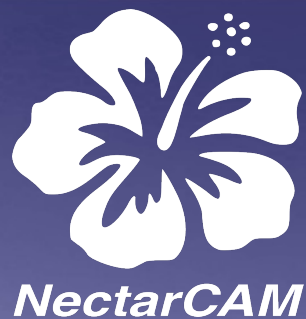


CTAO



LPNHE
PARIS

cnrs

Exploring the Multimessenger Emission of (Ultra)-Luminous Infrared Galaxies



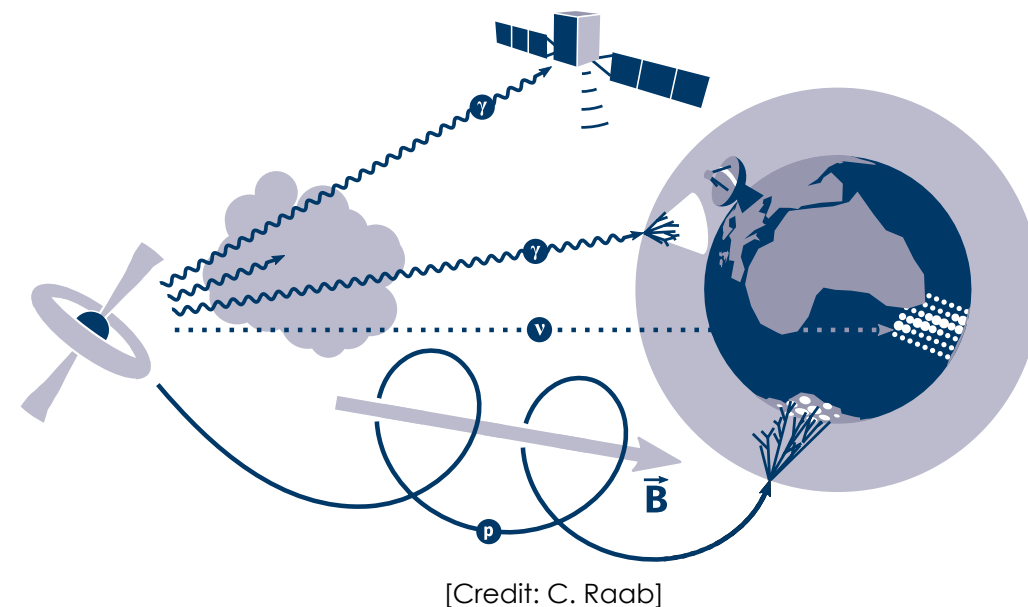
IFAE seminar
23 September 2026

Pablo Correa
pcorrea@lpnhe.in2p3.fr

Contents

1. Introduction to Multimessenger Astronomy*
2. The High-Energy Astrophysics of U/LIRGs
3. Probing U/LIRGs with TeV Neutrinos
4. Probing U/LIRGs with TeV Gamma Rays
5. Summary

*very brief



The High-Energy Universe

- ▶ **Violent processes** in the Universe accelerate particles up to high energies
- ▶ **High-energy cosmic messengers** allow us to study these processes

Galactic sources



Supernova remnants
(SNRs)

Pulsar wind nebulae
(PWNe)



and more

Extragalactic sources



Active galactic nuclei
(AGN)

Starburst galaxies

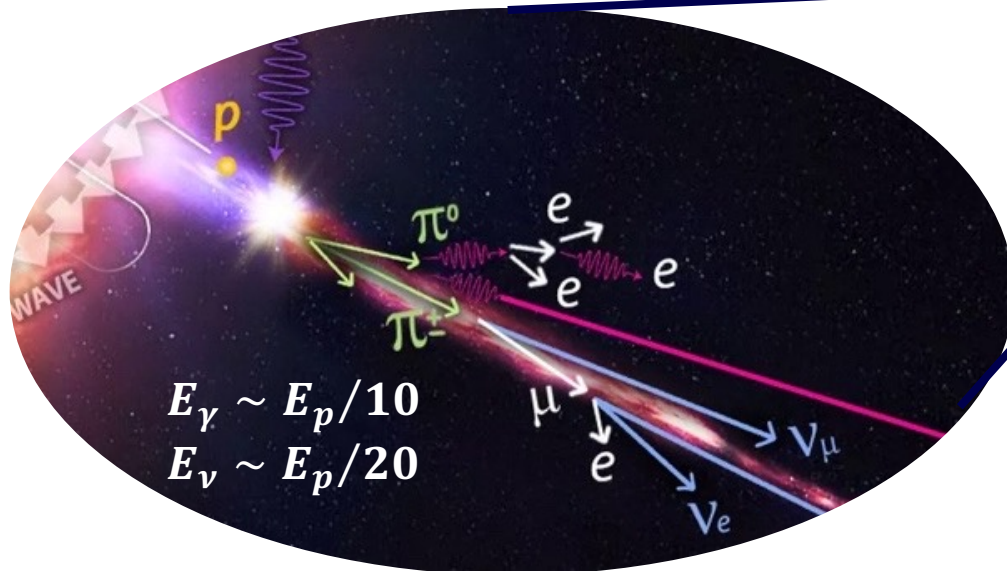


and more

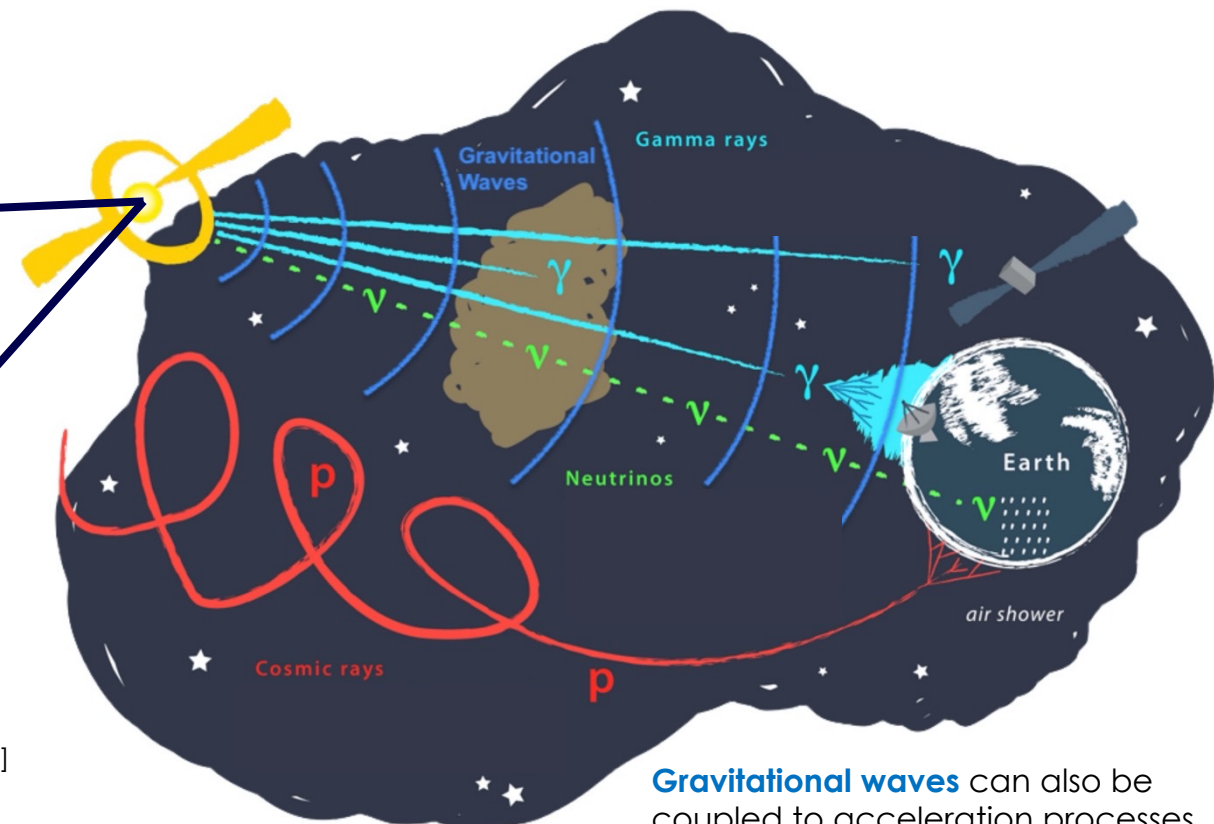
The Multimessenger Connection

- ▶ **Cosmic rays** (p)
 - ▶ **Energies** up to 3×10^{20} eV $\approx$ 48 J
 - ▶ **Deflected** by $\vec{B} \rightarrow$ **origin unknown!**
- ▶ **Gamma rays** (γ)
 - ▶ Produced in **leptonic & hadronic** processes
 - ▶ **Easy to detect but easily attenuated**

- ▶ **Neutrinos** (ν)
 - ▶ Smoking gun of **hadronic** interactions
 - ▶ **Not attenuated but hard to detect**



[IceCube/NSF]



Gravitational waves can also be coupled to acceleration processes

The Diffuse High-Energy Sky

EeV cosmic rays

- ▶ Cannot be confined by magnetic fields in Milky Way
- ▶ Sources must be **extragalactic**

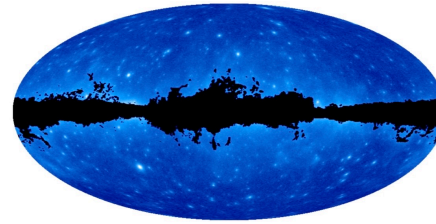
TeV–PeV neutrinos

- ▶ **Mostly extragalactic** (~90%)
- ▶ Sources remain largely unknown, but **first hints** are appearing

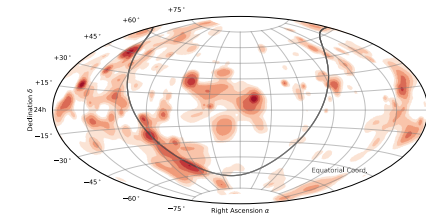
GeV gamma rays

- ▶ Extragalactic sky dominated by **blazars** (AGN with jet towards us)
- ▶ Gamma-ray bright sources in **tension** with neutrinos

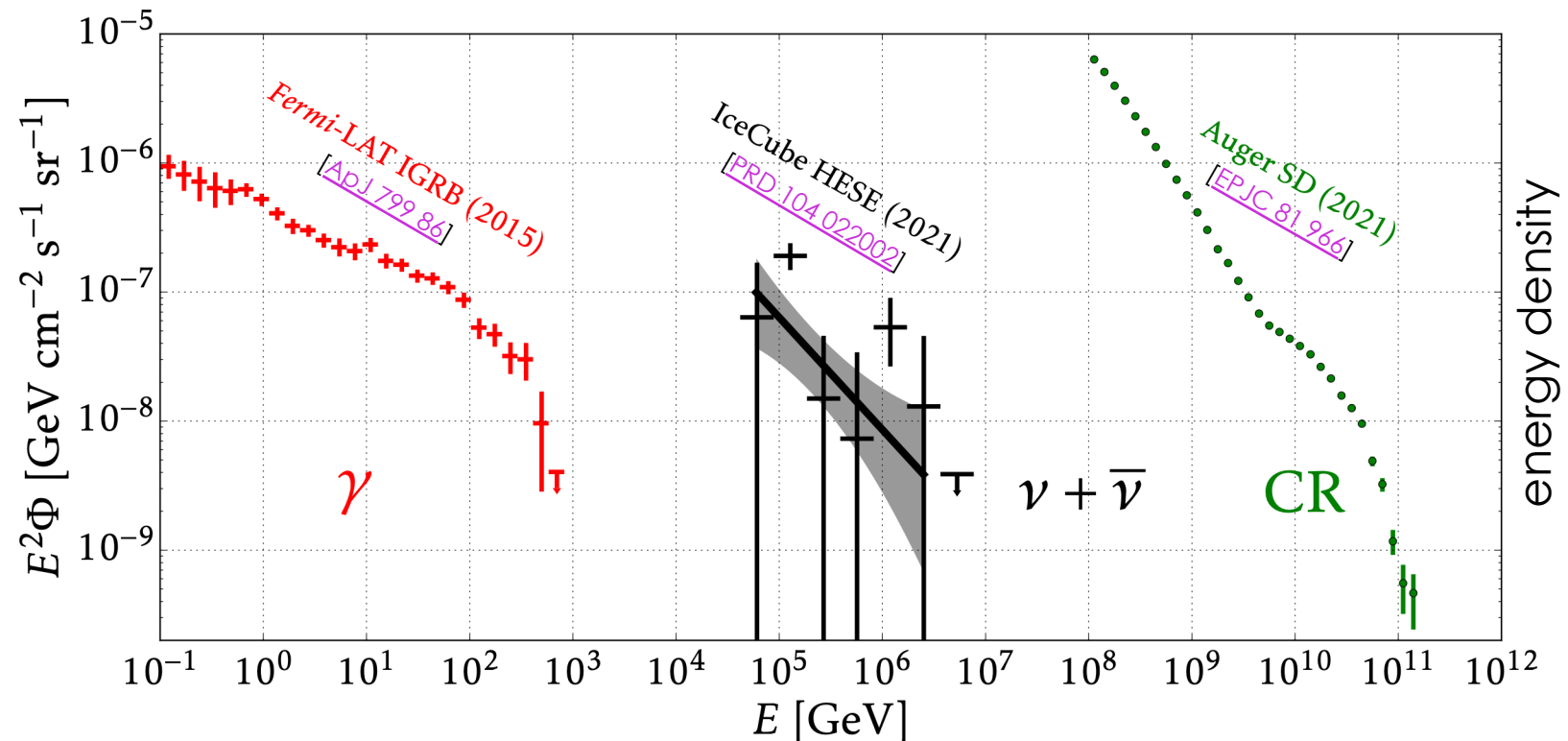
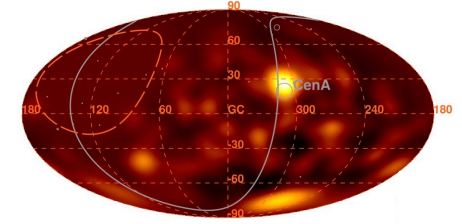
[Fermi-LAT (2017) ApJS 232 18]



[IceCube (2023) Science 380 1338]



[Auger (2018) ApJL 853 L29]

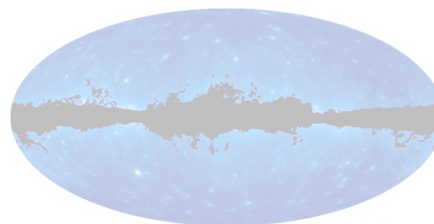


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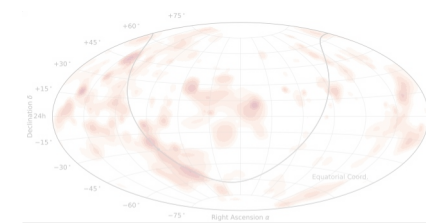
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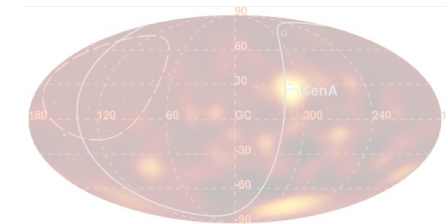
[Fermi-LAT (2017) ApJS 232 18]



[IceCube (2023) Science 380 1338]



[Auger (2018) ApJL 853 L29]



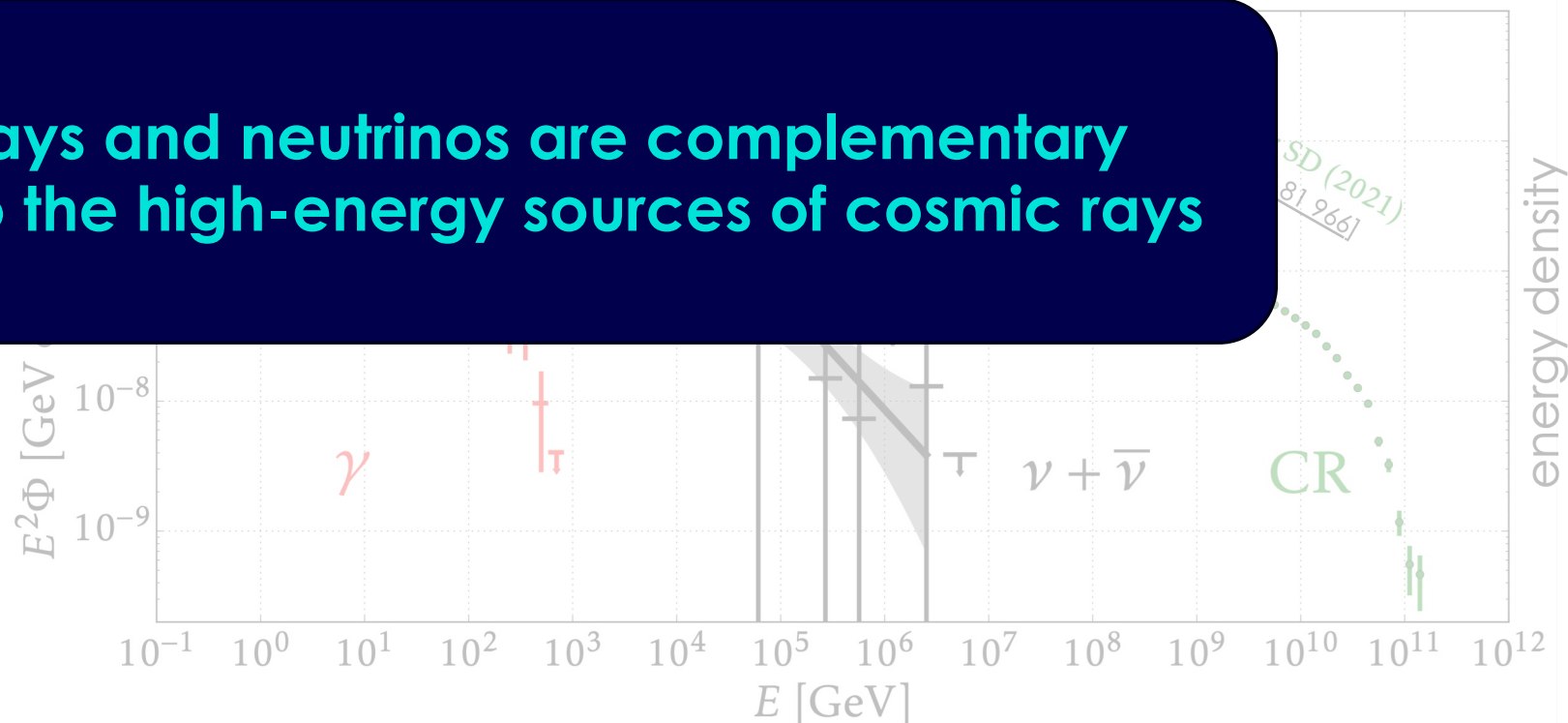
Gamma rays and neutrinos are complementary windows into the high-energy sources of cosmic rays

TeV-PeV

- ▶ Mostly extragalactic
- ▶ Sources remain elusive but **first hints** are appearing

GeV gamma rays

- ▶ Extragalactic sky dominated by **blazars** (AGN with jet towards us)
- ▶ Gamma-ray bright sources in **tension** with neutrinos



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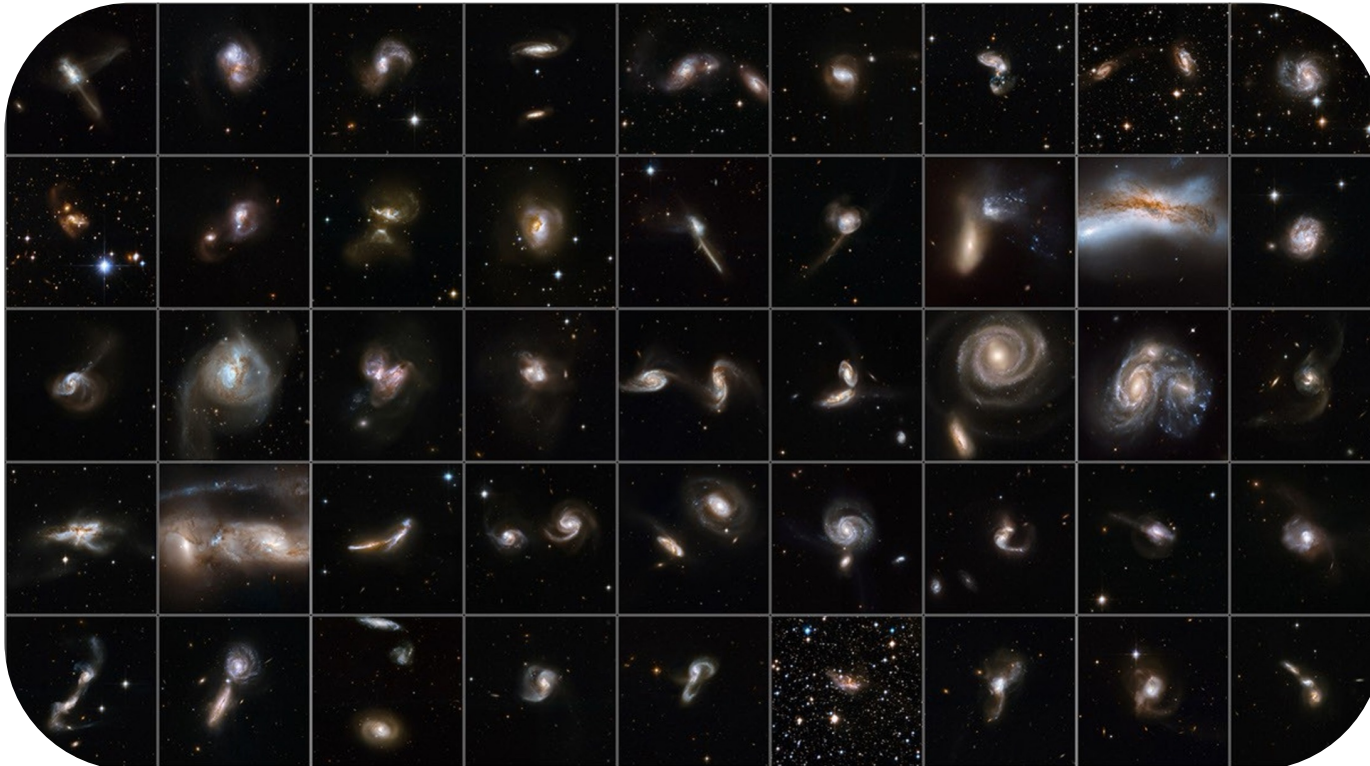
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[\[NASA/ESA/CSA – James Webb\]](#)

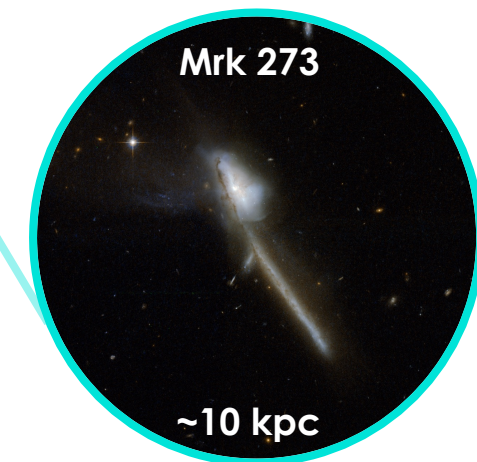
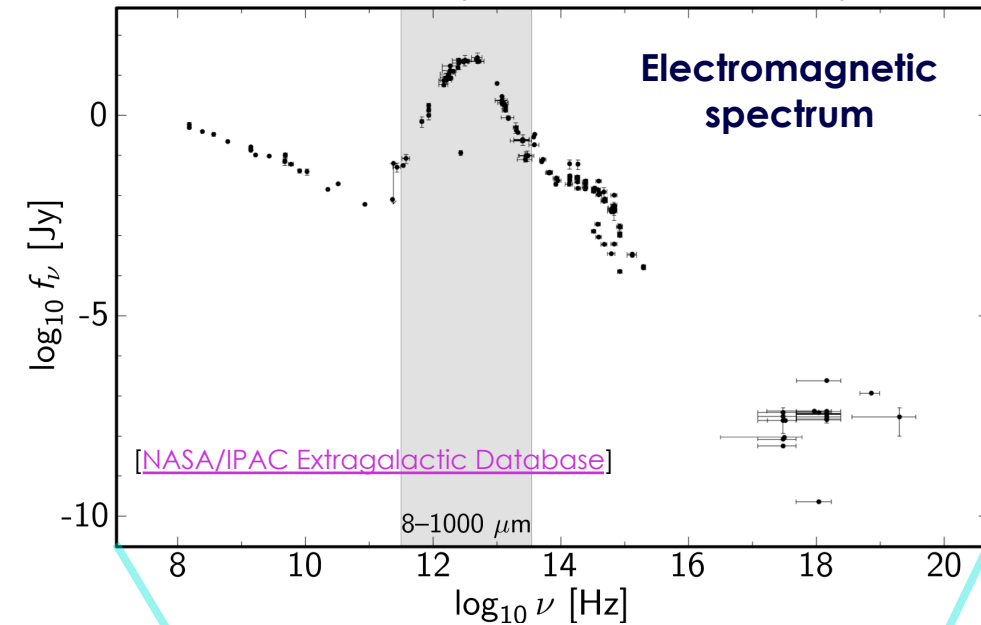
(Ultra)-Luminous Infrared Galaxies

- ▶ The **most luminous** objects in the **IR** sky
 - ▶ **LIRGs:** $L_{IR} \geq 10^{11} L_{\odot}$ ▶ **ULIRGs:** $L_{IR} \geq 10^{12} L_{\odot}$
 - ▶ Triggered by **galaxy interactions & bar instabilities**



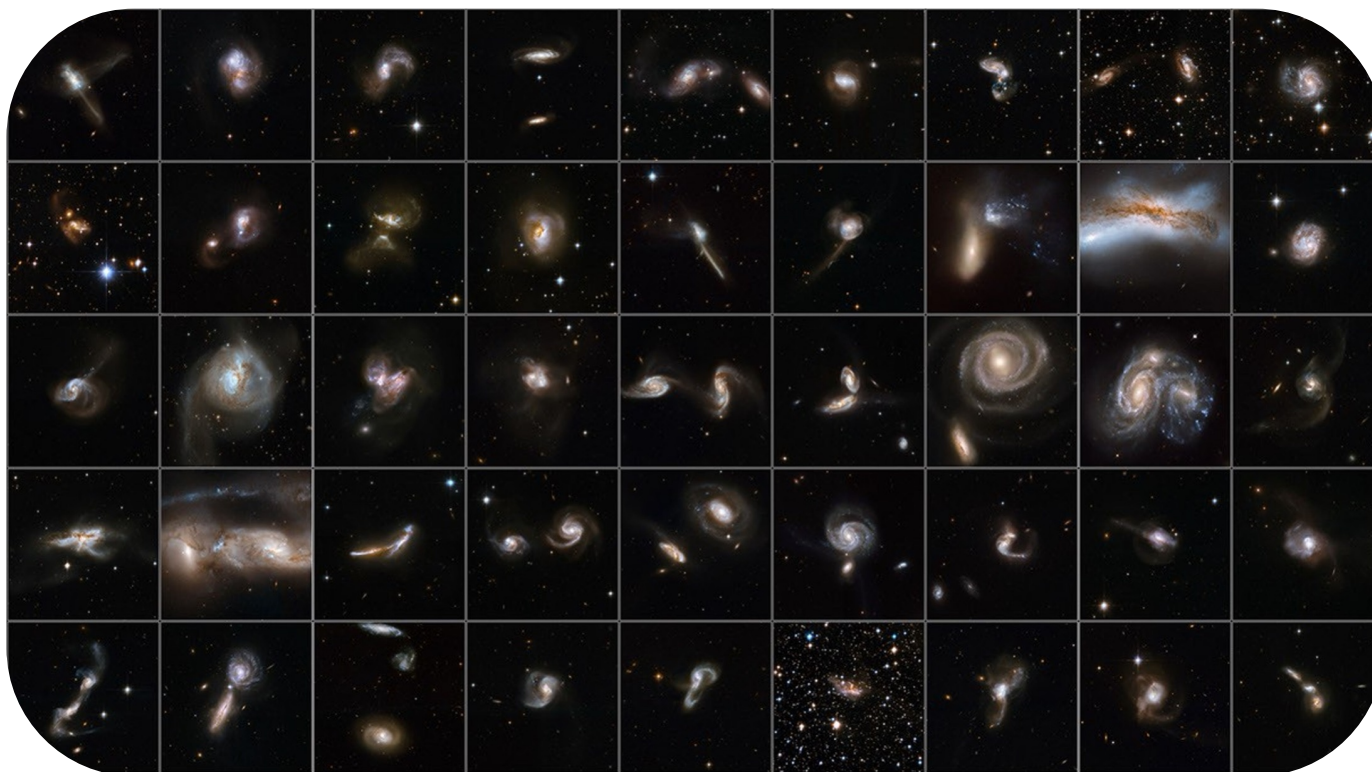
[NASA/ESA – Hubble]

MRK 273 (“Toothbrush Galaxy”)



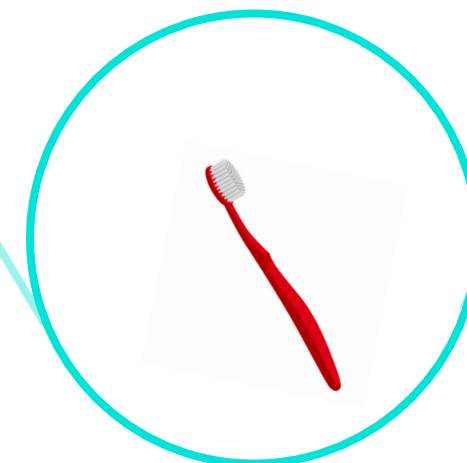
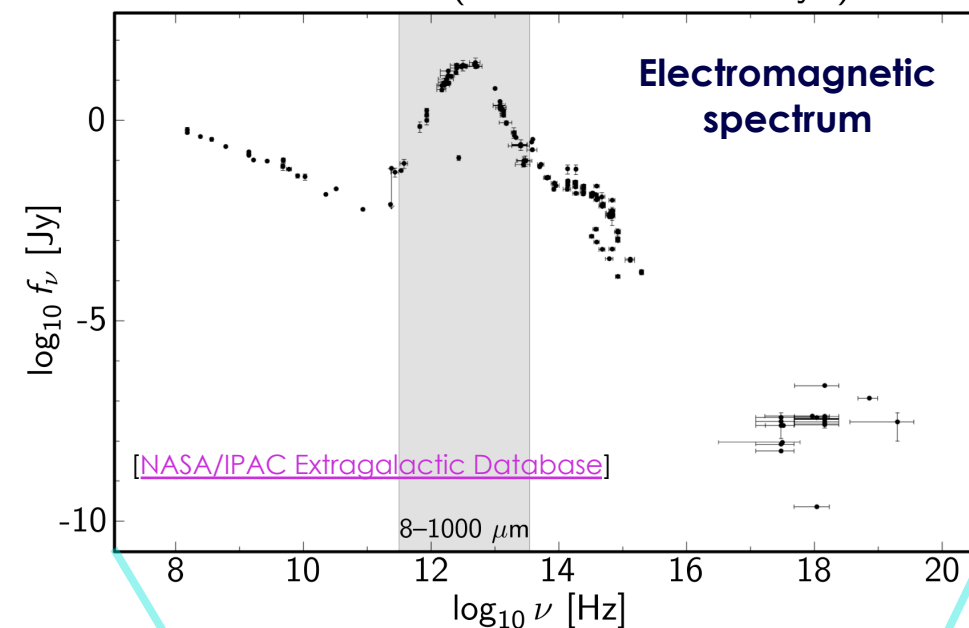
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[NASA/ESA – Hubble]

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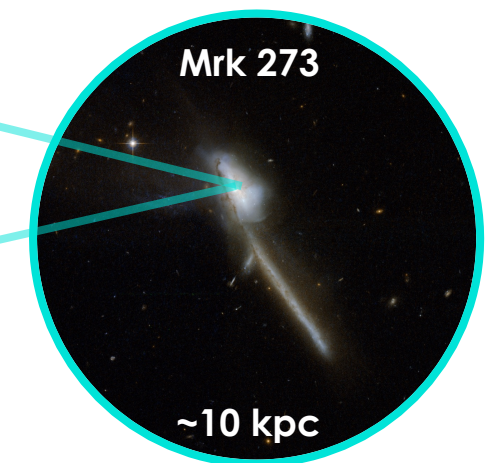
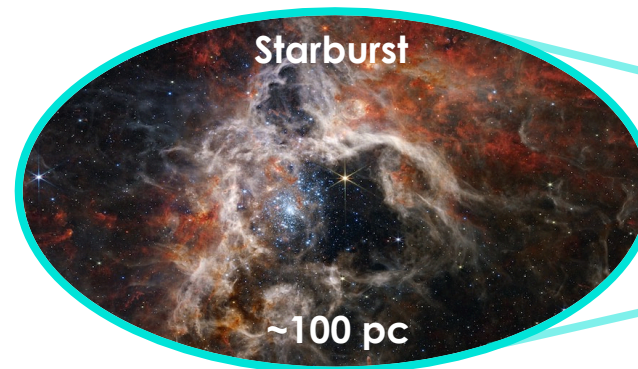


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- ▶ Mostly powered by **(circum)nuclear starburst**
 - ▶ **Gas & dust** reprocess UV emission from young stars to IR

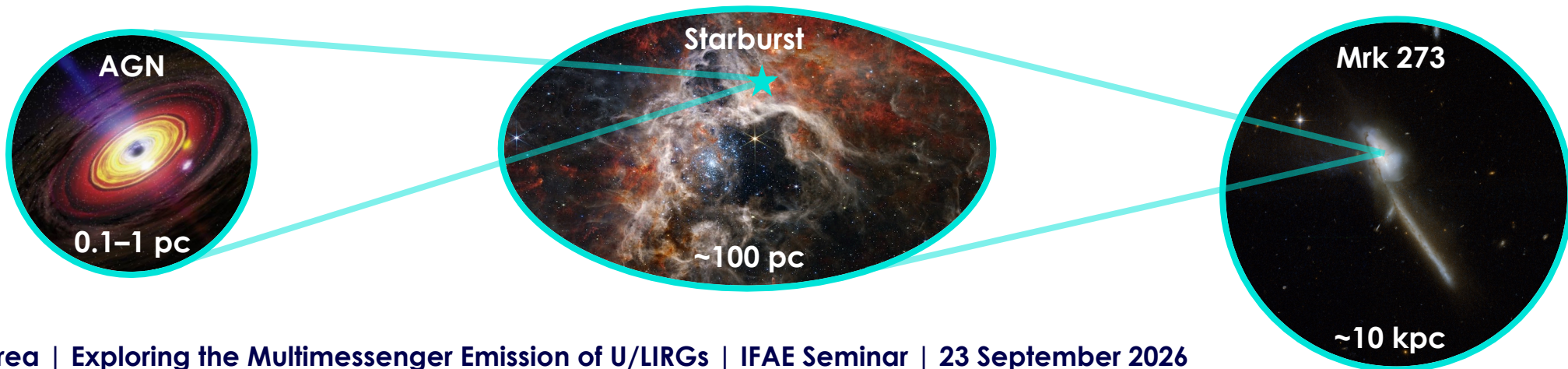
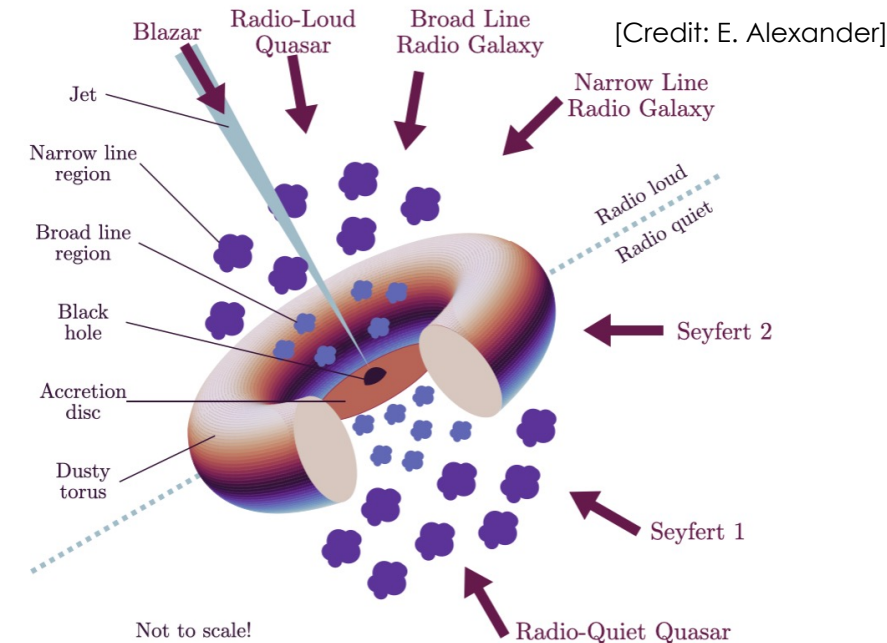


[NASA/ESA – Hubble]



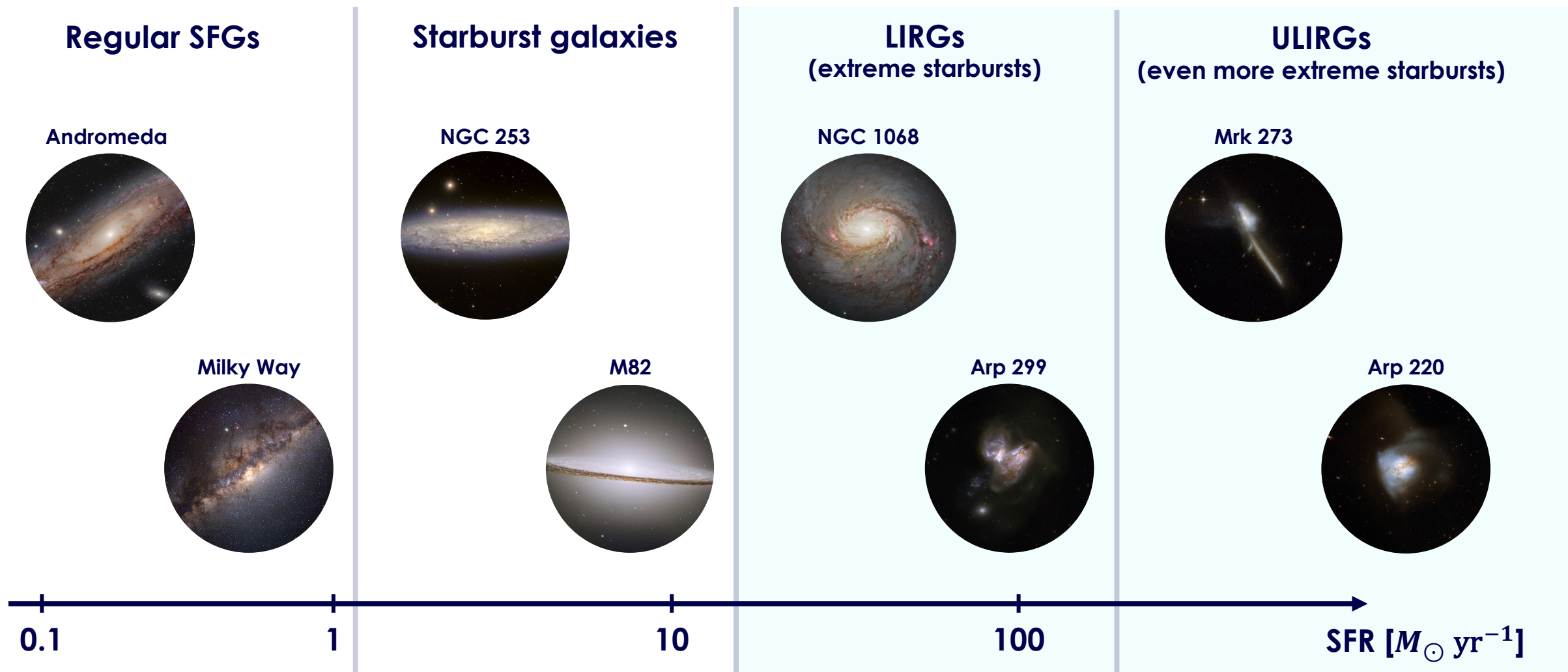
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- ▶ Mostly powered by **(circum)nuclear starburst**
 - ▶ **Gas & dust** reprocess UV emission from young stars to IR
- ▶ Secondary contribution from **AGN** (~10%)
 - ▶ Typically **dust-obscured Seyferts**
 - ▶ **Dust** reprocesses AGN emission from core to IR



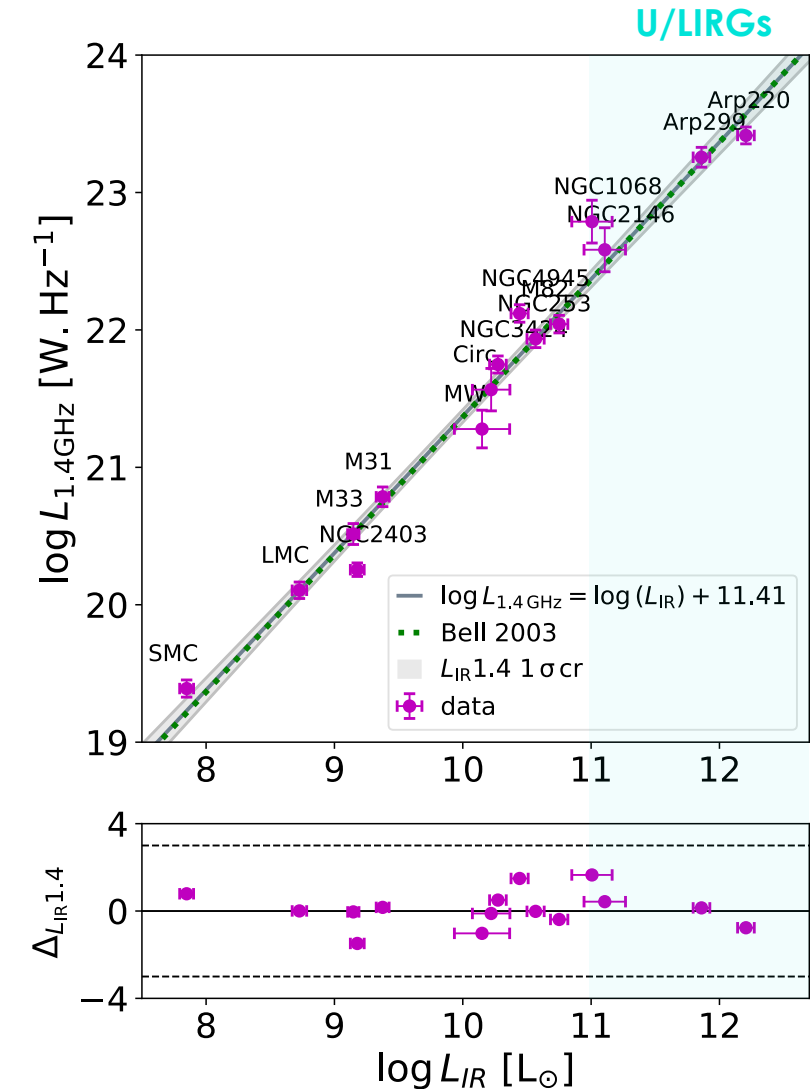
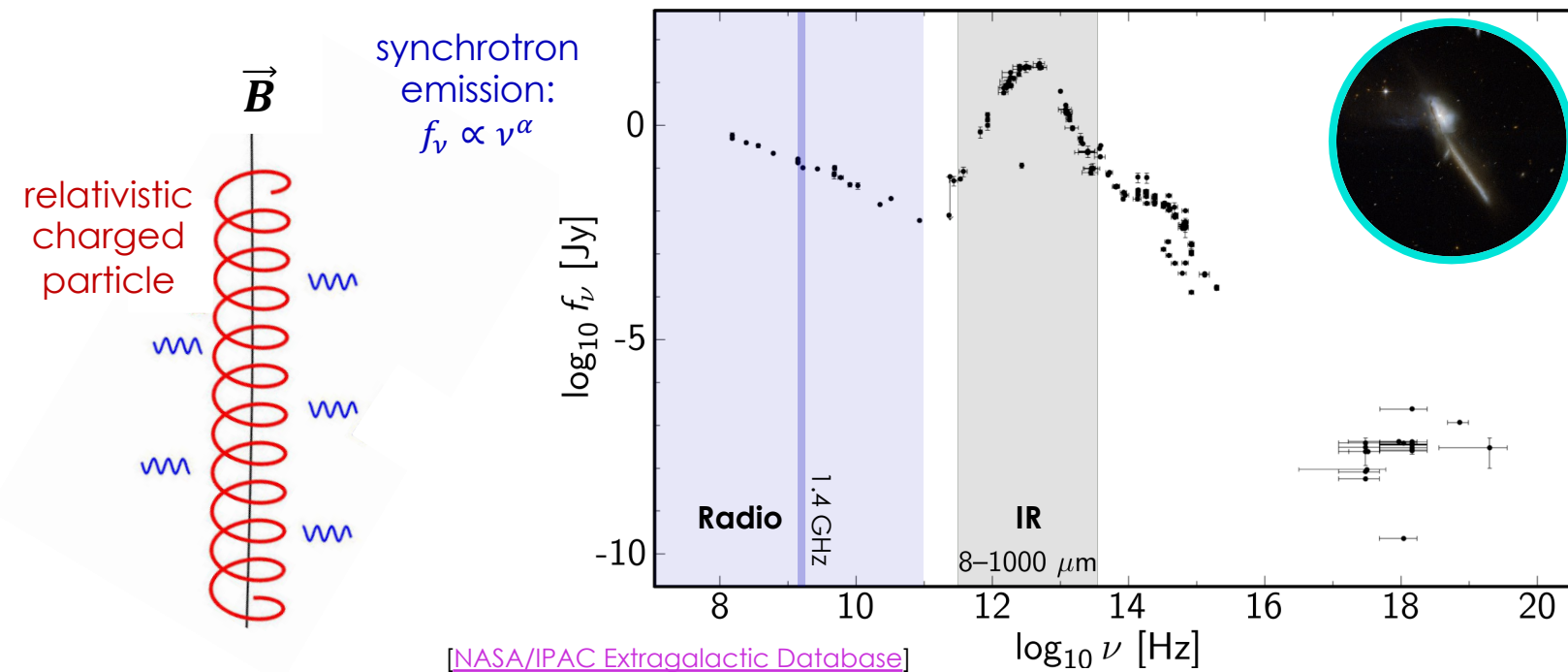
Range of Star-Forming Galaxies

$$\text{SFR} \propto 10^{-10} L_{\text{IR}}/L_{\odot}$$



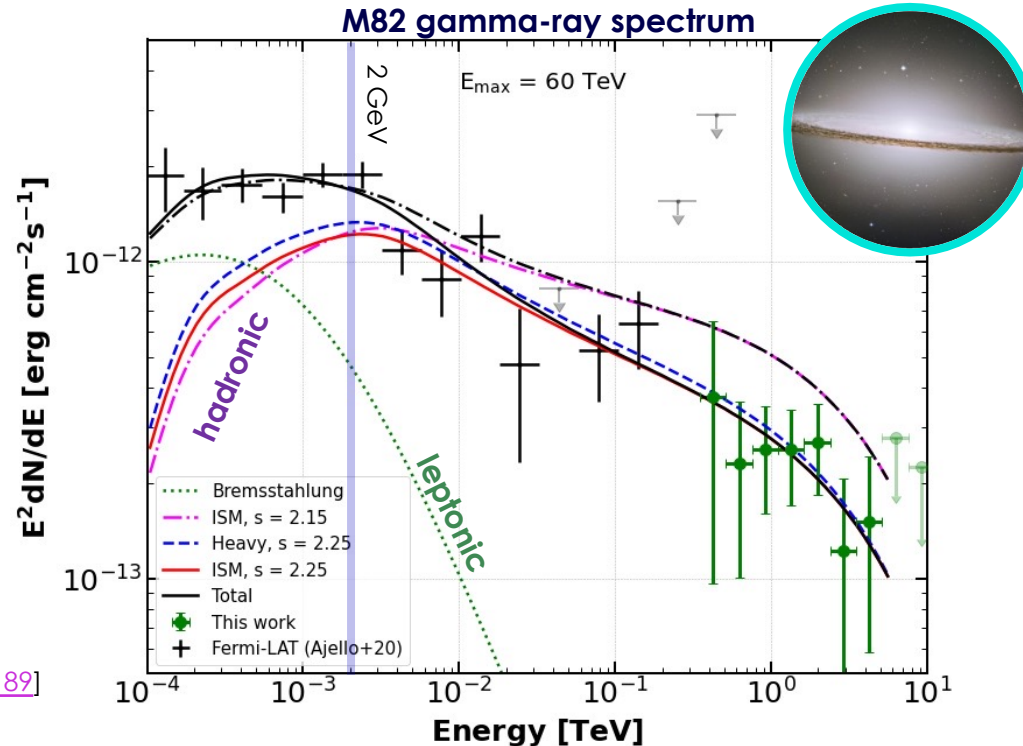
The Radio-Infrared Correlation of SFGs

- ▶ IR traces **star-forming activity**
- ▶ Radio traces non-thermal **particle acceleration**
- ▶ **Radio-IR correlation observed across SFG population**

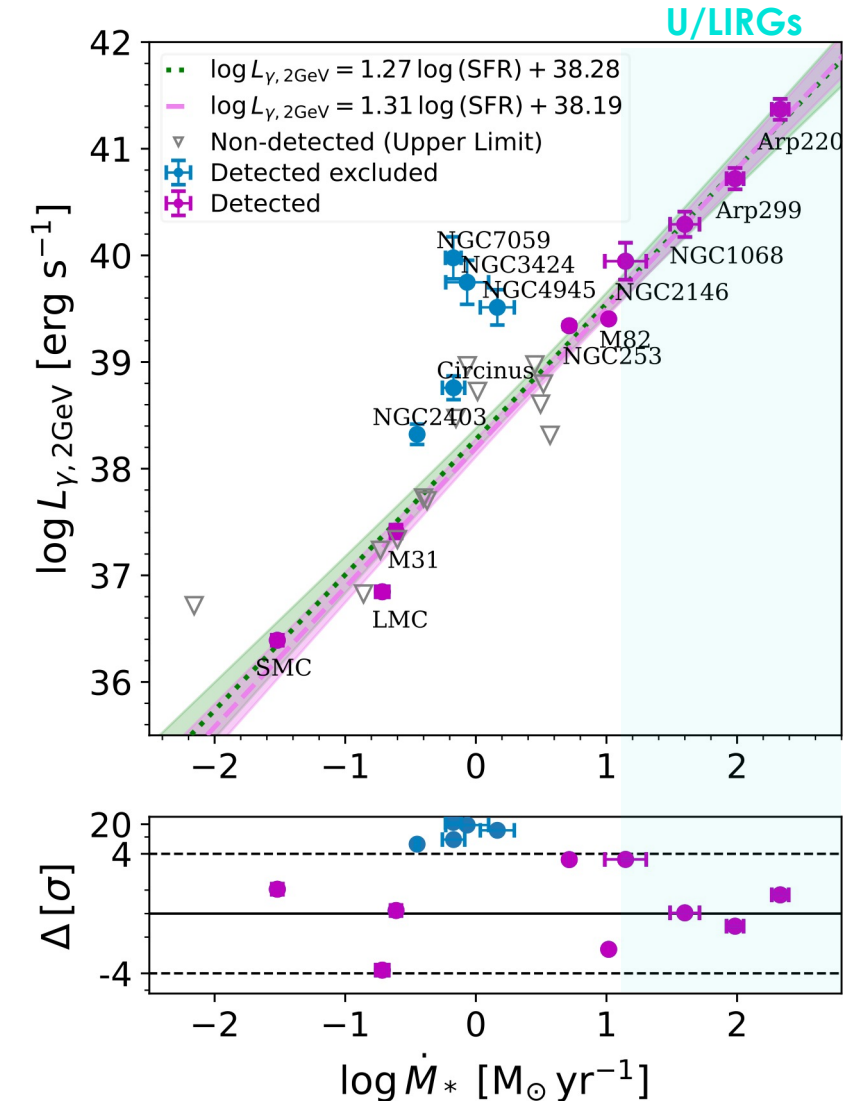


The Gamma-SFR Correlation of SFGs

- SFGs are **established gamma-ray sources**
- Gamma-ray emission requires **hadronic component**
- **Gamma-SFR correlation observed across population**



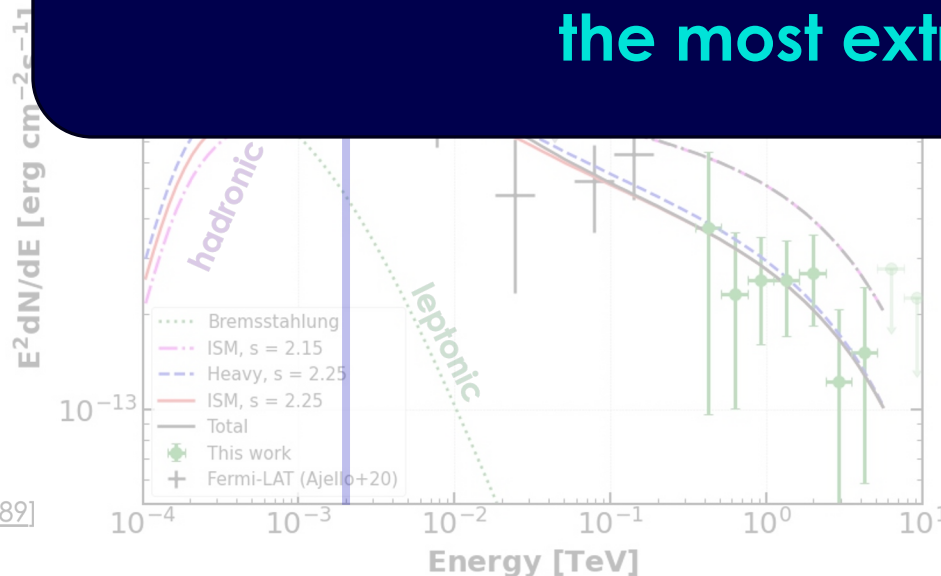
[VERITAS (2025) ApJ 981 189]



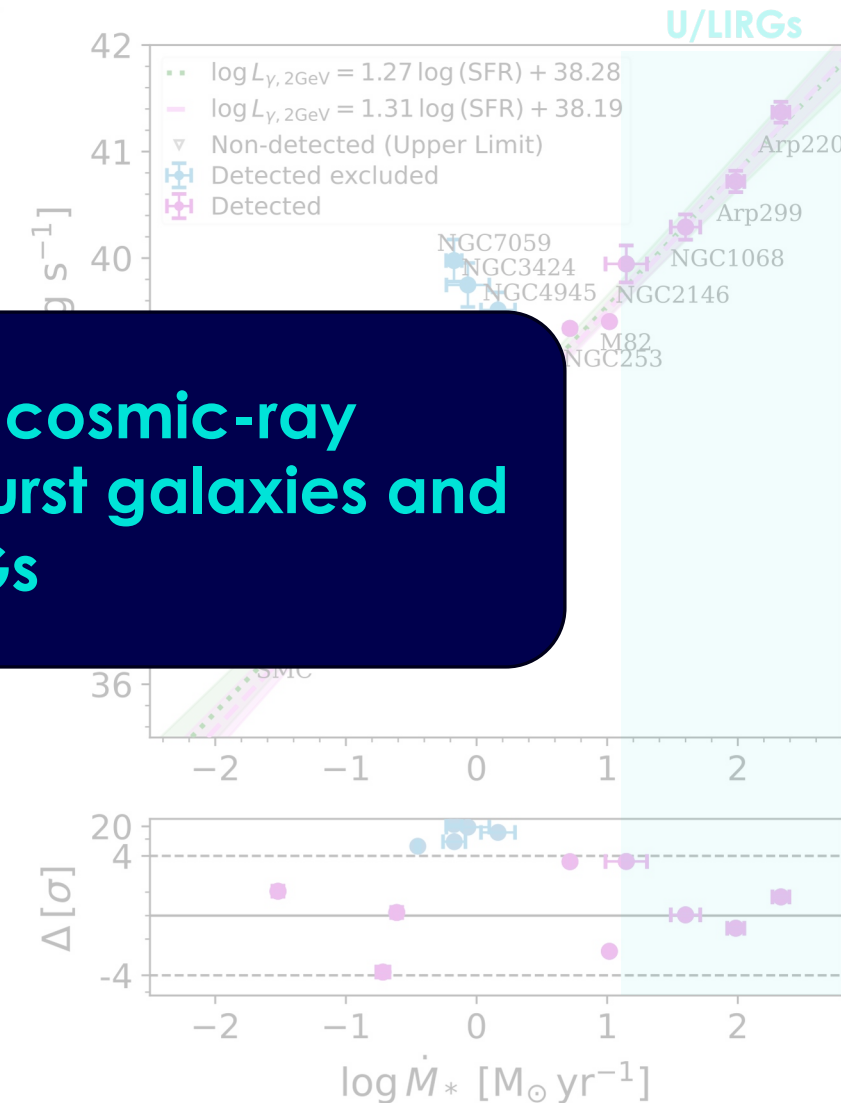
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Star formation is directly related to cosmic-ray acceleration from regular SFGs to starburst galaxies and the most extreme U/LIRGs



[VERITAS (2025) ApJ 981 189]



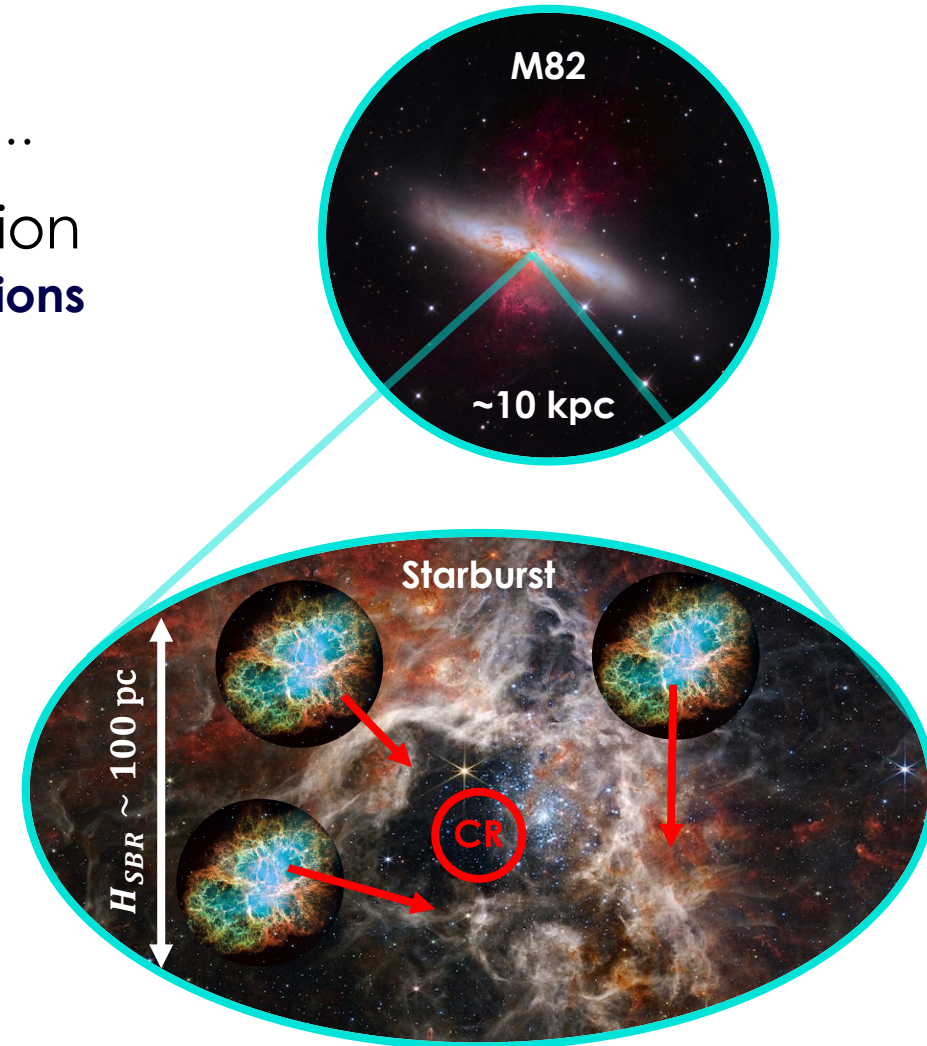
[Kornecki+ (2025) A&A 699 A43]

Starbursts as Cosmic-Ray Reservoirs

- ▶ Enhanced SFR yields **enhanced supernova rate**
 - ▶ **Cosmic-ray acceleration up to ~10–100 PeV** in SNRs, PWNe,...
- ▶ Cosmic rays perform **random walk** in starburst region
 - ▶ **Leaky box**: Lifetime τ depends on **propagation and interactions**

$$\tau = \left[\tau_{\text{diff}}^{-1} + \tau_{\text{adv}}^{-1} + \tau_{\text{pp}}^{-1} \right]^{-1}$$

[e.g. [Peretti+ \(2019\) MNRAS 487 168](#); [Ambrosone+ \(2021\) MNRAS 503 4032](#)]



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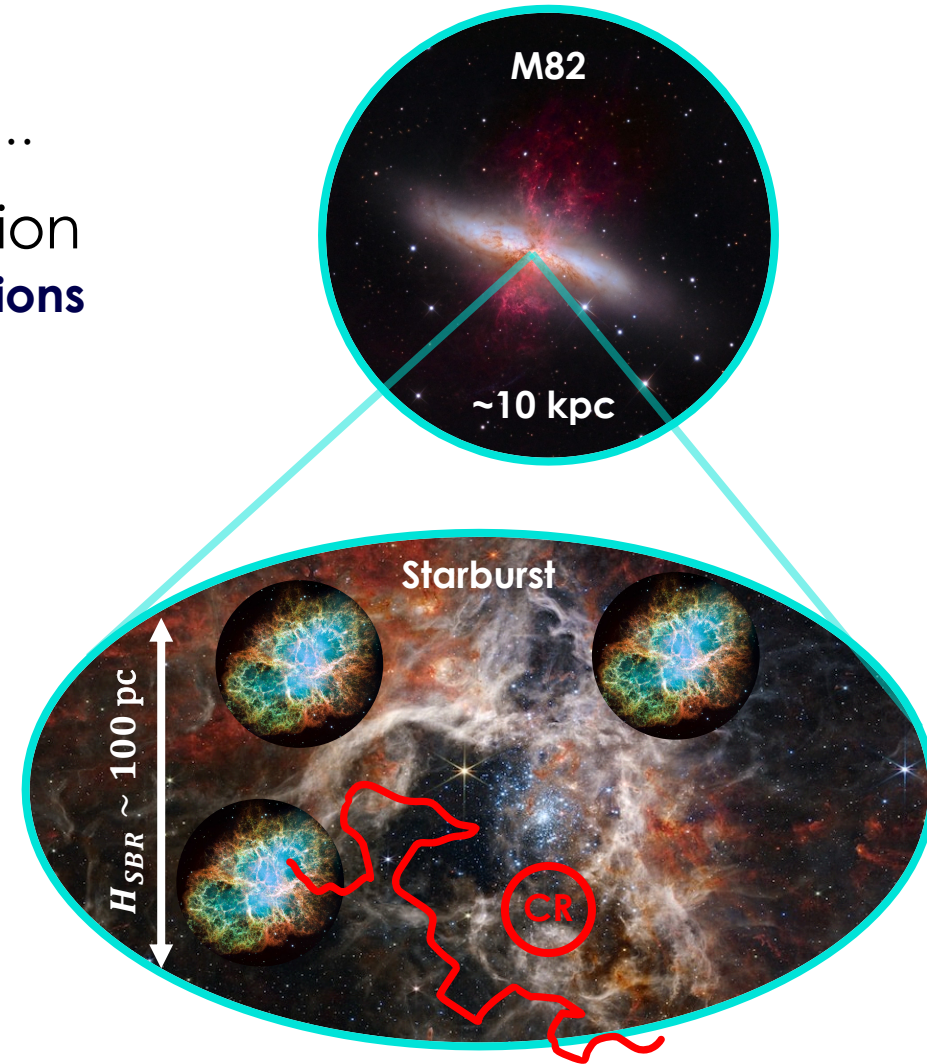
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Diffusion by magnetic fields

$$\tau_{\text{diff}} = \frac{H_{\text{SBR}}^2}{D}$$

Depends on
magnetic-field strength
 $B \sim 0.1\text{--}1 \text{ mG}$



Starbursts as Cosmic-Ray Reservoirs

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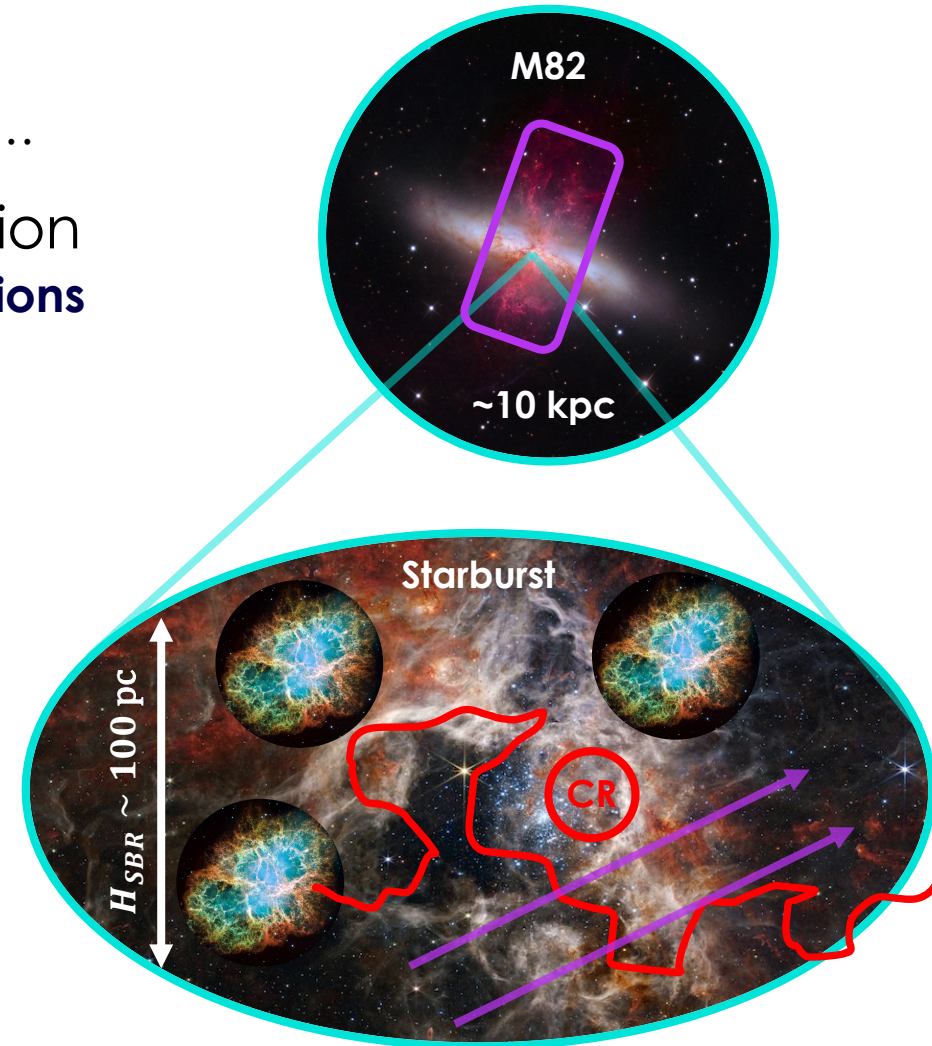
$$\tau_{\text{diff}} = \frac{H_{\text{SBR}}^2}{D}$$

Depends on
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 $B \sim 0.1\text{--}1$ mG

Advection by galactic superwinds

$$\tau_{\text{adv}} = \frac{H_{\text{SBR}}}{v_{\text{adv}}}$$

Depends on
superwind velocity
 $v_{\text{adv}} \sim 500\text{--}1500$ km s⁻¹



Starbursts as Cosmic-Ray Reservoirs

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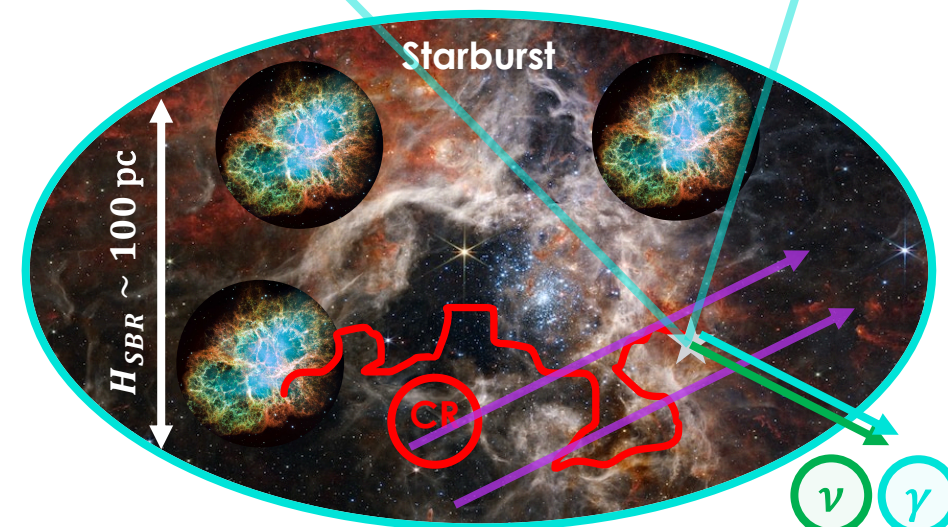
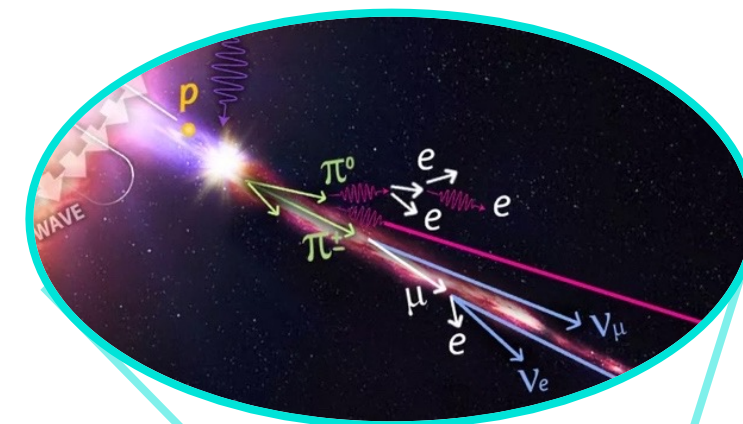
$$\tau_{\text{adv}} = \frac{H_{\text{SBR}}}{v_{\text{adv}}}$$

Depends on
superwind velocity
 $v_{\text{adv}} \sim 500\text{--}1500 \text{ km s}^{-1}$

Interactions with ambient gas

$$\tau_{\text{pp}} = \frac{1}{n \cdot \sigma_{\text{pp}}(E) \cdot c \cdot \zeta}$$

Depends on
gas density
 $n \gtrsim 100 \text{ cm}^{-3}$

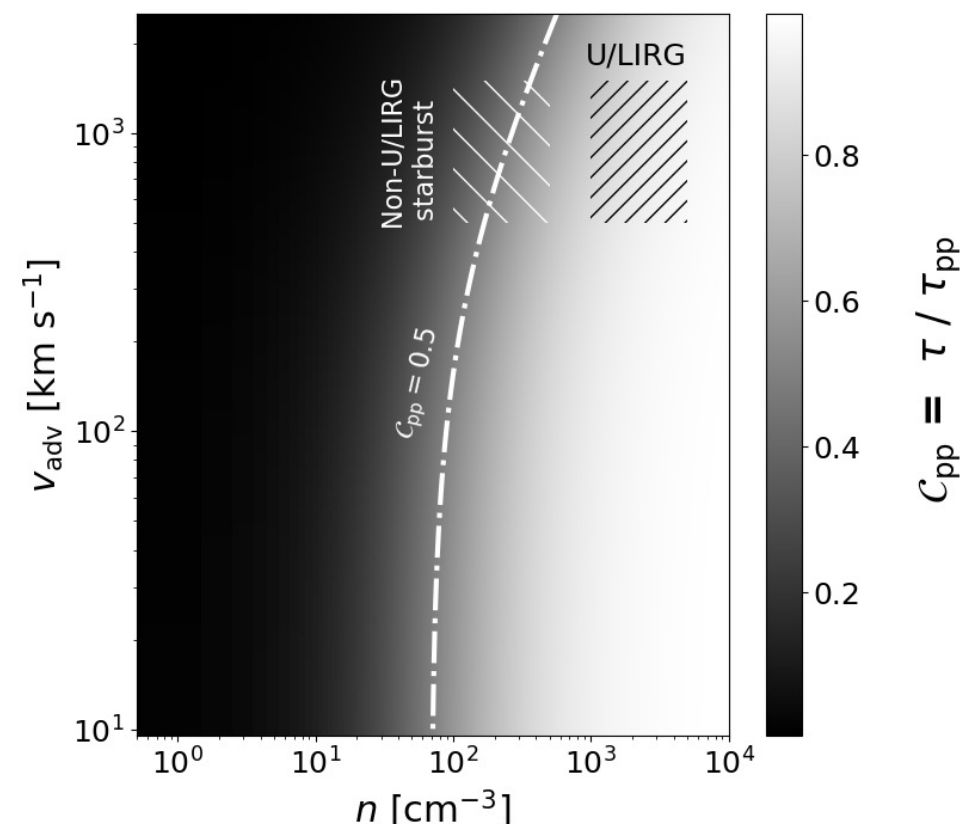
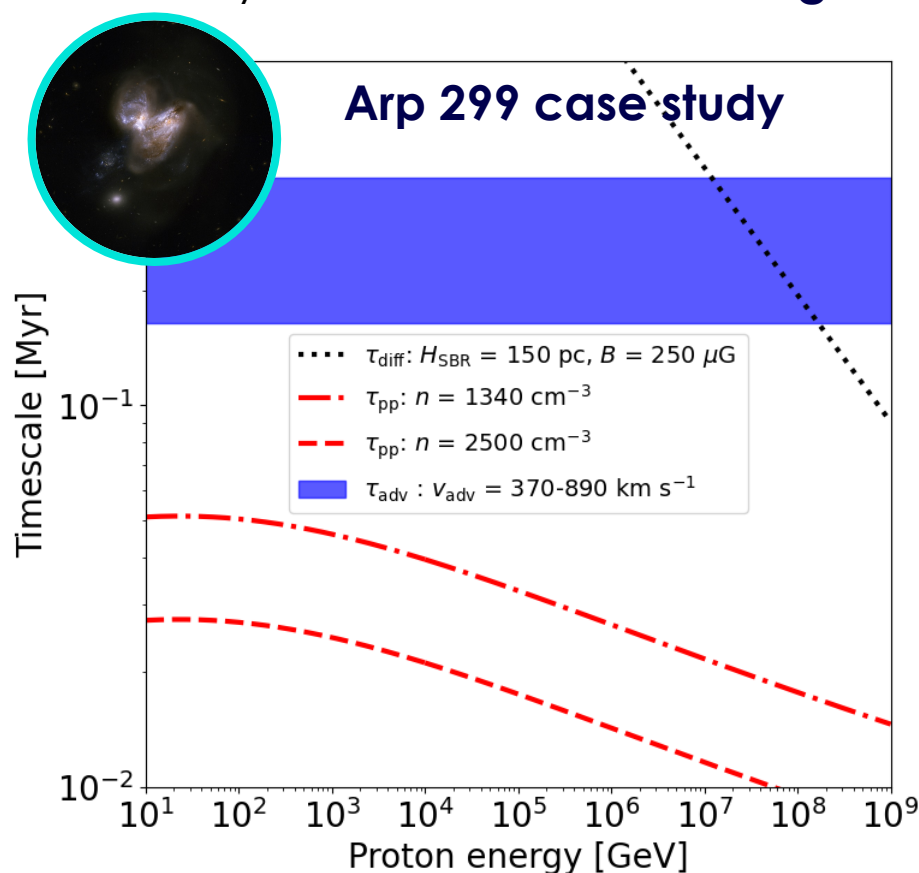


Starburst Activity in U/LIRGs

- ▶ U/LIRGs are expected to approach **calorimetric limit**
 - ▶ Much **larger gas densities** compared to regular starburst galaxies
 - ▶ Most cosmic rays **interact with ambient gas before escaping**

$$\tau = [\tau_{\text{diff}}^{-1} + \tau_{\text{adv}}^{-1} + \tau_{\text{pp}}^{-1}]^{-1}$$

[[Merckx, PC+ \(2023\) PRD 108 023015](#)]



Starburst Activity in U/LIRGs

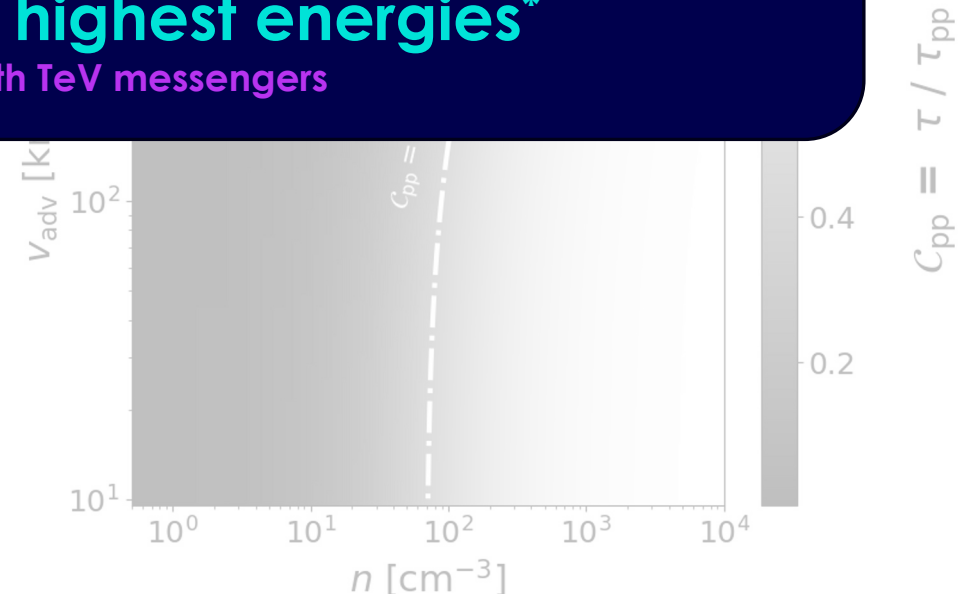
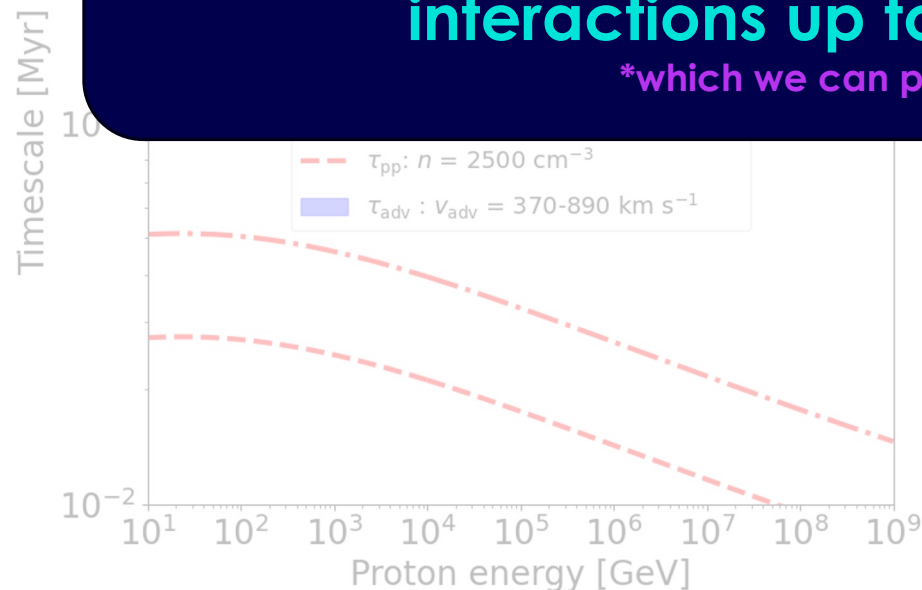
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[Merckx, **PC+** (2023) PRD 108 023015]

U/LIRGs are the most extreme star-forming systems to study cosmic-ray acceleration, transport, and interactions up to the highest energies*

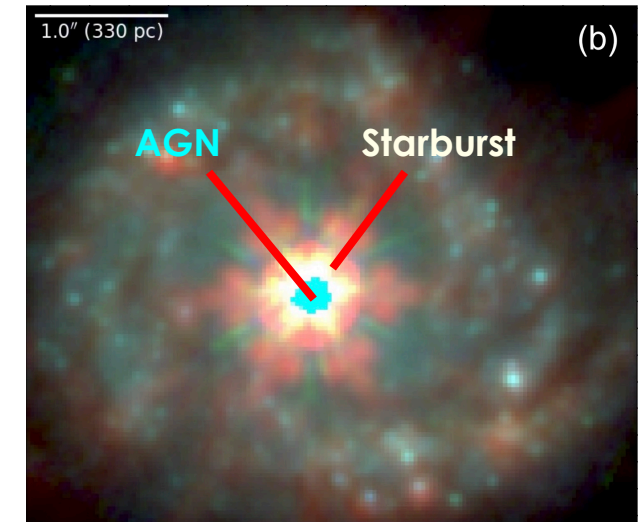
**which we can probe with TeV messengers*



Seyfert Activity in U/LIRGs

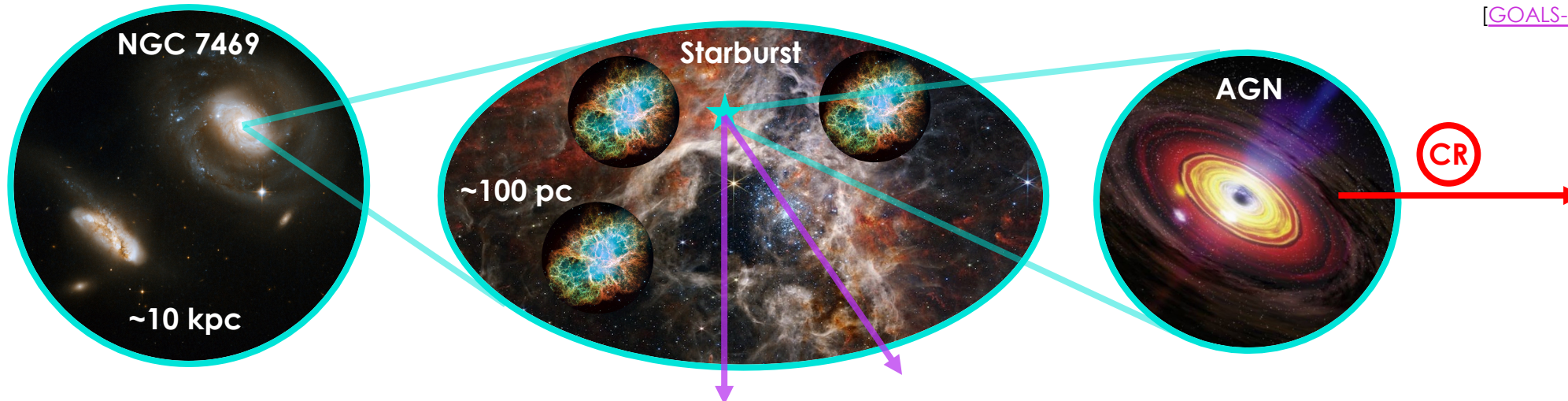
- ▶ **AGN is also candidate cosmic-ray source**
 - ▶ **Cosmic-ray acceleration up to at least 100 PeV possible** via magnetic reconnection and turbulence in **AGN corona, ultra-fast outflows**,...
 - ▶ **AGN feedback** can influence surrounding starburst

James Webb image of NGC 7469



[GOALS-JWST (2023) ApJL 942 L36]

[e.g. [Murase+ \(2020\) PRL 125 011101](#); [Le Nagat Neher+ \(2026\) A&A 709 A91](#); [Vereecken \(2019\) PhD thesis](#)]

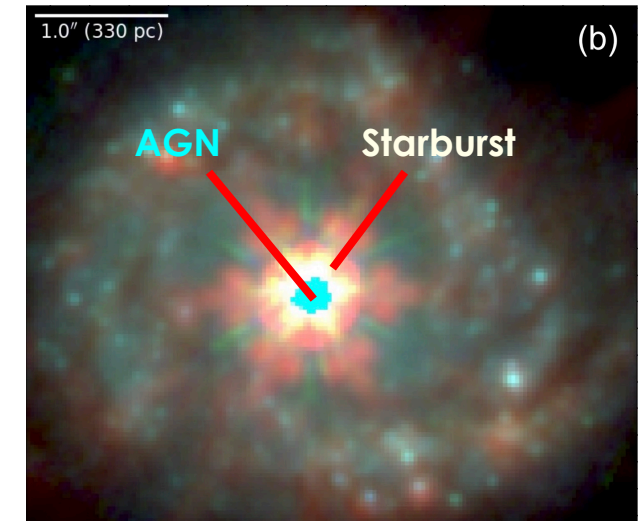


Seyfert Activity in U/LIRGs

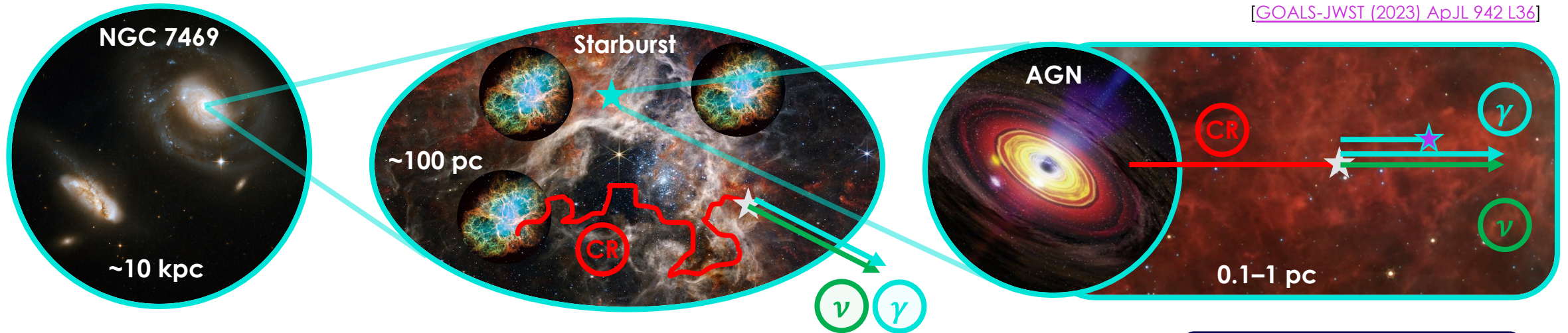
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 - ▶ **AGN feedback** can influence surrounding starburst
 - ▶ **Cosmic rays interact** near AGN environment
 - ▶ **Dense photon fields** (IR-optical-UV): $u_{rad} \gtrsim 10^5 \text{ erg cm}^{-3}$
 - ▶ **Compton-thick gas columns**: $N_H \gtrsim 10^{24} \text{ cm}^{-2}$
- } Can attenuate gamma rays!

[e.g. [Murase+ \(2020\) PRL 125 011101](#); [Le Nagat Neher+ \(2026\) A&A 709 A91](#); [Vereecken \(2019\) PhD thesis](#)]

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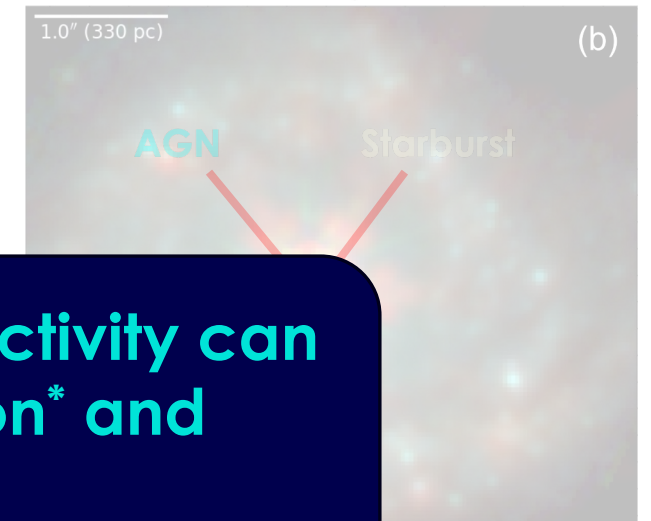
[GOALS-JWST (2023) ApJL 942 L36]



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James Webb image of NGC 7469



U/LIRGs are composite systems where AGN activity can lead to additional cosmic-ray acceleration* and influence surrounding starburst

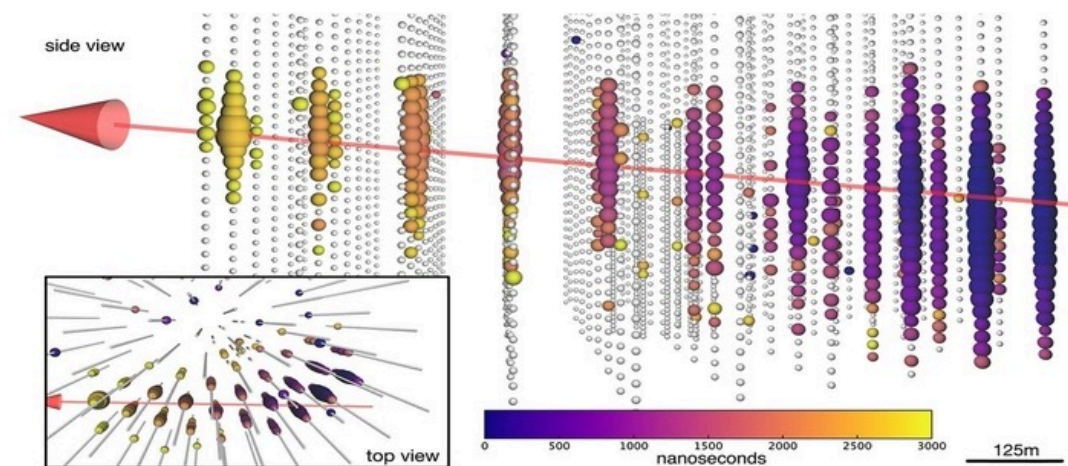
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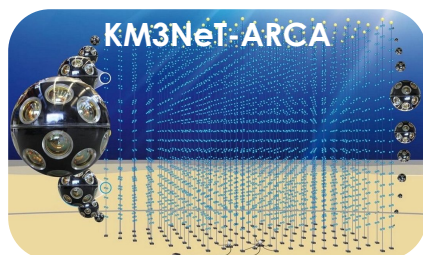
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*biased towards IceCube

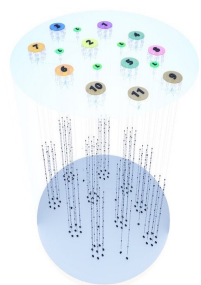


Detecting Neutrinos

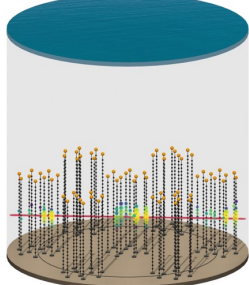
- **Indirect detection** with km^3 water-Cherenkov telescopes
- High-energy: **1 TeV – 10 PeV**



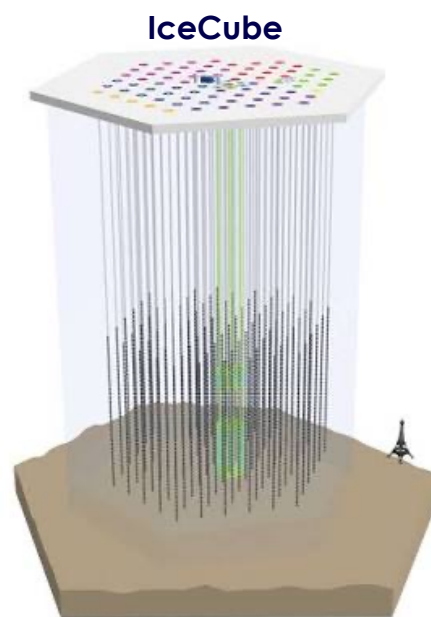
Baikal-GVD



P-ONE



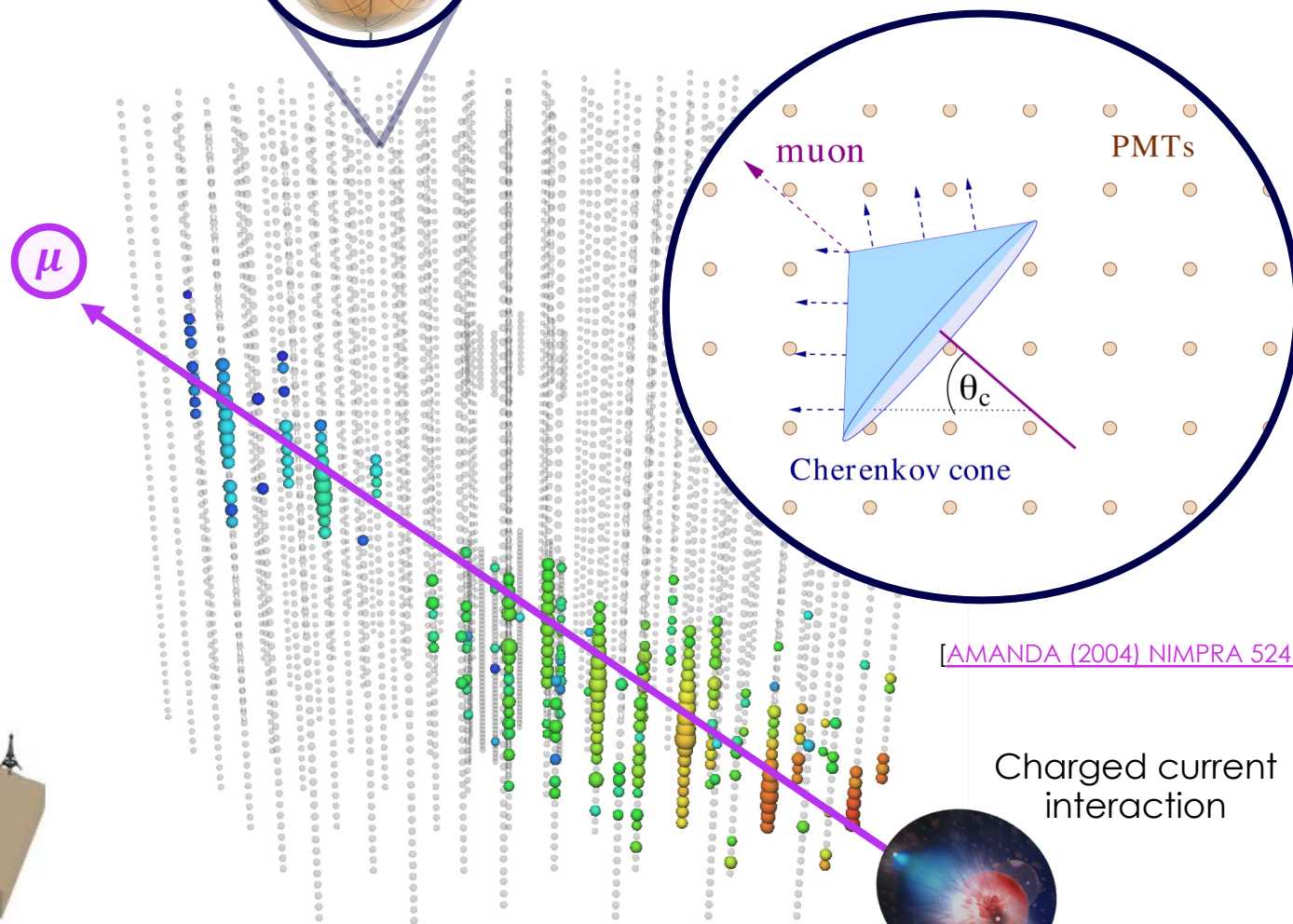
Under construction



Completed in 2011



Optical module



[AMANDA (2004) NIMPR 524 69]

Charged current interaction

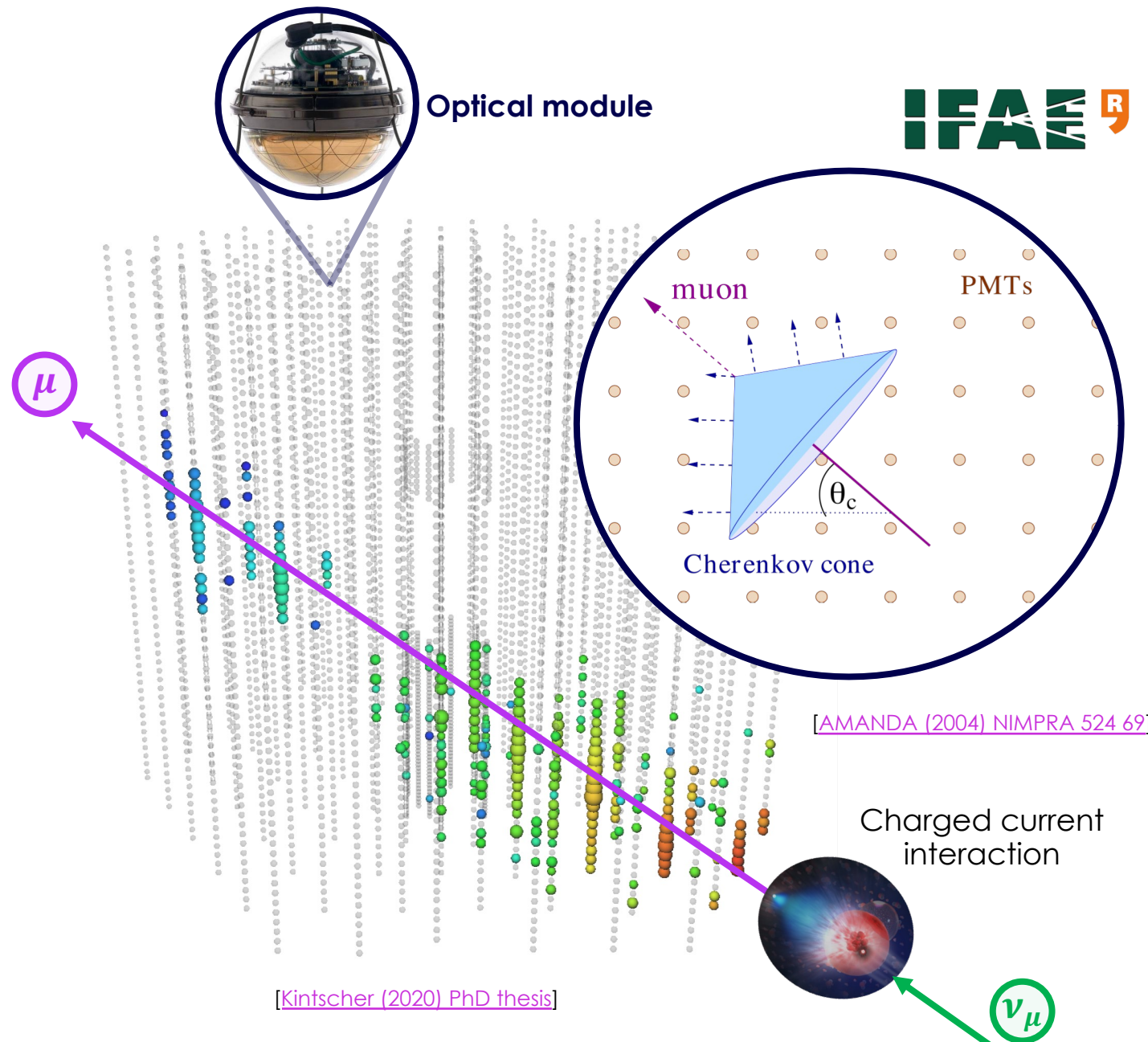
[Kintscher (2020) PhD thesis]

Detecting Neutrinos

- **Indirect detection** with km^3 water-Cherenkov telescopes
- High-energy: **1 TeV – 10 PeV**

Instrument	IceCube
Duty cycle	~100%
Field of view	~100% of sky
Angular resolution*	$<1^\circ$ (>1 TeV)
Energy resolution*	Factor ~2

*for track-like events

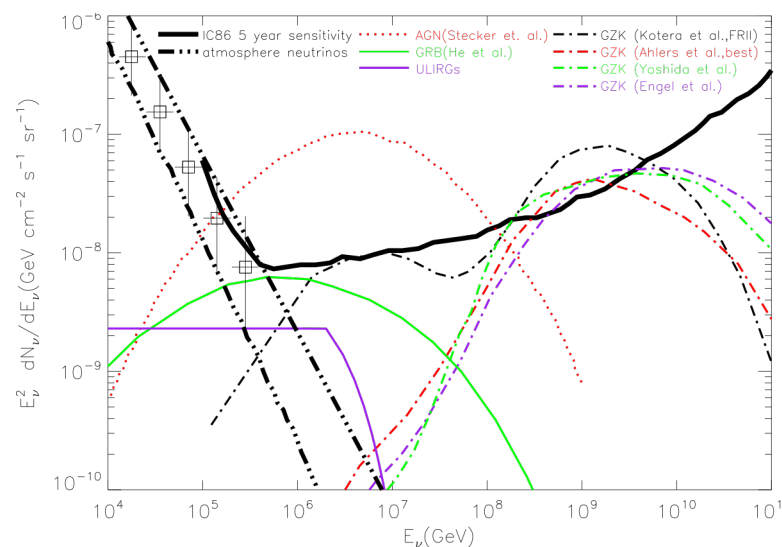


IceCube Search for ULIRG Neutrinos

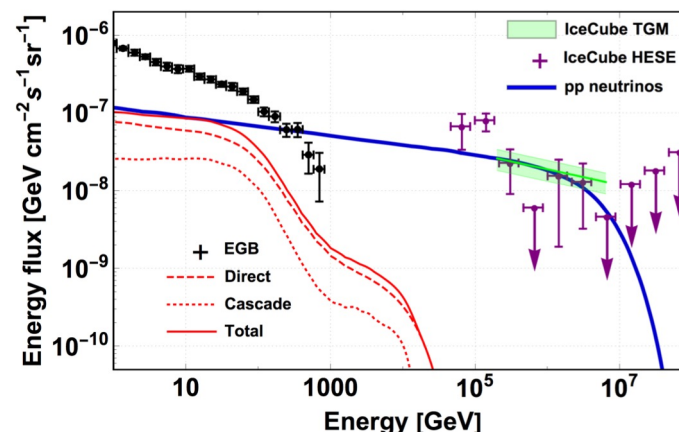
Motivation

ULIRG* source population proposed as significant contributors to IceCube observations, either through starburst or AGN activity

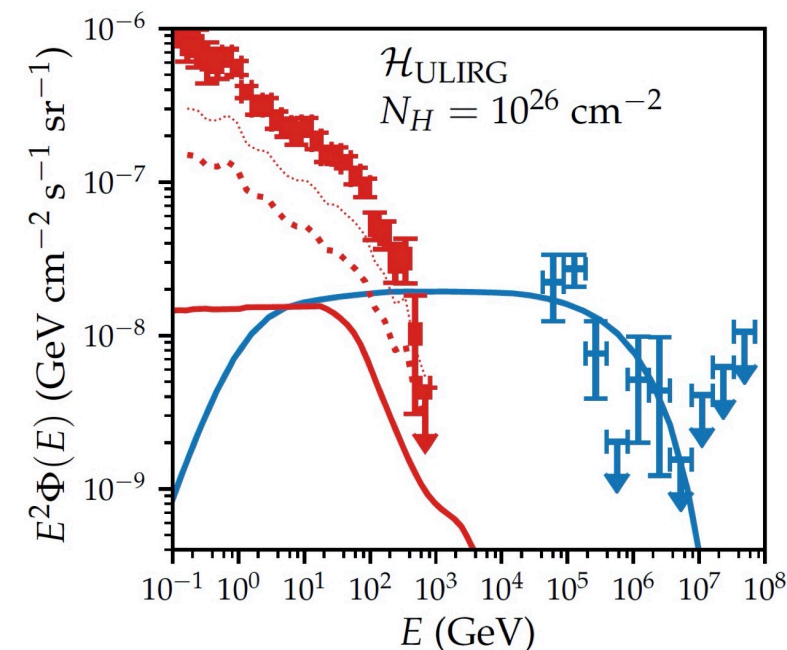
*LIRGs not included in this study ($L_{IR} < 10^{12} L_{\odot}$)



[He+ (2013) PRD 87 063011]



[Palladino+ (2019) JCAP 09 004]

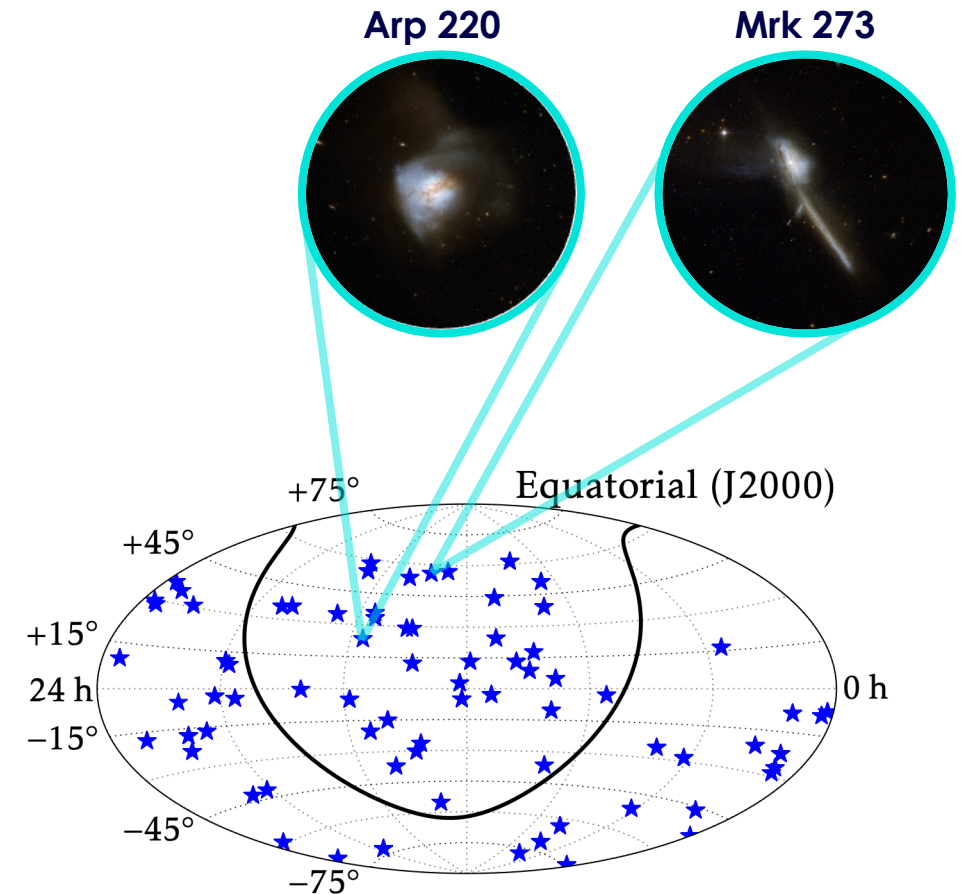
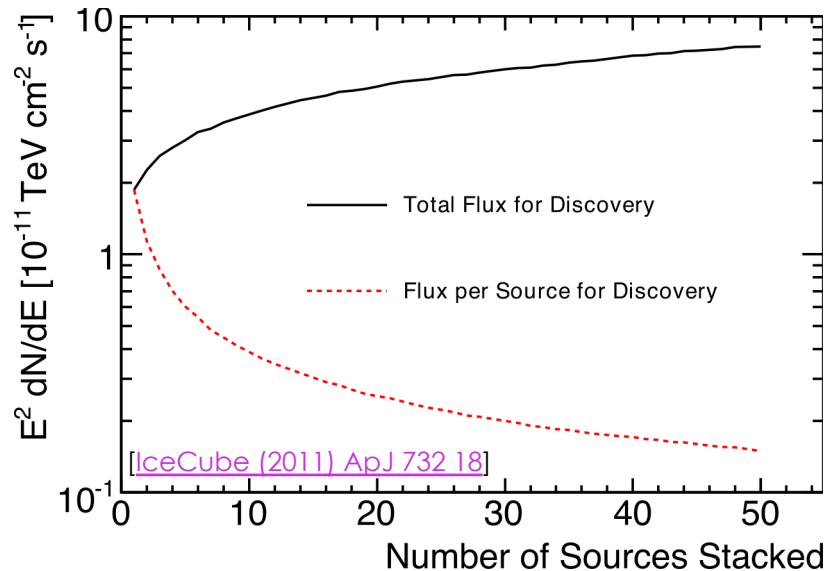


[Vereecken (2019) PhD thesis]

IceCube Search for ULIRG Neutrinos

[IceCube [PC] (2022) ApJ 926 59]

- **Selection of 75 ULIRGs** representative of ULIRG population within $z \leq 0.13$
- **Stacking analysis** using 7.5 years of IceCube track data



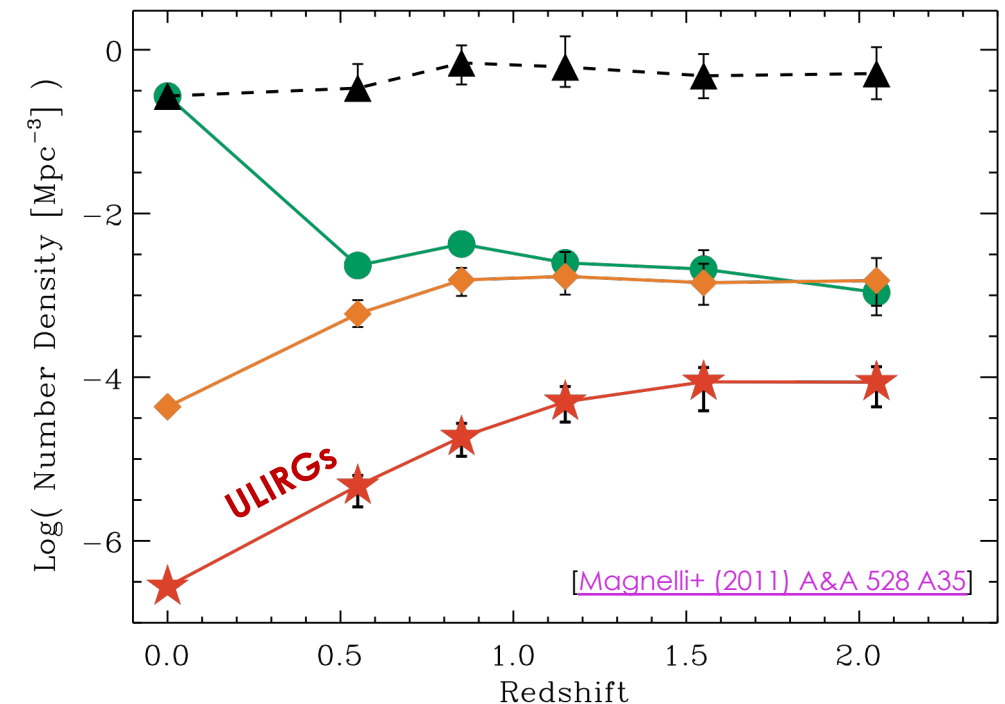
IceCube Search for ULIRG Neutrinos

- ▶ **Selection of 75 ULIRGs** representative of ULIRG population within $z \leq 0.13$
- ▶ **Stacking analysis** using 7.5 years of IceCube track data (p-value = 1)
- ▶ **Null results extrapolated** to entire ULIRG source population up to $z \sim 4$

$$\Phi_{\nu_{\mu} + \bar{\nu}_{\mu}}^{z \leq 4.0} = \xi \Phi_{\nu_{\mu} + \bar{\nu}_{\mu}}^{z \leq 0.13}$$

encodes ULIRG redshift evolution

[IceCube [PC] (2022) ApJ 926 59]

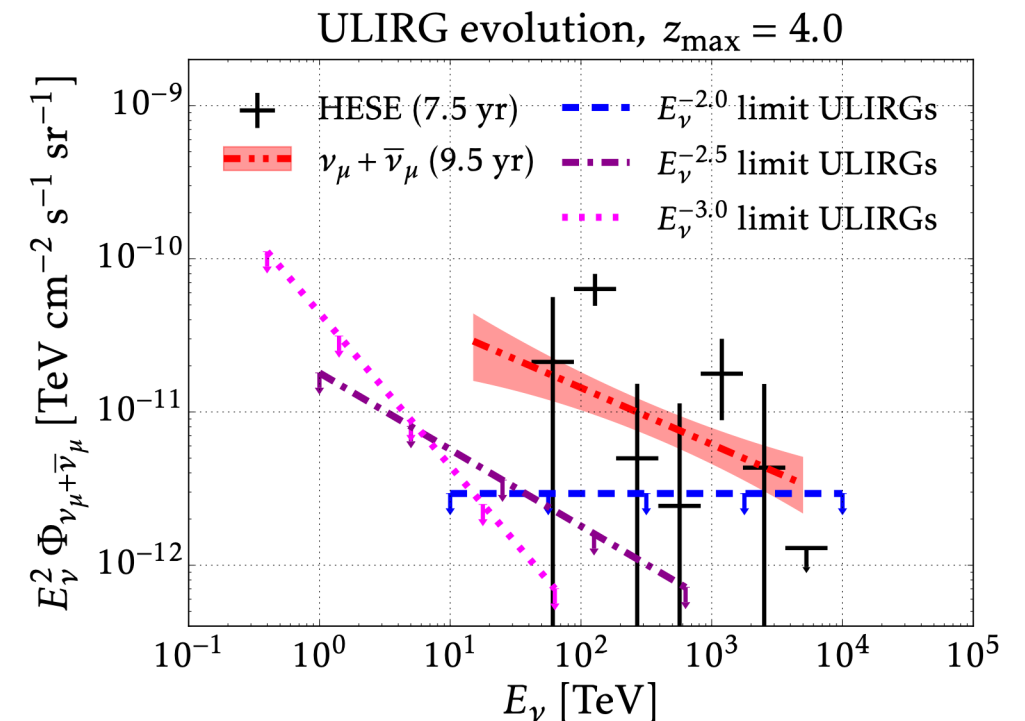


IceCube Search for ULIRG Neutrinos

[IceCube [PC] (2022) ApJ 926 59]

- ▶ **Selection of 75 ULIRGs** representative of ULIRG population within $z \leq 0.13$
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- ▶ **Null results extrapolated** to entire ULIRG source population up to $z \sim 4$

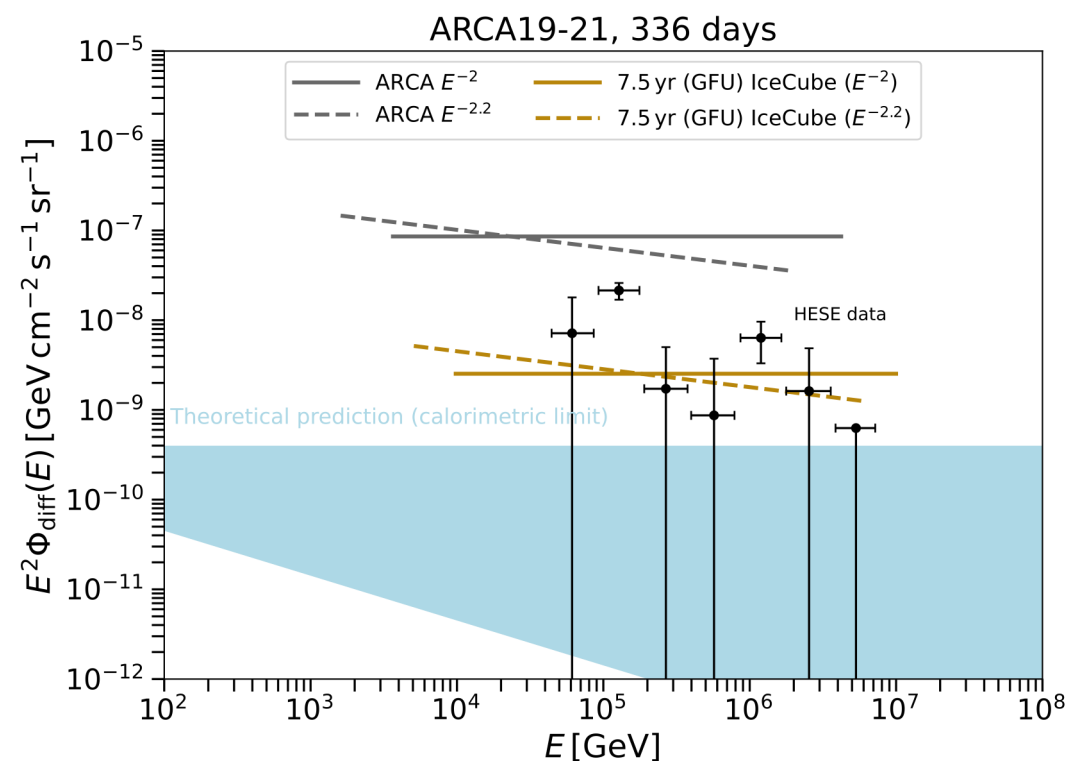
The ULIRG source population cannot account for more than ~10% of the total diffuse neutrino flux



KM3NeT Search for ULIRG Neutrinos

- ▶ **Selection of 75 ULIRGs** representative of ULIRG population within $z \leq 0.13$
- ▶ **Stacking analysis** using 336 days of ARCA19-21 track data (p-value = 0.2)
- ▶ **Null results extrapolated** to entire ULIRG source population up to $z \sim 4$

The ULIRG source population cannot account for more than ~10% of the total diffuse neutrino flux

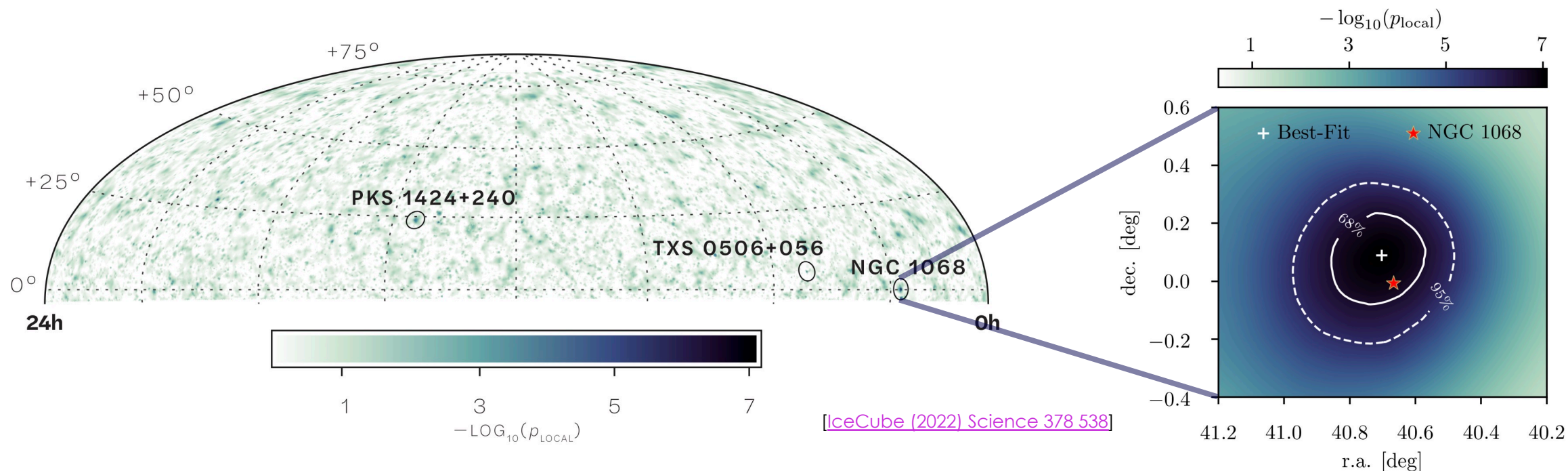


[KM3NeT (2026) arXiv:2609.03609]

Evidence for Neutrinos from Seyferts

► Evidence for NGC 1068

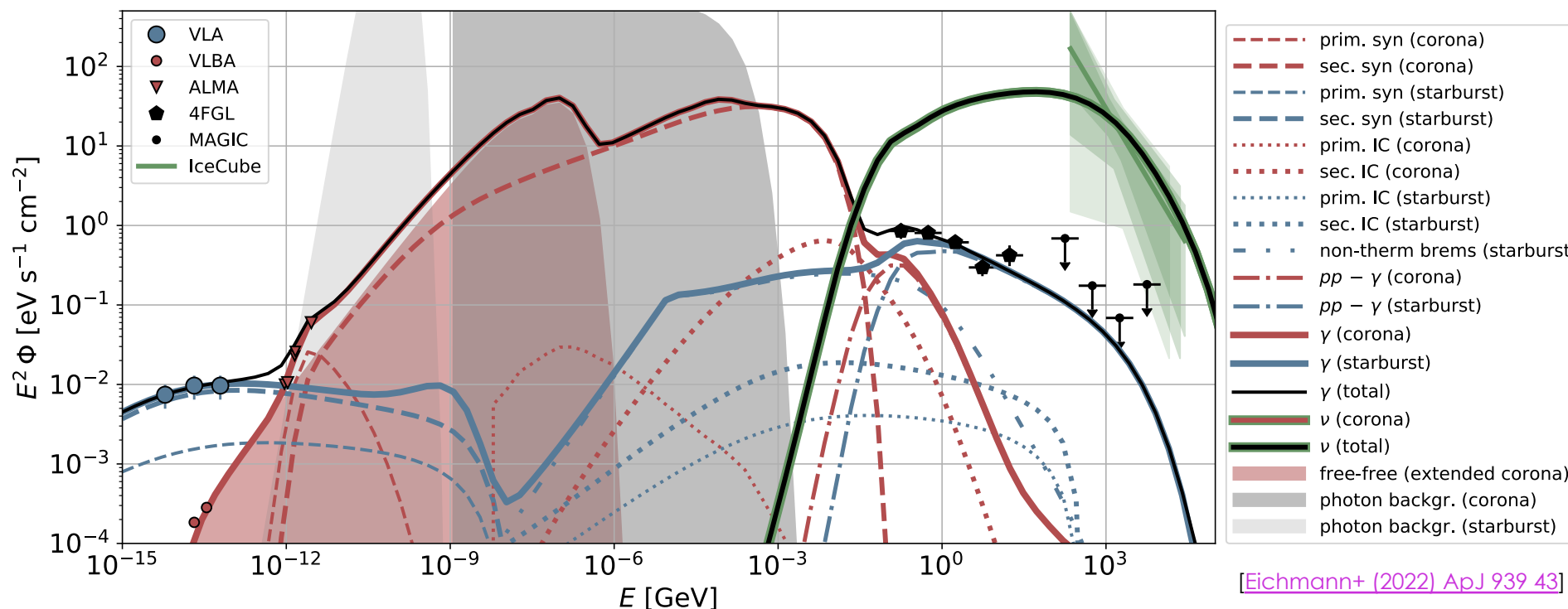
- First steady neutrino source (4.2σ)



Evidence for Neutrinos from Seyferts

► Evidence for NGC 1068

- First steady neutrino source (4.2σ)
- Preference for **AGN corona** models:
X-ray bright, gamma-ray opaque



Evidence for Neutrinos from Seyferts

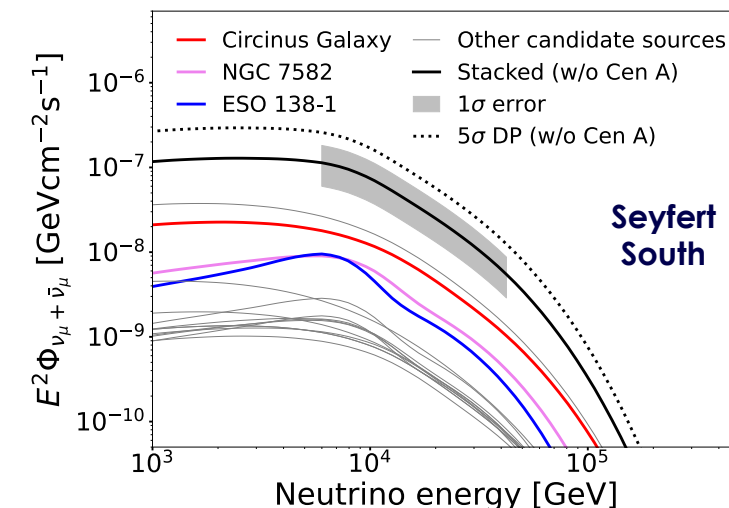
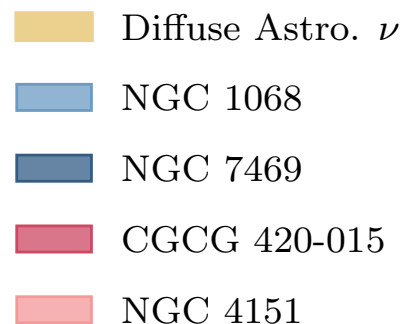
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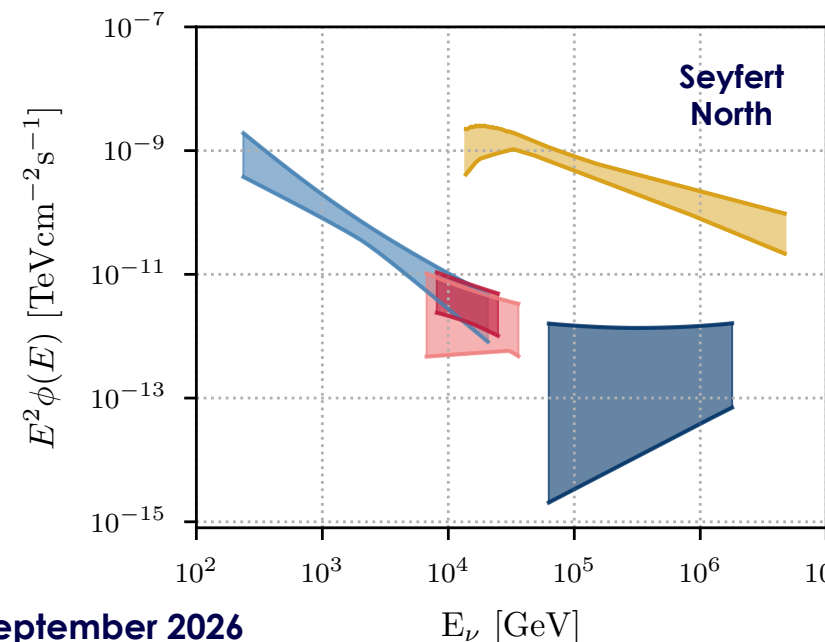


► Hints for X-ray-bright Seyferts

- **14 southern sources** (3.0σ) from stacking search
- **11 northern sources** (3.3σ) from binomial test
- **NGC 7469** prominent hard spectrum (two >100 TeV events)



[IceCube (2026) ApJL 1000 L37]



[IceCube (2026) ApJL 1000 L26]

Evidence for Neutrinos from Seyferts

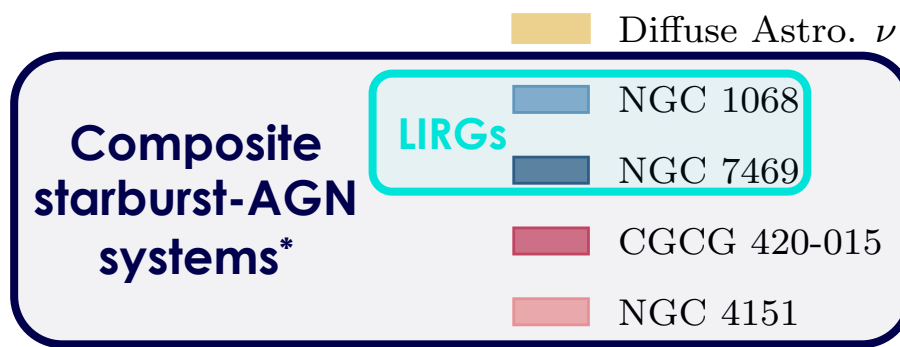
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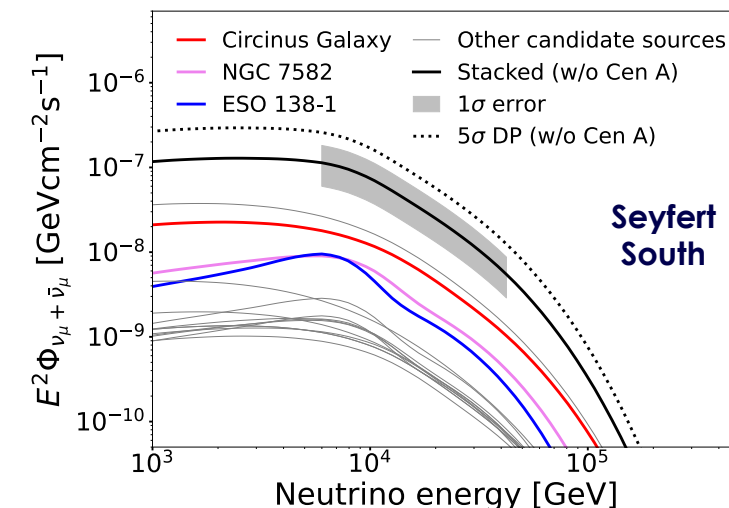


► Hints for X-ray-bright Seyferts

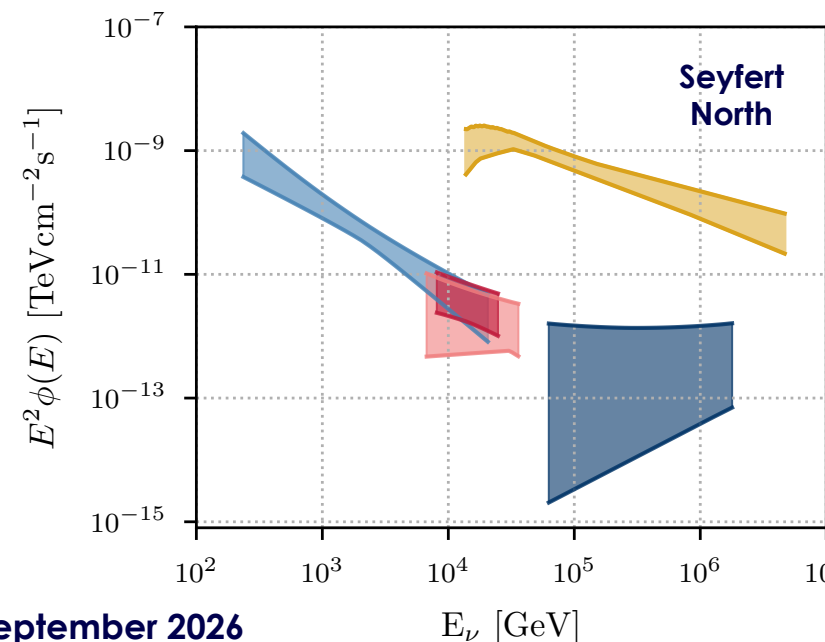
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*Not included in ULIRG stacking search ($L_{IR} < 10^{12} L_{\odot}$)



[IceCube (2026) ApJL 1000 L37]

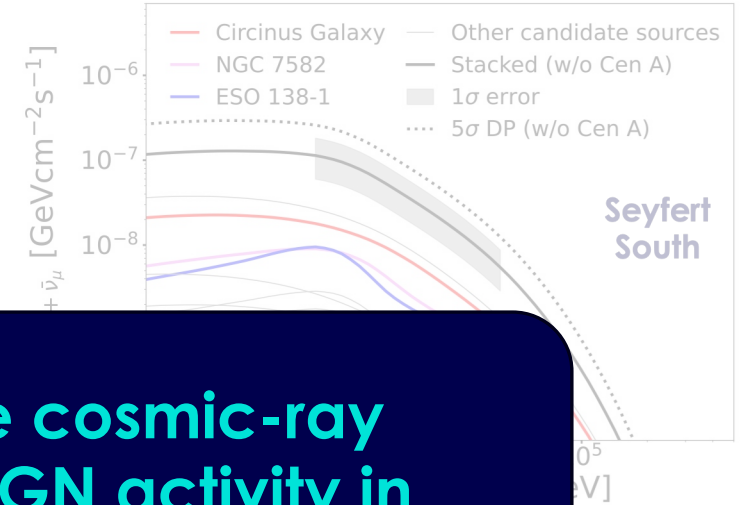


[IceCube (2026) ApJL 1000 L26]

Evidence for Neutrinos from Seyferts

► Evidence for NGC 1068

- First steady neutrino source (4.2σ)
- Preference for AGN corona models:
X-ray bright, gamma-ray opaque



[IceCube (2026) April 1000 L37]

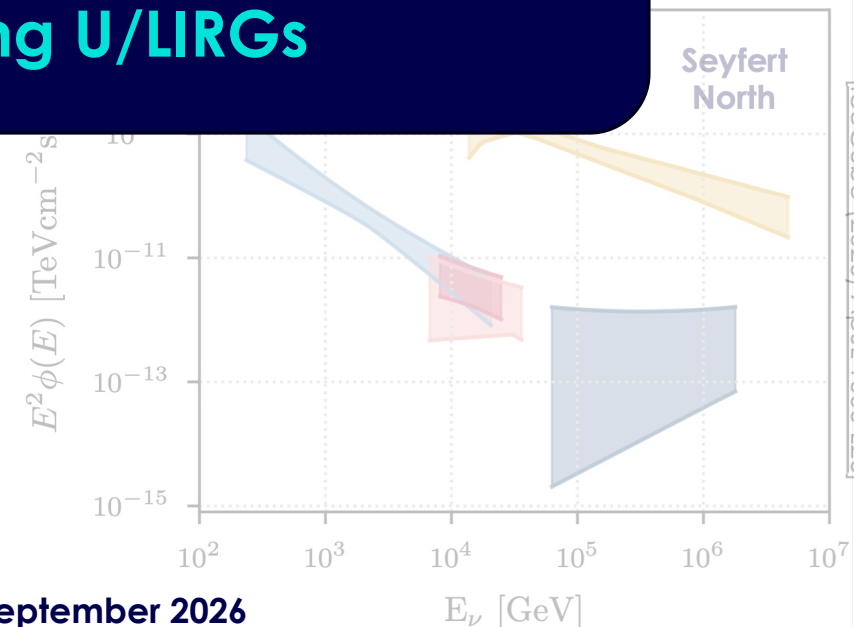
► Hints for

- 14 southern
- 11 northern
- NGC 7469

TeV neutrinos are a window into the cosmic-ray acceleration processes related to AGN activity in composite systems, including U/LIRGs



*Not included in ULIRG stacking search ($L_{IR} < 10^{12} L_\odot$)



[IceCube (2026) April 1000 L26]

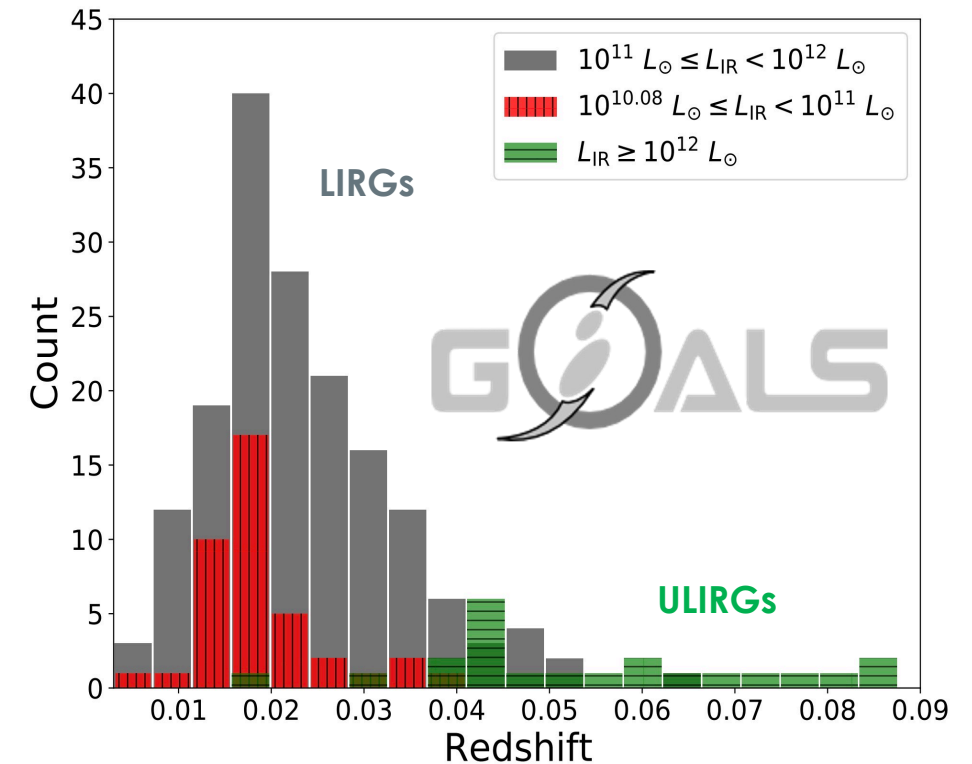
Starburst Neutrinos from GOALS Galaxies



► Great Observatories All-sky LIRG Survey

- Complete multiwavelength survey of nearby LIRGs (180) and ULIRGs (22)

[[Merckx, PC+ \(2023\) PRD 108 023015](#)]



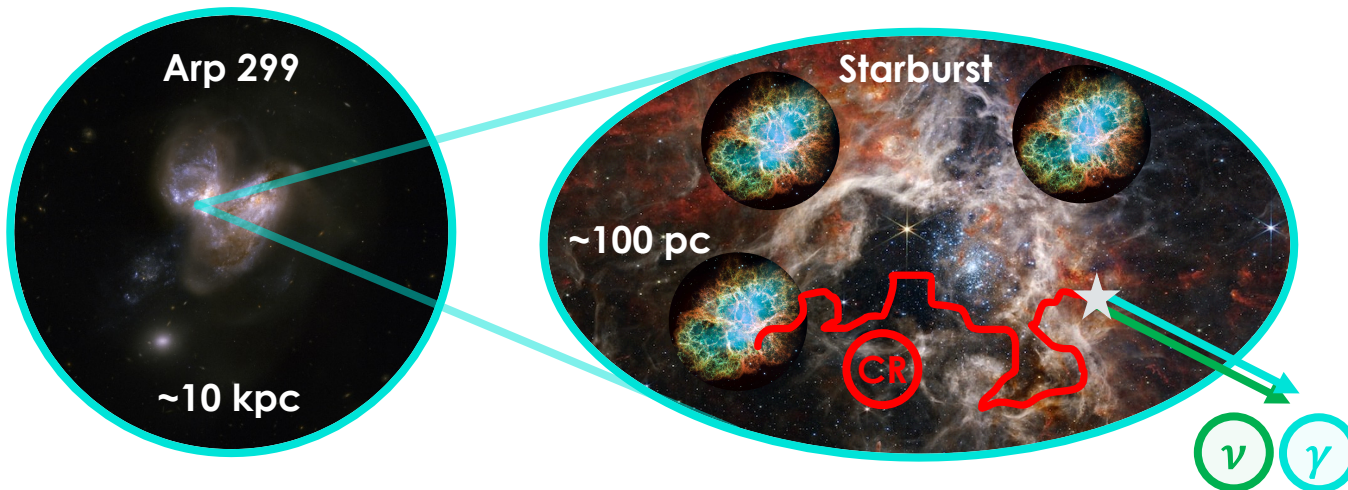
Starburst Neutrinos from GOALS Galaxies

- ▶ **Great Observatories All-sky LIRG Survey**

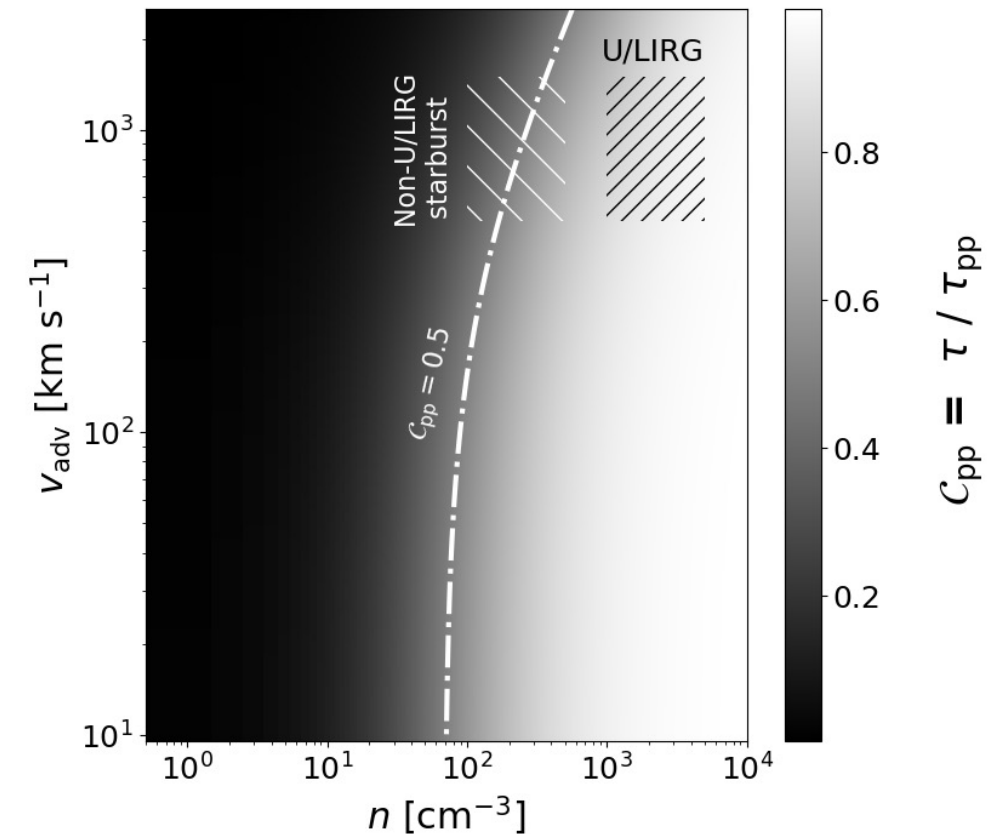
- ▶ **Complete multiwavelength survey** of nearby LIRGs (180) and ULIRGs (22)

- ▶ **Data-driven model of starburst neutrinos**

- ▶ Highly **calorimetric** leaky-box model
- ▶ **Normalize** cosmic-ray injection rate to L_{IR}



[Merckx, PC+ (2023) PRD 108 023015]



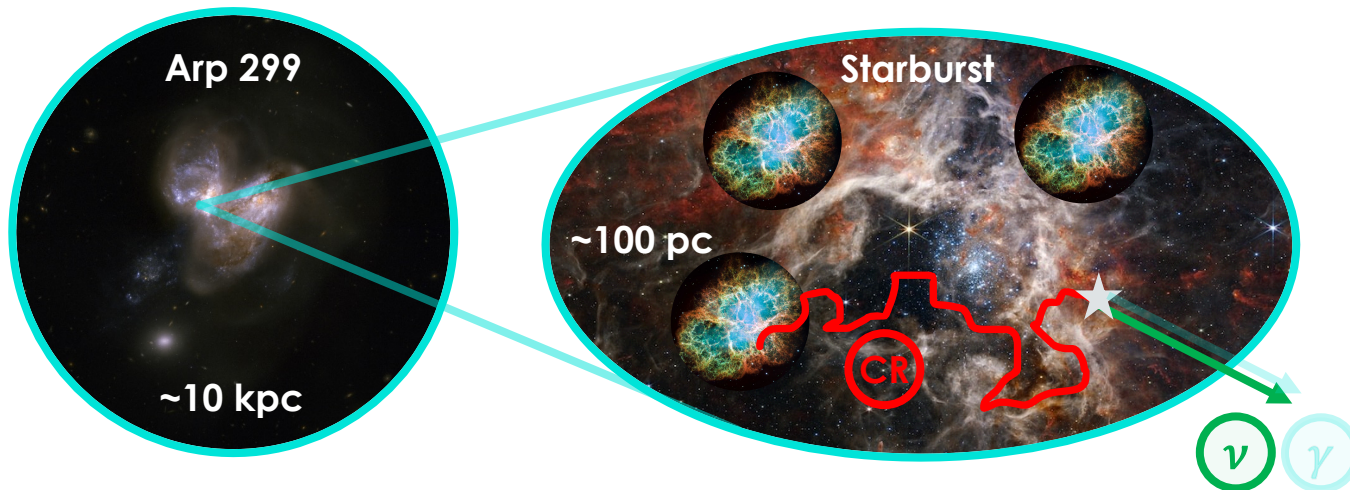
Starburst Neutrinos from GOALS Galaxies

- ▶ **Great Observatories All-sky LIRG Survey**

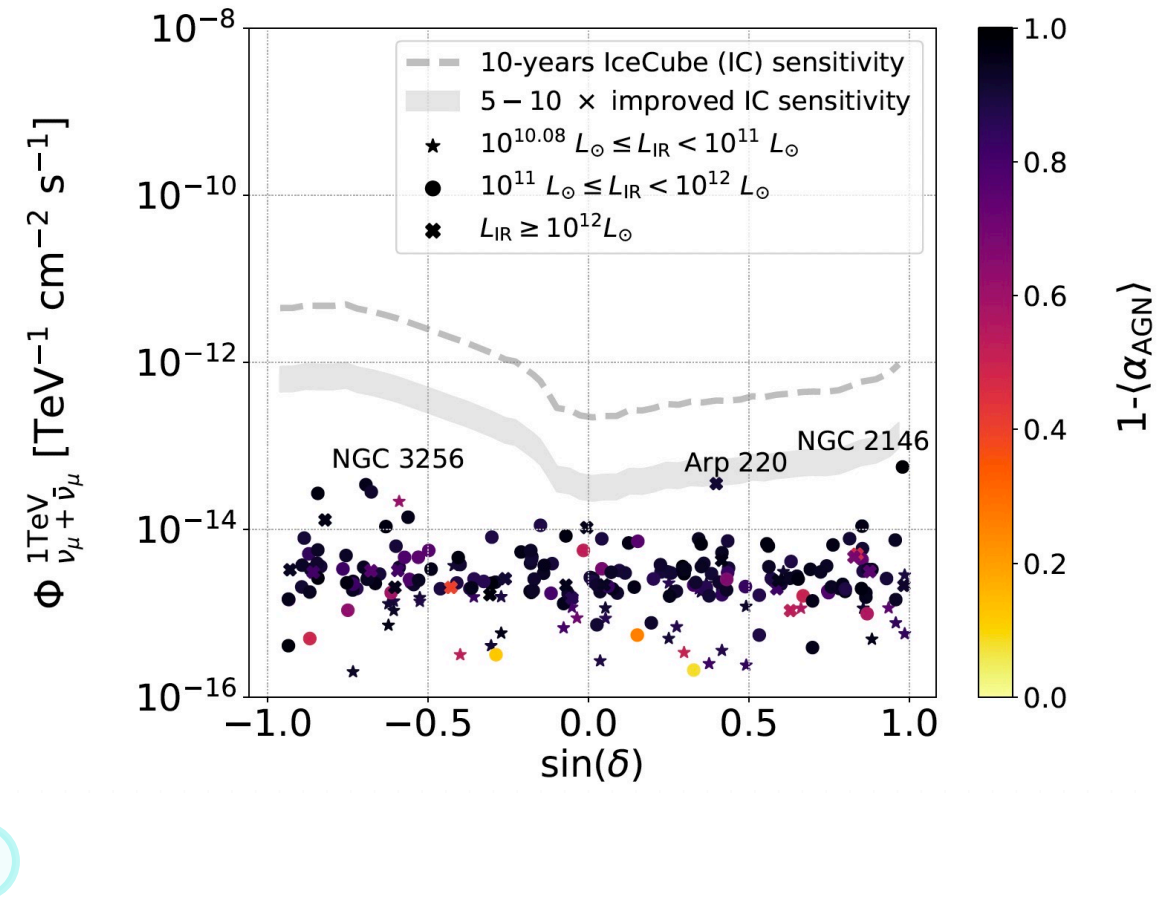
- ▶ **Complete multiwavelength survey** of nearby LIRGs (180) and ULIRGs (22)

- ▶ **Data-driven model of starburst neutrinos**

- ▶ Highly **calorimetric** leaky-box model
- ▶ **Normalize** cosmic-ray injection rate to L_{IR}
- ▶ Predict **neutrino flux** for each GOALS galaxy



[Merckx, PC+ (2023) PRD 108 023015]



Starburst Neutrinos from GOALS Galaxies



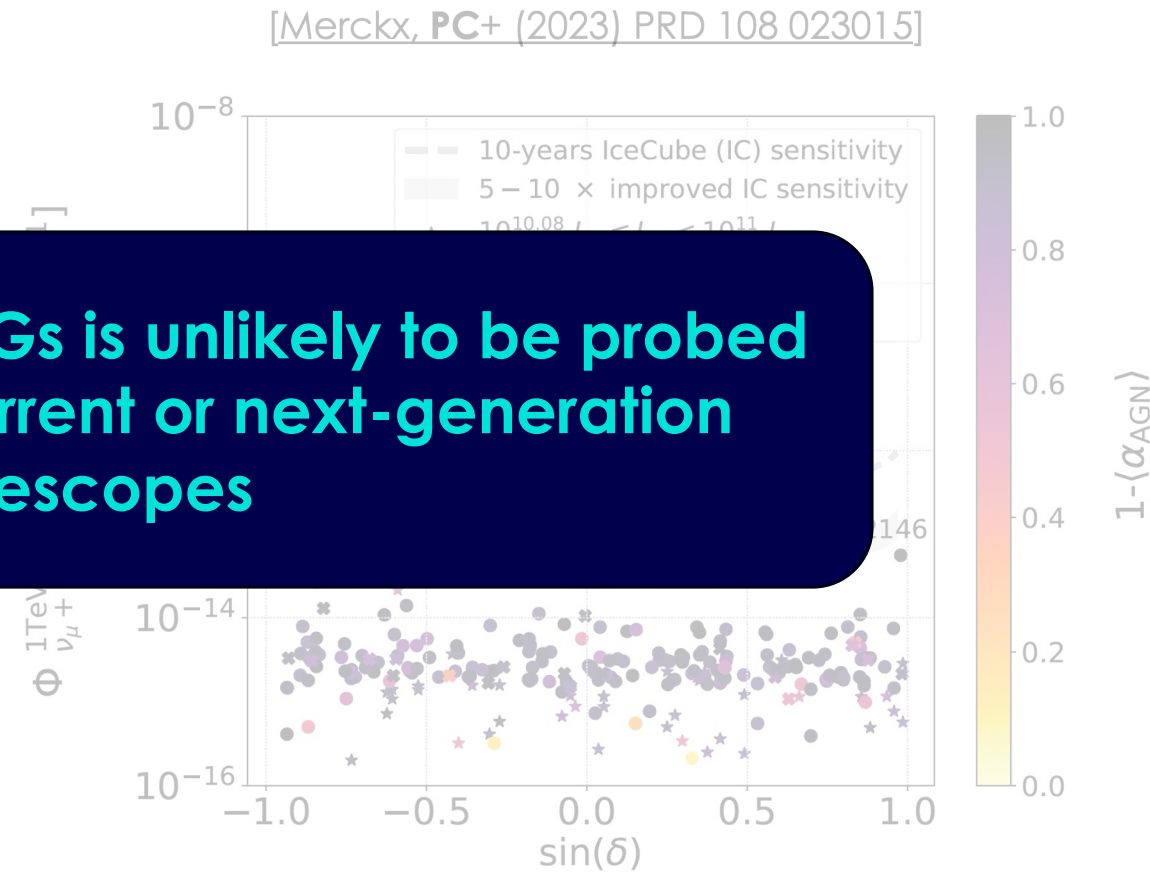
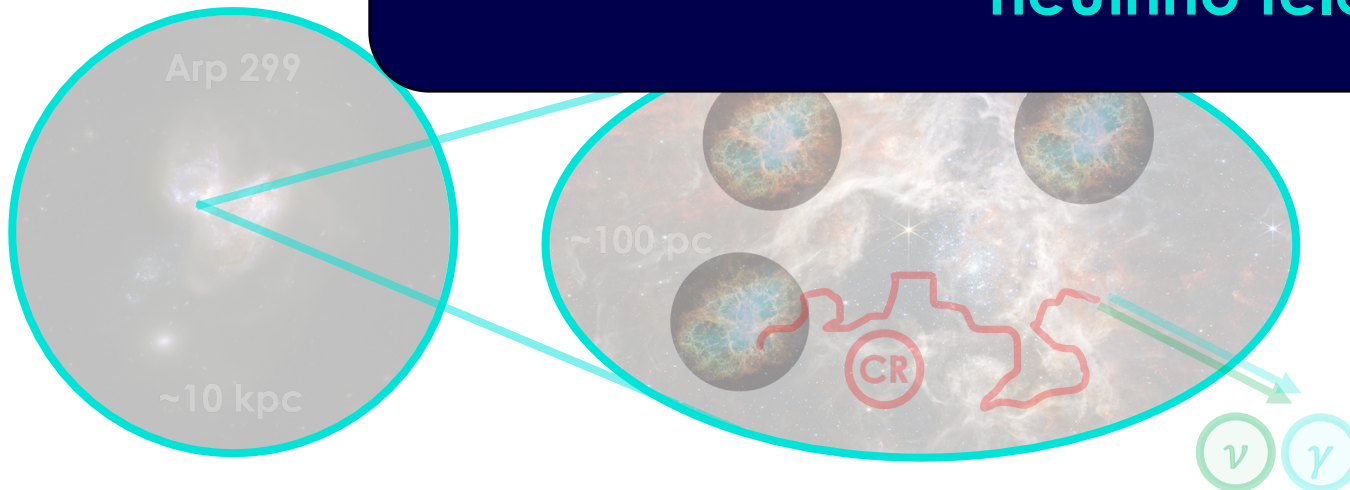
- ▶ **Great Observatories All-sky LIRG Survey**

- ▶ **Complete multiwavelength survey** of nearby LIRGs (180) and ULIRGs (22)

- ▶ **Data-driven model of starburst neutrinos**

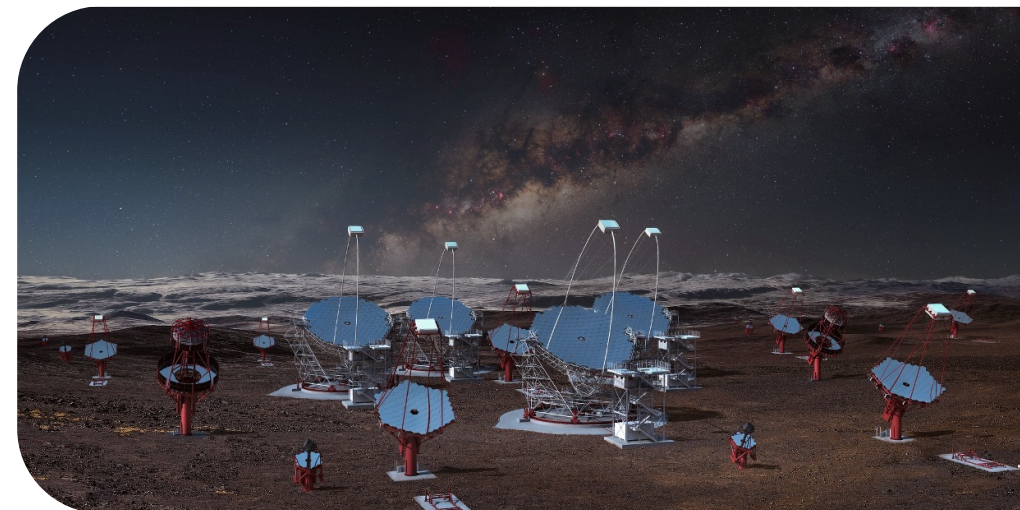
- ▶ Highly correlated
- ▶ Normalized
- ▶ Predict

Starburst component of U/LIRGs is unlikely to be probed with TeV neutrinos using current or next-generation neutrino telescopes



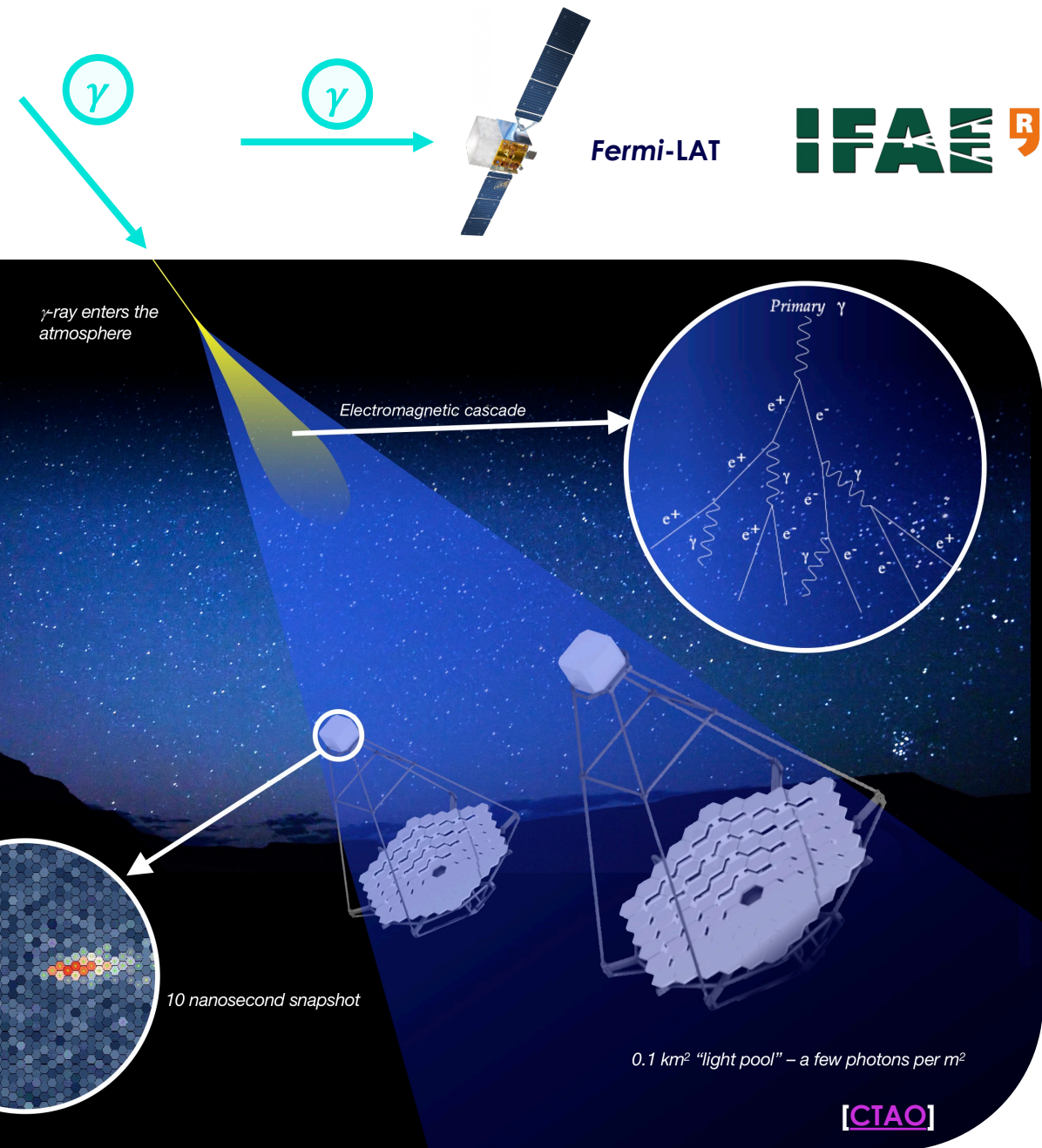
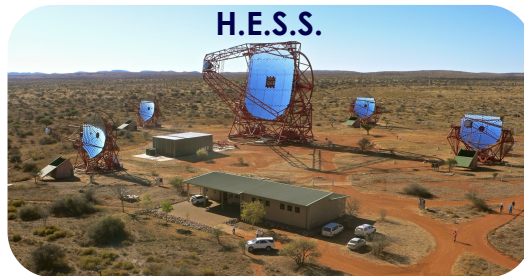
Contents

1. Introduction to Multimessenger Astronomy
2. The High-Energy Astrophysics of U/LIRGs
3. Probing U/LIRGs with TeV Neutrinos
4. Probing U/LIRGs with TeV Gamma Rays
5. Summary



Detecting Gamma Rays

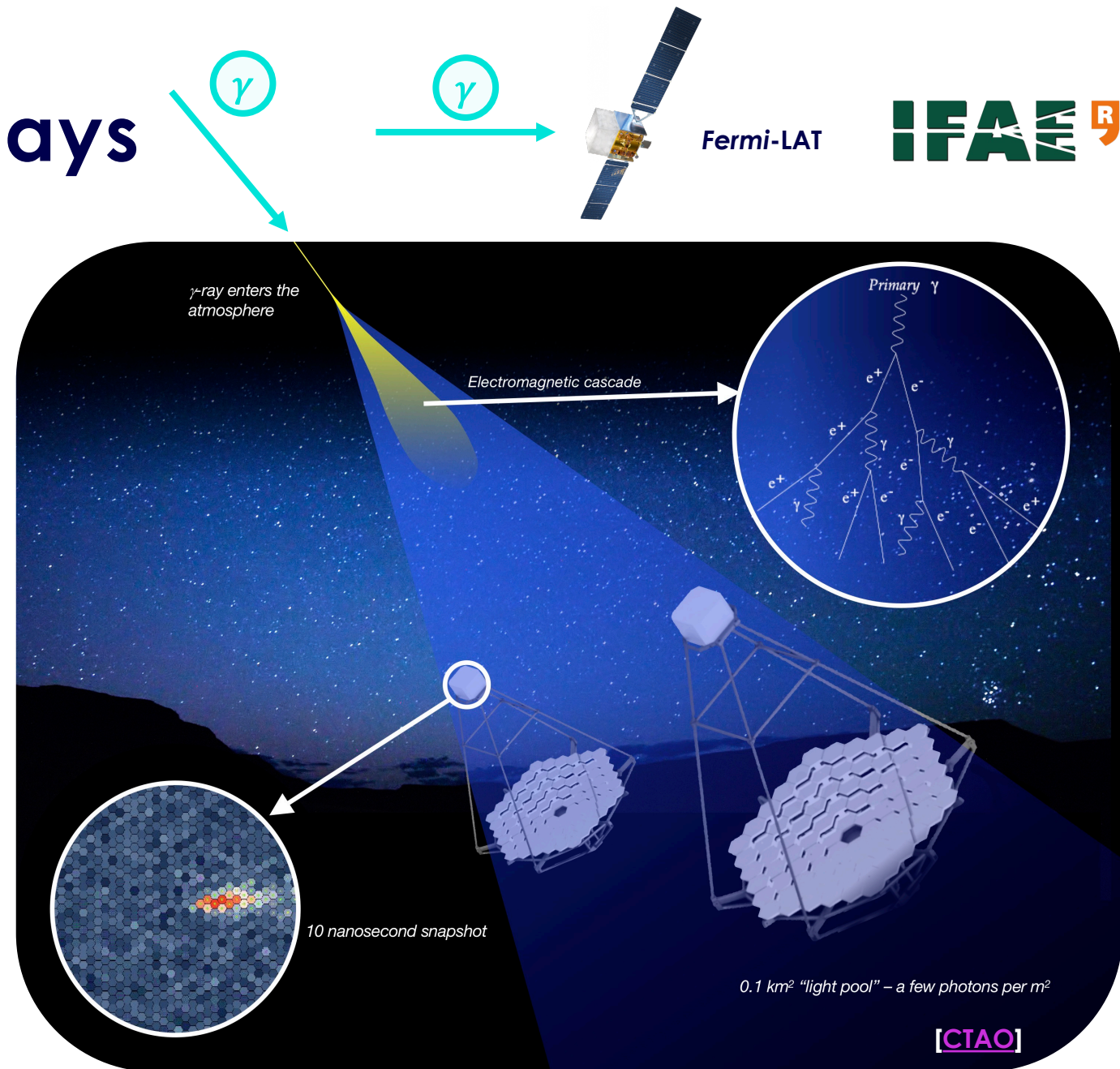
- ▶ **Direct detection** with satellites
 - ▶ High energy: **100 MeV – 100 GeV**
- ▶ **Indirect detection** with imaging air-Cherenkov telescopes (IACTs)
 - ▶ Very-high energy (VHE): **>100 GeV**



Detecting Gamma Rays

- ▶ **Direct detection** with satellites
 - ▶ High energy: **100 MeV – 100 GeV**
- ▶ **Indirect detection** with imaging air-Cherenkov telescopes (IACTs)
 - ▶ Very-high energy (VHE): **>100 GeV**

Instrument	<i>Fermi-LAT</i>	IACTs	
Duty cycle	~100%	~10–20%	
Field of view	~20% of sky	~3–5°	
Angular res.	~0.1°	<0.1°	
Energy res.	~10%	~15% (current)	5–10% (CTAO)

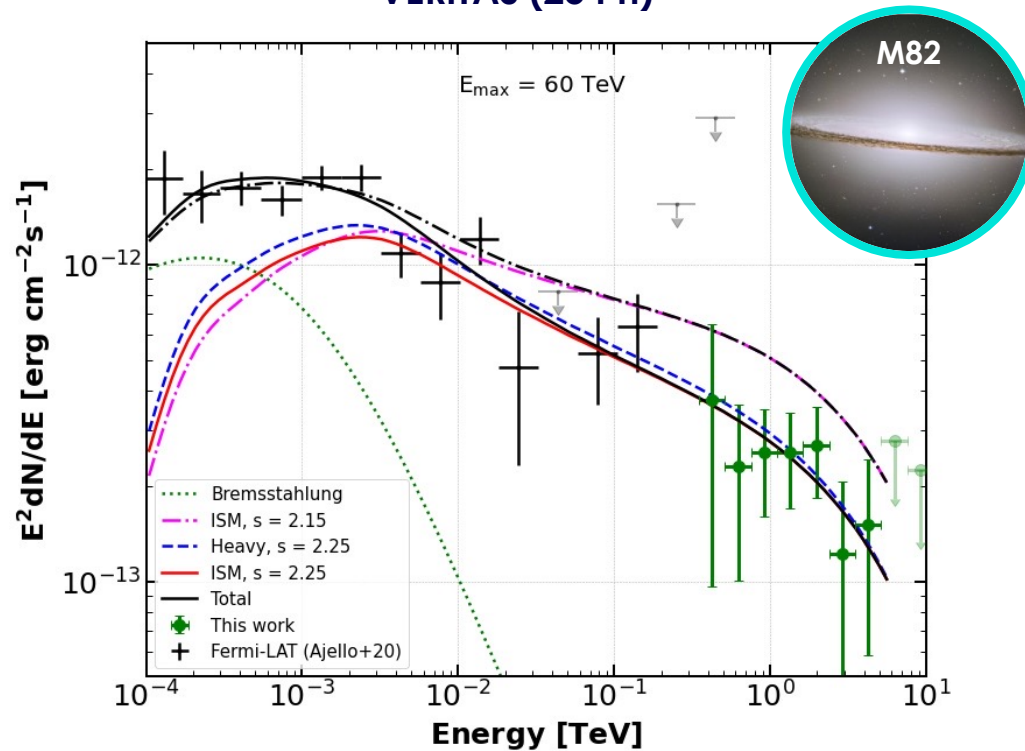


Starburst Galaxies in VHE Gamma Rays

Only two nearby starburst galaxies* detected so far at TeV energies

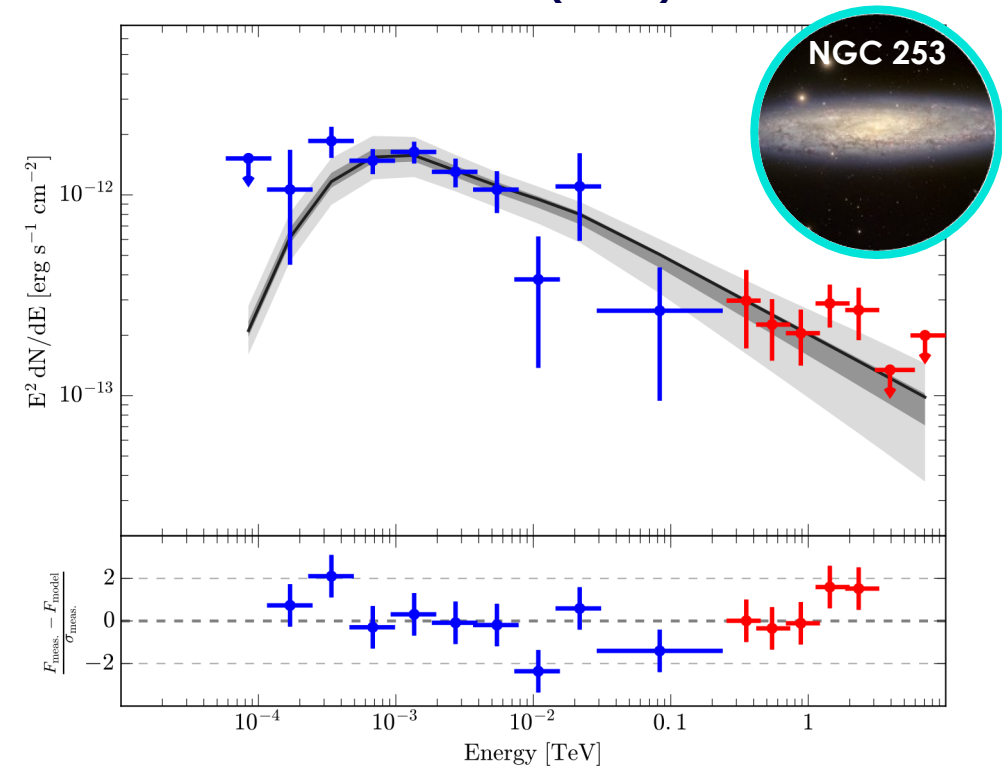
*not of extreme U/LIRG type

VERITAS (254 h)



[VERITAS (2025) ApJ 981 189]

H.E.S.S. (177 h)



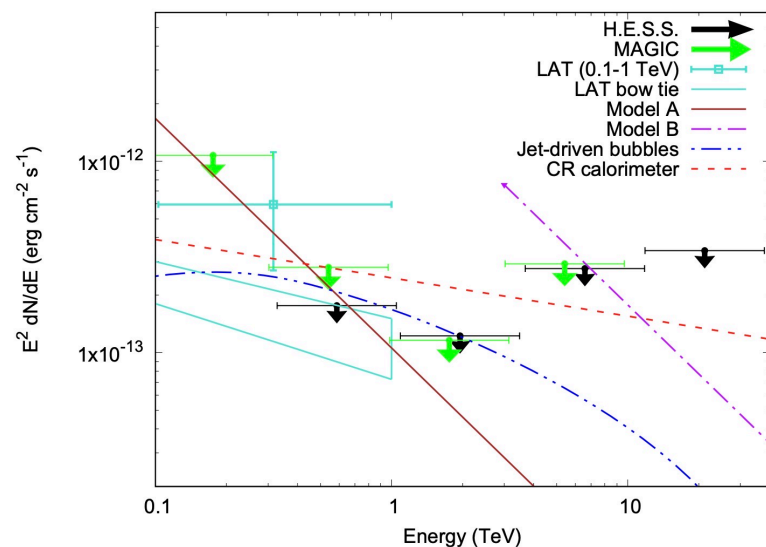
[H.E.S.S. (2018) A&A 617 A73]

VHE Observations of Composite Systems

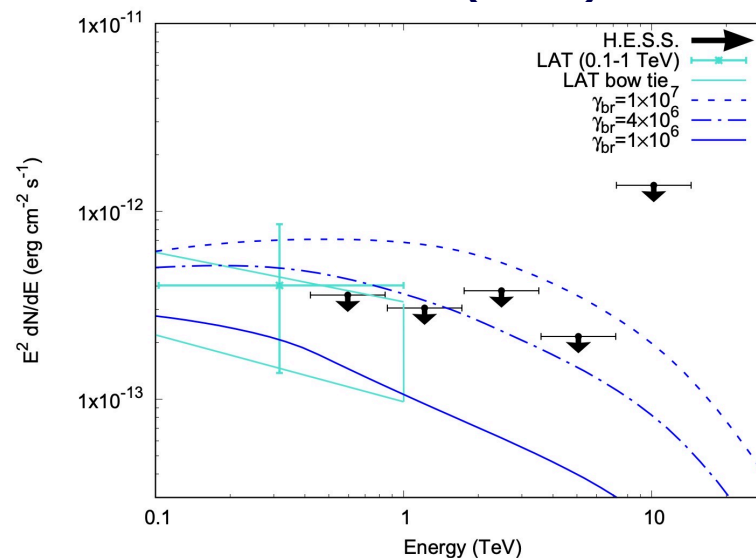
Latest constraints on starburst-AGN systems at TeV energies



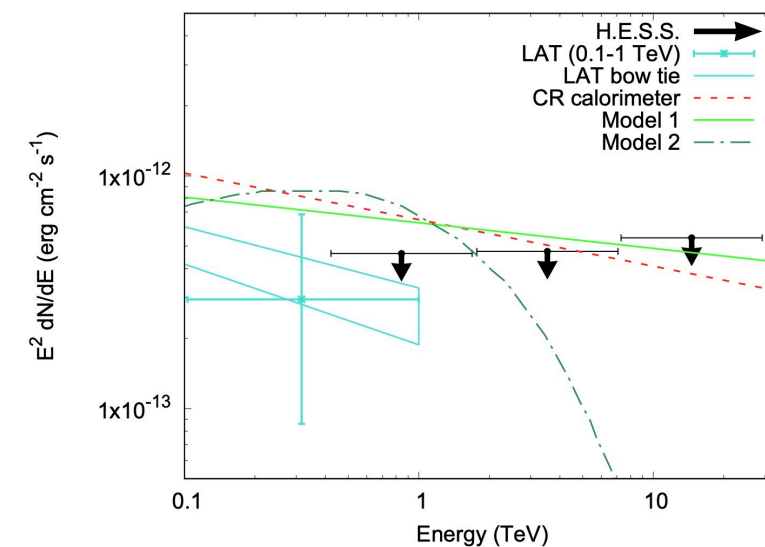
H.E.S.S. (168.5 h) + MAGIC (125 h)



H.E.S.S. (18.4 h)



H.E.S.S. (42.7 h)



VHE Observations of Composite Systems

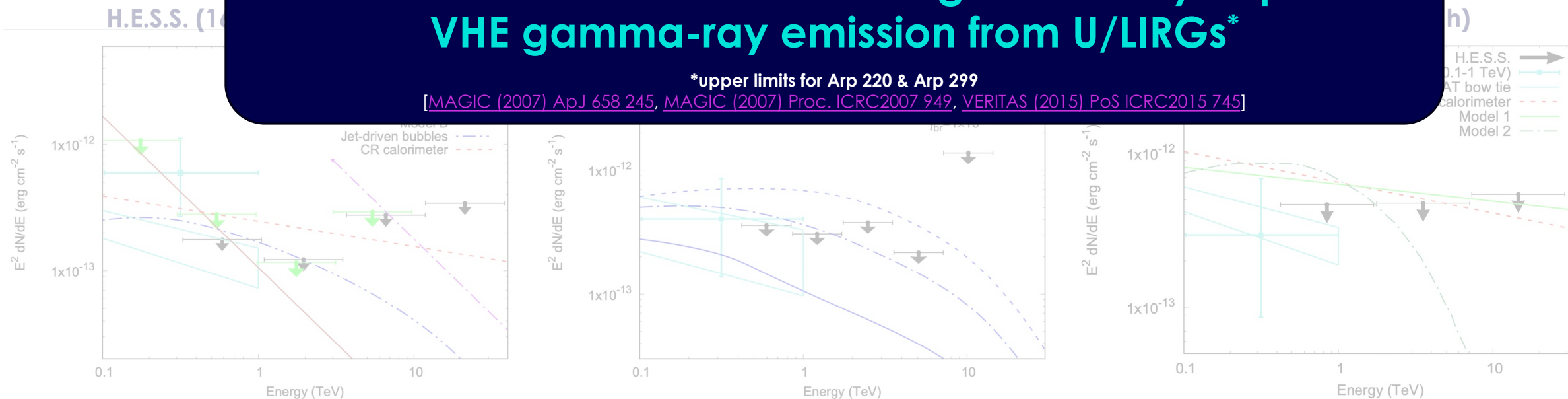
Latest constraints on starburst-AGN systems at TeV energies



Current IACTs do not have enough sensitivity to probe VHE gamma-ray emission from U/LIRGs*

*upper limits for Arp 220 & Arp 299

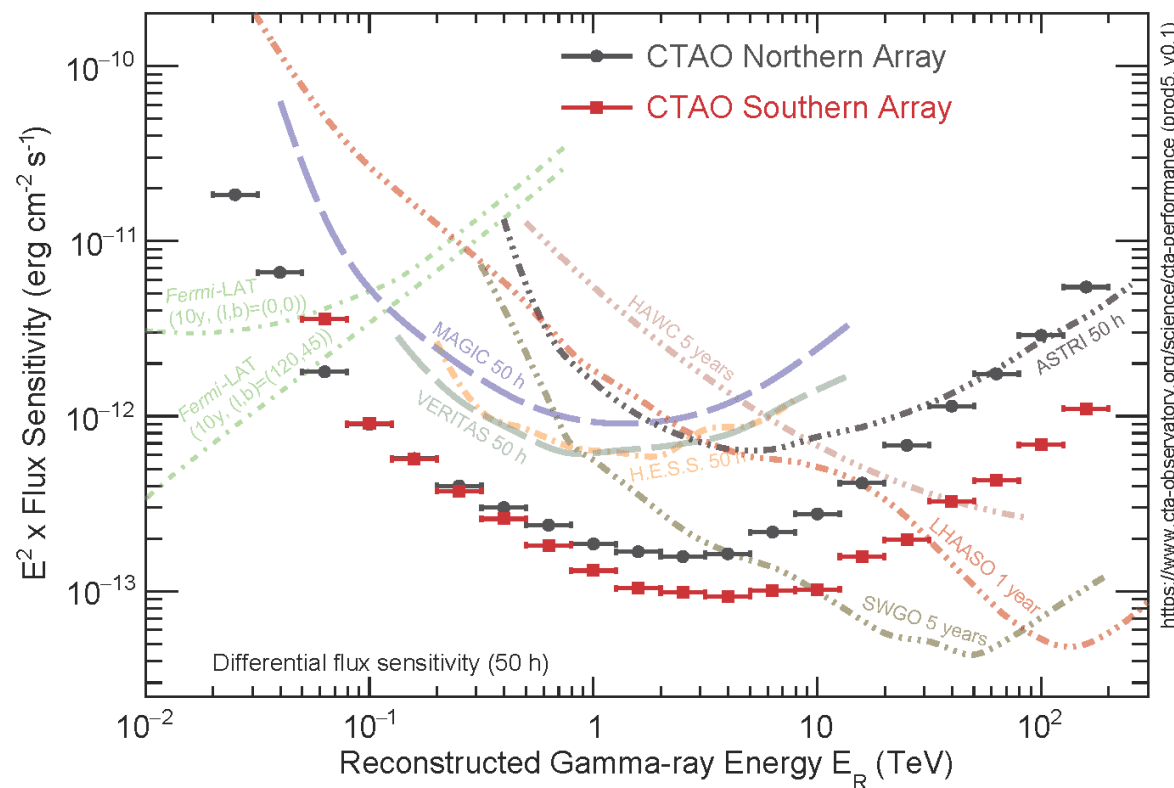
[MAGIC (2007) ApJ 658 245, MAGIC (2007) Proc. ICRC2007 949, VERITAS (2015) PoS ICRC2015 745]



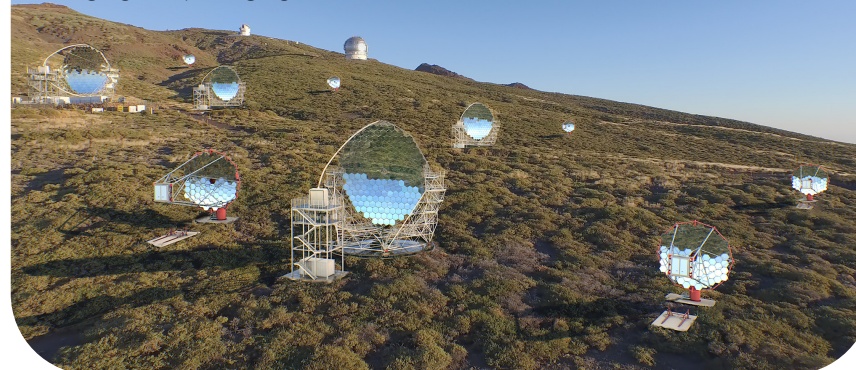
Cherenkov Telescope Array Observatory



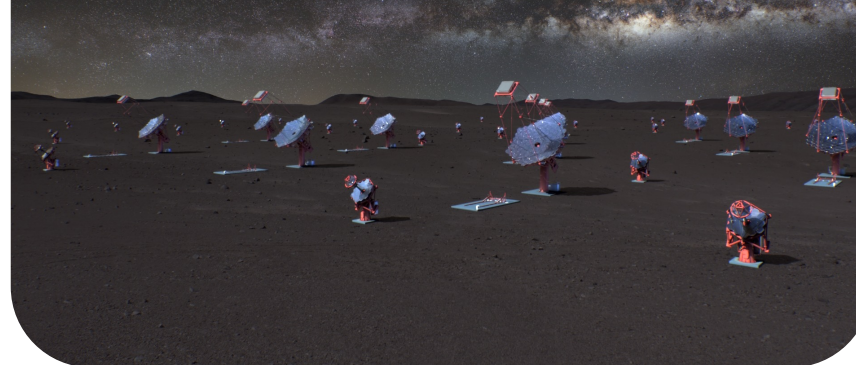
- ▶ CTAO will improve sensitivity of current IACTs by a factor ~ 10



CTAO-North, La Palma, Canary Islands, Spain
4 LSTs + 9 MSTs

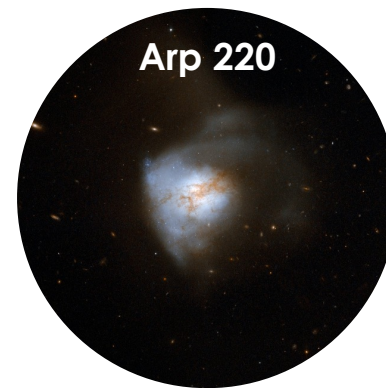
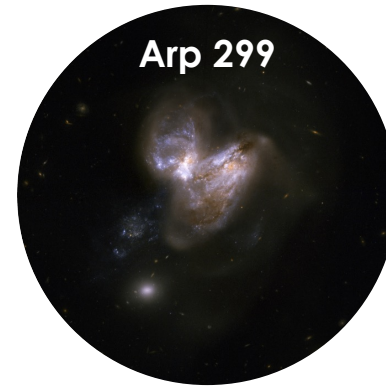


CTAO-South, Atacama Desert, Chile
14 MSTs + 37 SSTs



Prospects for U/LIRG Studies with CTAO

- Consider four **U/LIRGs** detected by *Fermi*-LAT

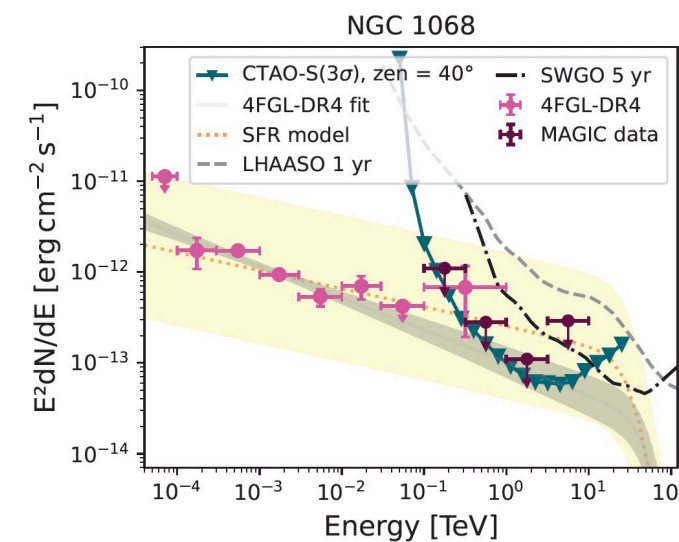
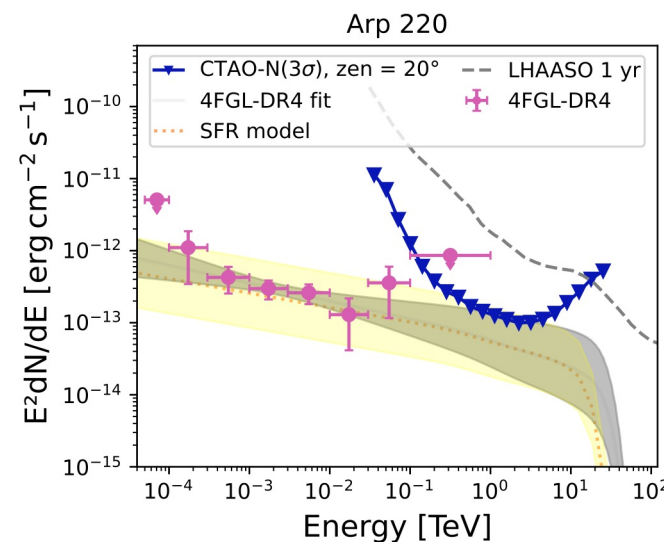
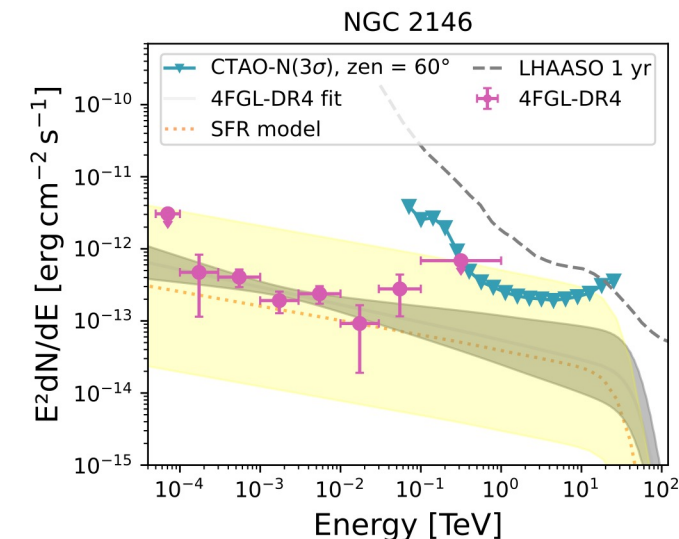
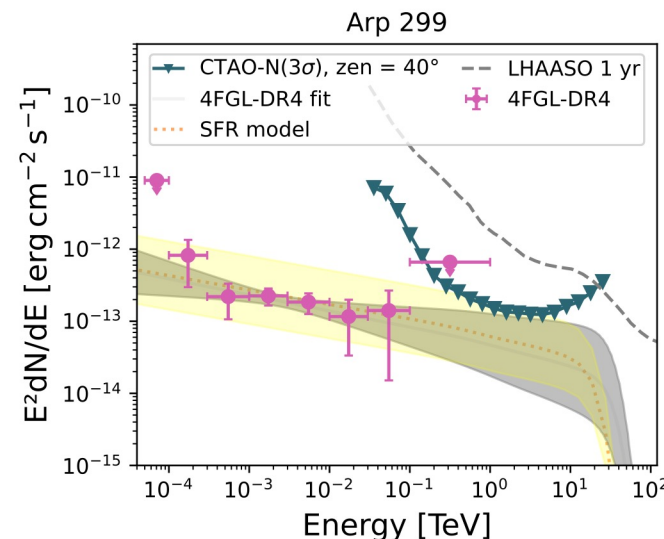


Prospects for U/LIRG Studies with CTAO

- ▶ Consider four **U/LIRGs detected by *Fermi*-LAT***
- ▶ Compare **extrapolated best-fit spectra** with **CTAO sensitivity****
- ▶ Spectra consistent with **starburst** emission model

*15 yr of data (4FGL-DR4)

**3 σ discovery potential for 50h of observations

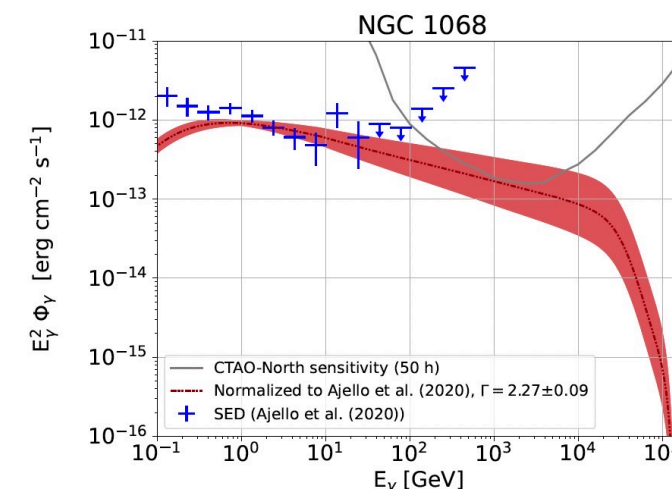
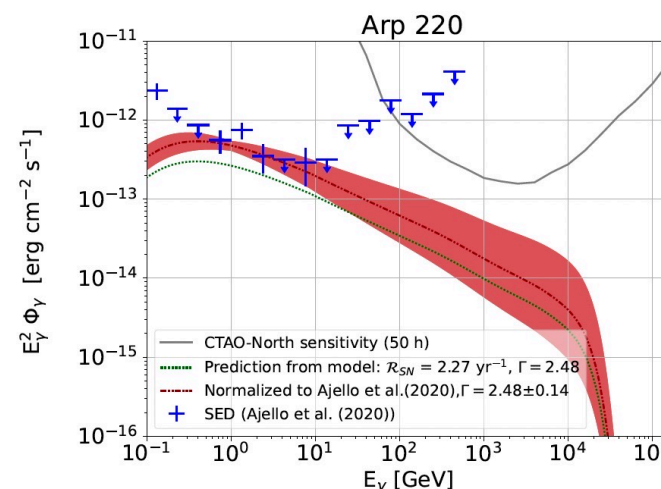
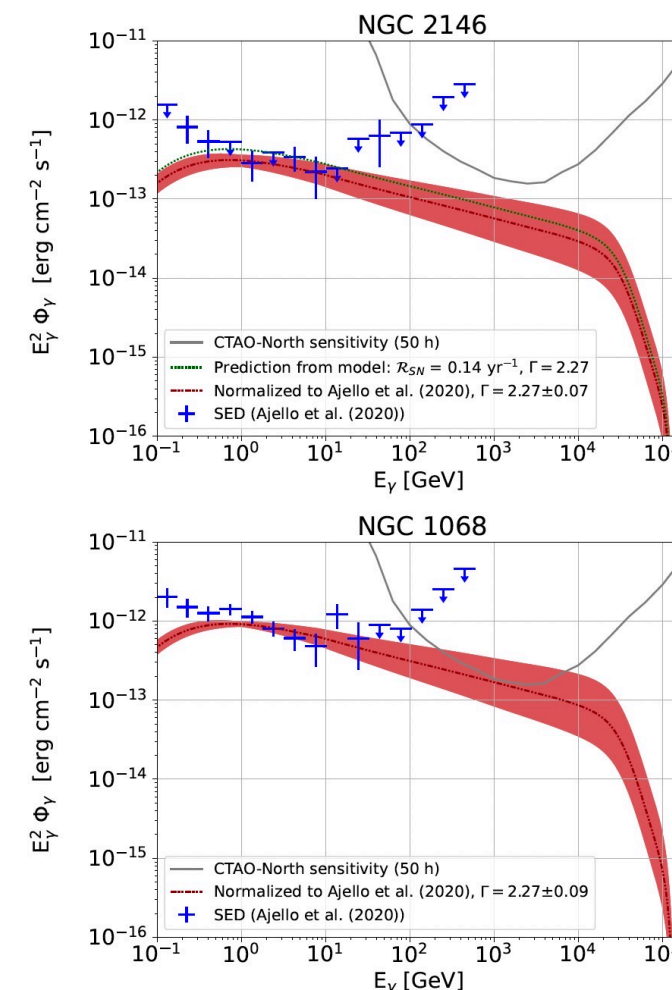
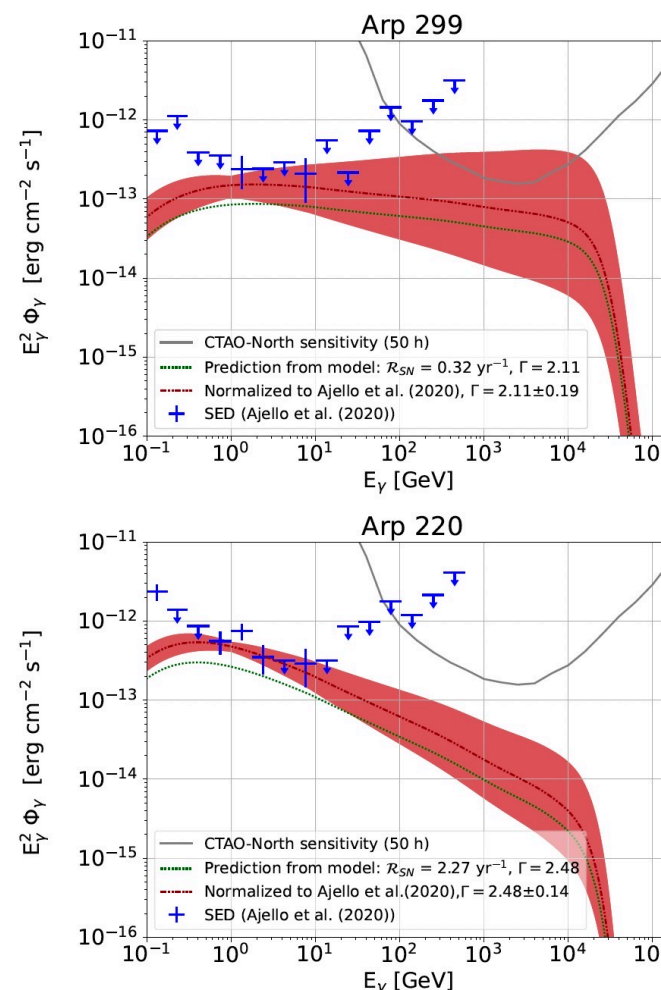


Prospects for U/LIRG Studies with CTAO

- ▶ Consider four **U/LIRGs detected by *Fermi*-LAT***
- ▶ Compare **extrapolated best-fit spectra** with **CTAO sensitivity****
- ▶ Spectra consistent with **starburst** emission model
- ▶ **Cross-checked** with GOALS starburst-driven framework
- ▶ Recent M1 internship of **Victor Courvoisier-Gernigon**

*10 yr of data [[Ajello+ \(2020\) ApJ 894 88](#)]

**5 σ discovery potential for 50h of observations



Prospects for U/LIRG Studies with CTAO

- ▶ Consider four U/LIRGs detected by *Fermi*-LAT*

- ▶ Component spectra

- ▶ Spectra of starbursts

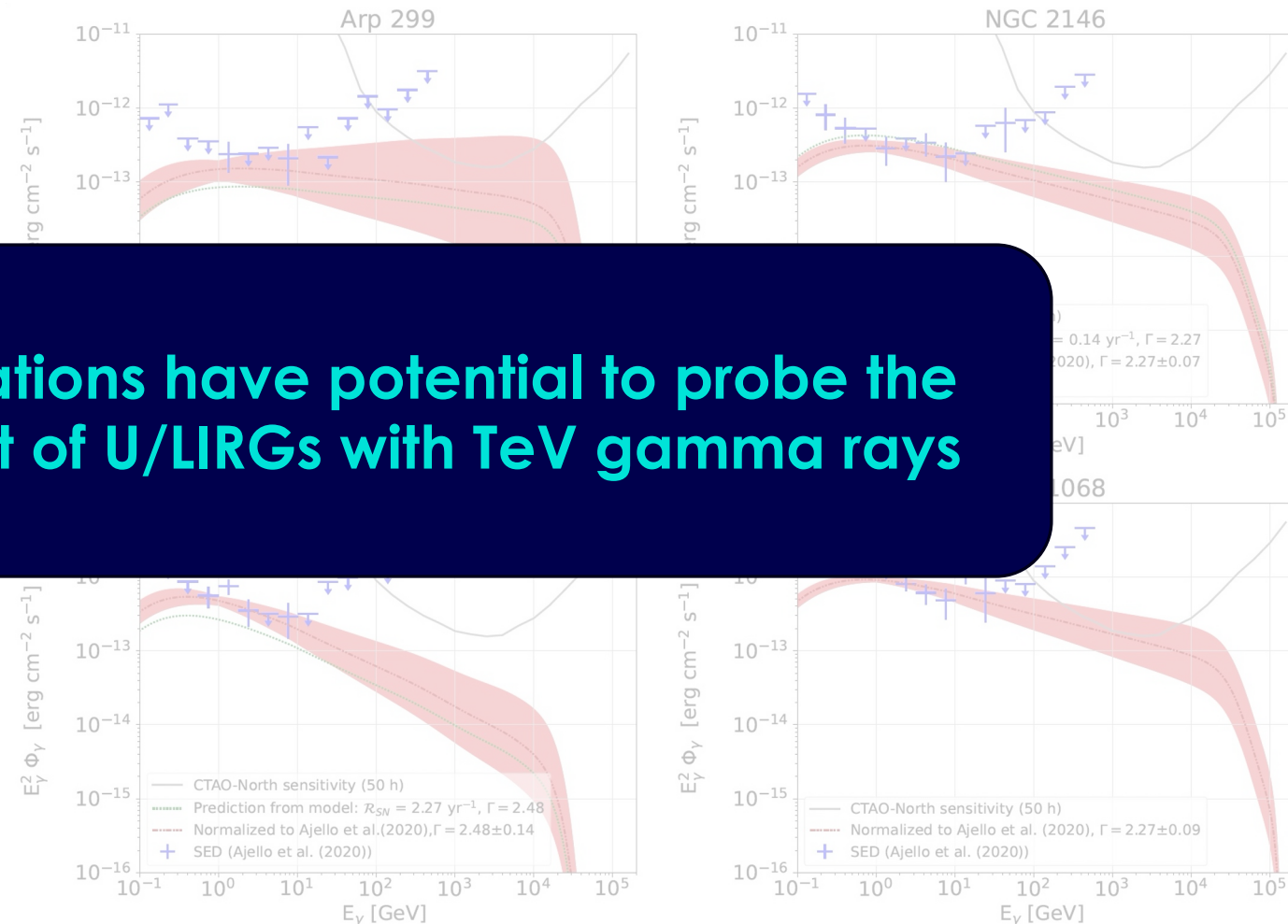
- ▶ Cross-checked with GOALS starburst-driven framework

- ▶ Recent M1 internship of Victor Courvoisier-Gernigon

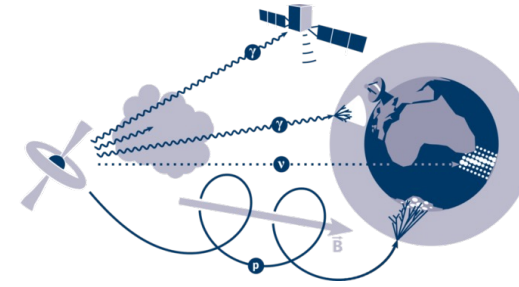
Deep CTAO observations have potential to probe the starburst component of U/LIRGs with TeV gamma rays

*10 yr of data [Ajello+ (2020) ApJ 894 88]

**5σ discovery potential for 50h of observations



Conclusions & Outlook



Summary

- ▶ **U/LIRGs** host **high-energy phenomena** that can produce **cosmic rays** (CRs)
- ▶ **GeV gamma rays** are associated with **starburst** activity in U/LIRGs
- ▶ **TeV neutrinos** suggest **gamma-ray-dim AGN** component in U/LIRGs

Outlook

- ▶ **Upcoming TeV neutrino telescopes** will improve upon **Seyfert** studies
- ▶ **CTAO** will be able to probe **TeV emission of U/LIRG starbursts**
- ▶ **MM observations key to complete picture of CR physics in U/LIRGs**



GRÀCIES!



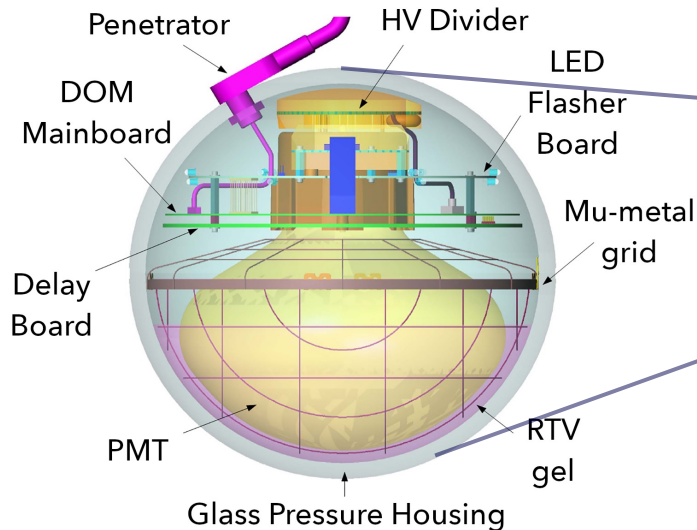
BACKUP



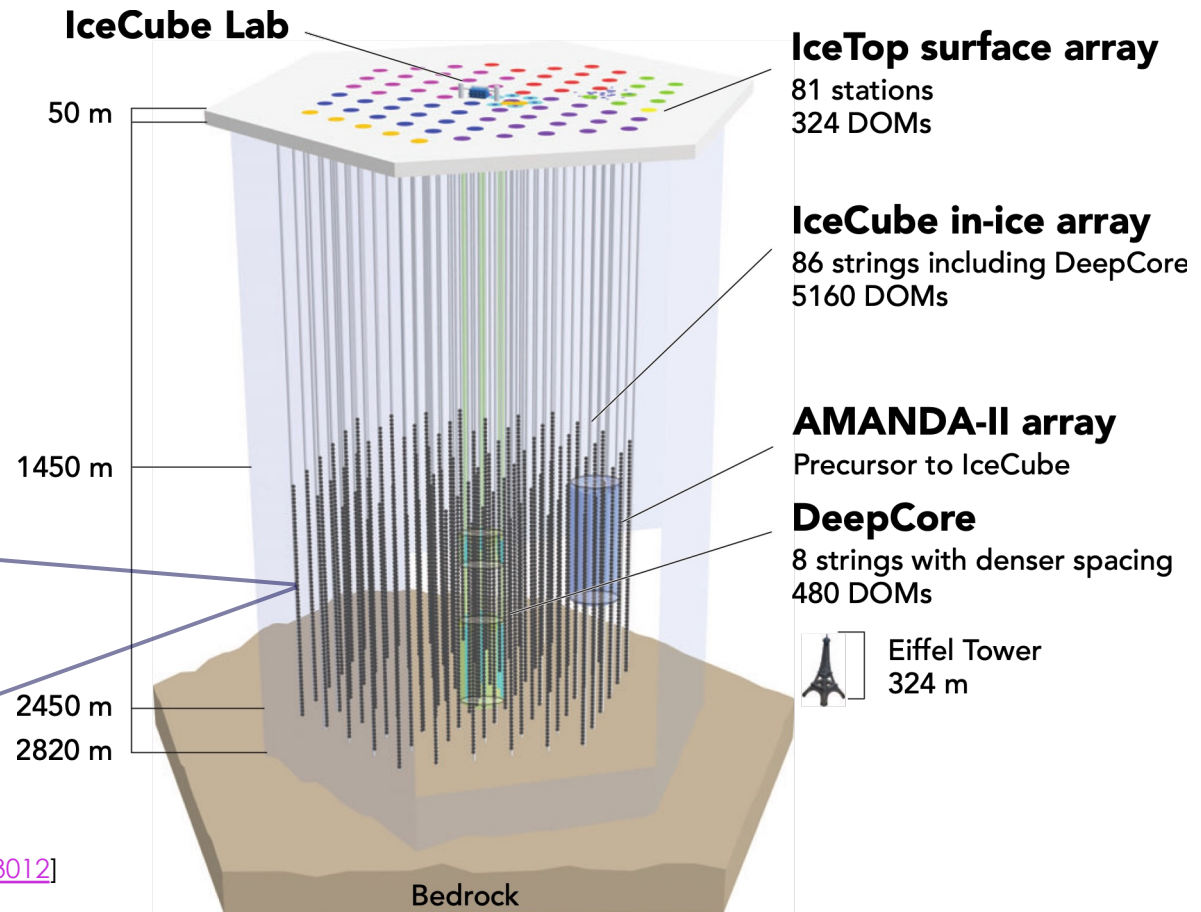
IceCube & Neutrino Sources

The IceCube Neutrino Observatory

- **1 km³ detector** at the South Pole
- **5160 digital optical modules (DOMs)**
- **86 strings** down to 2.45 km depth



[IC (2017) JINST 12 P03012]

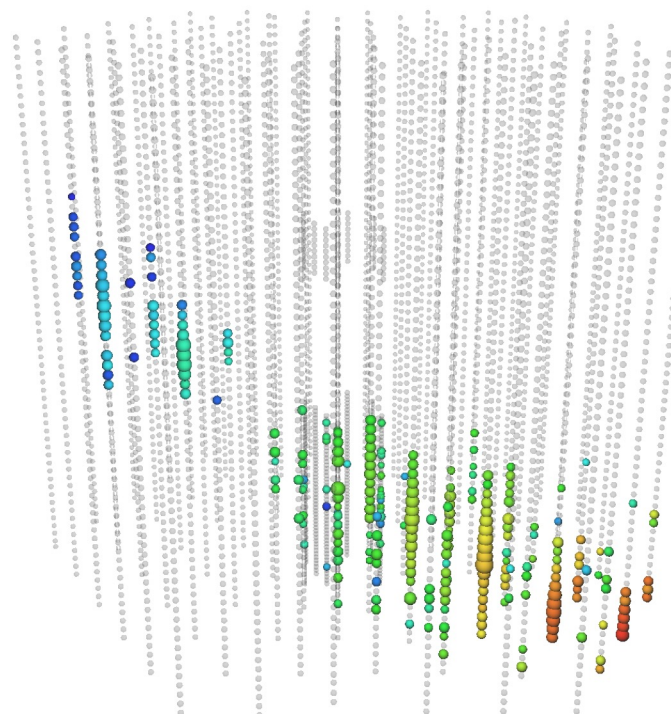


Detecting Neutrinos

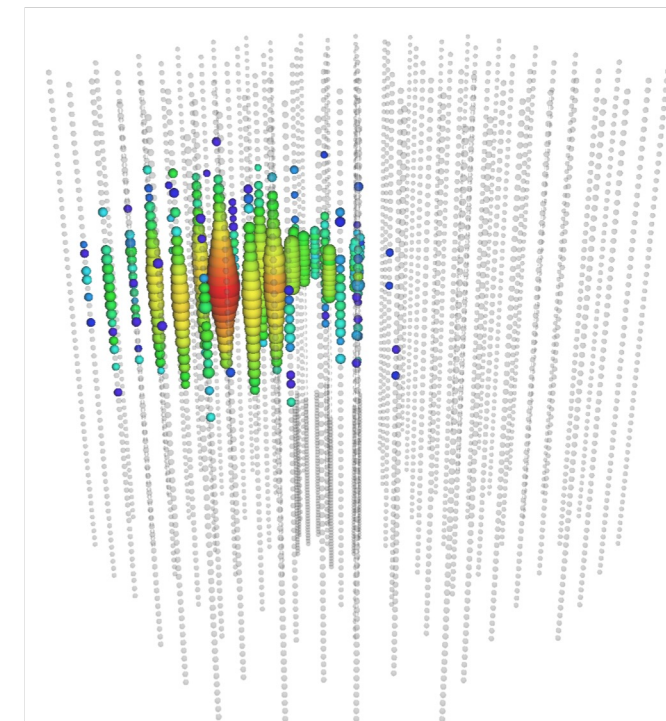
- **Indirect detection** with km^3 water-Cherenkov telescopes
- High-energy: **1 TeV – 10 PeV**

Instrument	IceCube	
Duty cycle	~100%	
Field of view	~100% of sky	
Event Type	Tracks	Cascades
Angular res.	$<1^\circ$ (>1 TeV)	$>8^\circ$
Energy res.	Factor ~2	~30%

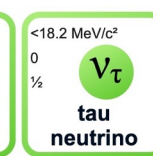
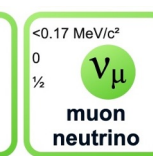
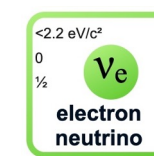
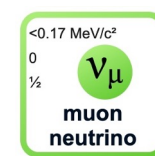
Track



Cascade



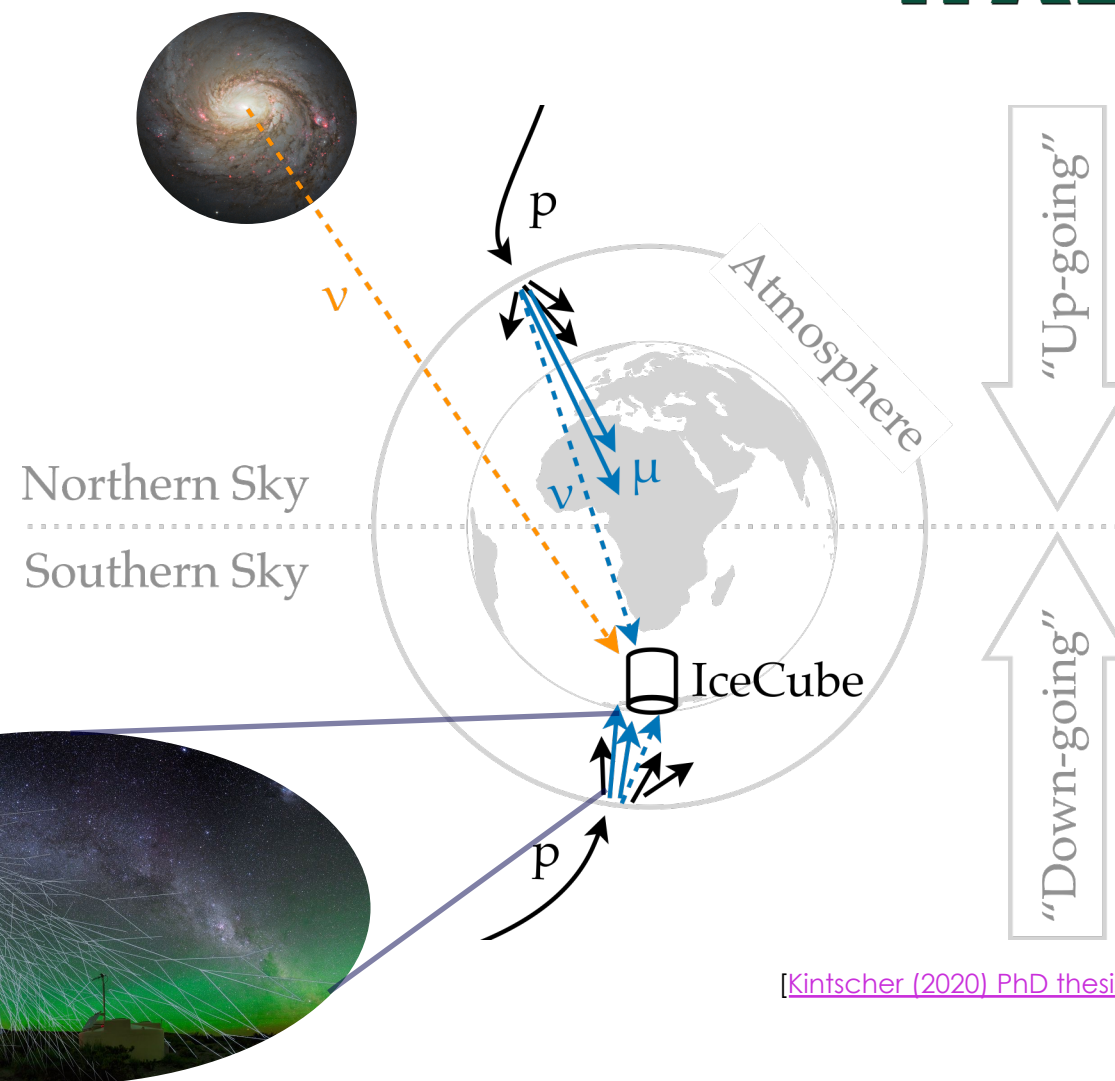
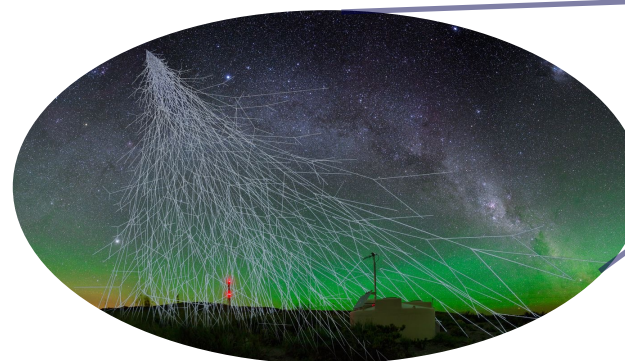
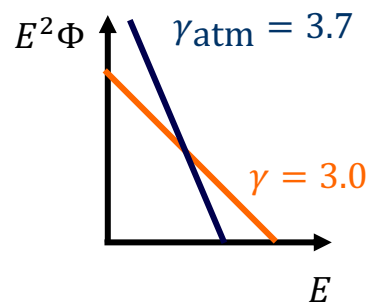
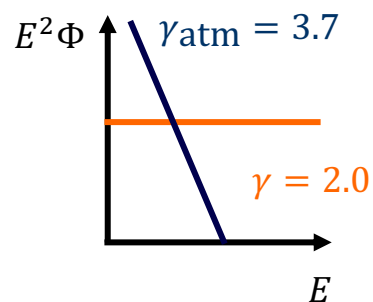
[Kintscher (2020) PhD thesis]



Background vs Signal

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

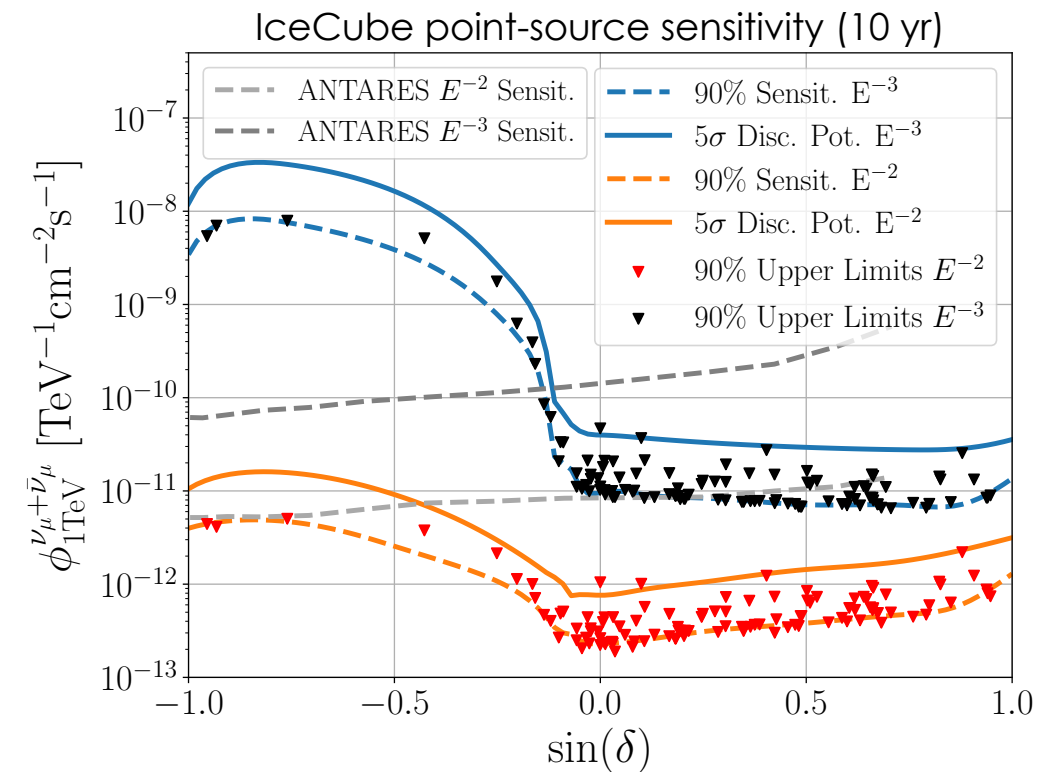
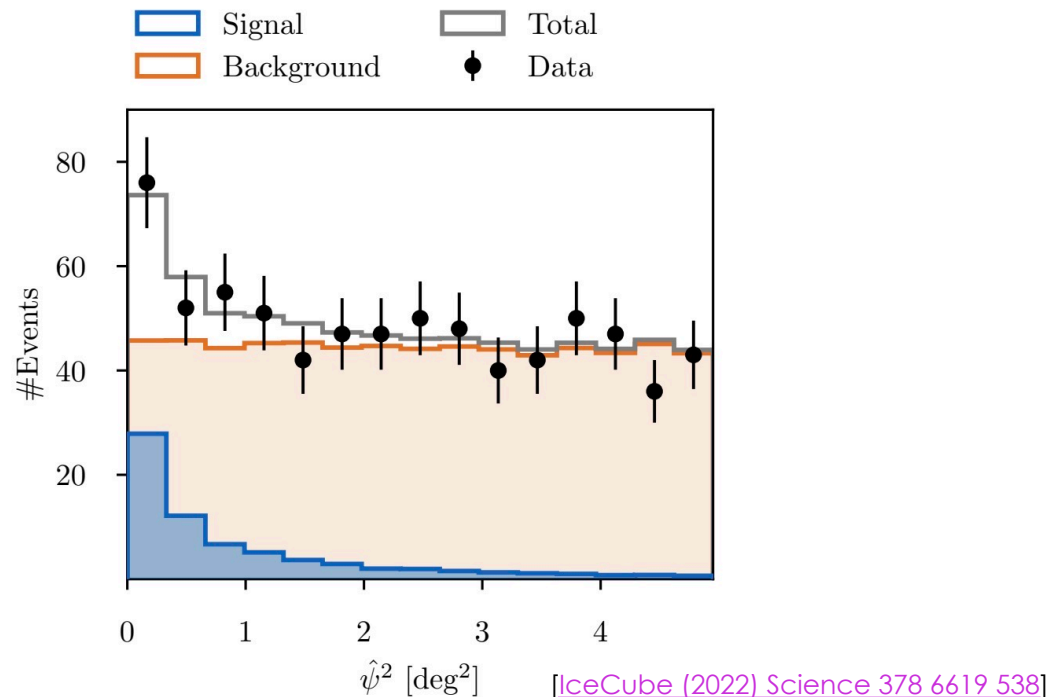
Atmospheric muons	Atmospheric neutrinos	Astrophysical neutrinos
2,700 per second	600 per hour	10–100 per year
South only	Full sky	Full sky



[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

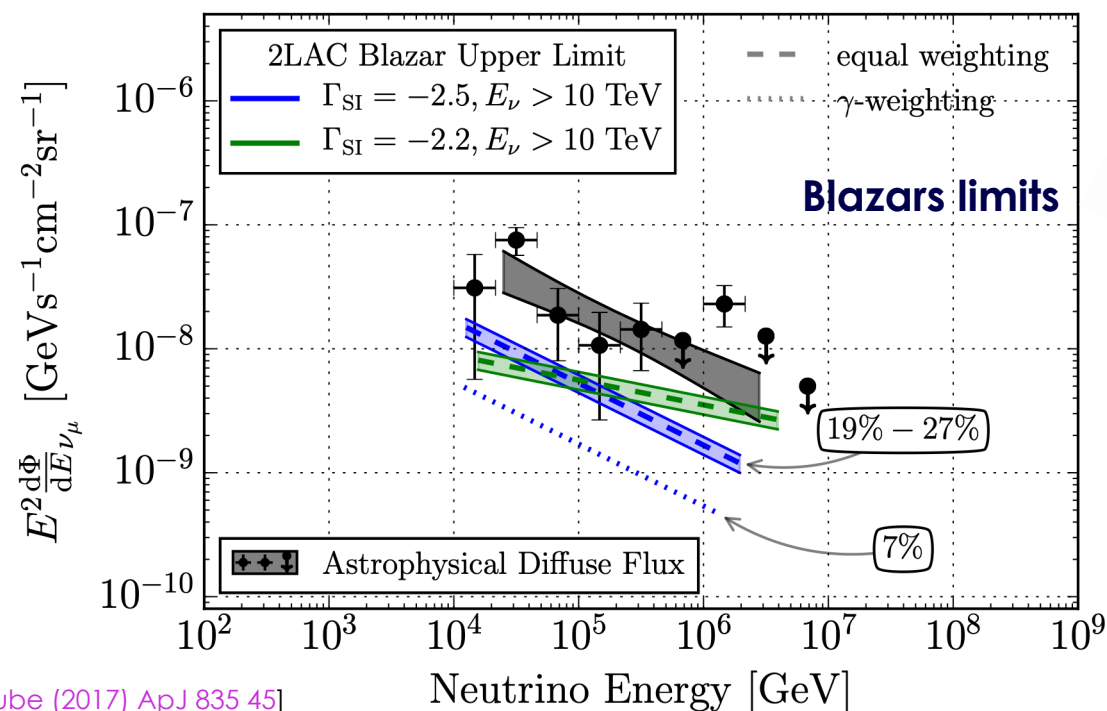
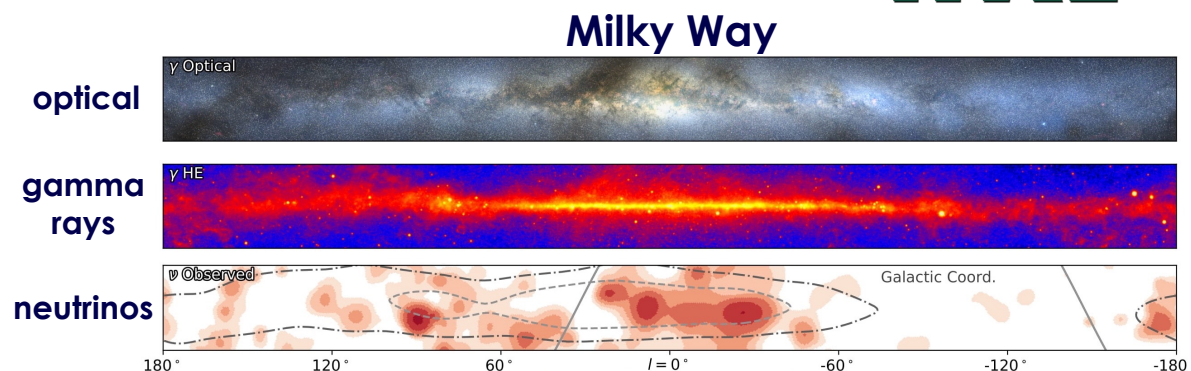


[IceCube (2020) PRL 124 051103]

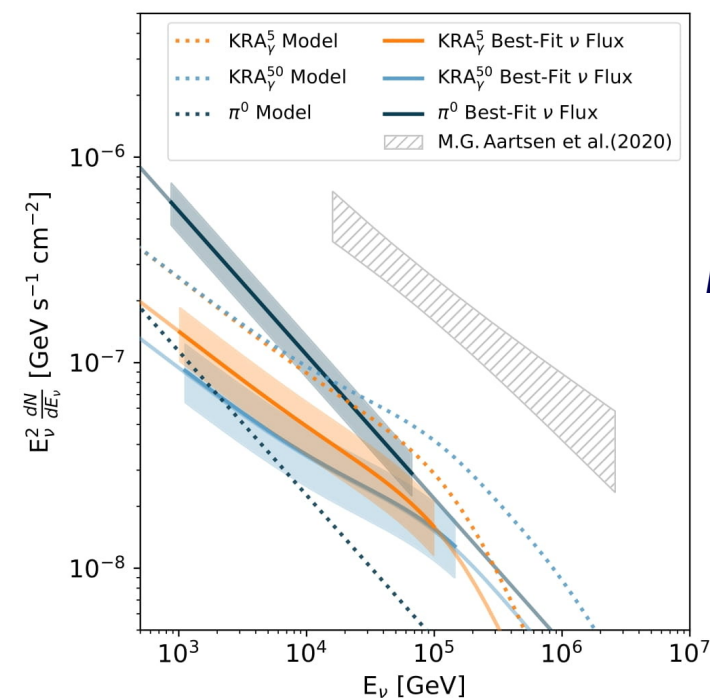
Diffuse Neutrinos

► IceCube (ν)

- Most neutrinos ($\sim 90\%$) are **extragalactic**
- Sources remain **largely unknown**
- Contribution of **blazars constrained**



[IceCube (2017) ApJ 835 45]



**Milky Way
detection**

[IceCube (2023) Science 380 1338]

Diffuse Neutrinos vs Gamma Rays

► IceCube (ν)

- Most neutrinos ($\sim 90\%$) are **extragalactic**
- Sources remain **largely unknown**
- Contribution of **blazars constrained**

► Fermi-LAT (γ)

- Extragalactic gamma-ray background (**EGB**) **dominated by blazars** ($\sim 86\%$ above 50 GeV)

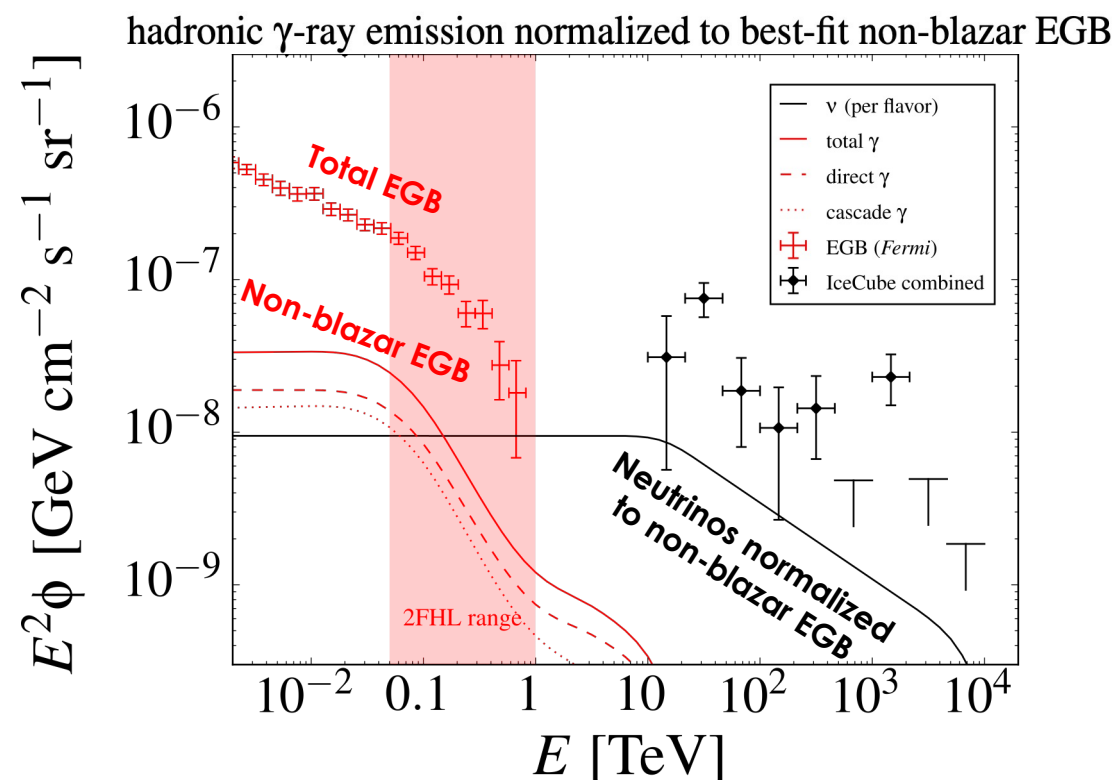
[Fermi-LAT (2016) PRL 116 151105]

Neutrino sources cannot exceed
non-blazar EGB



Neutrino sources are likely
opaque to gamma rays

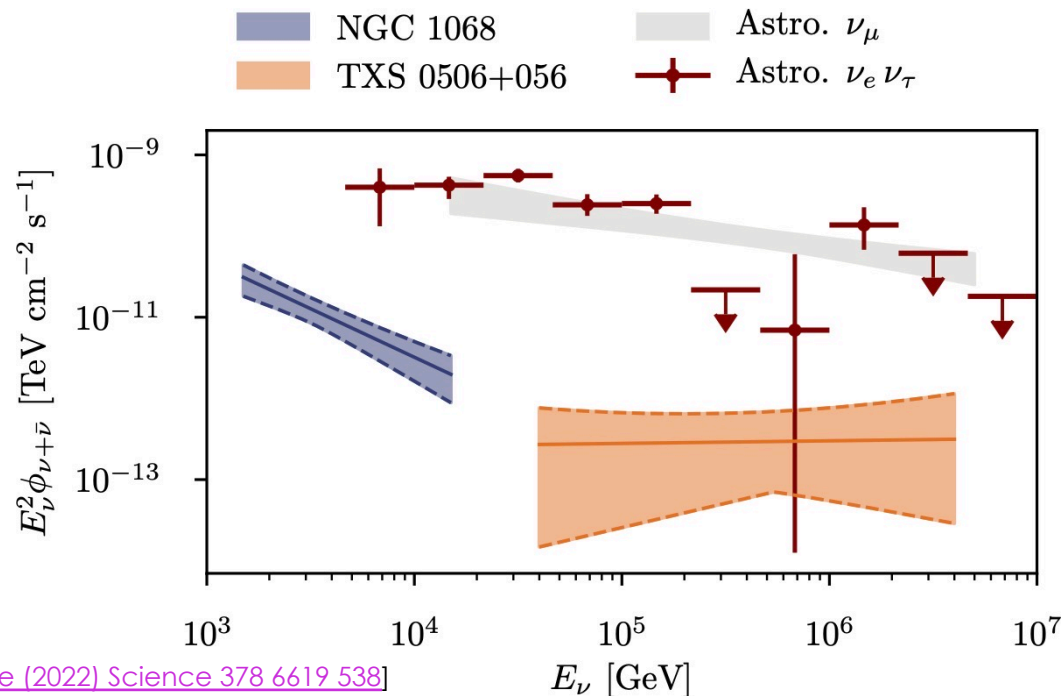
[e.g. Murase+ (2016) PRL 116 071101]



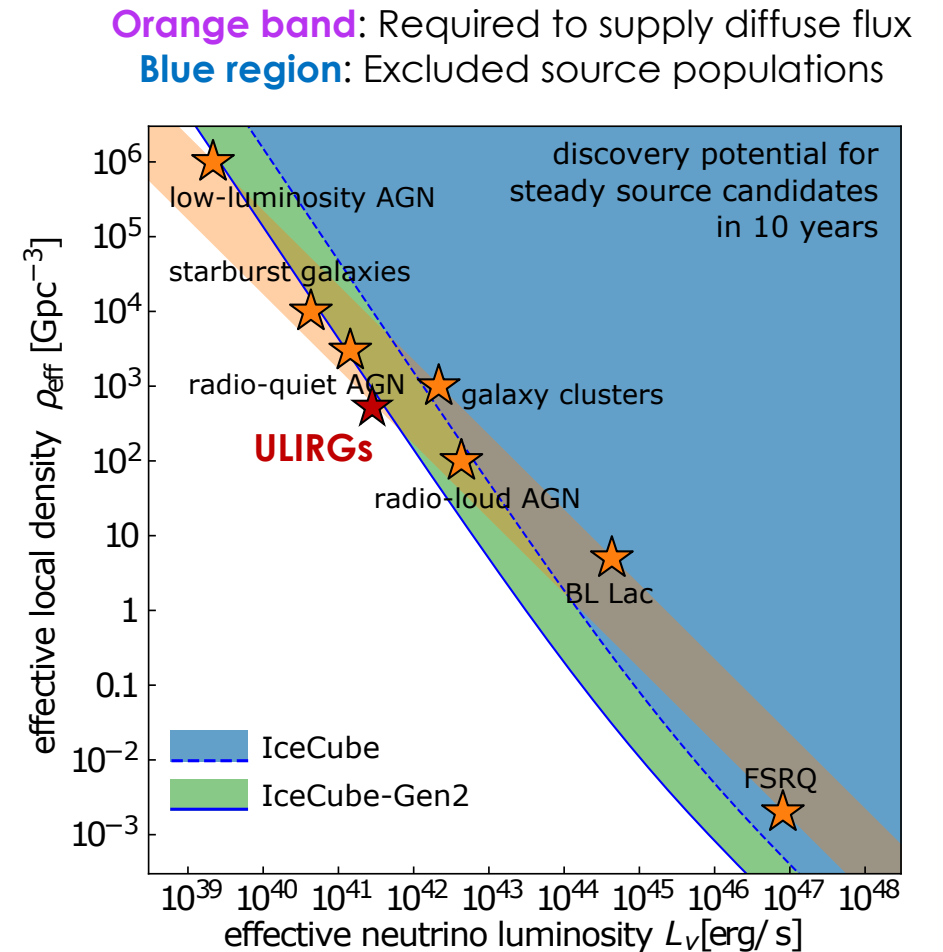
[Bechtol+ (2017) ApJ 836 47]

Status of Neutrino Astronomy

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



[IceCube (2022) Science 378 6619 538]



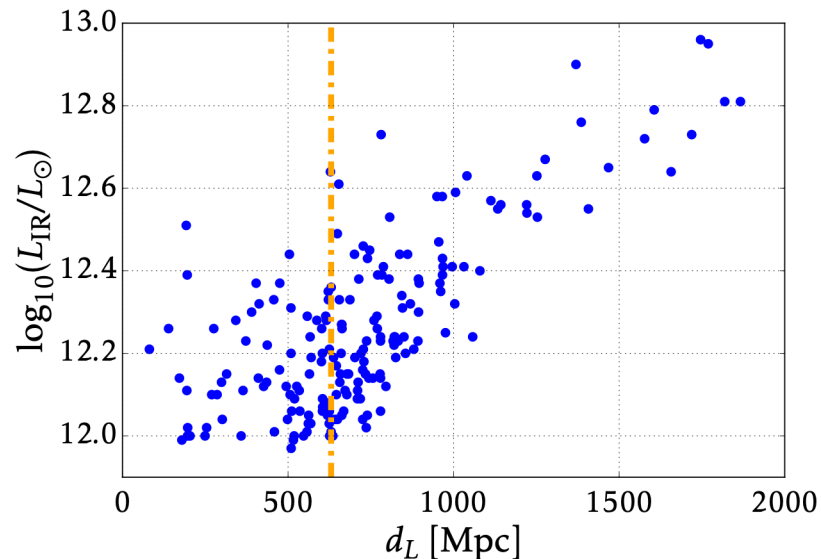
[IceCube-Gen2 (2021) JPG 6 060501]



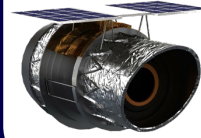
IceCube ULIRG Search

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 $f_{60} = 1 \text{ Jy}$
- ▶ **Final sample: 75 ULIRGs within $z \leq 0.13$**
 - ▶ **Representative** of local ULIRG population



Infrared Astronomical Satellite

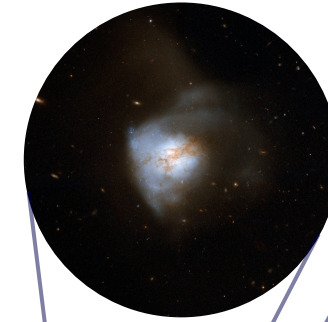


Jan-Nov 1983
12, 25, **60**, 100 micron

[Neugebauer+ (1984) ApJ 278 L1]



Arp 220

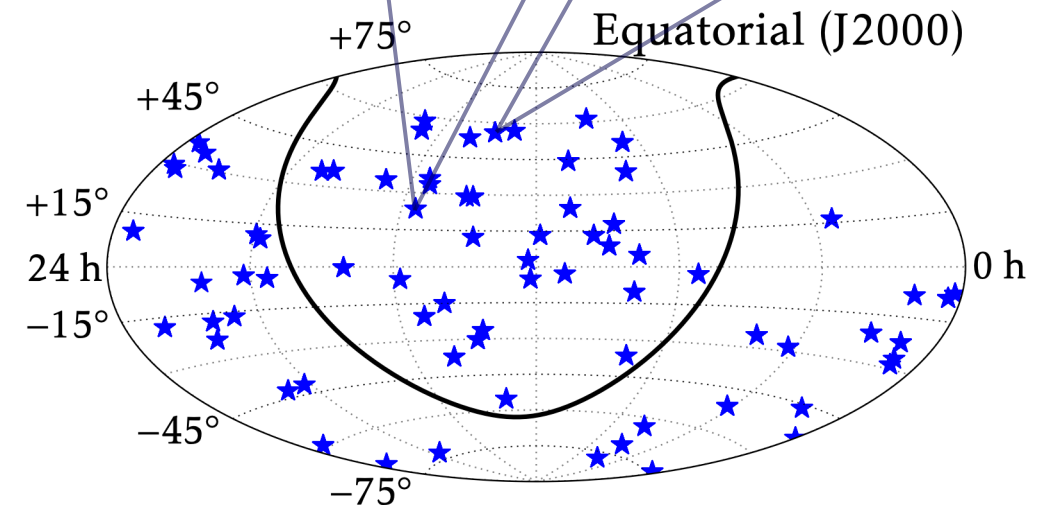


[NASA/ESA]

Mrk 273

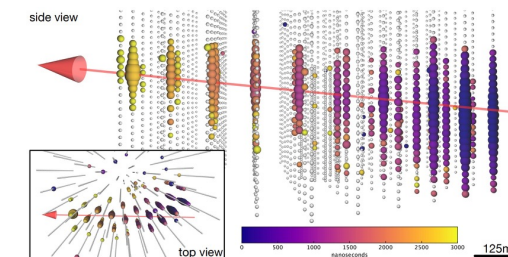
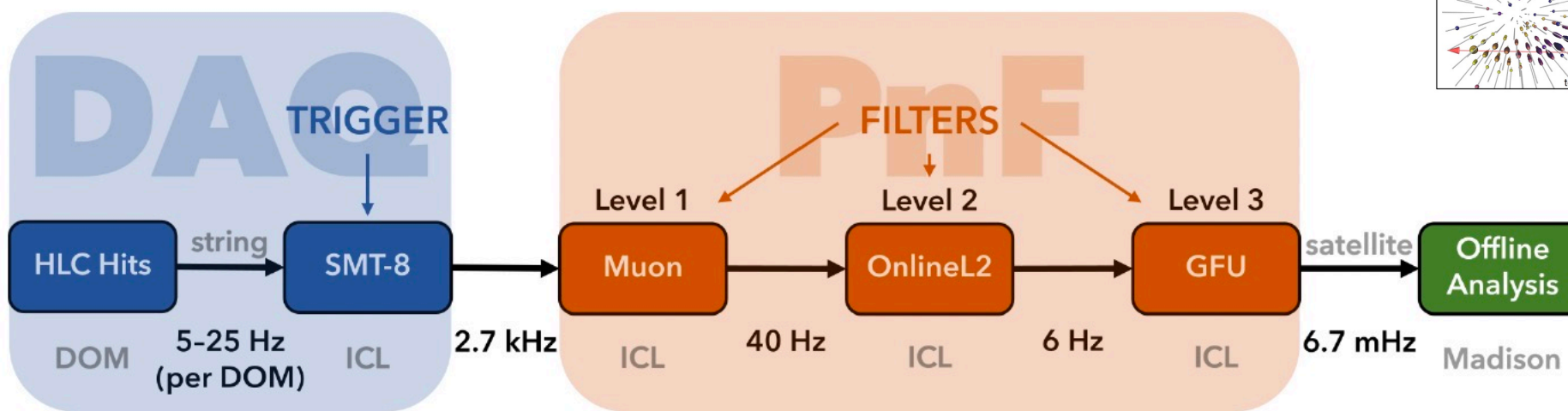
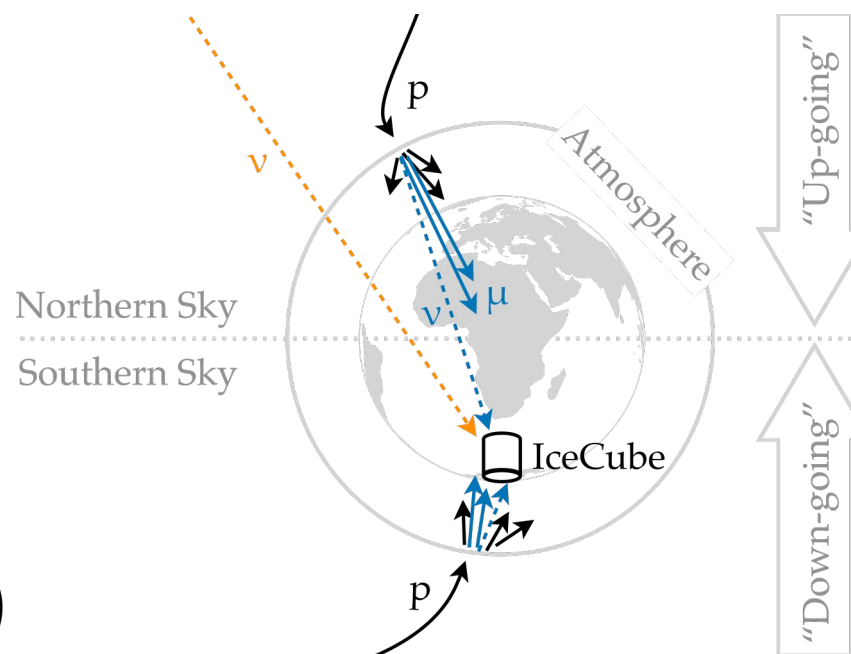


[NASA/ESA]



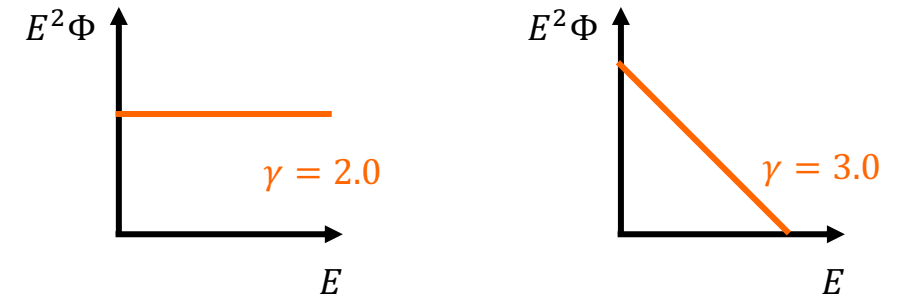
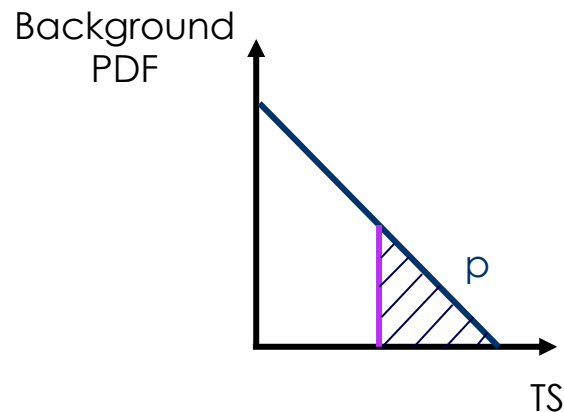
IceCube Dataset

- ▶ **GFU sample** [[IceCube \(2017\) 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, n_s
 - ▶ **Fit** for power-law spectral index, γ
- ▶ **Hypothesis test** (one-tailed)
 - ▶ $\mathcal{H}_0$: data only atmospheric background
 - ▶ $\mathcal{H}_s$: data contains signal from ULIRG locations
 - ▶ Larger TS $\longrightarrow$ smaller **p-value**



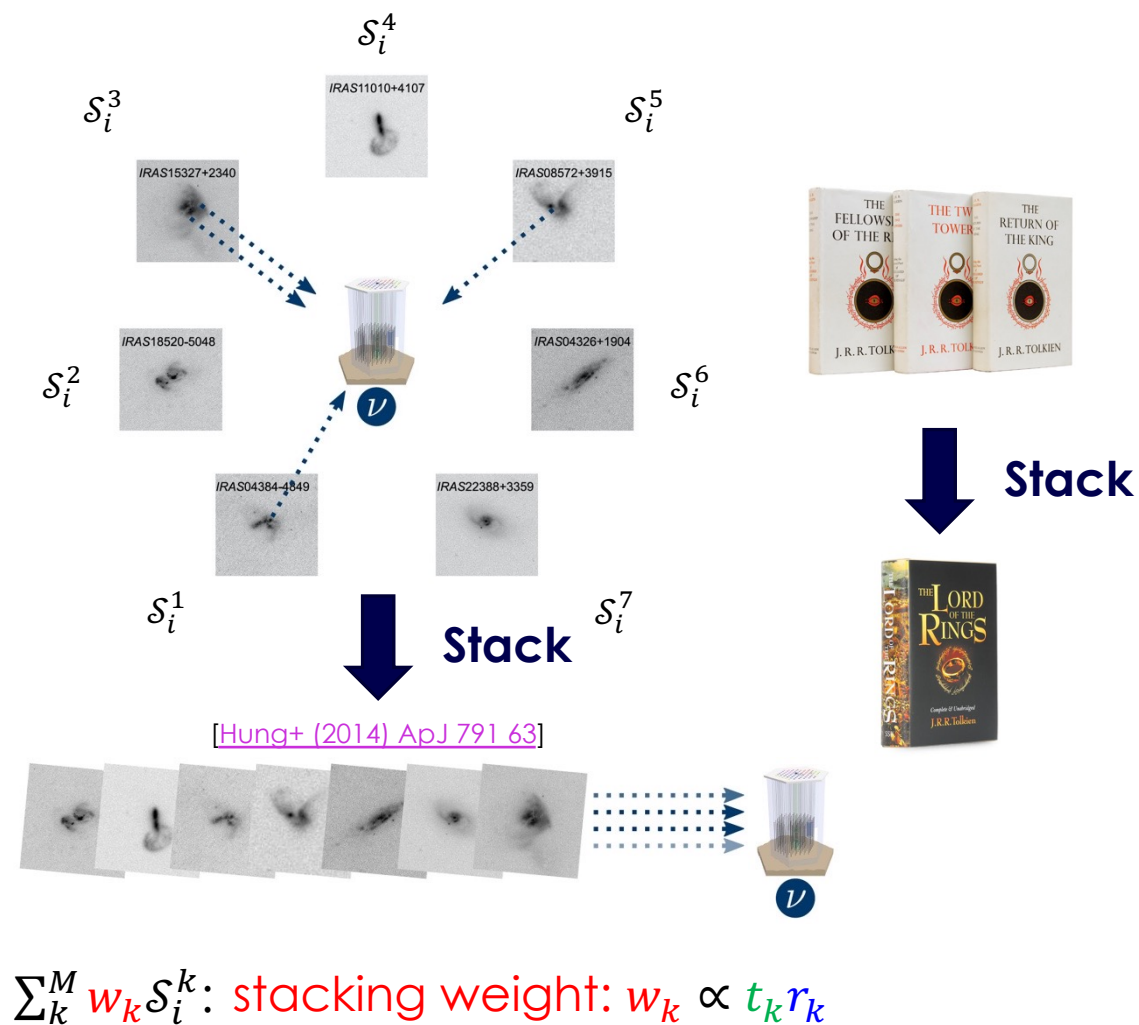
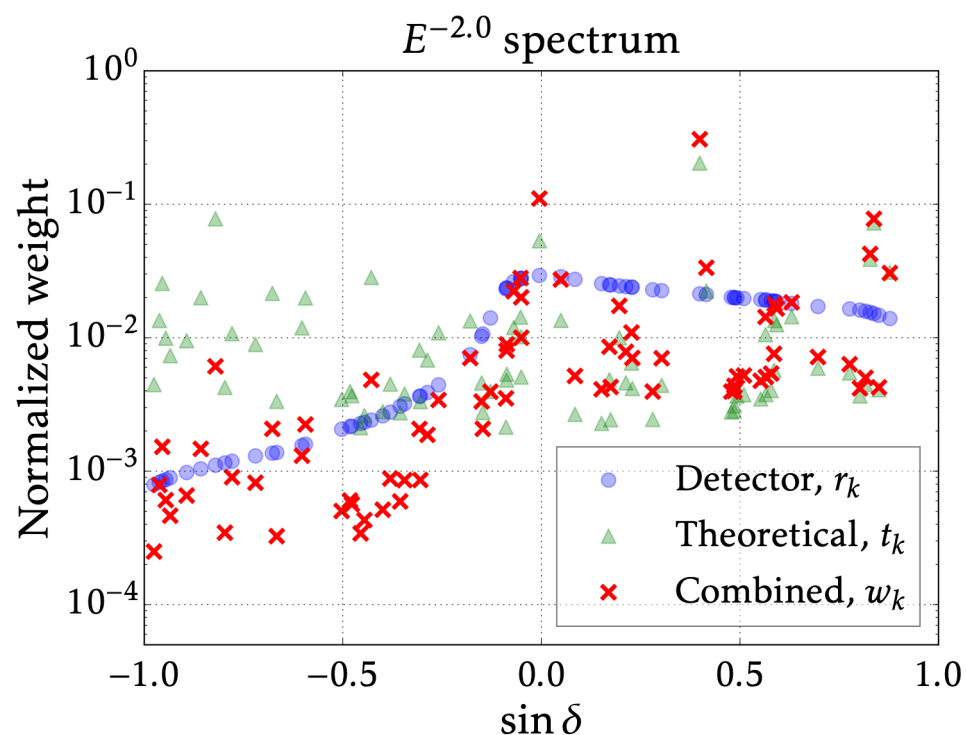
$$\mathcal{L}(n_s, \gamma) = \prod_i^N \left[\frac{n_s}{N} \sum_k^M w_k s_i^k(\gamma) + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \right]$$

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

$\mathcal{H}_s$ (top) and $\mathcal{H}_0$ (bottom)

Stacking Technique

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



Sensitivity & Discovery Potentials

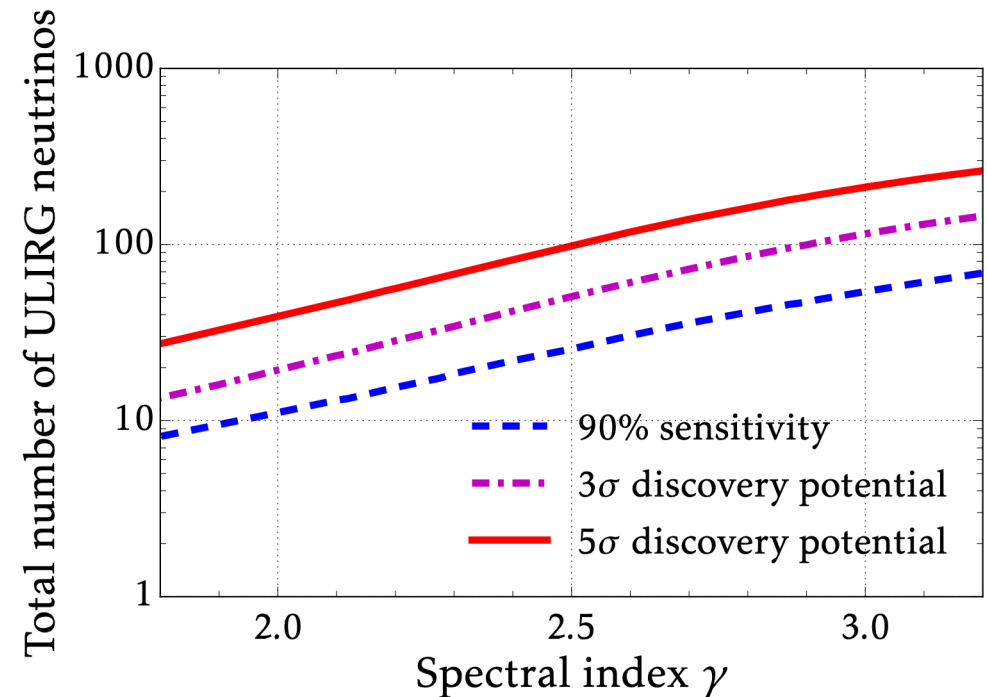
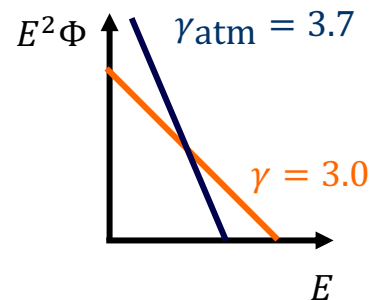
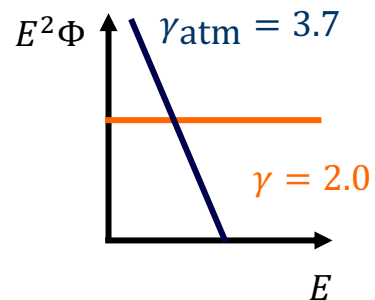
- ▶ Test **analysis performance**

- ▶ 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

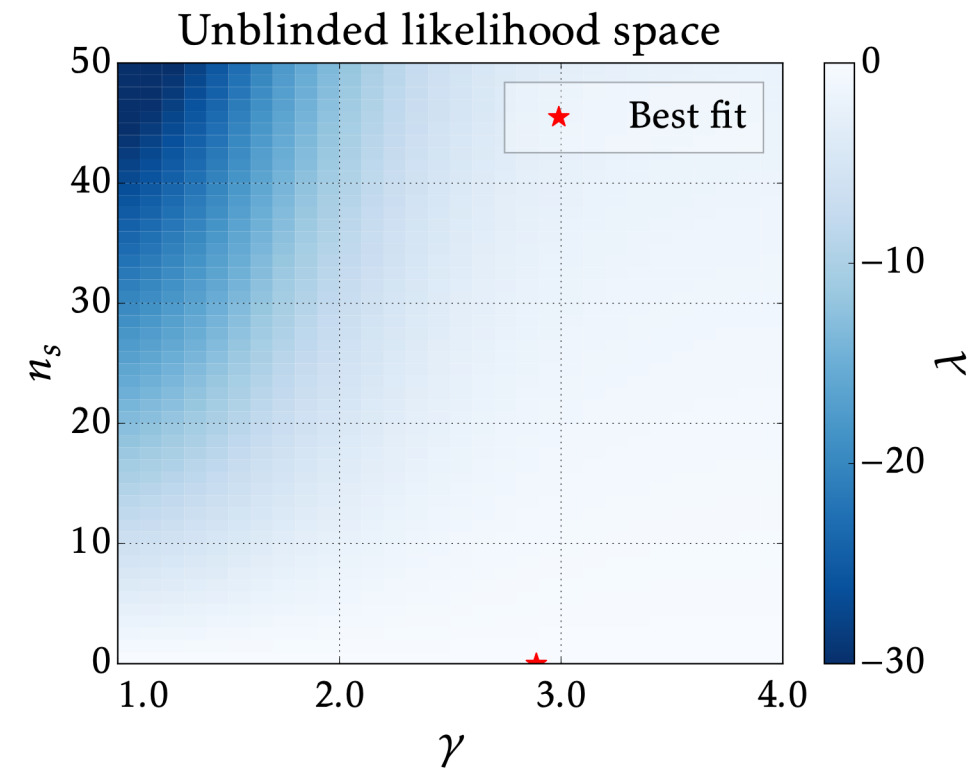
- ▶ More sensitive to **harder spectra**
 - ▶ **Easier to distinguish** from $E^{-3.7}$ background



Analysis Results

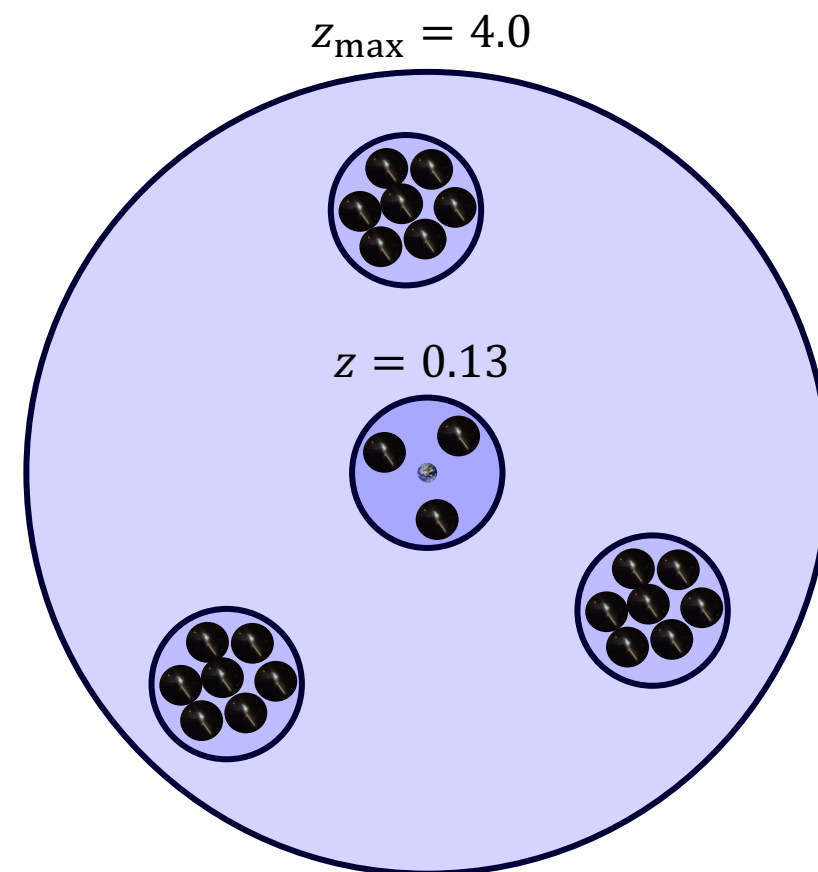
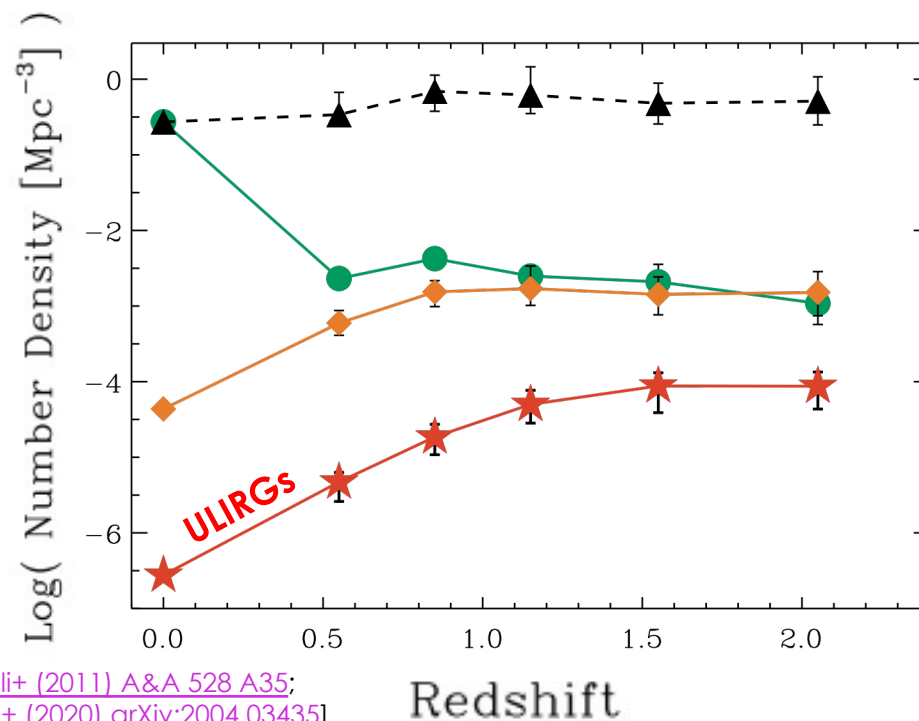
- ▶ Analysis **consistent with background**
- ▶ Set **upper limits** on flux from 75 ULIRGs ($z \leq 0.13$)
 - ▶ Limits equal to **sensitivity** (90% CL)
- ▶ Total **systematic uncertainty** $\sim 15\%$
 - ▶ DOM efficiency, ice properties, muon propagation

Analysis yields
 $TS = 0$
 $p\text{-value} = 1.0$



Extrapolating to Diffuse Limits

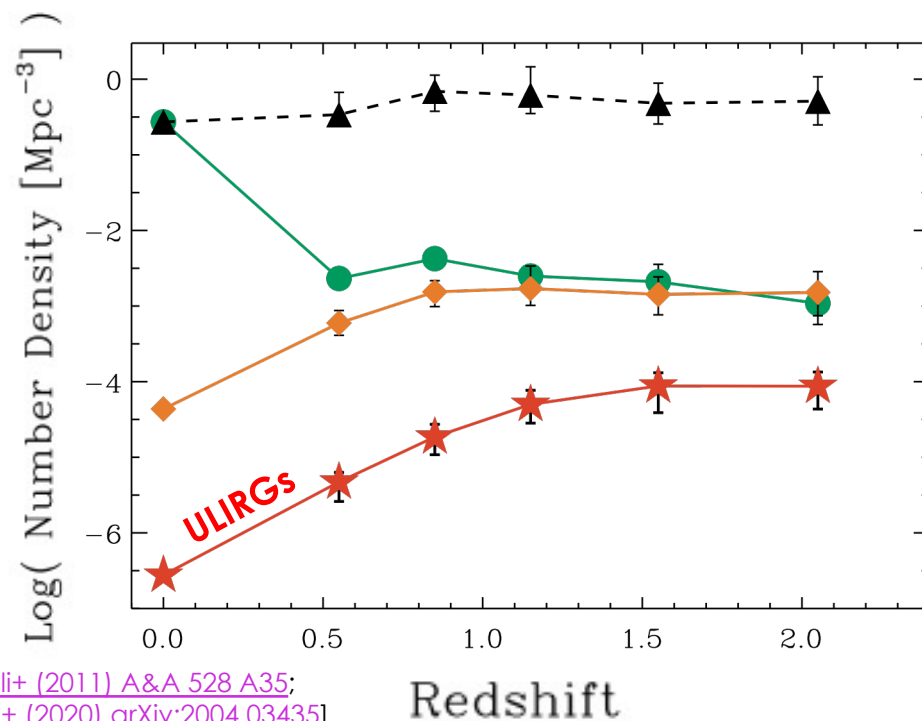
- ▶ Set **limits on diffuse flux** of full ULIRG population
 - ▶ **Integrate** contribution of ULIRGs up to $z_{\max}$
 - ▶ Assume $L_{IR} \propto L_V = \text{constant}$ and same $E^{-\gamma}$ spectrum



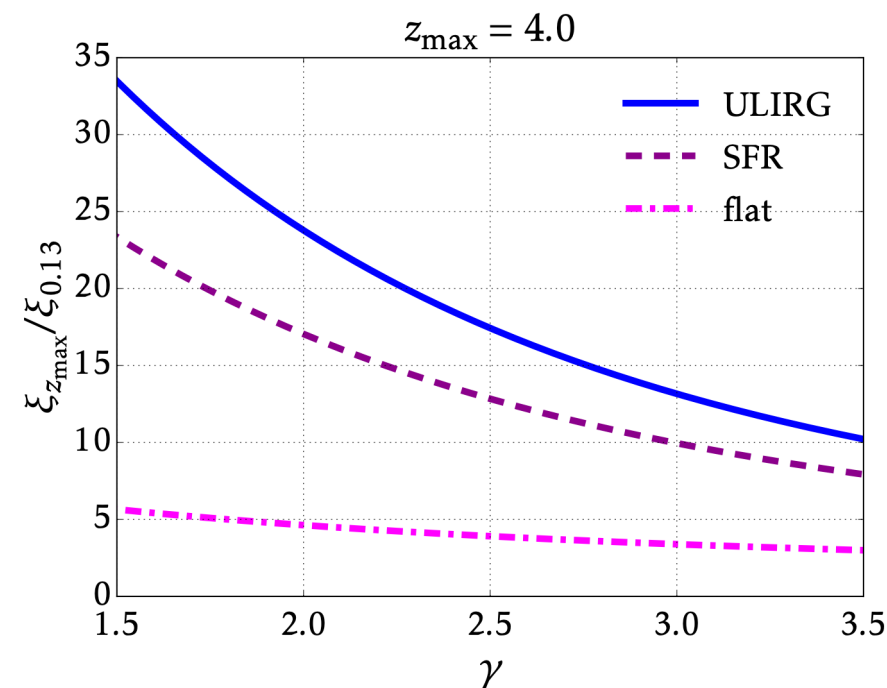
Extrapolating to Diffuse Limits

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

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



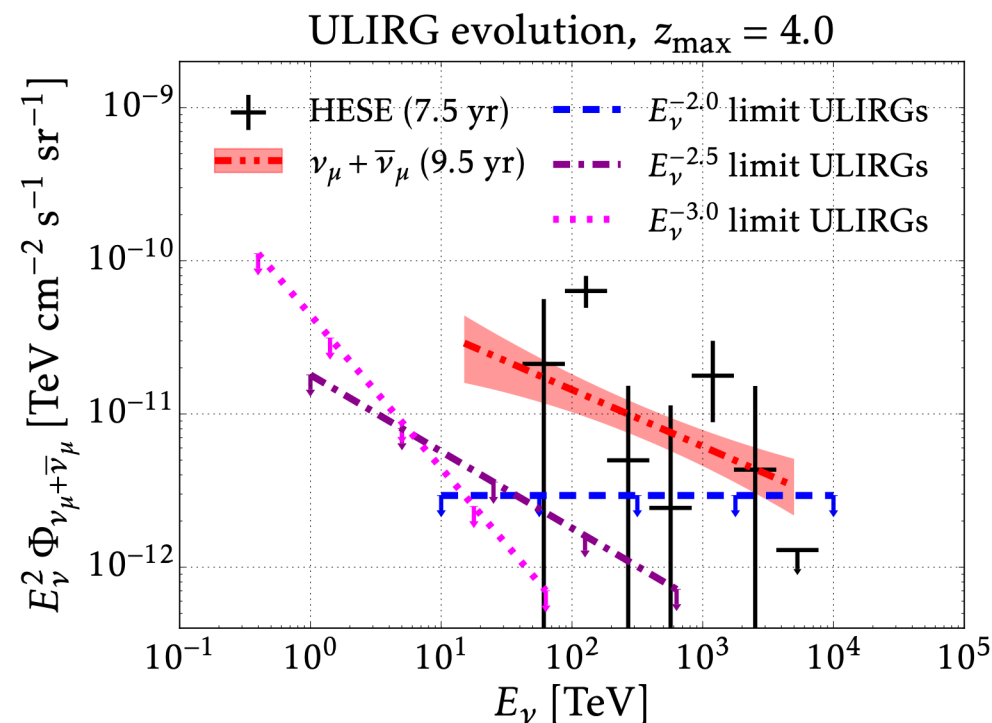
[Magnelli+ (2011) A&A 528 A35;
Vereecken+ (2020) arXiv:2004.03435]



Limits on ULIRG Population

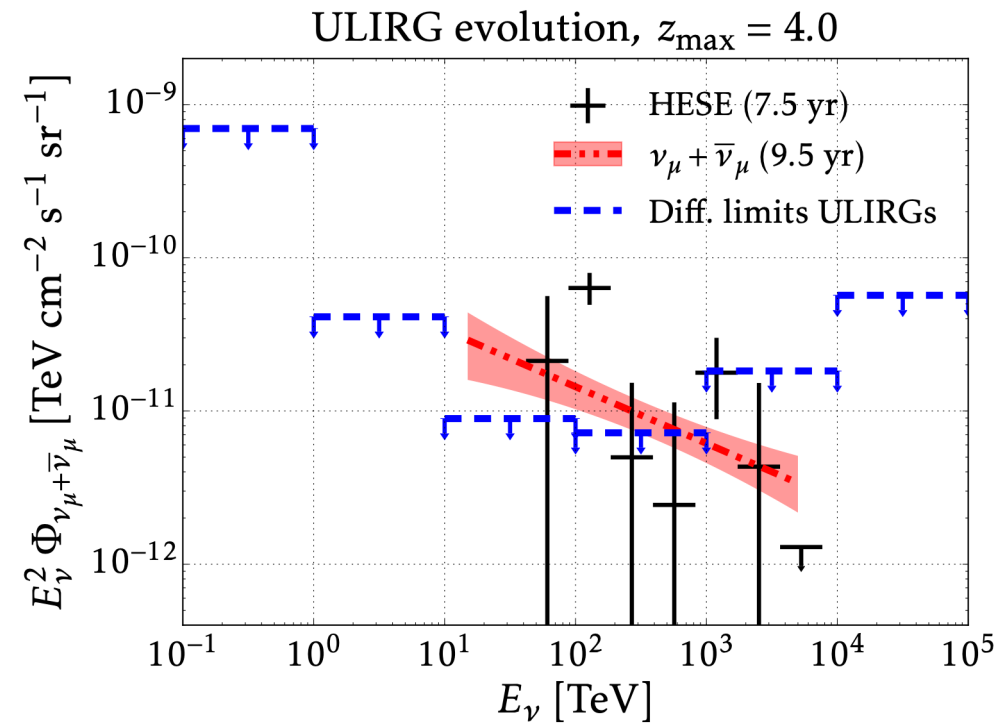
► Integral limits

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



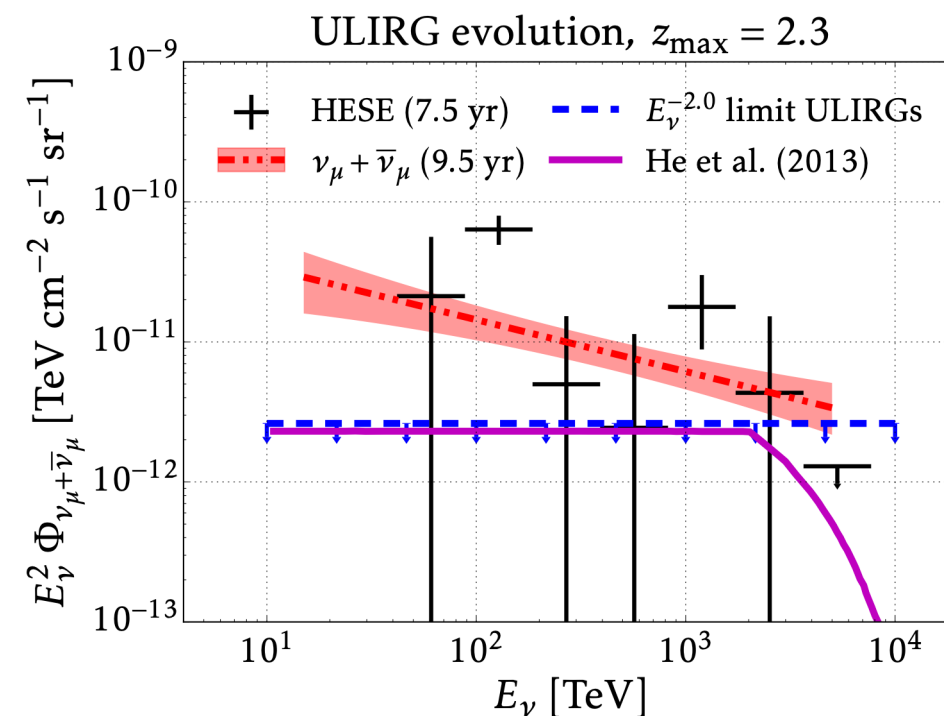
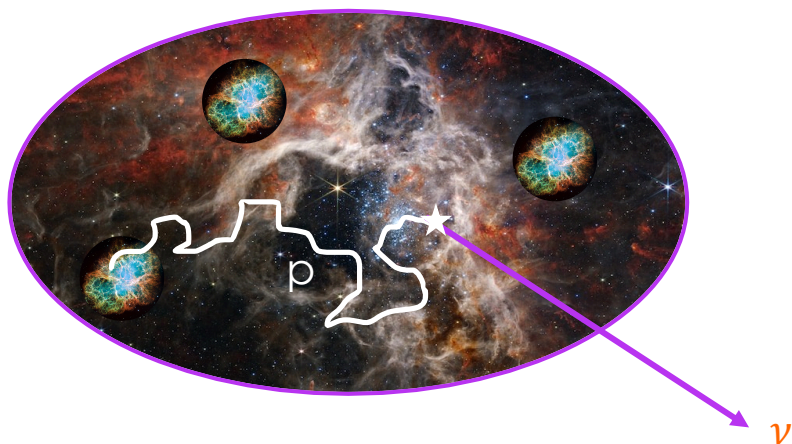
► Differential limits

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



Comparison with Reservoir Model I

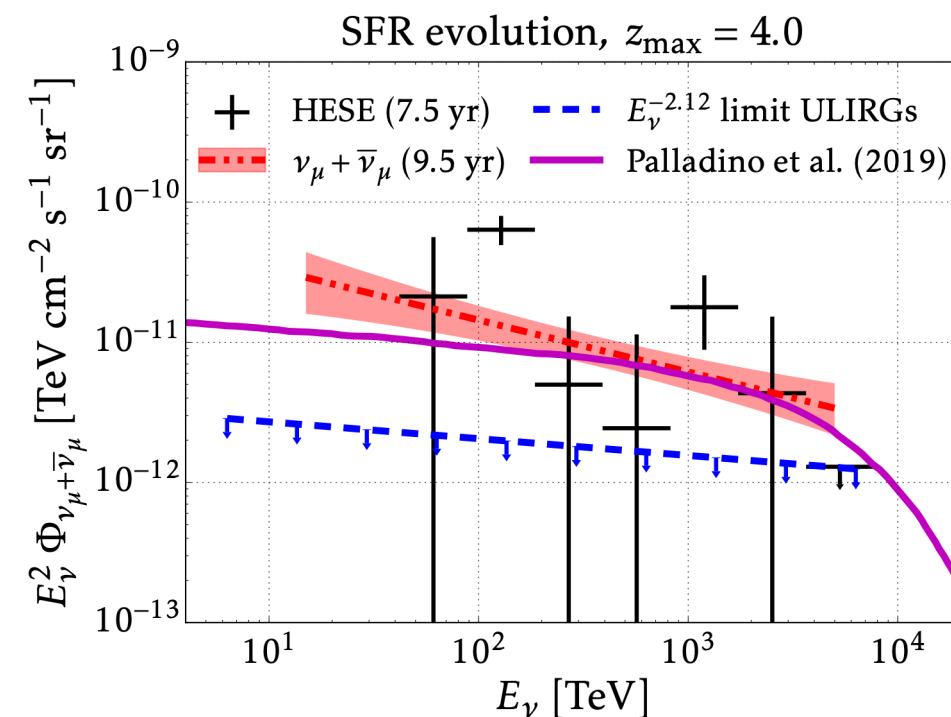
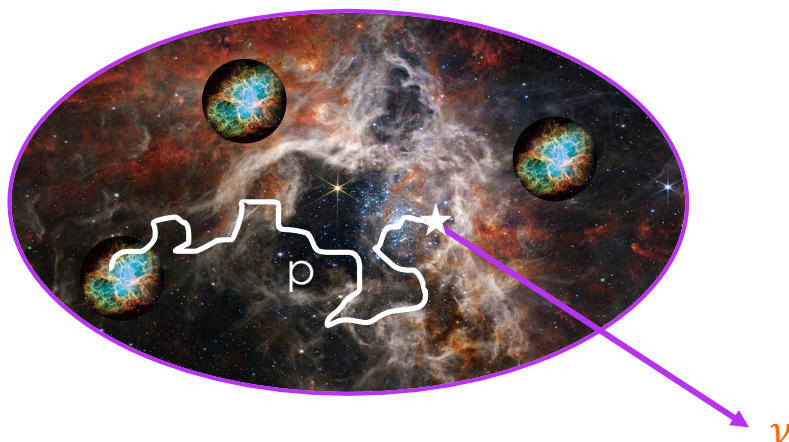
- ▶ [He+ \(2013\) PRD 87 063011](#)
 - ▶ Neutrino flux powered by **hypernovae**
 - ▶ **At level** of our upper limit
 - ▶ **More data** needed to exclude/validate



Comparison with Reservoir Model II

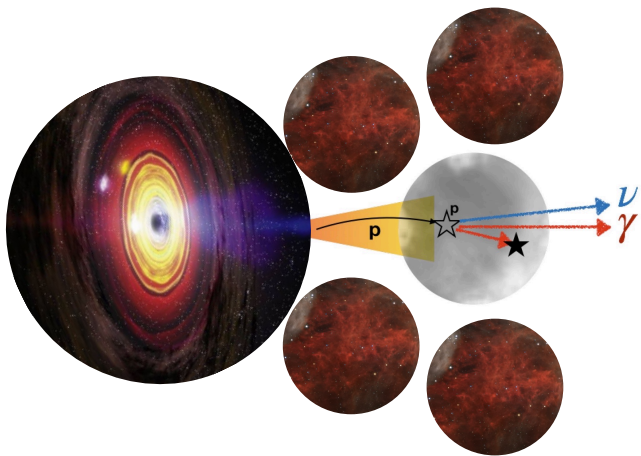
► [Palladino+ \(2019\) JCAP 09 004](#)

- **Generic model** of hadronically powered gamma-ray galaxies (HAGS)
- **ULIRGs excluded as sole HAGS** responsible for diffuse observations



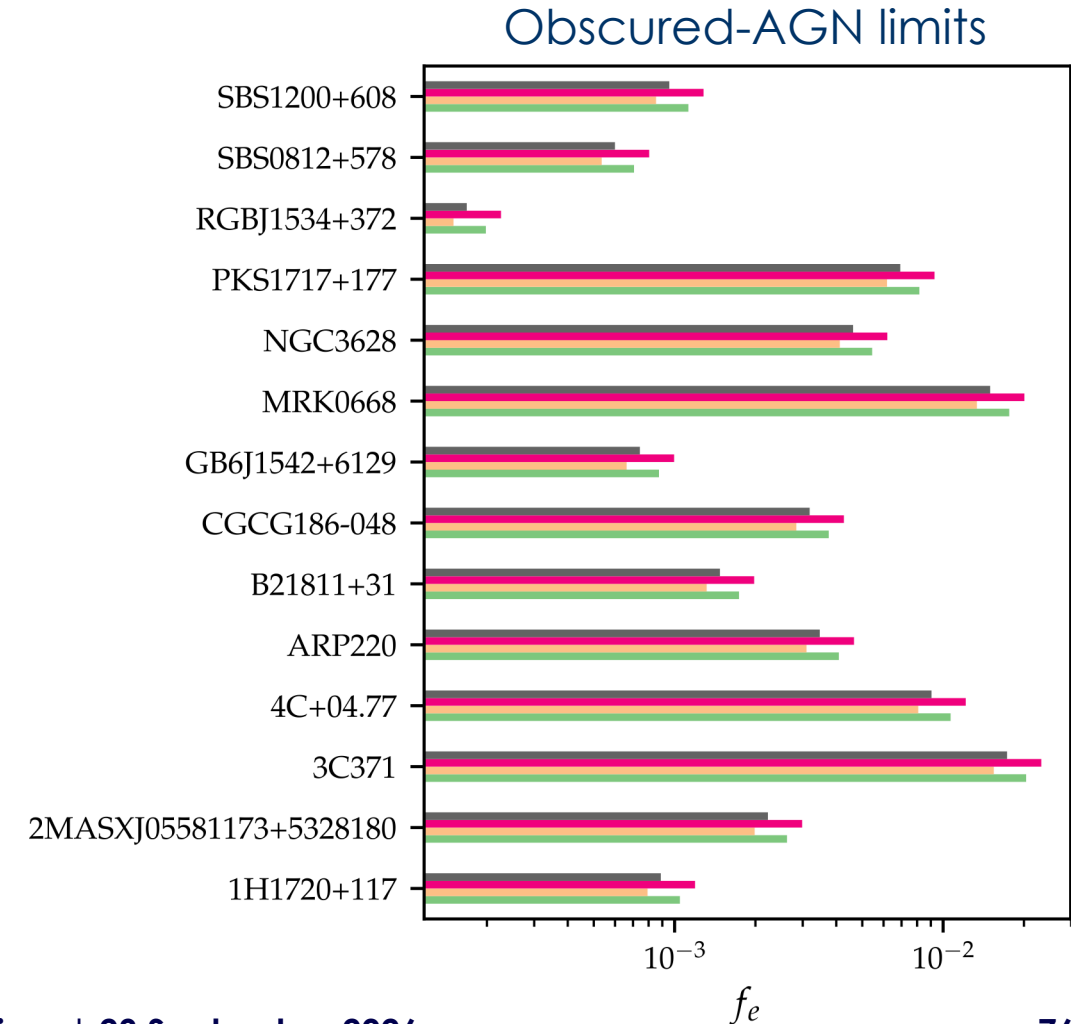
Comparison with Beam-Dump Model

- ▶ [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





GOALS Modeling

Modeling Neutrinos from GOALS Galaxies

Data-Driven Parameters



1. Core-collapse supernova rate, $\mathcal{R}_{SN}$
2. Spectral index of proton injection rate, γ_{SN}
3. Maximum momentum of proton injection rate, p_{max}
4. Advection velocity, v_{adv}
5. Magnetic-field strength, B
6. ISM particle density, n_{ISM}
7. Scale height of nuclear starburst disk, H_{SBR}
8. Distance to source, D_L

Injection of accelerated protons in starburst

CR escape vs neutrino production in starburst

Neutrino flux determination

Modeling Neutrinos from GOALS Galaxies

Core-Collapse Supernova Rate & Energy Output



► **Use Starburst99 software** to calibrate SN rate to IR luminosity

- **Input:** IMF, SFH, metallicity
- **Output:** Balmer spectrum (UV) of all stars, SFR evolution, SN rate
- Assumes **all UV is reprocessed in IR**

$$\left(\frac{\text{SFR}_{\text{SB99}}}{M_{\odot} \text{ yr}^{-1}} \right) = A_{\text{IR}} \cdot \left(\frac{L_{\text{IR,SED}}}{\text{erg s}^{-1}} \right)$$

► **Top-heavy IMF** preferred for starbursts

- Lower SN rate compensated by **higher average SN energy**

$$\left(\frac{\mathcal{R}_{\text{SN,SB99}}}{\text{yr}^{-1}} \right) = A_{\text{SFR}} \cdot \left(\frac{\text{SFR}_{\text{SB99}}}{M_{\odot} \text{ yr}^{-1}} \right)$$

	$A_{\text{IR}} \times 10^{44}$	A_{SFR}	$\Lambda_{\text{IR}} \times 10^{46}$	$\mathcal{R}_{\text{SN}} [\text{yr}^{-1}]$
Salpeter	7.48	0.008	5.98	0.23
Kroupa	4.93	0.012	5.97	0.23
TH $\beta_{\text{high}} = 1.5$	1.54	0.027	4.15	0.16
TH $\beta_{\text{high}} = 1.0$	1.24	0.026	3.24	0.12

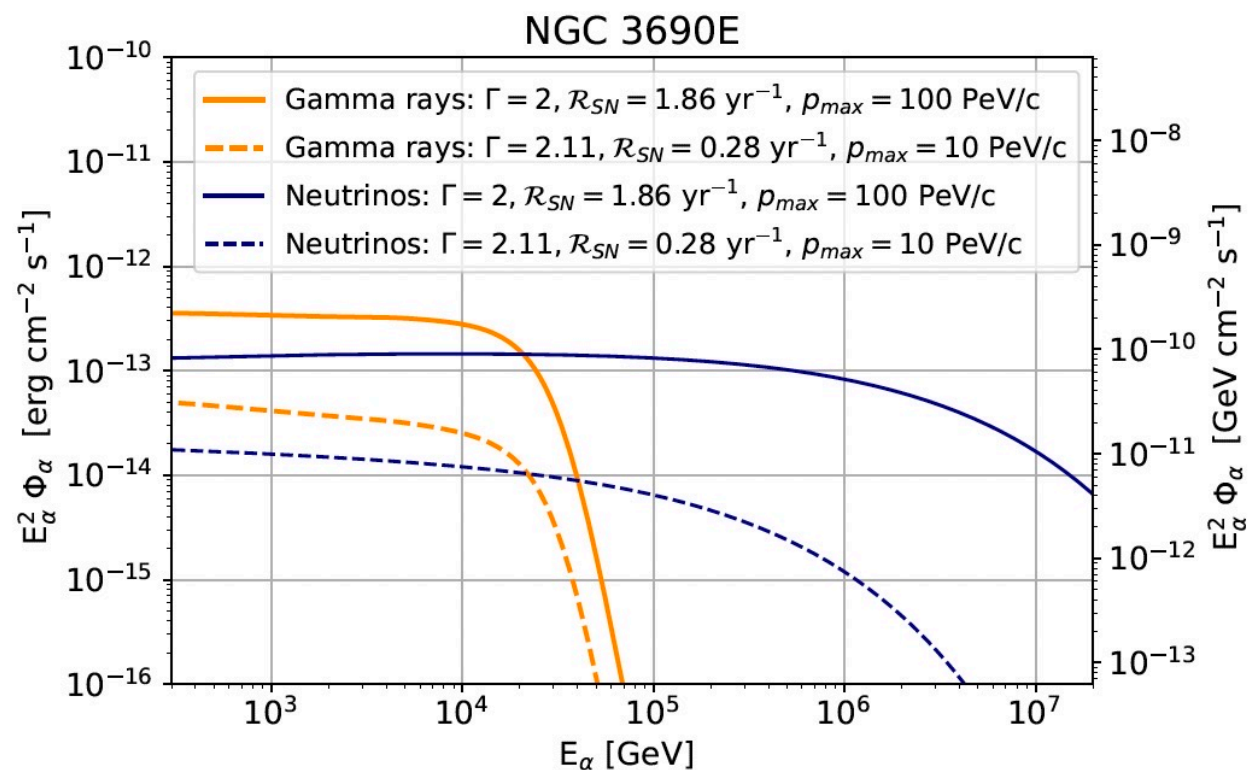
$$\left(\frac{\mathcal{R}_{\text{SN}}}{\text{yr}^{-1}} \right) = \Lambda_{\text{IR}} \cdot \left(\frac{L_{\text{IR}}}{\text{erg s}^{-1}} \right)$$

$$E_{\text{SN}} = \frac{\langle M_{\text{SN,IMF}} \rangle}{\langle M_{\text{SN,bm}} \rangle} \cdot E_{\text{SN,bm}}$$

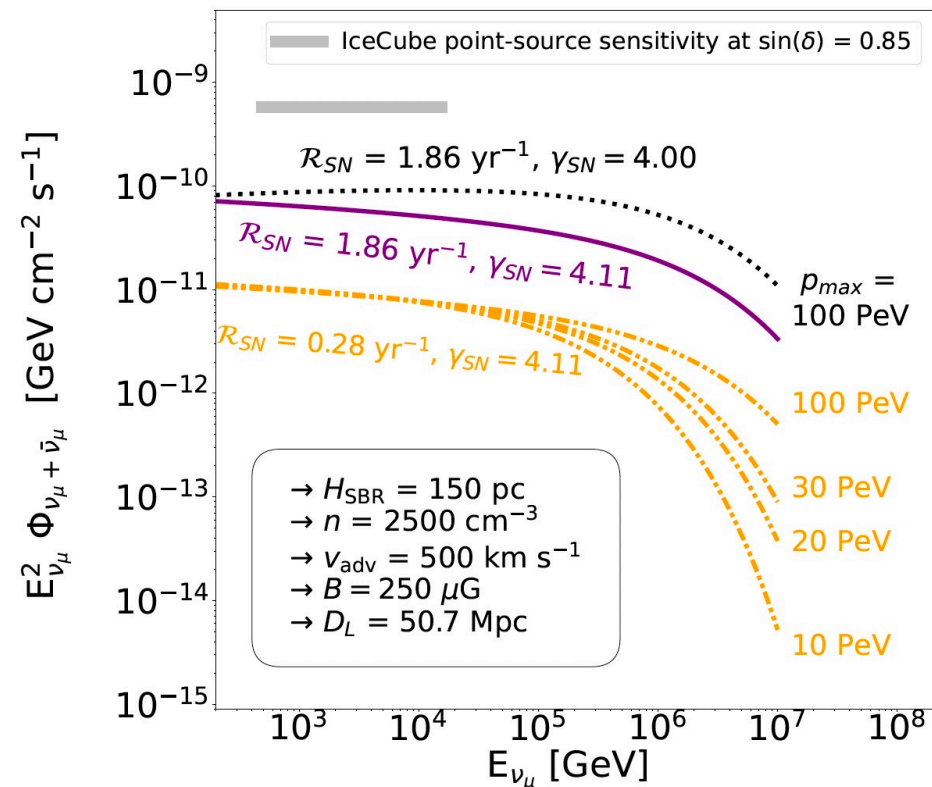
Predictions for Arp 299

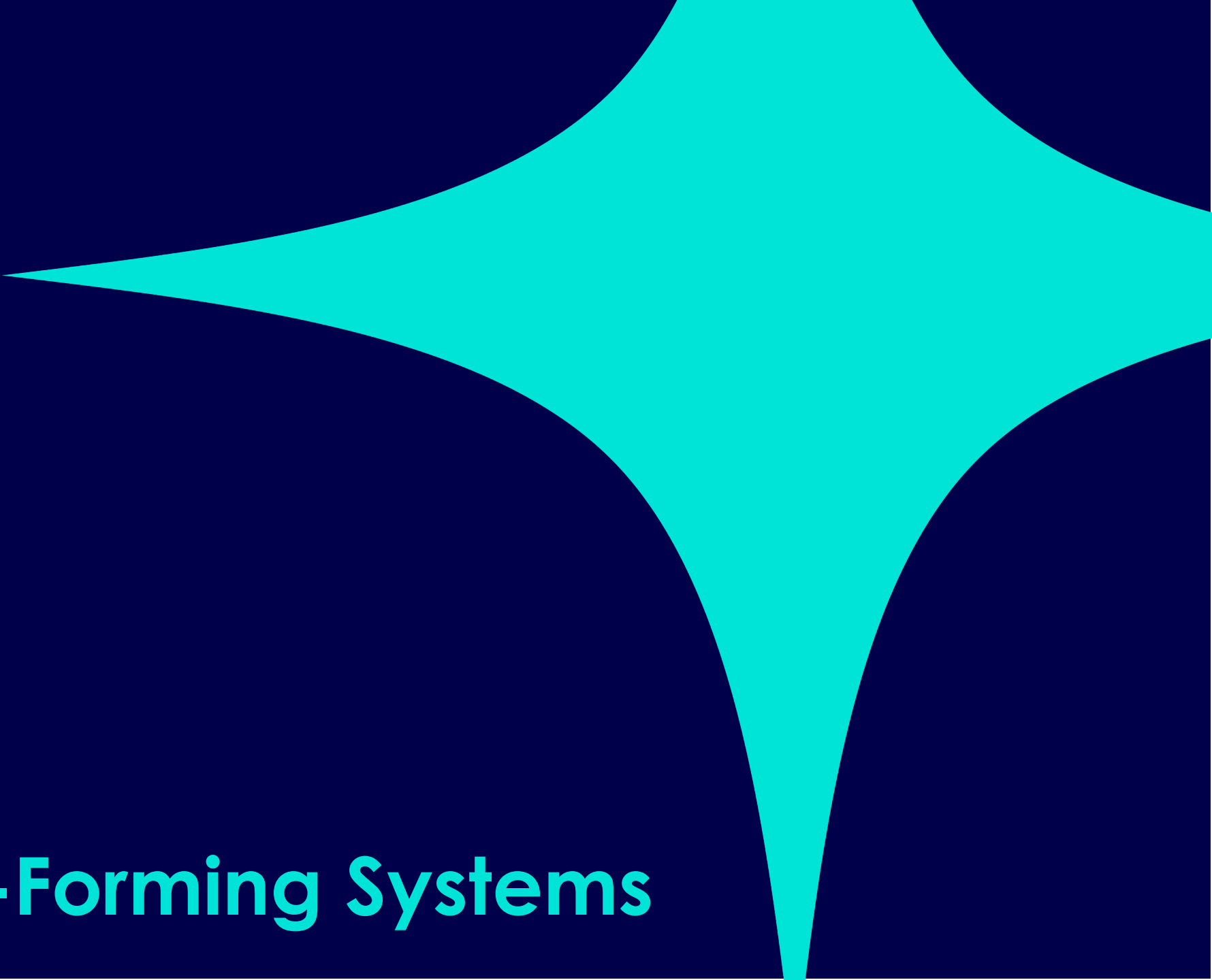


Multimessenger emission by Victor Courvoisier-Gernigon



Neutrino emission from GOALS framework paper



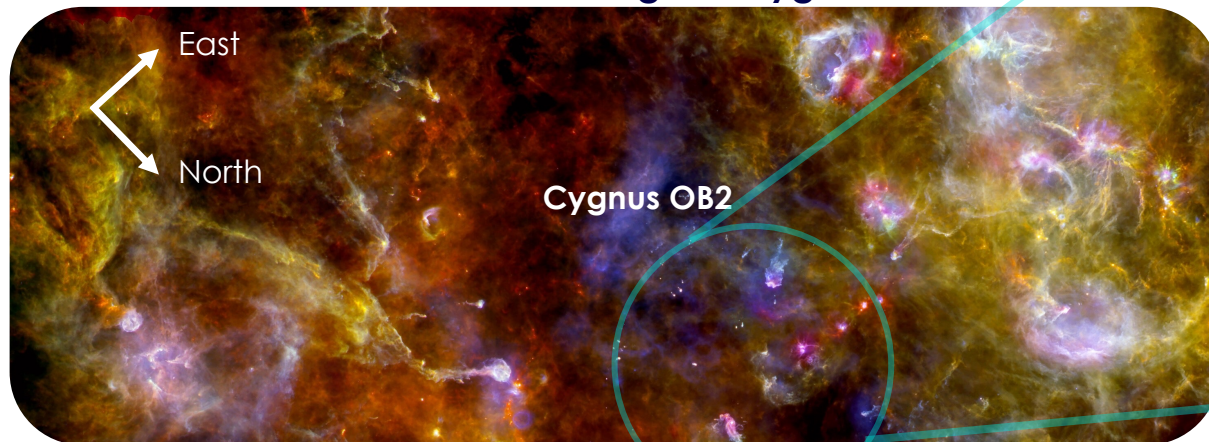


CTAO & Star-Forming Systems

Galactic Star-Forming Systems

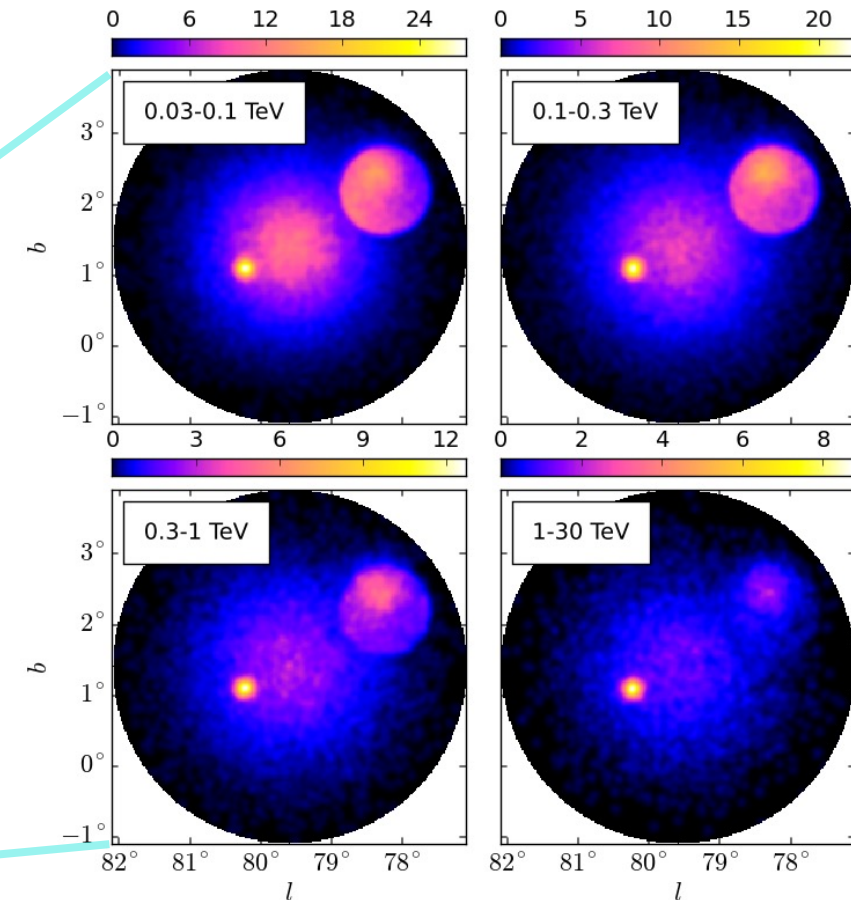
- ▶ **Stellar remnants** are VHE tracers of star formation
 - ▶ SNRs, PWNe, microquasars,...
- ▶ Resolve **star-forming regions** with many VHE sources
 - ▶ Cygnus region, Carina nebula, Westerlund 1 cluster
- ▶ Study **interplay of cosmic rays** and star formation
 - ▶ Acceleration, propagation, escape into ISM, feedback,...

Herschel IR image of Cygnus-X



[ESA]

Sensitivity to Cygnus OB2 (130 hr)

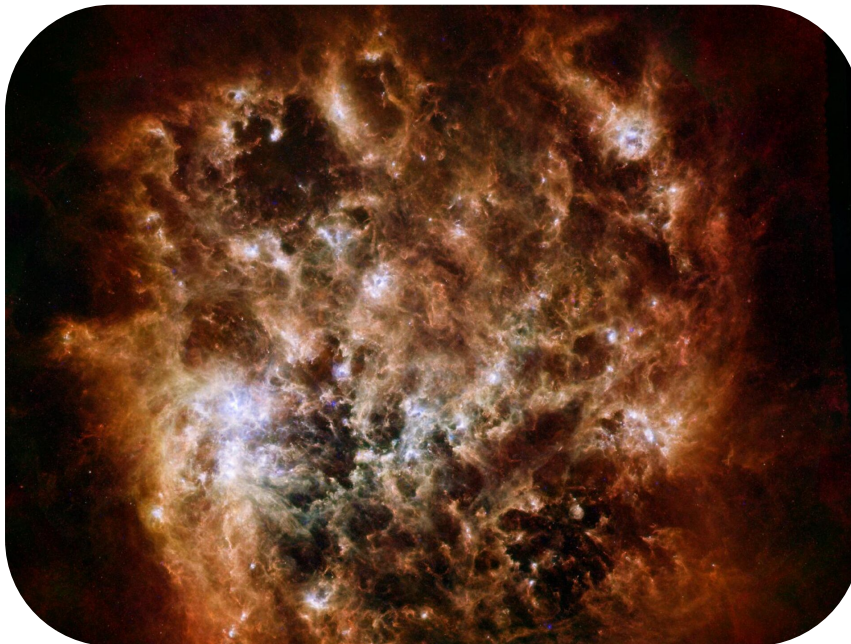


[CTAO (2019) World Scientific Publishing]

Neighboring Star-Forming Galaxies

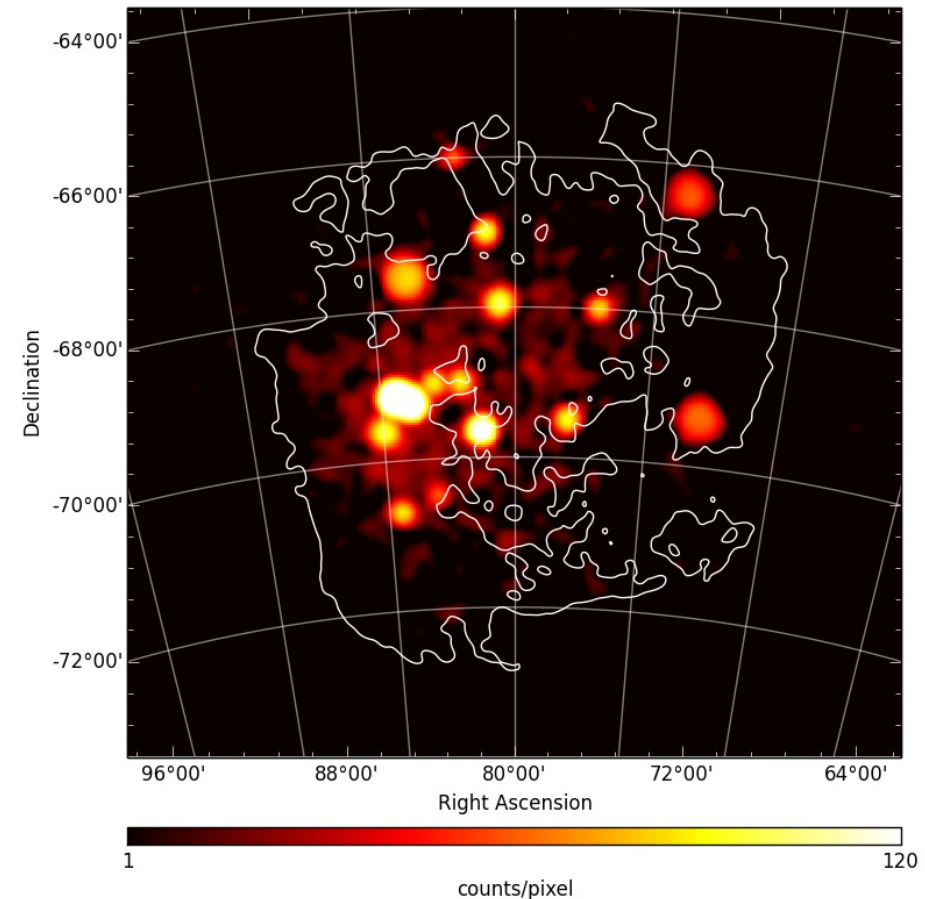
- ▶ Resolve local **star-forming galaxies**
 - ▶ Andromeda & Large Magellanic Cloud
- ▶ Probe **diffuse vs localized** VHE emission
 - ▶ Study cosmic-ray injection & diffusion across **entire galaxy**

Herschel + Spitzer IR image of LMC



[ESA/NASA]

LMC survey (340 hr; >200 GeV)

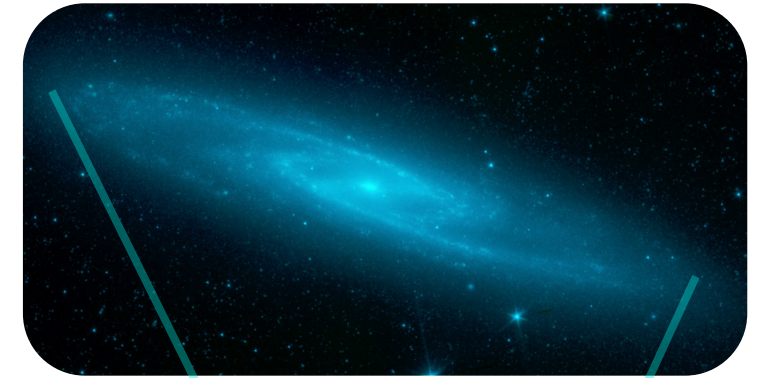


[CTAO (2019) World Scientific Publishing]

Starburst Galaxies

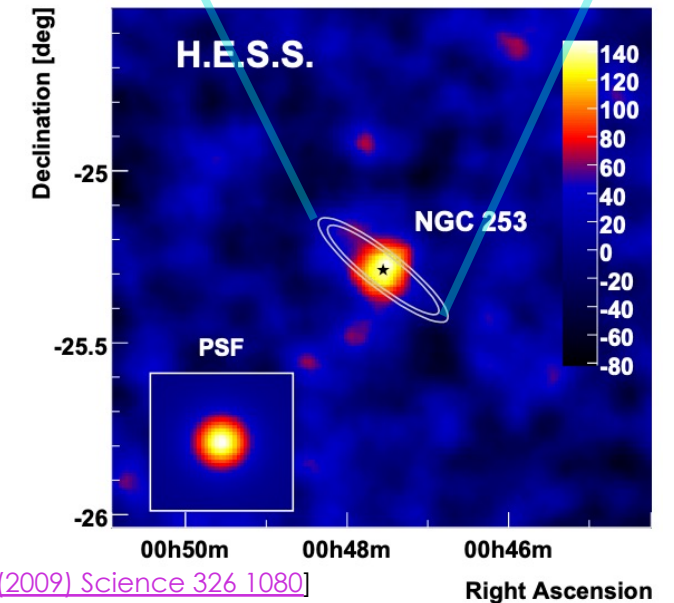
- ▶ **Starburst nuclei** in central ~ 100 pc
 - ▶ Typically triggered by **galaxy interactions & bar instabilities**
 - ▶ Enhanced star-formation rates $\text{SFR} \sim 10 M_{\odot} \text{ yr}^{-1}$ ($L_{\text{IR}} \sim 10^{10} L_{\odot}$)
- ▶ Study **equipartition of cosmic-ray reservoir**
 - ▶ **Energy balance** between cosmic rays, magnetic fields, radiation

Spitzer IR image of NGC 253

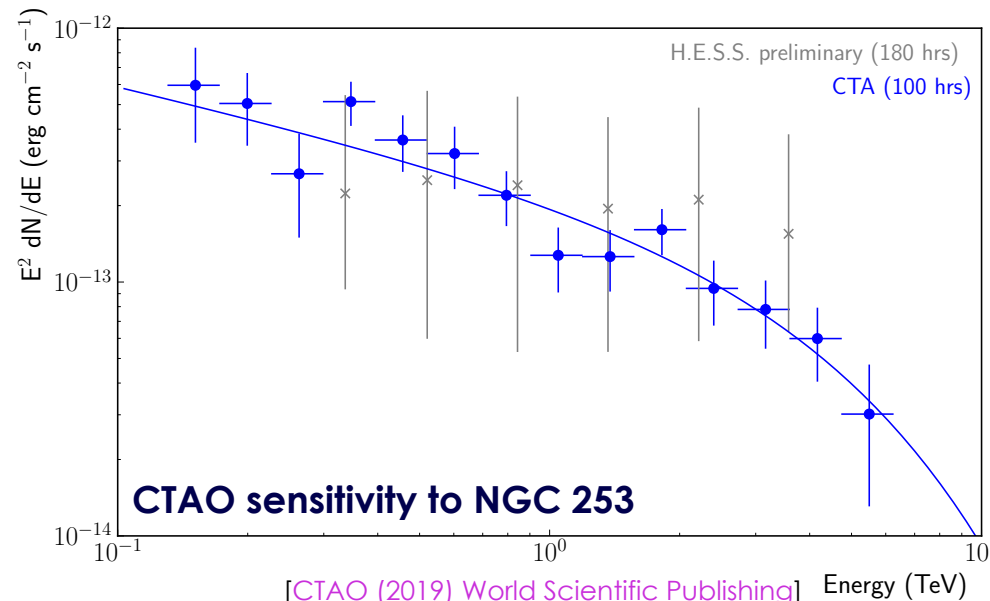


[NASA]

H.E.S.S. image of NGC 253



[H.E.S.S. (2009) Science 326 1080]

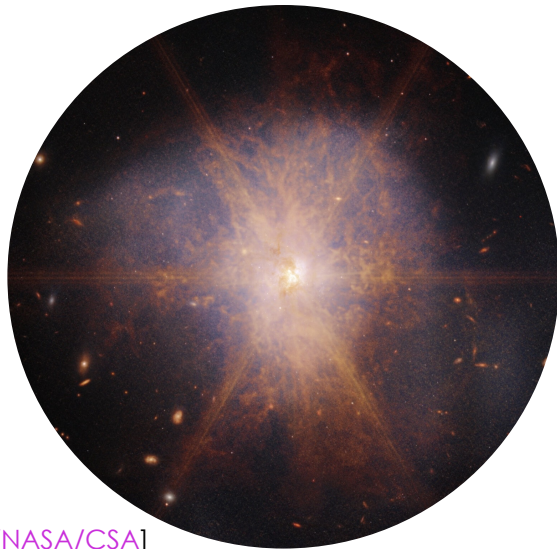


[CTAO (2019) World Scientific Publishing]

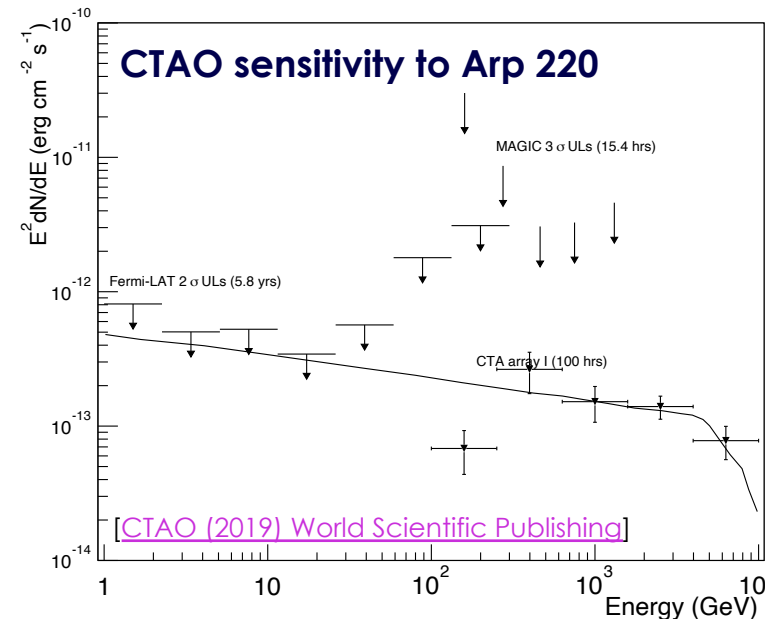
(Ultra)-Luminous Infrared Galaxies

- ▶ **Most extreme** starburst galaxies
 - ▶ LIRGs: $L_{IR} \geq 10^{11} L_{\odot}$; ULIRGs: $L_{IR} \geq 10^{12} L_{\odot}$
 - ▶ $SFR \gtrsim 10\text{--}100 M_{\odot} \text{ yr}^{-1}$
 - ▶ “Perfect” **calorimeters**
- ▶ Aim for **first U/LIRG observations** at VHE

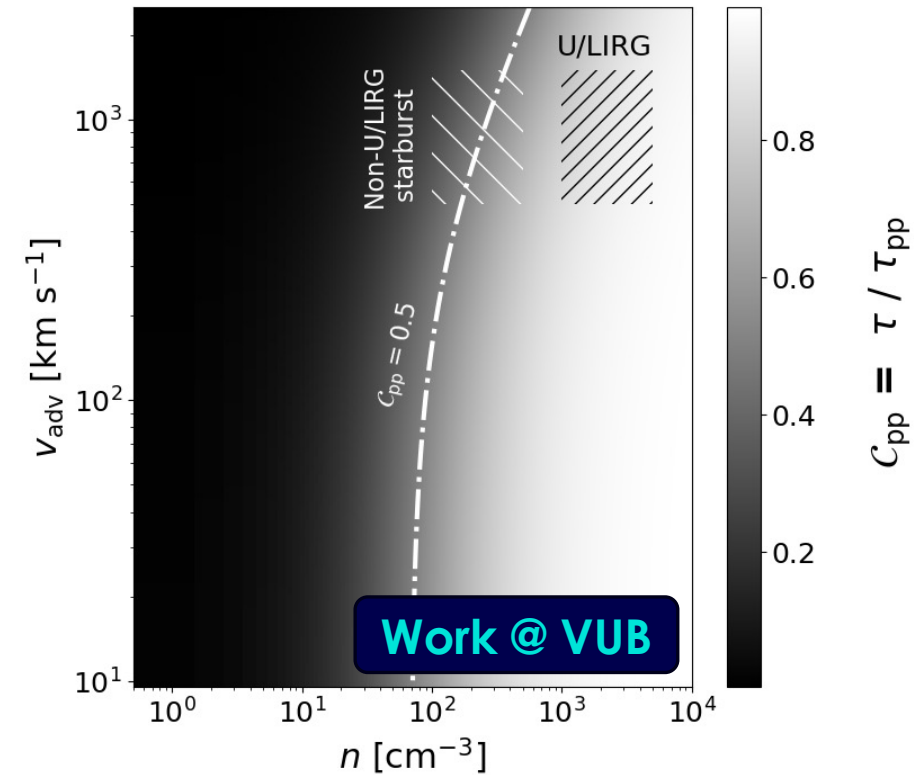
JWST IR image of Arp 220



[ESA/NASA/CSA]



Calorimetric conditions in U/LIRGs

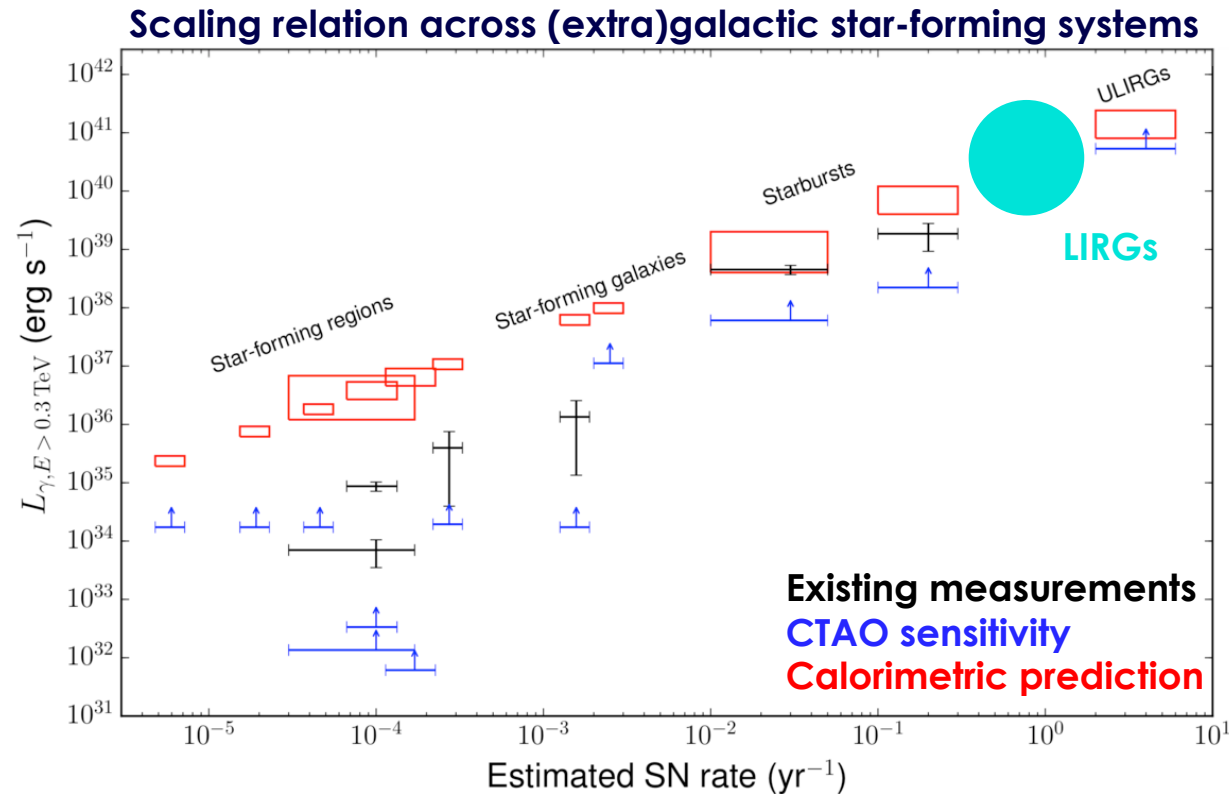


[Merckx+ (2023) PRD 108 023015]

The IR–VHE Connection

- **Scaling relation** between IR and VHE
 - Infrared traces star formation: $L_{IR} \propto \text{SFR}$
 - SFR yields supernova rate: $\text{SFR} \propto \text{SN rate}$
 - SNe drive cosmic-ray energy density: $\text{SN rate} \propto L_\gamma$
- **LIRGs** have not been explored yet
 - Build upon **starburst model** by Y. Merckx (VUB)
 - Target **GOALS galaxies** (nearest U/LIRGs)
 - Test **feasibility** of CTAO detection

Work to start soon by intern @LPNHE



[CTAO (2019) World Scientific Publishing]