EuCAPT

First Associations of High-Energy Neutrinos and Insights for the Future

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Technical University of Munich

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DFG

Bundesministerium für Bildung und Forschung

erc European Research Council

MAX-PLANCK-GESELLSCHAFT

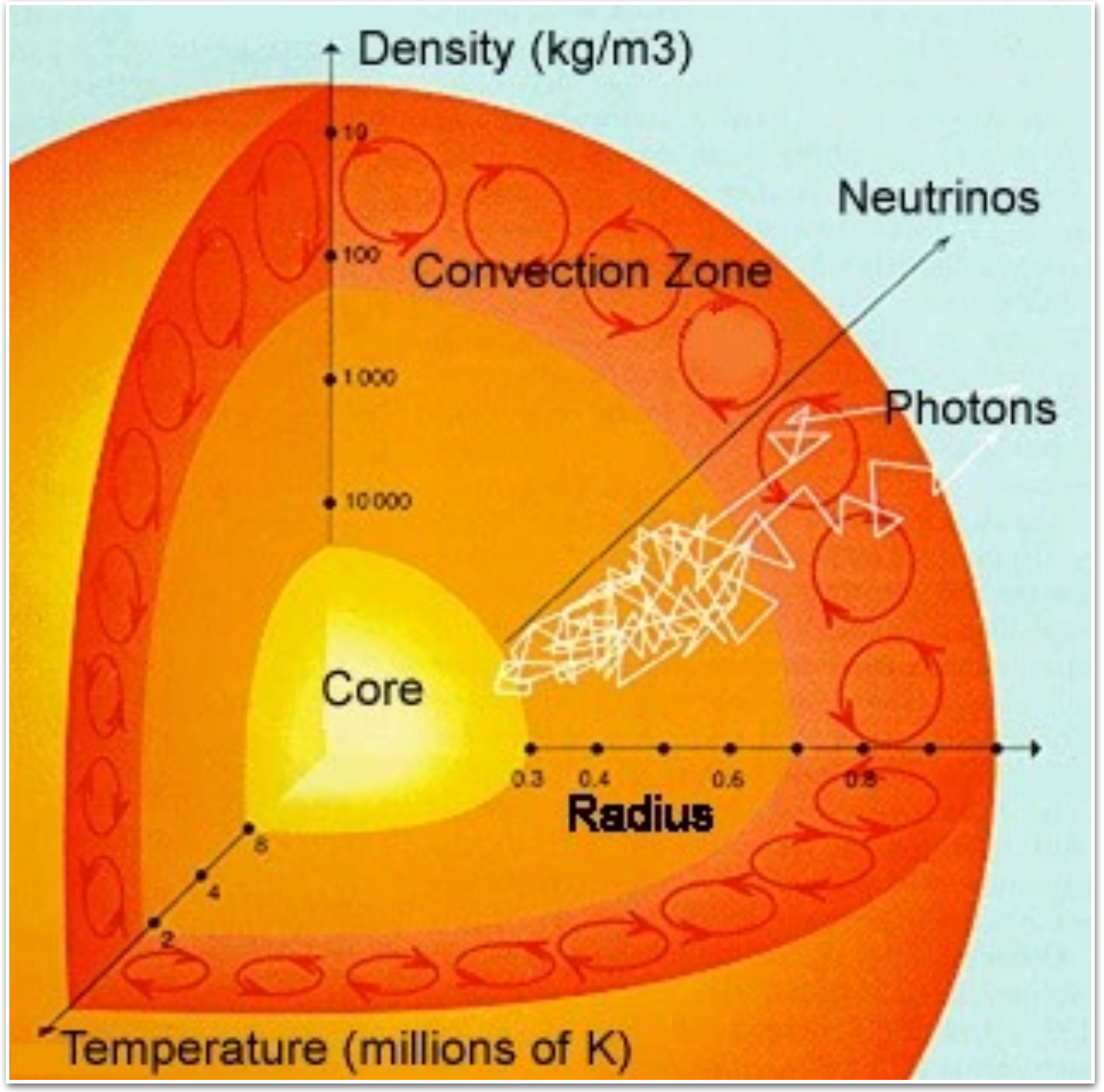
B 1258 Neutrinos Dark Matter Messengers

TUM LMU ORIGINS Excellence Cluster

Astronomy with neutrinos

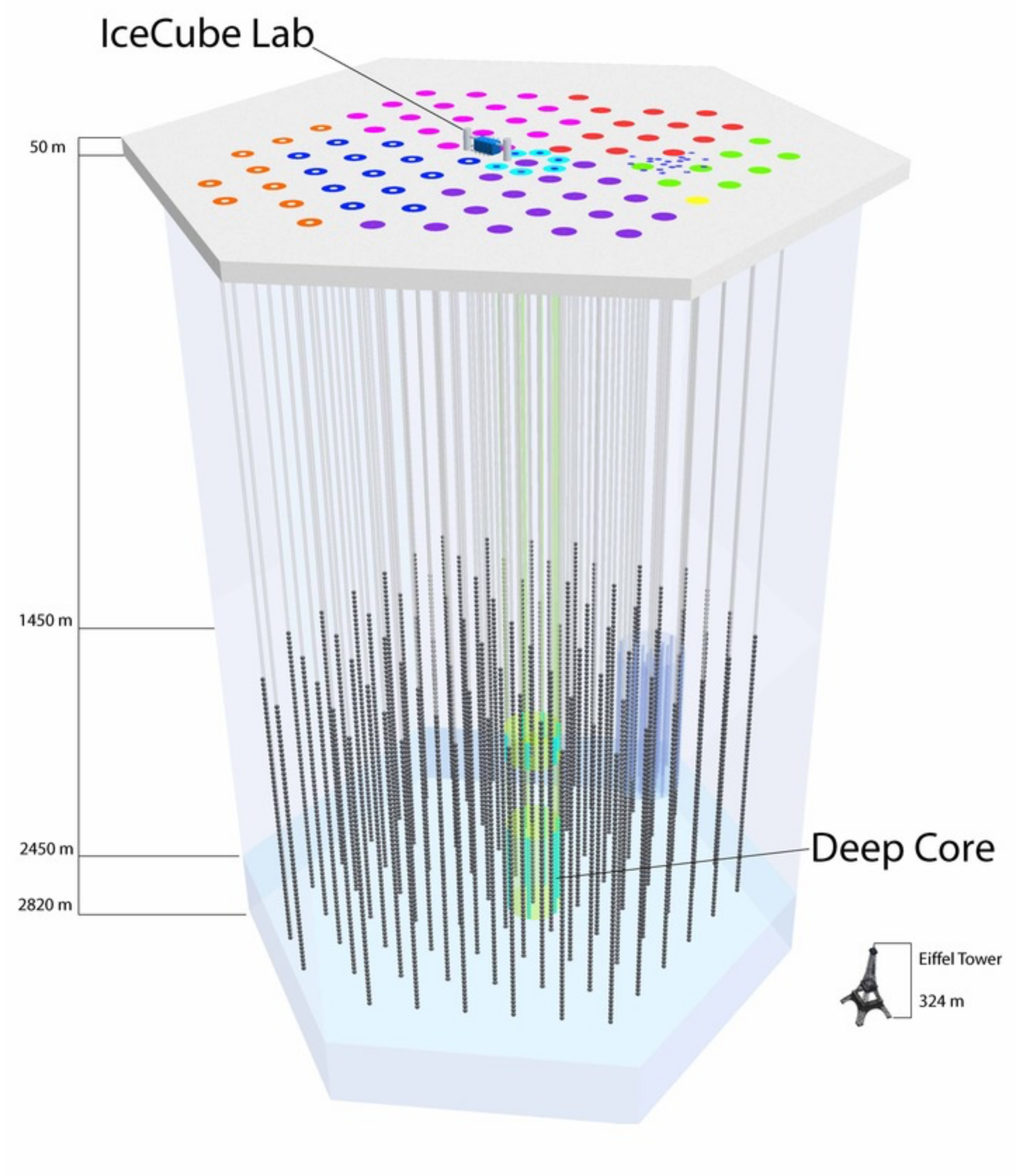
What do we hope to 'see'?

Something fundamental and unexpected (e.g., solar neutrinos)



From MeV to > TeV scale

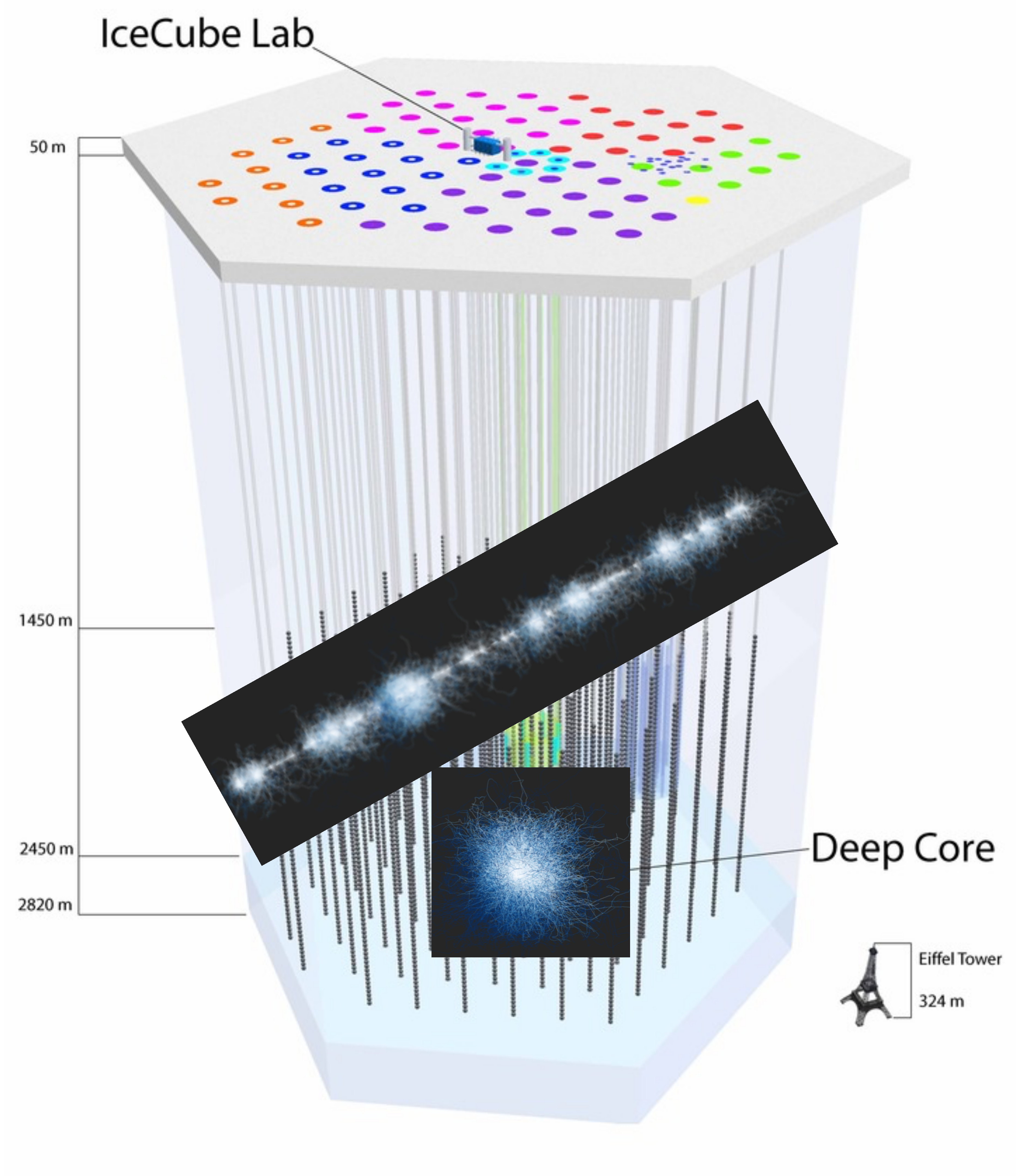
IceCube's First Decade: rigorous experimental work



Mission accomplished – instrumental:

- *Building what today is still the only cubic-km neutrino telescope*
- *Operating it with >99% life time and nearly zero technical troubles over more than a decade*
- *Mastering the ice optical properties*
- *Mastering a full MonteCarlo modelling of the detector and event interaction/propagation*
- *Advancing event reconstructions, achieving good resolutions and minimizing systematic uncertainties (machine learning)*

IceCube's First Decade: neutrino topologies



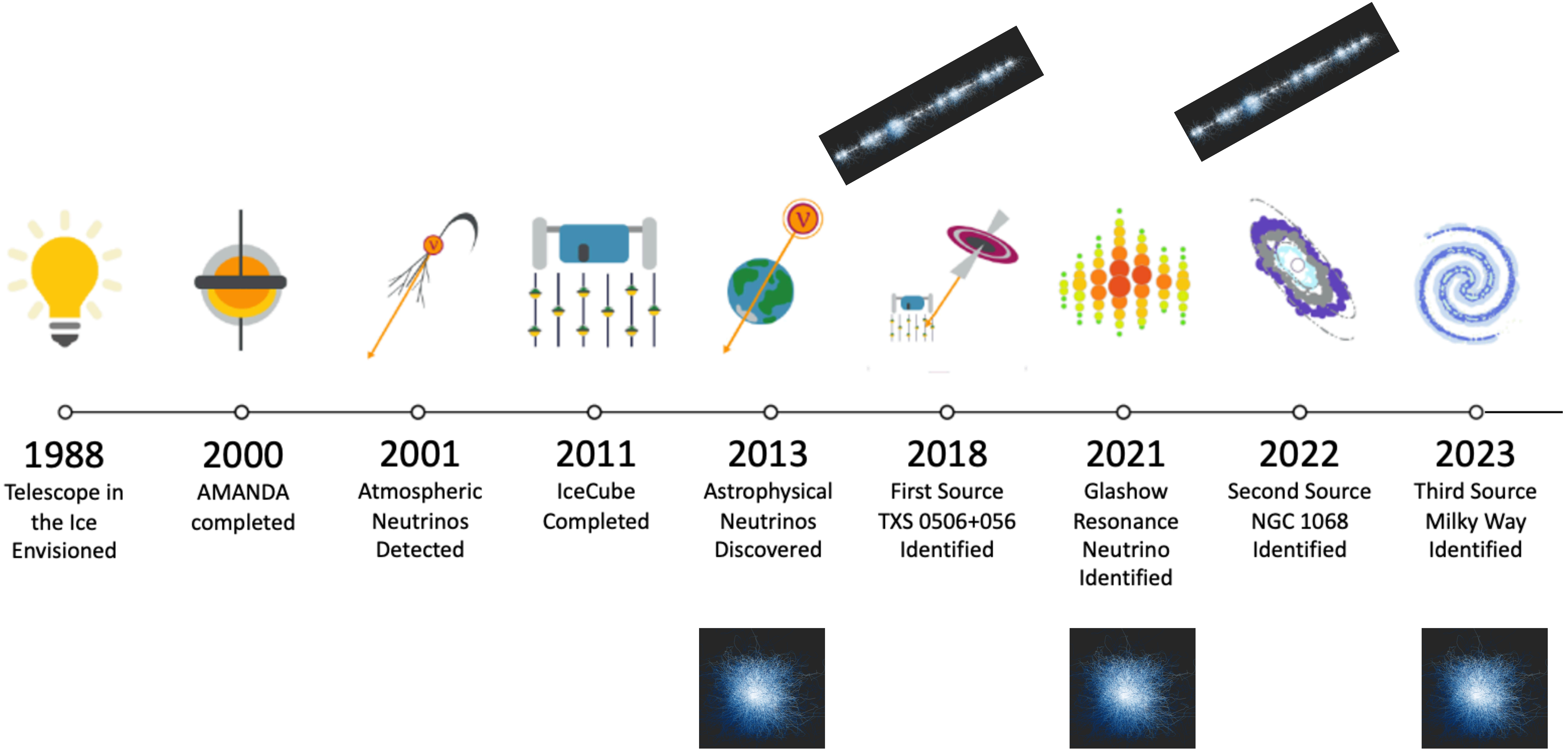
Tracks Detection Channel:

- Capture CC interaction of nu_mu
- Sub-degree Pointing
- Ok energy resolution
- Primarily in the Northern Hemisphere

Showers Detection Channel:

- Captures CC and NC interactions for all flavors
- Several-degree pointing capability
- Good energy resolution
- All-sky coverage (self-containment)

IceCube's First Decade: milestones



IceCube's First Decade: milestones

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2021
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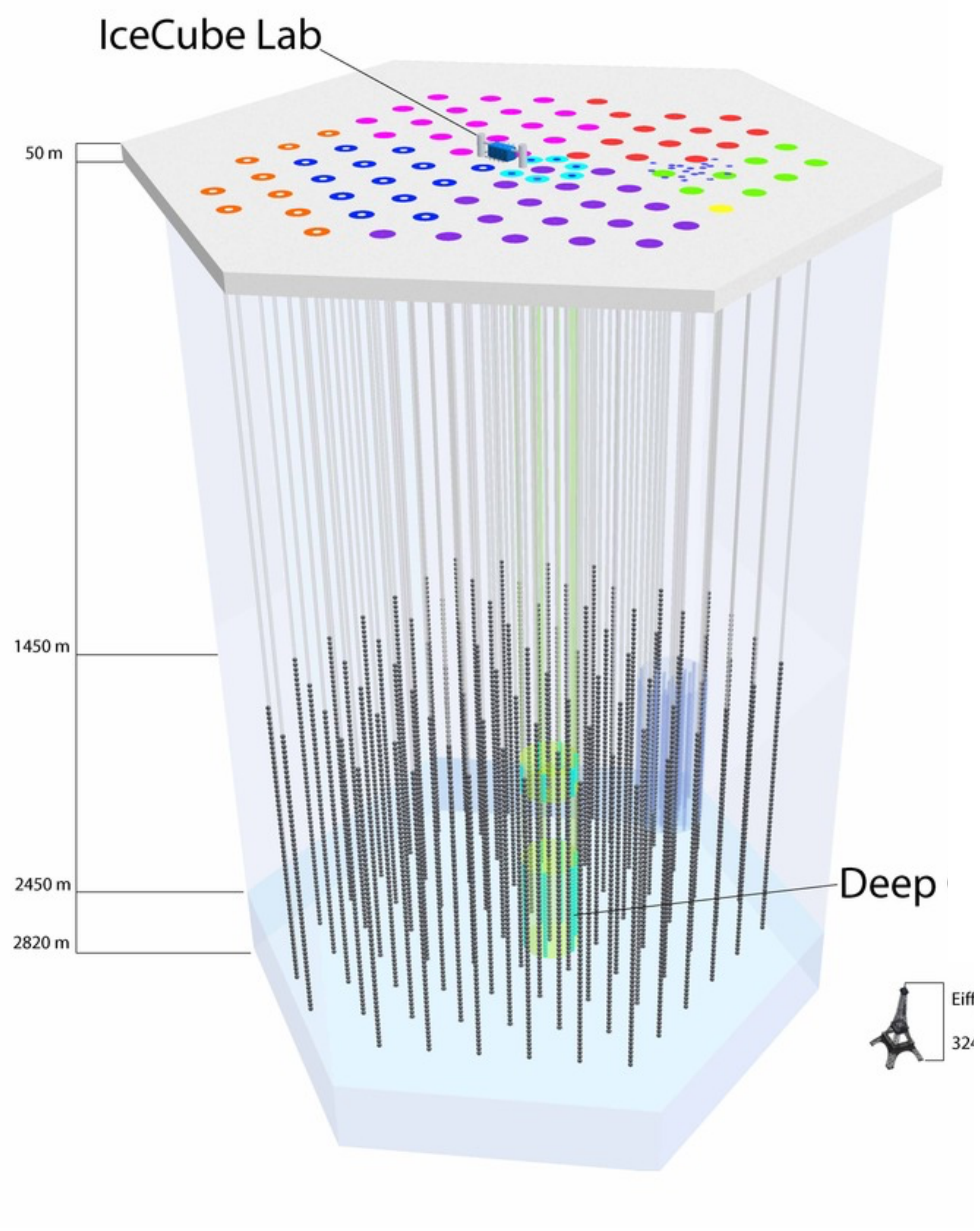
2022
Second Source NGC 1068 Identified

2023
Third Source Milky Way Identified

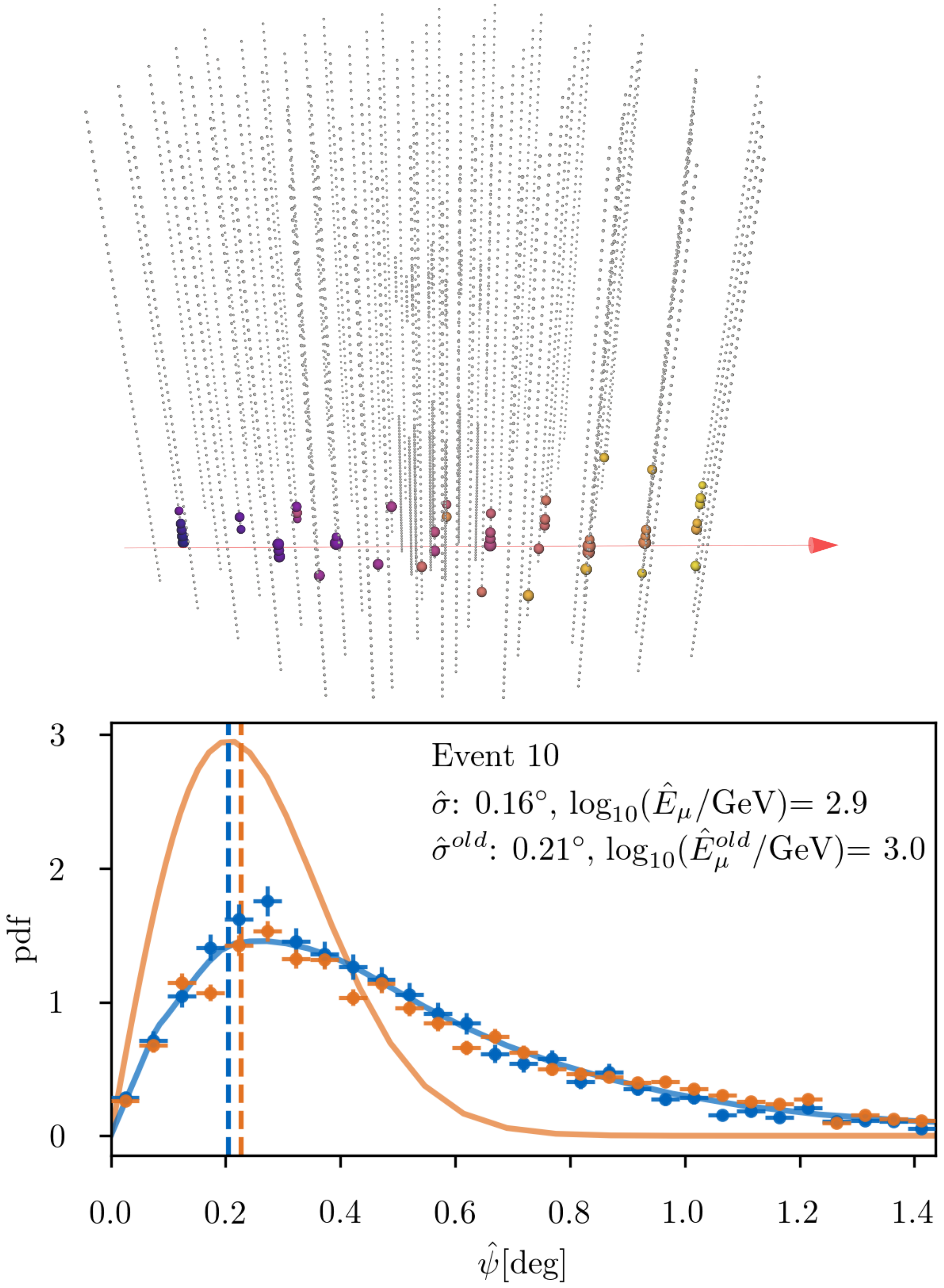
IceCube's First Decade: Revealing Neutrino Sources

The IceCube Coll., ***Science*** 378 (2022)

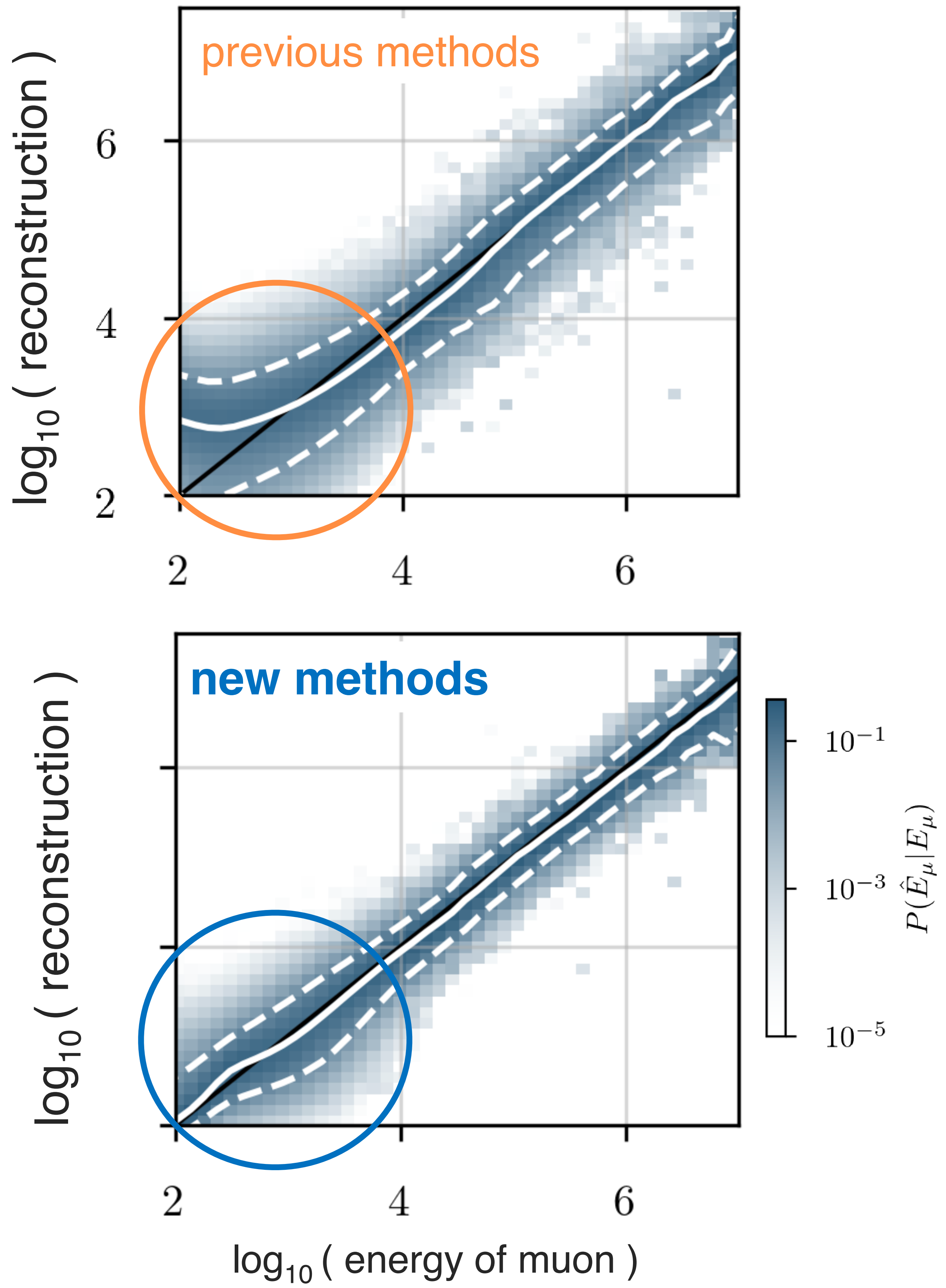


Enhanced Neutrino Directional Modeling

A

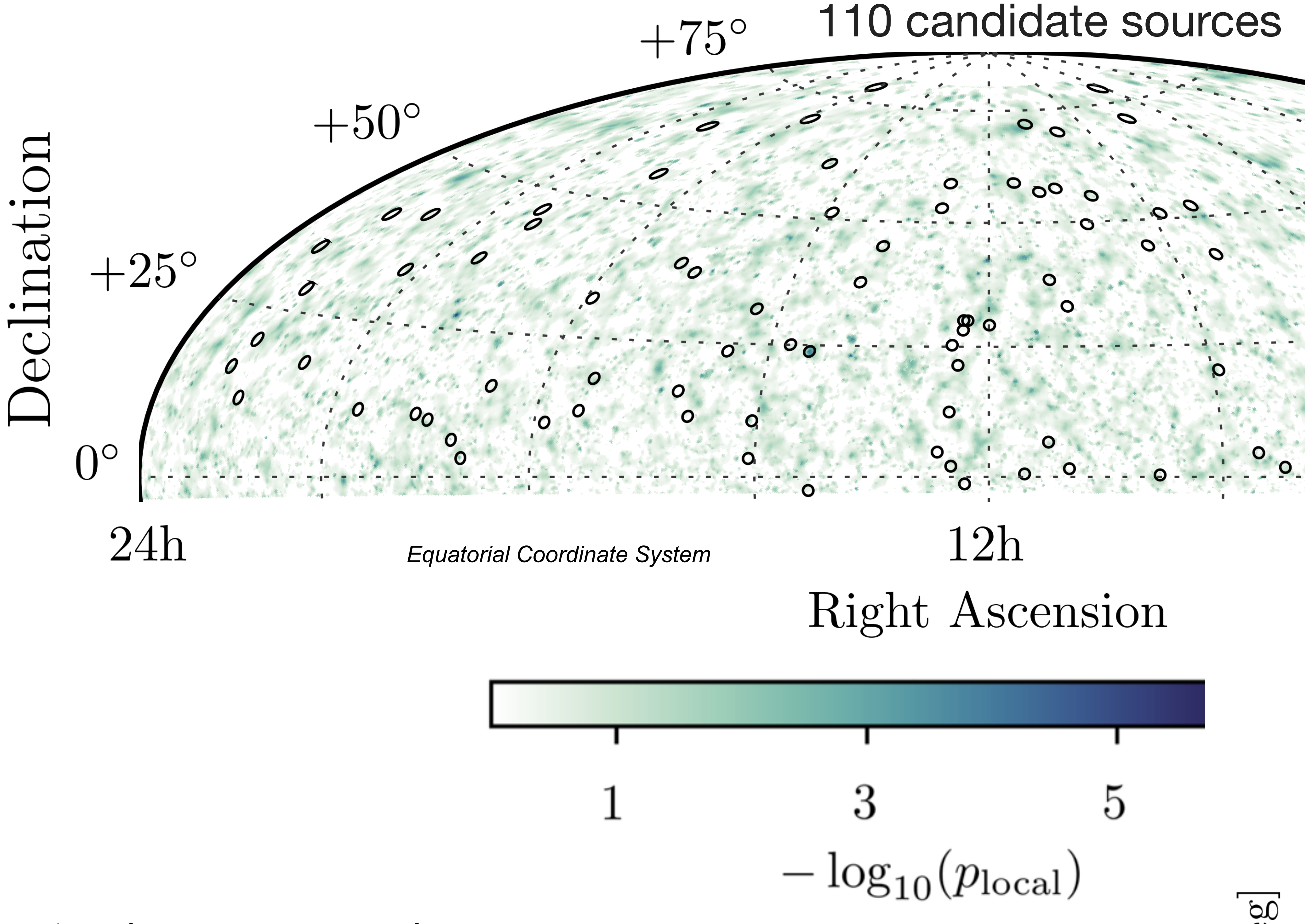


ML-Based Energy Reconstruction



Evidence of Neutrino Emission from NGC 1068

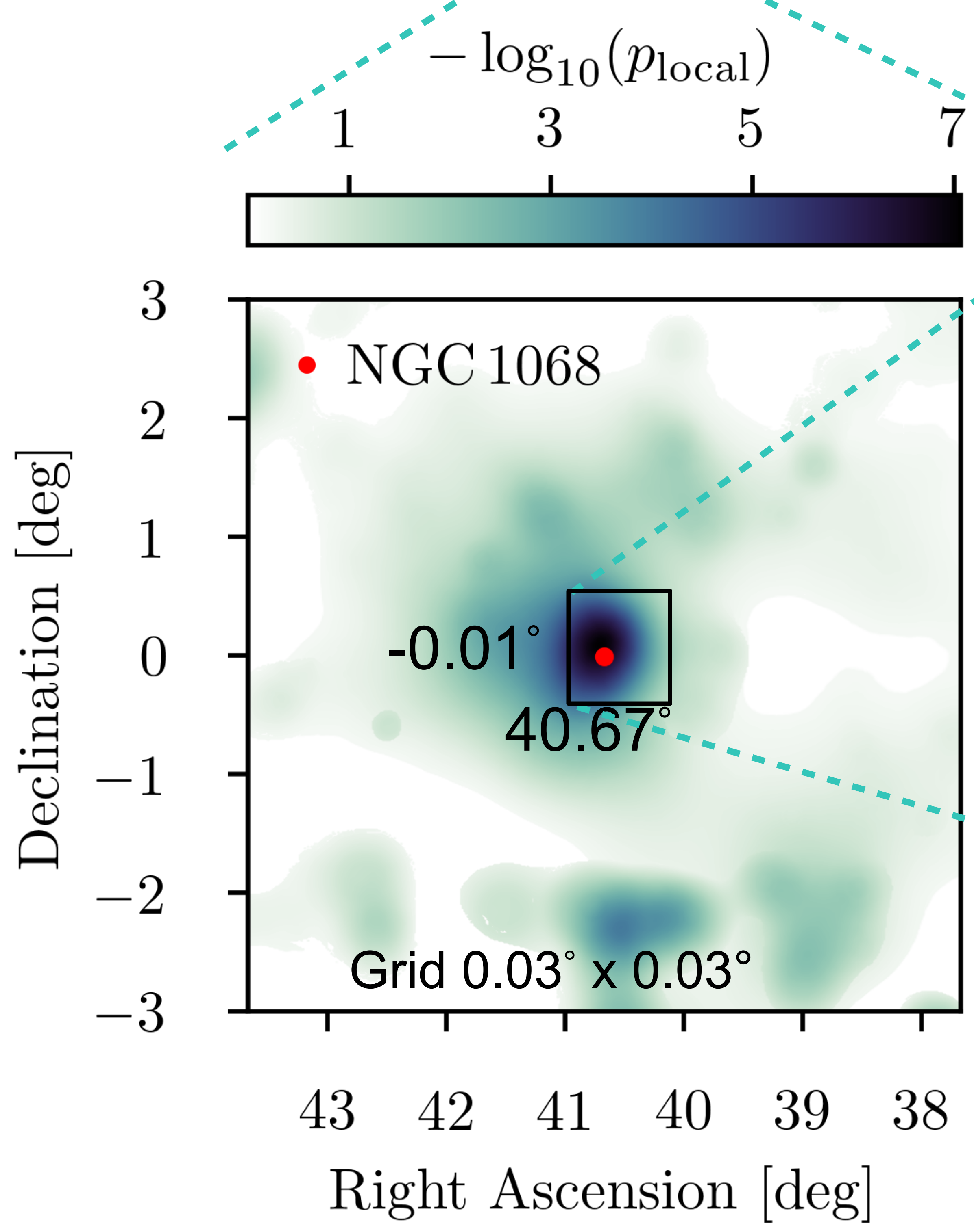
The IceCube Coll., ***Science*** 378 (2022)

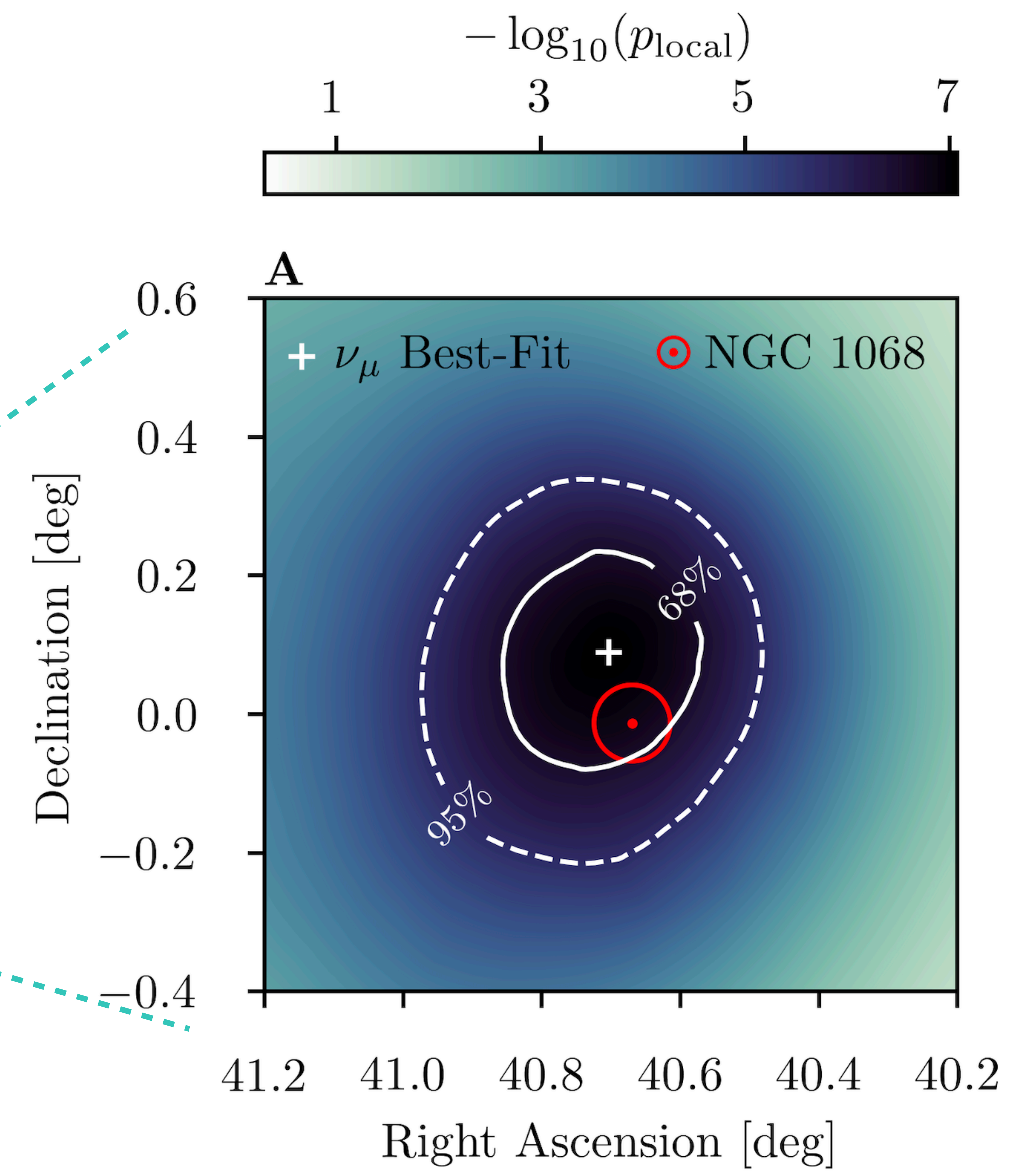


At the NGC1068 location:

- *Astrophysical neutrino events = 79^{+22}_{-20}*
- *Spectral index = 3.2 ± 0.2*

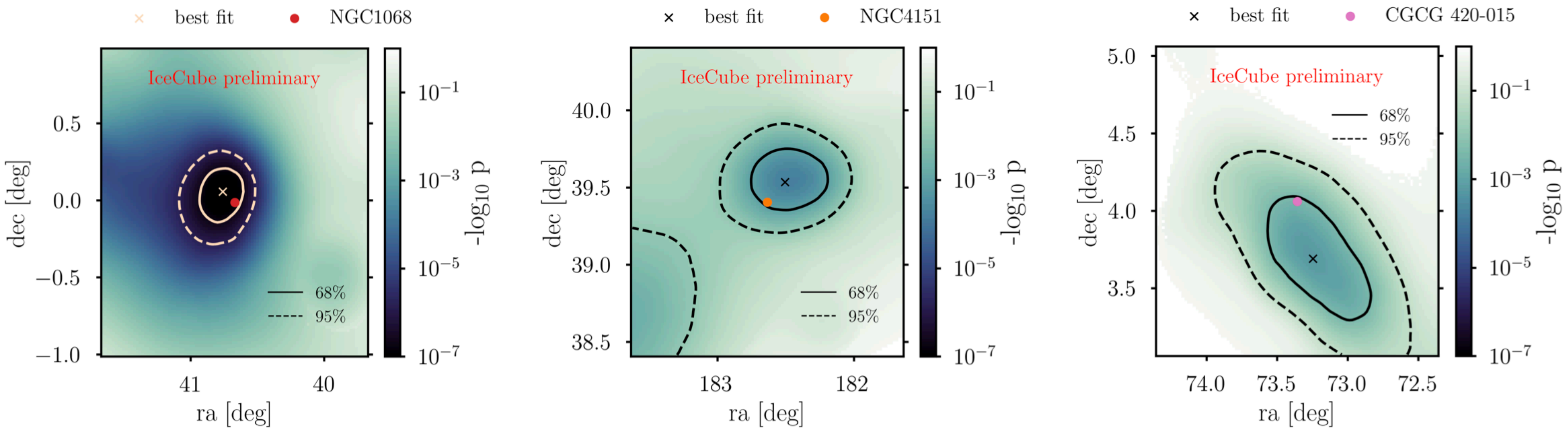
Global significance **4.2σ**





Indication of Neutrino Emission other Seyfert Galaxies

The IceCube Coll. (T. Glauch et al.), **ICRC'23**, https://pos.sissa.it/444/1052/pdf



Global significance **2.7σ**

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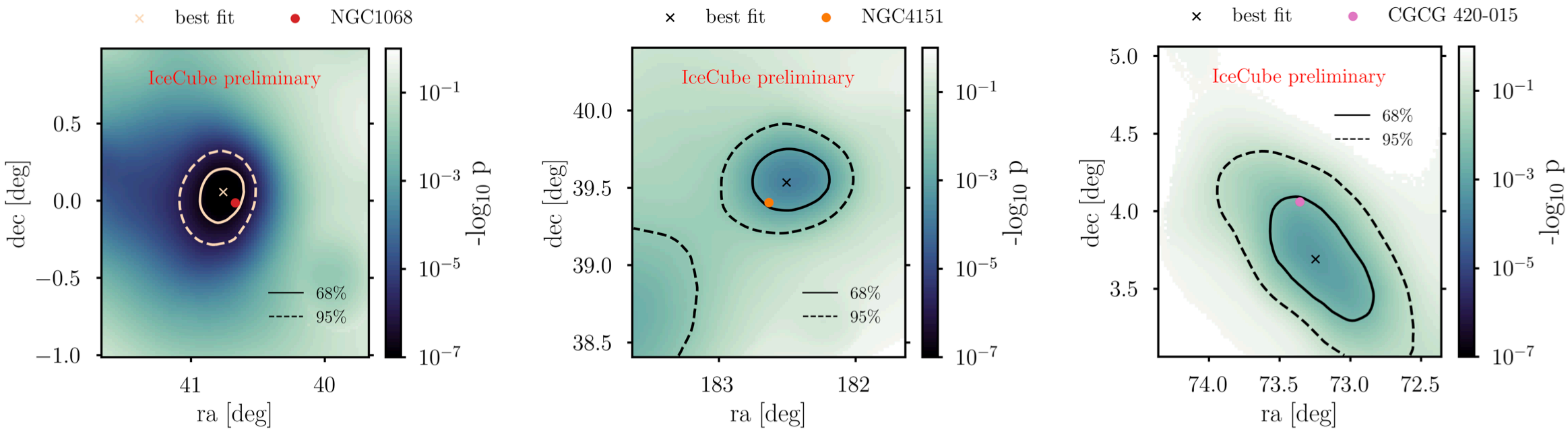
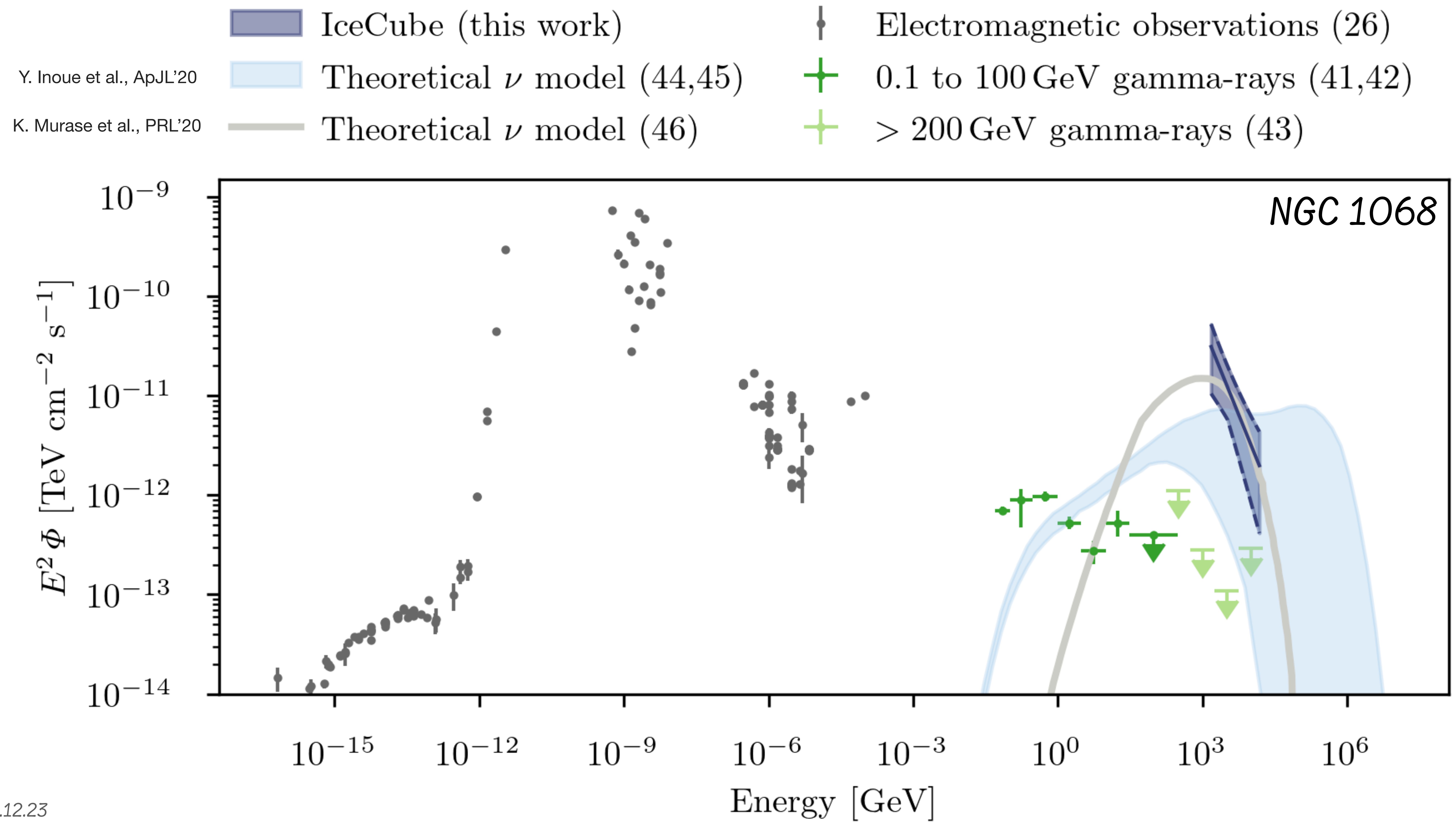


Global significance **2.7σ**

Coming up soon: Update with + 4 Years of Additional Statistics

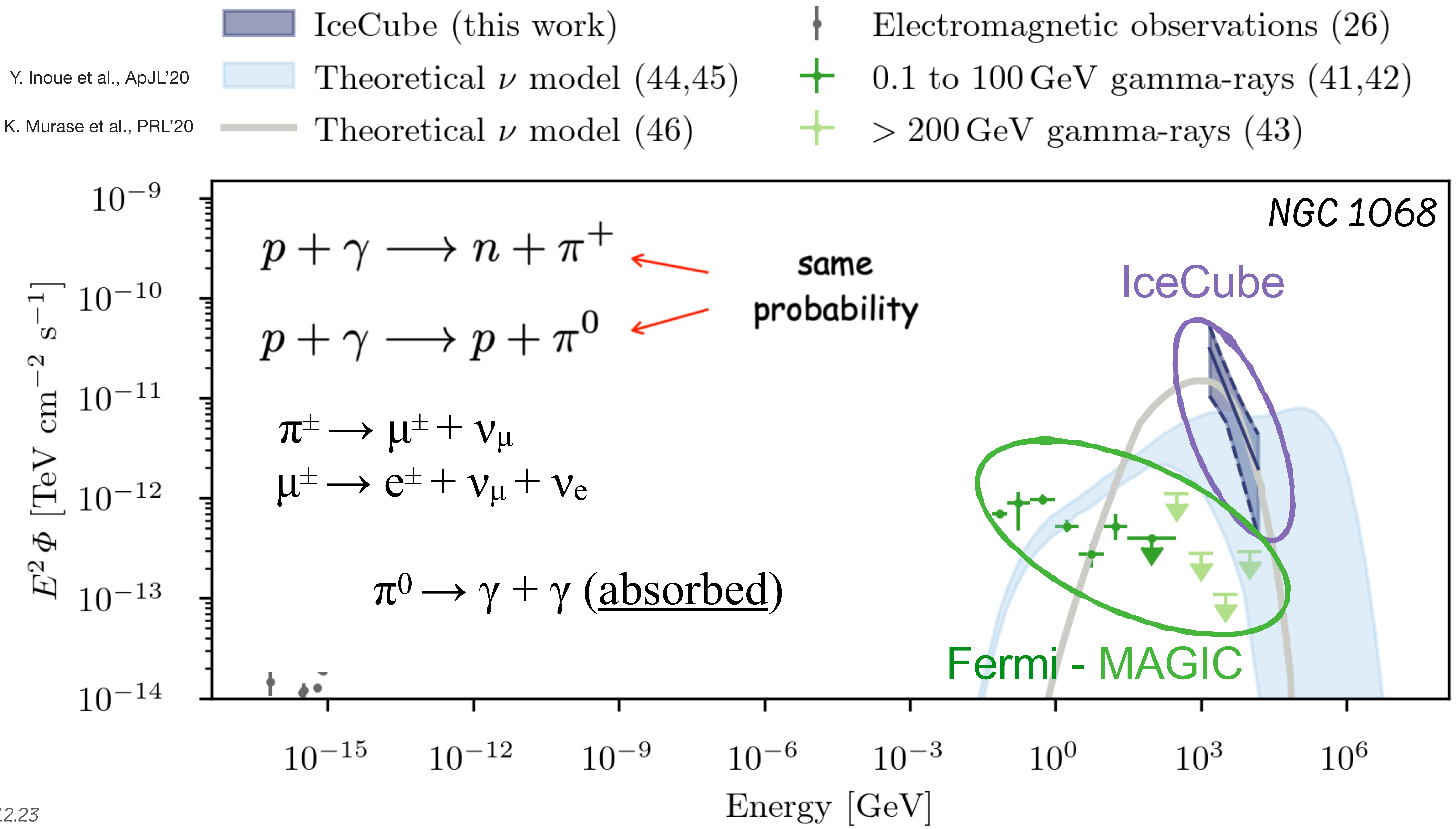
The Multiwavelength Picture of NGC 1068

The IceCube Coll., ***Science*** 378 (2022)



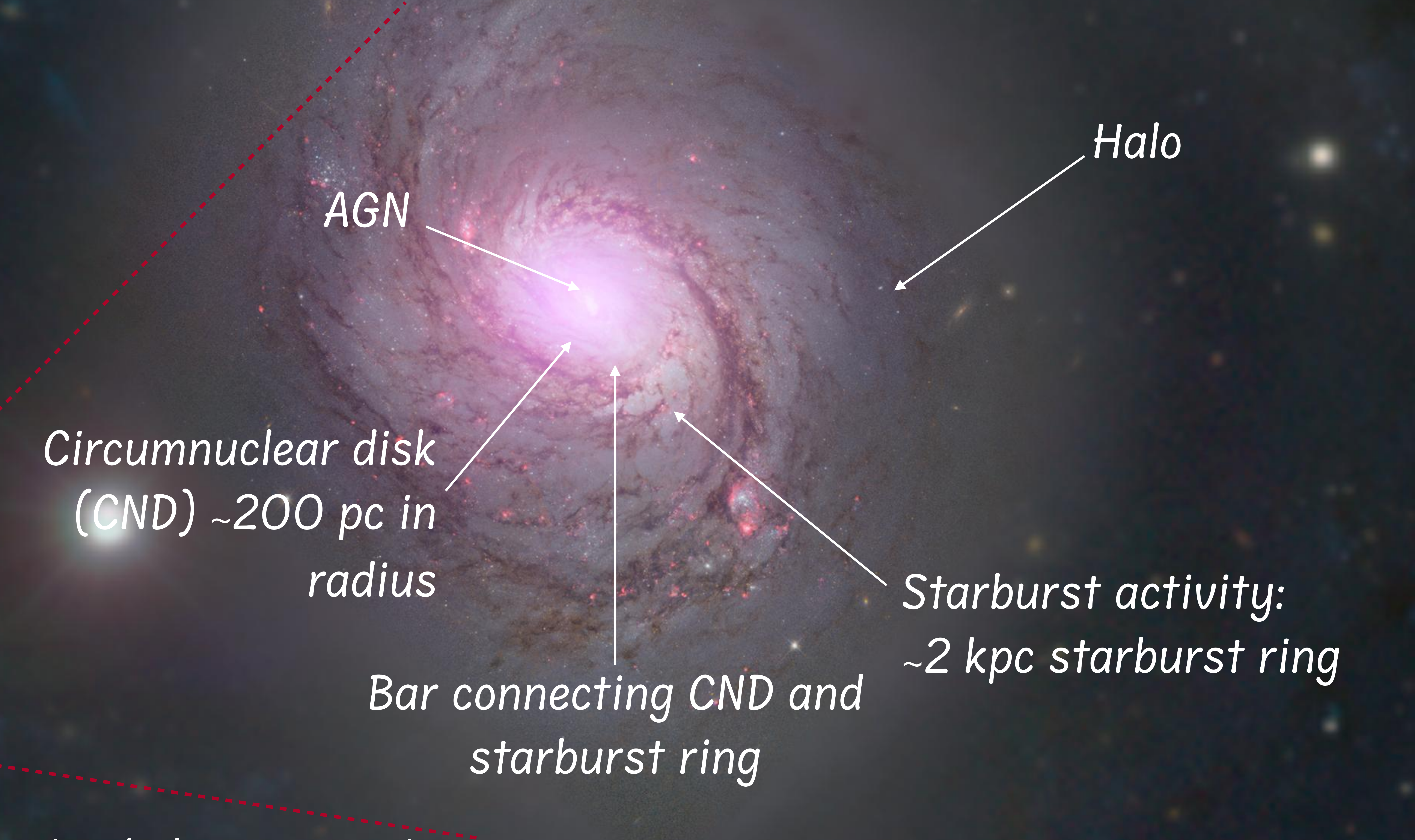
Gamma Ray Flux << Neutrino Flux: How?

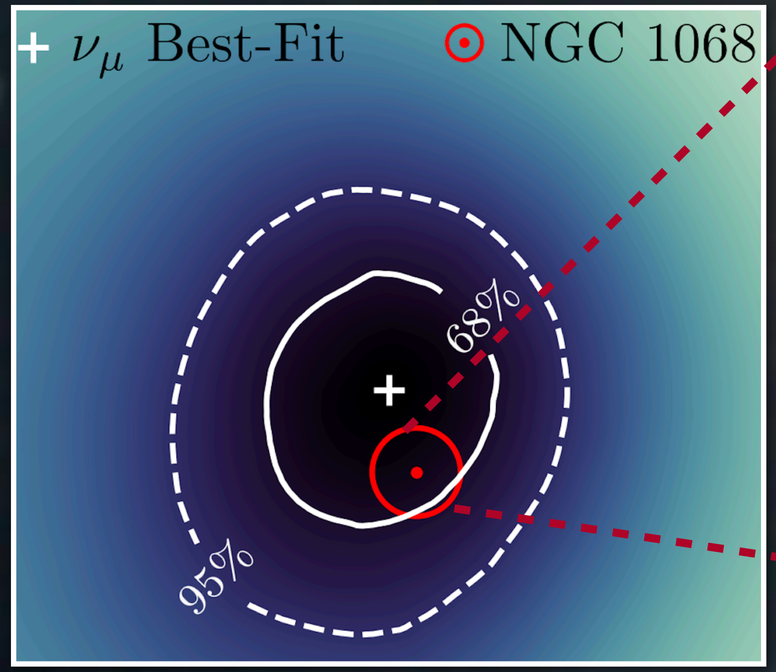
The IceCube Coll., ***Science*** 378 (2022)



NGC 1068: An Archetype of Obscured AGN

One of the nearest and most studied Seyfert 2





IceCube can't resolve different emission components

NASA/JPL-Caltech/Roma Tre Univ.

NGC 1068: An Archetype of <u>Obscured</u> AGN

- Usual Question:

  Origins of Neutrinos?

- Specific:

  Locations and Mechanisms of Gamma-ray Absorption?

NASA/JPL-Caltech/Roma Tre Univ.

Emission powers different components

P. Padovani et al., submitted

	Scale	Power (erg/s)	L_γ (erg/s)	L_ν (erg/s)
Star formation	> Kpc	$10^{44.5}$	$\sim 10^{40.9}$	$\sim 10^{40.6}$
Jet	~ Kpc	$10^{42.9\pm1}$	$\sim 10^{41.7}$ (M87-like) [absorbed]	$\sim 10^{41.4}$
Outflow	~ 100 pc	$10^{41.4\pm1.0}$	$< 10^{39.5}$	$< 10^{39.2}$
BH vicinity	~ 0.03 millipc (~ 50 R_S)	$10^{44.7\pm0.5}$	?	?

Total: $\sim 10^{41.5}$

Observed: $10^{40.92\pm0.03}$ $10^{42.1\pm0.2}$

$$L_\nu = 1.4 \cdot 10^{42}\ \mathrm{erg/s}$$

Black Hole vicinity

Seyferts: radio quiet AGN

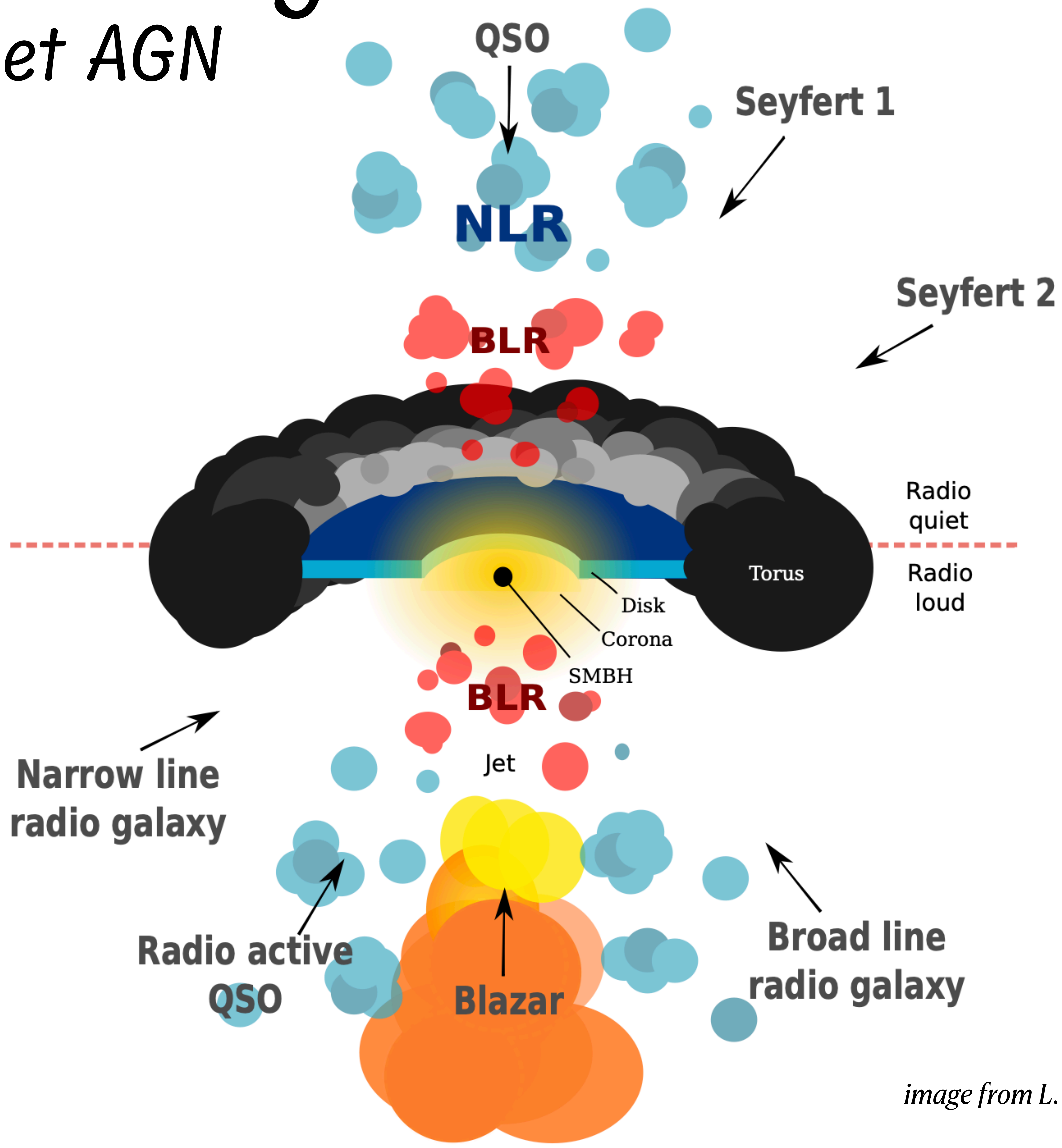
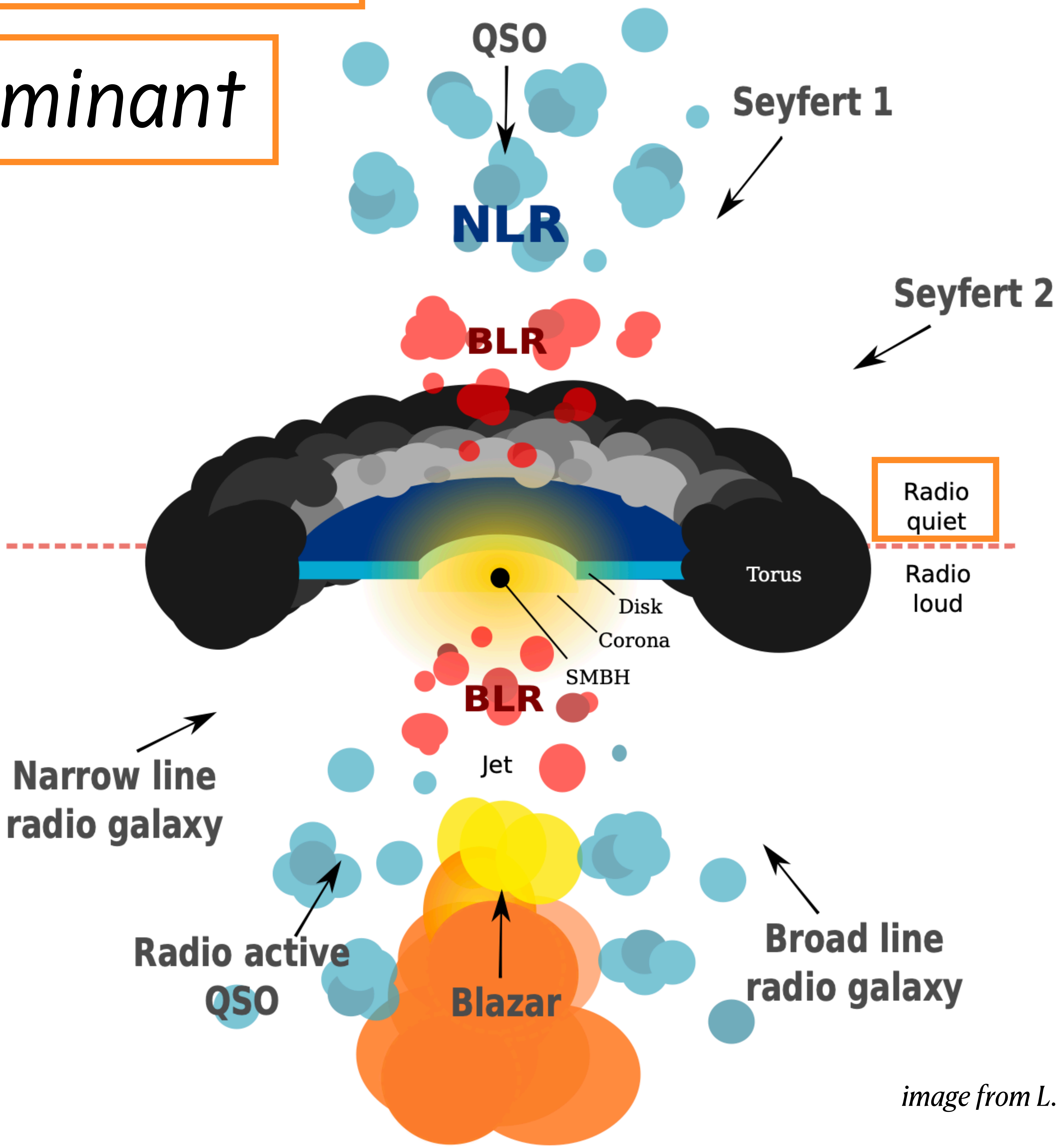


image from L. Baronchelli

Seyferts = radio quiet Active Galactic Nuclei

jet not dominant



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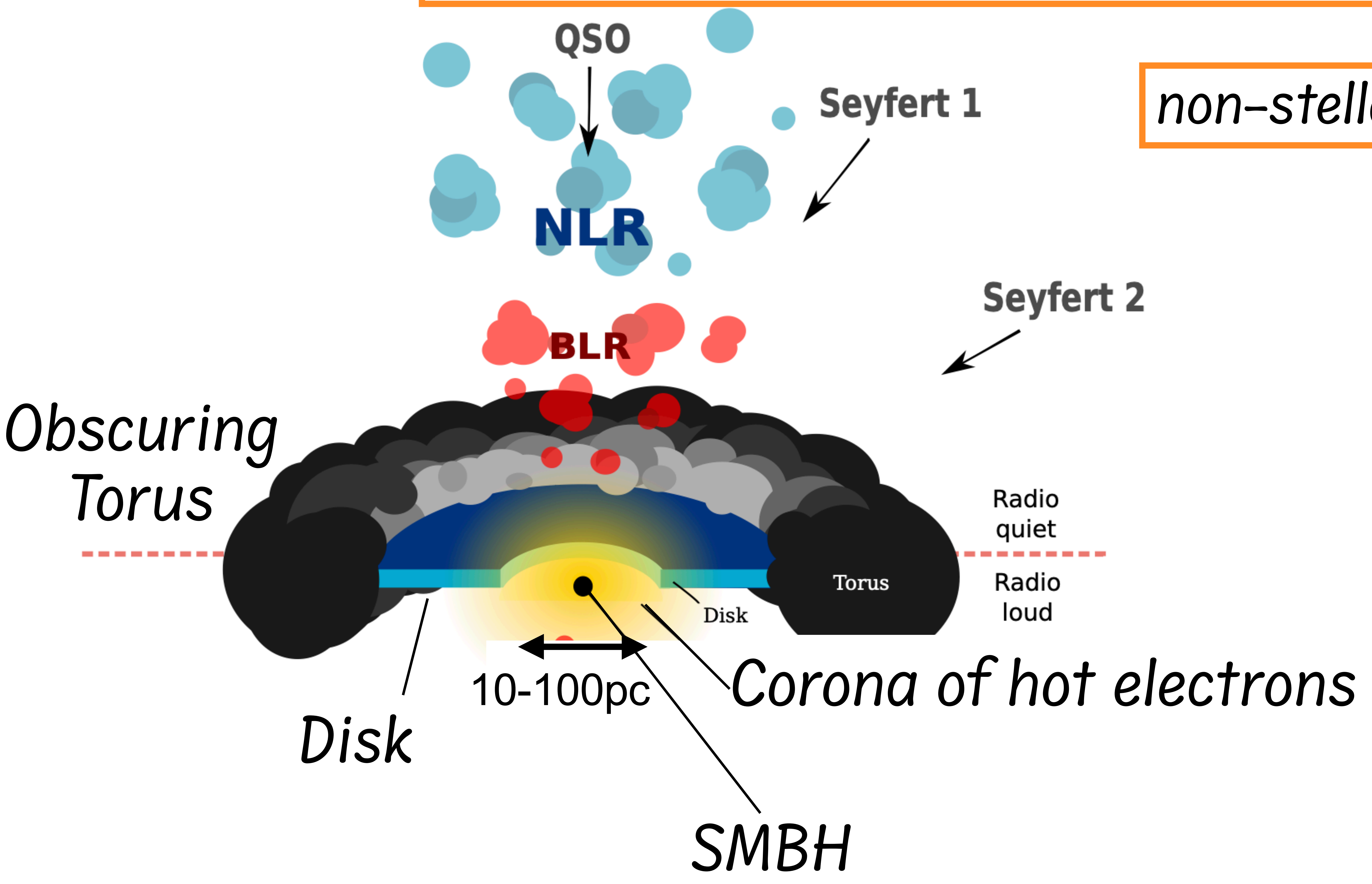
Seyferts = radio quiet Active Galactic Nuclei

non-stellar activities



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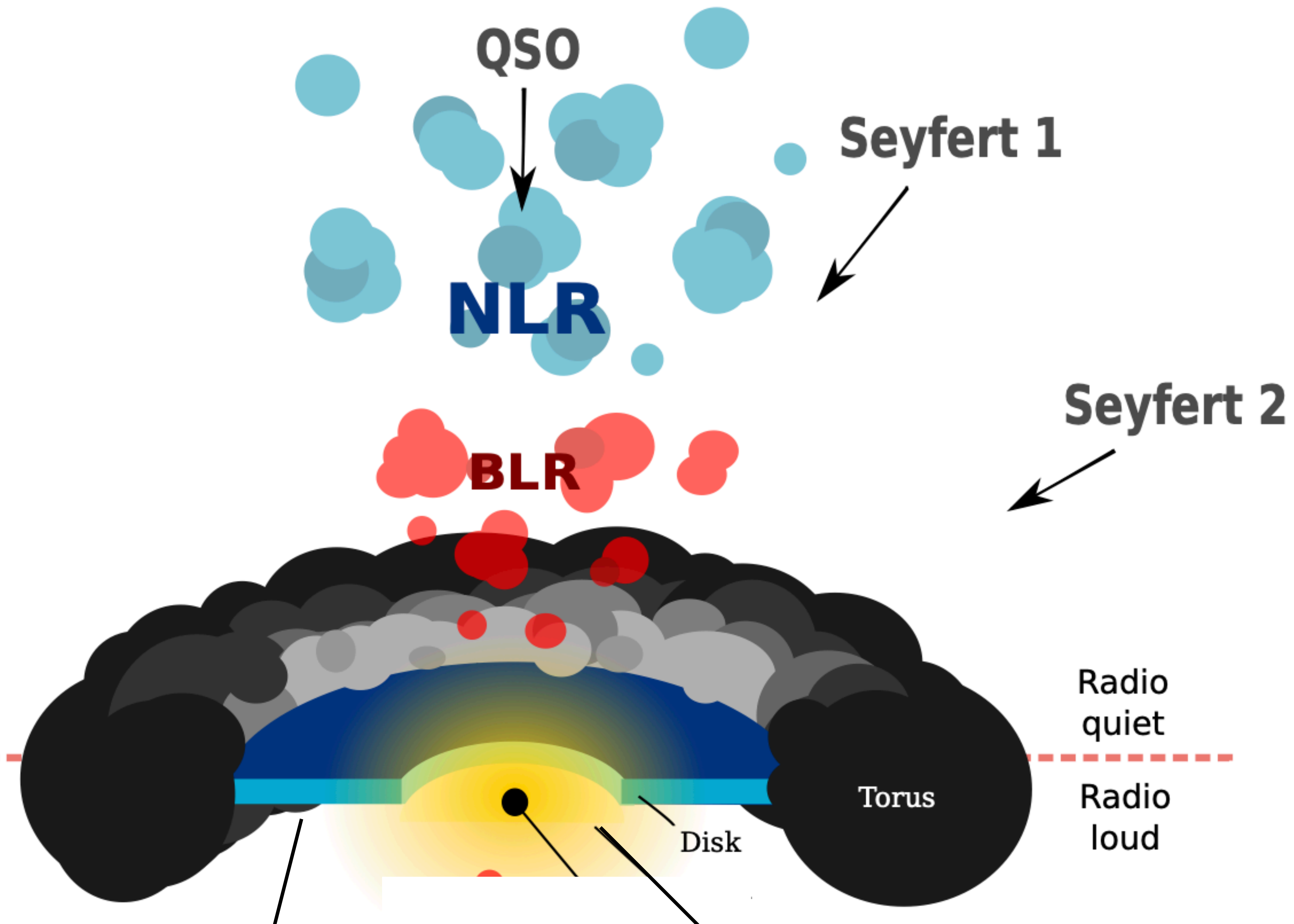
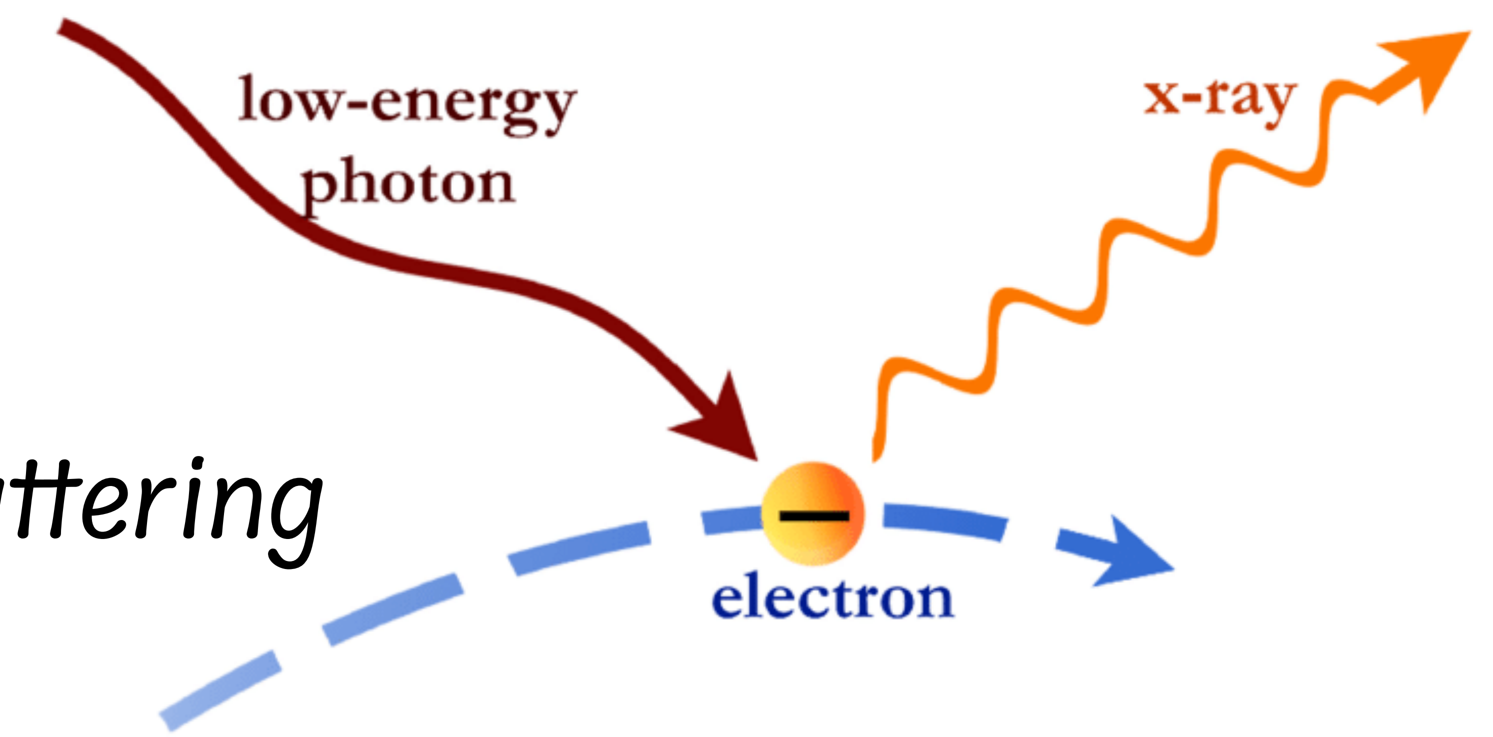
The Corona of hot electrons (and protons?)



Compton thick
($N_H > 10^{24}$ atoms cm^{-2})

Corona of hot electrons (X-ray)

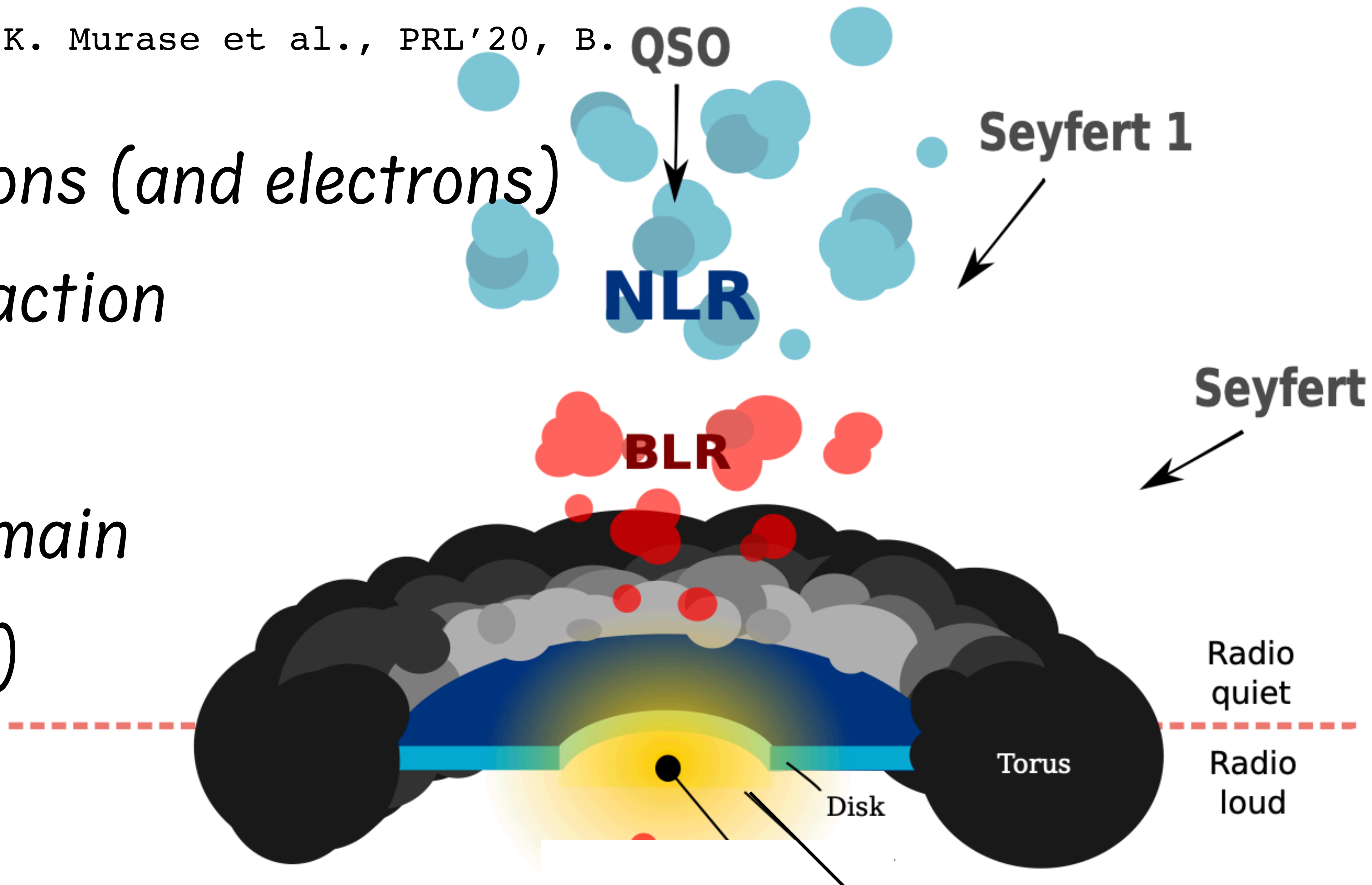
Disk: photons at optical and UV wavelengths



Inverse Compton Scattering

The ‘naive’ scenario

see also Y. Inoue et al., ApJL’20, K. Murase et al., PRL’20, B.



Step 1: acceleration of protons (and electrons)

Step 2: p–γ (also p–p) interaction

e.g., $E_p \sim 100$ TeV

target γ ~ X-ray domain

(Corona component)

Step 3: mesons production

Step 4: γ-ray → degraded into MeV region

neutrinos stream through

Note: the Fermi-LAT component most probably associated to the starburst component

see Eichmann et al., Astrophys. J. 939 (2022)

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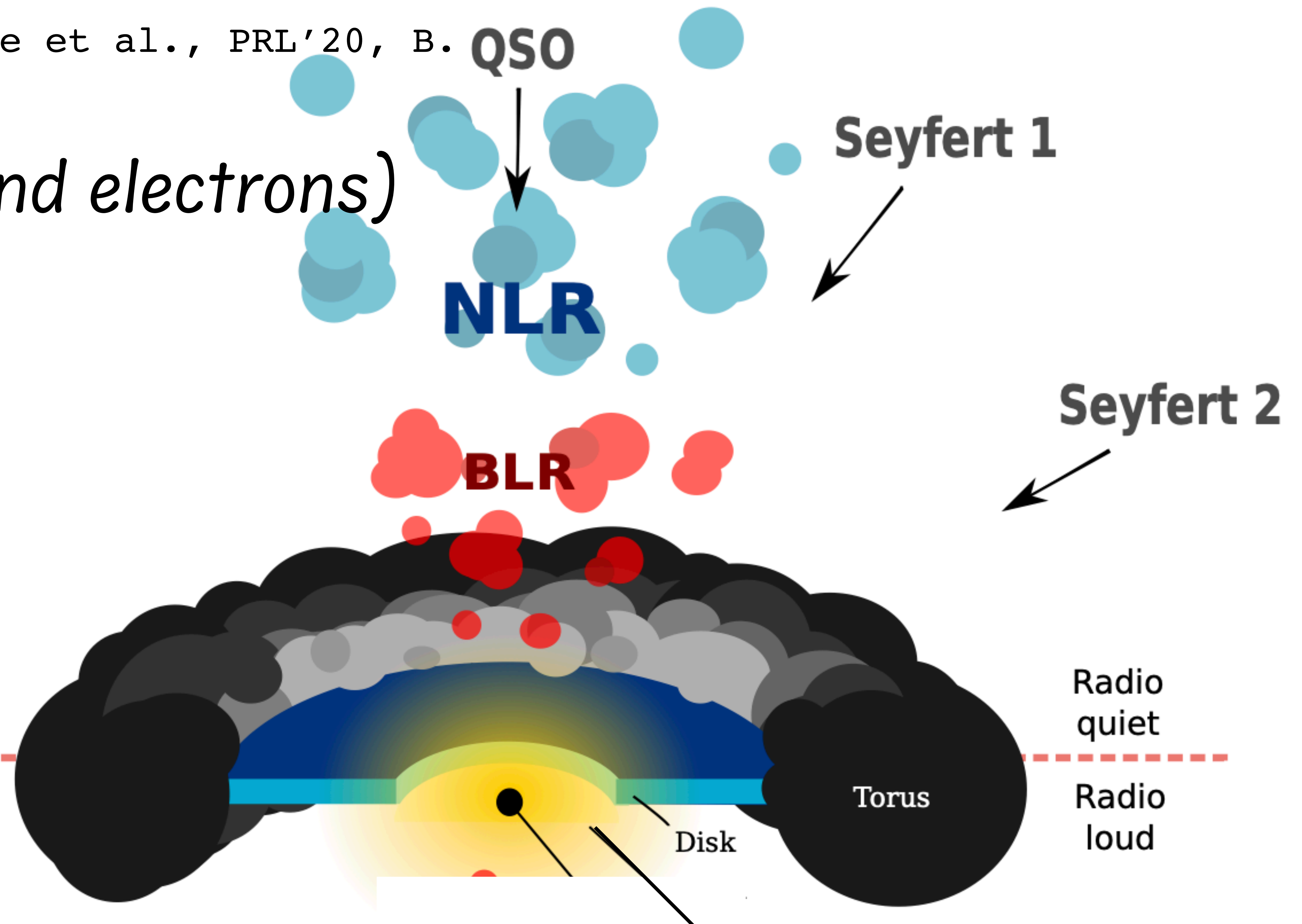

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Crucial Signature for Neutrino Validation & Search

Note: the Fermi-LAT component most probably associated to the starburst component

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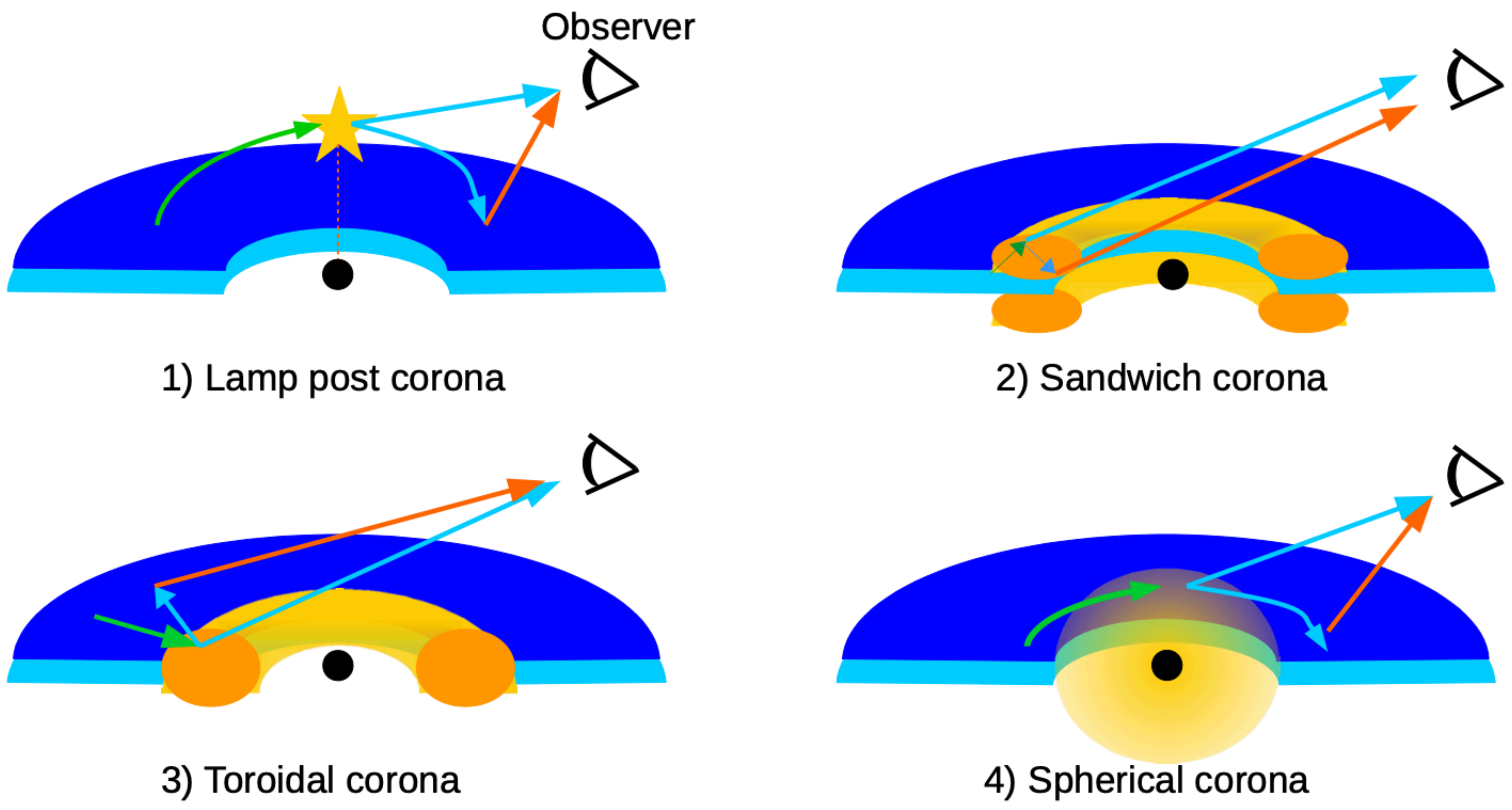
The Corona

see e.g., A.C. Fabian et al., MNRAS '15

- *<u>NGC1068 X-ray Emission:</u> Arises from scattered emission along our line of sight.*
- *<u>Rapid X-ray Variability (2-10 keV):</u> Implies a compact corona near the SMBH.*
- *<u>Anisotropic Coronae:</u> Influenced by corona position, black hole spin, and disc inclination.*
- *<u>Coronae Placement</u>: Many of the coronae are positioned within regions where*



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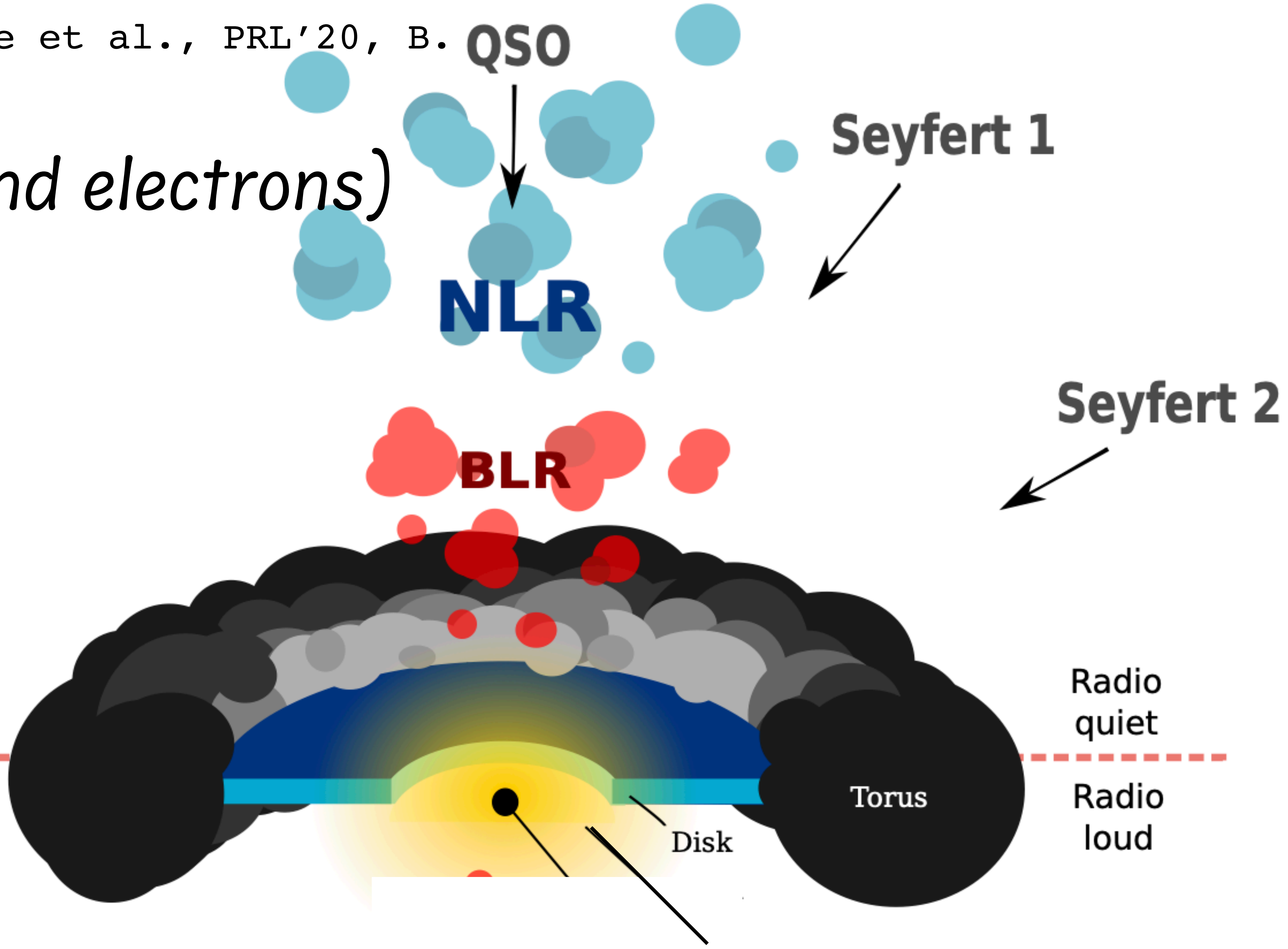

Step 1: acceleration of protons (and electrons)

Step 2: p–γ (also p–p) interaction

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What if we relax Step 1? anything fundamental and unexpected?

Questions to NGC1068 association

IceCube Connection to NGC1068 & Other Seyfert Galaxies Point to:

- *Proton Acceleration near SMBH: Mechanisms?*
- *Hot Corona's Photon Field: Origin, Composition, & Morphology?*
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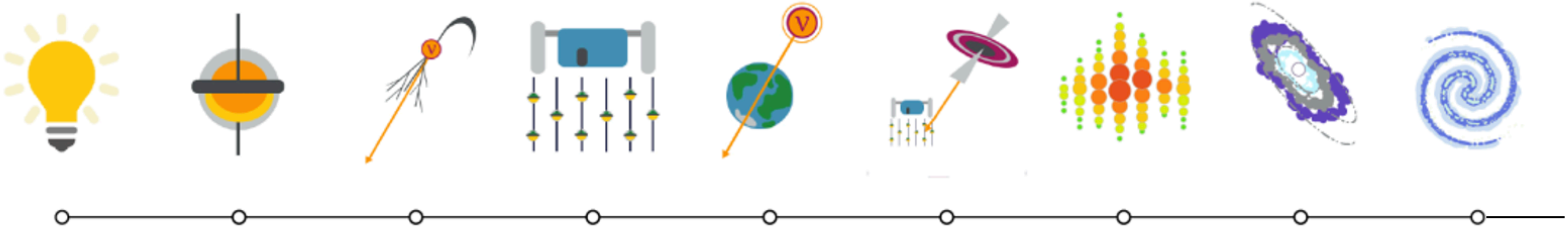
IceCube's First Decade: milestones



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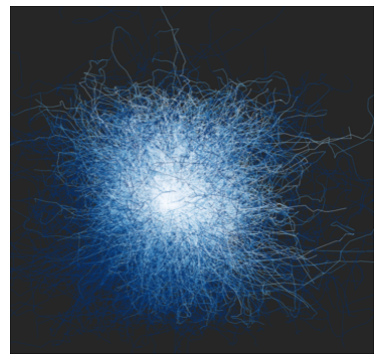
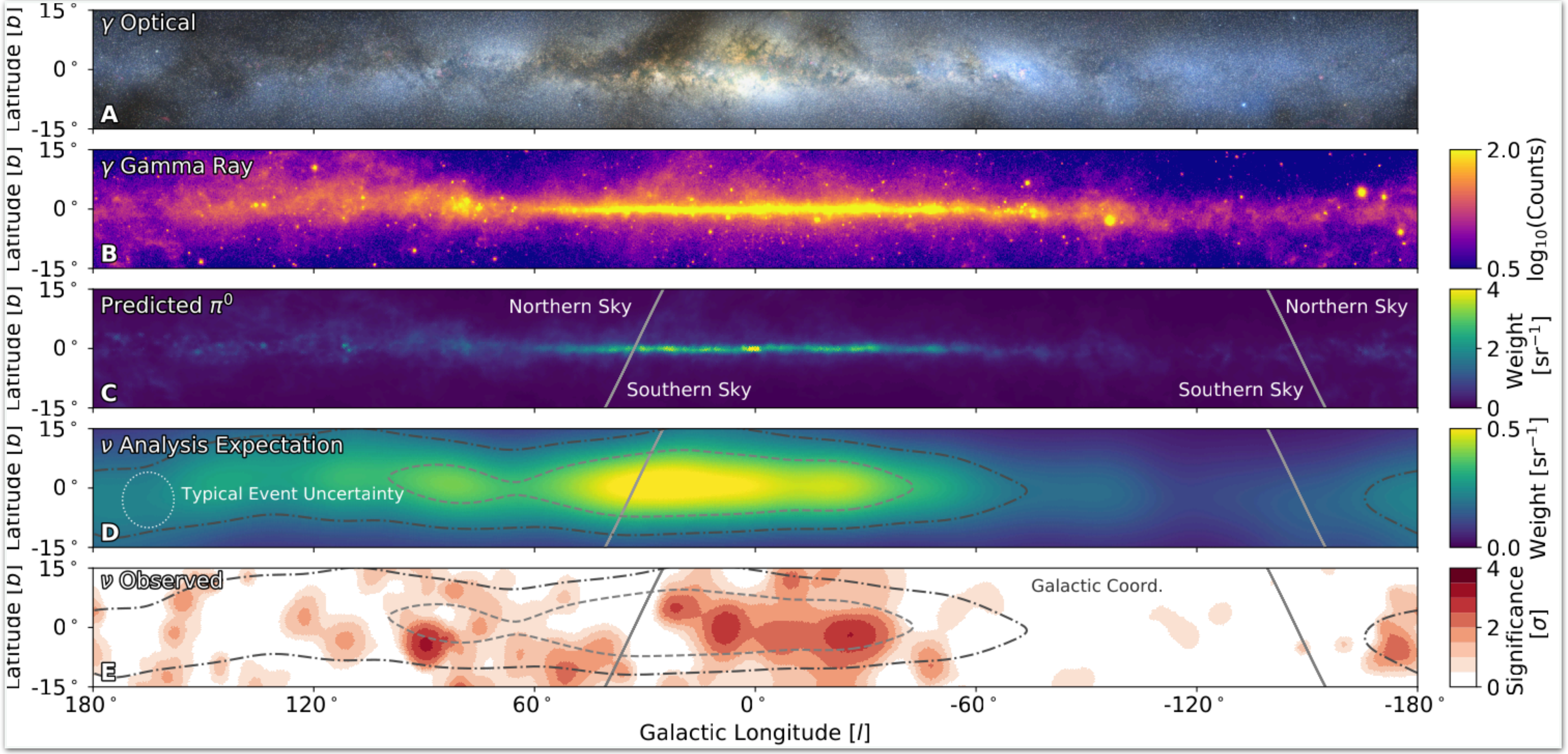


The Galactic plane in neutrinos

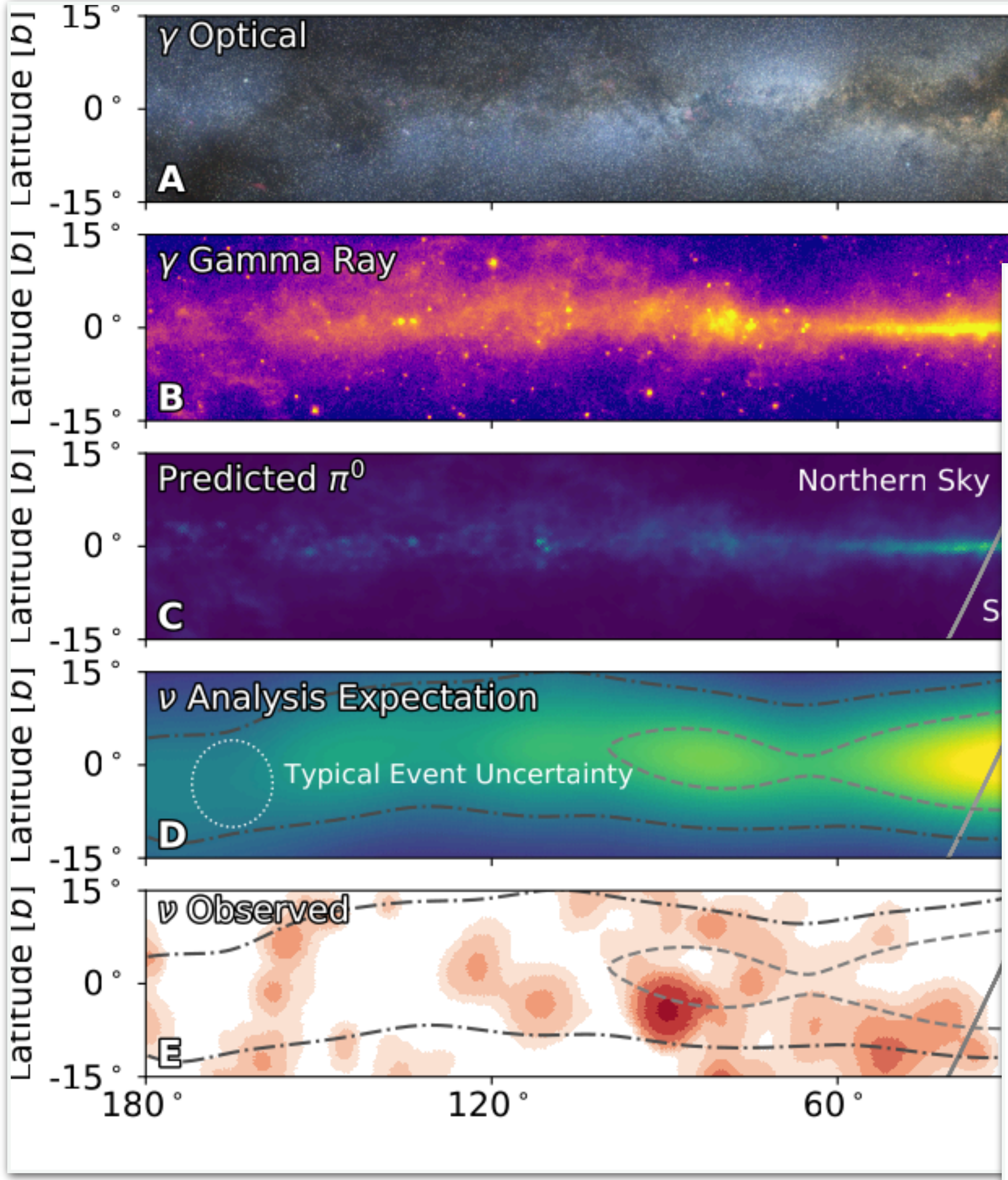
The IceCube Coll., ***Science*** 380 (2023)



Global significance **4.5σ**

The Galactic plane in neutrinos

The IceCube Coll., ***Science*** 380 (2023)



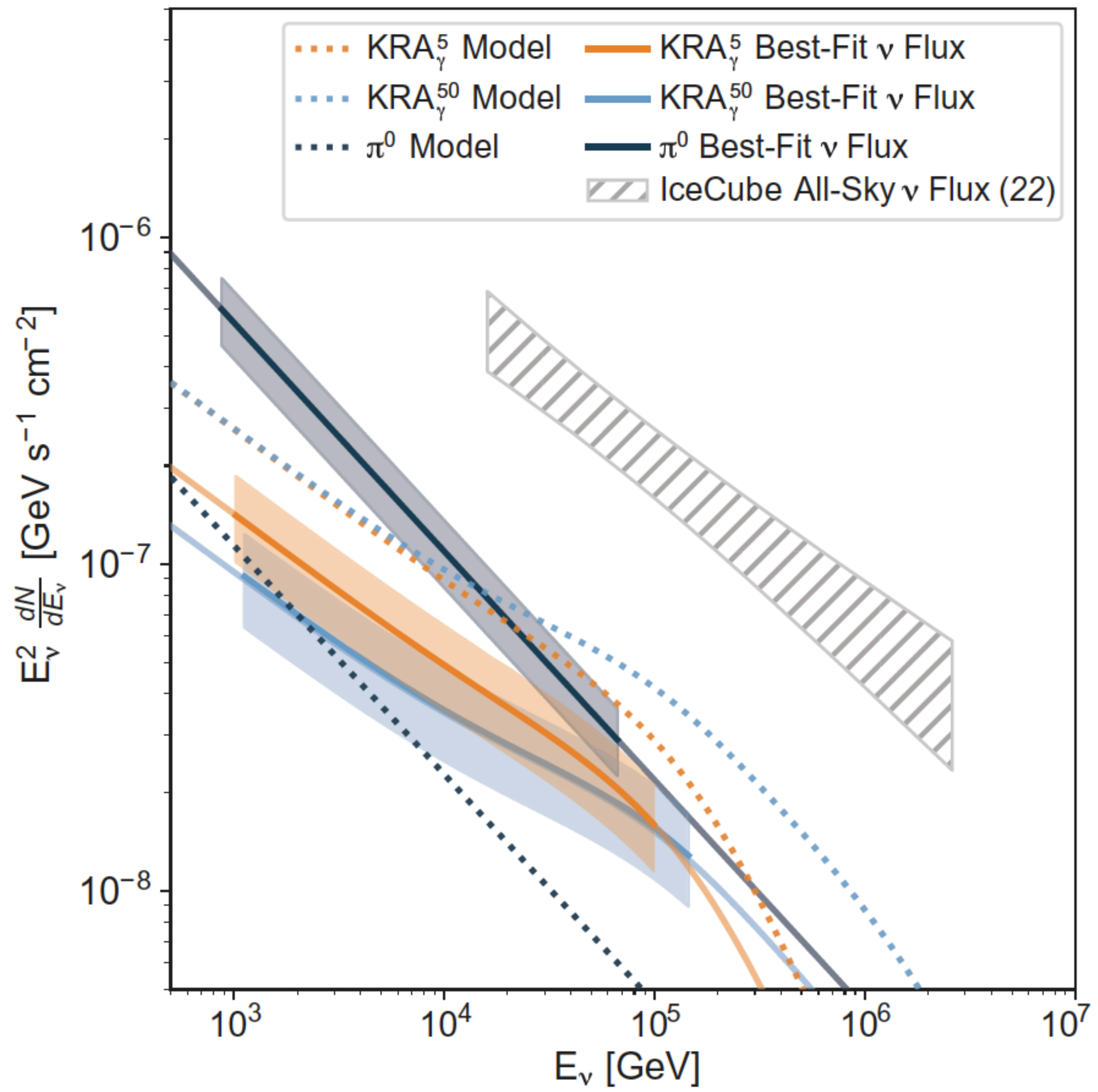


Fig. 5. Energy spectra for each of the Galactic plane models. Energy-scaled, sky-integrated, per-flavor neutrino flux is shown as a function of neutrino energy (E_ν) for each of the Galactic plane models. Dotted lines are the predicted values for the π^0 (dark blue), KRA$_\gamma^5$ (orange), and KRA$_\gamma^{50}$ (light blue) models. Solid lines are our best-fitting flux normalizations from the IceCube data. Shaded regions indicate the 1σ uncertainties; they extend over the energy range that contributes to 90% of the significance. These results are based on the all-sky (4π sr) template and are presented as an all-sky flux. For comparison, the gray hatching shows the IceCube total neutrino flux (*22*), scaled to an all-sky flux by multiplying by 4π, with its 1σ uncertainty.

The Galactic plane in neutrinos

The IceCube Coll., ***Science*** 380 (2023)

Three models of Galactic diffuse neutrino emission π^0, KRAγ^5, and KRAγ^{50}

Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8\,^{+5.3}_{-4.9}$
KRA_γ^5	$0.16\times$MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}\times$MF
KRA_γ^{50}	$0.11\times$MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}\times$MF

Standard 'naive' scenario: Cosmic-ray nuclei interacting with the interstellar gas.

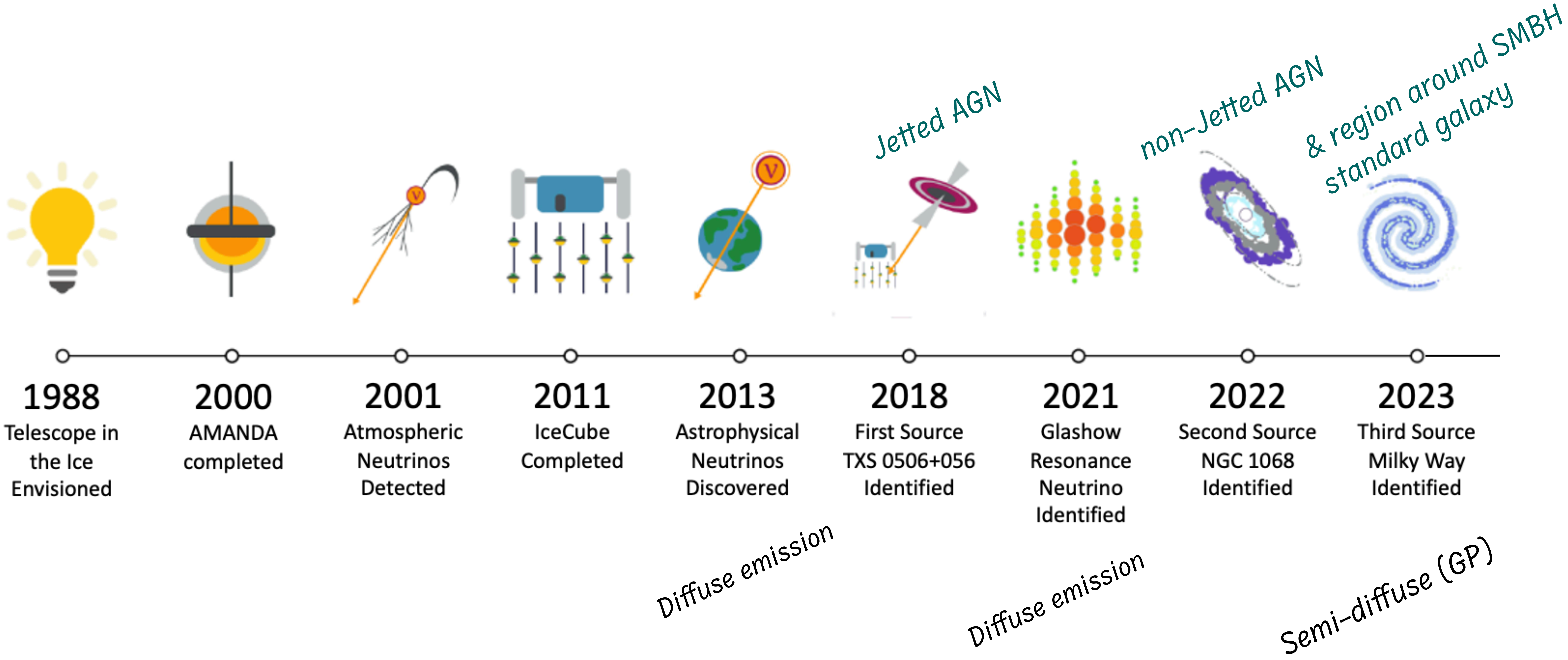
Several models, see e.g. CRINGE (Schwefer et al 2023 ApJ 949 16)

Questions to Galactic Plane association

IceCube Connection to GP Point to:

- Proton Acceleration within out Galaxy as expected. What is the role of the GC?
- GC as a PeVastron not strong enough. Role of Fermi Bubbles?
- What can we learn from the GC region vs Seyfert central regions?
- Anything fundamental and unexpected?

IceCube's First Decade: milestones

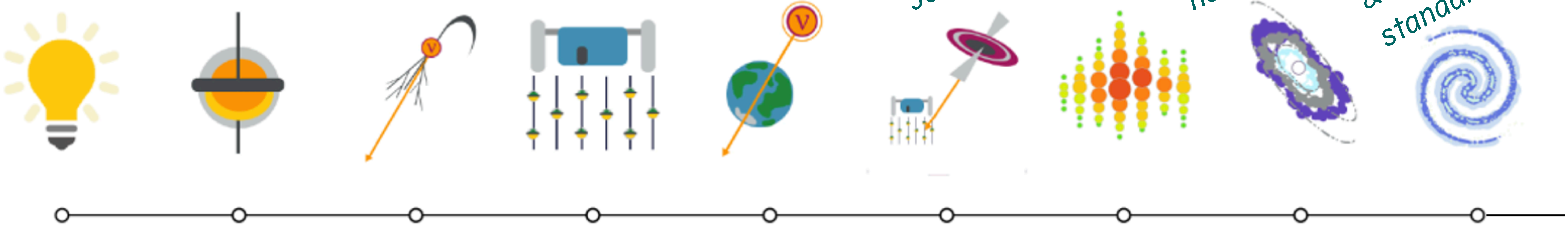


Is there any connection:
SgrA*, SMBH (non-jetted AGN), SMBH (jetted AGN)?

Jetted AGN

non-Jetted AGN

& region around SMBH
standard galaxy



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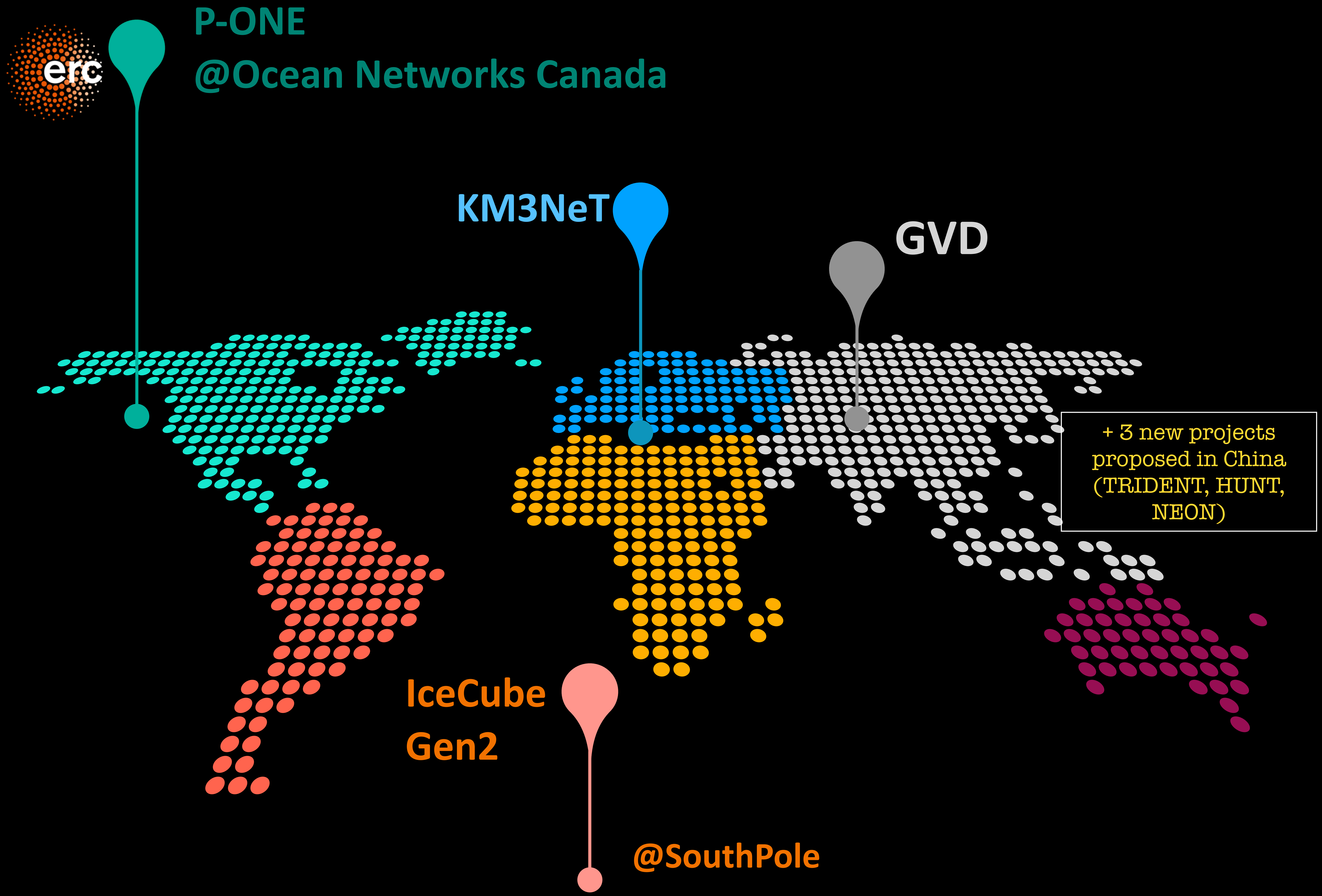
Diffuse emission

Diffuse emission

Semi-diffuse (GP)

We need more neutrinos: Expanding the Neutrino Net



OCEAN NETWORKS CANADA

Discover the ocean. Understand the planet.

https://www.oceannetworks.ca/

Cabled ocean observatory:
800 km loop of fibre-optic cables
in operation

P-ONE Collaboration, ***Nature Astron.* 4 (2020)**

The Roadmap to P-ONE: Phase 1, Pathfinders

P-ONE

DFG INNOVATION Canada Foundation for Innovation Fondation canadienne pour l'innovation

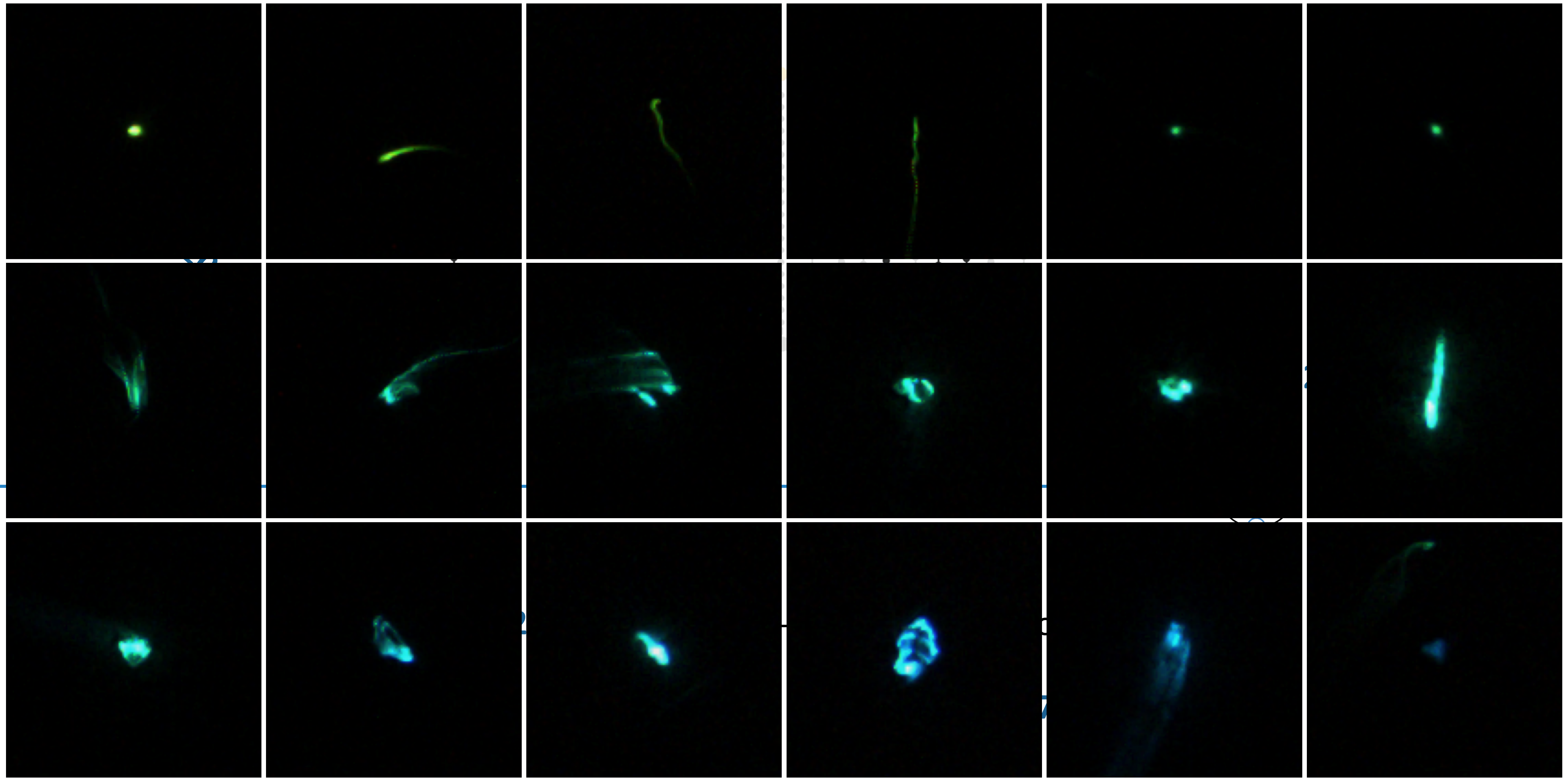
2018-2023

Deployed 2018 — STRAW

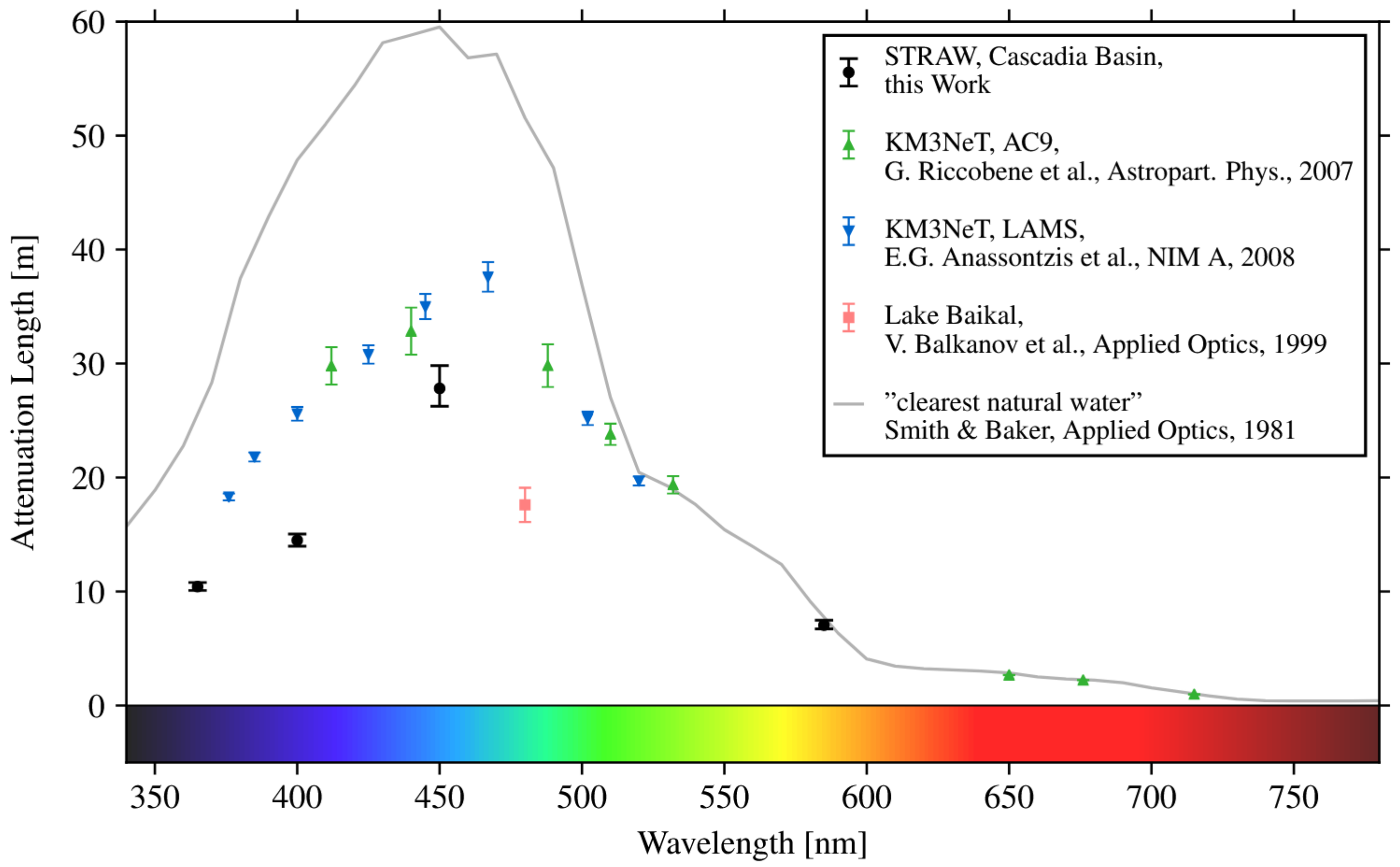
Deployed 2020 — STRAW$_b$

1st pathfinder 2nd pathfinder

Bioluminescence pictures from camera systems installed at -2.6km at the P-ONE side



P-ONE Coll, *EPJ C (2021)*



5-years operation of STRAW (98% uptime)

Attenuation Length ~30m @ 450nm

Bioluminescence, sedimentation and biofouling as main challenges identified.

Phase 1, Pathfinders Recovered (Summer '23)

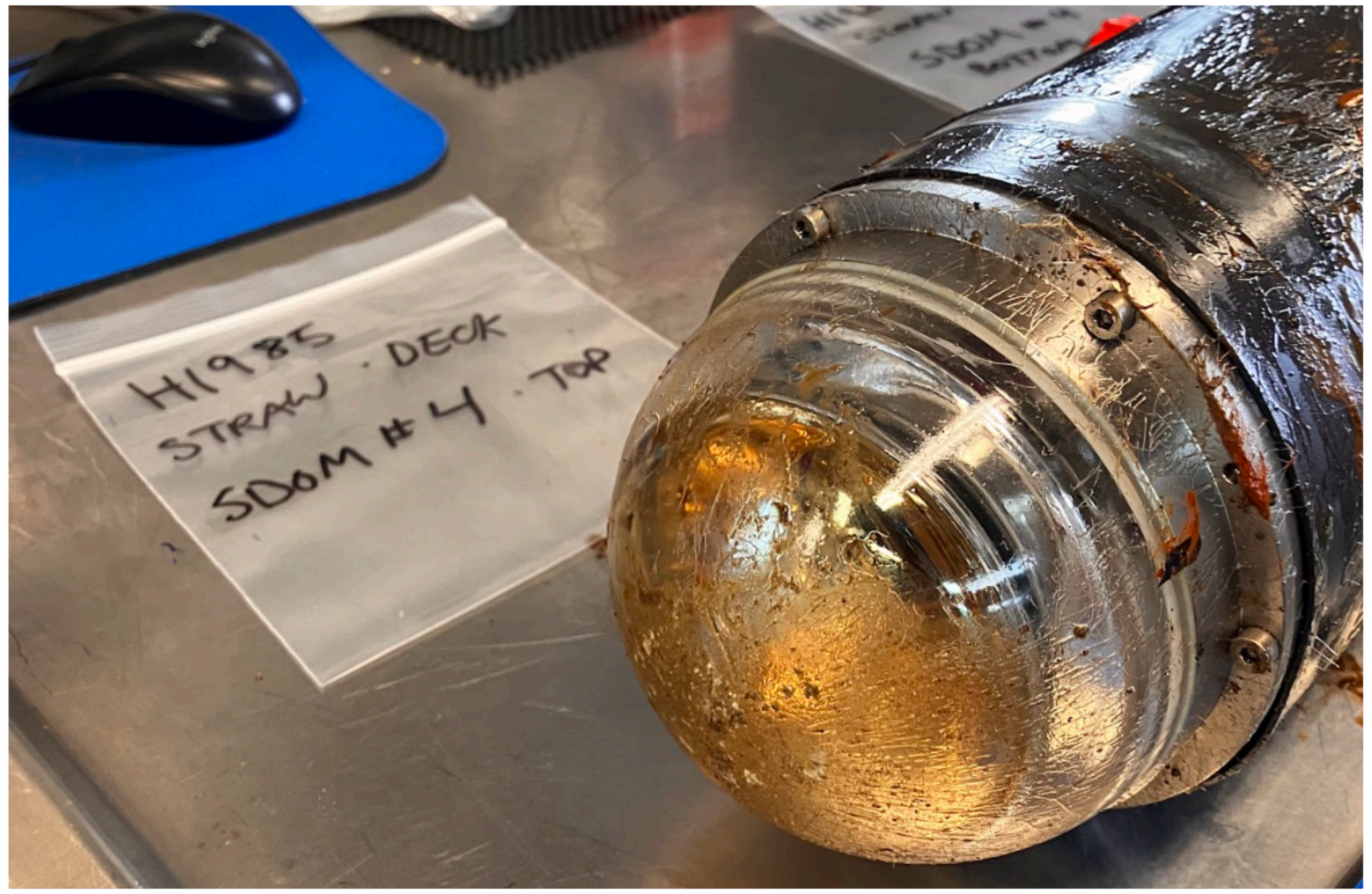
P-ONE

DFG INNOVATION
Canada Foundation for Innovation
Fondation canadienne pour l'innovation

2018-2023

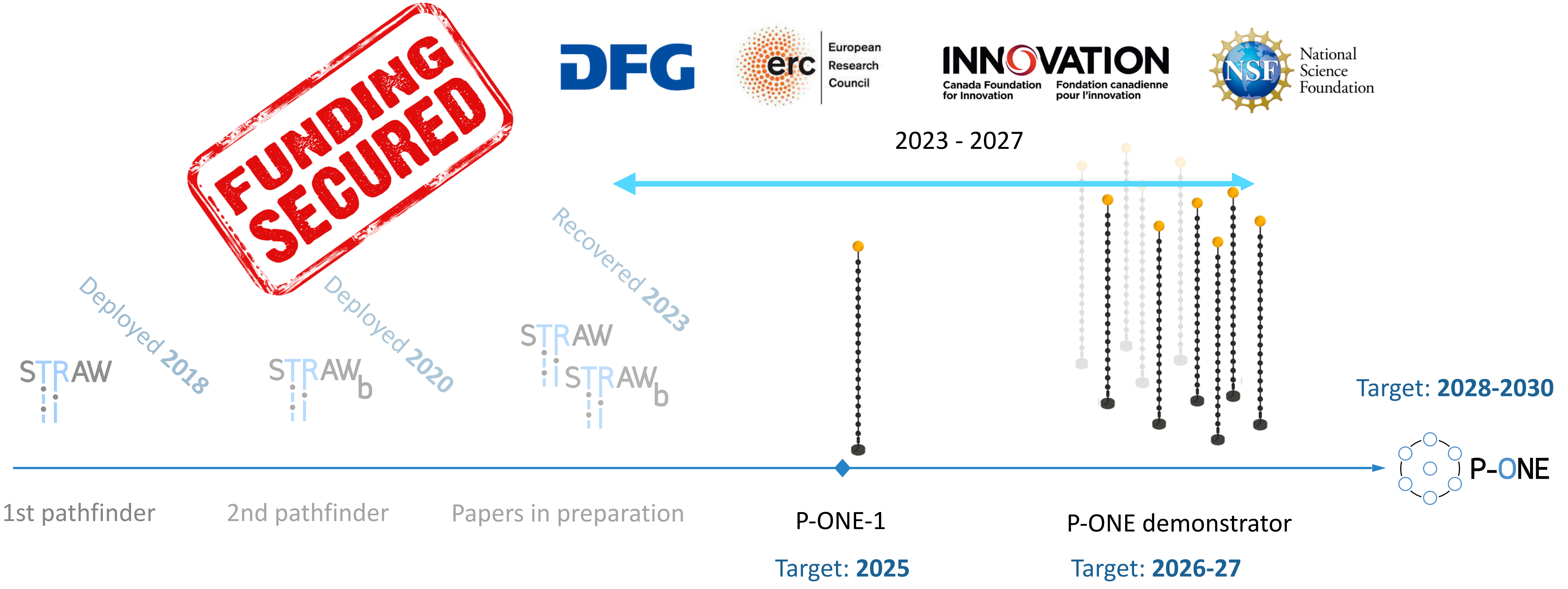
1st pathfinder	2nd pathfinder	Papers in preparation
STRAW — Deployed **2018**	STRAW$_b$ — Deployed **2020**	STRAW, STRAW$_b$ — Recovered **2023**

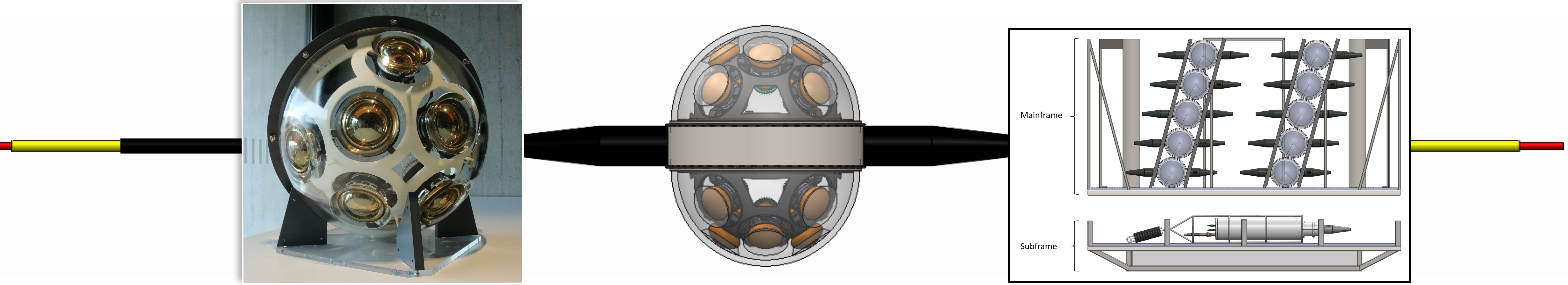
28-2030



Recovered Modules: biofouling observed on some of them (5 years of operations) - Mitigation strategies under study.

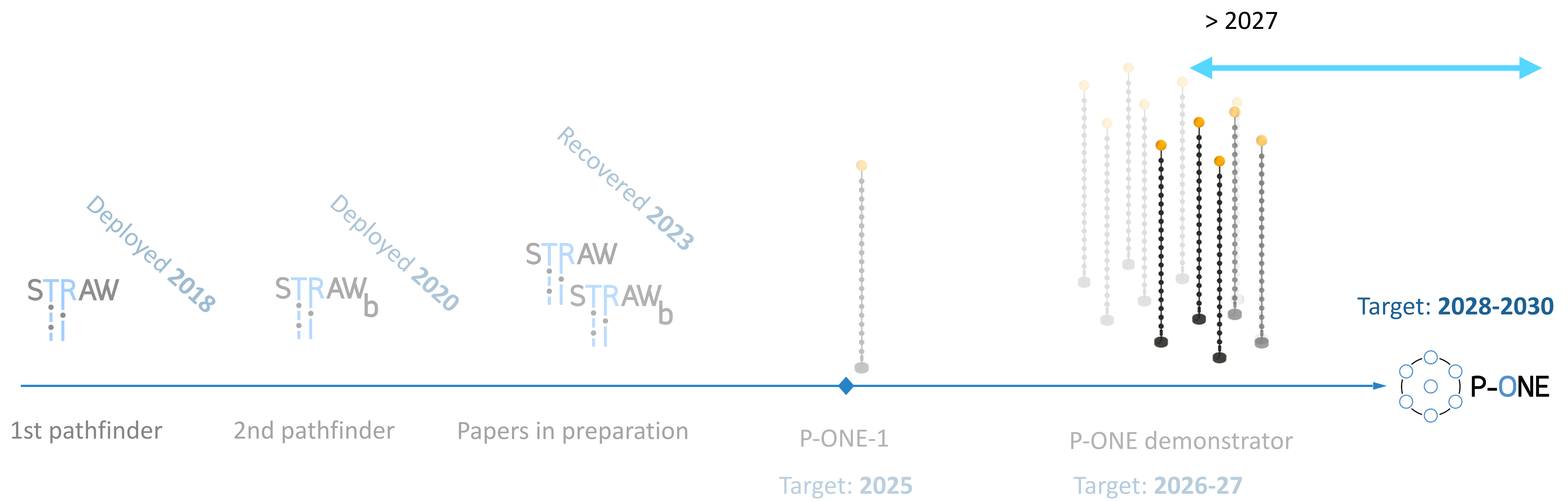
Phase 2, Demonstrator





P-ONE Based on Design Principles of Scalability

Target: O(100) Lines



P-ONE Science: Focus on particle and astrophysics with High Energy (HE) and Ultra High Energy (UHE) neutrinos.

P-ONE Design & Optimization: Currently underway to ensure optimal science return for investment.

Technical Design Report: Under development to provide a comprehensive overview of the project's technical aspects.

Funding Scheme: Possible contributions from Canada, USA, and Europe, ensuring a diverse and collaborative financial foundation that does not overlap with KM3NeT funding.

Conclusions, questions and a proposal

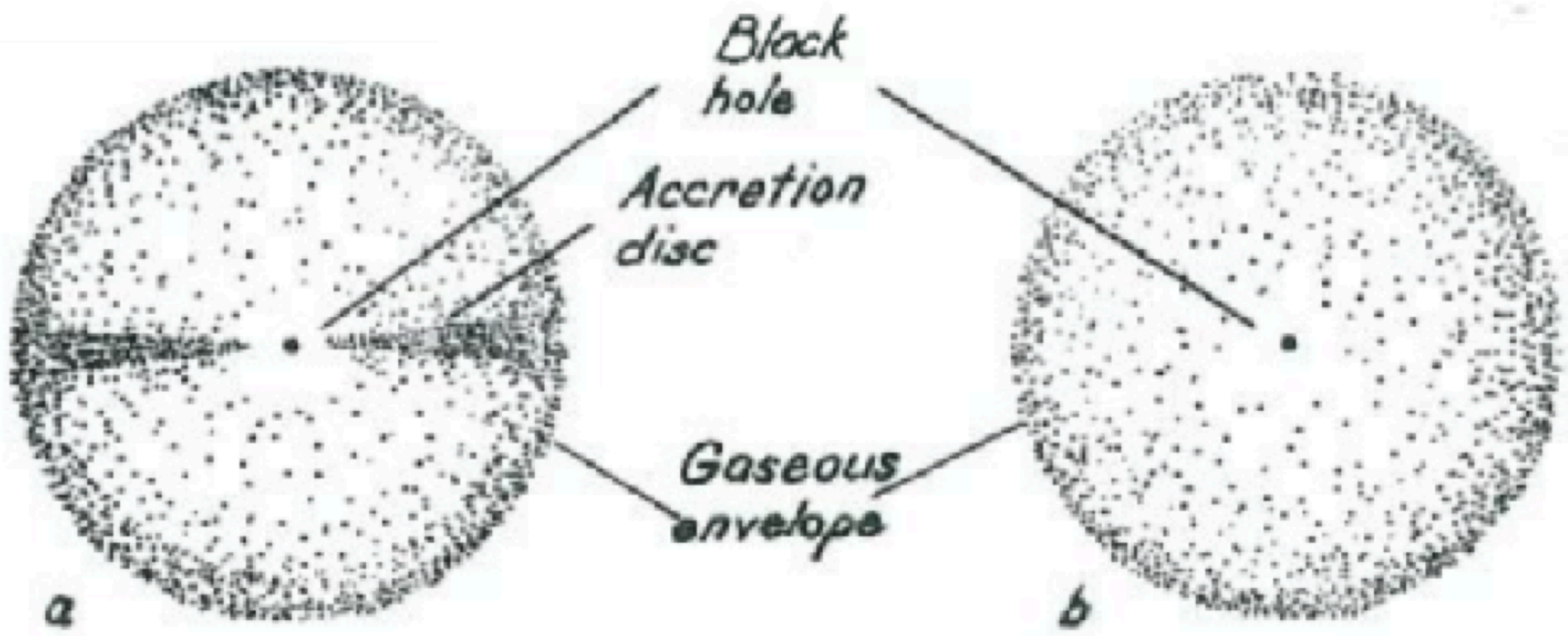
IceCube Connections:

- Proton Acceleration near SMBH: Mechanisms? Something Universal Emerging?
  - Hot Corona's Photon Field: Origin, Composition, & Morphology?
  - Gamma-Ray Showering & Implications: Cascade to MeV Range?
  - MeV Telescope Gap: How to Overcome Confirmation Challenges?
  - Compact, Obscured Region Interactions: General Relativity Corrections?
- Need More Neutrinos!! KM3NeT, IceCube-Gen2, P-ONE ....
- Berezinsky's 1981 Groundwork: Proposal to Label Seyfert Galaxies with Neutrino Component as 'Berezinsky Galaxies'

The ‘Hidden’ source idea

§9. Hidden sources

In the example of a massive black hole in a cocoon we encountered a model of a hidden source: an object which contains particles accelerated to high energies, but is not seen in high-energy electromagnetic radiation (X-ray and (or) gamma-ray radiation).



Berezinsky, Ginzburg, MNRAS 1981
Silberberg, Shapiro 1982