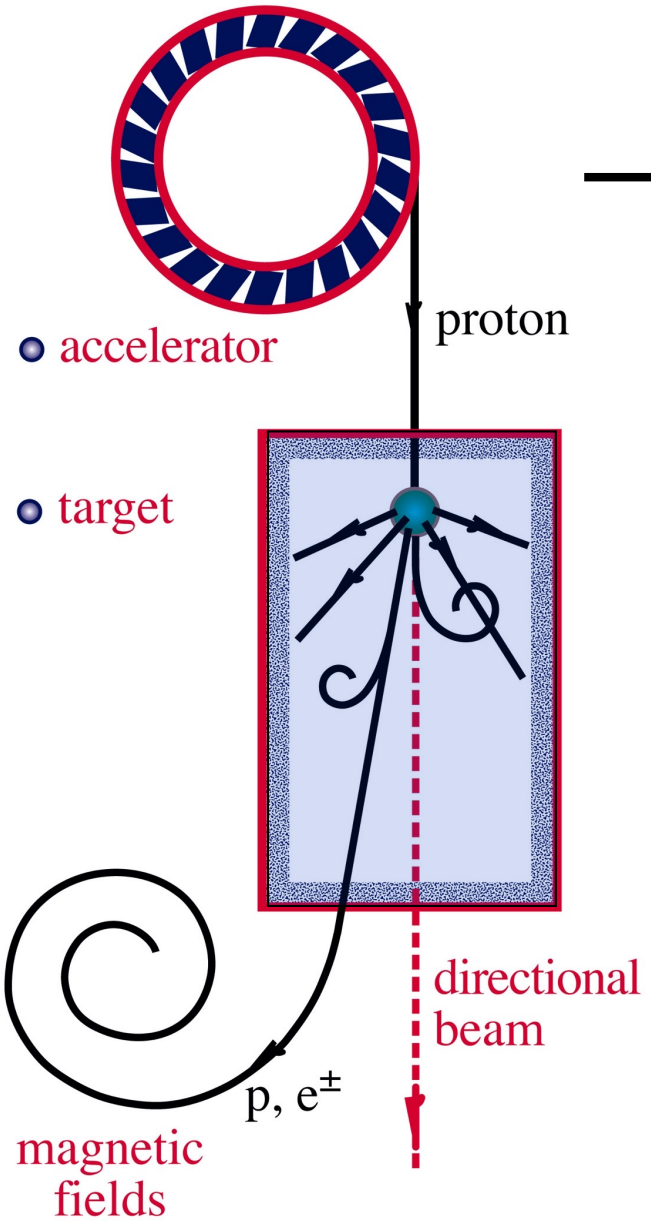
IceCube: The First Decade Of High Energy Neutrino Astronomy

francis halzen

- first neutrino view of the extreme Universe
- first sources of neutrinos (and cosmic rays!)
- search for dark matter, mostly from the sun
- cosmic neutrinos as a backlight of dark matter in our Galaxy
- neutrinos from the cores of active galaxies as a backlight for their dark matter profile

IceCube.wisc.edu

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

supermassive black hole

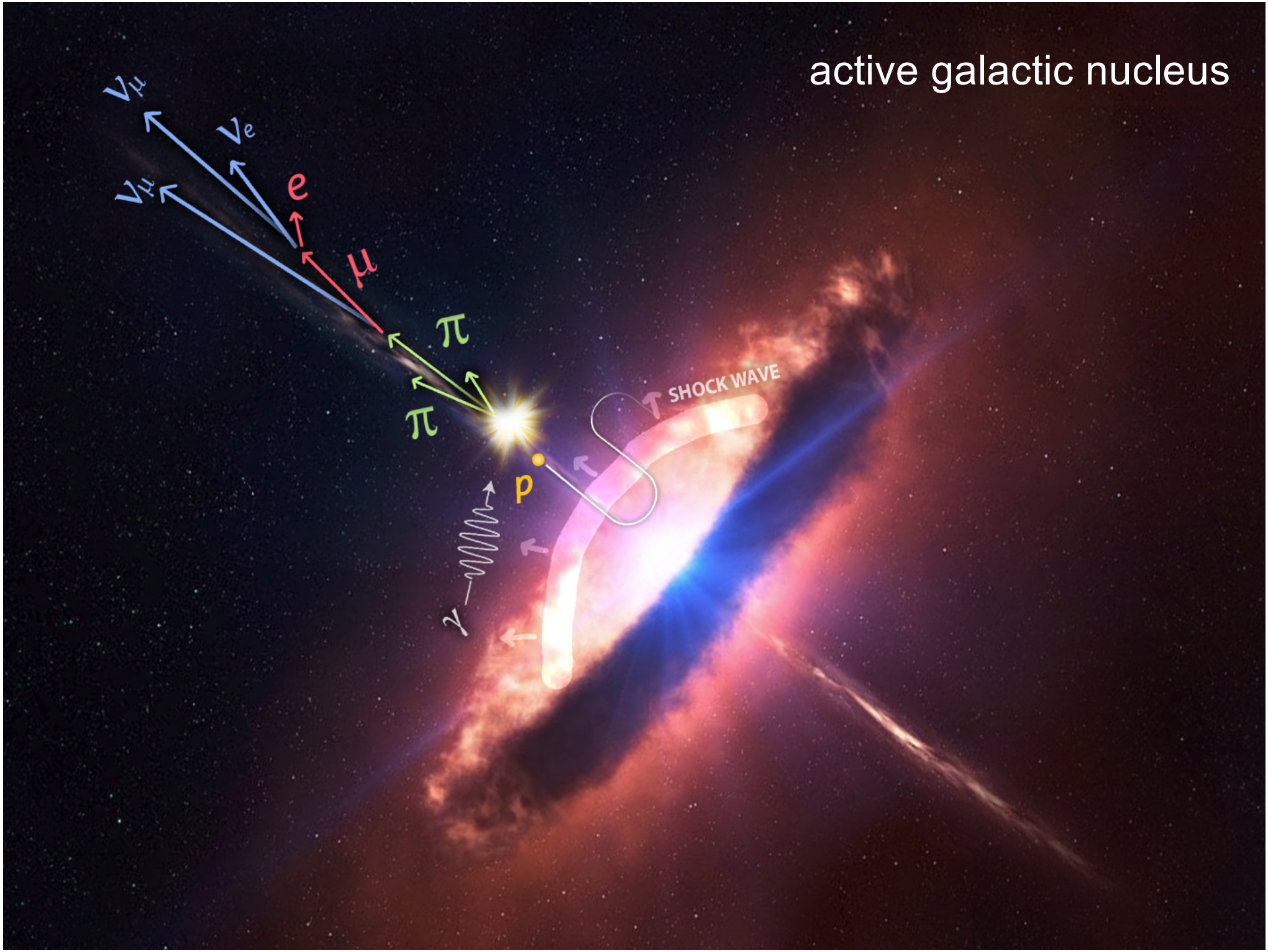
nearby radiation or hydrogen, or...

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

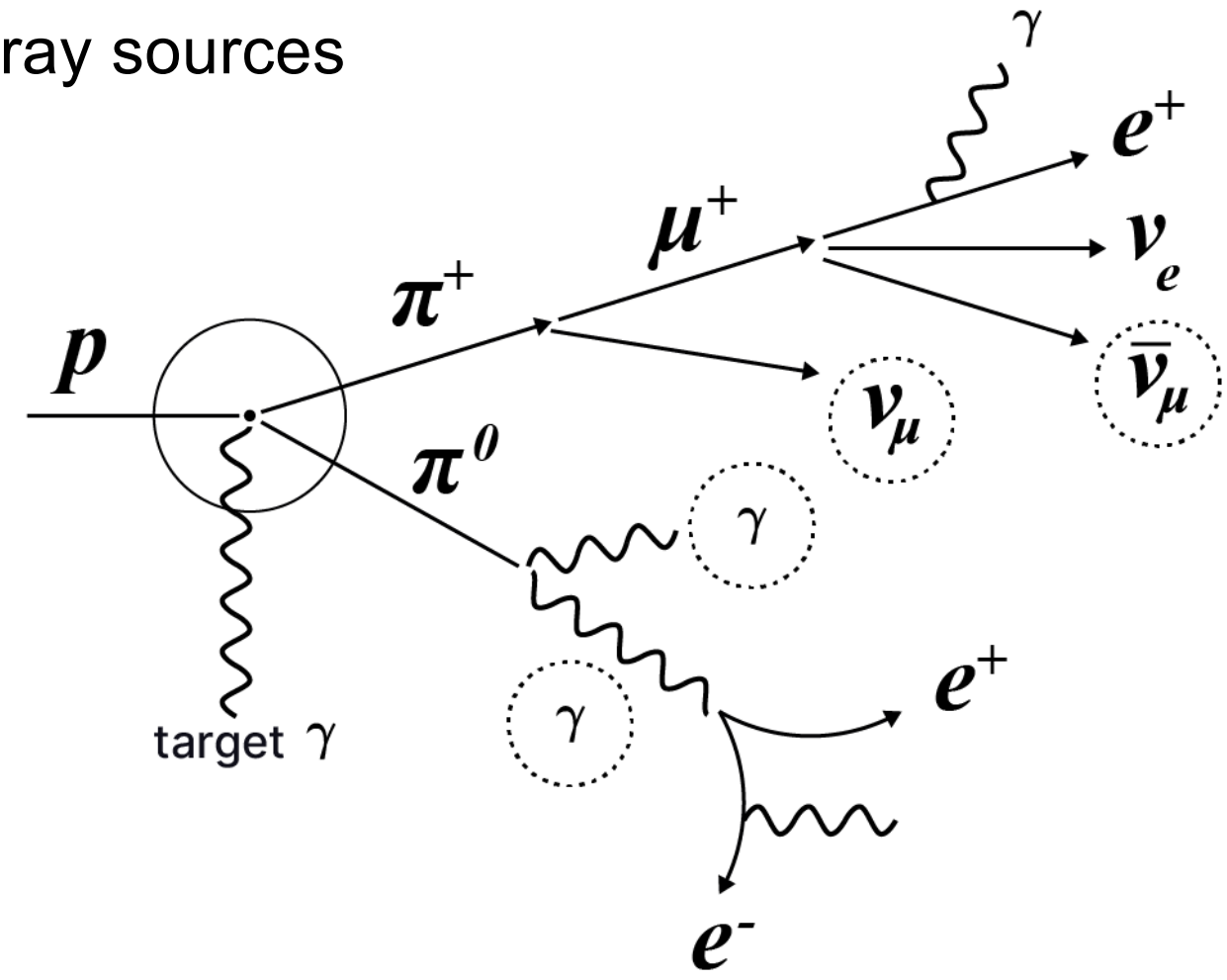
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

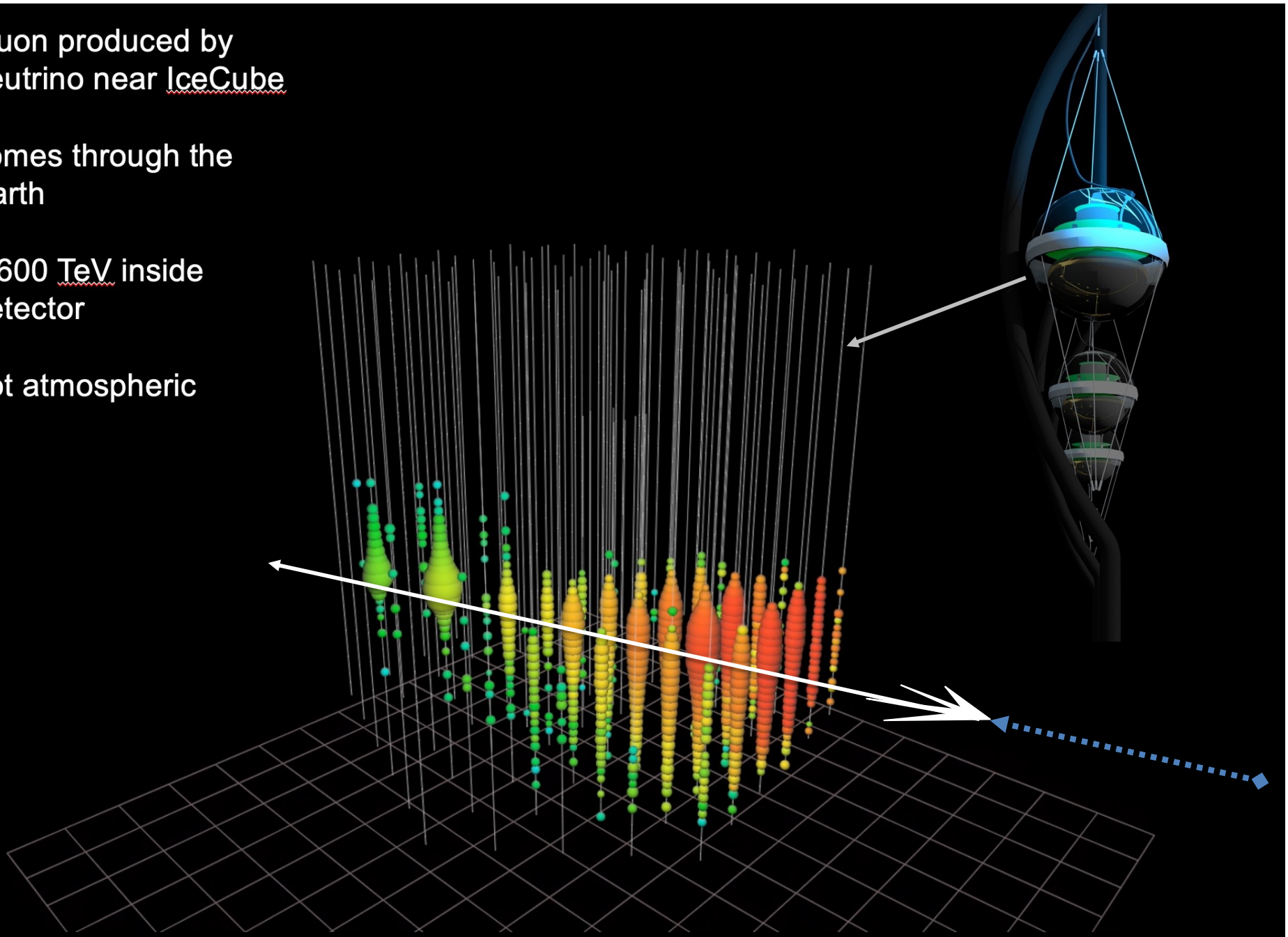

active galactic nucleus
ν_μ
ν_e
ν_μ
e
μ
π
π
SHOCK WAVE
p
γ

cosmic ray sources

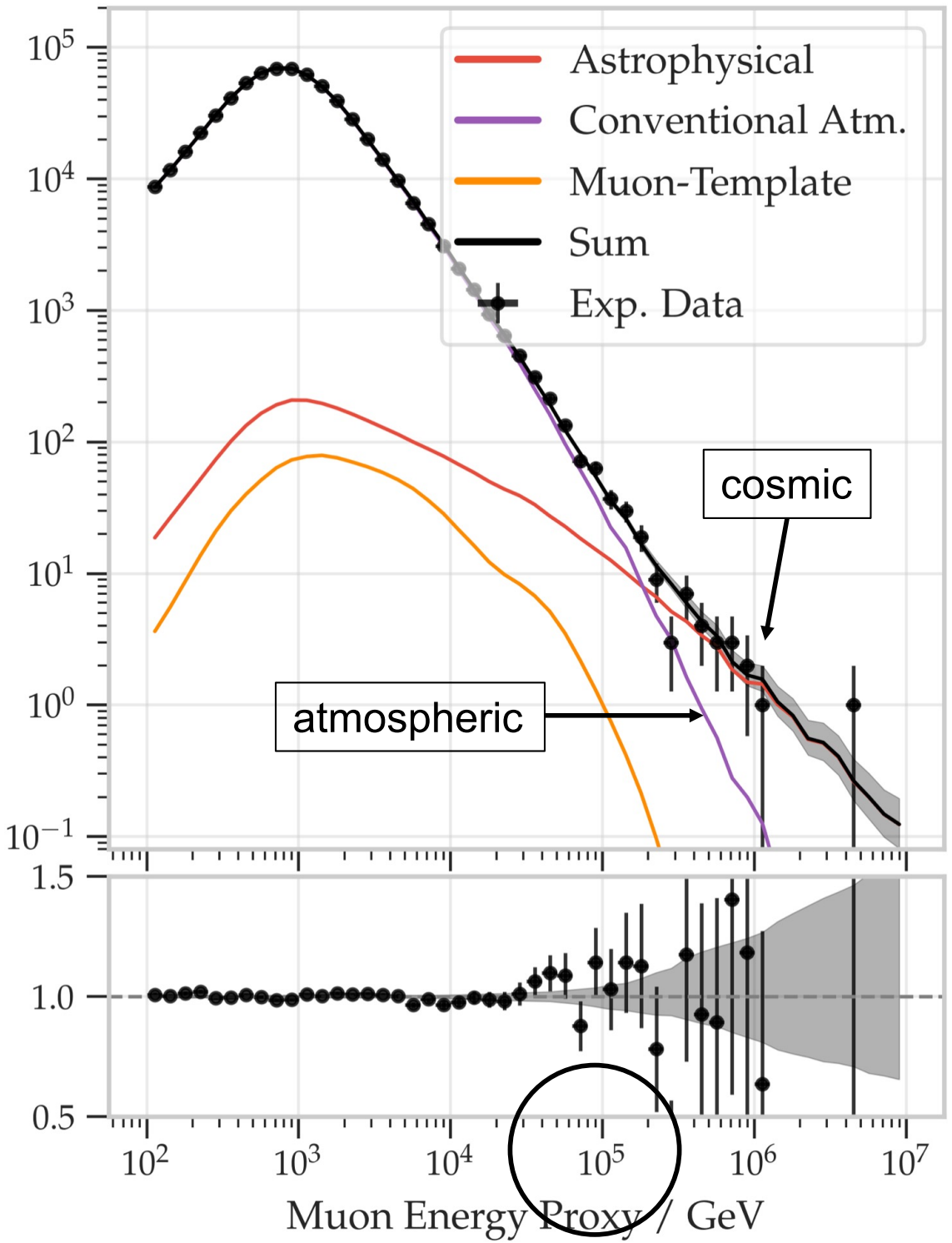


$$\gamma \simeq \nu_\mu + \bar{\nu}_\mu$$

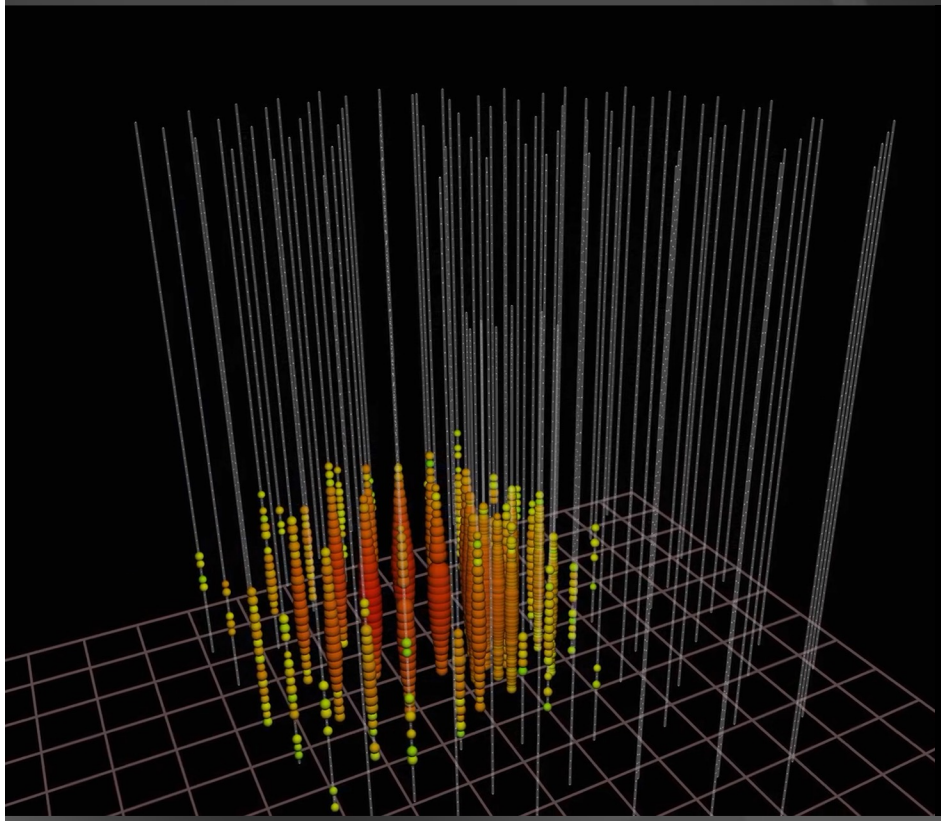
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric



muon neutrino flux filtered by the Earth: atmospheric vs cosmic

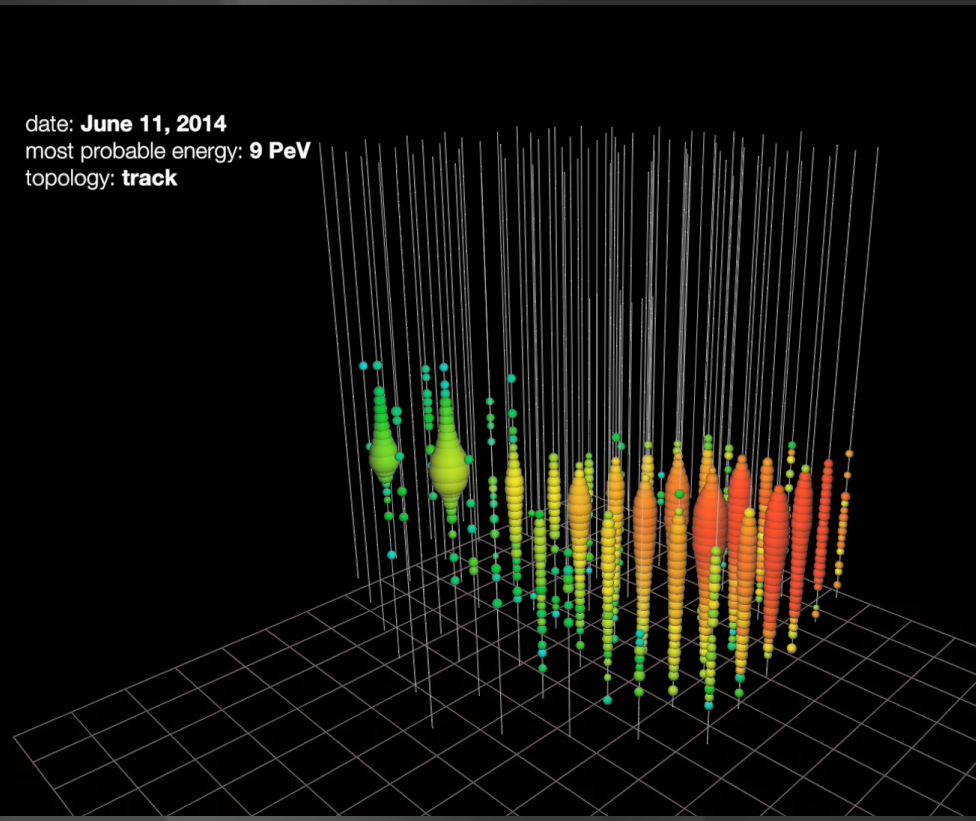


neutrinos interacting
inside the detector



superior total energy
measurement
to 10%, all flavors, all sky

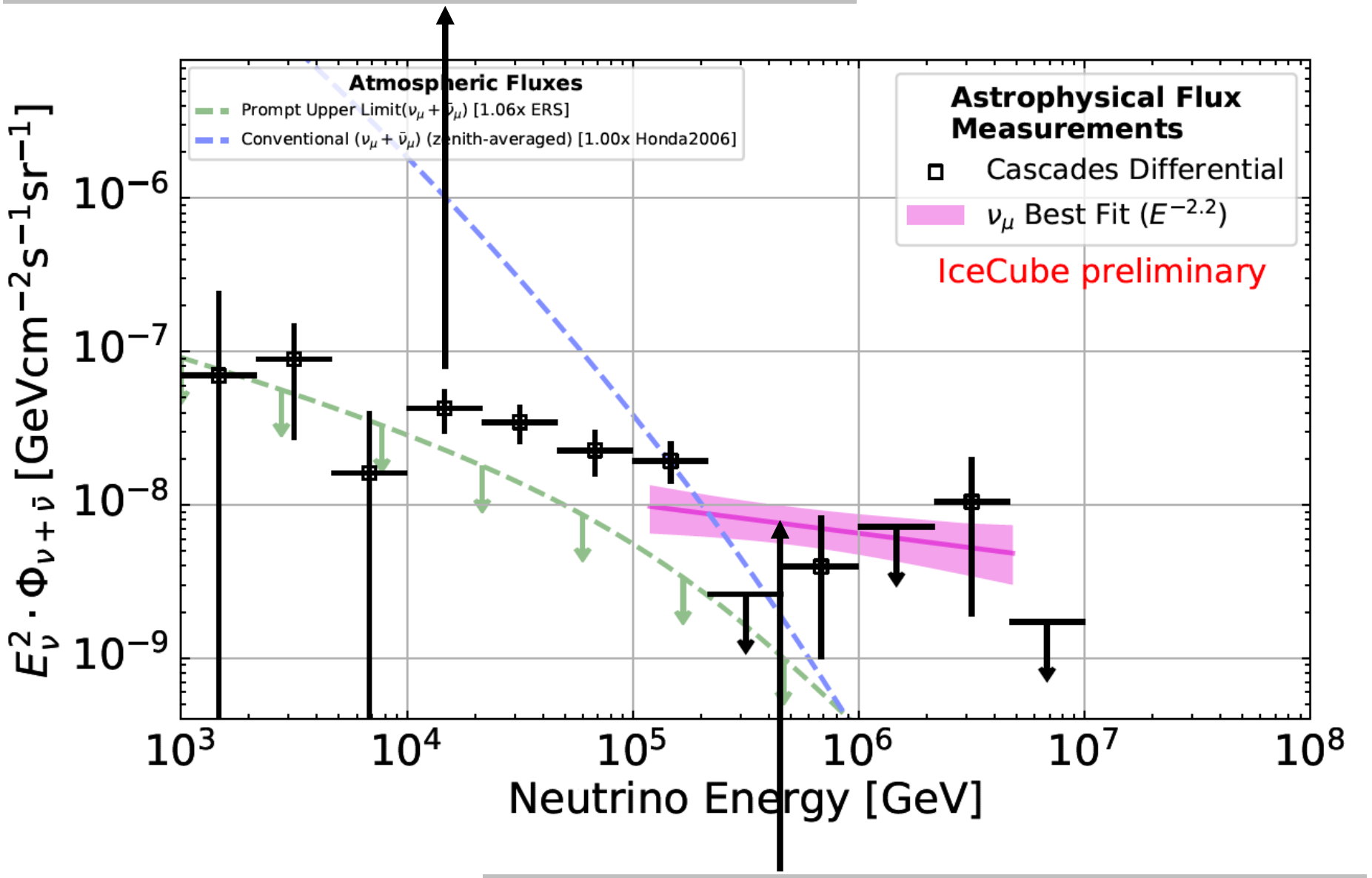
muon neutrinos
filtered by the Earth



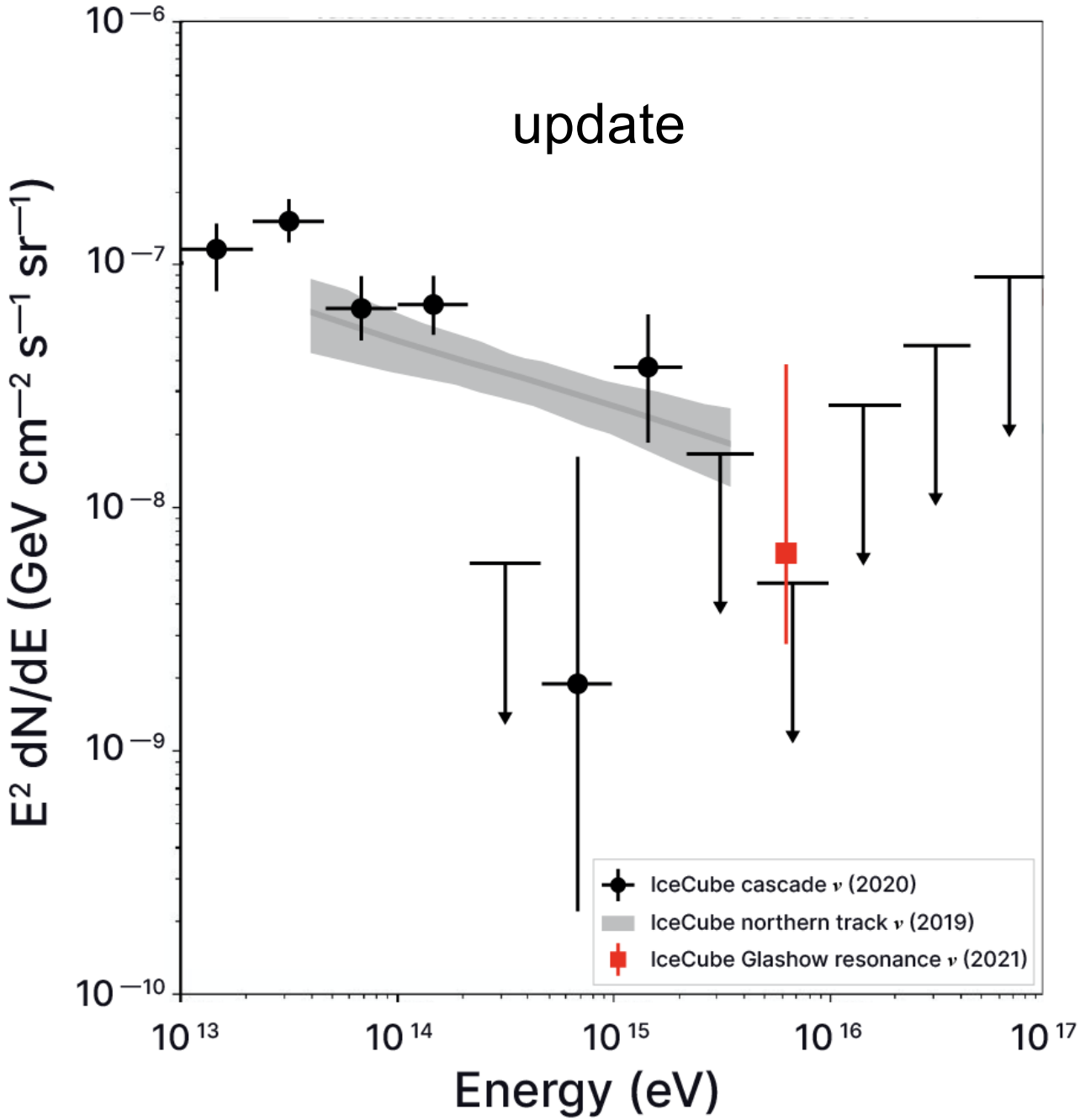
astronomy: superior
angular resolution
superior (0.3º)

electron and tau neutrinos (showers)

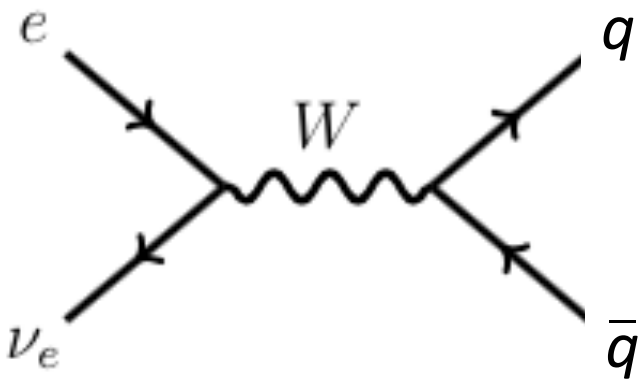
$E^2dN/dE \sim E^{-2.5}$



muon neutrinos through Earth (tracks)

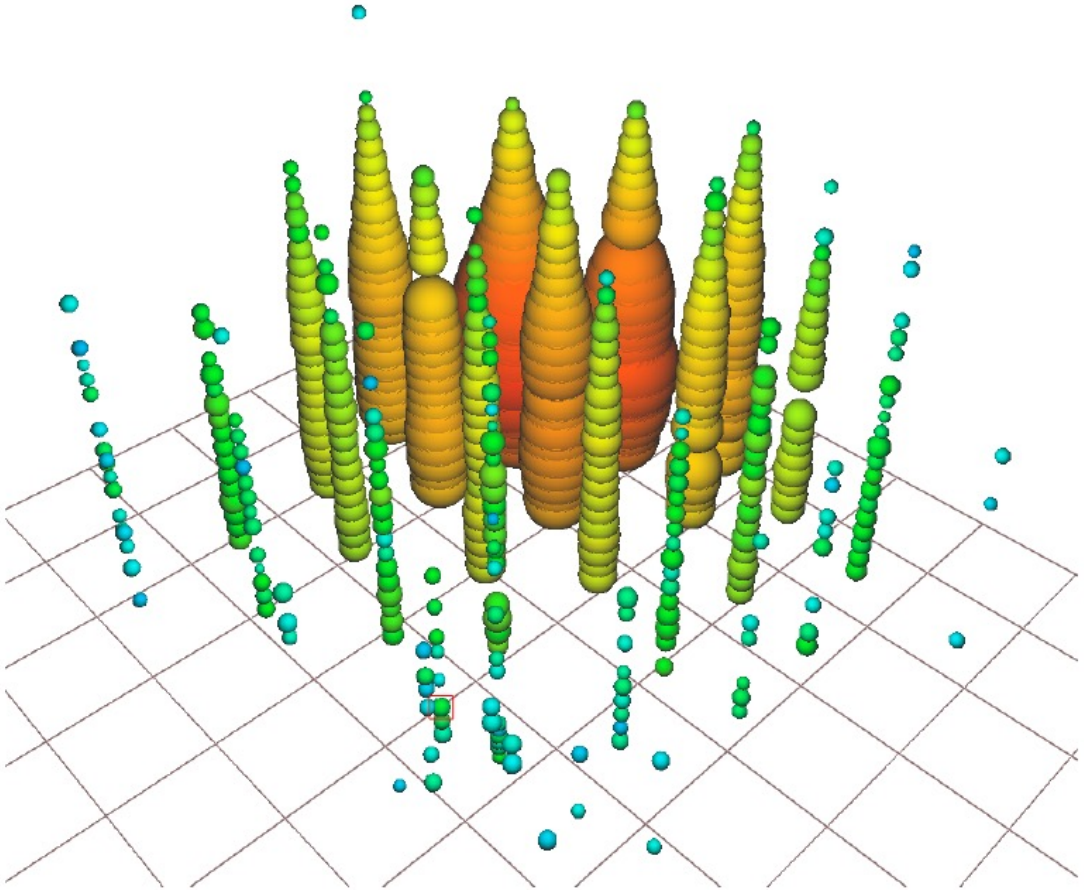

update
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
E^2 dN/dE (GeV cm^{-2} s^{-1} sr^{-1})
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
Energy (eV)
IceCube cascade ν (2020)
IceCube northern track ν (2019)
IceCube Glashow resonance ν (2021)

Glashow resonance event with energy 6.3 PeV

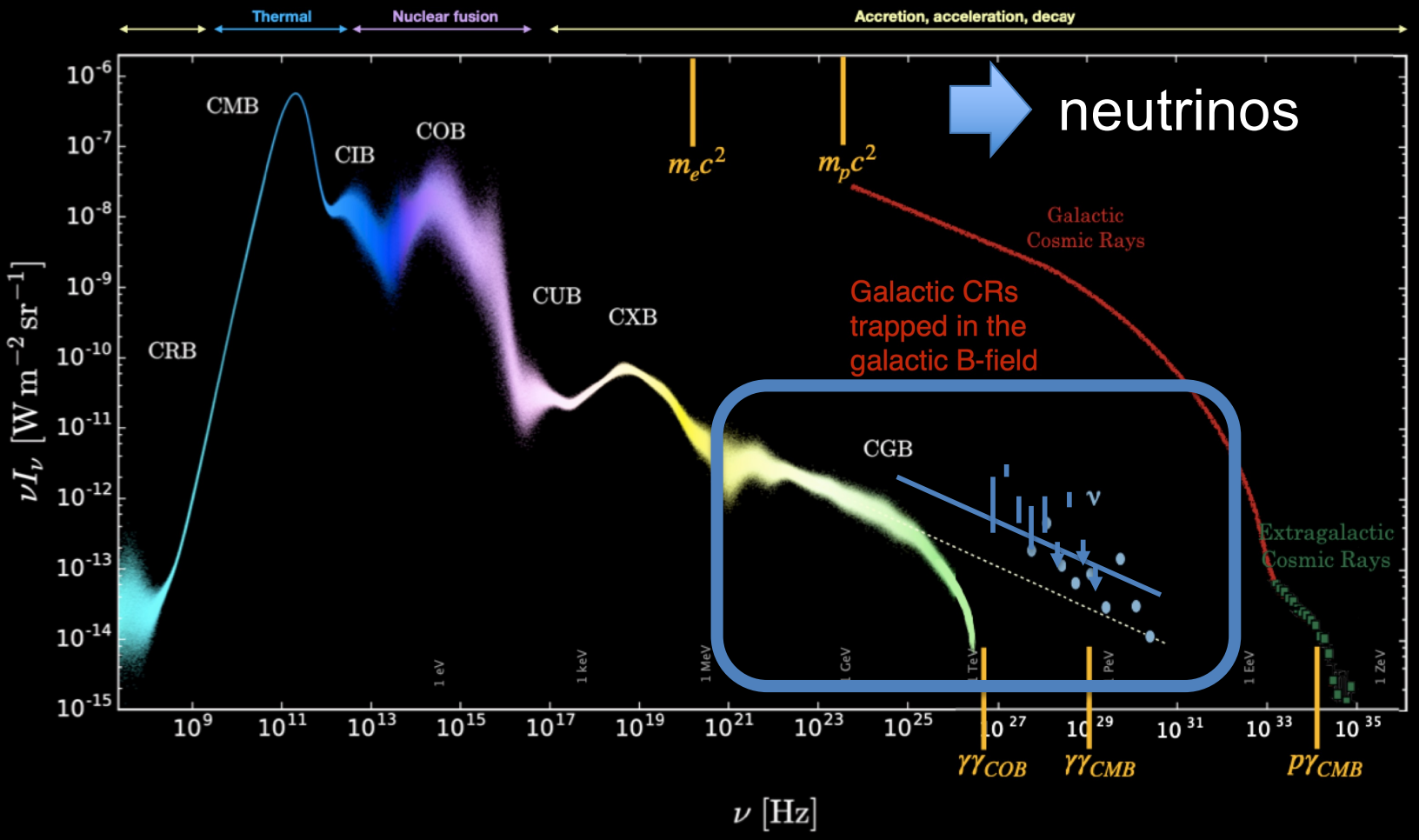


resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

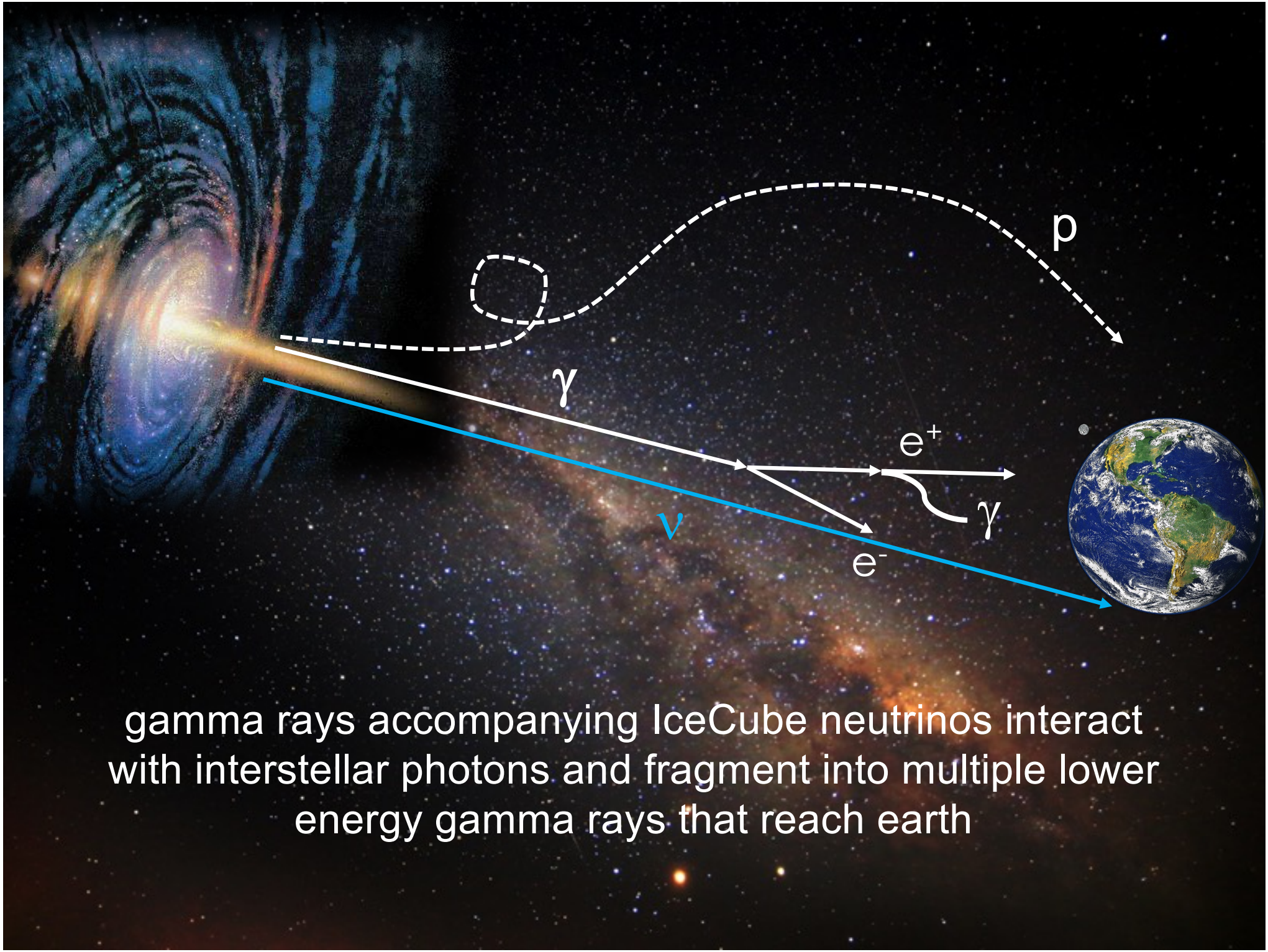
$$E_R = M_W^2/[2m_e]$$
$$= 6.32\,\mathrm{PeV}$$



energy density in the Universe as a function of frequency

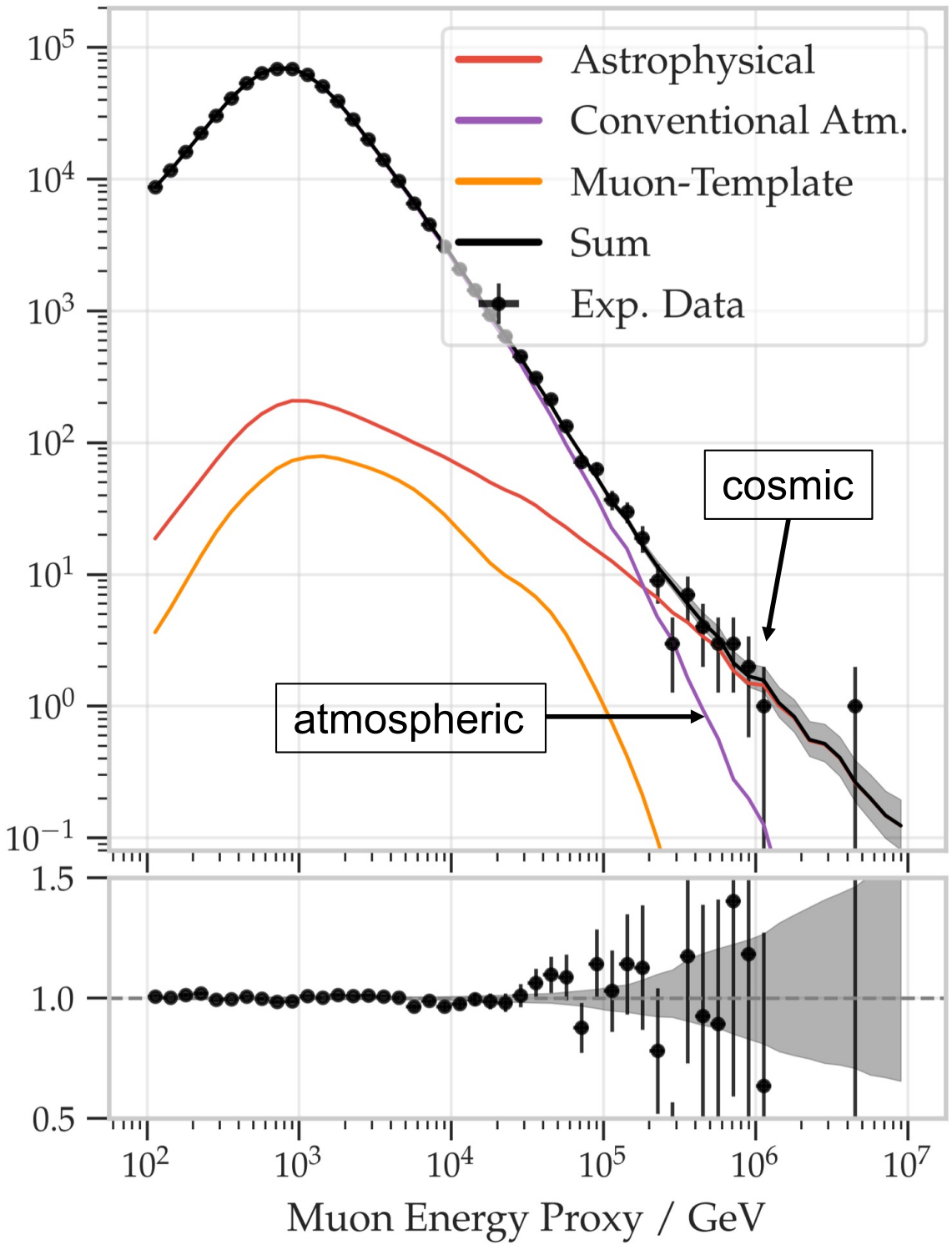


in the extreme universe the energy in neutrinos is larger than the energy in gamma rays



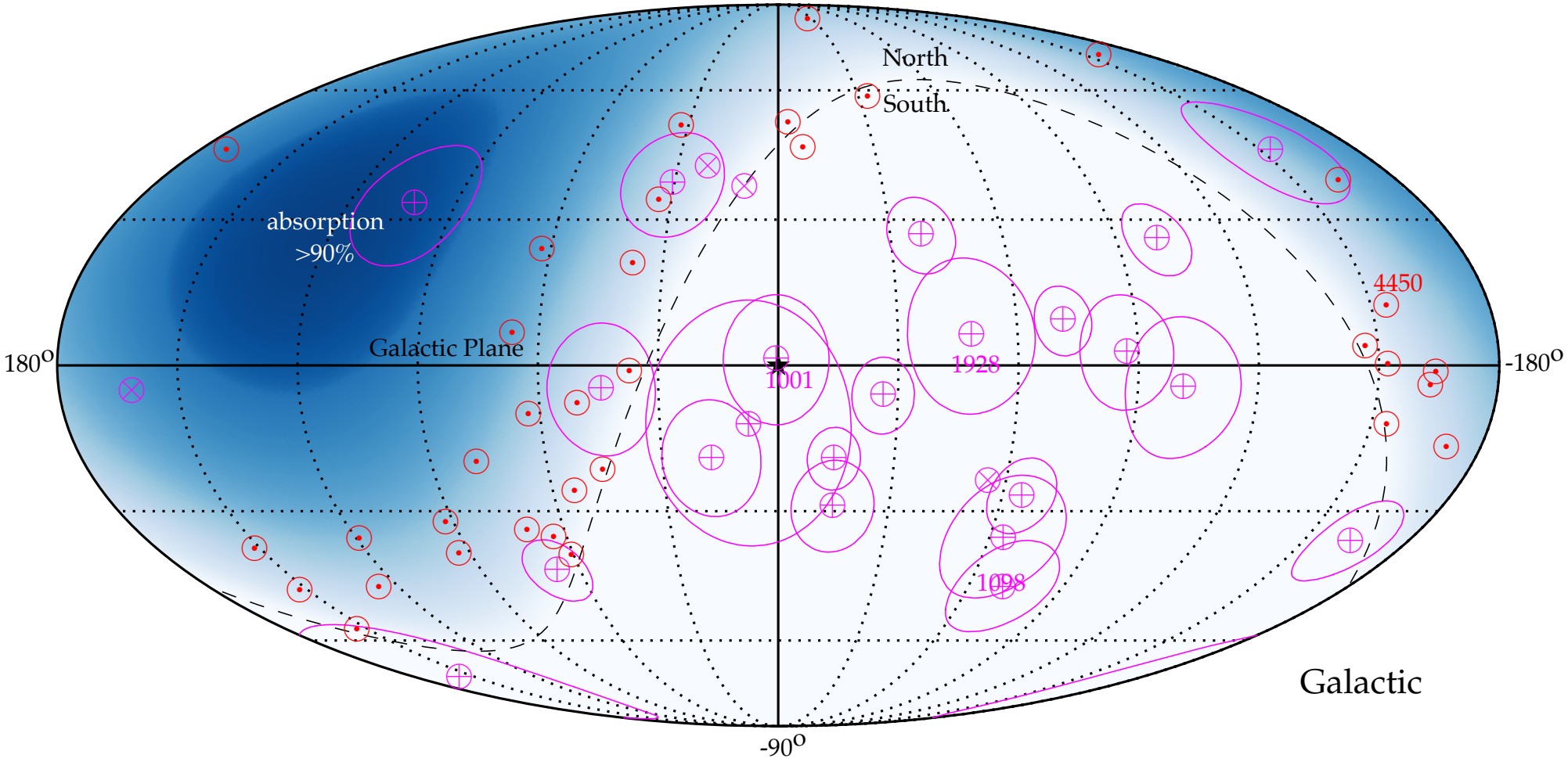
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

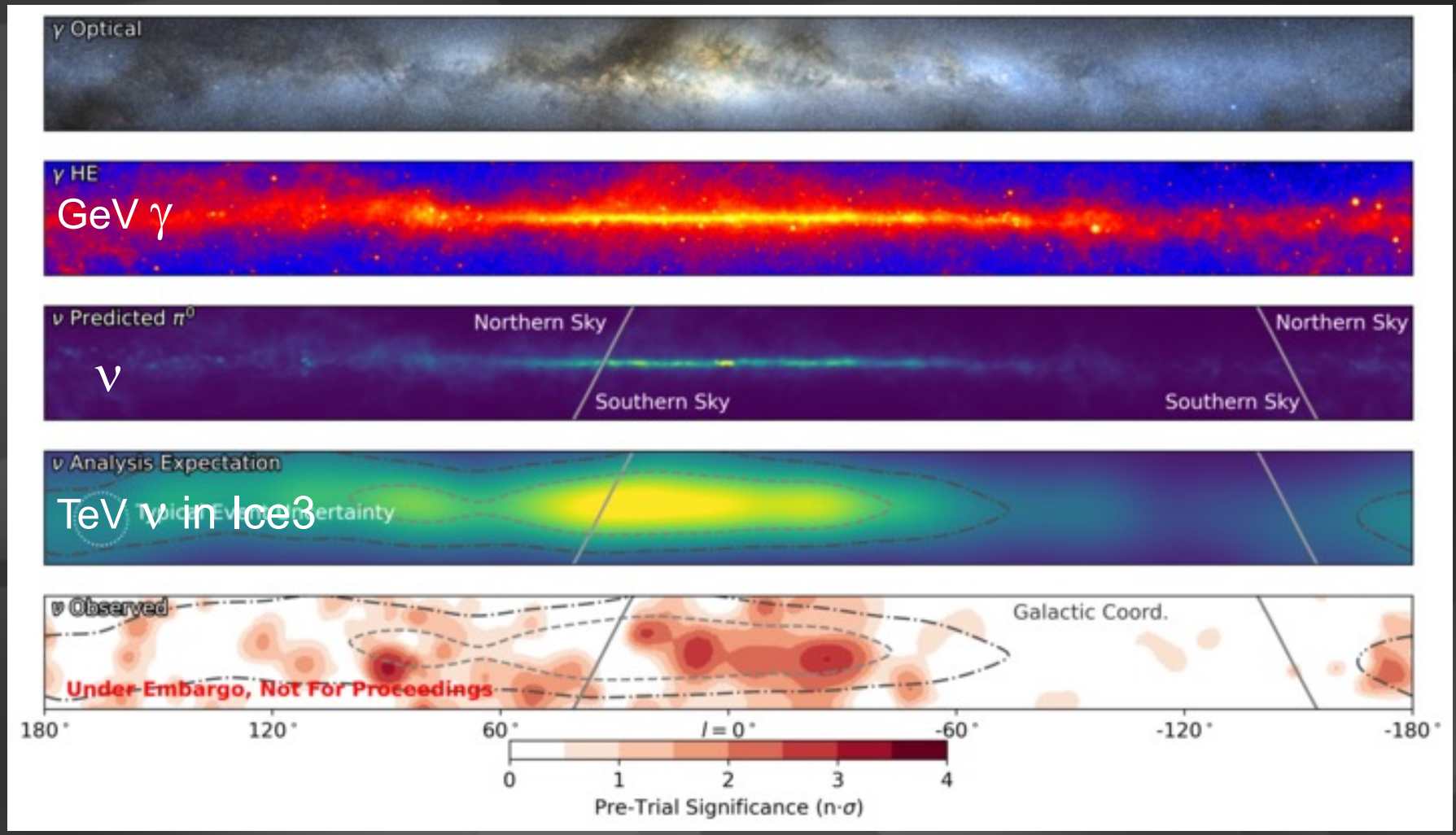
muon neutrino flux filtered by the Earth: atmospheric vs cosmic



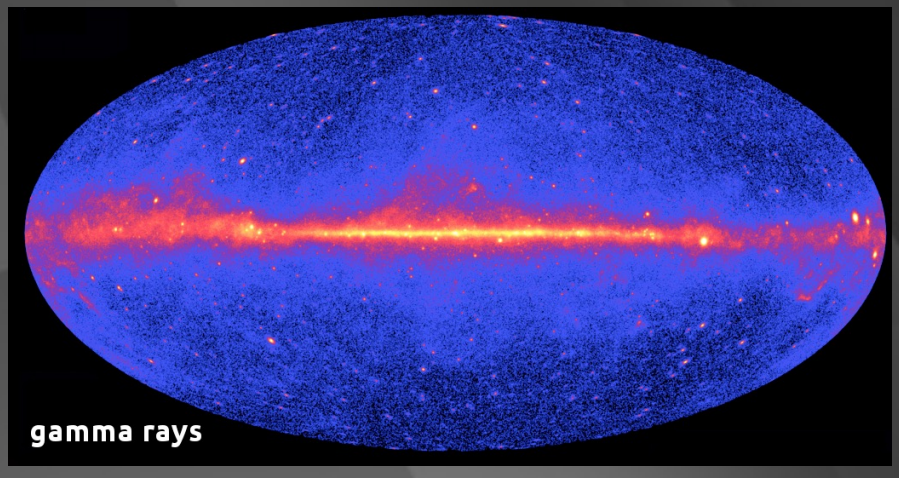
arrival directions of highest energy neutrinos of cosmic origin: where is our Galaxy?

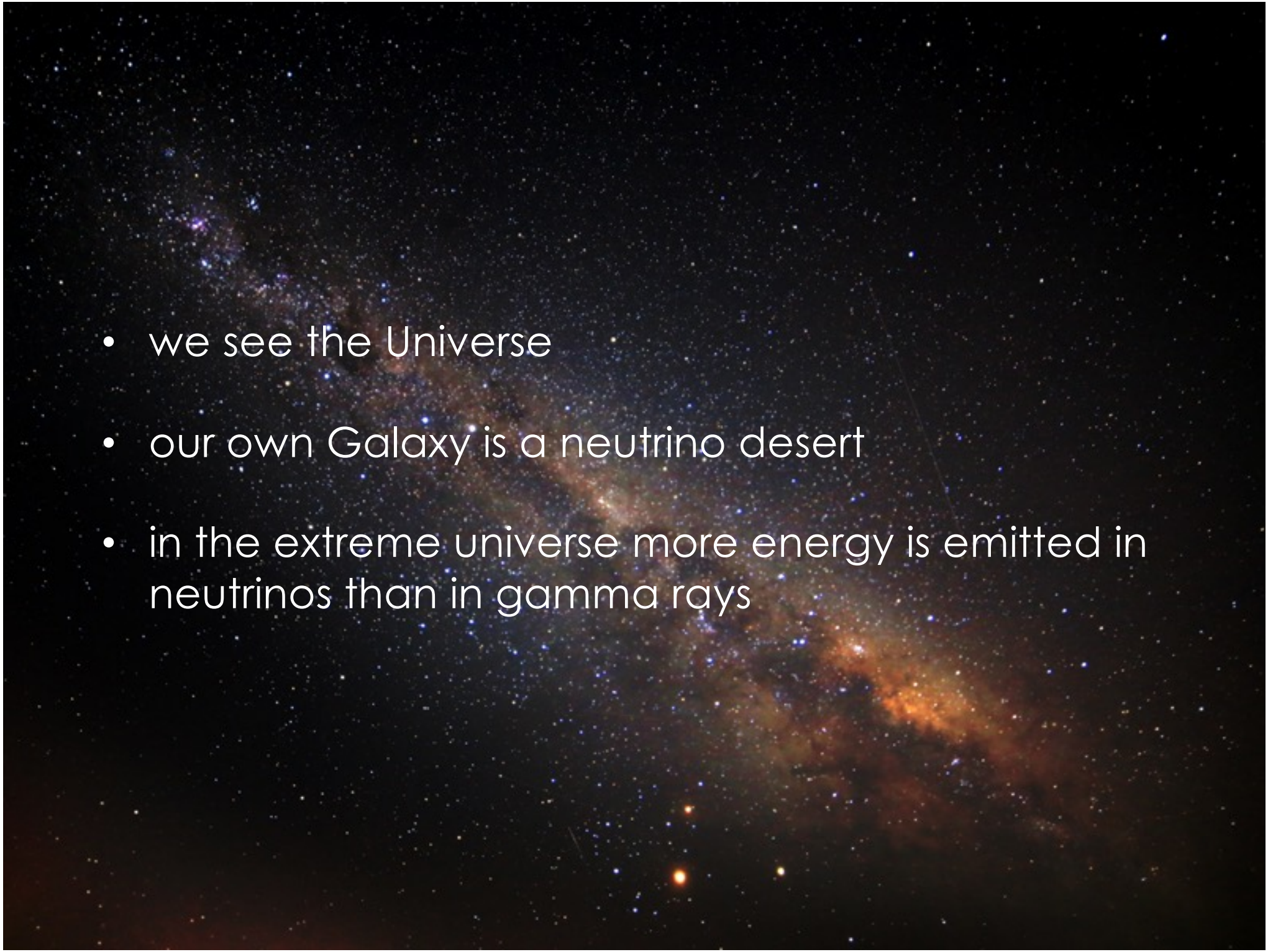
Arrival directions of most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))



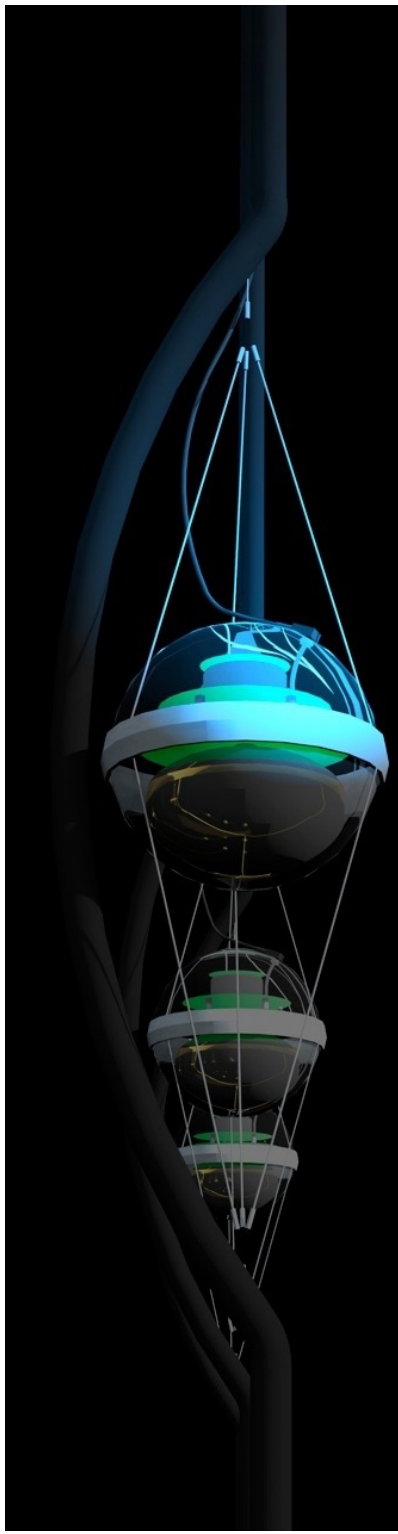

γ Optical
γ HE
GeV γ
ν Predicted π0
Northern Sky
Southern Sky
Northern Sky
Southern Sky
ν
ν Analysis Expectation
TeV ν in Ice3
ν Observed
Galactic Coord.
Under Embargo, Not For Proceedings
180°
120°
60°
l = 0°
-60°
-120°
-180°
0
1
2
3
4
Pre-Trial Significance (n·σ)


Visible


gamma rays



- we see the Universe
- our own Galaxy is a neutrino desert
- in the extreme universe more energy is emitted in neutrinos than in gamma rays



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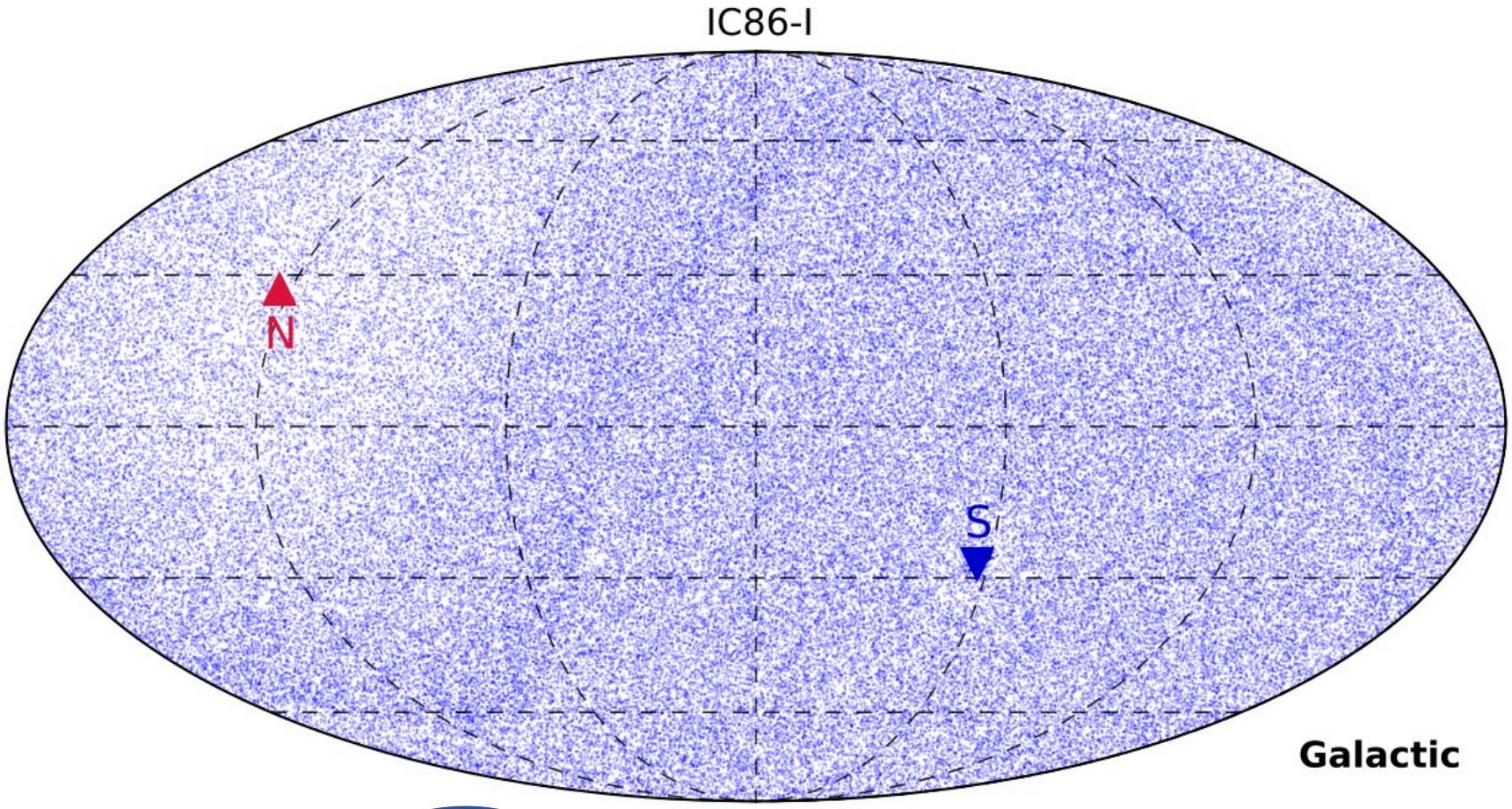
icecube.wisc.edu

one year of IceCube neutrinos >100 GeV

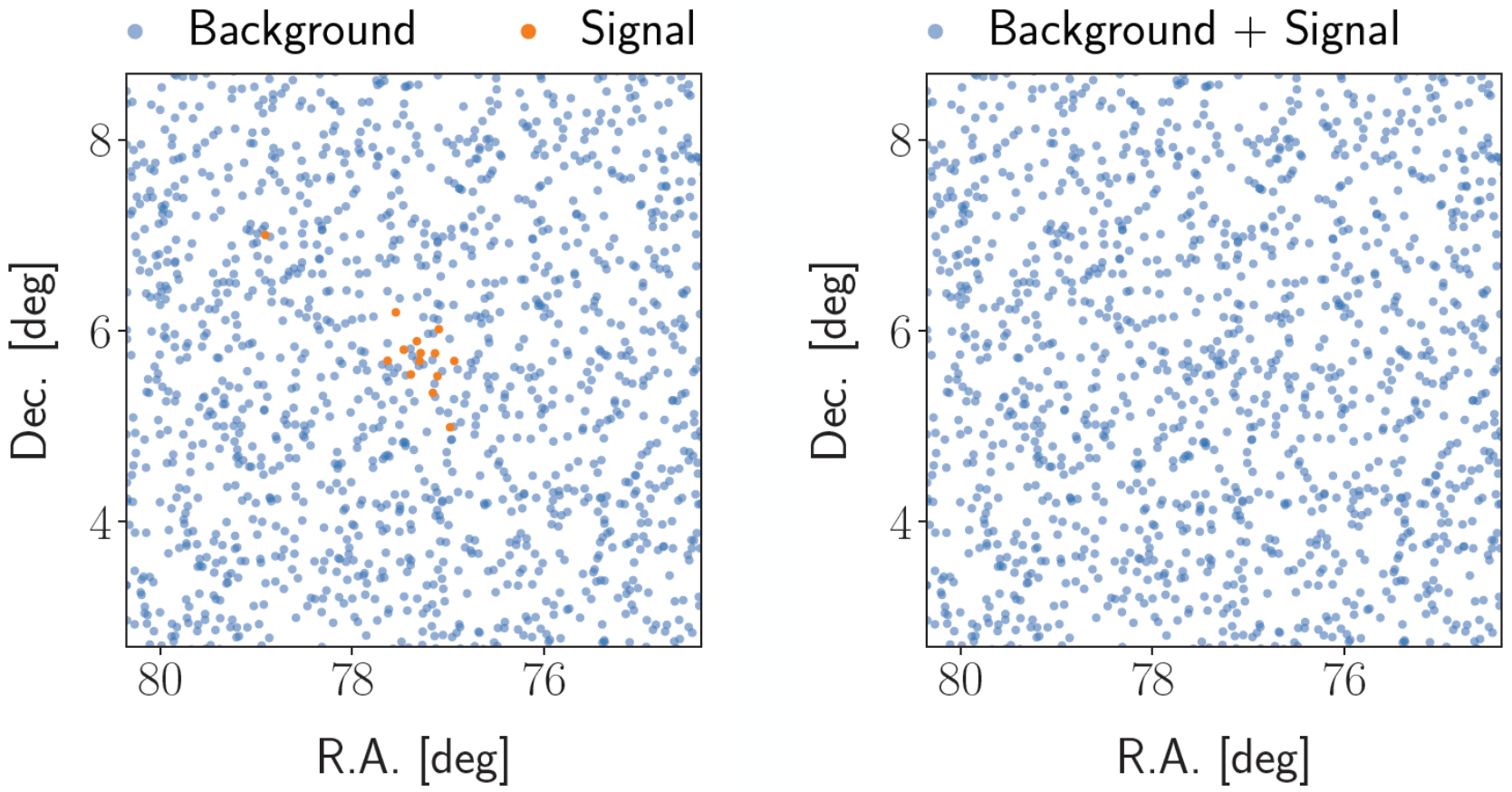
(reaches neutrino purity of 97% but overwhelmingly atmospheric)



138322 neutrino candidates in one year

~ 200 cosmic neutrinos

~12 separated from atmospheric background with E>60 TeV



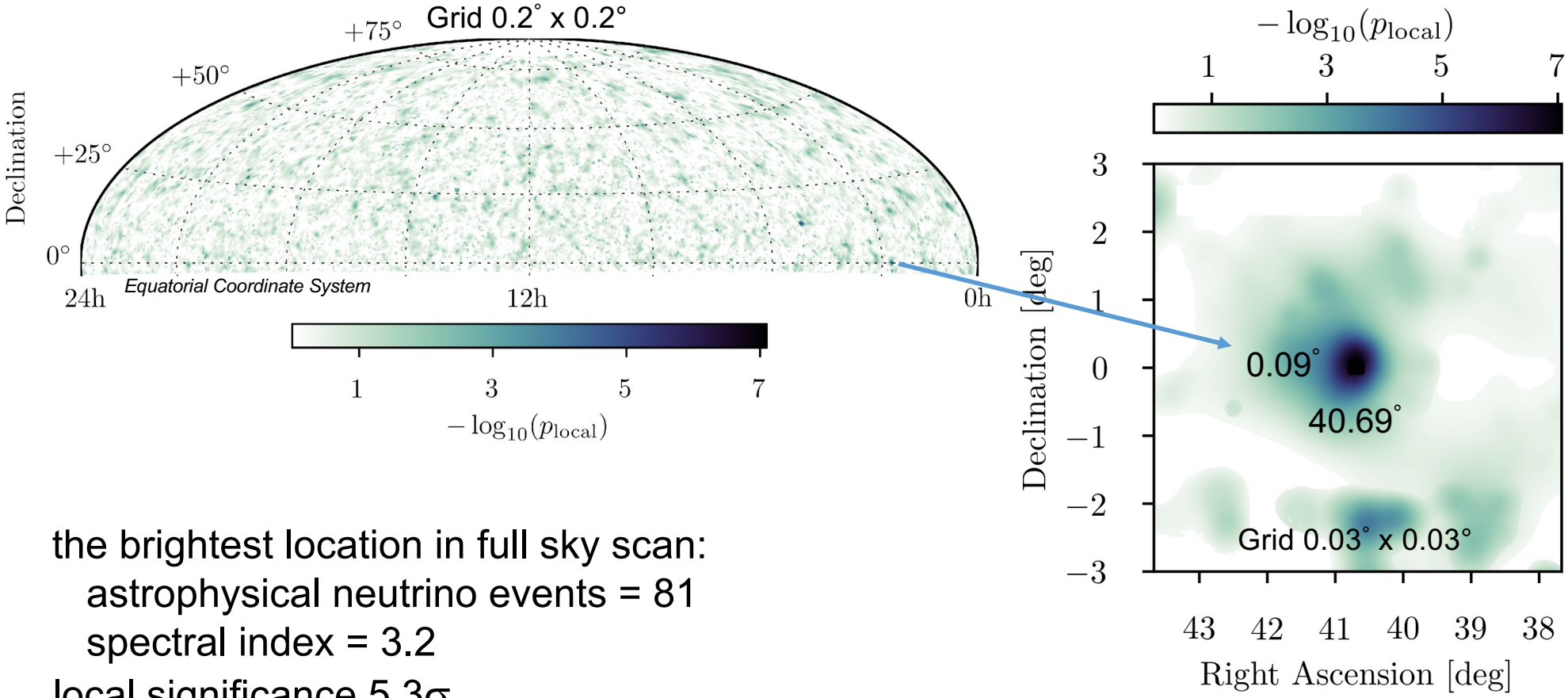
- maximize the likelihood *L* at each point in the sky
- usually, add energy term to the signal likelihood *S*

$$L(n_s, x_s, \gamma) = \prod_{i}^{events} \left(\frac{n_s}{N} S_i(|x_i - x_s|\sigma_i, E_i, \gamma) + \frac{N - n_s}{N} B_i(\delta_i, E_i)\right)$$

$$\downarrow$$

$$S_i(|\vec{x}_i - \vec{x}_s|, \sigma_i) = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}\right)$$

the new IceCube neutrino map

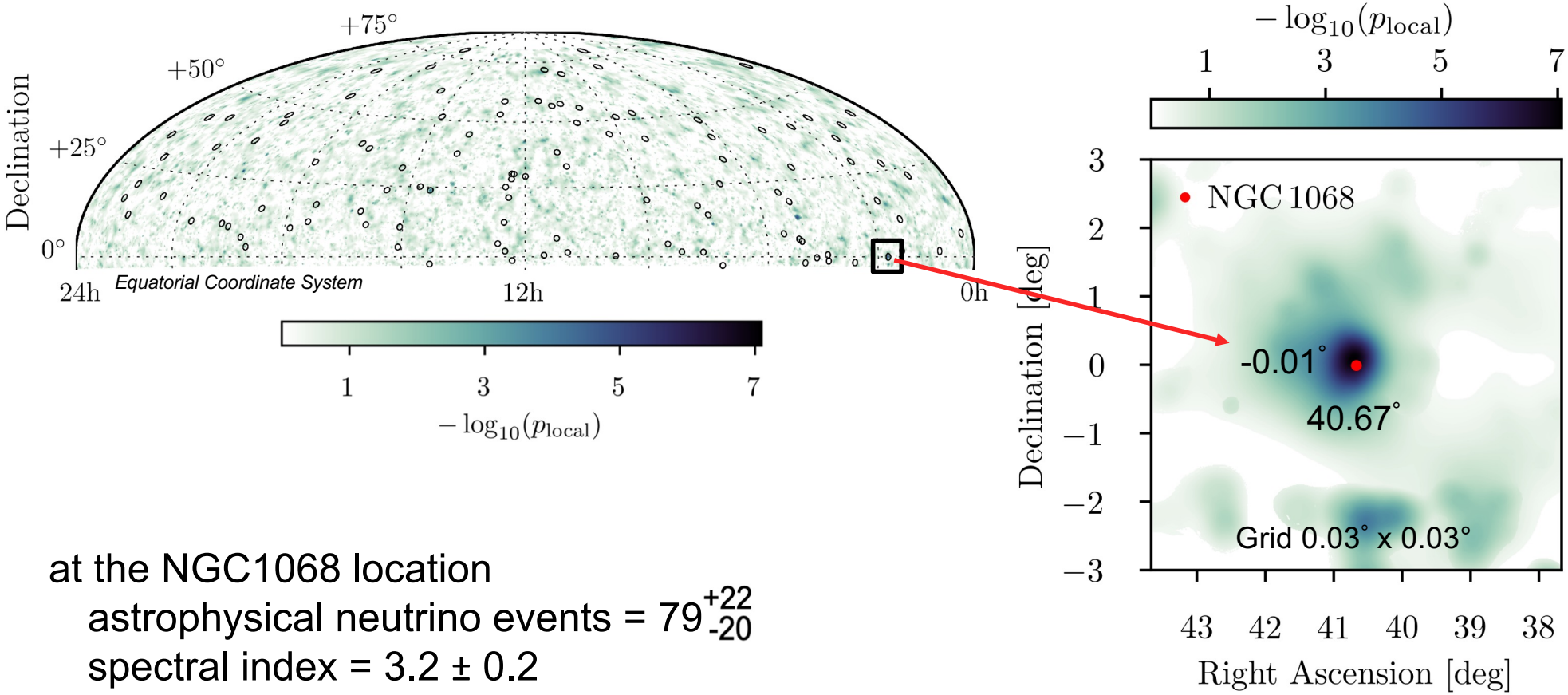


the brightest location in full sky scan:
- astrophysical neutrino events = 81
- spectral index = 3.2

local significance 5.3σ

1% of scrambled data sets have a spot ≥ 5.3**σ**

is the hot spot coincident with one of the 110 preselected sources?



at the NGC1068 location

astrophysical neutrino events = 79^{+22}_{-20}

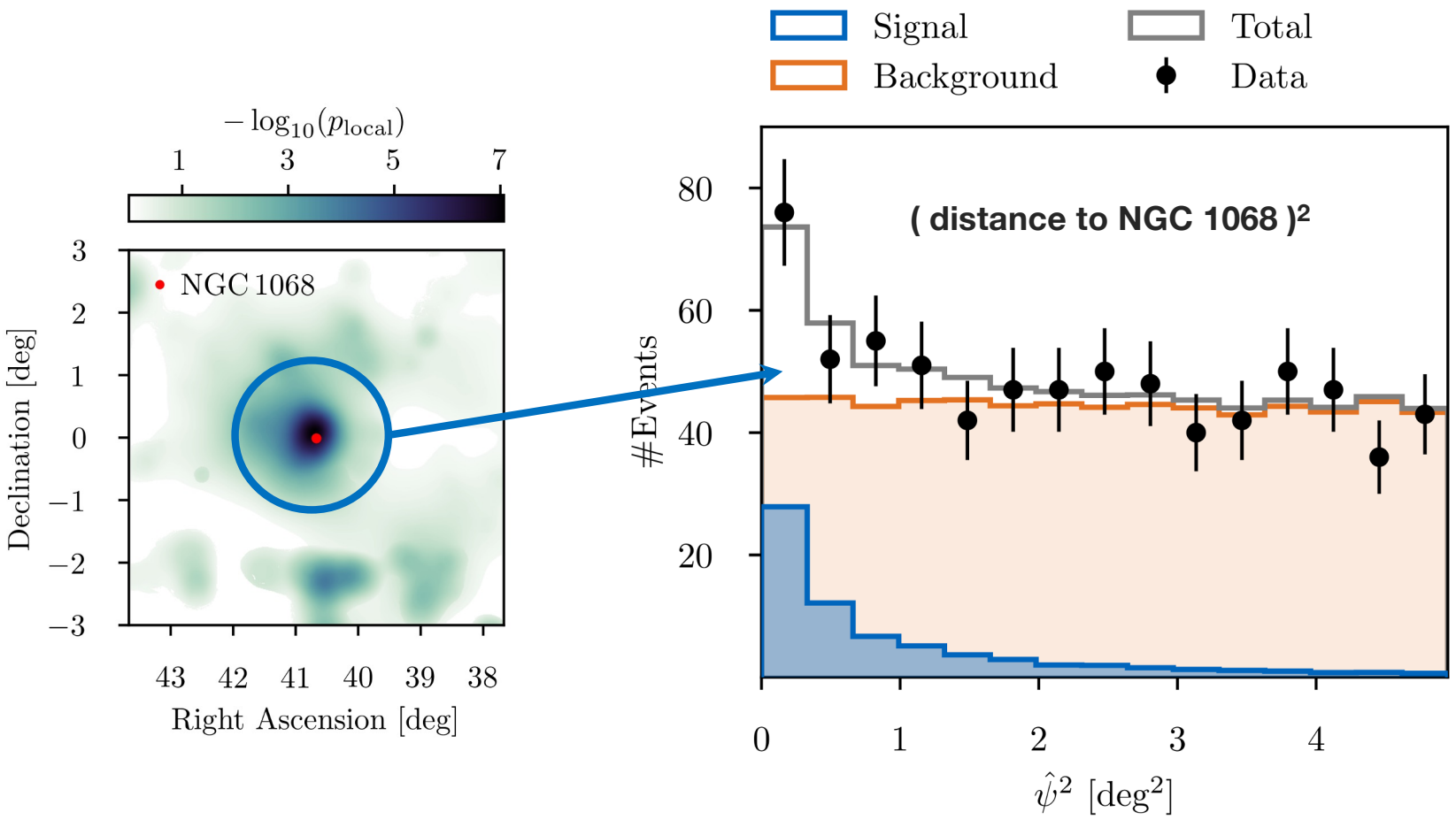
spectral index = 3.2 ± 0.2

single source significance 5.2σ

(offset 0.11^0)

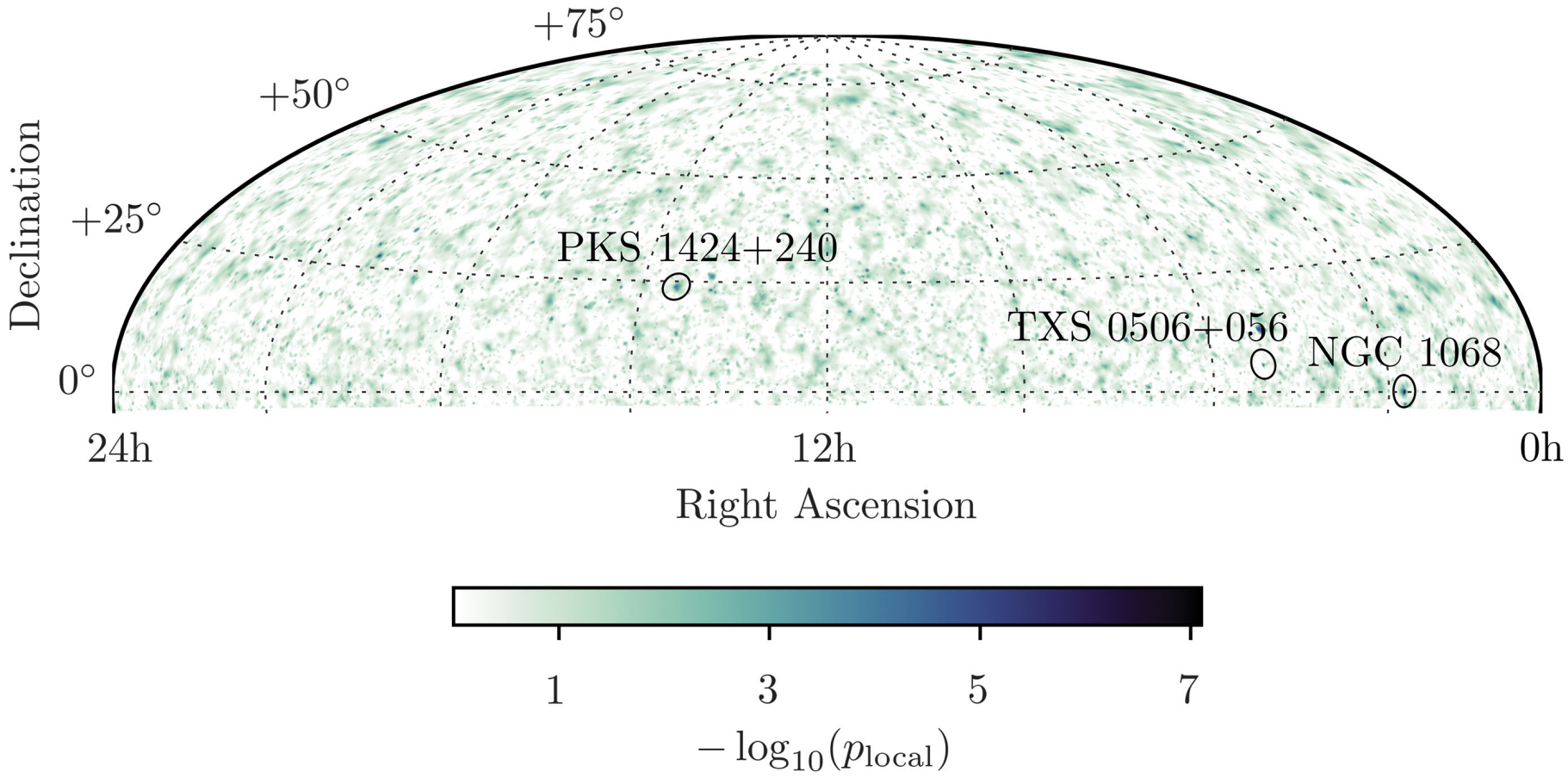
1 in 100,000 scrambled data sets have object ≥ 5.2 **σ** = 4.2 **σ** evidence

another look at the result



- measured astrophysical neutrino events = 79^{+22}_{-20}
- the angular distribution of the events matches simulation

sub-leading sources?



also NGC 4151

RESEARCH ARTICLE SUMMARY

Science 2017

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

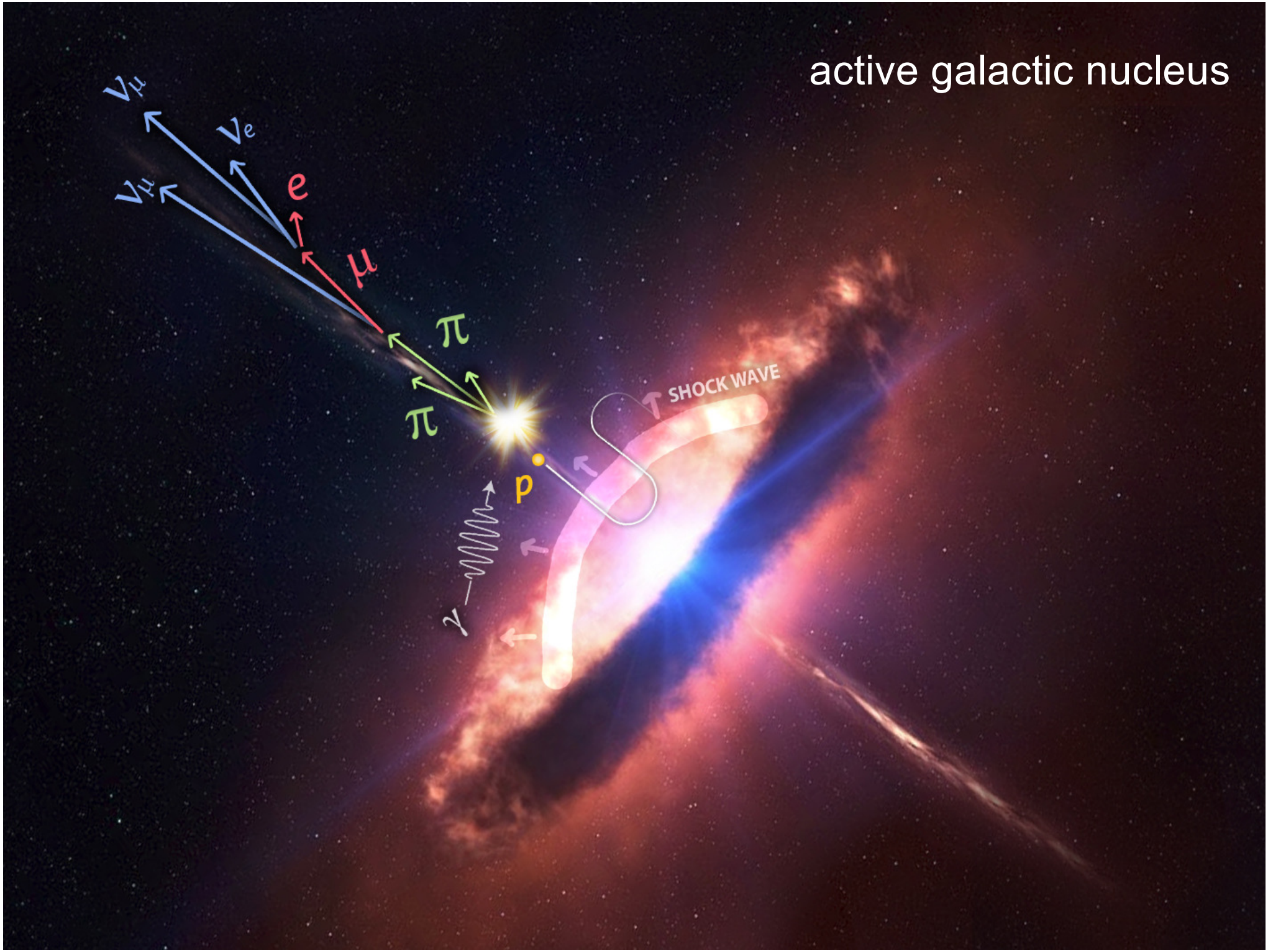
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

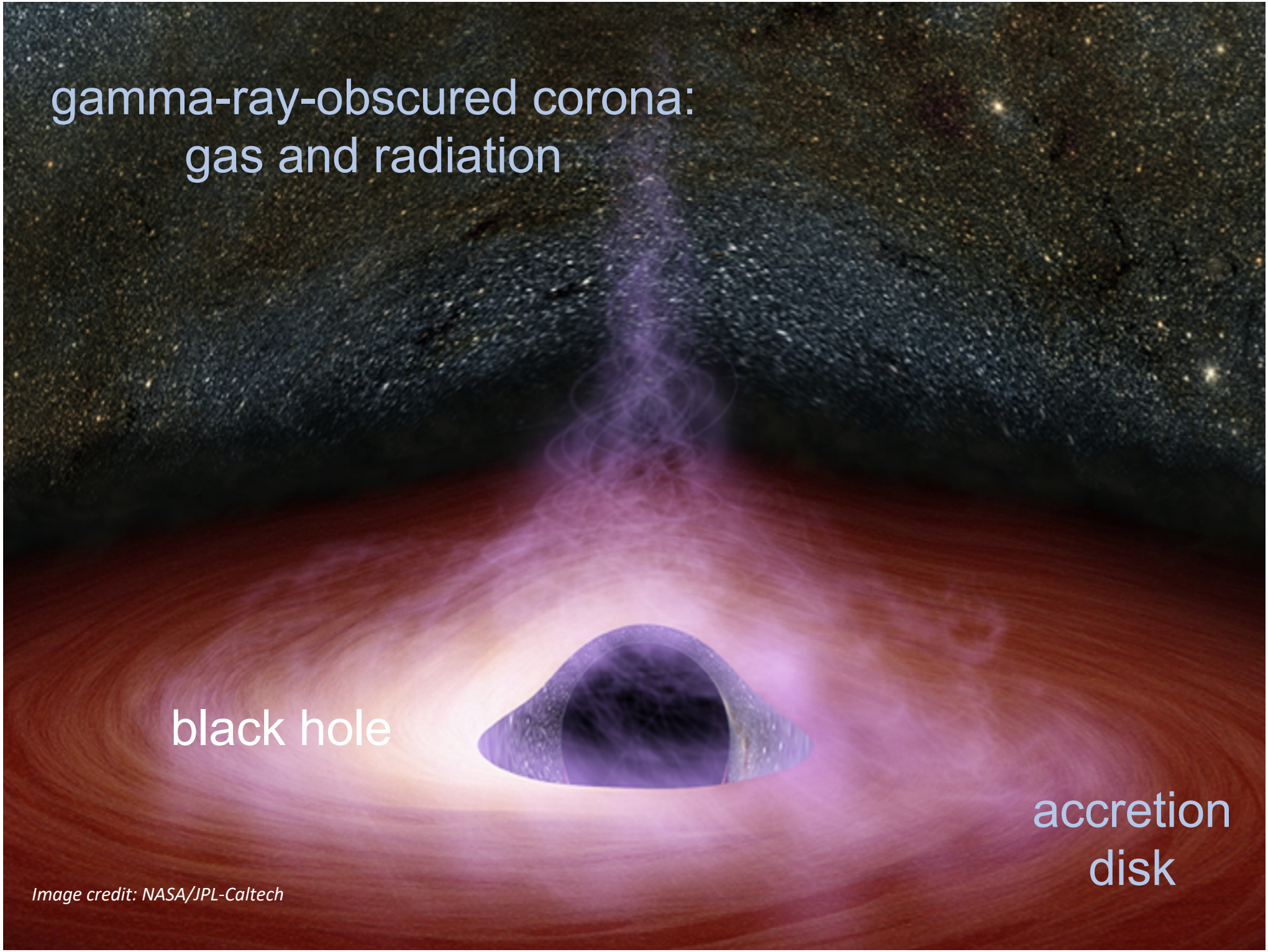
RESEARCH ARTICLE

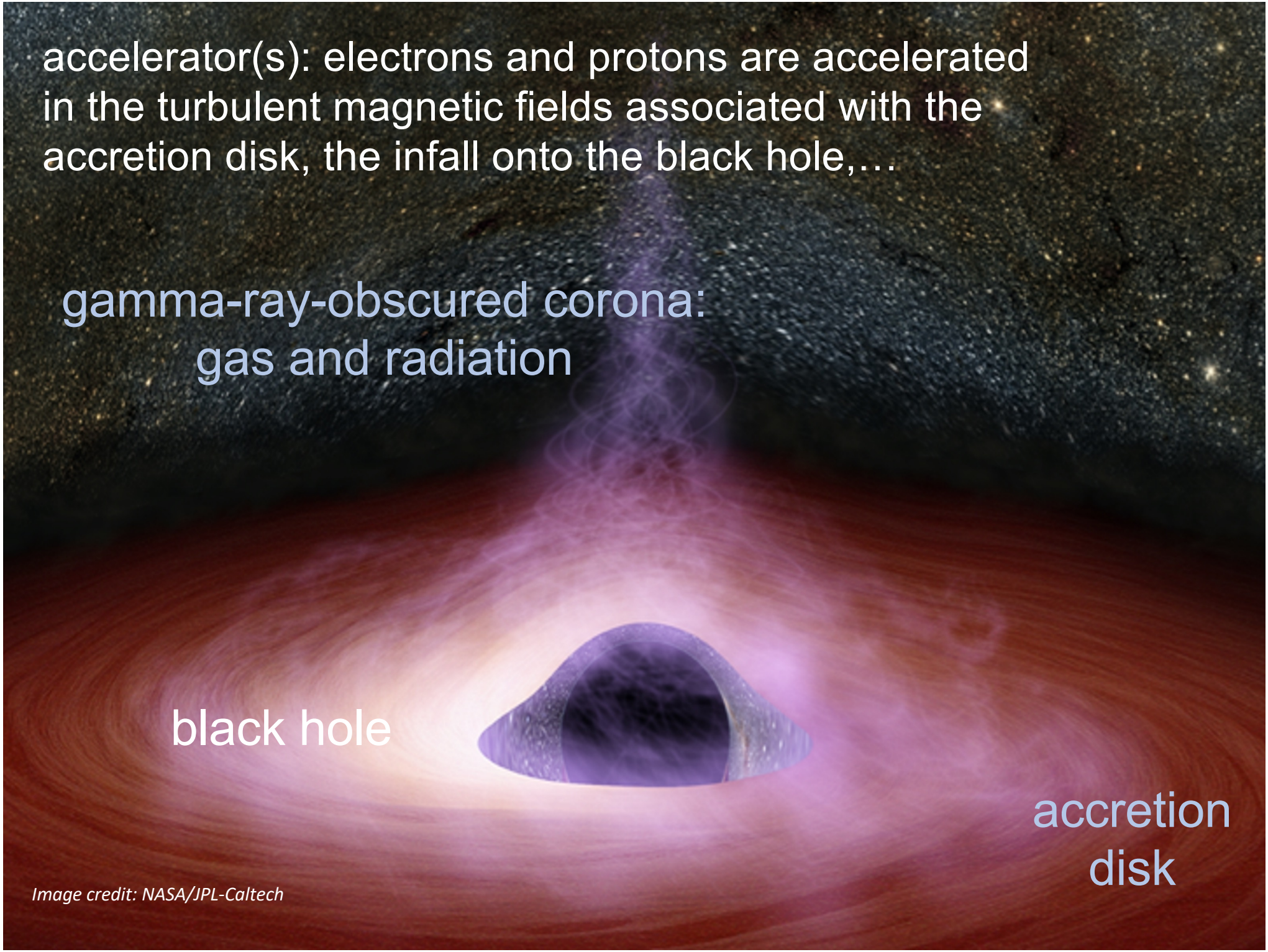
NEUTRINO ASTROPHYSICS

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†

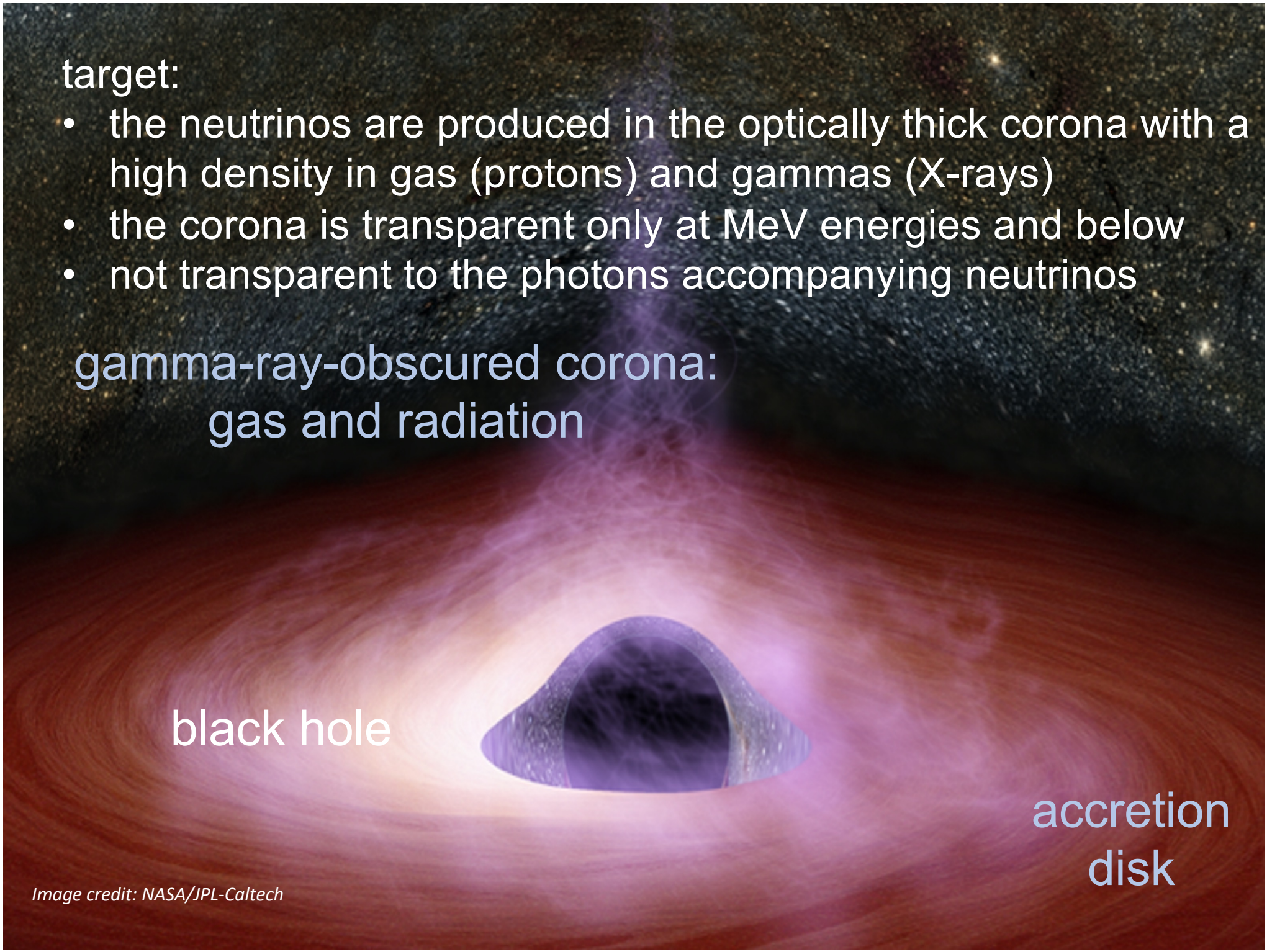

active galactic nucleus
ν_μ
ν_e
ν_μ
e
μ
π
π
SHOCK WAVE
p
γ


gamma-ray-obscured corona:
gas and radiation
black hole
accretion
disk
Image credit: NASA/JPL-Caltech

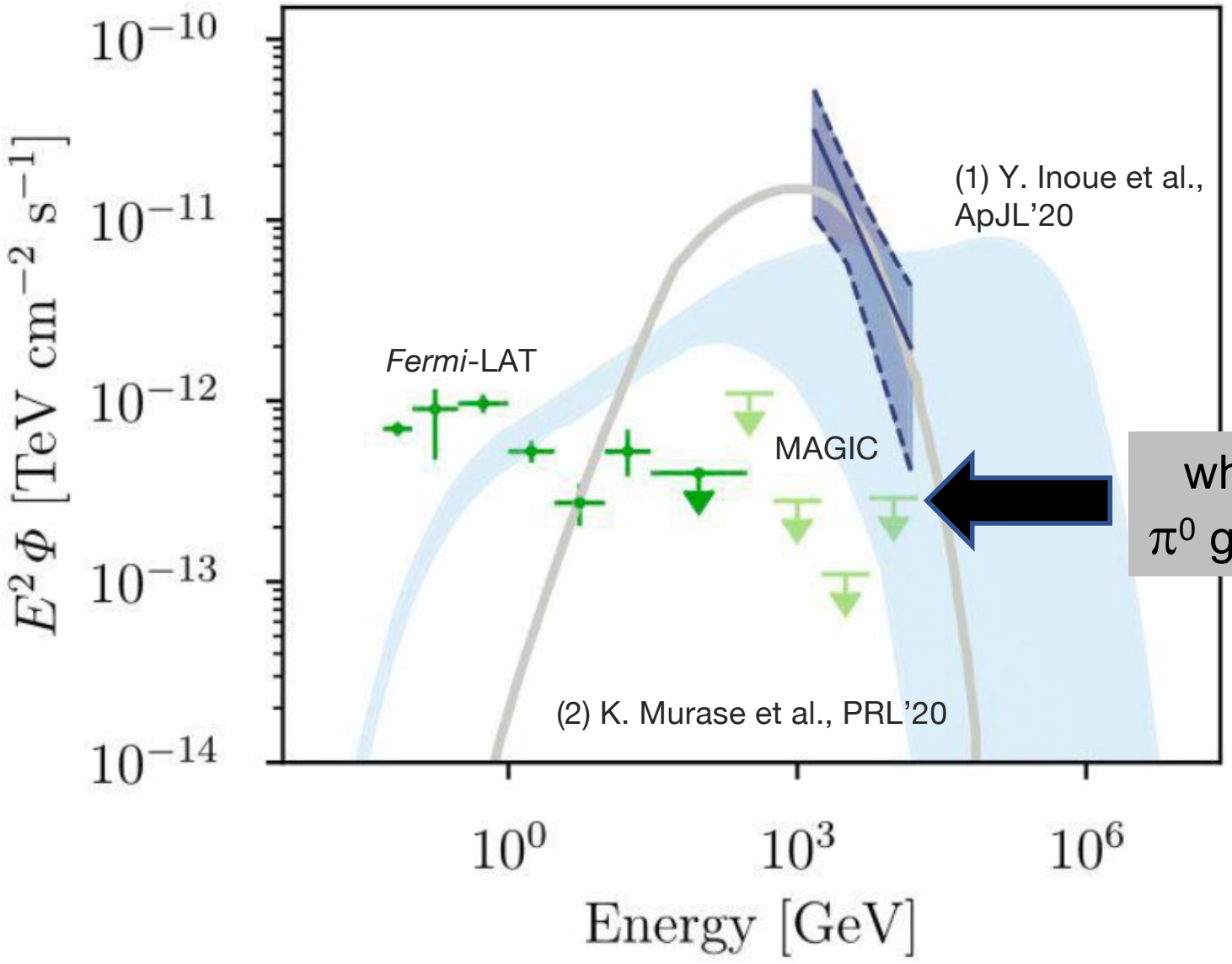

accelerator(s): electrons and protons are accelerated in the turbulent magnetic fields associated with the accretion disk, the infall onto the black hole,…
gamma-ray-obscured corona: gas and radiation
black hole
accretion disk
Image credit: NASA/JPL-Caltech

target:

- the neutrinos are produced in the optically thick corona with a high density in gas (protons) and gammas (X-rays)
- the corona is transparent only at MeV energies and below
- not transparent to the photons accompanying neutrinos



NGC 1068: an obscured cosmic accelerator



where are the π^0 gamma rays ?

the neutrino view:
in order to suppress the gamma rays that accompany the neutrinos observed:
$R \sim 10\ R_s$
emerge at MeV and below

- dense target of X-ray photons
- dense target of protons
- $\tau_{p\gamma}$ and $\tau_{pp} > 1$
- opacity is cross section x density

$$\tau_{\gamma\gamma} \sim \sigma_{\gamma\gamma} \left[\frac{1}{R} \frac{L_X}{E_X}\right]$$

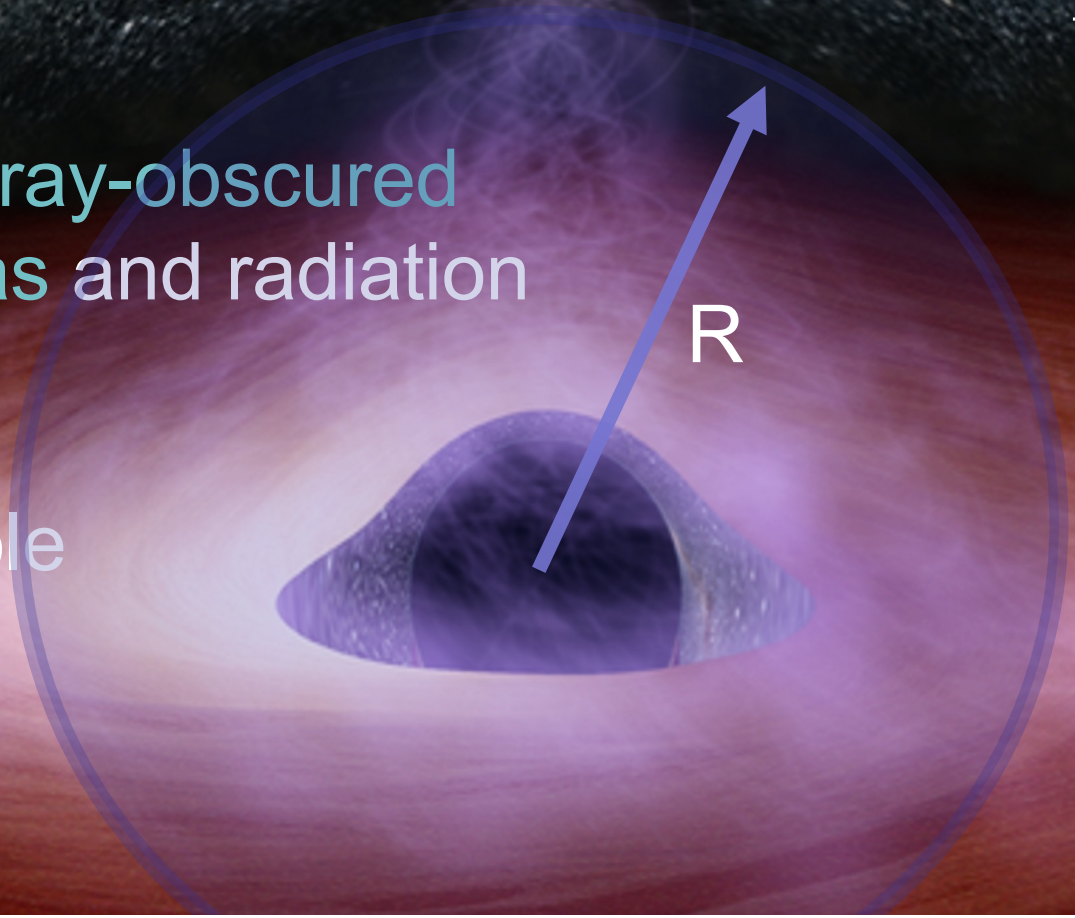
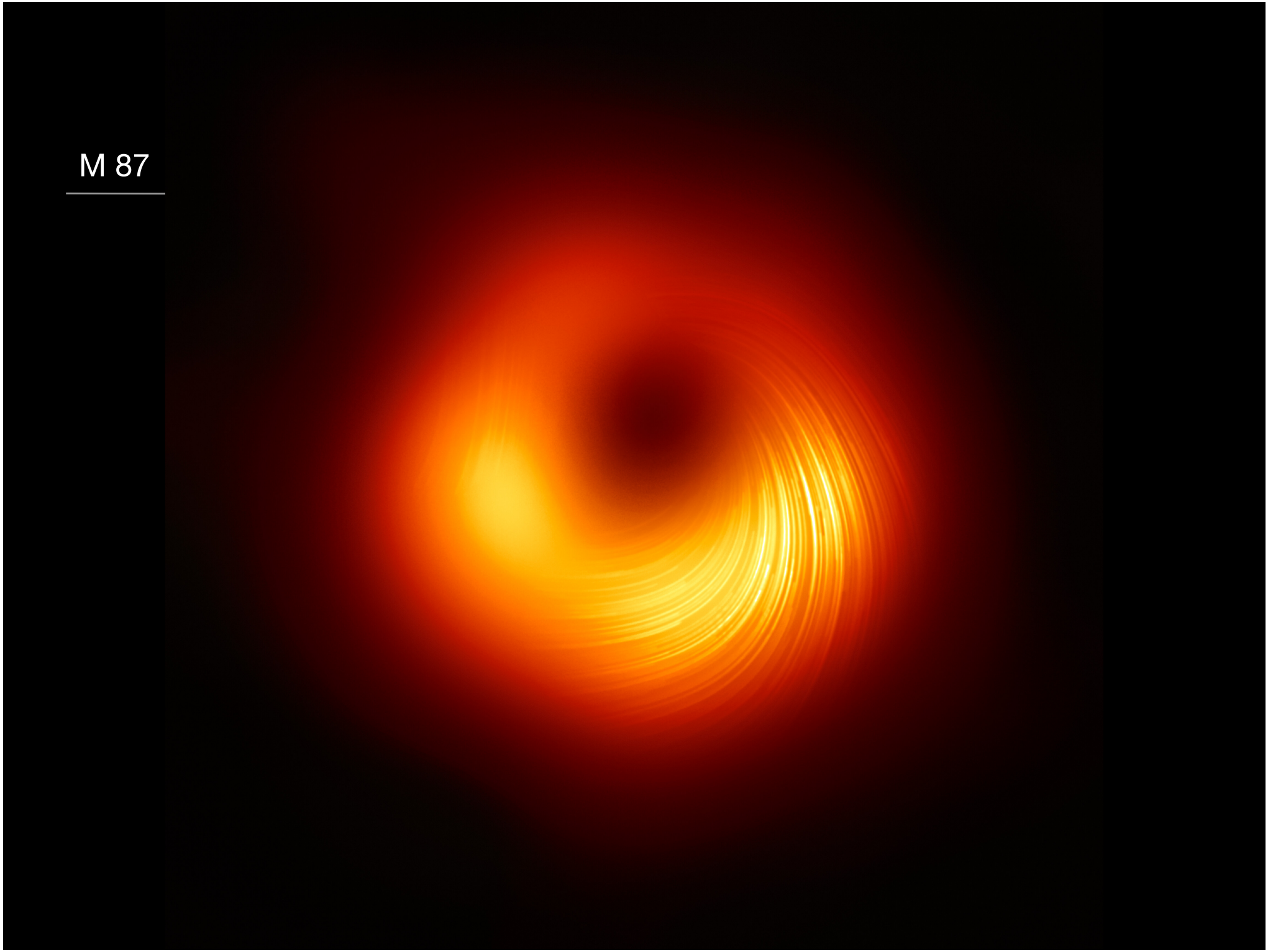
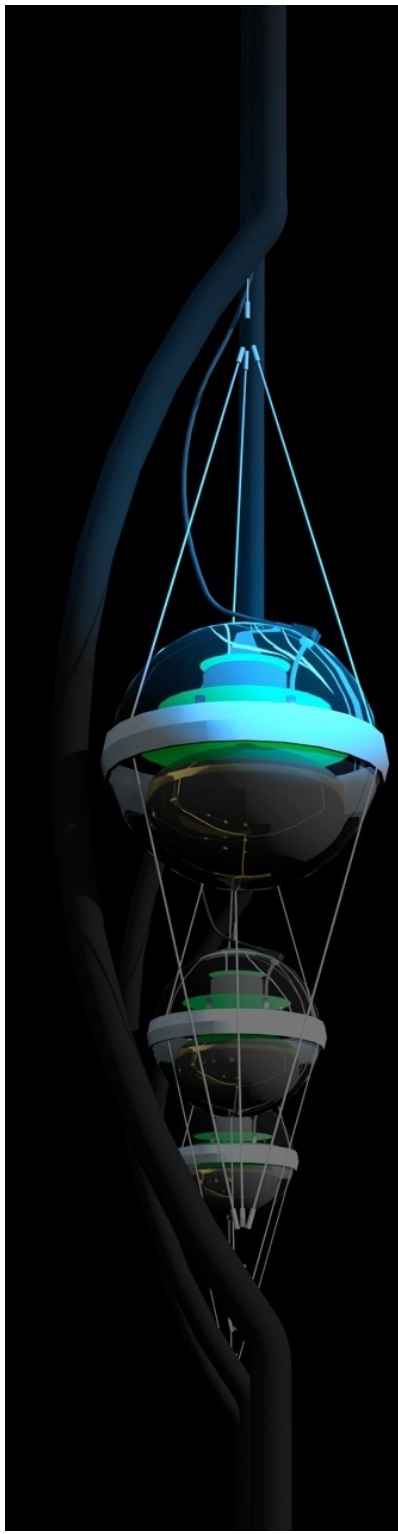


Image credit: NASA/JPL-Caltech


M 87



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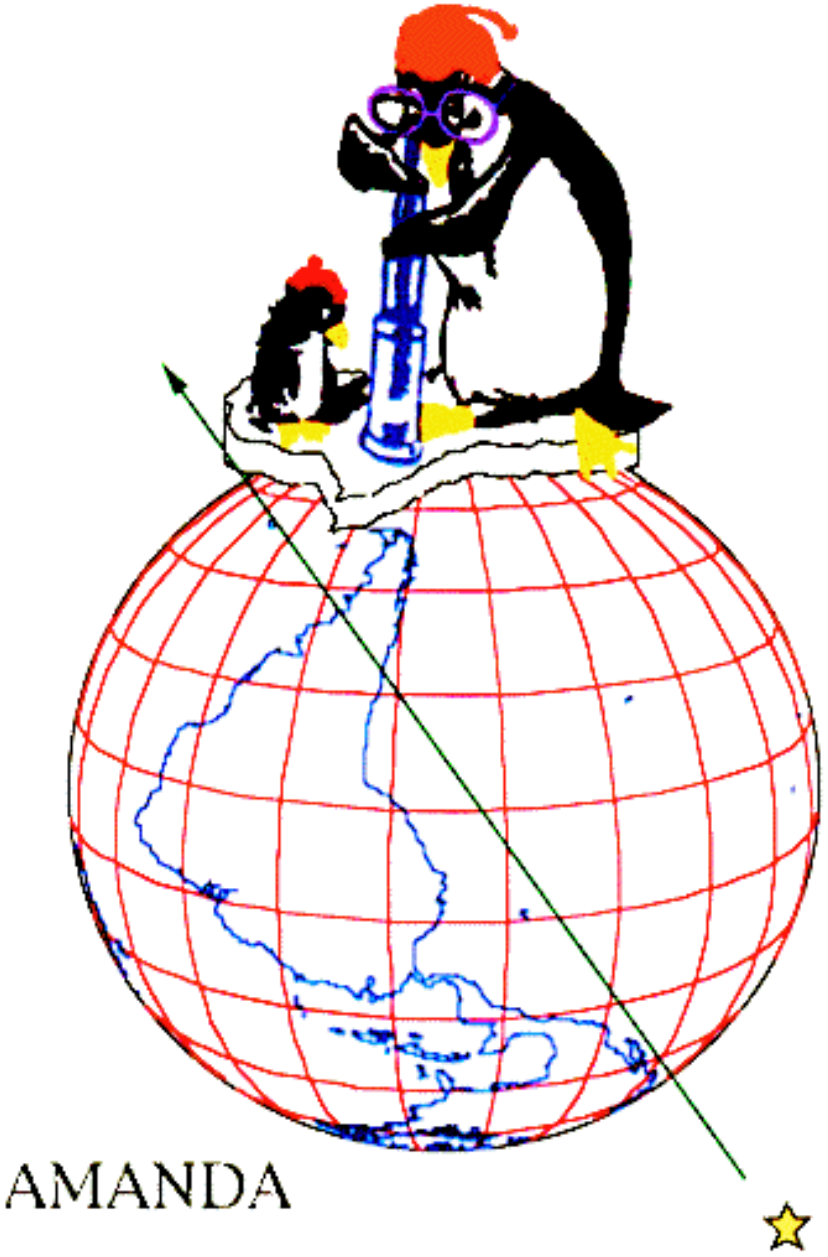
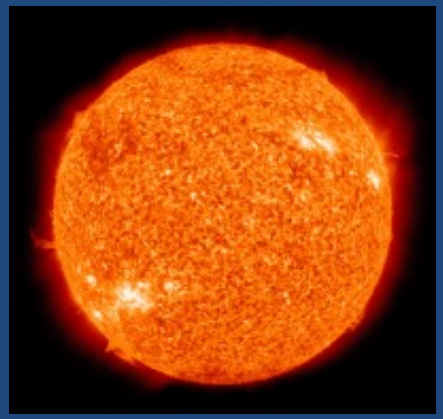
1992 Cline meeting at UCLA



IceCube targets for dark matter annihilation

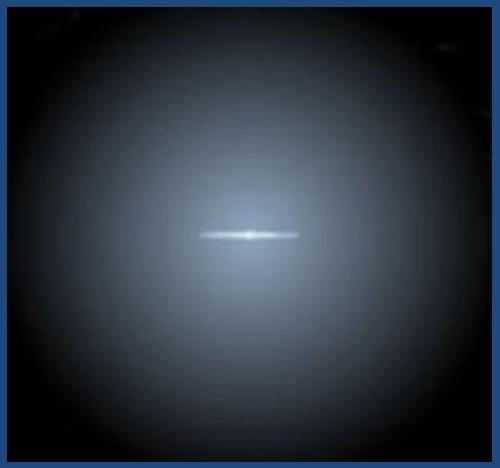
Sun



Galactic Centre

Dwarf galaxies

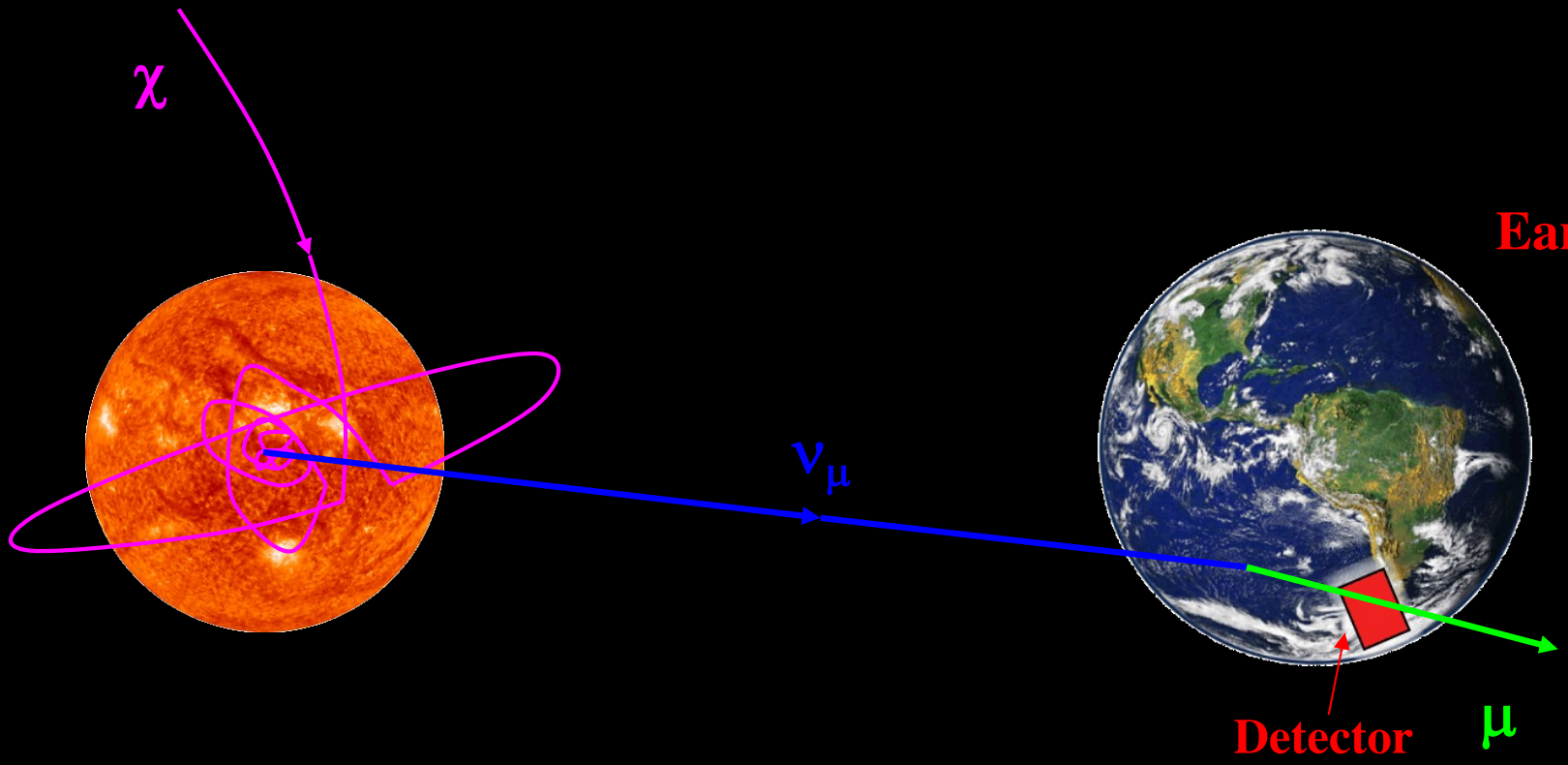
Earth



Galactic Halo

Galaxy clusters

dark matter capture and annihilation



$$\chi + \chi \rightarrow \mathrm{W}^+ + \mathrm{W}^-$$

$$\chi + \chi \rightarrow \mathrm{b} + \bar{\mathrm{b}}$$

$$\ldots$$

dark matter capture and annihilation

1. Halo WIMPs scatter on nuclei in the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the south pole, convert into muons in the ice

$$\chi + \chi \rightarrow \mathrm{W}^{+} + \mathrm{W}^{-}$$

$$\chi + \chi \rightarrow \mathrm{b} + \bar{\mathrm{b}}$$

$$\ldots$$

$$\frac{dN_\chi}{dt} = C_{sun} = \varphi_\chi \sigma_{sun}$$

- $\varphi_\chi = \left[\frac{\rho}{m_\chi}\right] \mathrm{v}_\chi$
- $\sigma_{sun} = \frac{M_{sun}}{m_p} \sigma_{\chi p}$
- $C_{sun} = 2\, C_{annihilation}$ (equilibrium)

given a cross section on protons and a branching ratio of the annihilation products into neutrinos (via τ, b or W for instance) the model is seen or ruled out

$$\frac{dN_\chi}{dt} = C_{sun} = \varphi_\chi \sigma_{sun}$$

- $\varphi_\chi = \left[\frac{\rho}{m_\chi}\right] \mathrm{v}_\chi$
- $\sigma_{sun} = \left(\frac{M_{sun}}{m_p}\right) \sigma_{\chi p}$
- $C_{sun} = 2\, C_{annihilation}$ (equilibrium)

astrophysical "ambiguities"

number of protons in the sun

given a cross section on protons and a branching ratio of the annihilation products into neutrinos (via τ, b or W for instance) the model is seen or ruled out

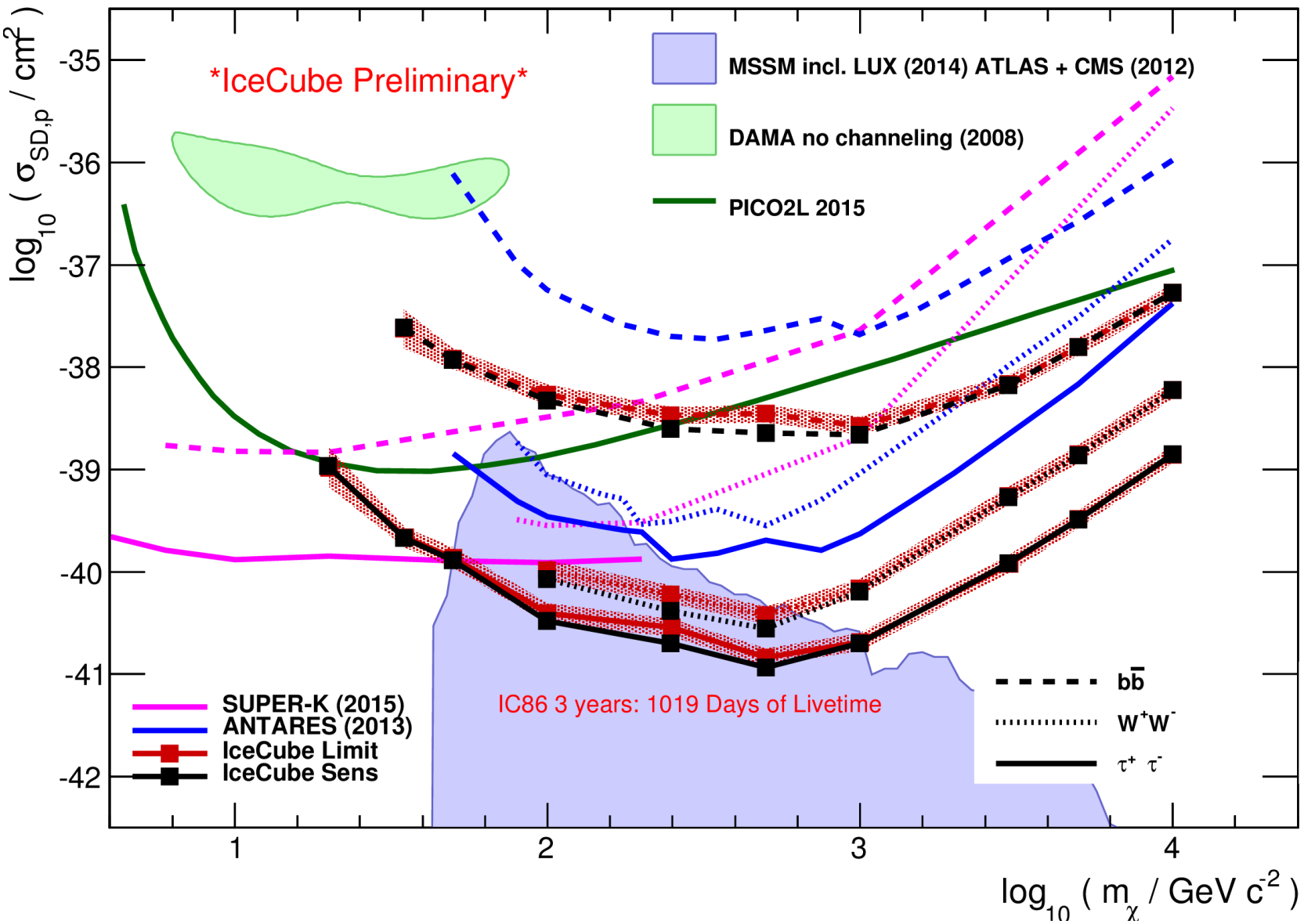
detection is a smoking gun

- indirect rates are dictated by the interaction cross section of WIMPS with hydrogen.
  → no unknown astrophysics

- in the neutrino case there is a direct connection between theory and observation and the background is understood.

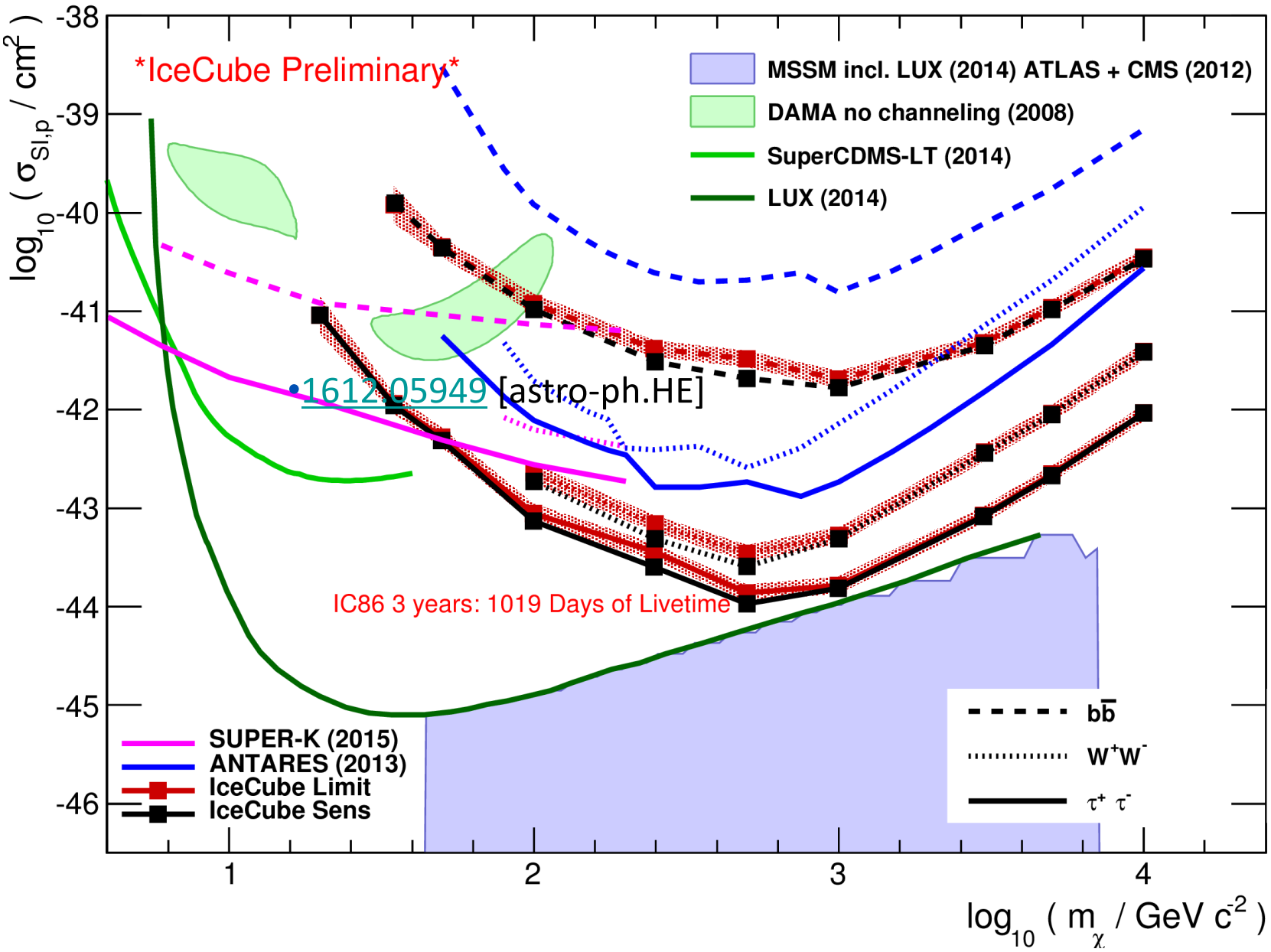
limits after 3 years
spin independent (A^2 handicap)

1612.05949 [astro-ph.HE]

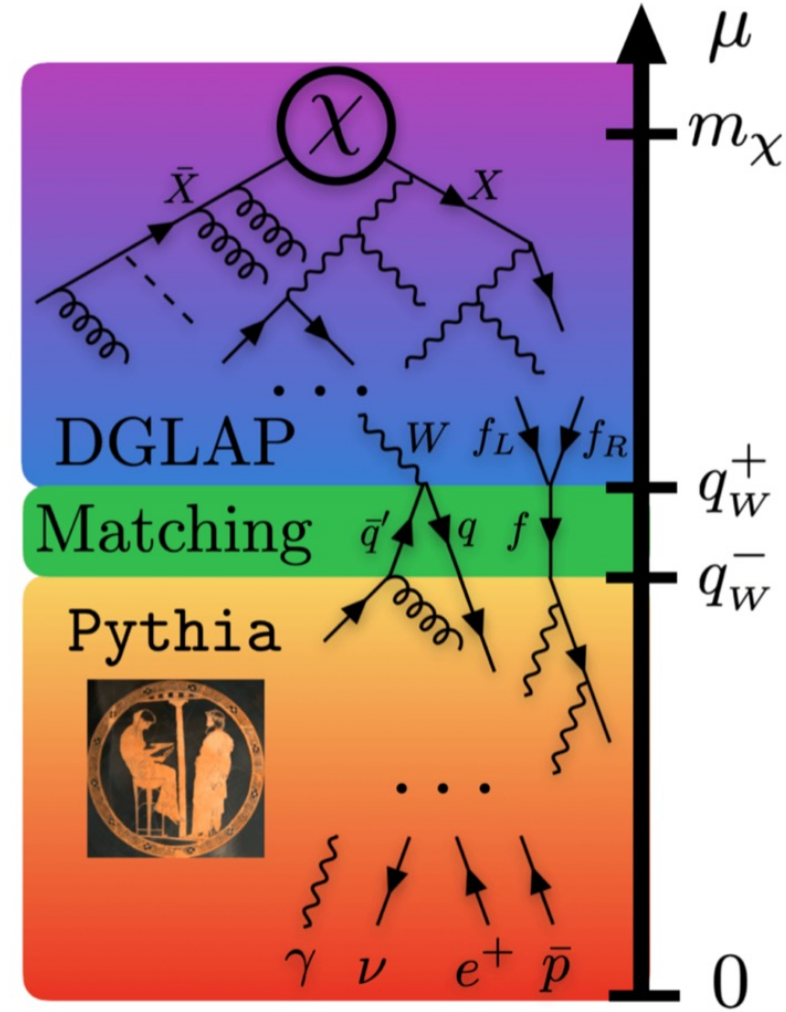


limits after 3 years spin dependent (A~1)

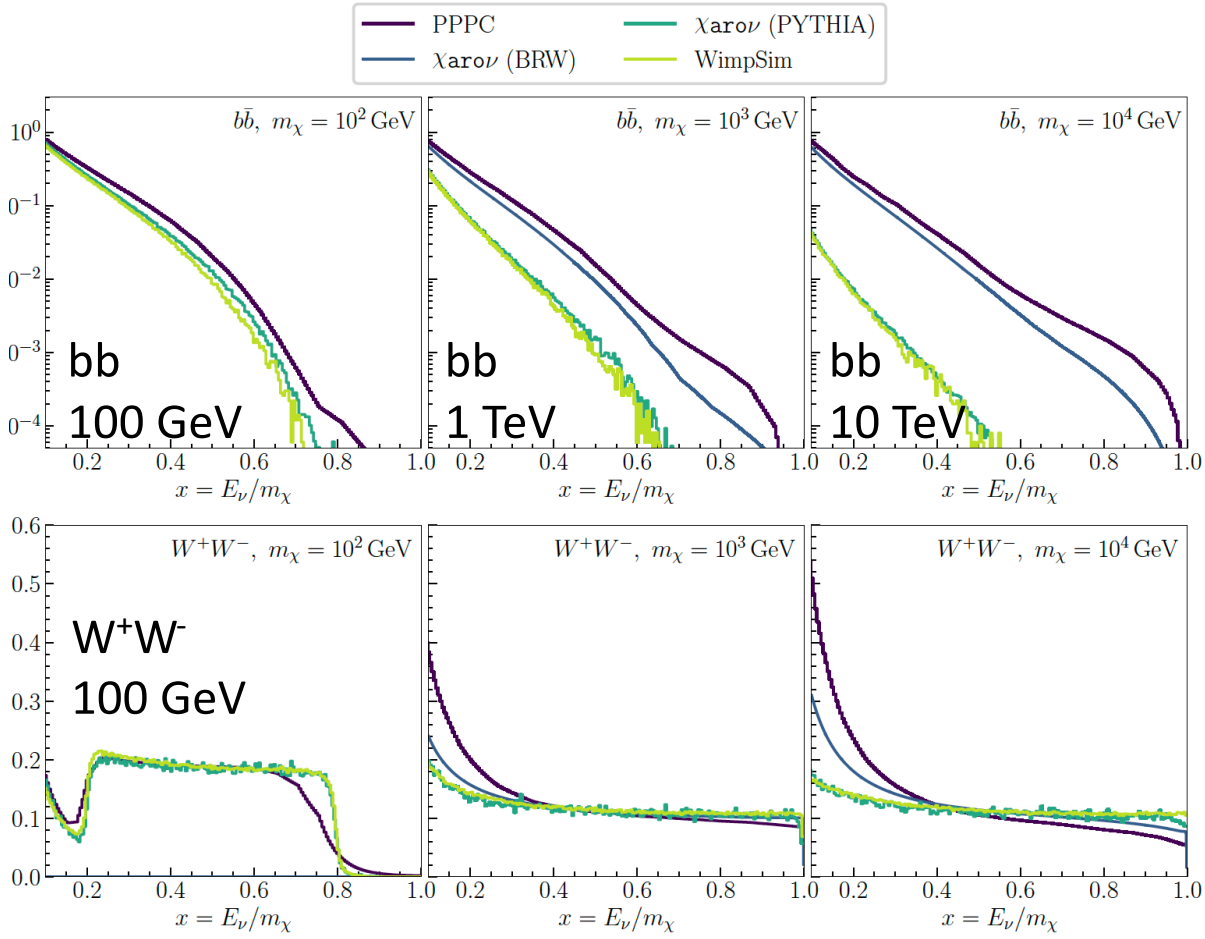
•1612.05949 [astro-ph.HE]



neutrino spectra from dark matter annihilations in the sun a decade of data

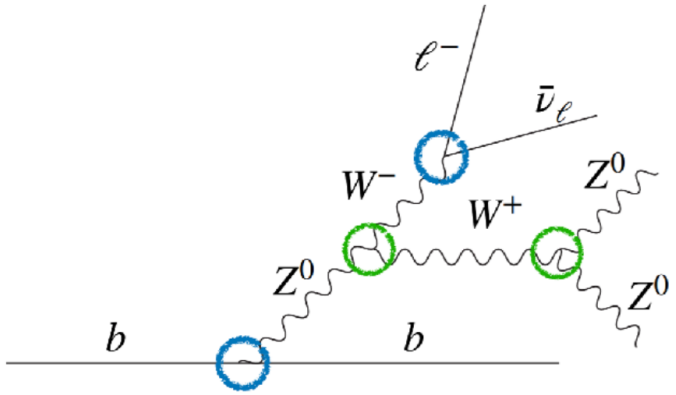


Bauer, Rodd, Webber JHEP 06 (2021) 121

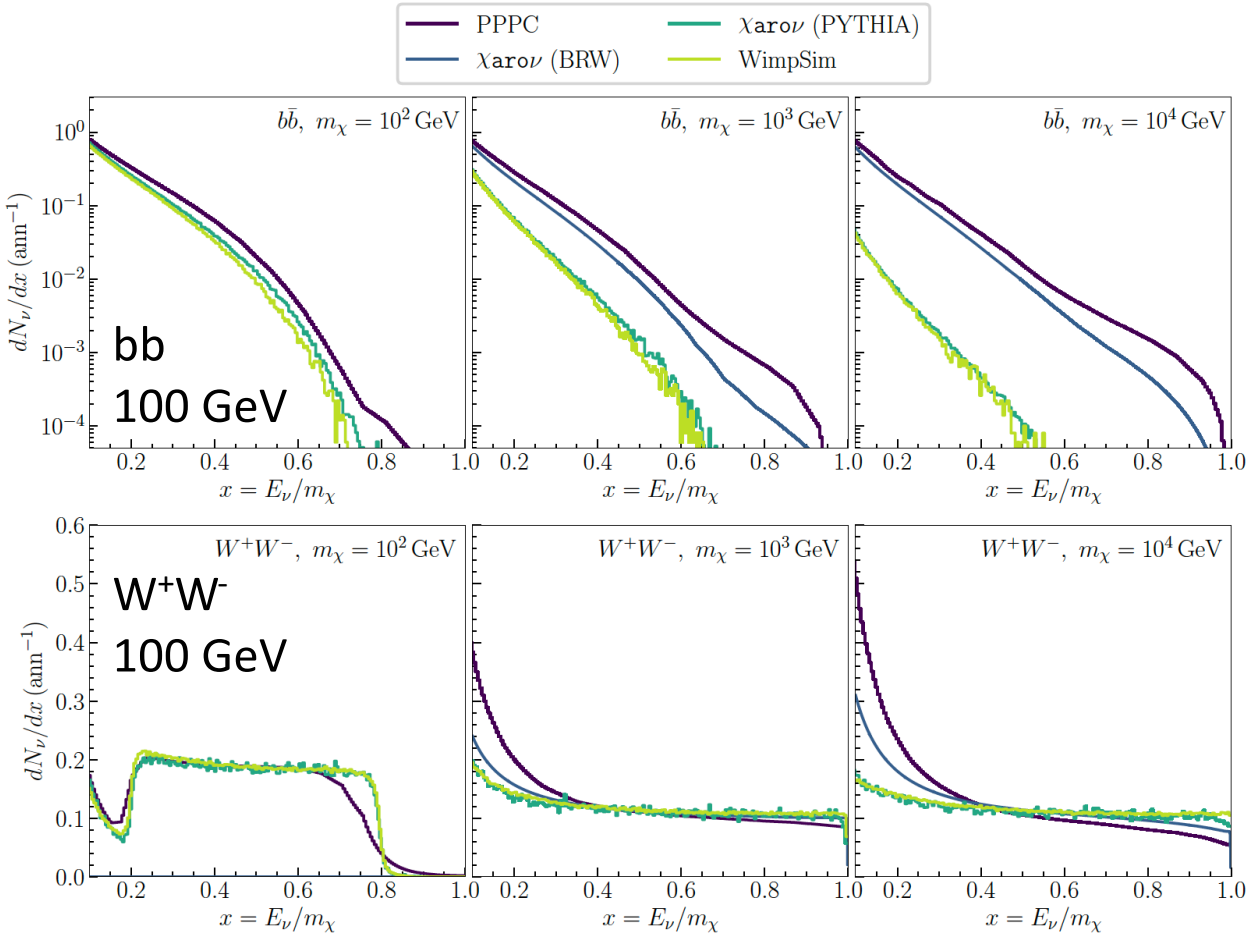


neutrino energy distribution E_ν/m_χ

Charon

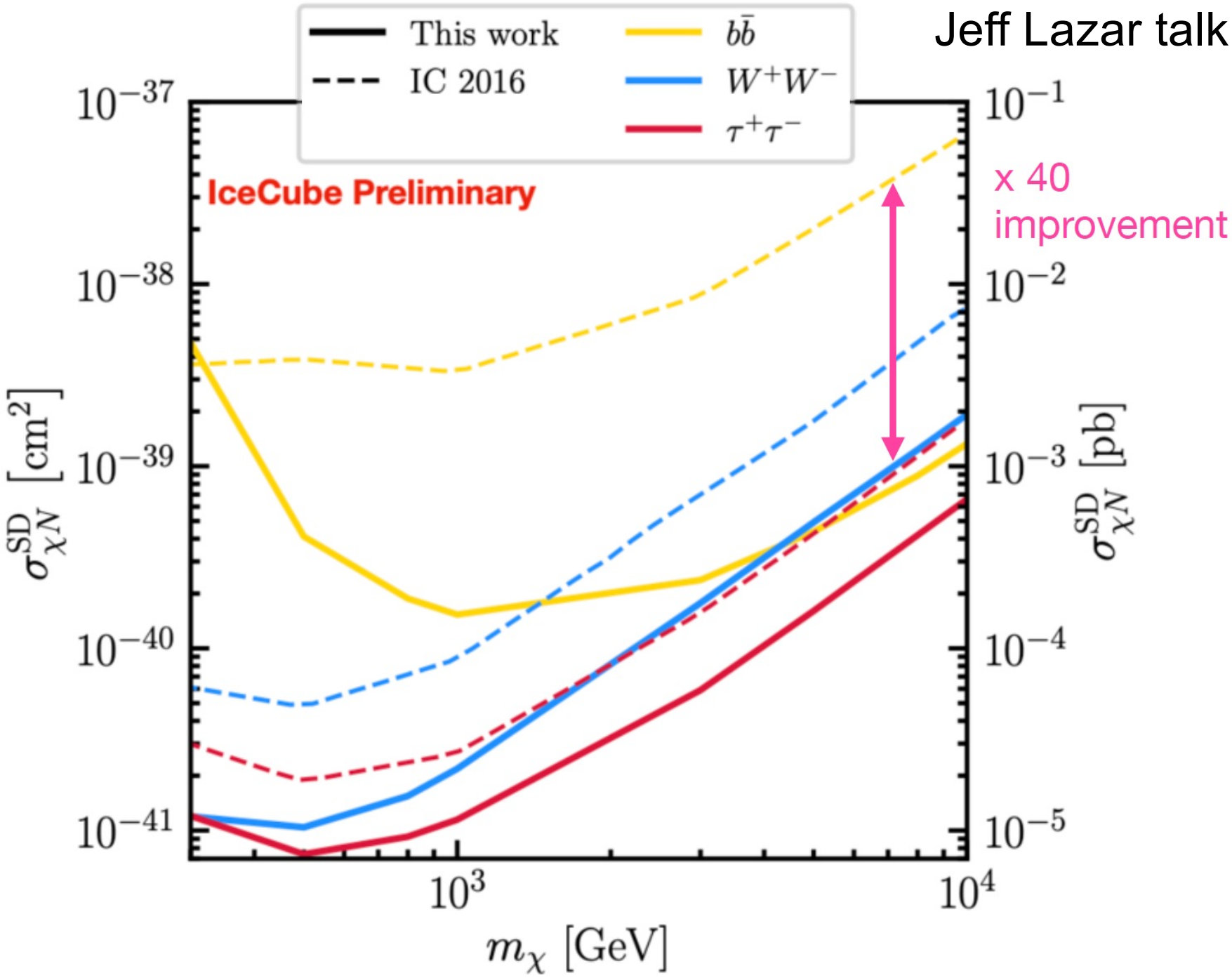


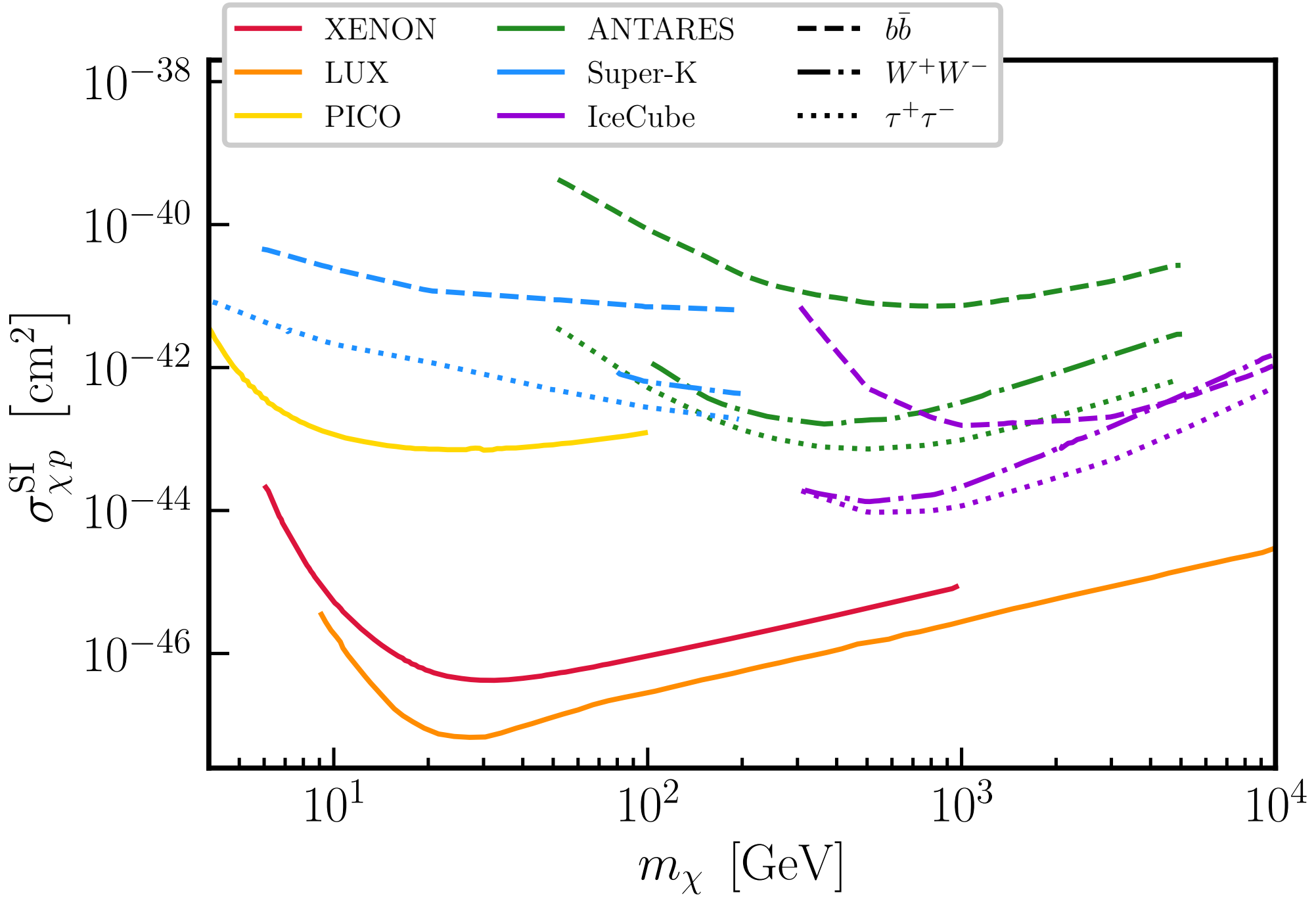
GitHub

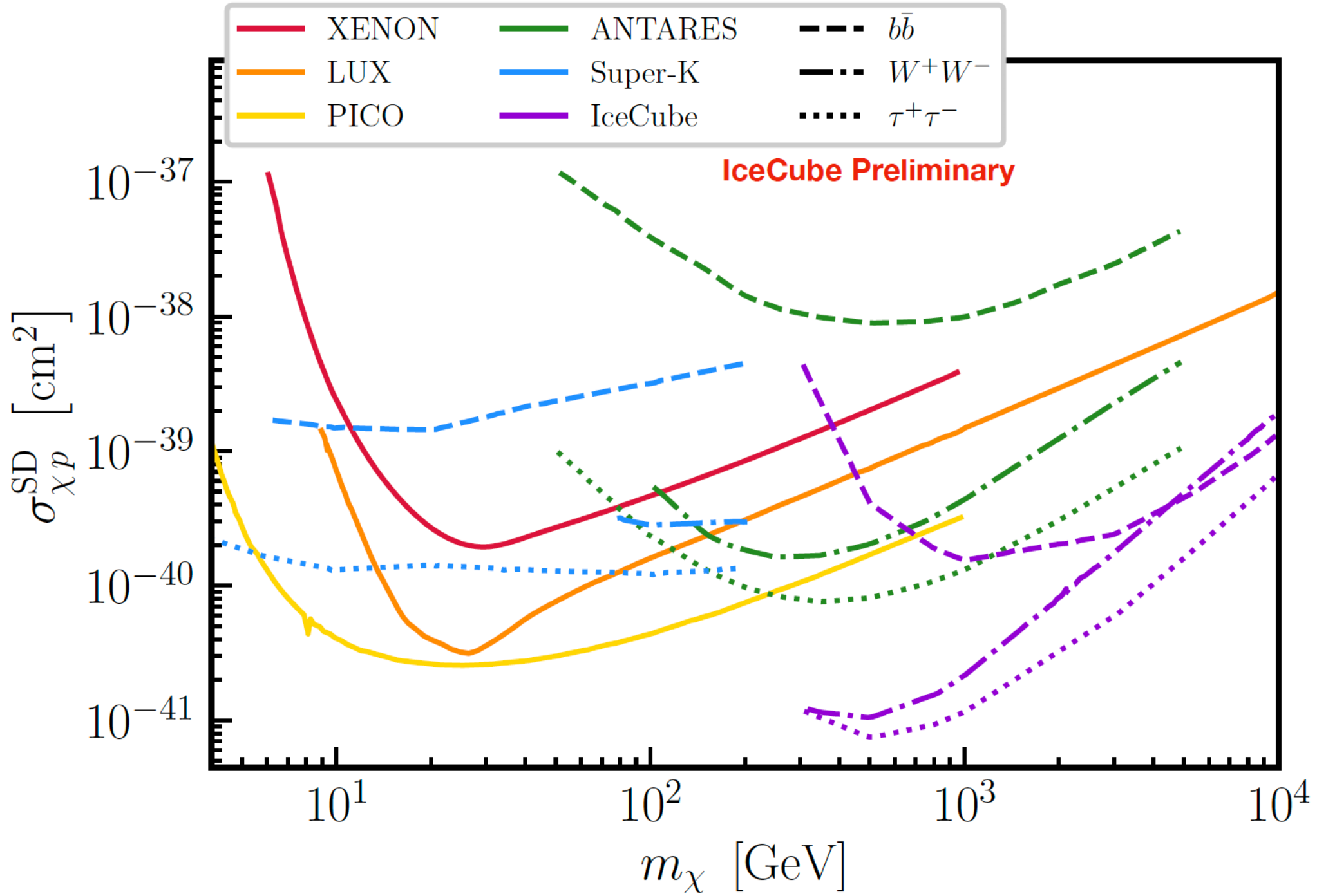


neutrino energy distribution E_ν / m_χ

Jeff Lazar talk



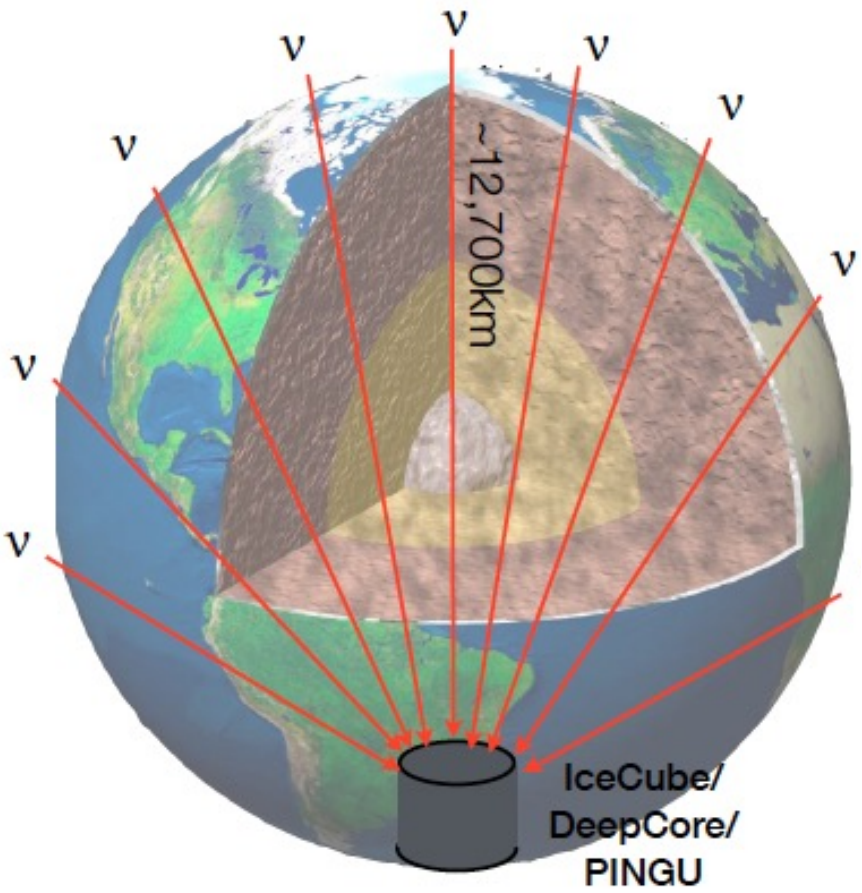

XENON
LUX
PICO
ANTARES
Super-K
IceCube
$b\bar{b}$
W^+W^-
$\tau^+\tau^-$
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
$\sigma^{\rm SI}_{\chi p}$ [cm^2]
10^1
10^2
10^3
10^4
m_χ [GeV]

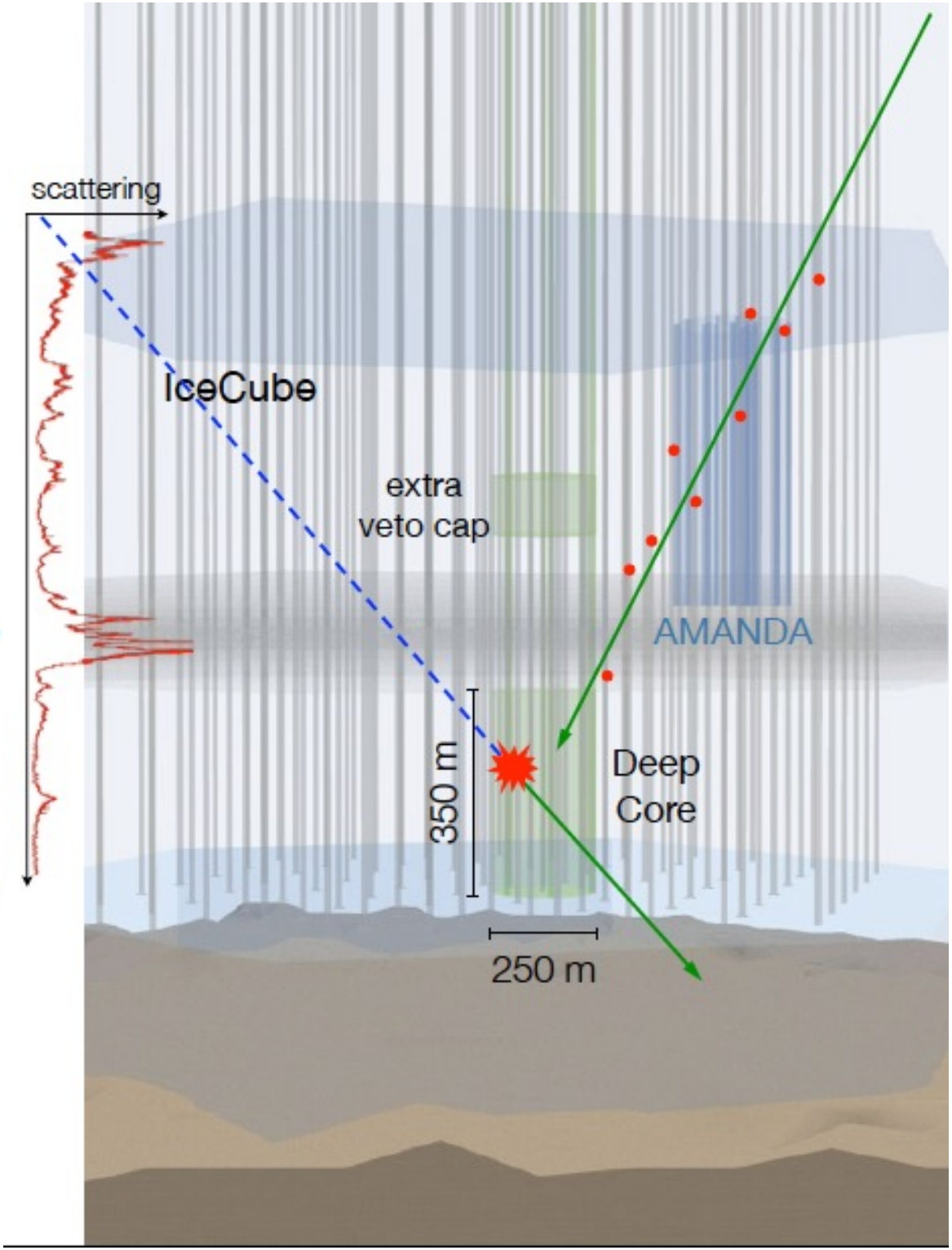

XENON
LUX
PICO
ANTARES
Super-K
IceCube
$b\bar{b}$
W^+W^-
$\tau^+\tau^-$
IceCube Preliminary
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
$\sigma^{\mathrm{SD}}_{\chi p}$ [cm^2]
10^1
10^2
10^3
10^4
m_χ [GeV]

one million atmospheric neutrinos…

at analysis level:

- DeepCore: one every 15 min
- Upgrade: one every 4 min

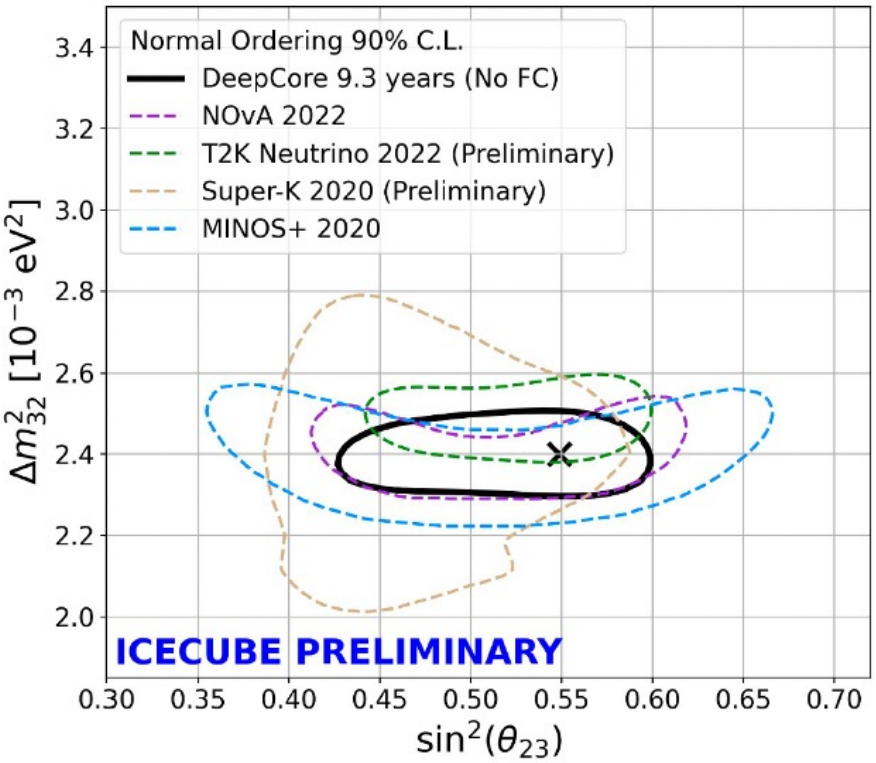


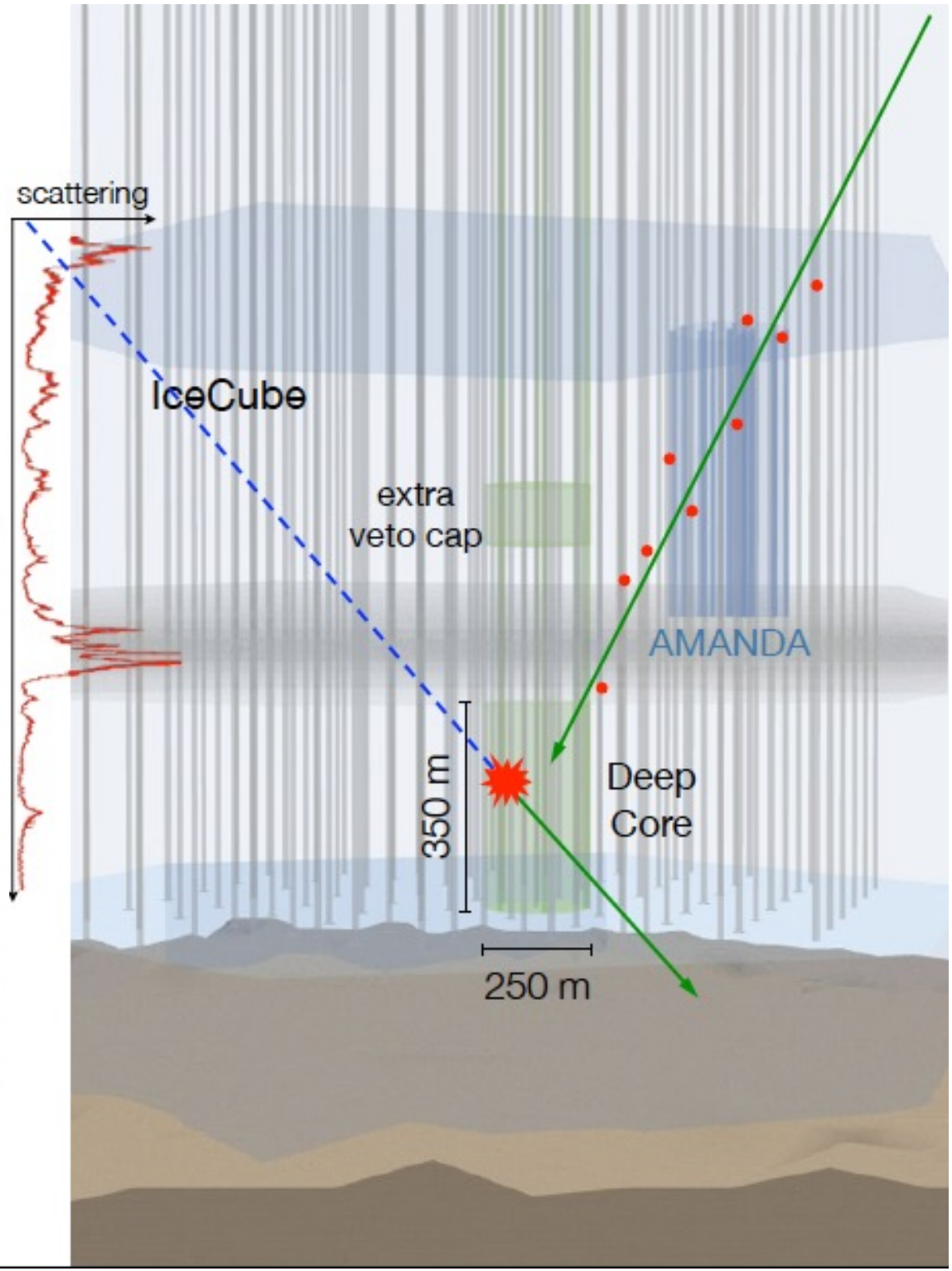


one million atmospheric neutrinos…

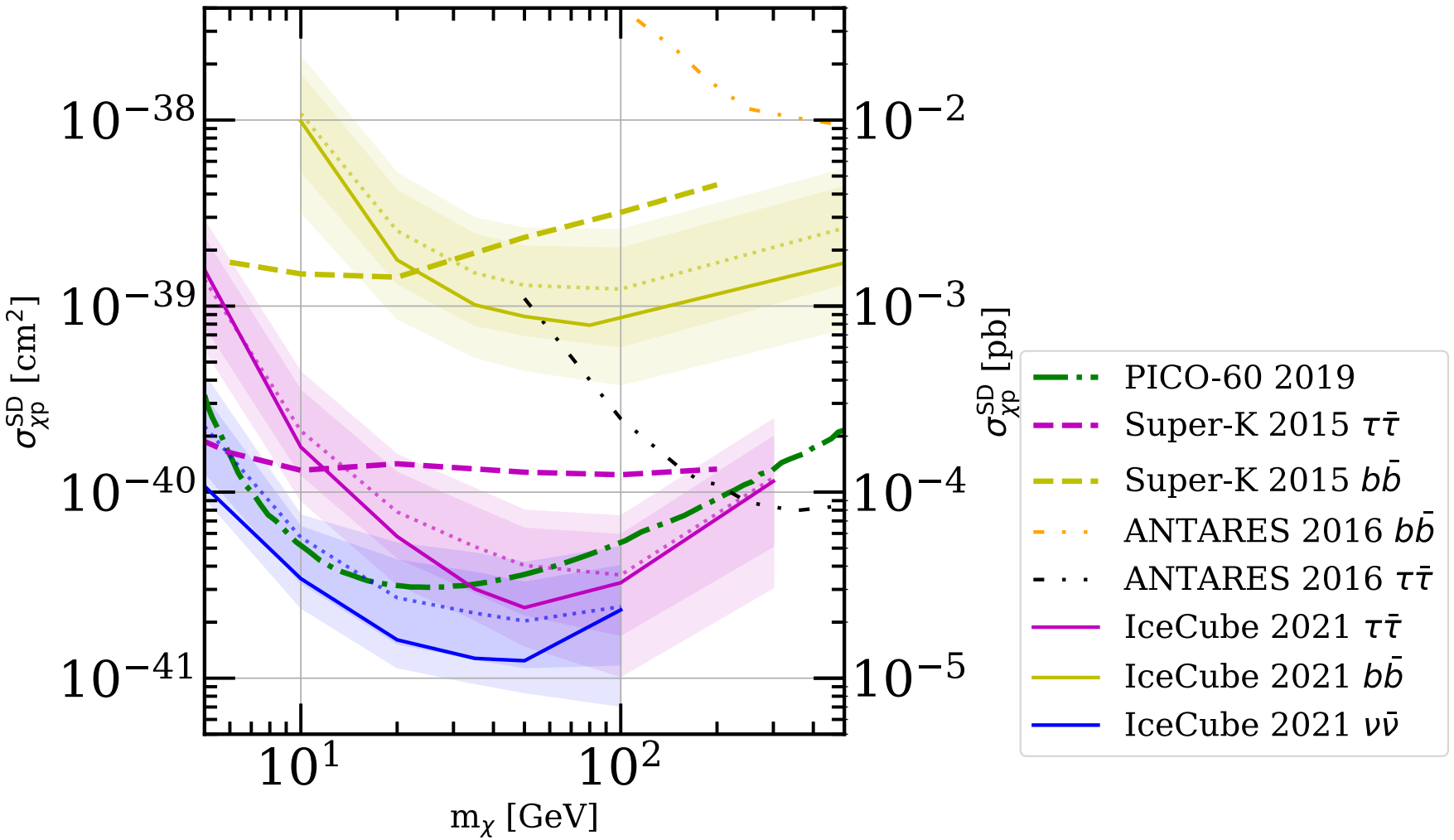
at analysis level:

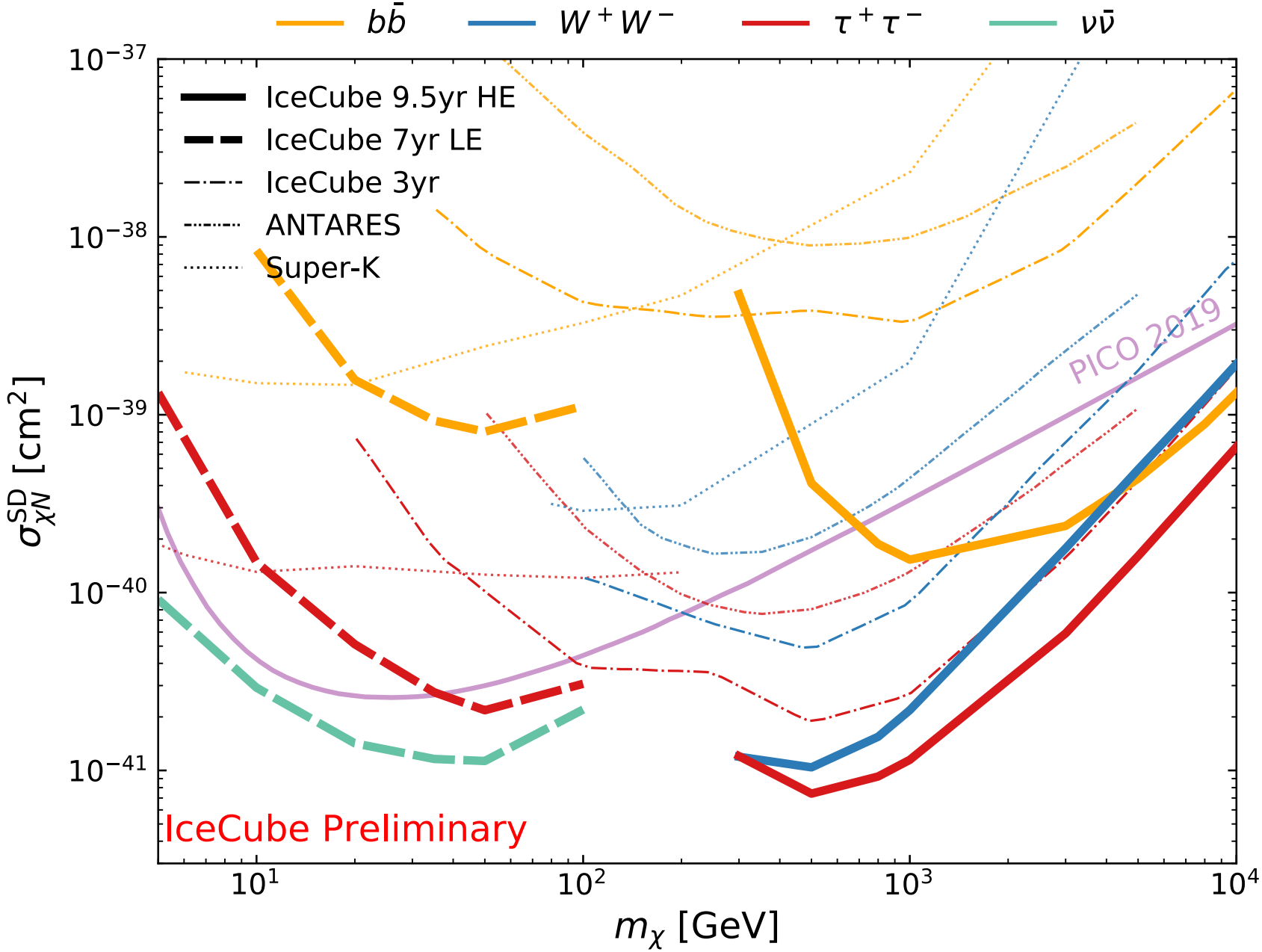
- DeepCore: one every 15 min
- 2 megaton



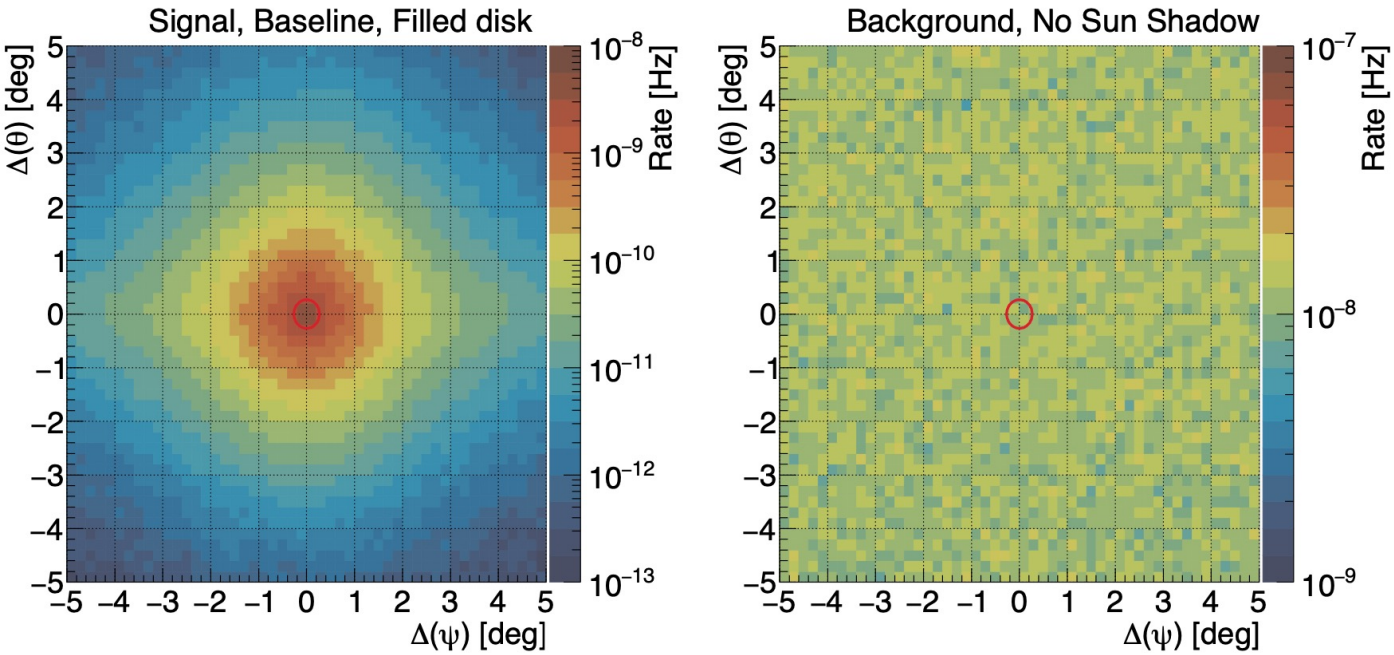


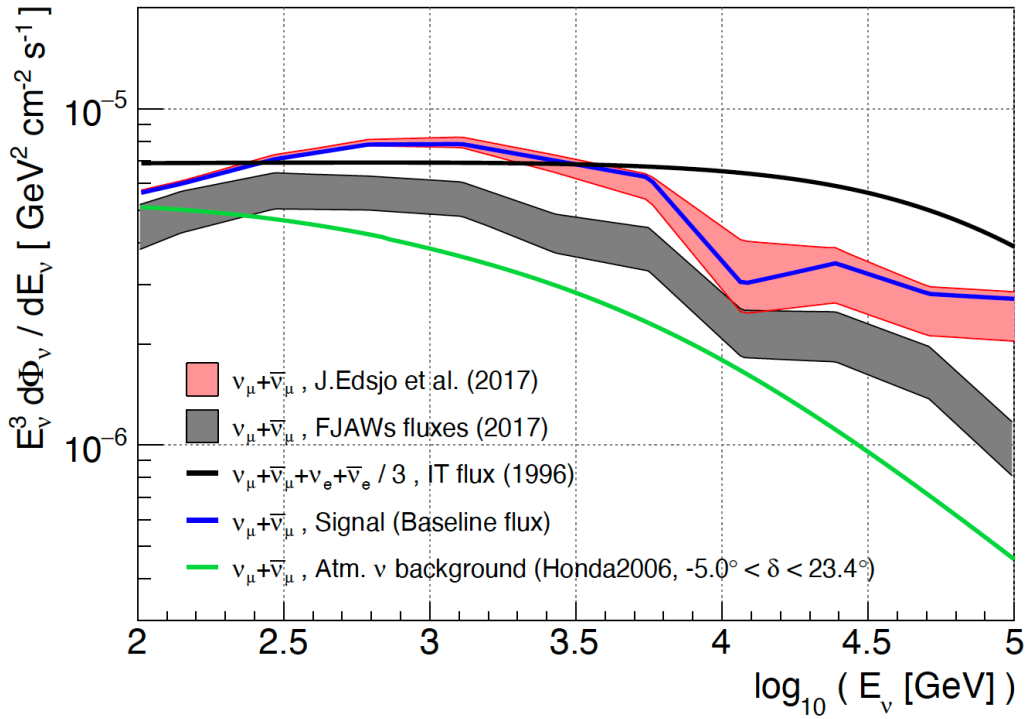
Moriond 2023


10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{1}
10^{2}
$\sigma^{SD}_{\chi p}$ [cm^2]
$\sigma^{SD}_{\chi p}$ [pb]
m$_\chi$ [GeV]
PICO-60 2019
Super-K 2015 $\tau\bar{\tau}$
Super-K 2015 $b\bar{b}$
ANTARES 2016 $b\bar{b}$
ANTARES 2016 $\tau\bar{\tau}$
IceCube 2021 $\tau\bar{\tau}$
IceCube 2021 $b\bar{b}$
IceCube 2021 $\nu\bar{\nu}$

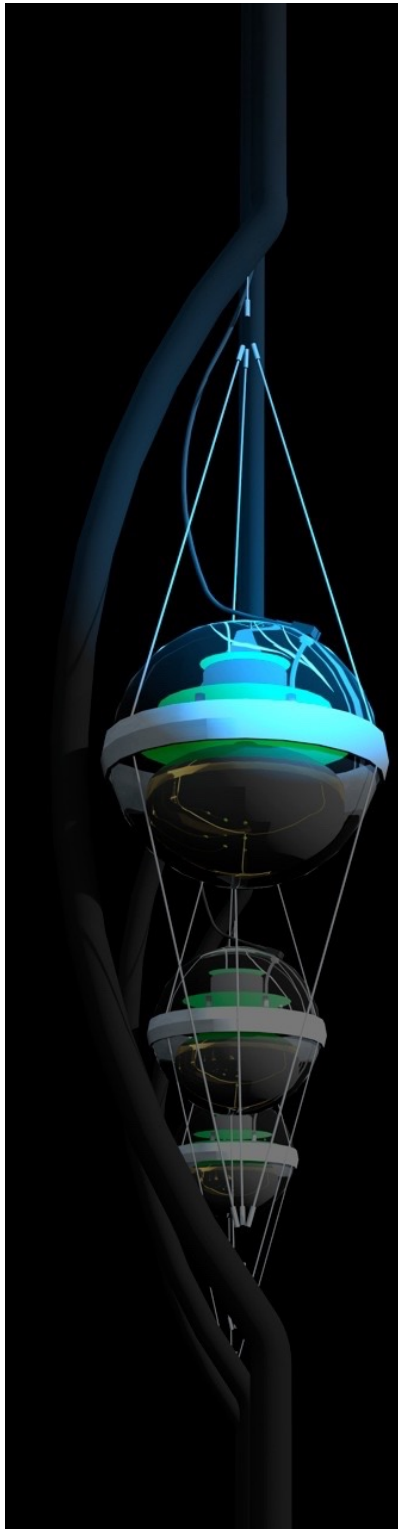

$b\bar{b}$
W^+W^-
$\tau^+\tau^-$
$\nu\bar{\nu}$
IceCube 9.5yr HE
IceCube 7yr LE
IceCube 3yr
ANTARES
Super-K
PICO 2019
IceCube Preliminary
$\sigma^{SD}_{\chi N}$ [cm^2]
m_χ [GeV]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^1
10^2
10^3
10^4

neutrinos produced by cosmic rays in the sun
(future background)





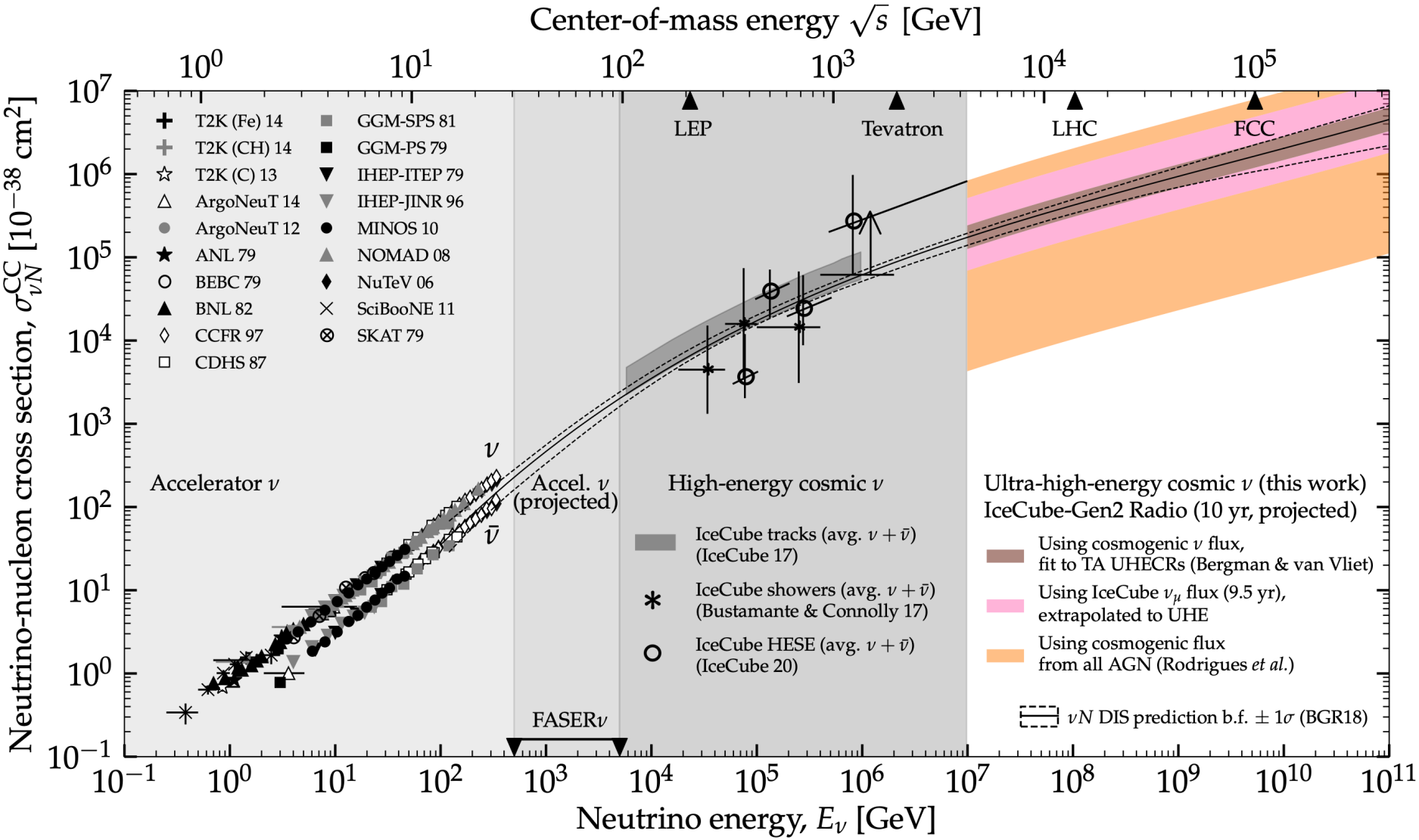
- integrated over the solid angle of the solar disk.
- averaged over energy bins smearing out neutrino oscillations.



- first neutrino view of the extreme Universe
- first sources of neutrinos (and cosmic rays!)
- search for dark matter, mostly from the sun
- cosmic neutrinos as a backlight of dark matter in our Galaxy
- neutrinos from the cores of active galaxies as a backlight for their dark matter profile

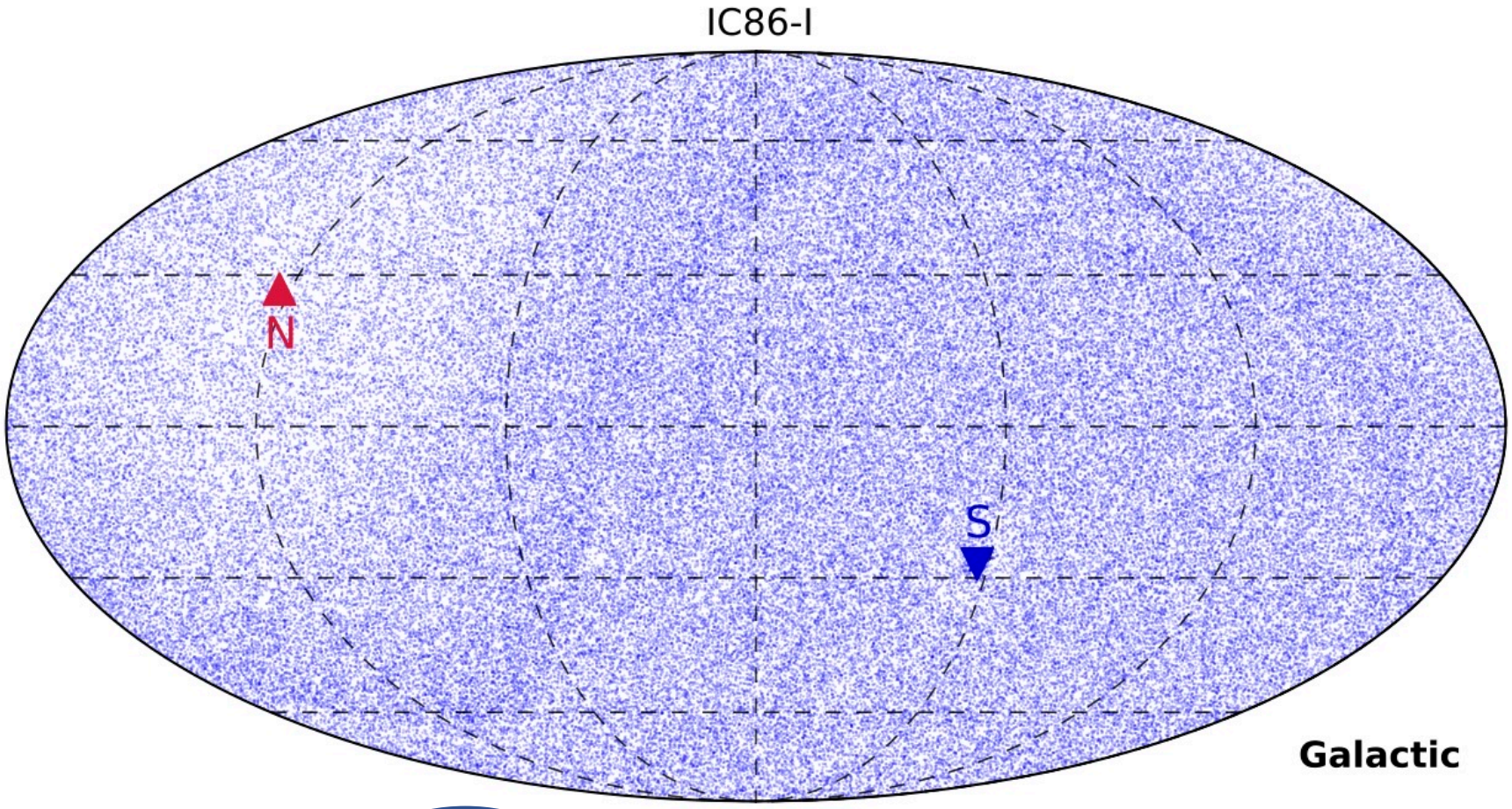
icecube.wisc.edu

cosmic neutrinos as a backlight for determining the neutrino interaction cross section by absorption in the Earth



one year of IceCube neutrinos >100 GeV

(reaches neutrino purity of 97% but overwhelmingly atmospheric)

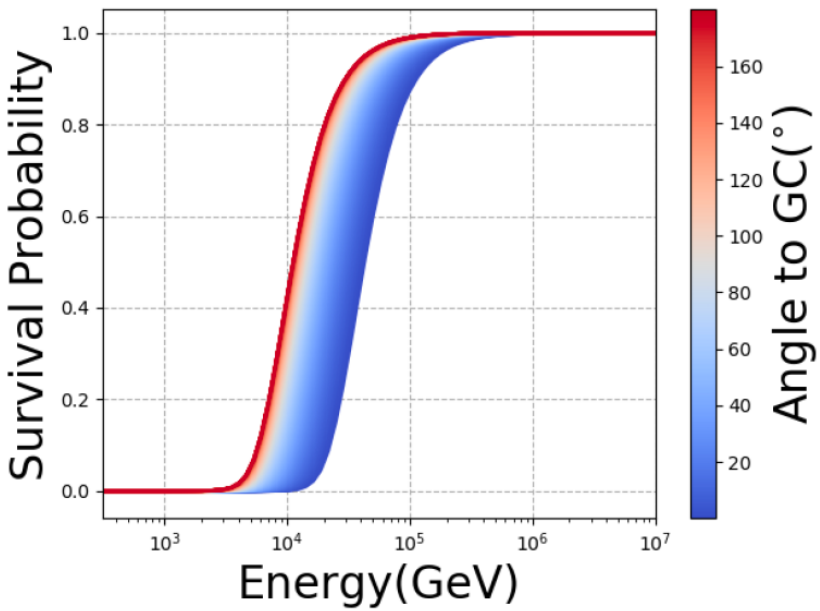


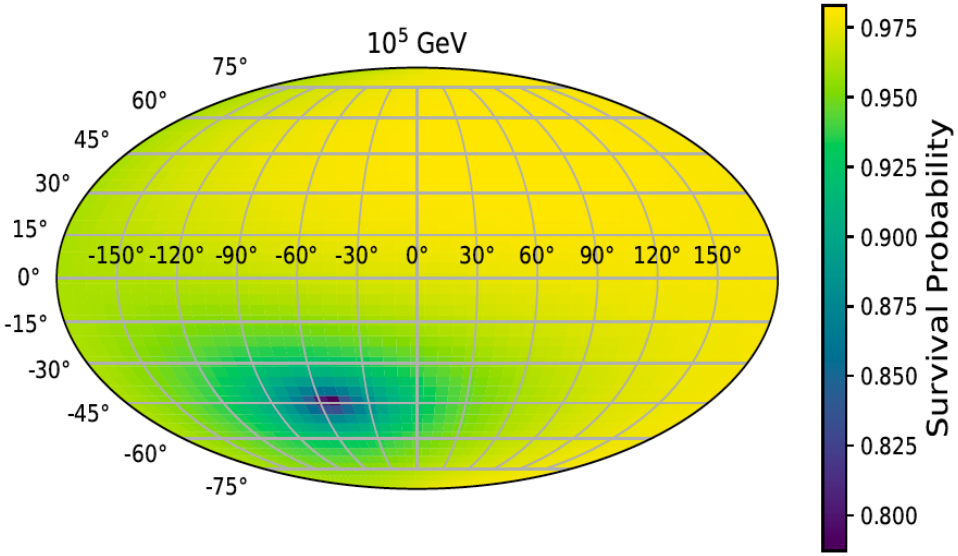
138322 neutrino candidates in one year

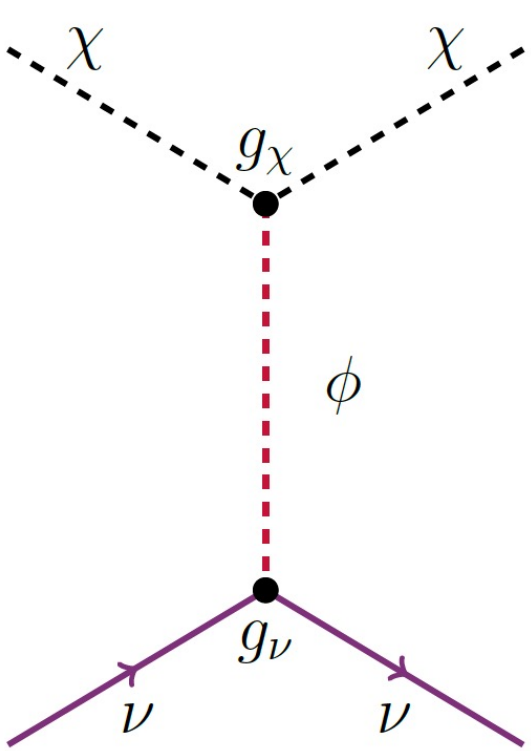
~ 200 cosmic neutrinos

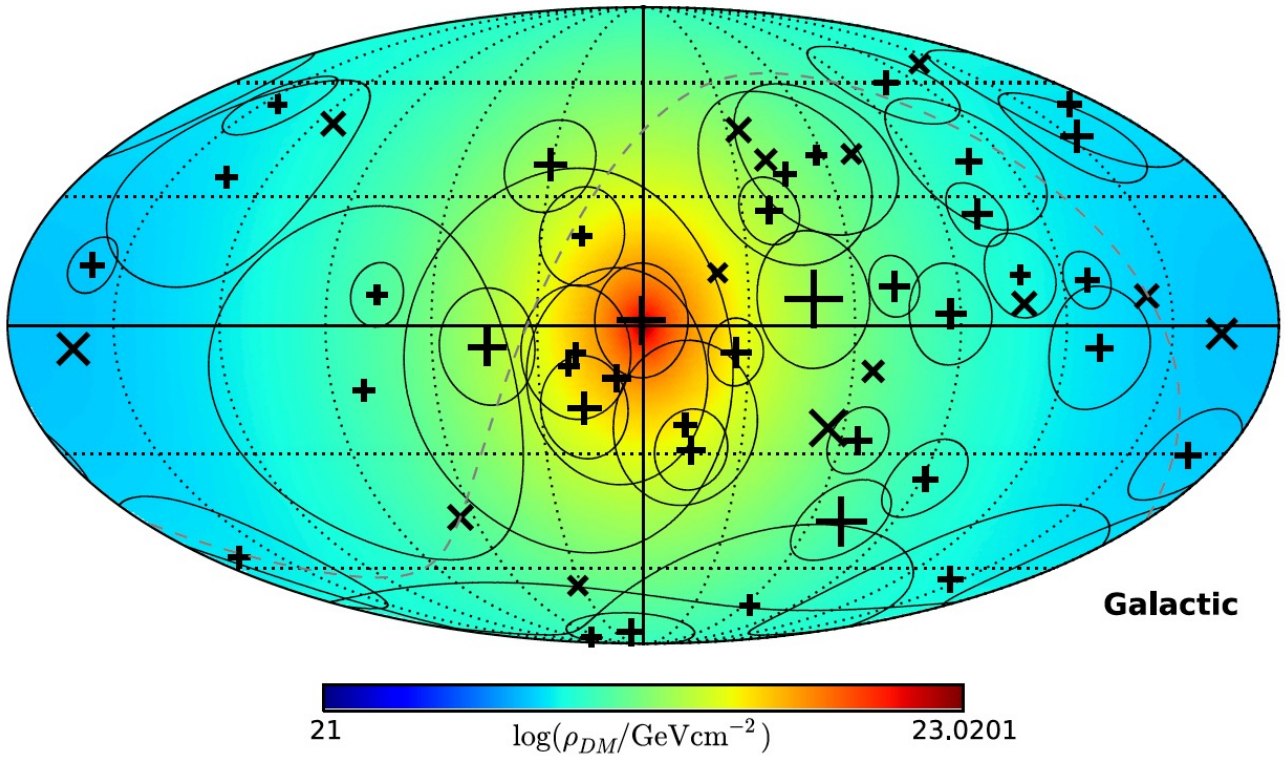
~12 separated from atmospheric background with E>60 TeV

- do dark matter particles interact with neutrinos?
- cosmic neutrinos as a backlight for the dark matter distribution in our Galaxy

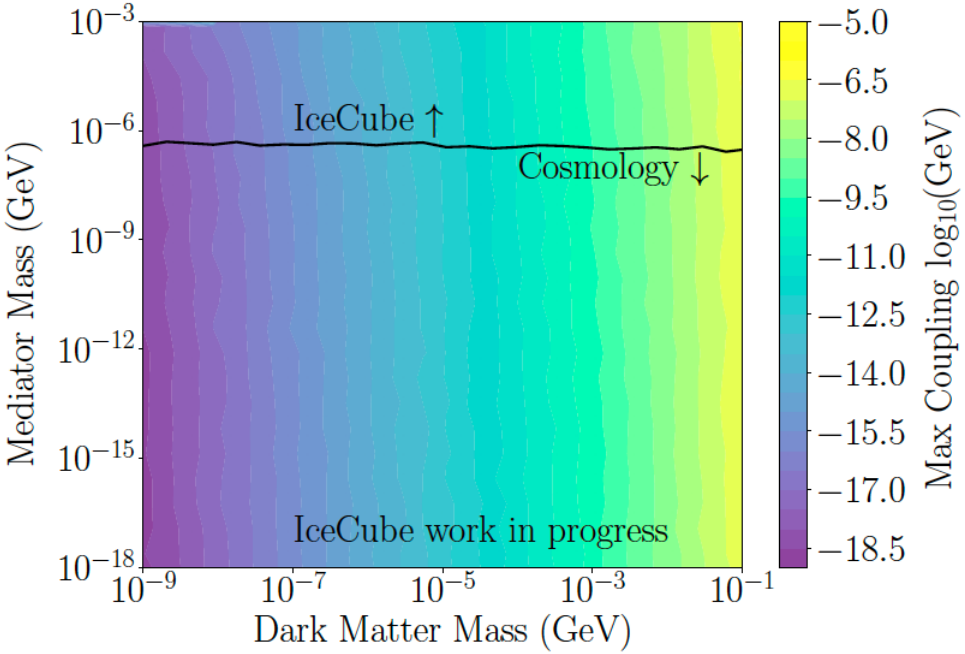


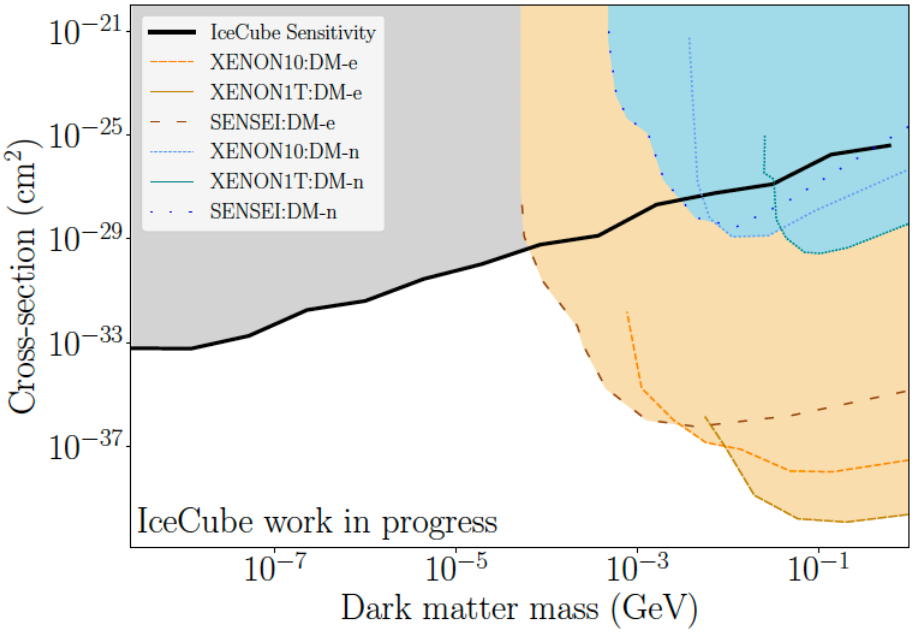


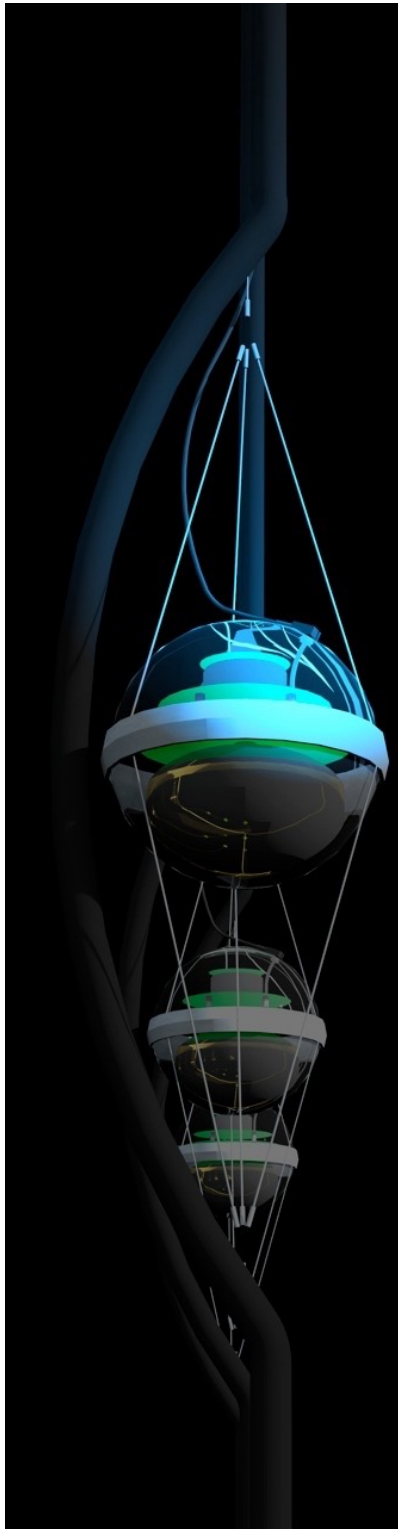

χ
χ
g_χ
ϕ
g_ν
ν
ν


Galactic
21
$\log(\rho_{DM}/\mathrm{GeVcm}^{-2})$
23.0201

competitive/complementary limits on the neutrino-dark matter cross section from IceCube and cosmology







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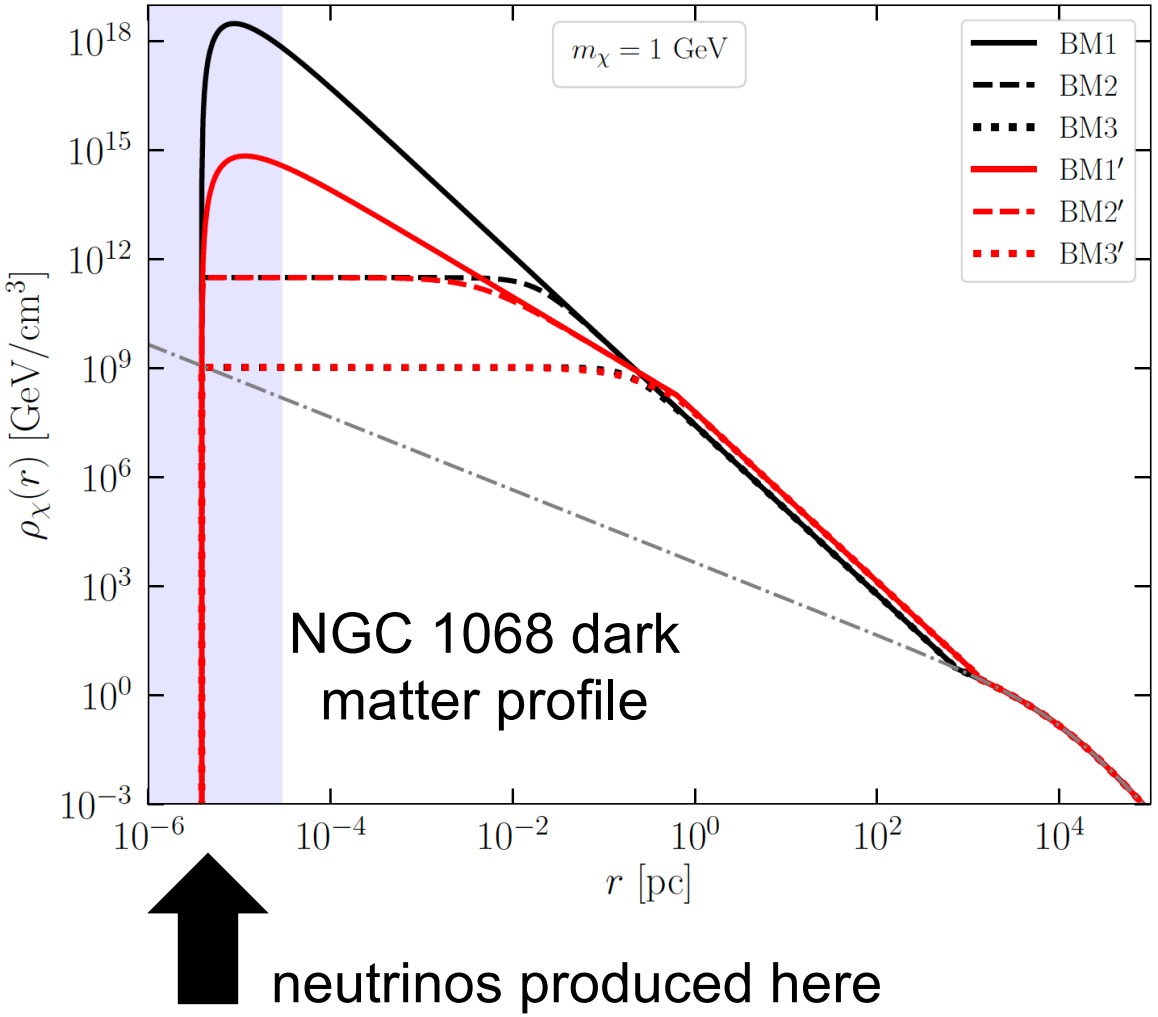

- neutrino flux at the source from the photon flux accompanying the neutrinos
- compare gamma ray flux with observed neutrino flux
- measure cusp profile
- … but this flux is at MeV energy, or below, and not the γ- ray flux Fermi measures → use a model or decipher the multiwavelength γ spectrum

Recent publications covering dark matter:

1. *Combined Search for neutrinos from Dark Matter Self-Annihilation in the Galactic Centre with ANTARES and IceCube* Phys. Rev. D 102, 082002 (2020)
2. *Velocity independent constraints on spin-dependent DM-nucleon interactions from IceCube and PICO.* Eur. Phys. J. C 80 (2020) 819
3. *Search for neutrinos from decaying dark matter with IceCube* Eur.Phys.J. C78 (2018) no.10, 831
4. *Search for Neutrinos from Dark Matter Self-Annihilations in the center of the Milky Way with 3 years of IceCube/DeepCore* Eur. Phys. J. C (2017) 77: 627
5. *First search for dark matter annihilations in the Earth with the IceCube Detector* Eur. Phys. J. C (2017) 77: 82
6. *Search for Secluded Dark Matter with 6 years of IceCube Data* – arXiv:2107.10778
7. *A search for Neutrinos from Decaying Dark Matter in Galacy Clusters and Galaxies with IceCube* – arXiv:2107.11527
8. *Search for Dark Matter from the Center of the Earth with 8 Years of IceCube Data* – arXiv:2107.11244
9. *Indirect Searches for Dark Matter in the Galactic Center with IceCube* – arXiv:2107.11224
10. *Constraining Non-Standard Dark Matter-Nucleon Interactions with IceCube* – arXiv:2108.05203
11. *Dark Matter Neutrino Scattering in the Galactic Center with IceCube* – arXiv:2107.11491
12. *Searching for Dark Matter from the Sun with the IceCube Detector* – **doi:** 10.22323/1.395.0020

THE ICECUBE COLLABORATION

ISTRALIA 1

NGDOM 1

UNITED STATES 25

IceCube
South Pole Neutrino Observatory