On the Gamma-Ray and Neutrino Emissions from Nearby Starburst Galaxies

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Collaborators：Youliang Feng （冯有亮）, Yi Zhang（张毅），et al.

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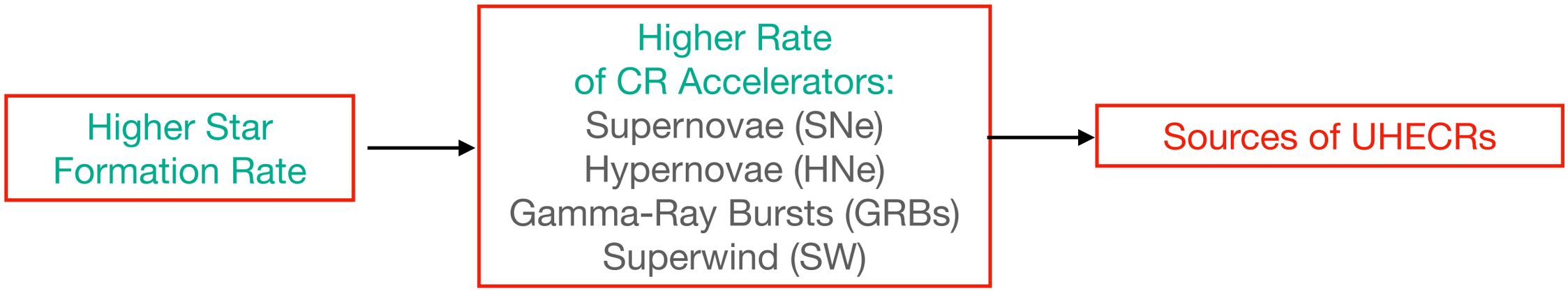
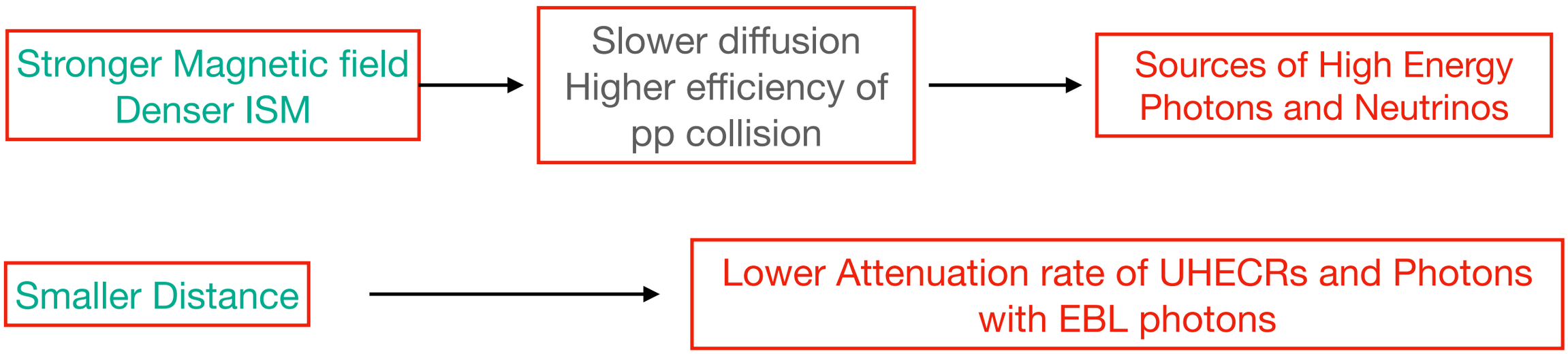
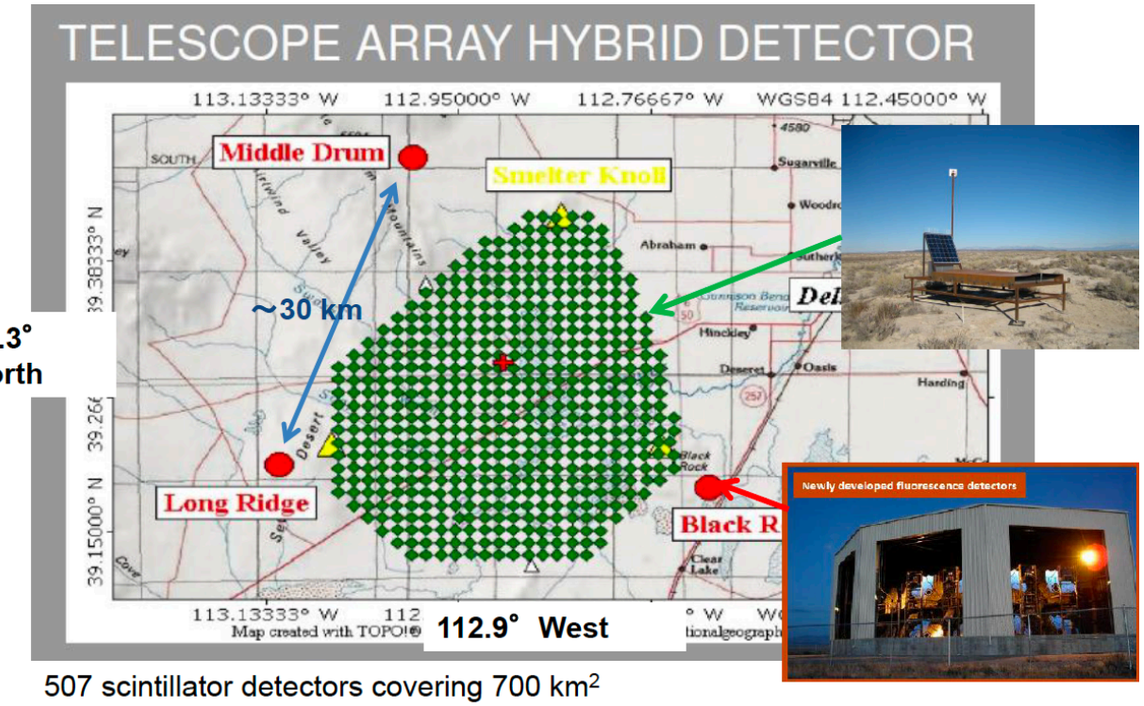
Nearby Starburst Galaxies

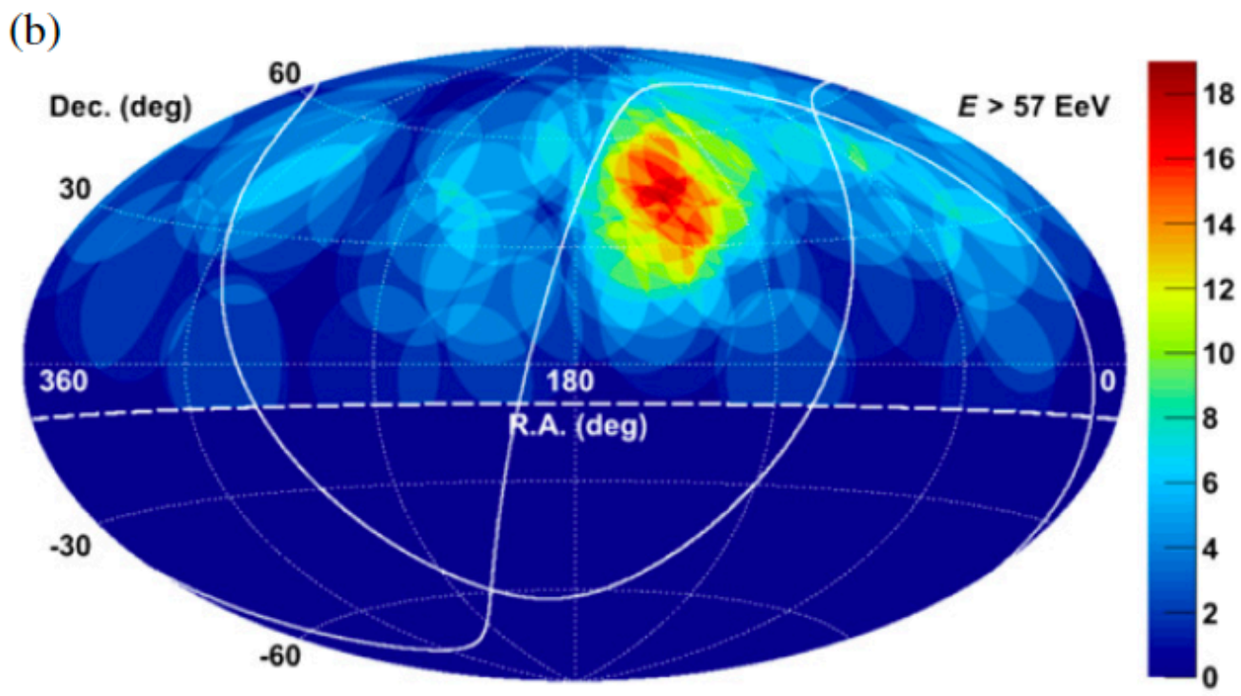




UHECRs Hotspot Observed by the Telescope Array



507 scintillator detectors covering 700 km^2
3 fluorescence sites, 38 telescopes (~10% duty cycle)
Surface detector full operation (~100% duty cycle)

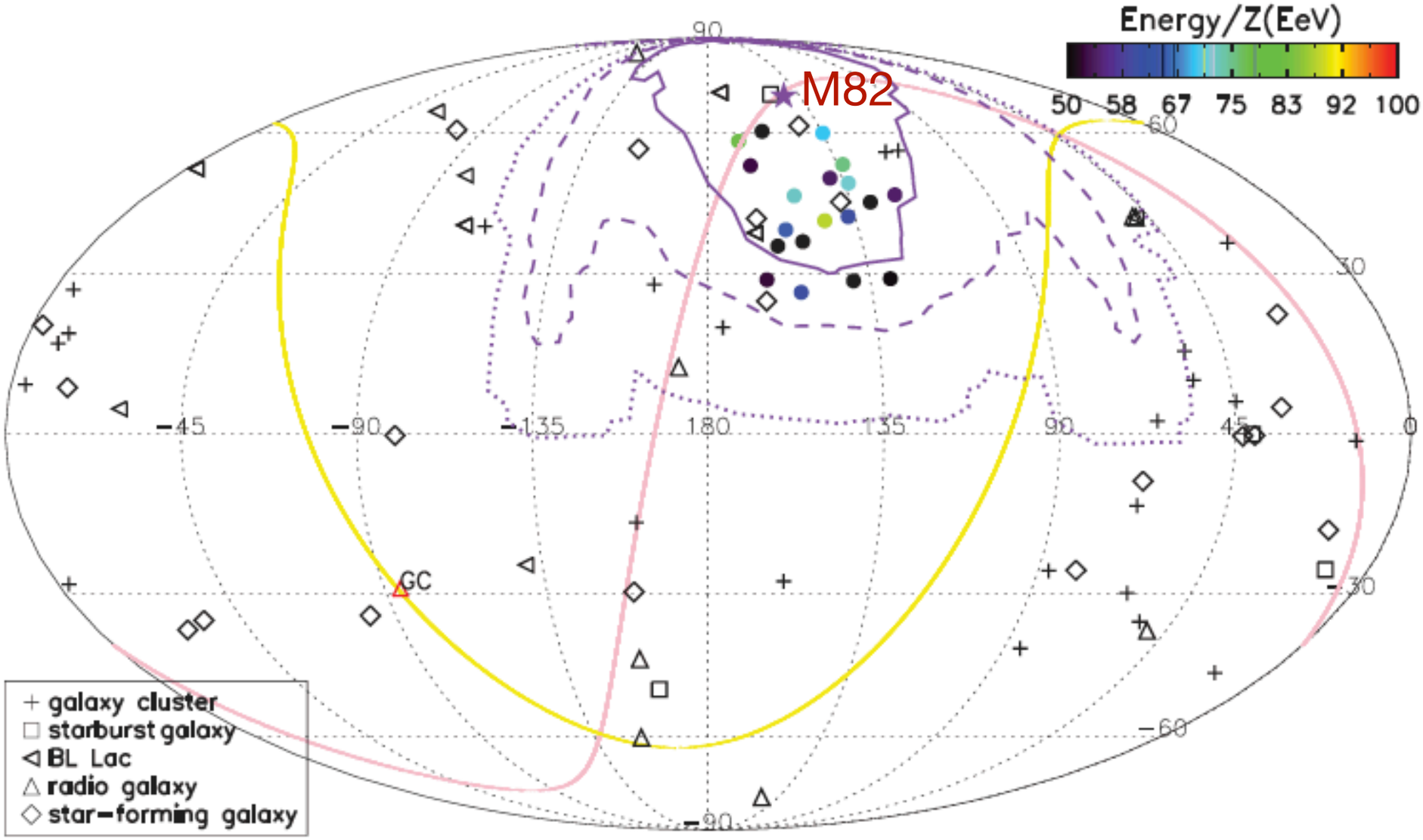


The TA collaboration, 2014

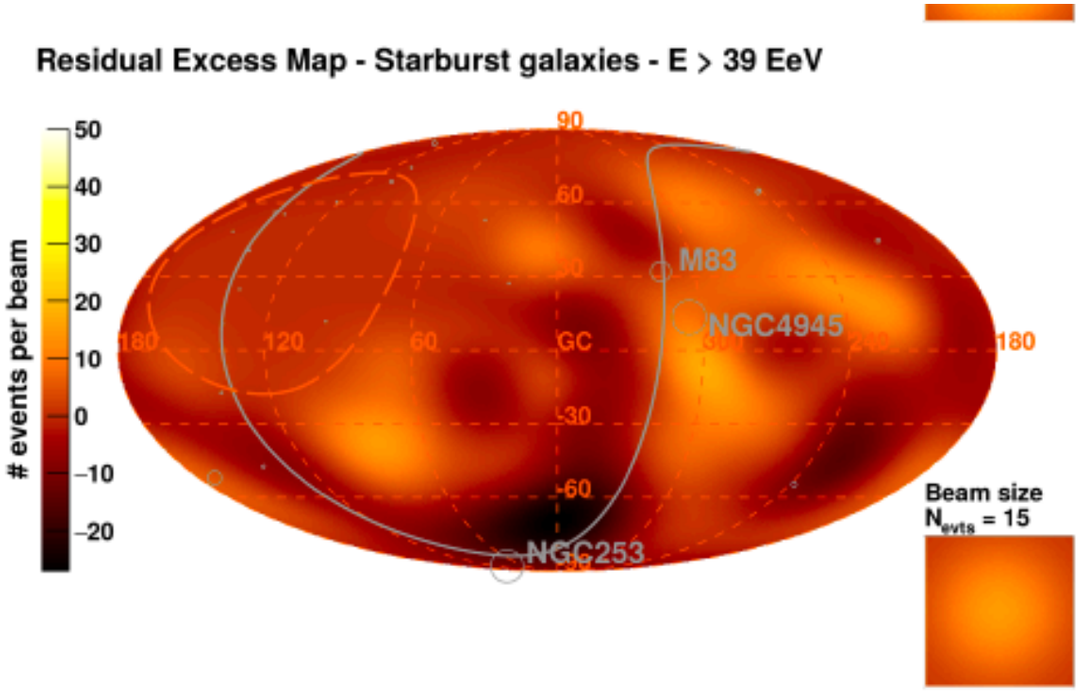
PHYSICAL REVIEW D **93,** 043011 (2016)

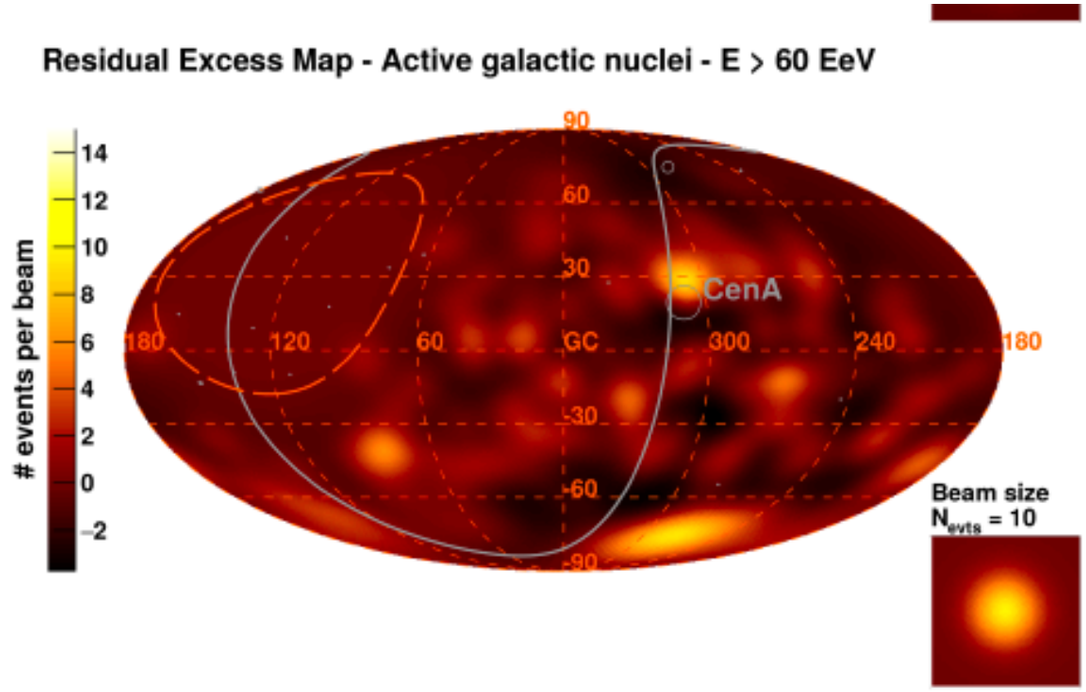
Monte Carlo Bayesian search for the plausible source of the Telescope Array hotspot

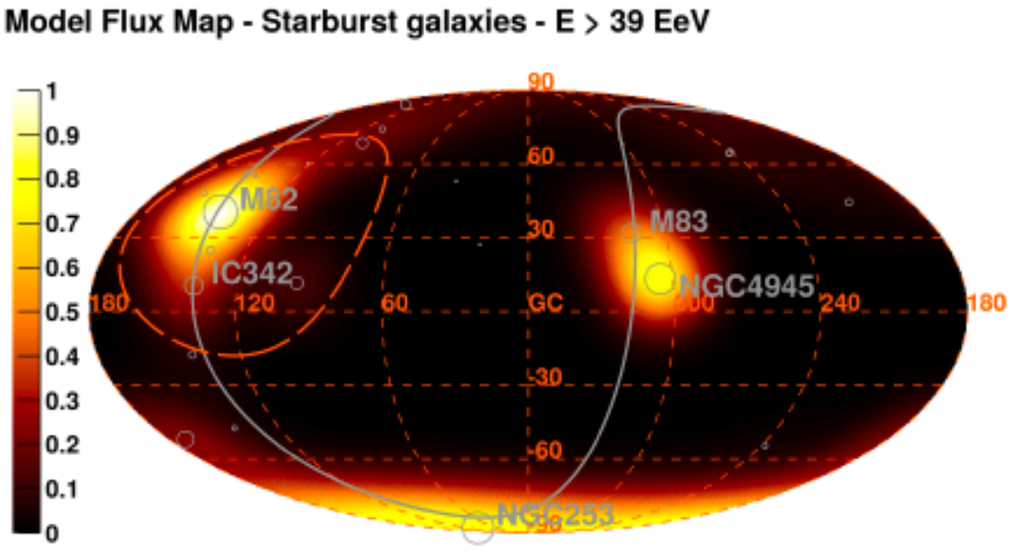
Hao-Ning He,[1,2] Alexander Kusenko,[1,3] Shigehiro Nagataki,[4] Bin-Bin Zhang,[5,6] Rui-Zhi Yang,[7,2] and Yi-Zhong Fan[2]

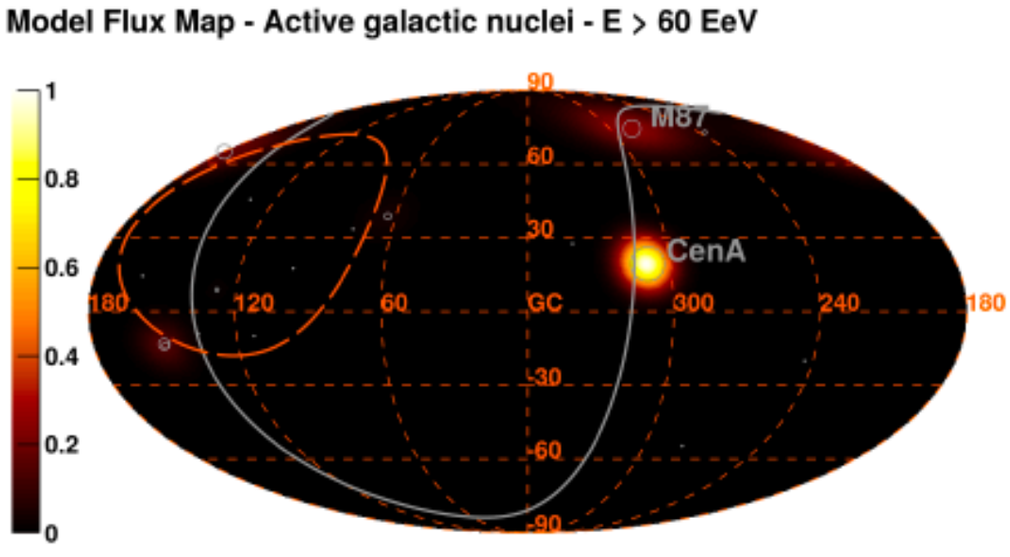


The Pierre Auger Observatory's Analysis on the Association Between Starburst Galaxies and UHECRs







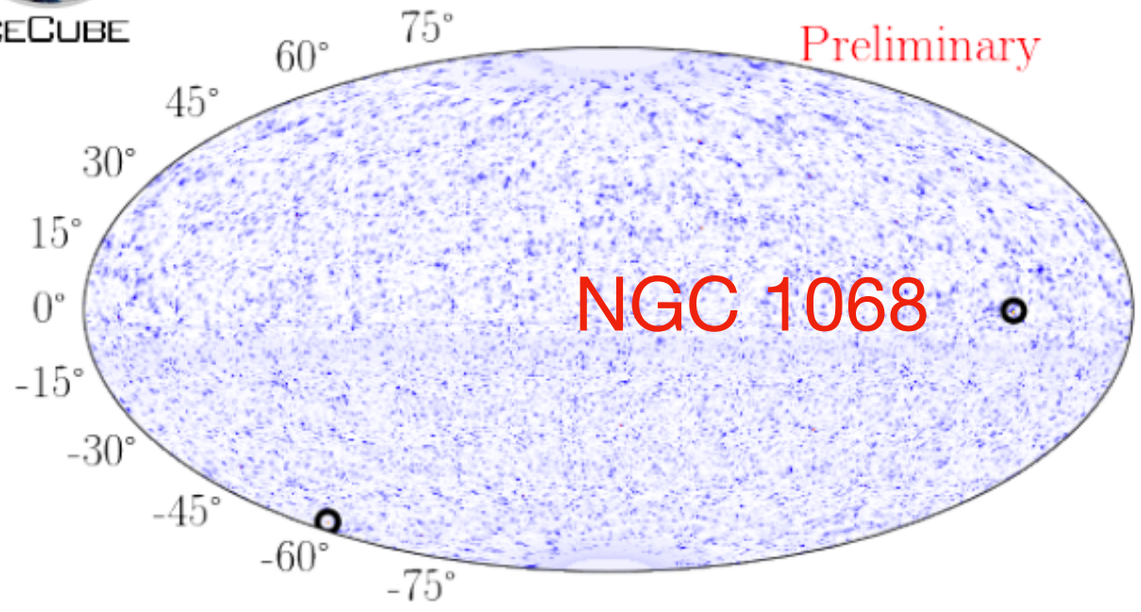


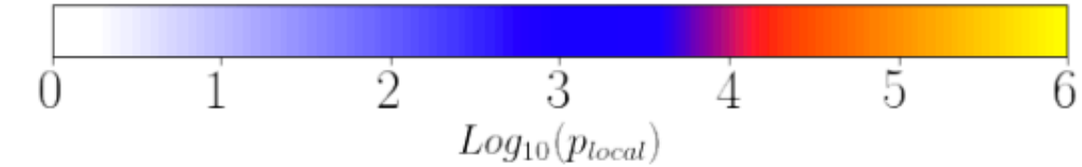
It is found that the starburst model fits the data better than the hypothesis of isotropy with a statistical significance of 4sigma, the highest value of the test statistic being for energies above 39EeV

The PAO collaboration, 2018

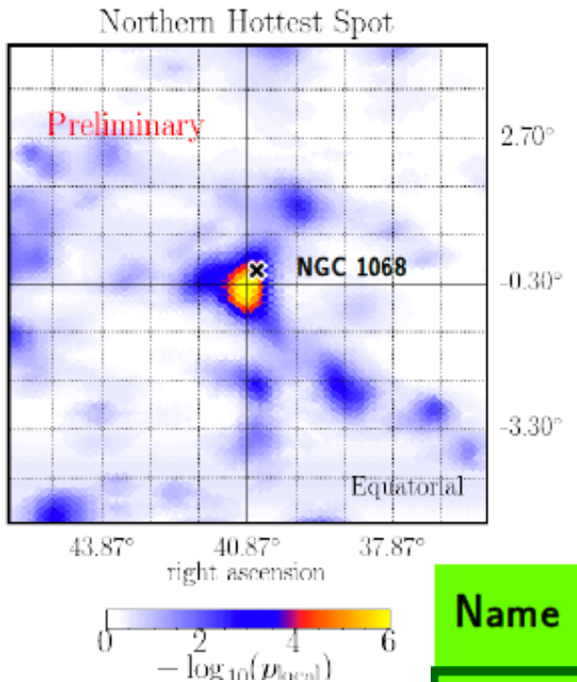
IceCube Neutrinos

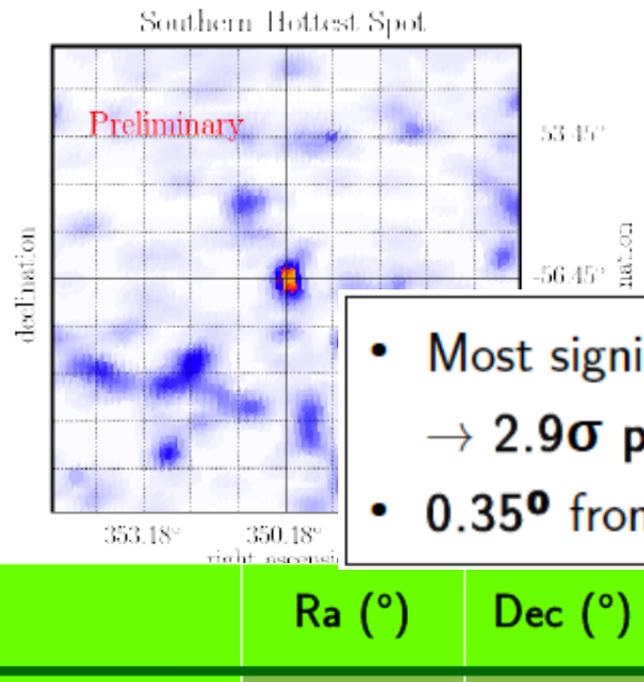
10 year All-Sky Scan Results





- Scan the entire sky and evaluate the likelihood of signal over background.
- The position with the smallest p-value in each hemisphere is taken as the hottest spot.
- The post-trial pvalue is calculated by comparing this p-value with many background hotspots.





Hottest Point in Northern Hemisphere : $\delta \geq -5^o$

RA = 40.87° , Dec = -0.30°

n_{signal} = 61.45 , γ = 3.411

Pval = 6.45, TS = 25.34 ⇒ 9.9 % post-trial

- Most signifcant excess in the Northern Source List.
  → **2.9σ post-trial**
- **0.35°** from the hottest point in the sky.

Name	Ra (°)	Dec (°)	TS	n_{signal}	γ	$-\log_{10}(p_{local})$	Pre-trial σ
NGC 1068	40.67	-0.01	17.04	50.4	3.16	4.74	4.13

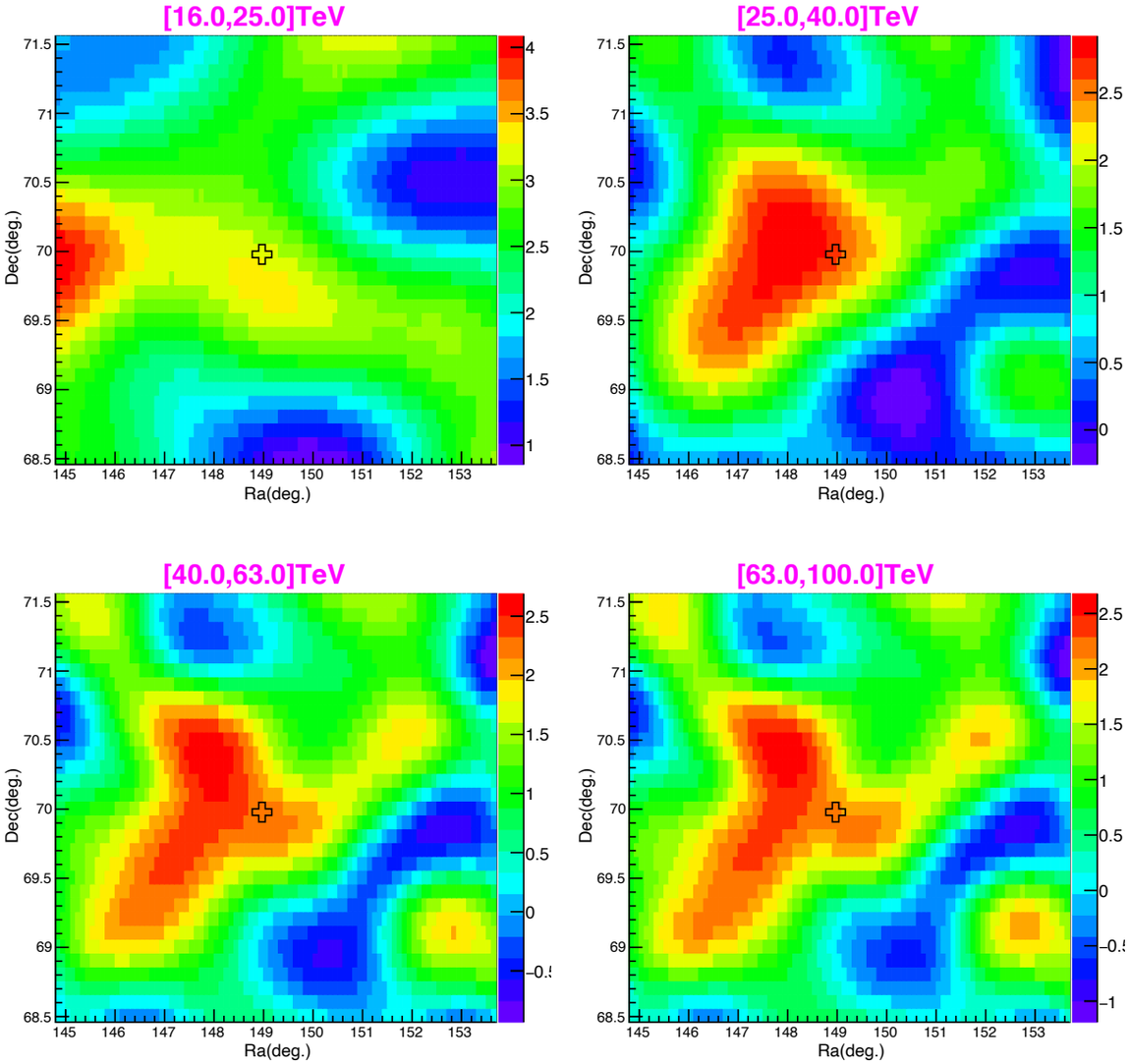
Star Forming Galaxies with Gamma-ray emissions

Table 1. Distances, SFRs, IR and γ-ray fluxes and luminosities for all γ-ray emitting SFGs known.

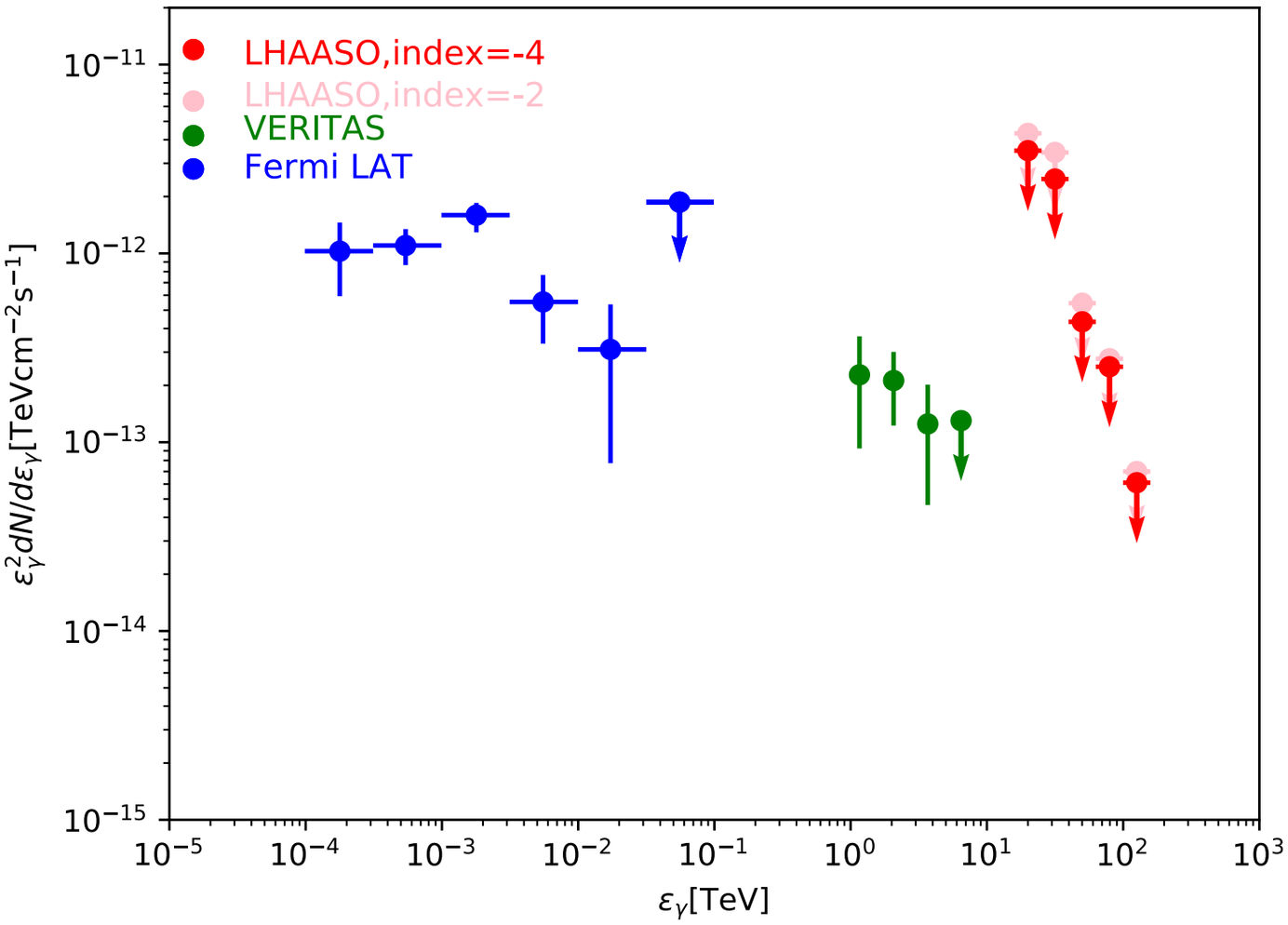
Galaxy	D_L	F_γ [0.1 – 100 GeV]	F_{IR} [8 – 1000 μm][l]	$\dot{M}_*$	$\log(L_\gamma)$ [0.1 – 100 GeV]	$\log(L_{IR}/L_\odot)$ [8 – 1000 μm]
	Mpc	10^{-12} erg cm^{-2} s^{-1}	10^{-9} erg cm^{-2} s^{-1}	$M_\odot$ yr^{-1}	erg s^{-1}	
M31	0.77 ± 0.04^a	2.29 ± 0.70^f	127.2 ± 6.4	0.26 ± 0.02^h	38.21 ± 0.14	9.37 ± 0.05
NGC 253	3.56 ± 0.26^a	8.78 ± 0.60^f	92.5 ± 4.6	5.03 ± 0.76^h	40.12 ± 0.07	10.56 ± 0.07
SMC	0.060 ± 0.003^a	29.2 ± 1.2^f	622 ± 31	0.027 ± 0.003^i	37.10 ± 0.05	7.85 ± 0.05
M33	0.91 ± 0.04^a	2.02 ± 0.38^g	53.8 ± 2.7	0.29 ± 0.02^h	38.30 ± 0.09	9.14 ± 0.04
NGC 1068	10.1 ± 1.8^b	7.46 ± 0.55^f	31.6 ± 1.6	22.7 ± 8.1^h	40.96 ± 0.16	11.00 ± 0.16
LMC	0.050 ± 0.003^a	195.1 ± 8.5^f	6777 ± 339	0.20 ± 0.03^i	37.77 ± 0.06	8.72 ± 0.06
NGC 2146	17.2 ± 3.2^c	1.83 ± 0.36^f	13.71 ± 0.69	14.0 ± 5.2^h	40.81 ± 0.18	11.10 ± 0.16
NGC 2403	3.18 ± 0.18^a	1.22 ± 0.28^g	4.73 ± 0.24	0.37 ± 0.03^h	39.17 ± 0.11	9.17 ± 0.05
M82	3.53 ± 0.26^a	10.36 ± 0.52^f	143.6 ± 7.2	10.4 ± 1.6^h	40.19 ± 0.07	10.75 ± 0.07
NGC 3424	25.6 ± 1.8^d	1.59 ± 0.35^f	0.910 ± 0.046	1.59 ± 0.23^j	41.10 ± 0.11	10.27 ± 0.07
Arp 299	46.8 ± 3.3^d	1.10 ± 0.33^g	10.50 ± 0.52	97 ± 14^k	41.46 ± 0.14	11.86 ± 0.07
NGC 4945	3.72 ± 0.27^a	11.51 ± 0.79^f	63.6 ± 3.2	1.22 ± 0.16^i	40.28 ± 0.07	10.44 ± 0.07
Circinus	4.21 ± 0.70^e	7.1 ± 1.2^f	29.8 ± 1.5	2.05 ± 0.63^i	40.18 ± 0.16	10.22 ± 0.15
Arp 220	80.9 ± 5.7^d	2.91 ± 0.48^f	7.80 ± 0.39	214 ± 32^k	42.36 ± 0.09	12.20 ± 0.07
Milky Way	*	*	*	1.90 ± 0.04^m	38.91 ± 0.13^n	10.15 ± 0.21^n

Kornecki et al. 2020

M82



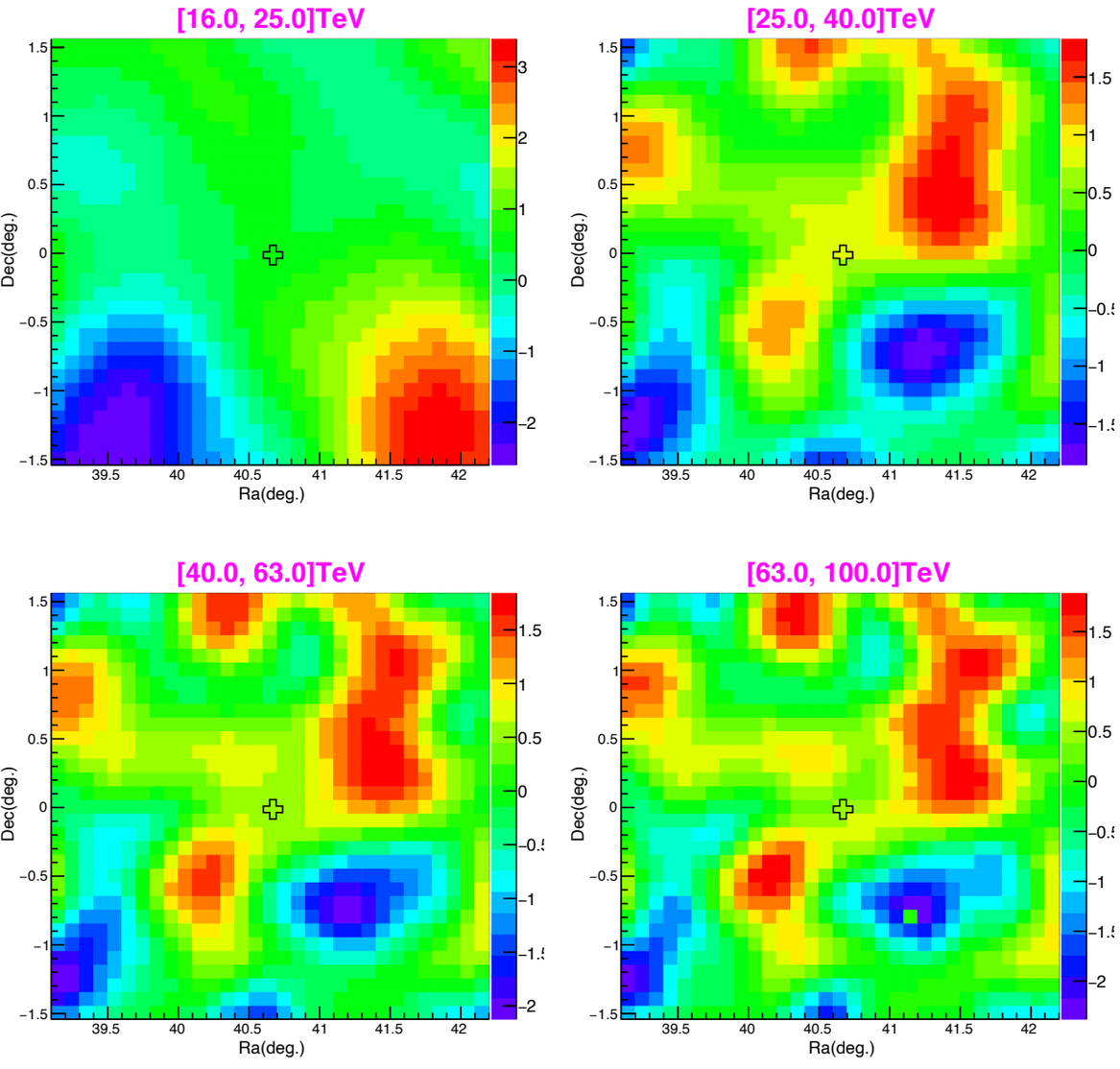
Significance Map



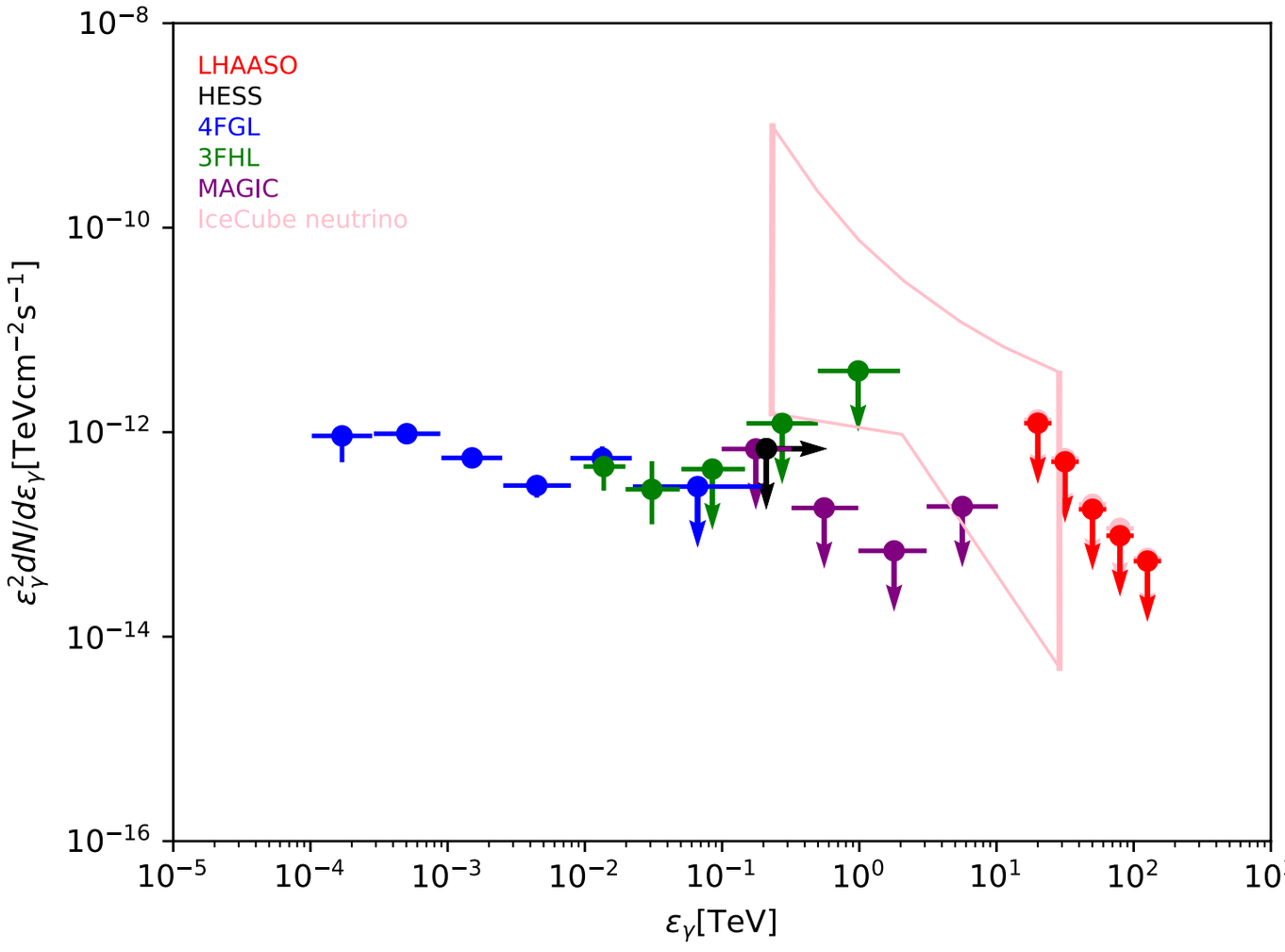
Spectrum

KM2A 1/2 array, 308 days, Dr. Youliang Feng's Analysis

NGC 1068



Significance Map



Spectrum

KM2A 1/2 array, 308 days, Dr. Youliang Feng's Analysis

Parameters of M82 and NGC 1068

	M82
z^a	9×10^{-4}
$D_{\rm L}$ [Mpc]^a	3.9
$R_{\rm SBN}$ [pc]^a	220
$n_{\rm SBN}$ [cm^{-3}]^a	175
$\mathcal{R}_{\rm SN}$ [yr^{-1}]^a	0.05
$v_{\rm SBNwind}$ [km s^{-1}]^a	600
$H_{\rm gas}$ [pc]^b	73
$M^b_{\rm A,turb}$	2
$v_{\rm Ai}$ [km s^{-1}]^b	880
$\mathcal{L}_{\rm SN}$ [10^{40}erg s^{-1}]^c	159
$\mathcal{L}_{\rm SW}$ [10^{40}erg s^{-1}]^c	49

Ha et al. 2020

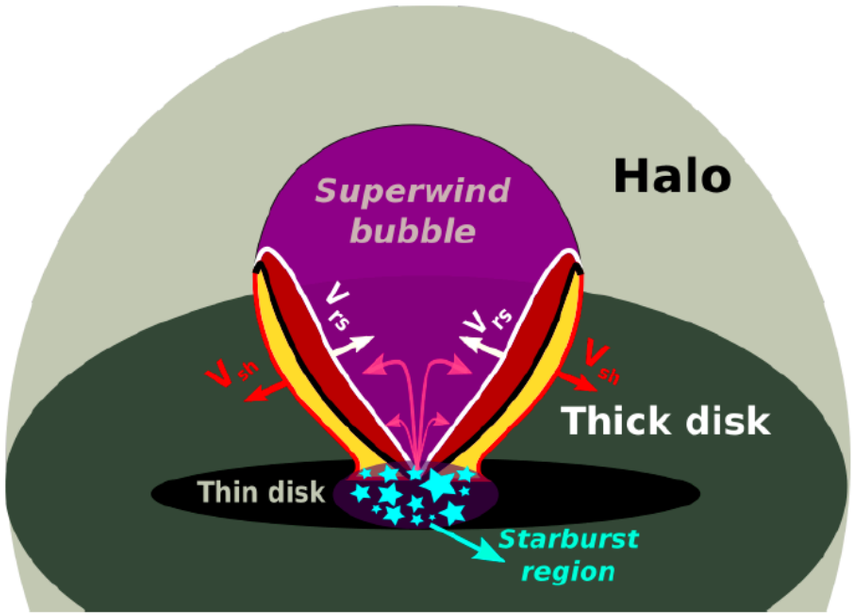
Dense ISM
High SN rate

Physical Parameters	NGC 1068 Values
Distance	14.4 Mpc
Central Molecular Zone (CMZ) Radius	200 pc
Molecular Gas Mass	5×10^7 $M_\odot$
Average ISM Density[a]	250 cm^{-3}
IR Luminosity	1.5×10^{11} $L_\odot$
Radiation Field Energy Density[a]	10^4 eV cm^{-3}
SN Explosion Rate	0.07 yr^{-1}
SN Explosion Energy[b]	10^{51} ergs
SN Energy Transferred to CR[b]	10%
Ratio of Primary Protons to Electrons (N_p/N_e)	50

Yoast-Hull et al. 2013

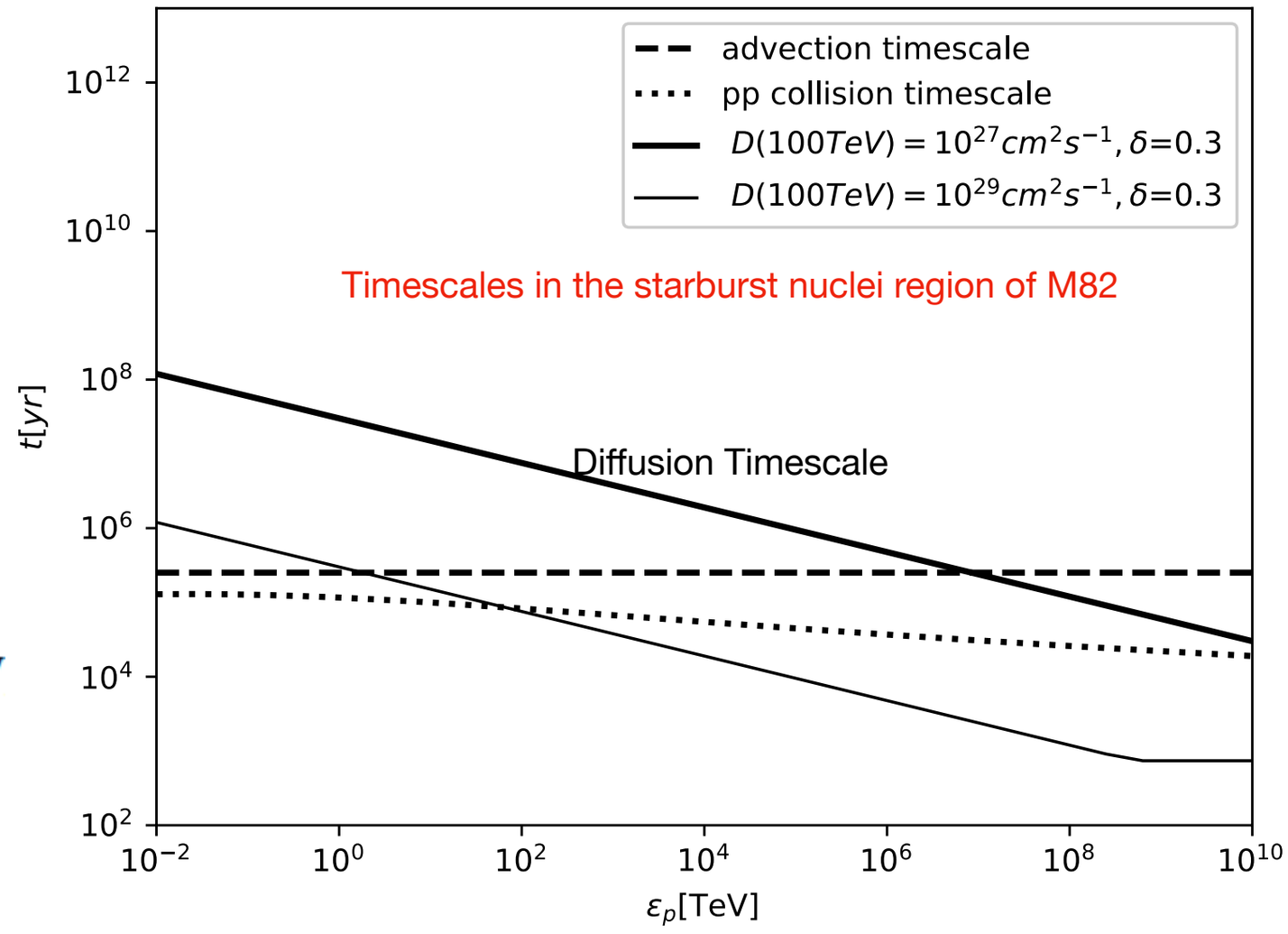
CRs Accelerators:
Supernovae (SNe)
Hypernovae (HNe)
Superwind (SW)
The activity of the central black hole

Is M82 a Calorimeter?



$$E_{\max} \sim 10\,Z\left(\frac{u_s}{1000\ \mathrm{km/s}}\right)^2\left(\frac{B}{150\mu\mathrm{G}}\right)\left(\frac{\tau}{50\ \mathrm{Myr}}\right)\ \mathrm{EeV}$$

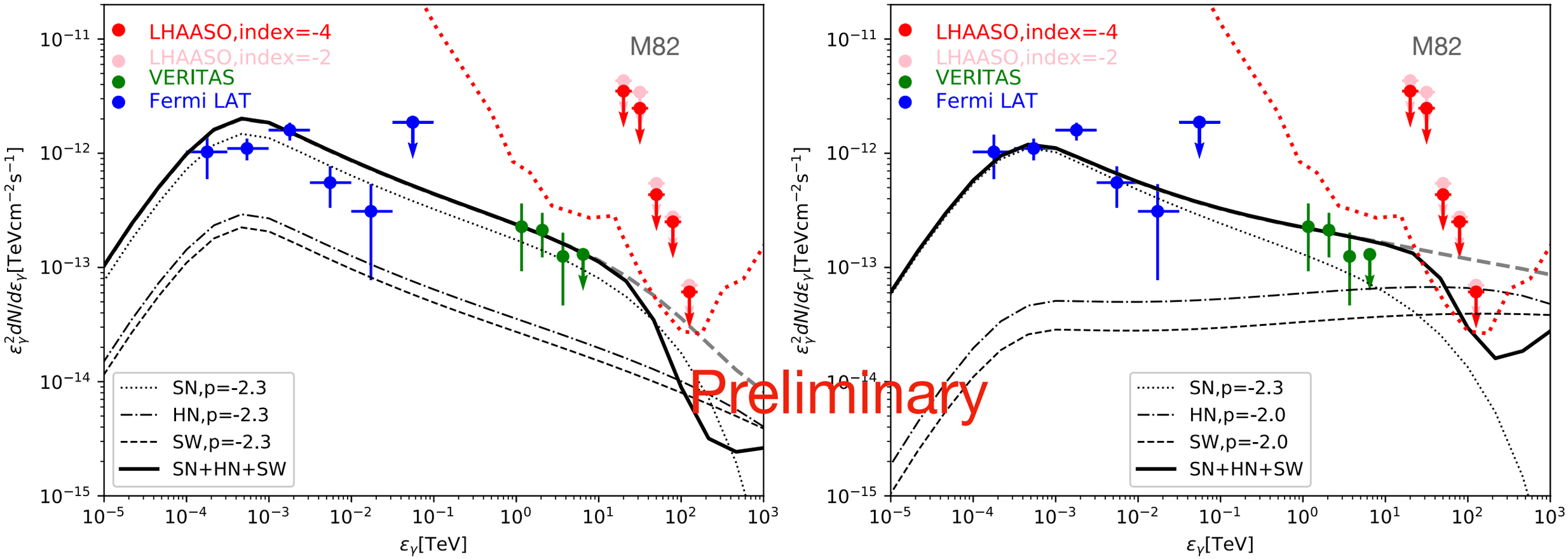
Strickland (2002)



Model: SN(1 PeV)+HN(100 PeV)+SW(100 EeV) inject protons into the Starburst Region.

The starburst region is a calorimeter for D(100 TeV)=1e27cm^2s^-1.
The CRs accelerated via the superwind and injected into the halo can escape.

Theoretical spectra compared with observations and LHAASO sensitivity



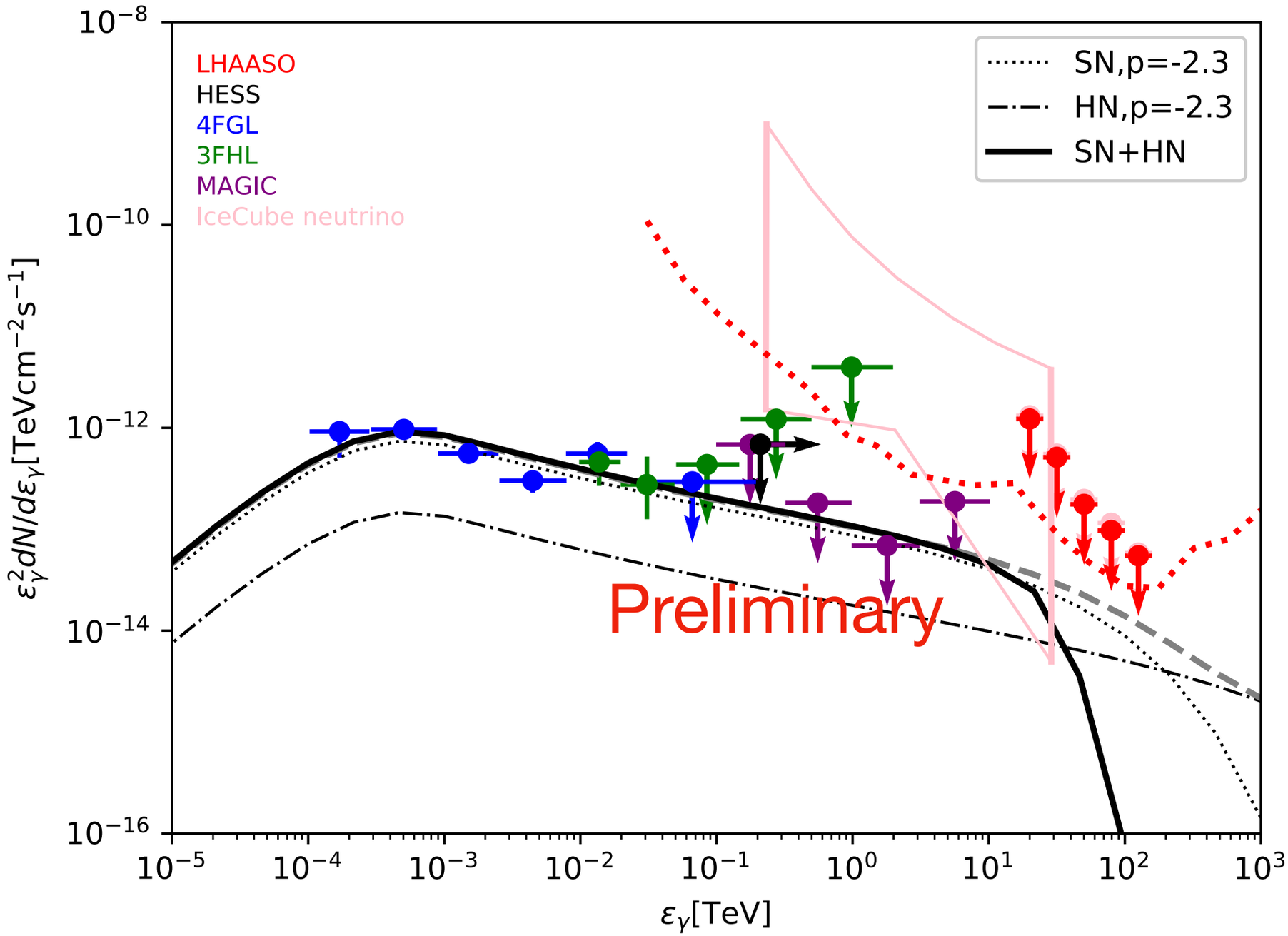
Preliminary

Red dotted curves: LHAASO 1 year sensitivity adopted from the white paper

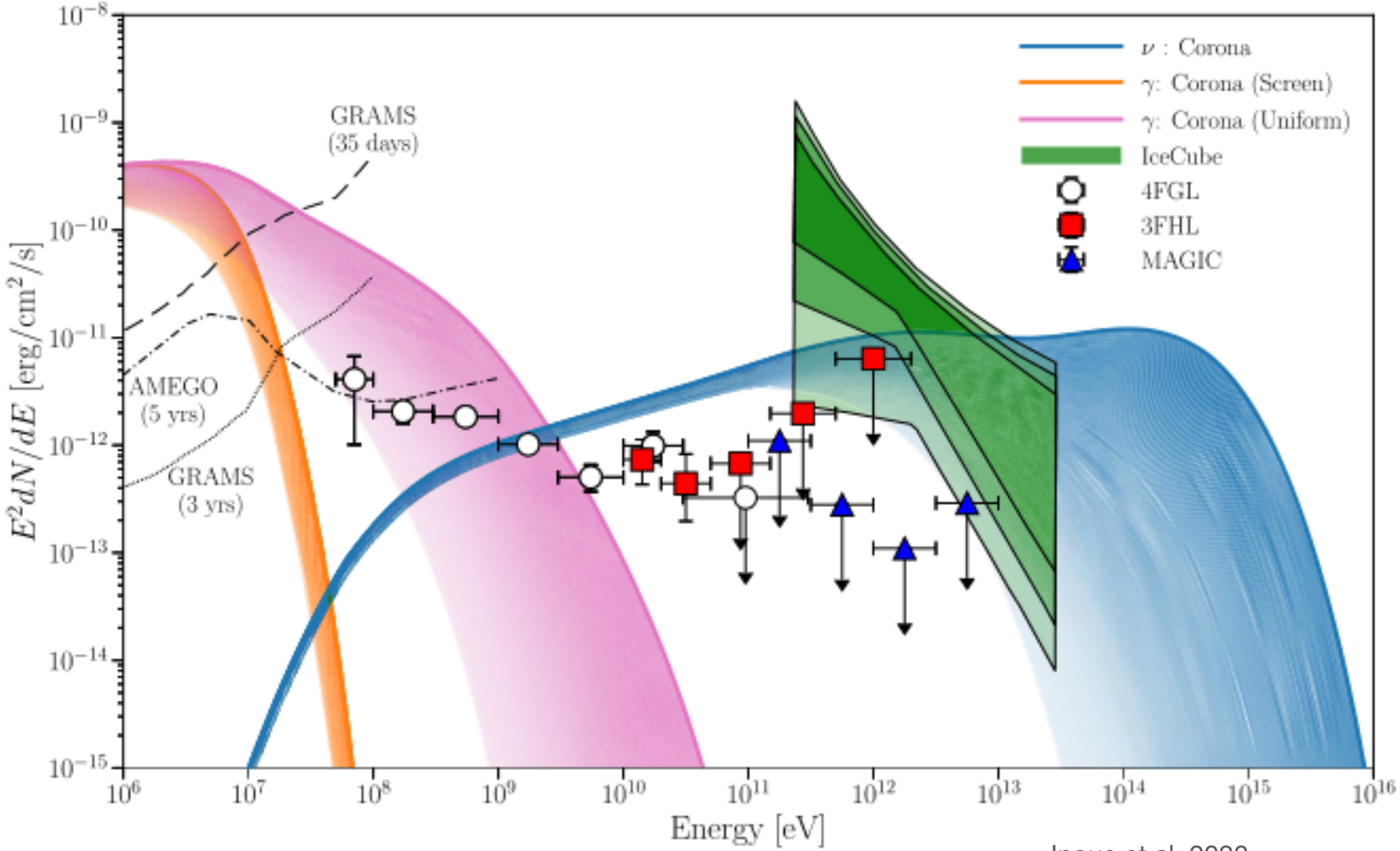
Black solid curves: Attenuation by EBL photons considered.

Integrated neutrino count is as small as ~0.1 for IceCube 10 years operation.

NGC 1068


LHAASO
HESS
4FGL
3FHL
MAGIC
IceCube neutrino
SN,p=-2.3
HN,p=-2.3
SN+HN
Preliminary
$\varepsilon_\gamma^2 dN/d\varepsilon_\gamma$[TeVcm^{-2}s^{-1}]
ε_γ[TeV]
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

NGC 1068



Inoue et al. 2020

Neutrinos are from the central region, which holds an active black hole, and is opaque for high energy photons.

Star Forming Galaxies M31 & M33

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Stacking Nearby Starburst Galaxies in LHAASO's FOV with Distance <15Mpc

Name	RA [deg]	DEC [deg]	z	DL[Gpc]	S12 μm	S25 μm	S60 μm	S100 μm	References
NGC660	25.7598	13.6457	0.00283	0.01233	3.05	7.3	65.52	114.74	1
NGC891	35.6392	42.3491	0.00176	0.00857	5.27	7	66.46	172.23	1
NGC1055	40.4385	0.443167	0.00332	0.01131	2.24	2.84	23.37	65.26	1
Maffei2	40.4795	59.6041	–5.7e–05	0.00332	3.624	9.238	135	225	6
NGC1068(M77)	**40.6696**	**–0.0132806**	**0.00379**	**0.0137**	**39.84**	**87.57**	**196.37**	**257.37**	**1**
IC342	56.7021	68.0961	0.0001	0.0046	14.92	34.48	180.8	391.66	1
NGC1569	67.7044	64.8479	0.00035	0.0046	1.24	9.03	54.36	55.29	1
NGC2403	114.214	65.6026	0.00044	0.00247	2.82	3.57	41.47	99.13	1
NGC2903	143.042	21.5008	0.00186	0.00826	5.29	8.64	60.54	130.43	1
NGC3034(M82)	**148.968**	**69.6797**	**0.00068**	**0.00363**	**79.43**	**332.63**	**1480.42**	**1373.69**	**1**
NGC3556(M108)	167.879	55.6741	0.00233	0.01385	2.29	4.19	32.55	76.9	1
NGC3627(M66)	170.063	12.9915	0.00243	0.01004	4.82	8.55	66.31	136.56	1
NGC3628	170.071	13.5895	0.00281	0.01004	3.13	4.85	54.8	105.76	1
NGC4102	181.596	52.7109	0.002823	0.0141	1.77	6.83	46.85	70.29	1
NGC4214	183.913	36.3269	0.00097	0.00367	0.58	2.46	17.57	29.08	2
NGC4631	190.533	32.5415	0.00202	0.00773	5.16	8.97	85.4	160.08	1
NGC5055(M63)	198.956	42.0293	0.00168	0.00796	5.35	6.36	40	139.82	1
NGC5194(M51)	202.47	47.1952	0.00154	0.00873	7.21	9.56	97.42	221.21	1
NGC6946	308.718	60.1539	0.00016	0.00532	12.11	20.7	129.78	290.69	1
NGC7331	339.267	34.4156	0.00272	0.01471	3.94	5.92	45	110.16	1

Summary

- More exposure is needed to observe photons >10 TeV and neutrinos for nearby starburst galaxies M82 and NGC 1068.
- To do: Nearby star forming galaxies M31 and M33
- To do: Stacking analysis on nearby starburst galaxies and star forming galaxies

Thank you!