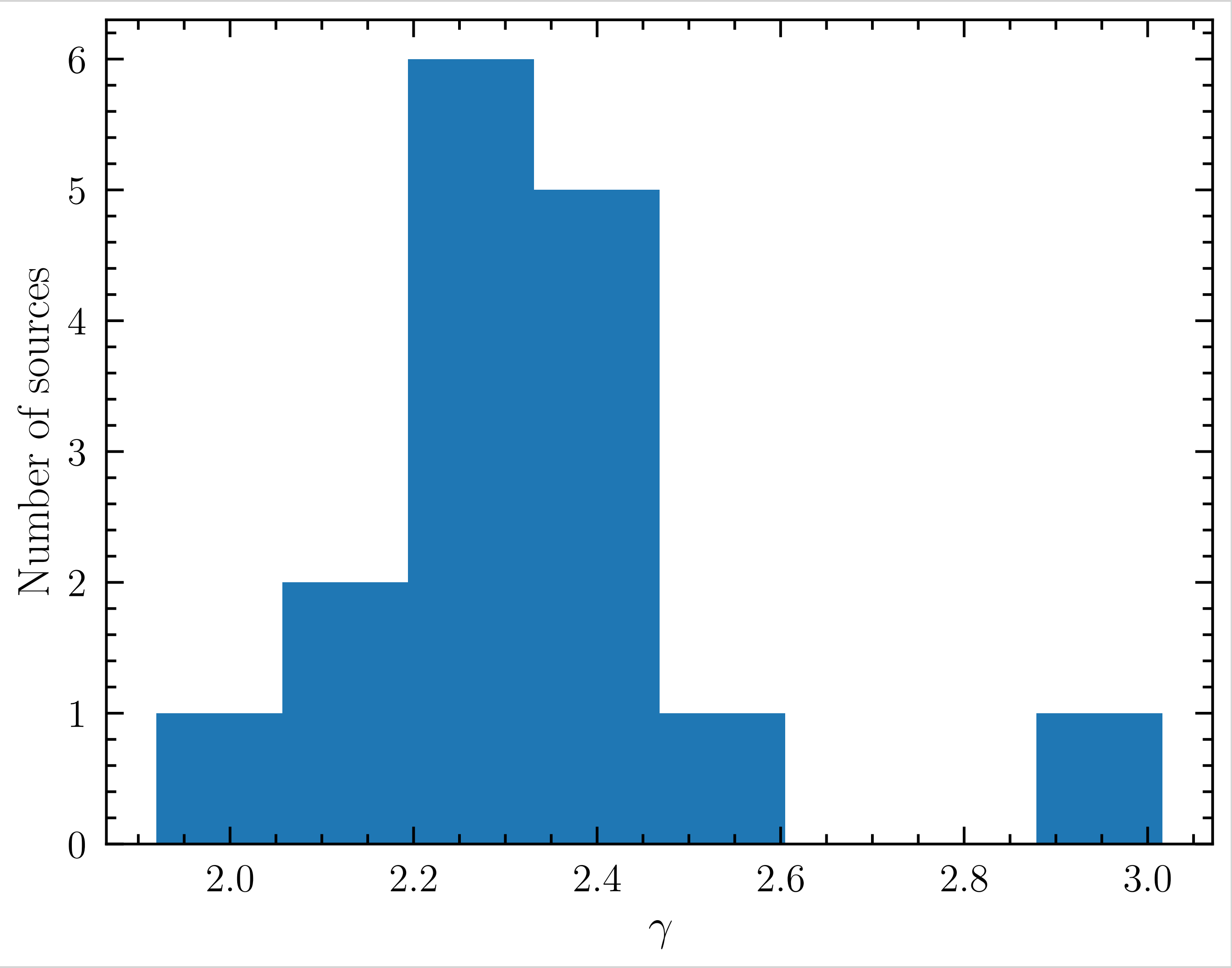
Source	D_L [Mpc]	L_{IR} [$10^{10}\,\mathrm{L}_\odot$]	$F_{1-1000\,\mathrm{GeV}}$ [$10^{-10}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$]	ϕ_0 [$10^{-12}\,\mathrm{MeV^{-1}\,cm^{-2}\,s^{-1}}$]	γ	TS (σ)	$\mathrm{TS_{SM}}$
M 82	3.53	5.6	9.8 ± 0.5	1.31 ± 0.10	2.34 ± 0.06	1104 (33)	0.35
NGC 253	3.56	3.6	8.1 ± 0.9	1.08 ± 0.10	2.33 ± 0.08	730 (27)	1.03
ARP 220	84.3	$1.7 \cdot 10^2$	1.6 ± 0.6	$(2.0 \pm 0.7) \cdot 10^{-1}$	2.2 ± 0.2	50 (7.1)	–
NGC 1068	10.1	10.0	4.5 ± 0.5	$(5.8 \pm 0.9) \cdot 10^{-1}$	2.28 ± 0.15	238 (15)	–
Circinus	4.21	1.7	5.1 ± 1.3	$(6.2 \pm 1.7) \cdot 10^{-1}$	2.23 ± 0.14	78 (8.8)	–
SMC	0.06	$7.1 \cdot 10^{-3}$	$(3.0 \pm 0.3) \cdot 10^1$	4.4 ± 0.3	2.44 ± 0.06	801 (28)	4.13
M 31	0.77	$2.3 \cdot 10^{-1}$	3.1 ± 0.8	$(6.3 \pm 1.3) \cdot 10^{-1}$	3.0 ± 0.3	74.6 (8.6)	0.22
NGC 2146	17.2	12.6	1.3 ± 0.5	$(1.5 \pm 0.5) \cdot 10^{-1}$	2.16 ± 0.18	41.5 (6.4)	–
ARP 299	48.6	72.6	1.3 ± 0.5	$(1.7 \cdot 0.6) \cdot 10^{-1}$	2.3 ± 0.2	46.4 (6.8)	–
NGC 4945	3.72	2.8	9.6 ± 1.3	1.34 ± 0.15	2.40 ± 0.08	412 (20)	–
NGC 2403	3.18	0.15	1.5 ± 0.5	$(10 \pm 4) \cdot 10^{-2}$	1.92 ± 0.17	52.8 (7.3)	–
NGC 3424	27.2	2.1	10 ± 5	$(1.3 \pm 0.5) \cdot 10^{-1}$	2.3 ± 0.3	28 (5.3)	–
LMC	0.05	$5.2 \cdot 10^{-2}$	$(1.38 \pm 0.07) \cdot 10^2$	$(1.85 \pm 0.08) \cdot 10^1$	2.41 ± 0.04	1493 (38)	0.24
M 33	0.91	0.14	$1.2 \pm 0.6^\dagger$	$(1.8 \pm 0.7) \cdot 10^{-1}$	2.5 ± 0.3	16 (4)	–

Two sources have a strong hint of γ-ray emissions ($\sim 4\sigma$)

M83, NGC 1365

- ✦All spectra are consistent with simple power-laws





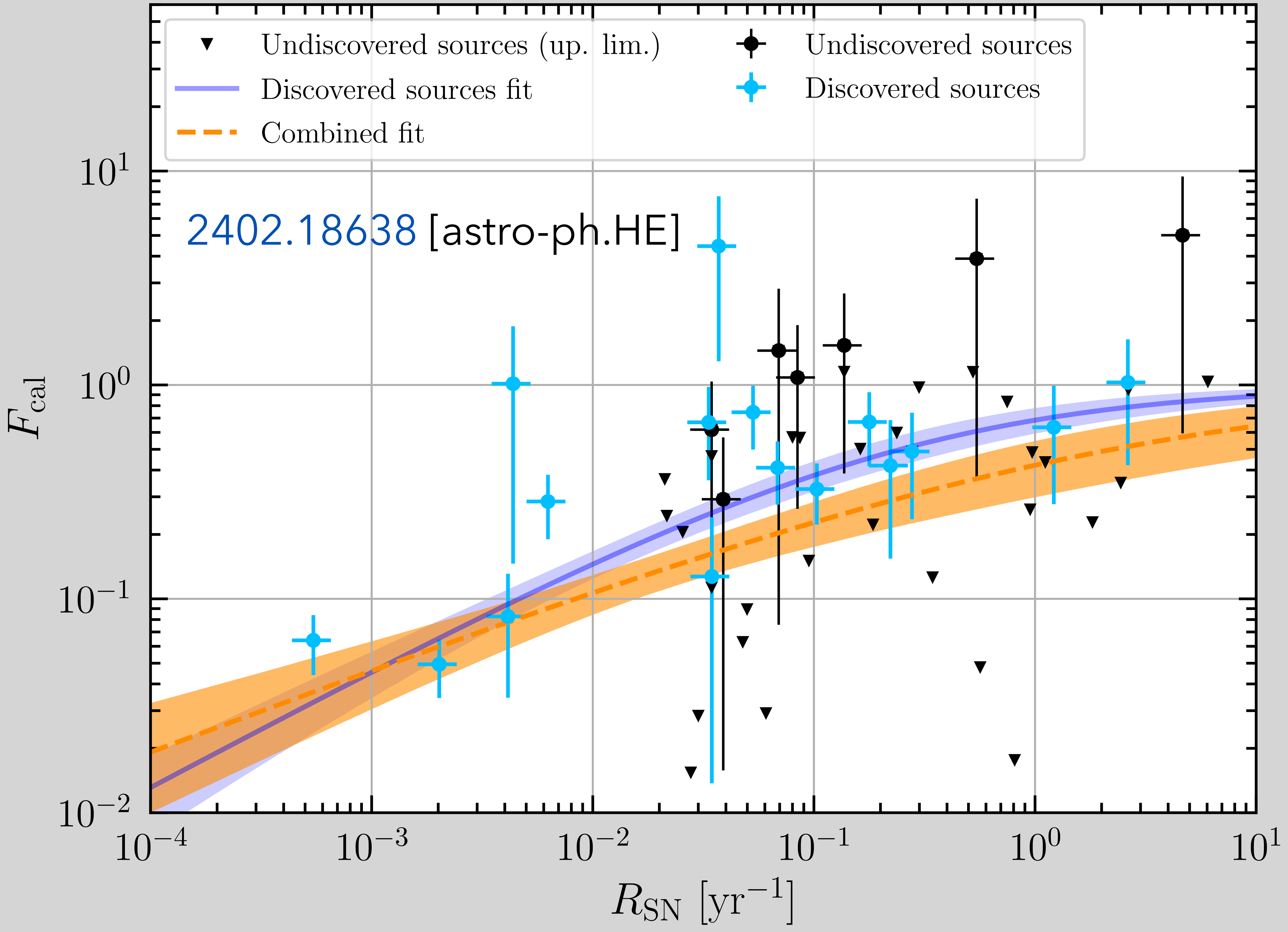
Calorimetric Fraction and Star Formation Rate

$$f(p)\left(\frac{1}{\tau_{\rm loss}(p)}+\frac{1}{\tau_{\rm adv}(p)}+\frac{1}{\tau_{\rm diff}(p)}\right)=Q(p) \quad \Longrightarrow \quad f(p)\simeq Q(p)\tau_{pp}\boxed{F_{\rm cal}}$$

Fraction of CRs which actually interact and produce γ and ν

$$\boxed{\phi_\gamma \propto F_{\rm cal}}$$

Average $F_{\rm cal}$ between $10 - 10^4\,{\rm GeV}$ for CRs



$F_{\rm cal}$ correlates with the SFR and the Supernovae explosion rate $R_{\rm SN}[{\rm yr}^{-1}]\simeq\frac{1}{83}{\rm SFR}[{\rm M}_\odot\,{\rm yr}^{-1}]$

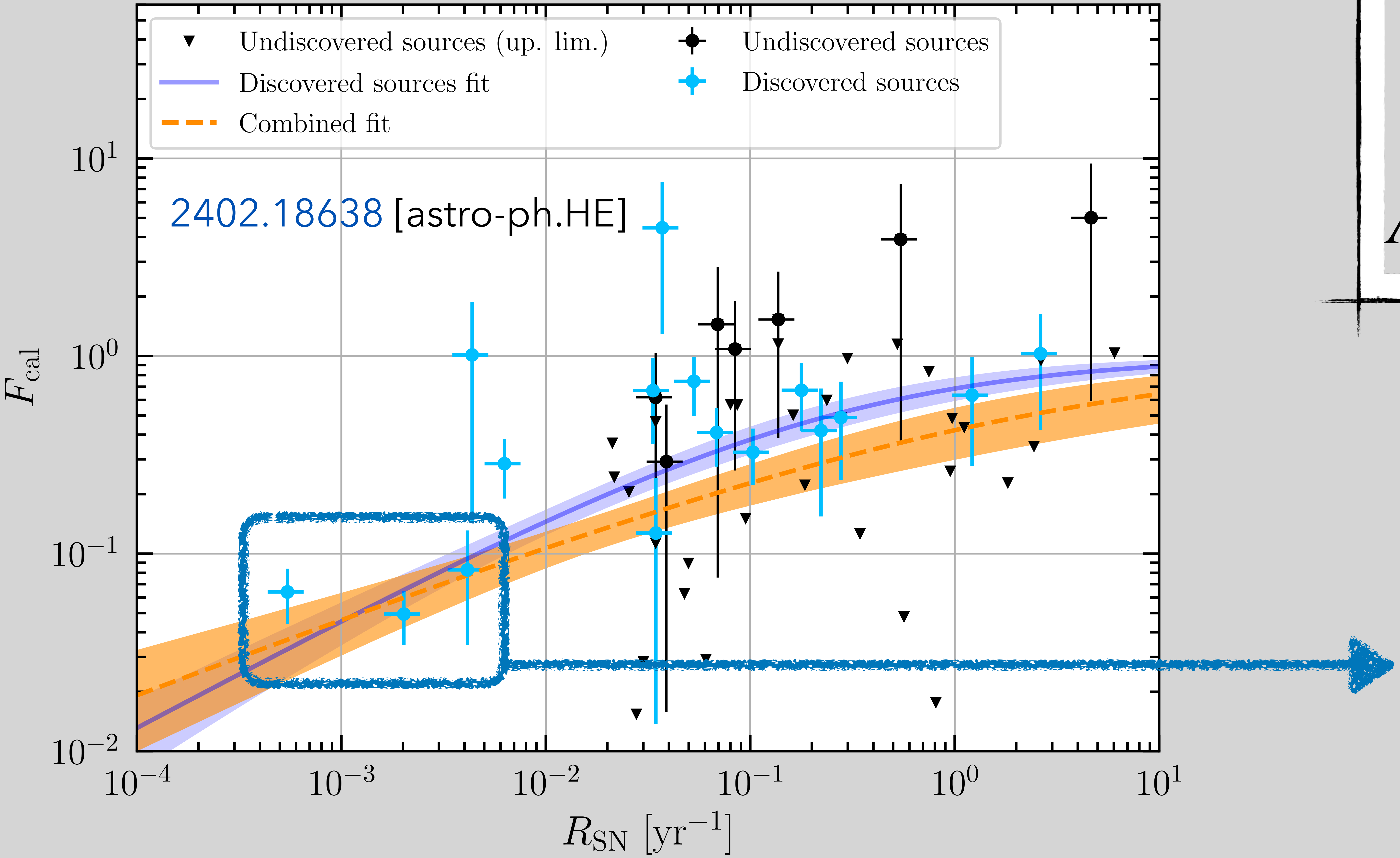
$$F_{\rm cal}=A\left(\frac{R_{\rm SN}}{{\rm yr}^{-1}}\right)^{\beta}\left(1+A\left(\frac{R_{\rm SN}}{{\rm yr}^{-1}}\right)^{\beta}\right)^{-1}$$

$$A=0.7^{+0.3}_{-0.2}\quad \beta=0.39\pm0.07$$

Calorimetric Fraction and Star Formation Rate

Undiscovered sources constrain F_{cal} of about a factor 2!

Average F_{cal} between $10 - 10^4$ GeV for CRs



$$F_{\mathrm{cal}} = A\left(\frac{R_{\mathrm{SN}}}{\mathrm{yr}^{-1}}\right)^{\beta}\left(1 + A\left(\frac{R_{\mathrm{SN}}}{\mathrm{yr}^{-1}}\right)^{\beta}\right)^{-1}$$

$$A = 0.7^{+0.3}_{-0.2} \quad \beta = 0.39 \pm 0.07$$

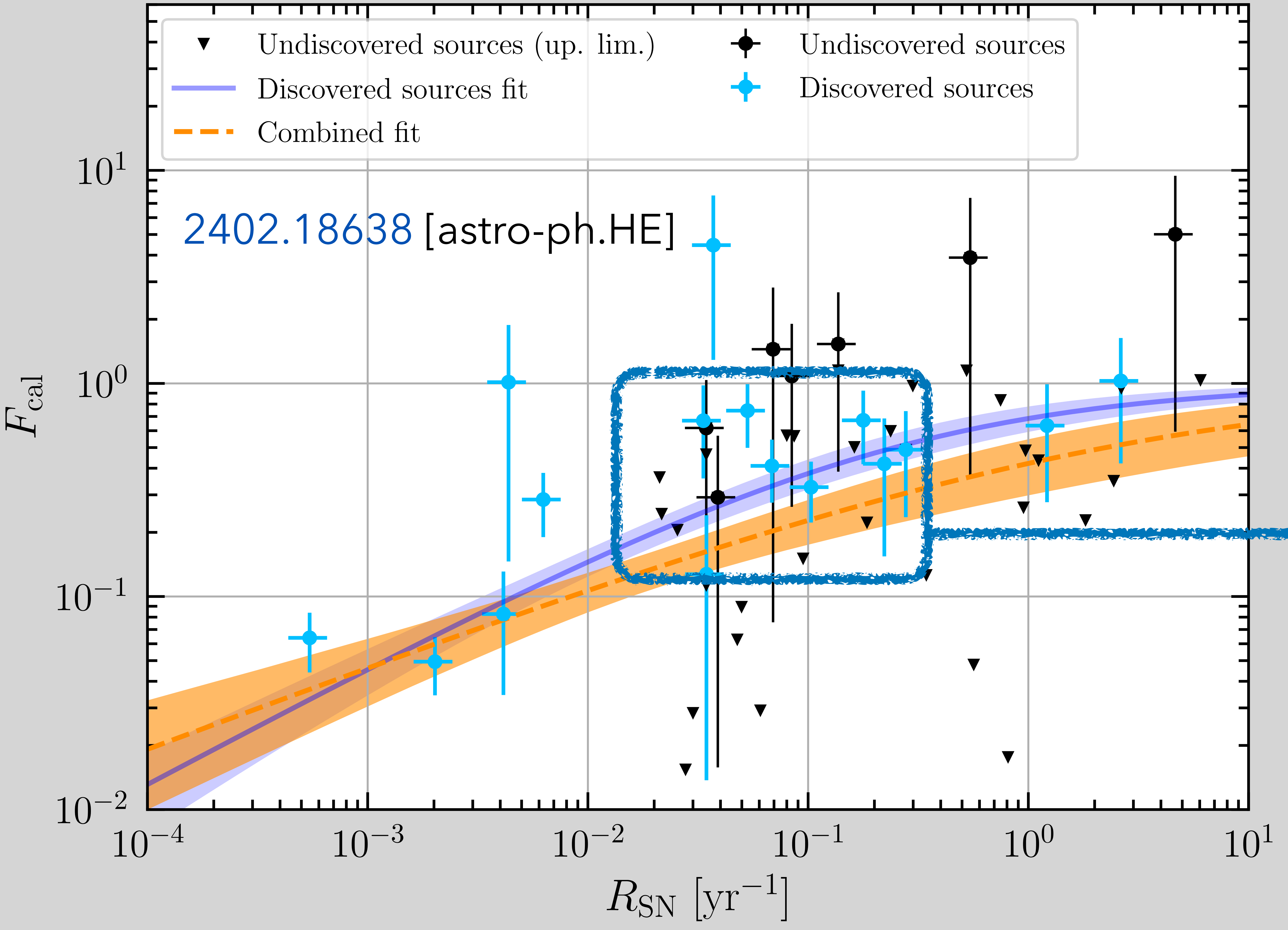
At low SFR, the local galaxies dominated (SMC, LMC, M31, M33)

$$\mathrm{SFR} \sim 10^{-2} - 10^{-1}\, \mathrm{M}_{\odot}\, \mathrm{yr}^{-1}$$

Calorimetric Fraction and Star Formation Rate

Undiscovered sources constrain F_{cal} of about a factor 2!

Average F_{cal} between $10 - 10^4\,\mathrm{GeV}$ for CRs



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$$F_{\mathrm{cal}} = A\left(\frac{R_{\mathrm{SN}}}{\mathrm{yr}^{-1}}\right)^{\beta}\left(1 + A\left(\frac{R_{\mathrm{SN}}}{\mathrm{yr}^{-1}}\right)^{\beta}\right)^{-1}$$

$$A = 0.7^{+0.3}_{-0.2} \quad \beta = 0.39 \pm 0.07$$

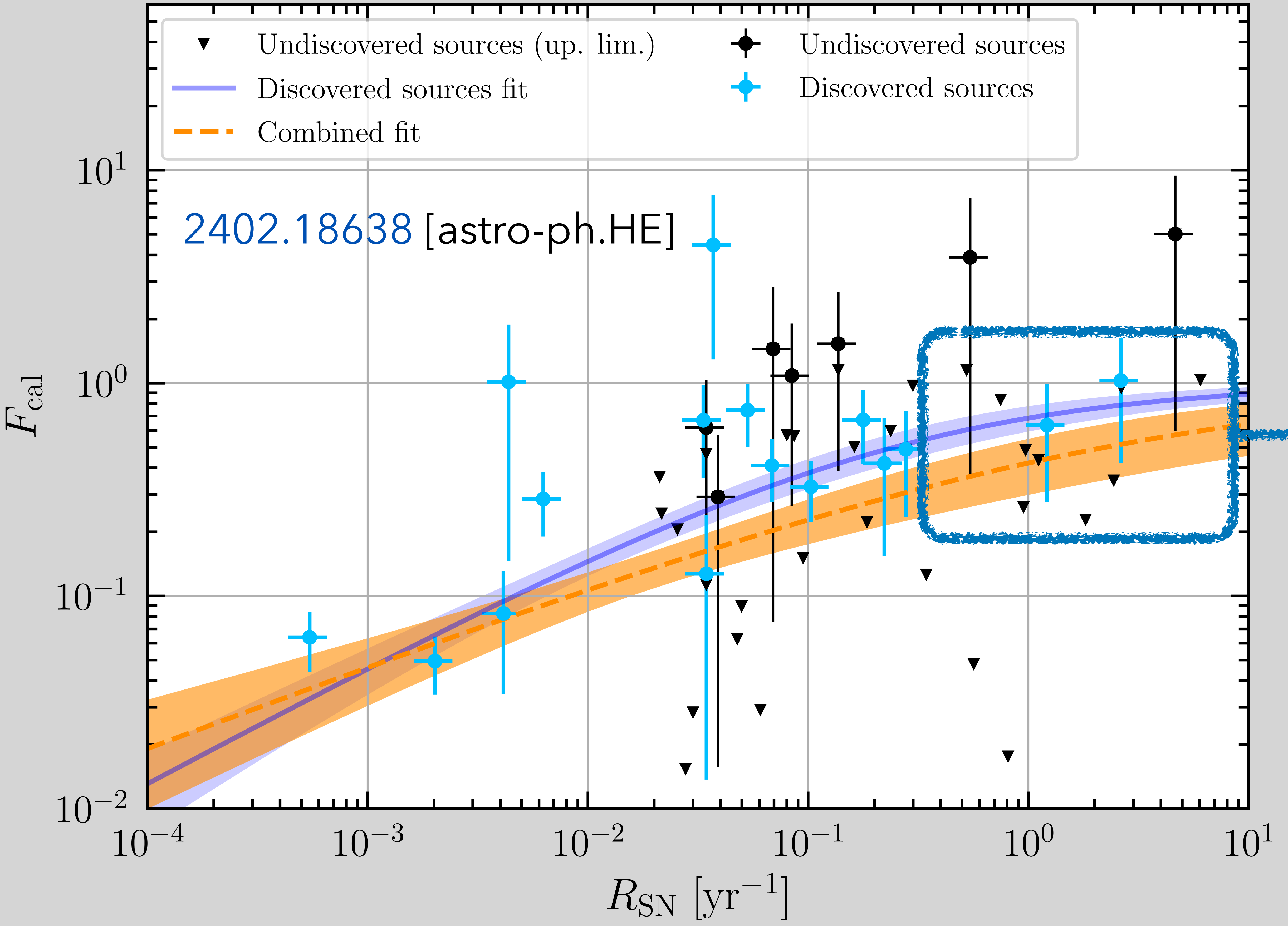
Mild Starburst: M82, NGC 253, NGC 1068

$\mathrm{SFR} \sim 5 - 20\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$

Calorimetric Fraction and Star Formation Rate

Undiscovered sources constrain $F_{\rm cal}$ of about a factor 2!

Average $F_{\rm cal}$ between $10 - 10^4\,$GeV for CRs



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$$F_{\rm cal} = A\left(\frac{R_{\rm SN}}{\rm yr^{-1}}\right)^{\beta}\left(1 + A\left(\frac{R_{\rm SN}}{\rm yr^{-1}}\right)^{\beta}\right)^{-1}$$

$$A = 0.7^{+0.3}_{-0.2}\ \beta = 0.39 \pm 0.07$$

Powerful Starburst: ARP 299, ARP 220

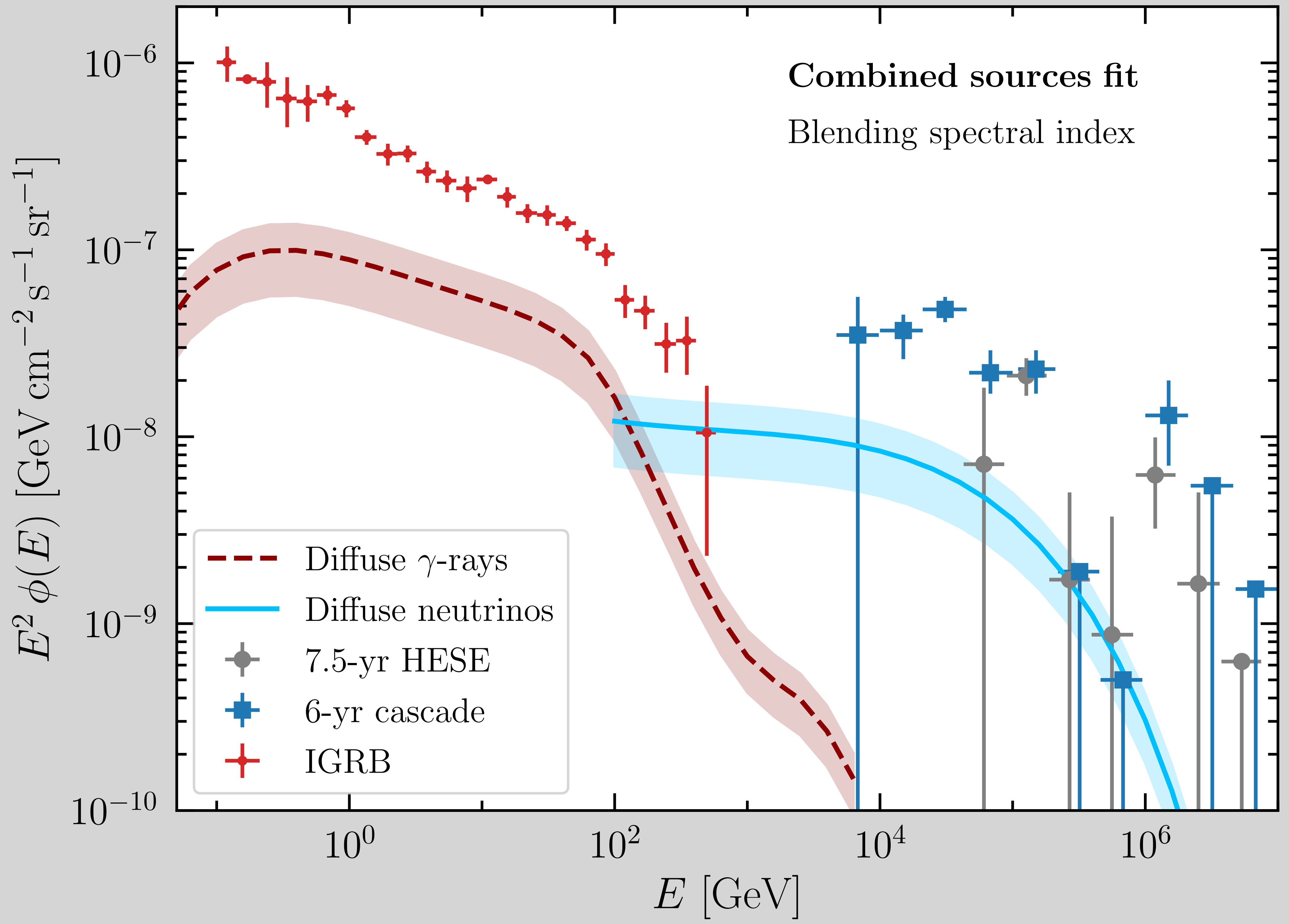
$$\mathrm{SFR} \sim 80 - 200\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$$

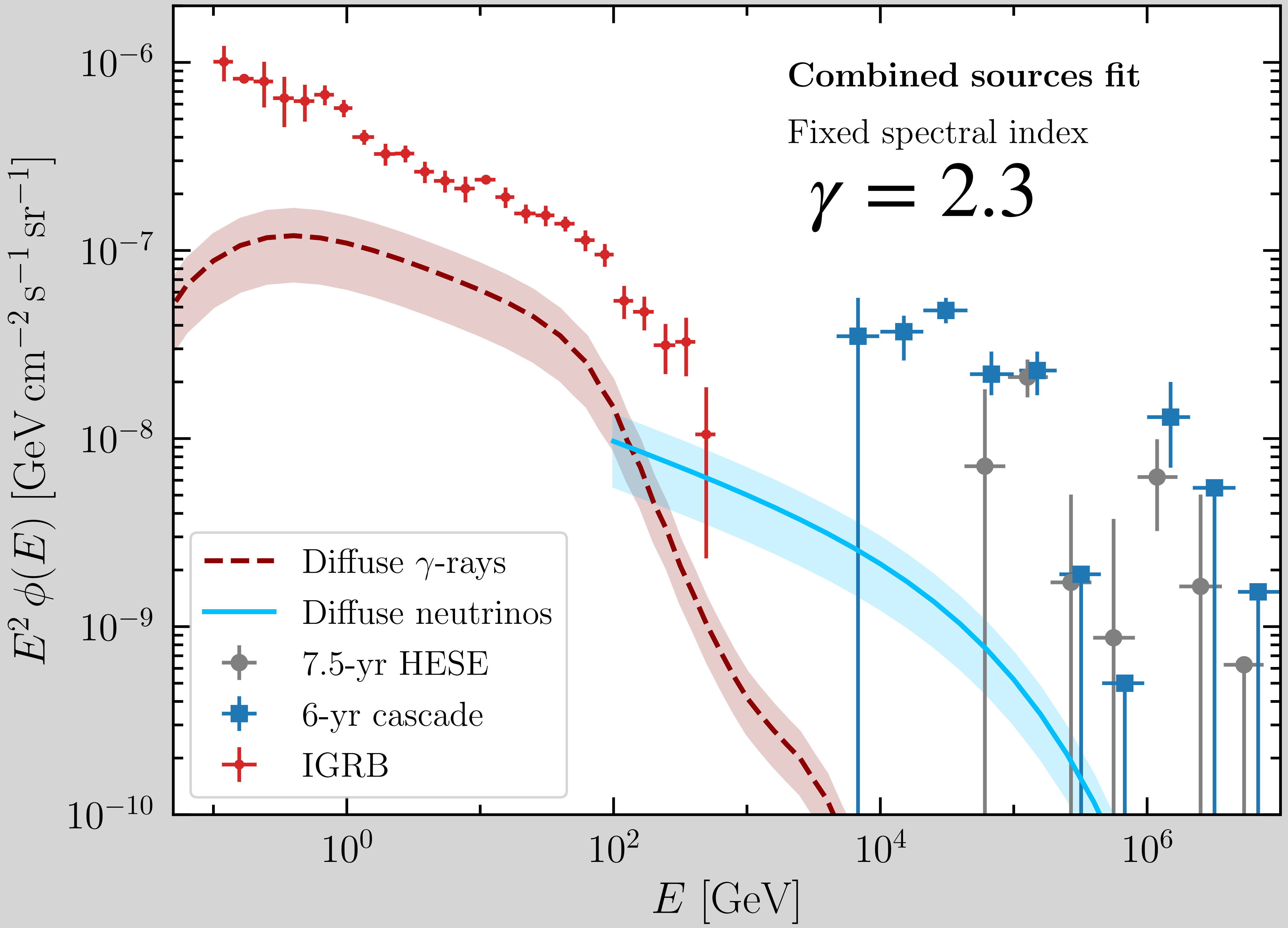
Diffuse Fluxes and Neutrinos

The emission from all SBGs in the Universe

$$\phi^{\text{diff}}_{\gamma,\nu} = \frac{c}{4\pi H_0}\int_0^{z_{\max}} \frac{\mathrm{d}z}{E(z)} \int_{10^6 L_\odot}^{\infty} \frac{\mathrm{d}L_{\mathrm{IR}}}{\ln(10)\, L_{\mathrm{IR}}} \mathcal{S}_{\mathrm{SFR}}(L_{\mathrm{IR}}, z) \times Q_{\gamma,\nu}\left(E(1+z), \mathrm{R_{SN}(L_{IR})}, \mathrm{F_{cal}(R_{SN}(L_{IR}))}\right)\, e^{-\tau_{\gamma,\nu}(E,z,L_{\mathrm{IR}})}$$

$E_{\max}$ assumed is $10\,\mathrm{PeV}$



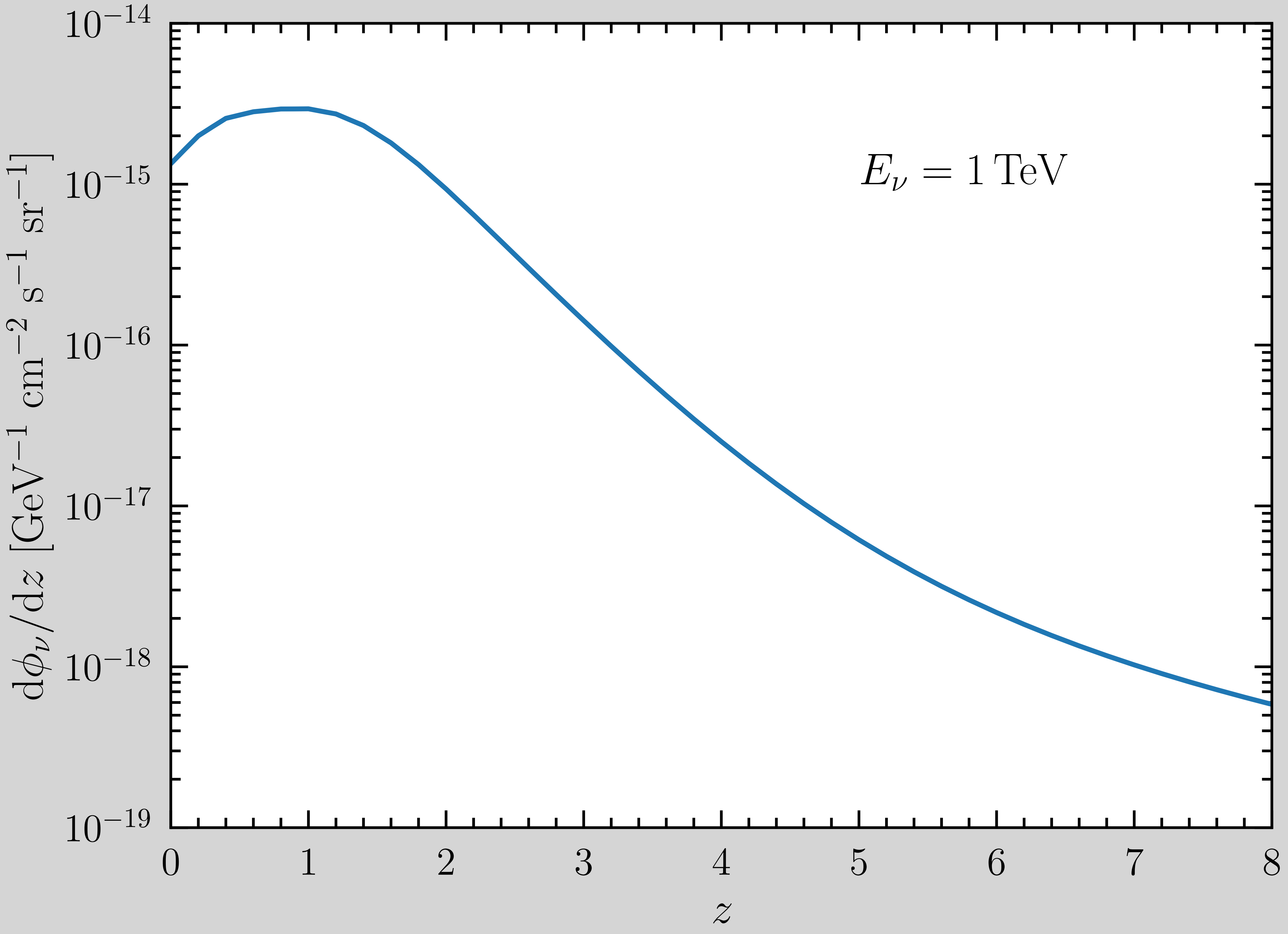


- The blending scenario increases the neutrino flux ($\sim 20\,\%$ of the IceCube measurements)

- The neutrino flux is constrained to be ~% of the IceCube diffuse Fluxes

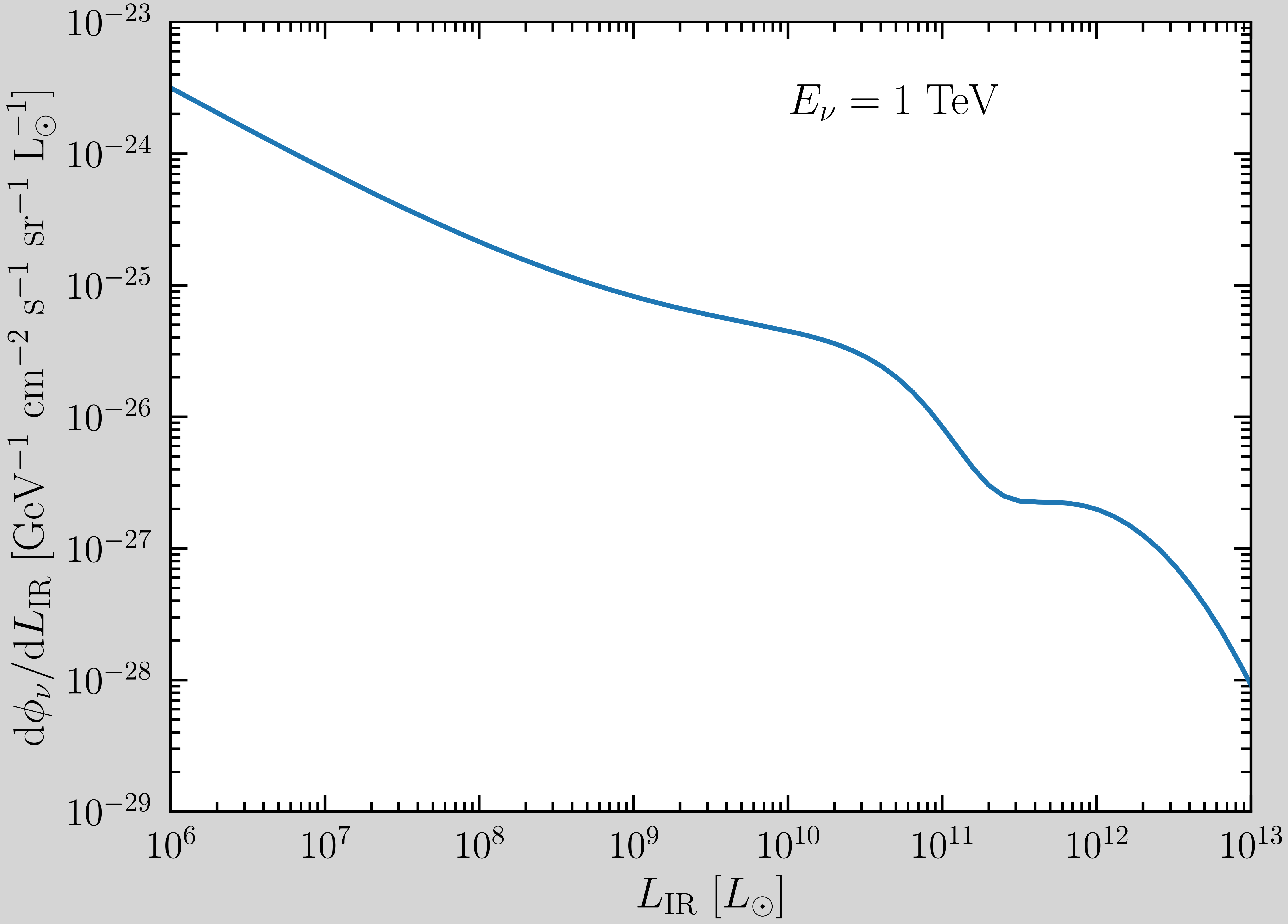
Properties of the Neutrino Flux

Redshift Distribution of the Neutrino Flux



Distant sources dominate the emission (peaking at $z \simeq 1$)

IR Luminosity Distribution of the Neutrino Flux

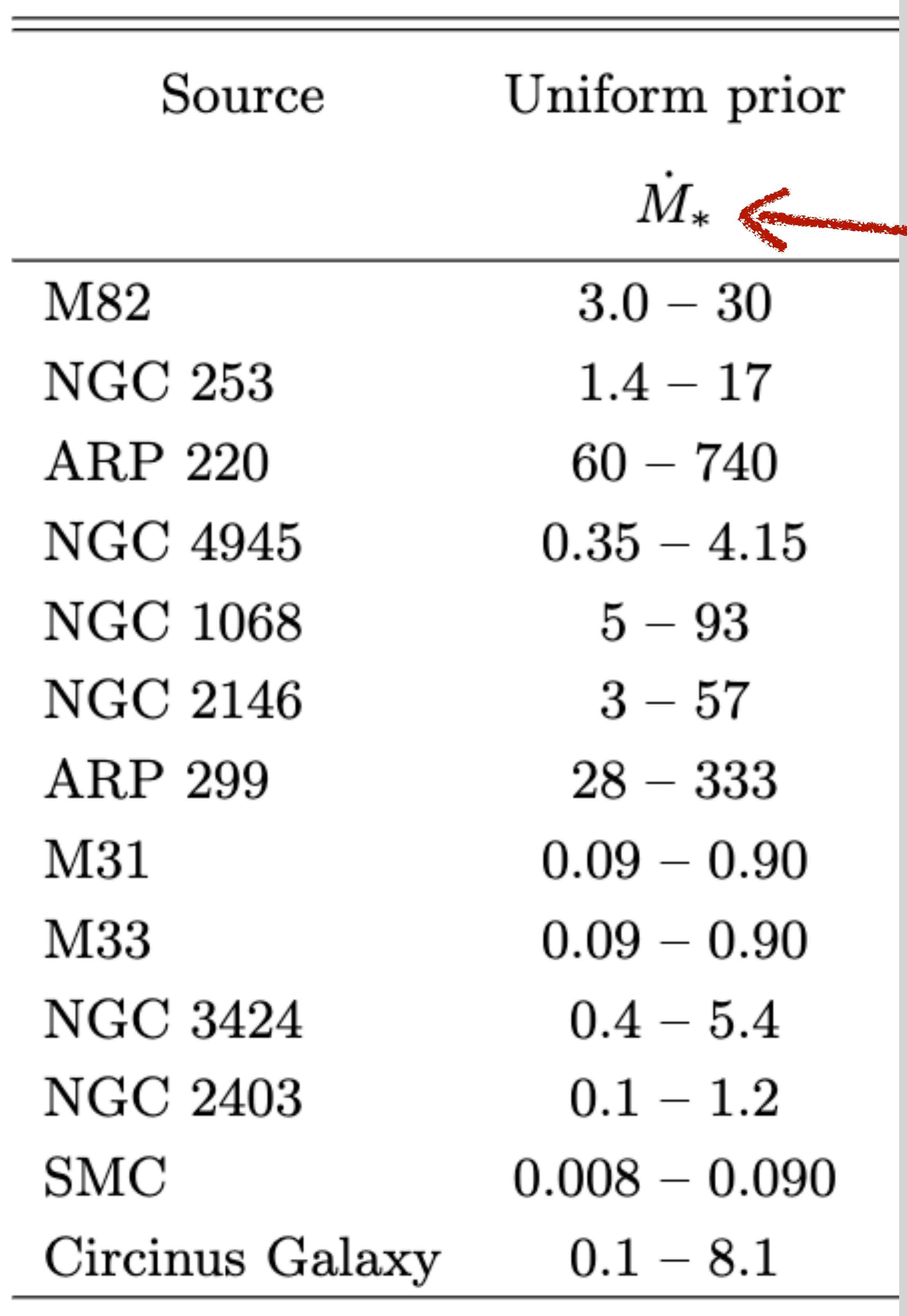


Powerful SBGs ($\mathrm{SFR} > 100\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$) dominate the emission (> 50% of the emission)

Can Neutrino Telescopes Trace Local SFGs?

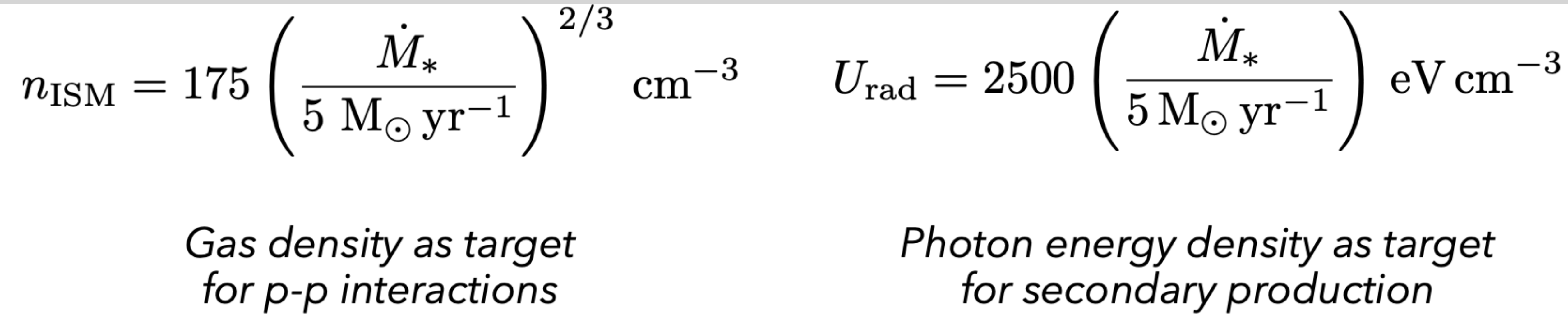
Ambrosone+, ApJL 919
[2106.12348]

We analyze the observed nearby SBG Gamma-ray SED: Bayesian approach



Source	Uniform prior $\dot{M}_*$
M82	3.0 – 30
NGC 253	1.4 – 17
ARP 220	60 – 740
NGC 4945	0.35 – 4.15
NGC 1068	5 – 93
NGC 2146	3 – 57
ARP 299	28 – 333
M31	0.09 – 0.90
M33	0.09 – 0.90
NGC 3424	0.4 – 5.4
NGC 2403	0.1 – 1.2
SMC	0.008 – 0.090
Circinus Galaxy	0.1 – 8.1

- ✦ We use both GeV and TeV gamma-ray data (Fermi-LAT + IACTs data)
- ✦ IR + UV data: Prior on the star formation rate
- ✦ Starburst Nucleus of the order of 10^2 pc
- ✦ Escaping phenomena dominated by advection
- ✦ Using Kennicutt's relations:



$$n_{\rm ISM} = 175 \left(\frac{\dot{M}_*}{5\ {\rm M_\odot\,yr^{-1}}} \right)^{2/3} {\rm cm^{-3}} \qquad U_{\rm rad} = 2500 \left(\frac{\dot{M}_*}{5\,{\rm M_\odot\,yr^{-1}}} \right) {\rm eV\,cm^{-3}}$$

Gas density as target for p-p interactions

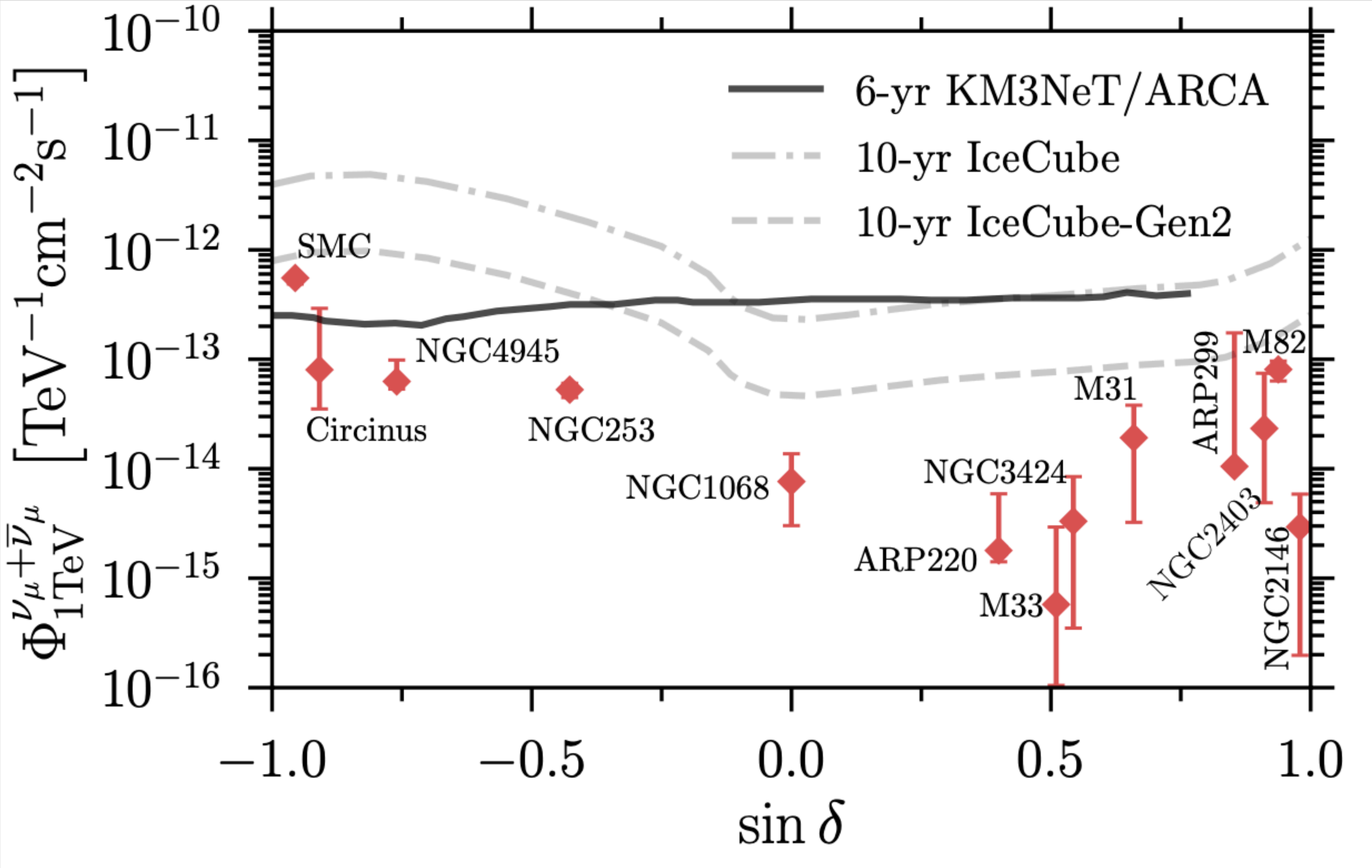
Photon energy density as target for secondary production

Kennicutt, ARA&A 36 (1998); Inoue+, PASJ 52 (2000); Hirashita+, A&A 410 (2003); Yuan+, PASJ 63 (2011); Kennicutt and Evans, ARA&A 50 (2012); Kennicutt & De Los Reyes, ApJ 908 (2021)

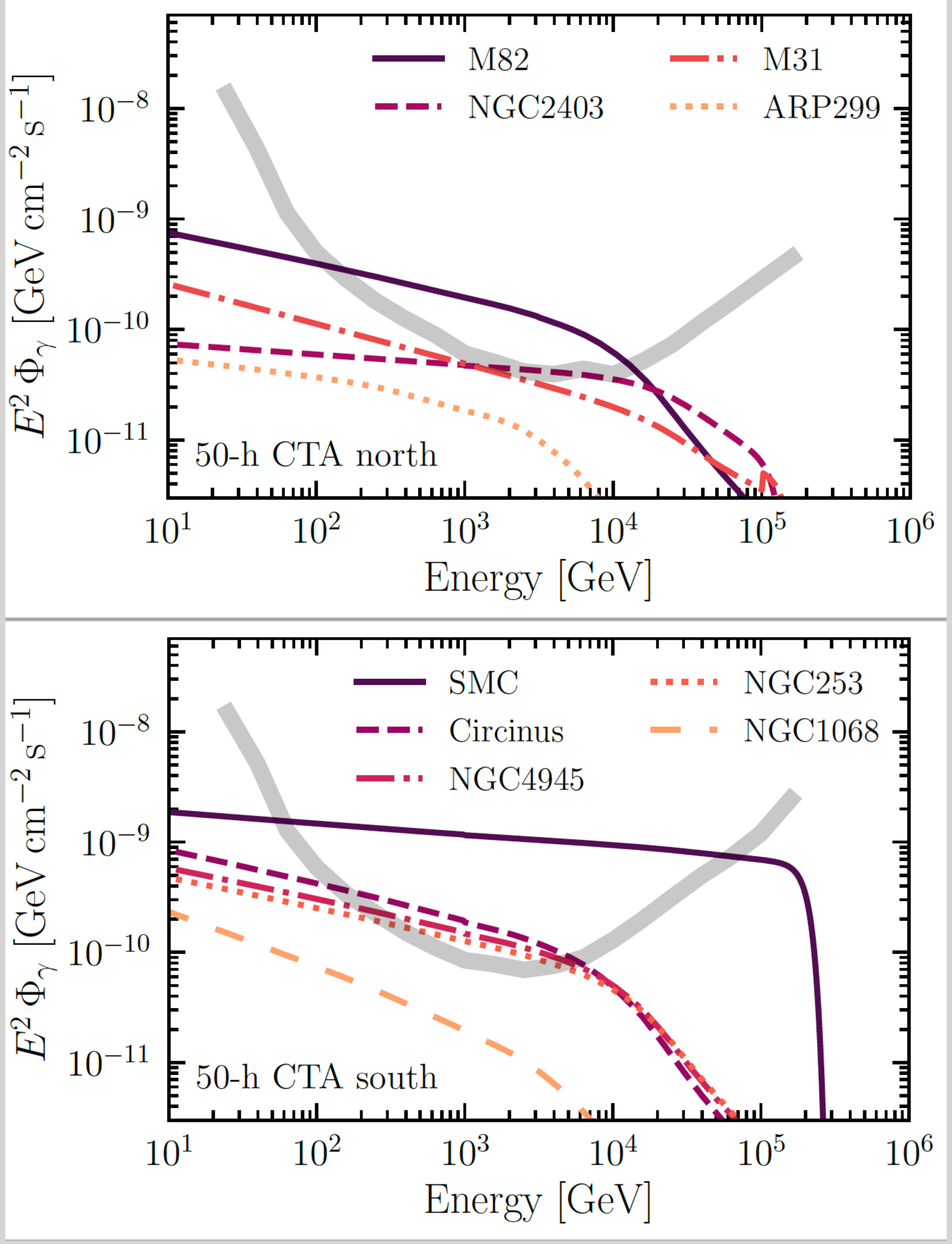
Can Neutrino Telescopes Trace Local SFGs?

Ambrosone+, ApJL 919 [2106.12348]

Neutrino Expectations: KM3NeT Forecast



Gamma-Rays Expectations. CTA Forecast



Future γ/ν observations will be fundamental to:

✦ Discover if Neutrino Astronomy is a tracer for star-forming activity

✦ Probe the calorimetric fraction inside SBG: If there will be no detection, nearby SBGs are dominated by diffusion and not by either p-p collisions or advection.

Conclusions and Outlooks

- There is a strong correlation between star formation and γ-ray emission
- Powerful SBGs are CR calorimeters, while SFGs only partially confine CRs
- The Neutrino Emission of SFGs and SBGs are dominated by distant sources
- SFGs and SBGs might contribute up to $\sim 20\,\%$ of the IceCube measurements
- The Small Magellanic Cloud and the Circus Galaxy might be suitable targets for future neutrino observations from the KM3NeT Detector