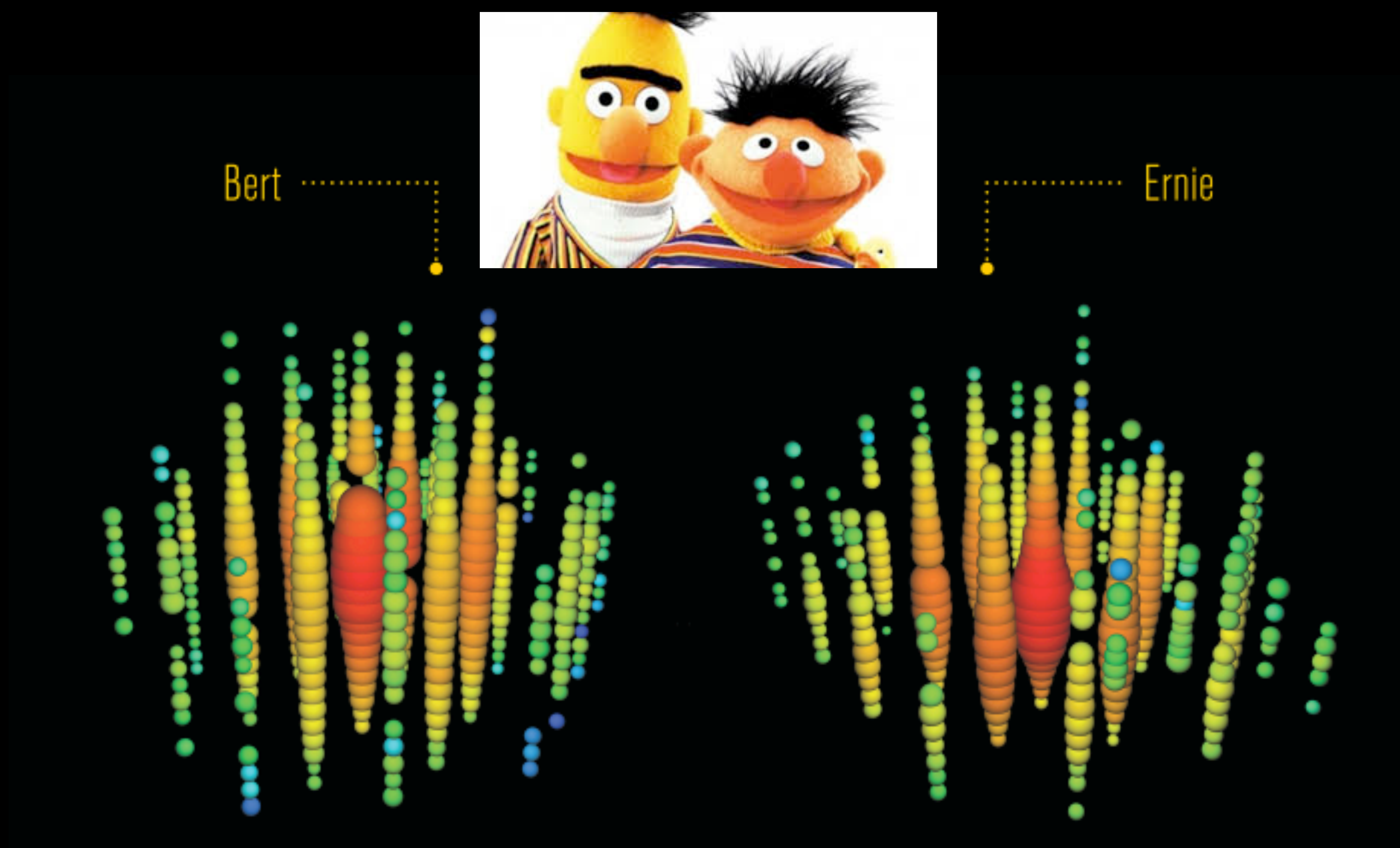
The signals

- The high energy neutrino background
- The first associations: AGN
- The Galactic plane

The IceCube **diffuse** neutrino signal

~2.8 sigma

The IceCube Coll., Phys. Rev. Lett. 111, 021103 (2013)



1041^{+132}_{-144} TeV

MJD 55783

Dec -27.9 deg, R.A. 265.6
Median Angular error 13.2 deg

1141^{+143}_{-133} TeV

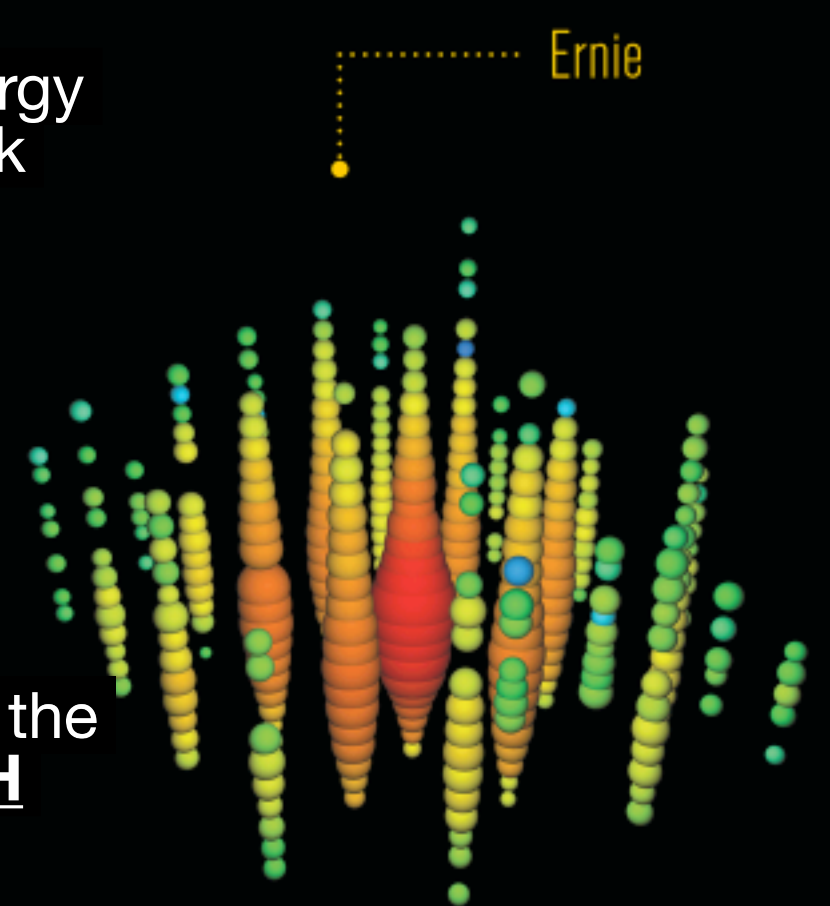
MJD 55929

Dec -67.2 deg, R.A. 38.3
Median Angular error 10.7 deg

The IceCube diffuse neutrino signal ~2.8 sigma

S. Schönert, T. Gaisser, E.R. O. Schulz, PRD, 79043009 (2009))

- Are these neutrinos?
  - YES: they could be stochastic energy losses of muons but no muon track around is visible - **importance of containment**
- Are these atmospheric neutrinos?
  - No other component of EAS! - **importance of containment**
  - PeV neutrinos are **not** expected in the atmosphere - **importance of HIGH ENERGY!**
  - Atmospheric Neutrinos are **VETO** through containment.



1141^{+143}_{-133} TeV

MJD 55929

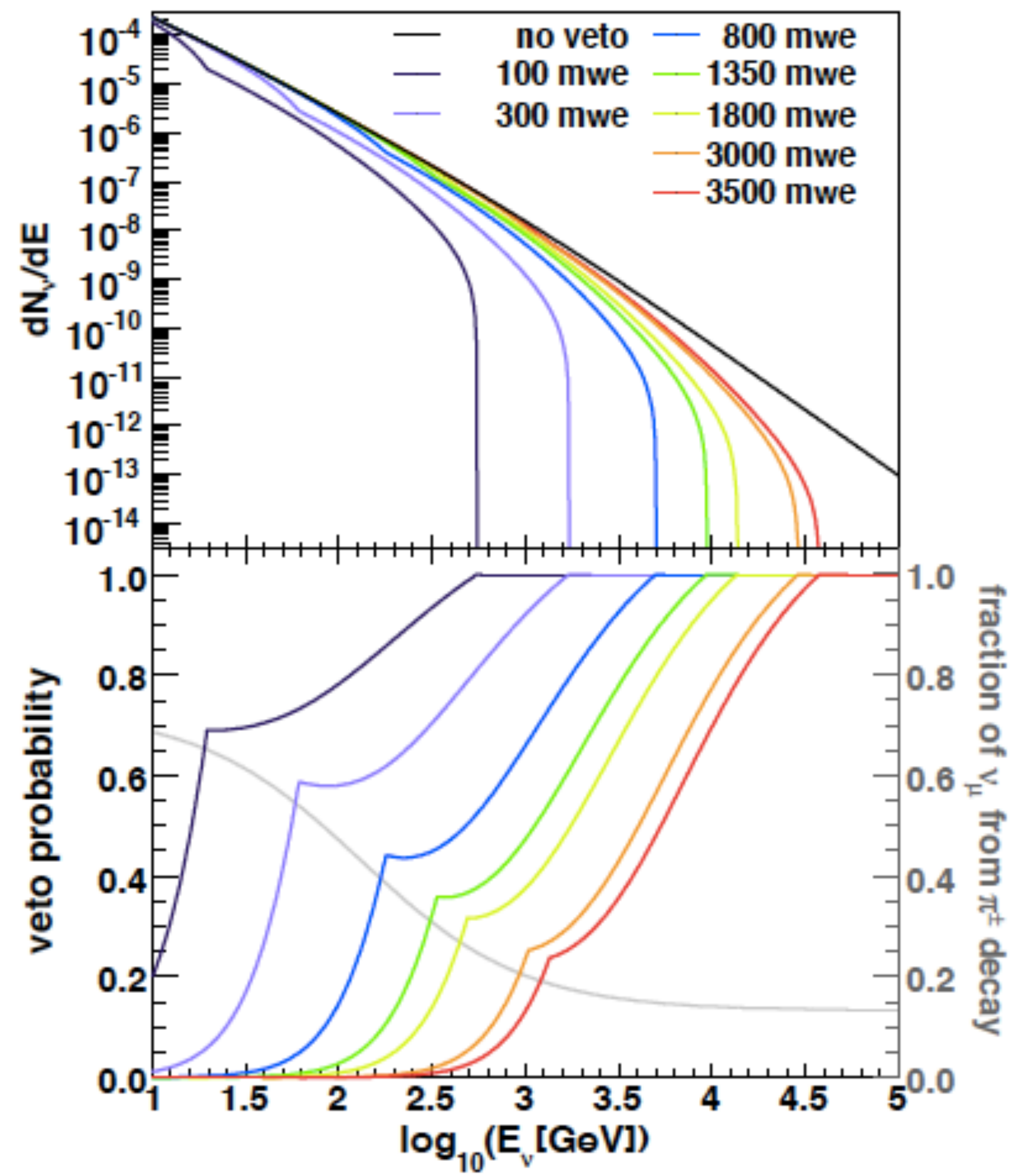
Dec -67.2 deg, R.A. 38.3

Median Angular error 10.7 deg

The IceCube **diffuse** neutrino signal

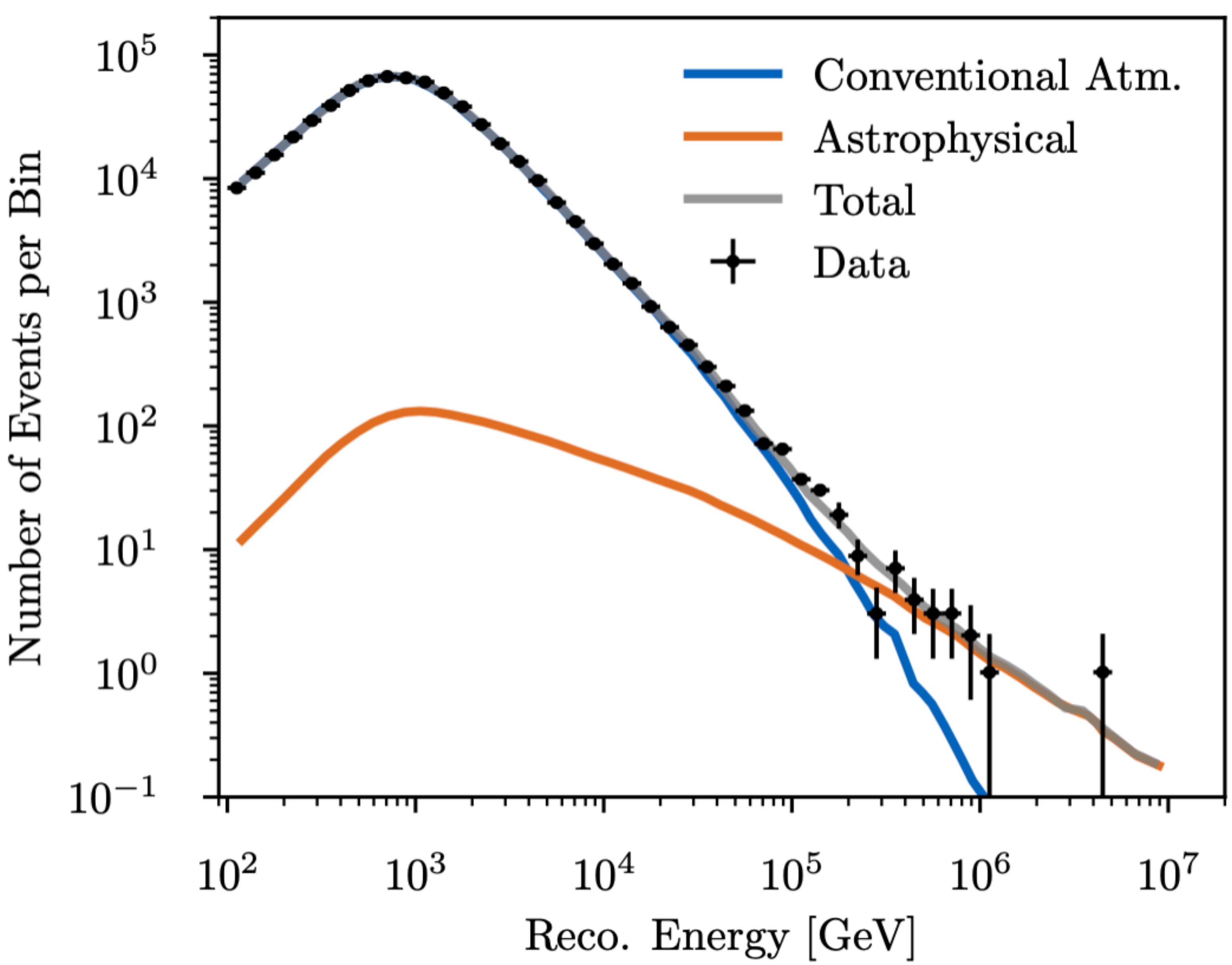
S. Schönert, T. Gaisser, E.R. O. Schulz, PRD, 79043009 (2009))

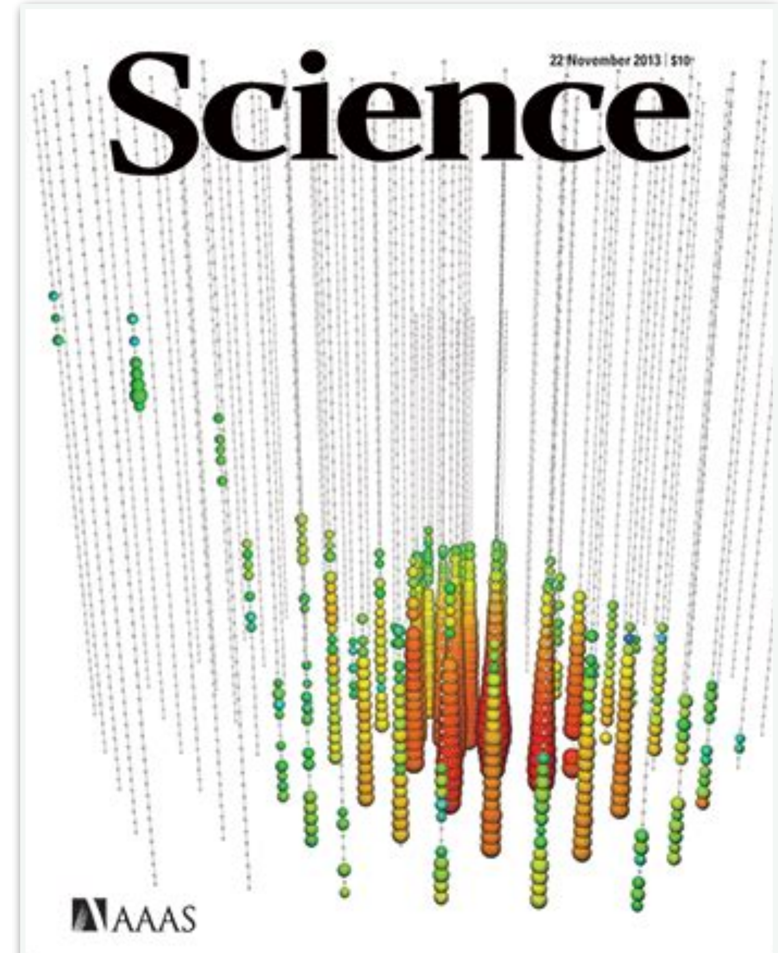
Atmospheric (Muon) and Neutrinos: **VETO** through containment.



The IceCube diffuse neutrino signal

The IceCube Coll., *Science* 342, 2013

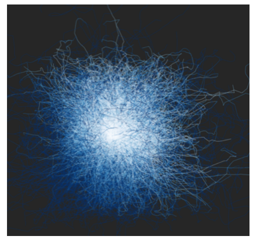




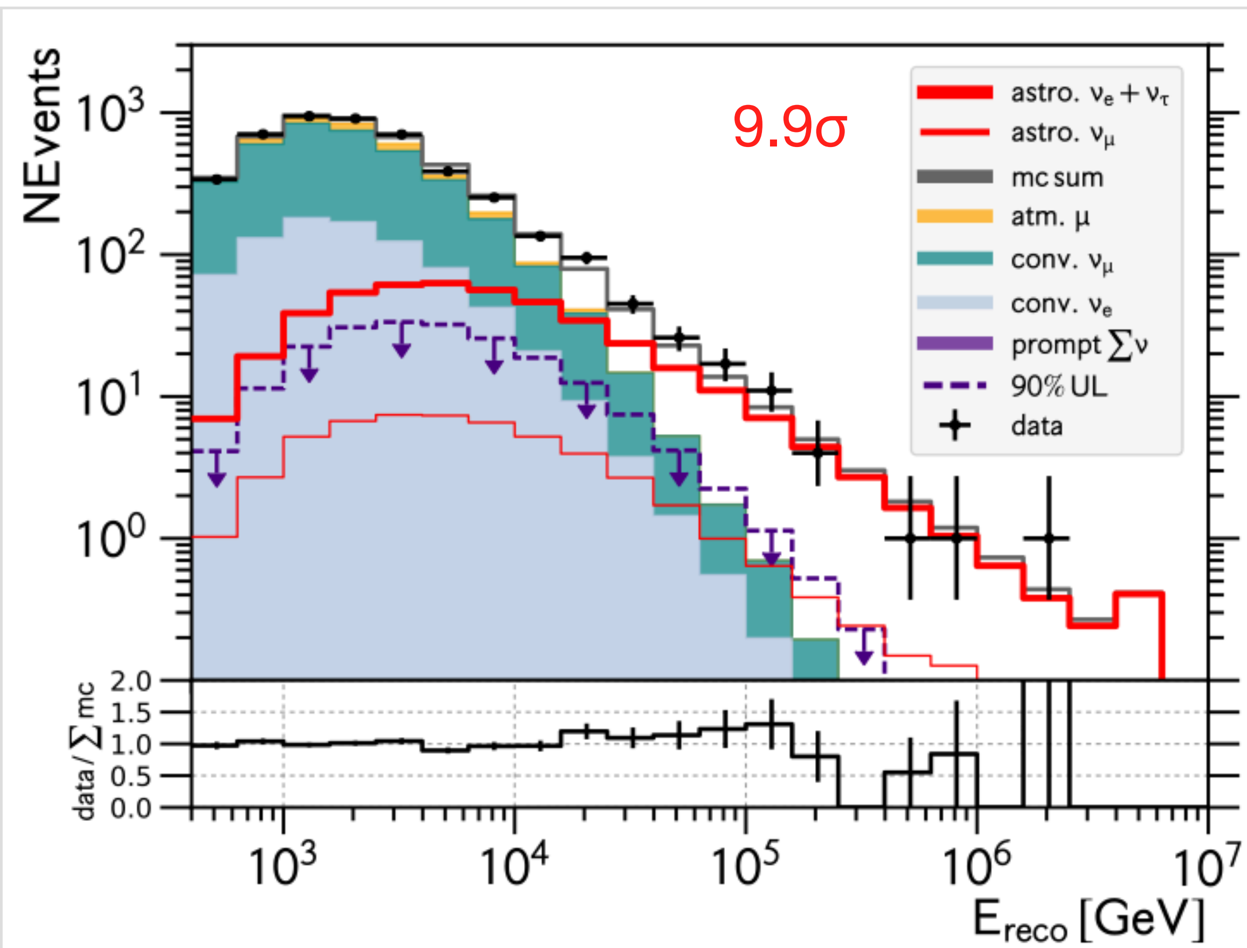
Record events:

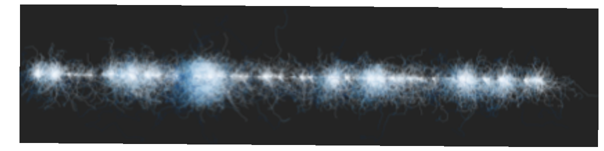
- 8.7 PeV track-like event
- 6.4 PeV shower-like (candidate Galshow event)
- 2 high-energy double peaked

The IceCube diffuse neutrino signal

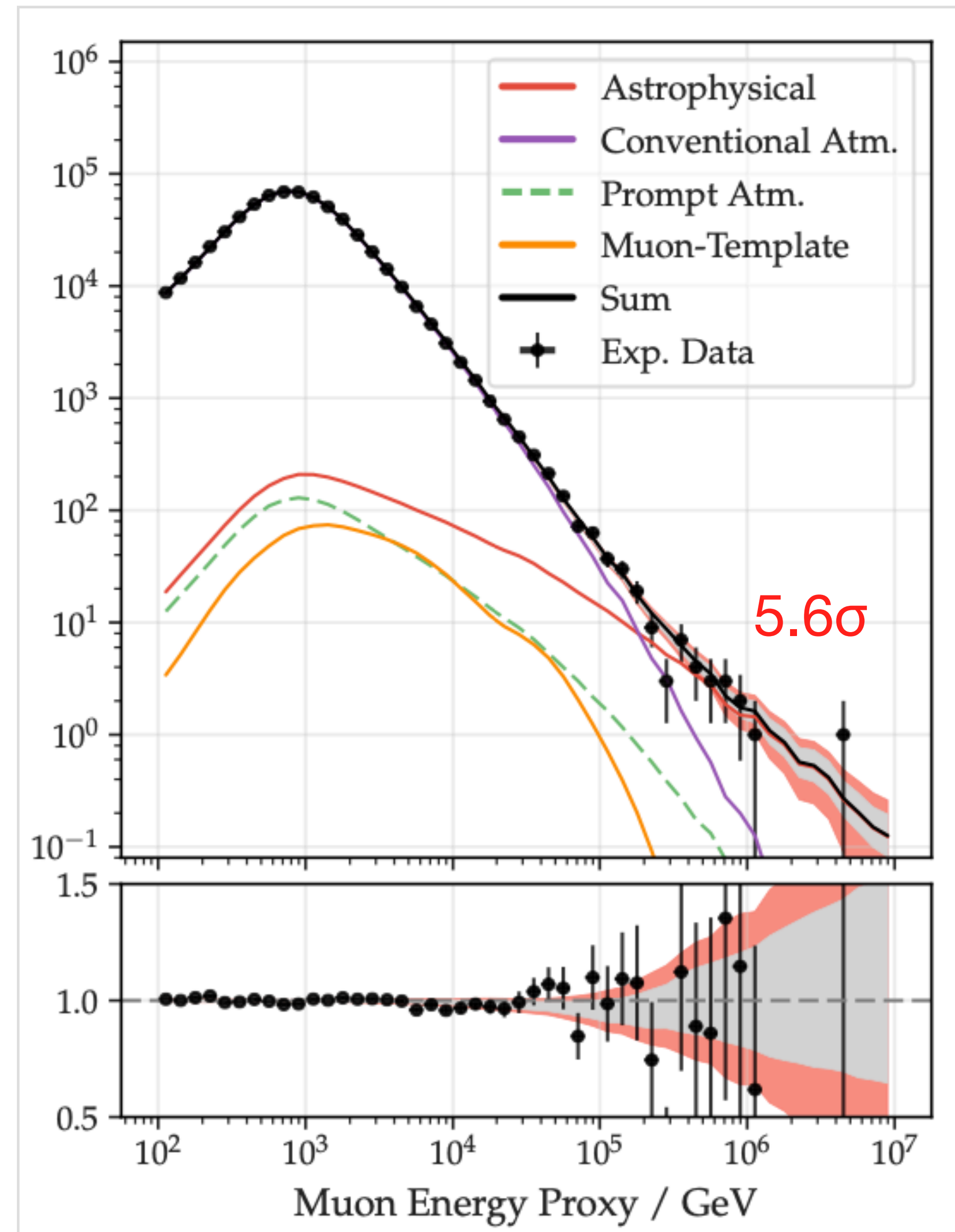


The IceCube Coll., PRL'20





The IceCube Coll., ApJ'22



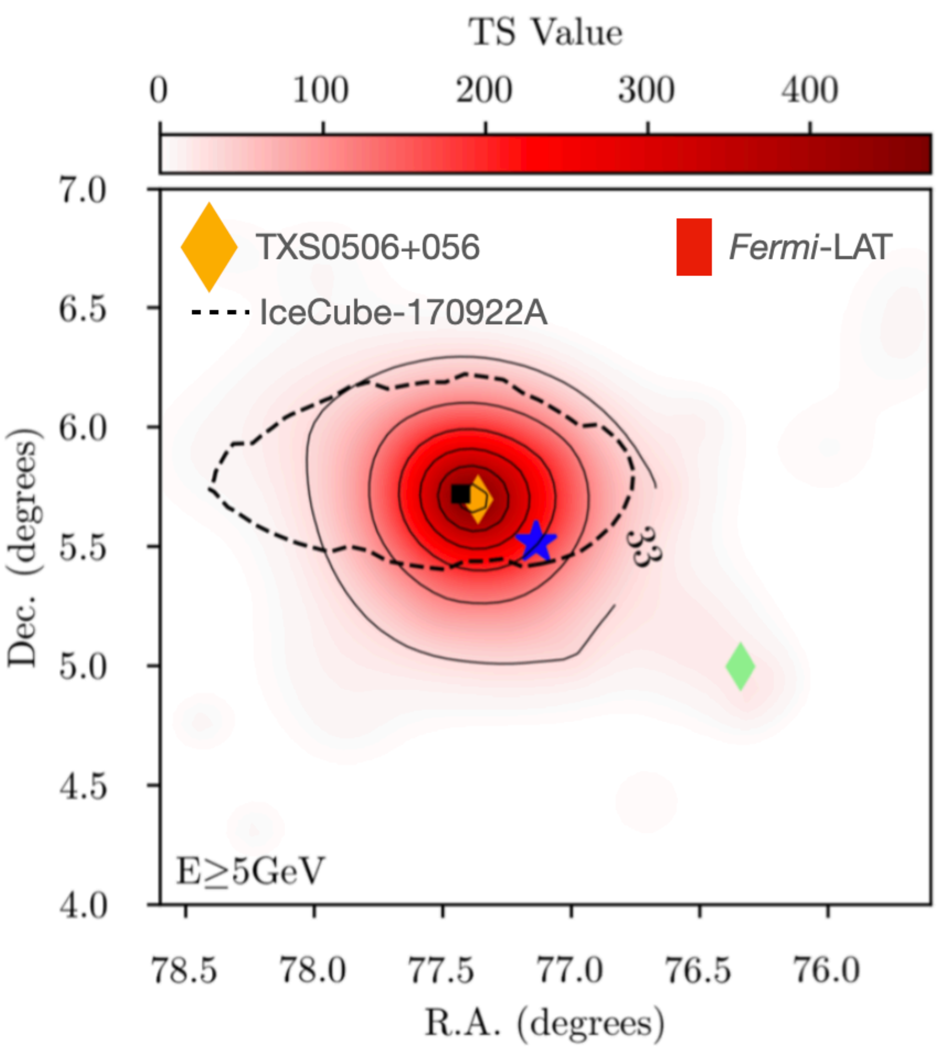
Where are the sources of the IceCube diffuse???

@rdvvector

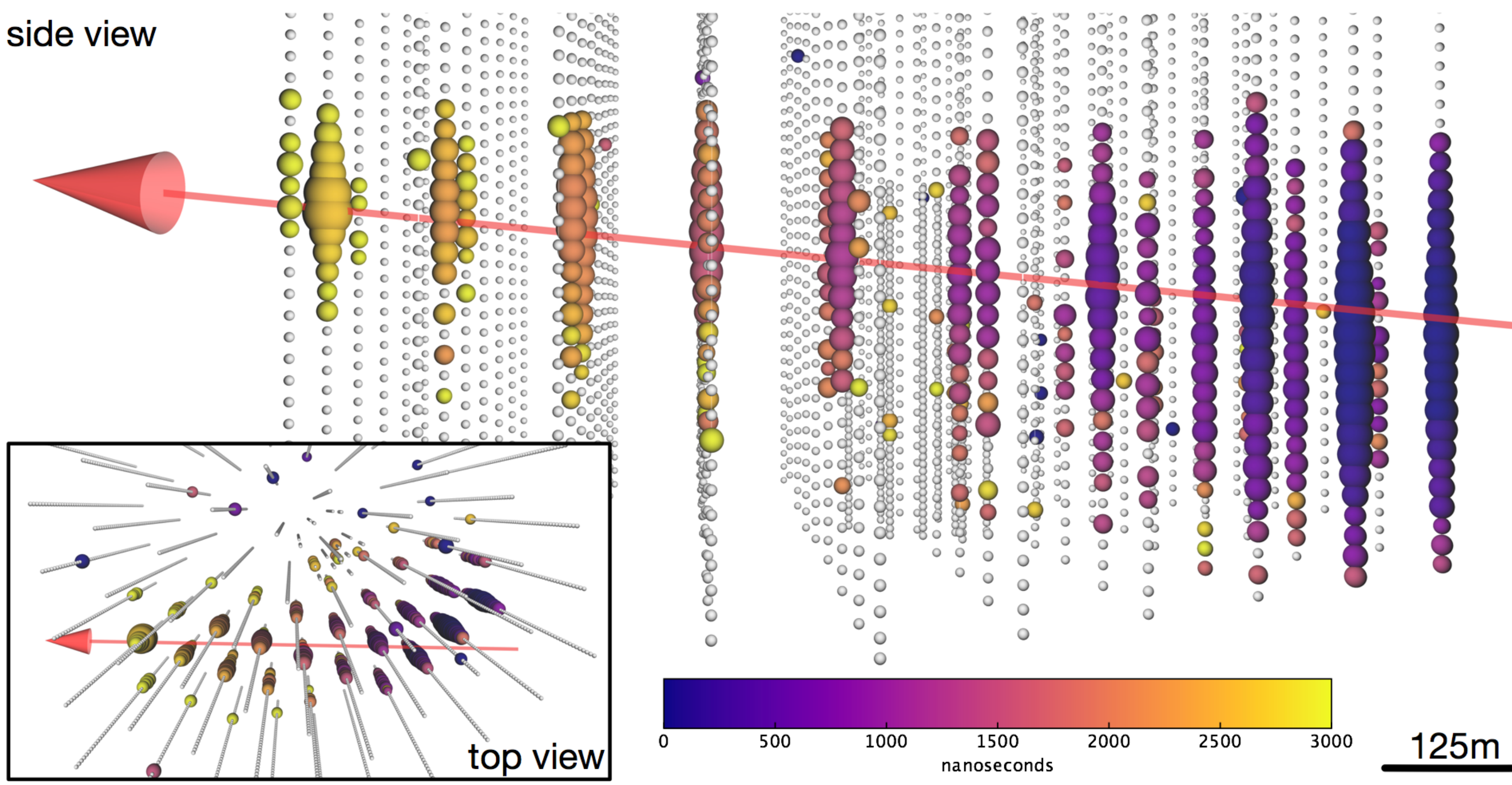
First Transient Source association (2017)

ICECUBE-170922A VS TXS0506+056: NEUTRINO ALERT [~290 TEV, DEC ~5.72 DEG]

The IceCube Coll. and others, ***Science* 361, 2018**
P. Padovani, P. Giommi, T. Glauch, E.R. et al., **MNRAS (2018, 2019)**



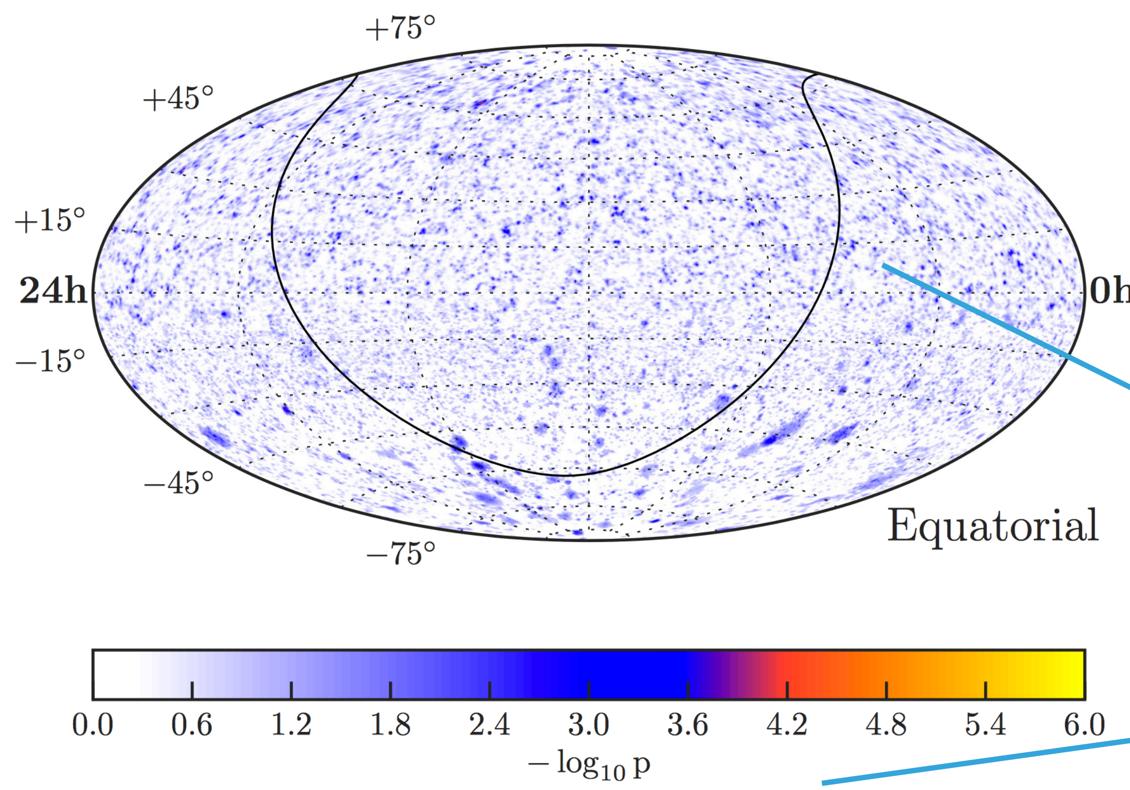
Chance coincidence excluded at 99.73% C.L



First Transient Source association (2017)

Identification of more neutrinos from the TXS 0506+056

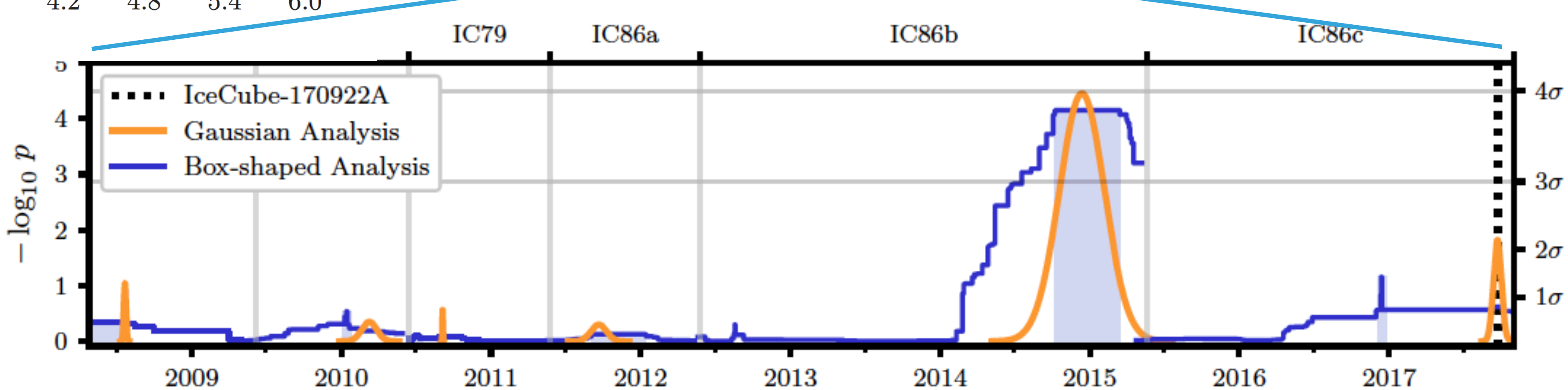
The IceCube Coll., Science 361, 147-151 (2018)
P. Padovani, P. Giommi, T. Glauch, E.R. et al., **MNRAS (2018, 2019)**



Background origin excluded at 99.95% C.L.

Neutrino energy information: included in the definition of the likelihood [$E^{-\gamma}$]

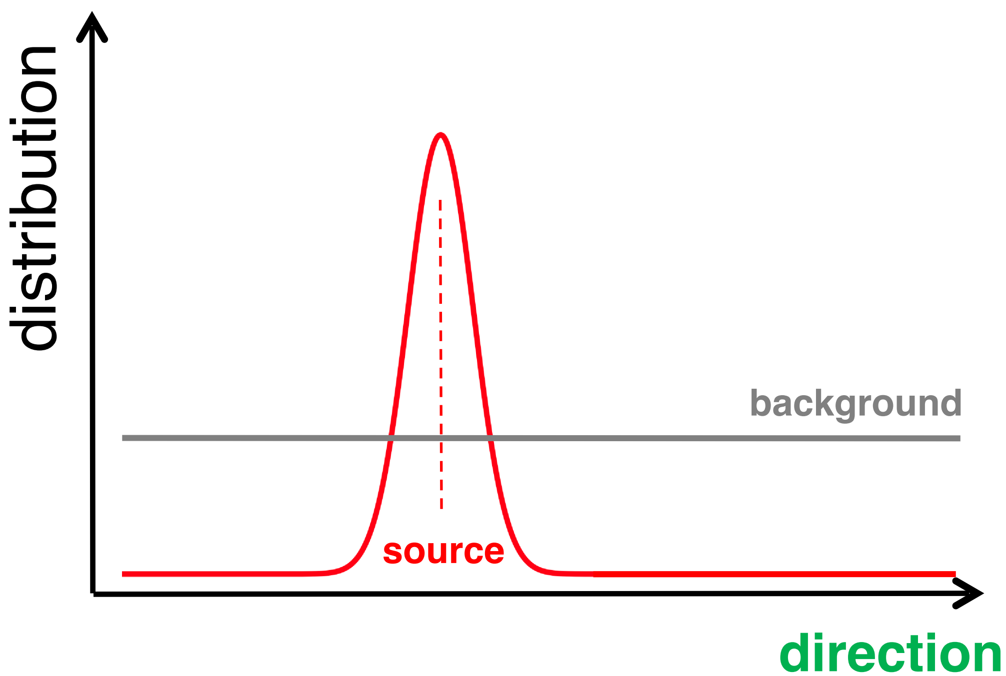
$\gamma = 2.1 \pm 0.2$

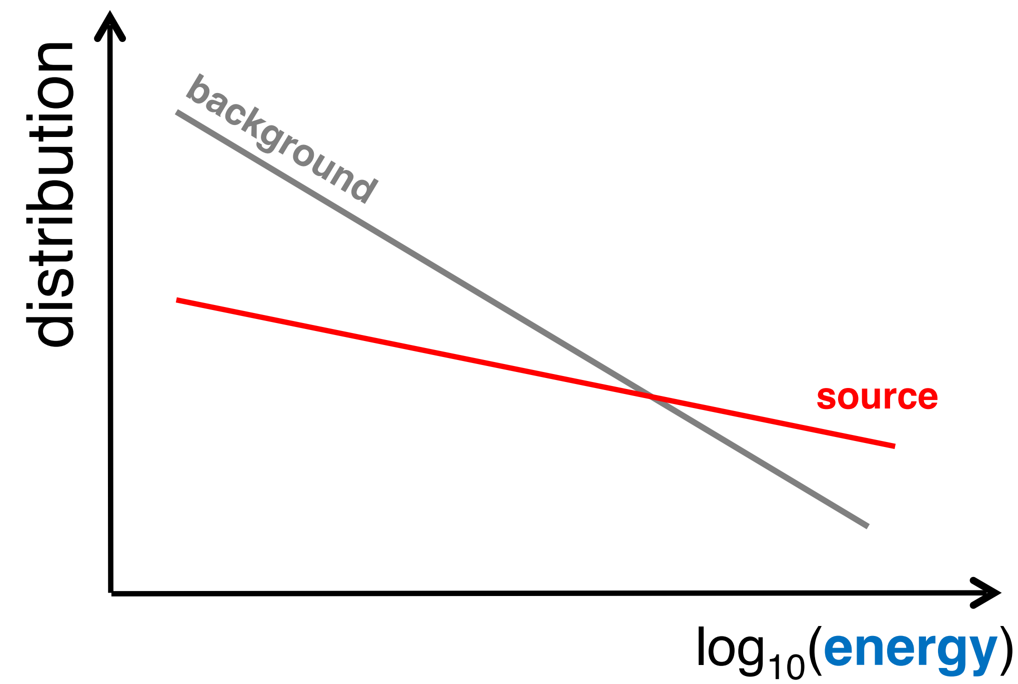


First Steady Source Association (2022)

Searching for Steady Neutrino Sources: long tradition in IceCube (since 2007)

Braun et al., Astropart. Phys. 29 (2008) 299305





$$L\left(\boldsymbol{\theta_s}\,|\,\hat{\boldsymbol{E}},\,\hat{\boldsymbol{\sigma}},\,\hat{\boldsymbol{d}}\right) = \prod_{i=1}^{N}\left\{\frac{\mu_s}{N}\times\frac{1}{2\pi\hat{\sigma}_i^2}\exp\left(-\frac{1}{2\hat{\sigma}_i^2}\left|\hat{\boldsymbol{d}}_{\boldsymbol{i}}-\boldsymbol{d_s}\right|^2\right)f_s\left(\hat{E}_i;\,\gamma\right)+\left(1-\frac{\mu_s}{N}\right)\times f_b\left(\hat{E}_i,\,\hat{\boldsymbol{d}}_{\boldsymbol{i}}\right)\right\}$$

2-D Gaussian (until '20)

First Steady Source Association (2022)

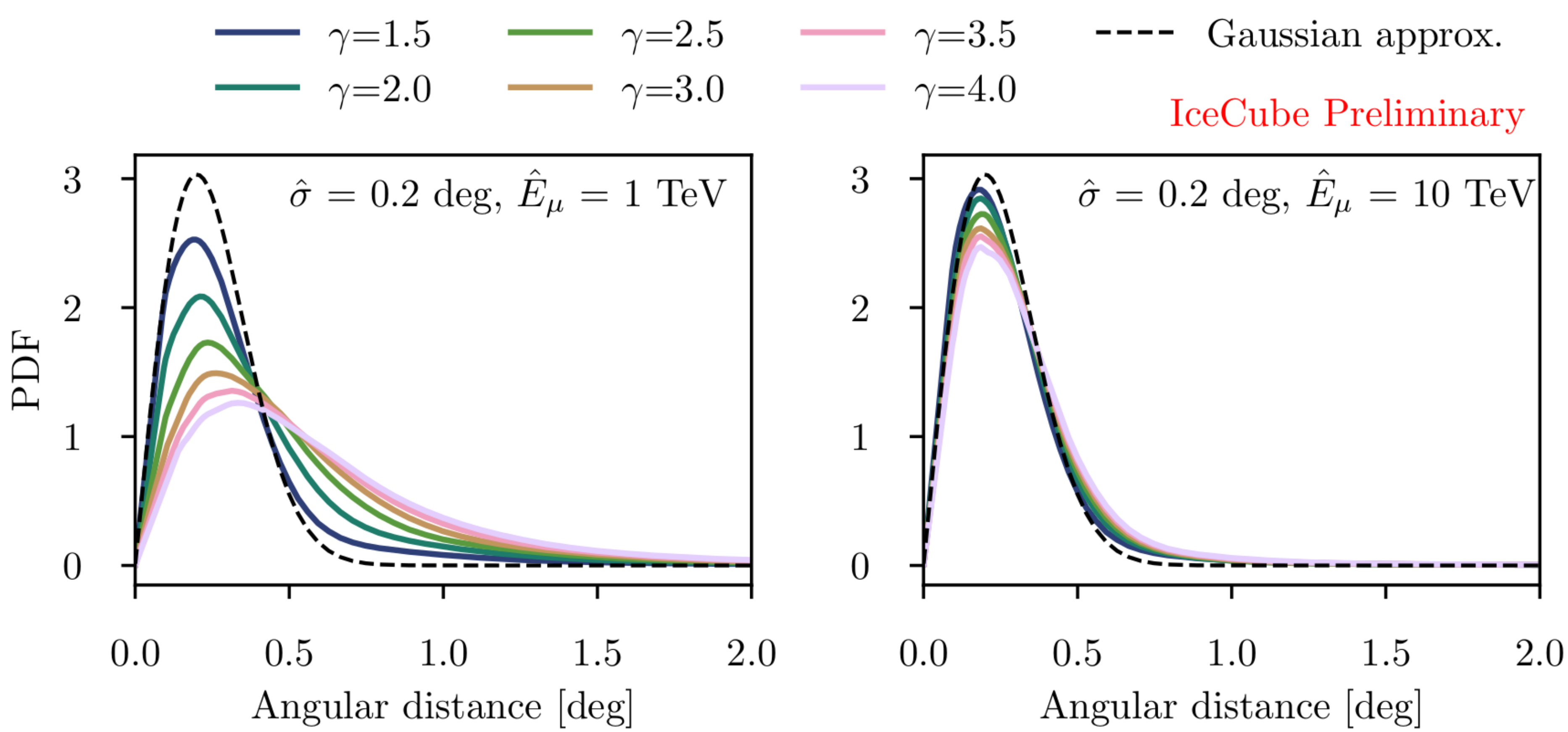
Recent major improvements applied

The IceCube Coll., *Science* 378, Issue 6619, 2022

1. detector calibration, data filtering and processing applied to entire dataset (all ~1 trillion events)

=> IceCube 'Pass 2' data

2. spatial pdf describes separation conditional on angular error and energy
=> now generated from Monte Carlo simulations of track events in IceCube

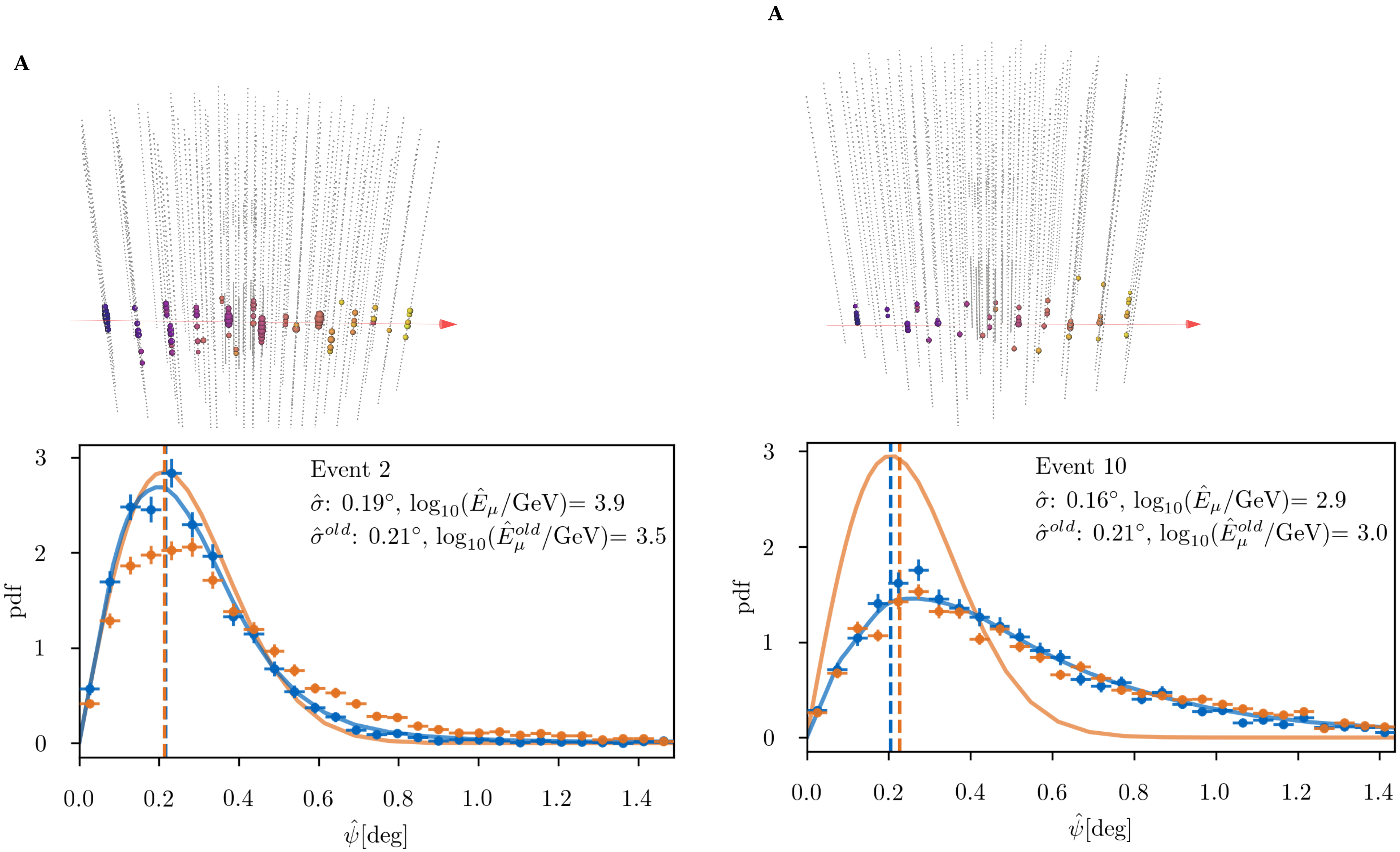


First Steady Source Association (2022)

Recent major improvements applied

The IceCube Coll., *Science* 378, Issue 6619, 2022

3. Improved modelling of directional distributions of individual neutrinos

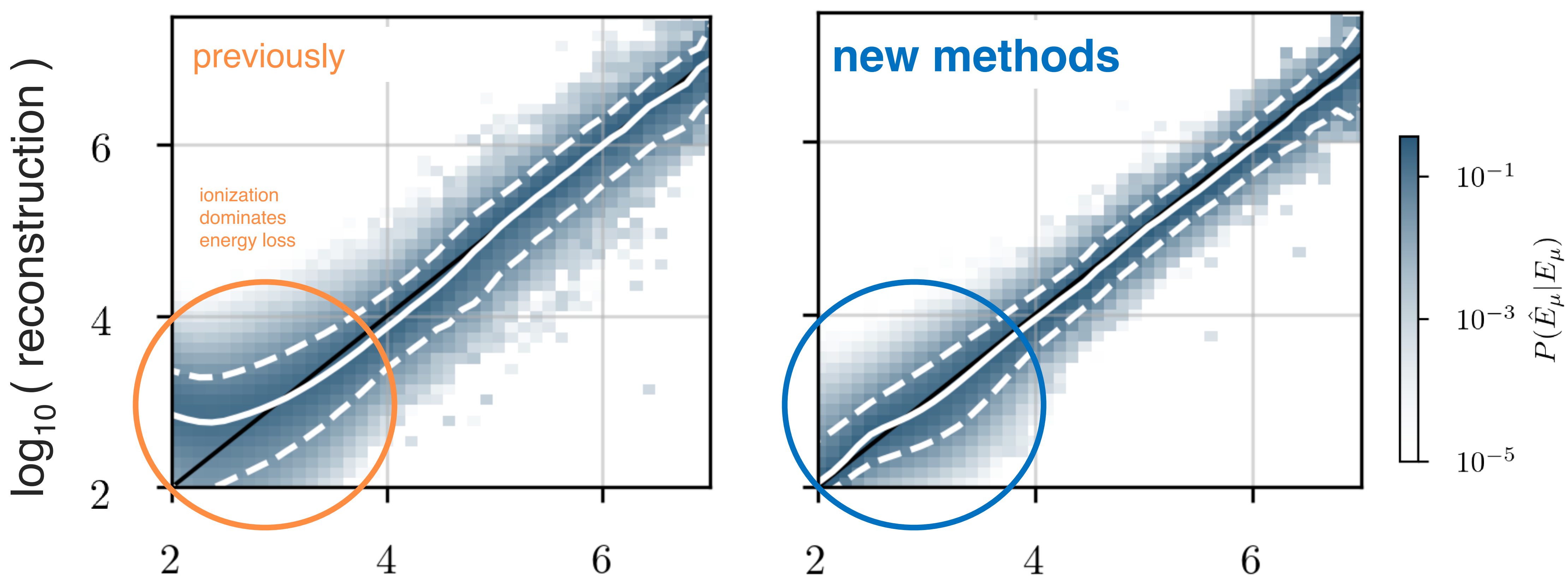


First Steady Source Association (2022)

Recent major improvements applied

The IceCube Coll., *Science* 378, Issue 6619, 2022

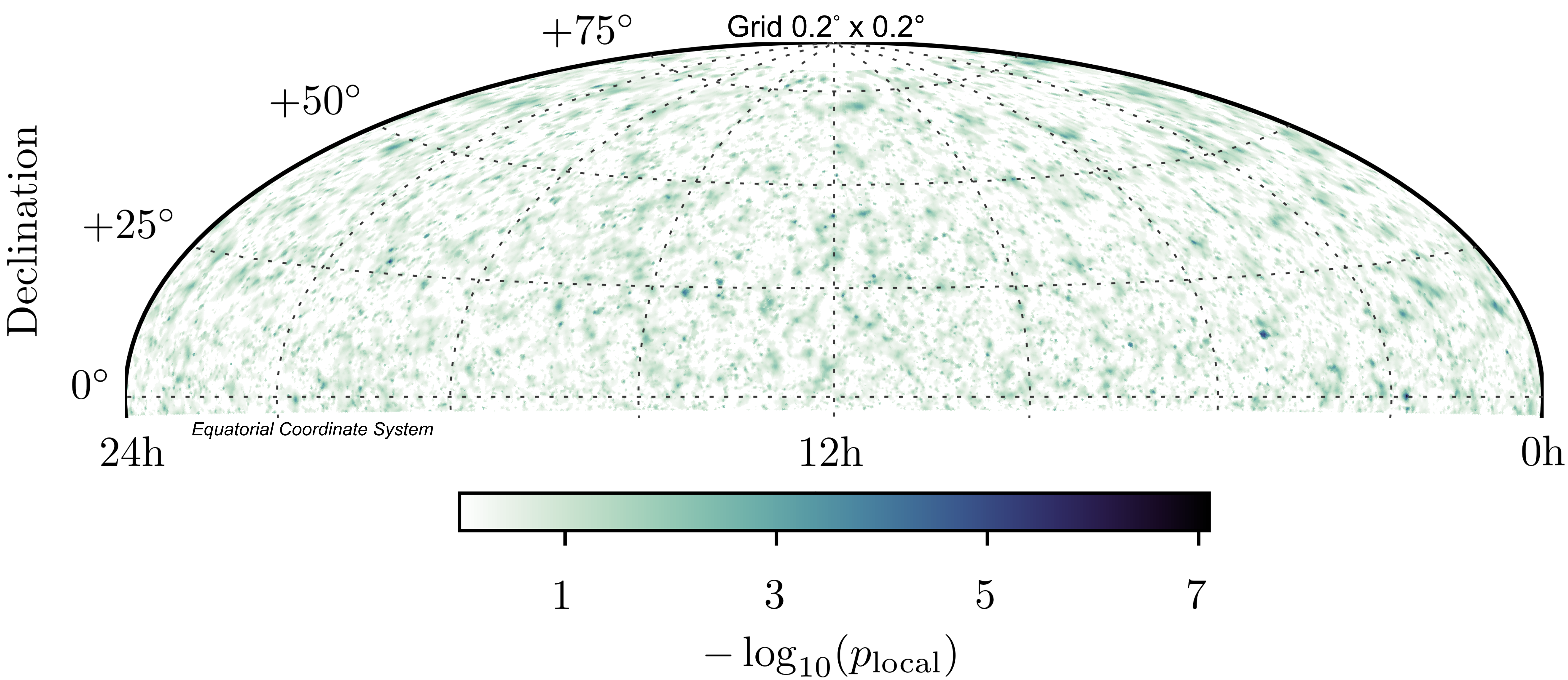
4. Energy reconstruction: machine learning, more accurate and more precise energy estimates



First Steady Source Association (2022)

The IceCube Coll., *Science* 378, Issue 6619, 2022

The new SkyMap based on data: May 2011 to May 2020. ~99% detector uptime.
~670,000 neutrinos selected out of ~1 trillion events recorded.

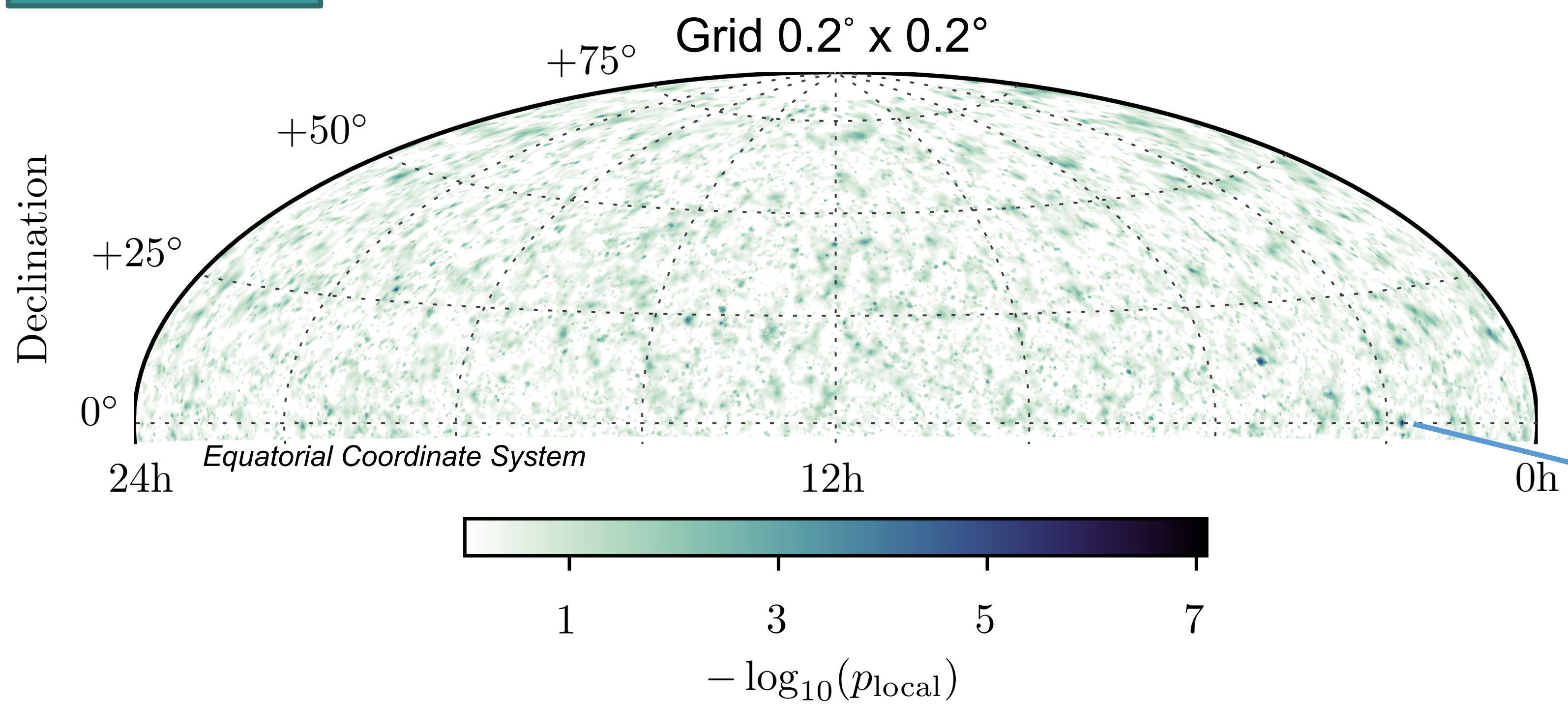


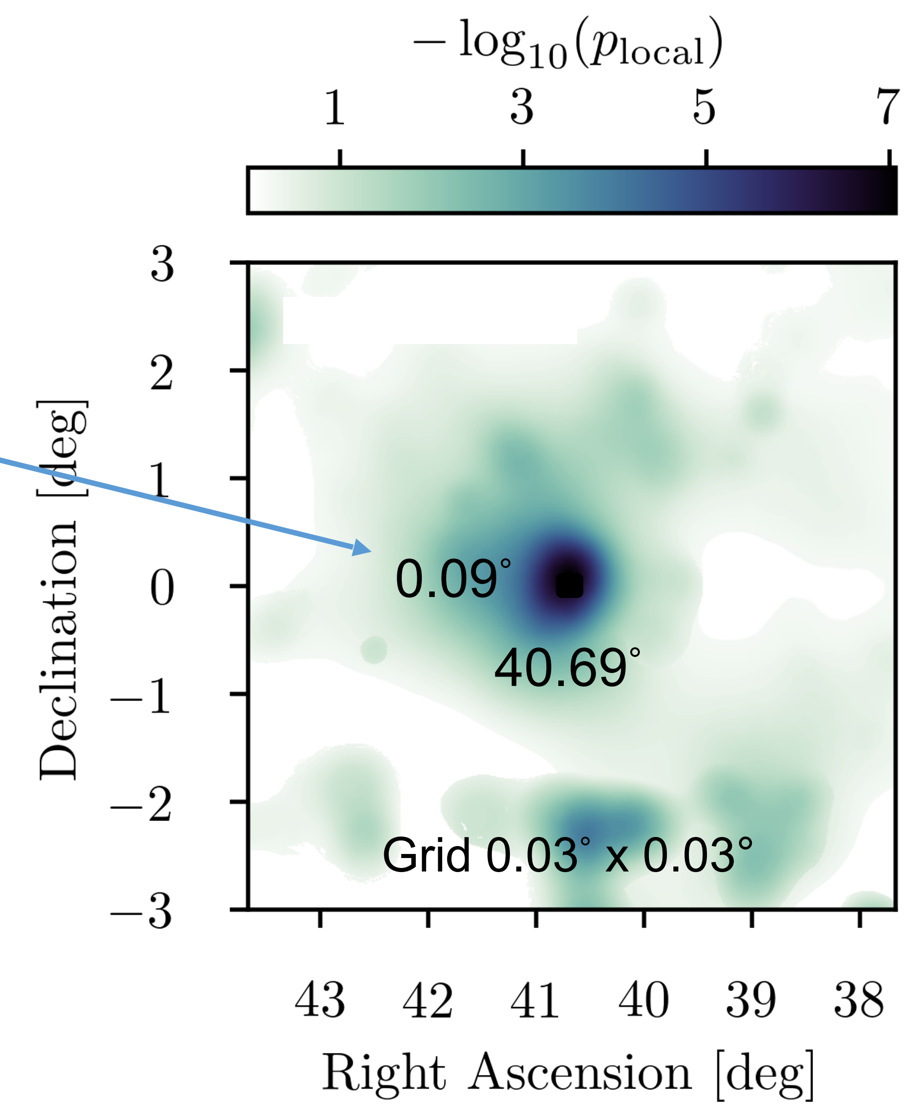
Three tests all defined a-priori following a blindness strategy (including post-unblinding checks)

First Steady Source Association (2022)

The IceCube Coll., *Science* 378, Issue 6619, 2022

Test No. 1





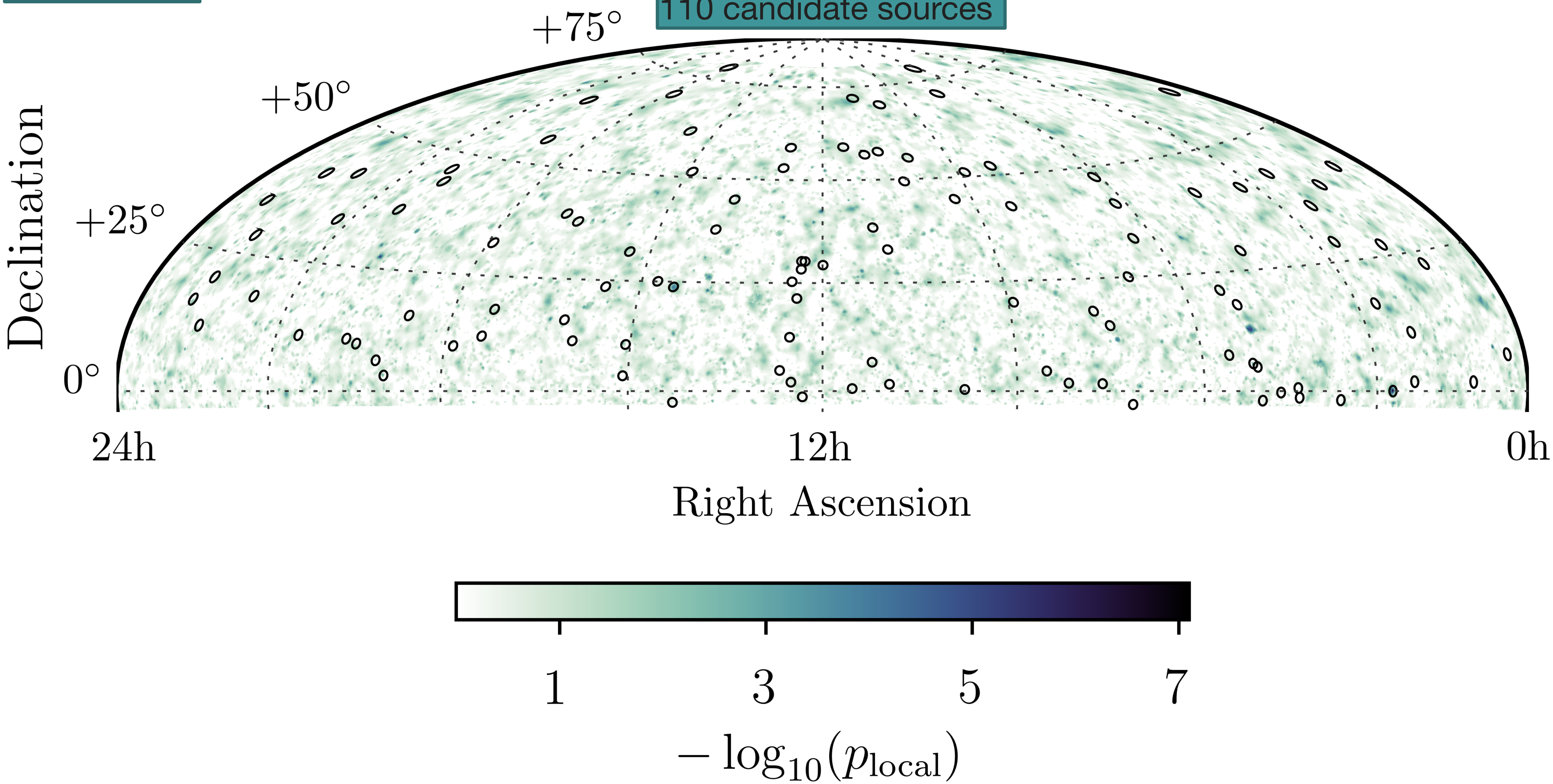
At the brightest location in full sky scan:
- Mean astrophysical neutrino events = 81
- Mean spectral index = 3.2

First Steady Source Association (2022)

The IceCube Coll., *Science* 378, Issue 6619, 2022

Test No. 2

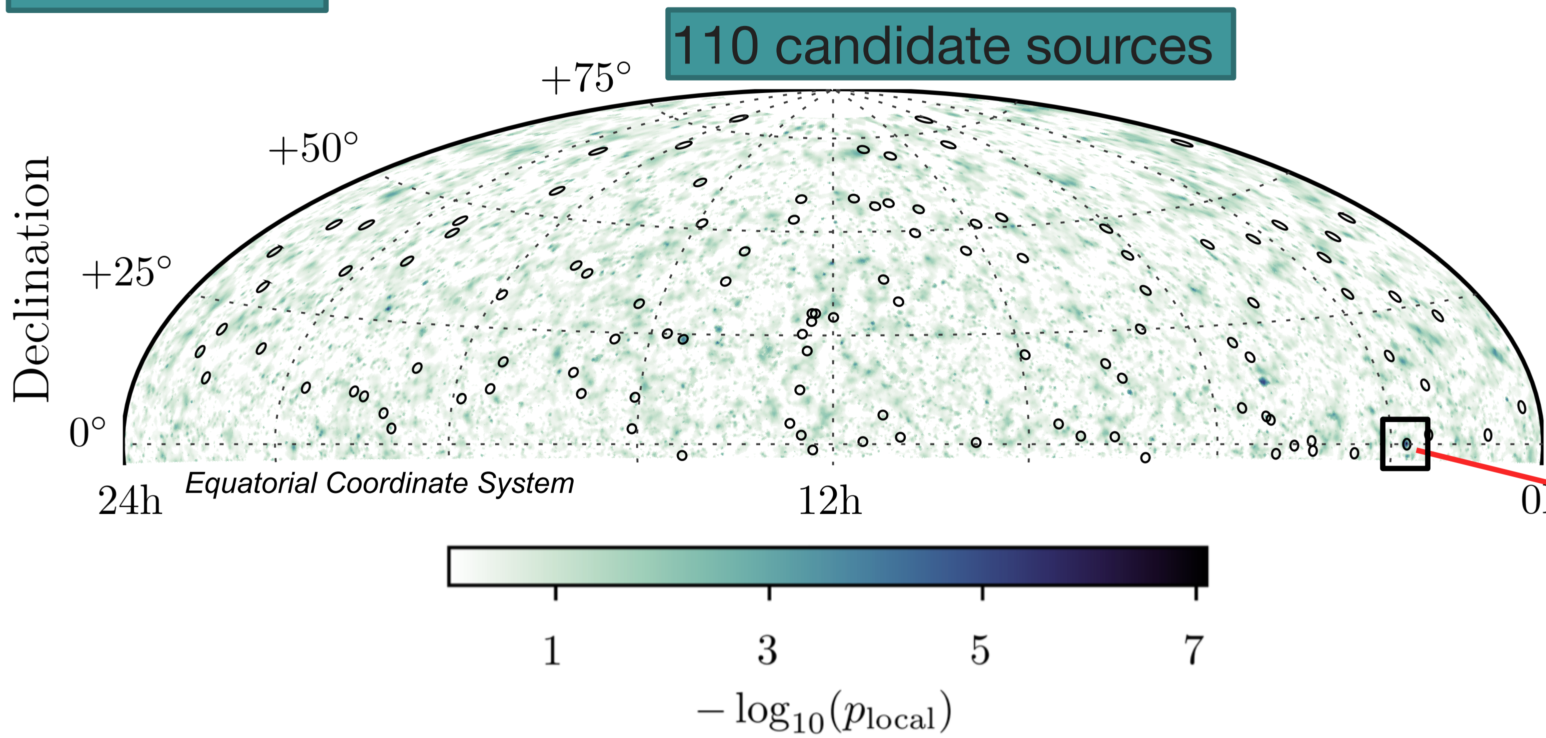
110 candidate sources

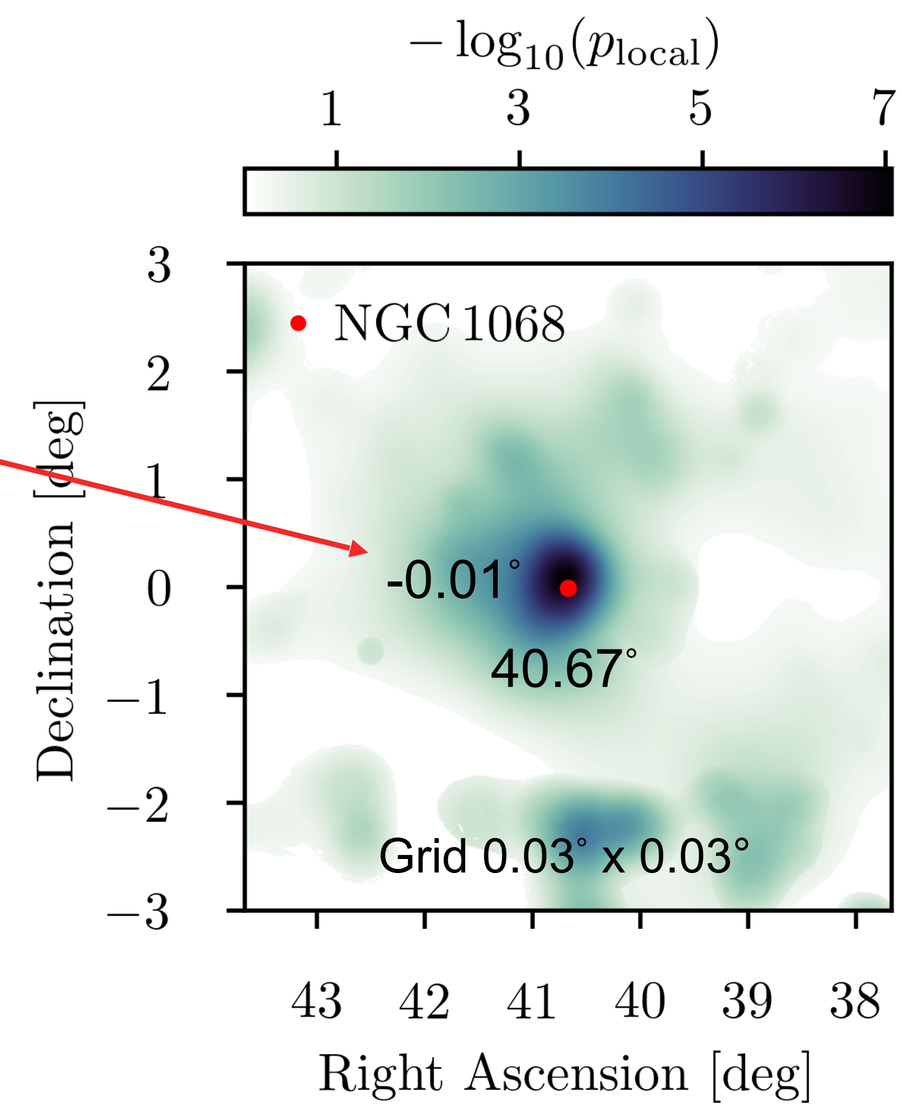


First Steady Source Association (2022)

The IceCube Coll., *Science* 378, Issue 6619, 2022

Test No. 2





At the NGC1068 location:

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

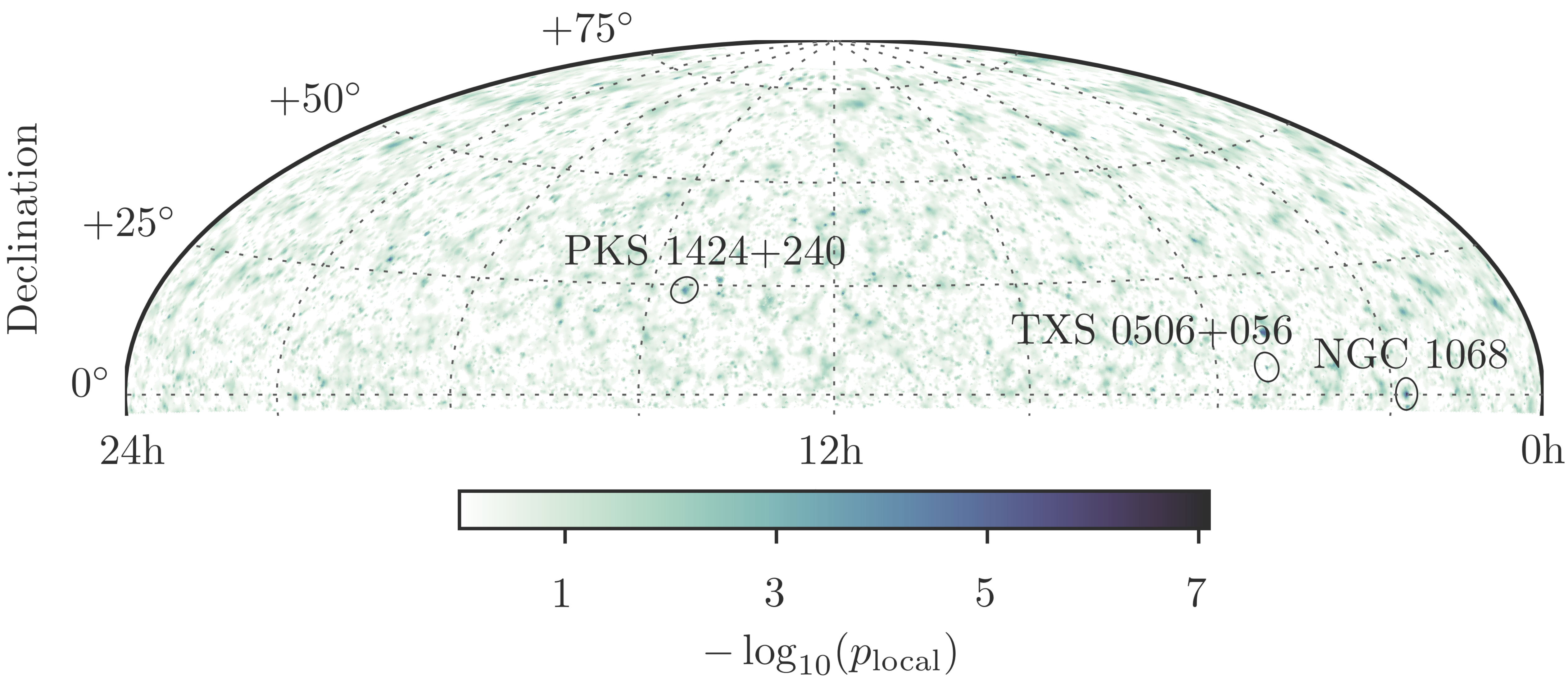
Global significance 4.2σ

First Steady Source Association (2022)

The IceCube Coll., *Science* 378, Issue 6619, 2022

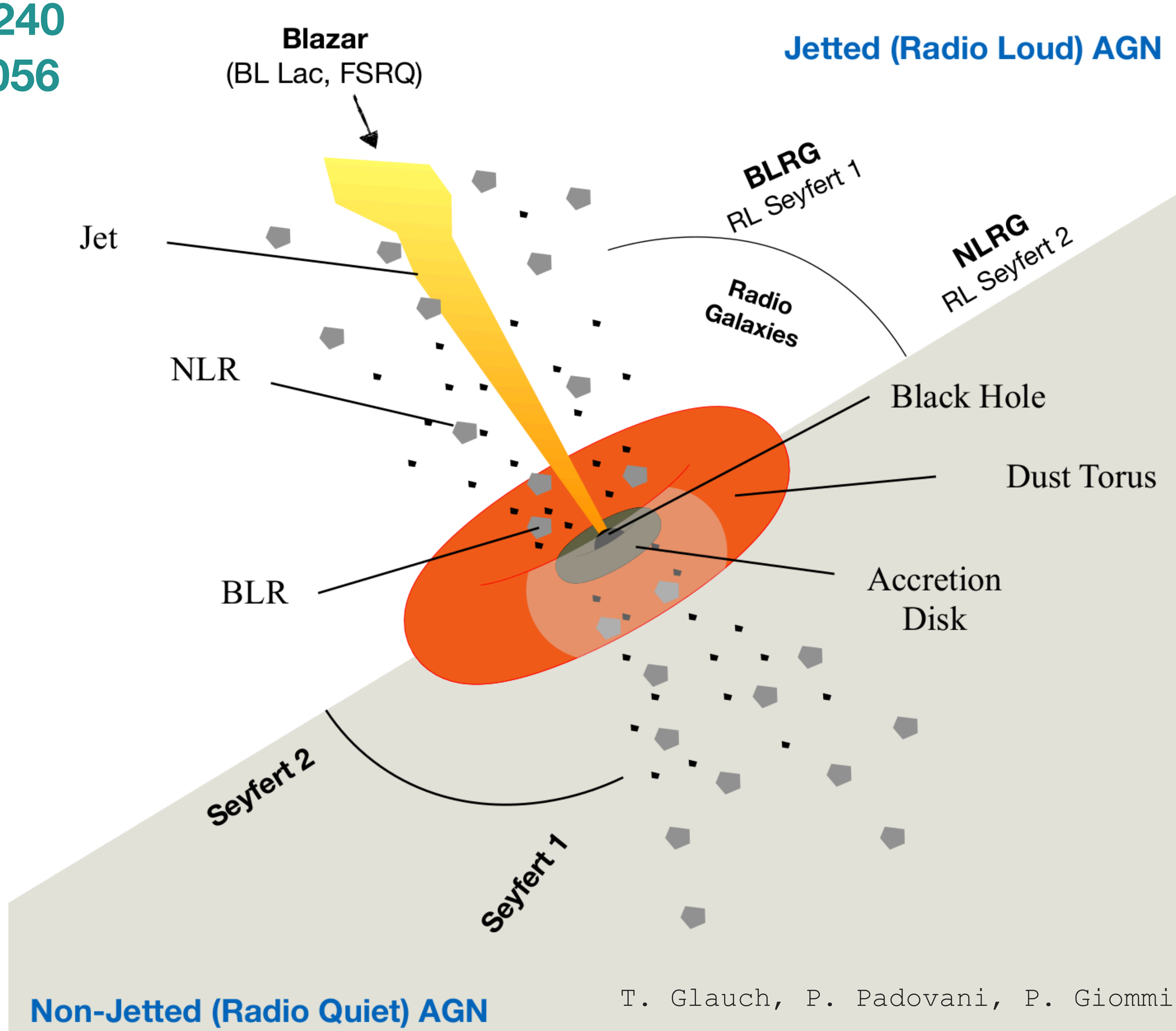
Test No. 3

3.4 σ excess in binomial test: NGC 1068, PKS 1424+240, TXS 0506+056.



Identifying Emerging Objects: The AGN zoo

PKS 1424+240
TXS 0506+056



NGC 1068

Exploring NGC 1068:
A Non-Jetted AGN with Obscured Black Hole

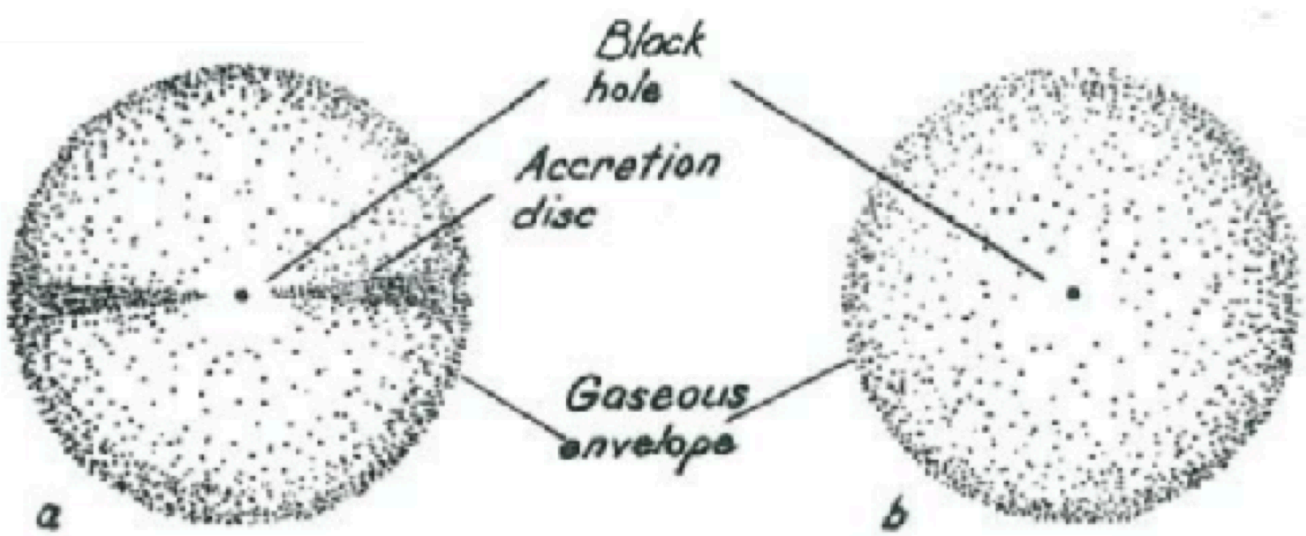
Credit: NASA/JPL-Caltech

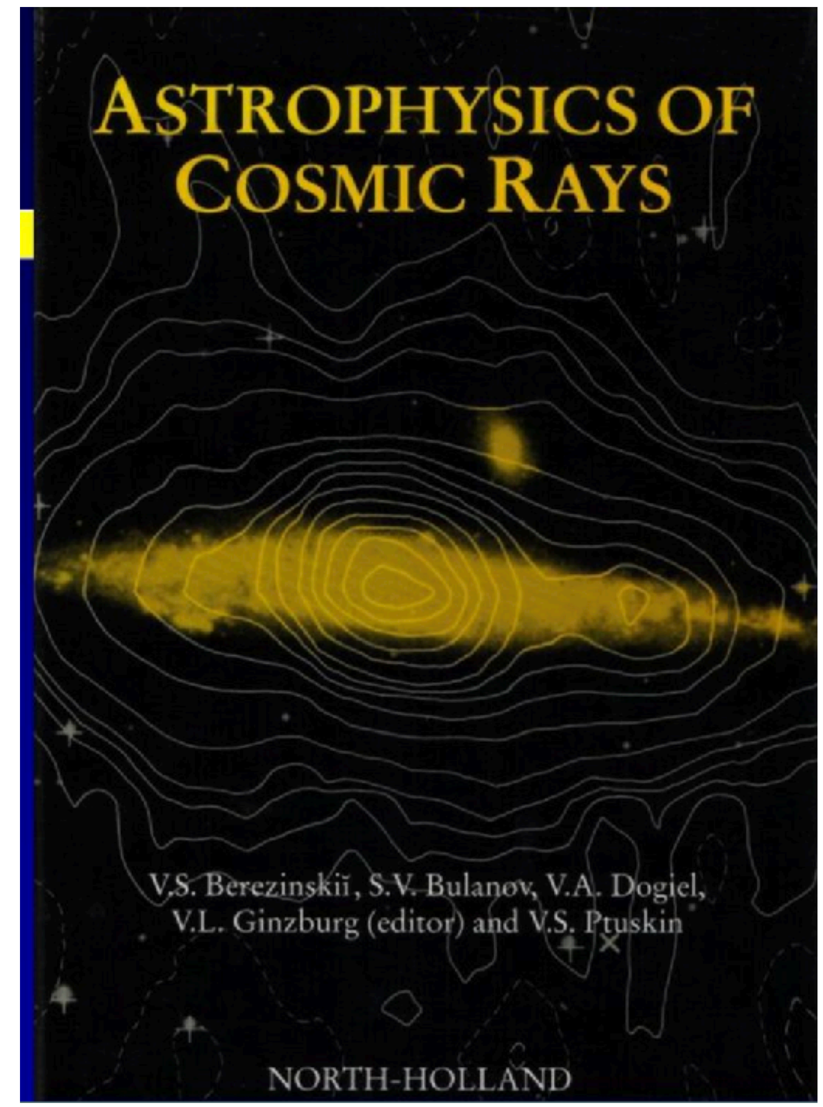
Exploring the nature of NGC1068

This is work on going

§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).





see S. Gabici (MIAPbP'23)

Exploring the nature of NGC1068

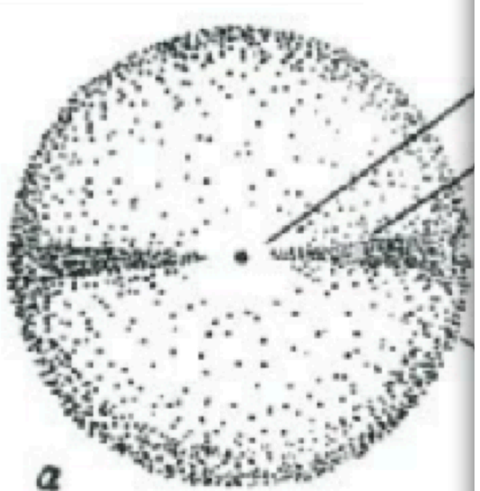
This is work on going

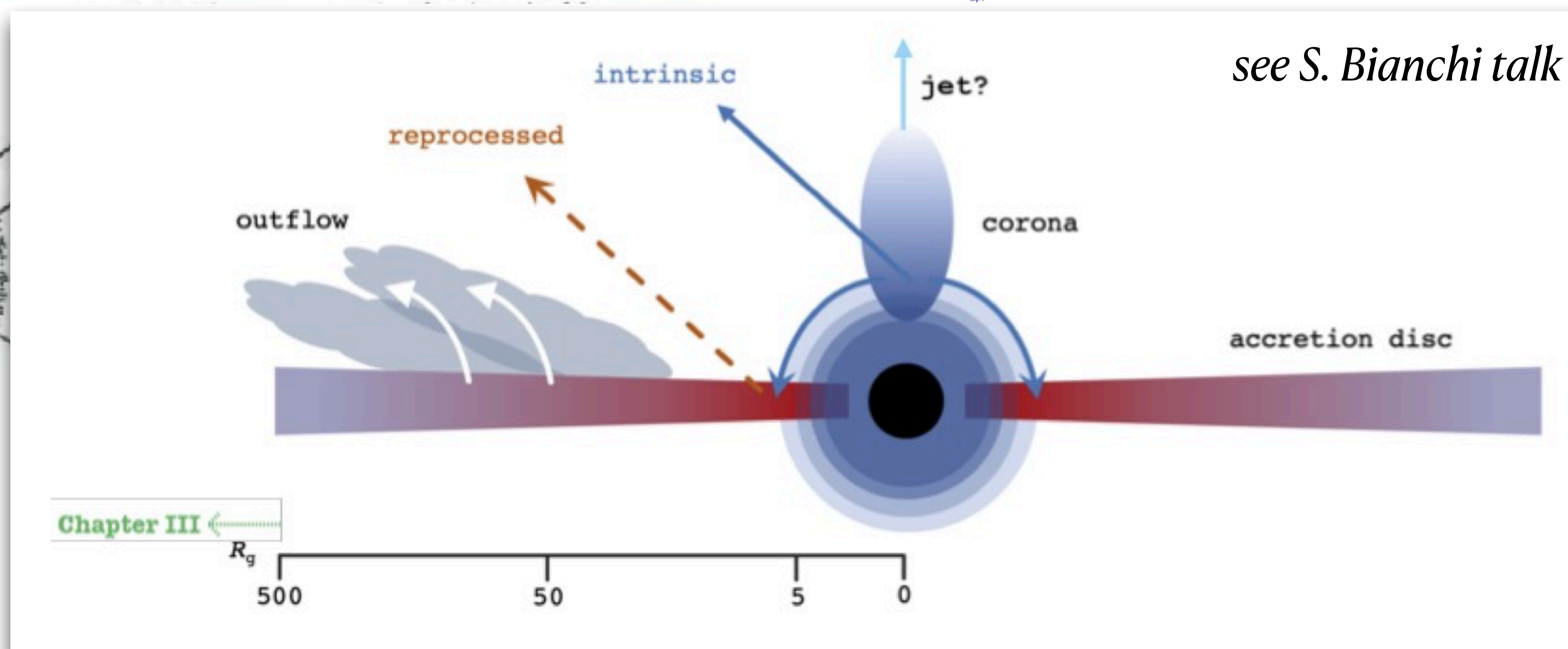
see S. Gabici (MIAPbP'23)

§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).

Idea consistent with the 'corona' X-ray field observed in Seyfert





On Particle Acceleration around Massive Black Holes

see P. Blasi (MIAPbP'23)

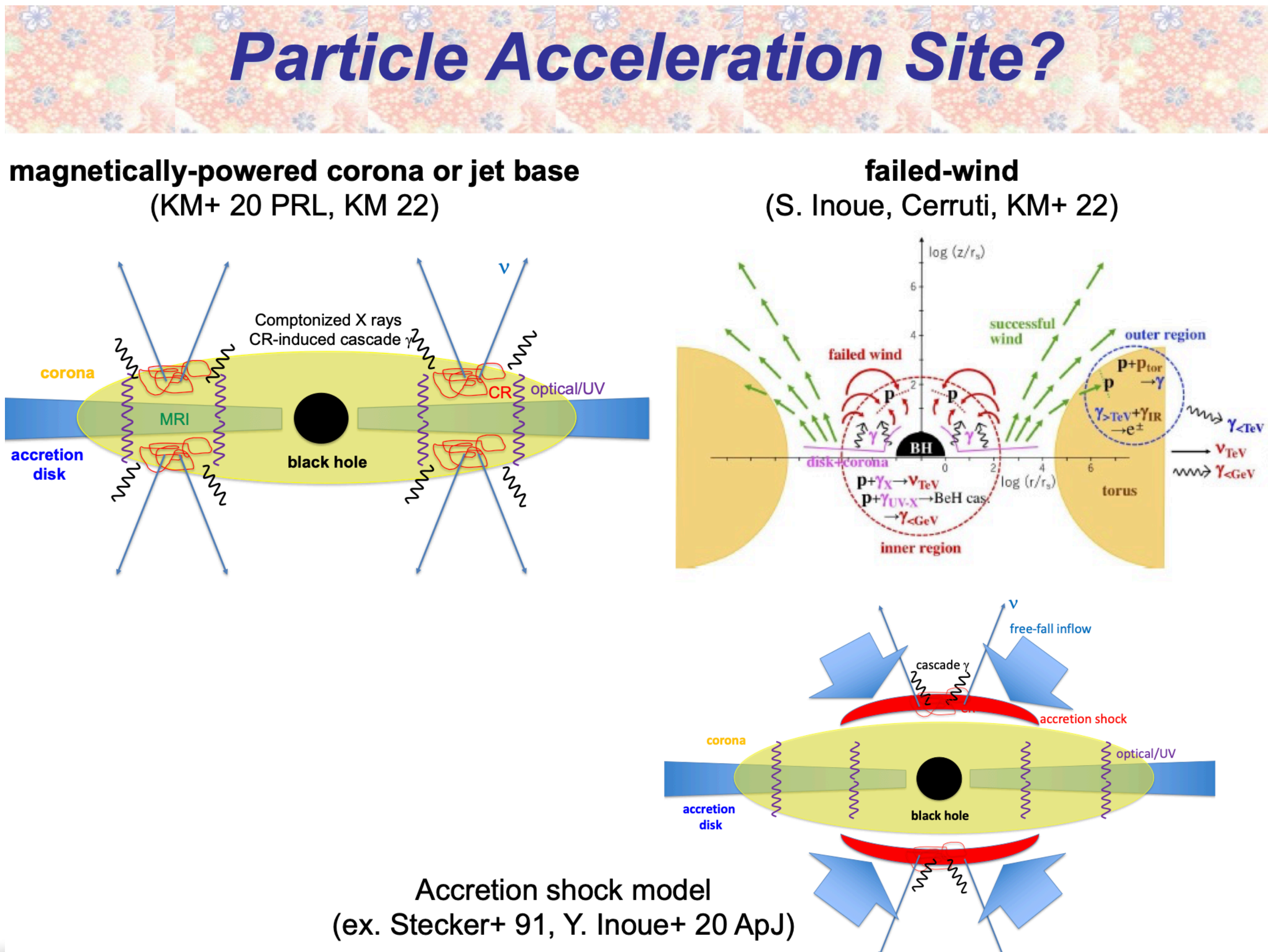
Summary and Conclusions

- Particle Acceleration near the black hole as due to interaction with turbulence seems to be possible given that $v_A/c \sim 0.1$ for typical values of the parameters
- Some care needs to be put however in assessing the cascade of the turbulence to the very small scales needed for injection (not trivial)
- Reconnection could serve as a useful injection mechanism for particles in MHD turbulence
- In MHD turbulence, acceleration is mainly a secular increase accompanied by first order processes in converging islands… very hard spectra in systems in which escape is impossible
- Unipolar induction due to the rotation of the accretion disc is in principle possible
- At larger distances from the BH, in the bubble excavated by the UFO, particle acceleration would take place at the termination shock. But gamma ray absorption not sufficient to also produce neutrinos without overshooting gamma rays

40

On Particle Acceleration around Massive Black Holes

see K. Murase (MIAPbP'23)



On the hidden source mechanisms

see P. Gabici talk

Berezinsky's prediction

$$p + \gamma \longrightarrow n + \pi^+$$

$$p + \gamma \longrightarrow p + \pi^0$$

same probability

- all protons interact w. a photon before escaping
  - if a neutron is generated, it escapes the system
    - otherwise, the proton loses a bit of its energy
      - the proton interacts then with another photon

M. Weiss

Which radiation field?

threshold energy

$$E_p^{min} \approx 60 \left(\frac{\epsilon_\gamma}{\mathrm{eV}}\right)^{-1} \mathrm{PeV}$$

$$\frac{E_\nu}{\mathrm{TeV}} \in [1.5 - 15]$$

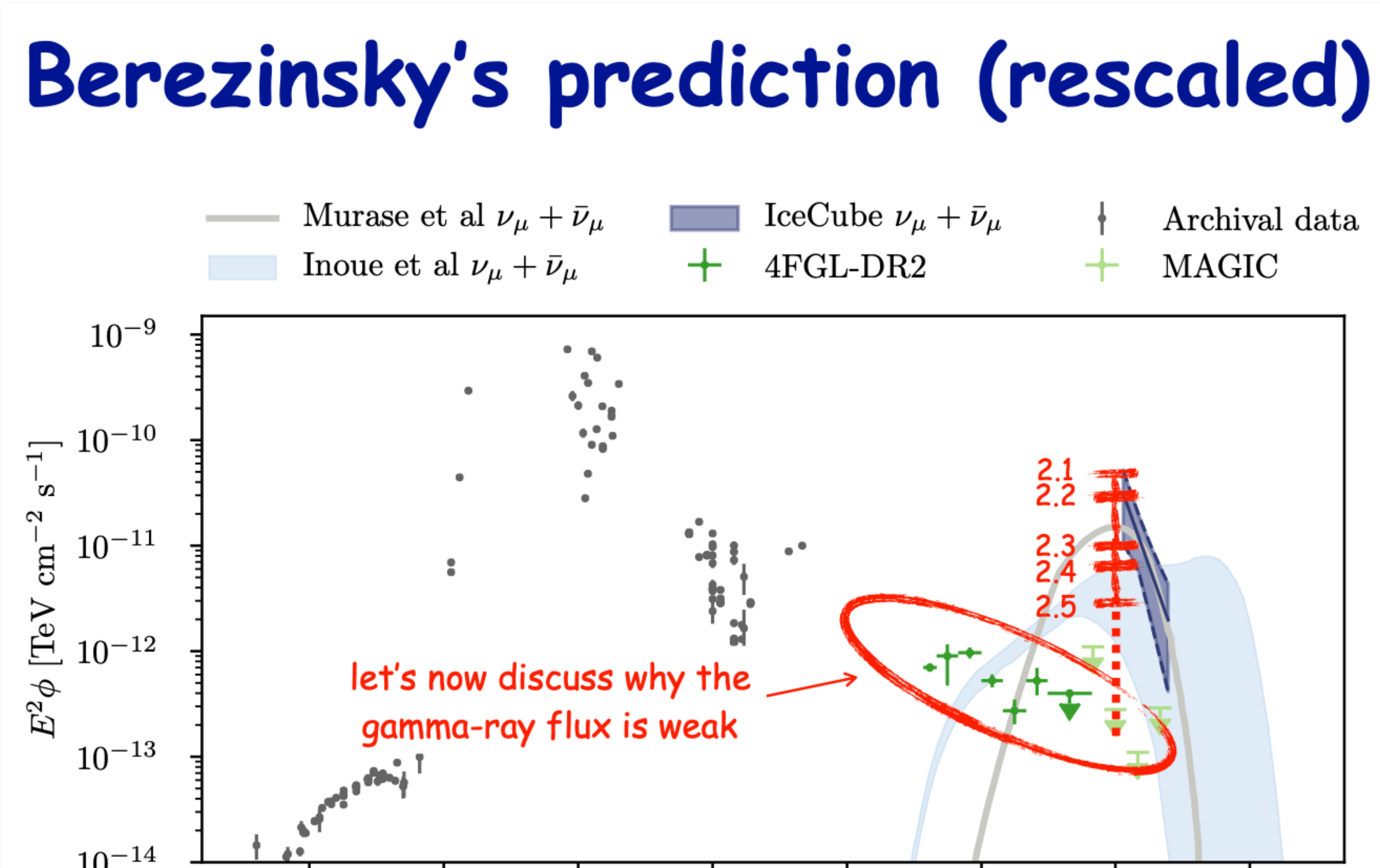
$$\frac{E_p}{\mathrm{TeV}} \in [40 - 400]$$

$$\frac{\epsilon_\gamma}{\mathrm{keV}} \in [0.2 - 2]$$

soft X-rays
an hot corona?

On the hidden source mechanisms

see P. Gabici talk

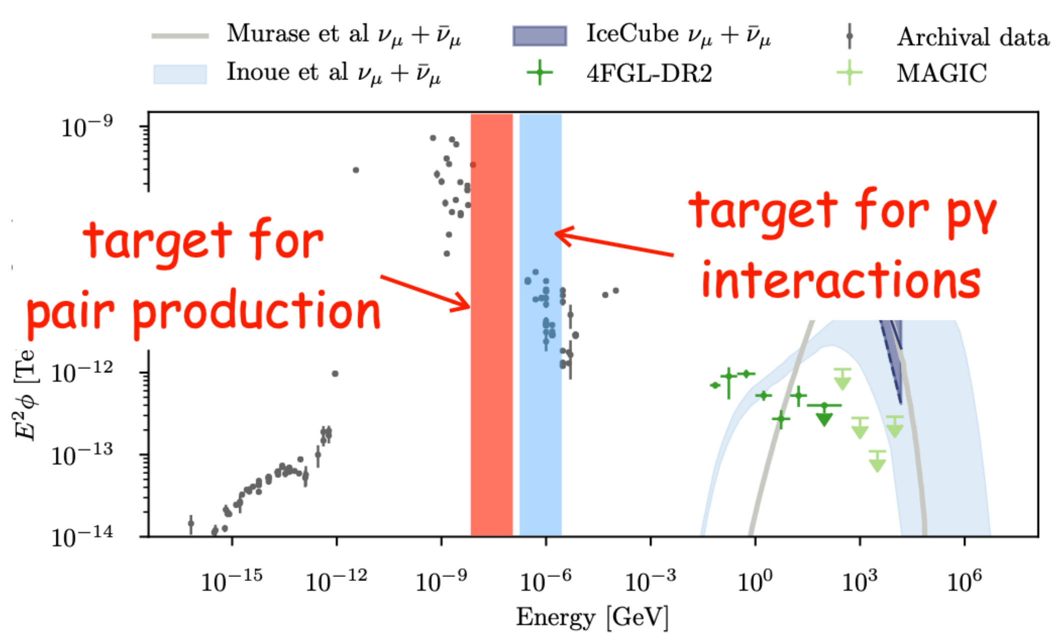


note that the equation derived by Berezinsky implicitly assumes that soft photons of the "right" energy are present

On the hidden source mechanisms

see P. Gabici talk

$$\frac{E_\gamma}{\mathrm{TeV}} \in [3 - 30] \quad \Rightarrow \quad \frac{\epsilon_\gamma}{\mathrm{keV}} \in [0.01 - 0.1]$$



and

$$\frac{\sigma_{\gamma\gamma}}{\sigma_{p\gamma}} \lesssim 1000$$

—> photons produced in pγ interactions cannot escape!

On distance: astronomy is not easy

How far is NGC1068?? we used 14.4 Mpc (Tully 1988)

see P. Padovani talk

recommended distance

NASA/CXC/M. Weiss

$$D_L = 10.1 \pm 1.8\,\mathrm{Mpc}$$

luminosity to be rescaled

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

(~0.5L_ν in IceCube - Science 2022)

Energetic arguments

see P. Padovani talk

Emission powers (erg/s)

	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: ~ $10^{41.5}$

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

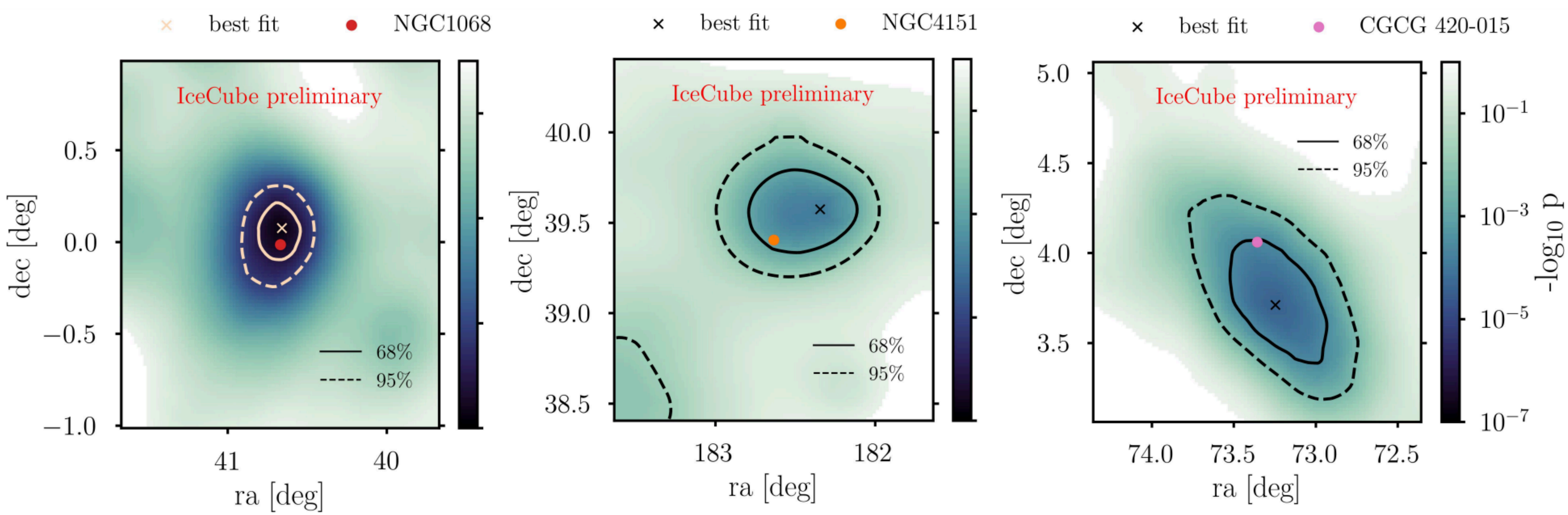
$L_\nu = 1.4 \cdot 10^{42}$ erg/s
(~0.5L_ν in IceCube - Science 2022)

What happens close to a supermassive black hole (SMBH)?

??????

@rdvvector

We don't know, but other Seyfert are appearing



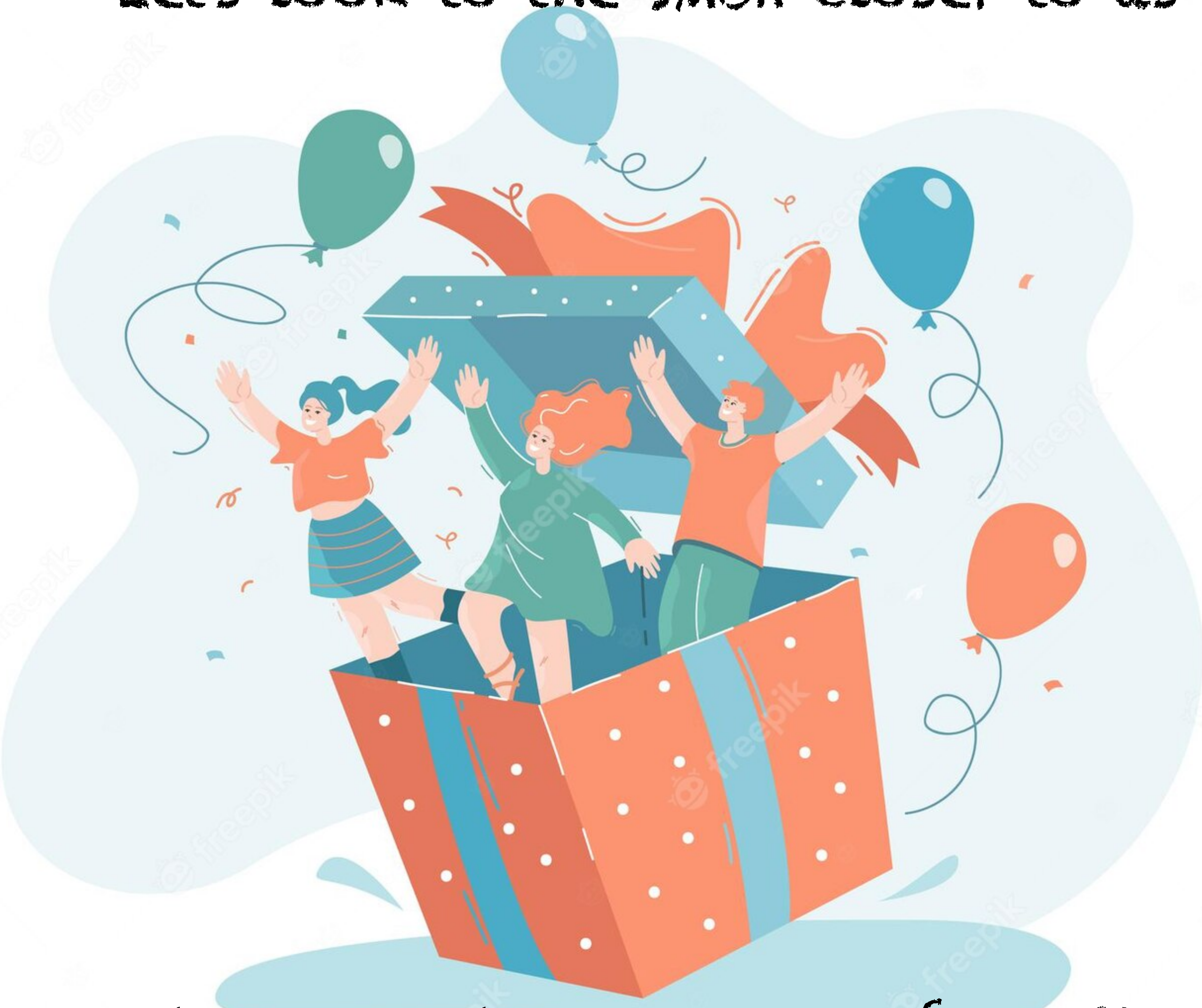
NGC 1068	NGC 4151	CGCG 420+15
contour / likelihood map differs from Science 378 (2022) due to choice of flux model (disc-corona model)	n_s = 22	n_s = 31
can not differentiate between flux models	p_{local} = 6x10^{-4}	p_{local} = 2x10^{-4}
excluded from blind searches		

catalog search **"hottest source"** (after accounting for trials) p = 0.01 (2.3σ)

13

see C. Bellenghi, H. Niederhausen (MIAPbP'23)

Let's look to the SMBH closer to us



A clear signal is emerging from the Galactic plane!!!

@rdvvector

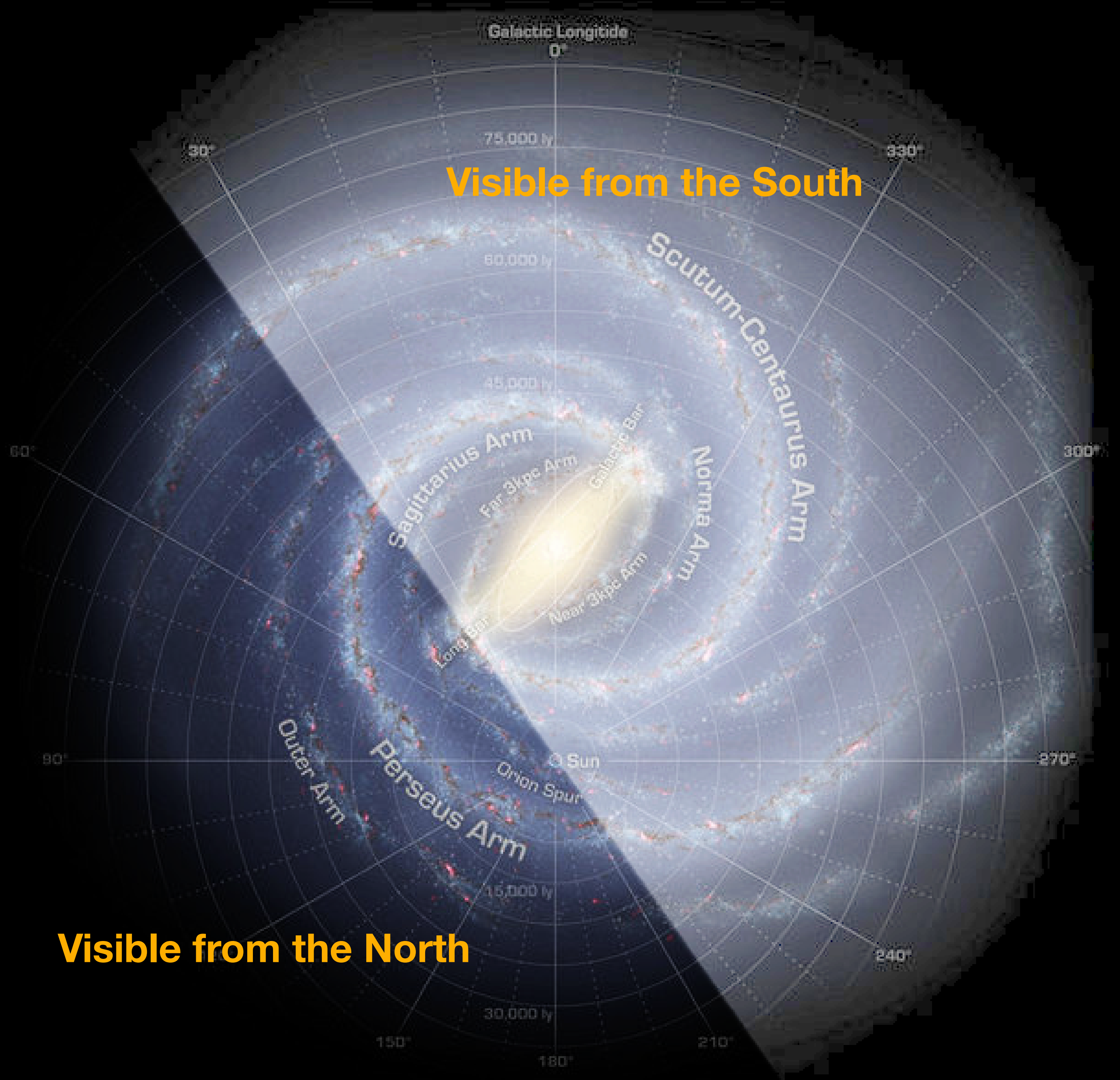
The Milky Way

Benjamin, R. A. (2008). "The Spiral Structure of the Galaxy: Something Old, Something New...". In Beuther, H.; Linz, H.; Henning, T. (ed.). *Massive Star Formation: Observations Confront Theory*. **387**. Astronomical Society of the Pacific Conference Series. pp. 375. Bibcode 2008ASPC..387..375B.
See also Bryner, Jeanna (2008-06-03). "New Images: Milky Way Loses Two Arms". *Space.com*. Retrieved 2008-06-04.

https://www.pablocarlosbudassi.com/2021/05/milky-way-map.html

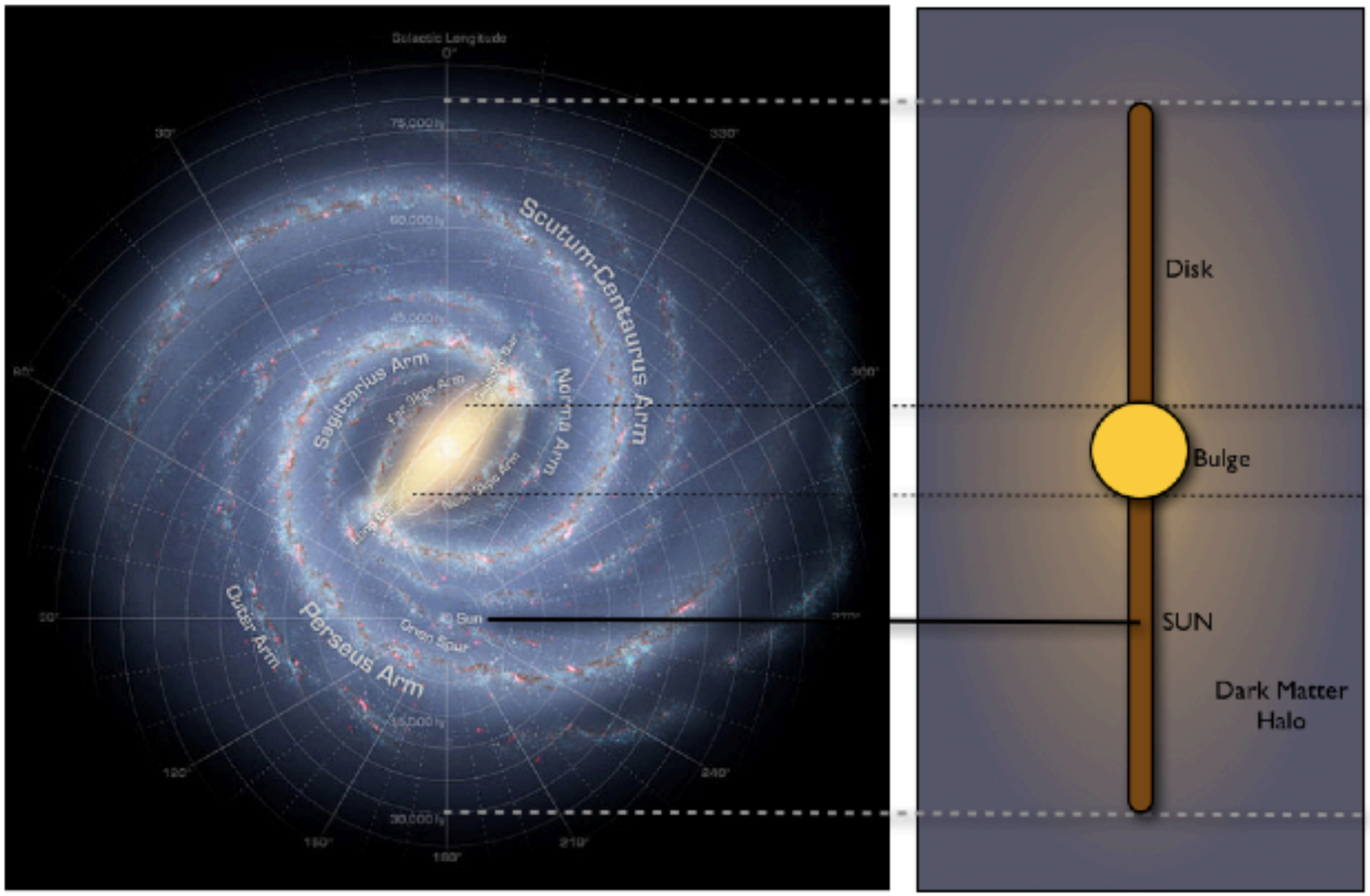
The Milky Way

Benjamin, R. A. (2008). "The Spiral Structure of the Galaxy: Something Old, Something New...". In Beuther, H.; Linz, H.; Henning, T. (ed.). *Massive Star Formation: Observations Confront Theory*. **387**. Astronomical Society of the Pacific Conference Series. pp. 375. Bibcode 2008ASPC..387..375B.
See also Bryner, Jeanna (2008-06-03). "New Images: Milky Way Loses Two Arms". *Space.com*. Retrieved 2008-06-04.



The Milky Way

The Sun lies within the galactic disk at about 8.5 kpc from the galactic center on the inner edge of the Orion-Cygnus Arm

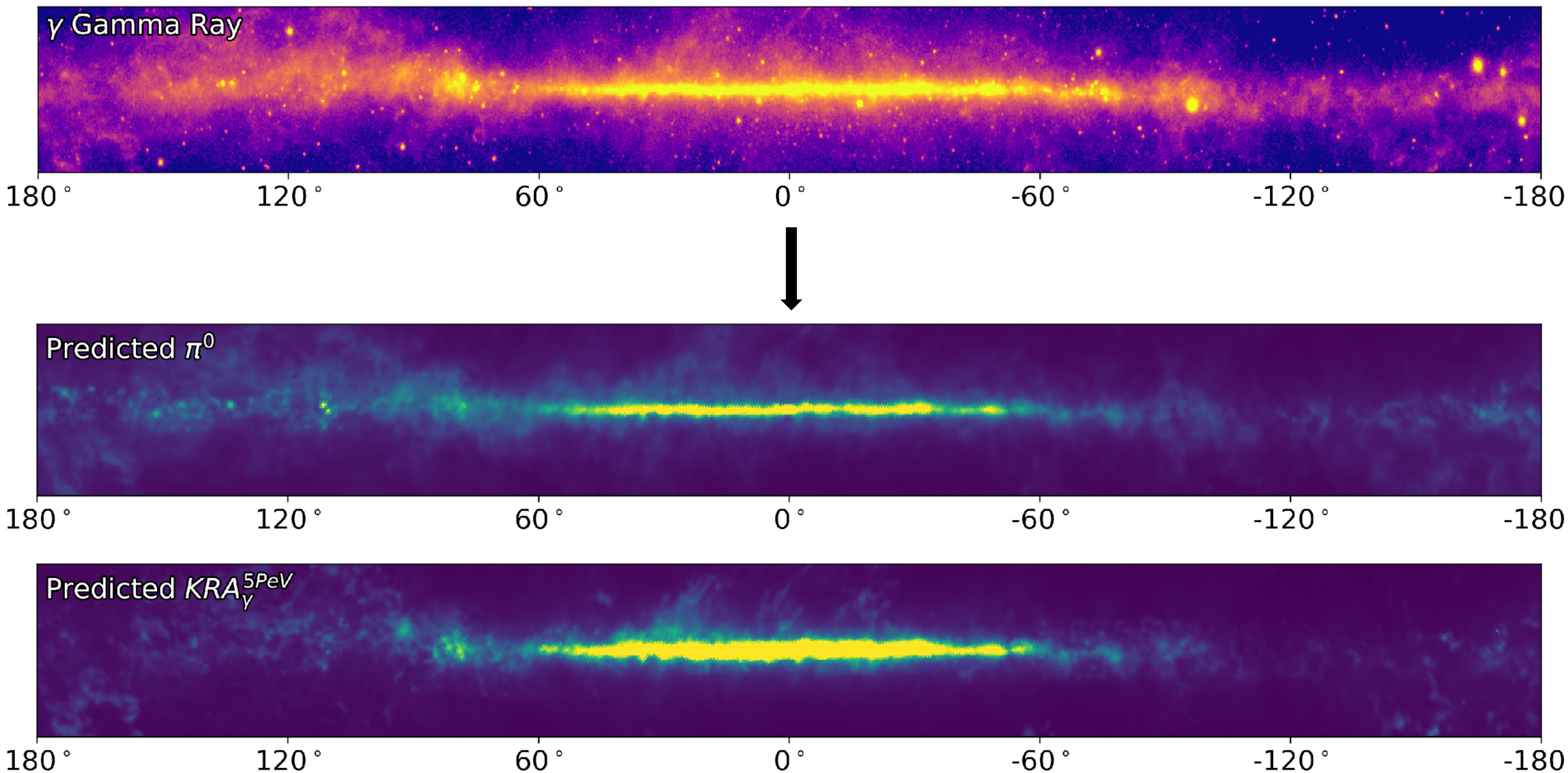


E.R.

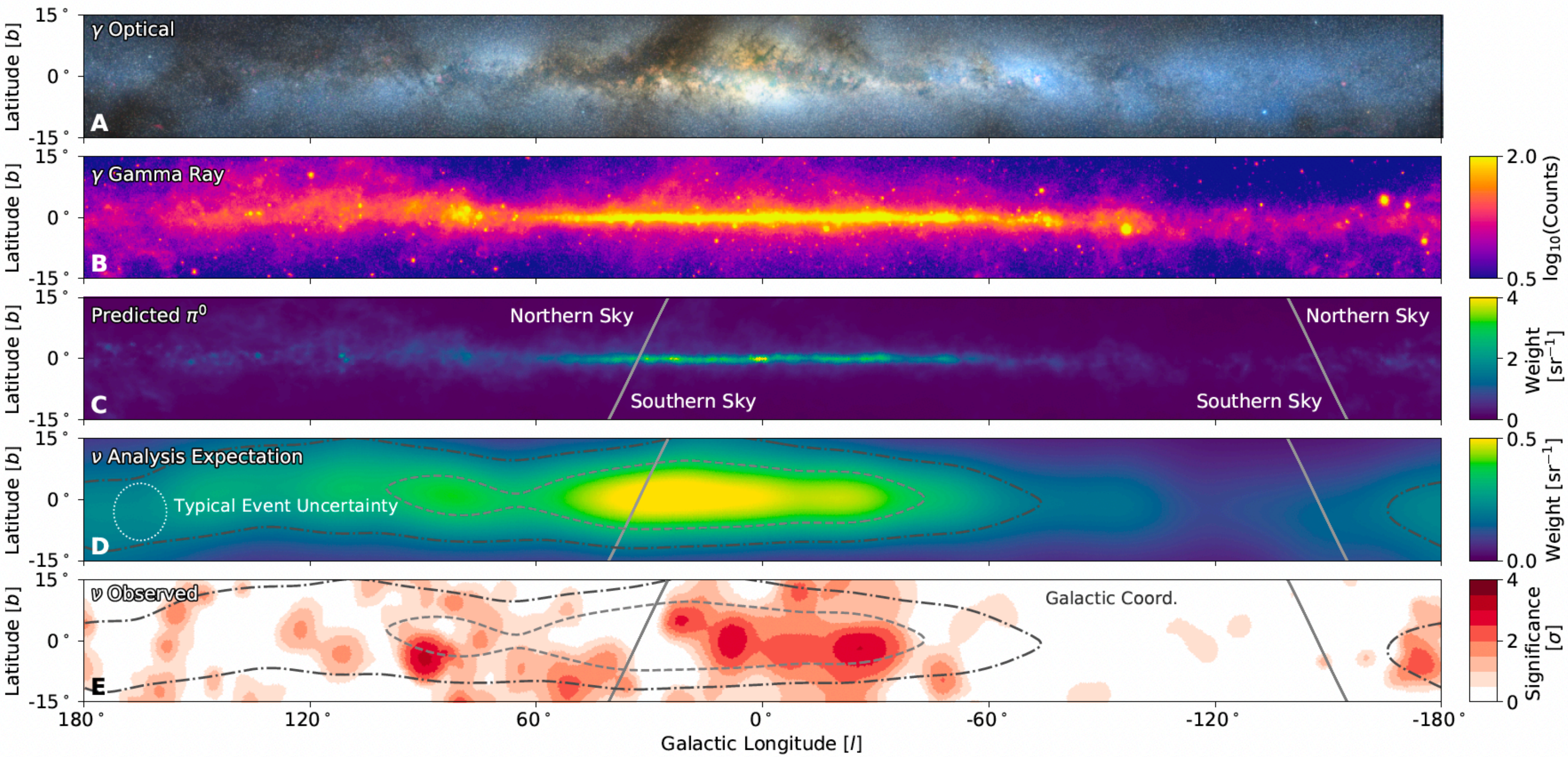
Thin disk or galactic plane, radius ~20 kpc, thickness 400-600 pc
Bulge or galactic center, radius 2-3 kpc
Halo, extended up to 30 kpc

Neutrino Counterpart to Diffuse Gamma Rays

1. Ackermann et al. *The Astrophysical Journal* 750, no. 1 (April 2012): 3.
2. Gaggero et al *The Astrophysical Journal* 815, no. 2 (December 2015): L25.



NEW: Neutrinos from the Galactic plane
4.5σ level of significance - IceCube 29.06.23



Neutrinos from the Milky Way

4.5σ evidence after accounting for multiple tests

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

The Milky Way: Candidate Galactic Cosmic Sources

Standard Matter (to be distinguished from Dark Matter) concentrated in the thin disk, composed of:
- stars of various ages
- interstellar matter (ISM)

ISM: filled with gas, dust and cosmic rays, it accounts for 10-15% of the total mass of the galactic plane. The gas is very inhomogeneously distributed at small scales and confined to discrete clouds;
- composition of the gas (by number): 90% H, 9% He + heavier elements;
- how to map the gas in our Galaxy? use atomic transition between two hyperfine levels of the hydrogen 1s ground state;
- 21 cm line of neutral hydrogen (HI) = electromagnetic radiation emitted @ 21 cm (wavelength) = radio wavelength;
- HI shows diffuse distribution in cool denser regions called clouds. Typical density: 1-500 atom/cm^3.
- H2 or molecular hydrogen is the most abundant interstellar molecule. It can't be observed directly. Spectral lines of CO and other tracers are used in order to map the molecular gas distribution. Molecular gas organized in discrete clouds of various sizes. From giant complexes down to small dense cores. Density in the clouds up to 10^8 atoms/cm^3.

- **Giant Molecular Clouds (GMCs)**: mass 10^4-10^6 $M_\odot$
- A gas cloud becomes unstable with respect to its own gravity if its mass

M_C > critical mass = Jeans' mass
(gravitational collapse within a gaseous cloud)

- possible (but not yet proved) trigger of star formation one Jeans' instability reached in GMCs

The Milky Way: Candidate Galactic Cosmic Sources

Star formation:
NOT clear how triggered and how sustained but observed in GMC;

Associations: group of newly formed stars found in clusters:
- OB associations: bright and heavy O and B type stars;
- T (Tauri stars) associations made up of light stars close to the solar mass .

Important for us: stars are formed in star forming regions which are somehow connected to GMCs. In GMCs stars get formed, evolved and eventually dies in **SUPER-NOVAE** (SN) and producing SUPERNOVAE REMNANTS (SNRs).

SN and SNRs "feedback" the ISM from the chemical and energetic point of view. They can trigger new star formation … eventually the Galaxy it is a closed loop!

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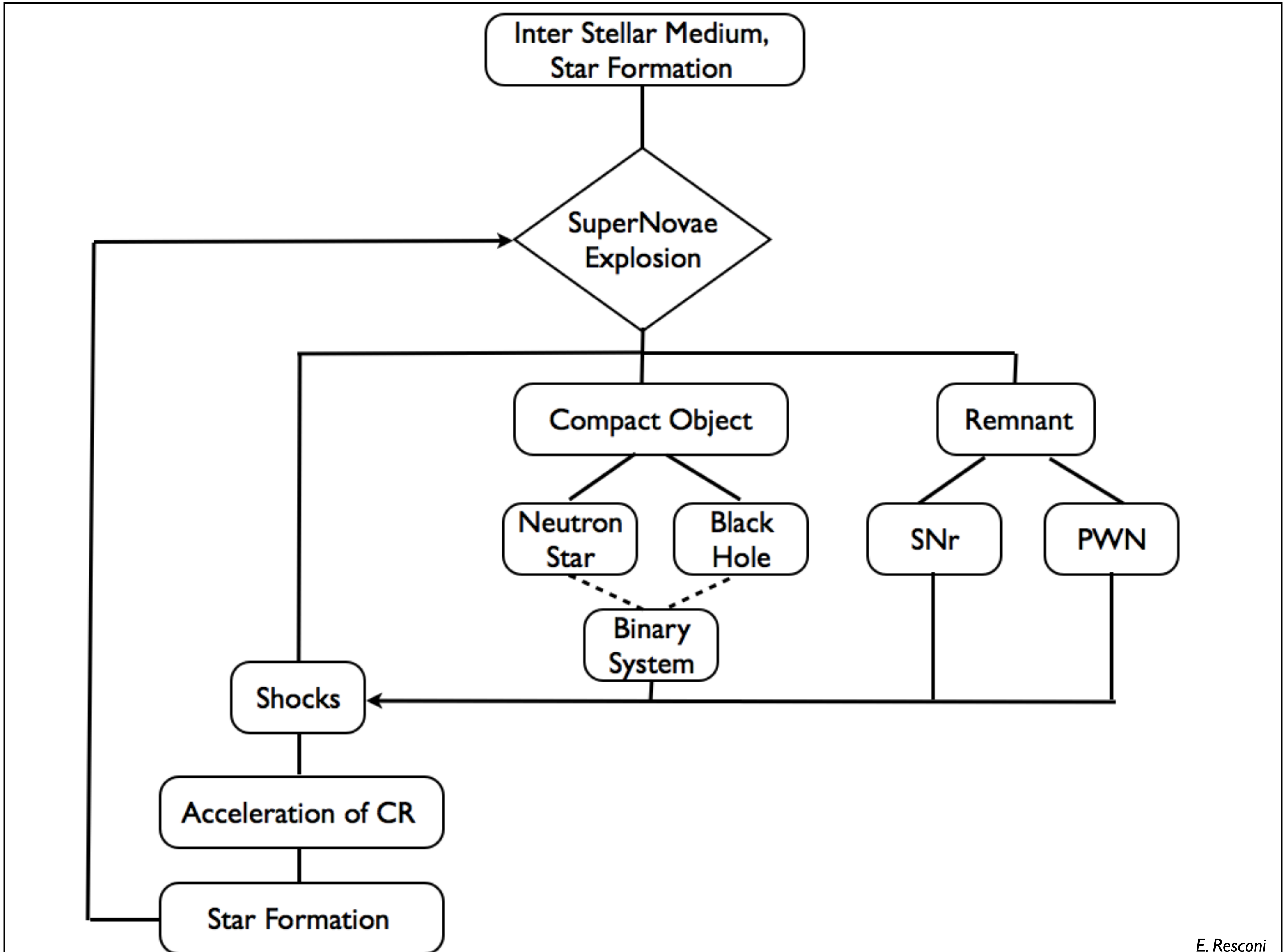


SuperNovae Remnants (SNRs)

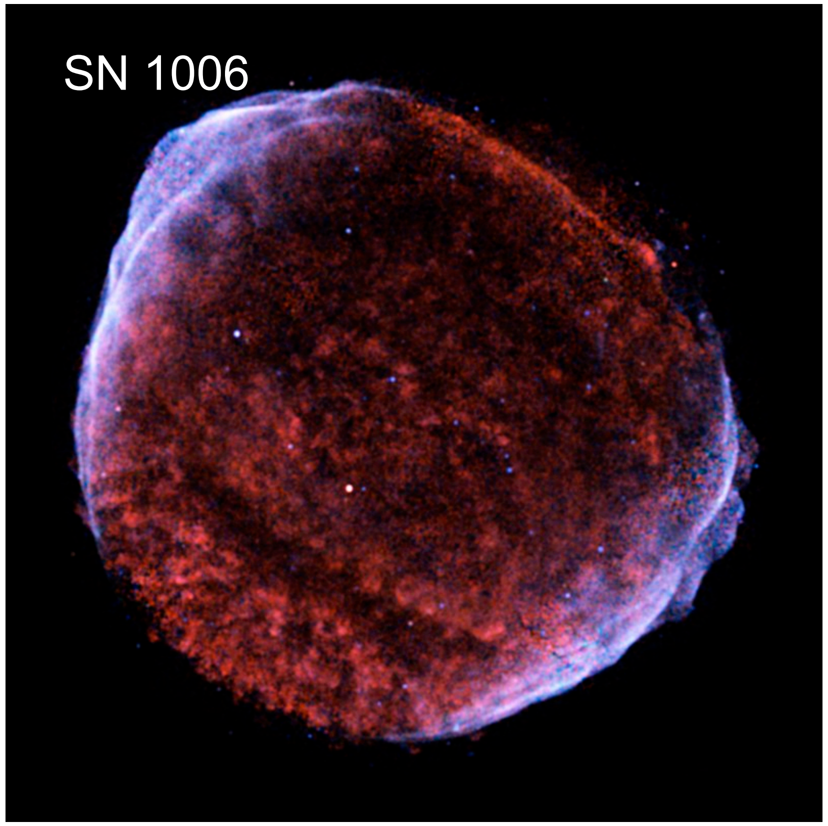
SN observed by “eye” in our Galaxy during the last 1000 years

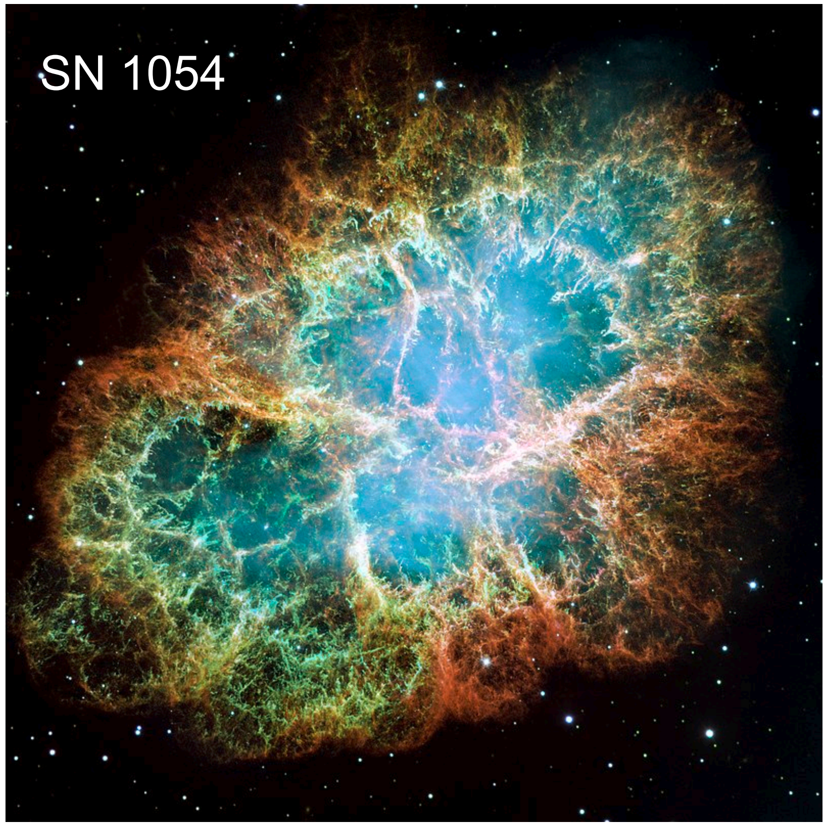
➔ SN 1006, SN 1054 (Crab Nebula), SN 1572 (Tyco), SN 1604 (Kepler)

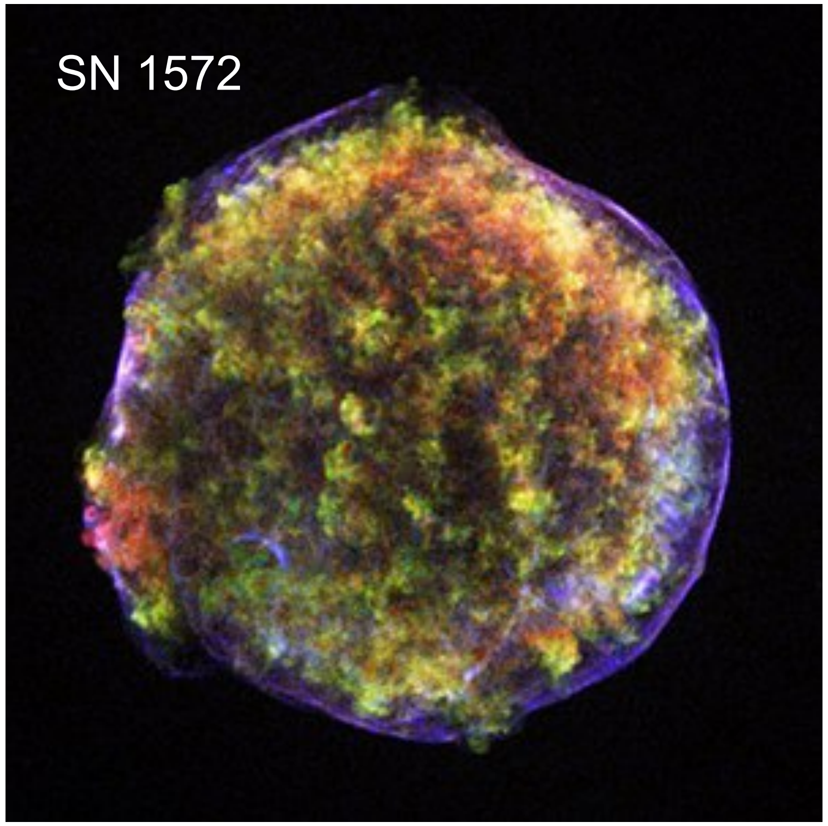
➔ SN1987A

Others could have been obscured by dust (for example. Cassiopaeia A).

Powered by a pulsar







SuperNovae Remnants (SNRs)

Supernovae Remnants as cosmic particle accelerators? plausible idea since 1934.

First idea: W. Baade, F. Zwicky, Proceeding of the National Academy of Science, 20, 259. 1934 (http://www.pnas.org/content/20/5/254)

- the intensity of CR is practically independent of time;
- in order to maintain the CR level in the galaxy at the observed one, it is enough that about 10% of the kinetic energy of the galactic SN is converted in CR;
- the kinetic energy of the SN can be efficiently transmitted to the CR via shock waves formed during the expansion of SN remnants (SNRs) in the interstellar medium (Fermi mechanism);

In order to accelerate particles at sufficiently high energies, energetic particles have to cross the shock front multiple times and be scattered by turbulent magnetic fields which are self-generated by the particles themselves (see Bell, A.R., 1978a, MNRAS, 182, 147, L.O.Drury, Reports on Progress in Physics, 46, 973, 1983).

First investigations revealed that the maximum energy reachable in shocks in supernova remnants is quite lower than the energy at which the knee is observed (Lagage, P.O., and Cesarsky, C.J., 1983, A&A, 118, 223).

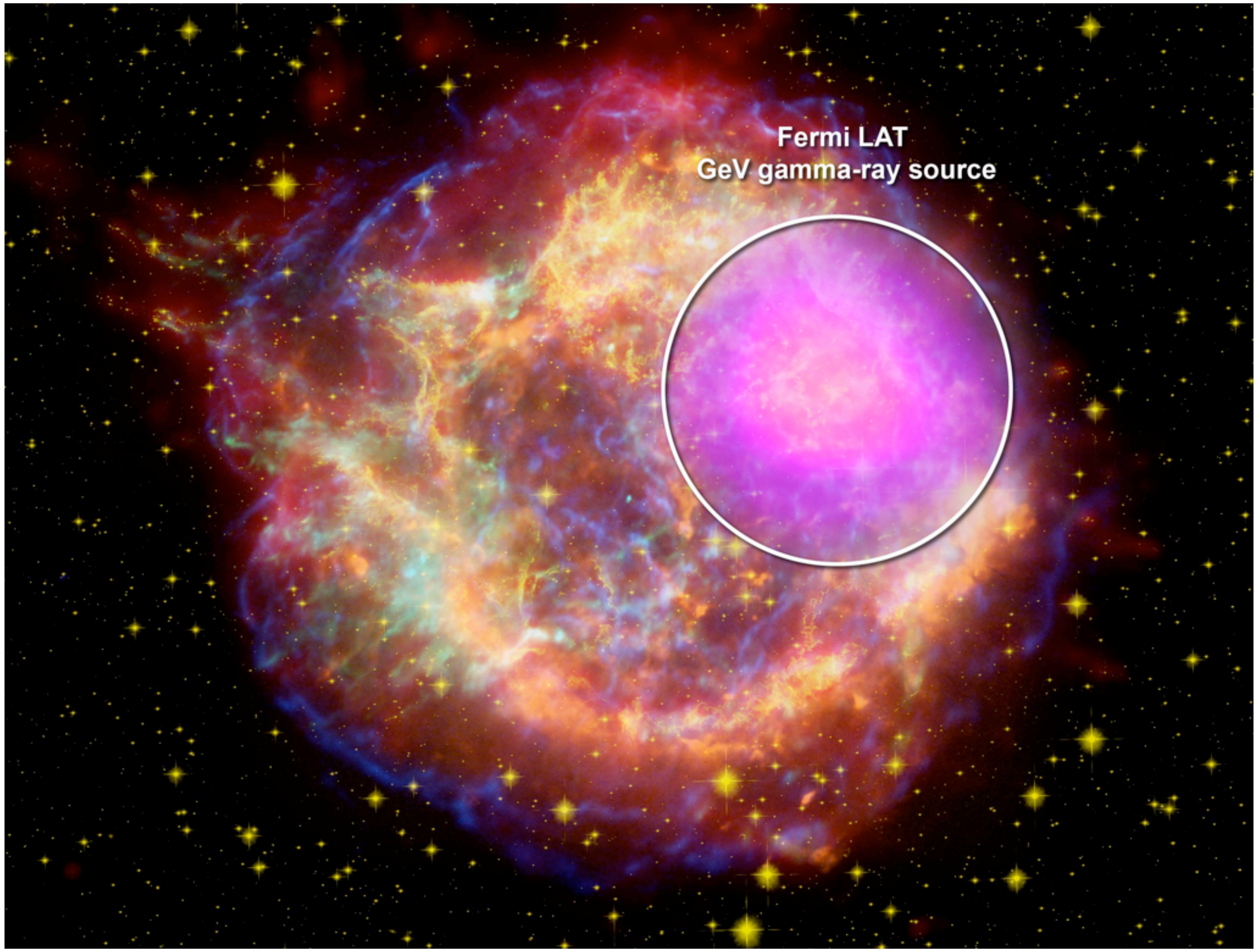
Only once all the relevant non-linear effects are taken into account as in (Blasi, Monthly Notices of the Royal Astronomical Society Volume 375, Issue 4, pages 1471–1478, March 2007), the maximum momentum of accelerated particles can be as high as $p_{max} \sim 10^6$ GeV/c.

➔ diffusive shock acceleration in SNRs gives the theoretical framework for efficient GCR acceleration
➔ predicted emission spectra proportional to $E^{-2.1}$
➔ what about experimental confirmation of this scenario?

SuperNovae Remnants (SNRs): phases

Example of SNR in between Phase I and Phase II: Cassiopeia A

Explosion around 1667 but no record (probably obscured)
Strongest radio source in our sky!



Composite shows the Cassiopeia A supernova remnant across the spectrum: Gamma rays (magenta) from NASA's Fermi Gamma-ray Space Telescope; X-rays (blue, green) from NASA's Chandra X-ray Observatory; visible light (yellow) from the Hubble Space Telescope; infrared (red) from NASA's Spitzer Space Telescope; and radio (orange) from the Very Large Array near Socorro, N.M.
Credit: NASA/DOE/Fermi LAT Collaboration, CXC/SAO/JPL-Caltech/Steward/O. Krause et al., and NRAO/AUI

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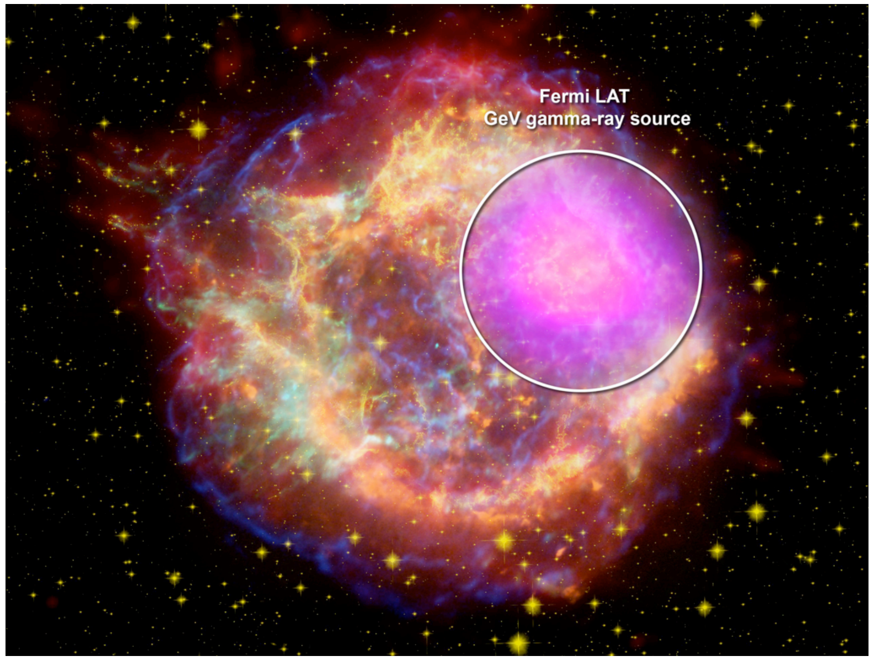


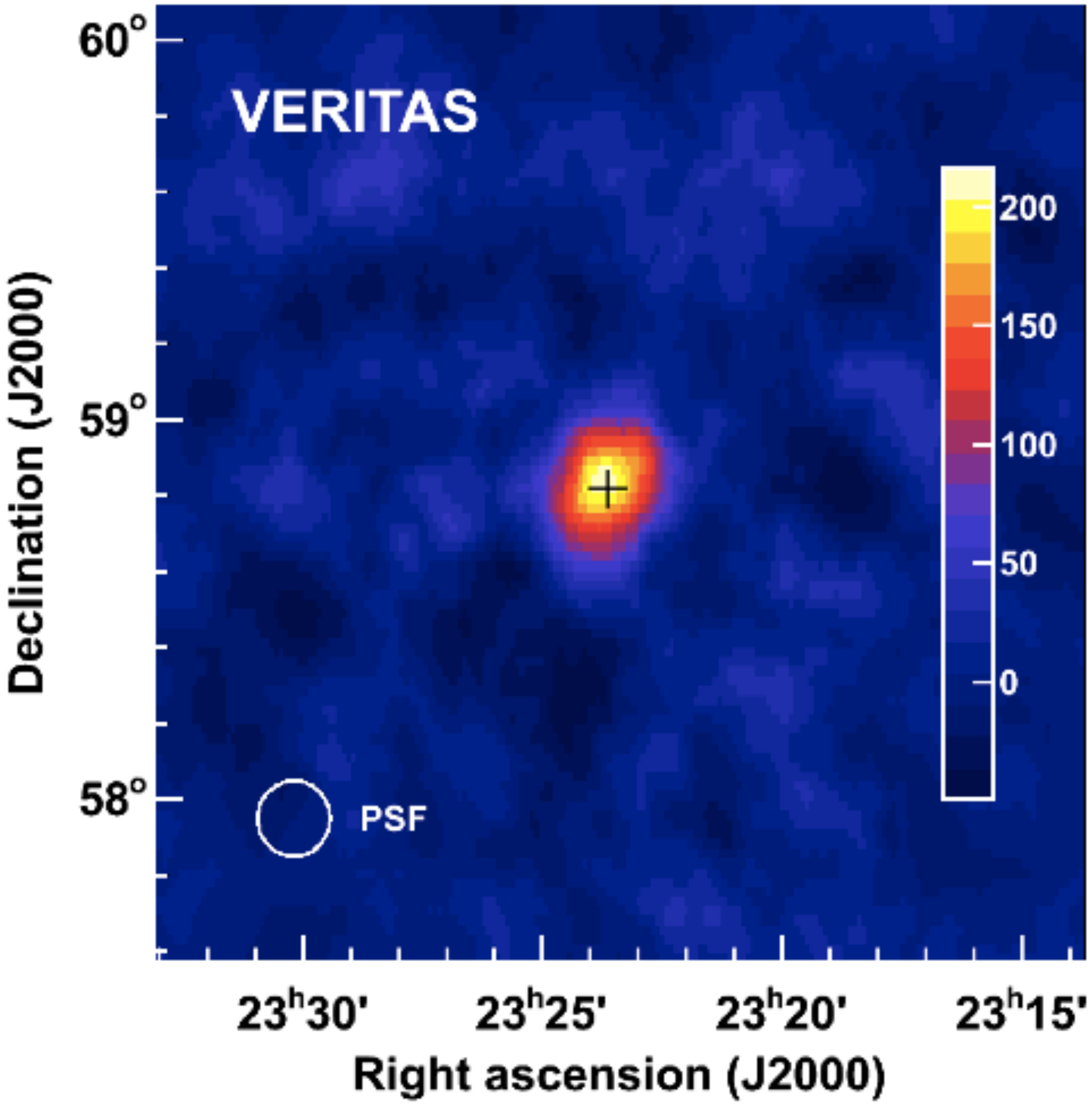


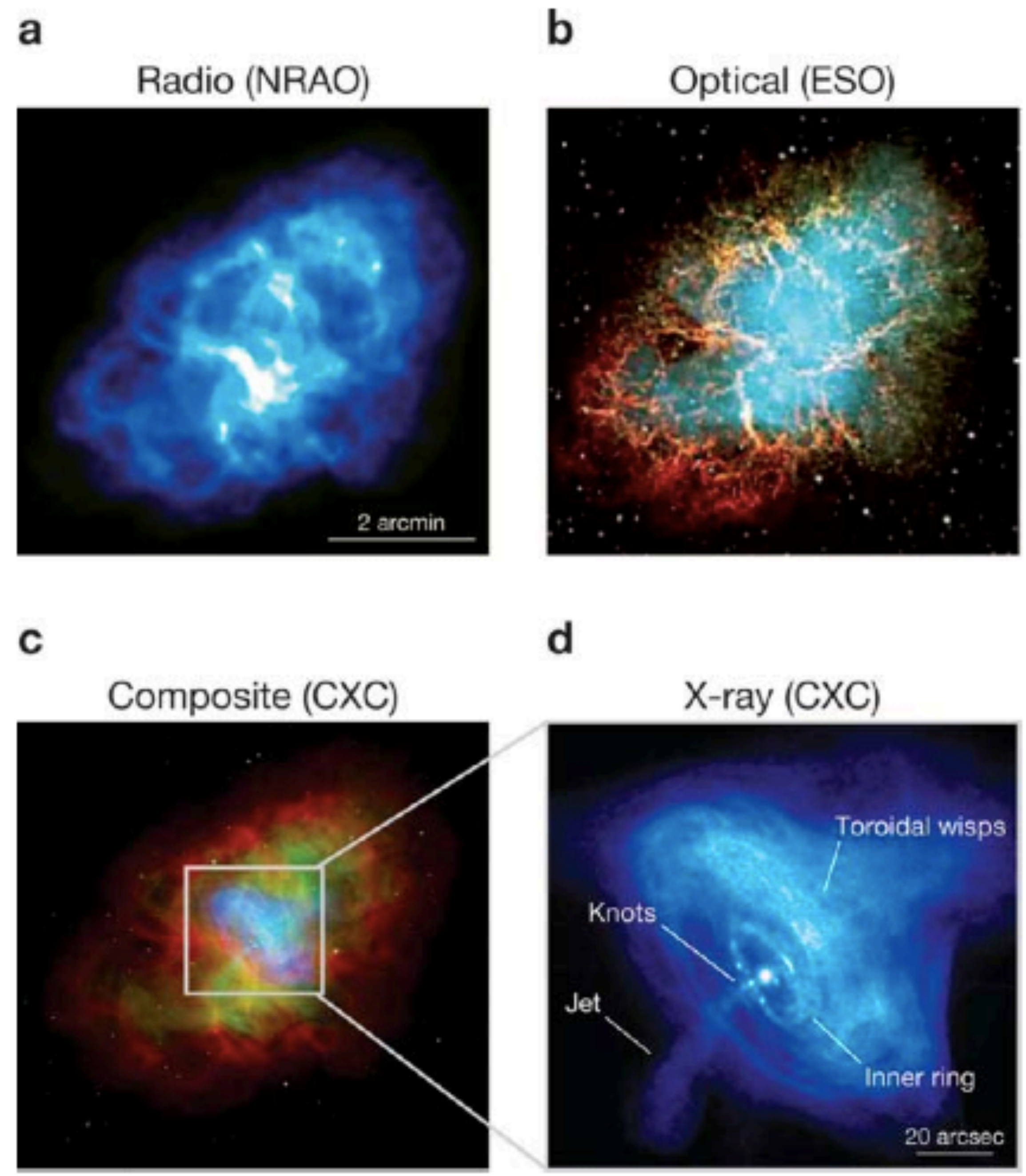
Fig. 1.— Smoothed sky map of excess counts from the region centered at Cassiopeia A observed with VERITAS for a total of 22 hours in 2007. The color bar represents the excess event counts. The white circle indicates the size of the VERITAS point-spread function. The cross indicates the measured position of the TeV γ-ray source. The radius of a smoothing circular window was 0.115°.

Again SN remnant: Pulsar Wind Nebulae (PWN)

Bryan M. Gaensler1 and Patrick O. Slane, Annu. Rev. Astro. Astrophys. 2006.44:17-47.
http://www.ira.inaf.it/~ddallaca/Gaensler_Slane.pdf

The Crab Nebula is almost certainly associated with a supernova explosion observed in 1054 CE
The remnant looks different respect shell type SNR: its energetics dominated by continuous injection of magnetic fields and relativistic particles from a central source.

Images of the Crab Nebula (G184.6–5.8). (a) Radio synchrotron emission from the confined wind, with enhancements along filaments. (b) Optical synchrotron emission (blue-green) surrounded by emission lines from filaments (red). (c) Composite image of radio (red), optical (green), and X-ray (blue) emission. (d) X-ray synchrotron emission from jets and wind downstream of the termination shock, marked by the inner ring. Note the decreasing size of the synchrotron nebula going from the radio to the X-ray band. Each image is oriented with north up and east to the left. The scale is indicated by the 2 arcmin scale bar, except for panel (d), where the 20 arcsec scale bar applies.



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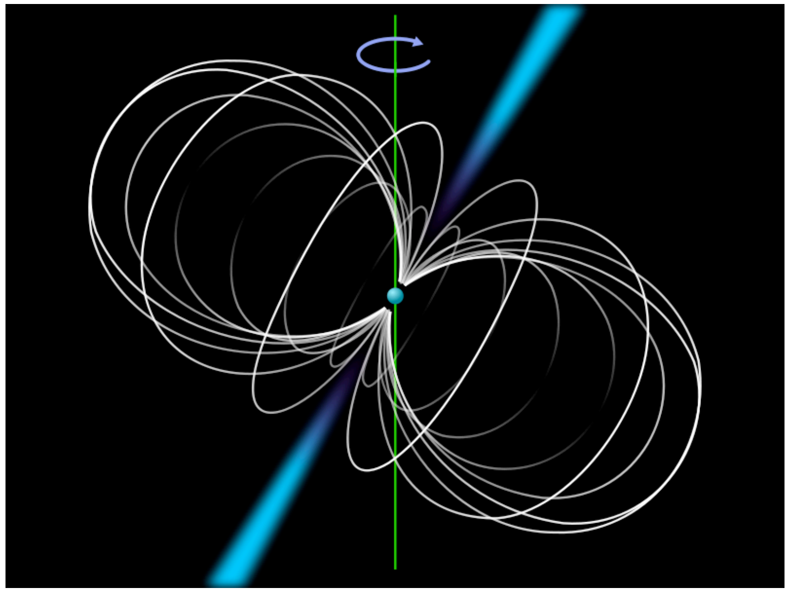
The Crab Nebula contains a **33 msec pulsar (**observed in optical and radio) 1960.

Pulsar = rapidly rotating young neutron star
Neutron Star = stellar remnant formed in the core-collapse of the massive star (left over from the explosion)

The Crab Nebula is a **Pulsar Wind Nebula** = a bubble of shocked relativistic particles produced when a pulsar's relativistic wind interact with its environment.

Central pulsar generates a magnetized particle wind, whose ultrarelativistic electrons and positrons radiate synchrotron emission across the electromagnetic spectrum (Pacini & Salvati 1973; Rees & Gunn 1974). Is there space for hadrons too??

- In PWNe: energy is steadily released by the central pulsar.
- In shell-type SNRs: energy is released as kinetic energy at the moment of the SN explosion.
- In "composite" systems: the PWN is surrounded by a shell- like SNR.



Spin-Down Luminosity:

P = spin period (second);
"spin-down luminosity" :

$$\dot{E} = -dE_{rot}/dt$$

rate at which rotational kinetic energy is dissipated.
Only pulsars with

$$\dot{E} \geq 4 \cdot 10^{36} erg/s$$

produce prominent PWNe

$$\dot{E}_{Crab} \sim 5 \cdot 10^{38} erg/s$$

From the spin-down luminosity one can extrapolate the age of a pulsar.

X-ray Binary Systems

System composed by:
- compact object (neutron star or black hole)
- non-degenerate star

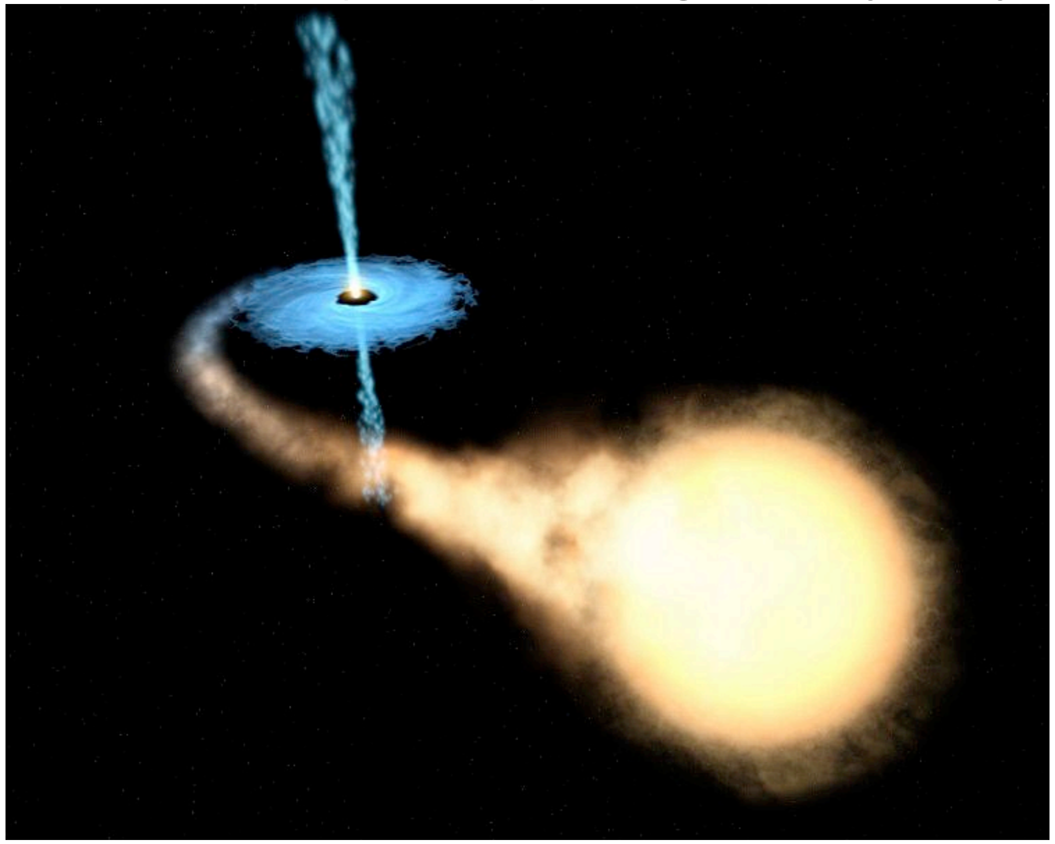
Strong variability in time, periodicity of the system not always associated with the non-thermal variability

Depending on the star they are classified as:
- High Mass X-ray Binaries (HMXBs): companion star = O, B star with strong stellar winds, UV radiation. Strong accelerators and target mass (compact photon field). Good candidates for cosmic rays-gamma and neutrino emission.

- Low Mass X-ray Binaries (LMXBs): companion star = low or intermediate mass star. Strong accelerators but target mass small.

- Microquasar (µQSO): binary system with jets and strong radio emission. The name recalls similarities with Quasars. But a microquasar is a binary system!

http://en.wikipedia.org/wiki/X-ray_binary



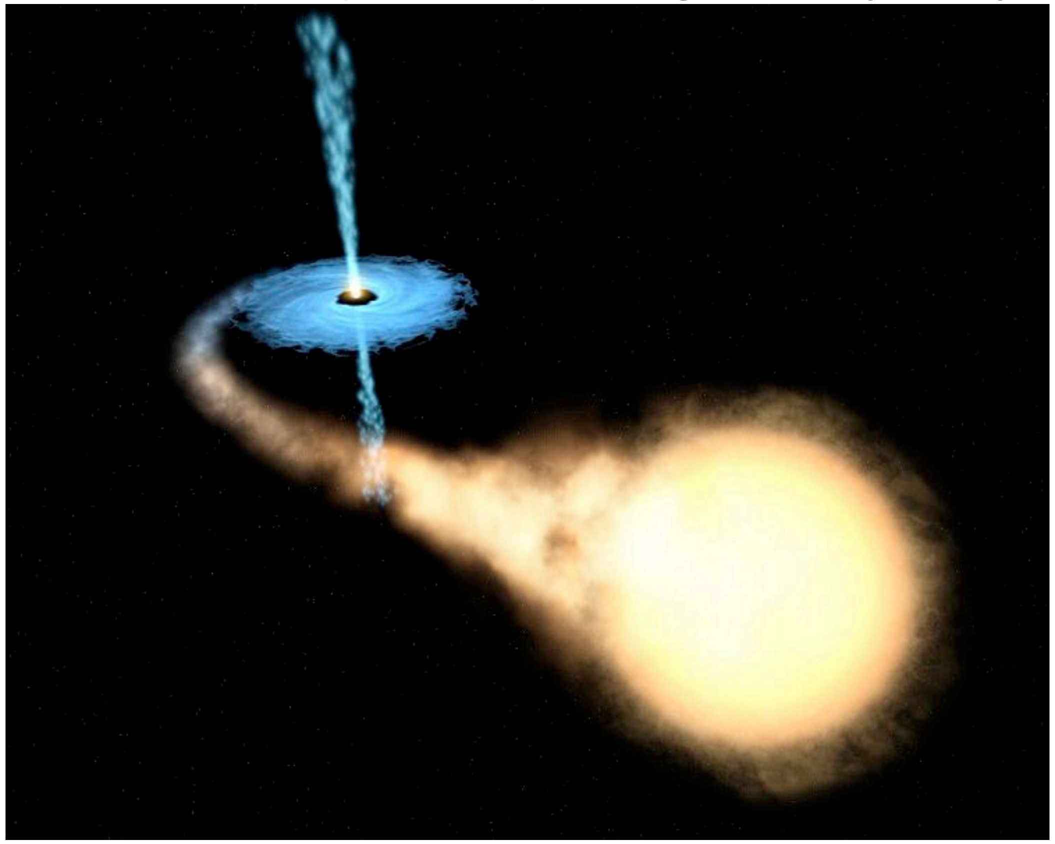
Powering mechanisms for HMXBs:

- Rotation Power: young spinning-down pulsar powers a relativistic wind by rotation. Shocks between the PSR and the wind of the companion star are produced. Acceleration happens. Accelerated particles interact with the photon field of the star. Strong photon absorption. Non trivial relation between high energy photons and neutrinos.

- Accretion Power: compact object accrets matter from its companion star through strong stellar winds. A jet can be formed (one or two side).

In microquasars: particle acceleration happens inside and along the jet.

http://en.wikipedia.org/wiki/X-ray_binary



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Population:

114 XRBs in our Galaxy (X-ray observation);

Most of them are neutron star in orbit with a Be star.

Particularly interesting sources are microquasars and rotation-power HMXBs with associated radio synchrotron emission:

LS I+61 303 μQSO? Period= 26.5 days
Cygnus X-1 μQSO Period = 5.6 days
Cygnus X-3 μQSO Period = 0.2 days
SS 433 μQSO Period = 13.1 days
LS 5039 μQSO? Period= 4.1 days
V4641 Sgr μQSO Period = 2.8 days
PSR B1259-63 binary pulsar Period = 1241 days

X-ray Binary Systems: Cygnus X-1

Compact Object = Black hole

One of the first black hole to be identified (too compact to be anything else).

Very strong X-ray source.

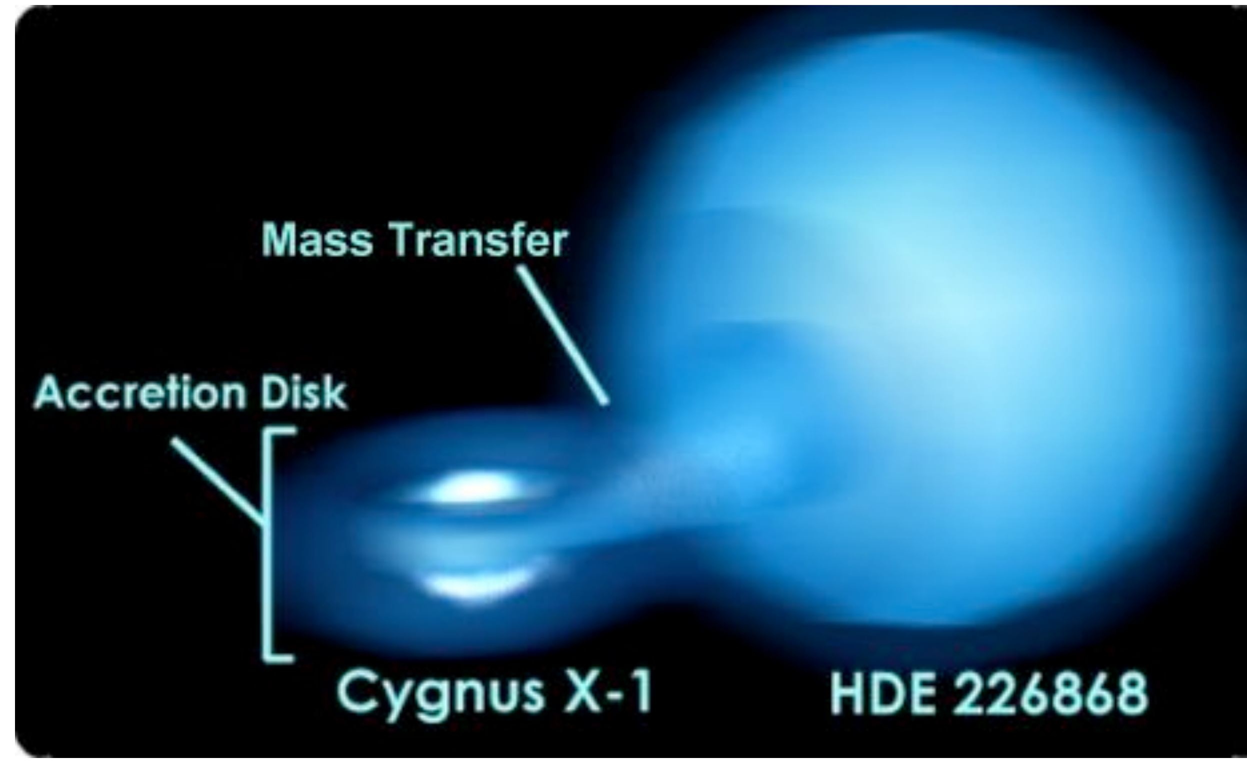
The companion star is a blu supergiant star in orbit at a distance of about 20% of the distance Earth-Sun. Mass 20-30 solar mass!

Cygnus X-1 is a HMXR.

A strong stellar wind provide matter for accretion.

Two-sided compact and steady jets and discrete transient jets.

http://library.thinkquest.org/25715/discovery/binary.htm



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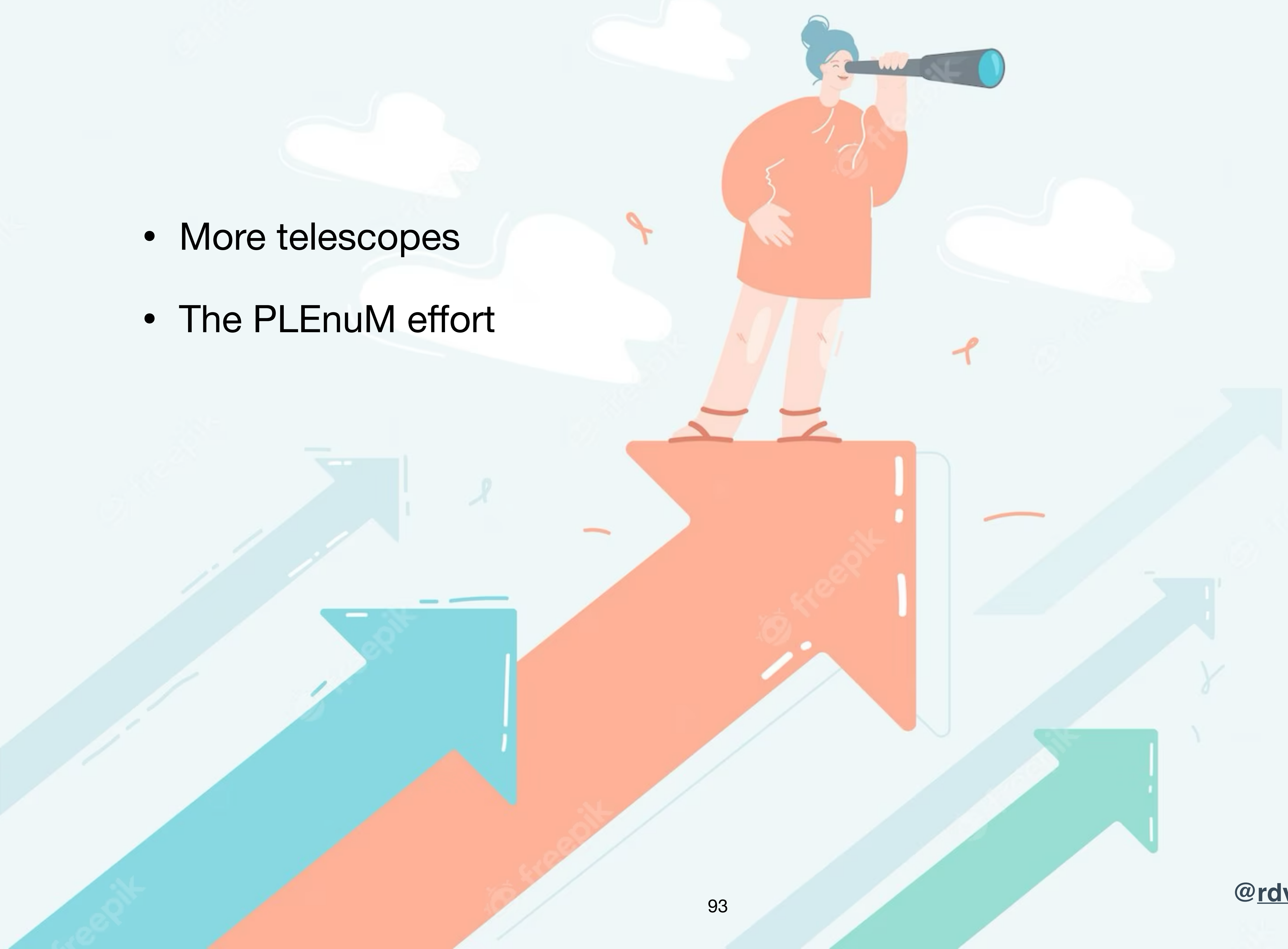
Cygnus X-1 contains a 21–solar mass black hole—Implications for massive star winds

JAMES C. A. MILLER-JONES, ARASH BAHRAMIAN, JEROME A. OROSZ, ILYA MANDEL, LIJUN GOU, THOMAS J. MACCARONE, COENRAAD J. NEIJSSEL, XUESHAN ZHAO, JANUSZ ZIÓŁKOWSKI, [...], AND JOERN WILMS +16 authors Authors Info & Affiliations

SCIENCE • 18 Feb 2021 • Vol 371, Issue 6533 • pp. 1046-1049 • DOI: 10.1126/science.abb3363

The future

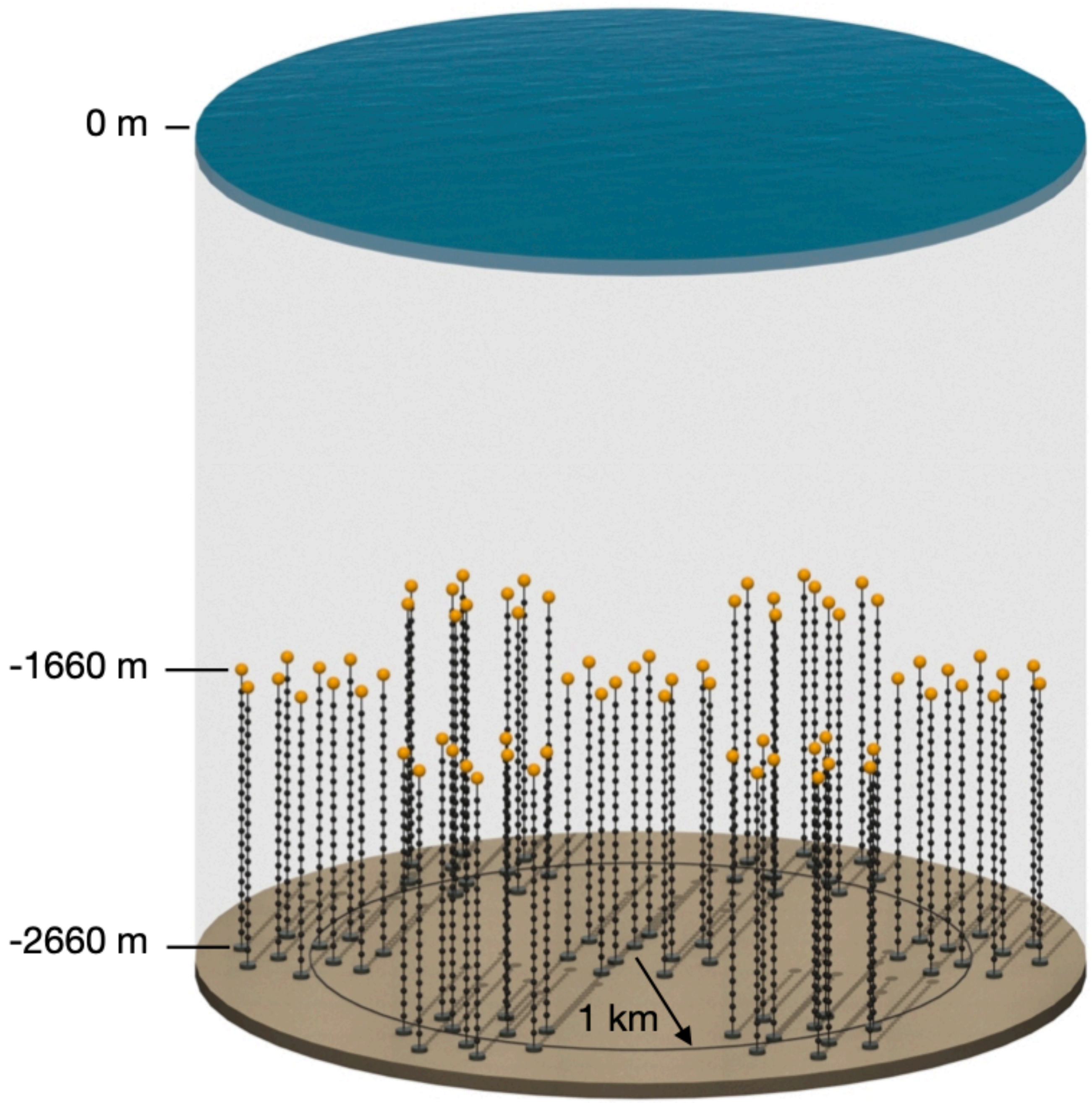
- More telescopes
- The PLEnuM effort



@rdvvector

Pacific Ocean Neutrino Experiment

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

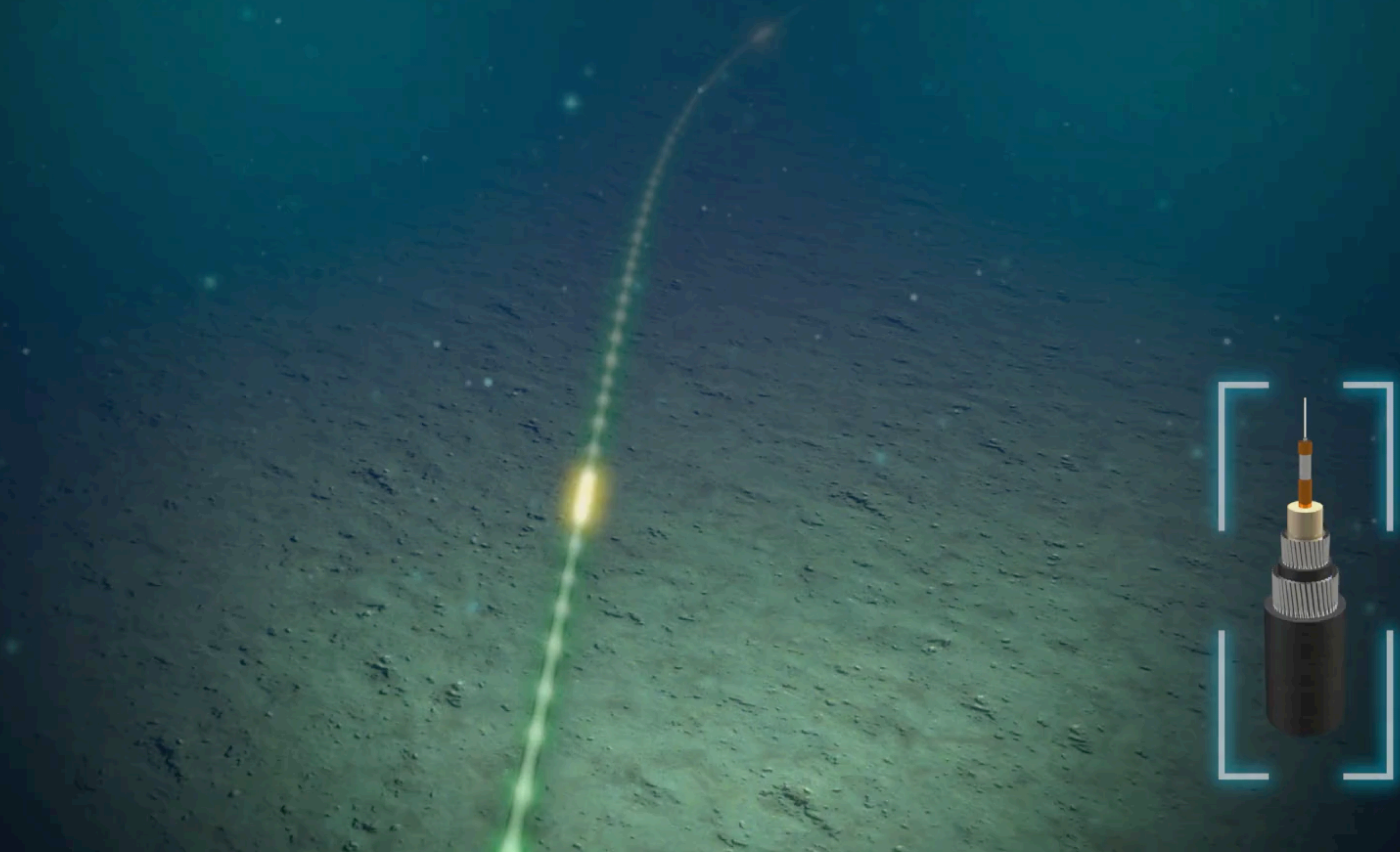


First Neutrino Telescope hosted by an **existing** large scale oceanographic infrastructure:

Ocean Networks Canada

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

https://www.oceannetworks.ca/



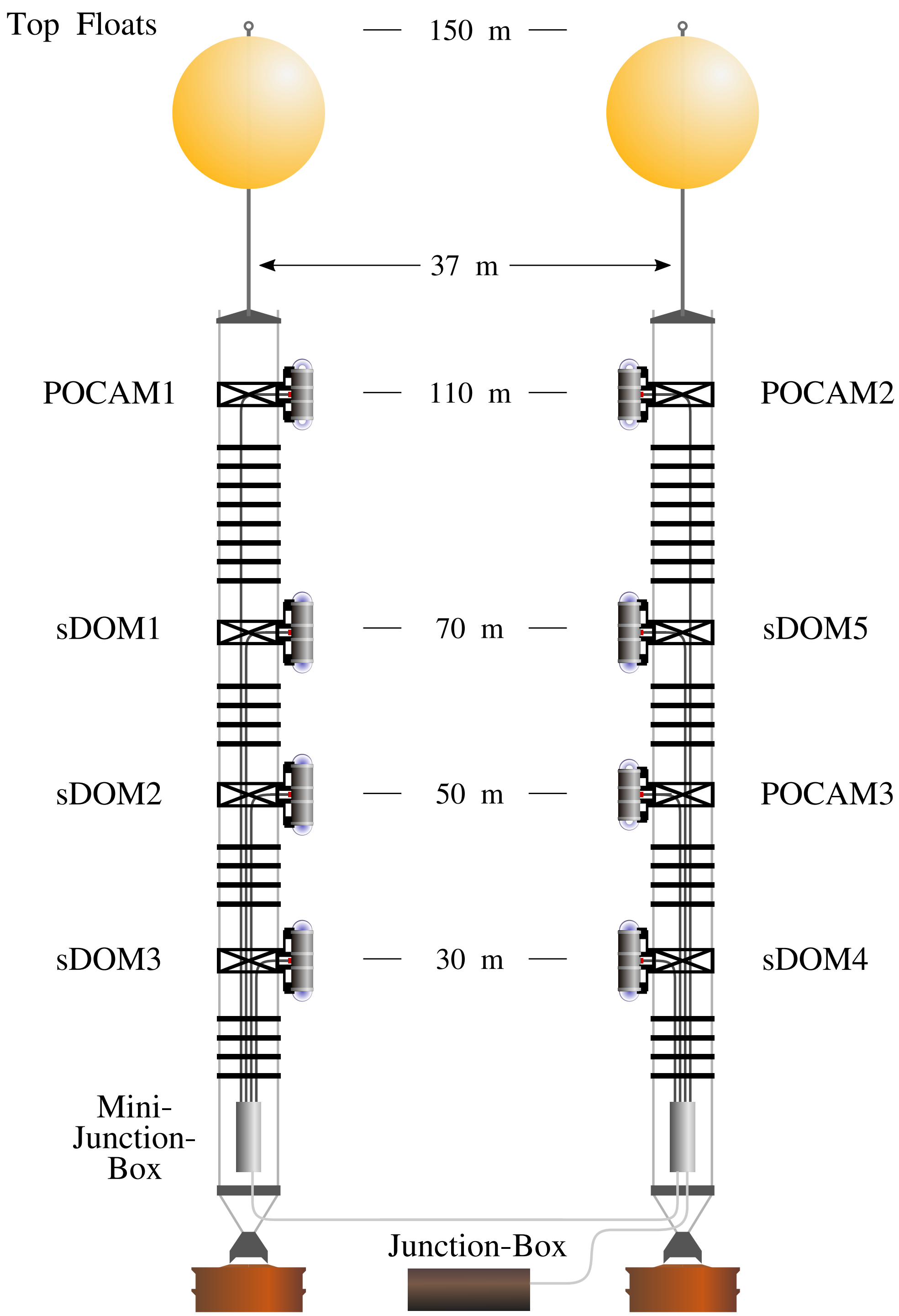
THE INTERNET-CONNECTED OCEAN

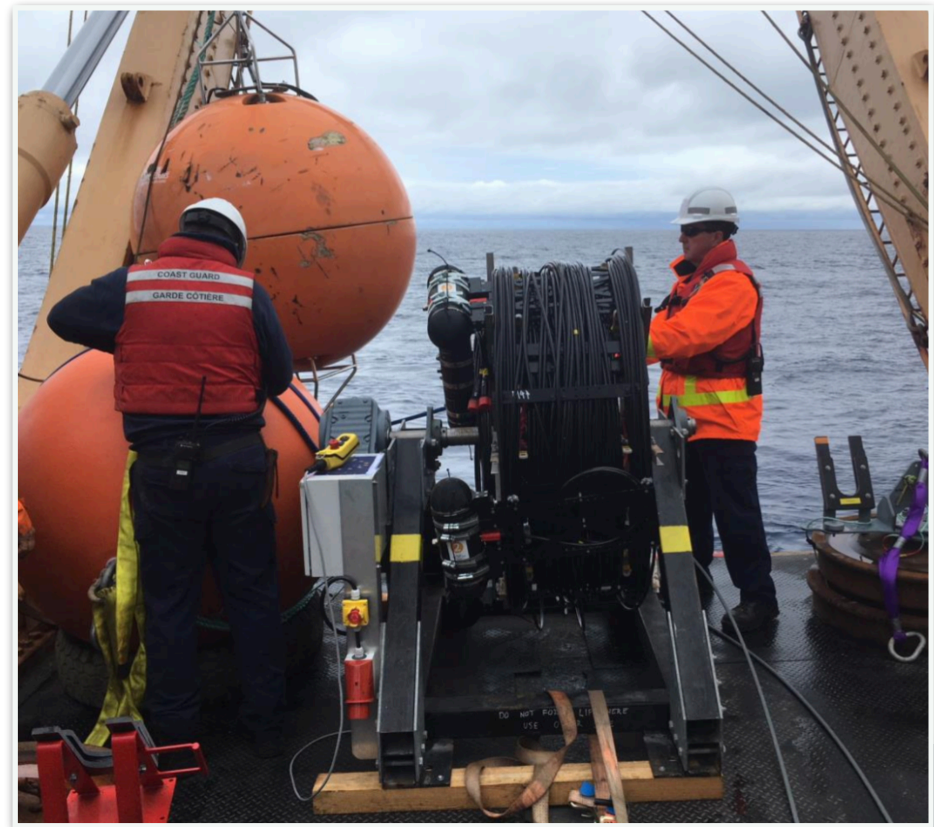
OCEAN NETWORKS CANADA (UNIVERSITY OF VICTORIA)

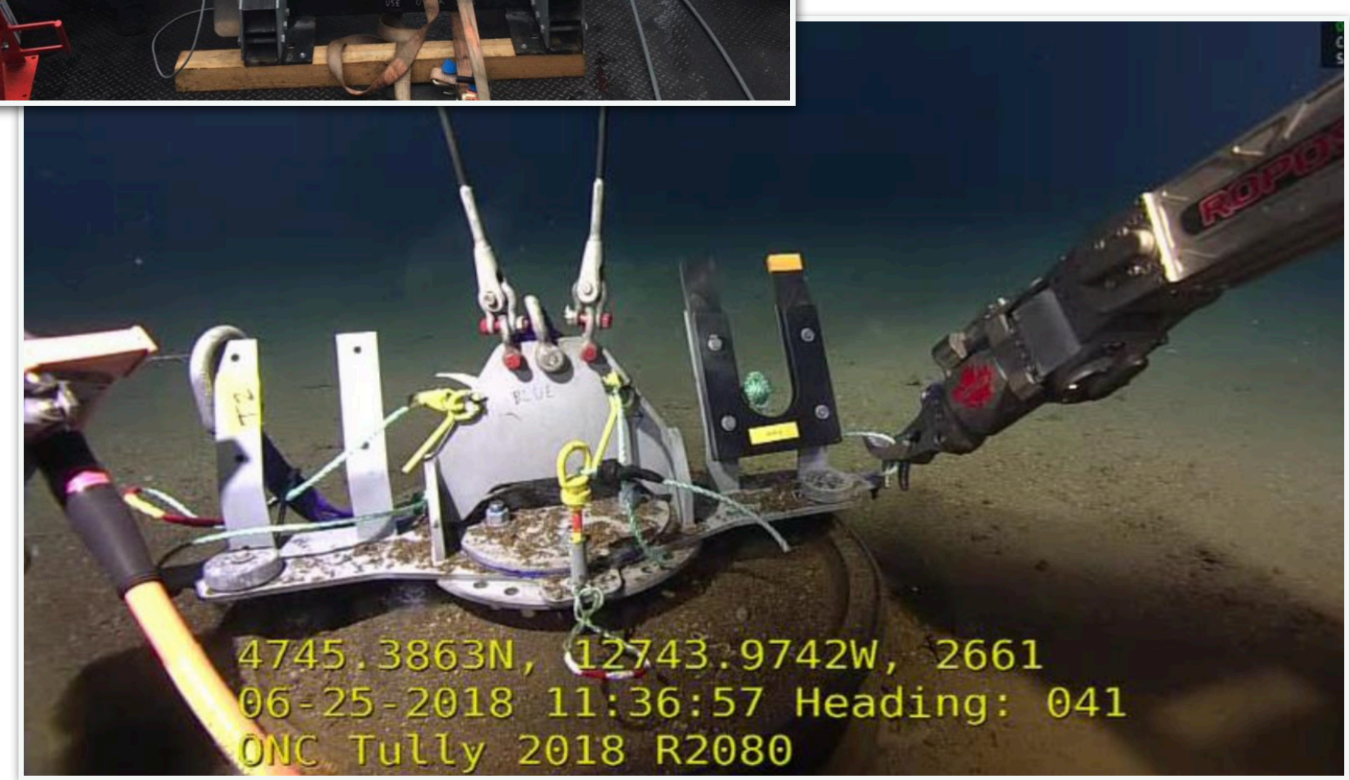
<u>Cabled ocean observatory</u>: North East Pacific Time-series Underwater Networked Experiment (NEPTUNE), completed in 2009, multidisciplinary subsea system.

P-ONE: pathfinder missions

P-ONE Coll., **JINST (2019)**
P-ONE Coll., **Eur. Phys. J. C (2021)**







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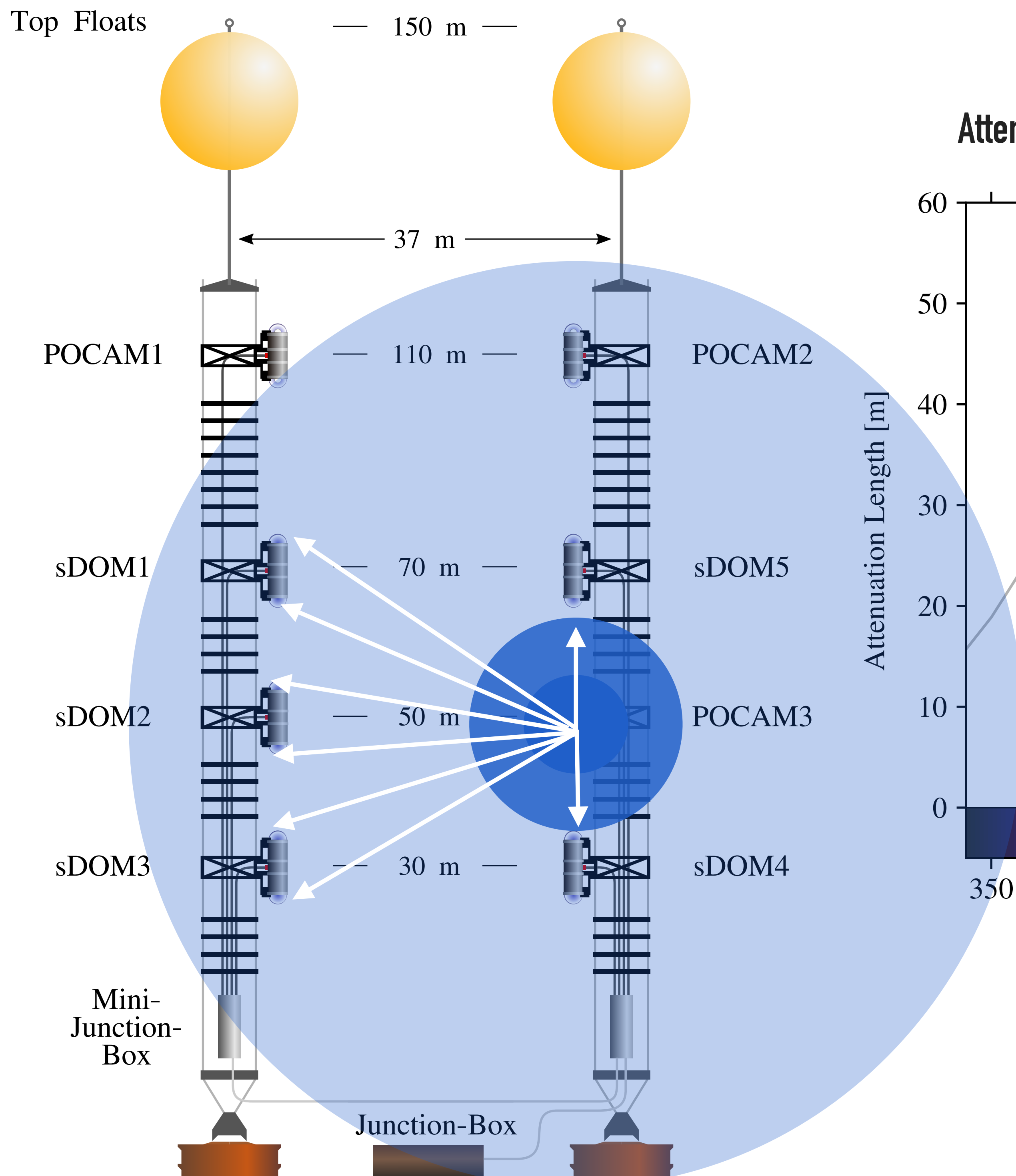
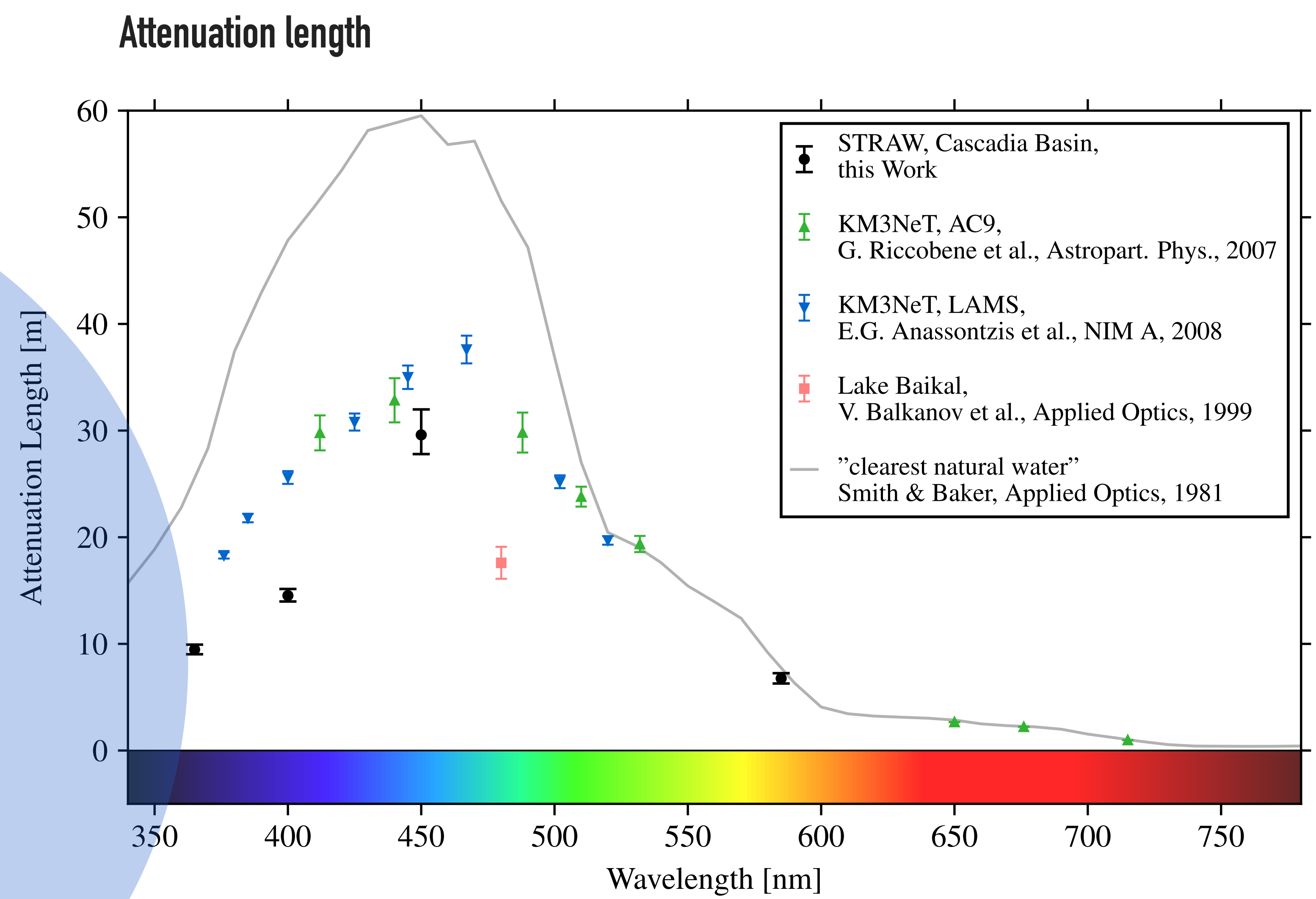


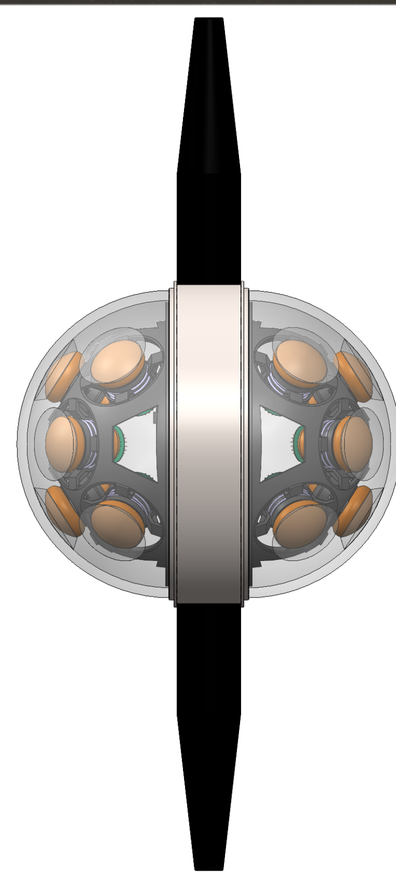


P-ONE: pathfinder missions

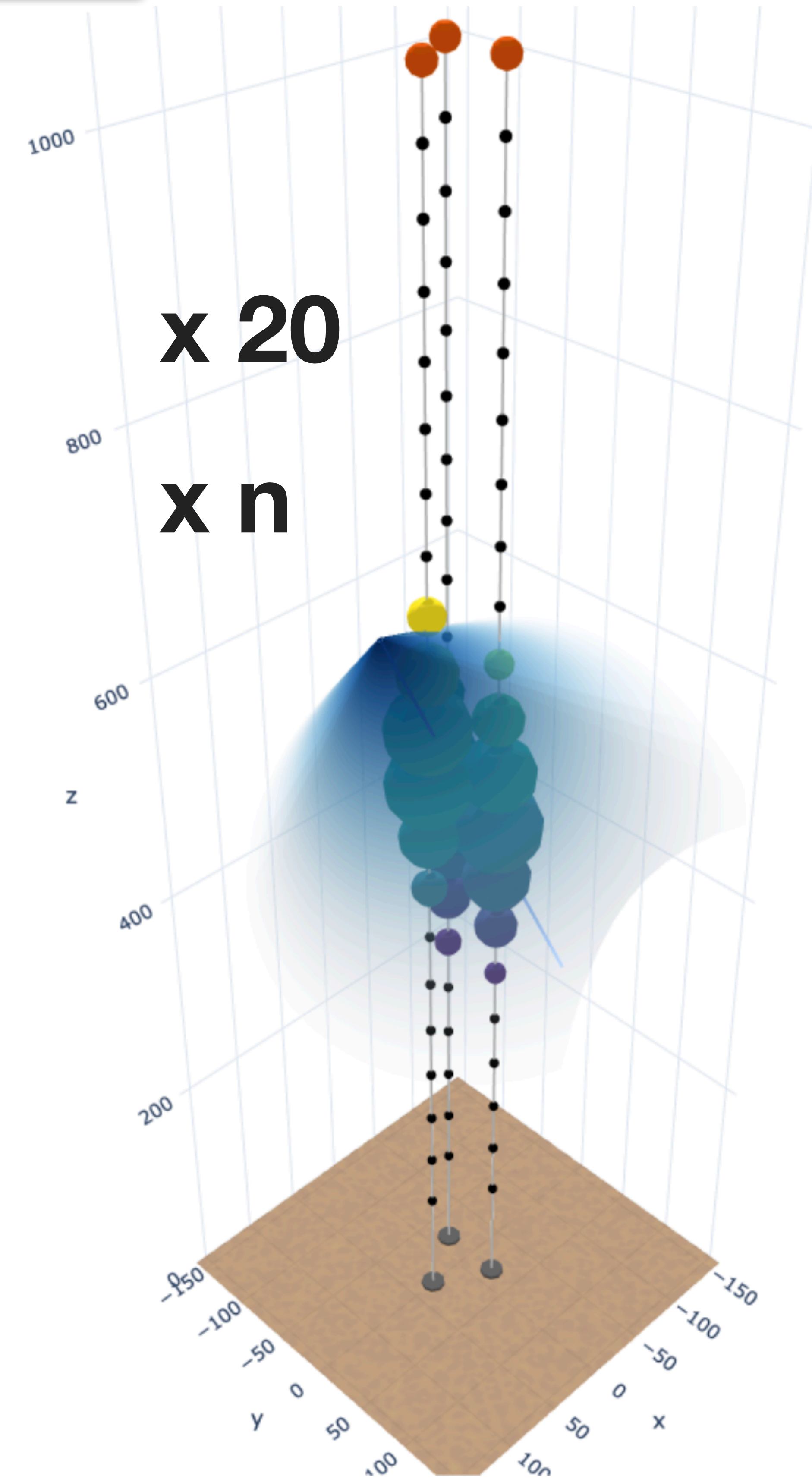
European Research Council

P-ONE

x 16



x 2



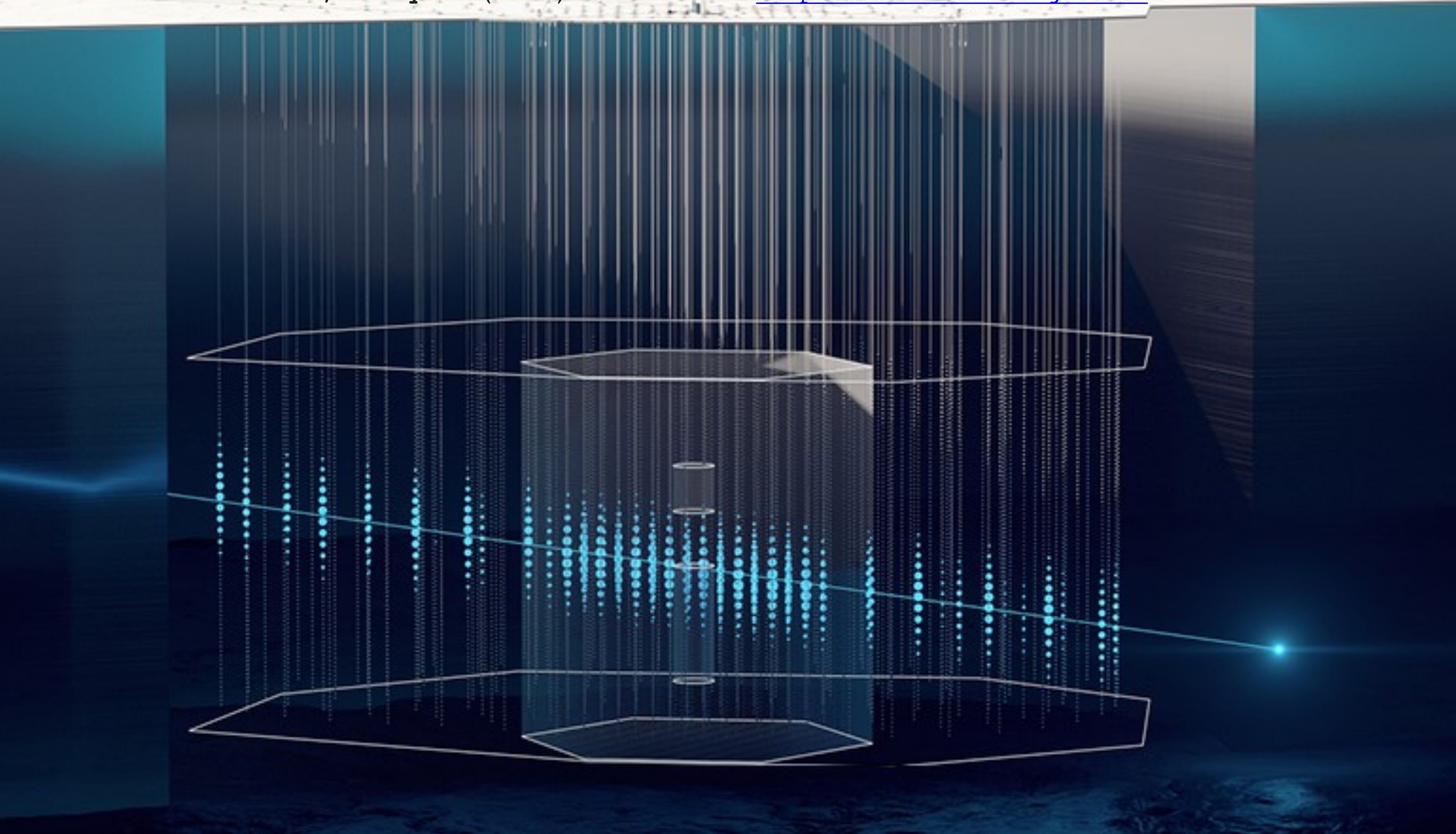
x 20

x n

P-ONE GENERAL MEETING IN KRAKOW MAY '23

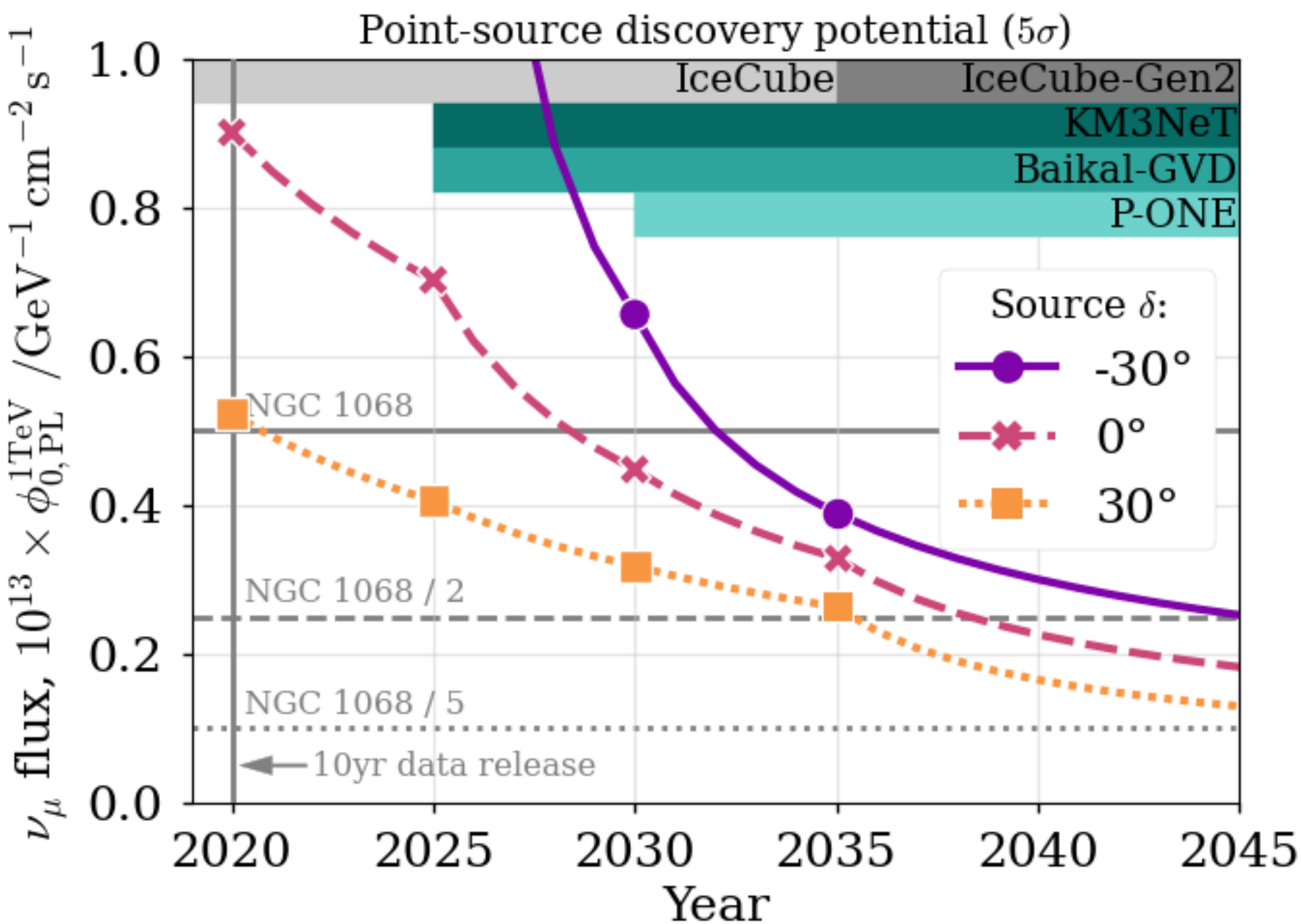
ON THE ICECUBE SIDE: UPGRADE AND ICECUBE-GEN2

IceCube-Gen2 Coll., **J.Phys.G** (2021)   https://www.icecube-gen2.de



The PLEnuM Effort

Lisa Schumacher et al.
https://doi.org/10.22323/1.395.1185
https://github.com/PLEnuM-group/Plenum



Extra

Production of secondary particles (leptons)

The cascade equation

One-dimensional cascade equation

$$\frac{dN(E,X)}{dX} = -\frac{N(E,X)}{\lambda_N(E)} + \int_E^\infty \frac{N(E',X)}{\lambda_N(E')} F_{NN}(E,E') \frac{dE'}{E}$$

where:

- $N(E,X)dE$ = flux of nucleons (n,p) at depth X in the atmosphere with energy interval E, E+dE

- X [g/cm^2]= slant depth = distance from the top of the atmosphere downward along the direction of the incident

- $F_{NN}(E,E')$ = dimensionless inclusive cross section for an incident nucleon of energy E' to collide with an air nucleus and produce an outgoing nucleon of energy E

λ_N [g/cm^2] = nucleon interaction length in air =~ 80 g/cm^2 in the atmosphere

Production of secondary particles (leptons)

The cascade equation

$$\lambda_N = \frac{\rho}{\rho_N \sigma_N^{air}} = \frac{A m_p}{\sigma_N^{air}}$$

ρ (h) = density of atmosphere at altitude h
ρ_N = number density of nuclei
A = nucleon number = mass number of incident nucleus
σ_N = cross section ~ 300 mb = nucleon interaction with air in the TeV regime

- Boundary Conditions
The one dimensional transport equation is valid IF the production of nucleons by other types of particles can be neglected, then it is an approximation. In order to follow all the particles: MonteCarlo approach.

(1) $N(E,0) = N_0(E)$ = ~ 1.8 $E^{-2.7}$ nucleons / cm^2 sr s GeV/A
This boundary condition is relevant for single detectors that measures the rate at which particles are detected. Condition valid up to the PeV energies (knee region)

(2) Superposition approximation = incident nuclei of mass A and total energy E_0 can be treated as A independent nucleons each of with energy $E = E_0 / A$

(3) $N(E,0) = A\,\delta\,(E - E_0/A)$
This boundary condition is relevant for air shower experiments. The primary particle has to have sufficient energy to give a measurable cascades at the Earth surface.