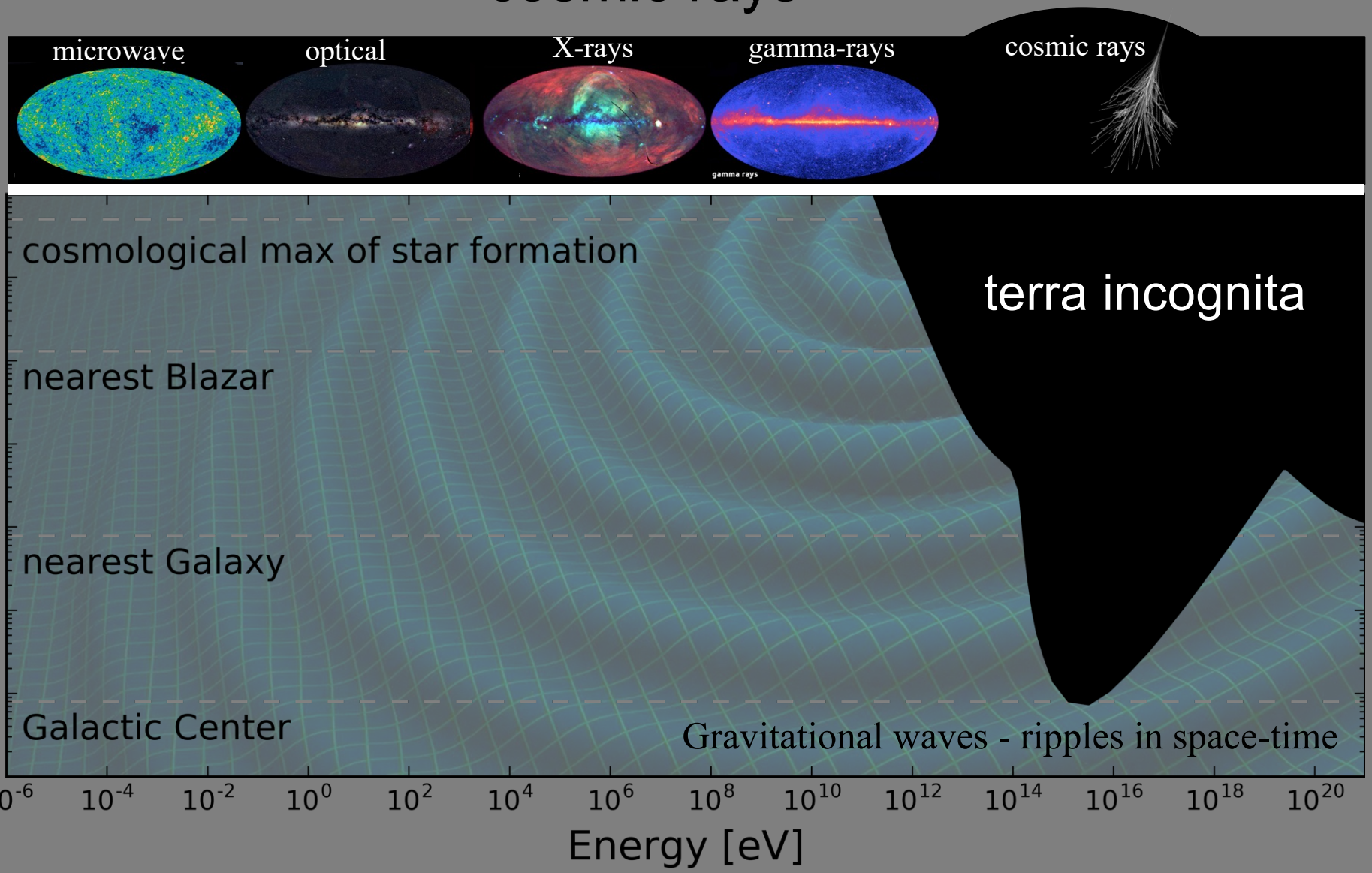
High-Energy Cosmic Neutrinos: a Personal Tour

francis halzen

- neutrino astronomy and IceCube
- the diffuse high-energy neutrino flux
- observation of the first sources
- a PeV beam for neutrino physics

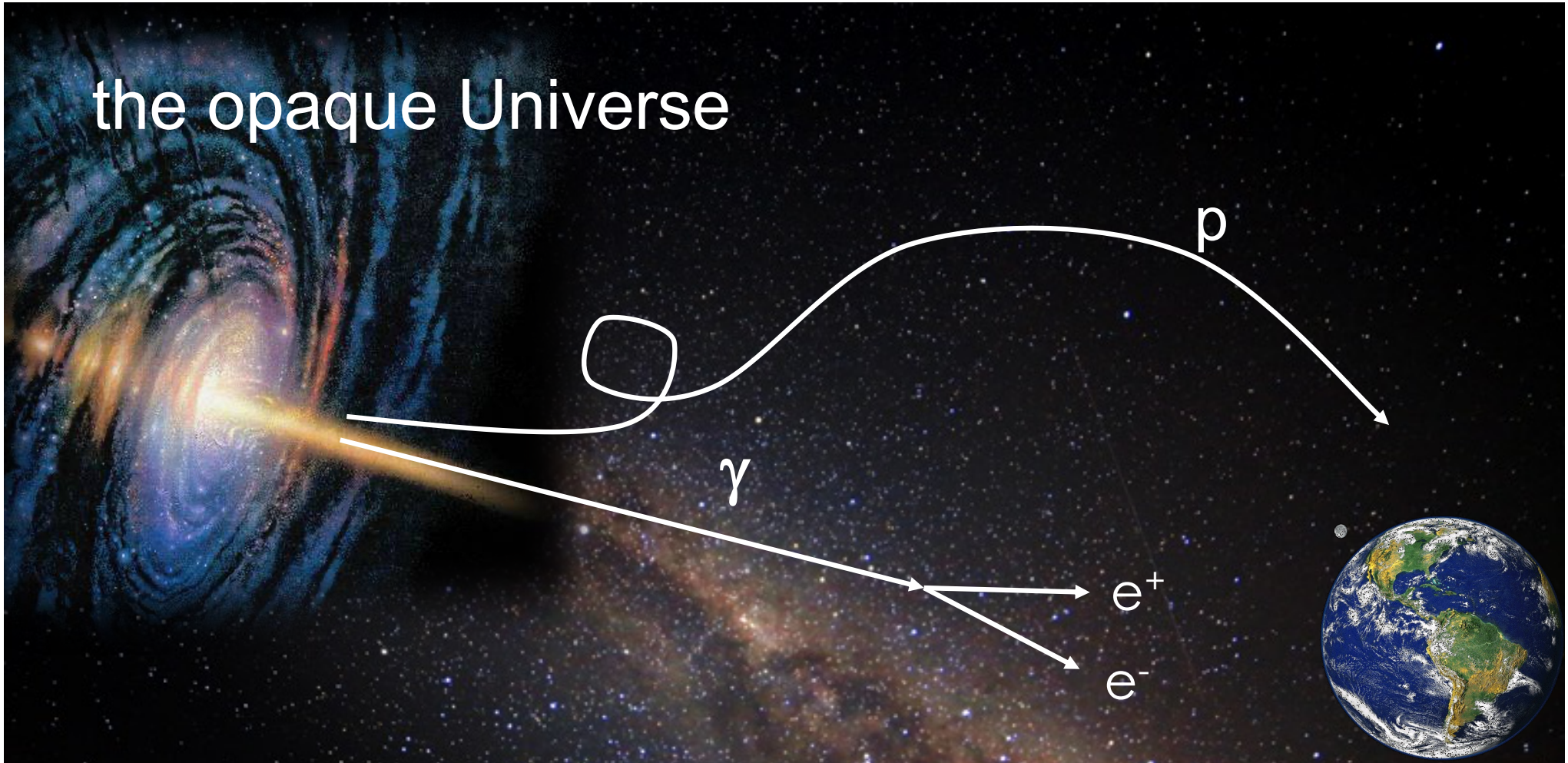
IceCube.wisc.edu

highest energy “radiation” from the Universe: cosmic rays



Universe beyond our Galaxy is eventually opaque to gamma rays

the opaque Universe

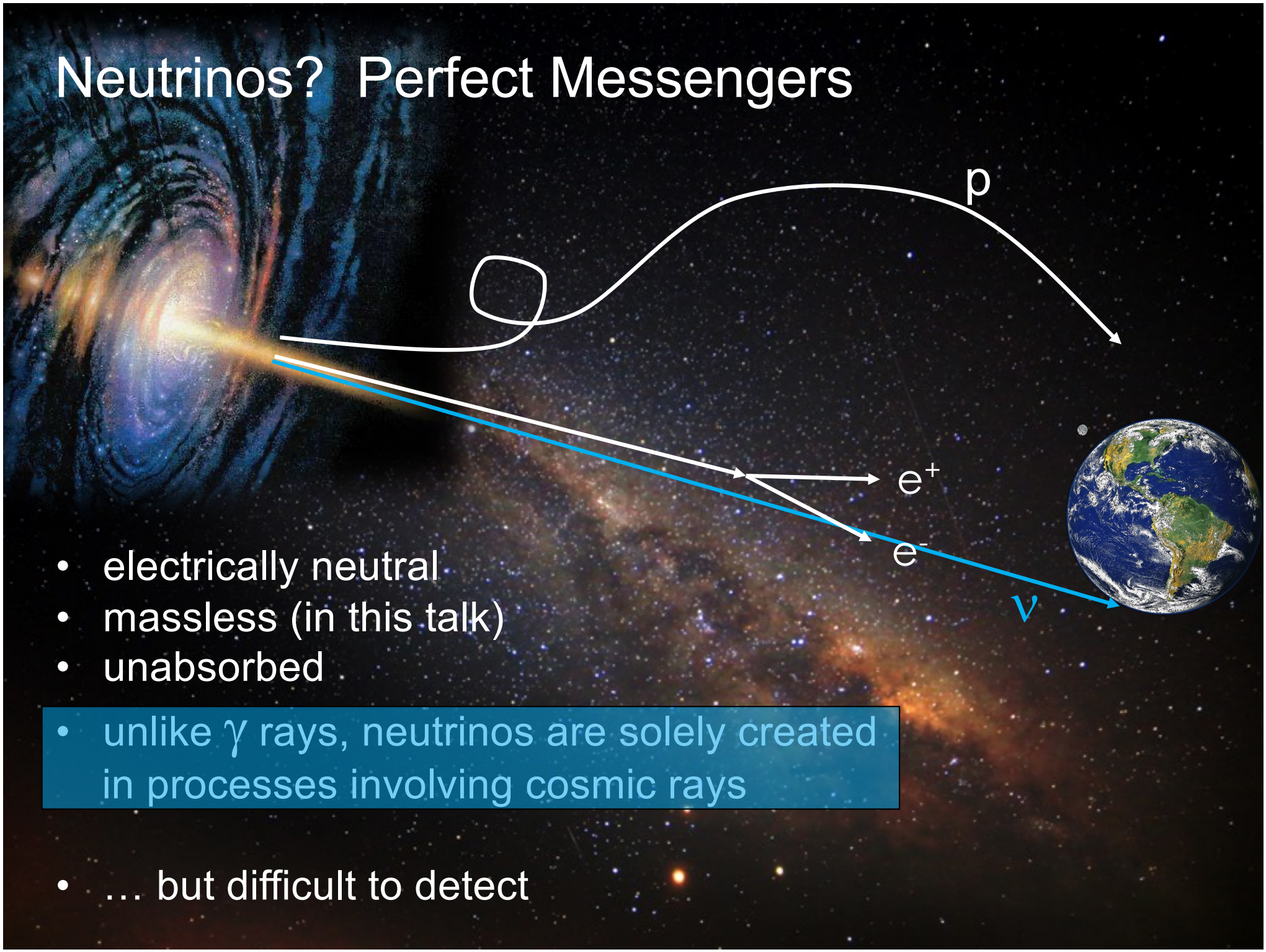


$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

PeV photons interact with microwave photons ($411/cm^3$) before reaching our telescopes

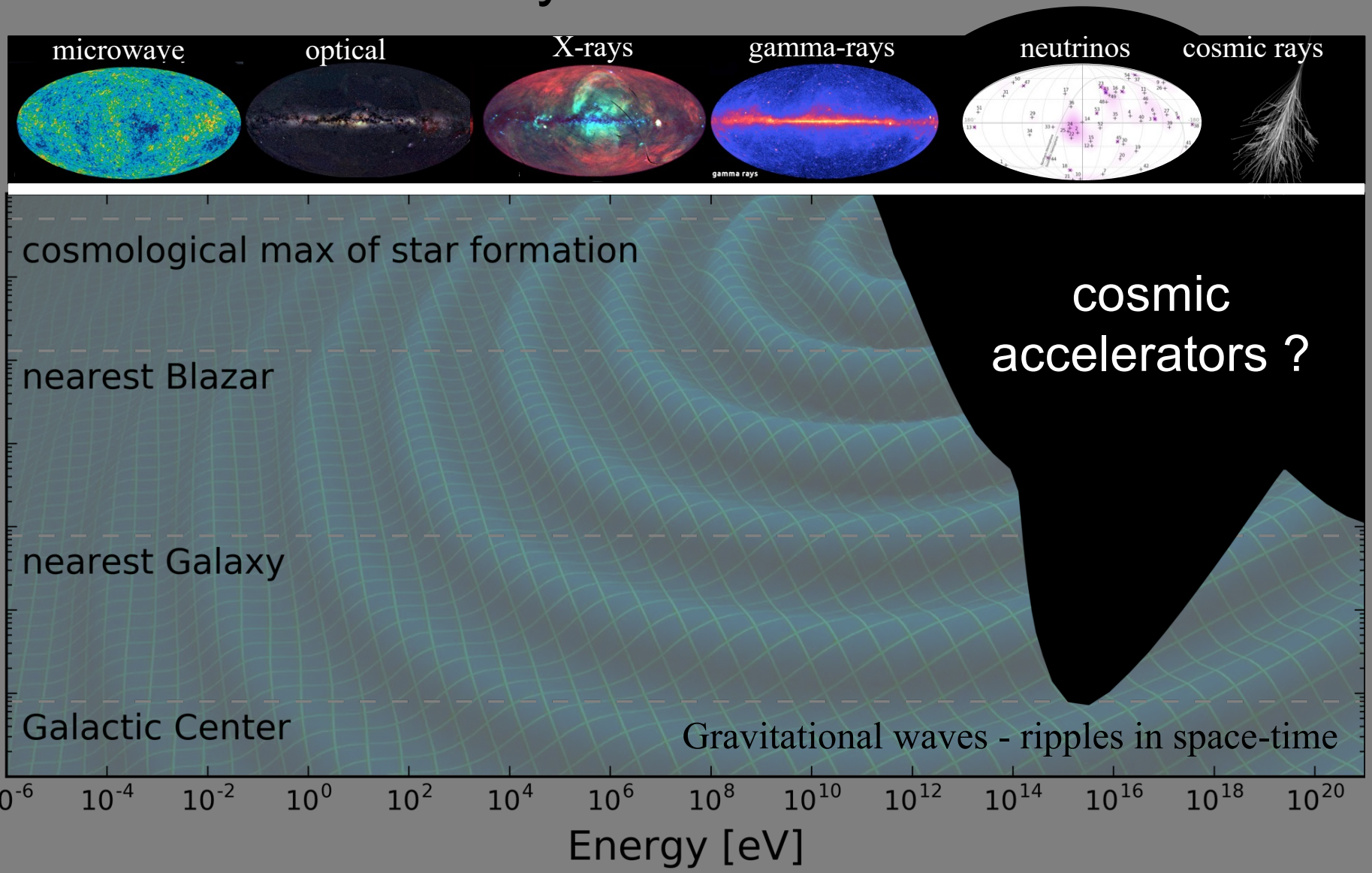
enter: neutrinos

Neutrinos? Perfect Messengers



- electrically neutral
- massless (in this talk)
- unabsorbed
- unlike γ rays, neutrinos are solely created in processes involving cosmic rays
- … but difficult to detect

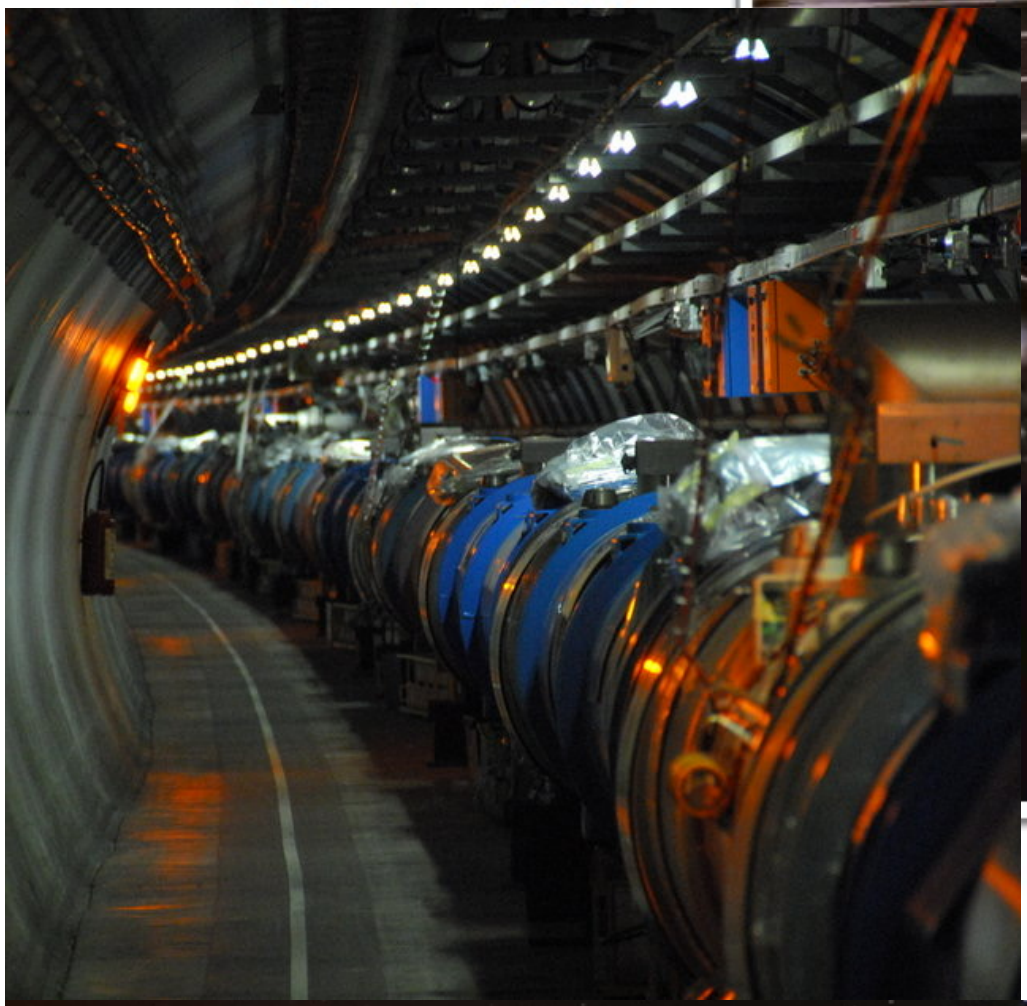
highest energy “radiation” from the Universe: cosmic rays *and neutrinos?*

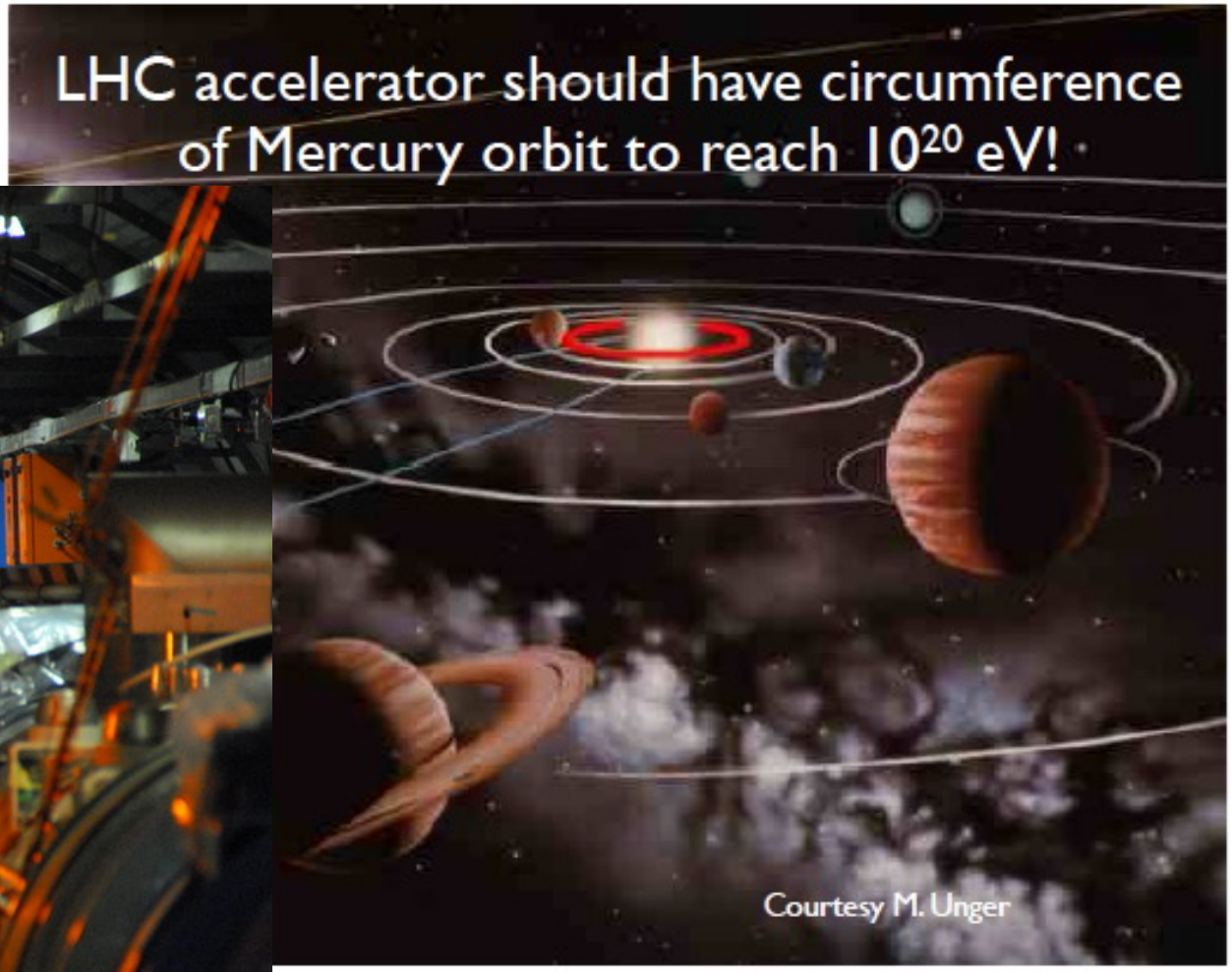


Universe beyond our Galaxy is eventually opaque to gamma rays

highest energy radiation from the Universe: not γ-rays !

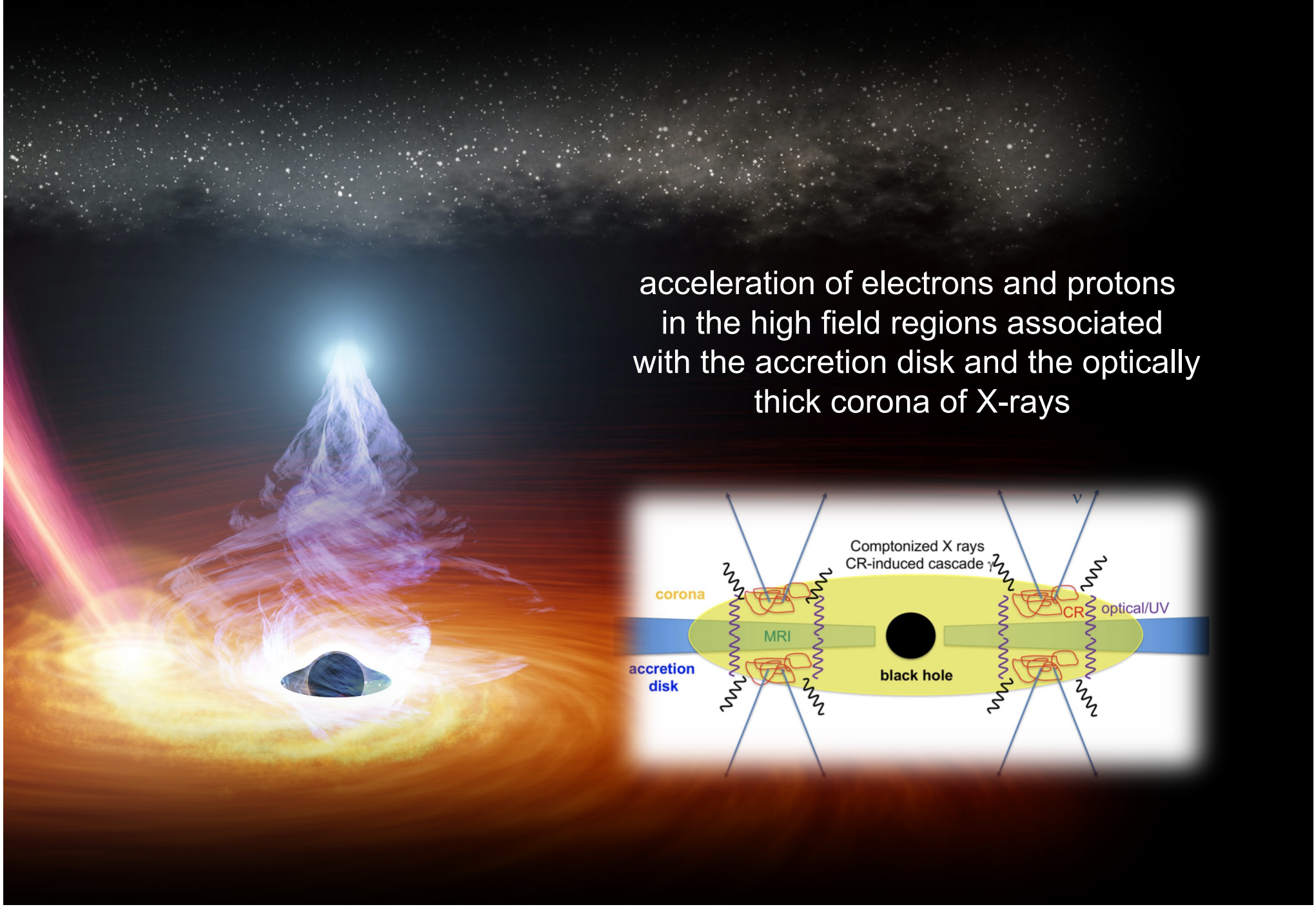
high energy
high luminosity





Fly's Eye 1991
300,000,000 TeV

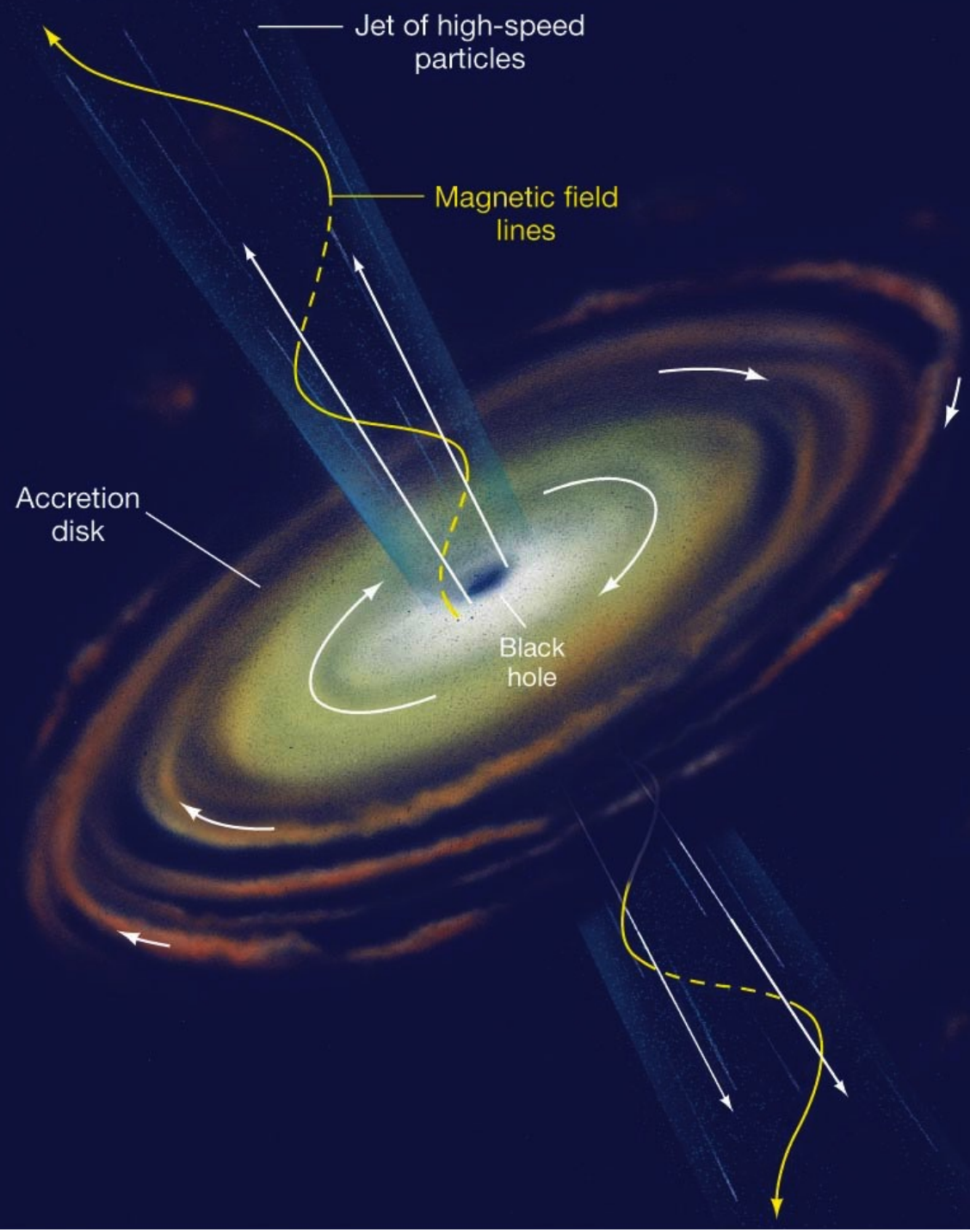
cores of active galaxies as cosmic accelerators

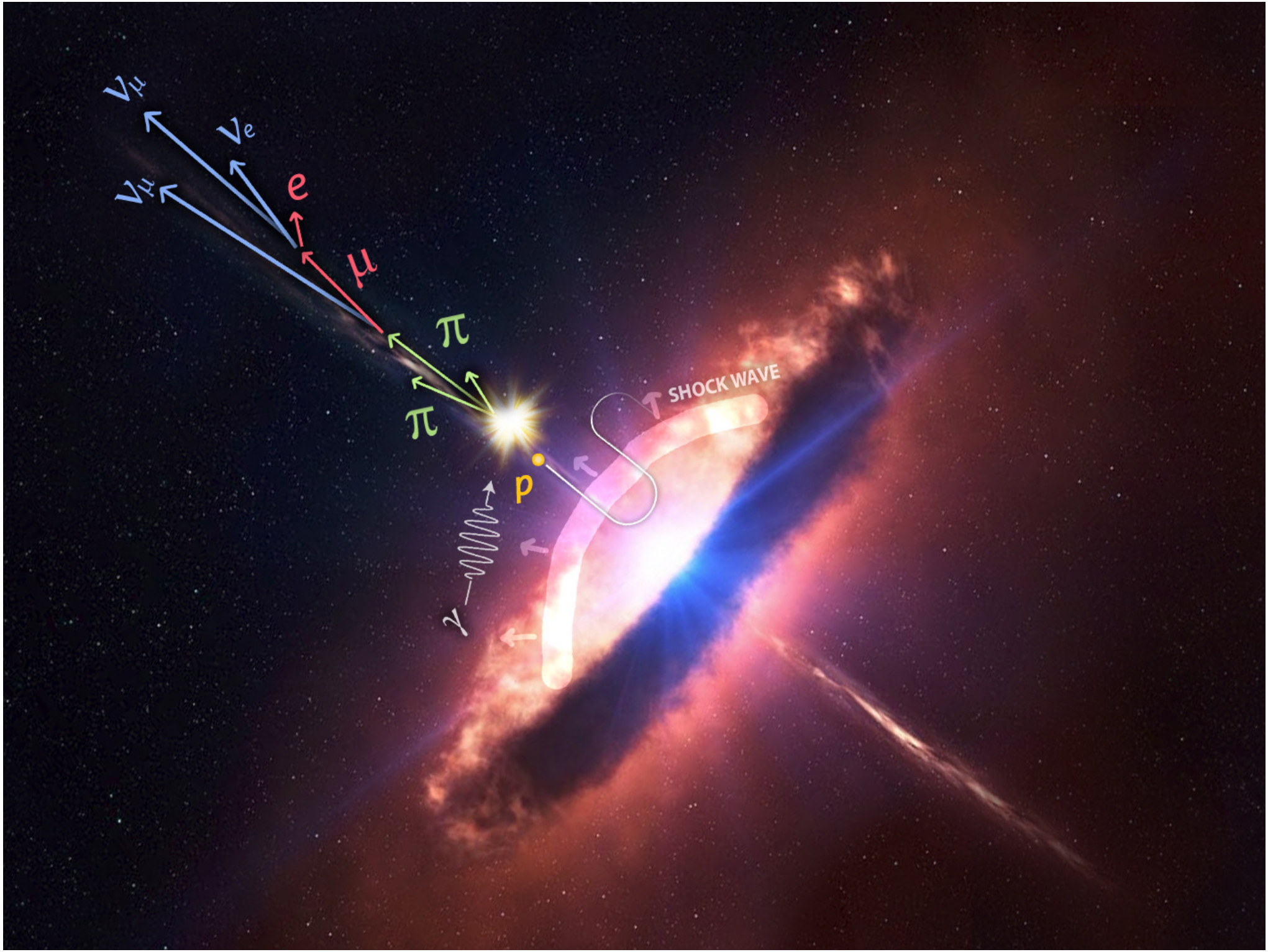


acceleration of electrons and protons in the high field regions associated with the accretion disk and the optically thick corona of X-rays

cores of active galaxies and jets

- some of the matter falling into a supermassive black hole is accelerated in a jet along its rotation axis
- fast spinning infalling matter comes in contact with the rotating black hole
- spacetime around spinning black hole drags on the field winding it into a tight cone around the rotation axes
- plasma from the accretion disk is then flung out along these field lines




ν_μ
ν_e
ν_μ
e
μ
π
π
p
γ
SHOCK WAVE

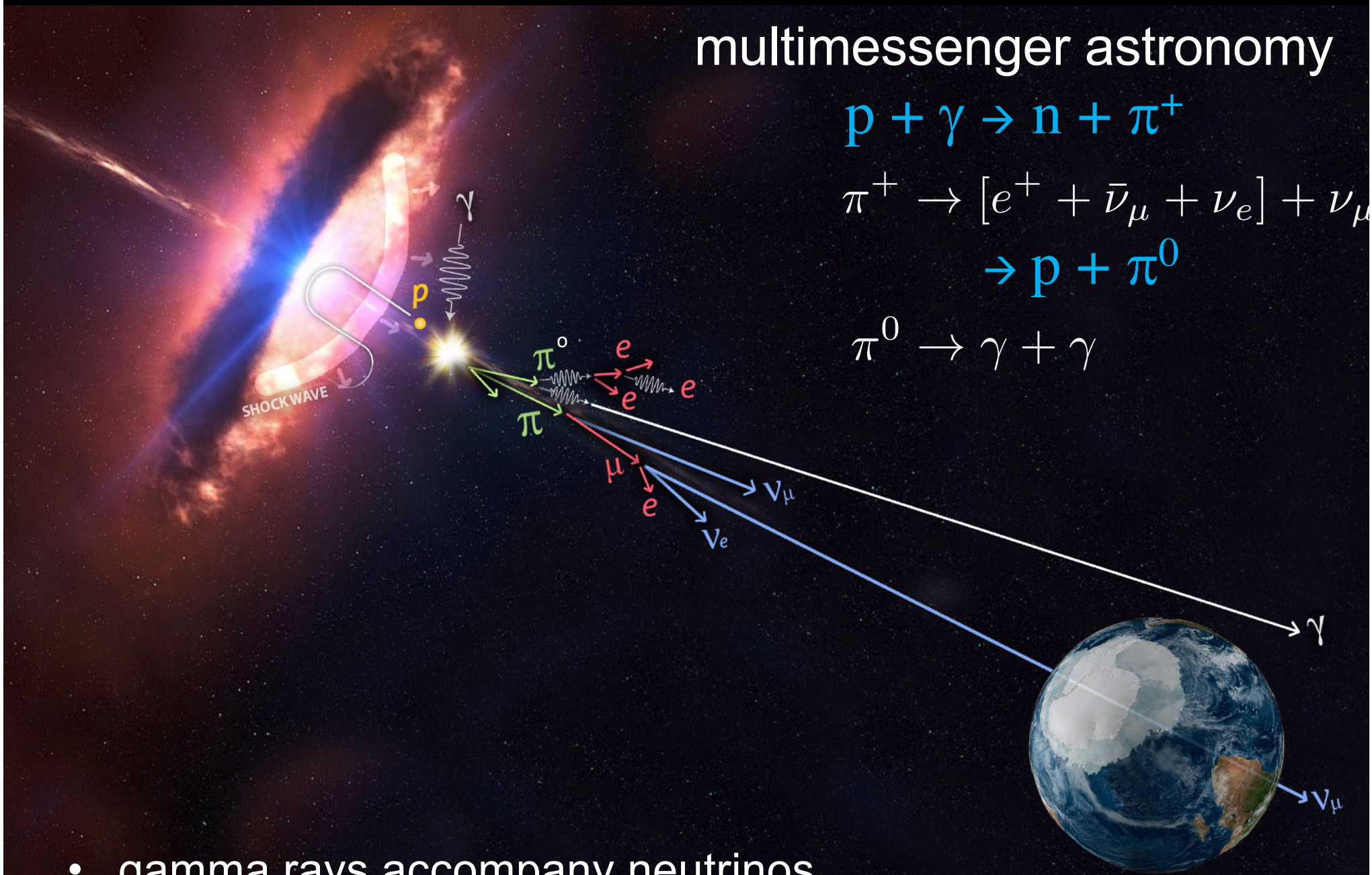
multimessenger astronomy

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

$$\pi^+ \rightarrow [e^+ + \bar{\nu}_\mu + \nu_e] + \nu_\mu$$

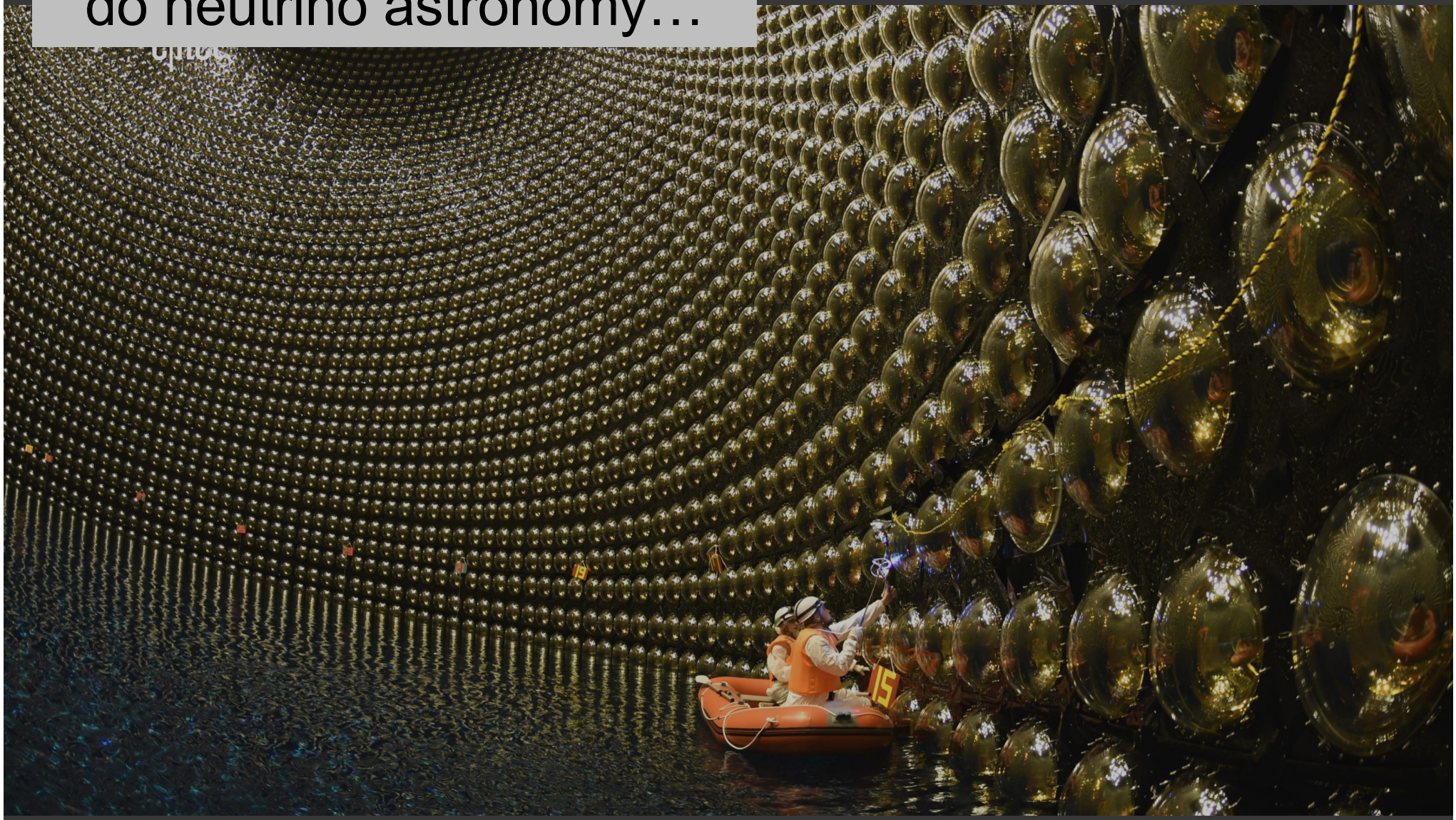
$$\rightarrow p + \pi^0$$

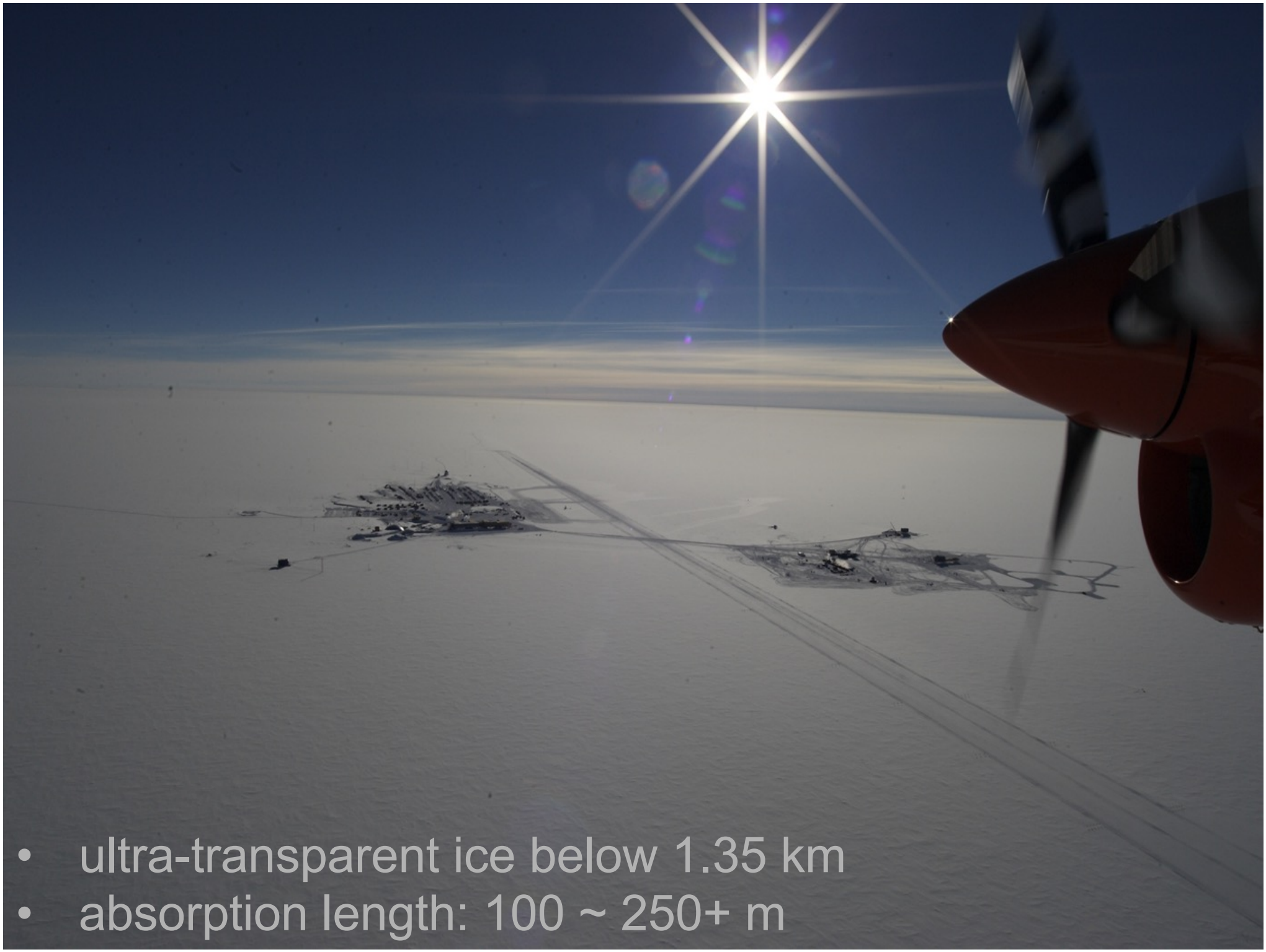
$$\pi^0 \rightarrow \gamma + \gamma$$



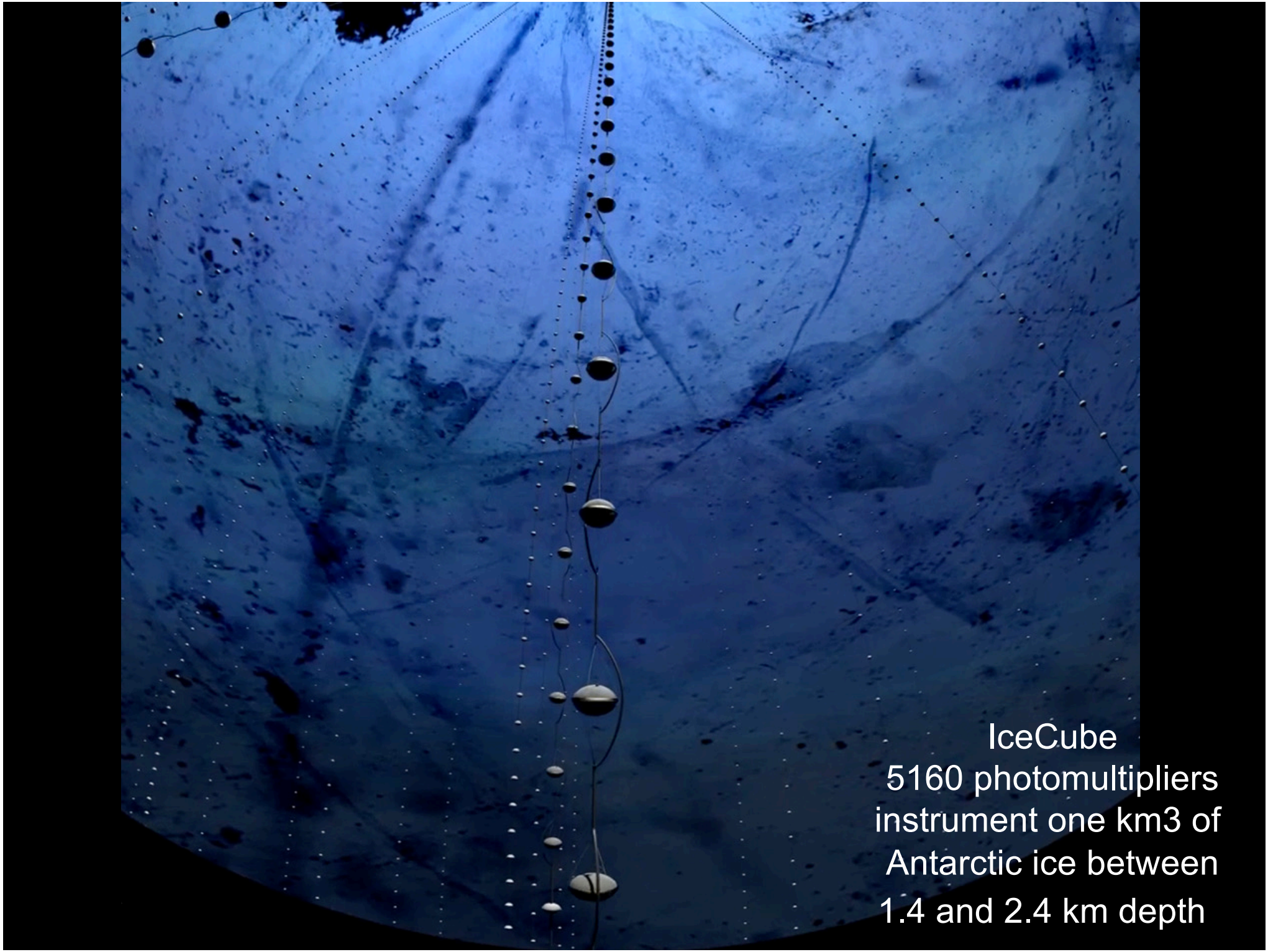
- gamma rays accompany neutrinos
- gamma rays are absorbed by background (EBL) photons

10,000 times too small to do neutrino astronomy…

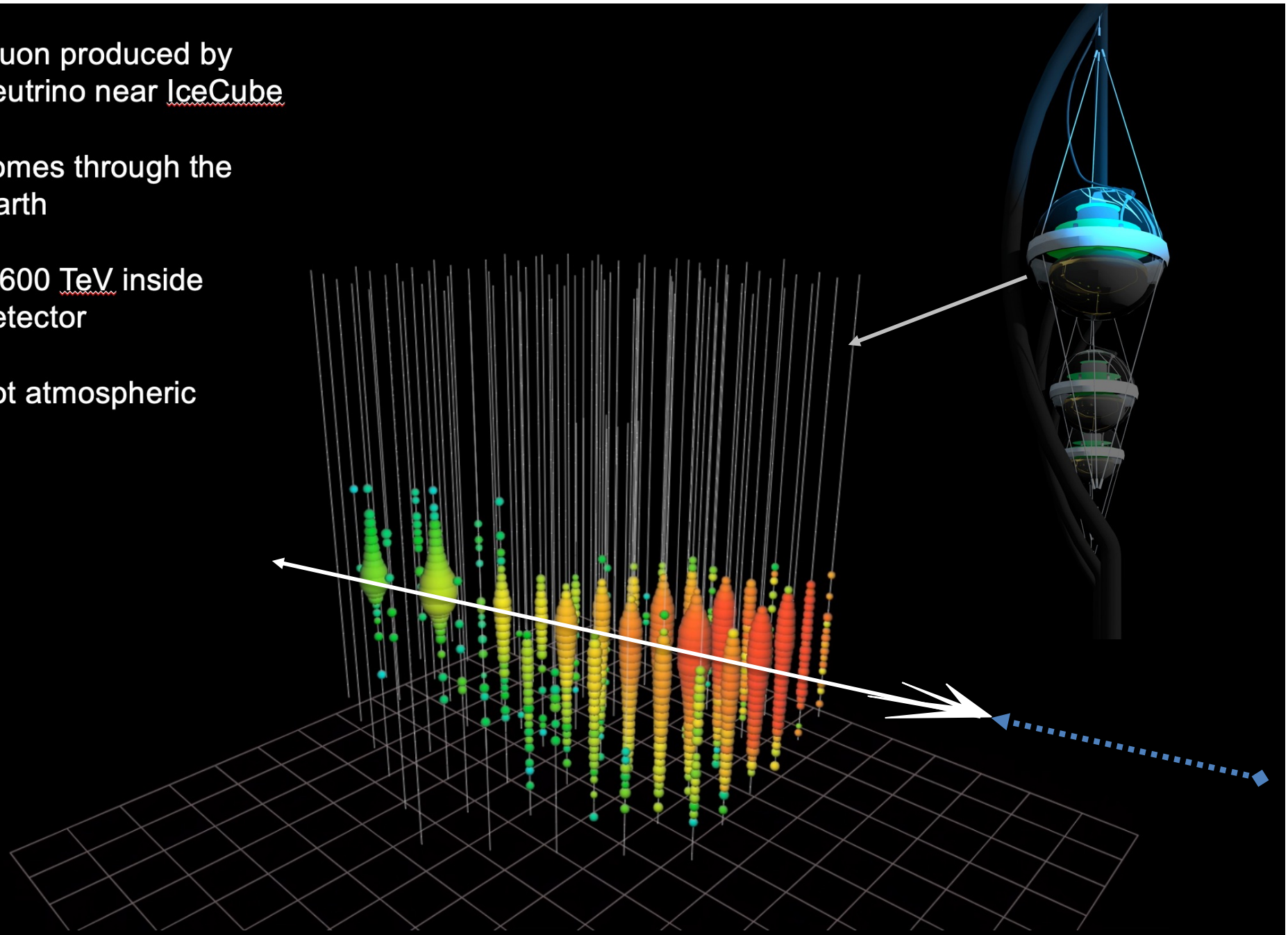


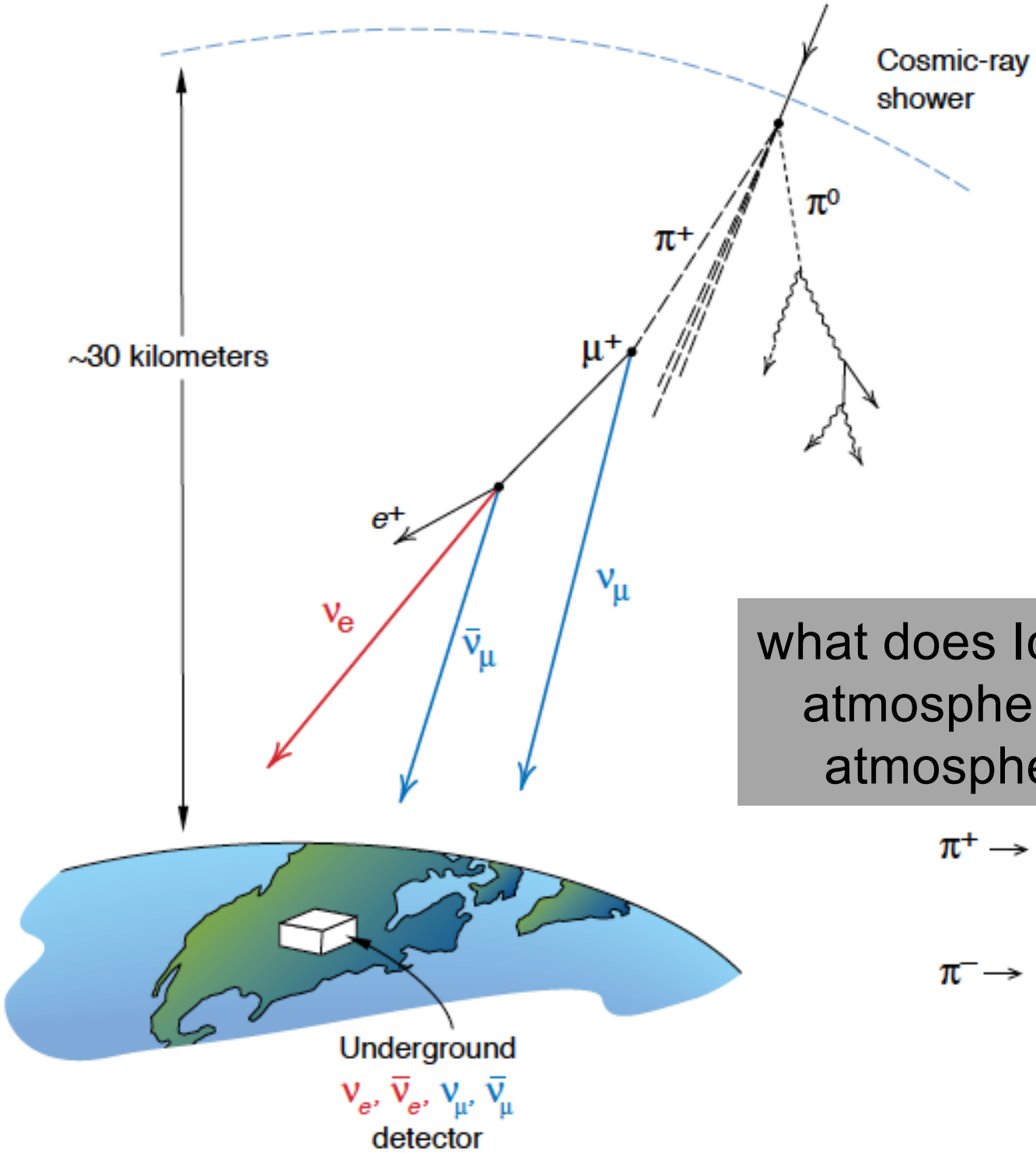


- ultra-transparent ice below 1.35 km
- absorption length: 100 ~ 250+ m


IceCube
5160 photomultipliers
instrument one km3 of
Antarctic ice between
1.4 and 2.4 km depth

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





what does IceCube reveal ?
atmospheric muons and
atmospheric neutrinos

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

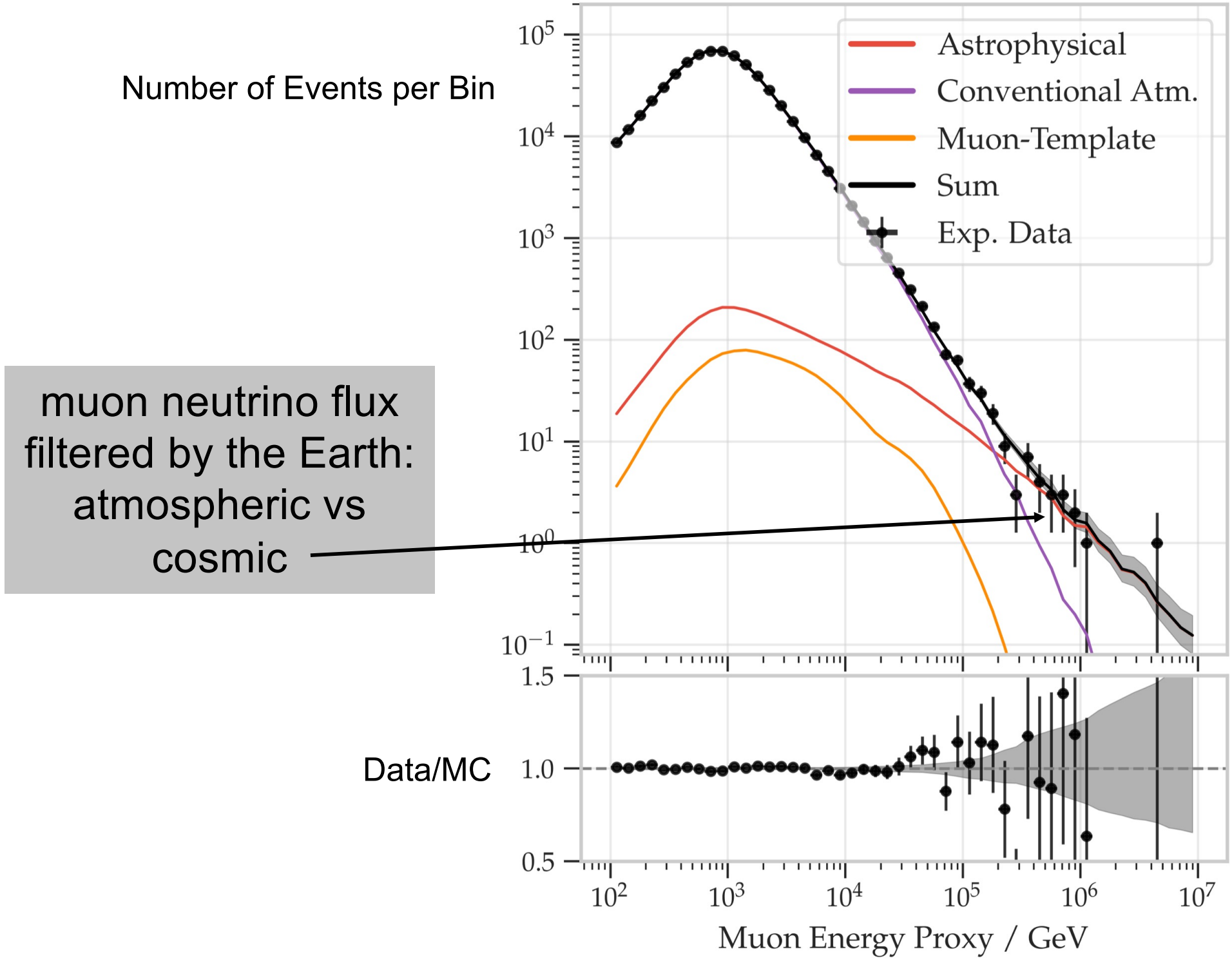
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

signal and background

muons detected per year:

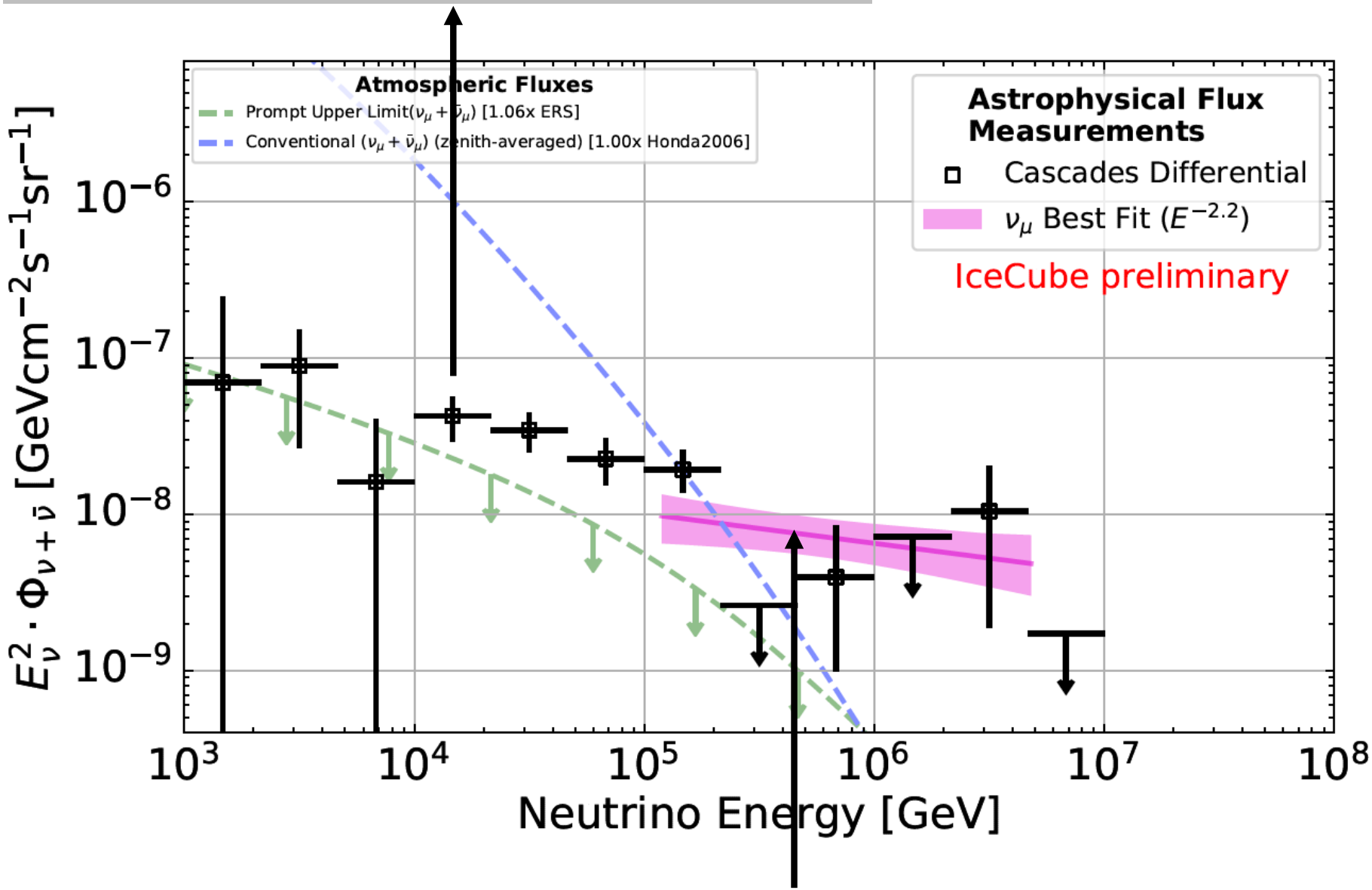
- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^{5}$
- cosmic*** $\nu \rightarrow \mu$ ~ 200

* 3000 per second
** 1 every 5 minutes
*** depends on precise spectrum


Number of Events per Bin
Astrophysical
Conventional Atm.
Muon-Template
Sum
Exp. Data
Data/MC
Muon Energy Proxy / GeV
muon neutrino flux filtered by the Earth: atmospheric vs cosmic

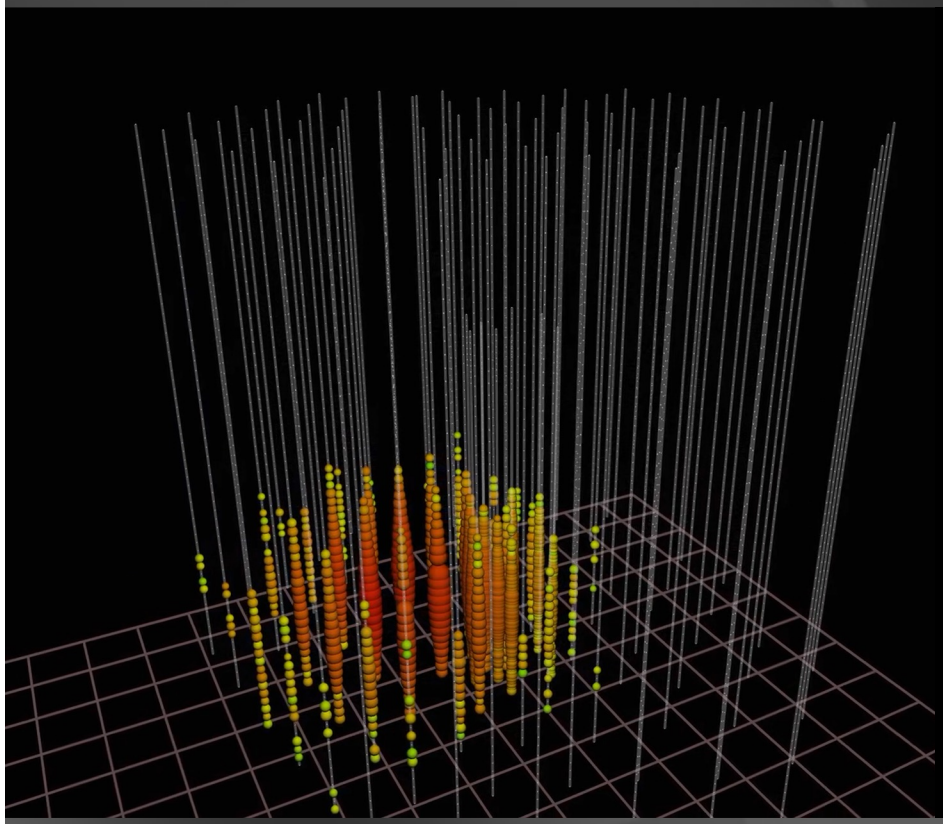
electron and tau neutrinos (showers)

flux $\Phi = dN/dE \sim E^{-2.5}$



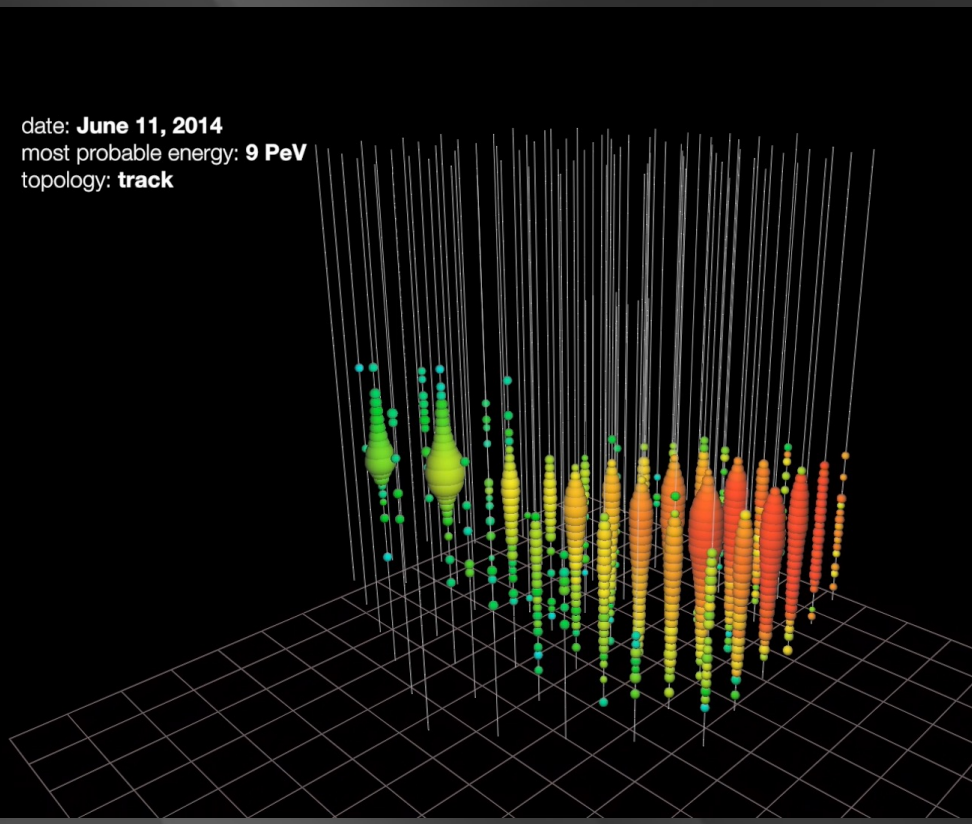
muon neutrinos through Earth (tracks)

neutrinos interacting inside the detector



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

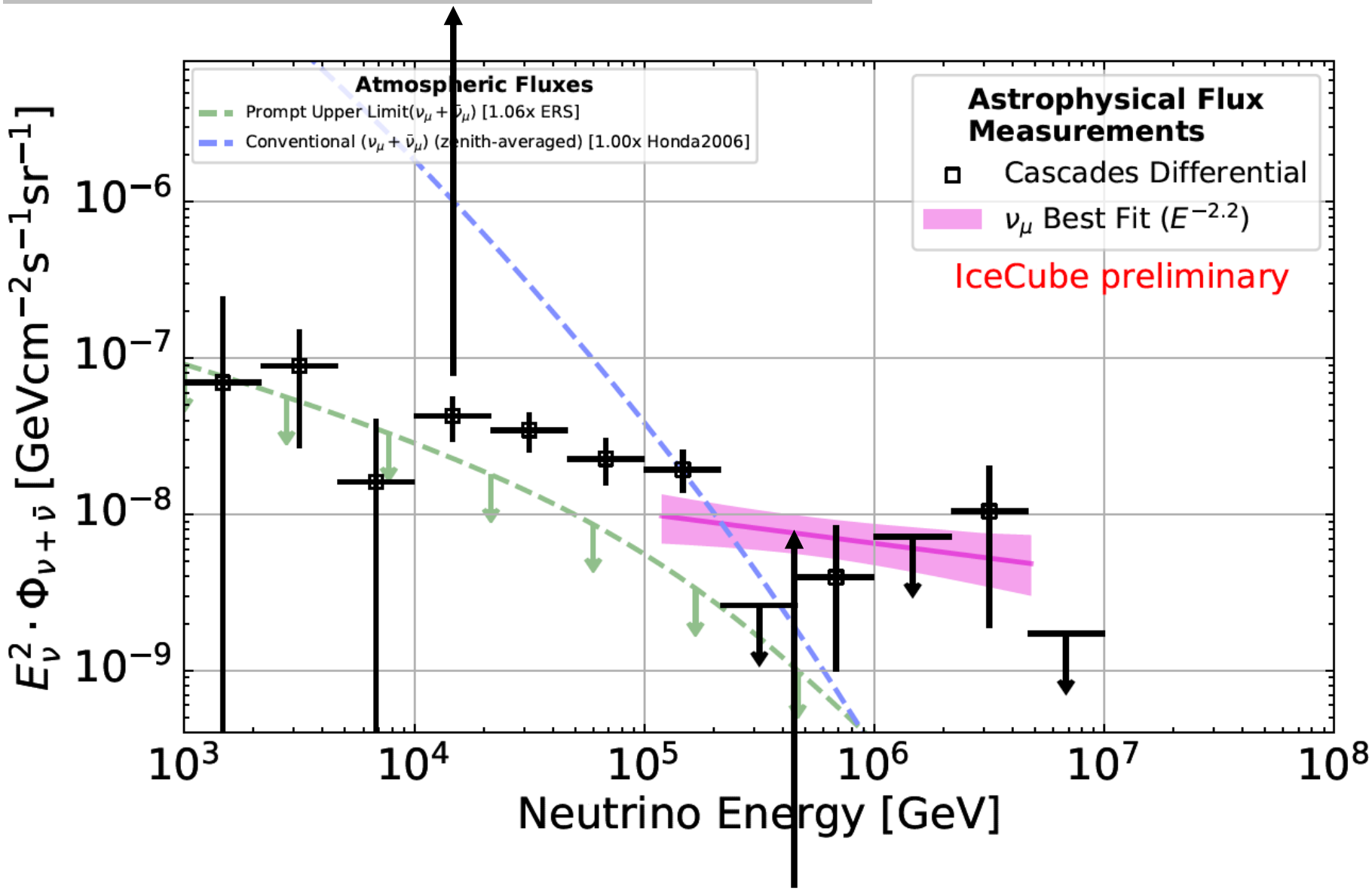
muon neutrinos filtered by the Earth



astronomy: superior angular resolution
superior (0.2~0.4°)

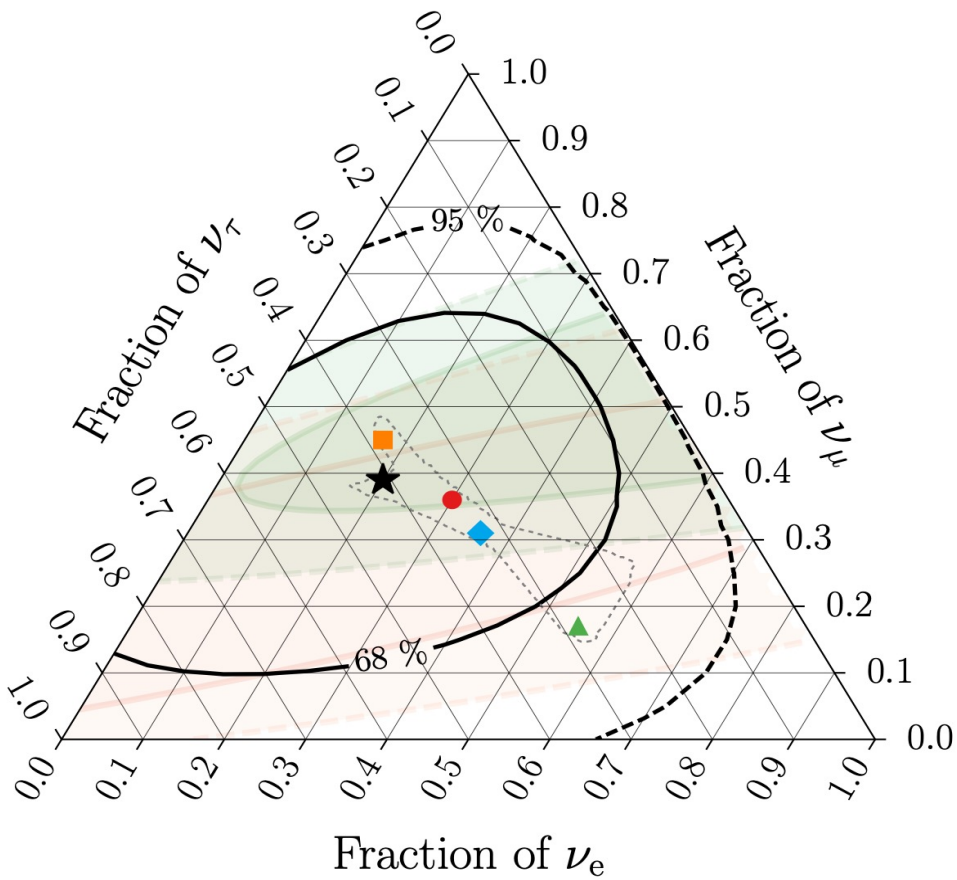
electron and tau neutrinos (showers)

flux $\Phi = dN/dE \sim E^{-2.5}$

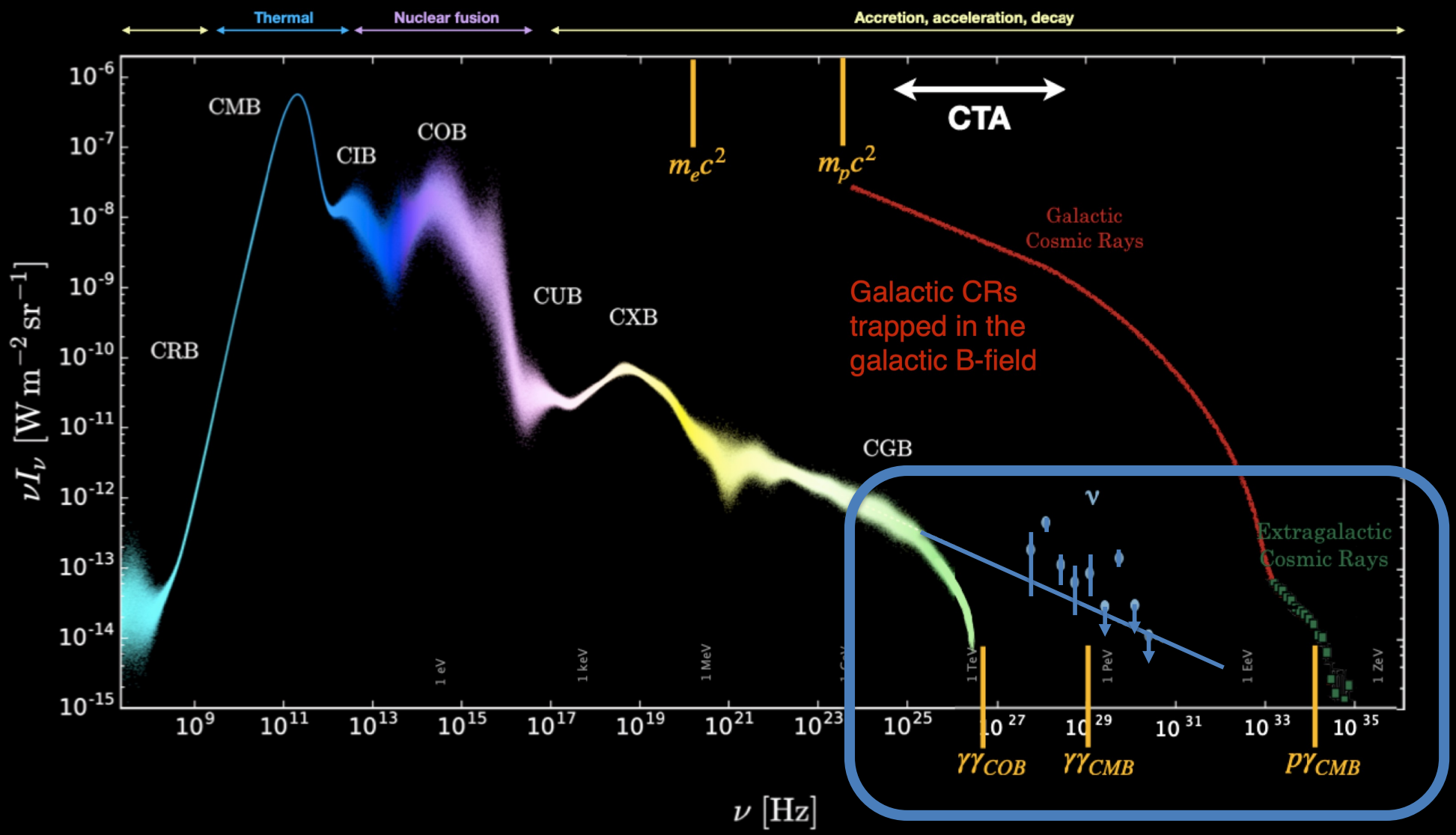


muon neutrinos through Earth (tracks)

oscillations of PeV neutrinos over cosmic distances to 1:1:1



oscillating PeV neutrinos (7.5 years starting events)



energy in neutrinos similar to the energy in gamma rays and cosmic rays

- we observe a diffuse flux of neutrinos from extragalactic sources
- energy flux of neutrinos in the non-thermal Universe is similar to that in gamma-rays
- extragalactic cosmic accelerators outshine nearby neutrino sources in our own Galaxy

High-Energy Cosmic Neutrinos

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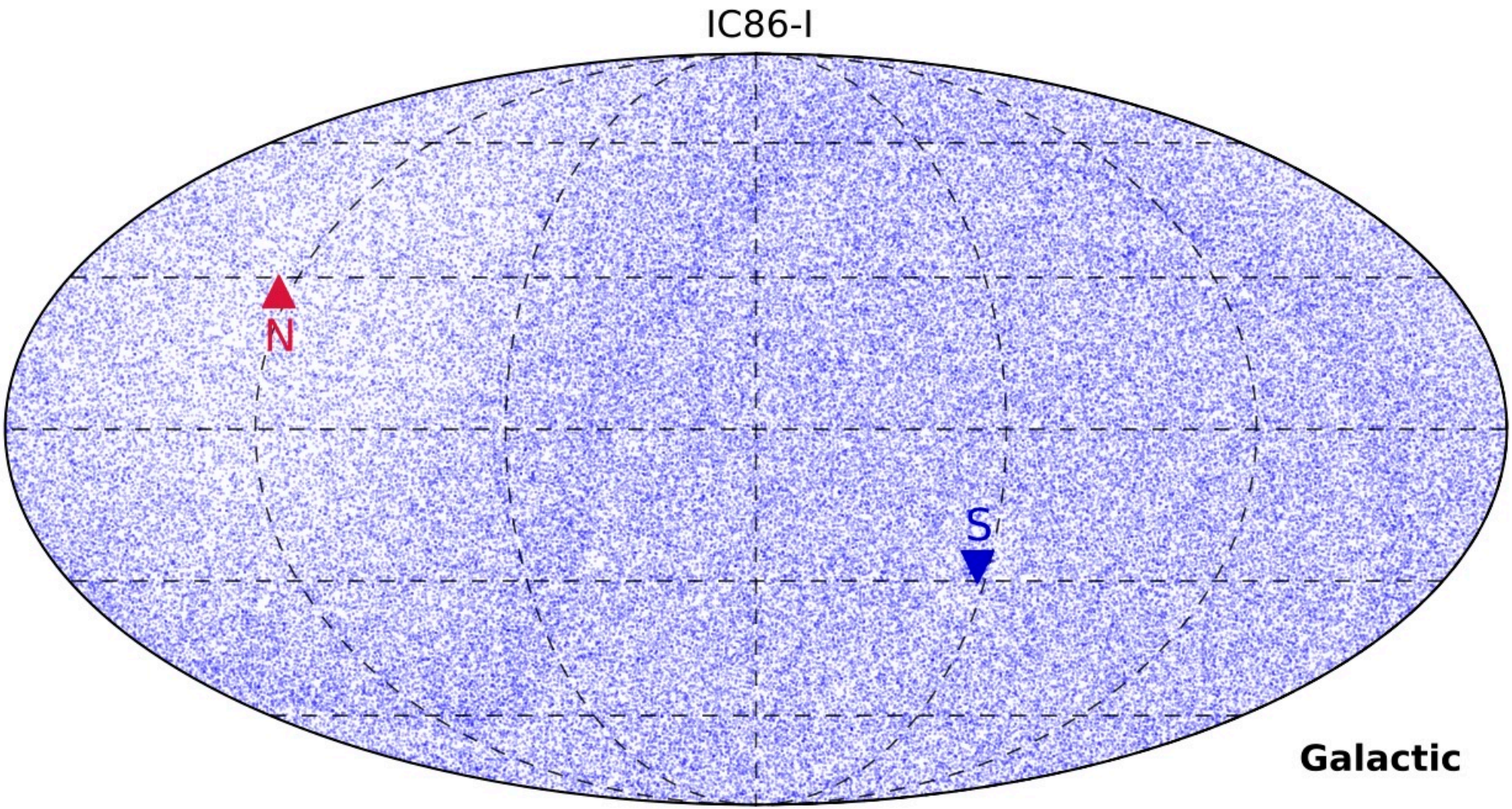
- the diffuse high-energy neutrino flux
- observation of the first sources
- neutrinos and multimessenger astronomy

IceCube.wisc.edu

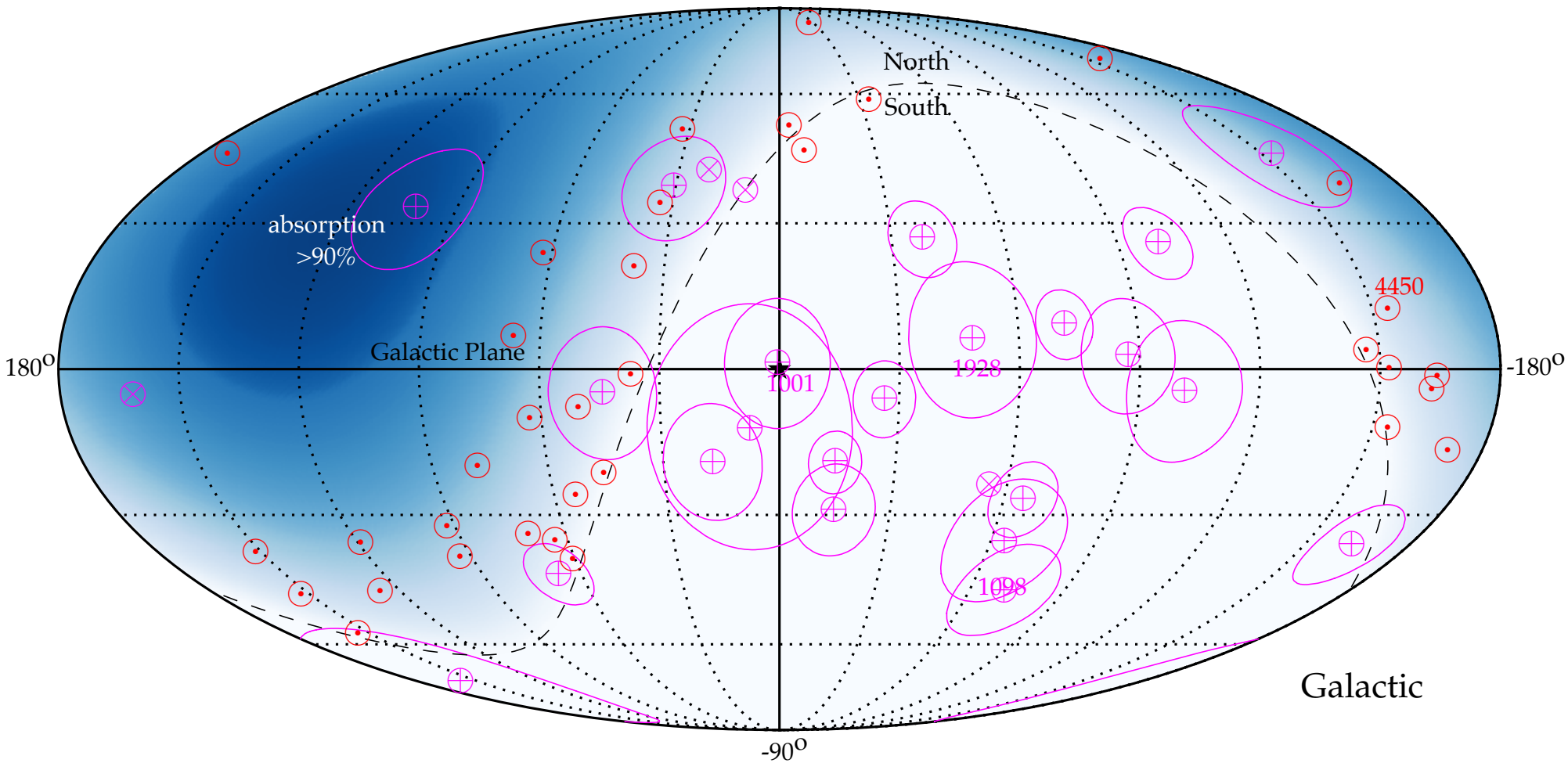


138322 neutrinos in 2011

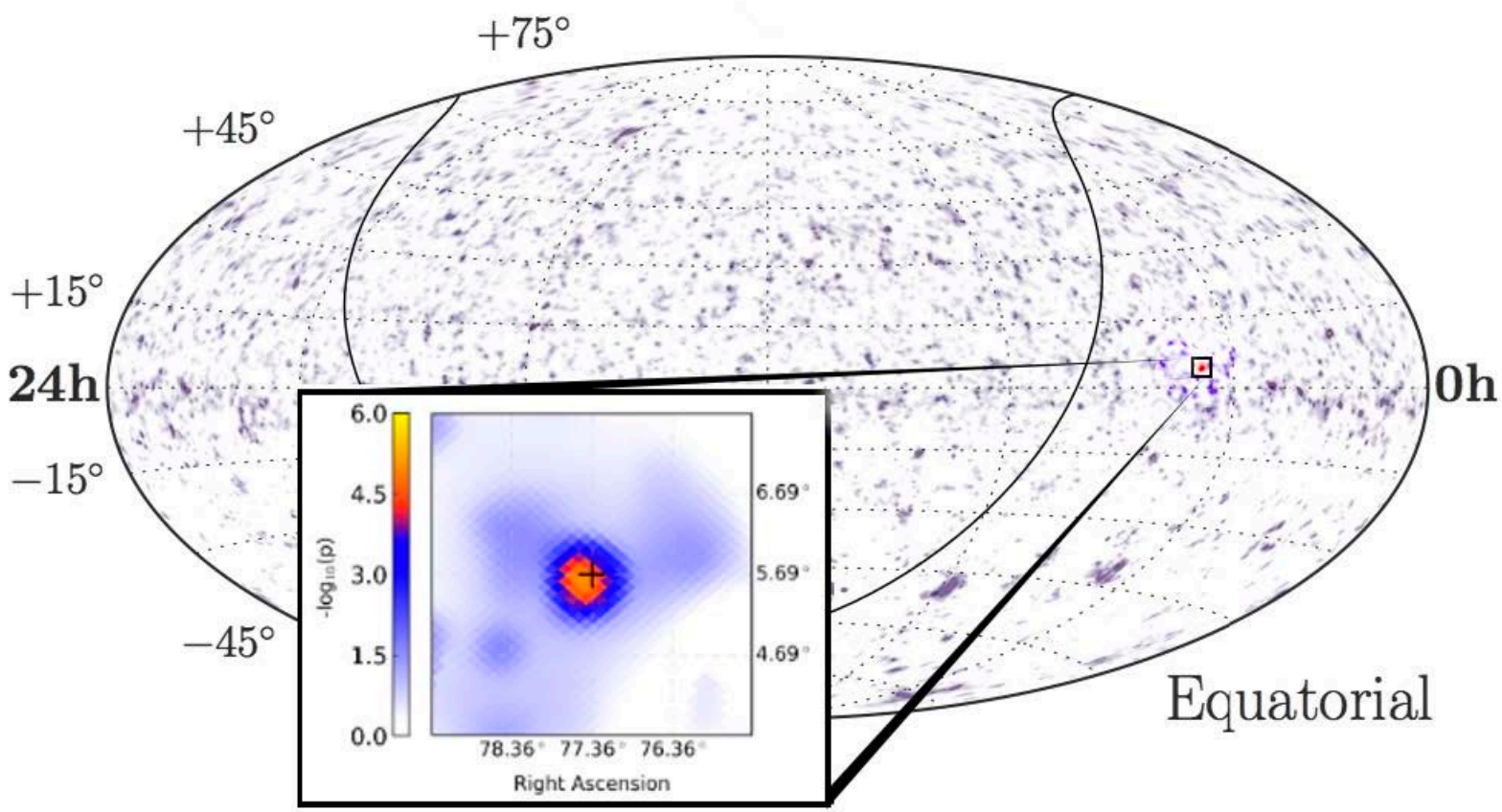
> 200 cosmic neutrinos (depending on the spectrum)
~12 separated from atmospheric background with E>60 TeV

neutrinos with probable cosmic origin:
are they correlated to astronomical sources?

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

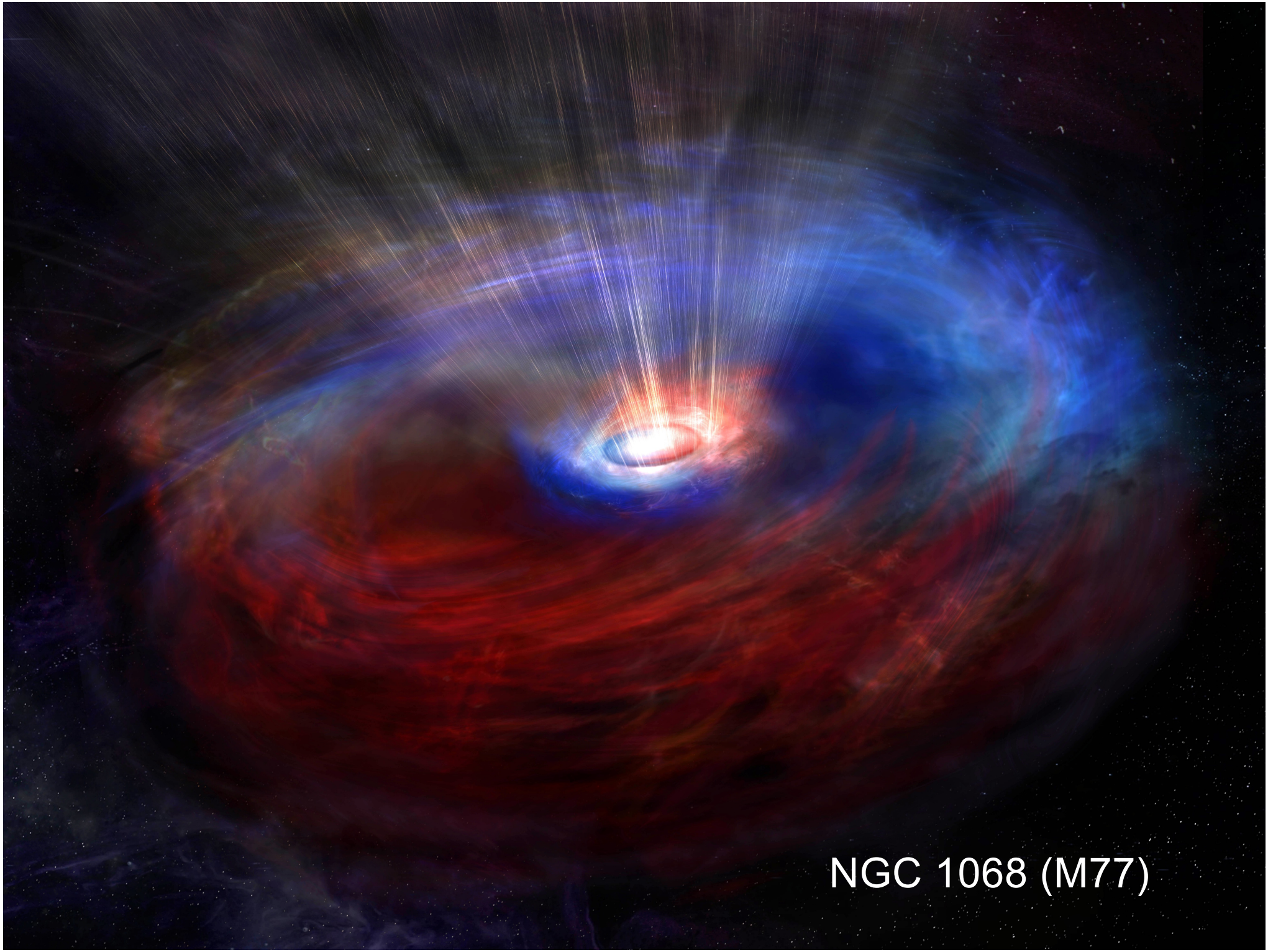


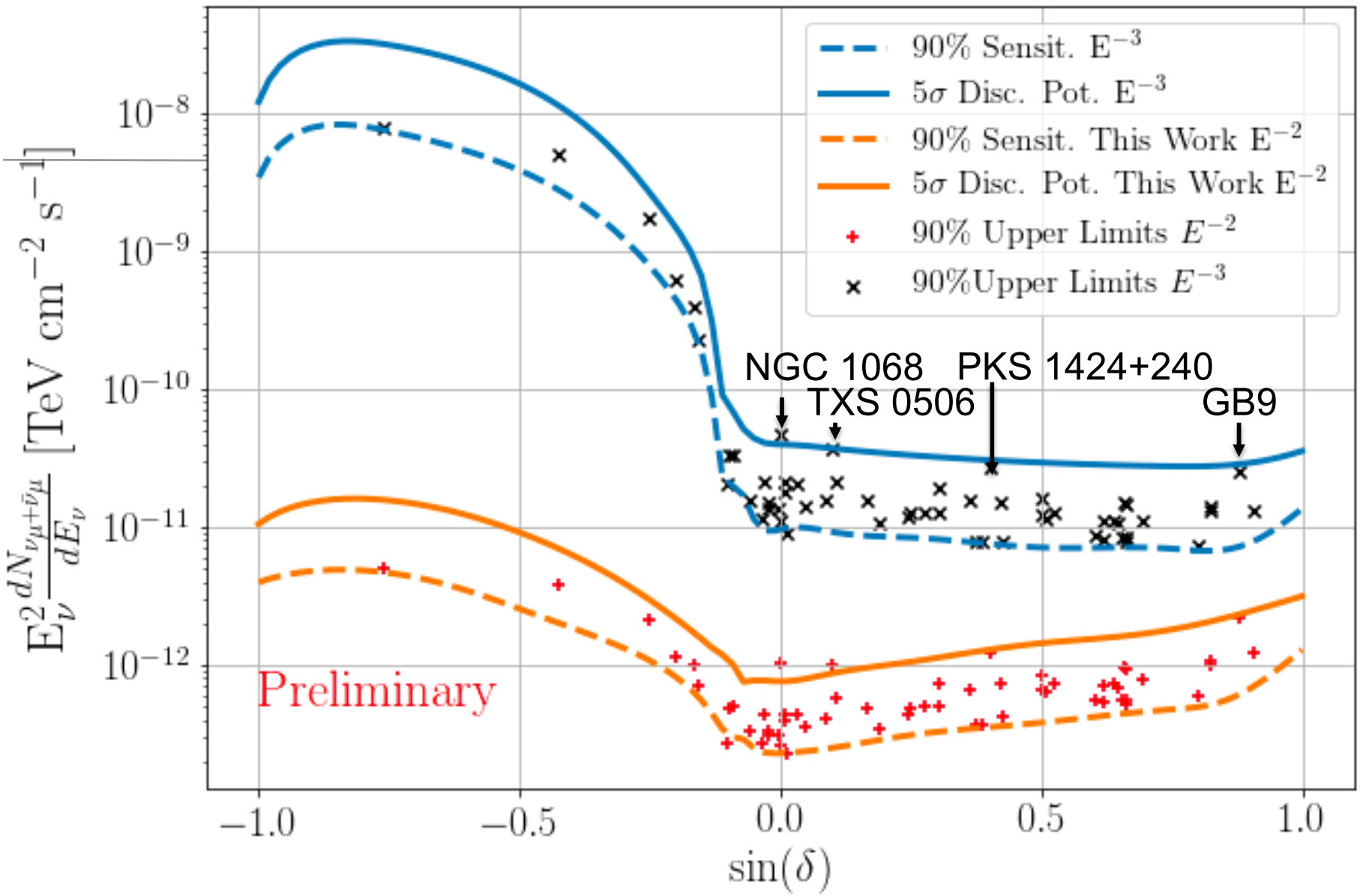
pre-trial p-value for clustering of high energy neutrinos



hottest spot coincident with
NGC 1068 (M77) (2.9σ)

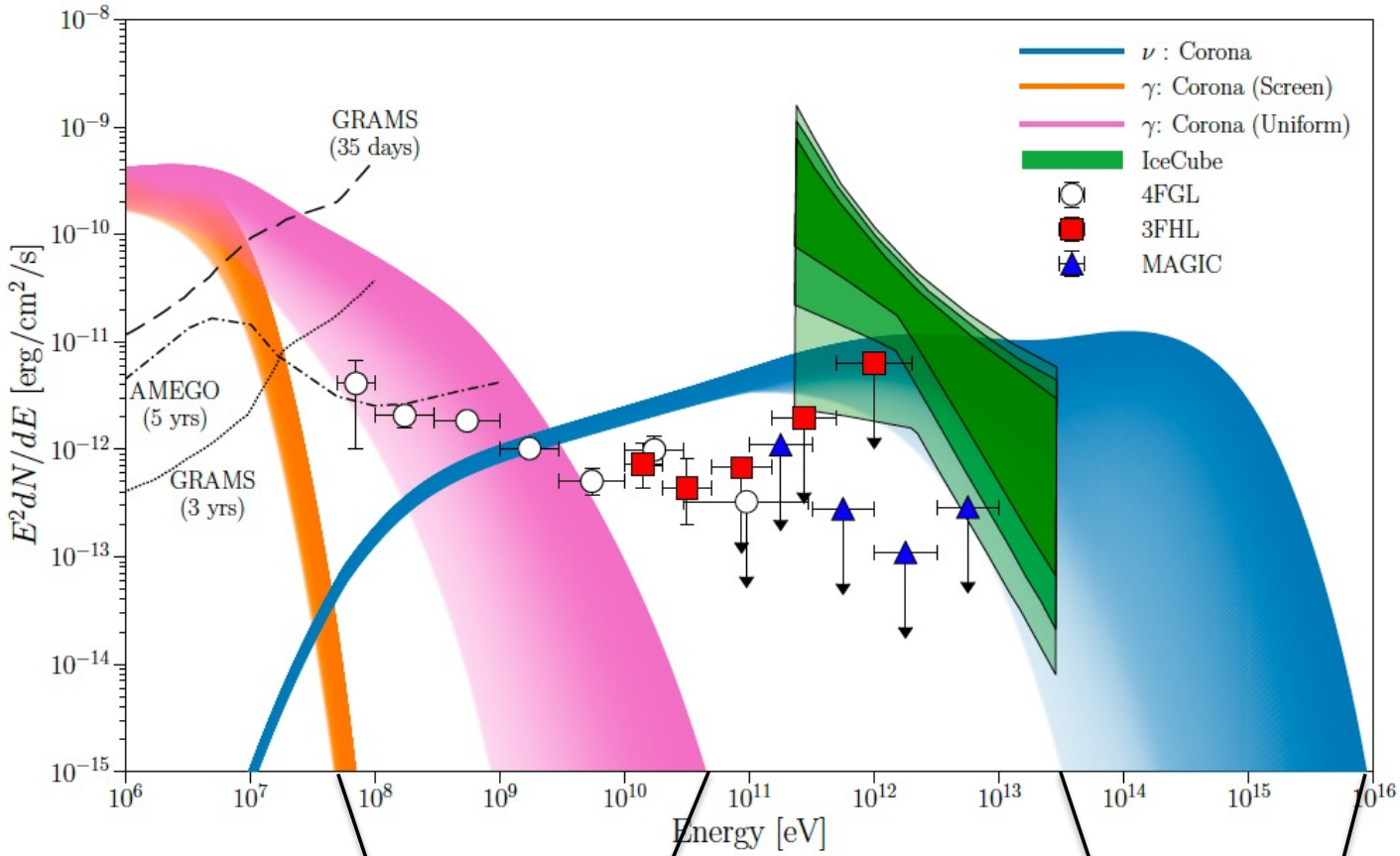
evidence for non-uniform sky map in 10 years of IceCube data :
mostly resulting from 4 extragalactic source candidates


NGC 1068 (M77)



limits and interesting fluctuations (?)

neutrinos produced in the gamma-ray obscured core of NGC 1068



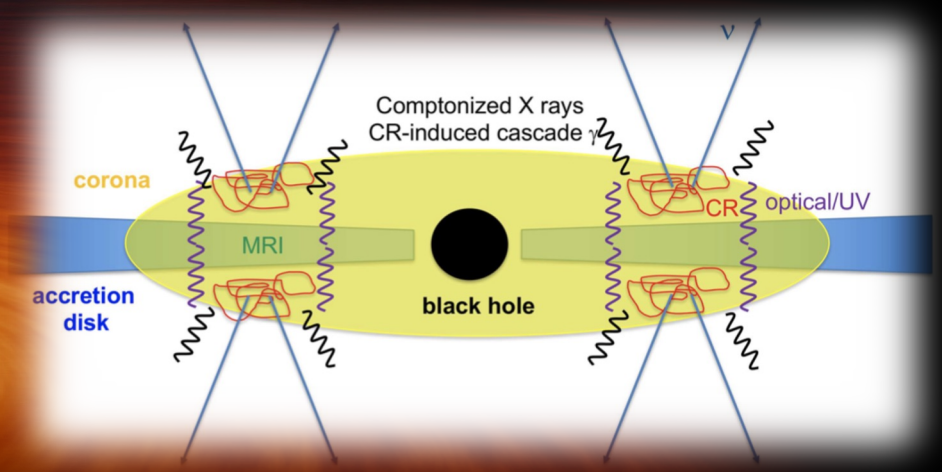
accompanying pionic photons

range of neutrino flux: protons versus electrons

obscured cores of active galaxies as cosmic accelerators

→ active core (radio)
→ jet disrupted near core (masquerading blazars)
→ not a blazar at the time neutrinos are emitted

acceleration of electrons and protons in the high field regions associated with the accretion disk, the optically thick corona of X-rays, and the base of the jet.



interesting fluctuations or neutrino sources?

ongoing program to upgrade the performance of IceCube

- improved detector calibration and ice model (pass 2)

improved muon track reconstruction

- DNN (energy) and BDT (pointing) reconstruction
- point spread function consistent with simulation
- insensitive to systematics
- improved modeling of the optics of the ice

answer very soon…

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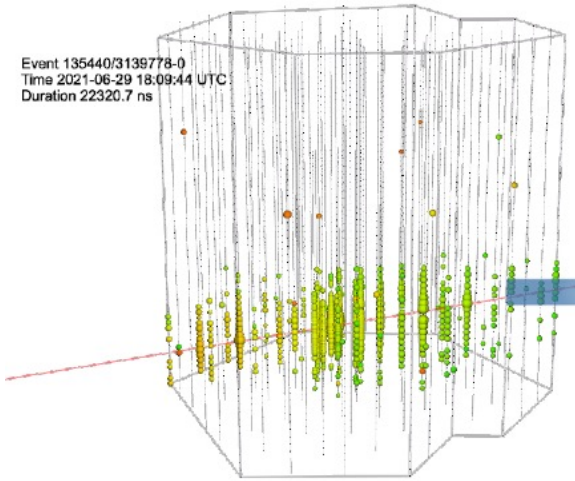
IceCube.wisc.edu



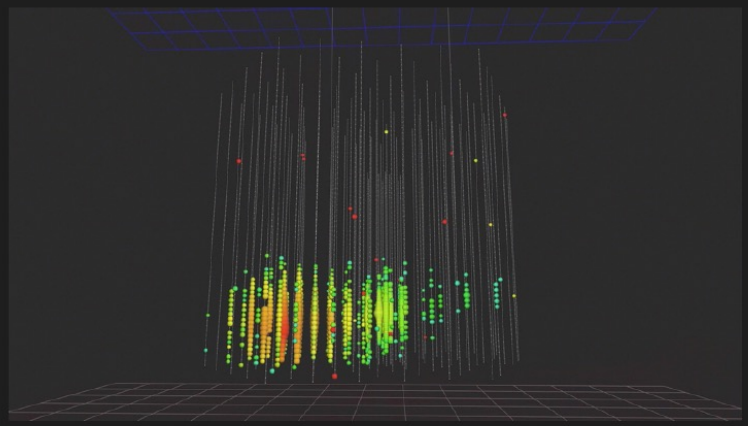
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

We send our high-energy events in real-time as public GCN alerts now!

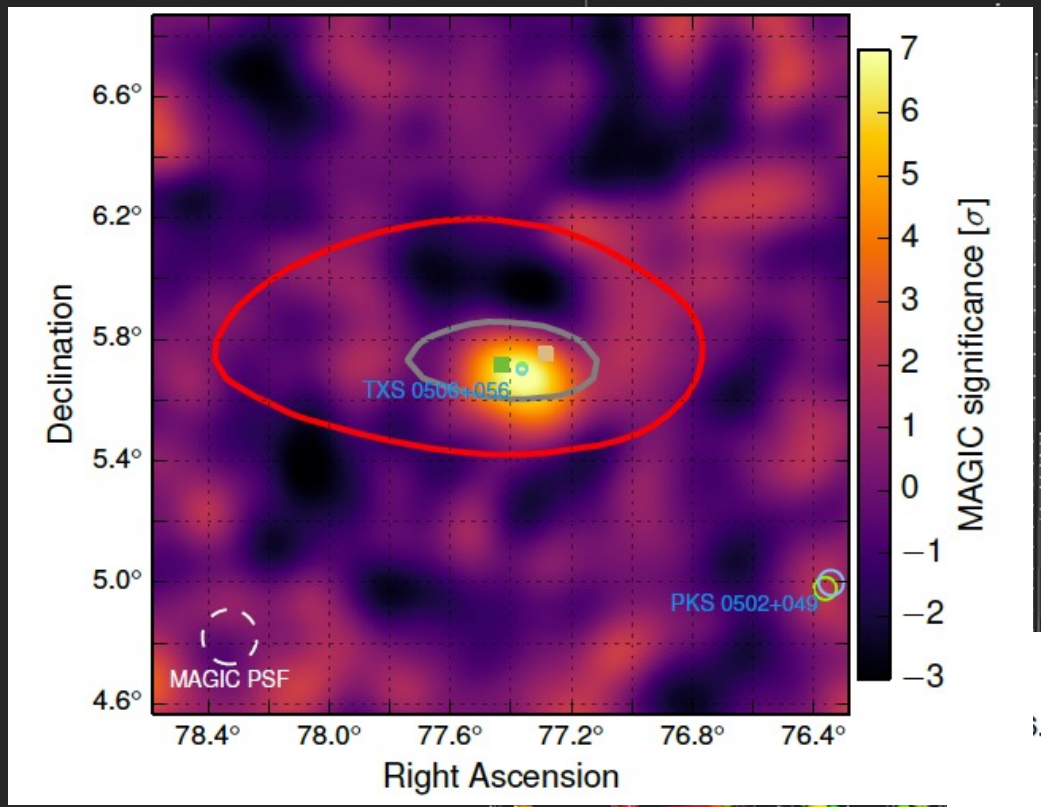
```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:      AMON ICECUBE HESE
RUN_NUM:          127853
EVENT_NUM:        67093193
SRC_RA:           240.5683d {+16h 02m 16s} (J2000),
                 240.7644d {+16h 03m 03s} (current),
                 239.9678d {+15h 59m 52s} (1950)
SRC_DEC:           +9.3417d {+09d 20' 30"} (J2000),
                  +9.2972d {+09d 17' 50"} (current),
                  +9.4798d {+09d 28' 47"} (1950)
SRC_ERROR:        35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   17505 TJD;   118 DOY;   16/04/27 (yy/mm/dd)
DISCOVERY_TIME:   21152 SOD {05:52:32.00} UT
REVISION:         2
N_EVENTS:         1 [number of neutrinos]
STREAM:           1
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000 [sec]
FALSE_POS:        0.0000e+00 [s^-1 sr^-1]
PVALUE:           0.0000e+00 [dn]
CHARGE:           18883.62 [pe]
SIGNAL_TRACKNESS: 0.92 [dn]
SUN_POSTN:         35.75d {+02h 23m 00s}  +14.21d {+14d 12' 45"}
```

GCN notice for starting track sent Apr 27

We send **rough reconstructions first** and then **update them.**

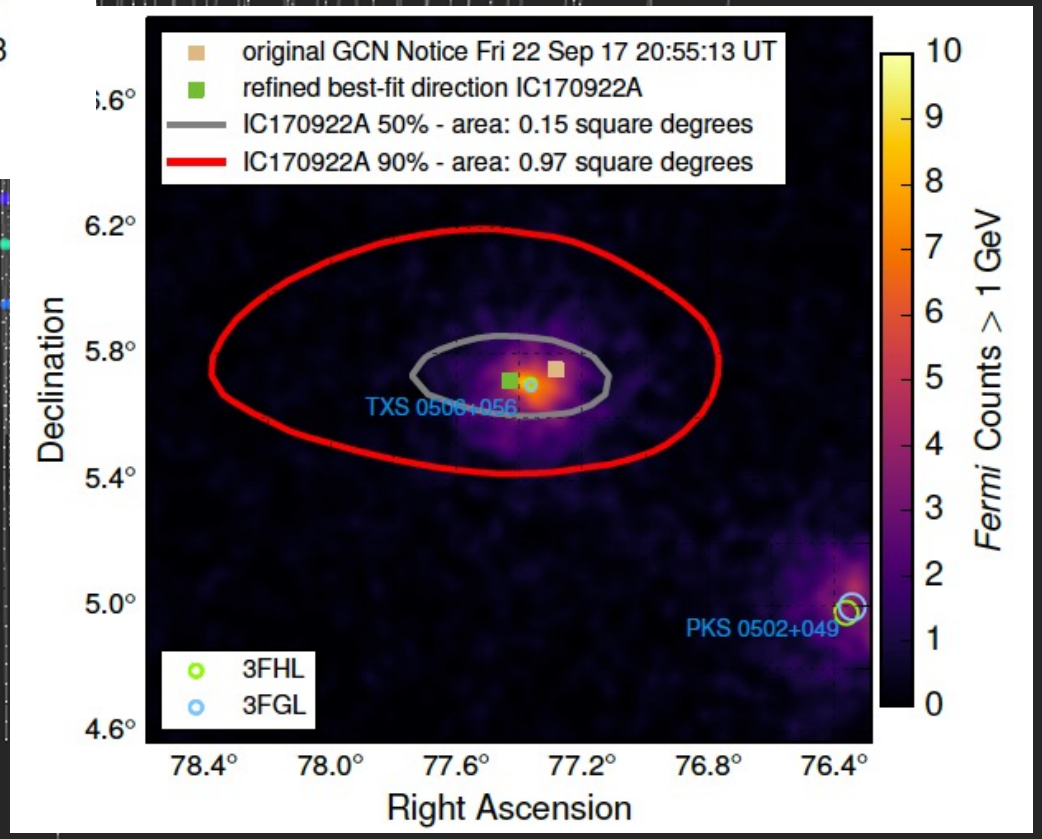


from light in the ice to astronomer in less than one minute



IceCube 170922
290 TeV

Fermi
detects a flaring
blazar within 0.06°



MAGIC
detects emission of
> 100 GeV gammas

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

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

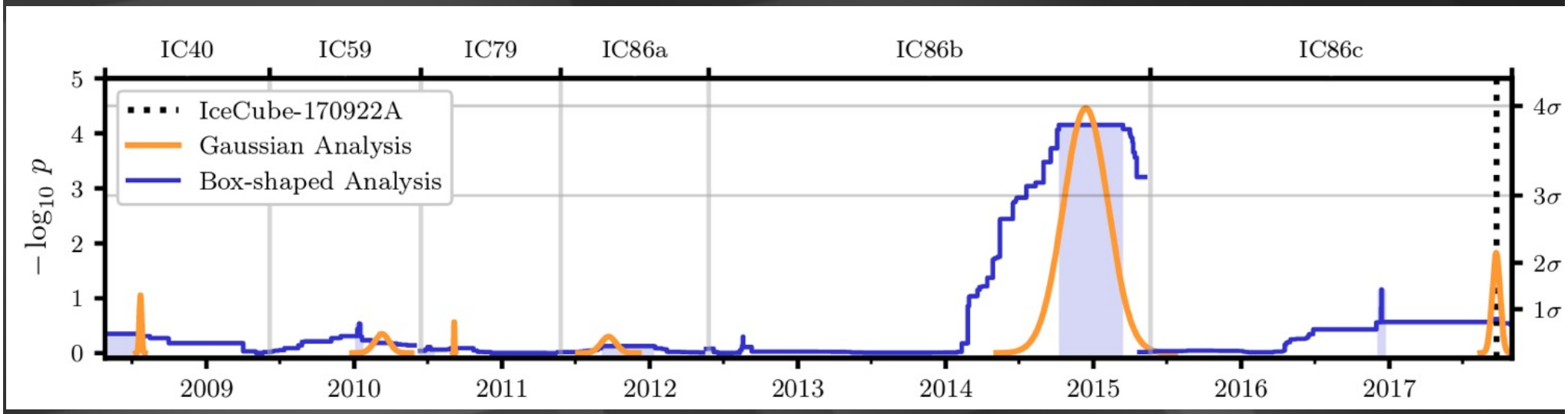
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

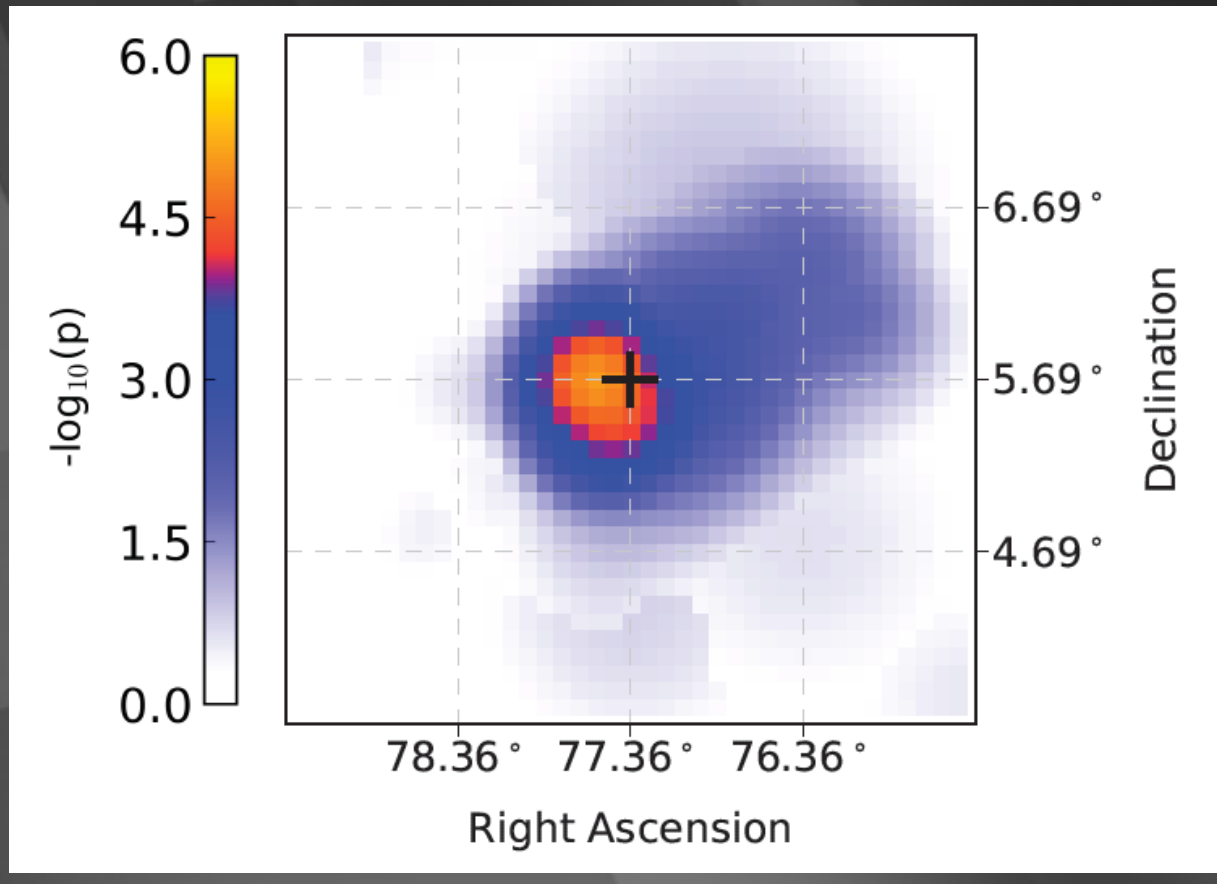
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†



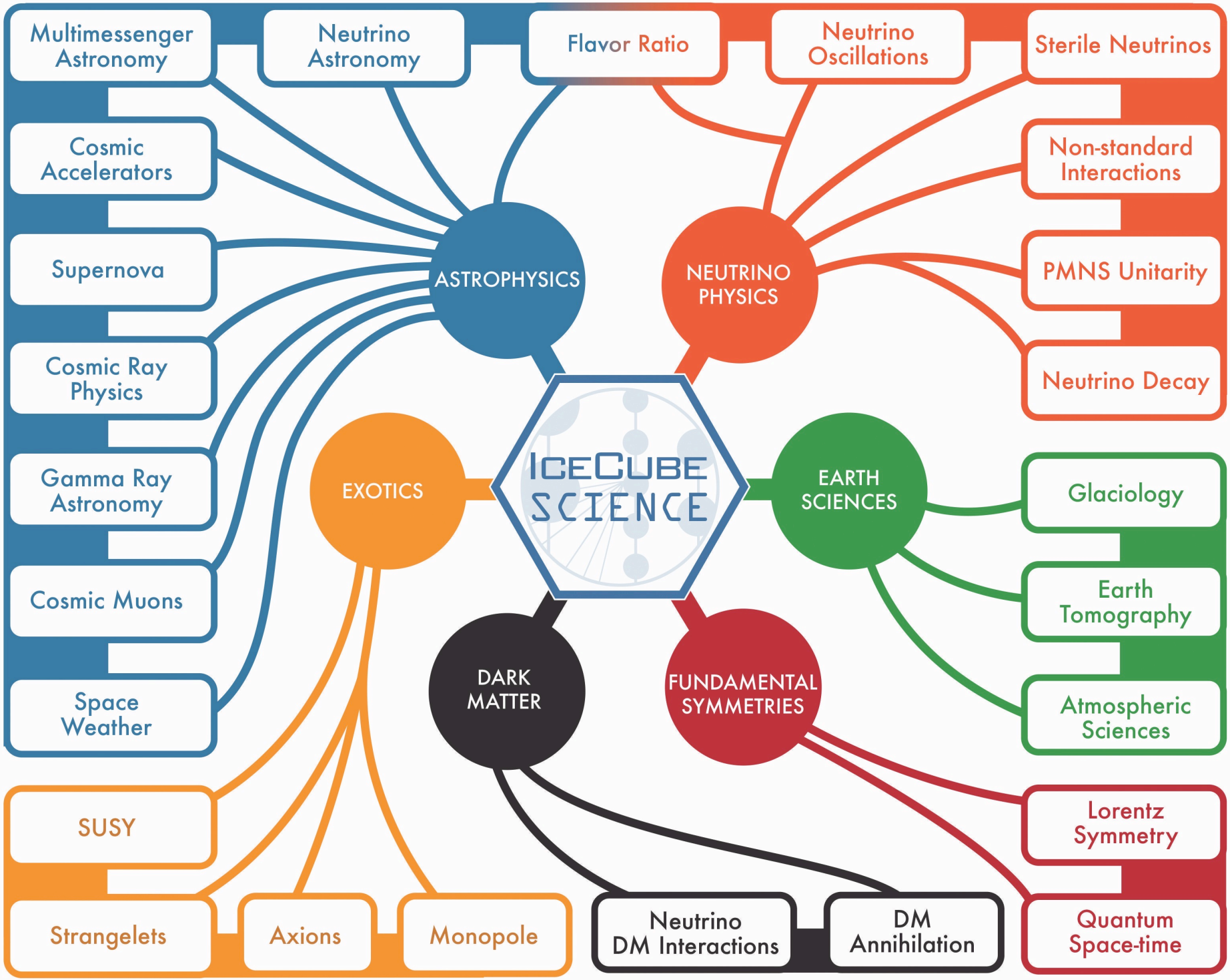
search in archival IceCube data:

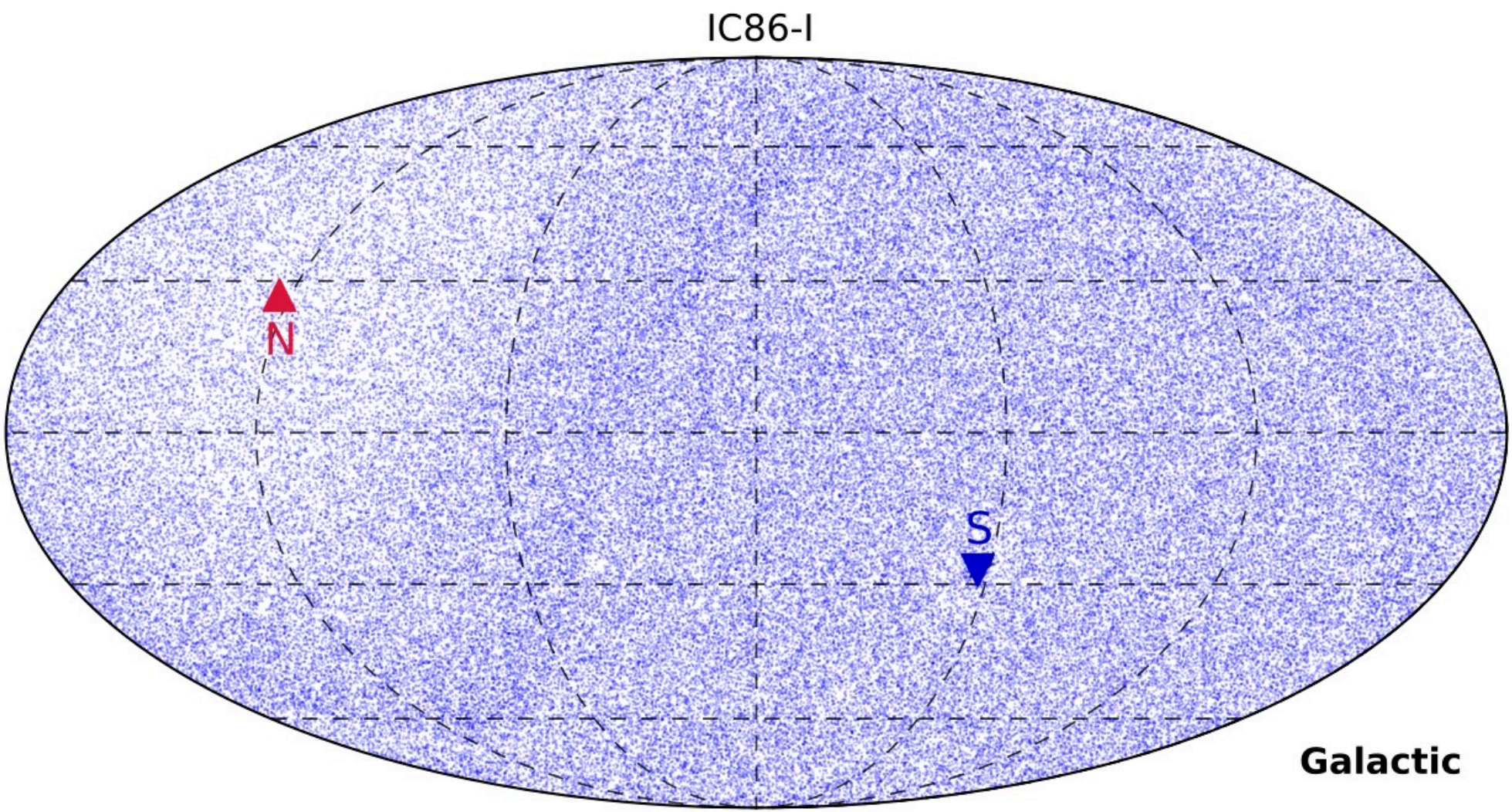
- 100-day flare in 2014
- spectrum $E^{-2.2}$
- $L_\nu > 10^{47}$ erg/s
- no gamma ray flare!



TXS 0506+056

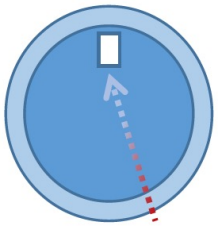
- two statistically independent observations above the > 3σ level
- it is also the second source in the all-sky search
- supported by TeV gamma ray, optical observations and by radio imaging of the core
- association of IC170922 with optical variation in time domain

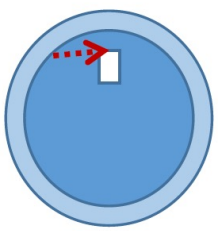

ICECUBE SCIENCE
ASTROPHYSICS
Multimessenger Astronomy
Neutrino Astronomy
Cosmic Accelerators
Supernova
Cosmic Ray Physics
Gamma Ray Astronomy
Cosmic Muons
Space Weather
NEUTRINO PHYSICS
Flavor Ratio
Neutrino Oscillations
Sterile Neutrinos
Non-standard Interactions
PMNS Unitarity
Neutrino Decay
EARTH SCIENCES
Glaciology
Earth Tomography
Atmospheric Sciences
EXOTICS
SUSY
Strangelets
Axions
Monopole
DARK MATTER
Neutrino DM Interactions
DM Annihilation
FUNDAMENTAL SYMMETRIES
Lorentz Symmetry
Quantum Space-time

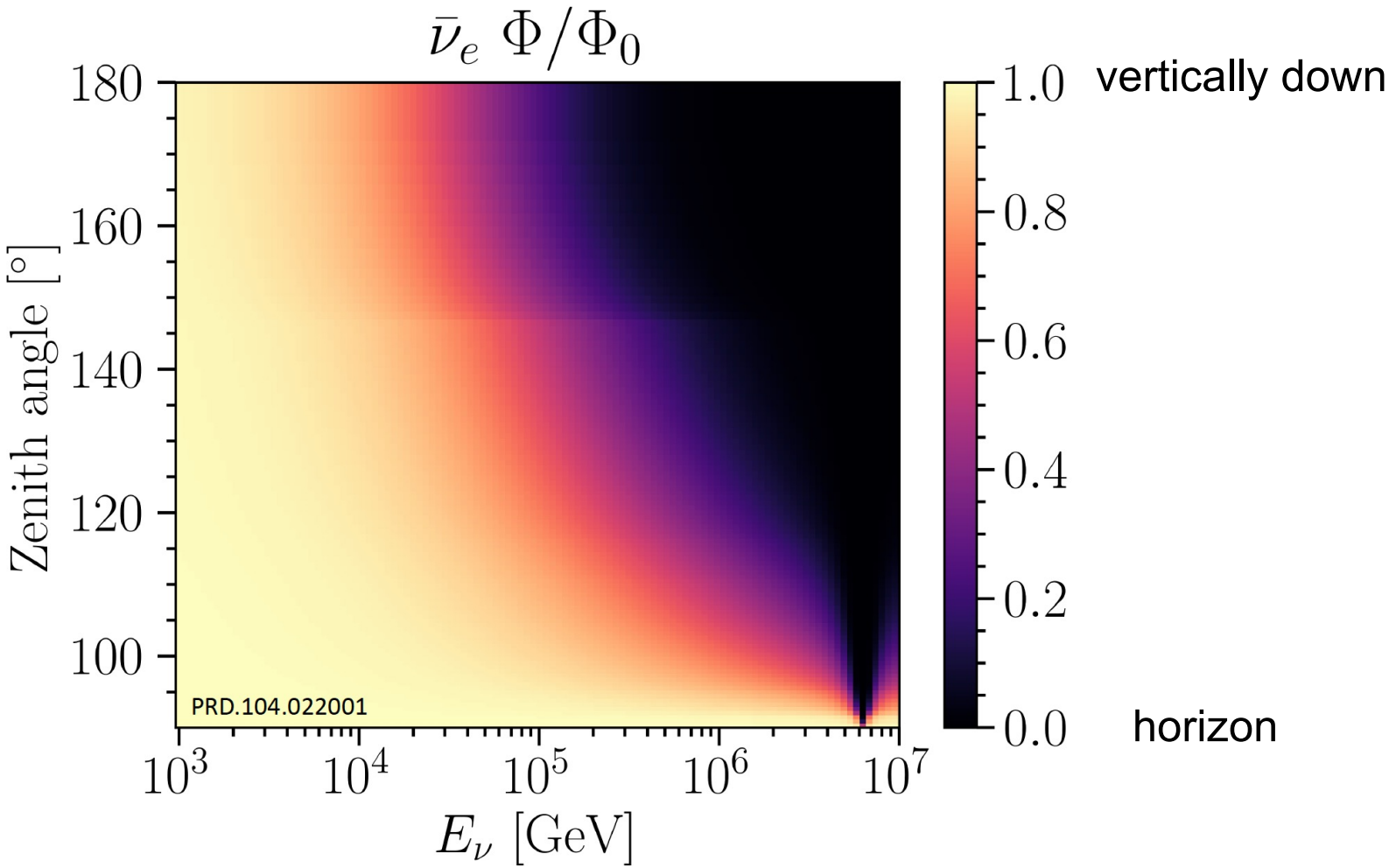


138322 neutrinos in 2011

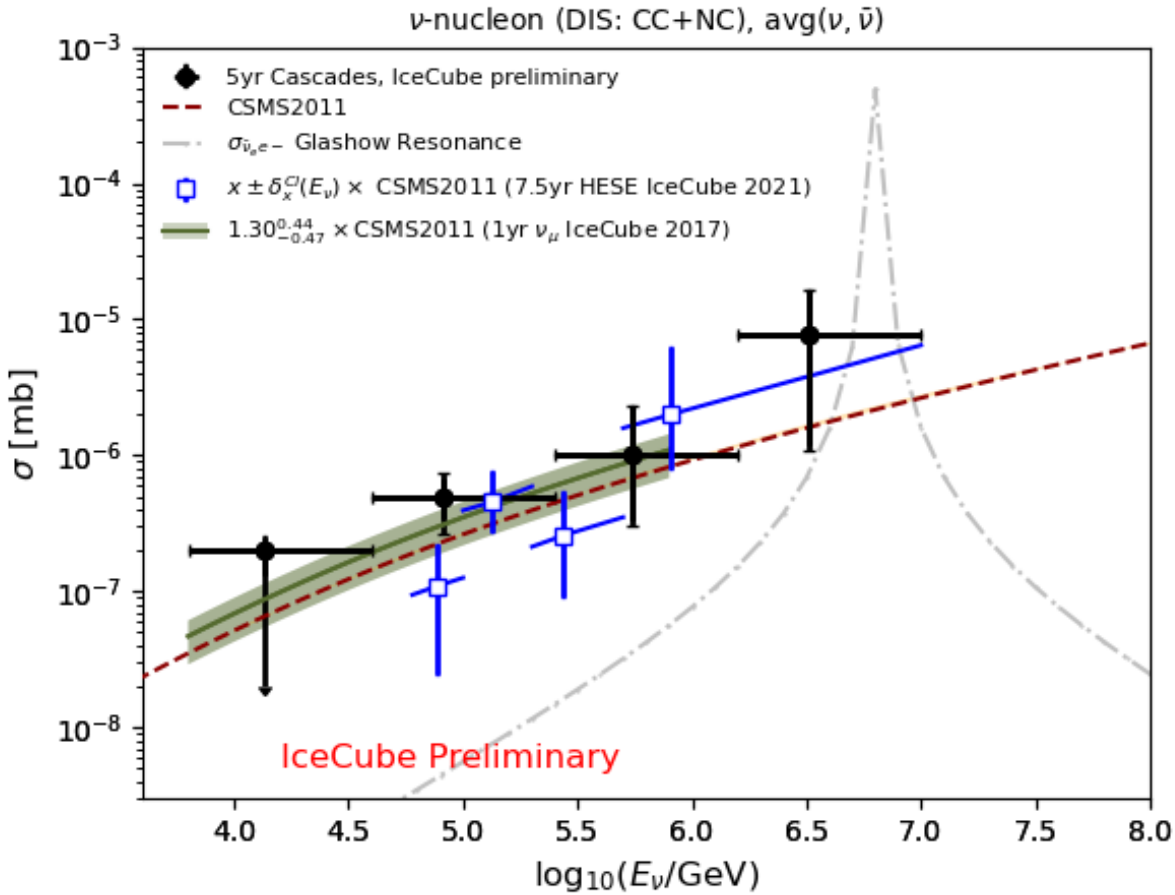
> 200 cosmic neutrinos (depending on the spectrum)
~12 separated from atmospheric background with E>60 TeV



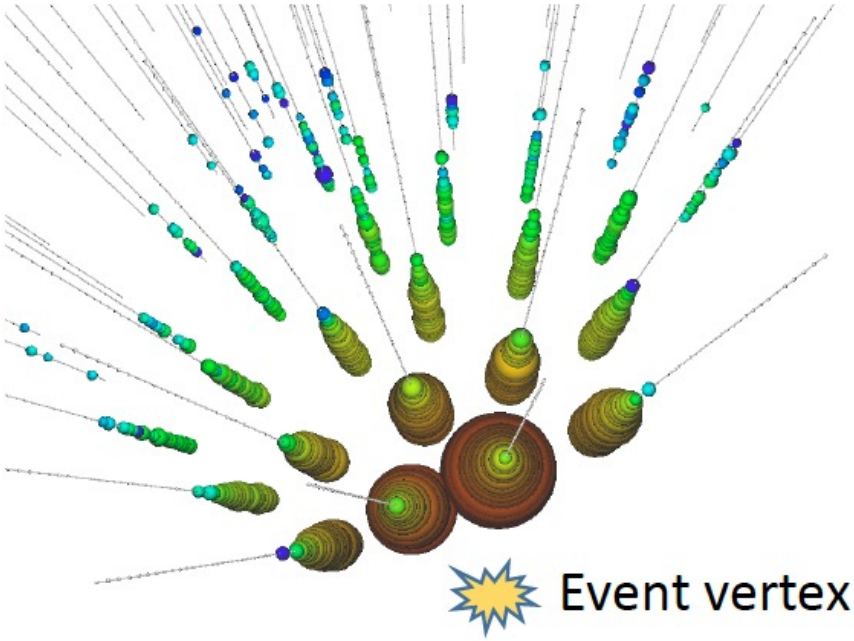




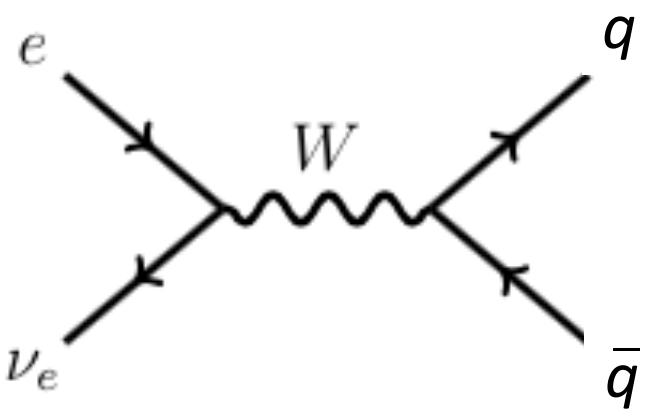
the earth diameter is 1 absorption length at 70 TeV

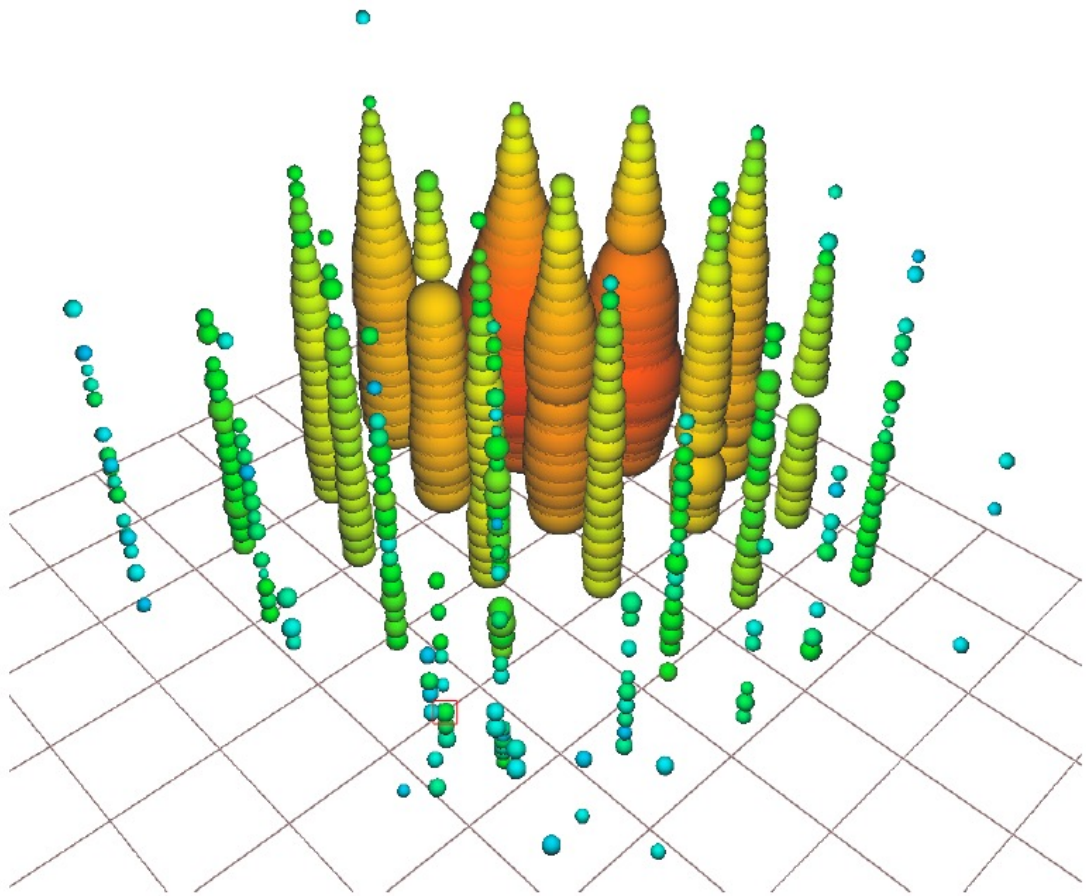

ν-nucleon (DIS: CC+NC), avg(ν, ν̄)
5yr Cascades, IceCube preliminary
CSMS2011
$\sigma_{\bar{\nu}_e e^-}$ Glashow Resonance
$x \pm \delta_x^{CI}(E_\nu) \times$ CSMS2011 (7.5yr HESE IceCube 2021)
$1.30^{0.44}_{-0.47} \times$ CSMS2011 (1yr ν_μ IceCube 2017)
IceCube Preliminary
σ [mb]
$\log_{10}(E_\nu/\mathrm{GeV})$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0

partially contained event with energy 6.3 PeV

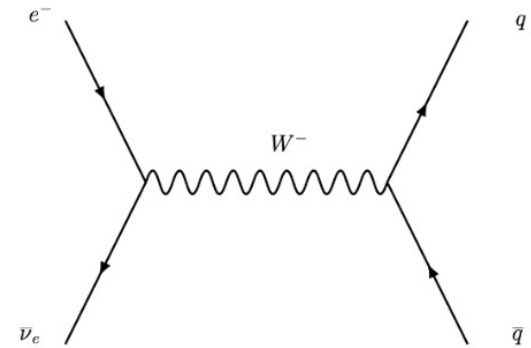


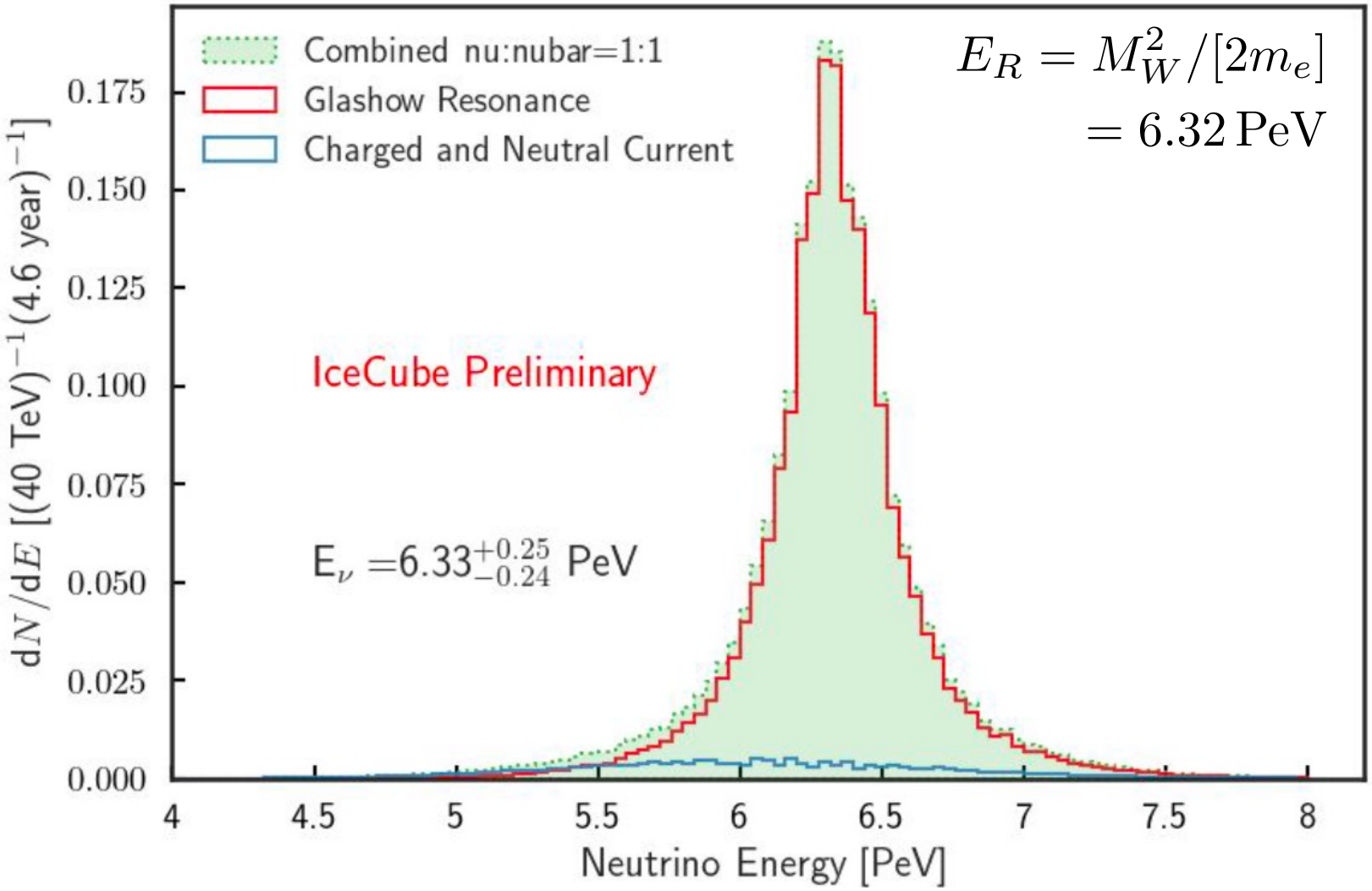
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron



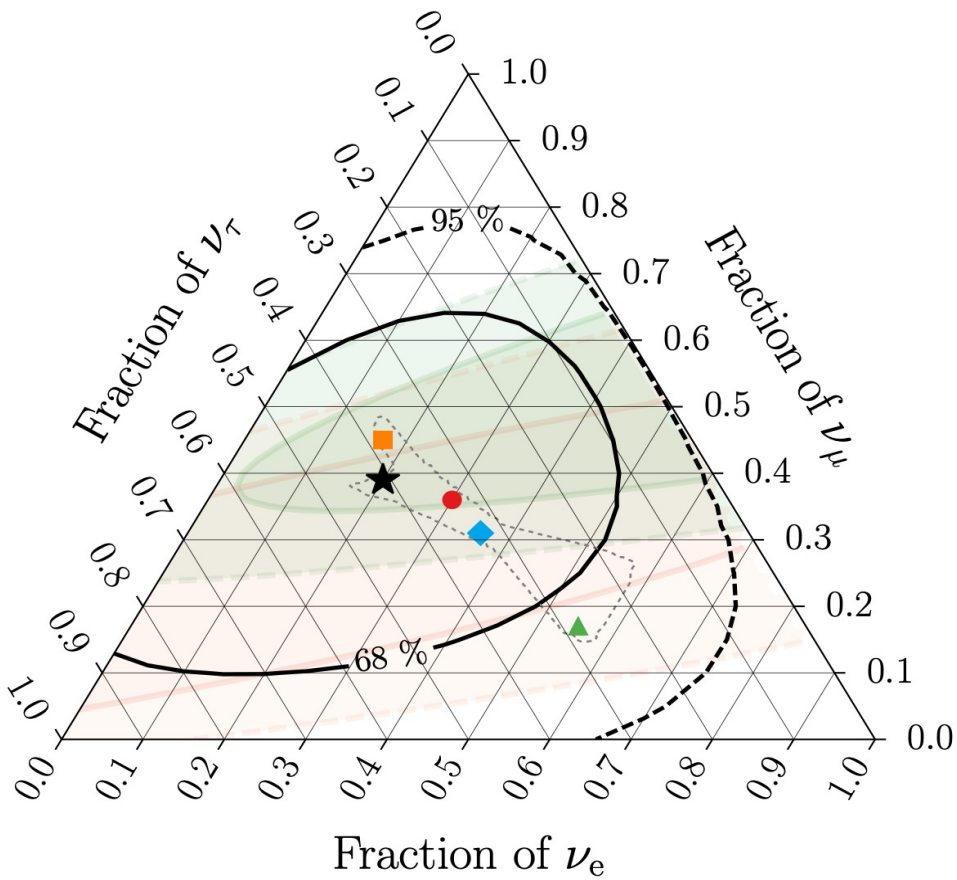


- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino





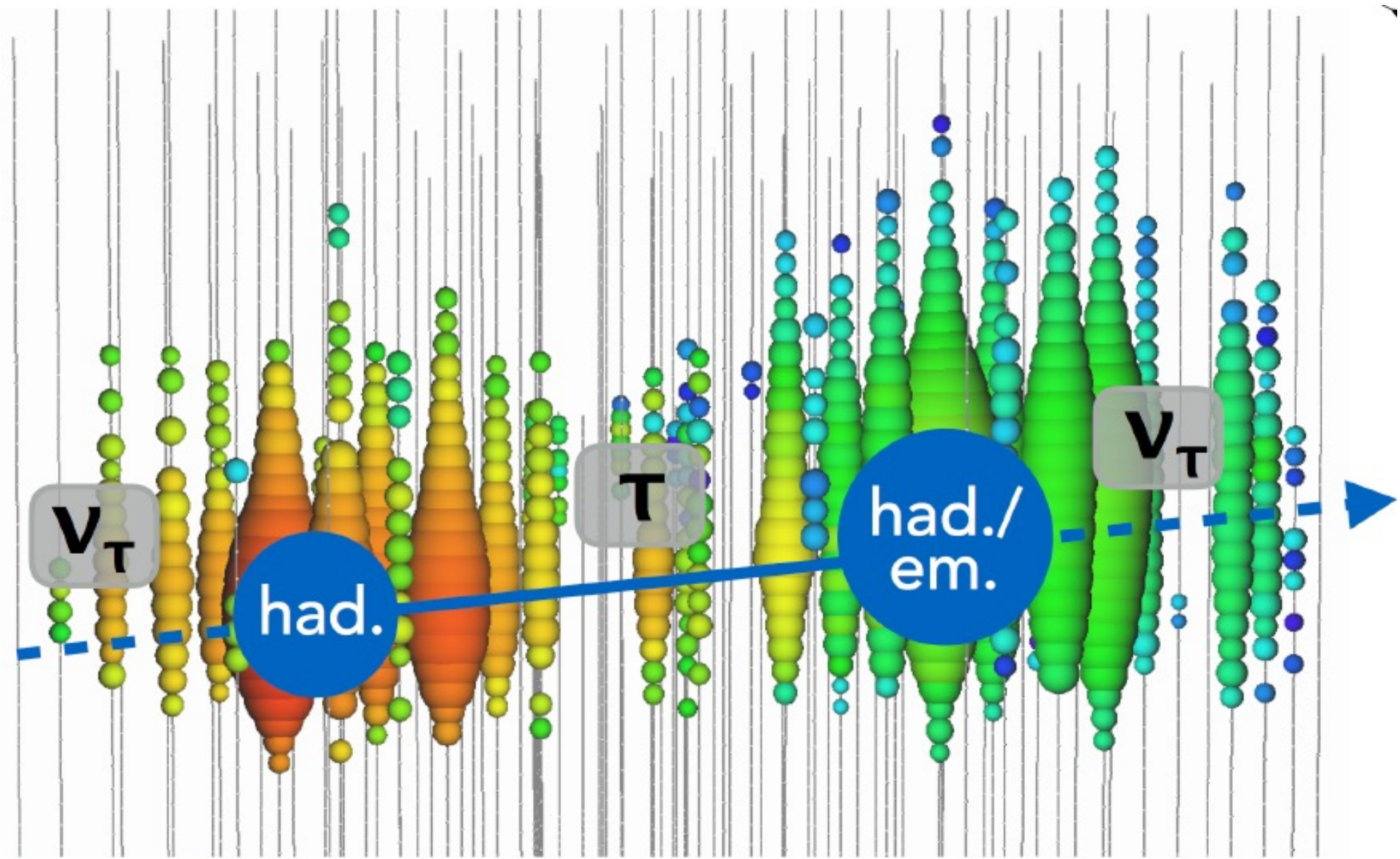
oscillations of PeV neutrinos over cosmic distances to 1:1:1



oscillating PeV neutrinos (7.5 years starting events)

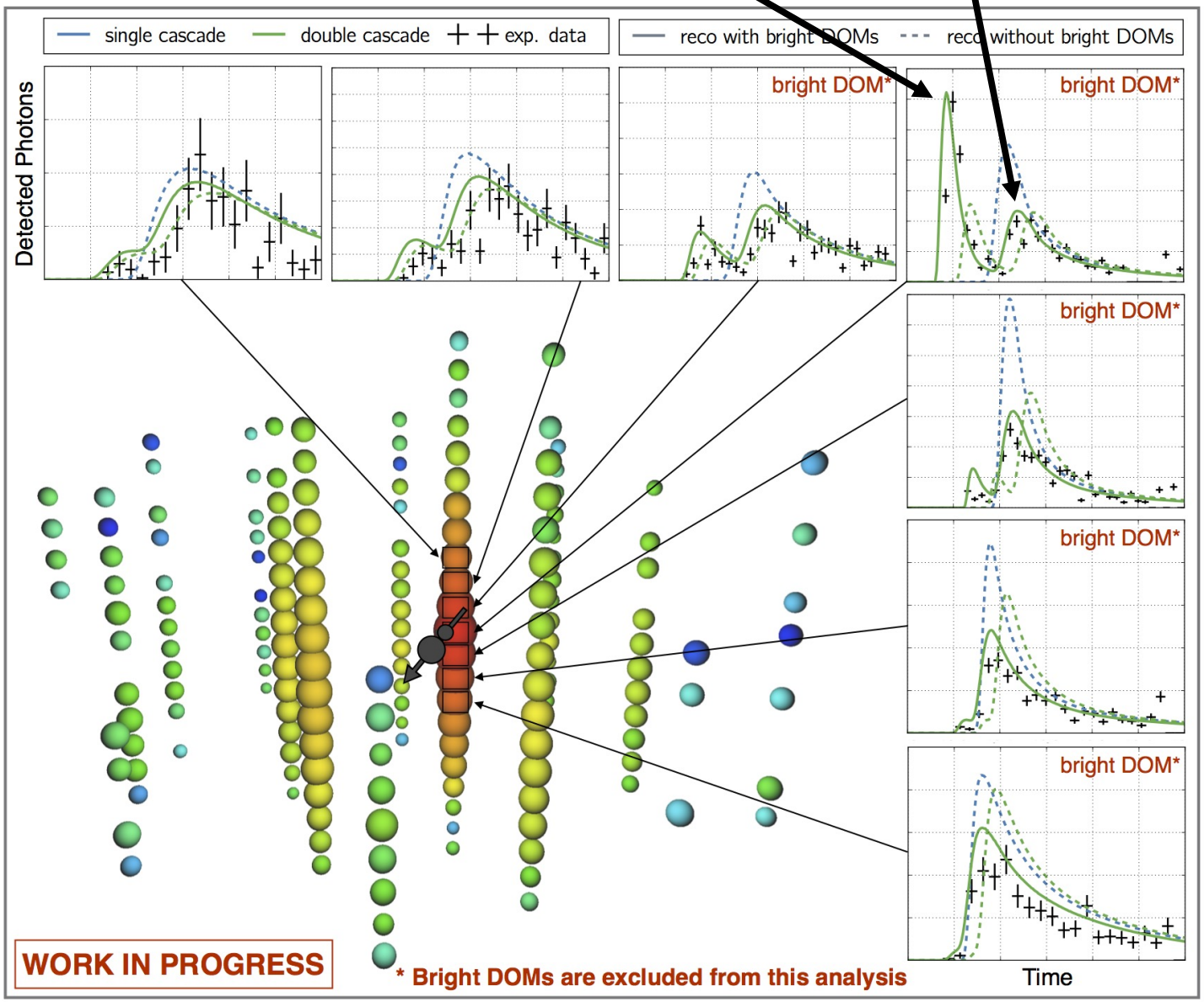
tau neutrino production and decay

tau decay length:
$\gamma c\tau$ = 50m per PeV

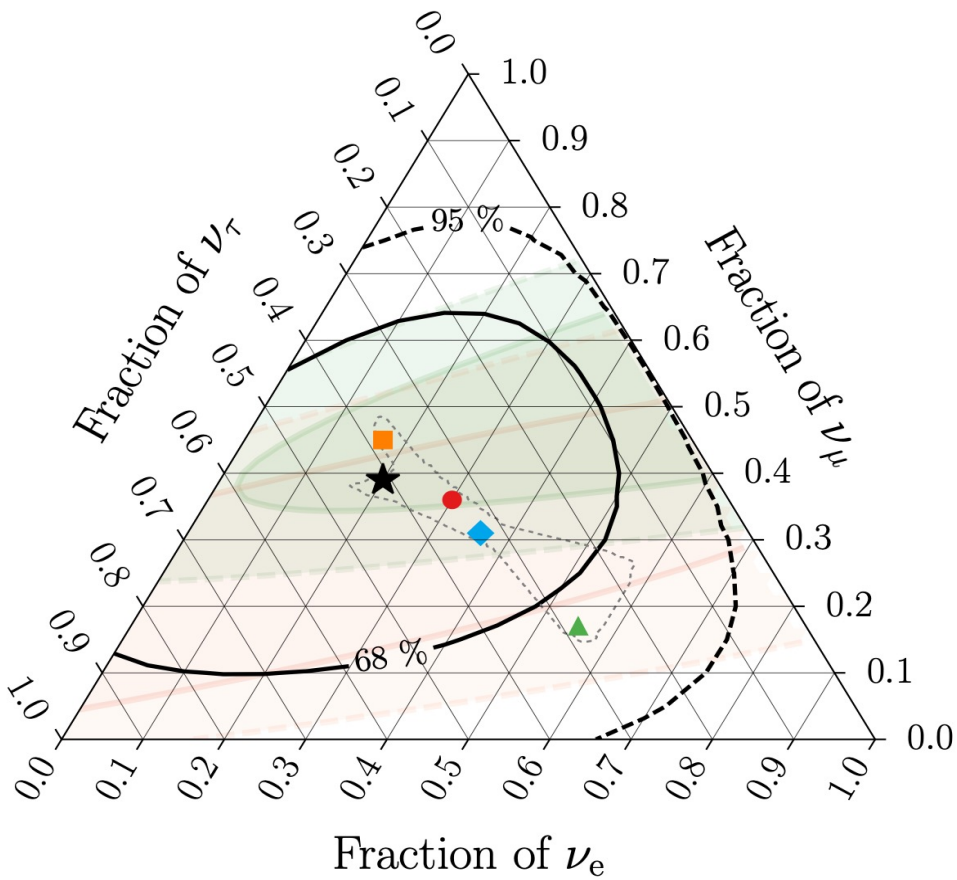


a cosmic tau neutrino with 17m lifetime

light from nutau interaction and tau decay

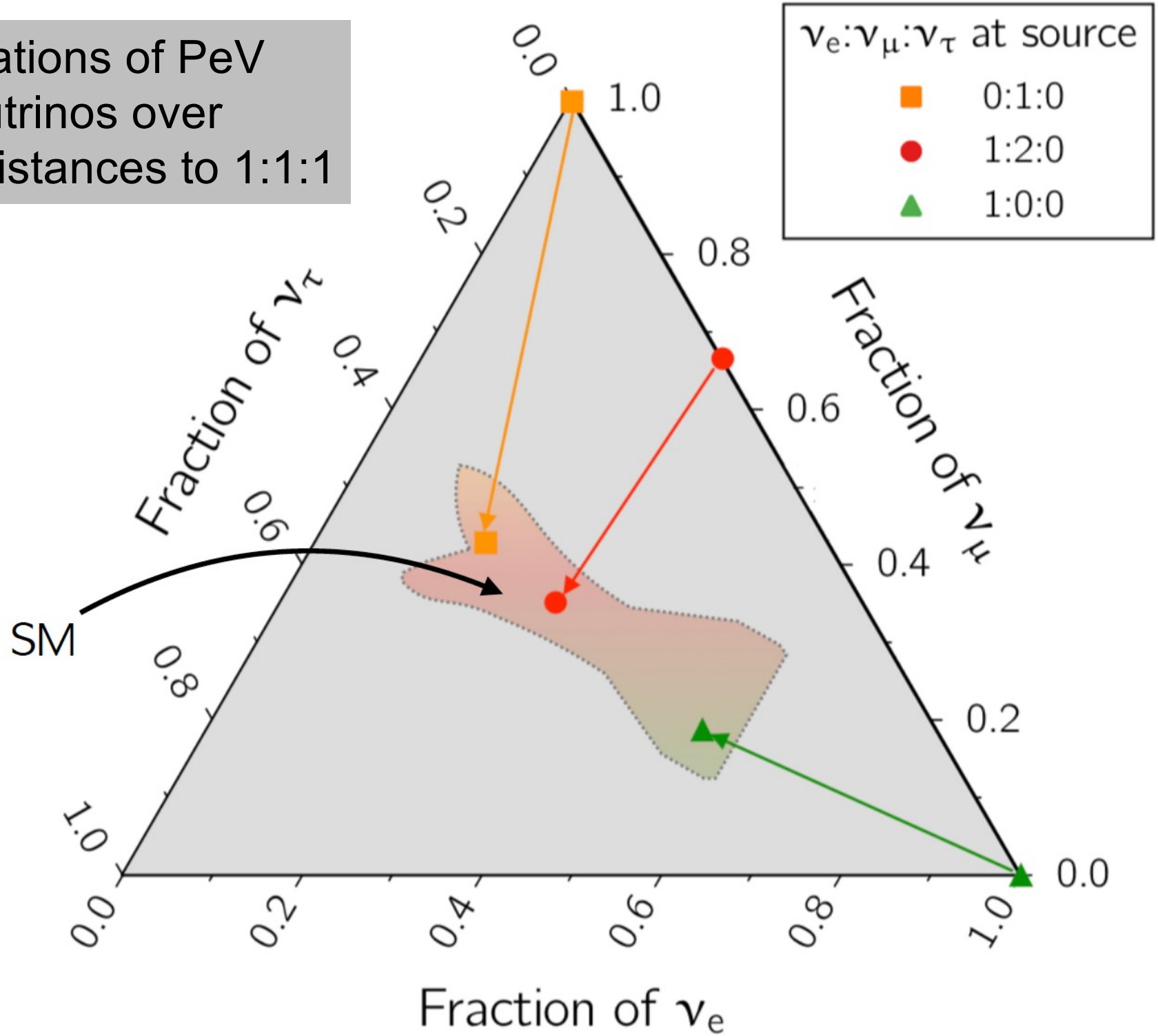


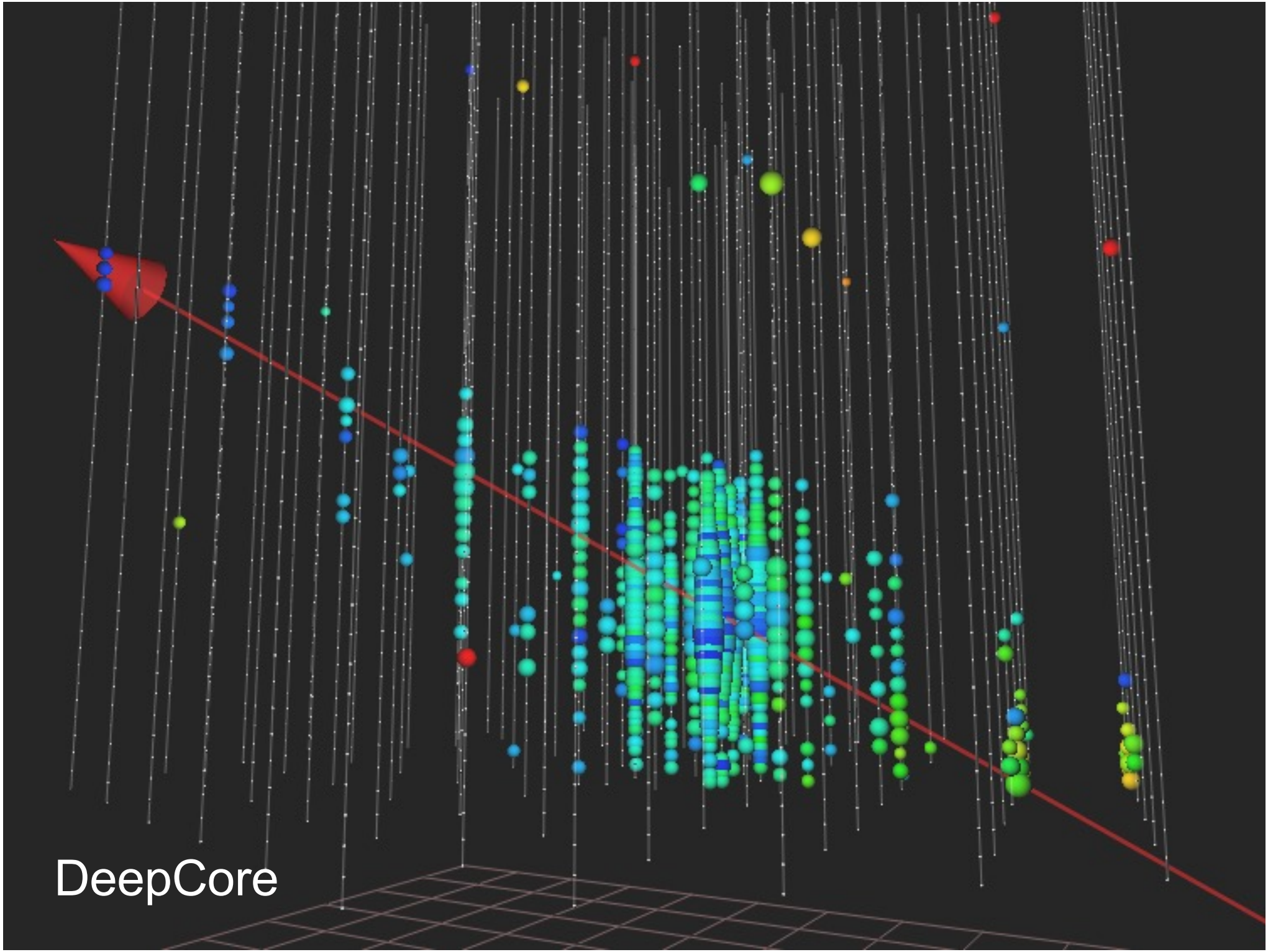
oscillations of PeV neutrinos over cosmic distances to 1:1:1



oscillating PeV neutrinos (7.5 years starting events)

oscillations of PeV neutrinos over cosmic distances to 1:1:1

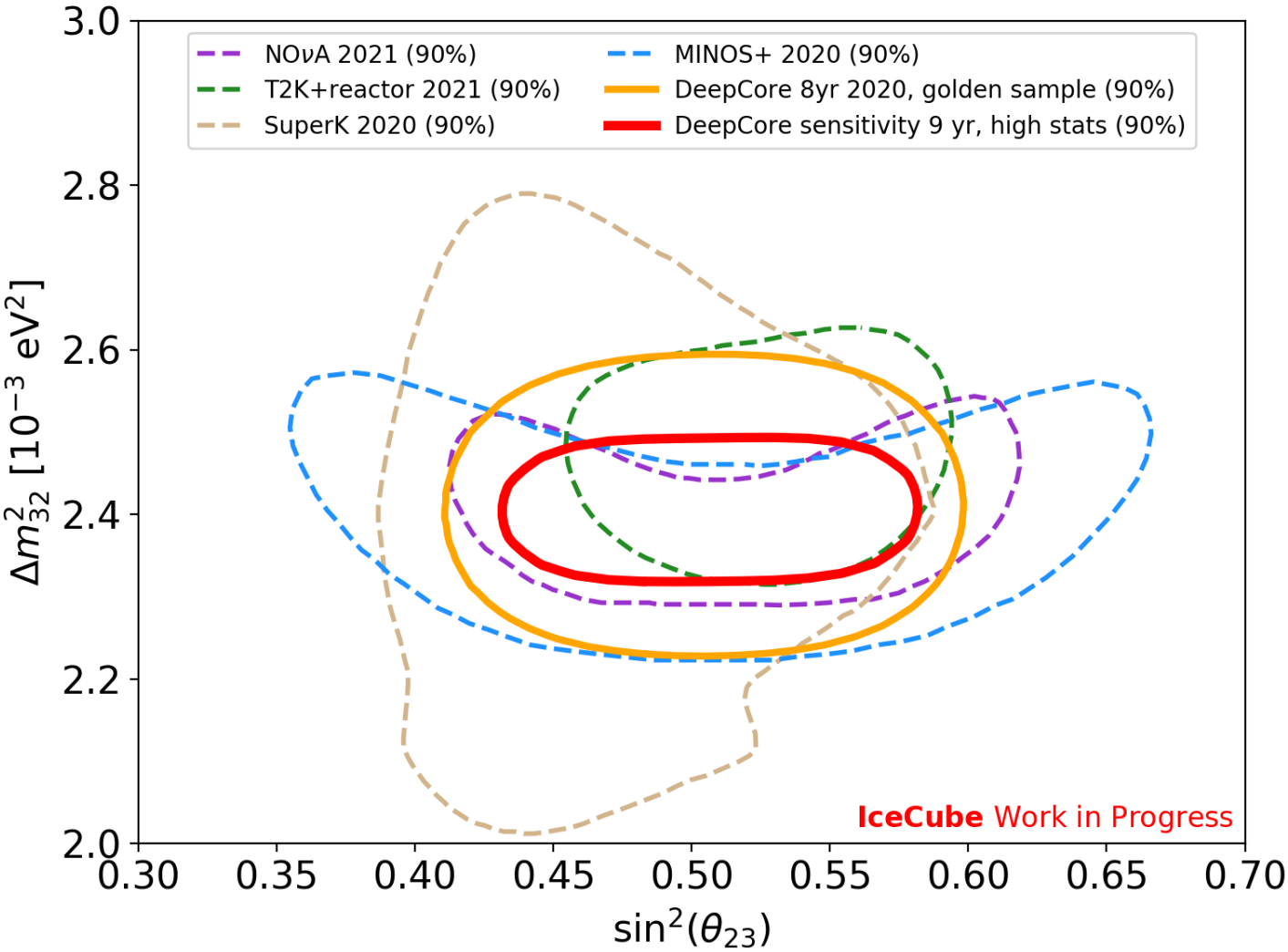


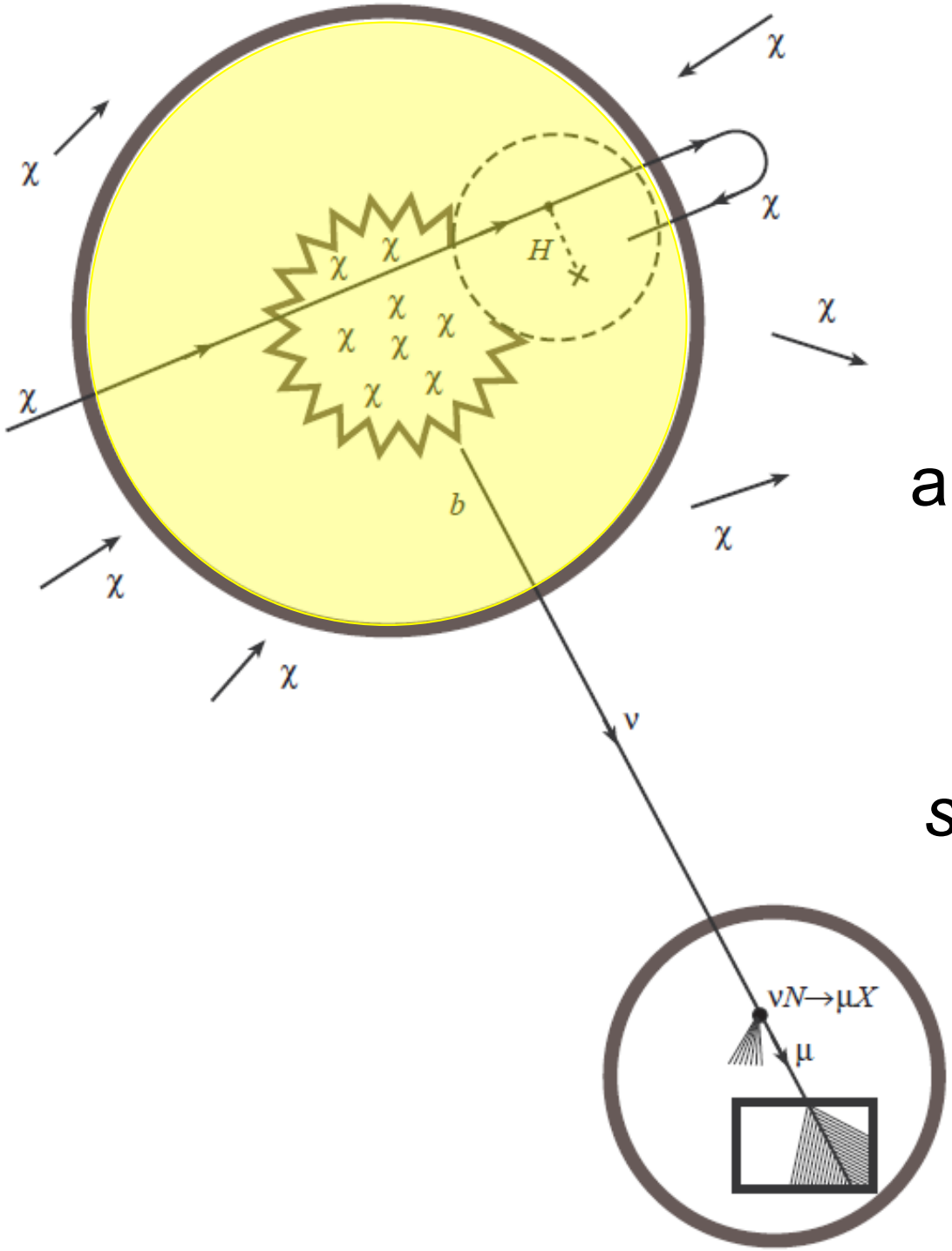

DeepCore

imminent unblinding:

- analysis with a sample of 210,000 atmospheric neutrinos
- 6900 tau neutrinos

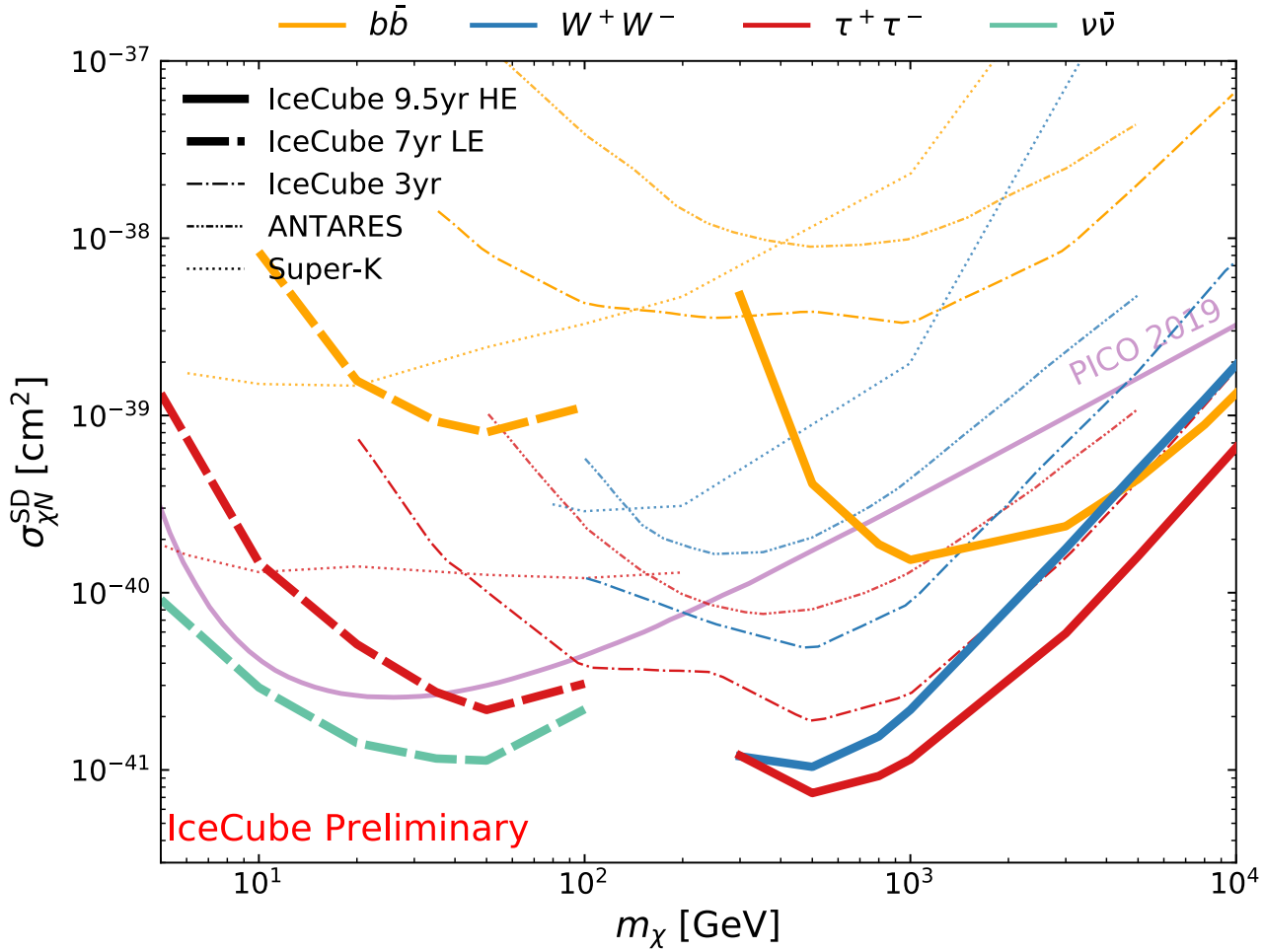
(9.3 years and 97.3% purity with energies of 5~55 GeV)

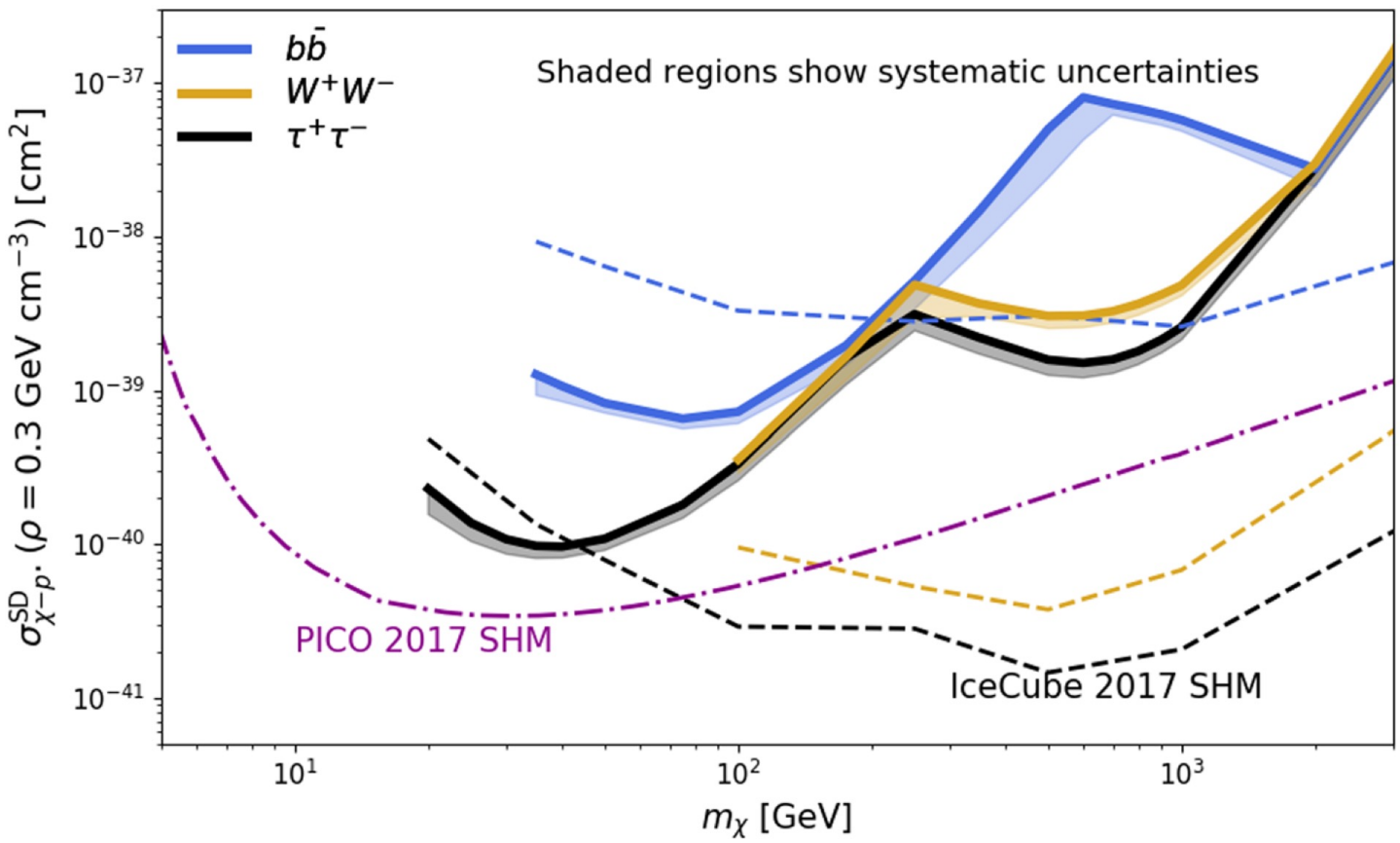




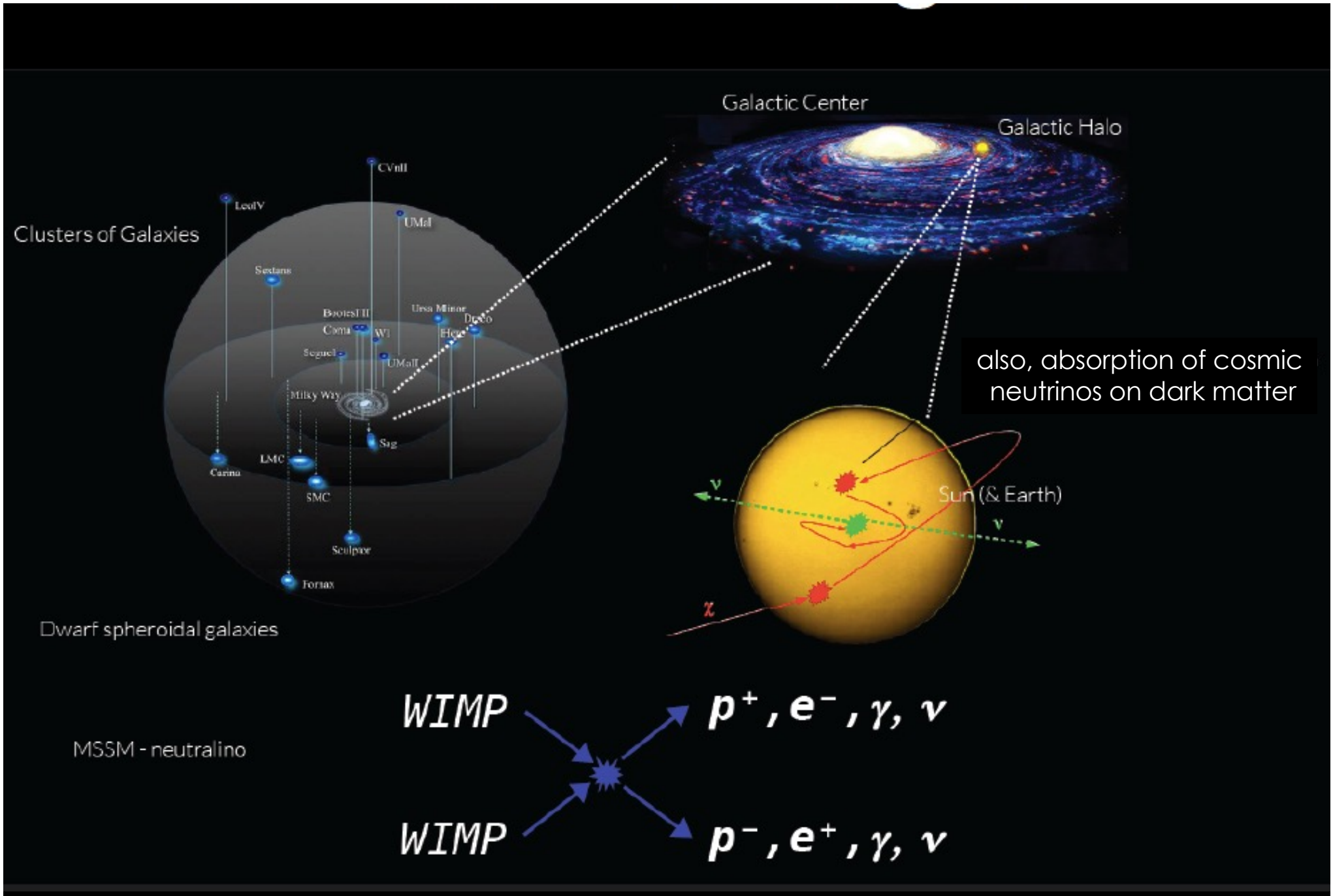
dark matter annihilation in the sun: a smoking gun

world-best limits on *spin-dependent* cross sections


$b\bar{b}$
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

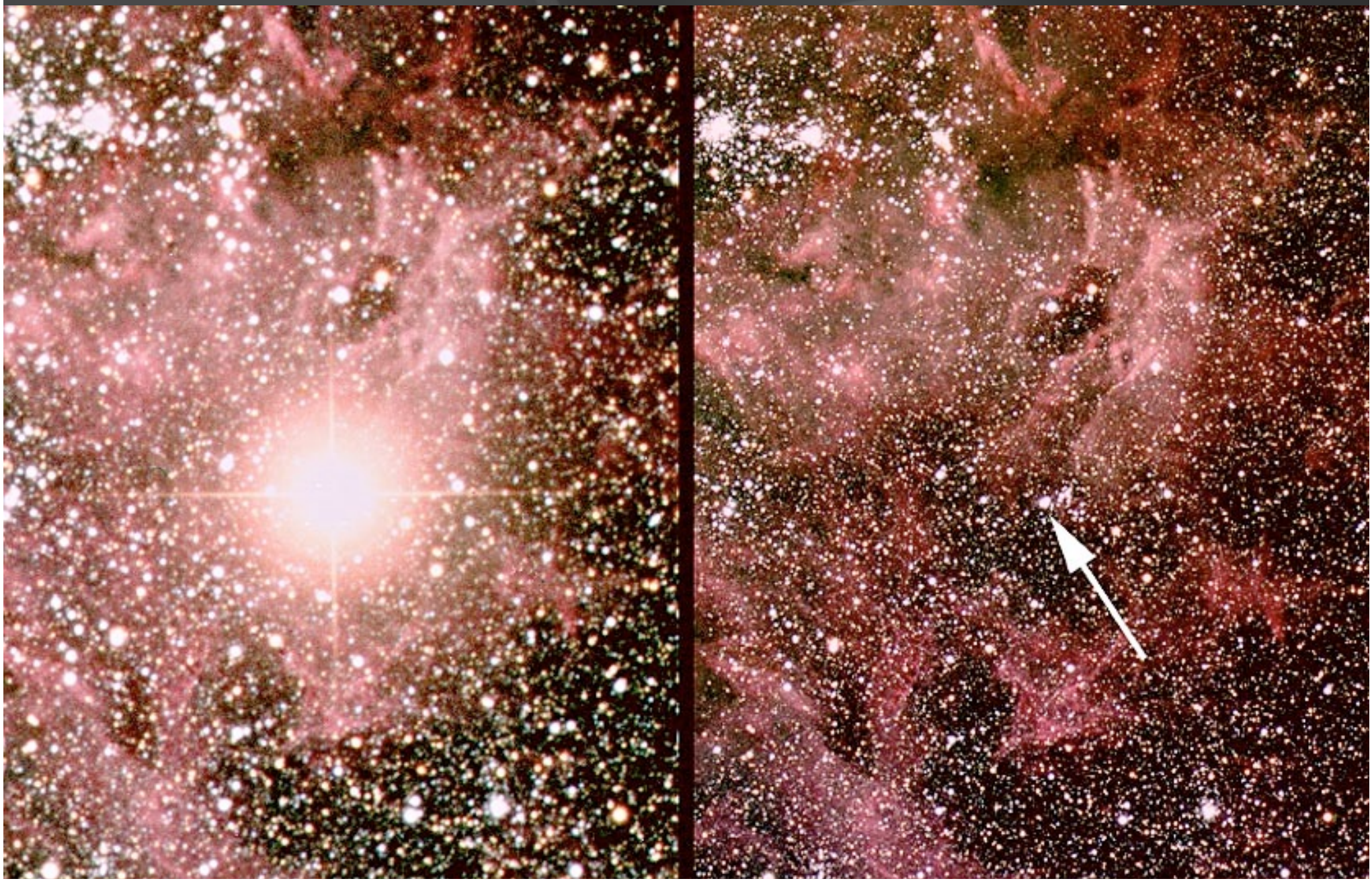


velocity-independent limits by combining IceCube (sensitive to low velocity) and PICO (sensitive to high velocity) data

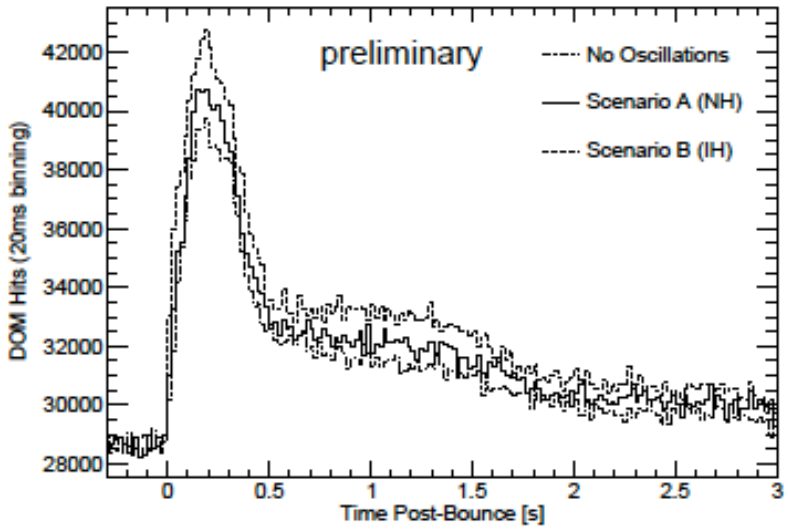


IceCube dark matter targets

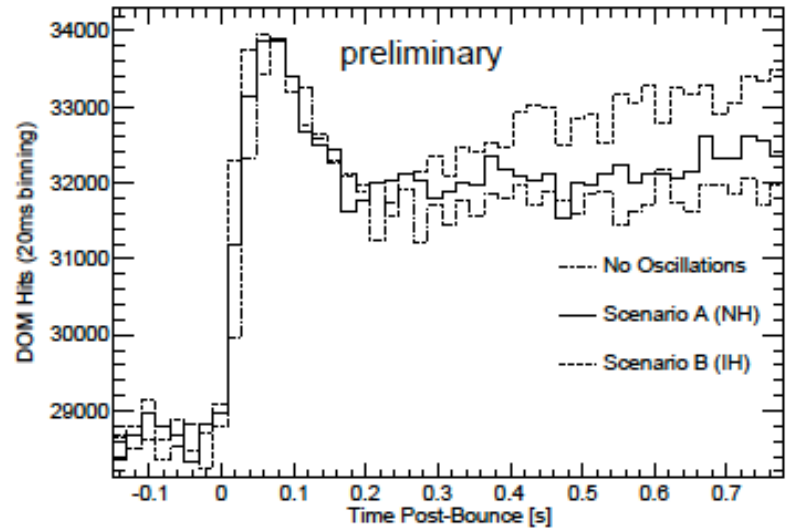
supernova 1987a: 24 neutrinos, thousands of papers



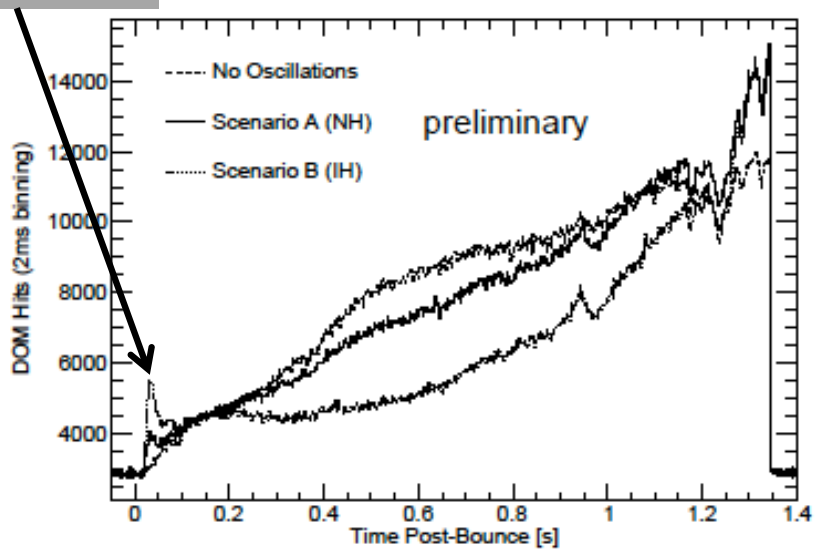
Livermore



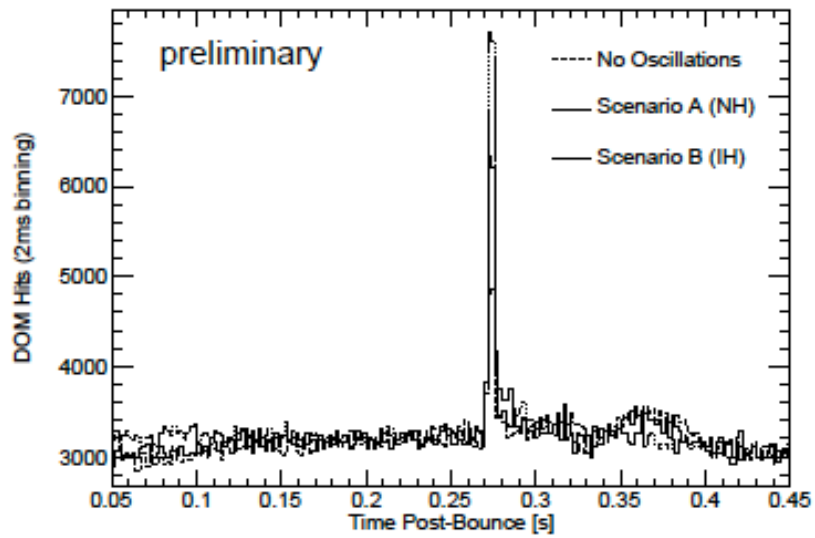
Garching



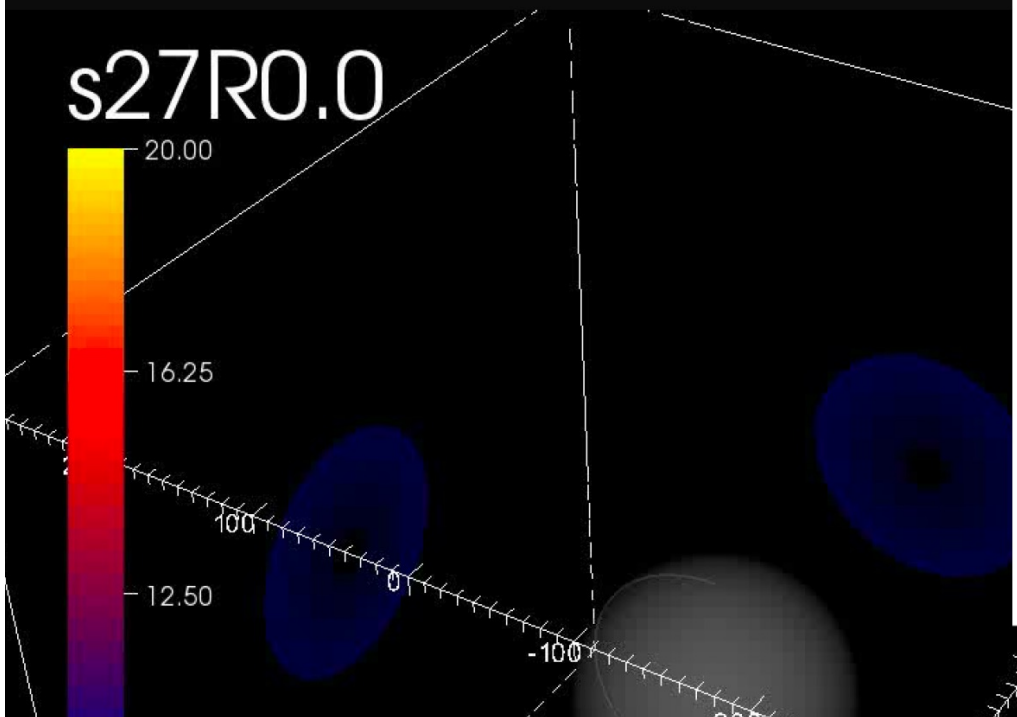
quark star

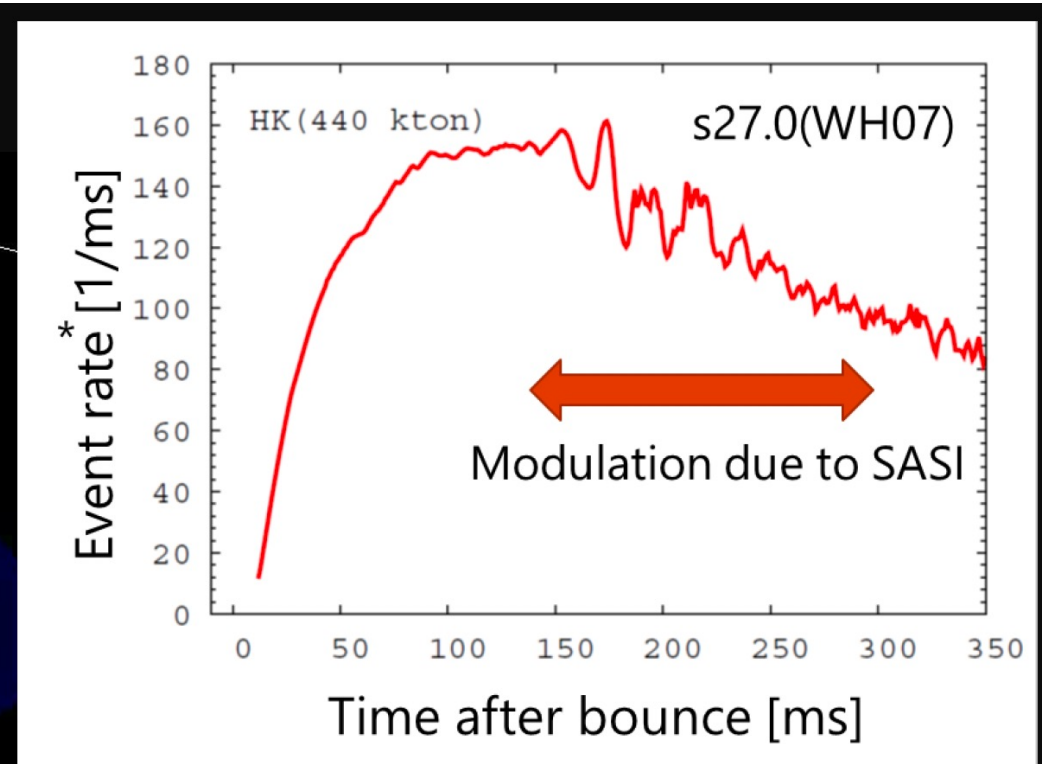


black hole



27 M_{sun} progenitor (WH07)

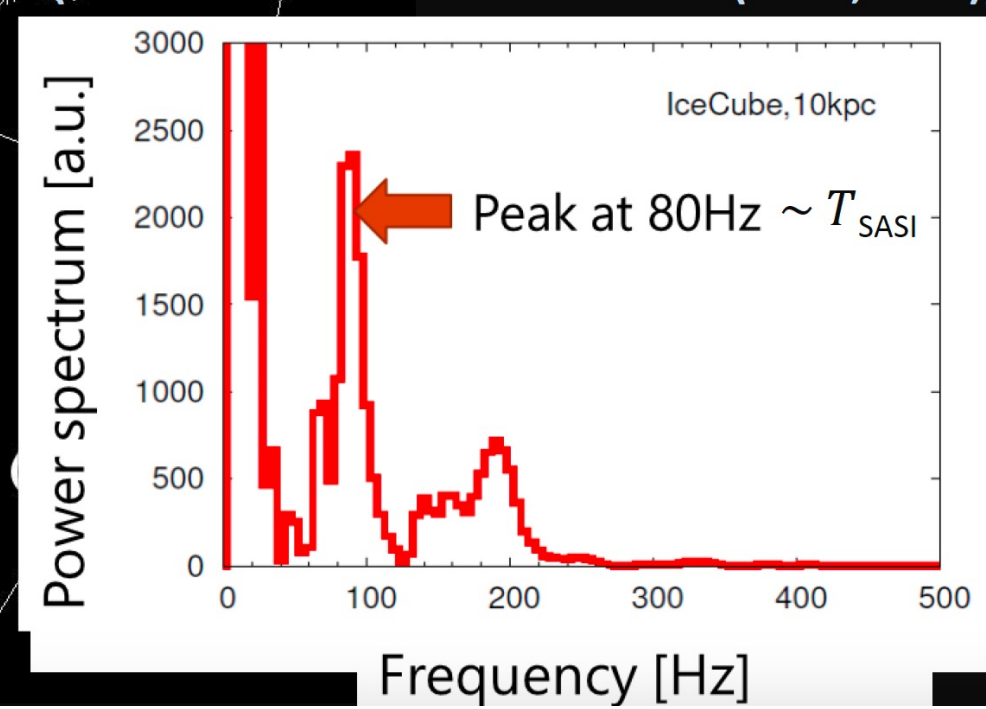




(consistent with Tamborra et al. (2013,2014))

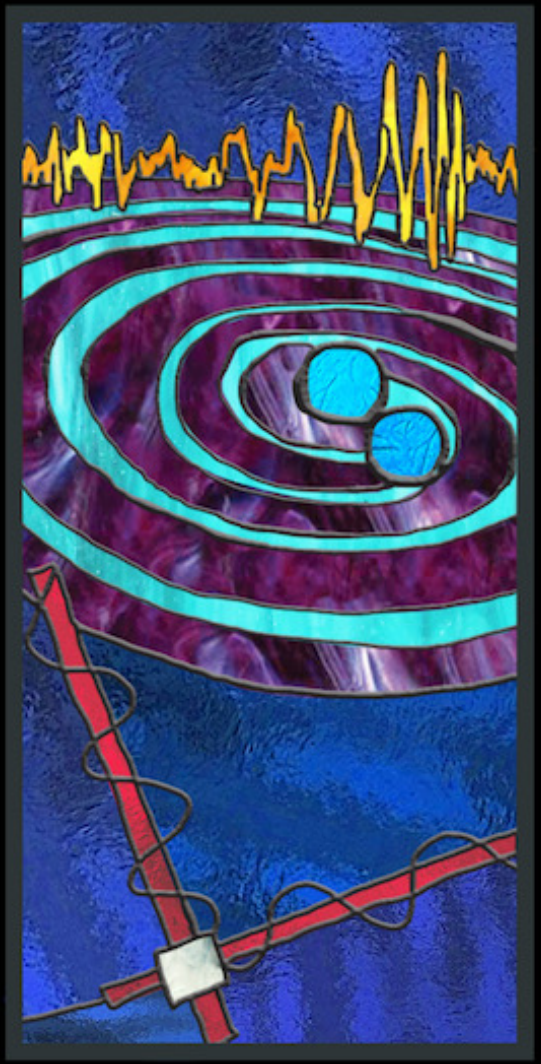
gravitation wave fundamental frequency:

$$f_{GW} = 2 \times f_{\nu}$$



Takiwaki, KK, Foglizzo (2021)

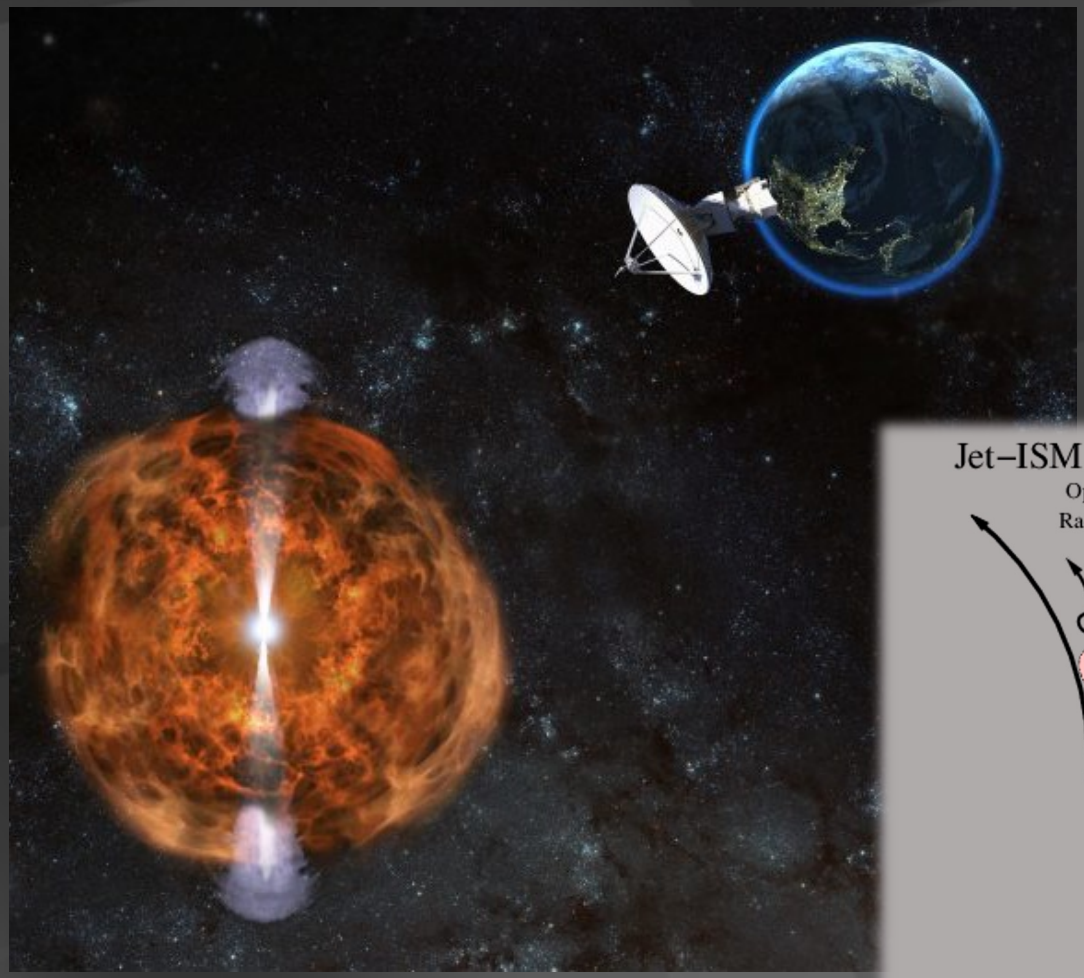
Angular resolution~1deg.



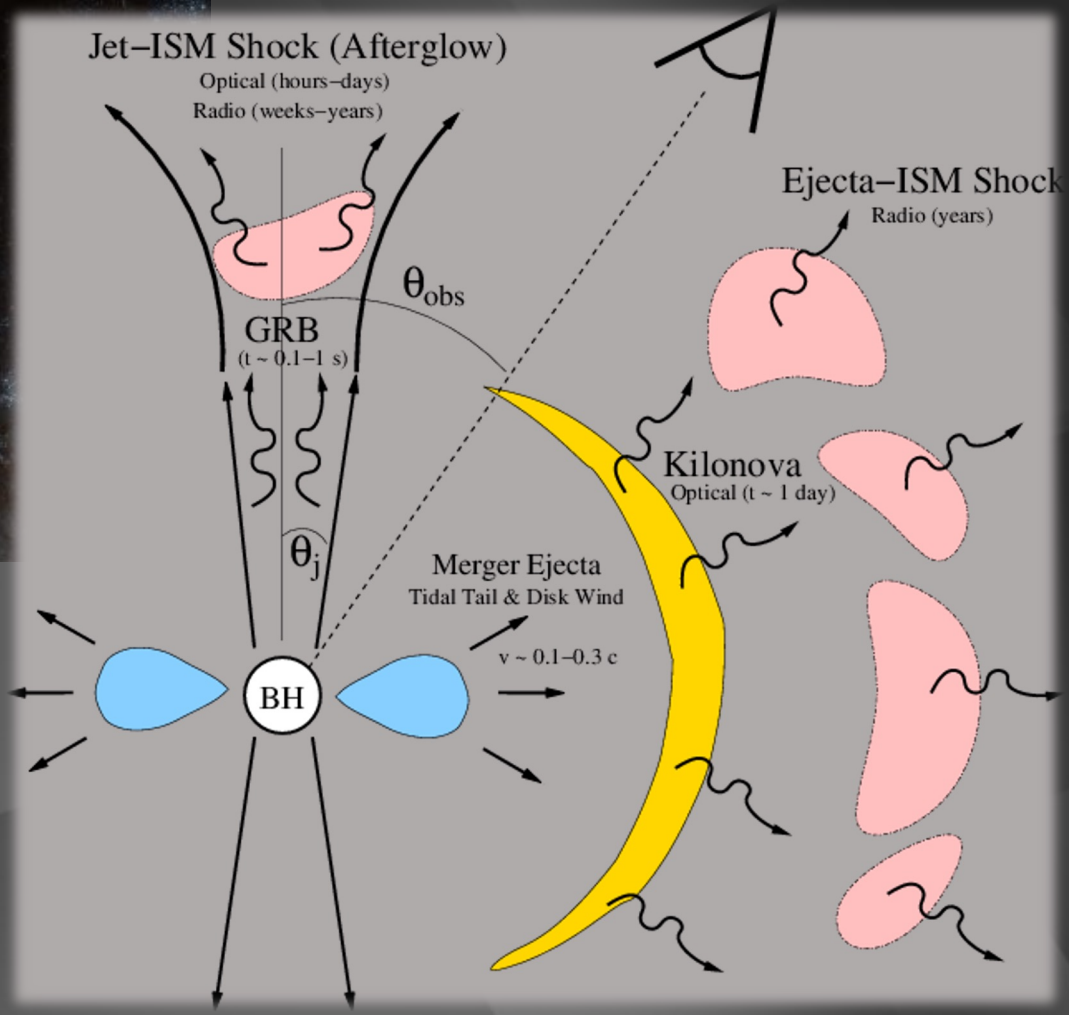
next attraction: gravitational waves + neutrinos?

(August 17, 2017 neutron star merger: jet not aligned ☹)

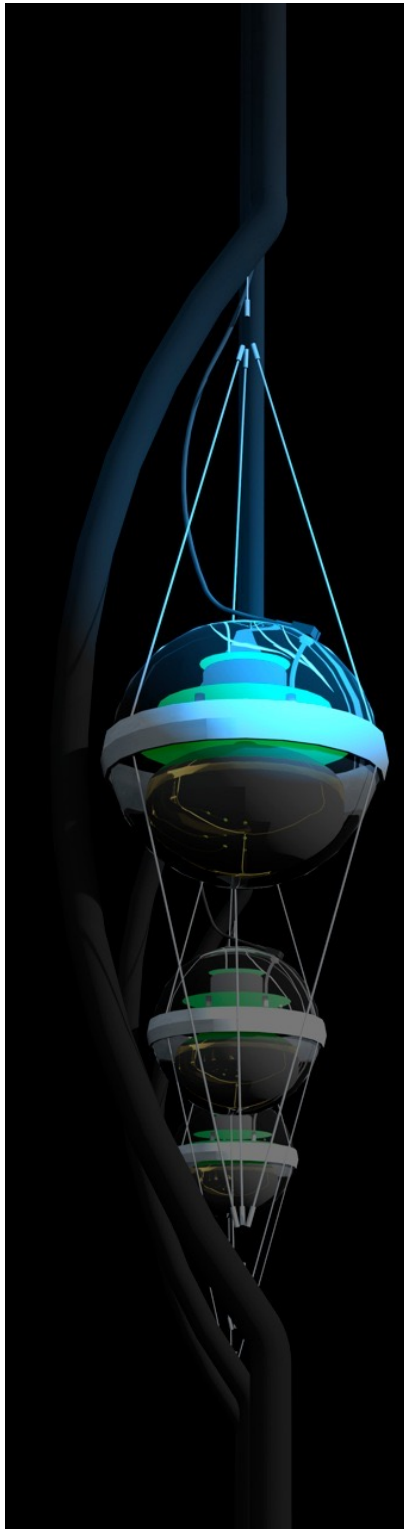
buildup of magnetic fields near merger launches jet



neutron star mergers



very weak short GRB seen by Fermi (off axis)



neutrino astronomy 2022

- it exists
- more neutrinos, better neutrinos, more telescopes
- closing in on cosmic ray sources
- [are active galaxies with obscured cores the sources of cosmic rays?]
- two beams for neutrino physics

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