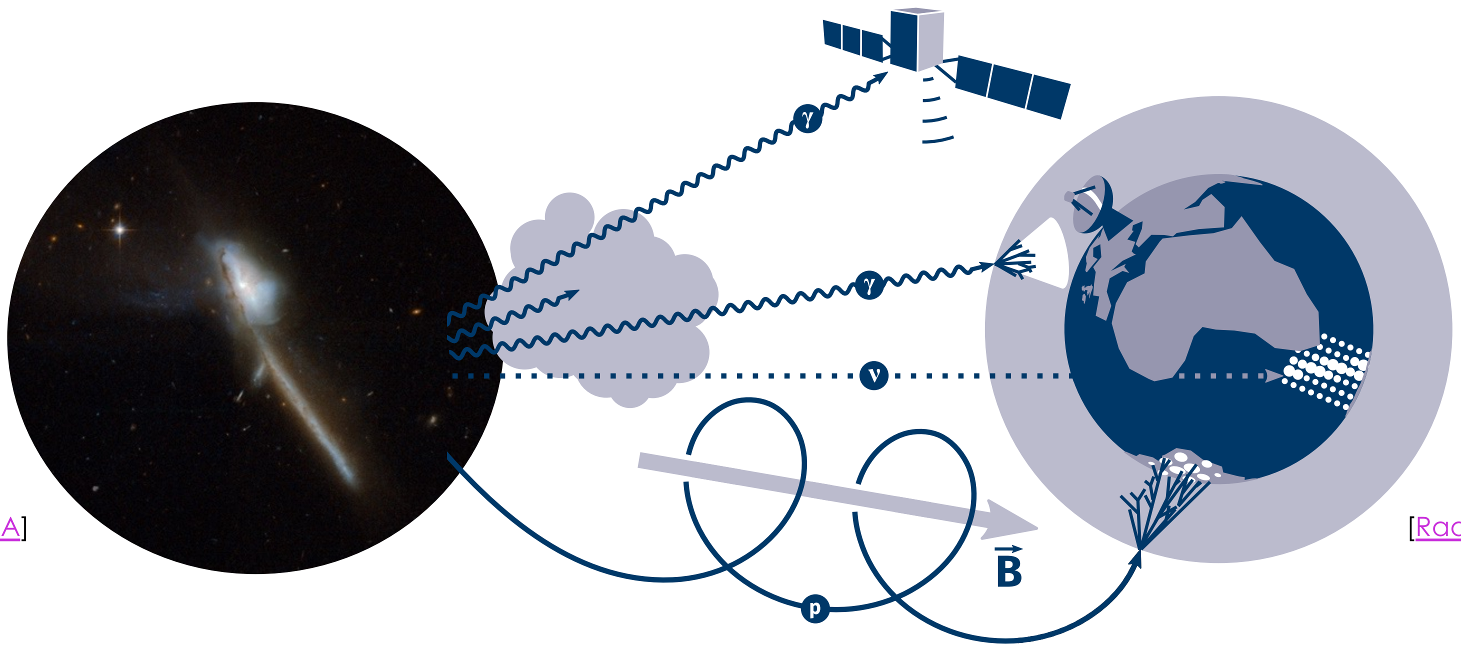


[NASA/ESA] [Raab (2021) PhD thesis]

Hunting the Sources of Cosmic Neutrinos with IceCube

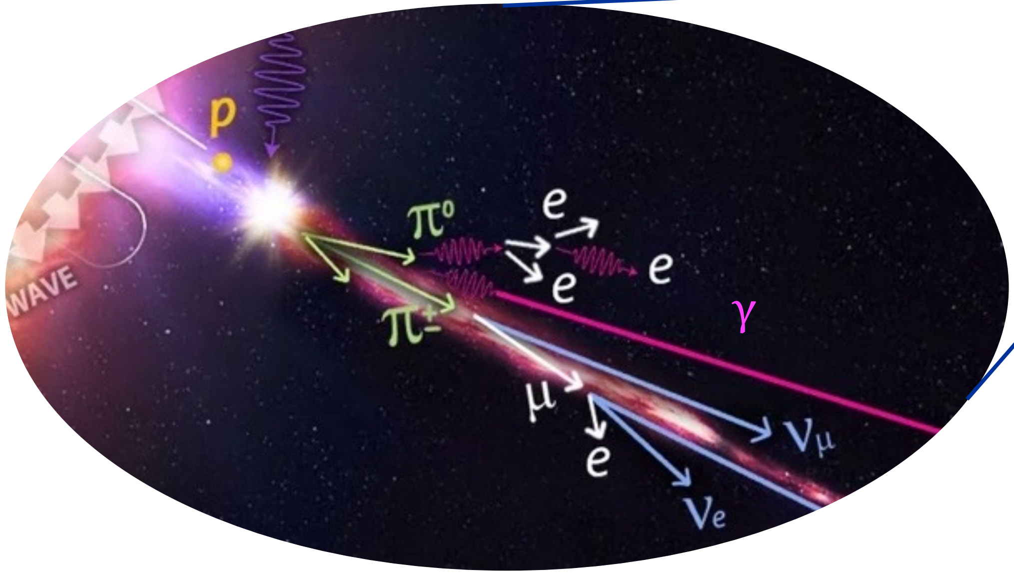
Pablo Correa

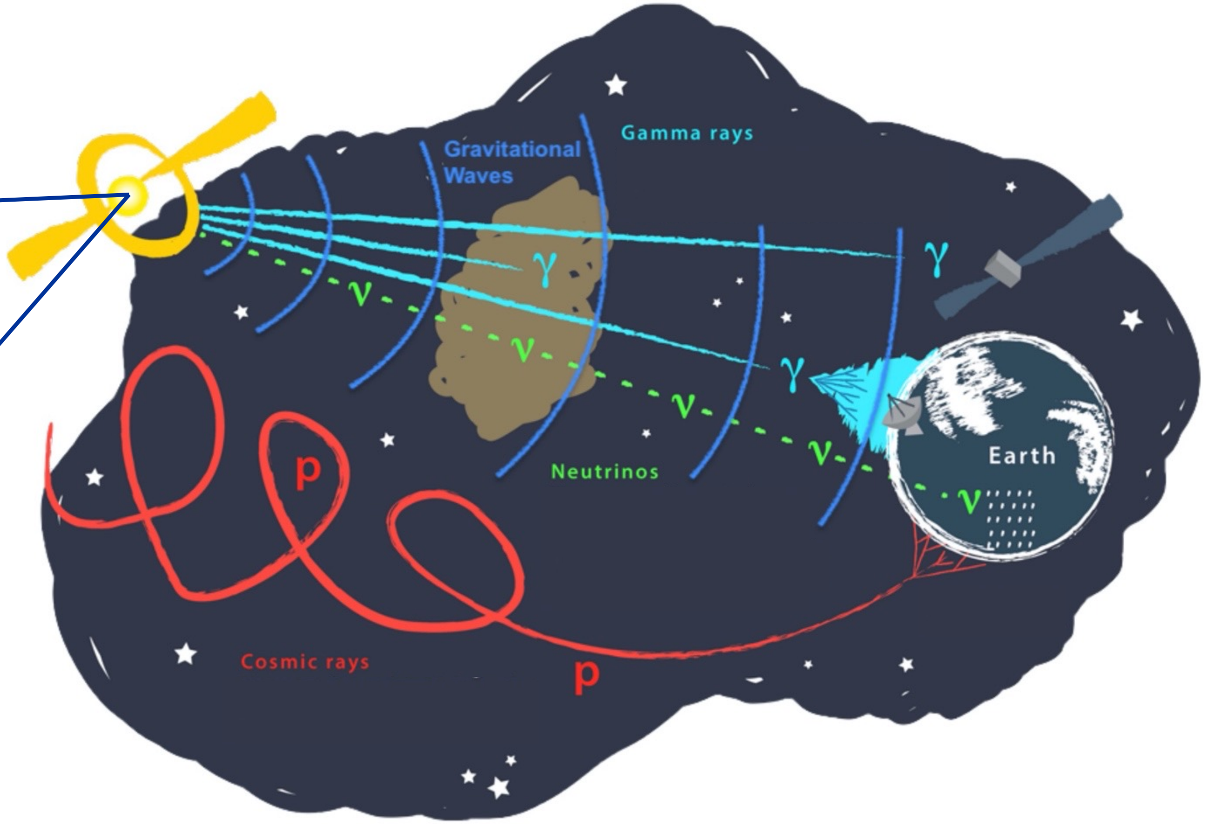
LPNHE Seminar | 13 February 2023

IceCube Neutrino Observatory · iihe Bruxelles Brussel · VUB Vrije Universiteit Brussel · fwo · LPNHE Paris

The Multimessenger Connection

- Cosmic rays (p)
  - Energies up to 10^{20} eV ≈ 16 J
  - Deflected by $\vec{B} \longrightarrow$ origin unknown!
- Gamma rays (γ)
  - Attenuated by matter & radiation
  - Also produced in leptonic processes
- Neutrinos (ν)
  - Not deflected or attenuated
  - Smoking gun of hadronic interactions



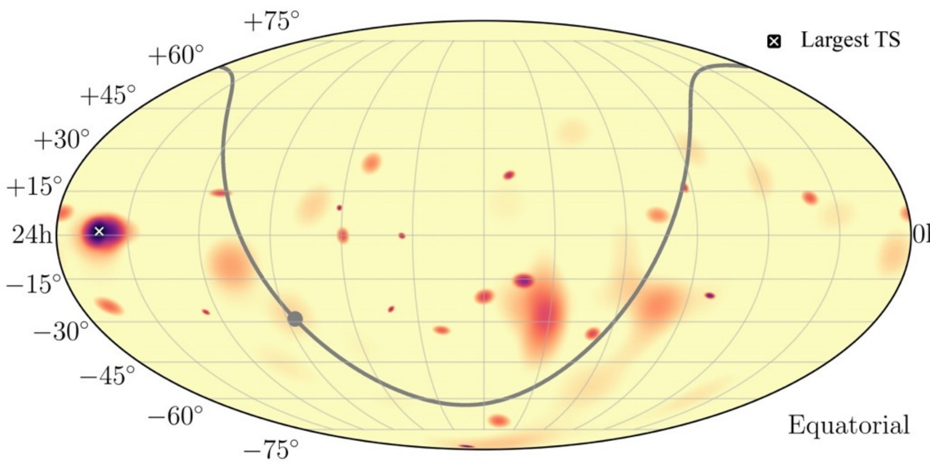


[IceCube/NSF]

The Diffuse High-Energy Neutrino Sky

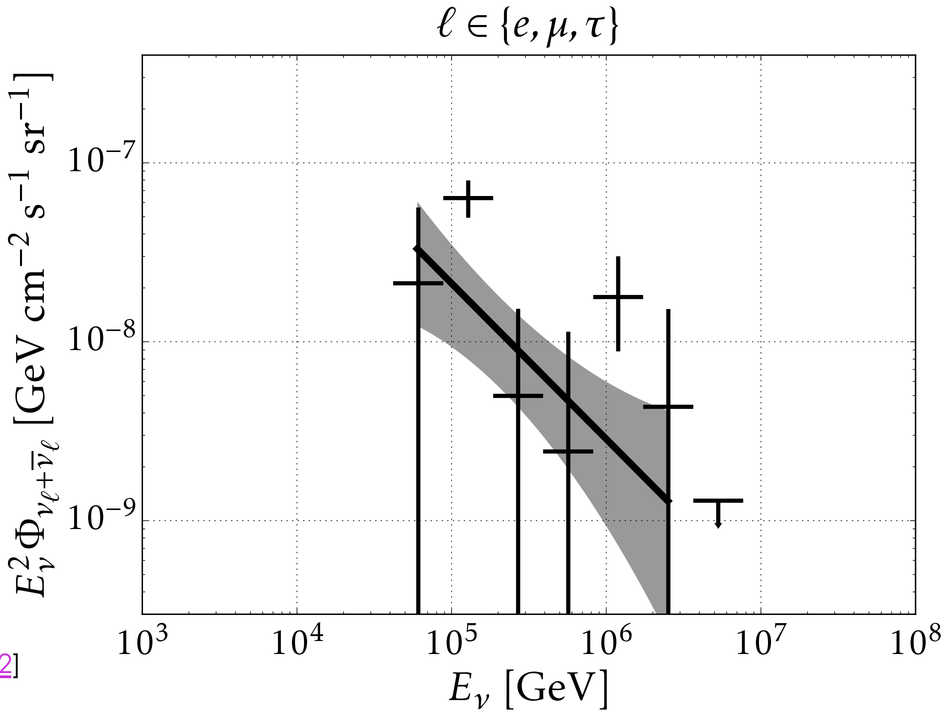
- Diffuse flux discovered by **IceCube** in 2013
- Spectrum described by single power law ($\gamma \sim 2.5$)
- Consistent with isotropic observations

What is the origin of high-energy neutrinos?



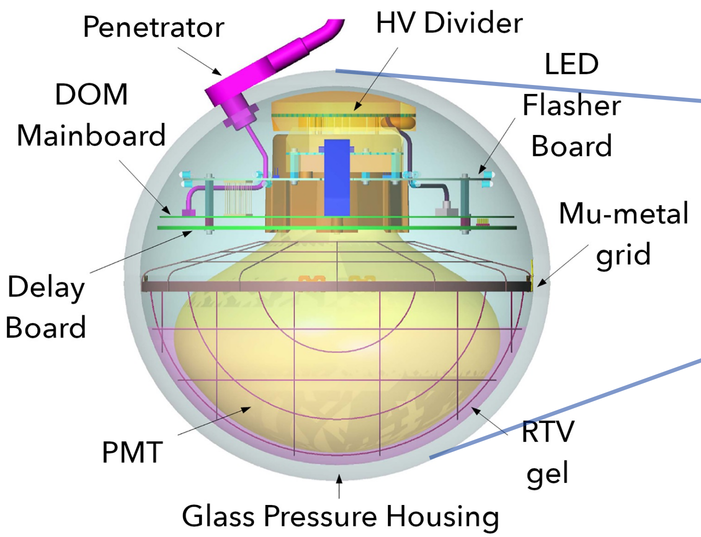
$$\Phi_{\nu+\bar{\nu}}(E_\nu) = \Phi_0 \left(\frac{E_\nu}{E_0}\right)^{-\gamma}$$

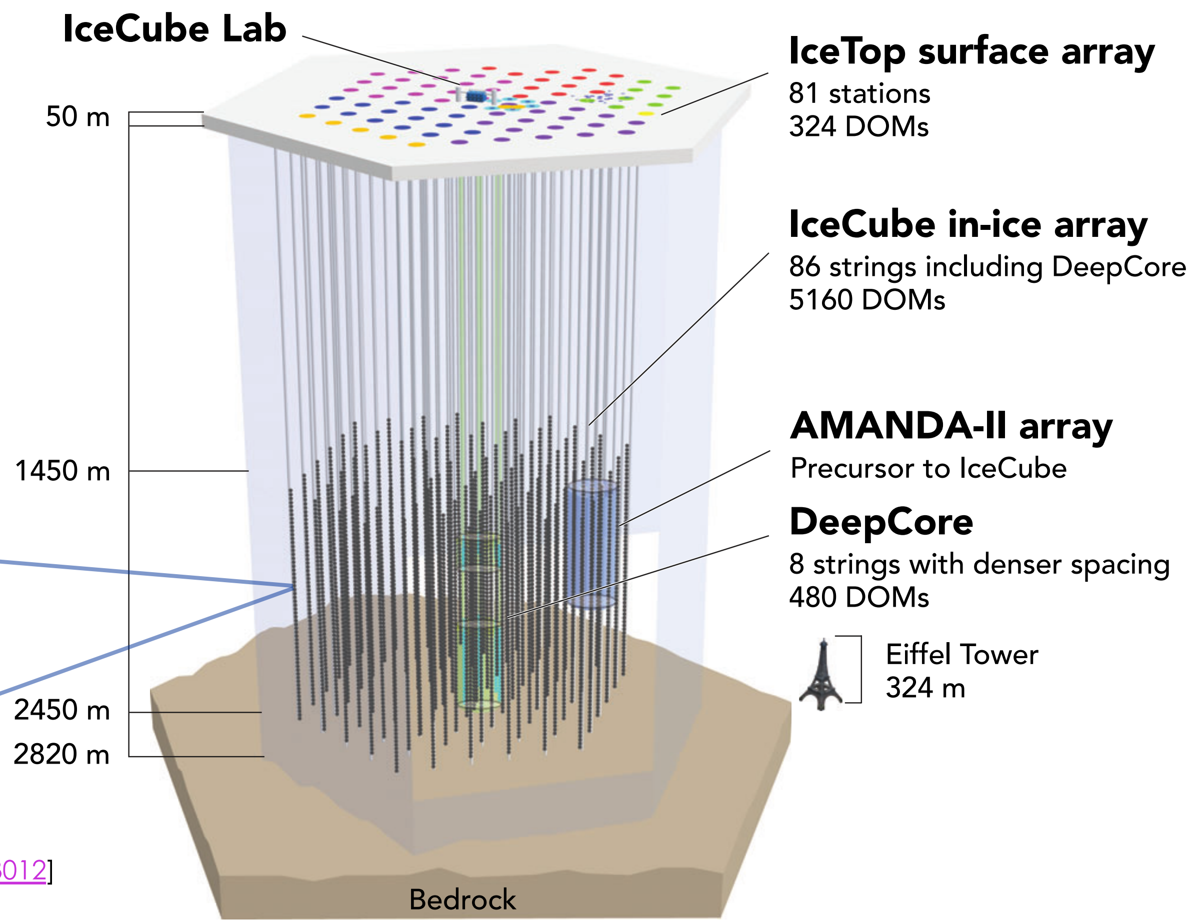
[IC (2021) PRD 104 022002]



The IceCube Neutrino Observatory

- 1 km^3 detector at the South Pole
- 5160 digital optical modules (DOMs)
- 86 strings down to 2.45 km depth

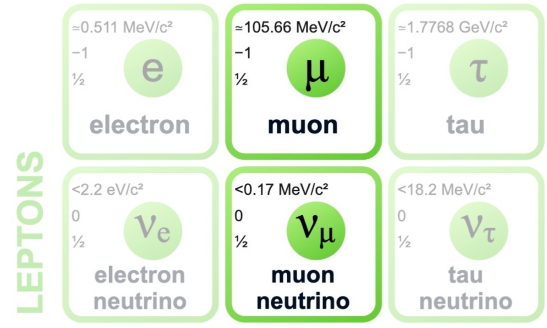


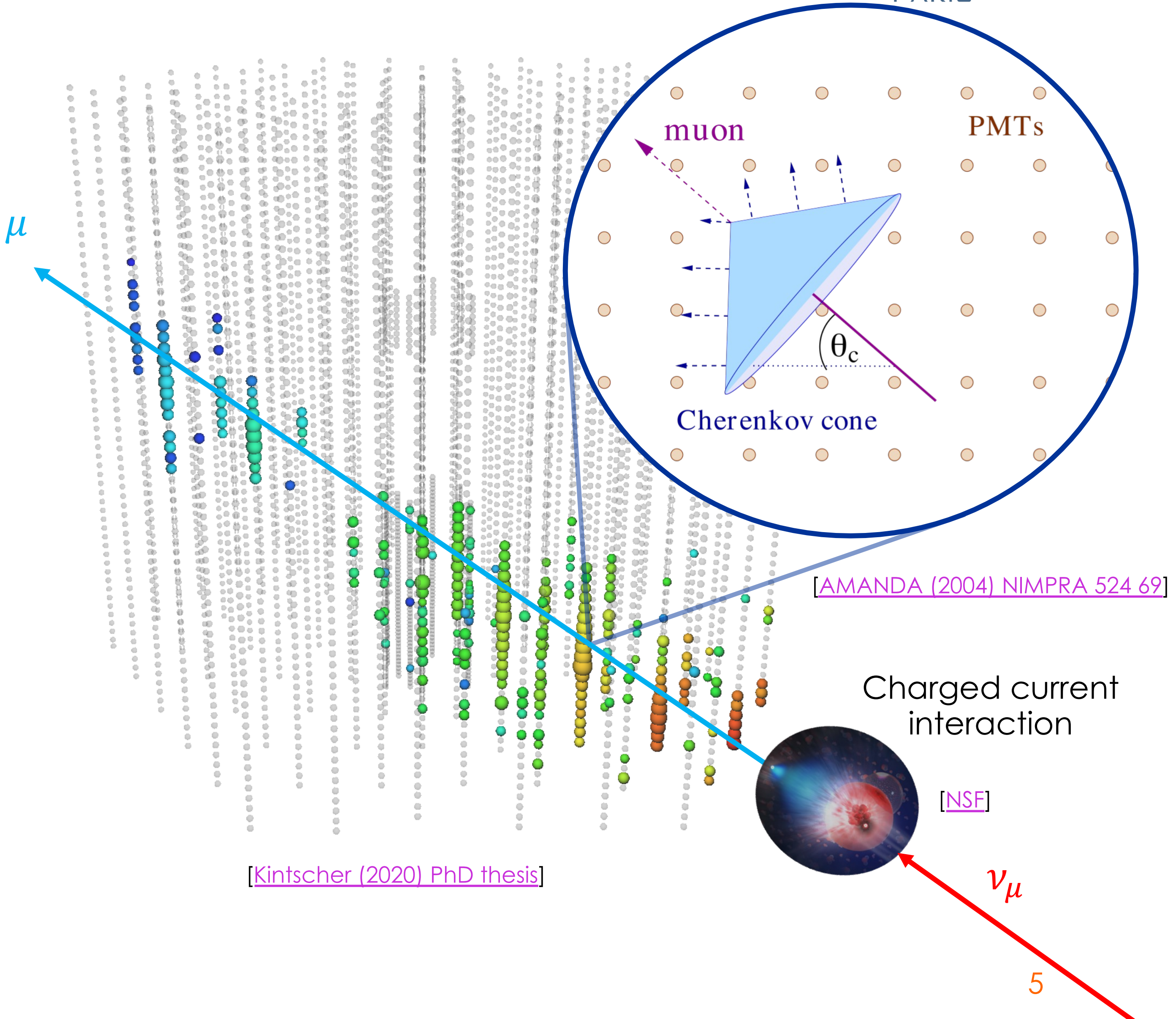


[IC (2017) JINST 12 P03012]

Detecting Neutrinos with IceCube

- Neutrinos can interact with ice
  - Produce secondary charged particles
  - These emit Cherenkov radiation
- Mostly focus on muon (μ) tracks
  - Signatures of ν_μ and $\bar{\nu}_\mu$
  - Typical angular resolution <1°





[AMANDA (2004) NIMPRA 524 69]

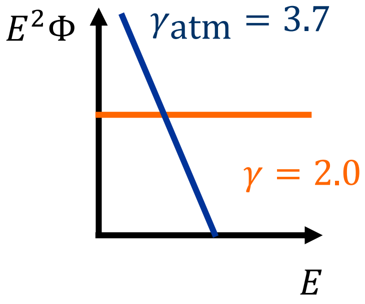
[NSF]

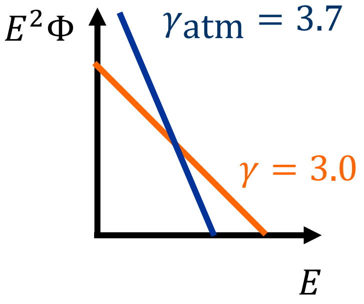
[Kintscher (2020) PhD thesis]

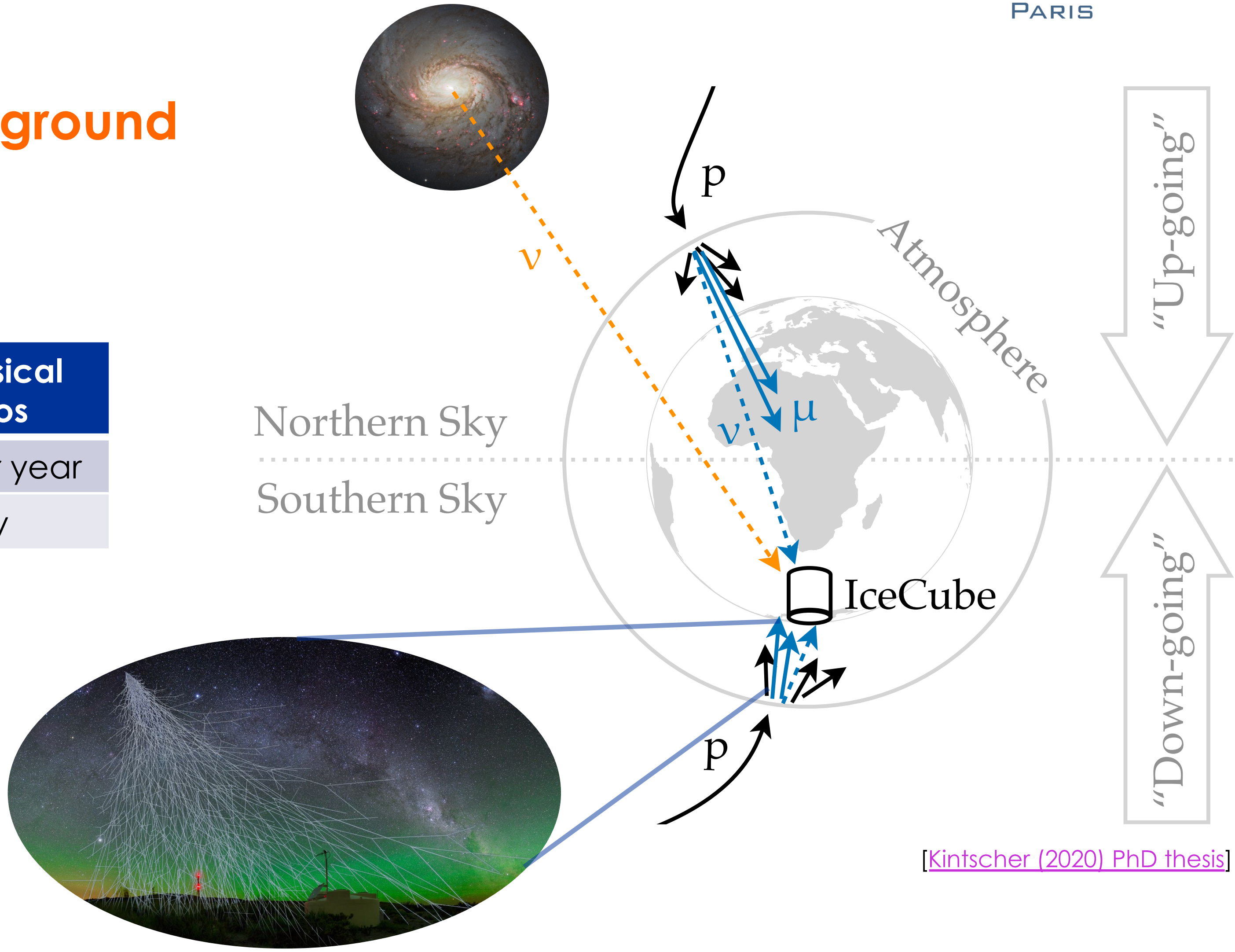
Background vs Signal

- Data mostly **atmospheric background**
  - Induced by cosmic-ray air showers
  - Relatively soft spectrum $\sim E^{-3.7}$

Atmospheric muons	Atmospheric neutrinos	Astrophysical neutrinos
2,700 per second	600 per hour	10–100 per year
South only	Full sky	Full sky



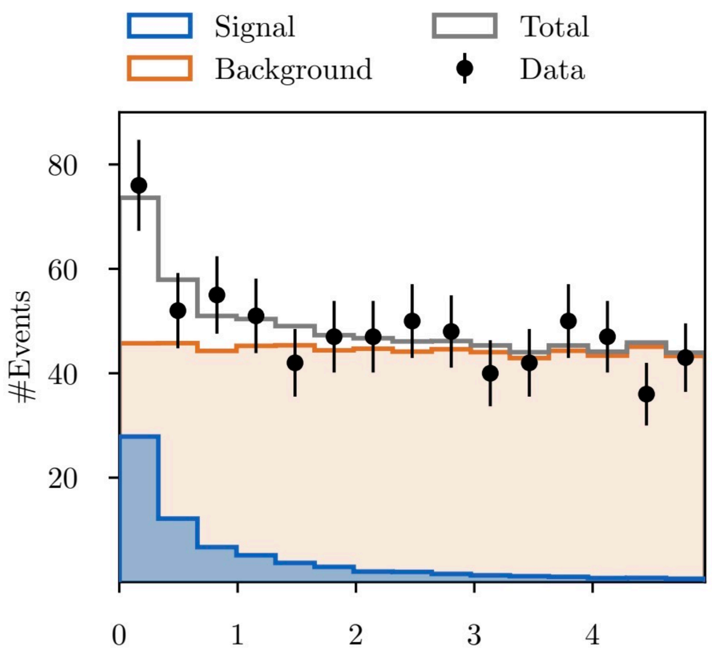




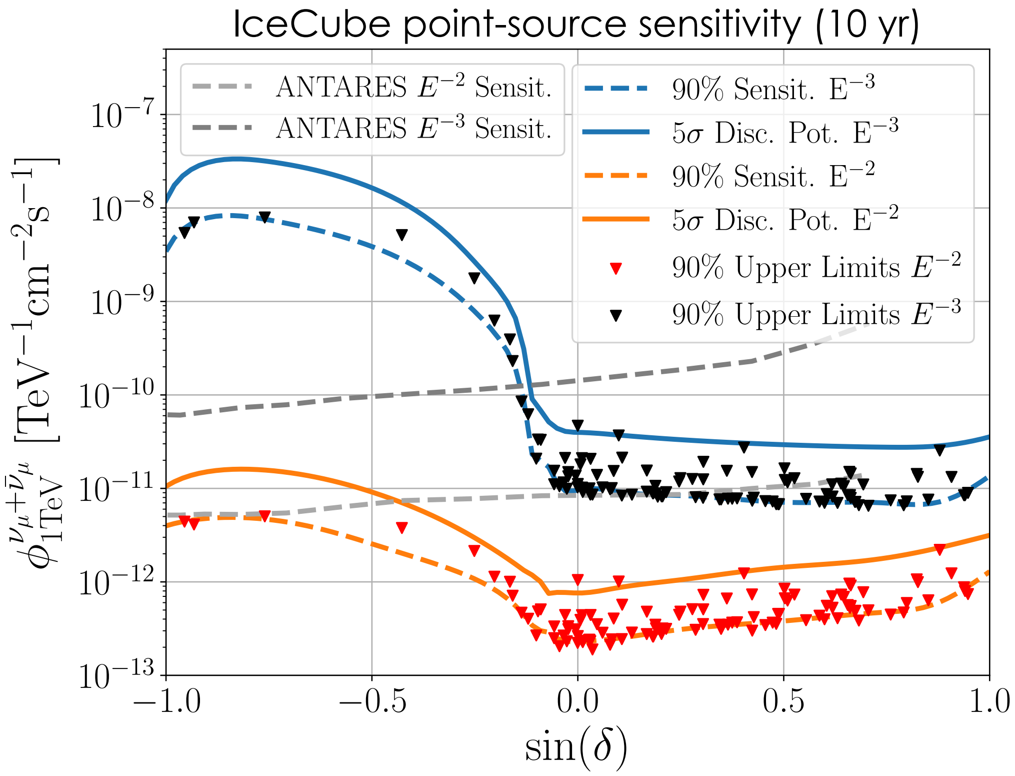
[Kintscher (2020) PhD thesis]

Searches for Neutrino Point Sources

- Look for **spatial clustering** of tracks
- Steady sources: integrate over total livetime
- Transients: look for clustering in time window



[IC (2022) Science 378 6619 538]



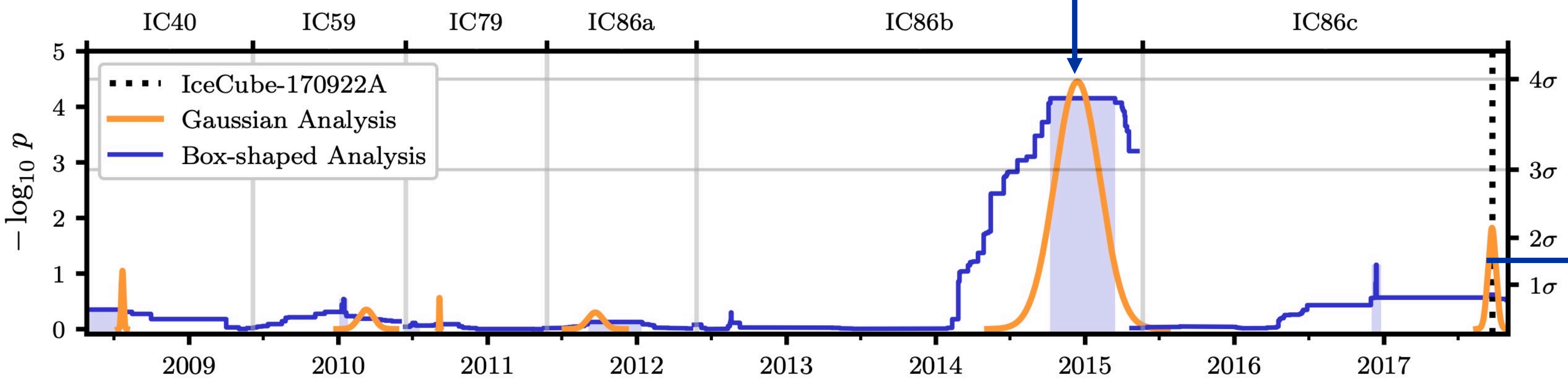
[IC (2020) PRL 124 051103]

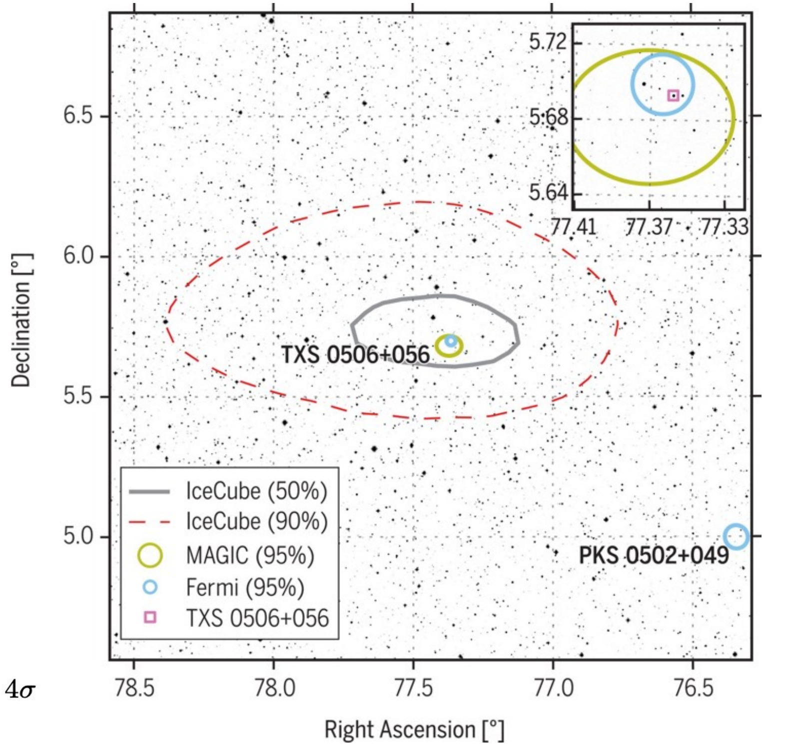
TXS 0506+056: First Transient Source (1/2)

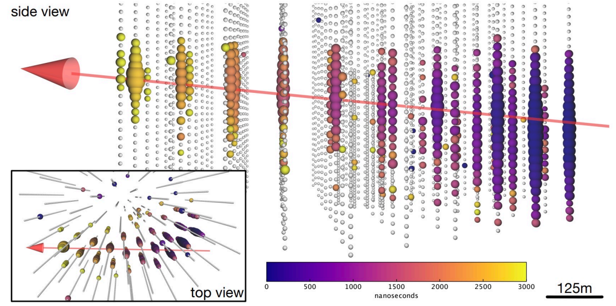
LPNHE PARIS

- Neutrino alert ($E_\nu \sim 200$ TeV) on 22 September 2017
  - 3σ coincidence with gamma-ray flaring blazar
- Archival analysis revealed neutrino flare at 3.5σ
  - But no coincident gamma-ray flare!
  - Other production mechanism?

13 ± 5 neutrinos
Spectral index: $\gamma = 2.1 \pm 0.2$





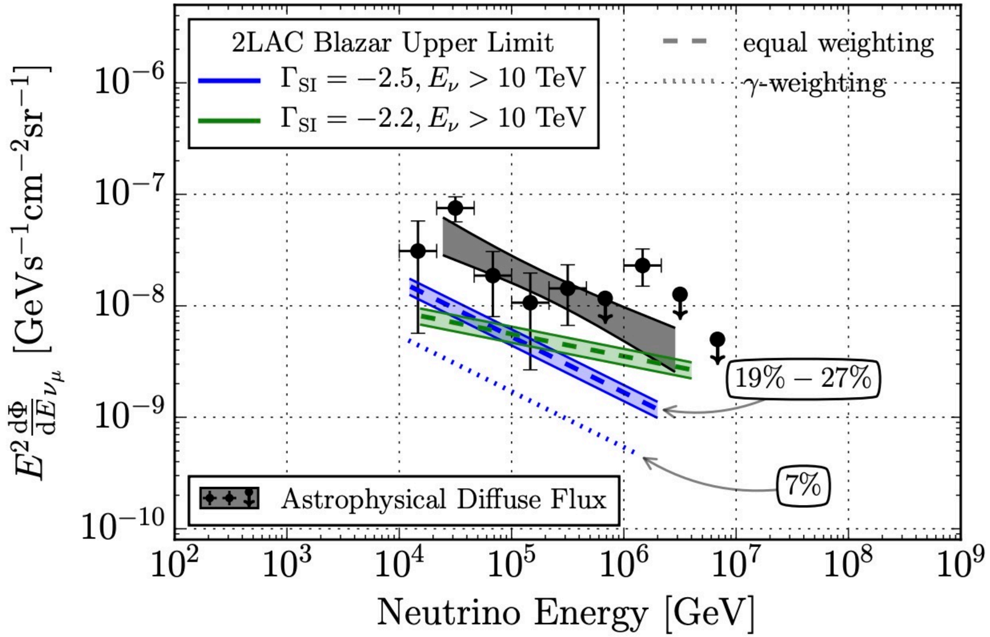


IC20170922A

[IC (2018) Science 361 147; IC+ (2018) Science 361 eaat1378]

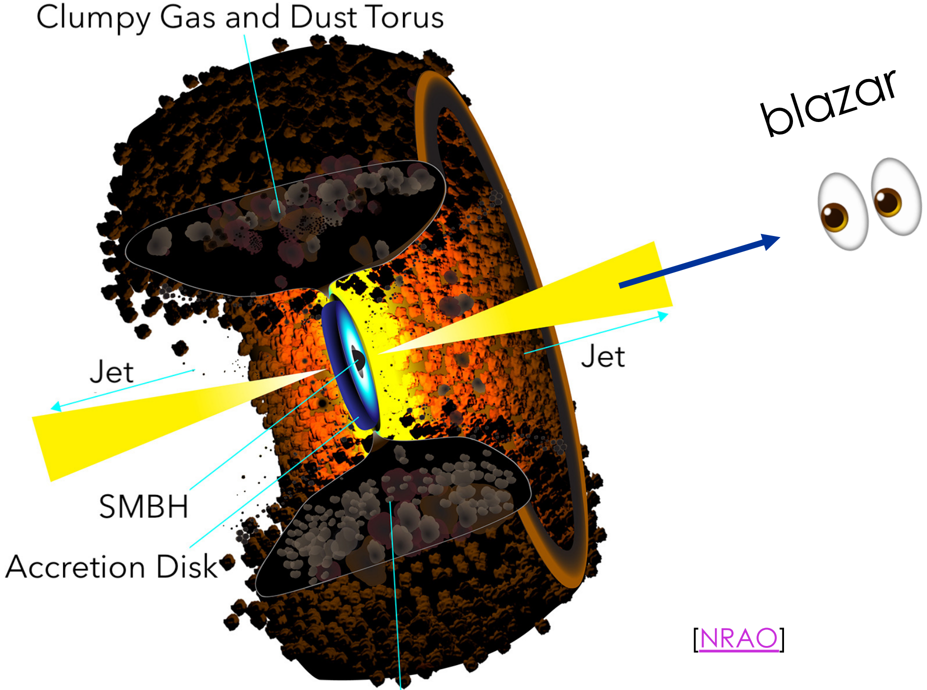
TXS 0506+056: First Transient Source (2/2)

- Blazar at redshift $z = 0.334$ (1.75 Gpc)
- TXS 0506+056 must be a "special" blazar
  - Contribution of *Fermi* 2LAC blazars constrained



[IC (2017) ApJ 835 45]

Active galactic nucleus (AGN)

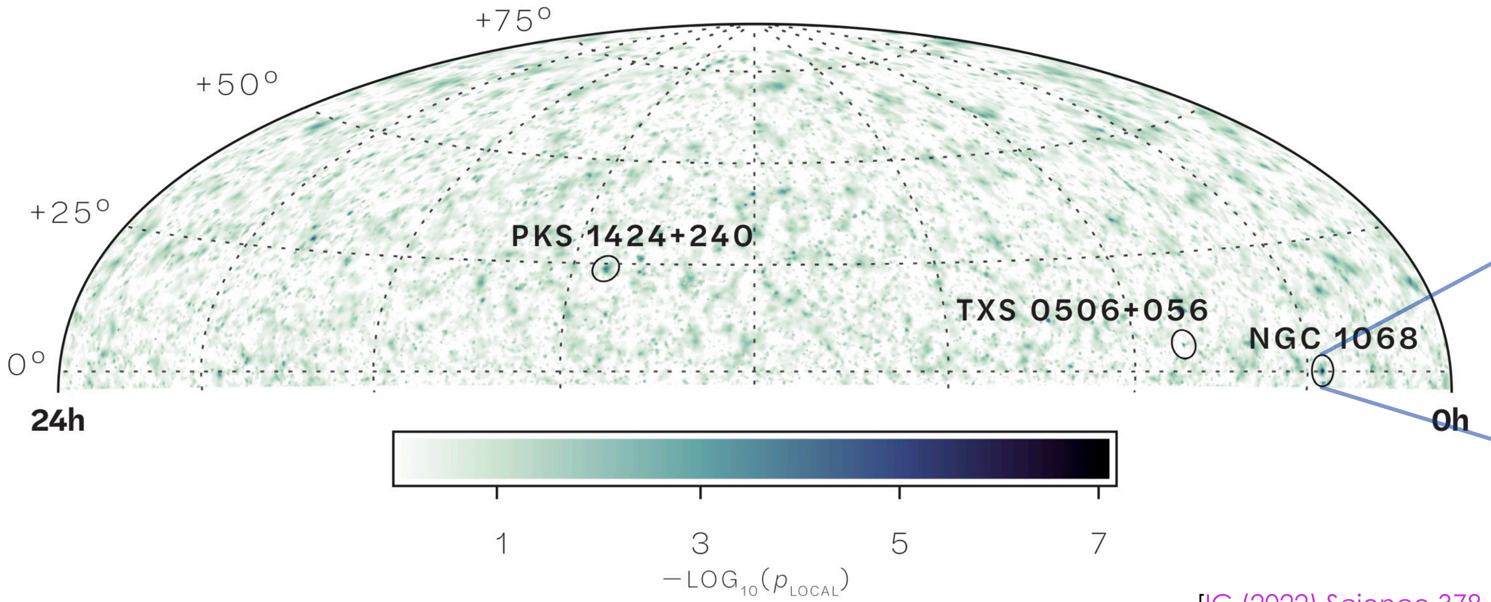


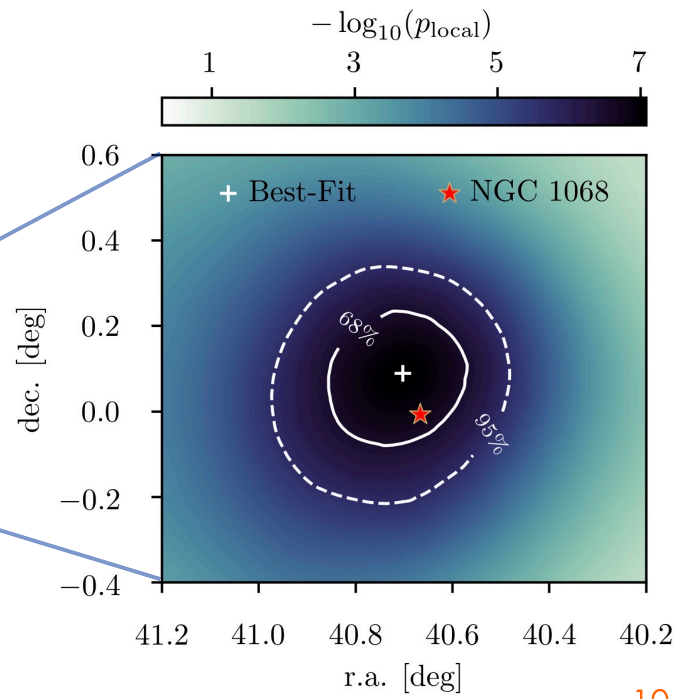
[NRAO]

NGC 1068: First Steady Source (1/2)

- Northern Sky scan with 10 years of data
  - Hotspot at location of NGC 1068: 2.0σ post-trial
- Parallel catalog search of 110 pre-selected sources
  - **Evidence** for 79^{+22}_{-20} neutrinos coming from NGC 1068: 4.2σ post-trial
  - Power-law spectral fit: $\gamma = 3.2 \pm 0.2$

[NASA/ESA]

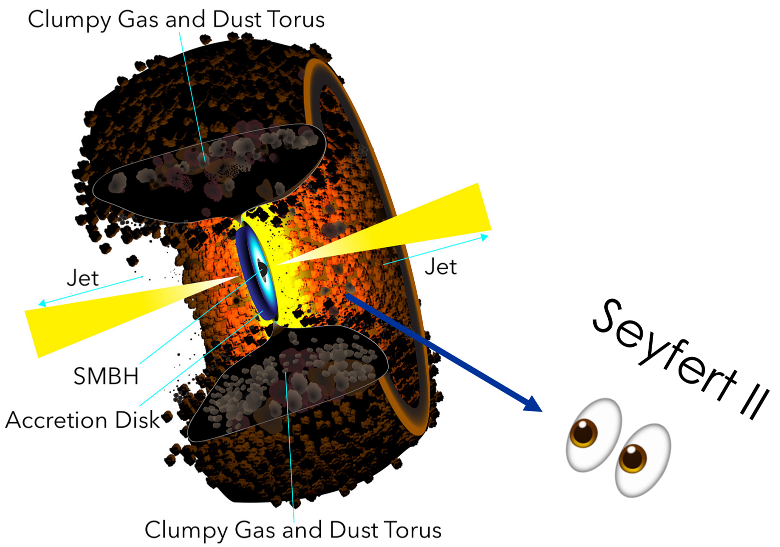


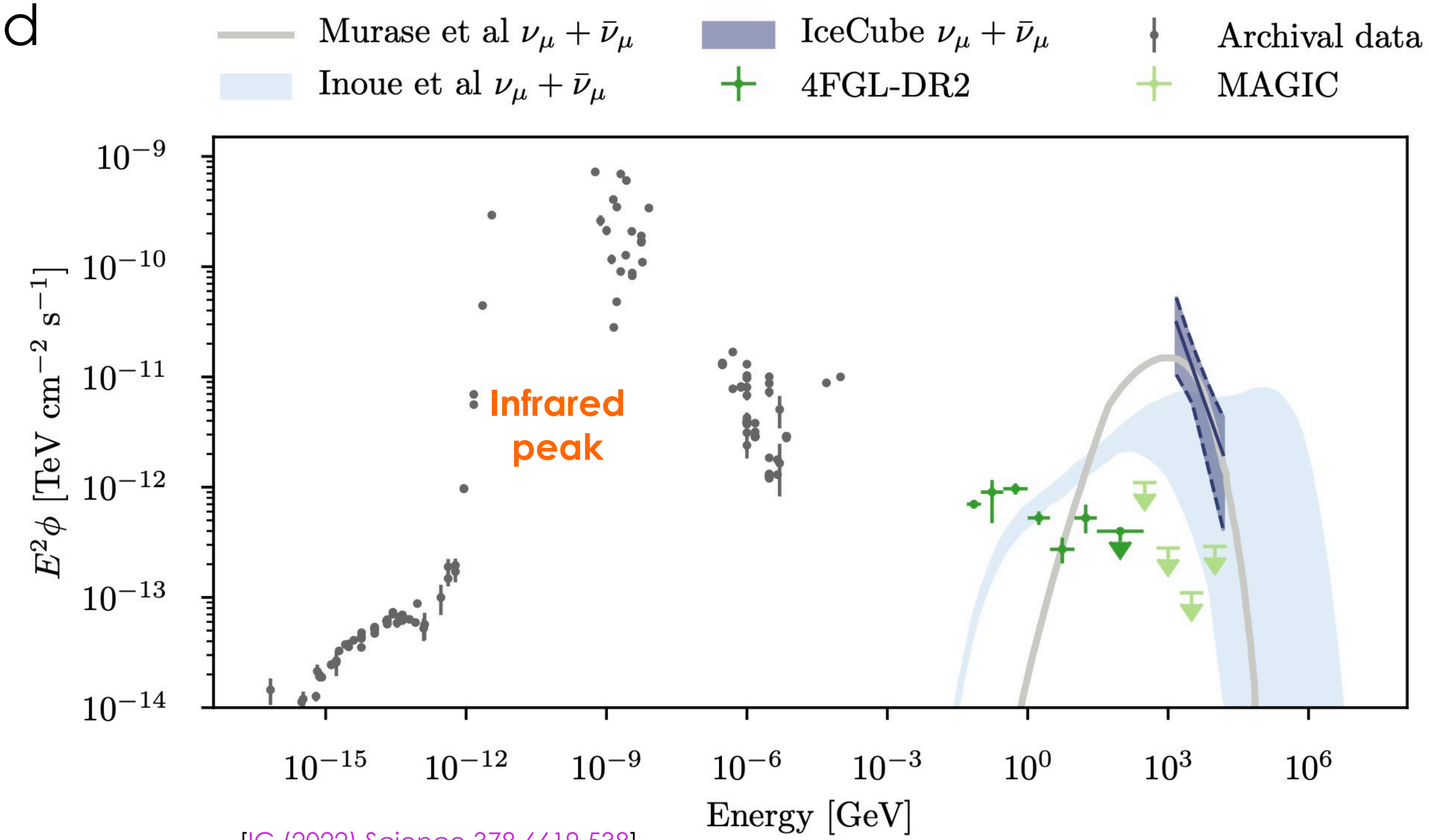


[IC (2022) Science 378 6619 538]

NGC 1068: First Steady Source (2/2)

- Well-known nearby Seyfert II galaxy (14.4 Mpc)
  - Coupled with strong starburst activity
- Obscured AGN models favored
  - Starburst reservoirs less favored

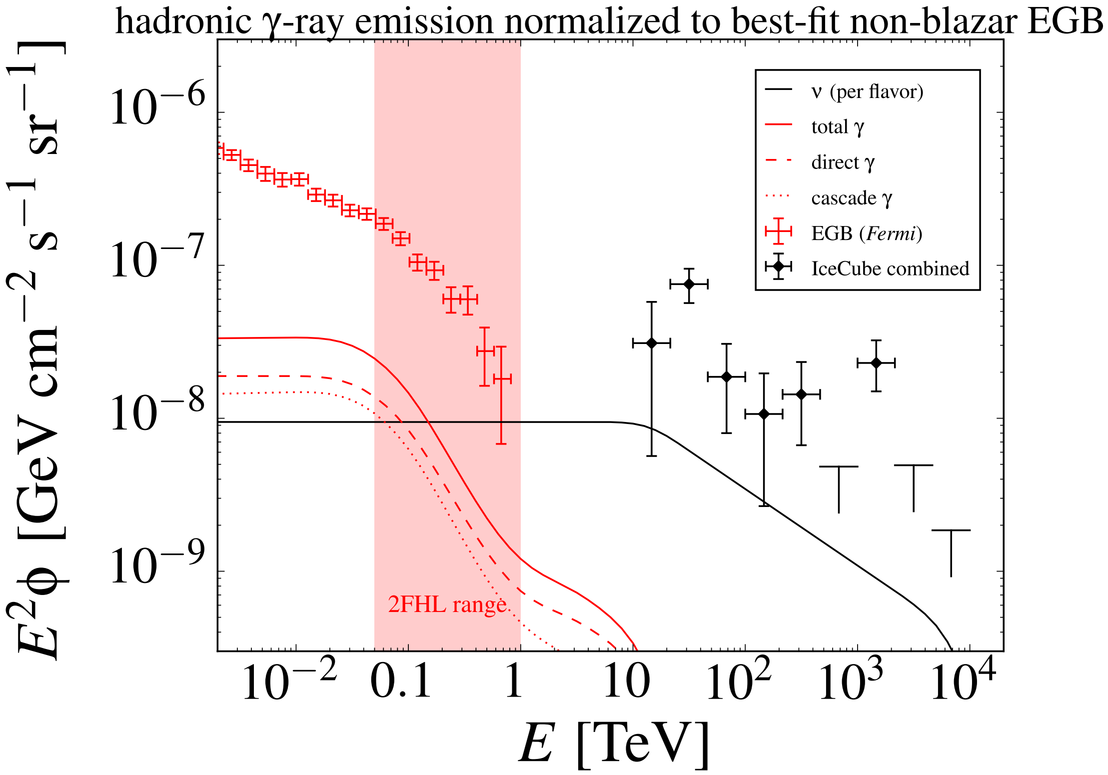




[IC (2022) Science 378 6619 538]

Status of Neutrino Astronomy (1/2)

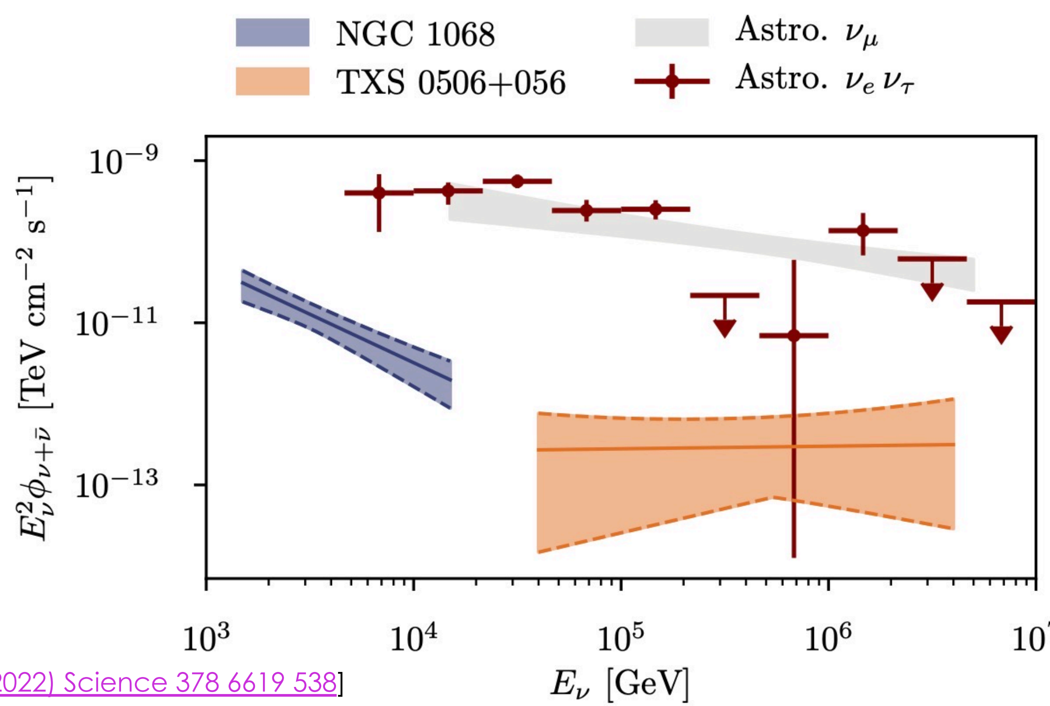
- ***Fermi*-LAT**: 86% of EGB from blazars
- **IceCube**: blazar contribution constrained
- Neutrino sources cannot exceed non-blazar EGB
- Points towards **gamma-ray opaque** neutrino sources [Murase+ (2016) PRL 116 071101]



[Bechtol+ (2017) ApJ 836 47]

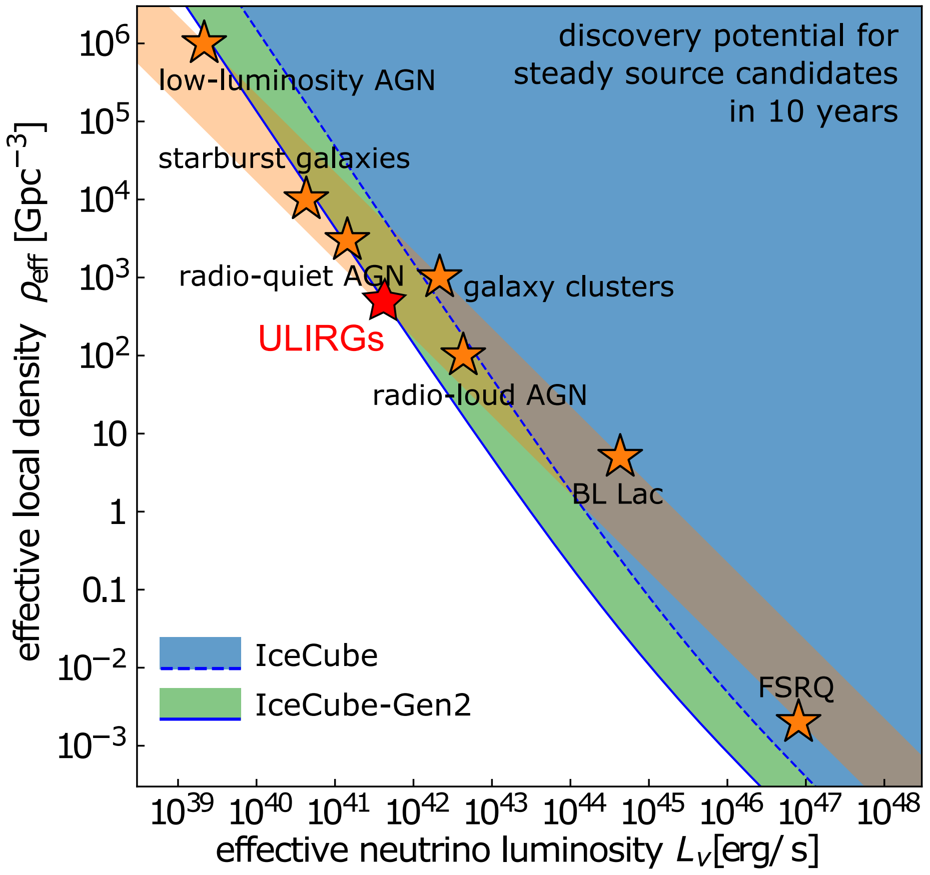
Status of Neutrino Astronomy (2/2)

- Sources of diffuse flux largely unidentified
  - At least two source types!
- Constraints after 10 years of IceCube data
  - Favor **numerous** populations of **dim** sources



[IC (2022) Science 378 6619 538]

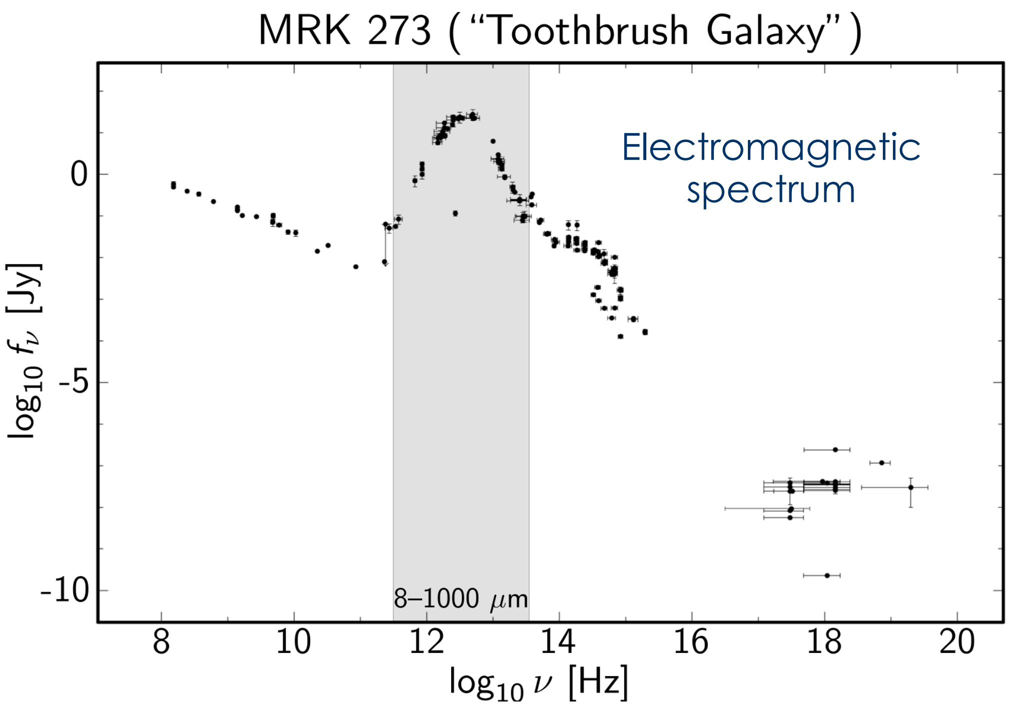
Orange band: required to supply diffuse flux
Blue region: excluded source populations



[IC-Gen2 (2021) JPG 6 060501]

Ultra-Luminous Infrared Galaxies

- The **most luminous** objects in the IR sky
  - Even more than NGC 1068!
  - $L_{IR} \geq 10^{12}\ L_{\odot}$ between 8–1000 micron
- Rich in obscuring gas and dust
- Mergers of spiral galaxies



[NASA/IPAC Extragalactic Database]

[NASA/ESA]

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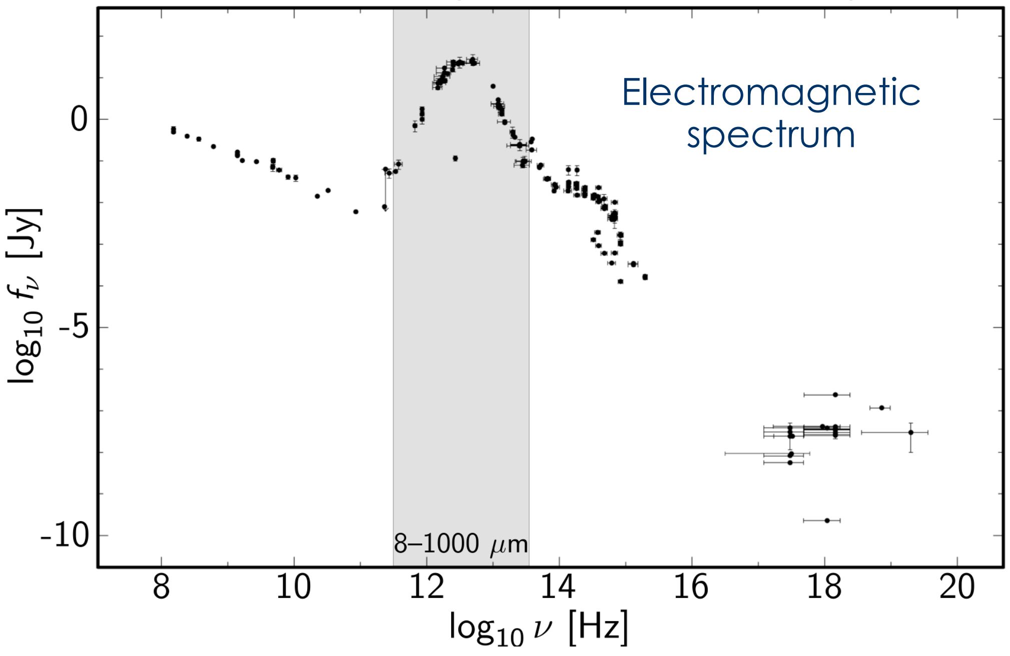
MRK 273 (“Toothbrush Galaxy”)



[NASA/IPAC Extragalactic Database]

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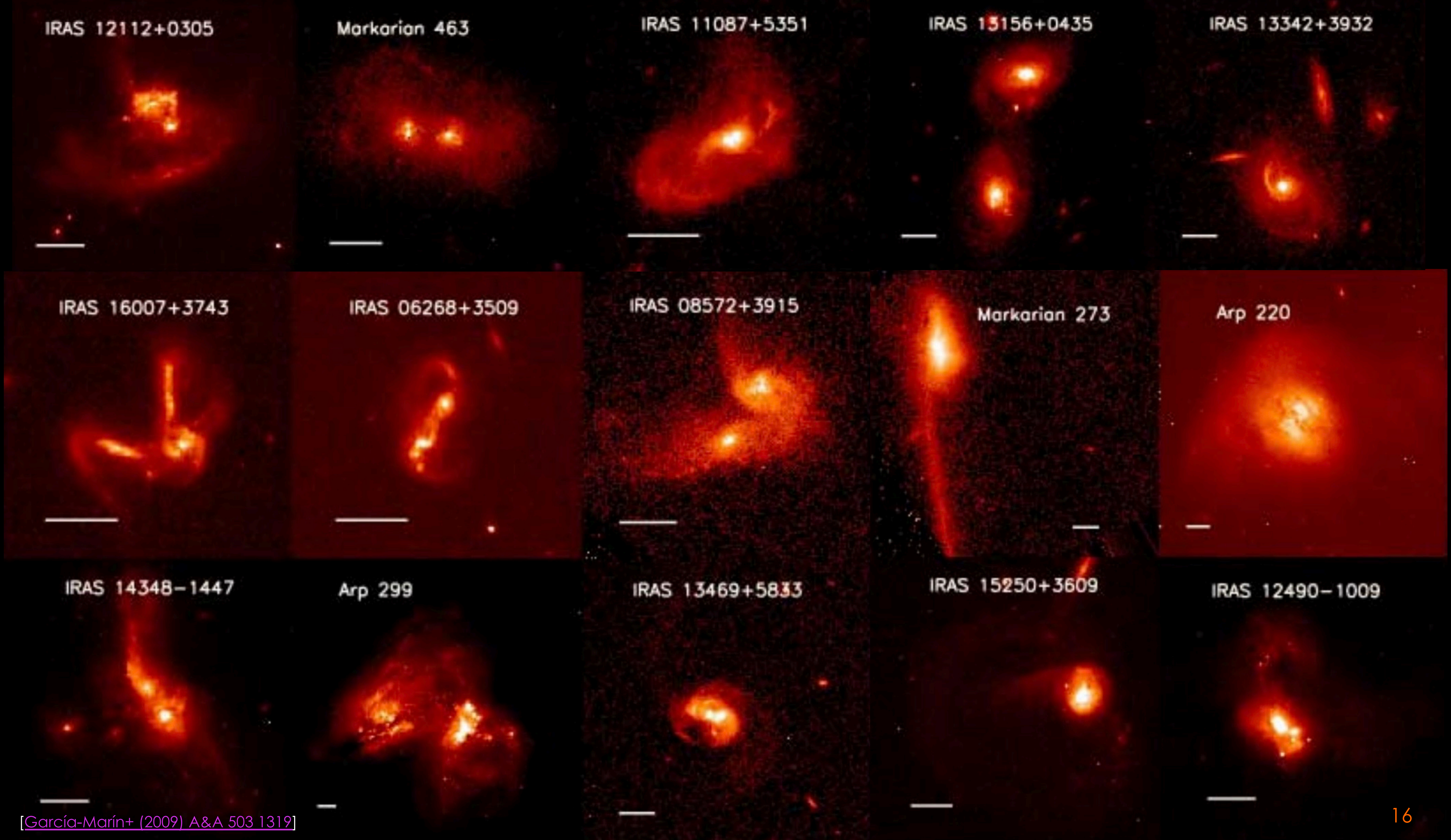
[NASA/ESA]

[not Oral-B]

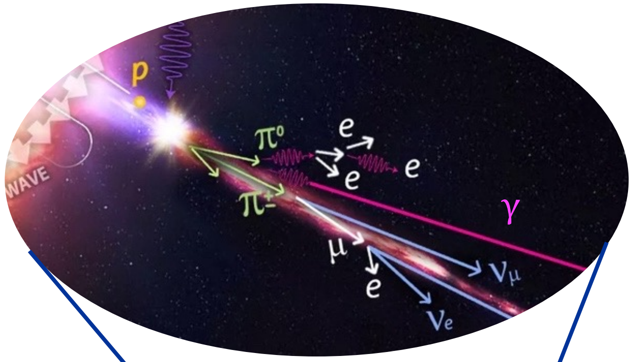


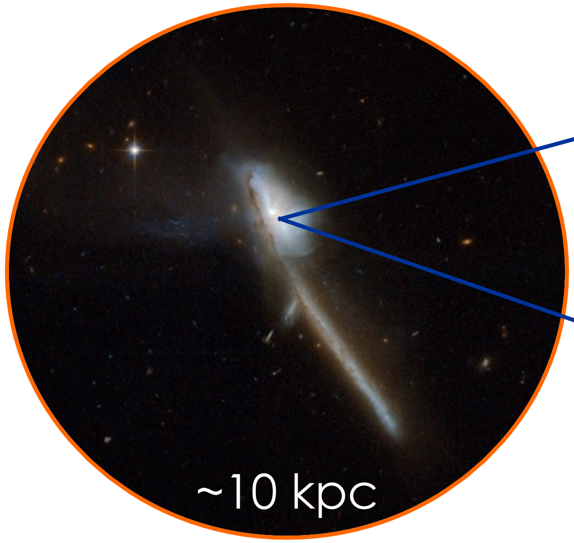
[García-Marín+ (2009) A&A 503 1319]

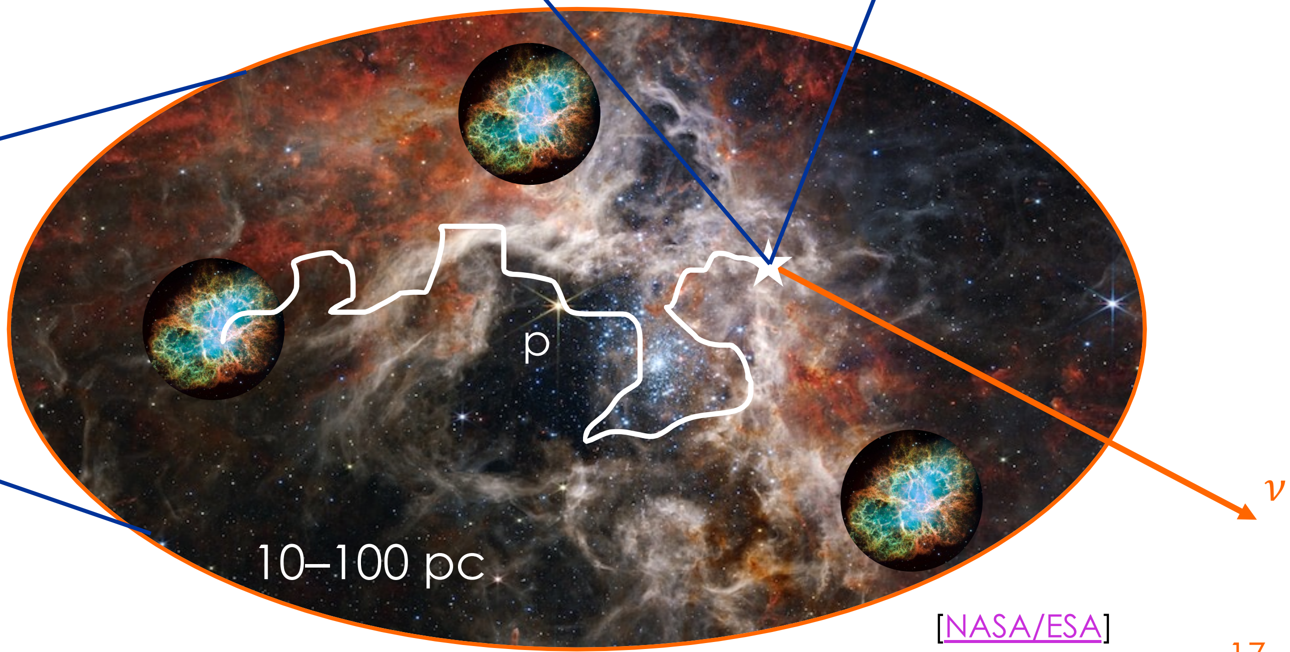
Neutrino Production in ULIRGs (1/2)

- Starburst activity
  - Stellar factories: $\gtrsim 100\ M_\odot\ \mathrm{yr}^{-1}$
  - Enhanced supernova rate
- **Cosmic-ray reservoir**
  - Cosmic rays confined
  - Interact with dust/gas (pp)

[He+ (2013) PRD 87 063011; Palladino+ (2019) JCAP 09 004]





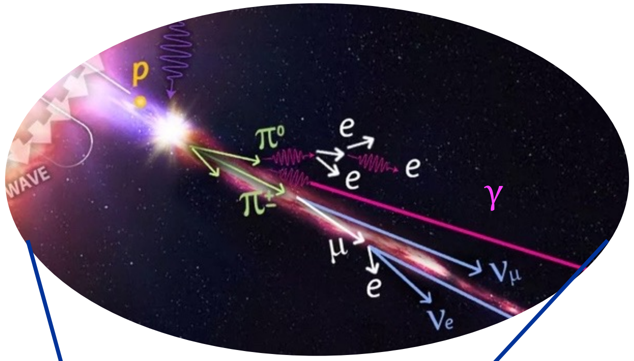


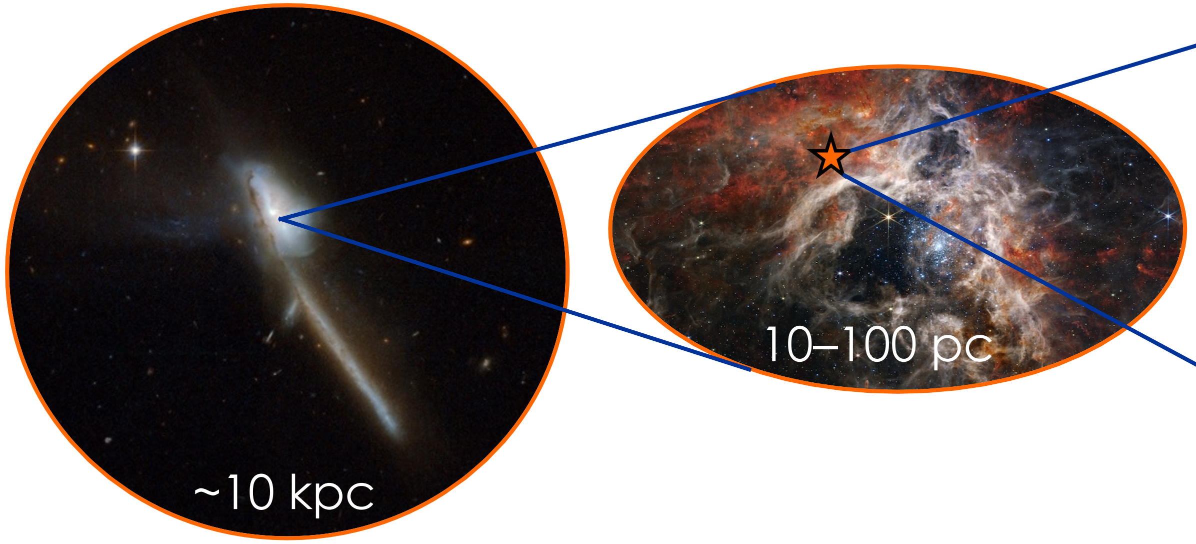
[NASA/ESA]

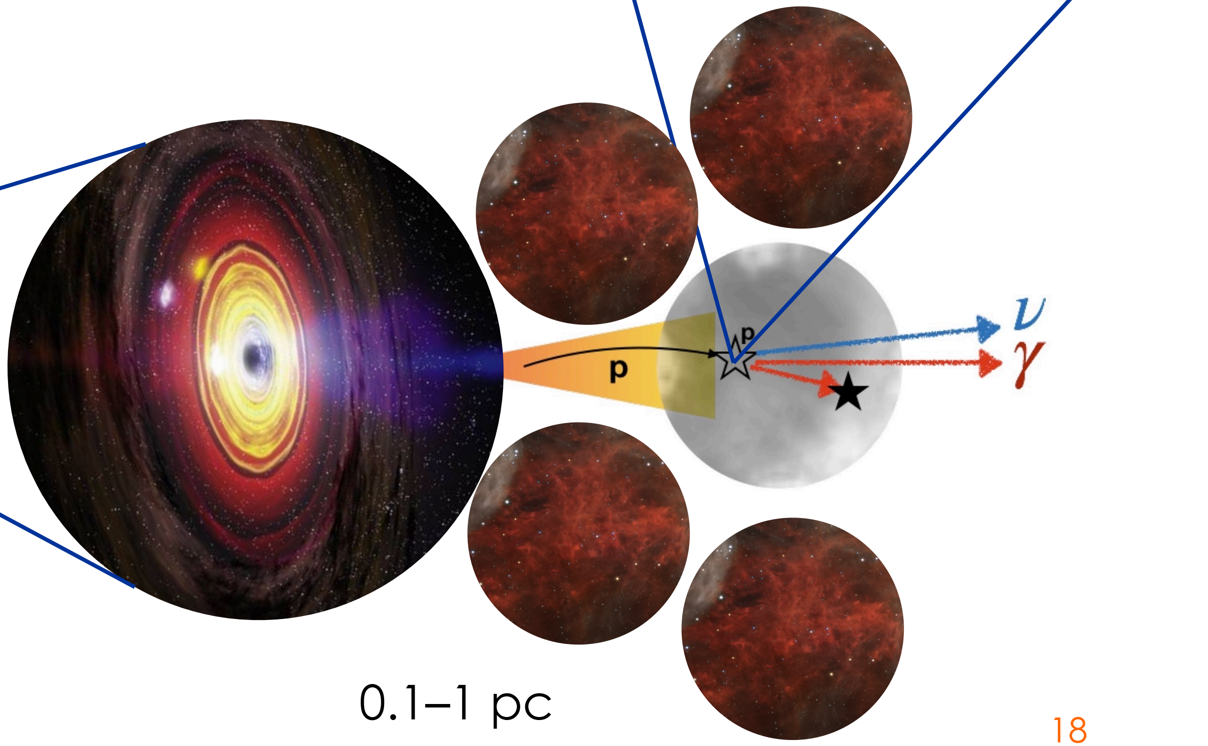
Neutrino Production in ULIRGs (2/2)

- Compton-thick AGN
  - Extremely obscured: $N_H \gtrsim 10^{24}\ \mathrm{cm}^{-2}$
  - Secondary IR component (~10%)
- **AGN beam dump**
  - Cosmic rays shot at dense target
  - Interact with dust/gas (pp)

[Vereecken+ (2020) arXiv:2004.03435]







ULIRG Analysis Motiviation

ULIRGs are most extreme infrared sources

ULIRGs are promising neutrino source candidates

→

Perform **first ever search** for high-energy neutrinos from ULIRGs with IceCube

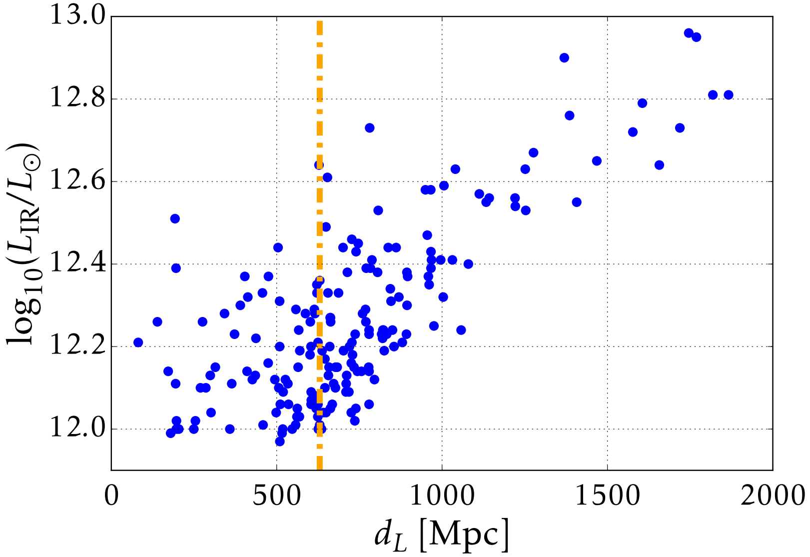
Selection of ULIRGs

- Start from three **IRAS** catalogs
- Determine redshift up to which:
  - All ULIRGs with $L_{IR} = 10^{12}\ L_{\odot}$ are observed
  - Given an IRAS sensitivity $f_{60} = 1\ \mathrm{Jy}$
- **Final sample**: 75 ULIRGs within $z \leq 0.13$
  - Representative of local ULIRG population

Infrared Astronomical Satellite

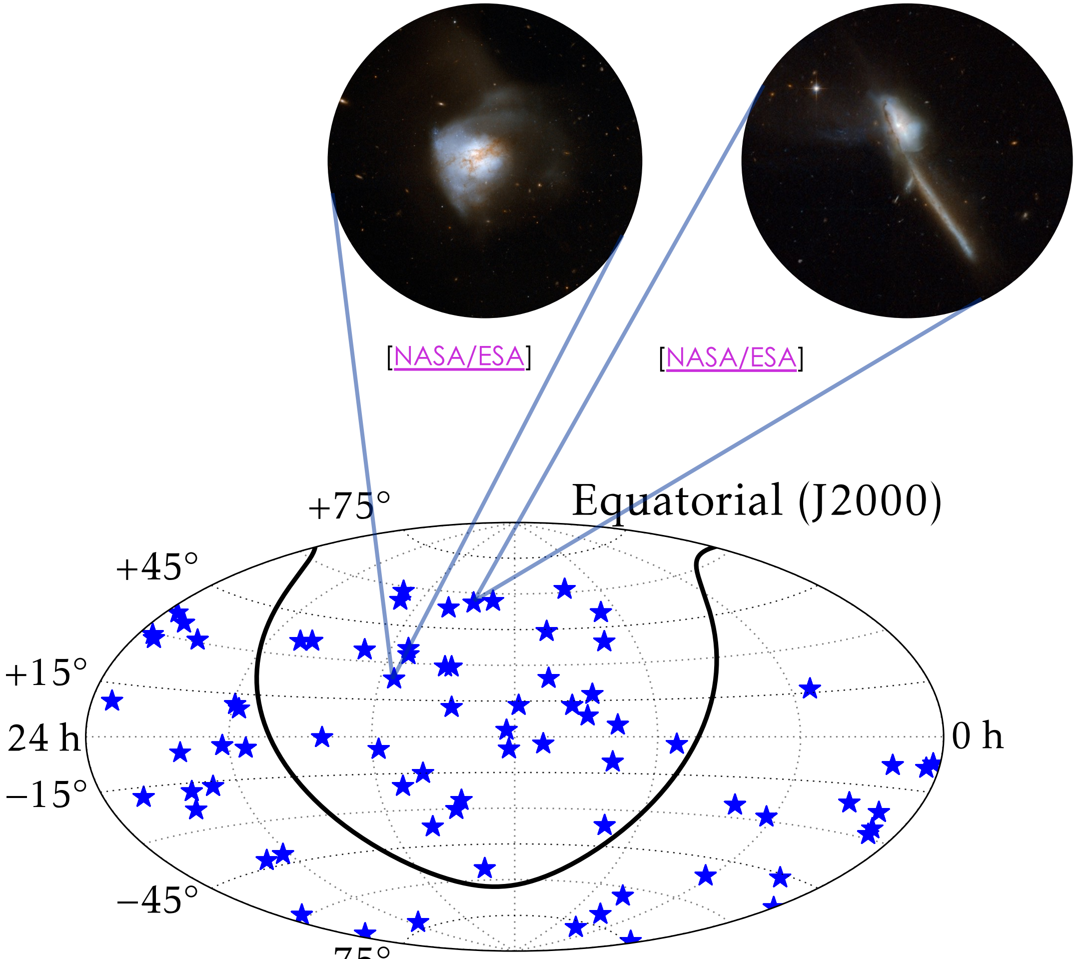
Jan-Nov 1983
12, 25, **60**, 100 micron

[Neugebauer+ (1984) ApJ 278 L1]



Arp 220

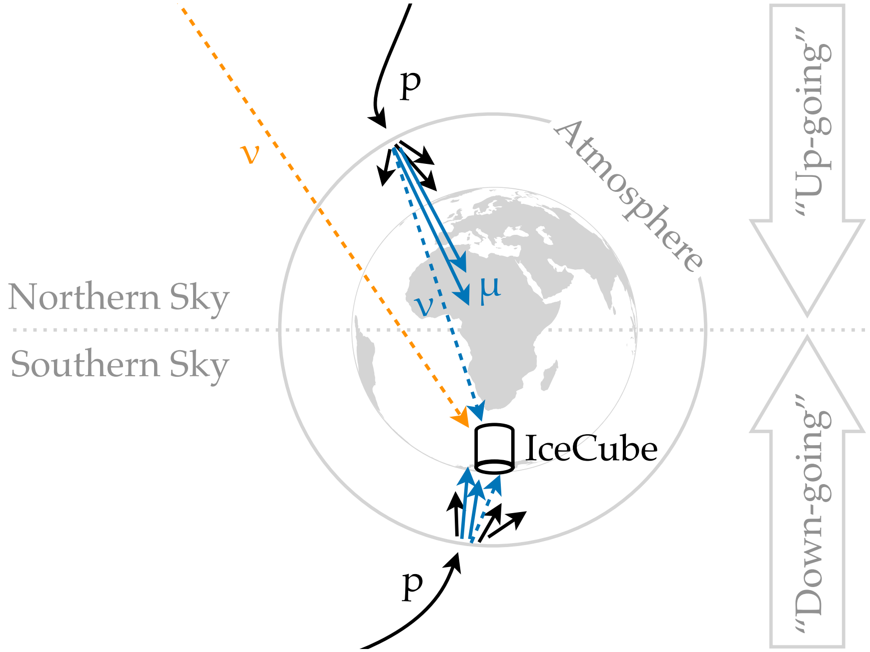
Mrk 273

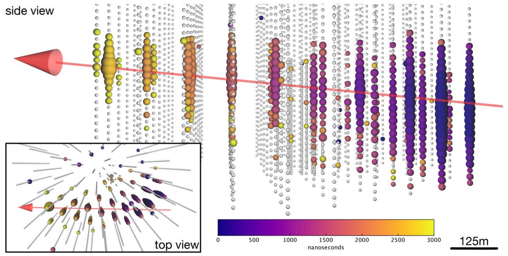


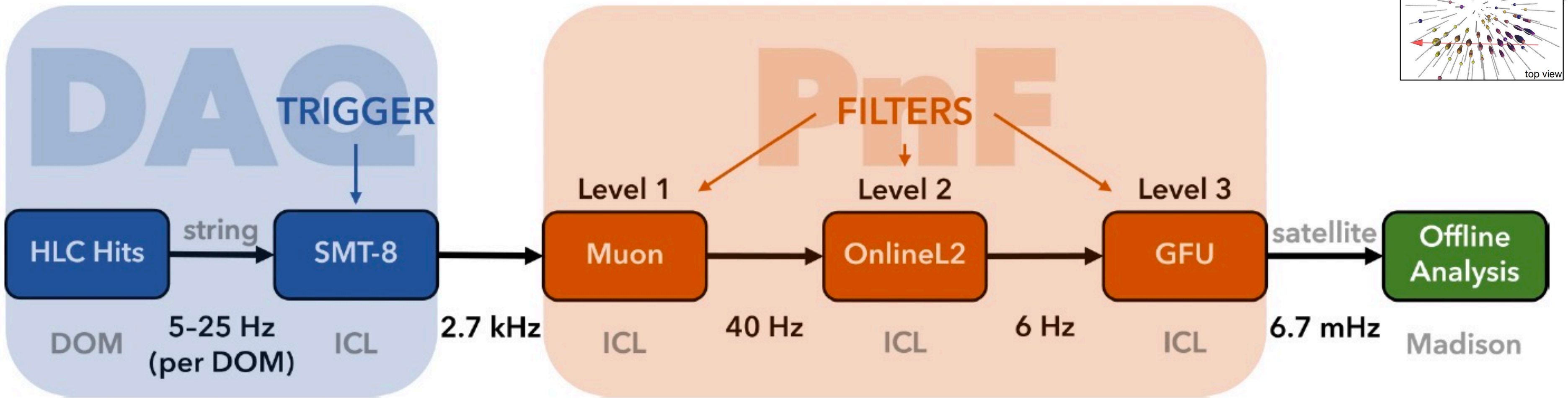
[NASA/ESA] [NASA/ESA]

IceCube Dataset

- **GFU sample** [IC (2017) Astropart. Phys. 92 30]
  - Well-reconstructed **tracks**
  - 7.2 years of data
  - 6.7 mHz all-sky rate
  - 1.5 million events (mostly background)

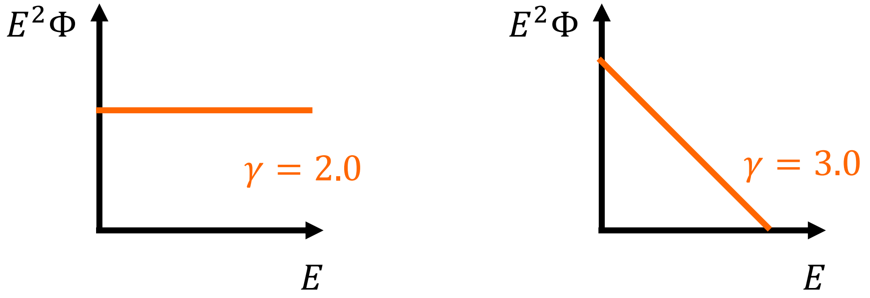






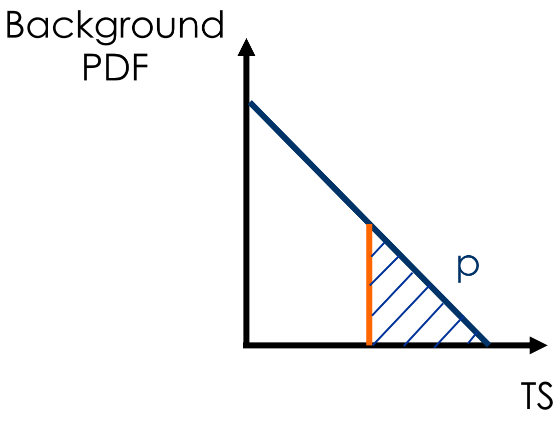
Analysis Method

- Maximum **likelihood** method
  - Fit for number of ULIRGs neutrinos, $\boldsymbol{n_s}$
  - Fit for power-law spectral index, $\boldsymbol{\gamma}$
- **Hypothesis test** (one-tailed)
  - $\mathcal{H}_0$: data only atmospheric background
  - $\mathcal{H}_s$: data contains signal from ULIRG locations
  - Larger TS ⟶ smaller p-value



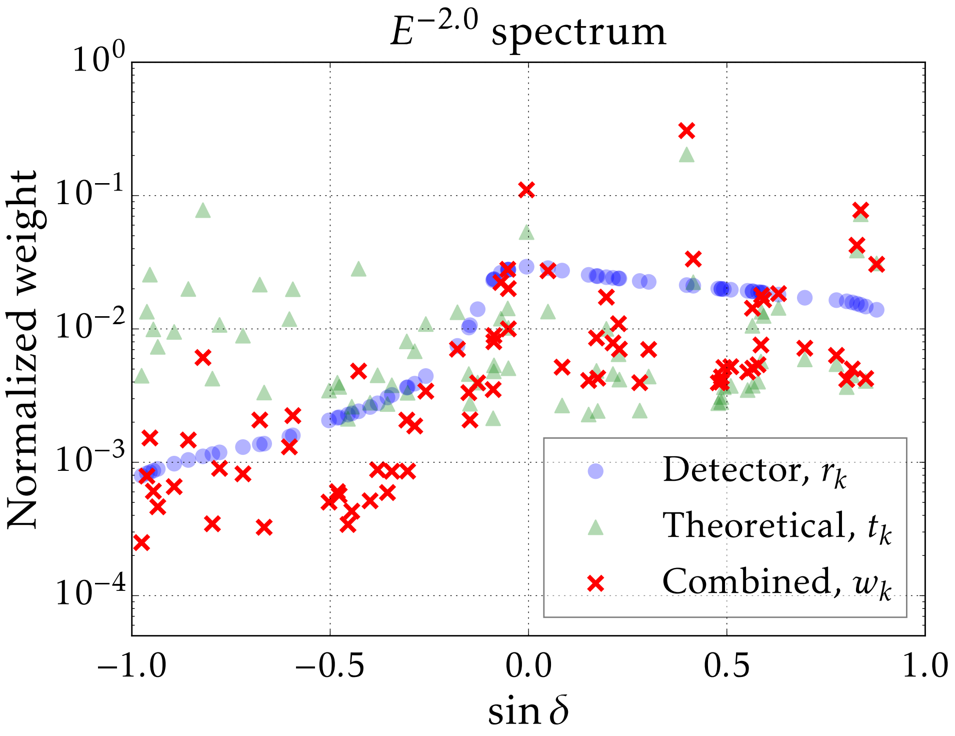
$$\mathcal{L}(\boldsymbol{n_s}, \boldsymbol{\gamma}) = \prod_{i}^{N} \left[\frac{\boldsymbol{n_s}}{N} \sum_{k}^{M} w_k \mathcal{S}_i^k(\boldsymbol{\gamma}) + \left(1 - \frac{\boldsymbol{n_s}}{N}\right) \mathcal{B}_i \right]$$

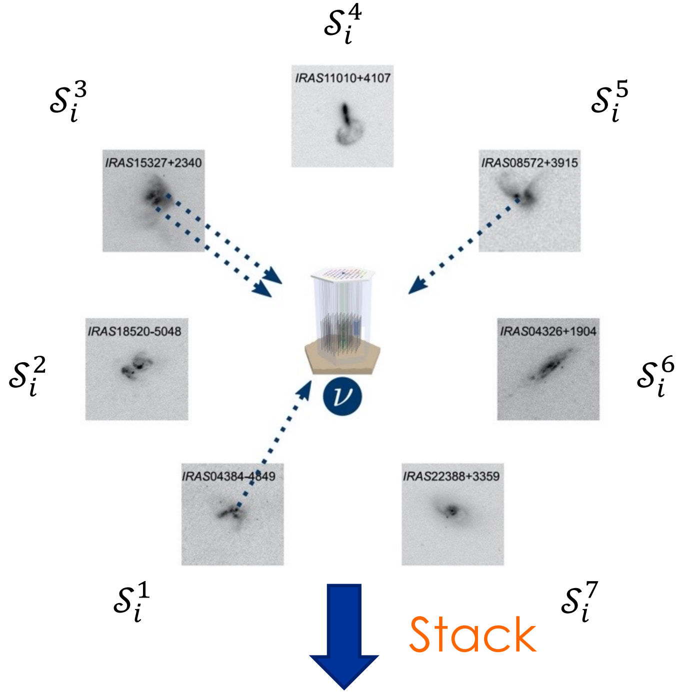
$$\mathrm{TS} = 2 \log \left(\frac{\overbrace{\mathcal{L}(n_s = \hat{n}_s, \gamma = \hat{\gamma})}^{\mathcal{H}_s}}{\underbrace{\mathcal{L}(n_s = 0)}_{\mathcal{H}_0}} \right)$$



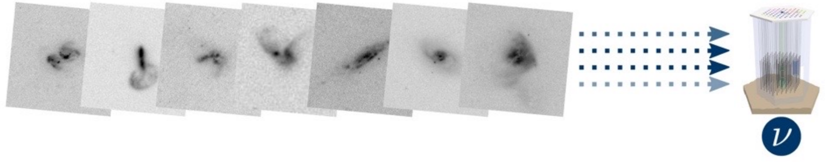
Stacking Technique

- Stack ULIRGs to enhance sensitivity
  - Theoretical weight t_k: total IR flux (8–1000 micron)
  - Detector weight r_k: detector response





[Hung+ (2014) ApJ 791 63]



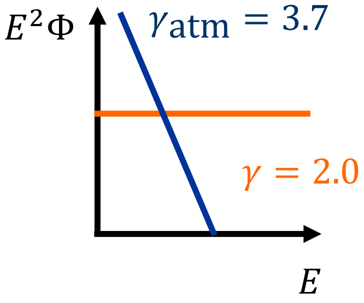
$\sum_k^M w_k S_i^k$: stacking weight: $w_k \propto t_k r_k$

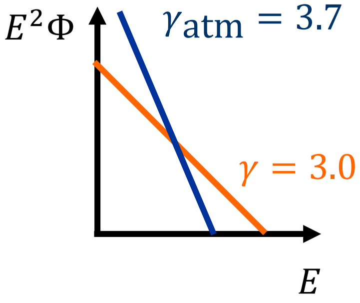
Sensitivity & Discovery Potentials

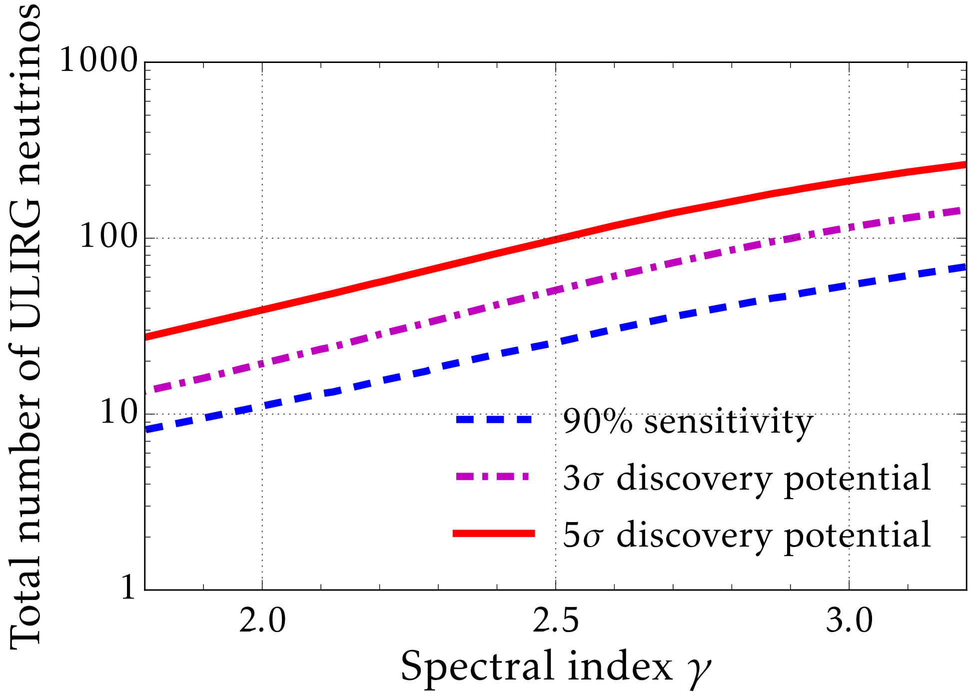
- Test **analysis performance**
  - Simulate pseudo-signal according to

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

- **Sensitive** to 10–100 ULIRG neutrinos
  - More sensitive to harder spectra
  - Easier to distinguish from $E^{-3.7}$ background



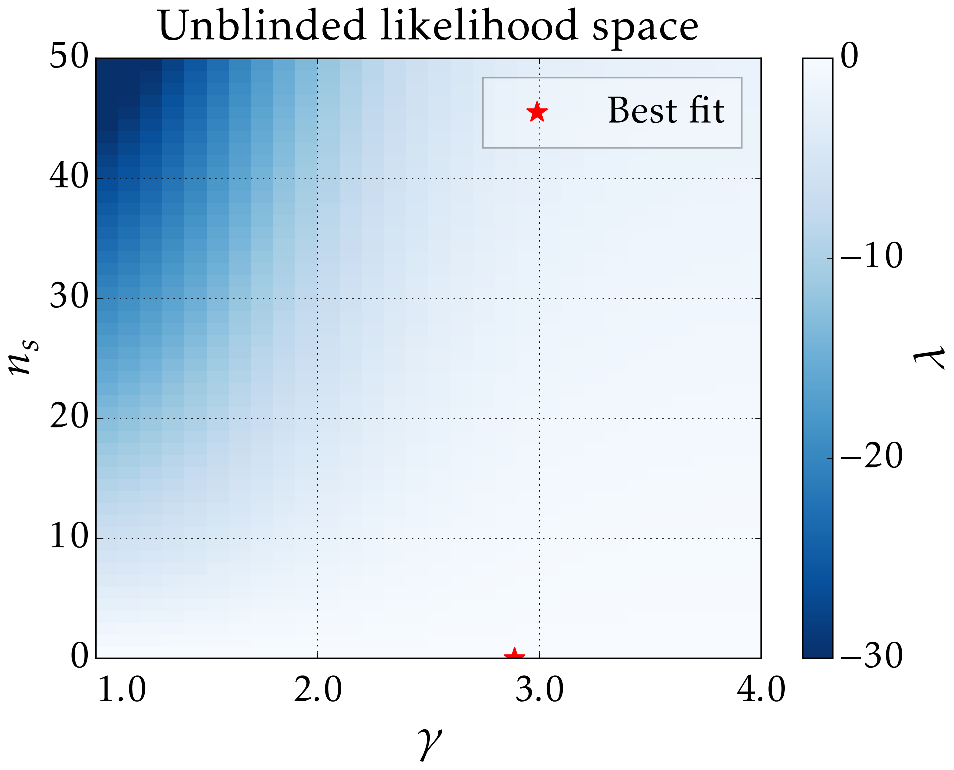




Analysis Results

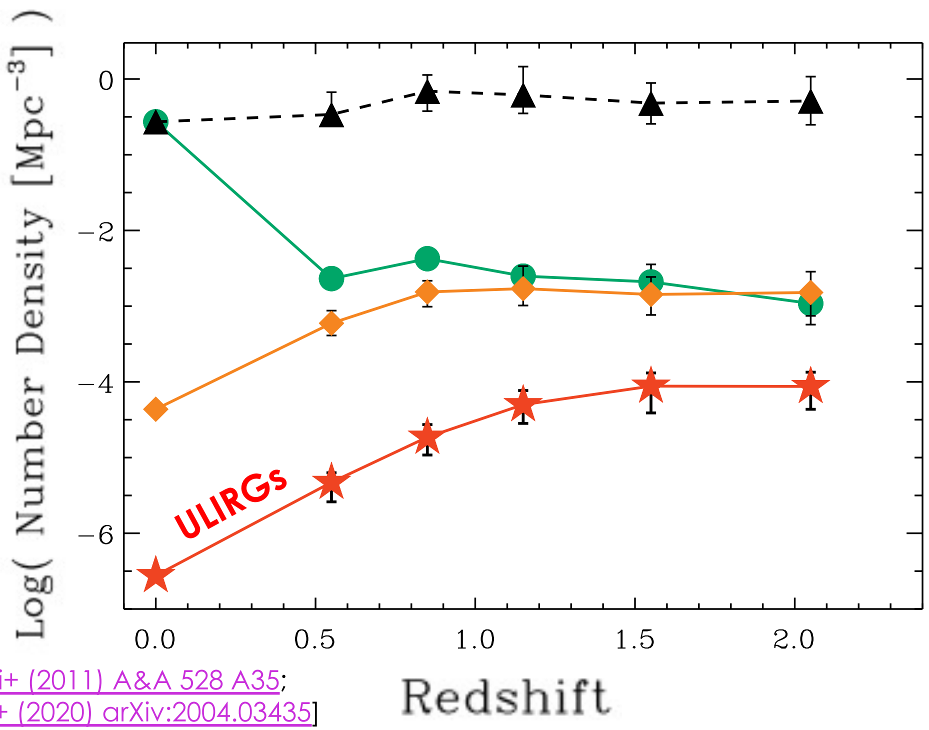
- Analysis consistent with background
- Set upper limits on flux from 75 ULIRGs ($z \leq 0.13$)
  - Limits equal to sensitivity (90% CL)
- Total systematic uncertainty ~15%
  - DOM efficiency, ice properties, muon propagation

Analysis yields
TS = 0
p-value = 1.0

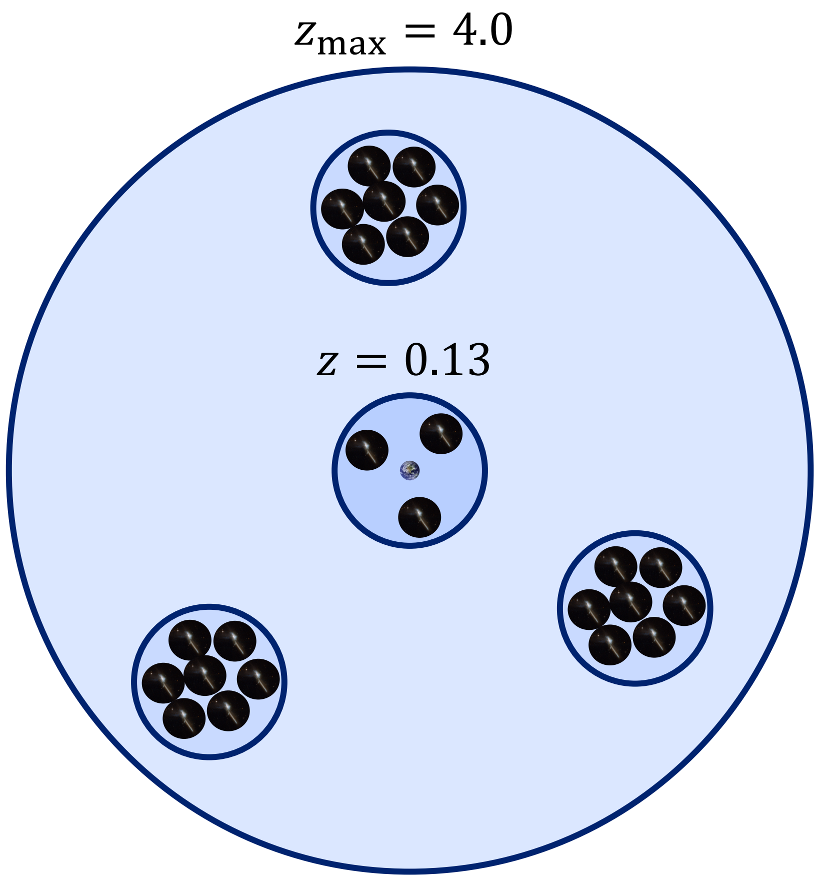


Extrapolating to Diffuse Limits

- Set **limits on diffuse flux** of full ULIRG population
  - Integrate contribution of ULIRGs up to $z_{\rm max}$
  - Assume $L_{IR} \propto L_\nu = \text{constant}$ and same $E^{-\gamma}$ spectrum



[Magnelli+ (2011) A&A 528 A35; Vereecken+ (2020) arXiv:2004.03435]



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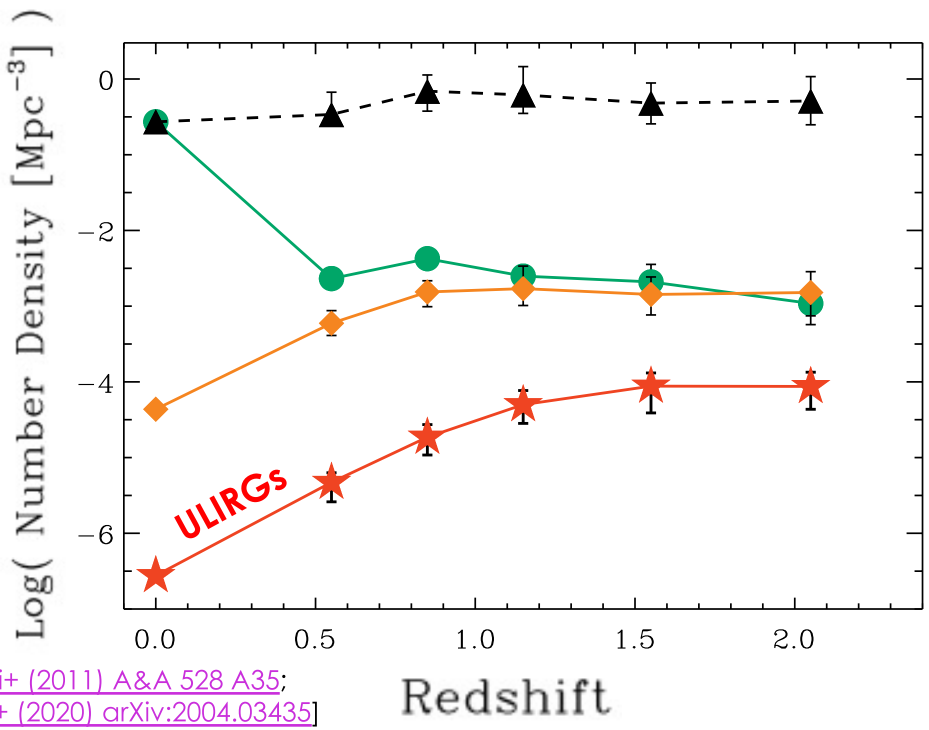
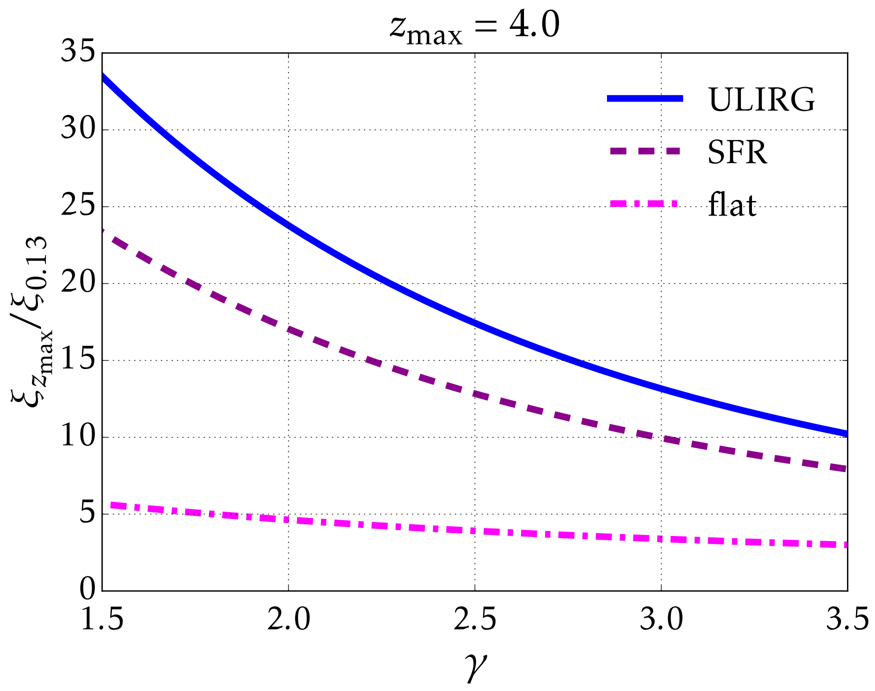
  - Integrate contribution of ULIRGs up to $z_{\max}$
  - Assume $L_{IR} \propto L_\nu = \text{constant}$ and same $E^{-\gamma}$ spectrum

$$\Phi^{z \le z_{\max}}_{\nu_\mu + \bar{\nu}_\mu} = \frac{\xi_{z=z_{\max}}}{\xi_{z=0.13}}(\gamma)\, \Phi^{z \le 0.13}_{\nu_\mu + \bar{\nu}_\mu}$$

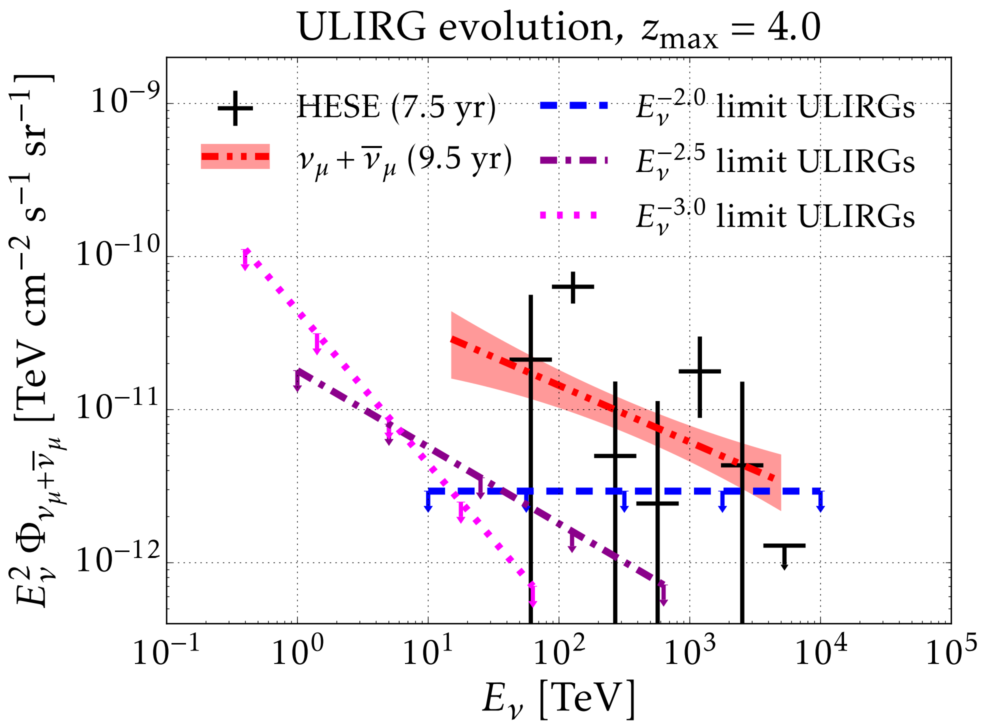


[Magnelli+ (2011) A&A 528 A35; Vereecken+ (2020) arXiv:2004.03435]

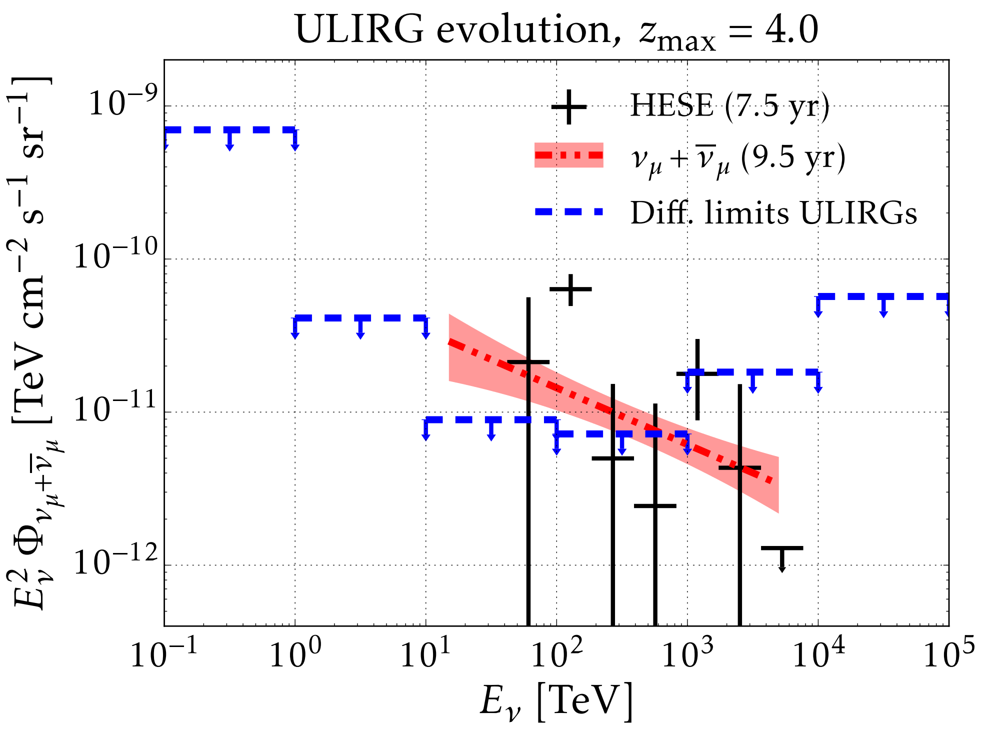


Limits on ULIRG Population

- **Integral limits**
  - Contribution to diffuse observations **constrained** for $E^{-2.0}$ and $E^{-2.5}$ spectra



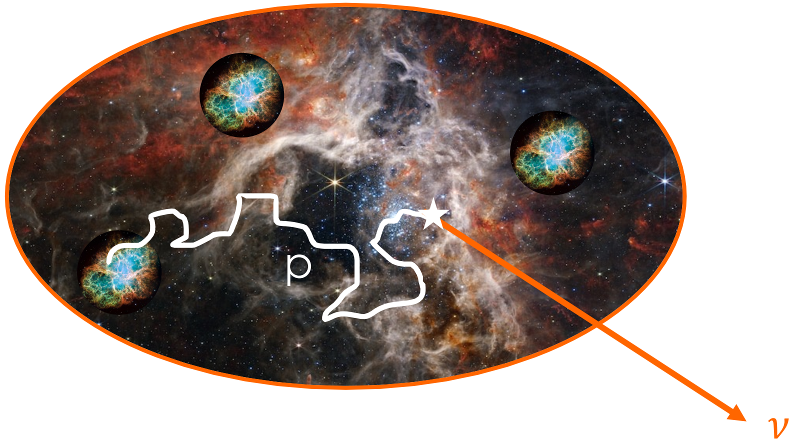
- **Differential limits**
  - Contribution to diffuse observations **constrained** for 10– 100 TeV and 100– 1000 TeV

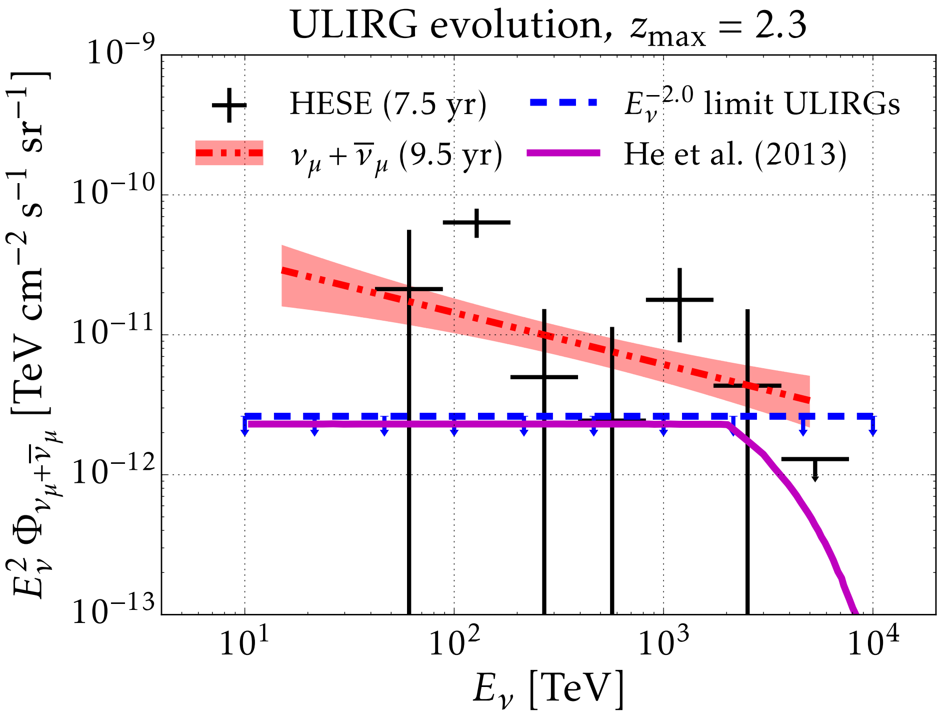


Comparison with Reservoir Model I

LPNHE PARIS

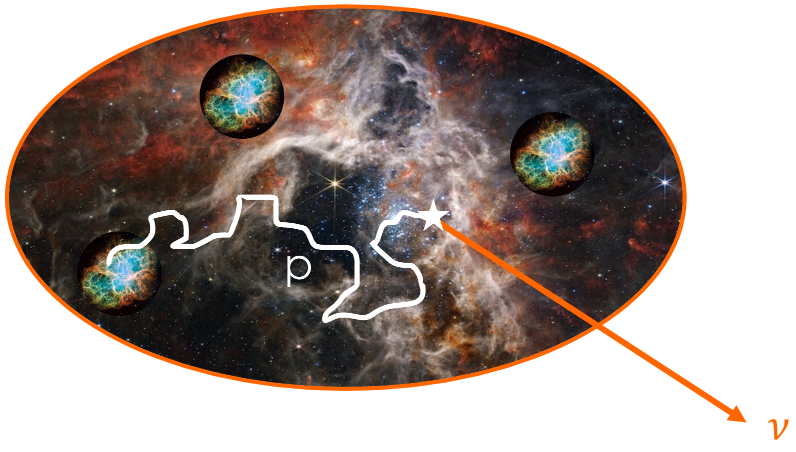
- [He+ (2013) PRD 87 063011]
  - Neutrino flux powered by hypernovae
  - **At level** of our upper limit
  - More data needed to exclude/validate

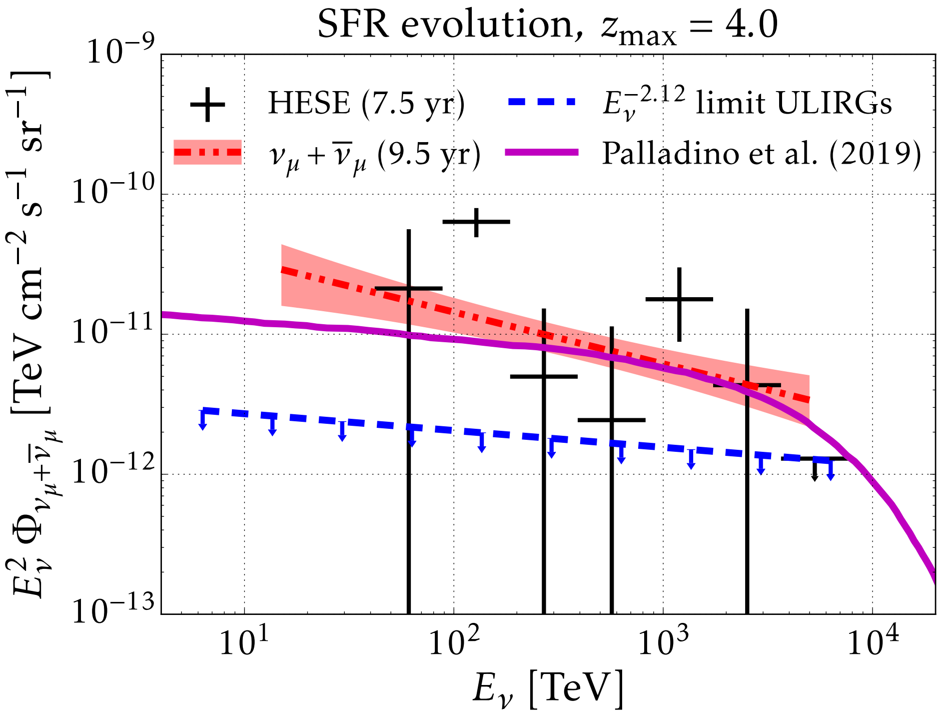




Comparison with Reservoir Model II

- Palladino+ (2019) JCAP 09 004
  - Generic model of hadronically powered gamma-ray galaxies (HAGS)
  - **ULIRGs excluded as sole HAGS** responsible for diffuse observations

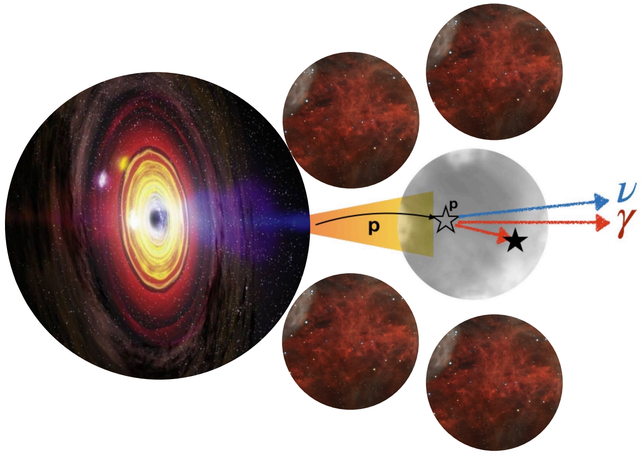




Comparison with Beam-Dump Model

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

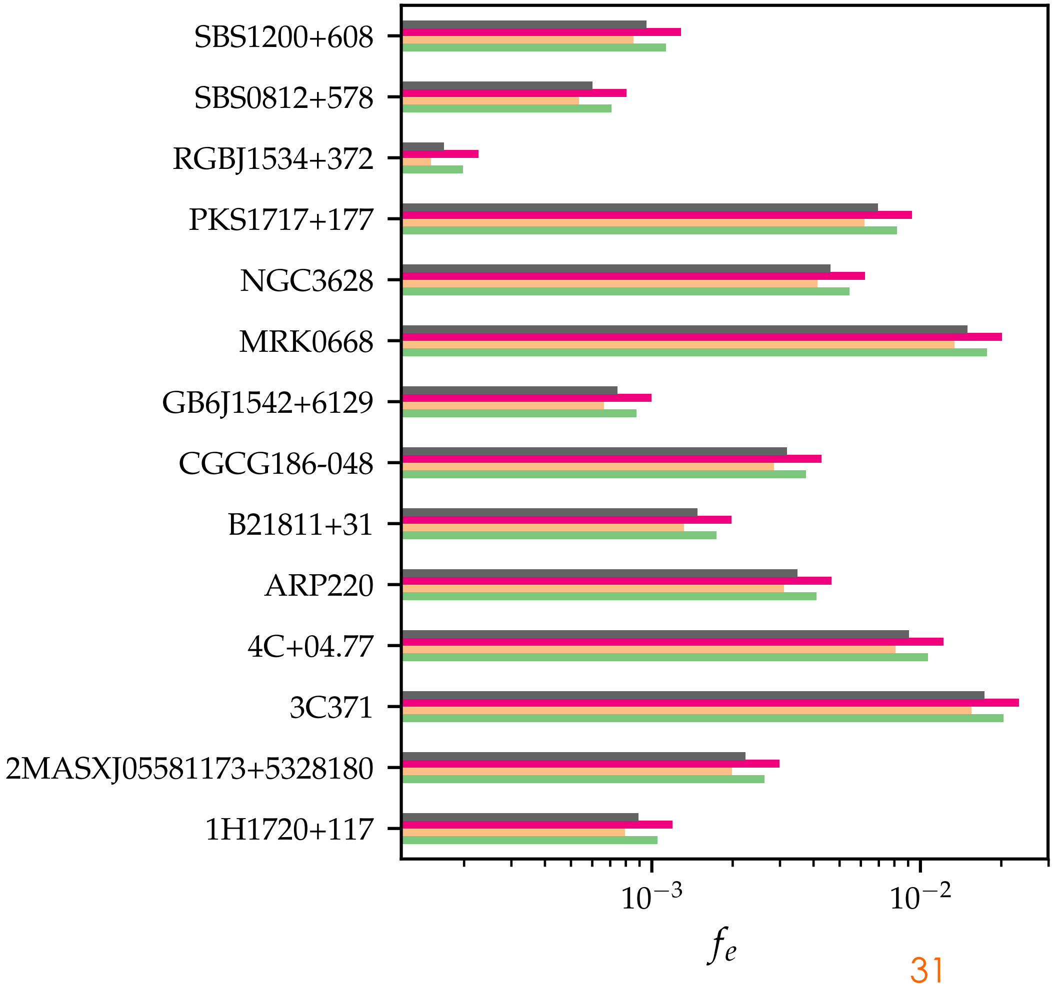
[PoS ICRC2017 1000]



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

Limit from our ULIRG analysis

Obscured-AGN limits



Conclusions & Outlook

Summary

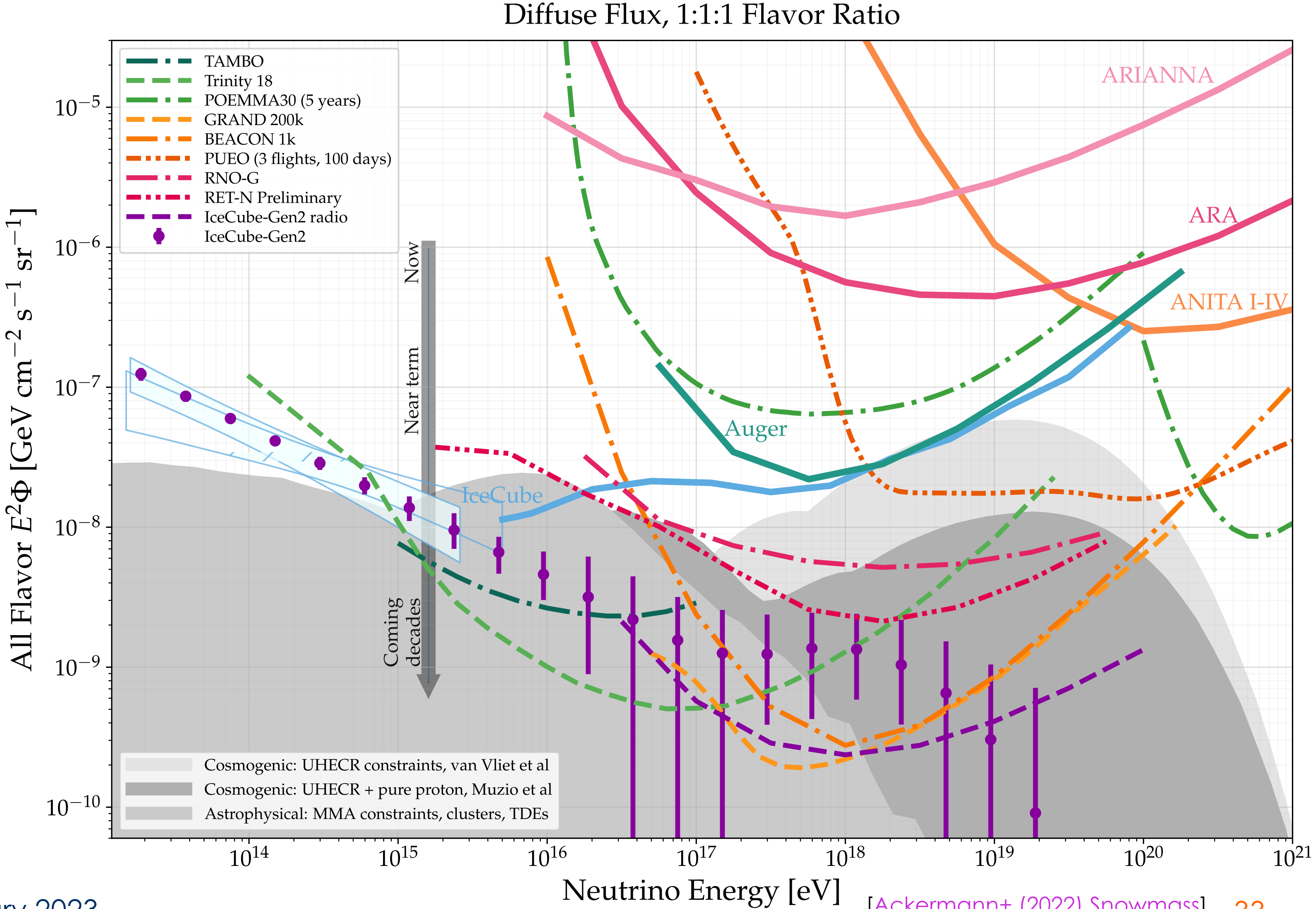
- Exciting times for neutrino astronomy!
  - First neutrino sources unveiled
  - MANY more to be discovered!
- Searched for ULIRG neutrinos
  - Upper limits on ULIRG source class
  - Constrained model predictions
  - Paper published [IC (2022) ApJ 926 59]

Outlook

- LIRGs
  - 10x less luminous but 100x more numerous
  - NGC 1068 is a LIRG!
  - IceCube analysis planned [Merckx (2021) MSc thesis]
- Compton-thick AGN
  - IceCube analysis underway [PoS ICRC2021 1142]
- Focus on X-ray sources of neutrinos

The Future of Neutrino Astronomy

- Towards ultra-high energies!
- **GRAND**@LPNHE



[Ackermann+ (2022) Snowmass]

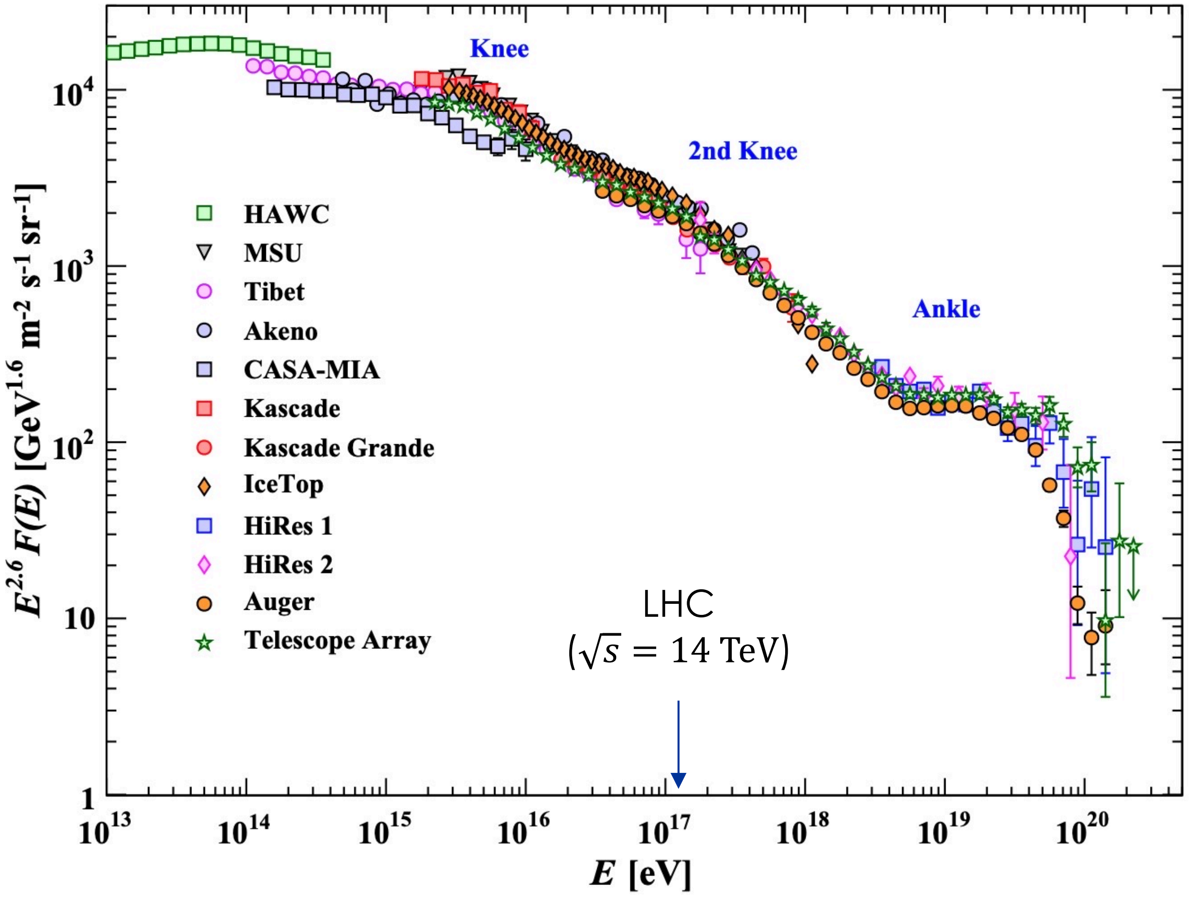
BACKUP

The Mystery of Astroparticle Physics

- Cosmic rays discovered in 1912
  - Charged atomic nuclei (p, He, …, Fe)
- Observed up to ultra-high energies
  - Highest energy 3×10^{20} eV ≈ 50 J

Where do (ultra)-high-energy cosmic rays come from?

Cosmic-ray energy spectrum



[PDG (2022) PTEP 083C01]

The Diffuse High-Energy Sky

What is the origin of (ultra)-high-energy cosmic rays?

Unresolved isotropic observations

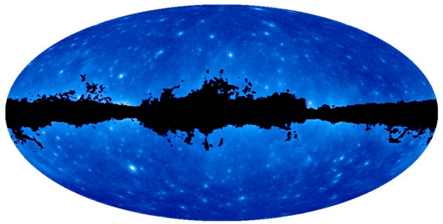
Similar energy budgets

Sources likely extragalactic

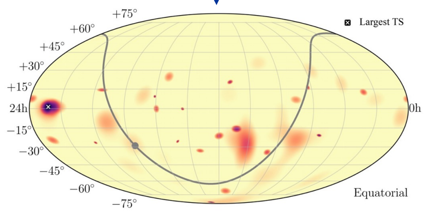
What is the origin of high-energy neutrinos?

Focus of this talk

[Fermi-LAT (2017) ApJS 232 18]

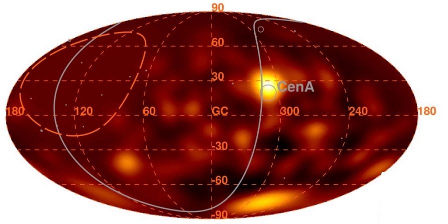


GeV gamma rays

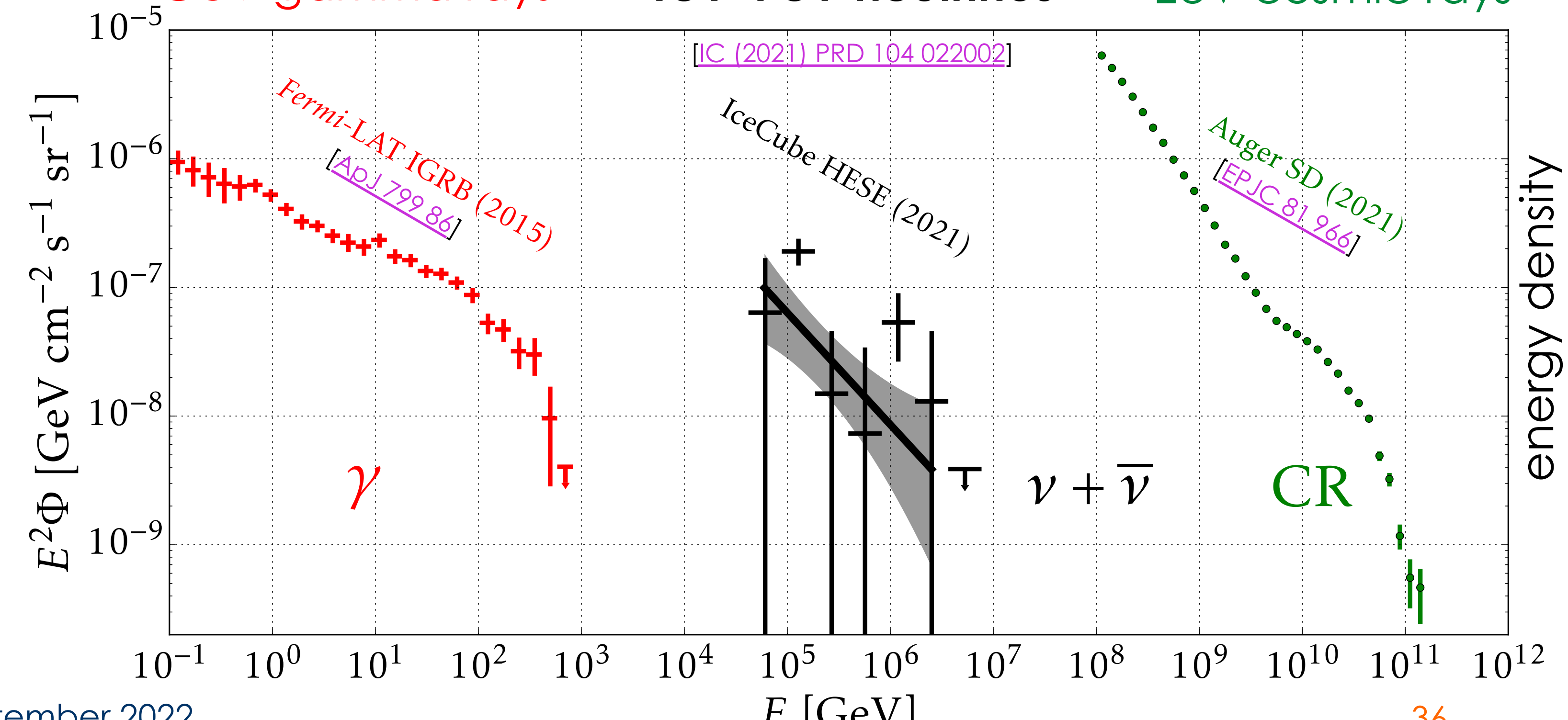


TeV–PeV neutrinos

[Auger (2018) ApJL 853 L29]



EeV cosmic rays

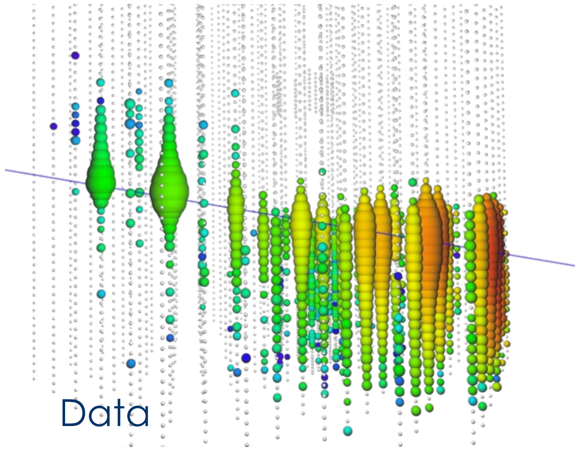


Event Signatures in IceCube

Track

ν_μ charged-current

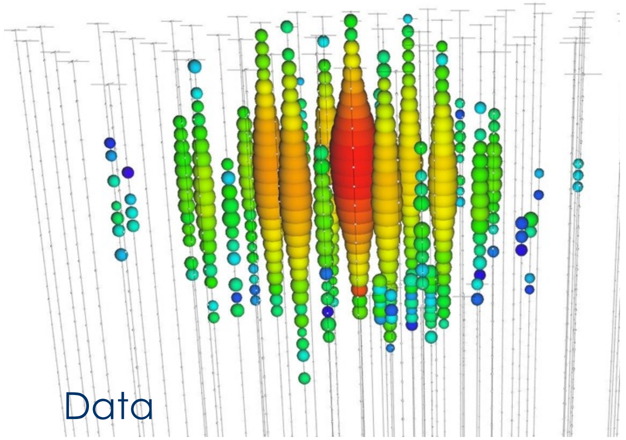
Good **angular resolution**, $\lesssim 1^\circ$



Cascade

ν_e (ν_τ) charged-current & all neutral-current

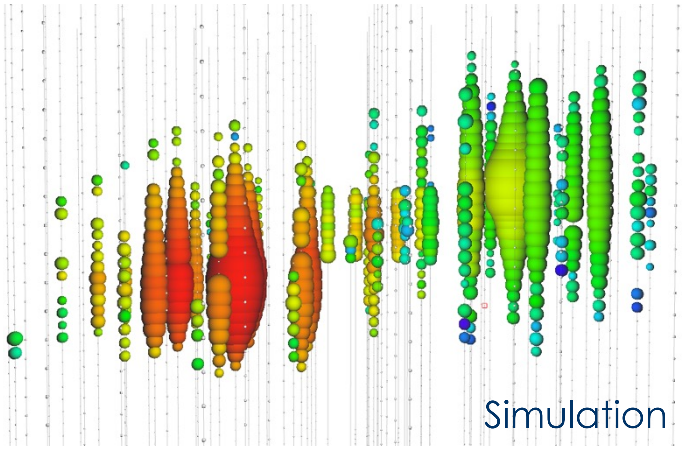
Good energy resolution, $\sim 15\%$



Double Bang

ν_τ charged-current at highest energies

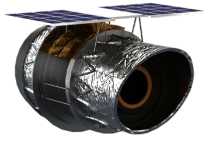
ν_τ candidates observed! [IC (2022) EPJC 82 1031]



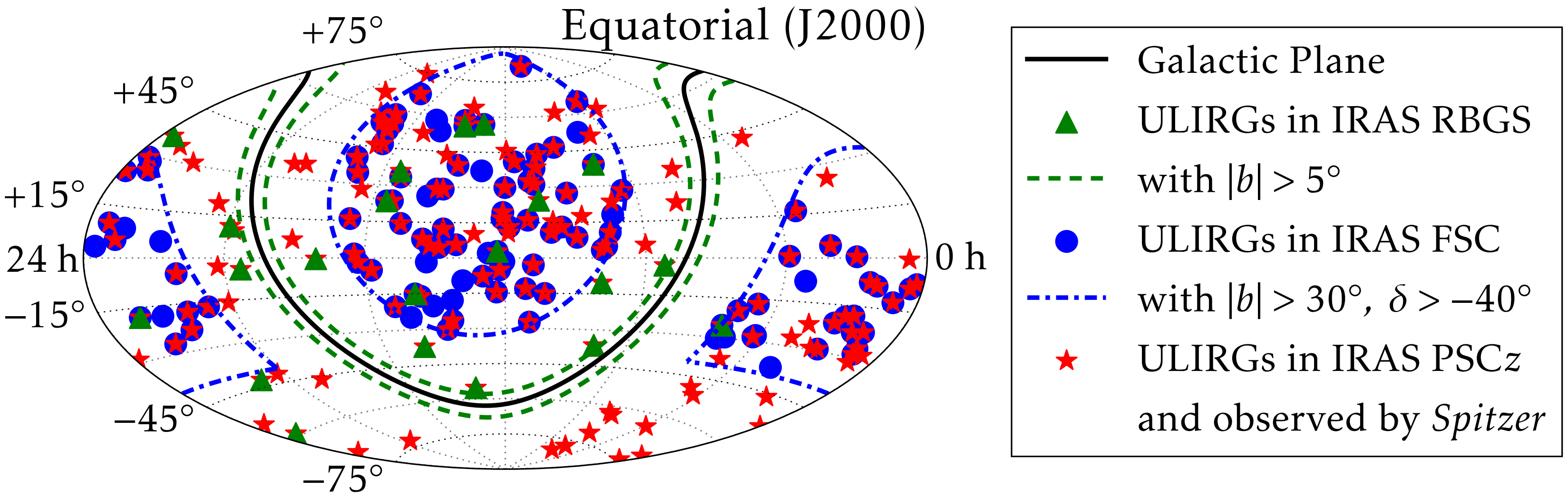
Initial Selection of ULIRGs

- Start from **three catalogs** based on IRAS data
- Mainly observe flux at 60 micron, f_{60}
- 189 unique ULIRGs

Infrared Astronomical Satellite



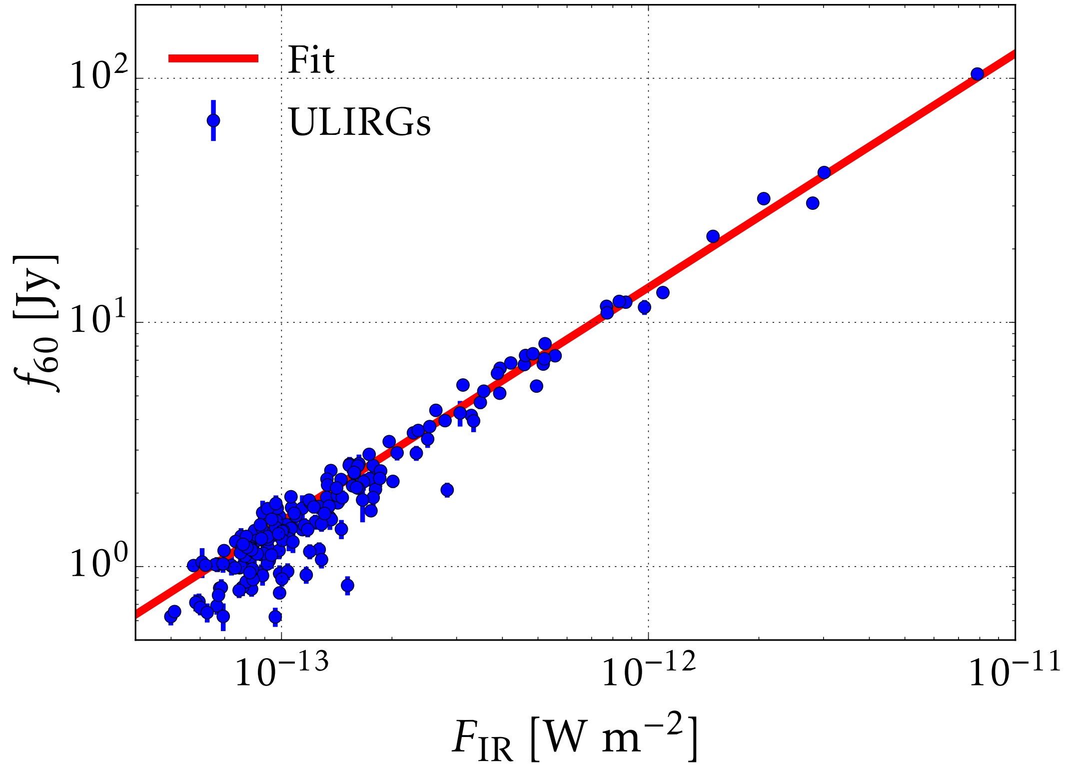
Jan-Nov 1983
12, 25, **60**, 100 micron
[Neugebauer+ (1984) ApJ 278 L1]



▲ [Sanders+ (2003) AJ 126 1607] ● [Kim+ (1998) ApJS 119 41] ★ [Nardini+ (2010) MNRAS 405 2505]

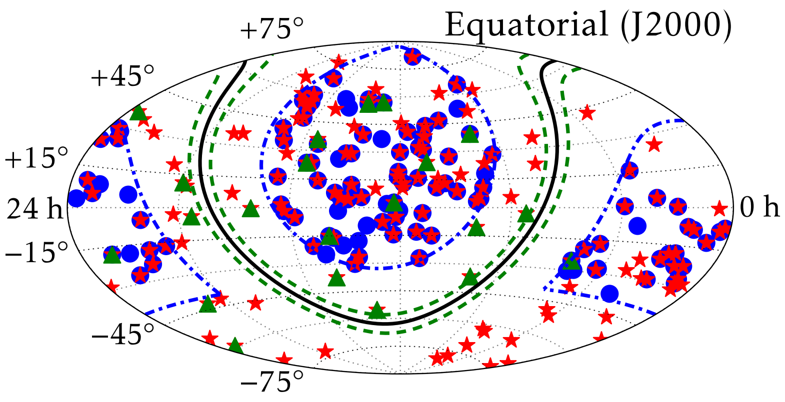
Completeness Estimation

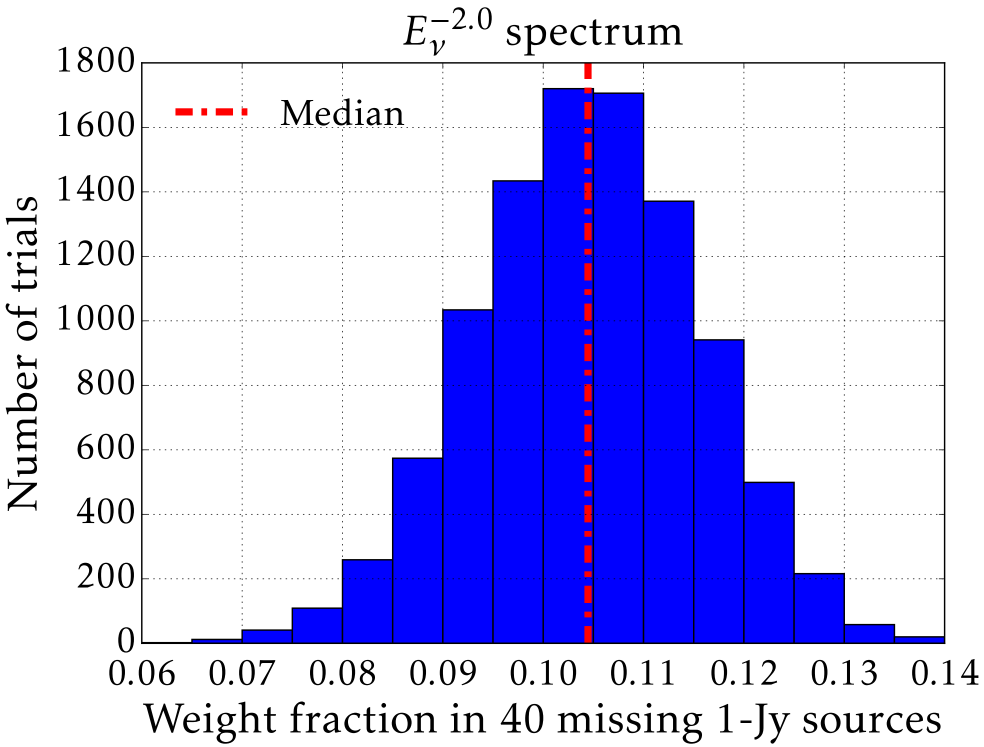
- Perform log-linear fit between f_{60} and F_{IR}
  - Flux density at 60 micron, f_{60}
  - Total IR flux (8–1000) micron, $F_{IR} = L_{IR}/(4\pi d_L^2)$
- Find maximum distance d_L from fit for
  - $f_{60} = 1\ \mathrm{Jy}$
  - $L_{IR} = 10^{12} L_\odot$
- Result: $d_L \sim 700\ \mathrm{Mpc}$ or $z \sim 0.143$
  - Make conservative choice $z = 0.13$ for cut



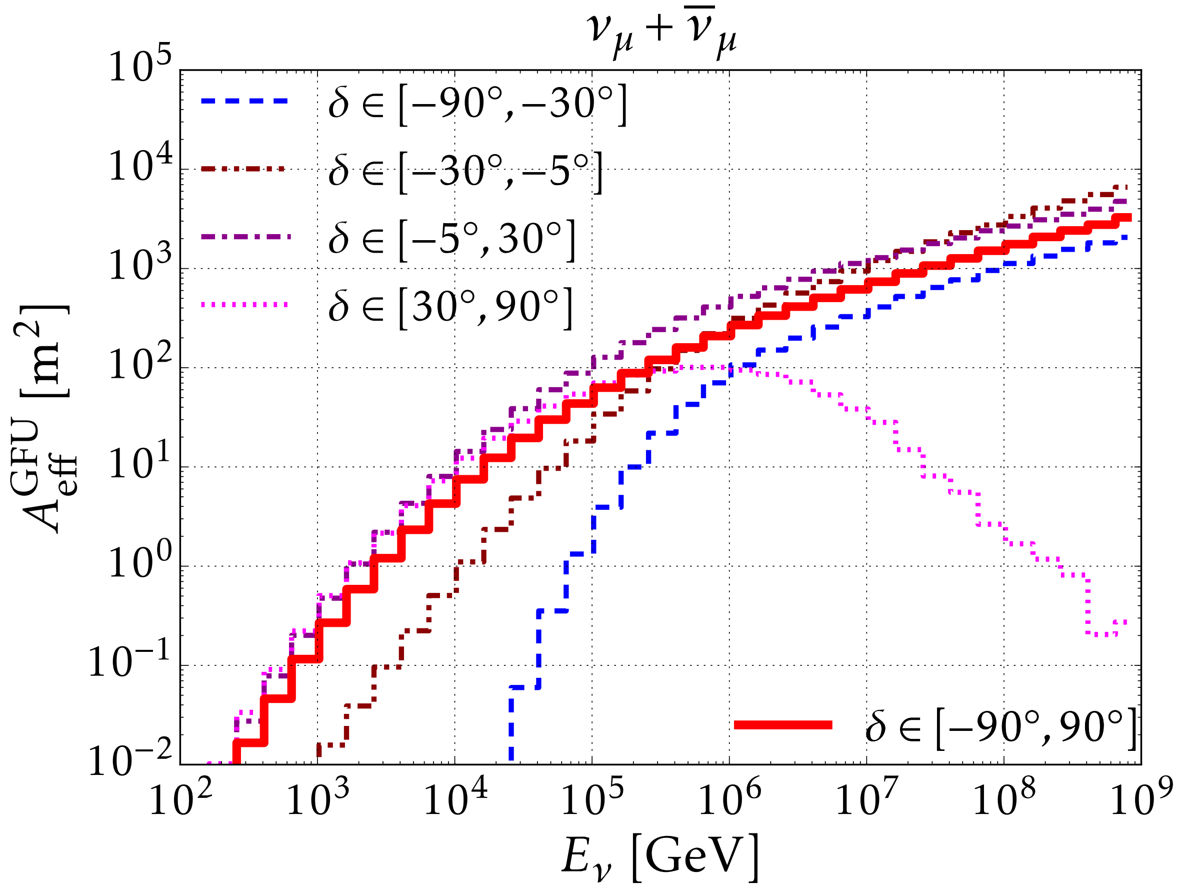
Effect of Missing Sources

- Final ULIRG selection: $f_{60} \geq 1$ Jy
  - For $f_{60} \geq 5.24$ Jy: complete
  - For $1\ \mathrm{Jy} \leq f_{60} < 5.24$ Jy: limited sky coverage
- Likely miss ~40 sources with $1\ \mathrm{Jy} \leq f_{60} < 5.24$ Jy
- Simulate 40 ULIRGs on patch not fully covered
  - Detector weight: declination dependent
  - Theoretical weight: average total IR flux of FSC ULIRGs
- Effect on final analysis result: ~10%
  - Taken into account in ULIRG population limits





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

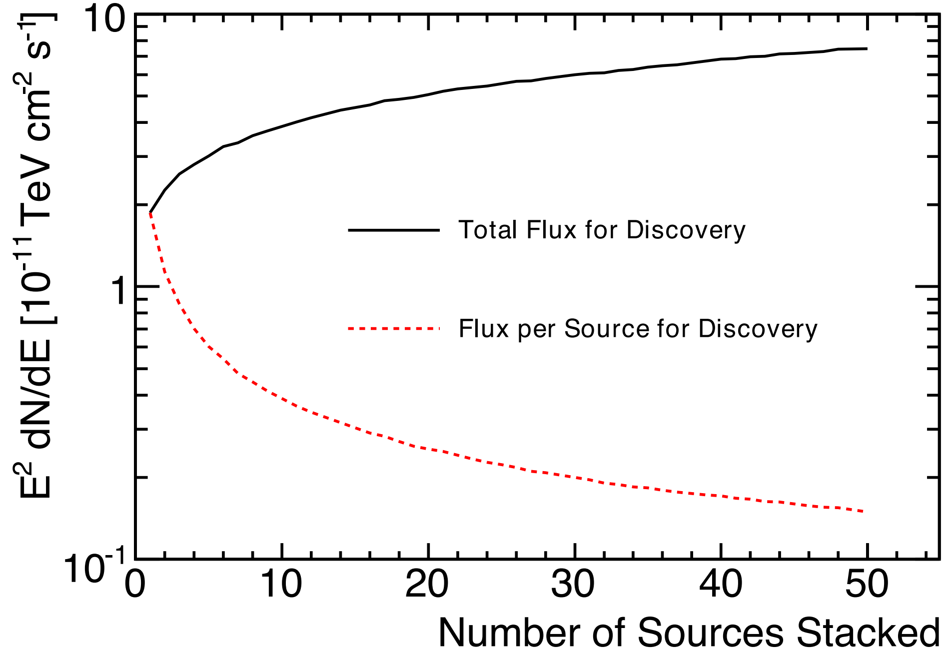
Alternative hypothesis
Data is compatible with background + ULIRG signal

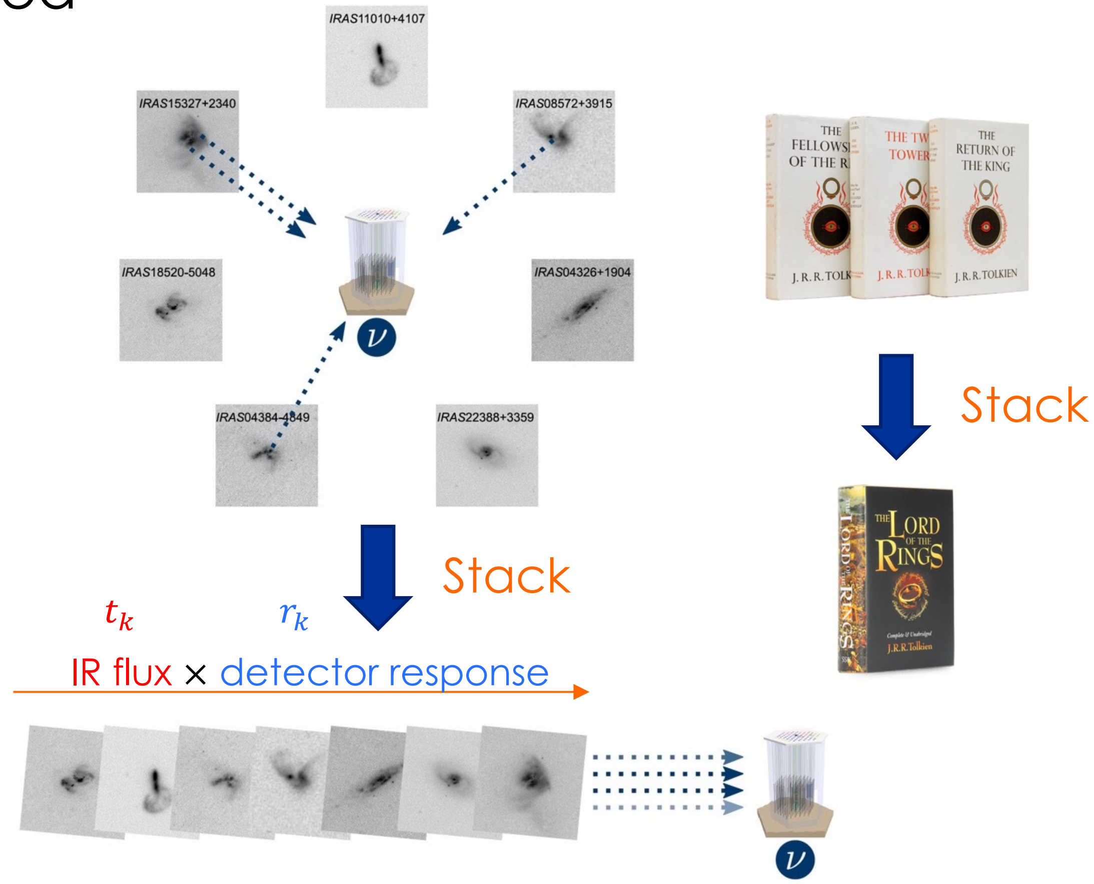
$$\mathrm{TS} = 2 \log \left(\frac{\mathcal{L}(n_s = \hat{n}_s, \gamma = \hat{\gamma})}{\mathcal{L}(n_s = 0)} \right)$$

Null hypothesis
Data is compatible with atmospheric background

The Power of Stacking

- Increase in sensitivity flux of sources combined
- Decrease in sensitivity flux per source
- Strongly depends on chosen weights



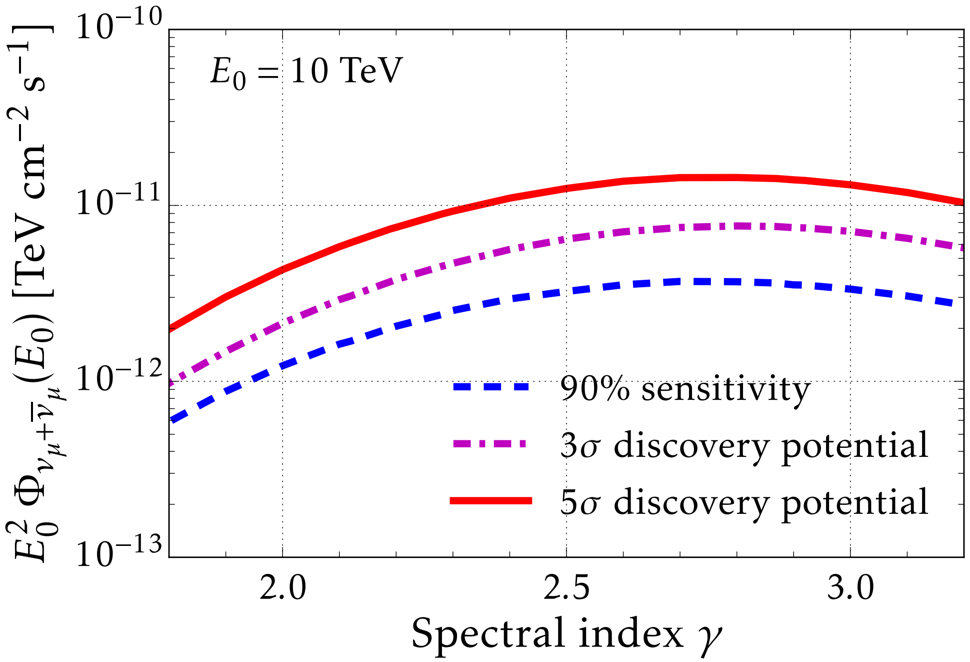


[Hung+ (2014) ApJ 791 63]

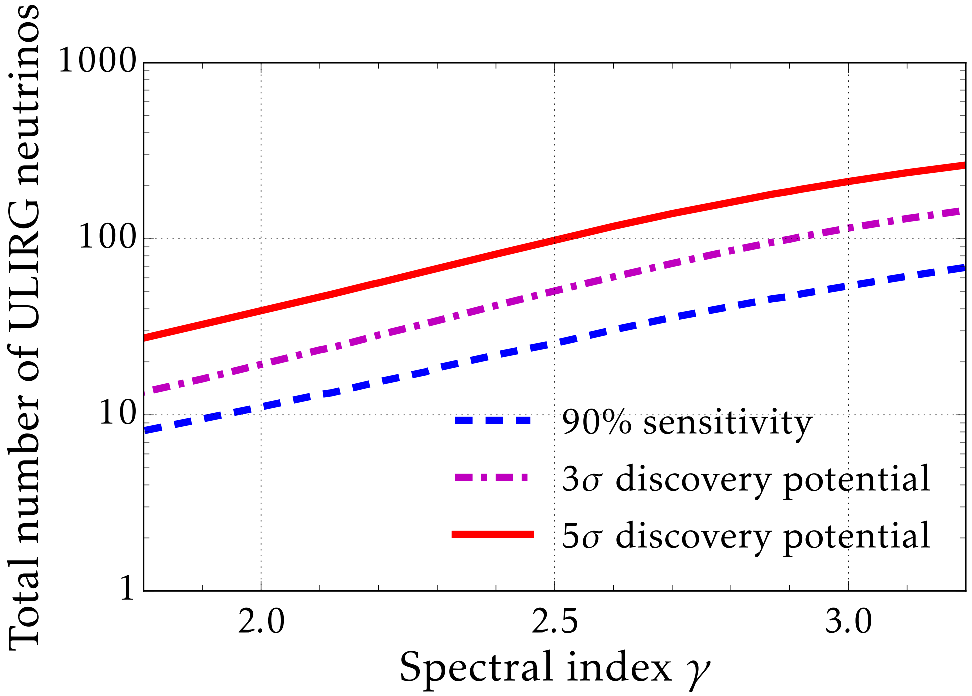
Sensitivity & Discovery Potentials

- Test analysis performance
  - Simulate pseudo-signal according to

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



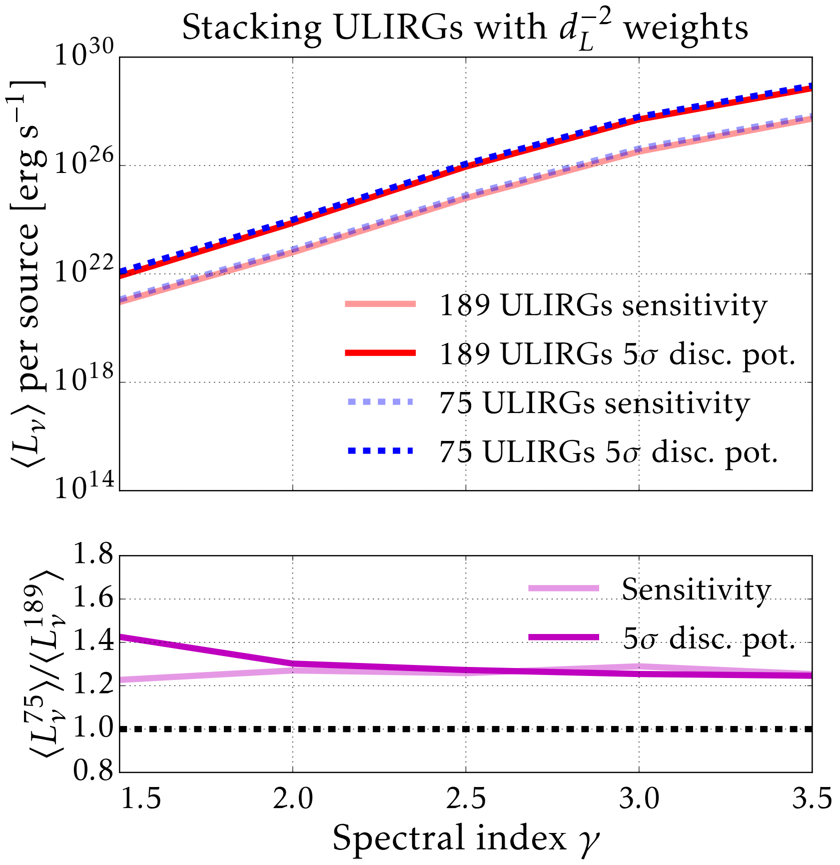
- Sensitive to 10–100 ULIRG neutrinos
  - More sensitive to harder spectra
  - Easier to distinguish from $E^{-3.7}$ background



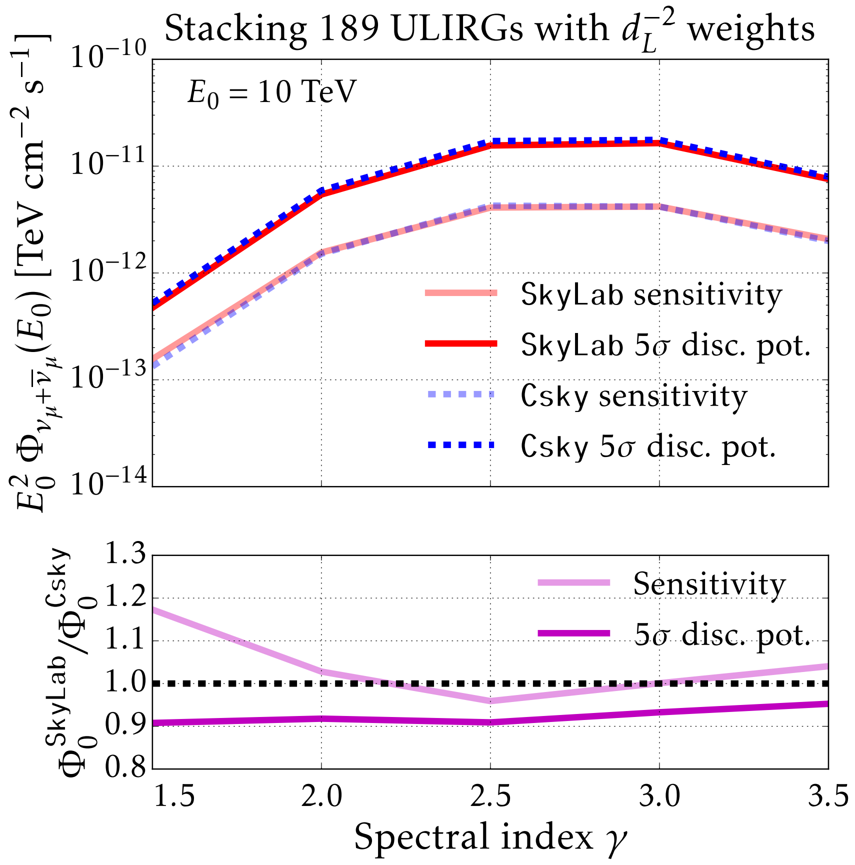
Crosschecks of Analysis Performance

LPNHE Paris

- Stacking 75 vs 189 ULIRGs
  - Small sensitivity loss of 20–40%



- Software comparison
  - Consistent results within 20%



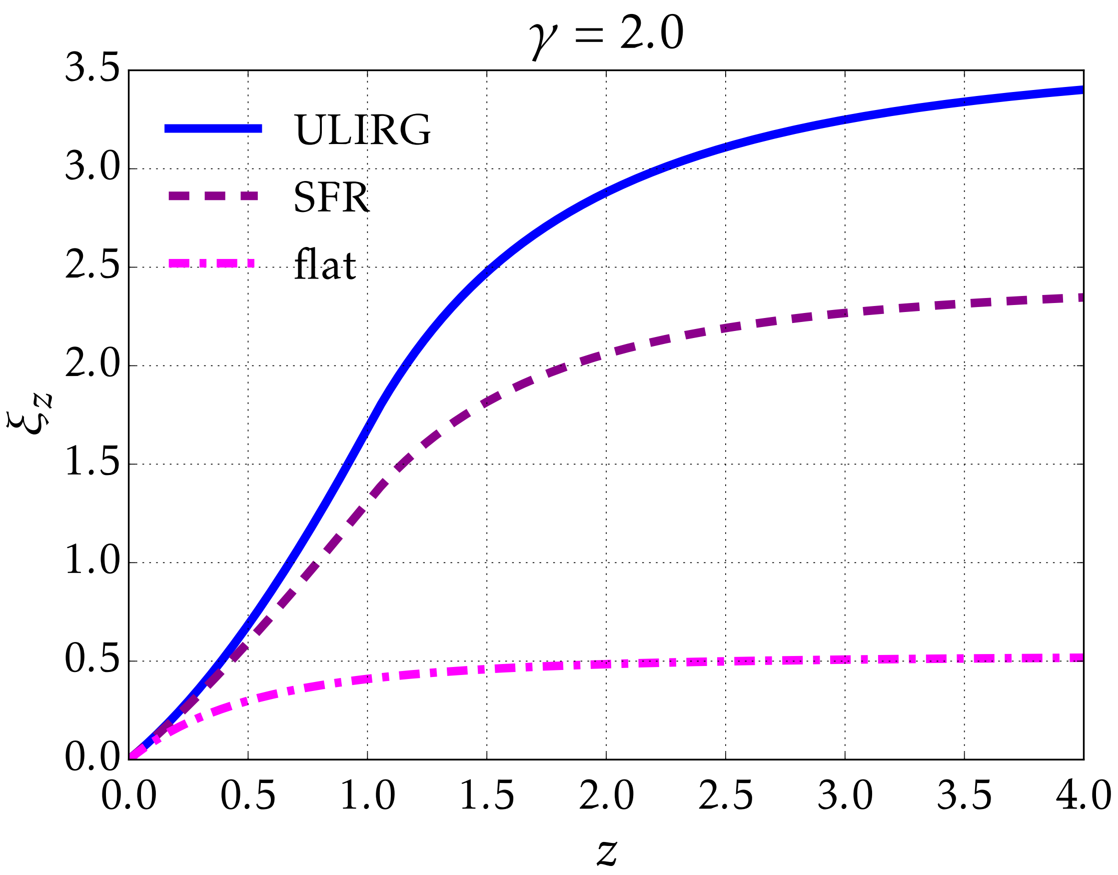
Redshift-Evolution Parameter

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

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

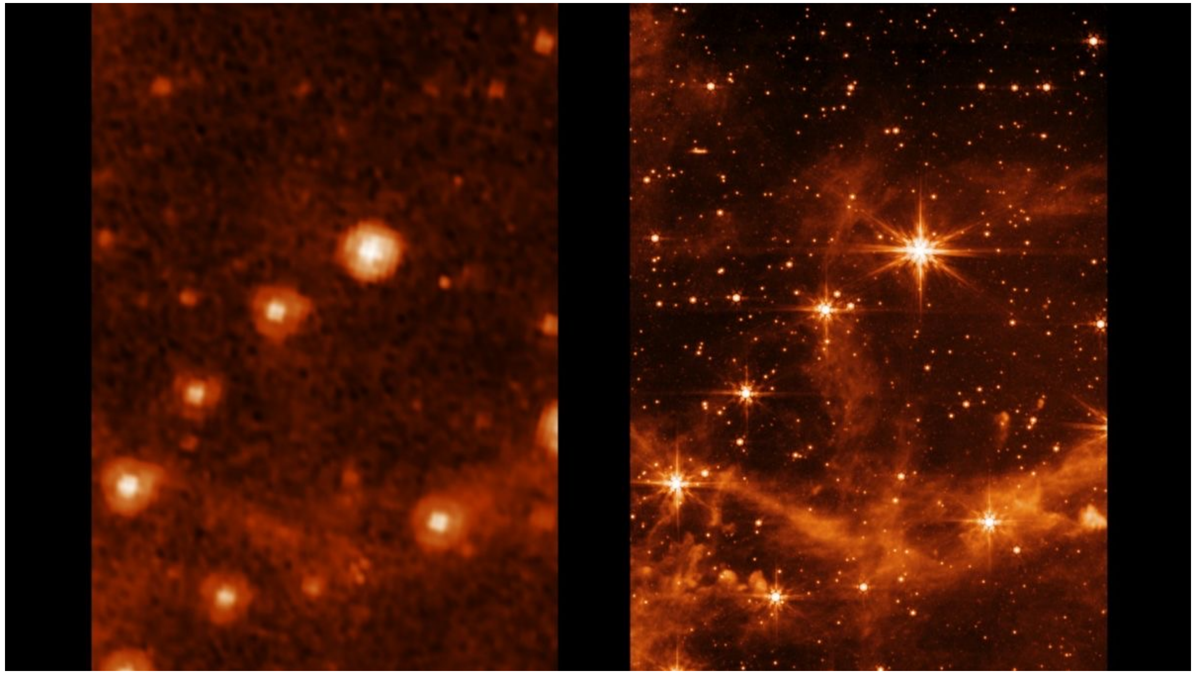
$$\mathcal{H}(z) = 1$$

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

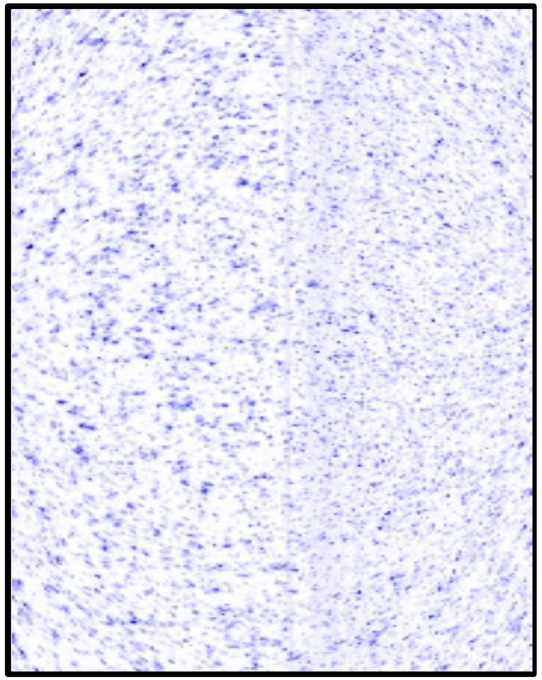


[Vereecken+ (2020) arXiv:2004.03435]

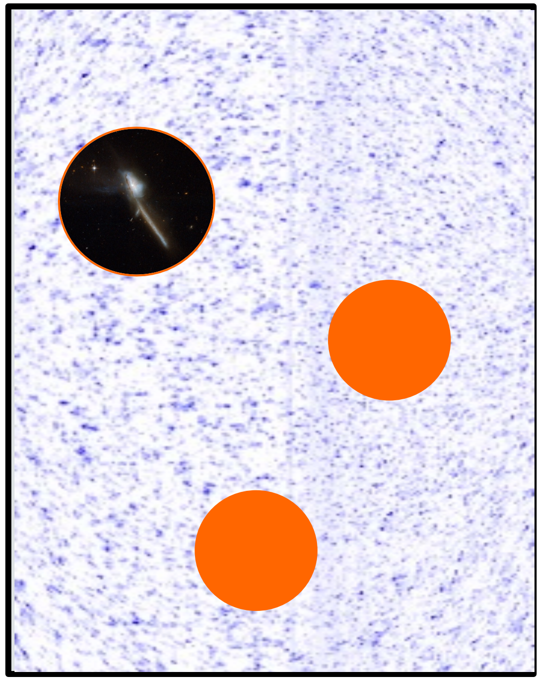
JWST vs IceCube-Gen2



Spitzer (2003) *James Webb* (2022)



IceCube (2021)



IceCube-Gen2? (2030+)