From Quiescence to Activity: Galactic Nuclei as Unified Cosmic Particle Laboratory

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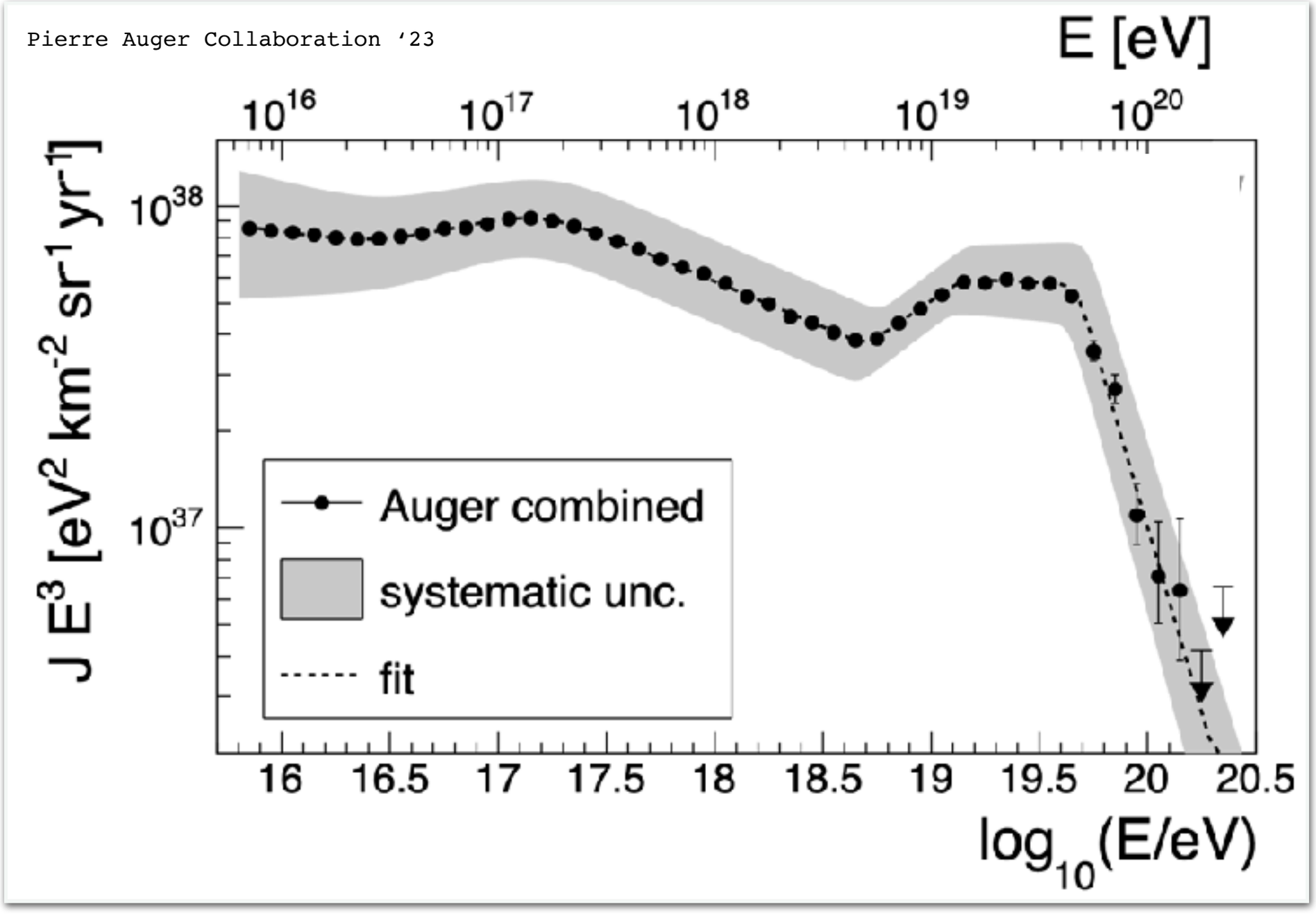
Technical University of Munich

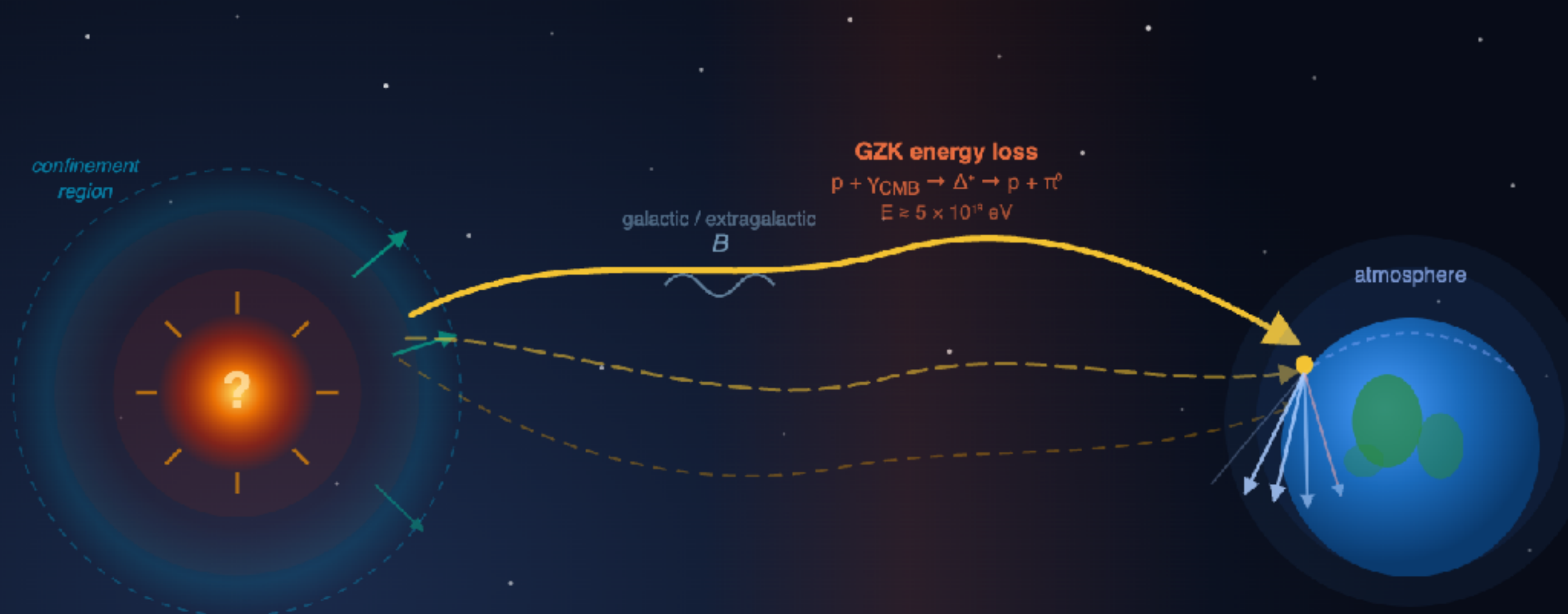
GSSI Colloquium | L'Aquila 08/04/2026

The Question:

The Origin of the Primary Cosmic Rays

Primary Cosmic Rays: Energy Spectrum





① Acceleration

Fermi shock mechanism

SNR, AGN, GRB …?

$E_{max} \sim Z \cdot B \cdot R$

② Escape

break free from source

$r_L \geq R_{source}$

energy loss during escape

③ Propagation

magnetic deflection

no directional info

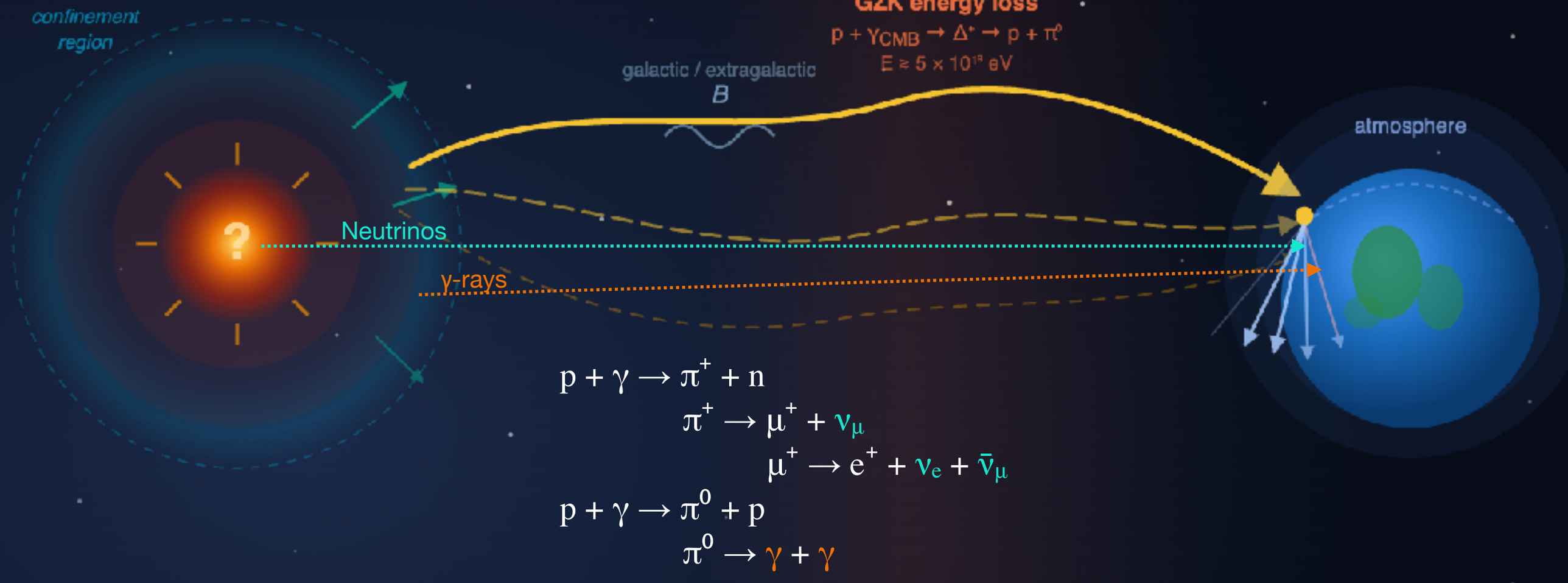
GZK cutoff $E \geq 5 \times 10^{19}$ eV

④ Detection

extensive air shower

ground arrays, fluorescence

Auger, TA, IceCube…



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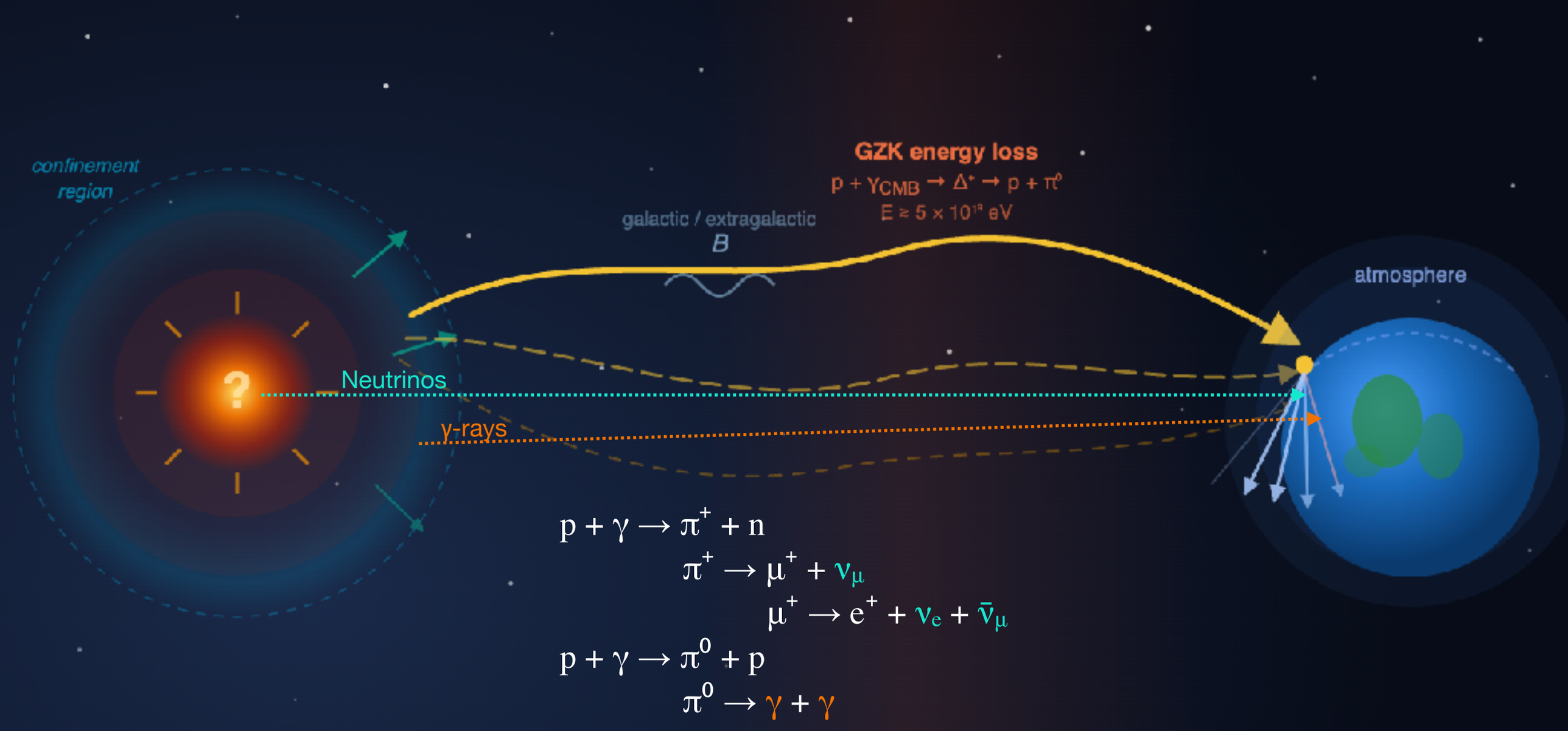

① **Cosmic Rays**

Limited horizon
heavy composition
hard to point

② **Gamma Rays**

limited horizon
reprocessed

③ **Neutrinos**

weakly interacting
penetrating
but hard to detect

④ **Photon Astronomy**

from radio to X-ray
they trace different
mechanisms, components,
sources

Are these messengers reporting about the same story?

The accelerators

Collider (e.g., LHC)

Power source: electricity

EM hardware: cavities + magnets

Size scale: R ~ O(10) km

Limiting factor: engineering

Energy reach: E_beam ≈ 7 TeV → √s ≈ 14 TeV

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Galactic Nuclei

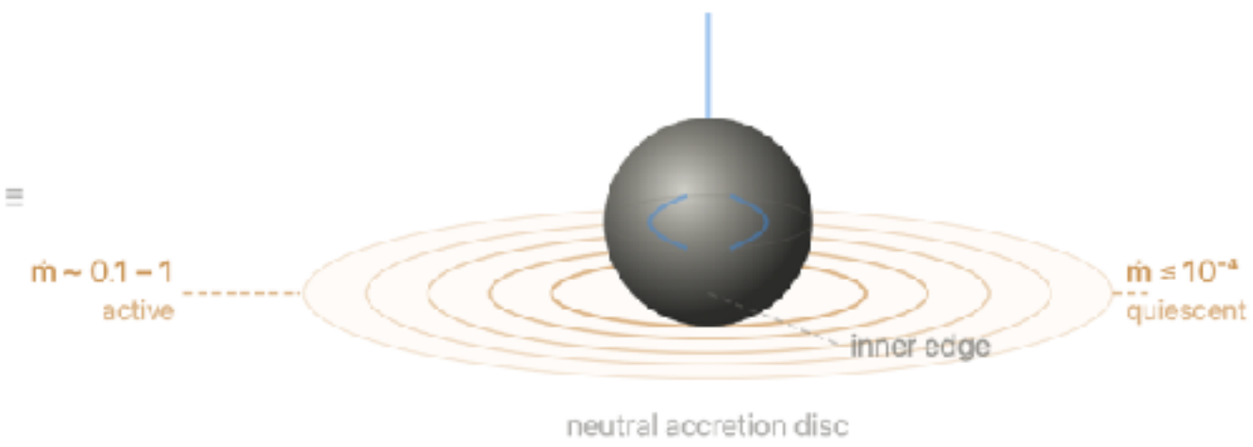
Power source: accretion / gravity

EM hardware: spacetime + EM fields

Size scale: R ~ r_H ~ 10^6-10^{10} km

Limiting factor: GR + electrodynamics

Energy reach: E_{CR} (th. limit)~ 10^{20} eV



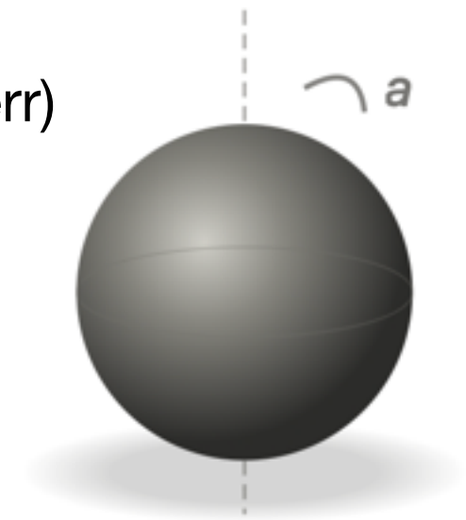
Galactic Nuclei: I

Kormendy & Ho (2013)

Virtually every massive galaxy hosts a **Super Massive Black Hole** (SMBH, 10^6 - 10^{10} $M_\odot$)

Theoretical BH defined (GR) by:

- Mass ***M***
- Spin 0 (Schwarzschild) ≤ ***a*** ≤ 1 (Kerr)
- Electric charge ***Q***



Astrophysical BH:

- Nearly neutral **(Q ≈ 0)**
- **Electromagnetic 'action':** interaction of BH with surrounding magnetic fields ***B*** (e.g., carried by the plasma)

Galactic Nuclei: II

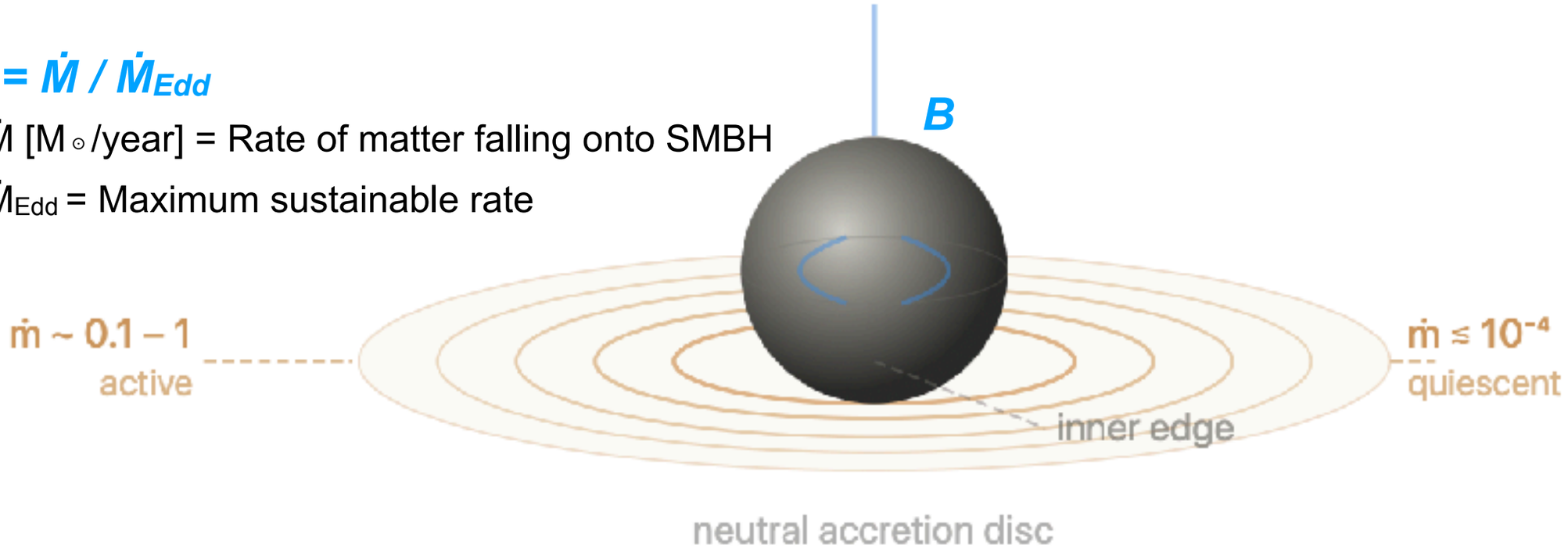
Yuan & Narayan (2014)

Accretion Disk: Rotating disk of gas and dust gravitationally captured by the SMBH

Characterised by *accretion rate* $\dot{m}$ *("how hungry is the black hole?")*

$\dot{m} = \dot{M} / \dot{M}_{Edd}$

- $\dot{M}$ [$M_\odot$/year] = Rate of matter falling onto SMBH
- $\dot{M}_{Edd}$ = Maximum sustainable rate



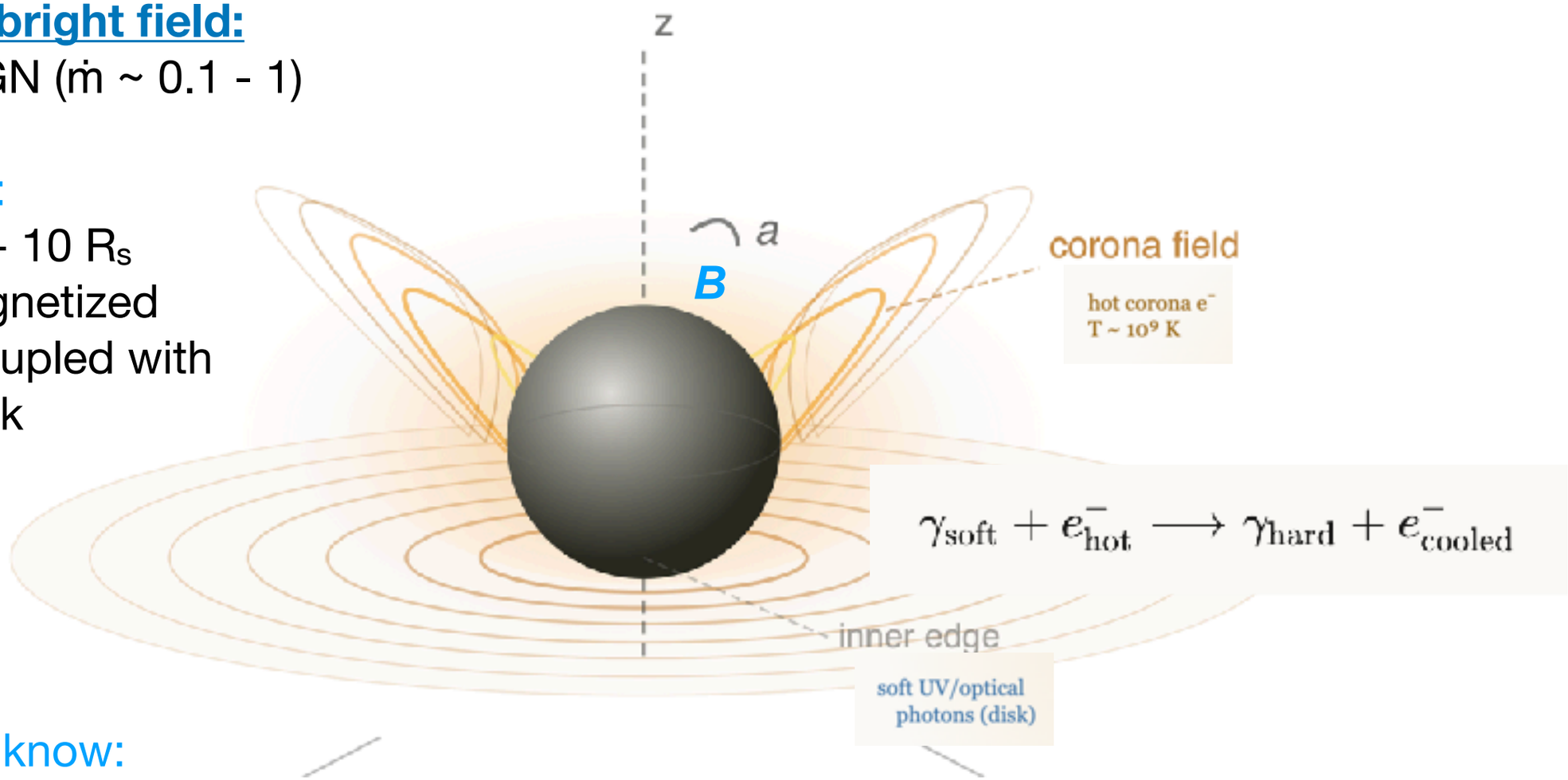
$\dot{m}$ sets the disk structure and radiative output:

- $\dot{m}$ ~ 0.1 - 1 → thin, bright, photon-rich disk moderate → **Active** Galactic Nuclei (AGN)
- $\dot{m} \lesssim 10^{-4}$ → hot, tenuous, dim flow → **Quiescent** galaxies
- $\dot{m} \sim 10^{-8}$ → essentially **starved** → Sgr A*

Galactic Nuclei: III

Haardt & Maraschi (1991), Tanaka et al. (1995), Reis & Miller (2013)

Corona X-ray bright field:
observed in AGN ($\dot{m}$ ~ 0.1 - 1)



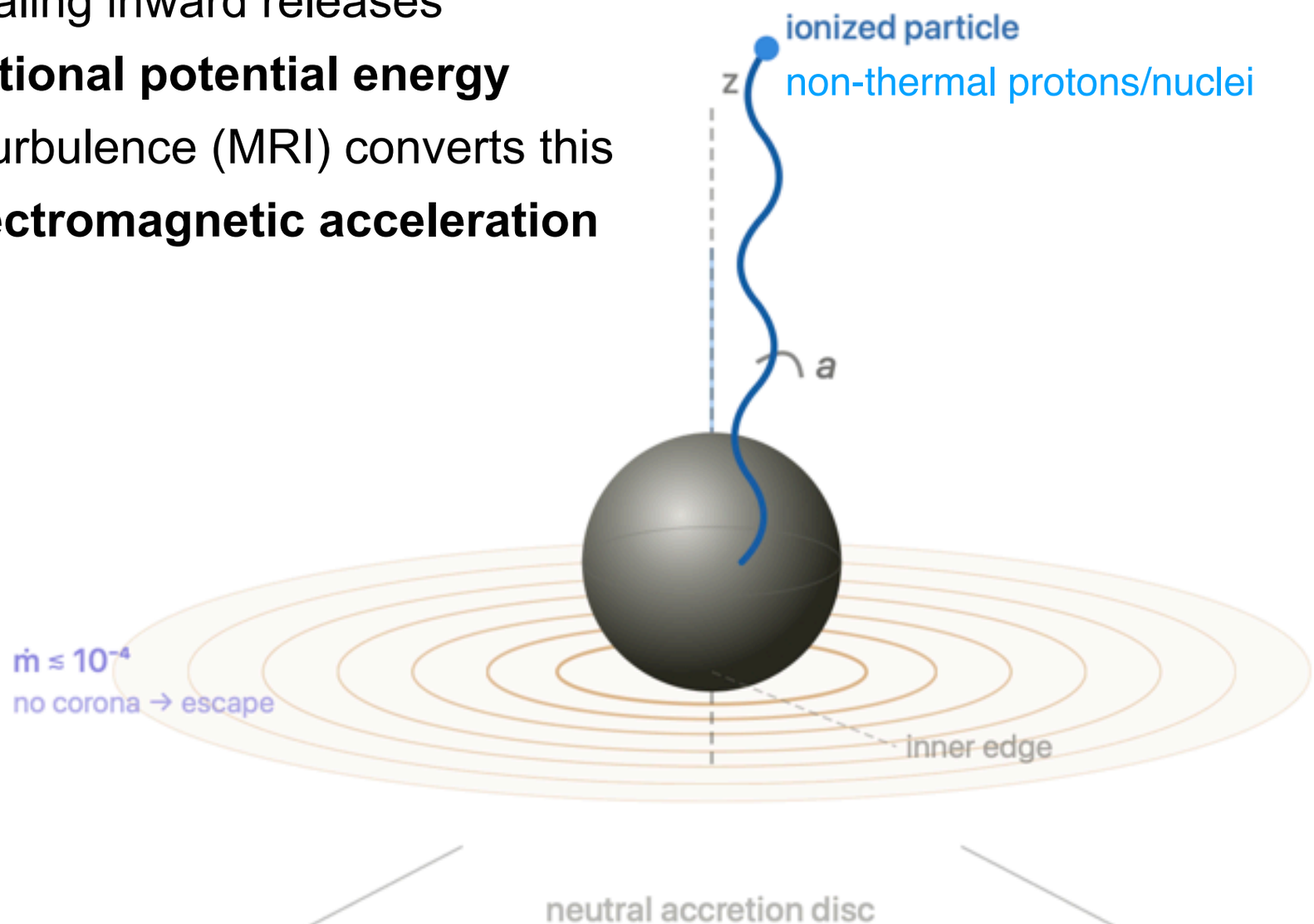
What we know:
- Compact: 3 - 10 R_s
- Strongly magnetized
- Thermally coupled with accretion disk

What we don't know:
- Why it exists
- How it is sustained against rapid radiative losses
- Its geometry
- Its composition (pair-dominated or baryon-loaded?)

The accelerators: Super Massive Black Holes and their Environments

e.g., Levinson PRL ’00, K. Hirotani Galaxies ’18

- Matter spiraling inward releases
  - **gravitational potential energy**
- Magnetic turbulence (MRI) converts this
  - into **electromagnetic acceleration**



The **maximum energy** is set by the potential drop across the disk.

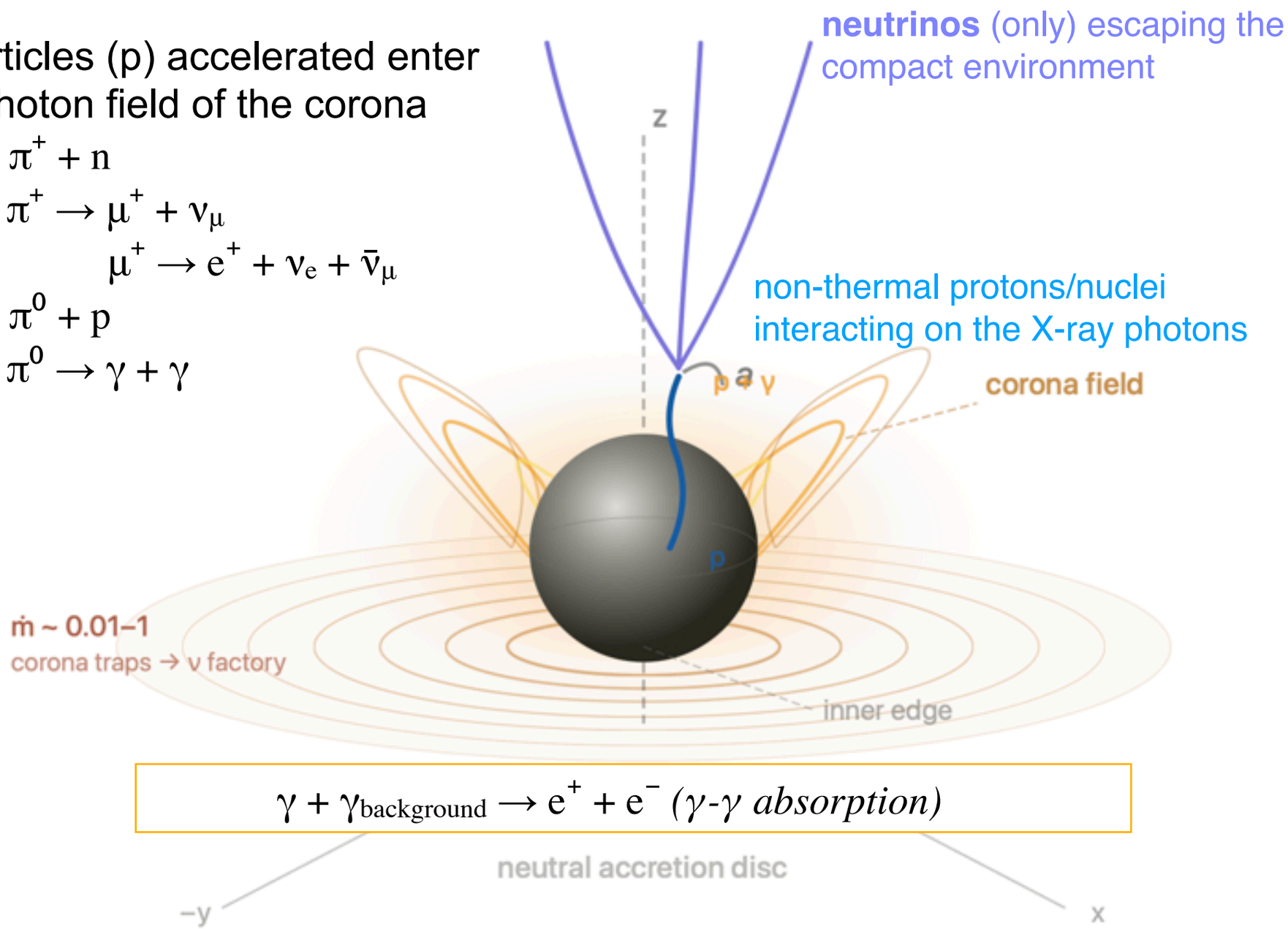
Are primaries able to escape their acceleration region?

The ‘hidden’ source idea

Berezinsky, Ginzburg, MNRAS 1981
Silberberg, Shapiro 1982

Cosmic particles (p) accelerated enter
→ dense photon field of the corona

- $p + \gamma \rightarrow \pi^+ + n$
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- $p + \gamma \rightarrow \pi^0 + p$
  $\pi^0 \rightarrow \gamma + \gamma$



$$\gamma + \gamma_{background} \rightarrow e^+ + e^- \ (\gamma\text{-}\gamma \ absorption)$$

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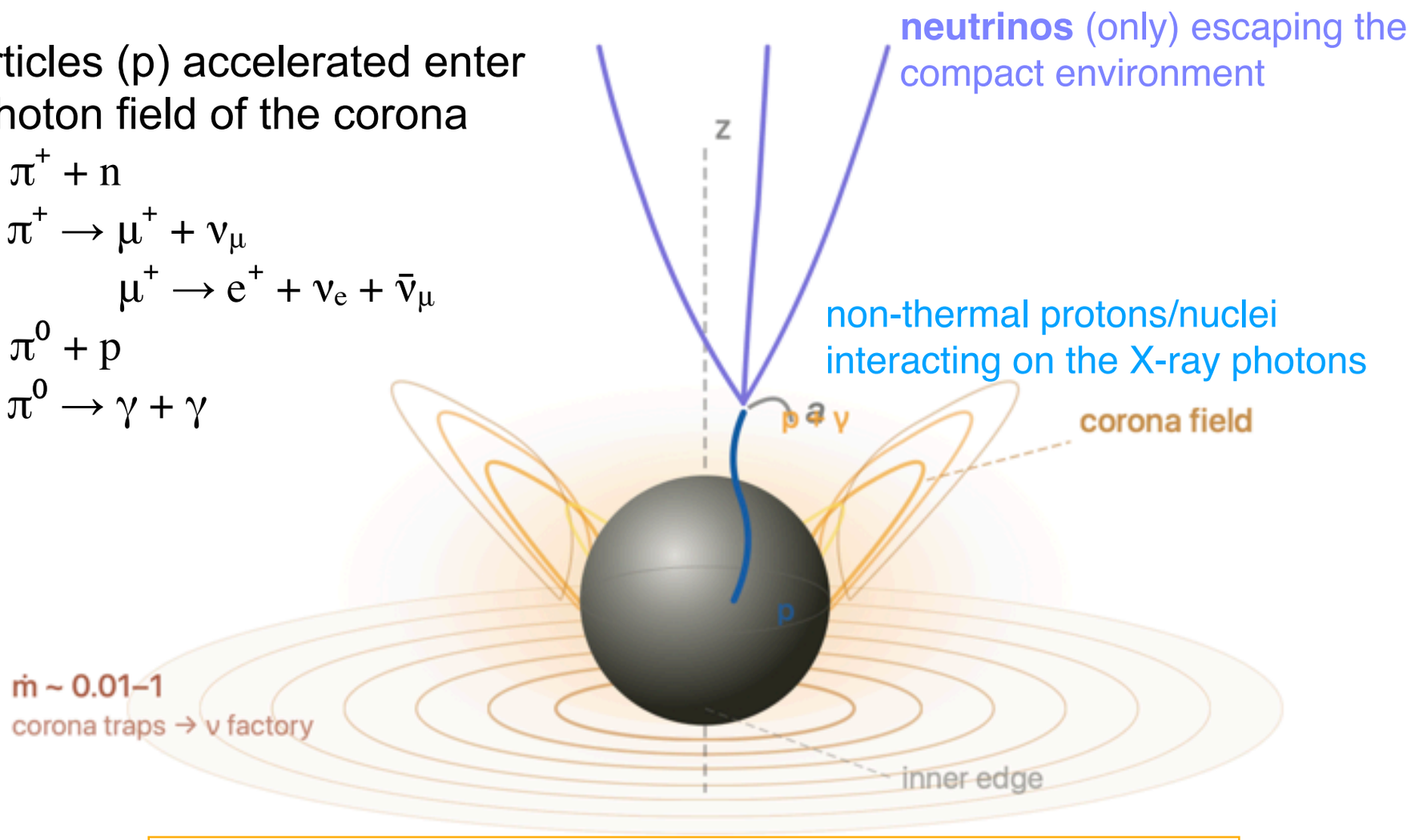


$$\gamma + \gamma_{\text{background}} \rightarrow e^+ + e^- \ (\gamma\text{-}\gamma \ absorption)$$

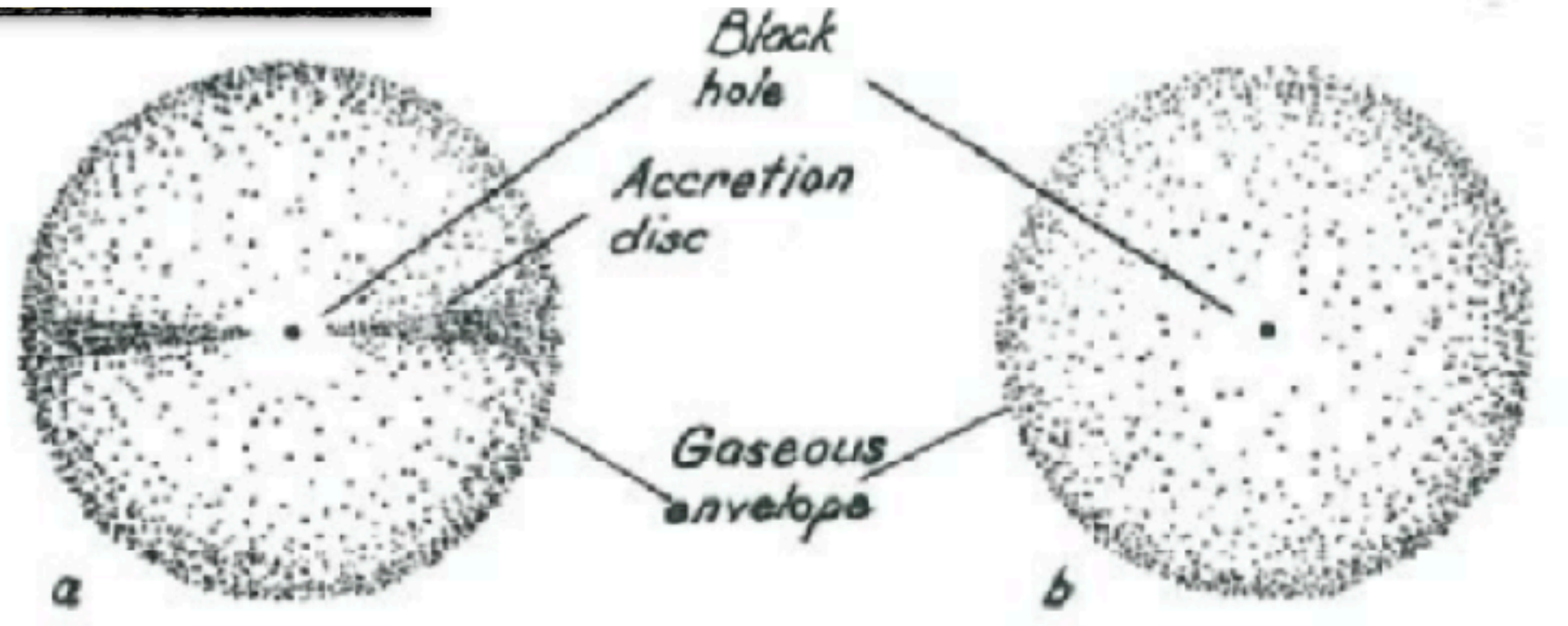
The source is ‘hidden’: **no gamma rays, no cosmic rays**
only <u>neutrinos</u> escape the galactic nuclei

The Berezinsky ‘hidden’ source

Berezinsky, Ginzburg, MNRAS 1981
Silberberg, Shapiro 1982

§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).

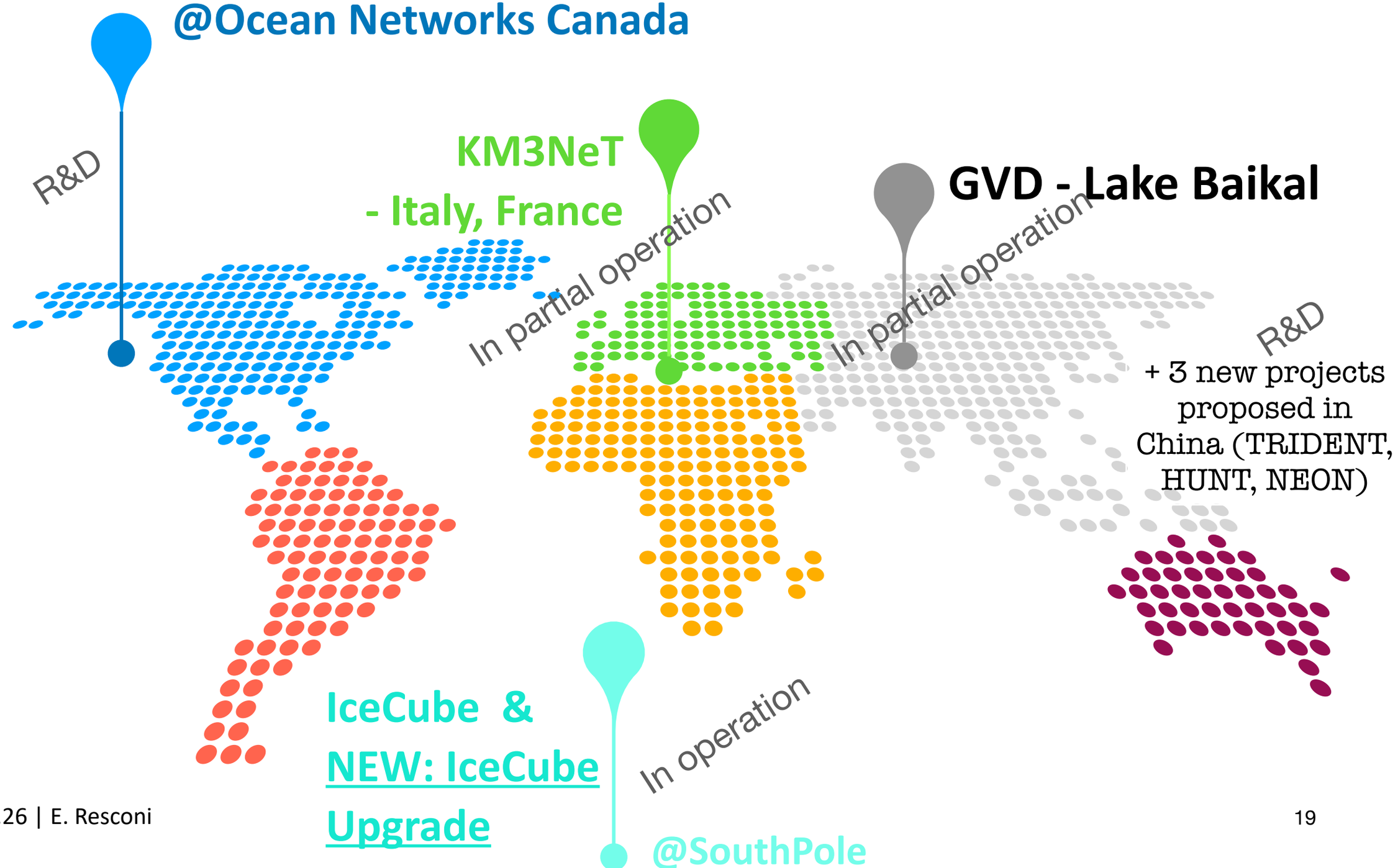


The observatories

Credits: Ben Nührenbörger/P-ONE

The observatories: HE neutrinos

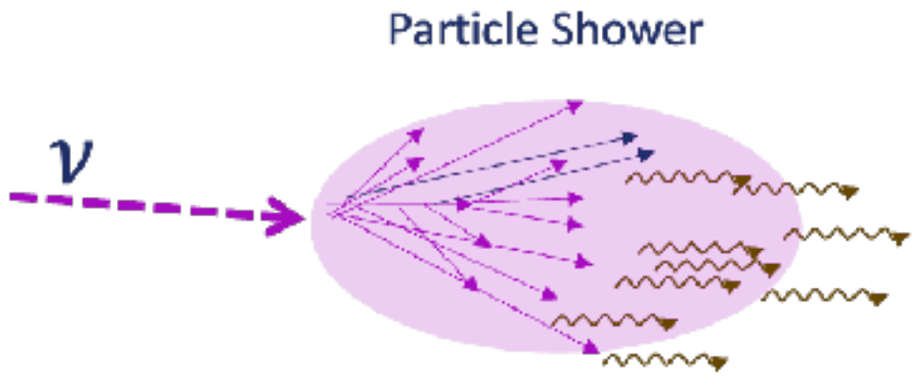
L. Schumacher, .., E.R. ***PRD '25***, PLEnuM
https://github.com/PLEnuM-group/Plenum

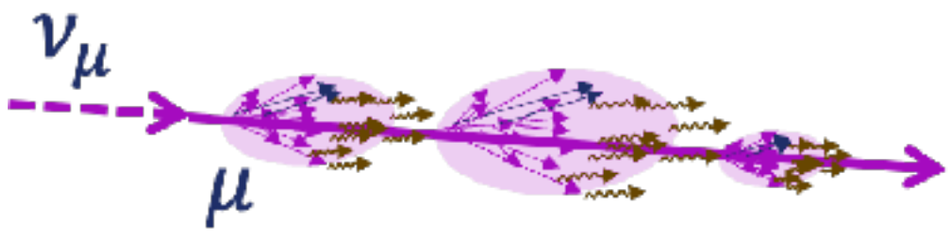


IceCube Neutrino Observatory

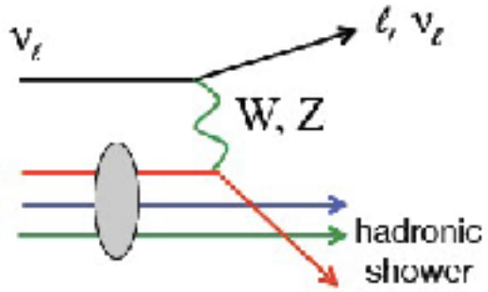
https://icecube.wisc.edu/

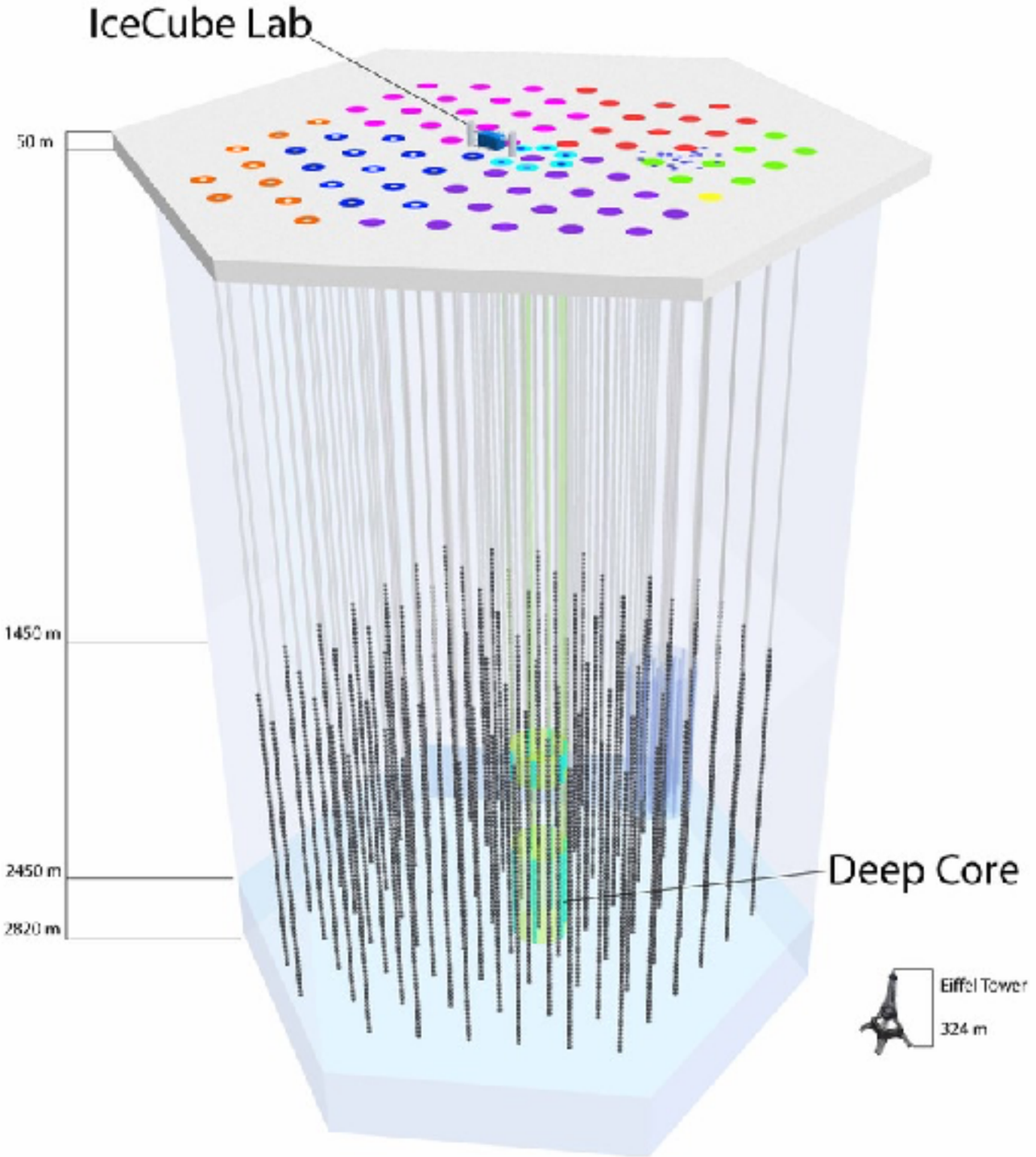
Two topological channels





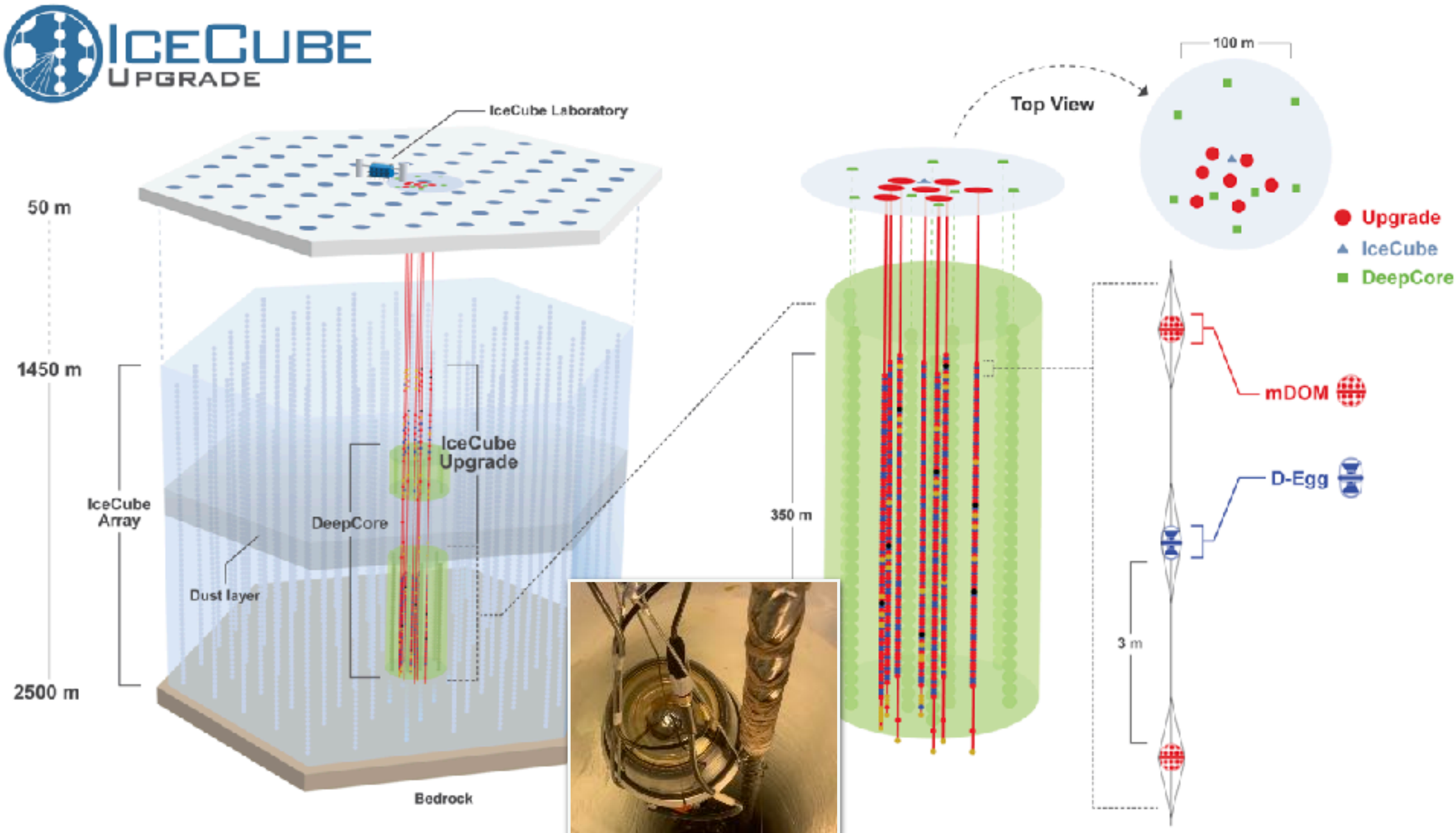
Tracks





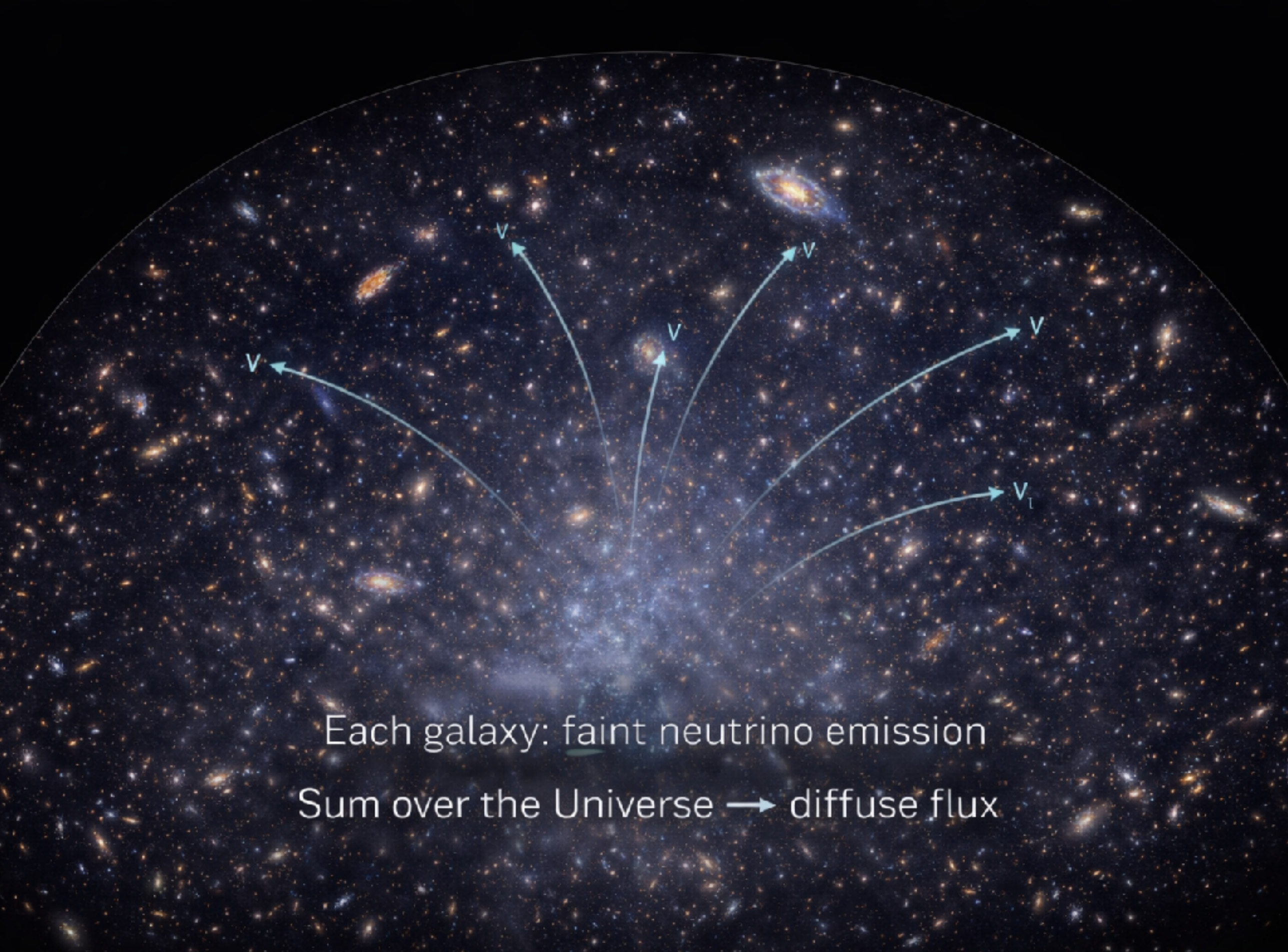
NEW: IceCube Upgrade Delivered!

IceCube Coll., astro-ph/2509.13066



Colton Hill (TUM)

The observations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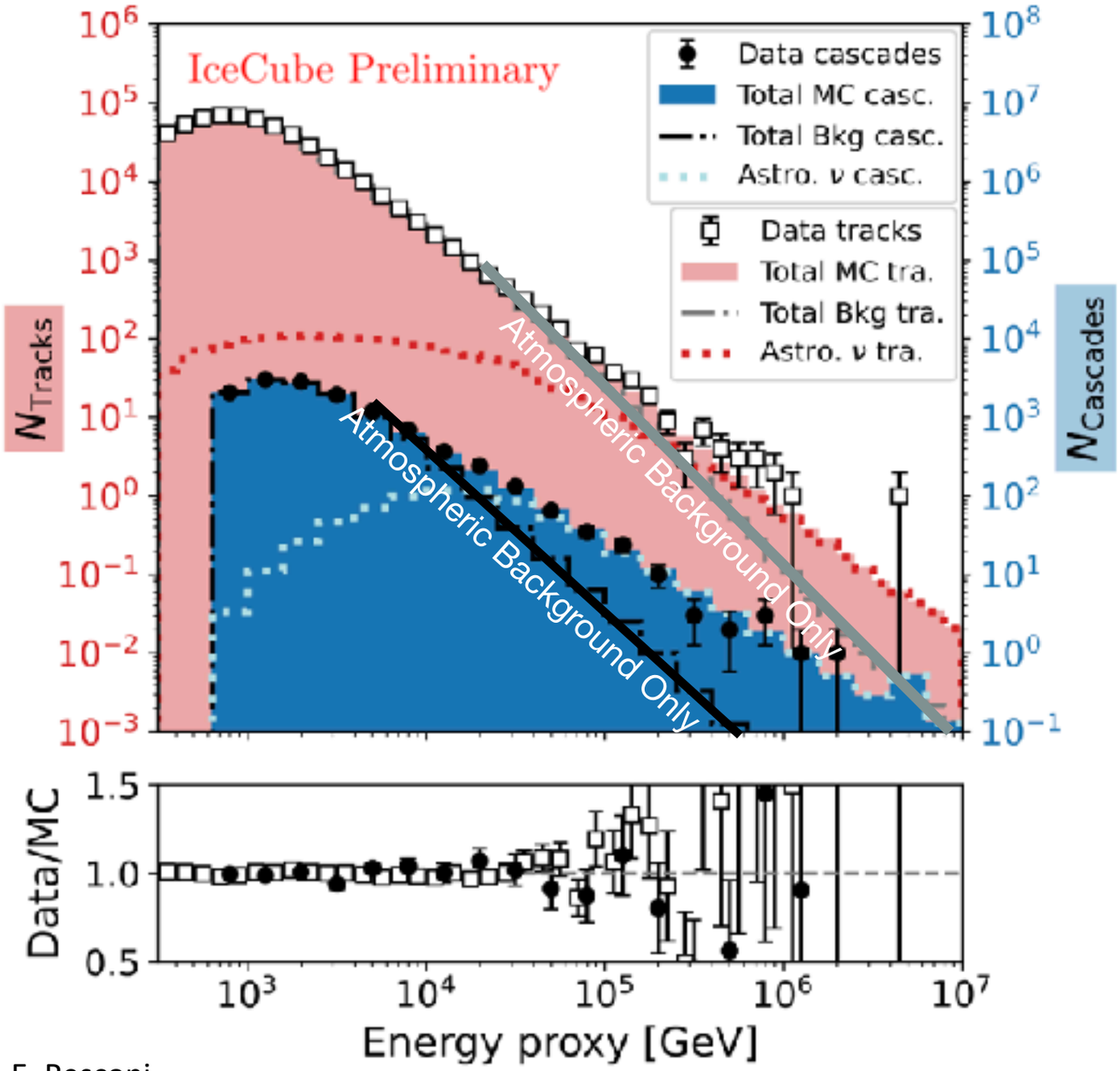
Each galaxy: faint neutrino emission
Sum over the Universe → diffuse flux

Energy spectrum of atmospheric and cosmic neutrinos

IceCube Coll., PRL '20; Nature '21; ApJ '22;
IceCube Coll., ***astro-ph/2507.22233***



Event rate in IceCube:
For every 1 cosmic neutrino,
~10^9 atmospheric muons
~10^3 atmospheric neutrinos

Cosmic neutrino flux: established with global significance > **5.0σ**

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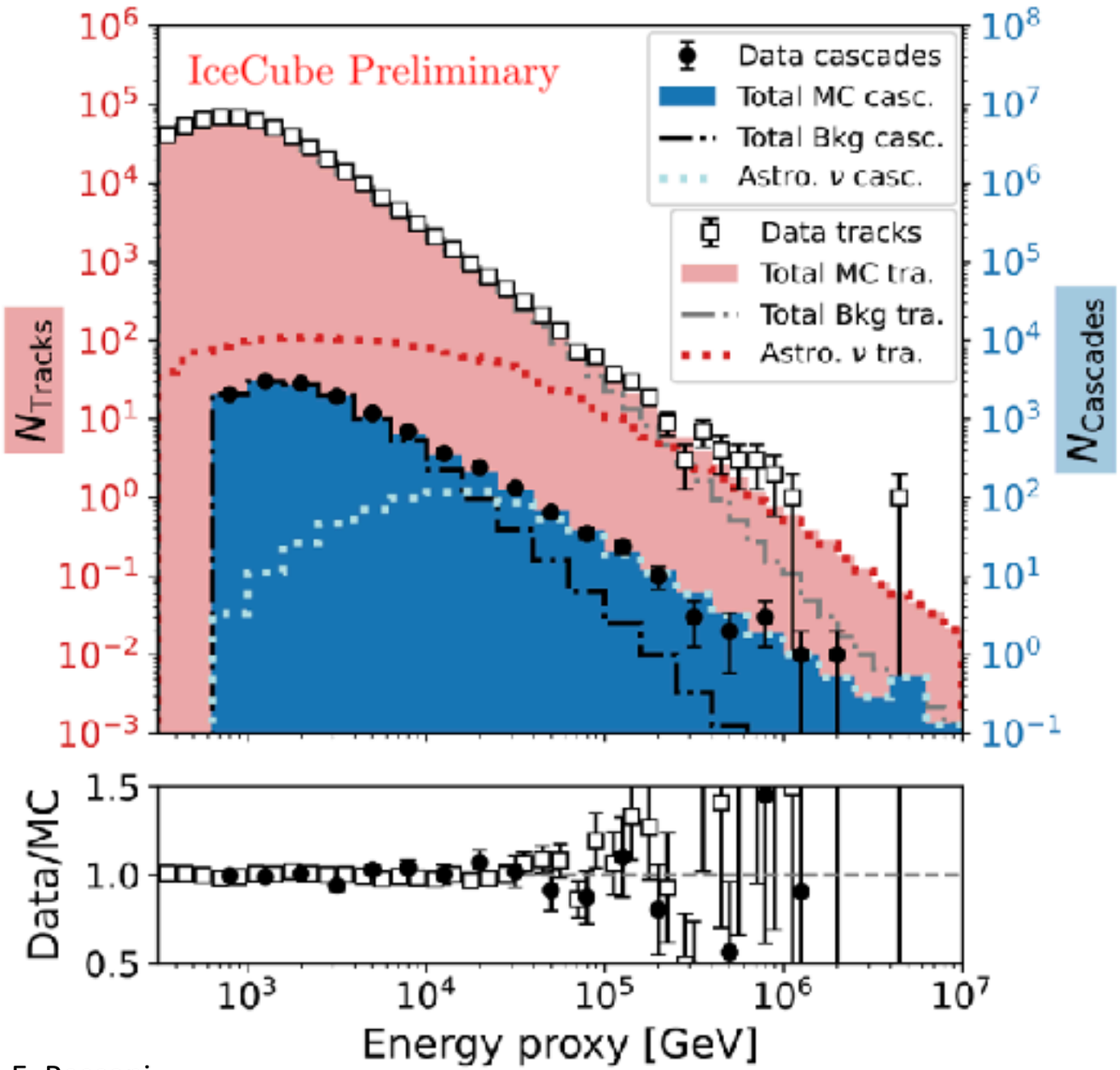

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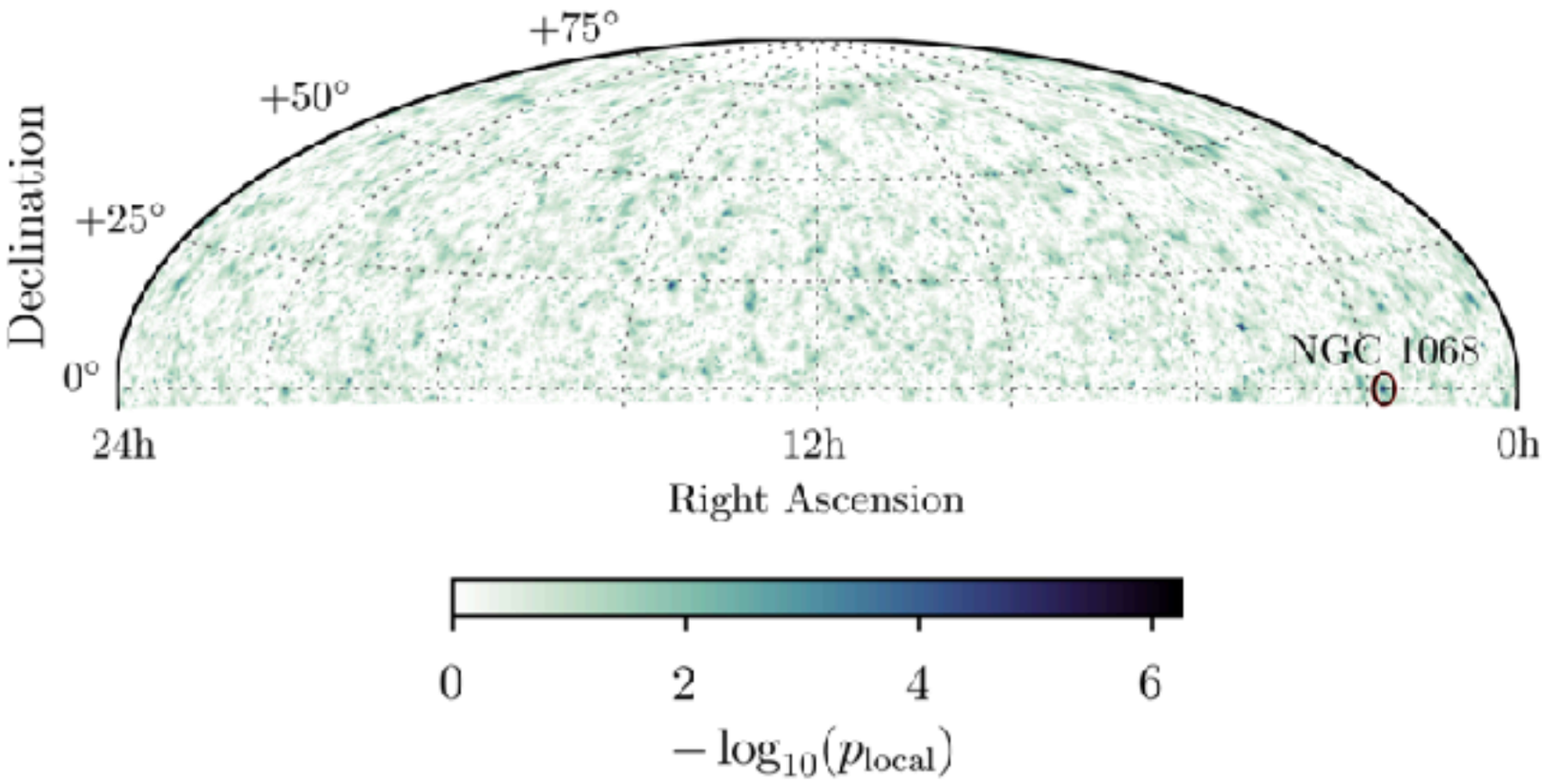
Cosmic neutrino flux: established with global significance > **5.0σ**

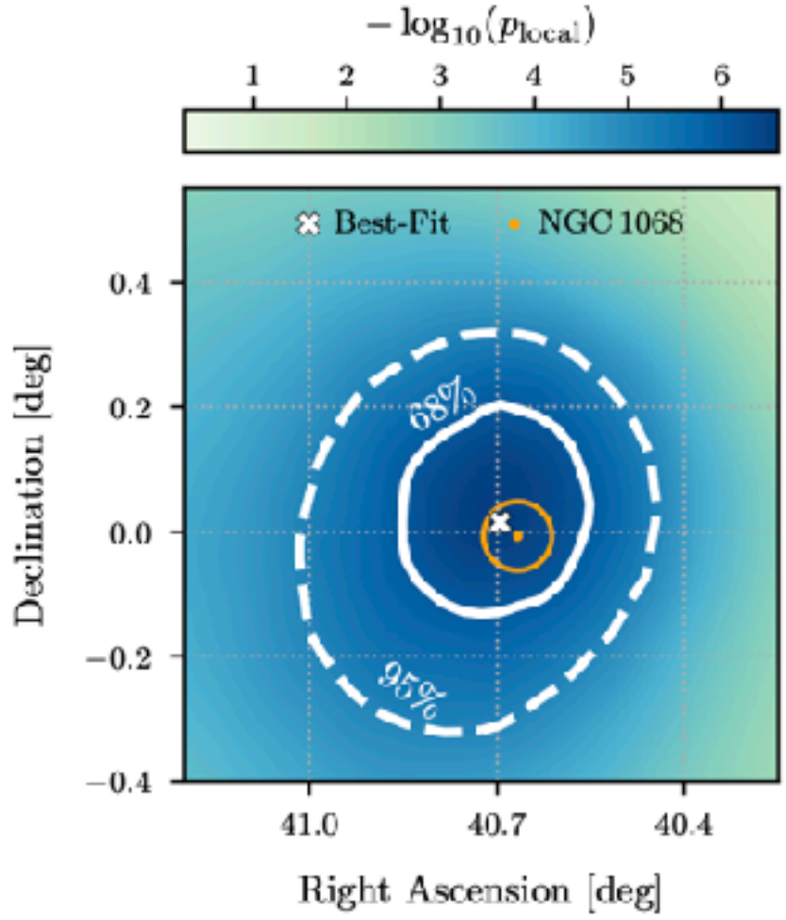
Where are the sources?

First evidence from NGC 1068: X-ray-bright Active Galactic Nuclei

IceCube Coll., ***Science* '22; *ApJL* '26**

Hottest spot in the Northern sky aligned with NGC1068;
global significance of **4.0σ (catalogue search)**





13.1 years
of IceCube data

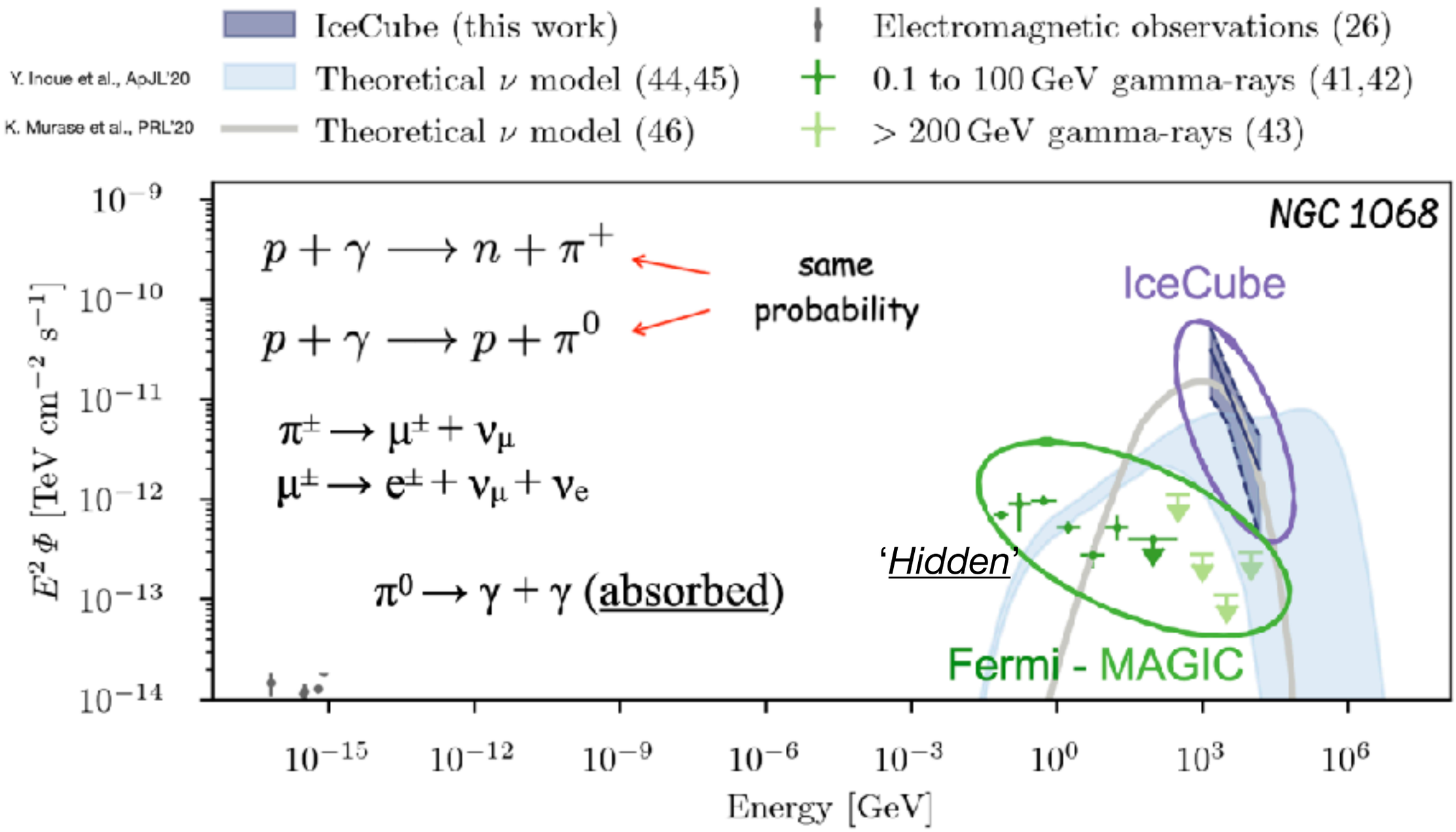
NGC 1068

IceCube Coll., ***Science*** '22; ***ApJL*** '26

P. Padovani, E.R., et al., ***Nature Astr. '24***

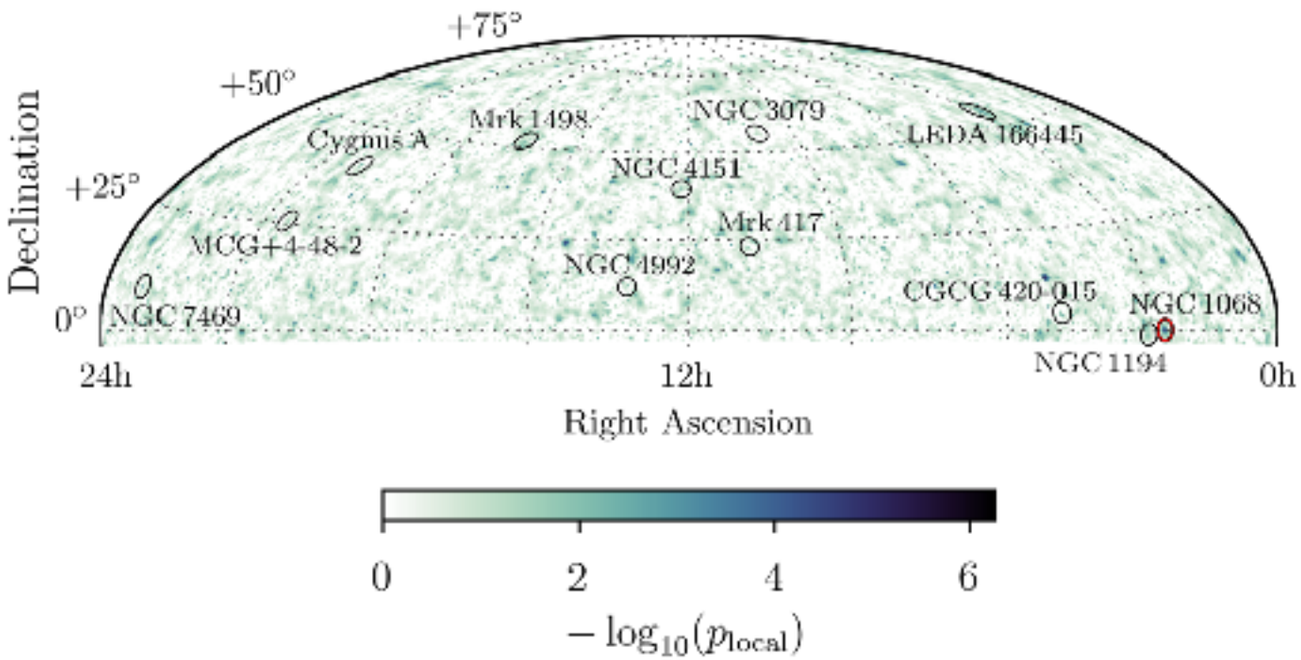
First evidence for ‘hidden’ galaxies

IceCube Coll., ***Science* ’22; *ApJL* ‘26**



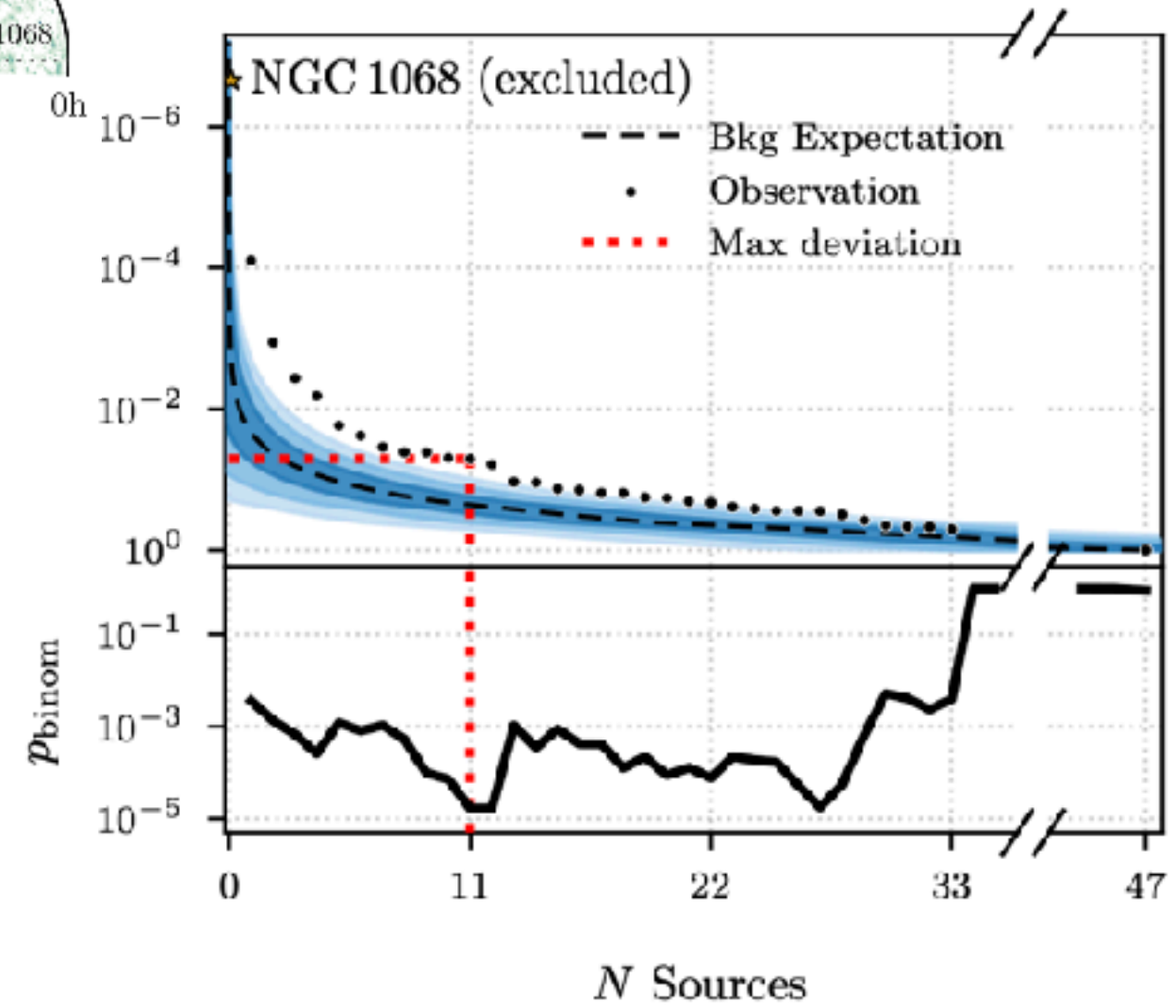
More X-ray-bright Active Galactic Nuclei are appearing at the neutrino horizon

IceCube Coll., ***ApJL '26, astro-ph/2602.10208***



Global significance **3.3σ**
(NGC1068 excluded)

+ **3.0σ evidence** stacking of X-ray bright in the South

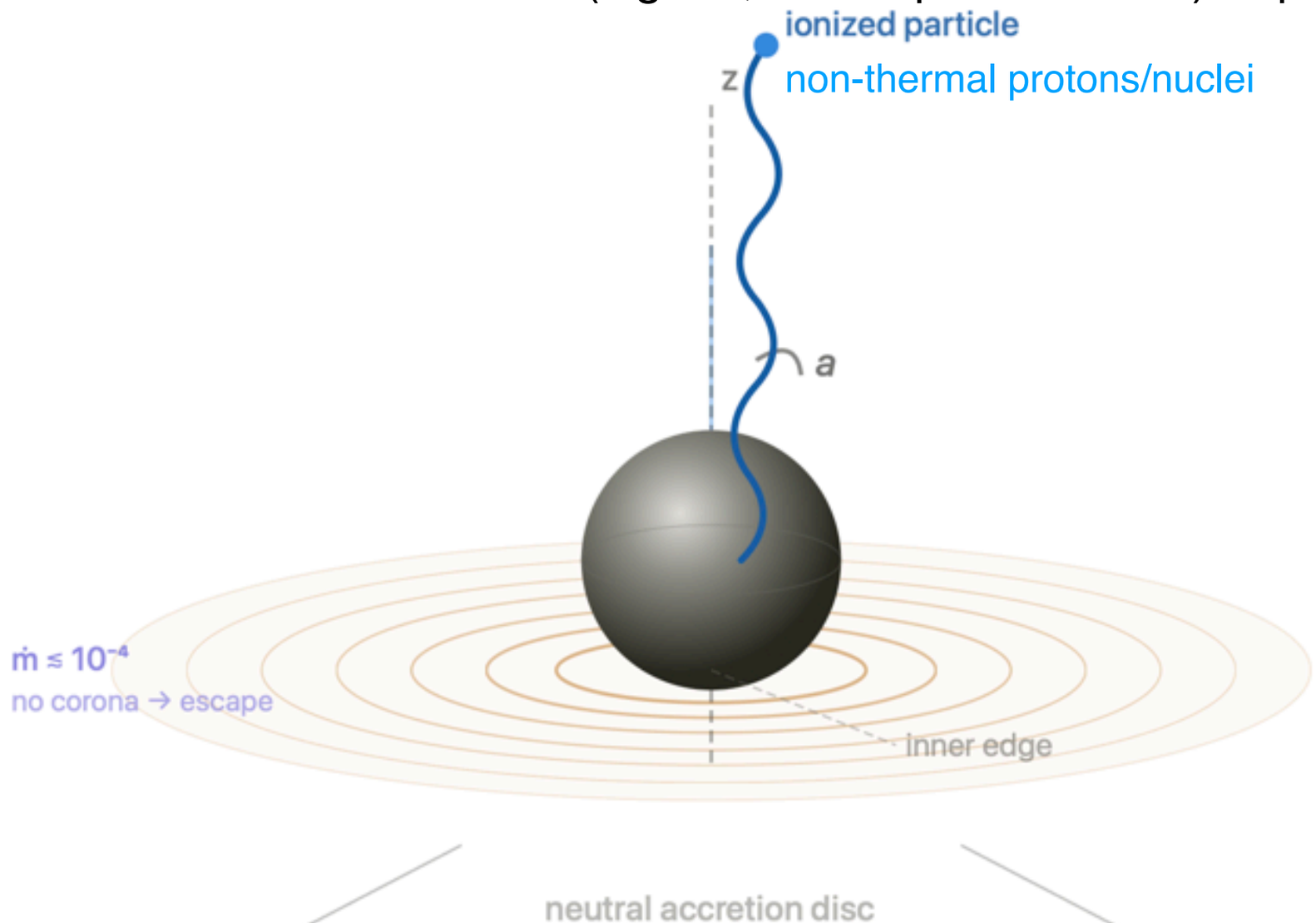


If neutrinos trace ‘hidden’ sources, where are (U)HECRs coming from?

The ‘hidden’ source idea: let’s remove the target

E.R., Manao, Padovani, Rieger, Dvali, in preparation

What makes disk acceleration efficient (high $\dot{m}$, dense photon fields) trap the particles.



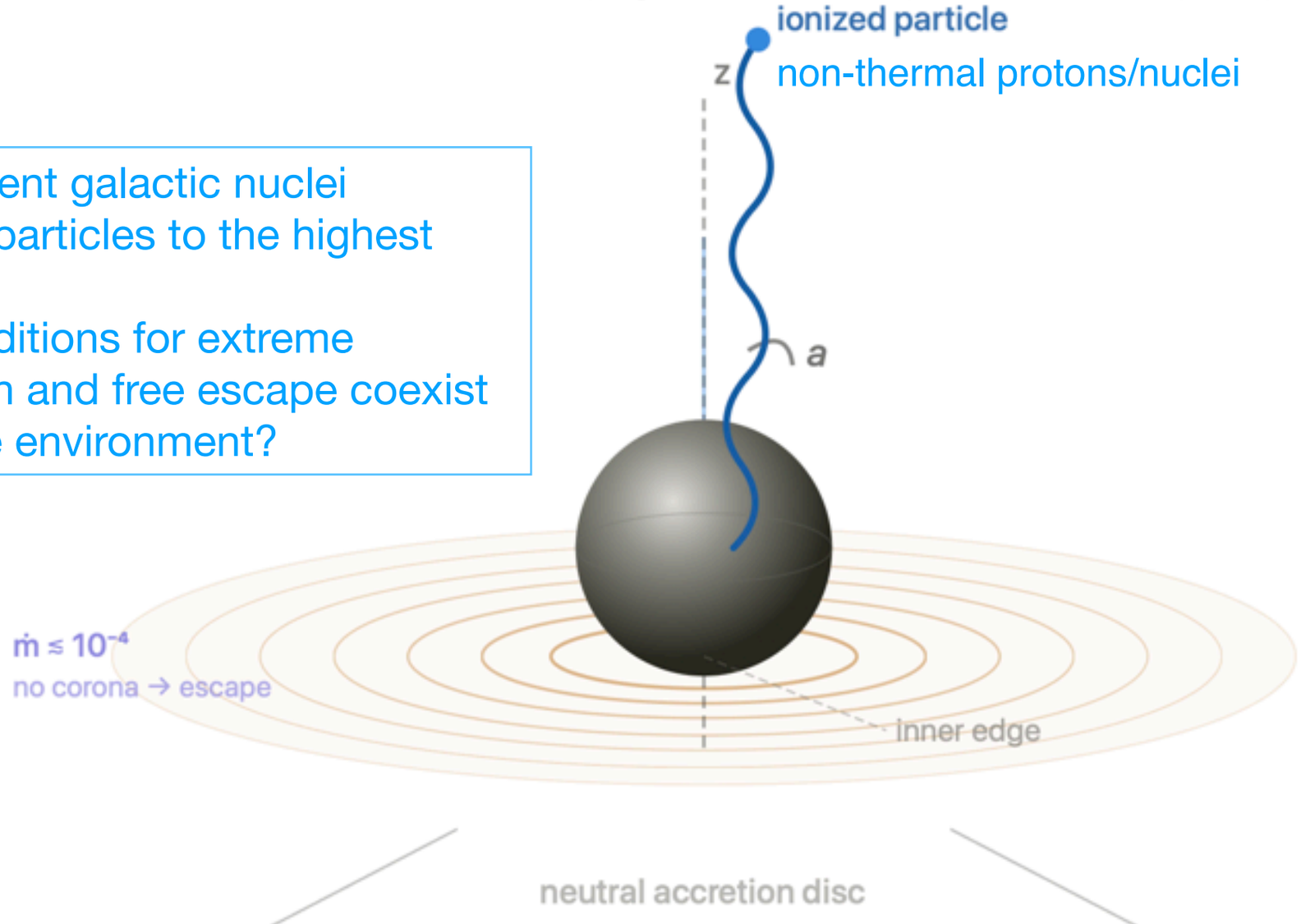
To reach UHECR energies and escape, we need to look elsewhere, at the horizon itself.

The ‘hidden’ source idea: let’s remove the target

E.R., Manao, Padovani, Rieger, Dvali, in preparation

What makes disk acceleration efficient (high ṁ, dense photon fields) trap the particles.

- Can quiescent galactic nuclei accelerate particles to the highest energies?
- Do the conditions for extreme acceleration and free escape coexist in the same environment?



To reach UHECR energies and escape, we need to look elsewhere, at the horizon itself.

The quest for (U)HECR sources: where we stand

What we know

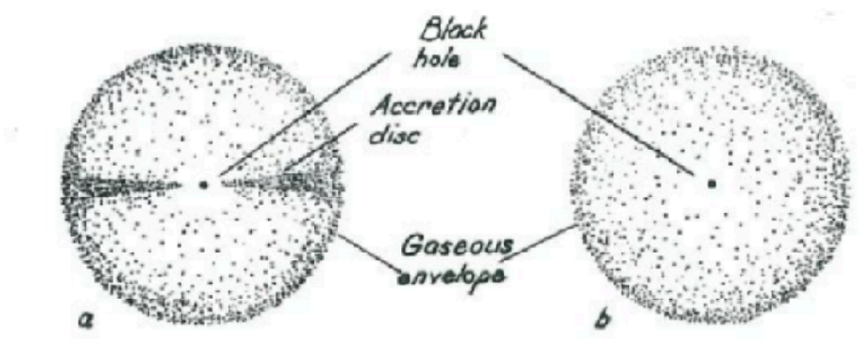
The ankle marks the extragalactic transition

A diffuse cosmic neutrino flux discovered

First sources emerging: NGC 1068 + population

The AGN corona is the natural production site

“Hidden source” emerging as neutrino factory



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What we do not know

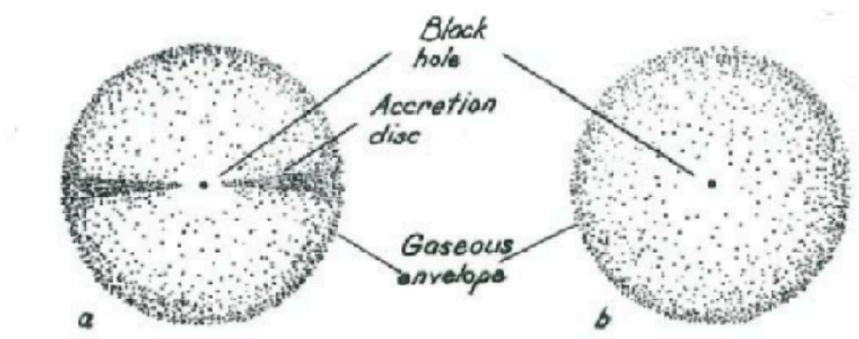
Acceleration / composition CR ?

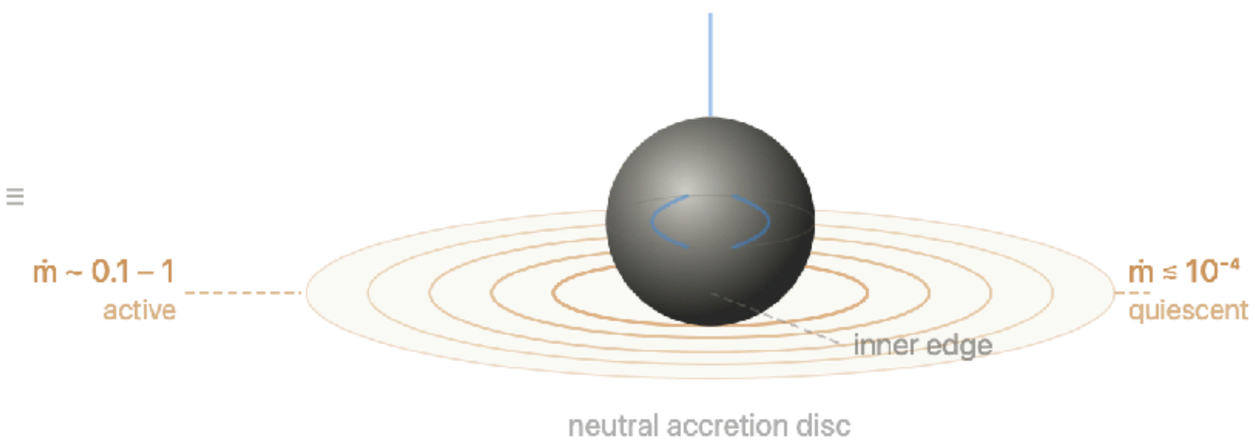
Corona heating / composition ?

Is there a unified galactic nuclei picture?

Active Galactic Nuclei: neutrino source ?

Quiescent Galactic Nuclei: CR source ?

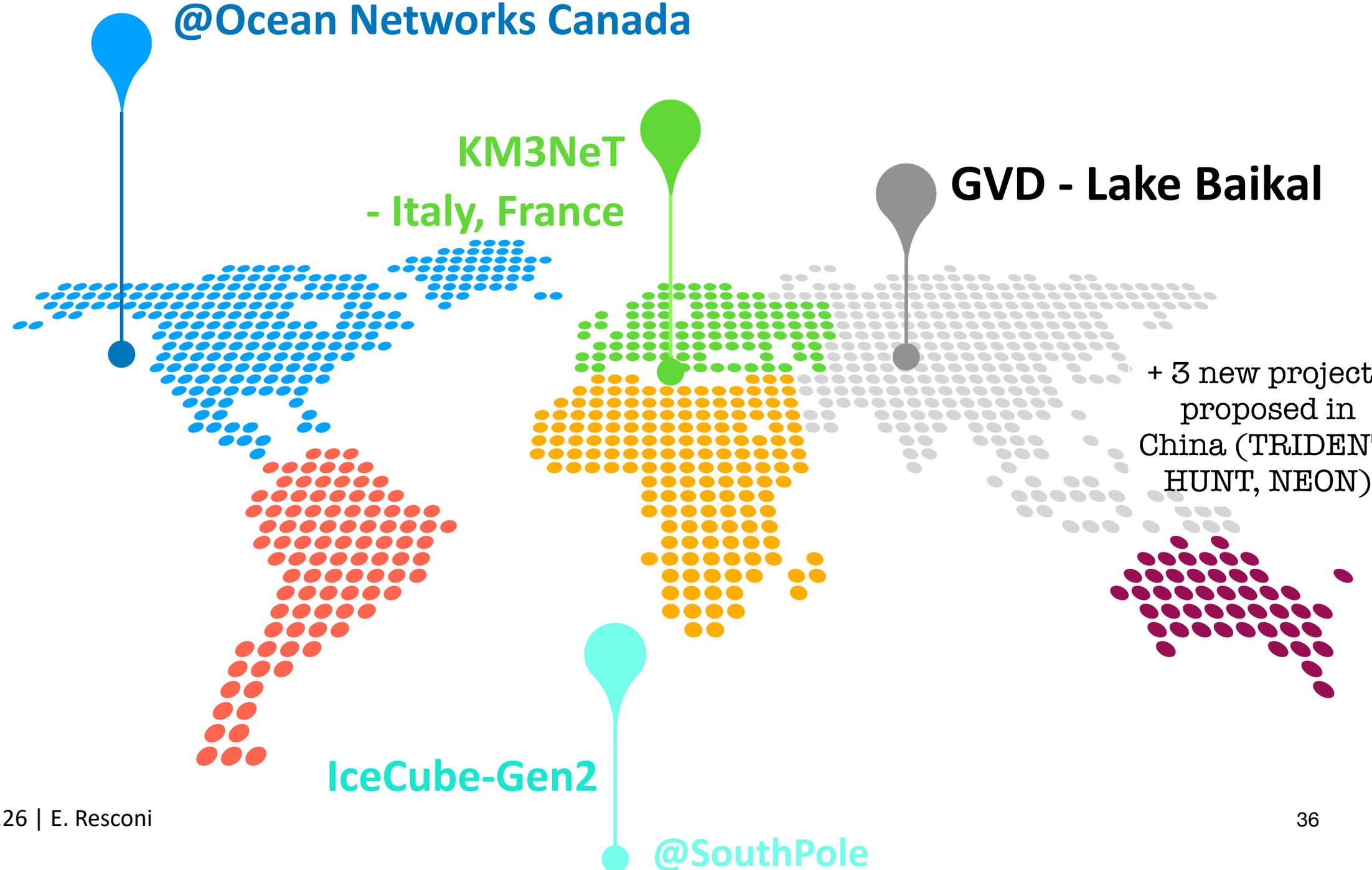




The future:
paving the way …

More observatories for HE neutrinos

L. Schumacher, .., E.R. ***PRD '25***, PLEnuM
https://github.com/PLEnuM-group/Plenum



The Pacific Ocean Neutrino Experiment @ Ocean Networks Canada

OCEANS 3.0
DATA MANAGEMENT PORTAL

Pacific Ocean

Atlantic Ocean

Antarctic Ocean

University of Victoria

University of Waterloo

Mobile Asset
AIS Receiver
RADAR
RADAR
RADAR

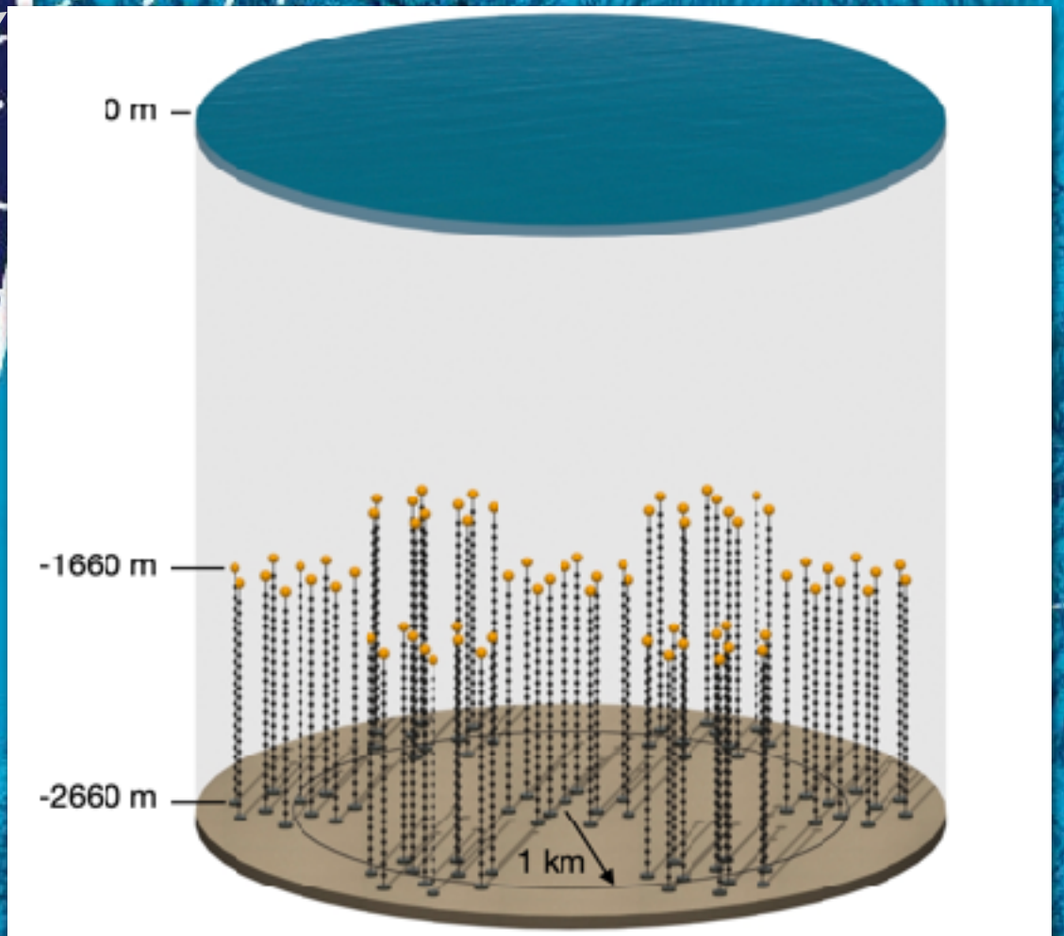
AN INITIATIVE OF University of Victoria

OCEAN NETWORKS CANADA

https://www.oceannetworks.ca/

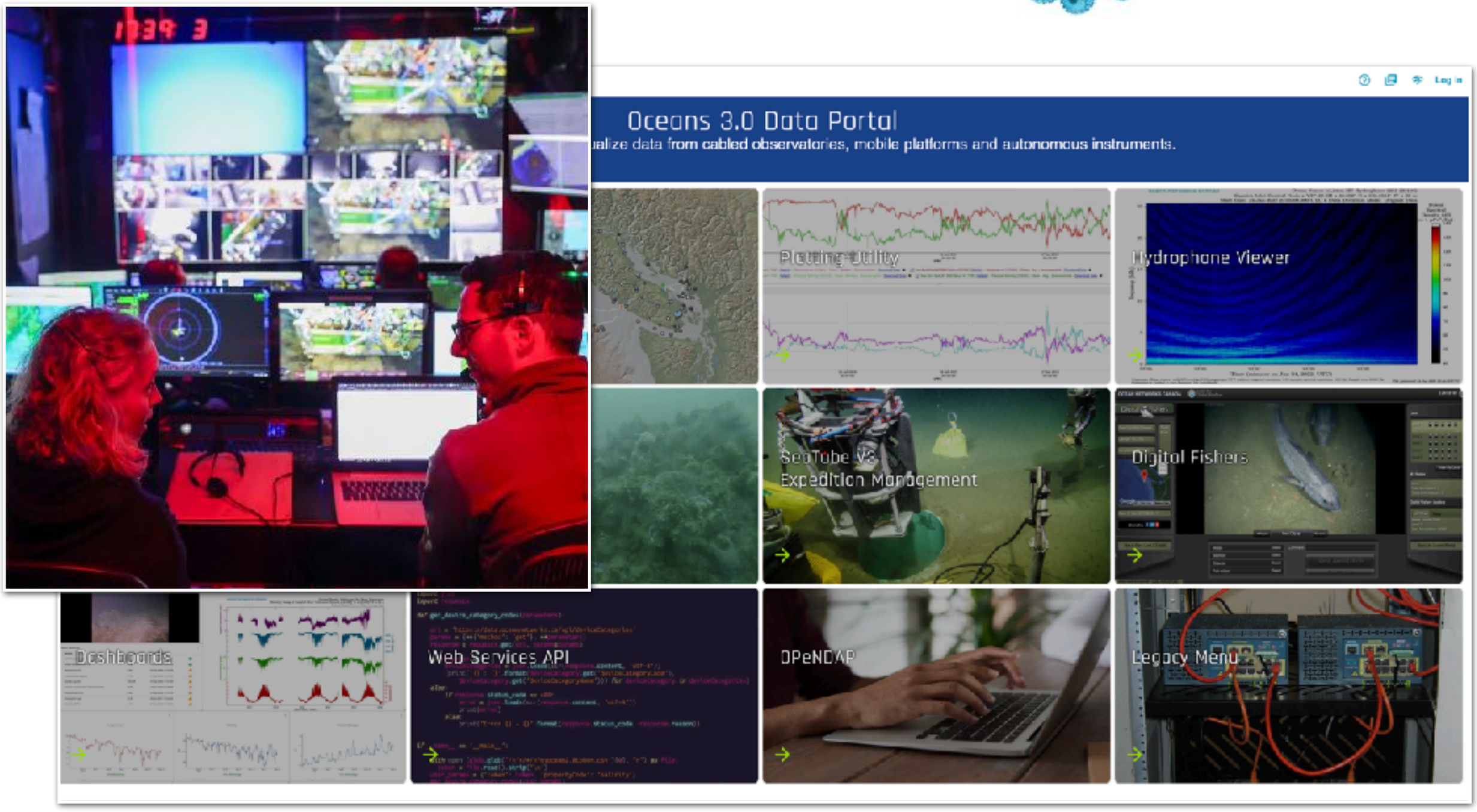
Kitamaat Village
Hartley Bay
NEPTUNE Observatory
P-ONE Neutrino Array
Port Renfrew
Campbell River
China Creek
Sooke
VENUS Observatory
Burrard Inlet
Iona
East Point
BC Ferries
ONC Rodor
Pacific Ocean
800 km loop
-2.6 km

The world's largest undersea, real-time observatory network -
800 km loop of fibre-optic cables,
8 kW x 6 nodes,
2 Gbit



P-ONE Collaboration, Nature Astron. 2020

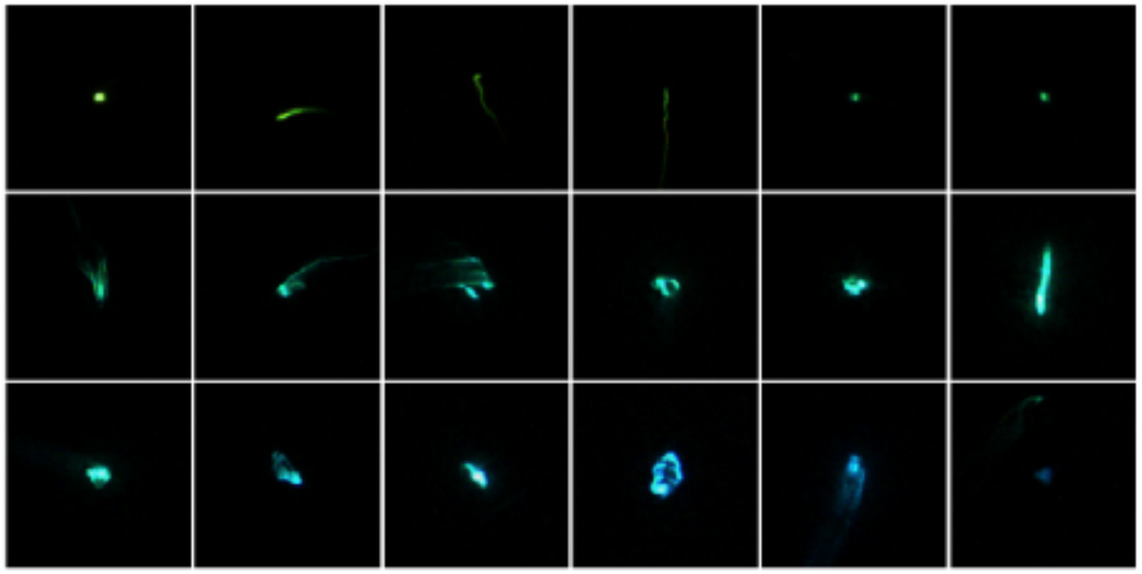
Ocean Networks Canada (ONC)

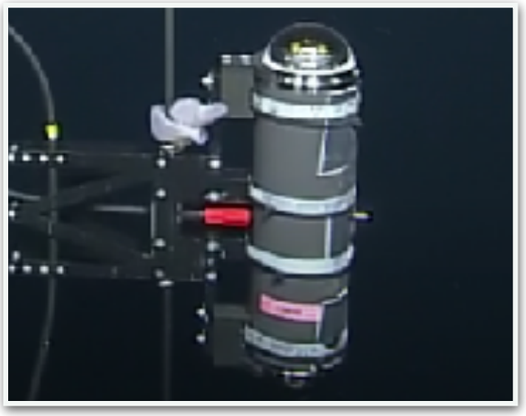


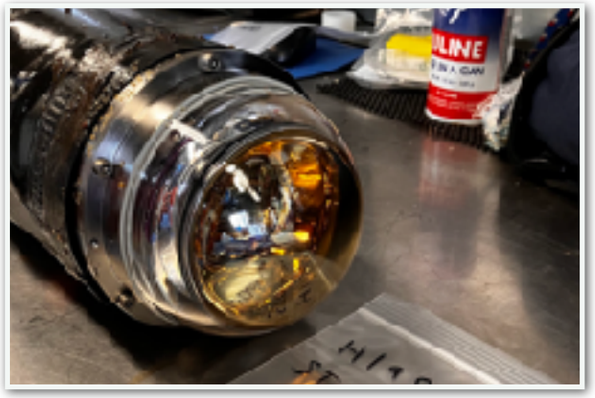
https://data.oceannetworks.ca/home

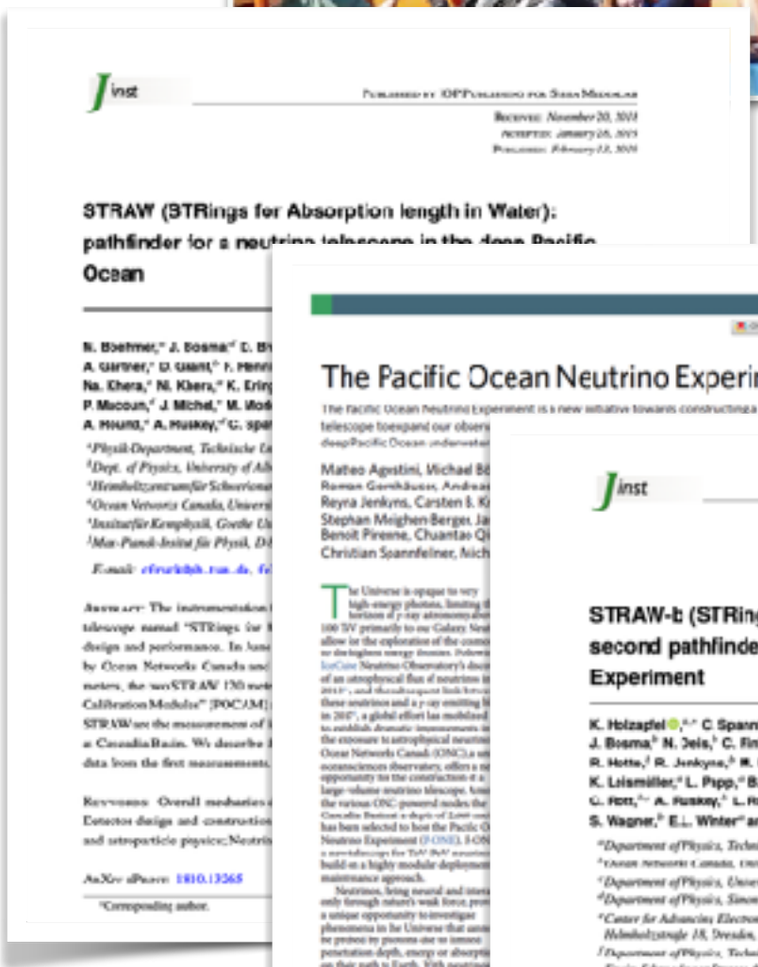
The Pacific Ocean Neutrino Experiment (P-ONE): pathfinders

1st pathfinder 2nd pathfinder Papers in preparatic





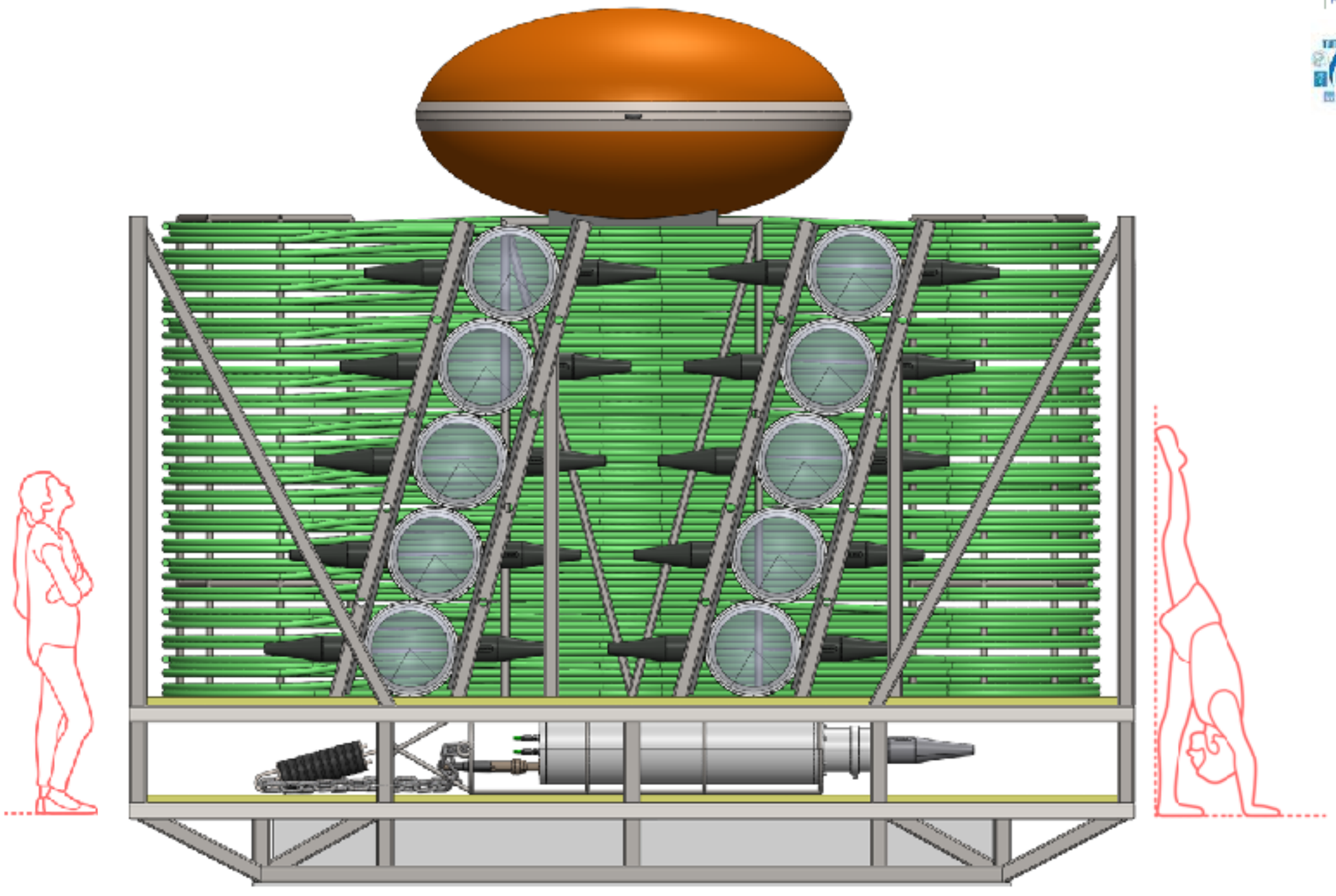




The Pacific Ocean Neutrino Experiment (P-ONE)

The Element: A 1 km Tall Instrumented Line Compactly Designed to Fit in a Transport Container

P-ONE Coll., ***Nature Astron.*** '20
C. Spannfellner et al., PoS ICRC23



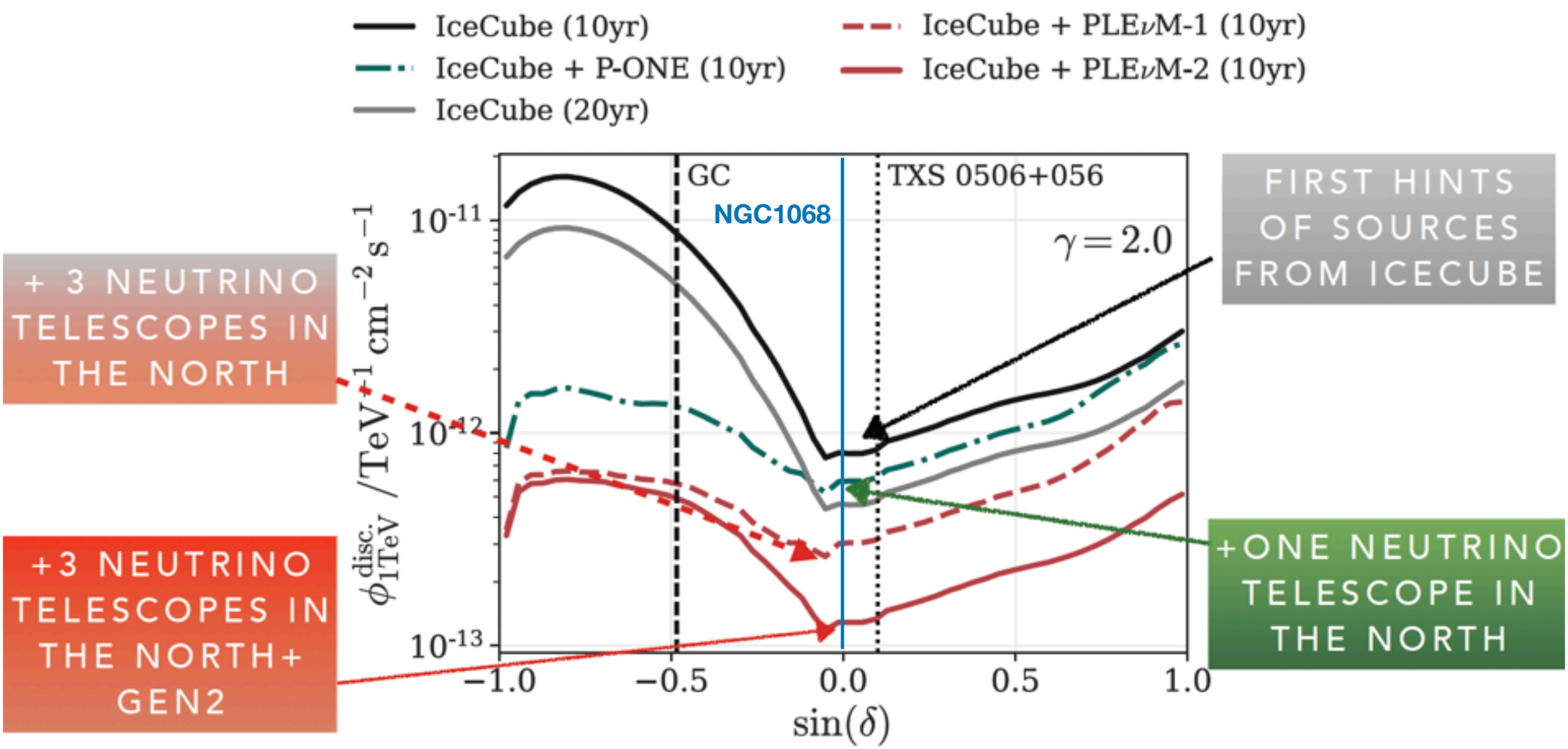
INNOVATION.CA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION
NSERC CRSNG
Arthur B. McDonald Canadian Astroparticle Physics Research Institute
DFG Deutsche Forschungsgemeinschaft German Research Foundation
NSF
UKRI Science and Technology Facilities Council
INSTYTUT FIZYKI JĄDROWEJ IM. HENRYKA NIEWODNICZAŃSKIEGO POLSKIEJ AKADEMII NAUK
INSTITUTE OF PARTICLE PHYSICS

The Pacific Ocean Neutrino Experiment (P-ONE)

P-ONE Coll. & June 2025, February 2026

The observatories: HE neutrinos

L. Schumacher, .., E.R. ***PRD '25***, PLEnuM
https://github.com/PLEnuM-group/Plenum



Summary & Outlook

A new observational window is open: High-energy neutrinos provide direct access to the most extreme particle accelerators in the Universe, invisible to photon.

First sources identified: IceCube has established a diffuse cosmic neutrino flux and delivered first evidence for individual hidden sources (AGN coronae)
- Blazars remain also interesting counterparts.

We need more neutrinos: To consolidate and breakthrough this (and other) scenarios.

The hidden source paradigm is central: The corona opacity that makes AGN invisible to gamma rays is precisely what makes them neutrino bright.

Broader physics reach: These extreme environments connect to fundamental open questions, the origin of UHECRs, the role of black hole spin, gravity-limited field strengths, and possibly dark matter.

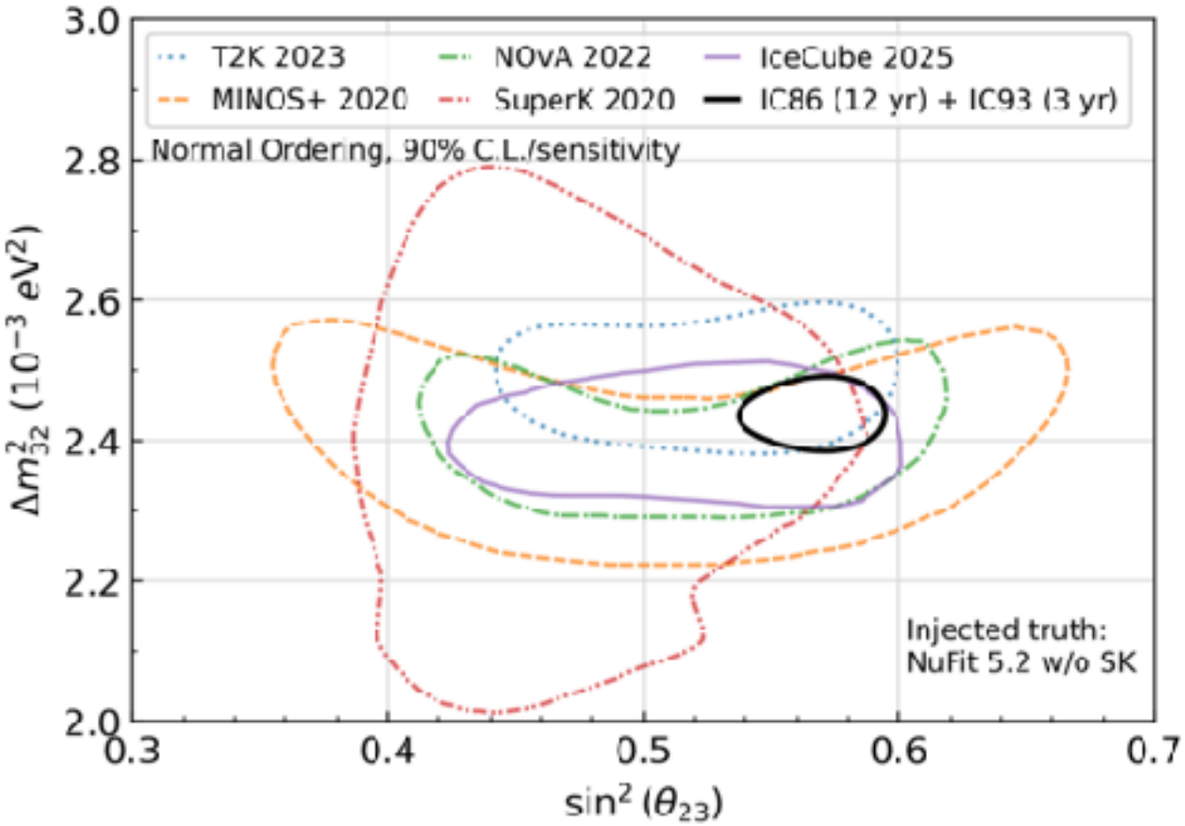
The next decade is decisive: Larger neutrinos datasets from IceCube, KM3NeT, and the future P-ONE, IceCube-Gen2 with CR primary data will sharpen sensitivity to galactic nuclei populations as unified cosmic particle laboratories.

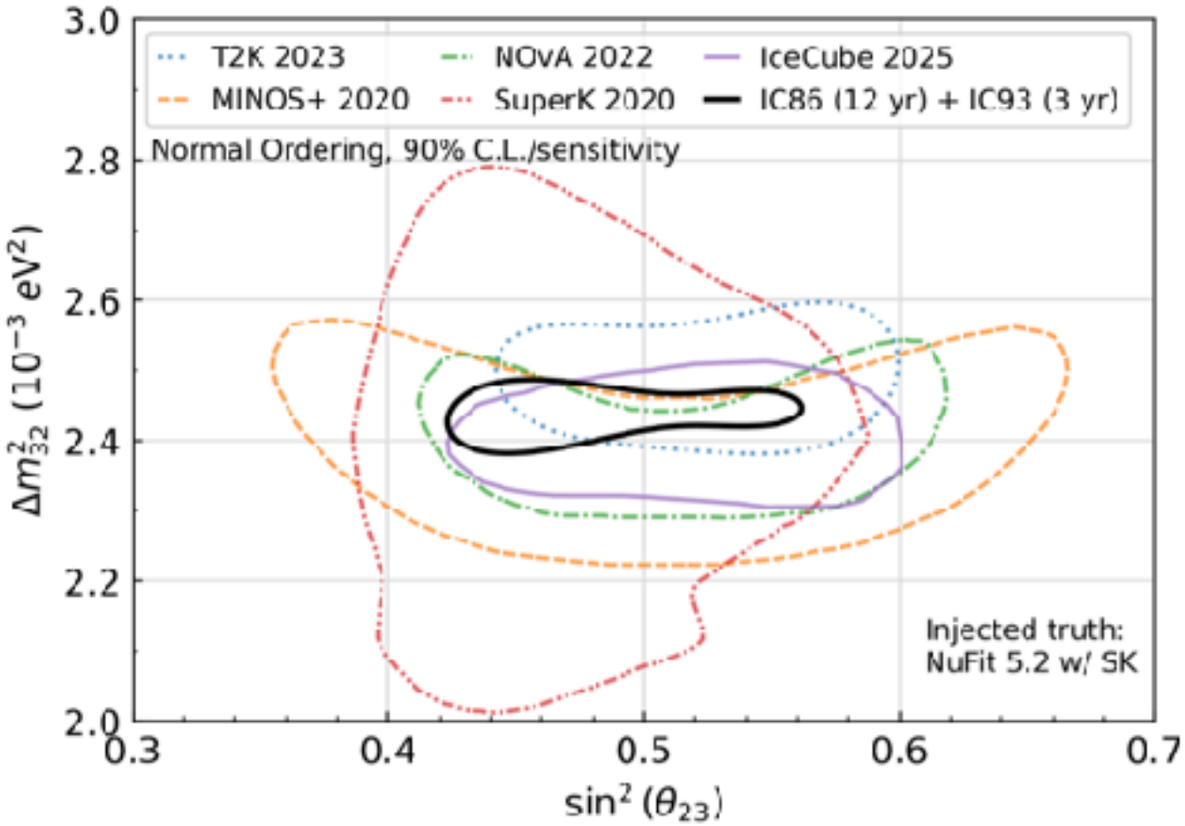
Thanks to IceCube Collaboration, P-ONE Collaboration,
M. Agostini, C. Bellenghi, M. Bustamante, G. Dvali, R. Gilli, P. Giommi, F. Henningsen, E. Manao, F. Oikonomou, P. Padovani, M. Petropolou, F. Rieger, L. J. Schumacher

South Pole Season ’25/’26 (C. Hill/NSF)

Backup

IceCube Upgrade sensitivity contours



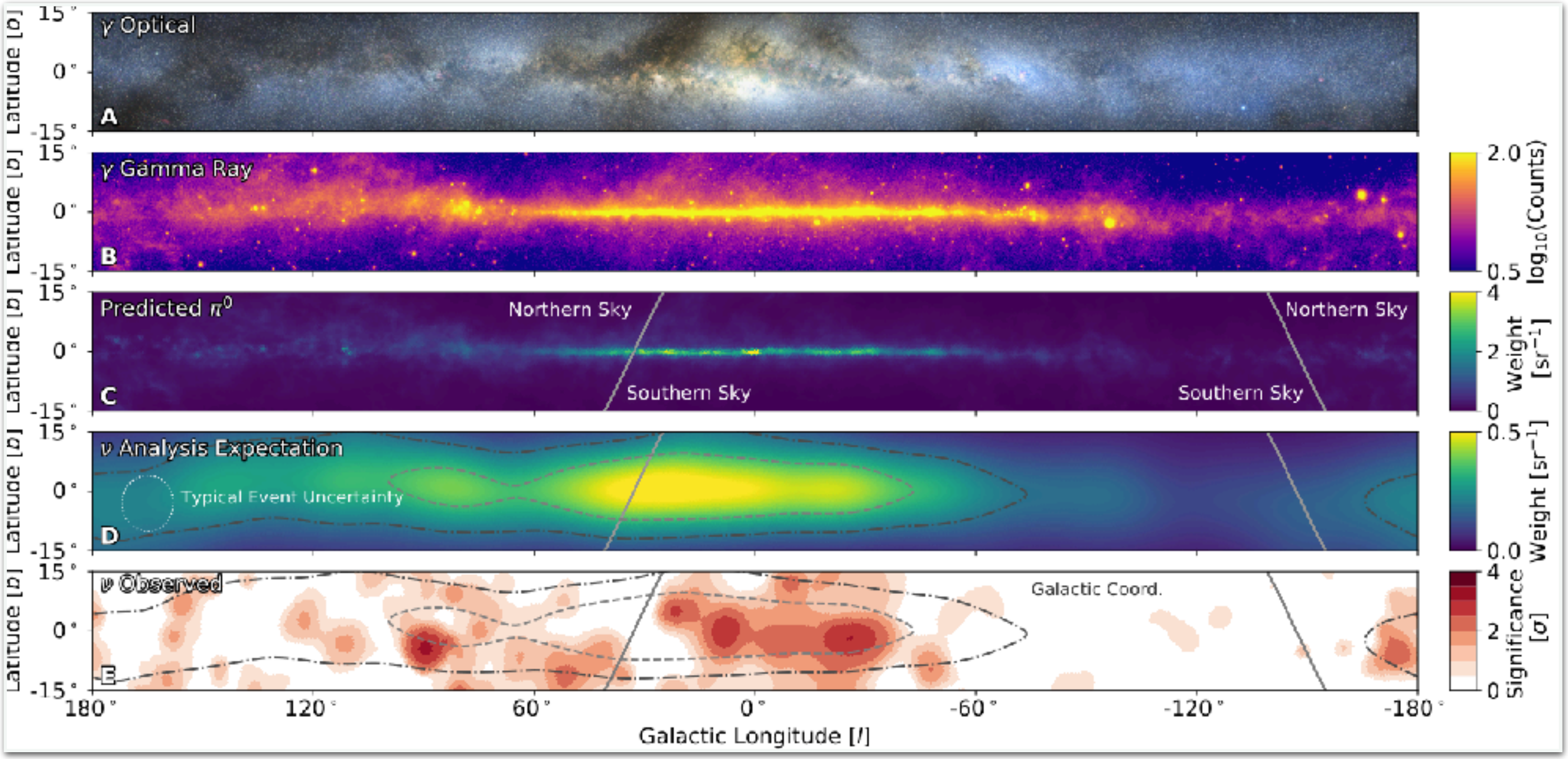


IceCube Coll., astro-ph/2509.13066

IceCube's scientific achievements → motivation

The Galactic plane in neutrinos: diffuse emission emerging

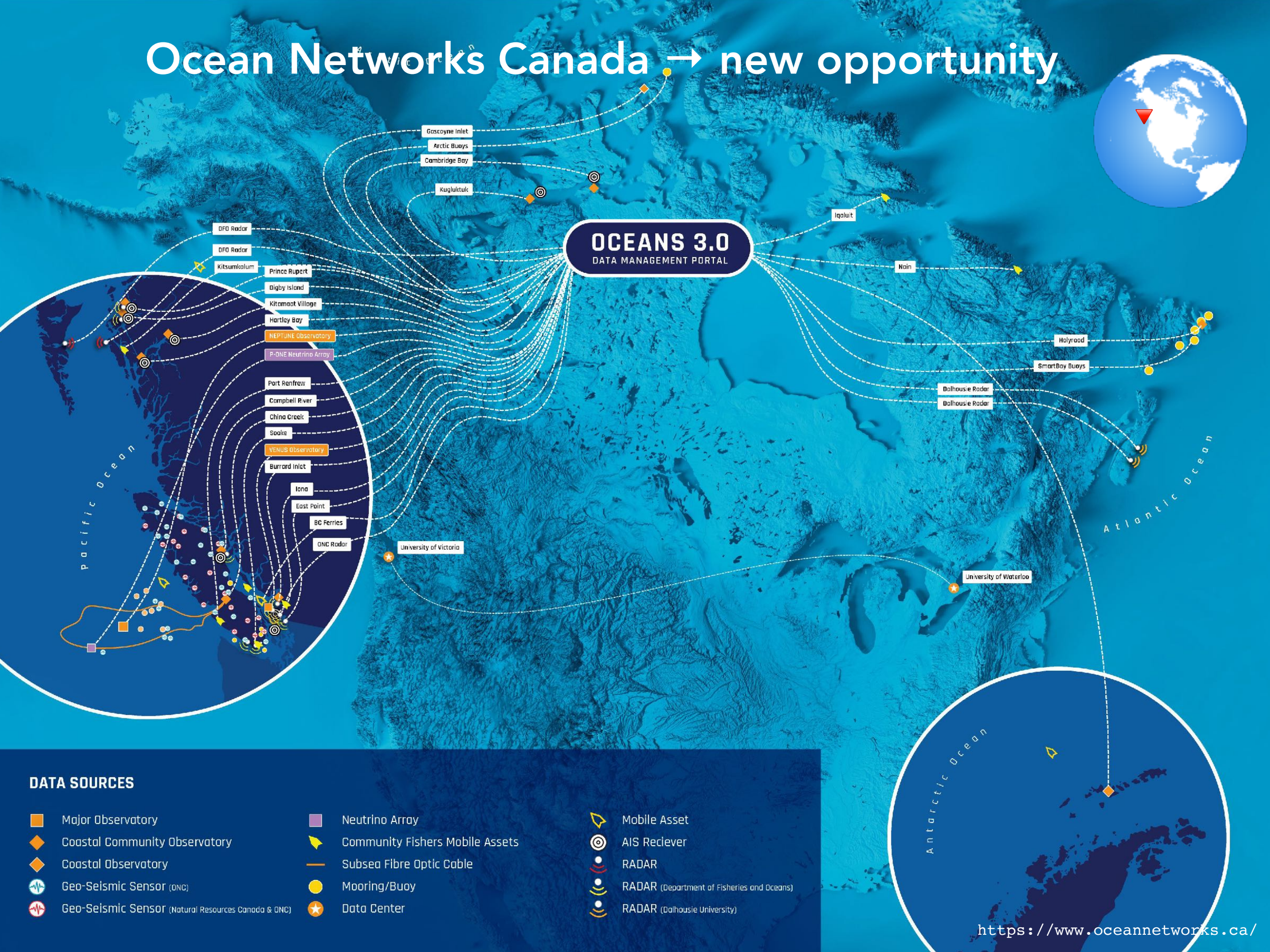
The IceCube Coll., ***Science*** 380 (2023)



Global significance **4.5σ**

Pacific Ocean Neutrino Experiment (P-ONE), Backup

Ocean Networks Canada → new opportunity



https://www.oceannetworks.ca/

Kitamaat Village

Hartley Bay

NEPTUNE Observatory

P-ONE Neutrino Array

Port Renfrew

Campbell River

China Creek

Sooke

VENUS Observatory

Burrard Inlet

Iona

East Point

BC Ferries

ONC Rodor

Pacific Ocean

800 km loop

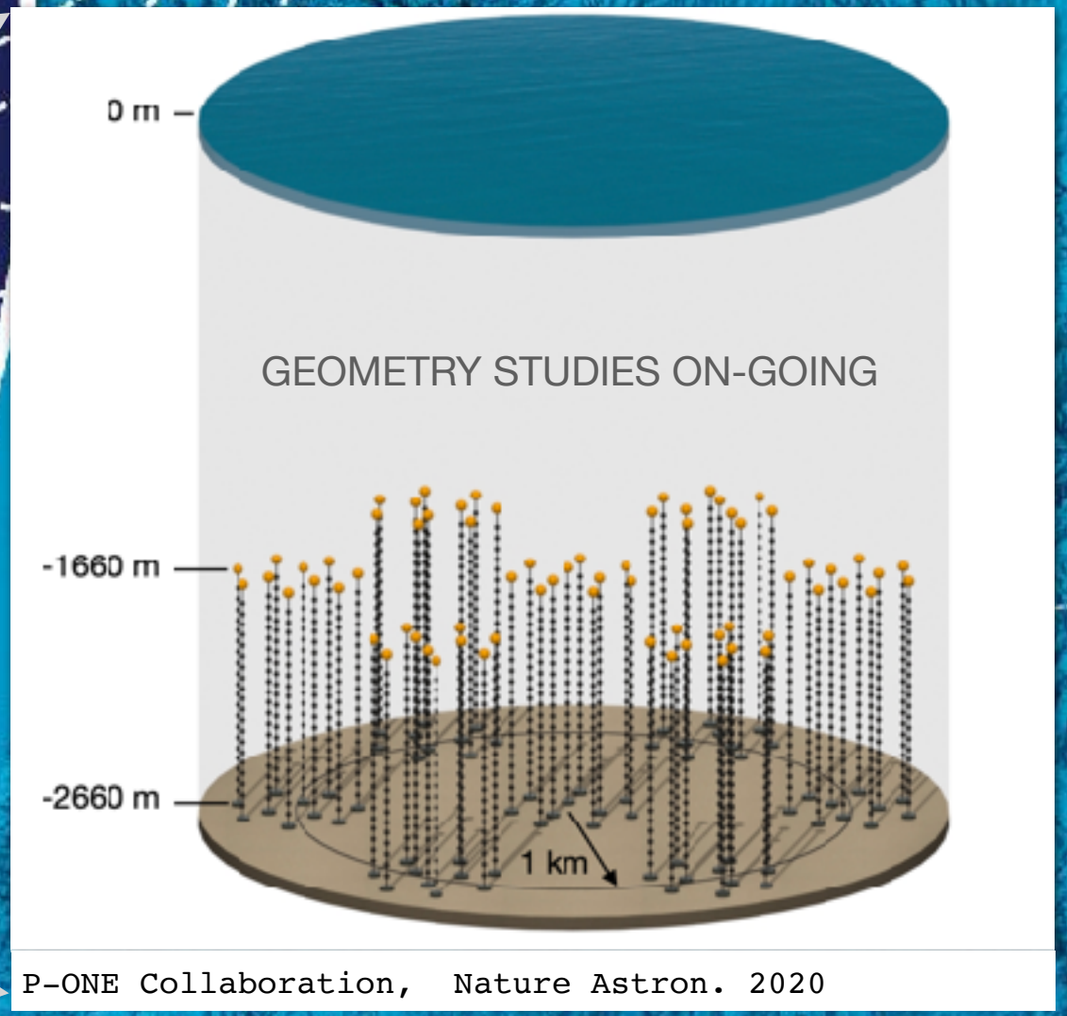
-2.6 km

The world's largest undersea, real-time observatory network -

800 km loop of fibre-optic cables,

8 kW x 6 nodes,

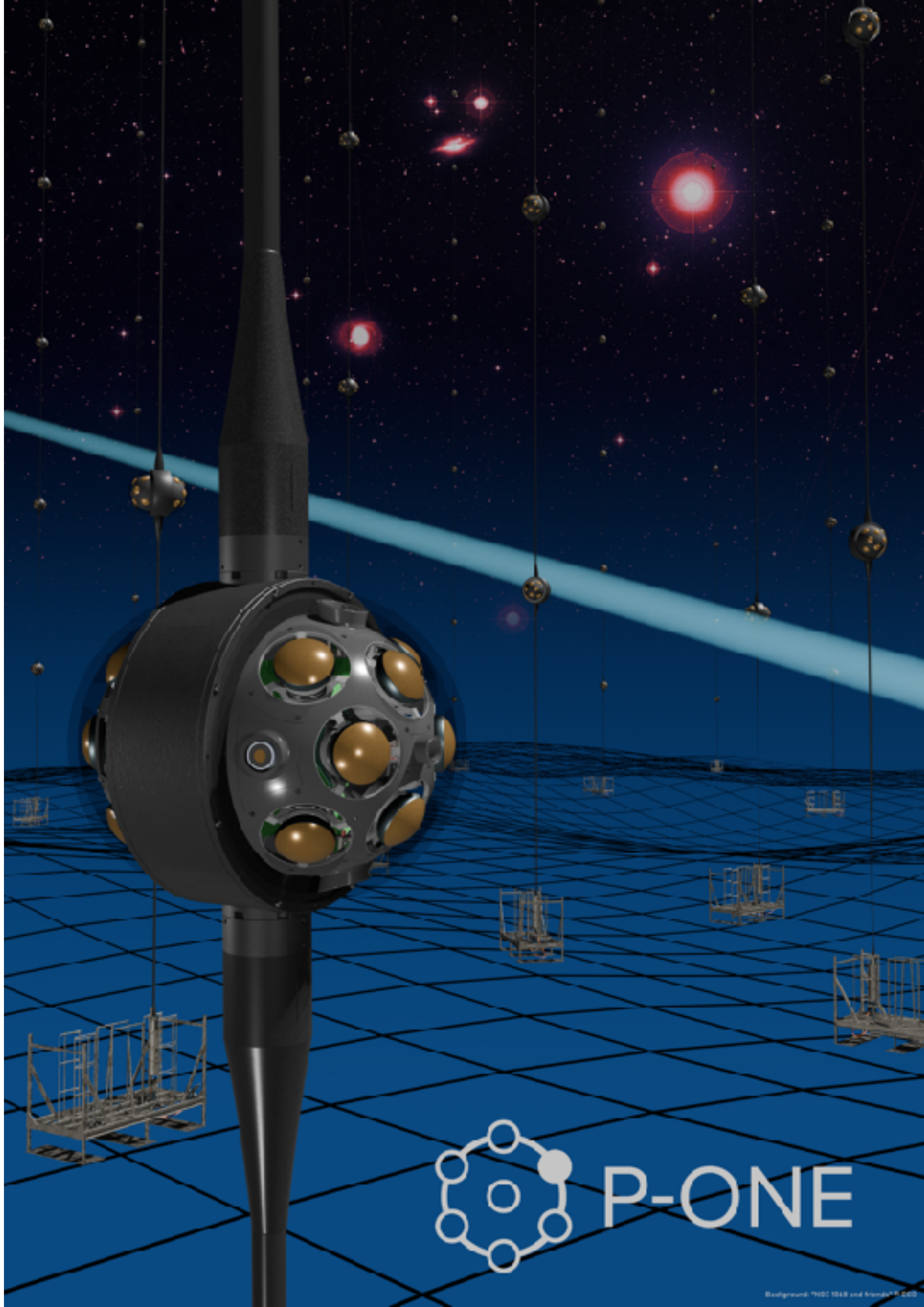
2 Gbit



P-ONE Collaboration, Nature Astron. 2020

P-ONE Baseline

- **O(100) vertical lines** 1 km tall;
- **20 multi-instrument sensor modules** per line;
- Equipped with **oceanography sensor interface, calibration devices, acoustic sensors;**
- At **Cascadia Basin**, covering a few cubic kilometers volume;
- **Permanent** installation for continuous deep-sea monitoring;
- **Phased approach** as a built-in risk mitigation strategy.



P-ONE Phases

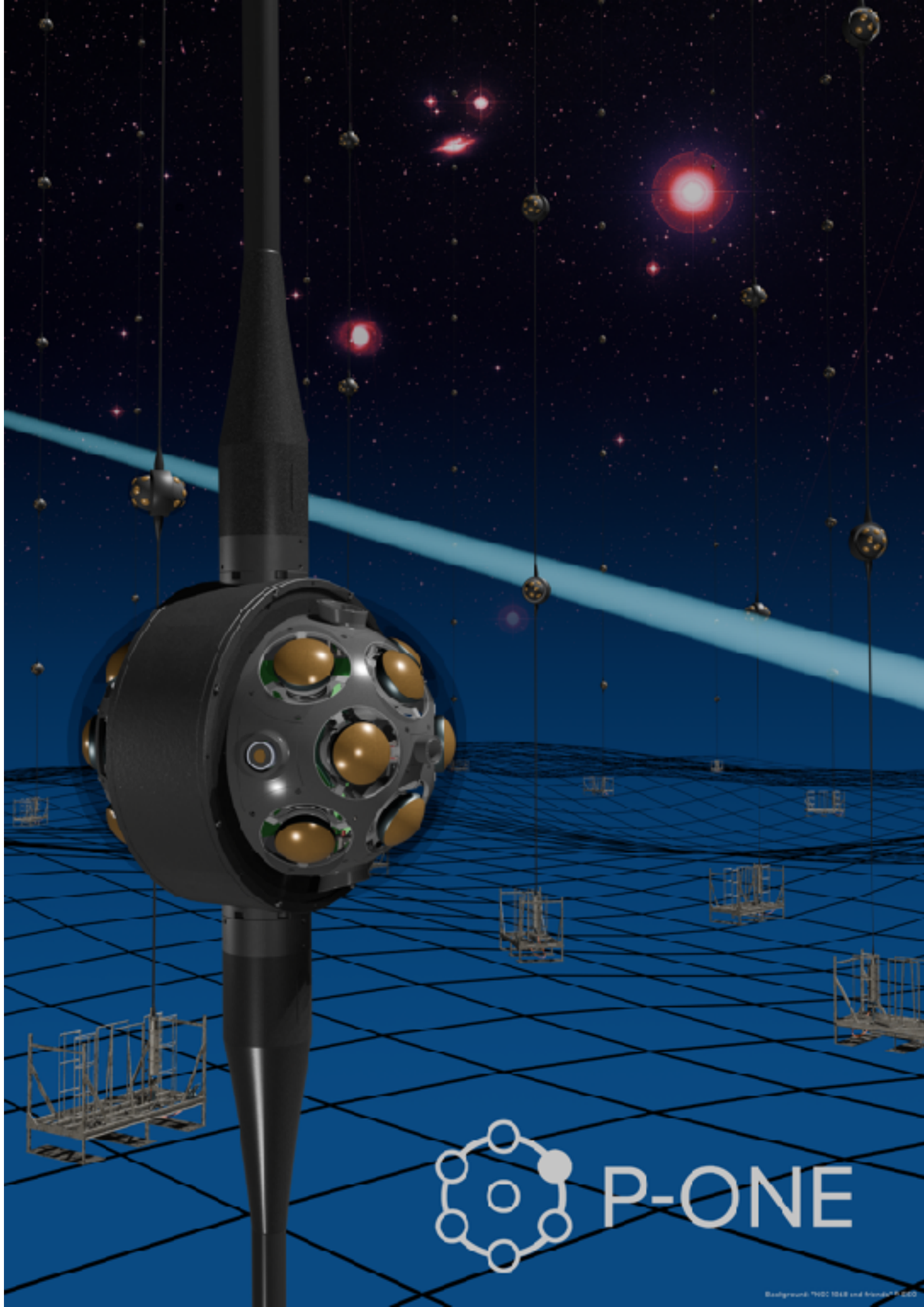
Pathfinders (2018-2024):
Successful operation, completed.

👉 **Phase 1 (2025-2029)**:
Demonstrator phase (financed)
(CFI, ERC/DFG, NSF)

- prototype deployment, testing of key components;
- P-ONE full array baseline, project finalization.

Phase 2 (2029-203?): Gradual deployment of the full array, increased integration with ONC infrastructure.

Phase 3 (203?-2045): Full operation, potential upgrades based on technological advancements.

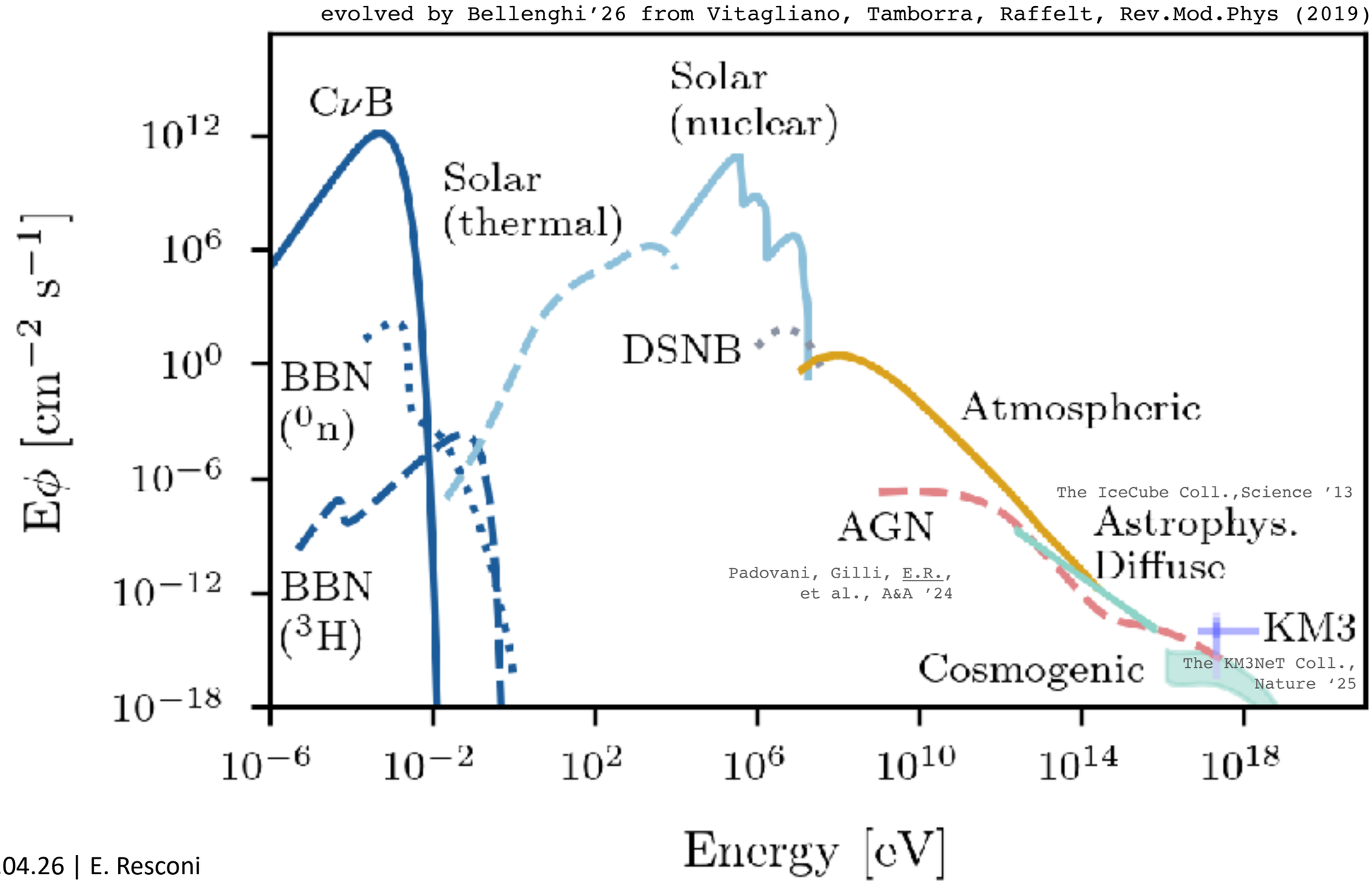


P-ONE: final integration on-going

Intro 2
Cosmic Neutrinos

Cosmic Neutrinos

Grand Unified Neutrino Spectrum (GUNS) at Earth integrated over directions, flavors



Cosmic Neutrinos

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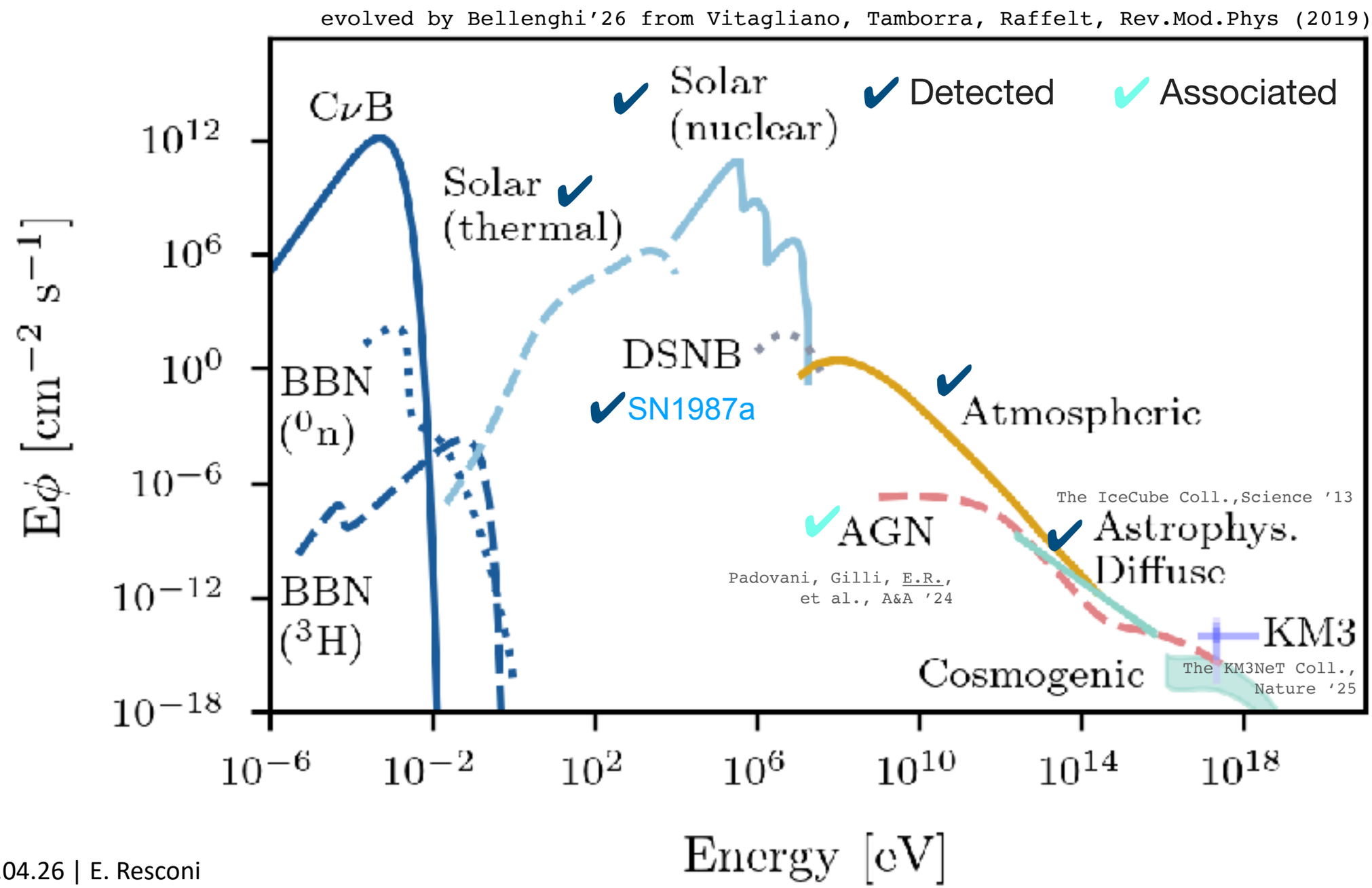

Cosmic Neutrinos

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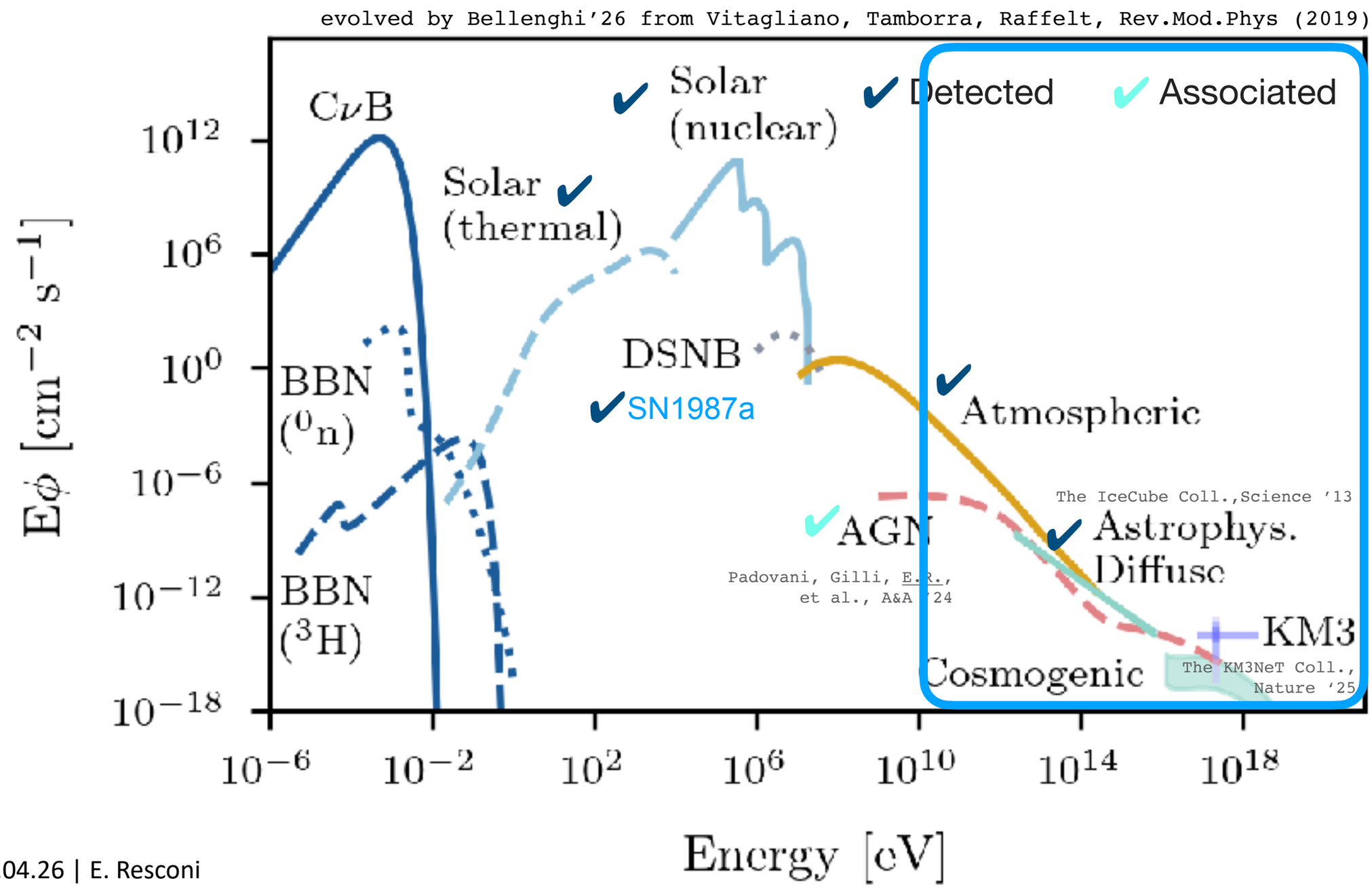
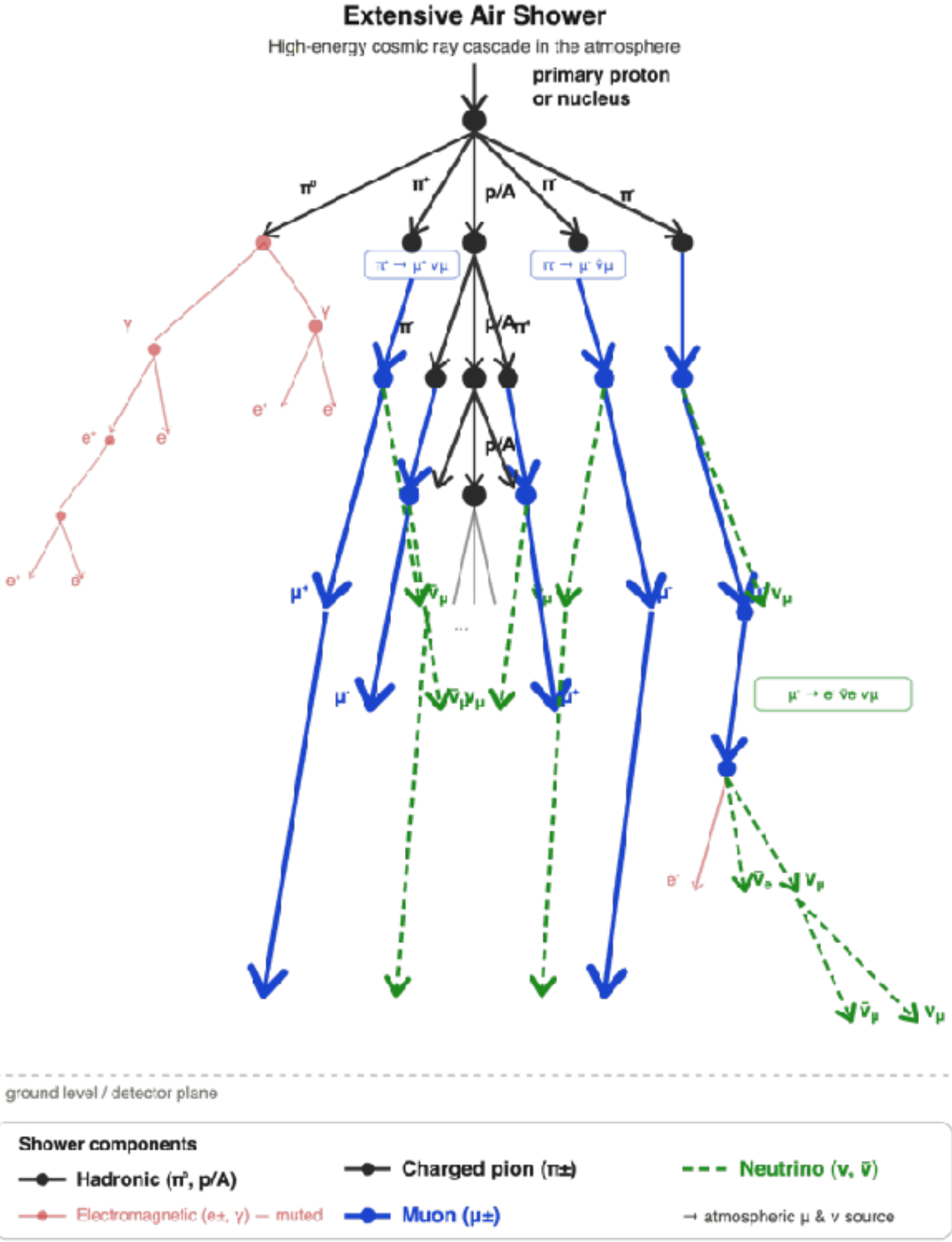
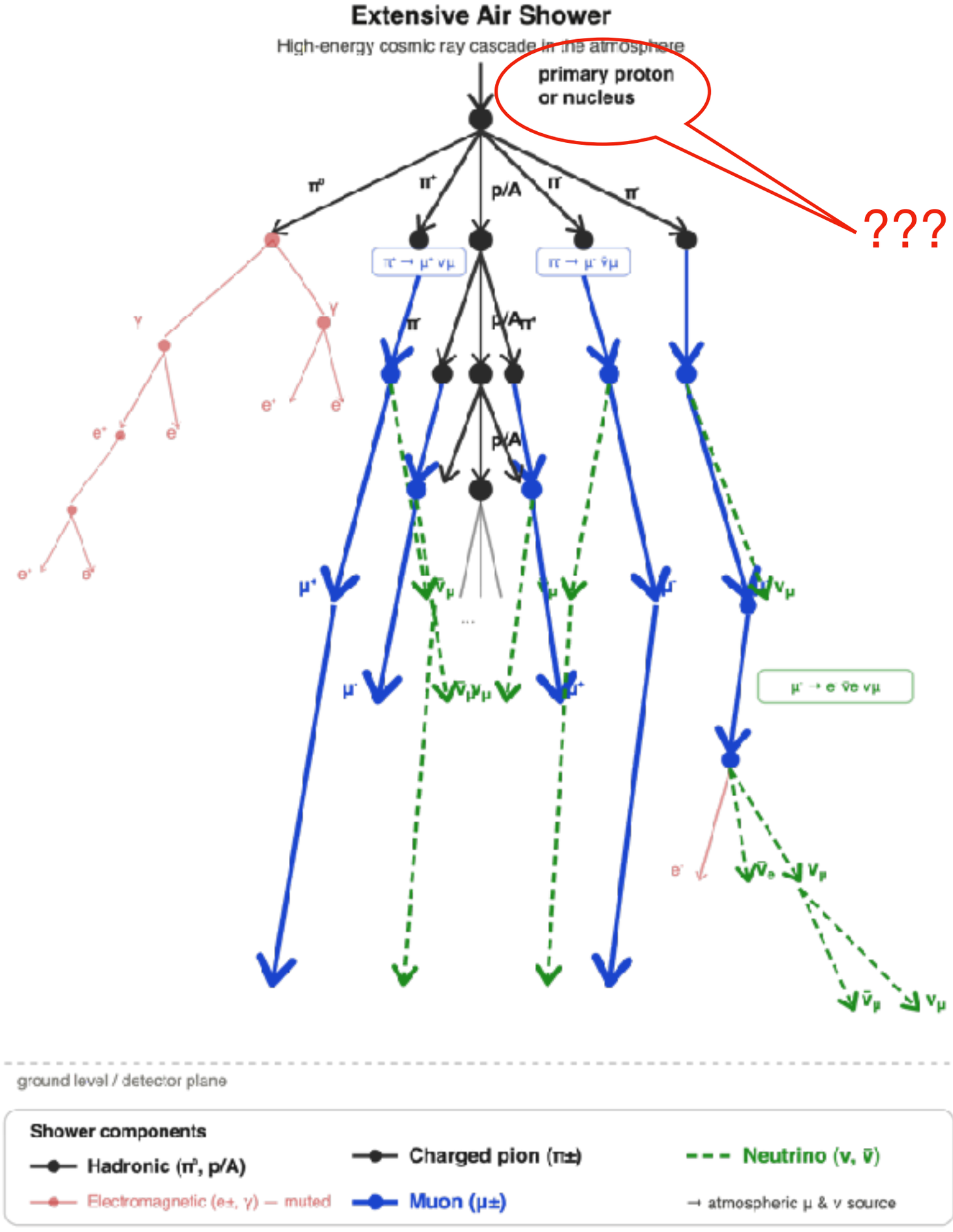


Atmospheric Neutrinos

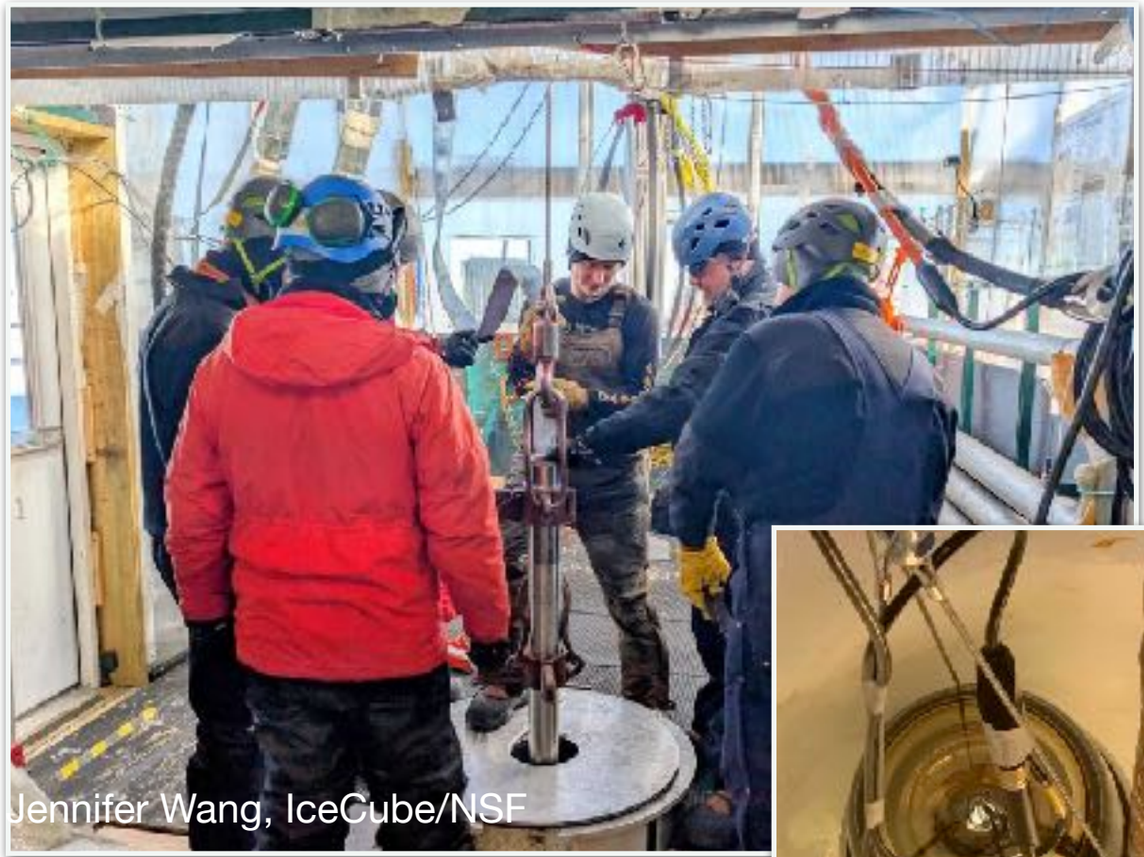


Atmospheric Neutrinos



NEW: IceCube Upgrade Delivered!

IceCube Coll., astro-ph/2509.13066


Jennifer Wang, IceCube/NSF


Colton Hill, TUM


Colton Hill, TUM

The ‘hidden’ source first experimental *evidence*

First evidence from NGC 1068: X-ray-bright Active Galactic Nuclei

IceCube Coll., ***Science* '22**; IceCube Coll., ***astro-ph/510.13403***

Event views of three of the events associated with the neutrino excess of NGC 1068.