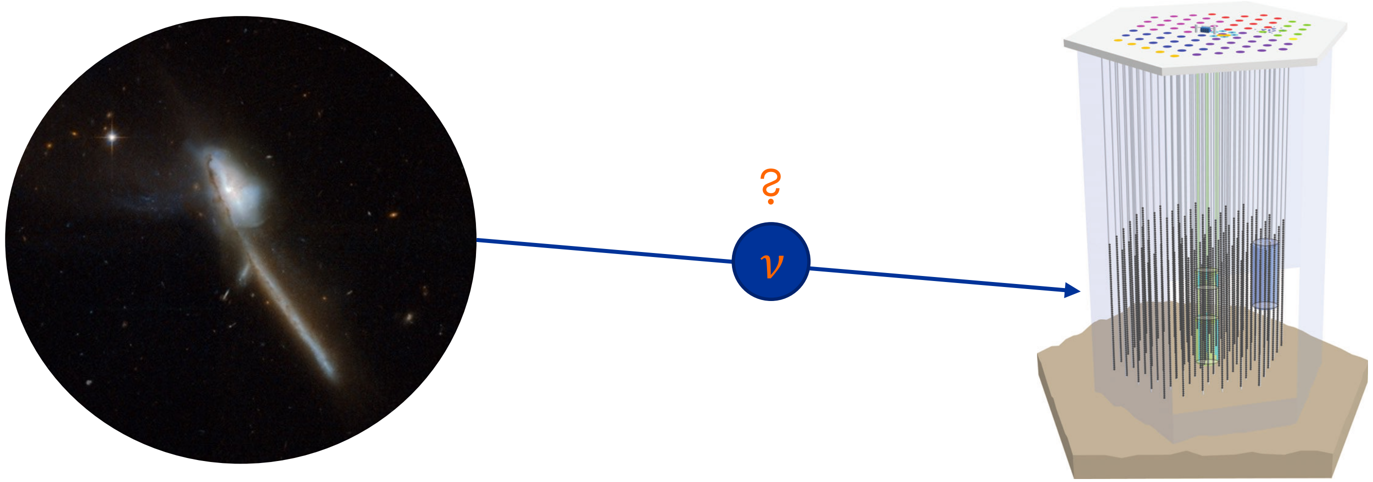

IceCube Search for High-Energy Neutrinos from Ultra-Luminous Infrared Galaxies

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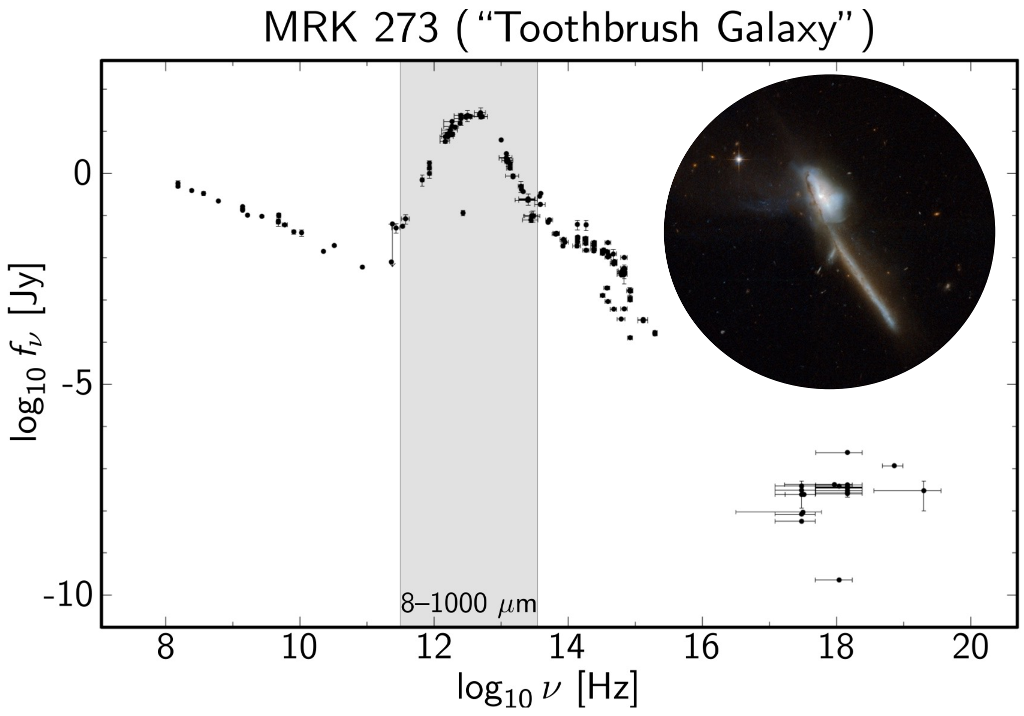
Ultra-Luminous Infrared Galaxies

- The most luminous objects in the IR sky
  - $L_{IR} \geq 10^{12}\ L_{\odot}$ between 8–1000 micron
  - Typically interacting galaxies
  - Numerous source population
- Plausible sources of neutrinos
  - ULIRGs are mainly powered by starbursts
  - Possible contribution from active galactic nucleus

[He+ (2013) PRD 87 063011; Palladino+ (2019) JCAP 09 004;
Vereecken+ (2020) arXiv:2004.03435]



[NASA/IPAC Extragalactic Database; NASA/ESA]

Selection of ULIRGs

- Initial selection [see also PoS ICRC2019 860]
  - From three IRAS based catalogs
  - 189 ULIRGs

Infrared Astronomical Satellite

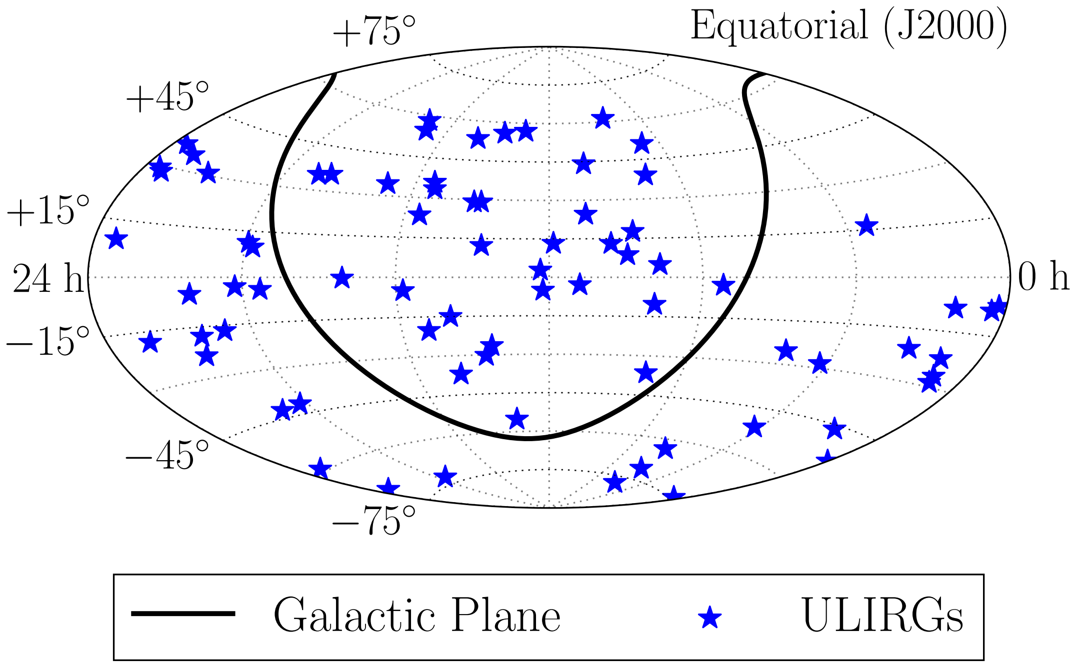
Jan-Nov 1983
12, 25, 60, 100 micron

[Neugebauer+ (1984) ApJ 278 L1]

ULIRG catalogs

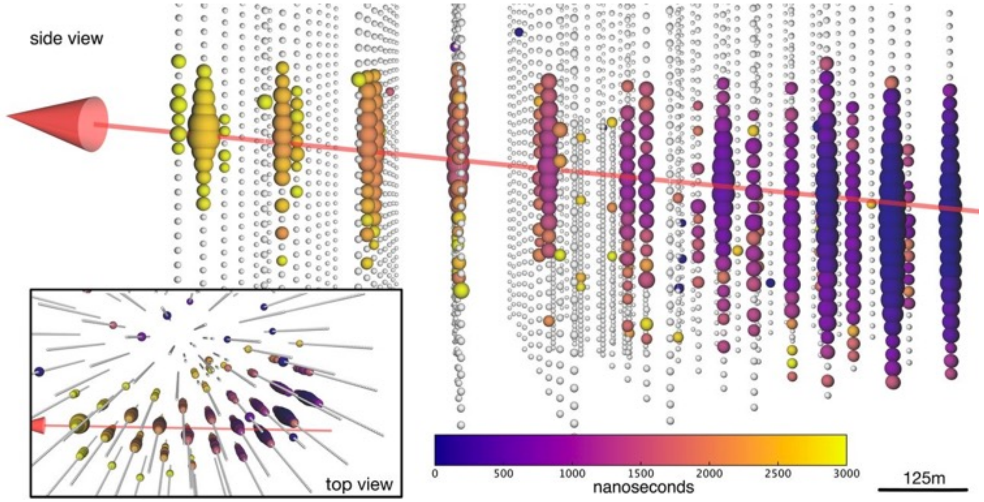
IRAS Revised Bright Galaxy Sample	Sanders+ (2003) AJ 126 1607
IRAS 1 Jy sample (40% of sky)	Kim+ (1998) ApJS 119 41
Nardini+ sample (IRAS + Spitzer)	Nardini+ (2010) MNRAS 405 2505

- Final selection
  - Completeness: find redshift to observe all ULIRGs
    - with $L_{IR} = 10^{12}\ L_{\odot}$
    - for IRAS sensitivity $f_{60} = 1$ Jy
  - Representative sample of 75 ULIRGs with $z \leq 0.13$



The IceCube Neutrino Observatory

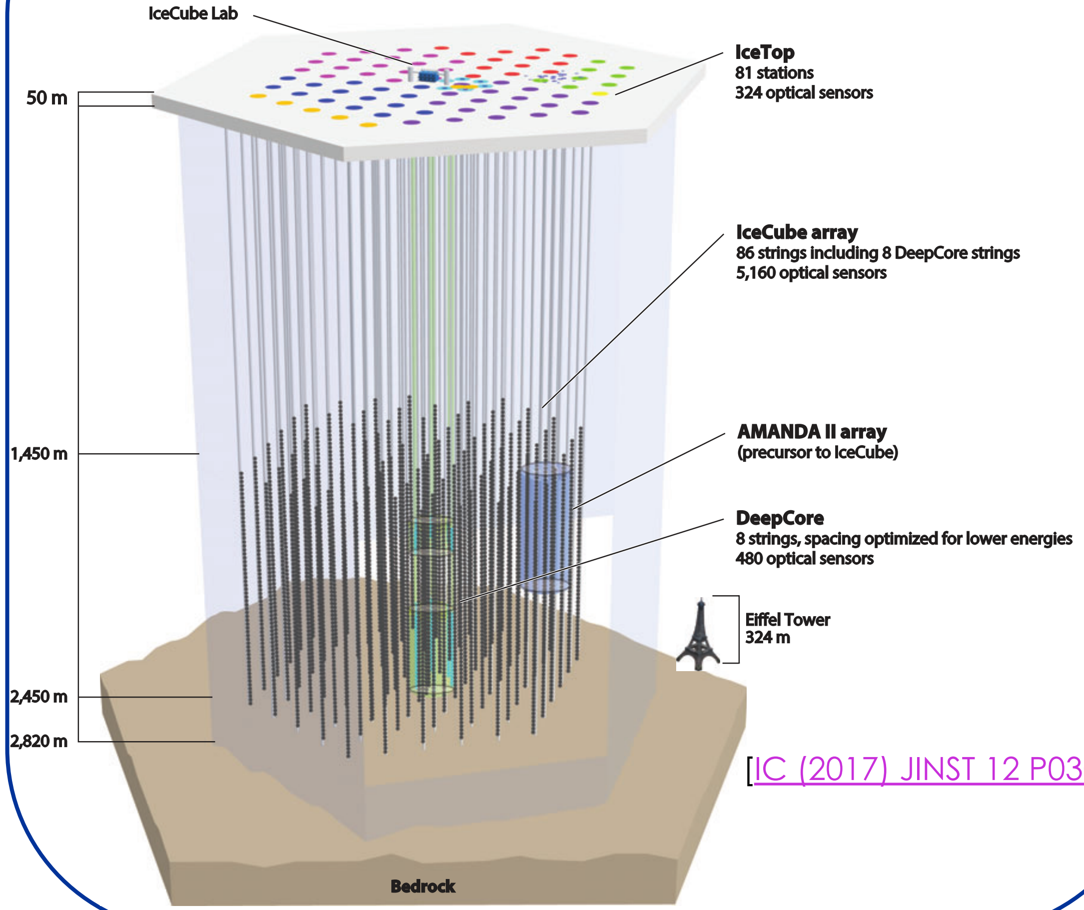
- Optical Cherenkov telescope
  - Observe secondaries of ν interactions
- Focus on muon tracks
  - Signatures of ν_μ and $\bar{\nu}_\mu$
  - Good angular resolution, $< 1^\circ$ for $E_\mu \gtrsim 1$ TeV



[IC (2018) Science 361 eeat1378]

IceCube

South Pole | 1 km^3 | 86 strings | 5160 sensors | 10^2–10^7 GeV



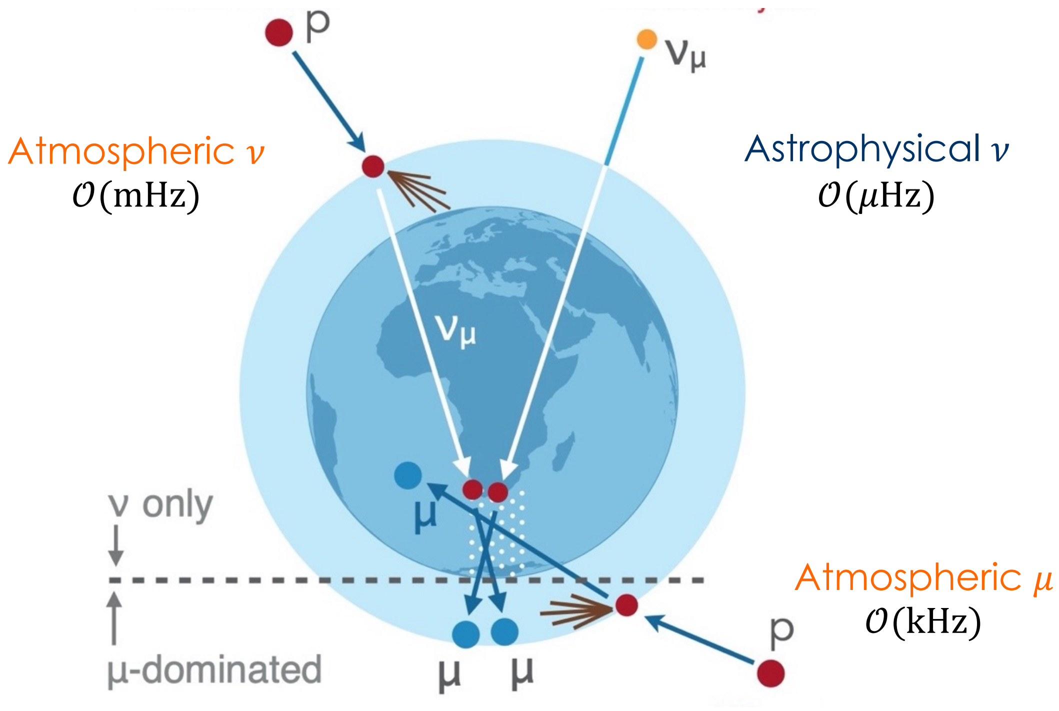
[IC (2017) JINST 12 P03012]

Dataset & Background

- Use GFU data sample
  - Well-reconstructed tracks
  - Full 86-string detector between 2011–2018
- Predominantly atmospheric background
  - Induced by cosmic-ray air showers
  - GFU reduced to 6.6 mHz all-sky rate

Sample	Livetime	Events
GFU	7.5 years	1.5 million

[IC (2017) Astropart. Phys. 92 30]



[Credit: J. Aguilar]

Analysis Method

- Maximum likelihood analysis
  - Time-integrated unbinned likelihood
  - Fit for
    - Number of signal events n_s
    - Power-law spectral index γ

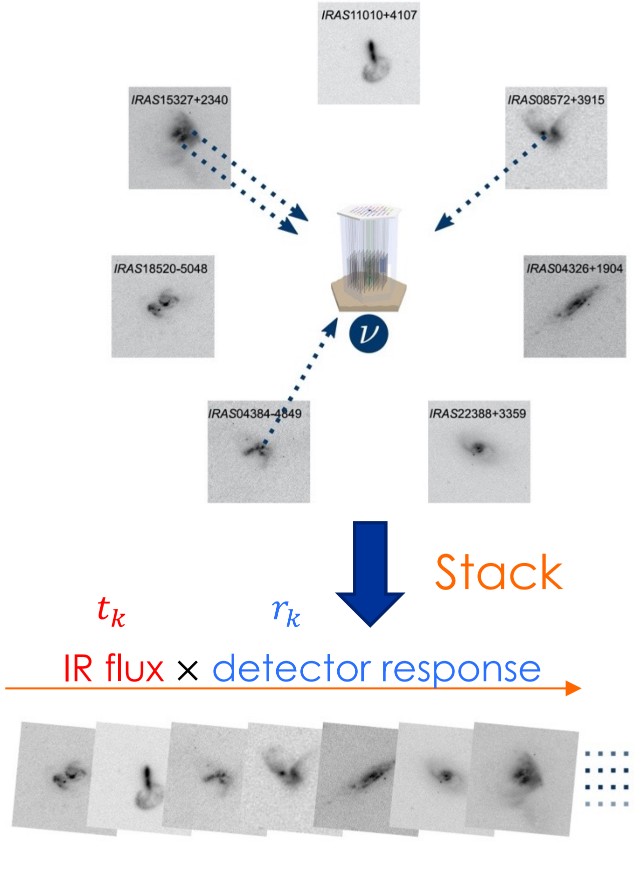
$$\mathcal{L}(n_s,\gamma) = \prod_{i}^{N}\left[\frac{n_s}{N}\sum_{k}^{M} w_k S_i^k(\gamma) + \left(1-\frac{n_s}{N}\right)\mathcal{B}_i\right]$$

Stacking term
$w_k \propto t_k r_k$

Signal PDF
2D Gaussian
$E^{-\gamma}$ spectrum

Background PDF
Uniform in RA
$E^{-3.7}$ spectrum

- Stack sources to enhance sensitivity
  - Weigh ULIRGs according to total IR flux



[Hung+ (2014) ApJ 791 63]

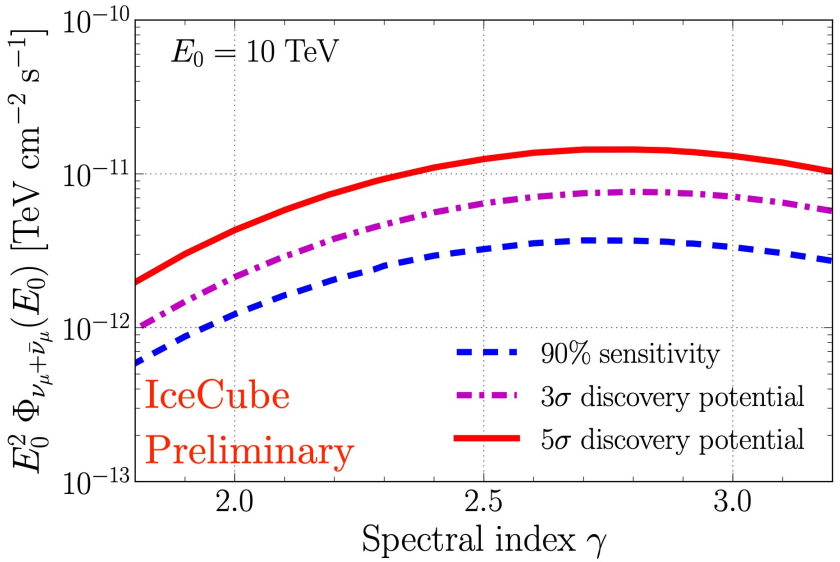
Sensitivity & Discovery Potentials

- Test analysis performance
  - Simulate pseudo-signal according to

$$\Phi_{\nu_\mu+\bar{\nu}_\mu}(E_\nu) = \Phi_0 \left(\frac{E_\nu}{E_0}\right)^{-\gamma}$$

- Sensitive to 10–100 ULIRG neutrinos
  - More sensitive to harder spectra
  - Easier to distinguish from atm. background

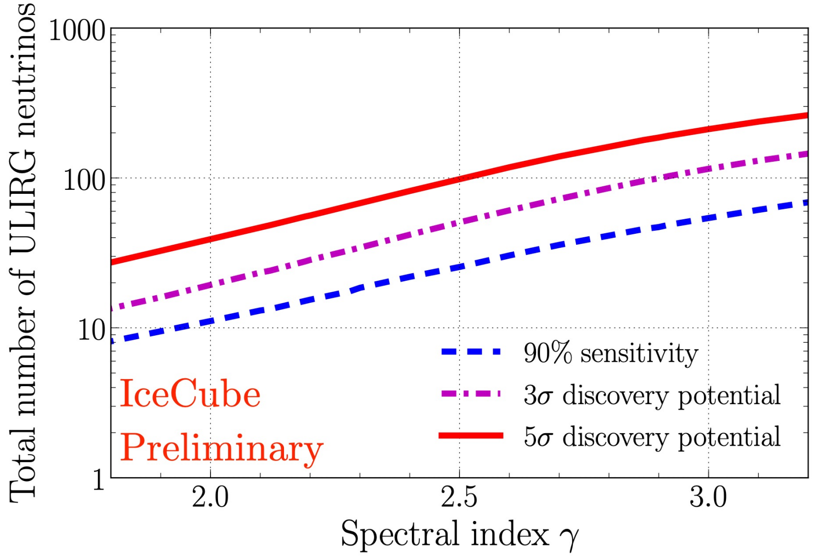
In terms of flux Φ_0 at $E_0 = 10$ TeV



effective area

$$\int \Phi_{\nu_\mu+\bar{\nu}_\mu}(E)\, A_{\text{eff}}(E)\, \mathrm{d}E\, \mathrm{d}t$$

In terms of total number of ν in 7.5 years of data



Results & Upper Limits

- Analysis consistent with background hypothesis
- Set upper limits on flux from our 75 ULIRGs ($z \leq 0.13$)
  - Limits equal to sensitivity (90% CL)
  - Extrapolate to limits on full ULIRG source population

Results	
n_s	0
γ	—
p-value	1.0

flux of all ULIRGs up to $z = z_{\max}$

flux of all ULIRGs up to $z = 0.13$

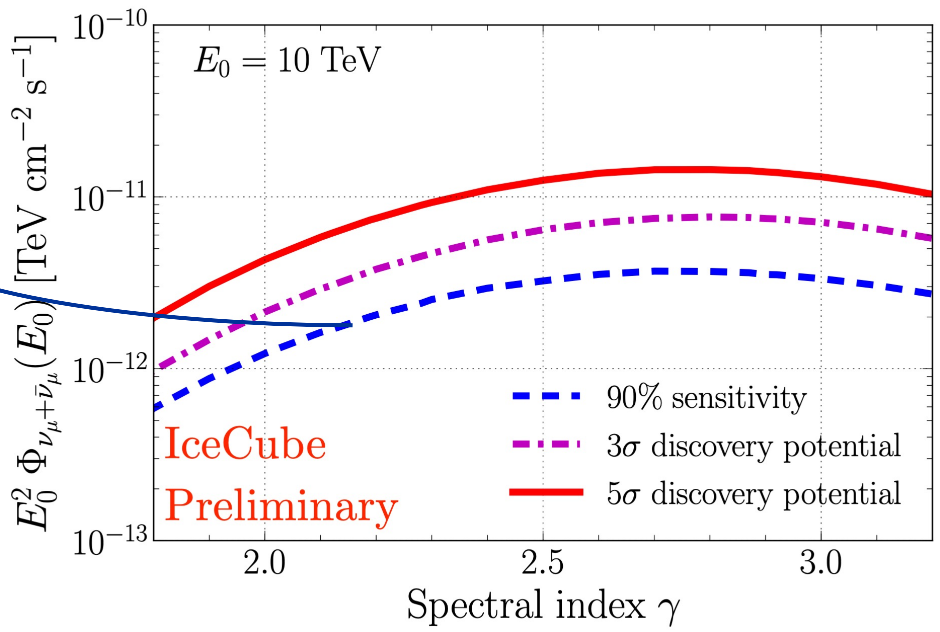
$$\Phi^{z \leq z_{\max}}_{\nu_\mu + \bar{\nu}_\mu} = \frac{\xi_{z=z_{\max}}}{\xi_{z=0.13}} \Phi^{z \leq 0.13}_{\nu_\mu + \bar{\nu}_\mu}$$

integrate over redshift

$$\mathcal{H}(z) = \begin{cases} (1+z)^4 & z \leq 1 \\ \text{flat} & z > 1 \end{cases}$$

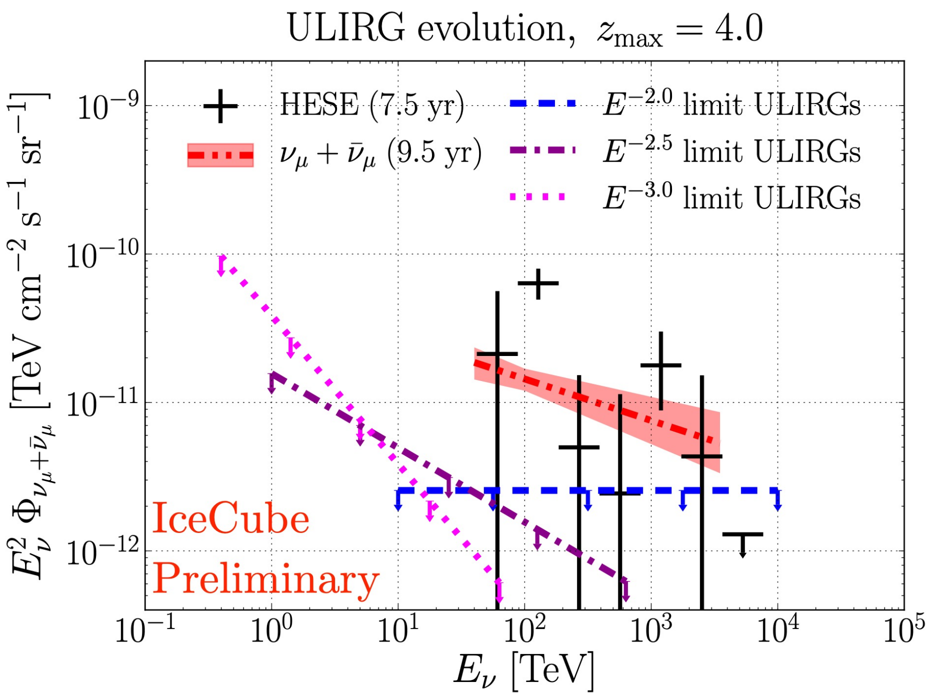
ULIRG redshift evolution

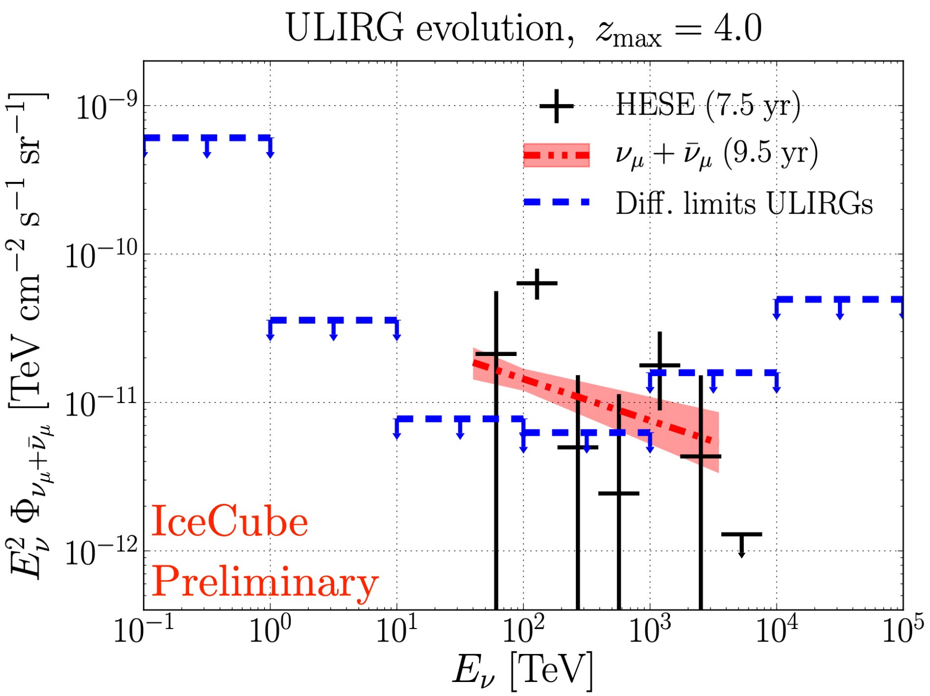
[Vereecken+ (2020) arXiv:2004.03435]



Limits on ULIRG Population

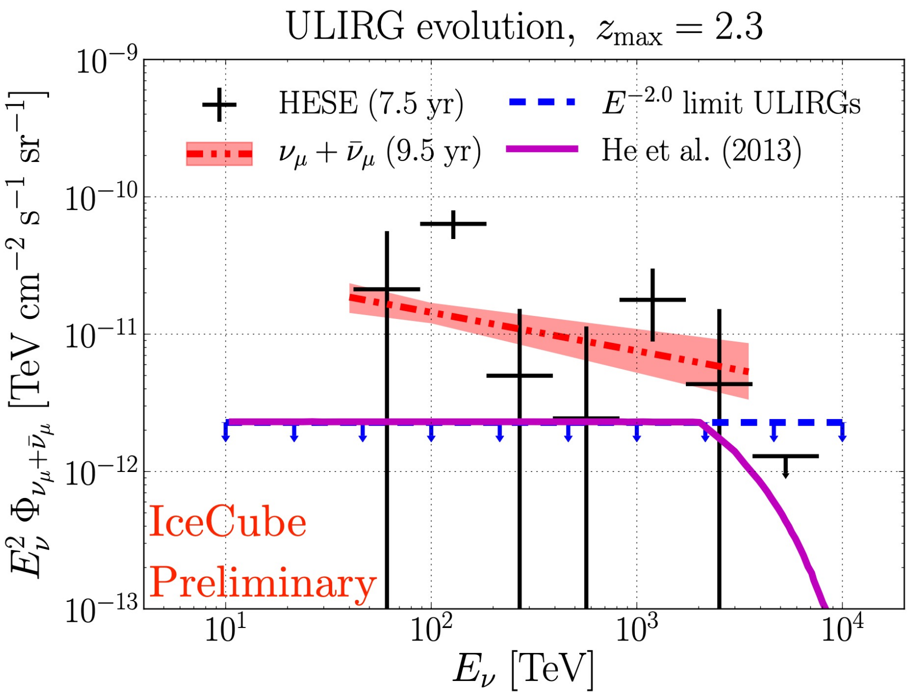
- Integral limits
  - 90% central energy range
  - Contribution to diffuse observations constrained for $E^{-2.0}$ and $E^{-2.5}$ spectra
- Quasi-differential limits
  - $E^{-2.0}$ limit in each energy decade
  - Contribution to diffuse observations constrained for 10– 100 TeV and 100– 1000 TeV

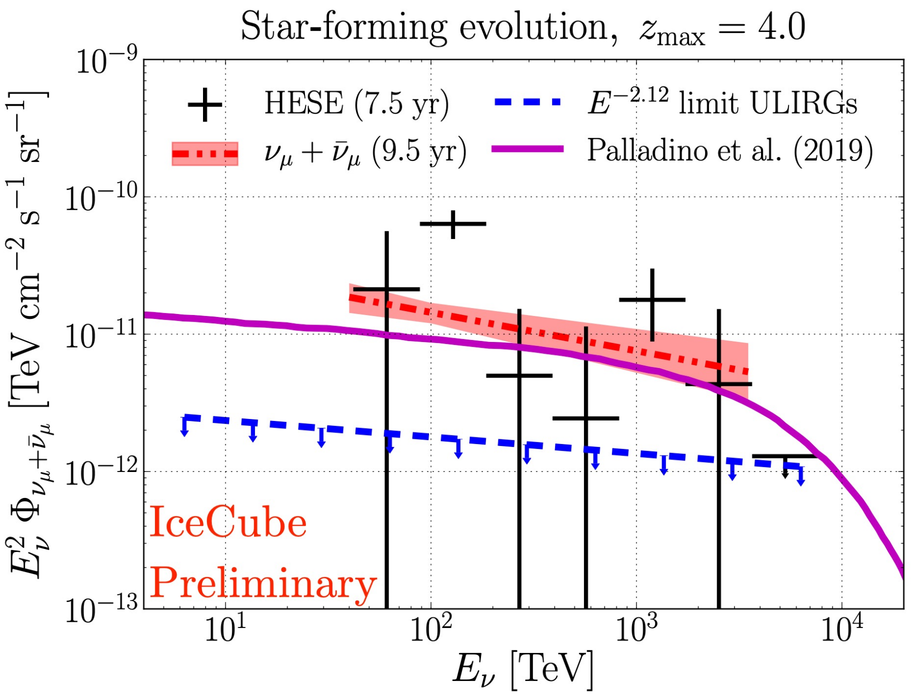




Comparison with Reservoir Models

- He+ (2013) PRD 87 063011
  - Neutrino flux powered by hypernovae
  - At level of our upper limit
  - More data needed to exclude/validate
- Palladino+ (2019) JCAP 09 004
  - Generic model of hadronically powered gamma-ray galaxies (HAGS)
  - ULIRGs excluded as sole HAGS responsible for diffuse observations





Comparison with Beam-Dump Model

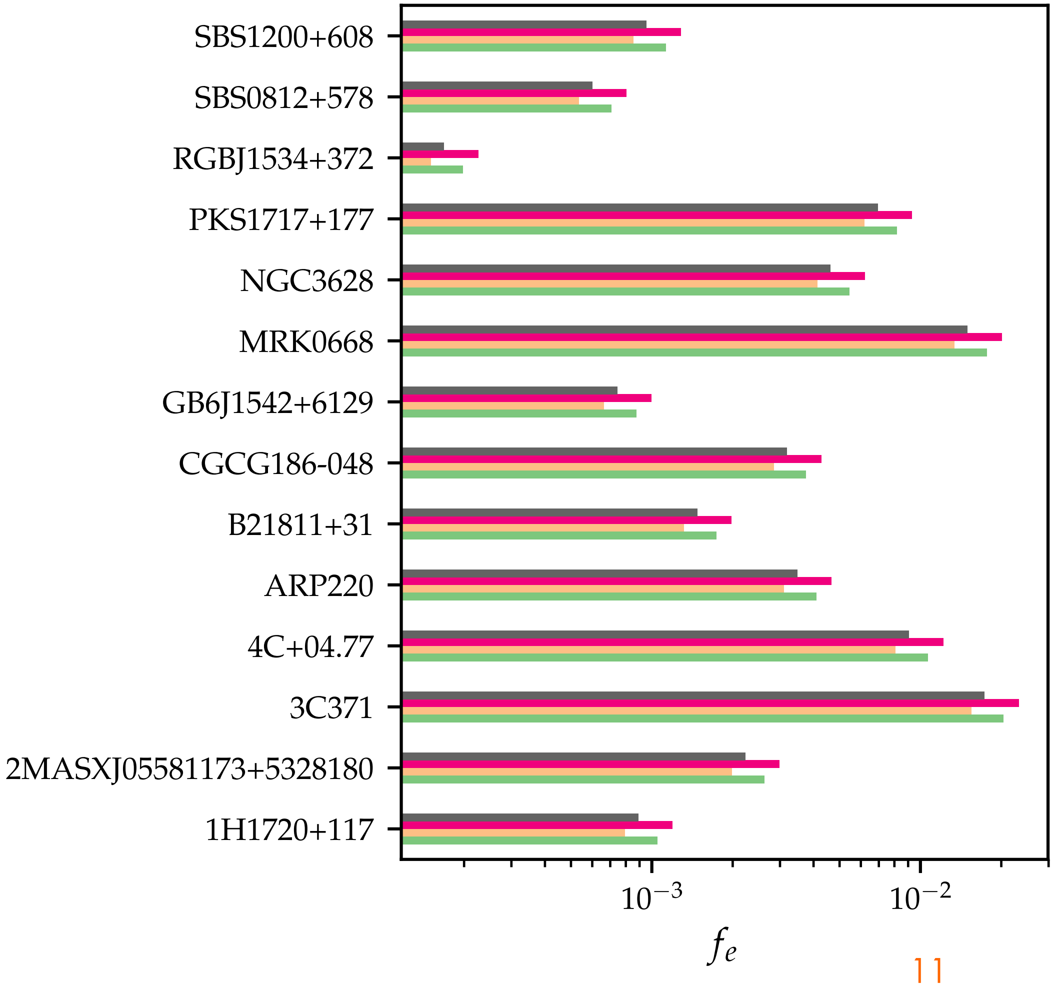
- Vereecken+ (2020) arXiv:2004.03435
  - Compton-thick AGN beam dump
- Set lower limit on parameter $f_e = L_e/L_p$
  - Fit model to our $E^{-2.0}$ ULIRG limit
  - Order of magnitude estimation
  - Consistent with previous limits on obscured AGN

[PoS ICRC2017 1000]

$$f_e \gtrsim 10^{-3}$$

Limit from our ULIRG analysis

Obscured-AGN limits



Conclusions & Outlook

Summary

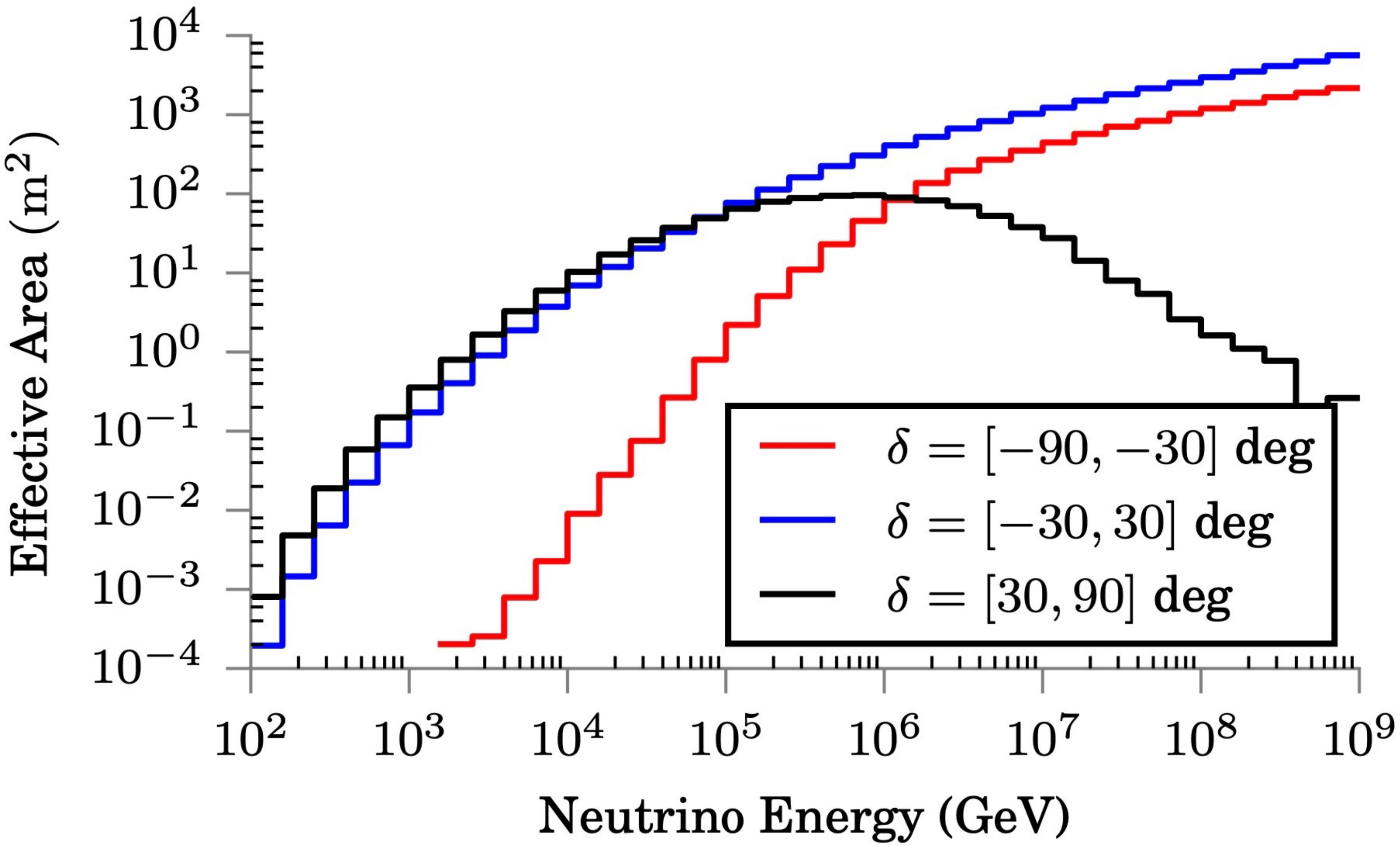
- Performed IceCube stacking search for neutrinos from ULIRGs
- No astrophysical signal identified
- Set upper limits on ULIRG source population
- Constrained model predictions
- Submit paper very soon!

Outlook

- Consider LIRGs as candidate neutrino sources
  - Less luminous: $L_{IR} \geq 10^{11} L_{\odot}$
  - More numerous: 10–50 higher IR lum. density
- Consider Compton-thick AGN as candidate neutrino sources
  - Possible gamma-ray dim neutrino sources
  - See e.g. the hard X-ray AGN analysis by Sreetama Goswami (PoS ID 1142)

BACKUP

GFU Effective Area



[IC (2017) Astropart. Phys. 92 30]

Maximum-Likelihood Method

- Construct likelihood
  - Fit for
    - Number of signal events n_s (get best fit $\hat{n}_s$)
    - Power-law spectral index γ (get best fit $\hat{\gamma}$)

$$\mathcal{L}(n_s, \gamma) = \prod_i^N \left[\frac{n_s}{N} \sum_k^M w_k S_i^k(\gamma) + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \right]$$

Stacking term

$w_k \propto t_k r_k$

t_k: Total IR flux

r_k: Detector response

Sum over each source k

Signal PDF

Simulation

Space: 2D Gaussian

Energy: $E^{-\gamma}$ spectrum

Evaluate for each event i

Background PDF

Scrambled data

Space: Uniform in RA

Energy: $E^{-3.7}$ spectrum

Evaluate for each event i

- Determine test statistic
  - Perform hypothesis test
  - Background-only TS PDF from data scrambles
  - Use to determine p-value

Alternative hypothesis

Data is compatible with background + ULIRG signal

$$\mathrm{TS} = 2 \log \left(\frac{\mathcal{L}(n_s = \hat{n}_s, \gamma = \hat{\gamma})}{\mathcal{L}(n_s = 0)} \right)$$

Null hypothesis

Data is compatible with atmospheric background

Redshift-Evolution Parameter

$$\mathcal{H}(z) = \begin{cases} (1+z)^4 & z \leq 1 \\ \text{flat} & z > 1 \end{cases}$$

$$\mathcal{H}(z) = \begin{cases} (1+z)^{3.4} & z \leq 1 \\ (1+z)^{-0.3} & z > 1 \end{cases}$$

$$\mathcal{H}(z) = 1$$

Evolution	Spectral index γ	$\xi_{z=0.13}$	$\xi_{z=2.3}$	$\xi_{z=4.0}$
ULIRG	2.0	0.14	3.0	3.4
	2.5	0.14	2.2	2.5
	3.0	0.13	1.7	1.8
Star-formation rate	2.0	0.14	2.2	2.4
	2.5	0.13	1.6	1.7
	3.0	0.13	1.2	1.3
Flat	2.0	0.11	0.49	0.53
	2.5	0.11	0.41	0.43
	3.0	0.11	0.35	0.36

$$\xi_z(\gamma) = \int_0^z \frac{\mathcal{H}(z')(1+z')^{-\gamma}}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} \, \mathrm{d}z'$$

[Vereecken+ (2020) arXiv:2004.03435]