

Searching for Neutrinos from Pulsar Wind Nebulae with IceCube

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Introduction

Galactic cosmic rays reach energies of at least several PeV and their interactions should generate high energy photons and neutrinos from secondary pion decays.

Possible Galactic Candidates

- **Point-like:** PWNe, SNR, binaries, unidentified TeV sources...
- **Extended Region:** Fermi Bubbles, Galactic Halo, Sagittarius A*...
- **Diffuse Emission:** CR interaction with hydrogen in Galaxy

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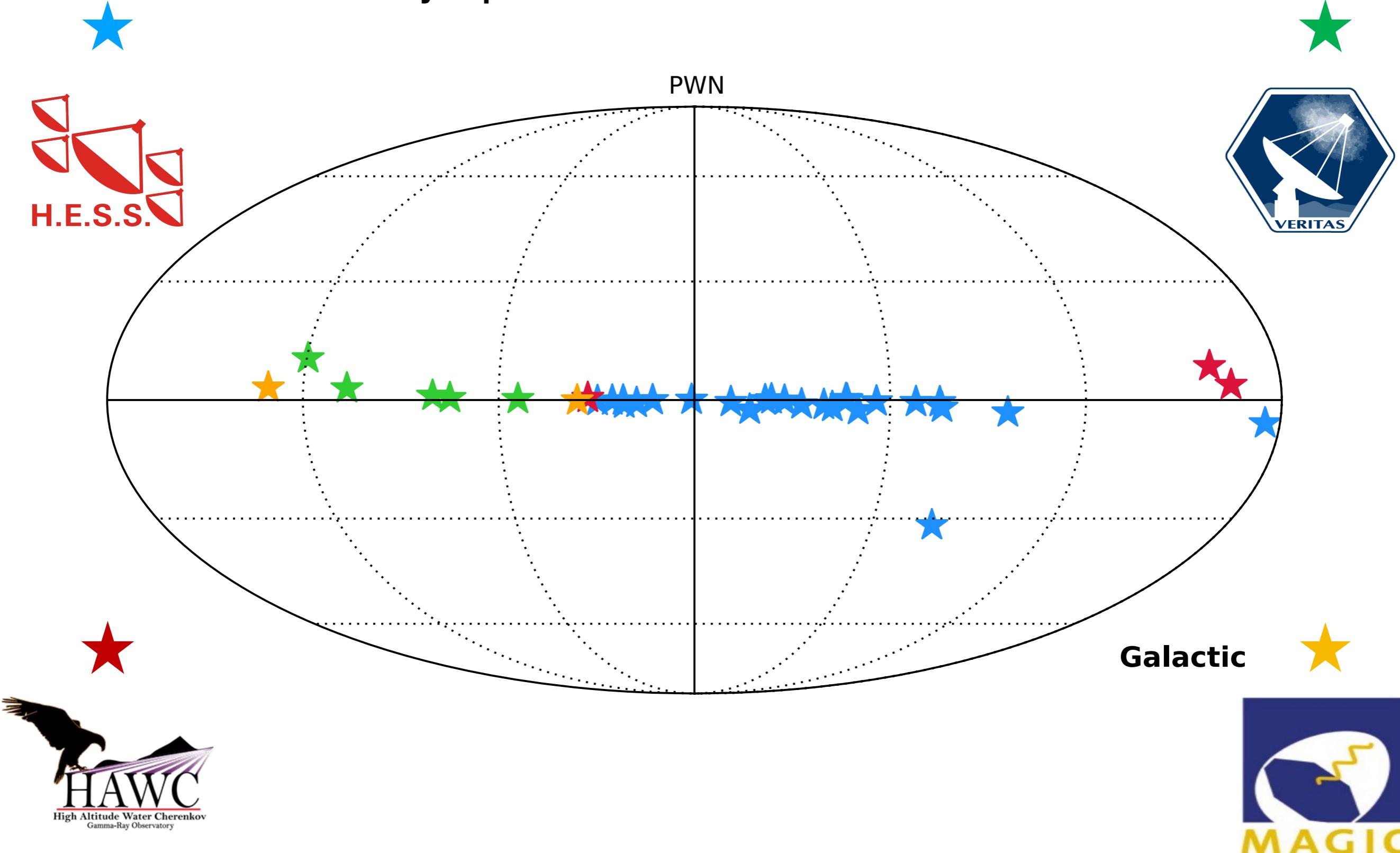
- Main TeV gamma-ray emitters in the Milky Way
- Hadronic scenario for some of the high energy emission in addition to lepton-only scenario cannot be excluded



crab-
optical (Hubble)+X-ray (Chandra)

Sources

Skymap of the 35 TeV PWNe in this search



Analysis Method

Unbinned Maximum Likelihood Method for Stacking Search

Combining signals from sources to improve the sensitivity

$$L(n_s, \gamma_s) = \prod_i^N \left(\sum_j^{N_{sources}} \omega_j \frac{n_s}{N} S_i^j + (1 - \frac{n_s}{N}) B_i \right)$$

Signal PDF

$$S_i^j = S^s(x_s, x_i, \sigma_{ij}) \times S^E(E_i, \gamma_s)$$

Background PDF

The background is from randomized data

Spatial PDF: 2D Gaussian Distribution

Energy PDF: Power-law Spectrum

Likelihood Ratio Test

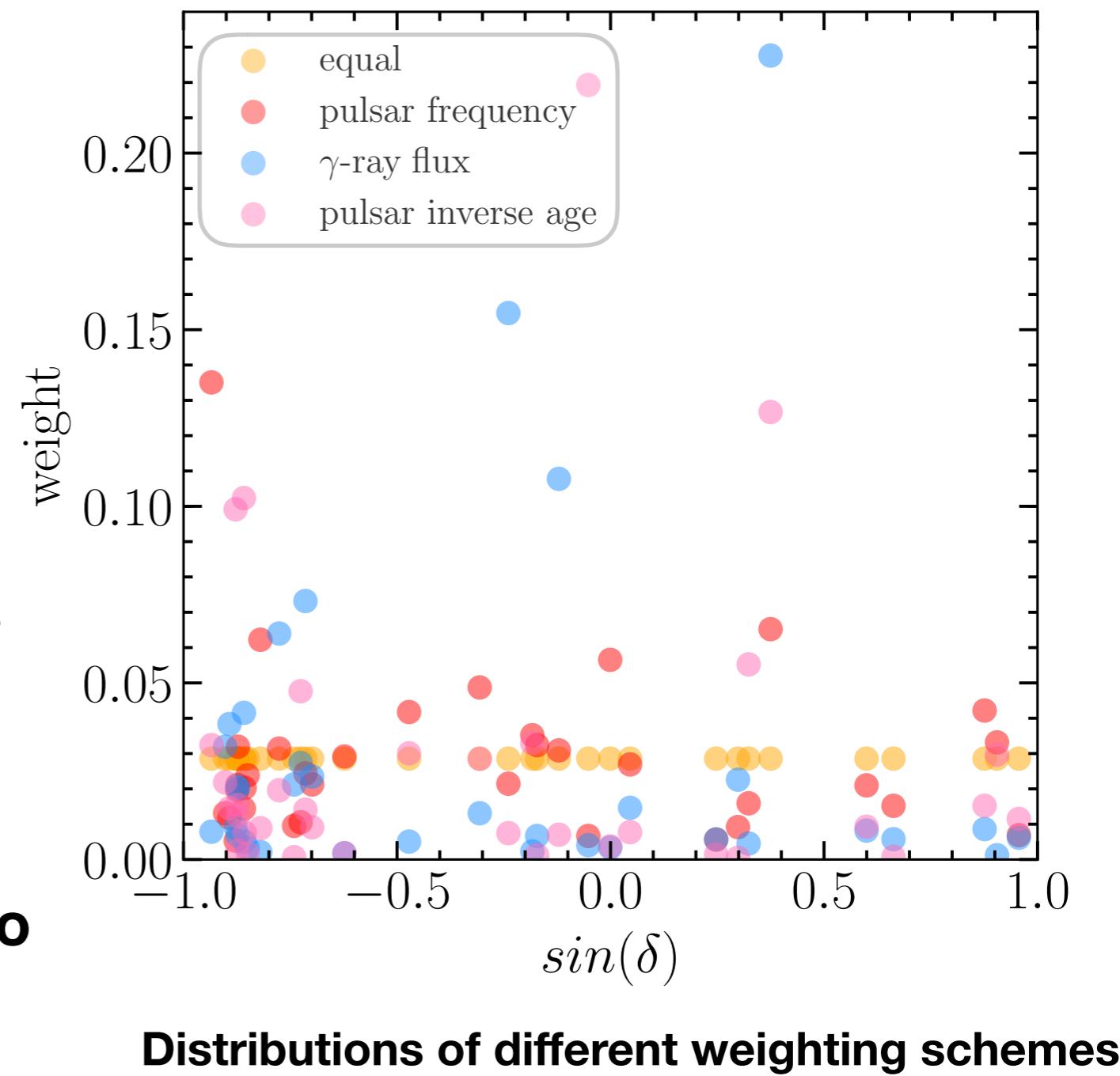
$$TS = -2\log \frac{L(n_s = 0)}{L(\hat{n}_s, \hat{\gamma}_s)}$$

Weighting - ω_j

4 Ways to Weight Sources

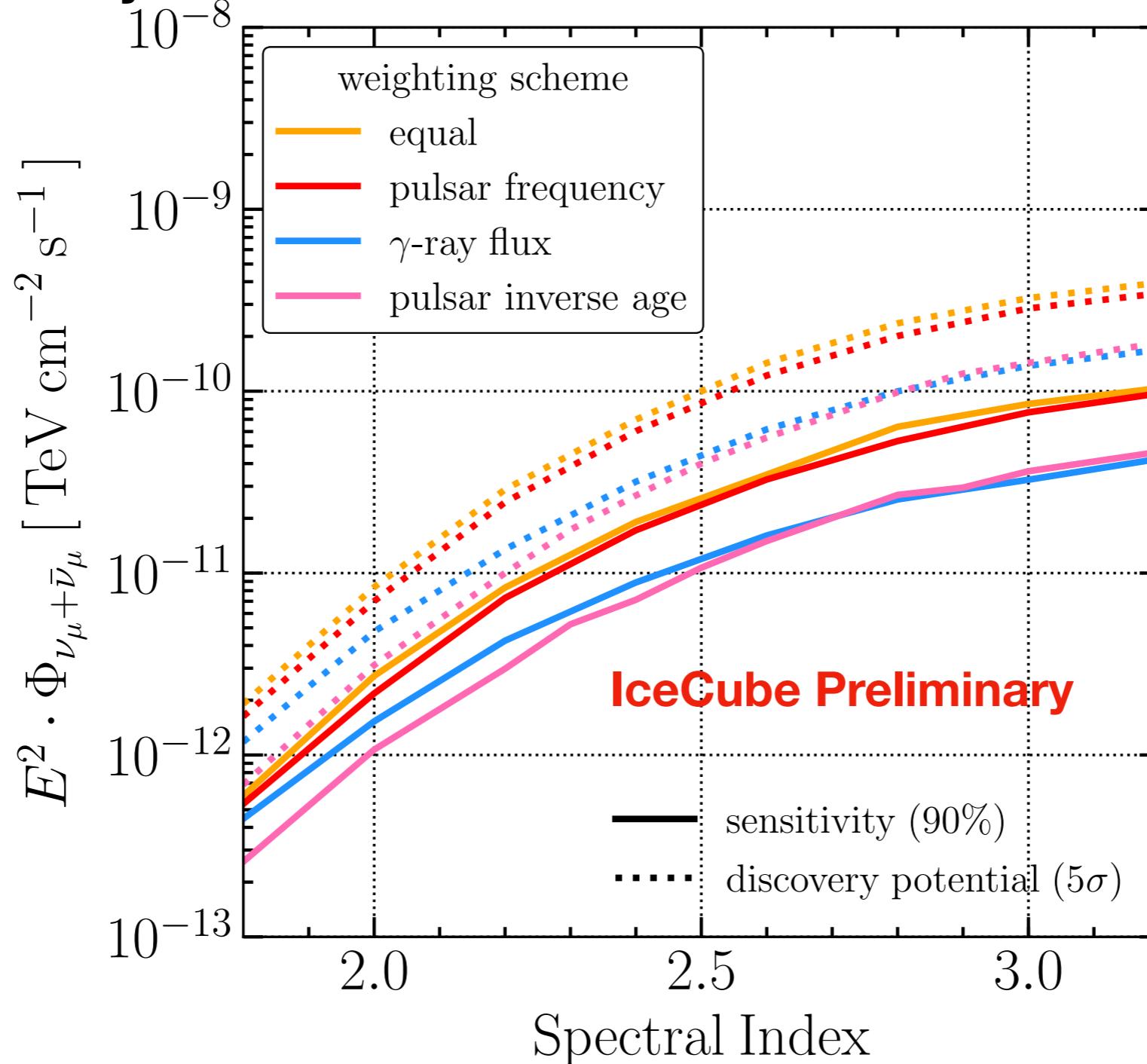
To test 4 different hypotheses

- **equal:** all sources are treated equally.
- **inverse age of the pulsar:** younger sources are more energetic.
- **frequency of the pulsar:** pulsars that spin faster have more rotational energy transferred to accelerate particles.
- **gamma-ray flux at 1TeV:** neutrino emission is proportional to HE gamma-ray emission.



Sensitivity

- The expected performance of this analysis for IceCube using 9.5 yr all sky muon neutrino tracks



Sensitivities and discovery potentials at 1TeV for four different hypotheses

Results

— Neutrino Flux

No excess found

Best-fits for the number of signal events and spectral index

weighting	TS	n_S	γ	p-value	$\Phi_{\nu_\mu + \bar{\nu}_\mu}^{90\%, E^{-2.0}}$	$\Phi_{\nu_\mu + \bar{\nu}_\mu}^{90\%, E^{-2.19}}$	$\Phi_{\nu_\mu + \bar{\nu}_\mu}^{90\%, E^{-2.5}}$
Equal	0.81	40.43	3.84	22.58%	3.91	11.6	44.5
Frequency	0.26	18.0	3.81	37.85%	2.64	7.79	28.2
Flux	0.21	8.73	4.00	36.17%	1.74	4.57	14.9
1/Age	0	0	-	-	1.07	2.82	10.7



Upper limits for the stacked flux with 90% confidence level assuming power-law spectra E^{-2} , $E^{-2.19}$ and $E^{-2.5}$.
The UL fluxes are normalized at 1 TeV with units $10^{-12} \text{ TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$.

Results

—Hadronic Components Constraints

- Hadronic component constraints: finding hadronic gamma ray contribution assuming pp interactions

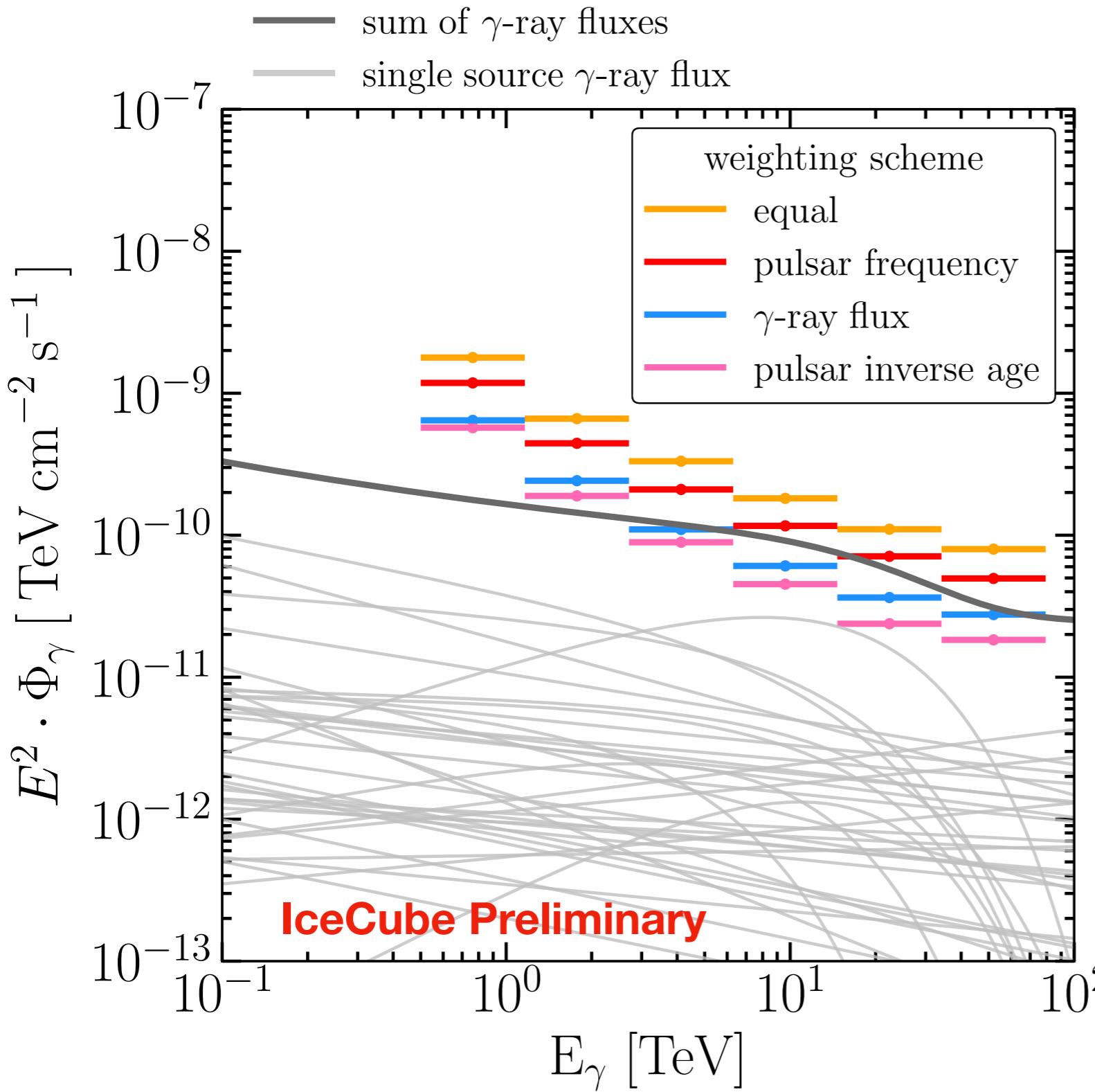
- pp interactions
- Assuming all neutrinos have gamma-ray companions

$$\Phi_{\nu}^{UL} \rightarrow \text{pionic } \Phi_{\gamma}^{UL}$$

- Energy differential upper limits.
- **Caveat:**
Reliable gamma-ray measurements $E_{\gamma} \lesssim \mathcal{O}(10) \text{ TeV}$
IceCube neutrino events can reach PeV
→ uncertainties in high energies if simply extrapolate
- **Solution:** Introducing differential upper limits

Results

— Hadronic Model Constraints



- **Neutrino 90% CL differential upper limits assuming a power-law spectrum E^{-2} .**
- **To avoid large uncertainties from extrapolation of gamma-ray, the energy cuts at 100 TeV in the plot.**

Conclusion & Outlook

- No significant signal found from 35 stacked TeV PWNe.
- 90% CL upper limits are set on the total neutrino flux from TeV PWNe.
- We also set constraints on hadronic components.
- More precise measurements of gamma-ray fluxes from PWNe in O(100) TeV energy range in the future are expected to shed more light on PWNe being possible PeVatrons.



Stay Tuned to
Multimessenger Astronomy !

Thank you!

Backup

TeV PWNe Sources

PWN	Pulsar	DEC	RA	Extension	Period	Age	N_0	γ	Cutoff	Telescope	Ref.
		deg	deg	deg	s	kyr	$TeV^{-1}cm^{-2}s^{-1}$		TeV		
Crab	B0531+21	22.01	83.63		0.033392	1.26	3.76	2.39	14.3	HESS	Aharonian et al. (2006)
Vela X	B0833-45	-45.6	128.75	0.585	0.089328	11.3	1.2089	1.35	12.27	HESS	Abdalla et al. (2018)
MSH15-52	B1509-58	-59.16	228.53	0.145	0.151251	1.56	0.686	2.05	19.2	HESS	Abdalla et al. (2018)
SNR G054.1+00.3	J1930+1852	18.87	292.63		0.136855	2.89	0.075	2.39		VERITAS	Acciari et al. (2010)
SNR G000.9+00.1	J1747-2809	-28.15	266.85		0.052153	5.31	0.0838	2.4		HESS	Abdalla et al. (2018)
HESS J1833-105	J1833-1034	-10.56	278.39		0.061884	4.85	0.0377	2.42		HESS	Abdalla et al. (2018)
HESS J1846-029	J1846-0258	-2.98	281.6		0.326571	0.728	0.0671	2.41		HESS	Abdalla et al. (2018)
HESS J1356-645	J1357-6429	-64.5	209.0	0.231	0.166108	7.31	0.5275	2.2		HESS	Abdalla et al. (2018)
CTA1	J0007+7303	72.98	1.61	0.25	0.315873	13.9	0.102	2.2		VERITAS	Aliu et al. (2013)
HESS J1616-508	J1617-5055	-50.9	244.1	0.232	0.069357	8.13	1.0569	2.32		HESS	Abdalla et al. (2018)
HESS J1640-465	J1640-4631	-46.53	250.18	0.11	0.206443	3.35	0.4515	2.12	4.13	HESS	Abdalla et al. (2018)
HESS J1813-178	J1813-1749	-17.84	273.4	0.049	0.044699	5.6	0.2165	1.64	7.37	HESS	Abdalla et al. (2018)
HESS J1632-478	J1632-4757	-47.82	248.04	0.182	0.228564	240.0	0.351	2.52		HESS	Abdalla et al. (2018)
HESS J1458-608	J1459-6053	-60.88	224.54	0.373	0.10315	64.7	0.1138	1.81		HESS	Abdalla et al. (2018)
Kookaburra(PWN)	J1420-6048	-60.76	215.04	0.081	0.06818	13.0	0.3333	2.2		HESS	Abdalla et al. (2018)
Kookaburra(Rabbit)	J1418-6058	-60.98	214.52	0.108	0.110573	10.3	0.3406	2.26		HESS	Abdalla et al. (2018)
HESS J1831-098	J1831-0952	-9.9	277.85	0.15	0.067267	128.0	0.11	2.1		HESS	Sheidaei et al. (2011)
HESS J1303-631	J1301-6305	-63.18	195.7	0.177	0.184528	11.0	0.6337	2.04	15.12	HESS	Abdalla et al. (2018)
LHA 120-N 157B	J0537-6910	-69.17	84.43	0.014	0.016122	4.93	0.13	2.8		HESS	Abramowski et al. (2015)
HESS J1837-069	J1838-0655	-6.95	279.41	0.355	0.070498	22.7	1.7801	2.54		HESS	Abdalla et al. (2018)
HESS J1708-443	B1706-44	-44.33	257.05	0.279	0.102459	17.5	0.3876	2.17		HESS	Abdalla et al. (2018)
HESS J1825-137	B1823-13	-13.84	276.42	0.461	0.101487	21.4	2.5557	2.15	13.57	HESS	Abdalla et al. (2018)
IGR J18490-0000	J1849-0001	-0.04	282.24	0.09	0.038519	42.9	0.0557	1.97		HESS	Abdalla et al. (2018)
Boomerang	J2229+6114	61.17	337.18	0.22	0.051624	10.5	0.142333	2.29		VERITAS	Acciari et al. (2009)
TeV J2032+4130	J2032+4127	41.51	308.03	0.158	0.143246	201.0	0.095	2.1		VERITAS	Aliu et al. (2014a)
MGRO J2019+37	J2021+3651	36.83	304.65	0.75	0.103741	17.2	0.13542	1.75		VERITAS	Aliu et al. (2014b)
MAGICJ1857.2+0263	J1856+0245	2.63	284.3	0.1	0.080907	20.6	0.24165	2.2		MAGIC	Aleksić et al. (2014a)
HESS J1018-589B	J1016-5857	-58.98	154.13	0.15	0.107386	21.0	0.0838	2.2		HESS	Abdalla et al. (2018)
HESS J1026-582	J1028-5819	-58.2	156.66	0.13	0.091403	90.0	0.0542	1.81		HESS	Abdalla et al. (2018)
SNR G327.1-01.1		-55.08	238.65		0.035	18.0	0.0347	2.19		HESS	Abdalla et al. (2018)
Geminga	J0633+1746	17.37	98.12	2.0	0.237099	342.0	0.373334	2.23		HAWC	Abeysekara et al. (2017)
3C 58	J0205+6449	64.85	31.38		0.065686	5.37	0.02	2.4		MAGIC	Aleksić et al. (2014b)
HESS J1718-385	J1718-3825	-38.55	259.53	0.115	0.07467	89.5	0.0295	0.98	10.57	HESS	Abdalla et al. (2018)
SNR G292.2-00.5	J1119-6127	-61.4	169.75	0.098	0.407963	1.61	0.1504	2.64		HESS	Abdalla et al. (2018)
2HWC J0700+143	B0656+14	14.32	105.12	1.0	0.384891	111.0	0.094113	2.17		HAWC	Abeysekara et al. (2017)

**PWN sources for
this stacking
search and their
information**

PDFs

Signal PDF

$$S_i = S^s(x_s, x_i, \sigma_i) \times S^E(E_i, \gamma_s)$$



Spatial PDF:

$$S_{ij}^s(x_s, x_i, \sigma_{ij}^2) = \frac{1}{2\pi\sigma_{ij}^2} \exp\left(-\frac{|x_i - x_s|^2}{\sigma_{ij}^2}\right)$$

Energy PDF:

$$S_i^E(E_i, \gamma_s) \propto \left(\frac{E_i}{E_0}\right)^{-\gamma_s}$$

Uncertainty

$$\sigma_{ij} = \sqrt{\sigma_i^2 + \sigma_j^2}$$

Angular
resolution of
event i

Angular
extension
of source j

ω_j is the normalized
weight of source j

Datasets

IC40 + IC59 + IC79 + IC86 2011-2014 all sky PS tracks + GFU 2015-2017

Sample	Livetime	Events
	days	#
IC40	376.36	36900
IC59	353.58	107011
IC79	316.05	93133
IC86 I	332.96	136244
IC86 II	1058.48	338590
GFU 2015-2017	989.95	571040

Data samples used in this analysis

Total events: 1,282,918
Livetime: 3427.38

Neutrino and Gamma-ray Relation

$$E_\gamma J_\gamma(E_\gamma) \simeq e^{-\frac{d}{\lambda_{\gamma\gamma}}} \frac{2}{K} \frac{1}{3} \sum_{\nu_\alpha} E_\nu J_{\nu_\alpha}(E_\nu)$$

$$E_\gamma \simeq 2E_\nu$$

- **K is the ratio of charged to neutral pions**
- **J is the differential flux**
- **d is the distance to the source**
- **$\lambda_{\gamma\gamma}$ is the interaction length accounting for the absorption of TeV-PeV gamma-rays in radiation backgrounds.**

