

Neutrinos in the Era of Multimessenger Astronomy

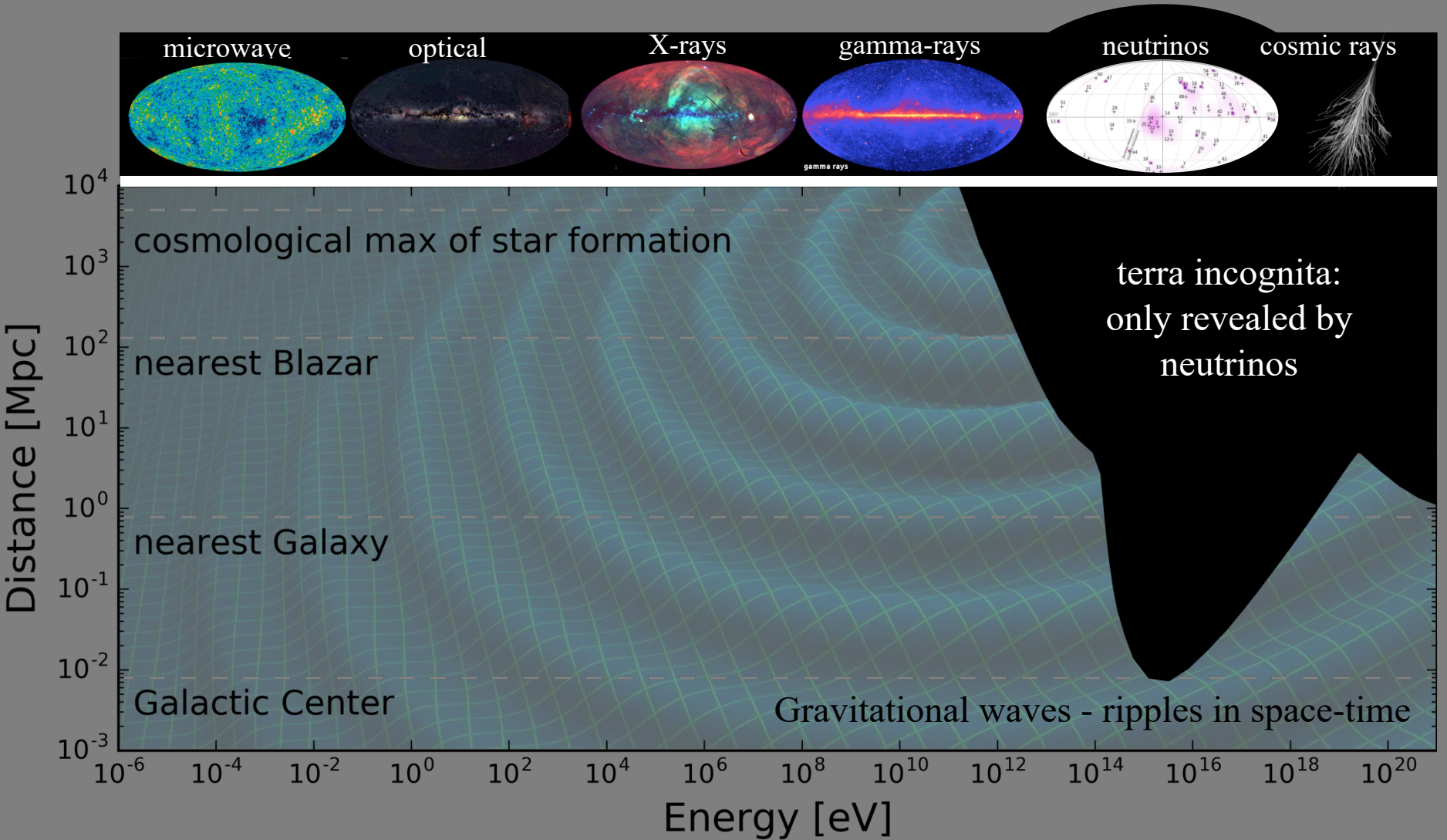
francis halzen



- cosmic neutrinos: many independent observations
 - muon neutrinos through the Earth
 - starting neutrinos: all flavors
- the first high-energy cosmic ray accelerator: a rotating supermassive black hole
- from discovery to astronomy: next-generation instruments
- also, a beam for PeV (1,000 TeV) neutrino physics

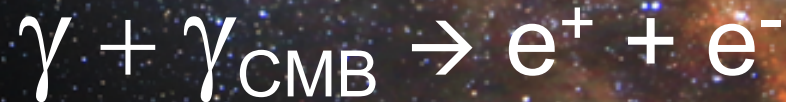
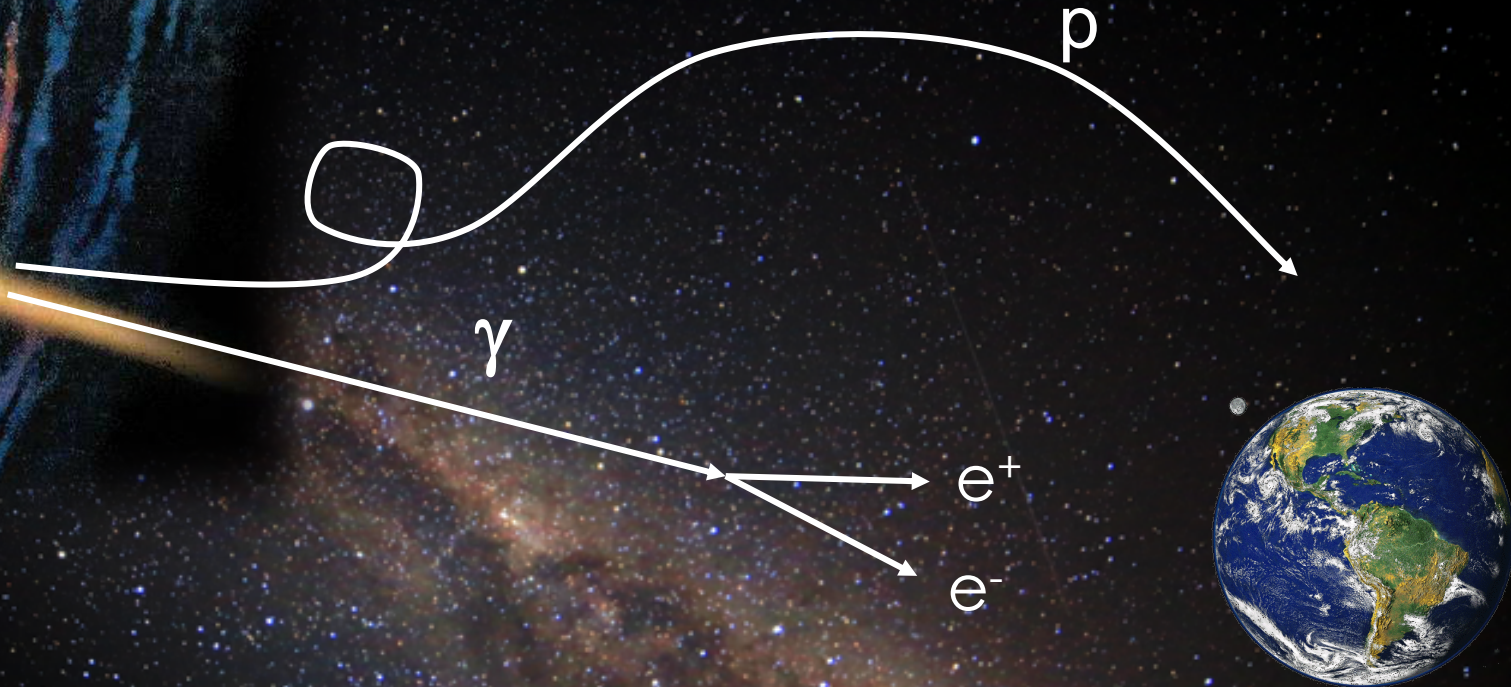


highest energy “radiation” from the Universe: neutrinos and cosmic rays



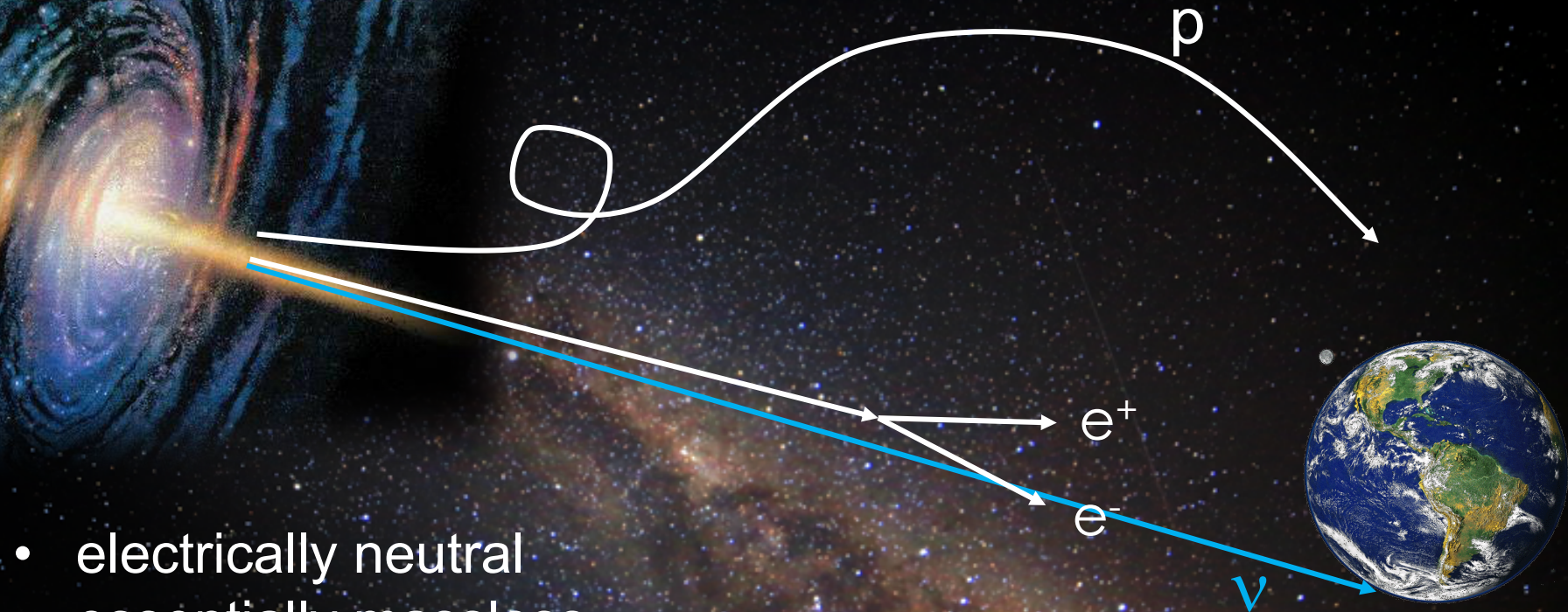
Universe is opaque above ~ 100 TeV energy

The opaque Universe



PeV photons interact with microwave photons
($411/\text{cm}^3$) before reaching our telescopes
enter: neutrinos

Neutrinos? Perfect Messenger



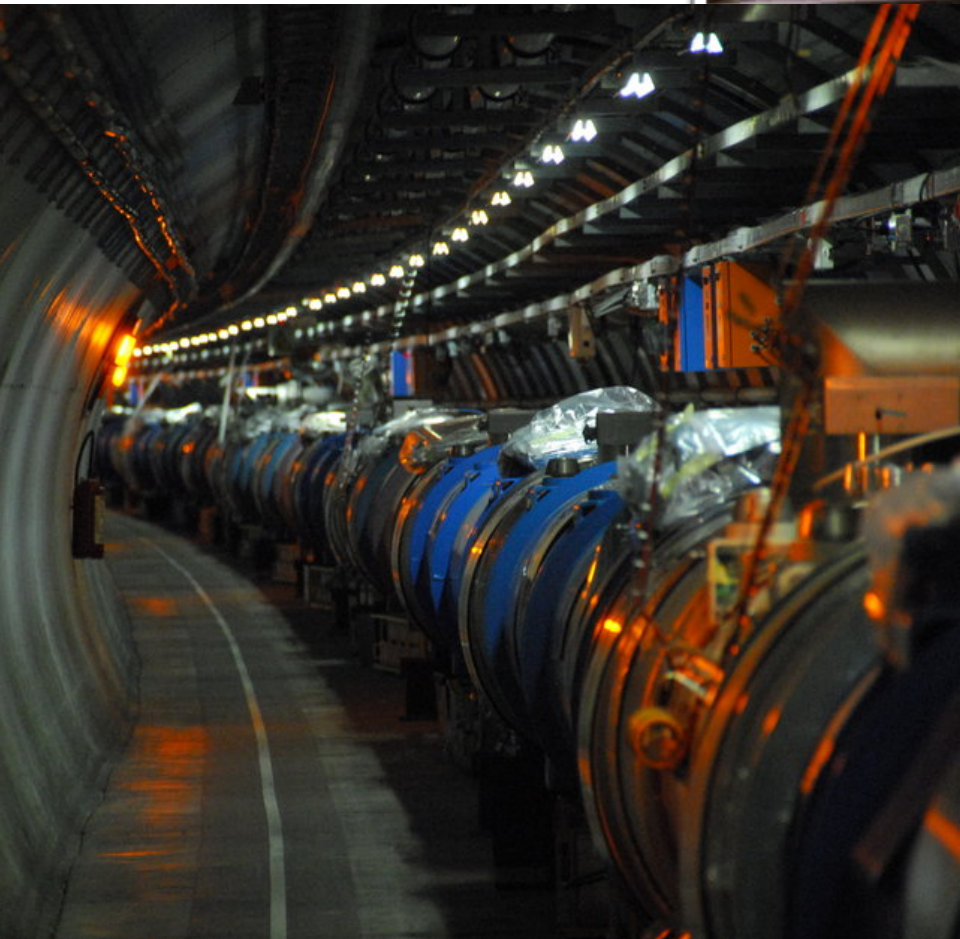
- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- ... but difficult to detect

highest energy radiation from the Universe: protons!

high energy
high luminosity

LHC accelerator should have circumference
of Mercury orbit to reach 10^{20} eV!

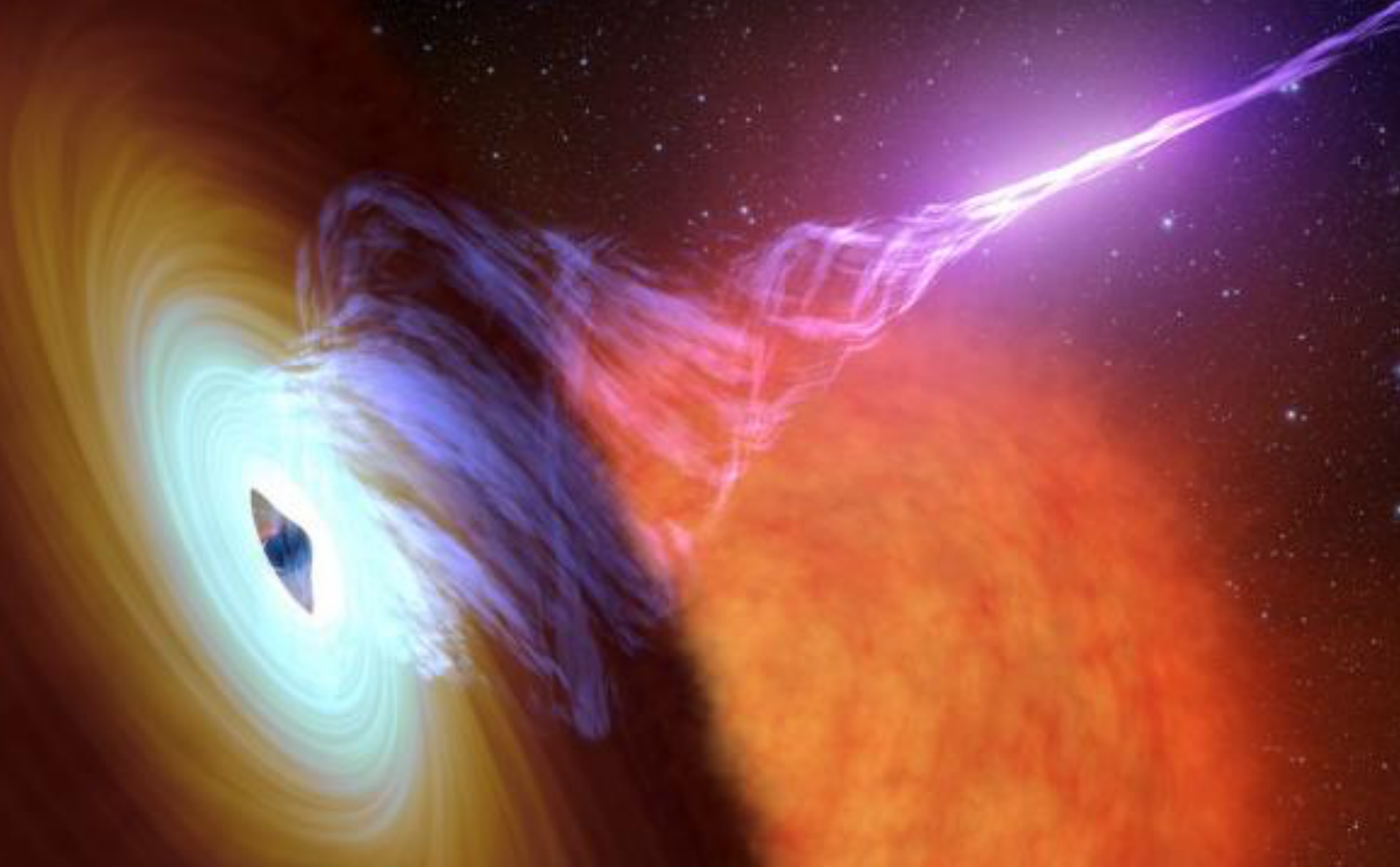


Courtesy M. Unger

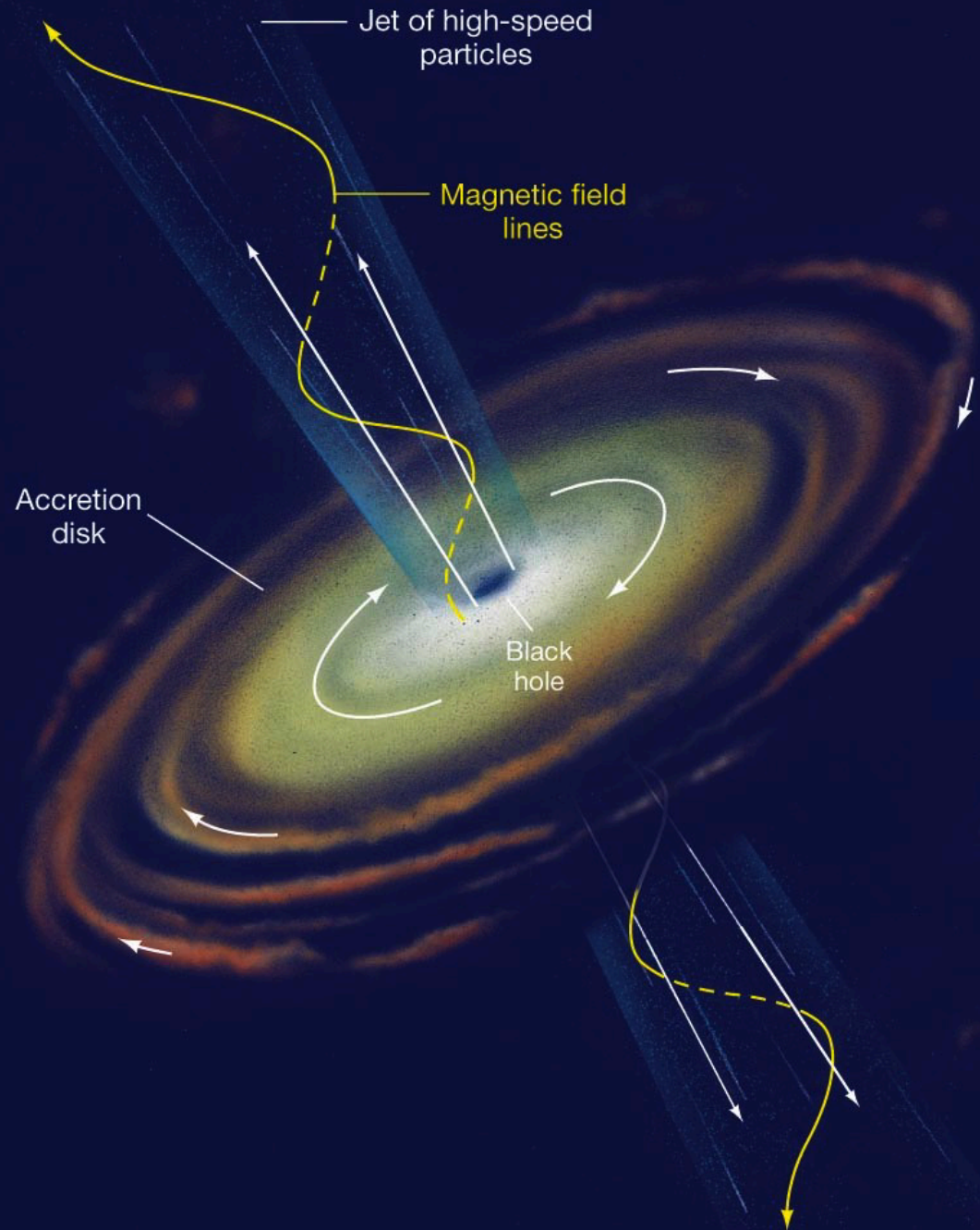
Fly's Eye 1991

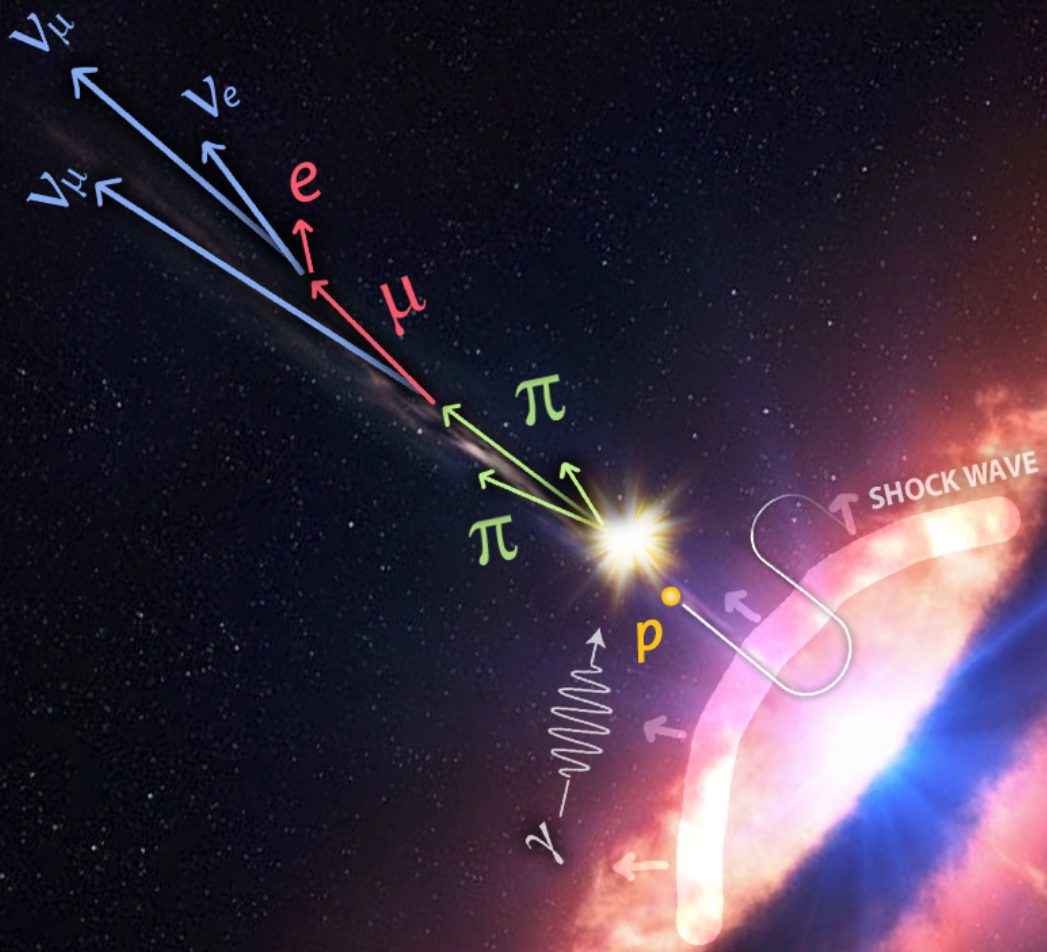
300,000,000 TeV

some of the matter falling into a supermassive black hole is accelerated in a jet along its rotation axis

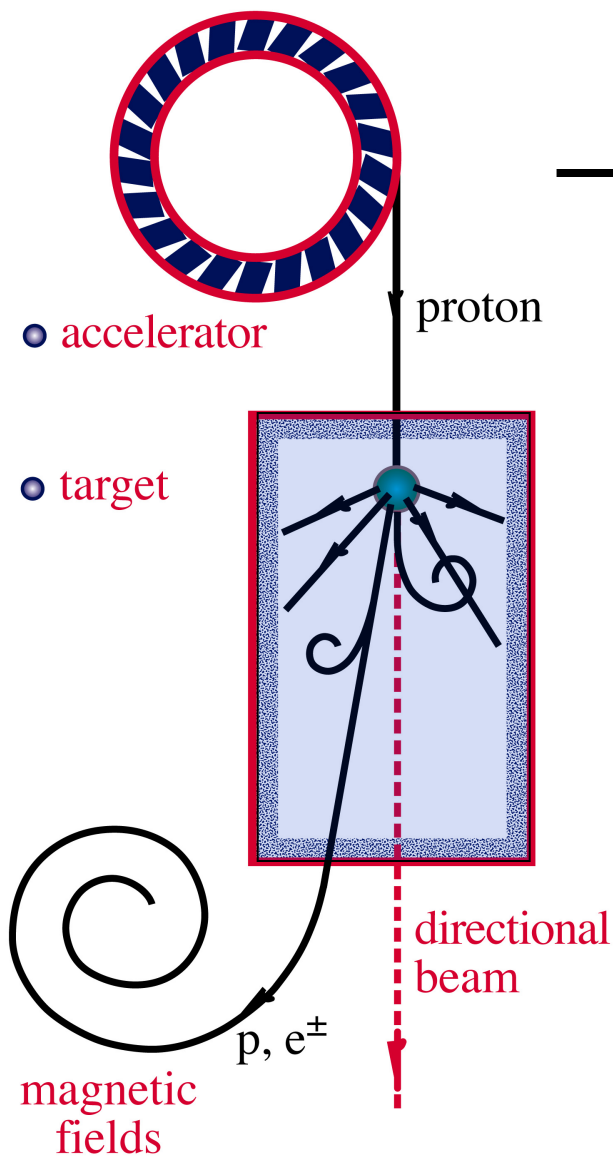


- fast spinning infalling matter comes in contact with rotating black hole
- spacetime around spinning black hole drags on the field winding it into a tight cone around the rotation axes
- plasma from the accretion disk is then flung out along these lines





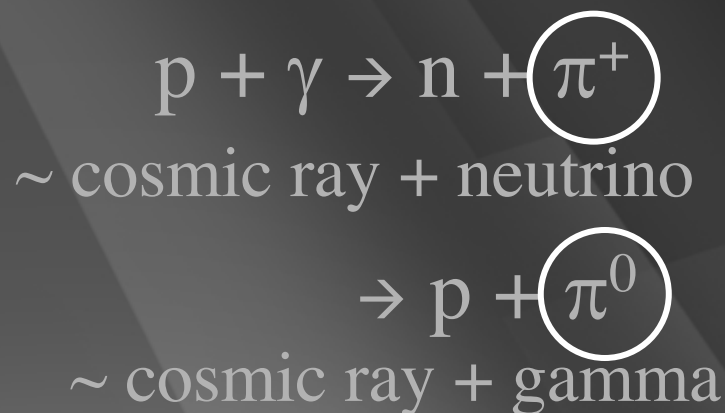
ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

→ **supermassive black hole**

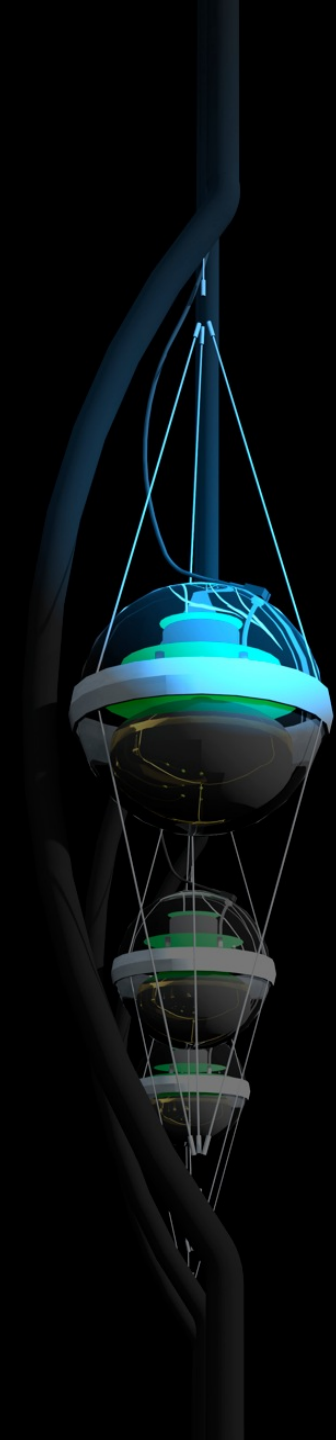
→ **nearby radiation**



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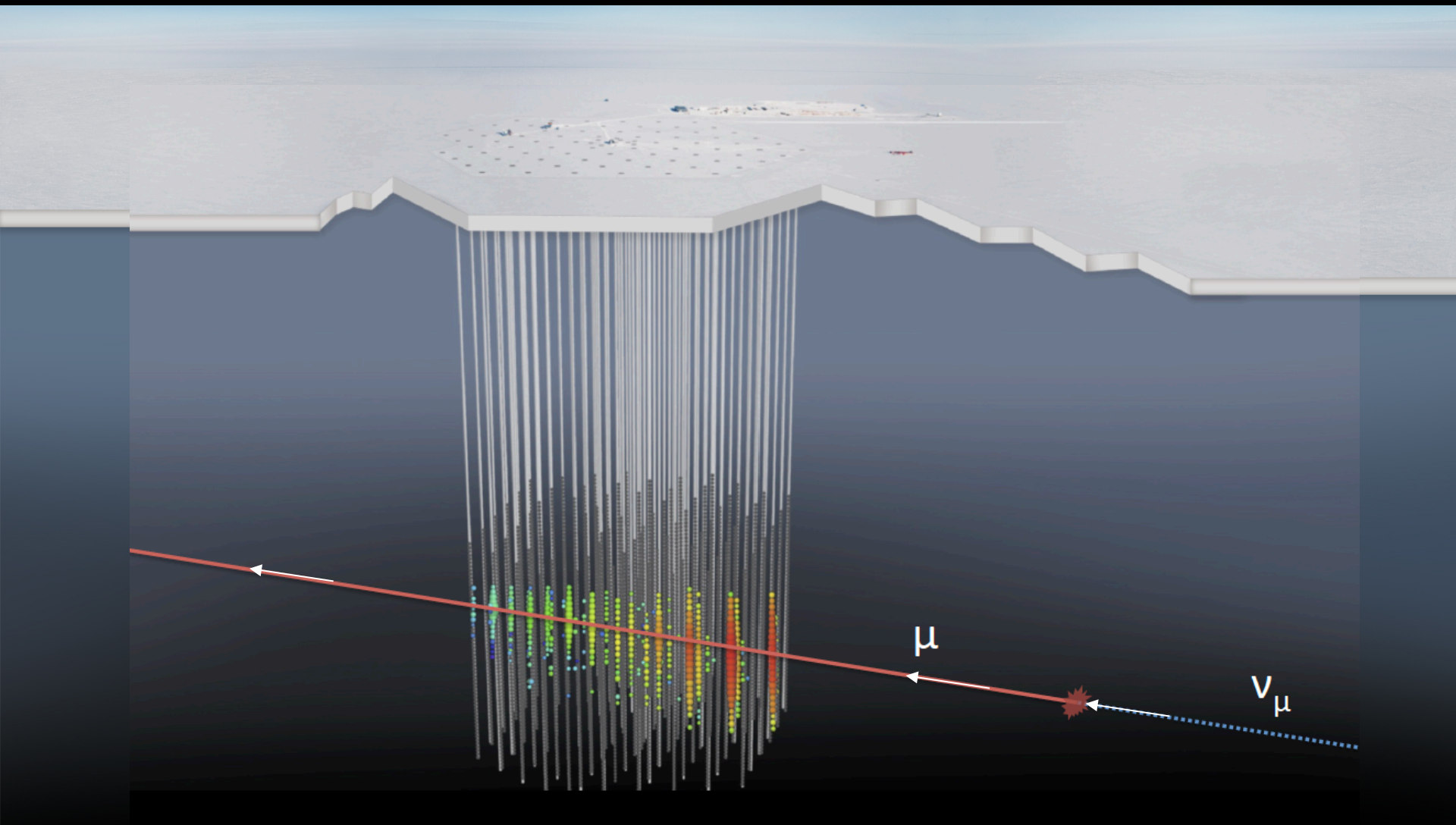
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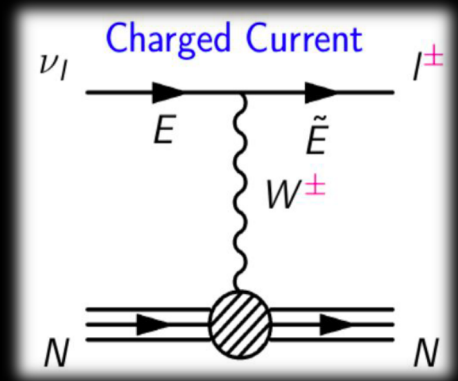
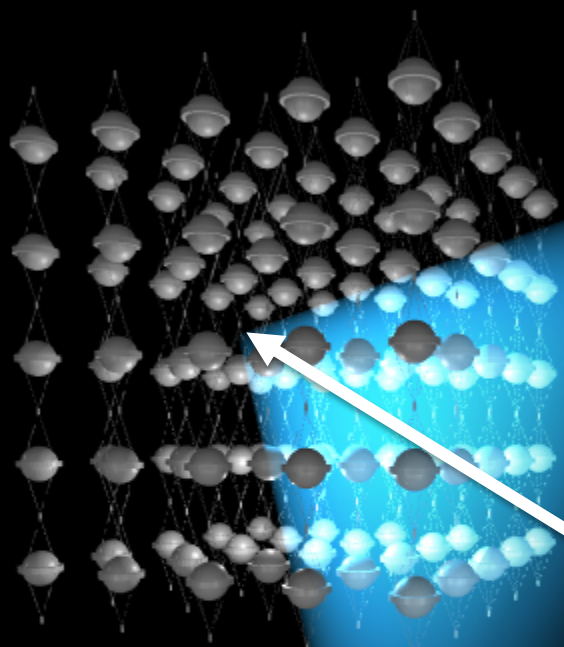




ultra-transparent ice below 1.35 km

instrument 1 cubic kilometer of natural ice below 1.45 km



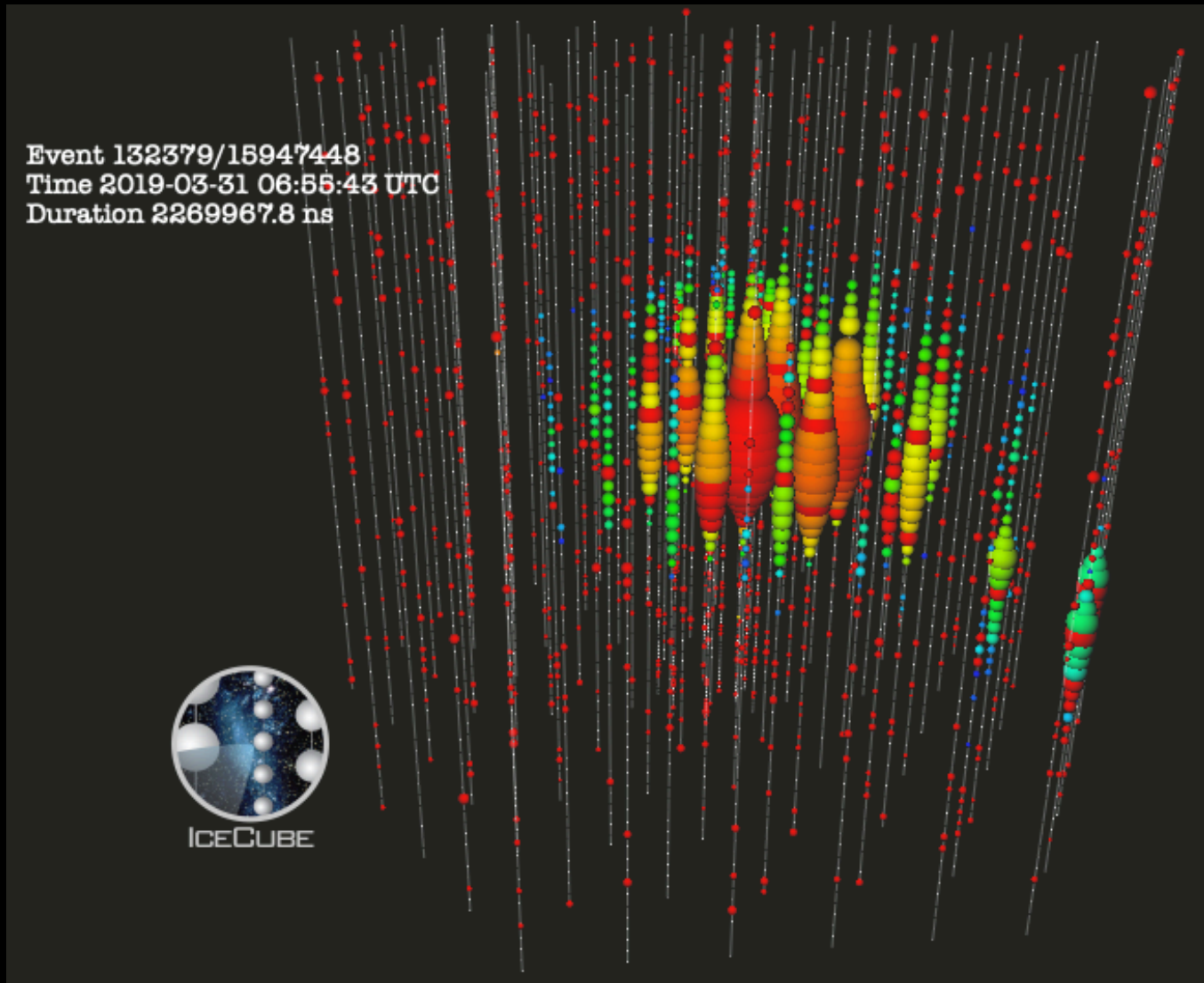


a muon neutrino produces a muon
with a range of kilometers

• lattice of photomultipliers

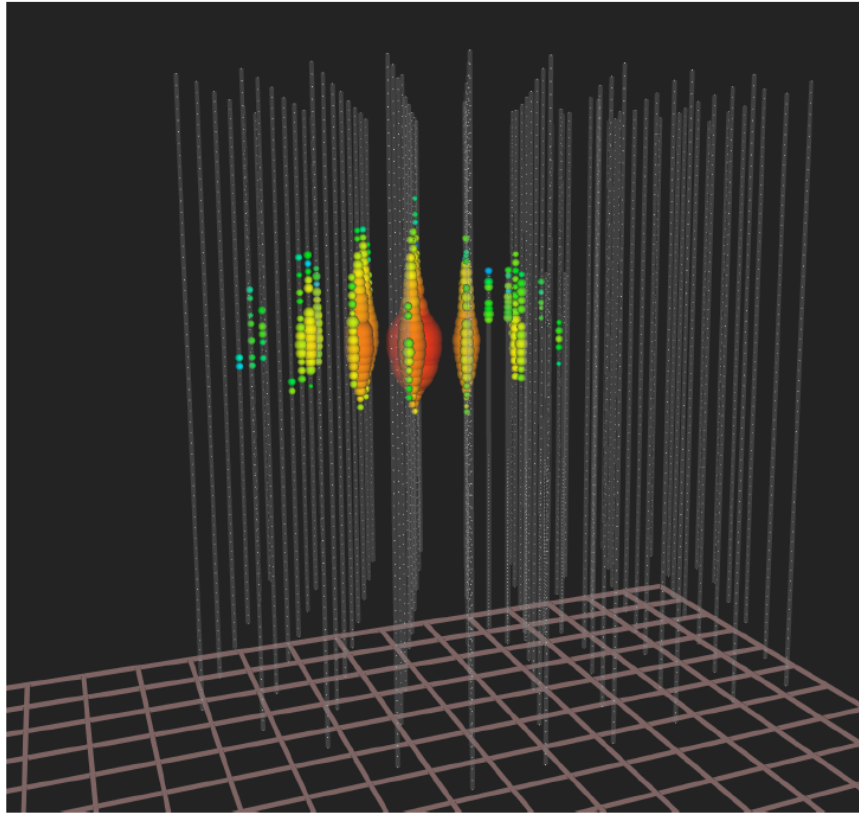
neutrino

IC190331: 5300 TeV deposited inside the detector

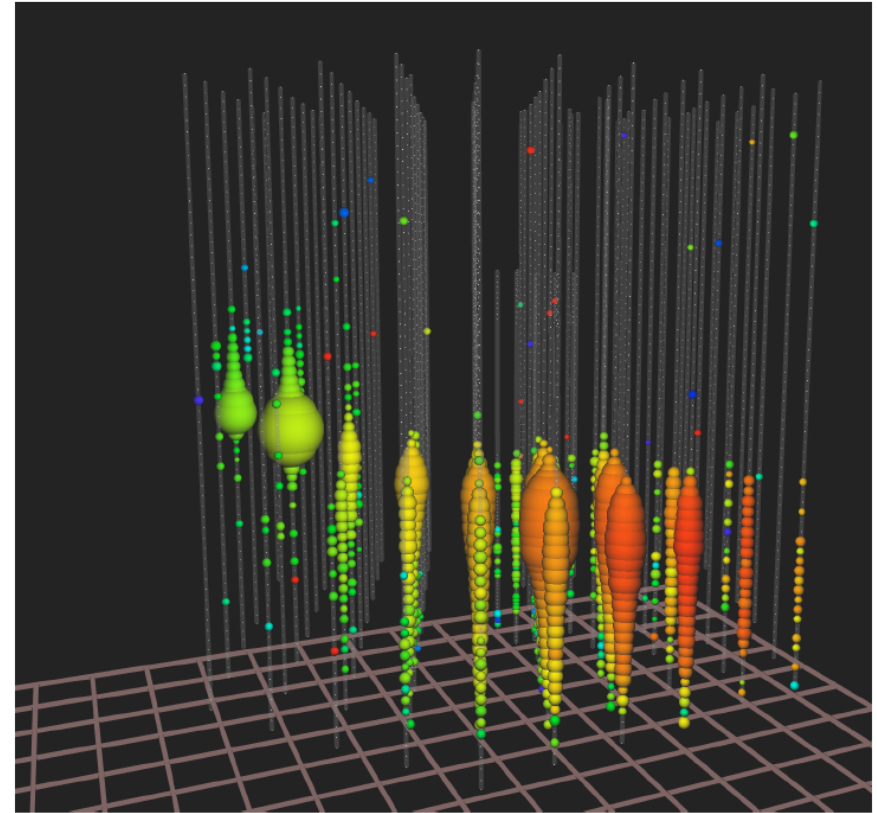


initial neutrino energy 10~20 PeV

neutrinos interacting
inside the detector

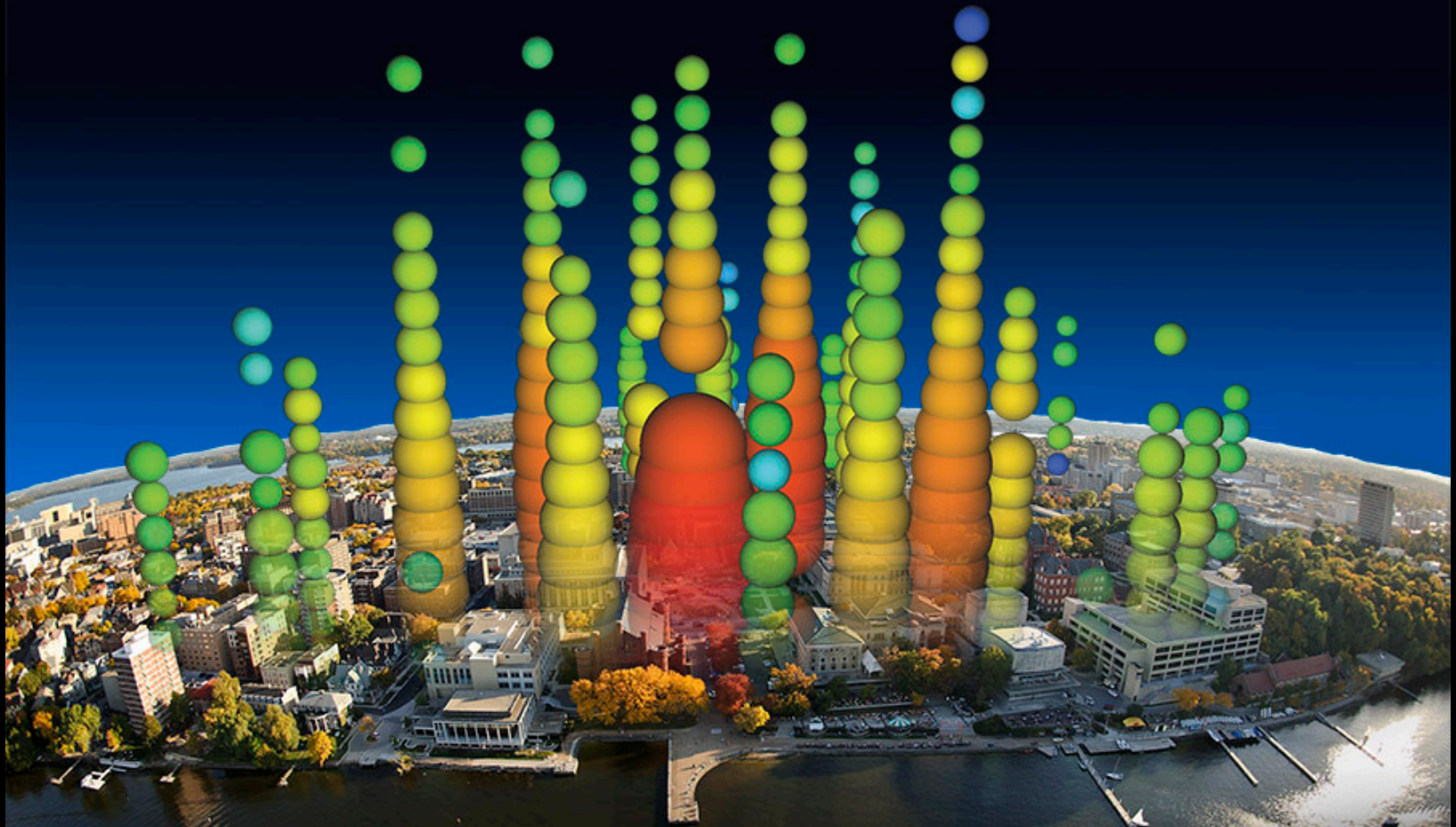


muon neutrinos
filtered by the Earth



total energy measurement
all flavors, all sky

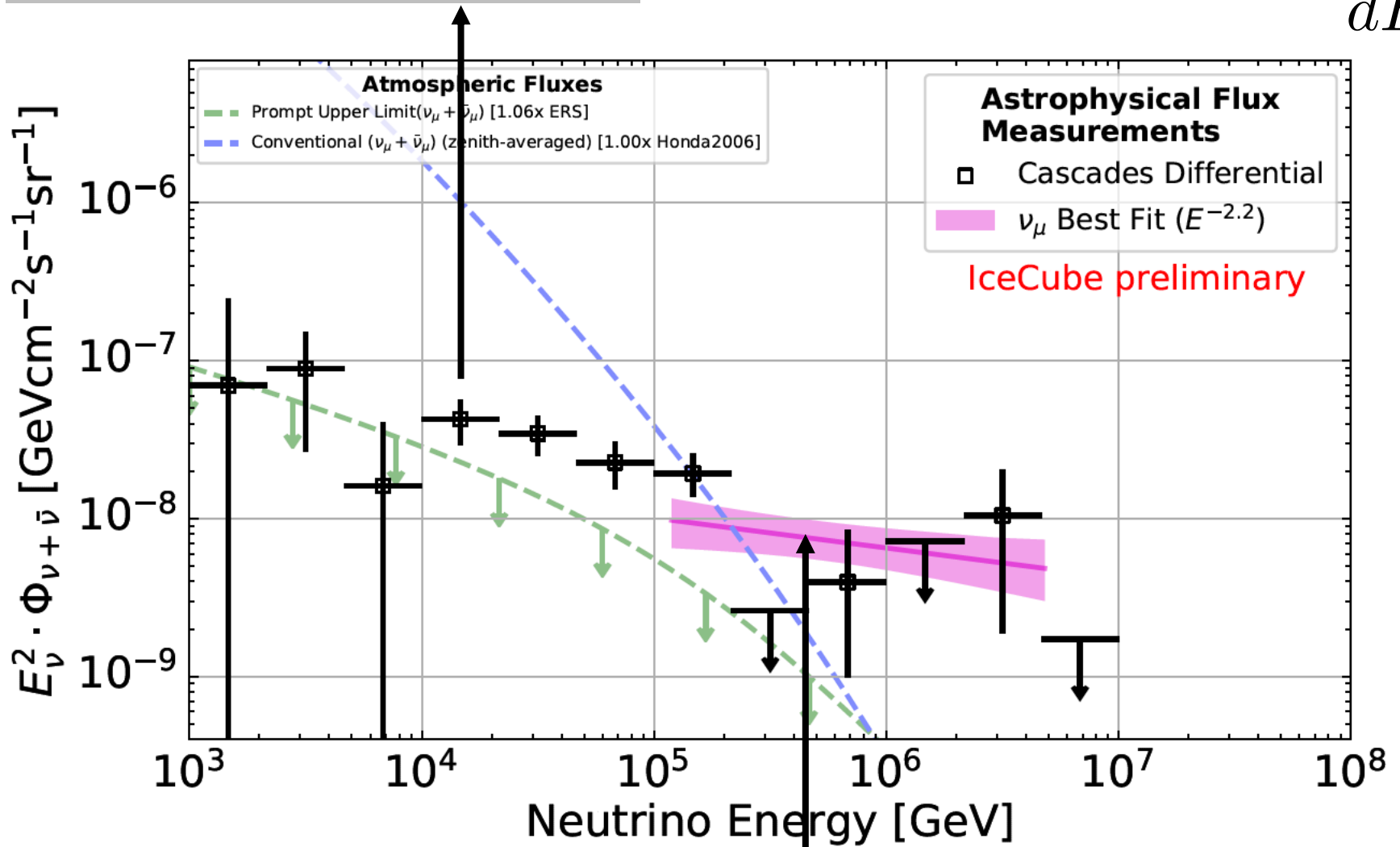
astronomy: angular resolution
superior ($0.2\sim 0.4^\circ$)



Cherenkov radiation from PeV electron (tau) shower
> 300 sensors > 100,000 pe reconstructed to 2 nsec

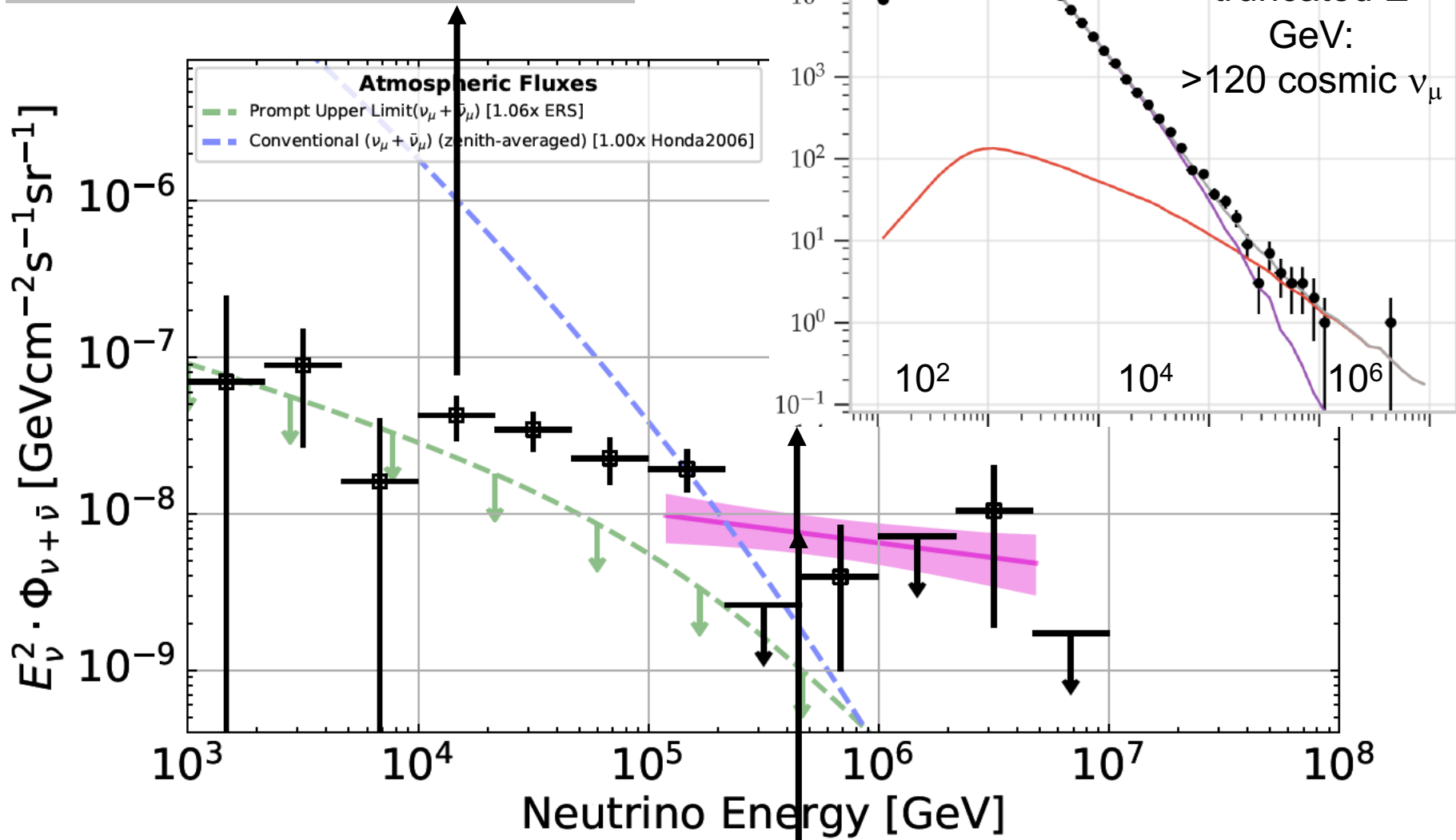
electron and tau neutrinos

$$E \times E \frac{dN}{dE}$$



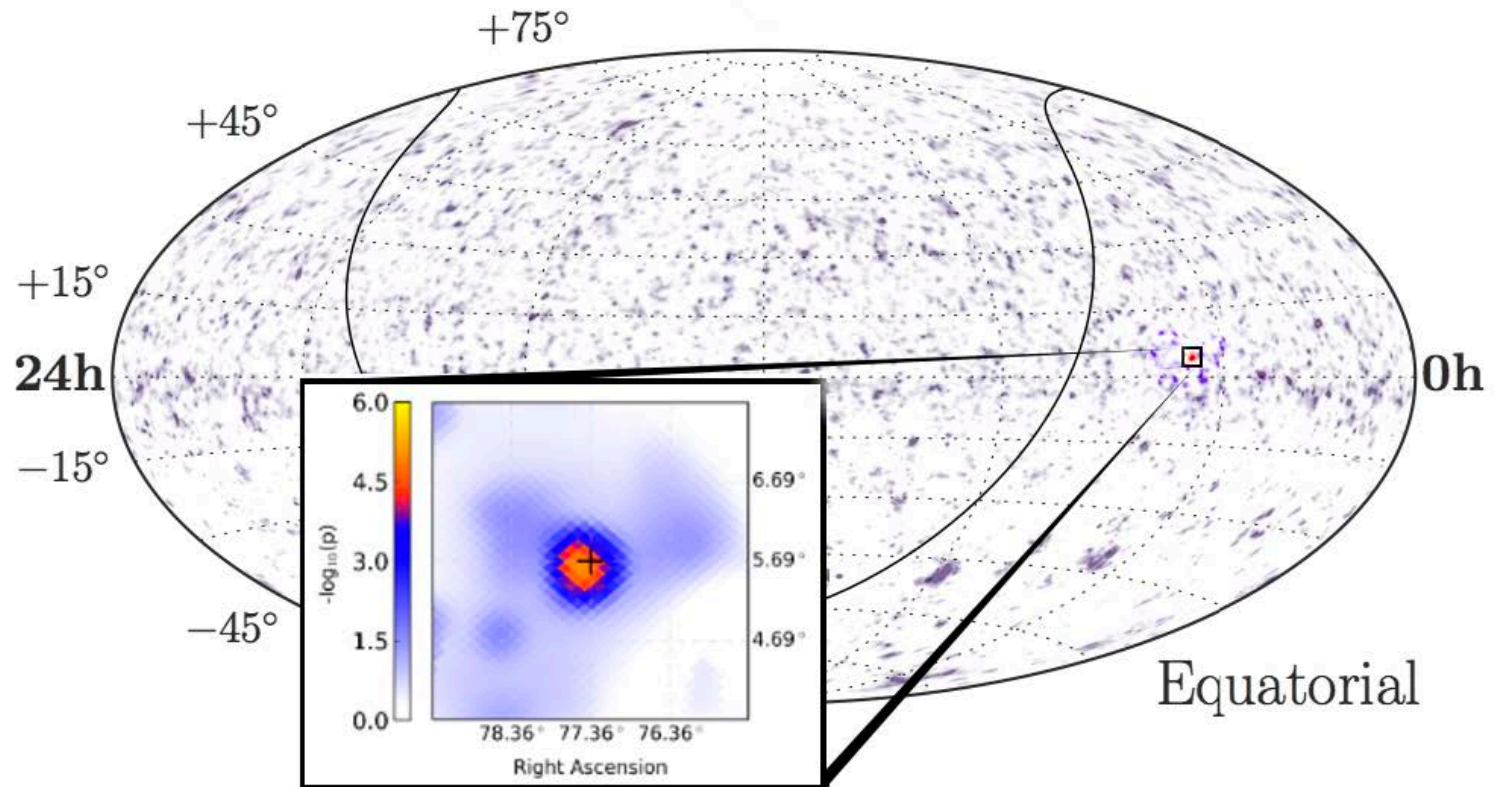
muon neutrinos

electron and tau neutrinos



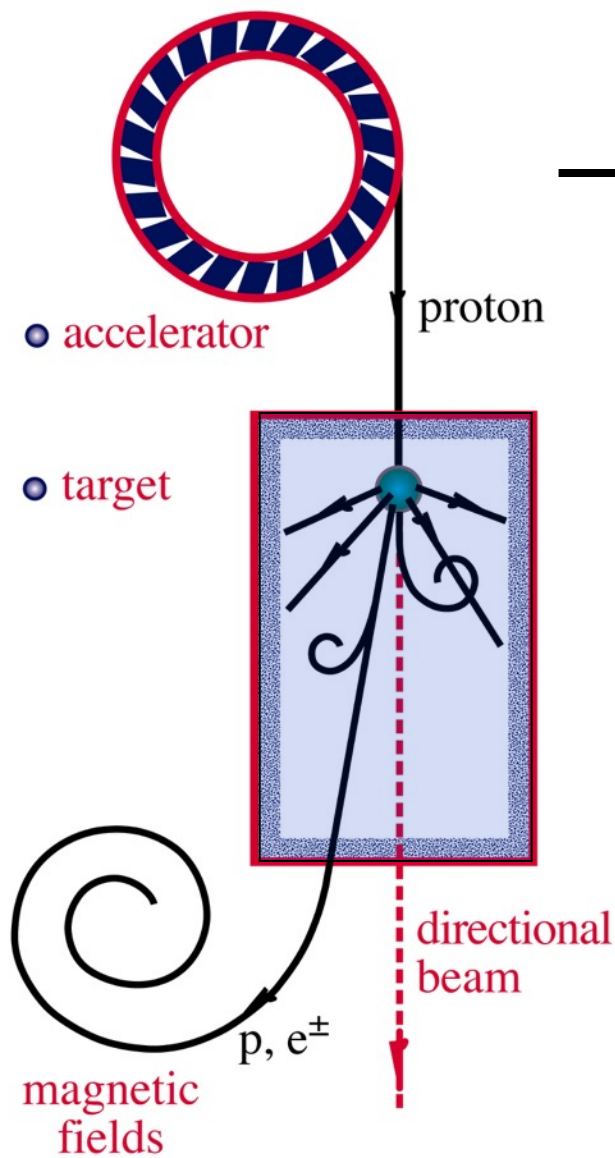
muon neutrinos

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



no evidence for neutrinos associated with Galactic sources

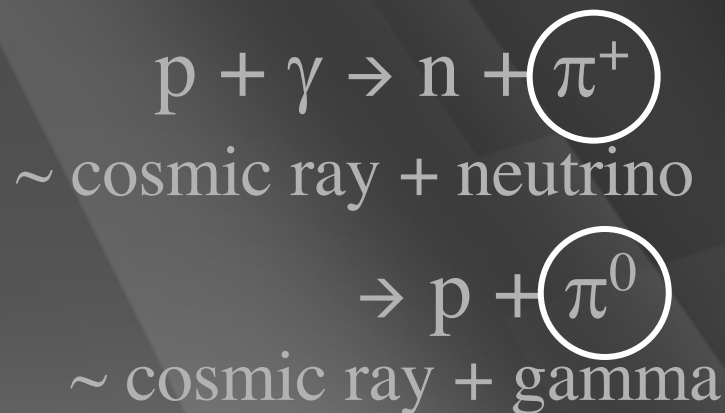
ν and γ beams : heaven and earth



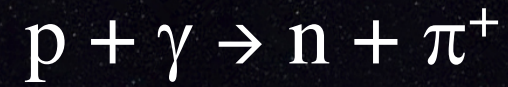
where are the gamma rays ?

supermassive black hole

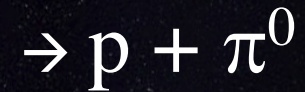
nearby radiation



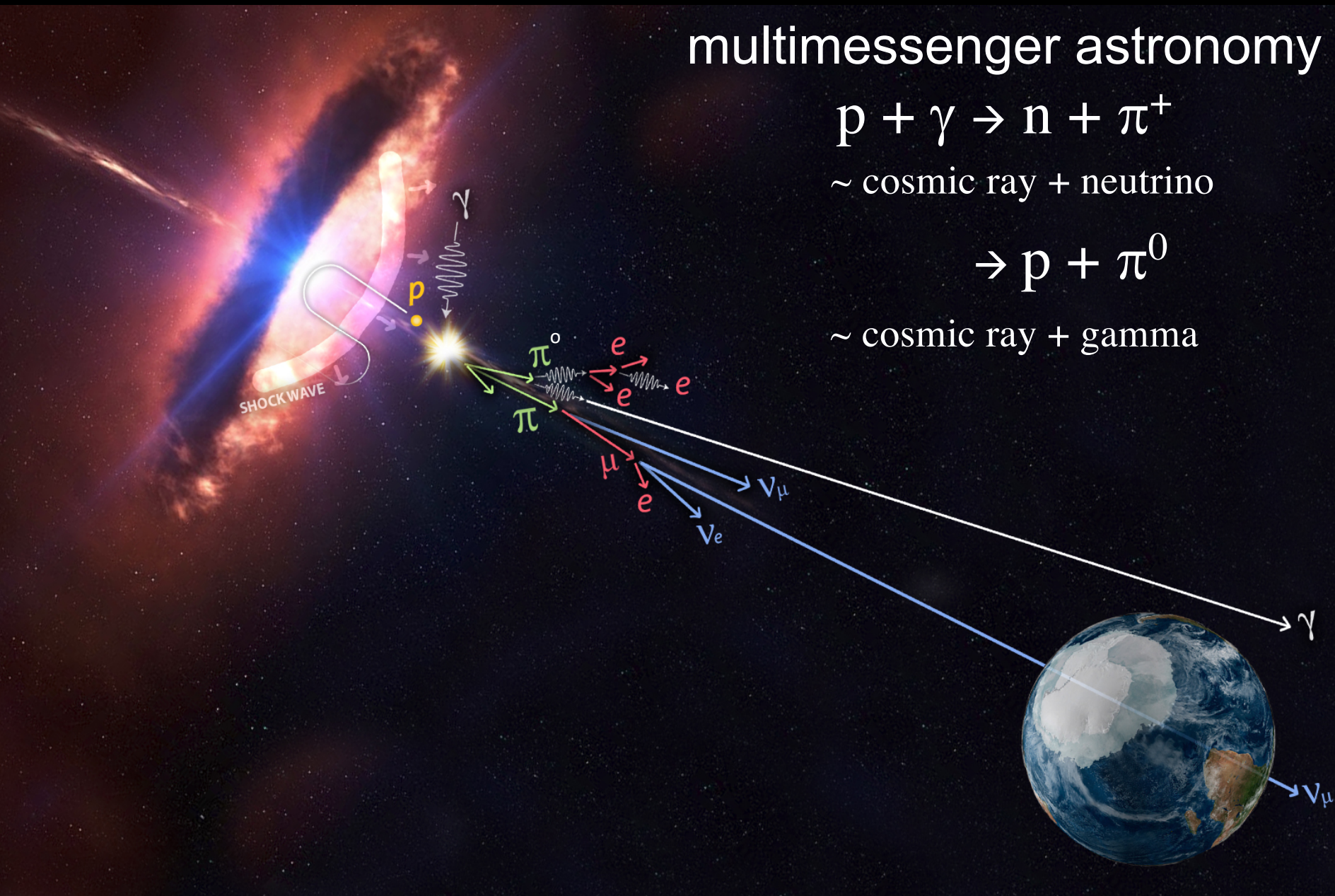
multimessenger astronomy



~ cosmic ray + neutrino



~ cosmic ray + gamma



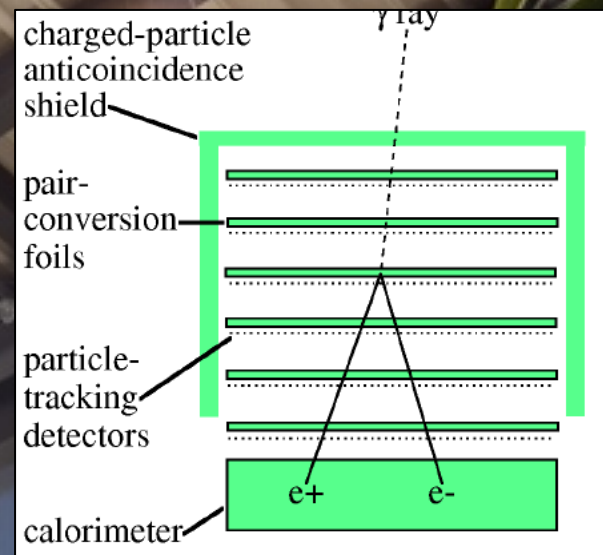
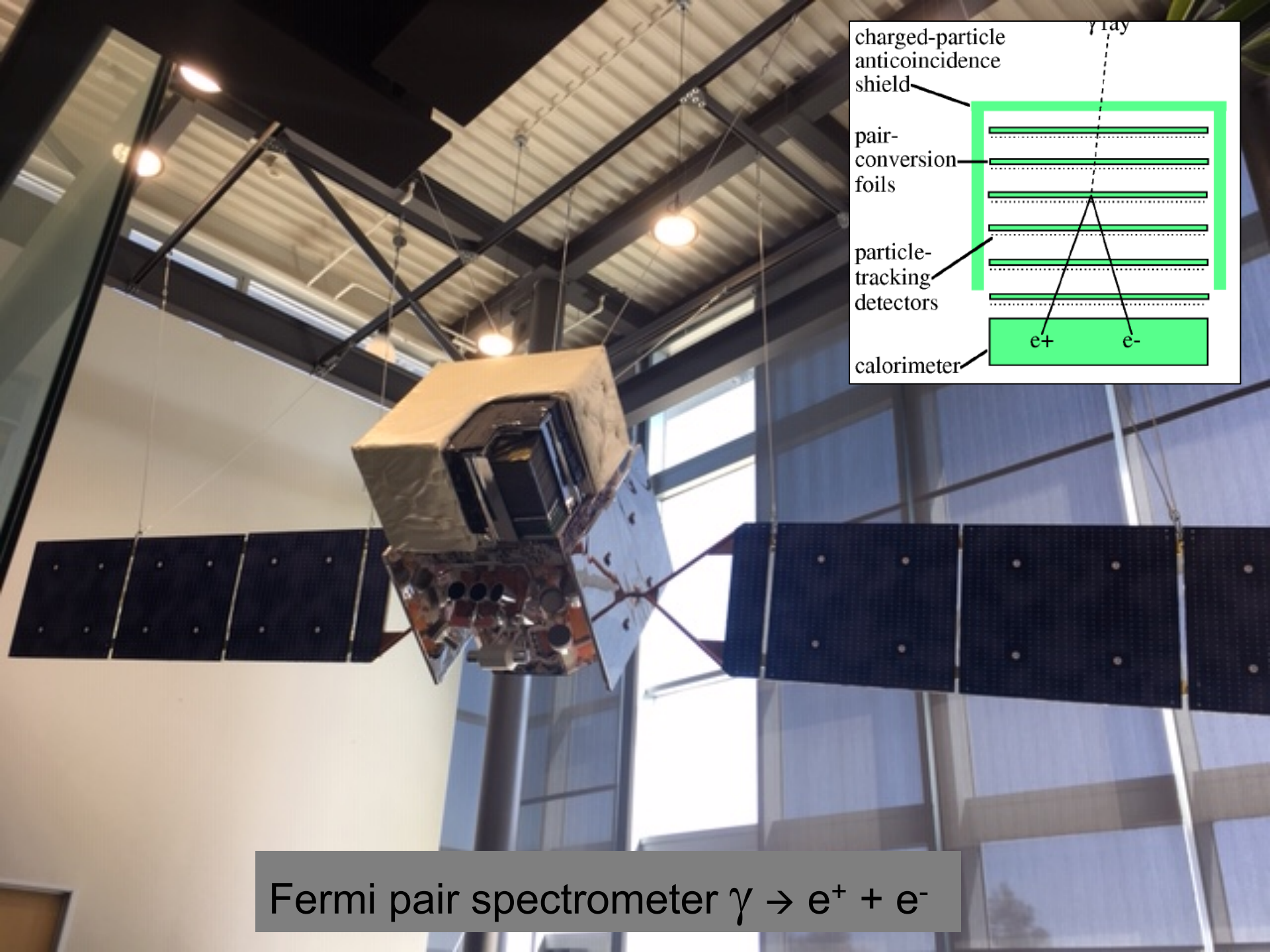


gamma ray

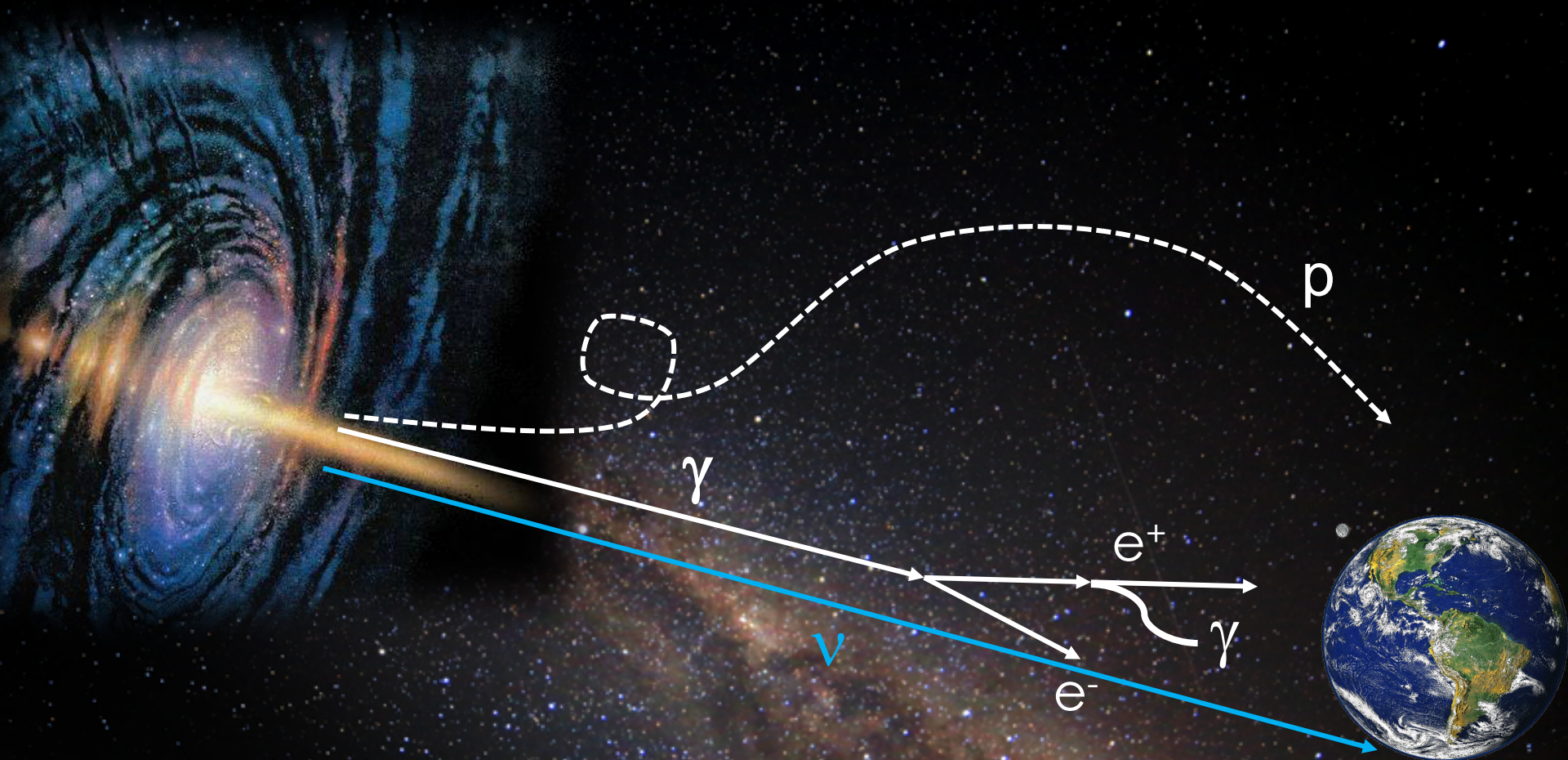
TeV
atmospheric Cherenkov
telescopes

HESS, MAGIC, VERITAS





Fermi pair spectrometer $\gamma \rightarrow e^+ + e^-$



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

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

γ

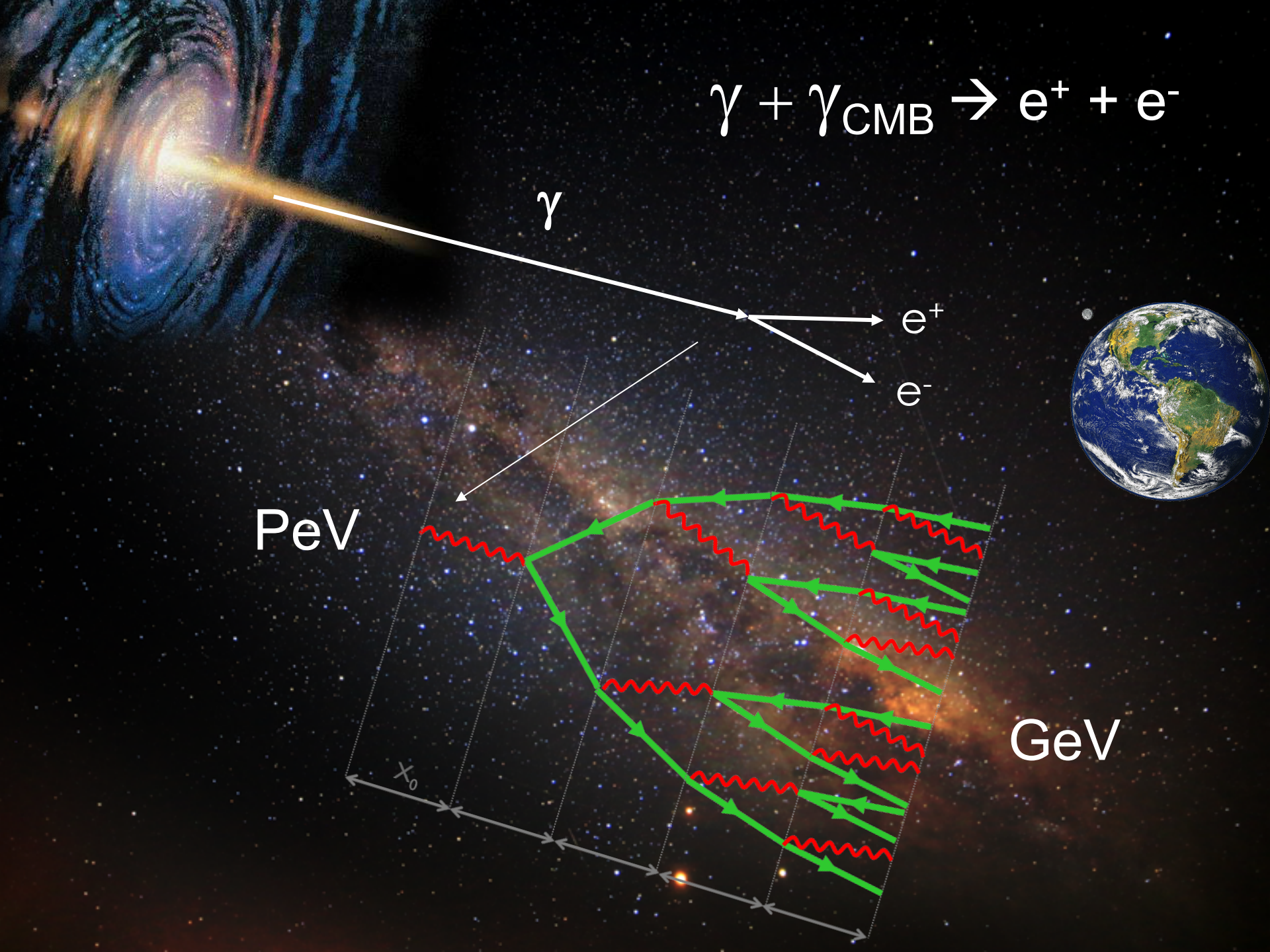
e^+

e^-

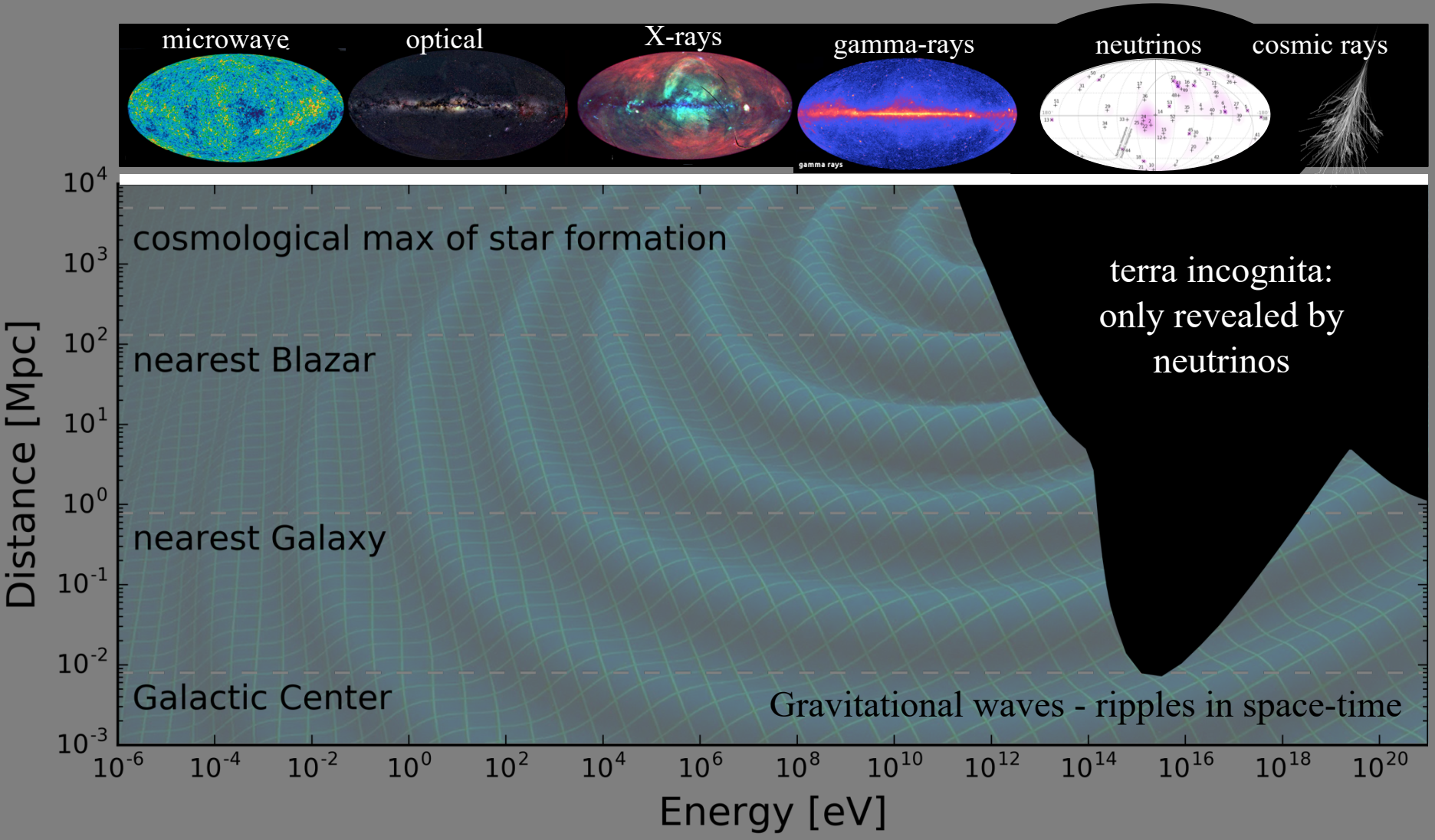
PeV

GeV

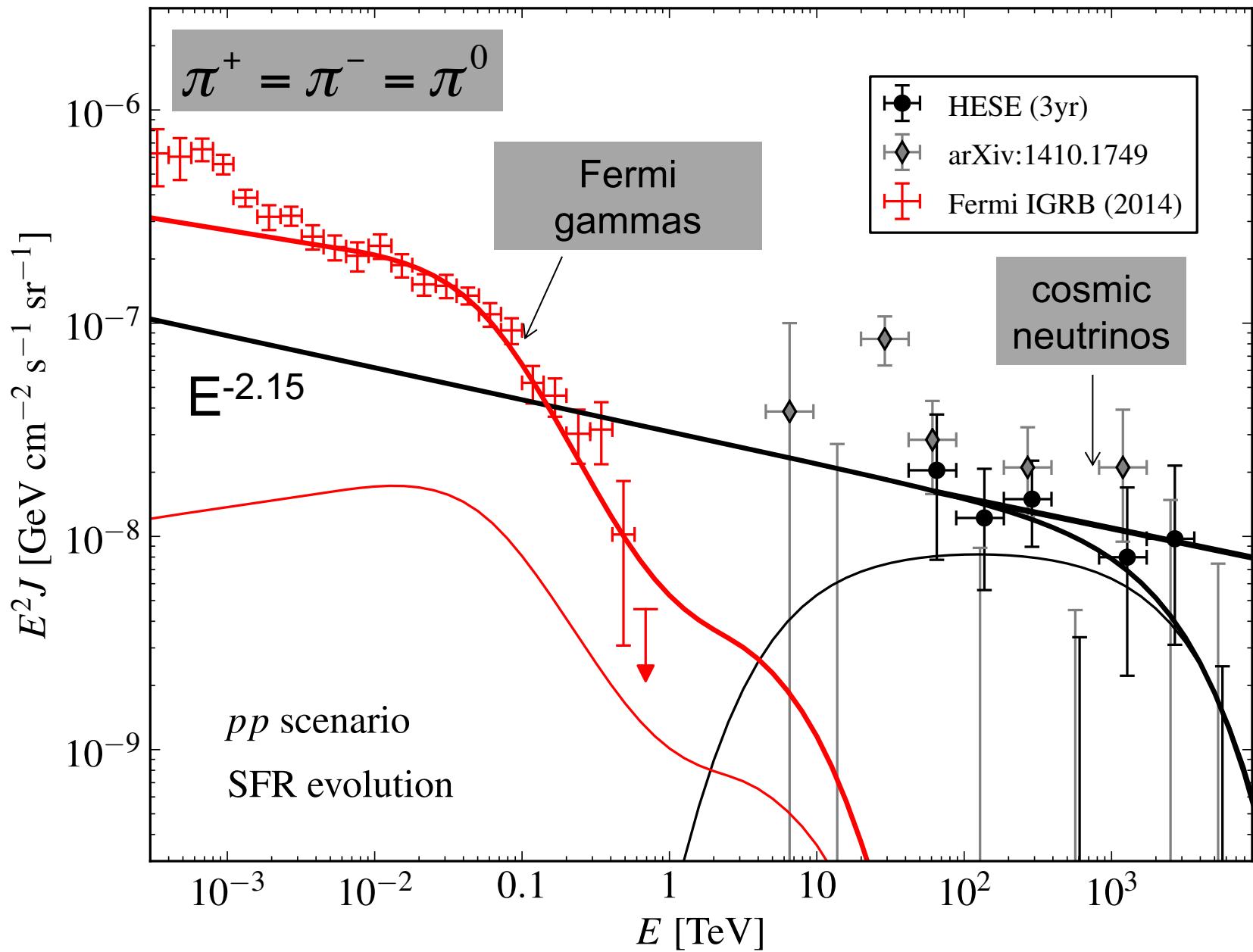
x_0



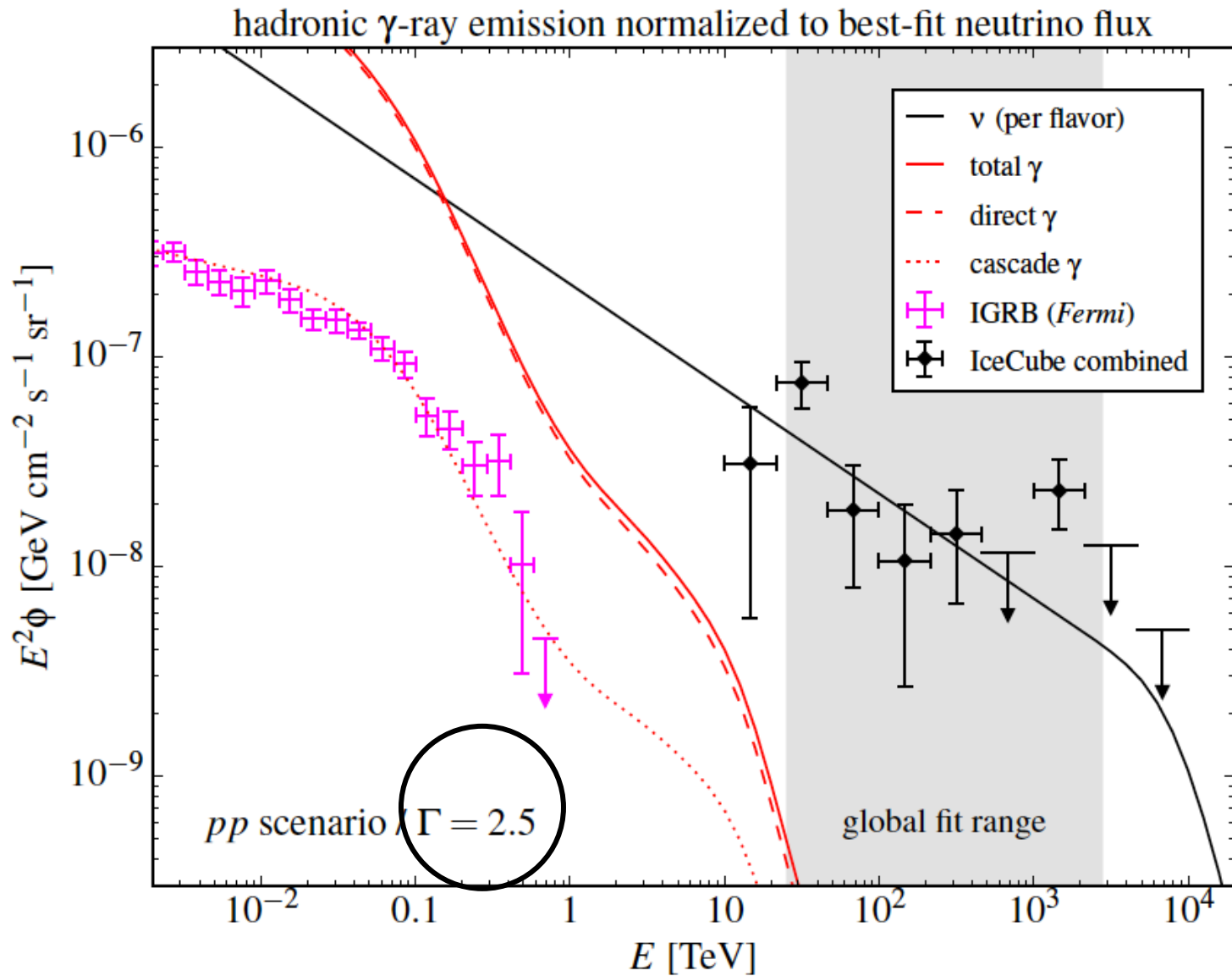
the energy of gamma rays accompanying PeV neutrinos is distributed over the electromagnetic spectrum



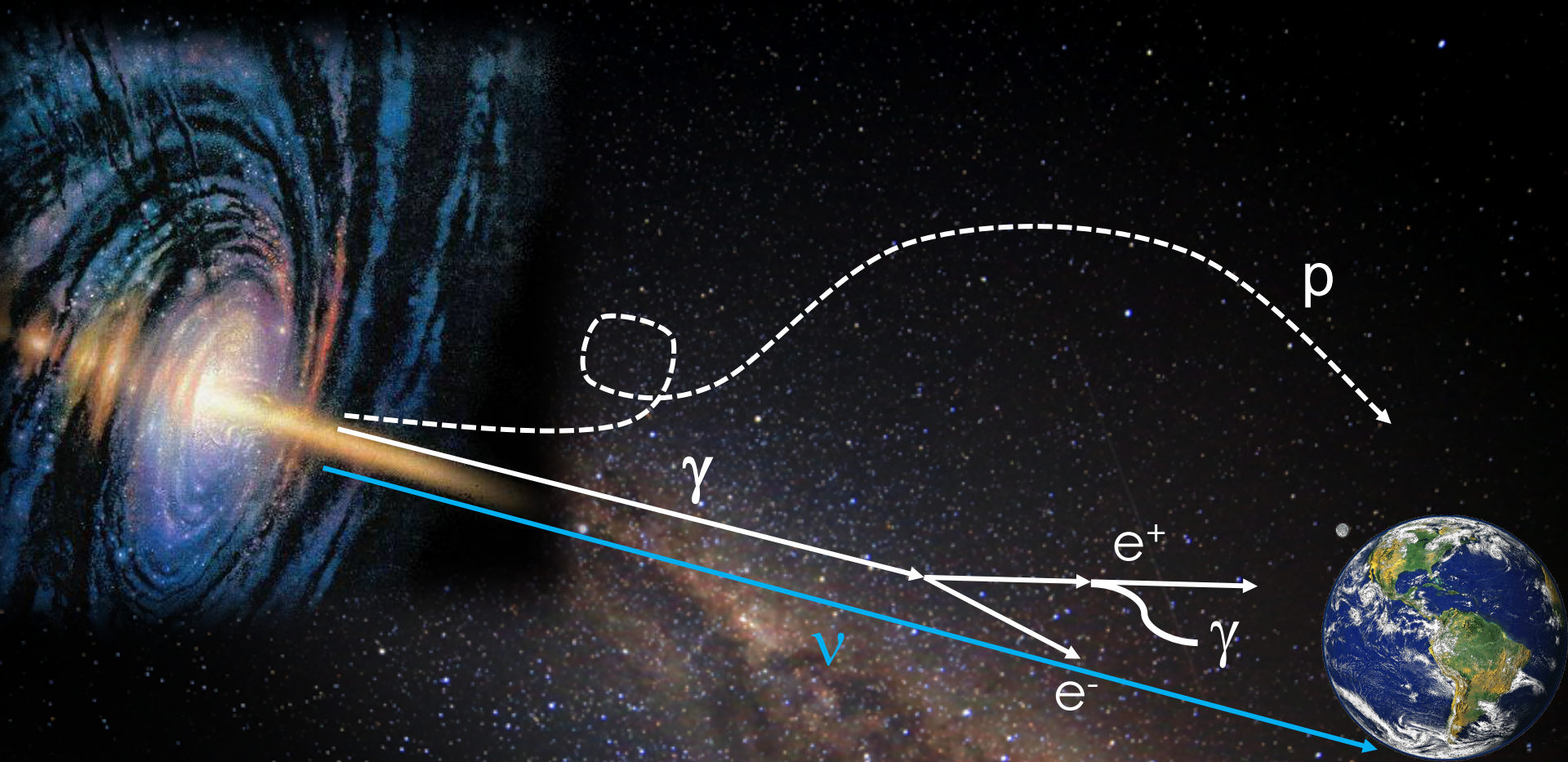
multimessenger astronomy



- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays



dark sources below 100 TeV not seen in γ 's ?
 gamma rays cascade in the source to lower energy



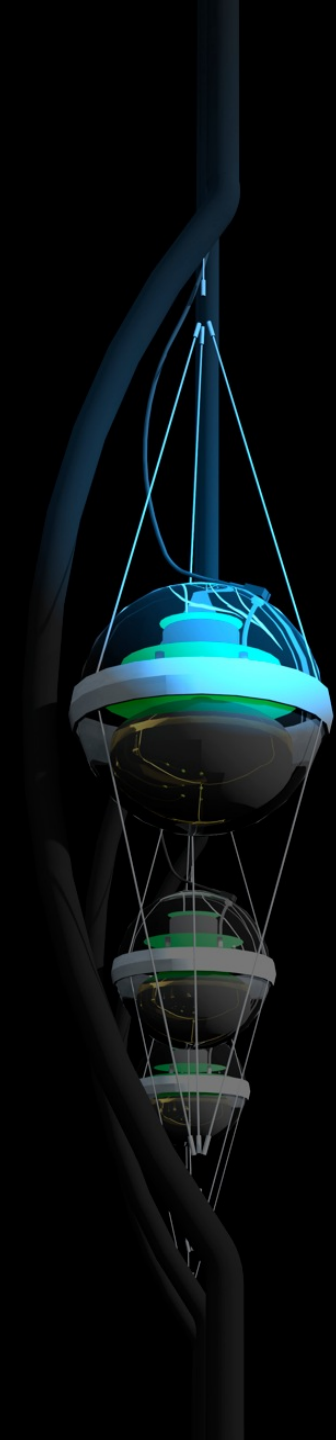
target may not be transparent to gamma rays:

gamma rays accompanying IceCube neutrinos lose energy in the source and in the interstellar medium and fragment into lower energy gamma rays, X-rays... that reach earth

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francis halzen

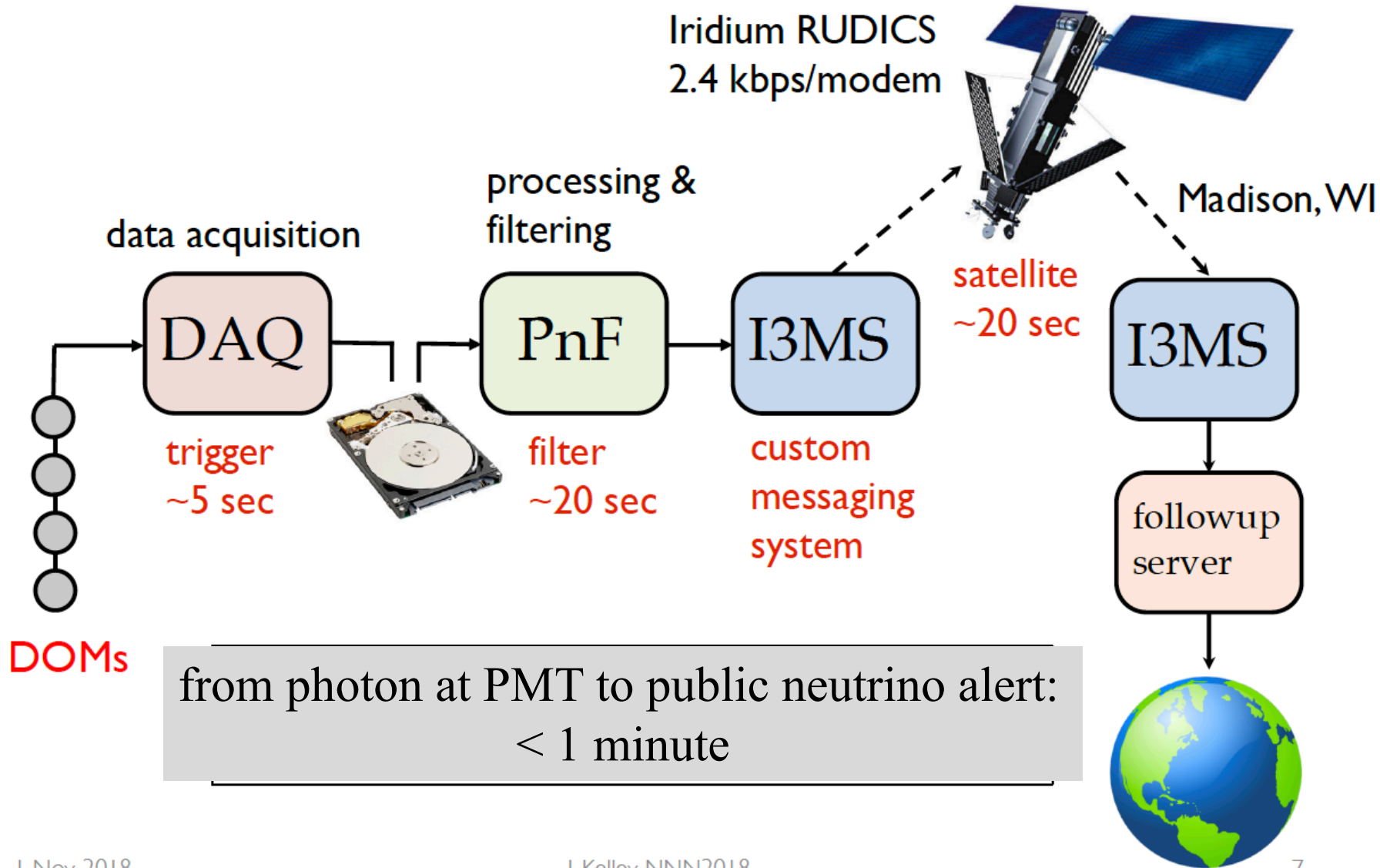
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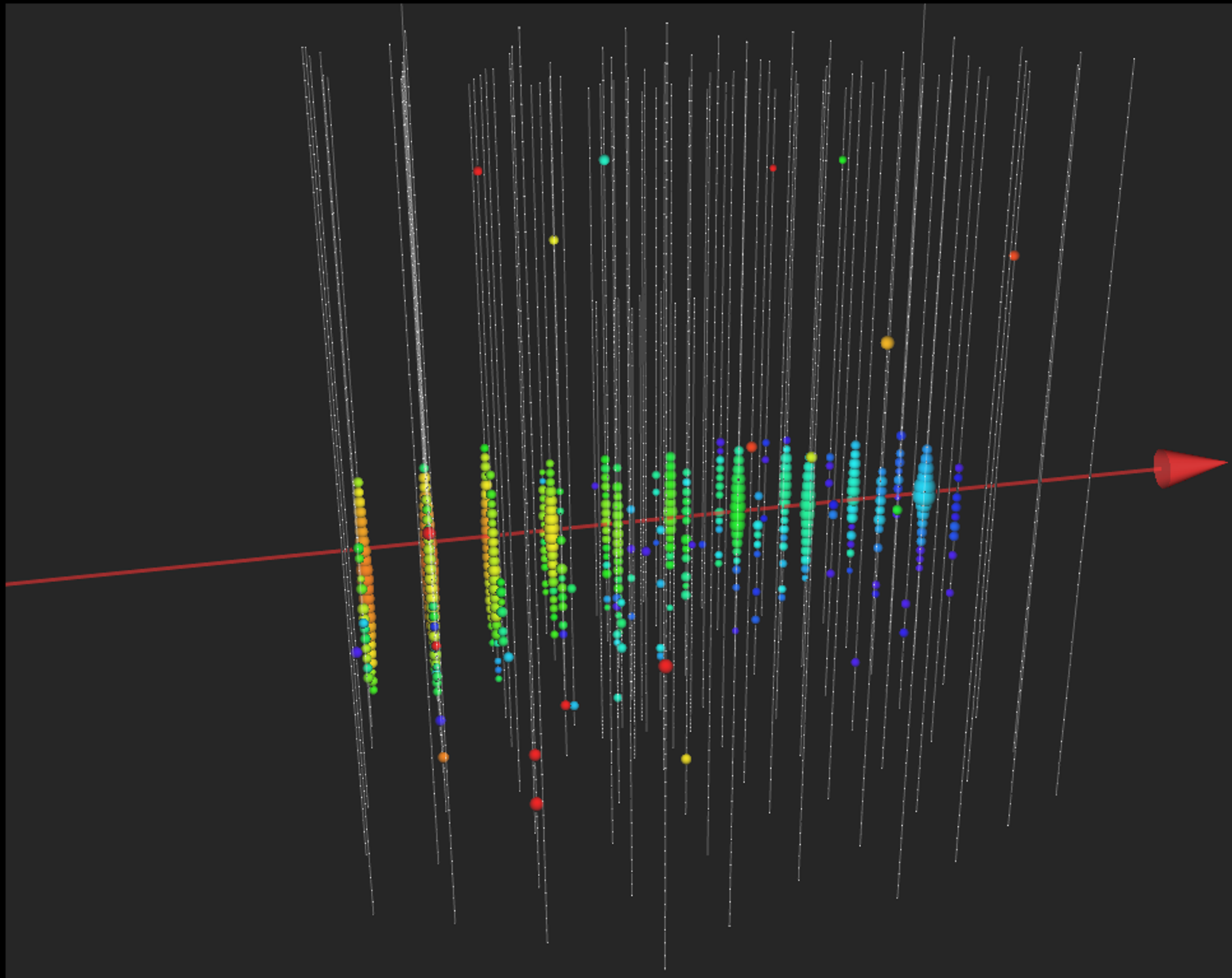


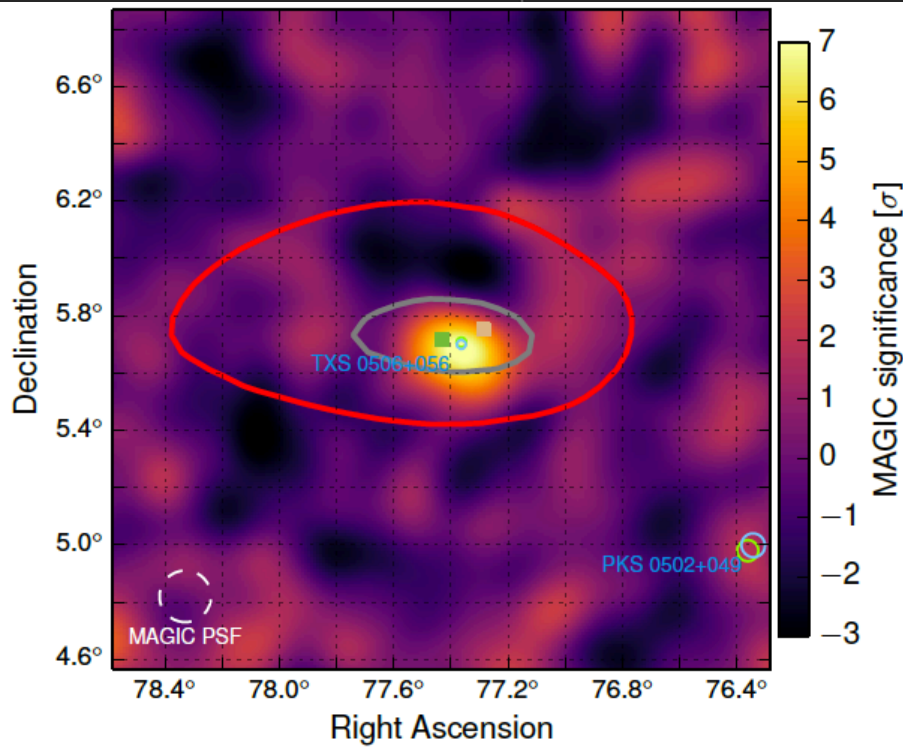


HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

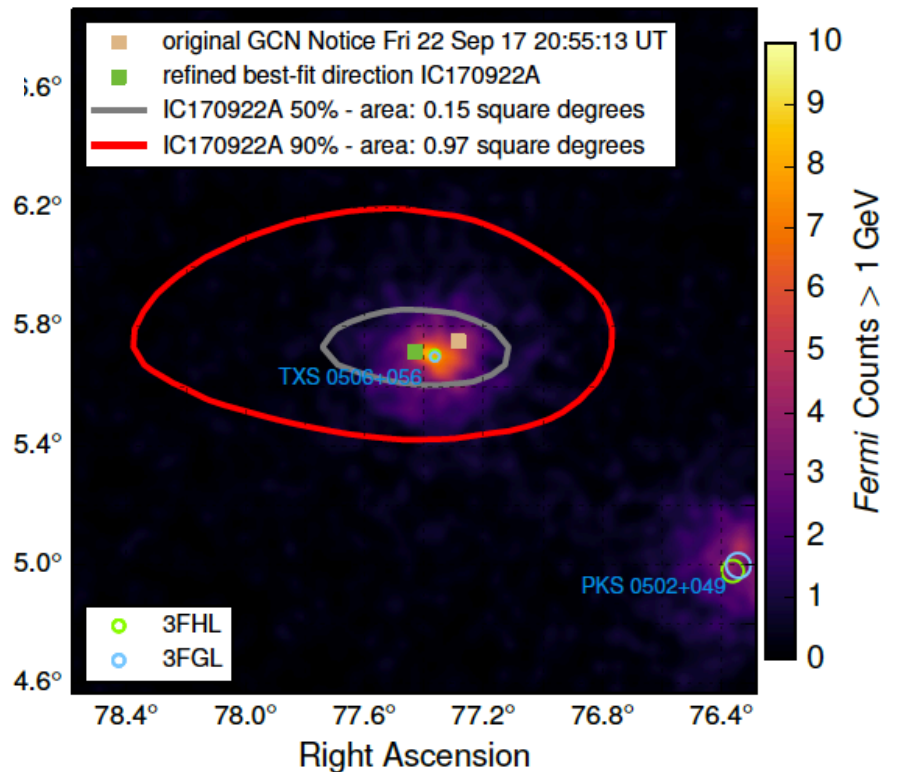






IceCube 170922
290 TeV

Fermi
detects a flaring
blazar within 0.06°



MAGIC
detects emission of
> 100 GeV gammas

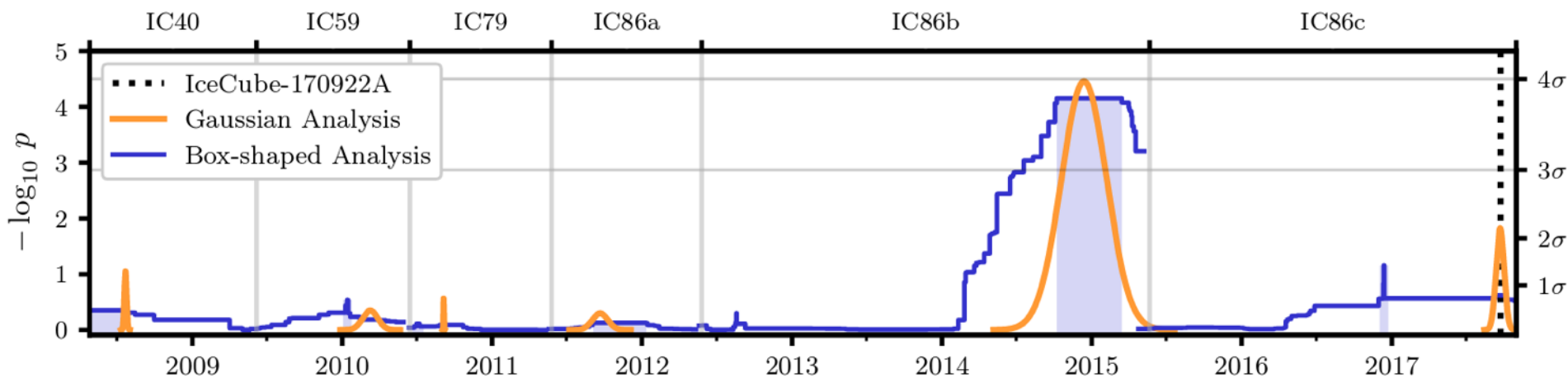
Follow-up detections of IC170922 based on public telegrams



multiwavelength campaign launched by IC 170922

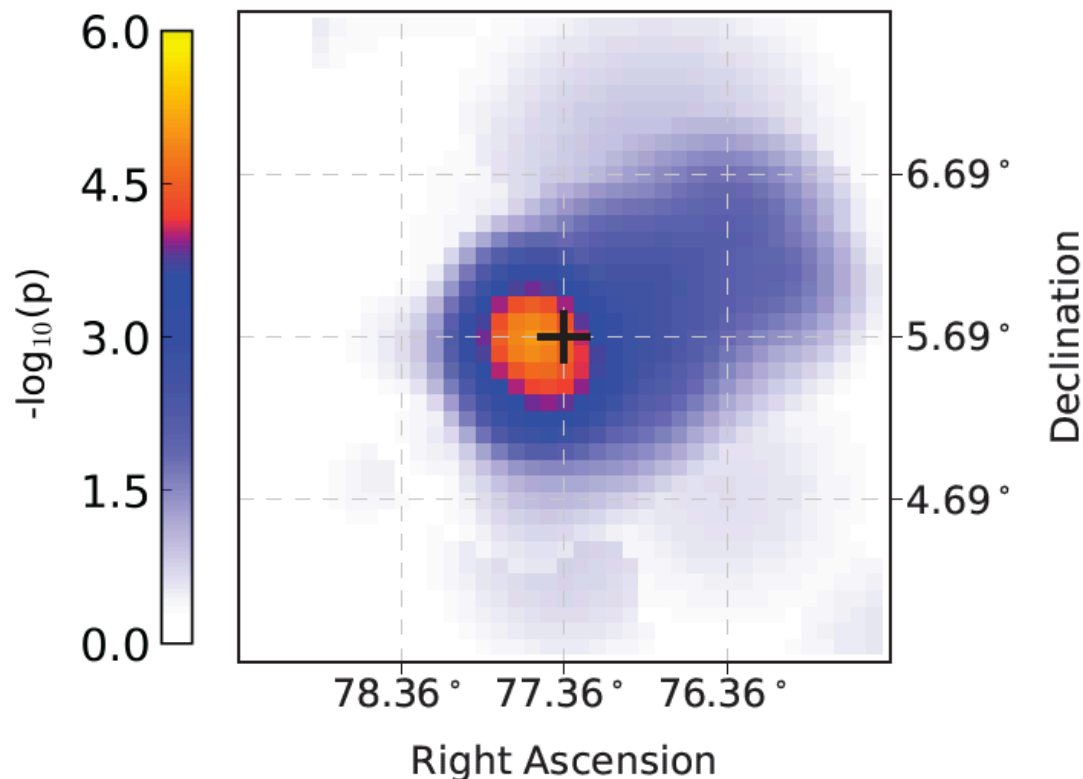
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- neutrino: time 22.09.17, 20:54:31 UTC
energy 290 TeV
direction RA 77.43° Dec 5.72°
 - Fermi-LAT: flaring blazar within 0.06° (7x steady flux, daily variations)
 - MAGIC: TeV source in follow-up observations
 - follow-up by more telescopes
- → IceCube archival data (without look-elsewhere effect)
 - → Fermi-LAT archival data



search in archival IceCube data:

- 150-day flare in December 2014 of 19 events ($\text{bkg} < 6$)
- spectrum $E^{-2.1}$
- $L_\nu > 10^{47}$ erg/s



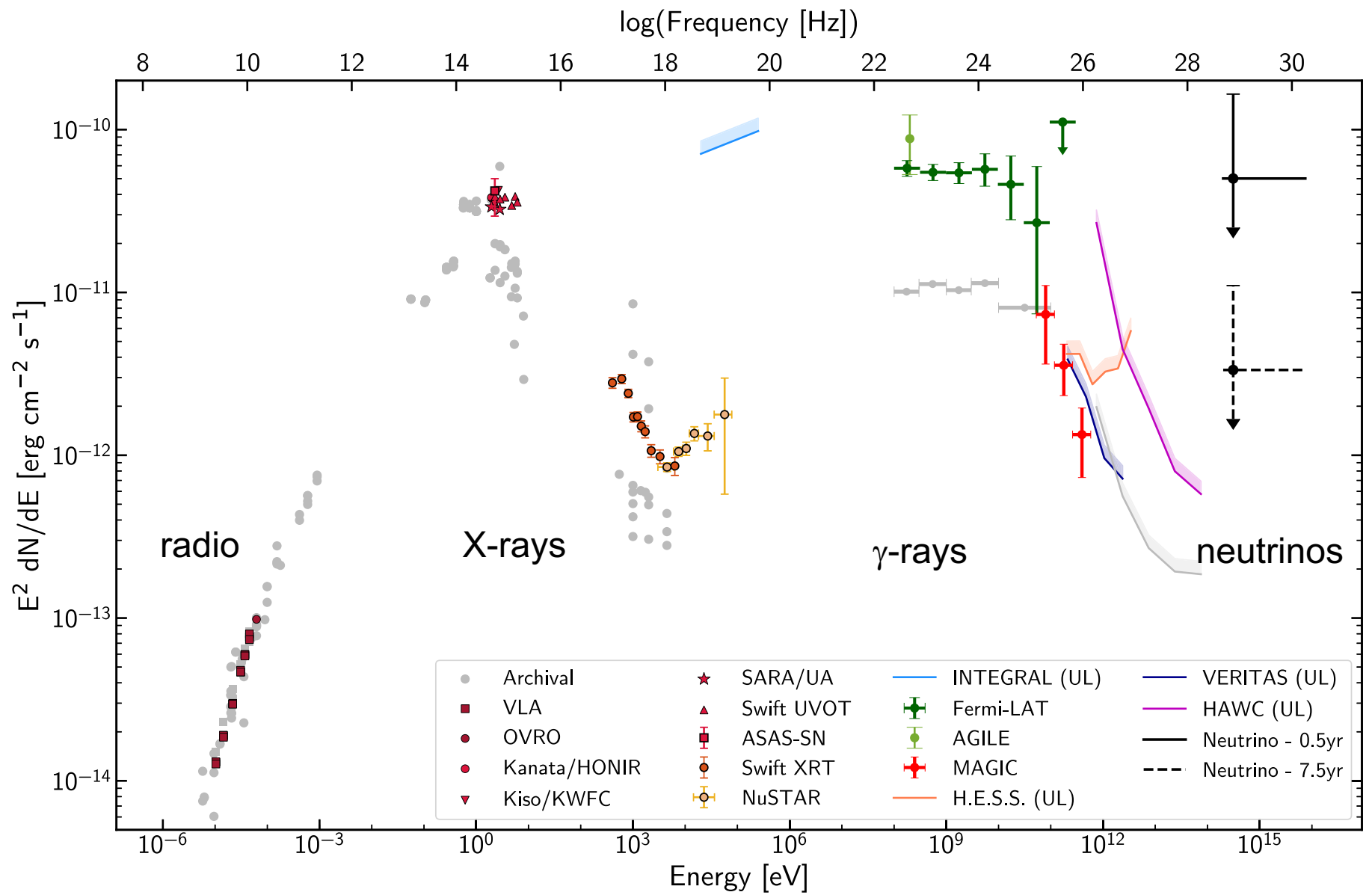
we identified a source of high energy cosmic rays:

the active galaxy (“blazar”) TXS 0506+056 at a
redshift of 0.33

at ten times further distance, it outshines nearby
active galaxies: is it special?

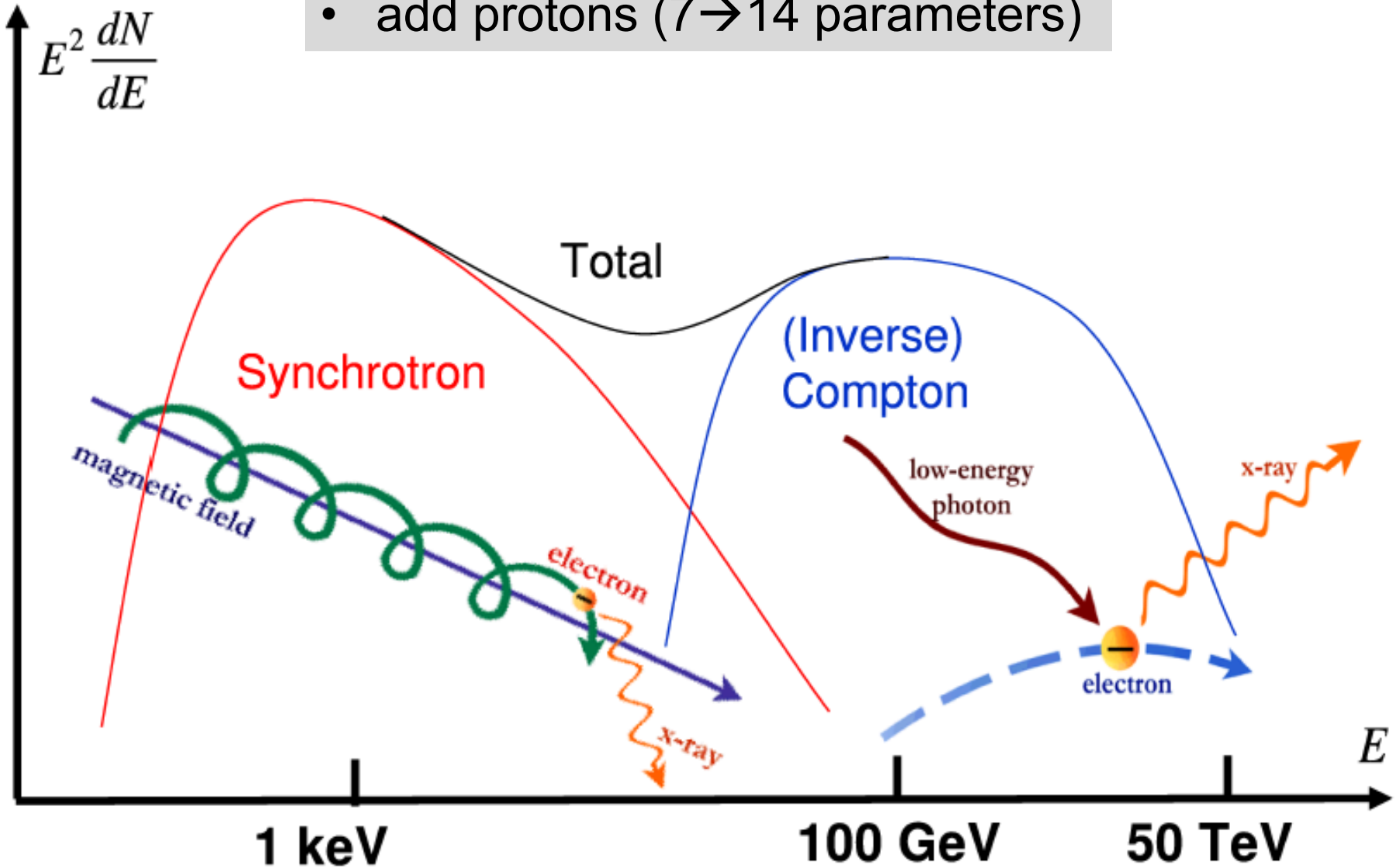
extensive multiwavelength campaign allows us
to study the first cosmic accelerator

a problem: theory



we know that this cosmic accelerator is a cosmic ray source

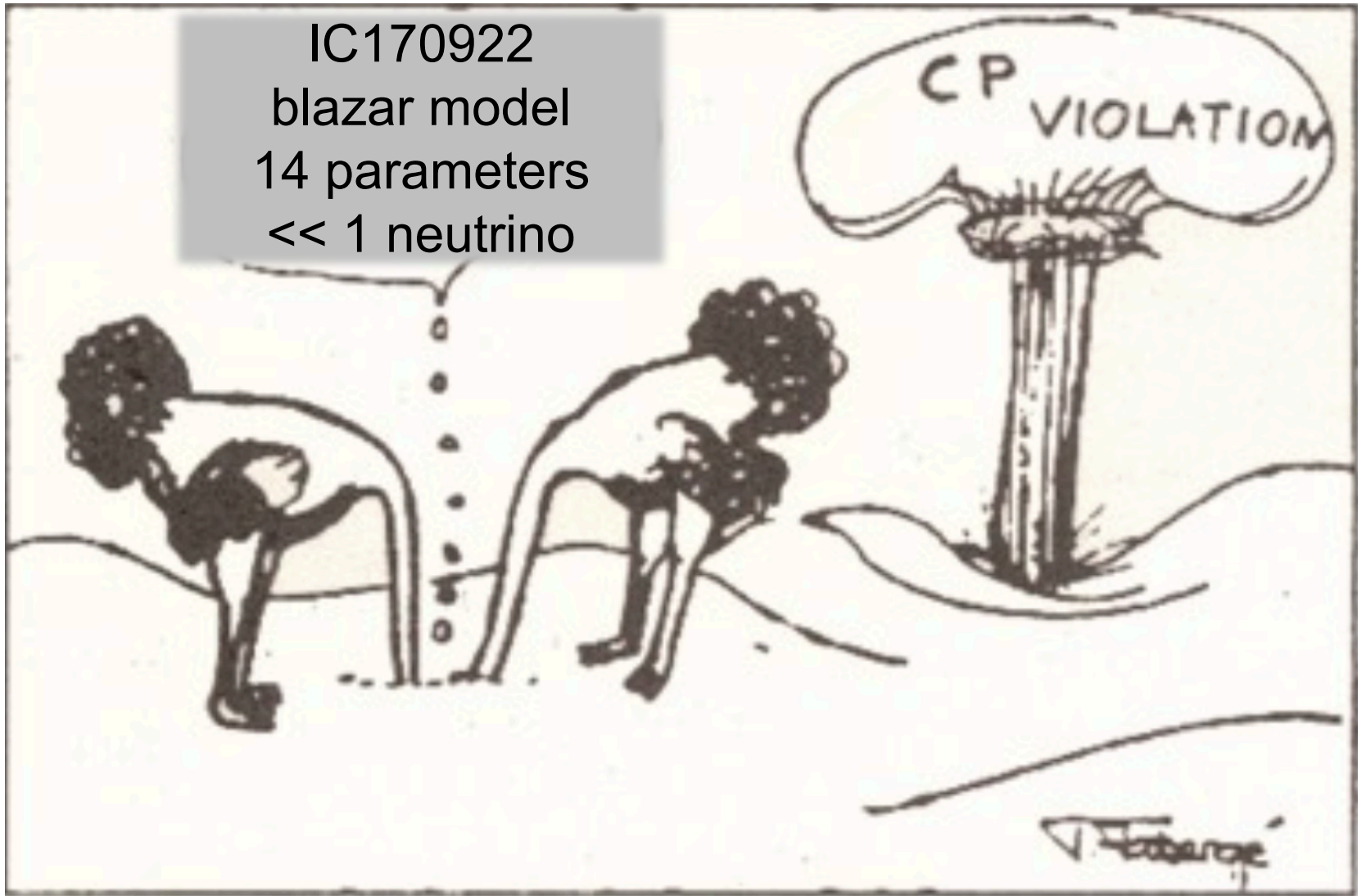
- blazar modeling well understood
- add protons (7 → 14 parameters)





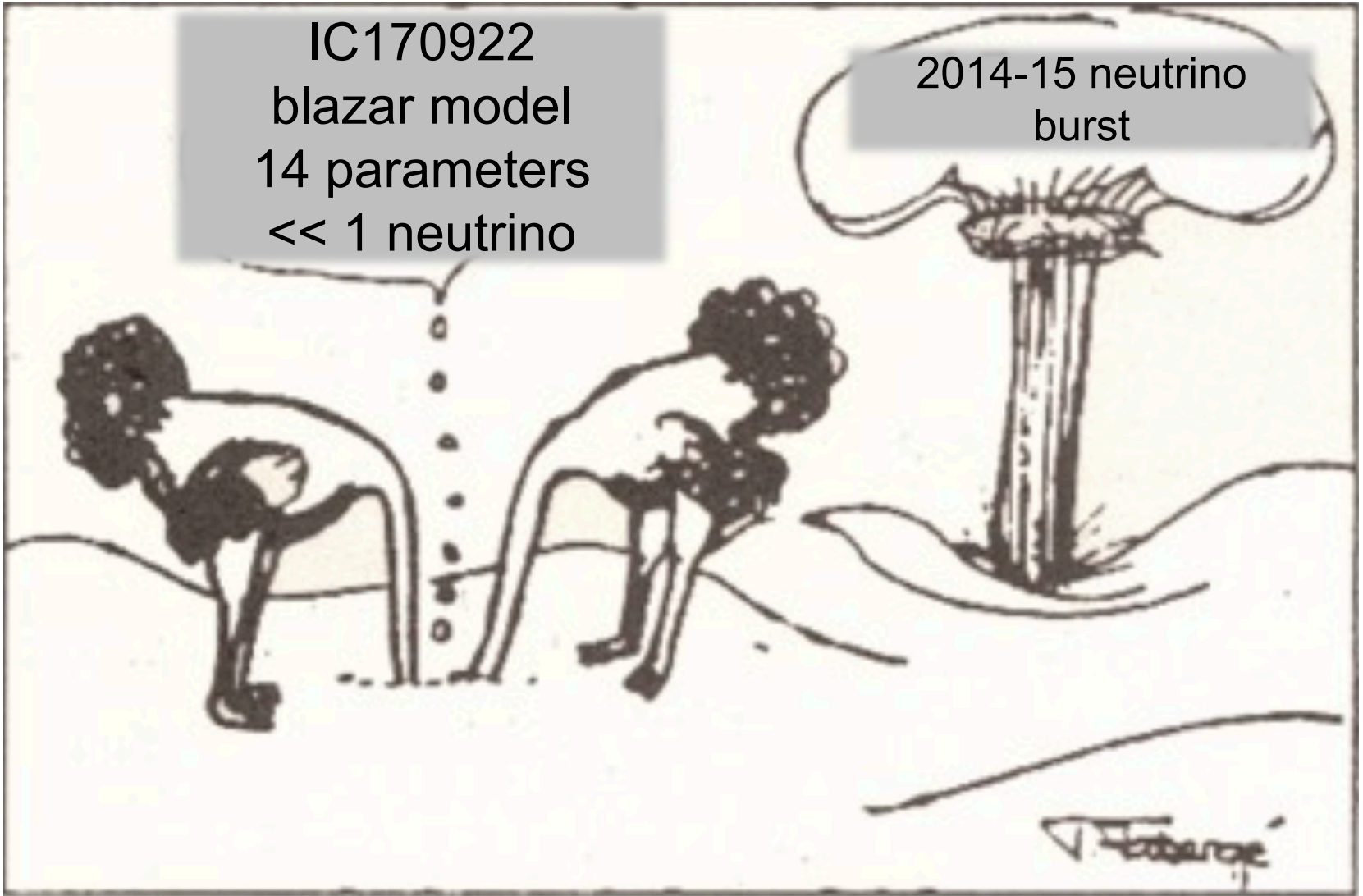
Cabibbo 1966

IC170922
blazar model
14 parameters
 $\ll 1$ neutrino

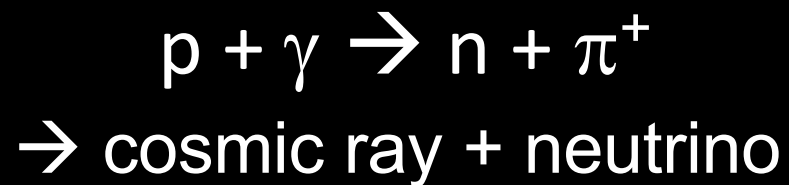
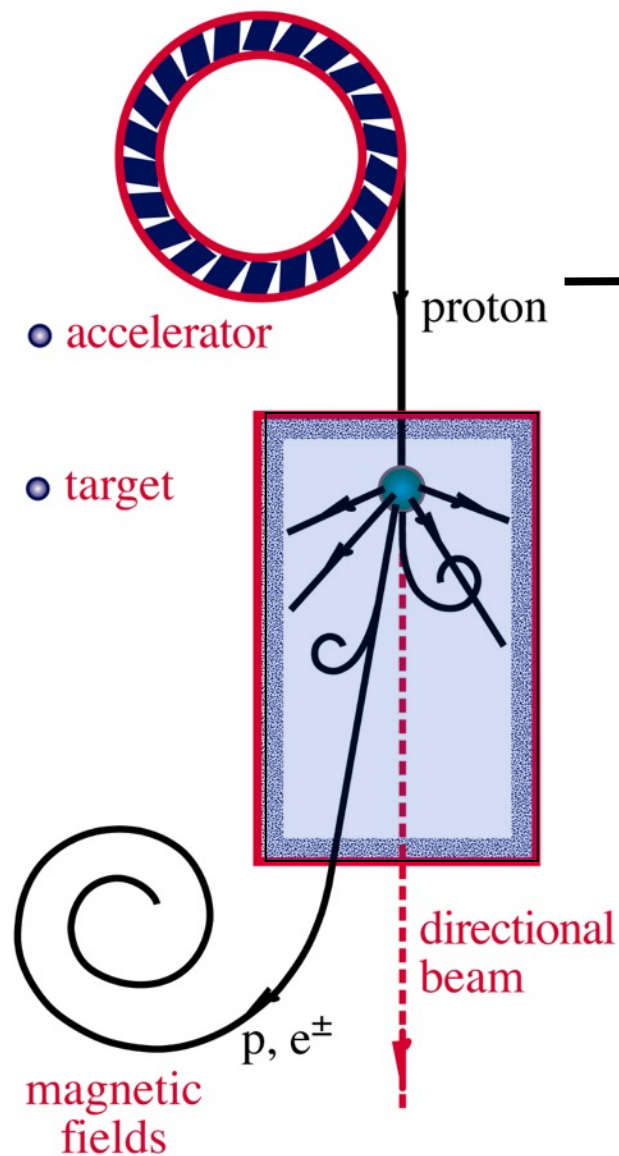


IC170922
blazar model
14 parameters
 \ll 1 neutrino

2014-15 neutrino
burst



ν and γ beams : heaven and earth



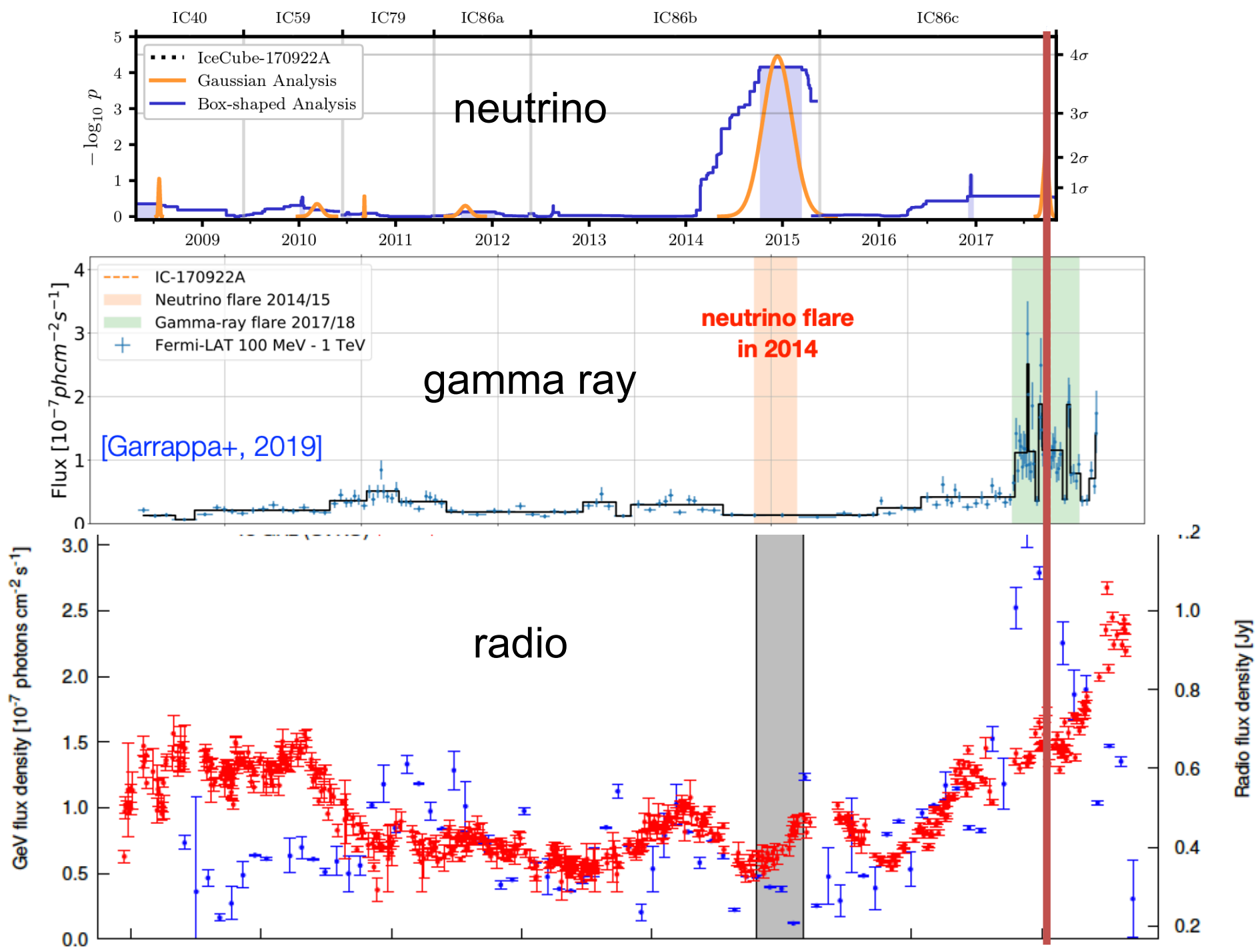
**supermassive
black hole**

target ?

- a neutrino source needs an accelerator and a target
- the target may be opaque to gamma rays

an efficient neutrino source is opaque to gamma rays

- efficiency for producing neutrinos: $L_\nu \sim \tau_{p\gamma} L_p$
opacity of the target's proton $\tau_{p\gamma}$
- requires large opacity of the target to protons and large target density $\tau_{p\gamma} \sim n_\gamma$
- gamma ray opacity is 10^2 times higher $\tau_{\gamma\gamma} \simeq 10^2 \tau_{p\gamma}$
- blazars are highly efficient gamma ray emitters, cannot be efficient neutrino sources
- radio interferometry images and optical robotic telescopes to the rescue!

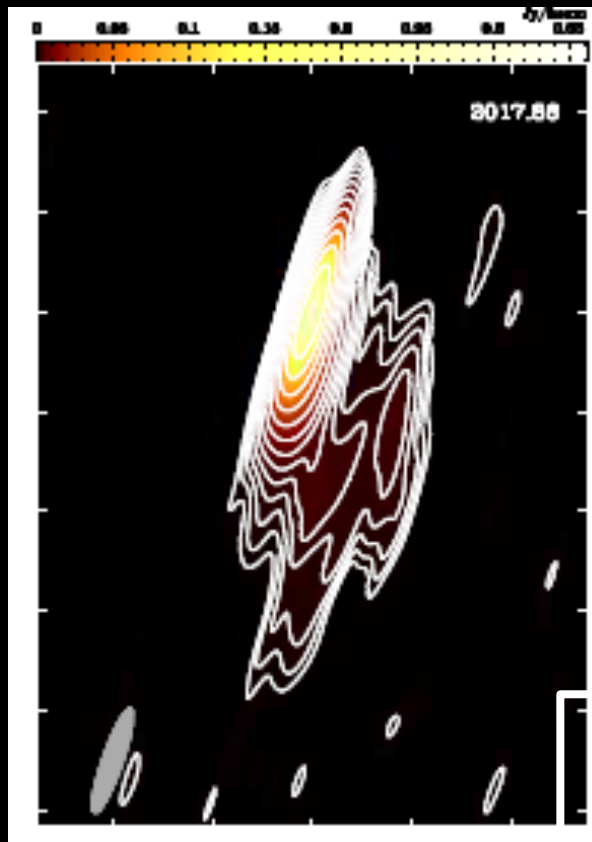


TXS 0506+056

- core brightening observed in a radio burst that started 5 years ago
- core expands with superluminal velocity
- beyond 5 mas the core loses its tight collimation...
- jet found a target after ~tens of pc

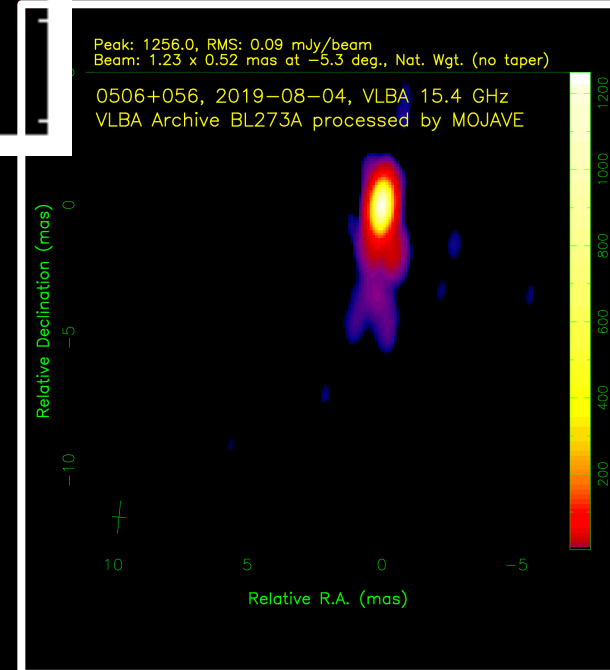
Theory confirms observations:

- jet star interaction?
- jet-jet encounter in a galaxy merger?

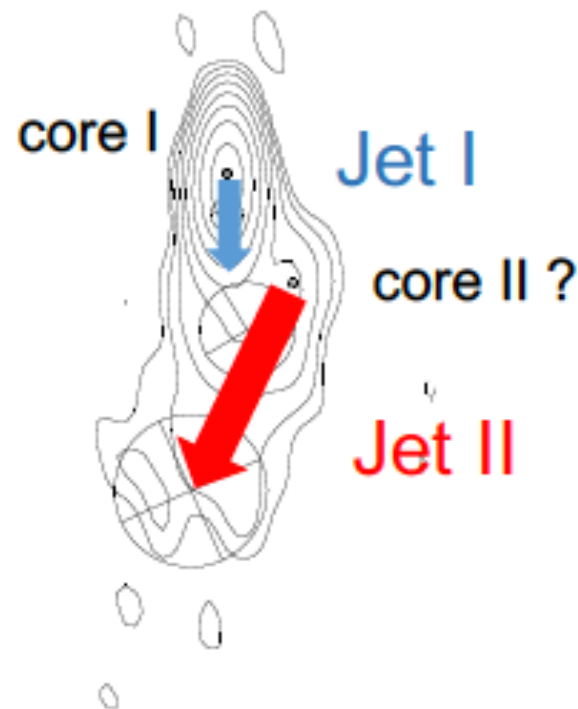
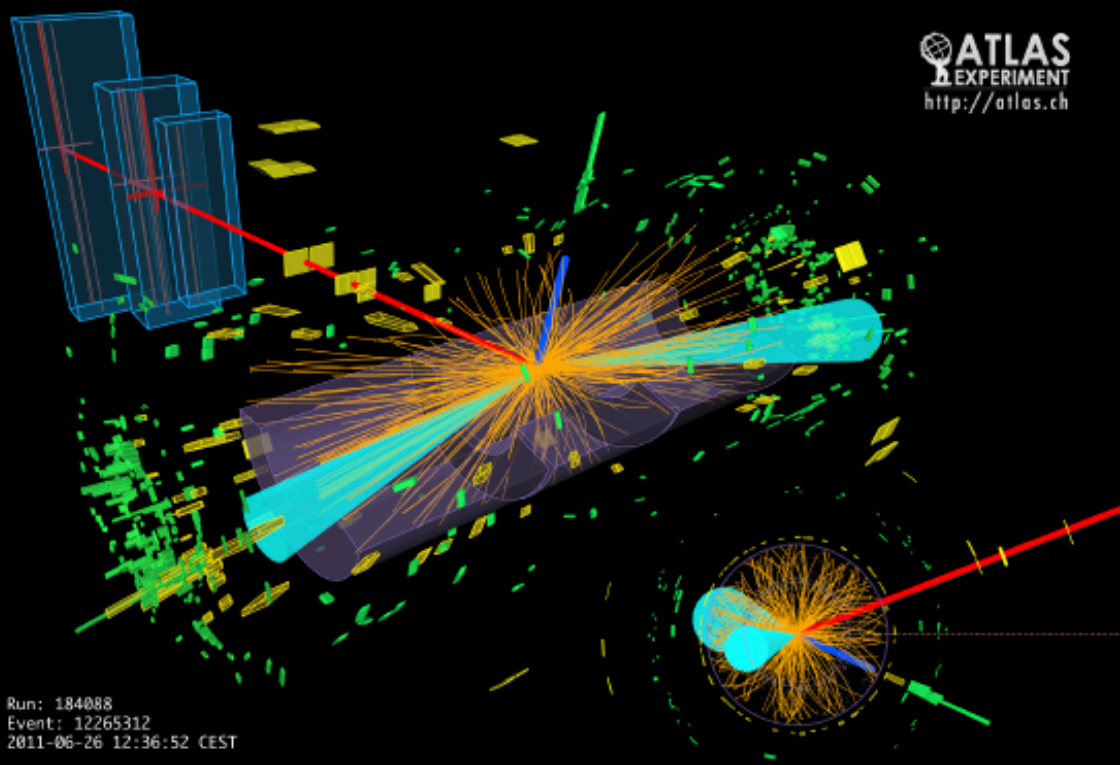


A&A. 630 A103
A&A. 632 C3

1912.01743v1
[astro-ph.GA]



analysis of 16 VLBA observations MOJAVE 15 GHz 2009-18



global robotic network of
optical telescopes
connects TXS 0506+056
to IC170922A



“MASTER found the blazar in the off-state *after one minute*
and then switched to on-state two hours after the event.
The effect is observed at a 50-sigma significance level”

Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

V.M. Lipunov^{1,2}, V.G. Kornilov^{1,2}, K.Zhirkov¹, E. Gorbovsyoy², N.M. Budnev⁴, D.A.H.Buckley³, R. Rebolo⁵, M. Serra-Ricart⁵, R. Podesta^{9,10}, N.Tyurina², O. Gress^{4,2}, Yu.Sergienko⁸, V. Yurkov⁸, A. Gabovich⁸, P.Balanutsa², I.Gorbunov², D.Vlasenko^{1,2}, F.Balakin^{1,2}, V.Topolev¹, A.Pozdnyakov¹, A.Kuznetsov², V.Vladimirov², A. Chasovnikov¹, D. Kuvshinov^{1,2}, V.Grinshpun^{1,2}, E.Minkina^{1,2}, V.B.Petkov⁷, S.I.Svertilov^{2,6}, C. Lopez⁹, F. Podesta⁹, H.Levato¹⁰, A. Tlatov¹¹, B. Van Soelen¹², S. Razzaque¹³, M. Böttcher¹⁴

MASTER

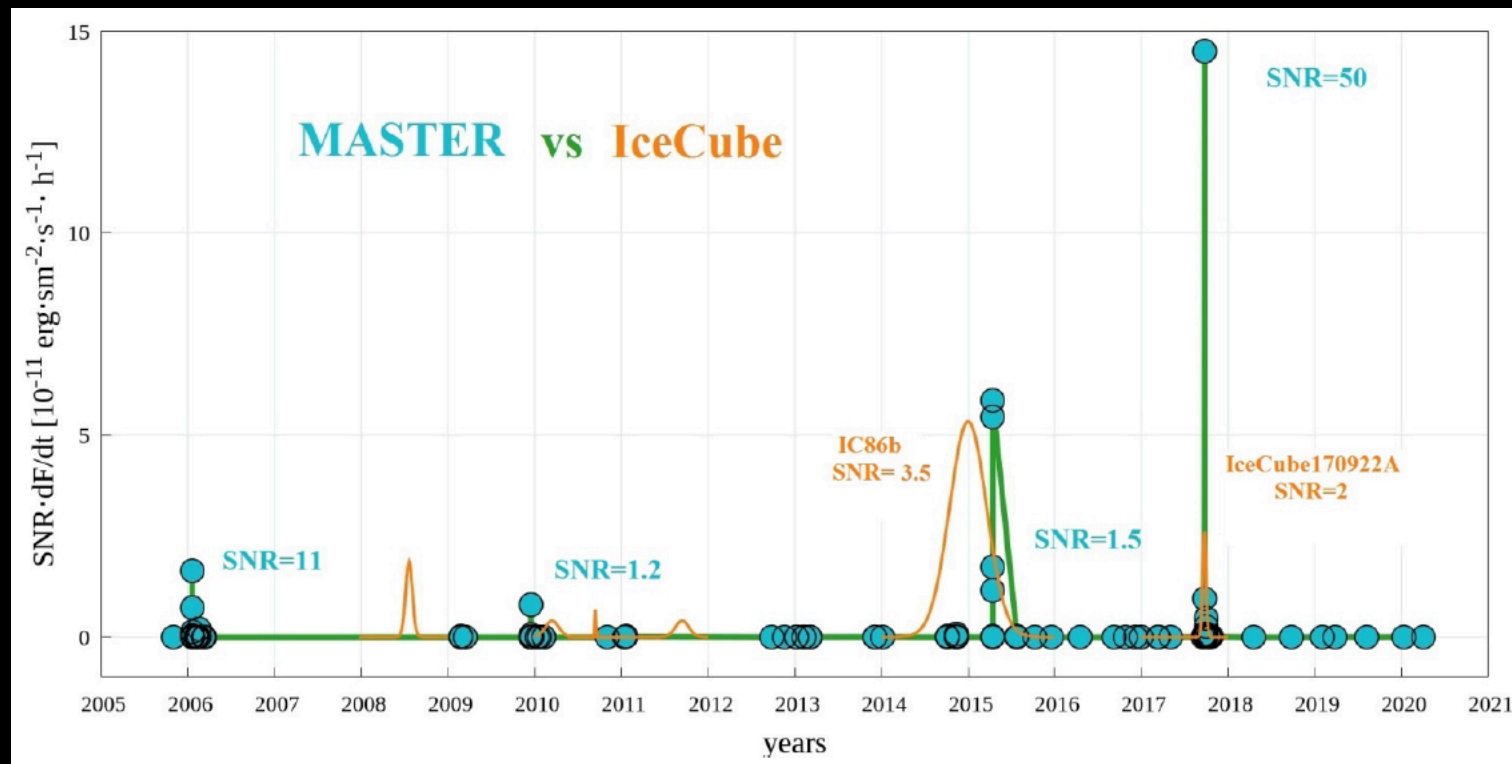
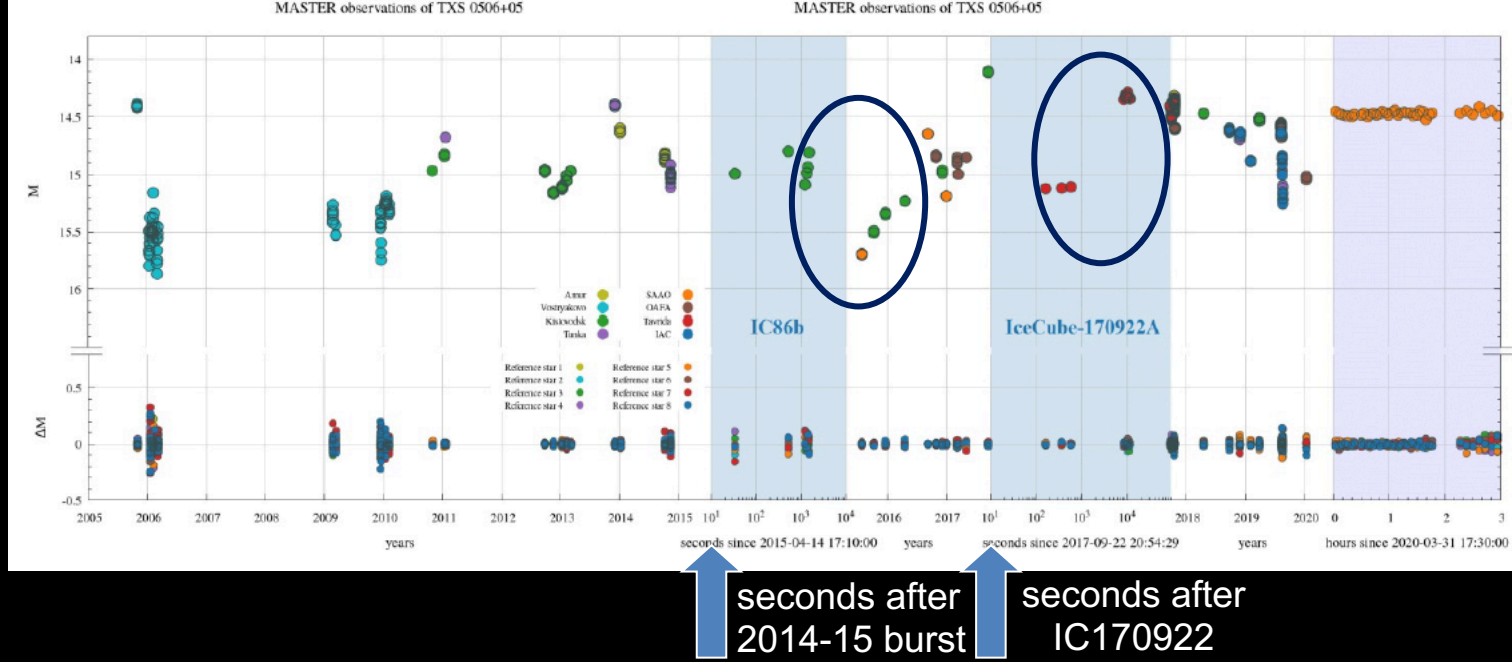
robotic network

optical observations
TXS 0506+056
since 2005

blue panels:
expanded time axis
years \rightarrow seconds

time variation of flux
times
signal-to-noise

hour-scale
variability of the
source after
neutrino emission



theory: not a “vanilla” blazar

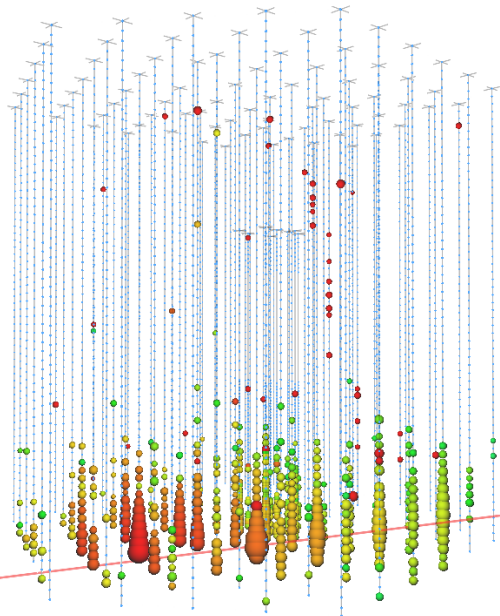
what is the target found in the radio and optical images?

blueprint of TXS accelerator still evolving

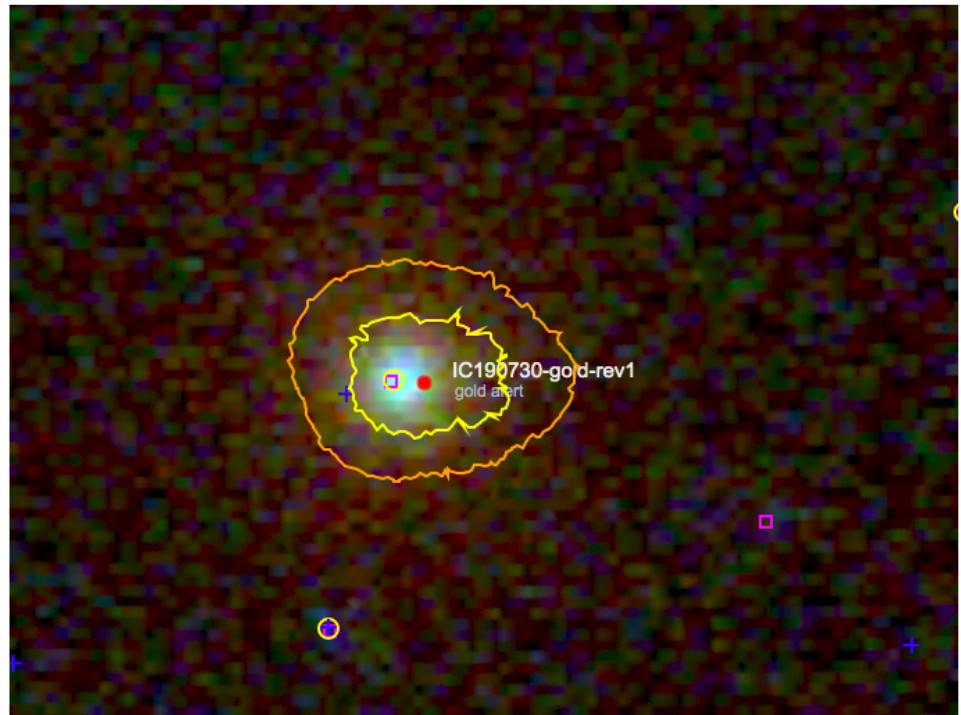
is cosmic ray origin really connected to blazars or do other sources also turn into TXS-type neutrino beam dumps?

multimessenger astronomy is “subtle but not malicious”

some other intriguing events: 190730, 191001, 200107...



```
[IceEventHeader:
  StartTime: 2019-07-30 20:50:41.311,032,730,0 U
  EndTime : 2019-07-30 20:50:41.311,062,007,2 U
  RunID : 132910
  SubrunID : 0
  EventID : 57145925
  SubEventID : 0
  SubEventStream : InIceSplit
]
```



IC 190730: 300 TeV

- coincident with PKS 1502+106
- radio burst

[[Previous](#) | [Next](#)]

Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; *S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. Würzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO) on 7 Aug 2019; 12:31 UT*

Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

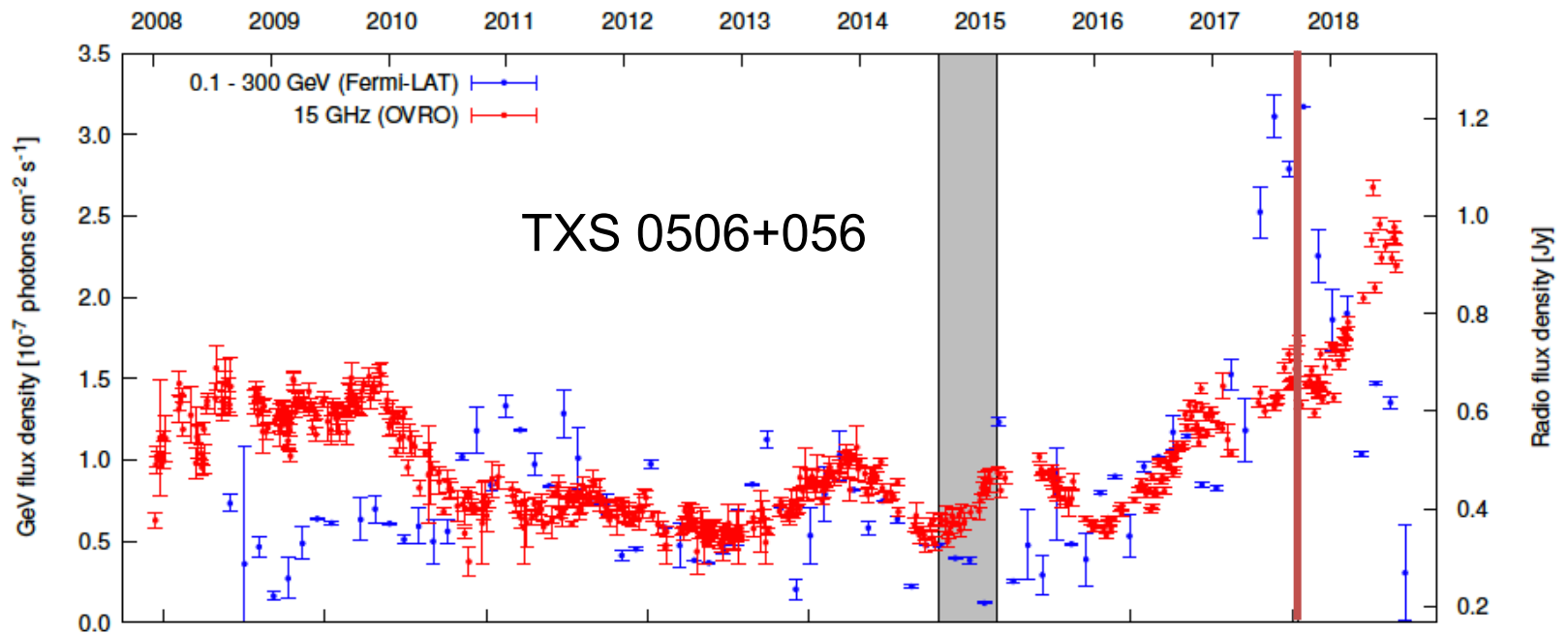
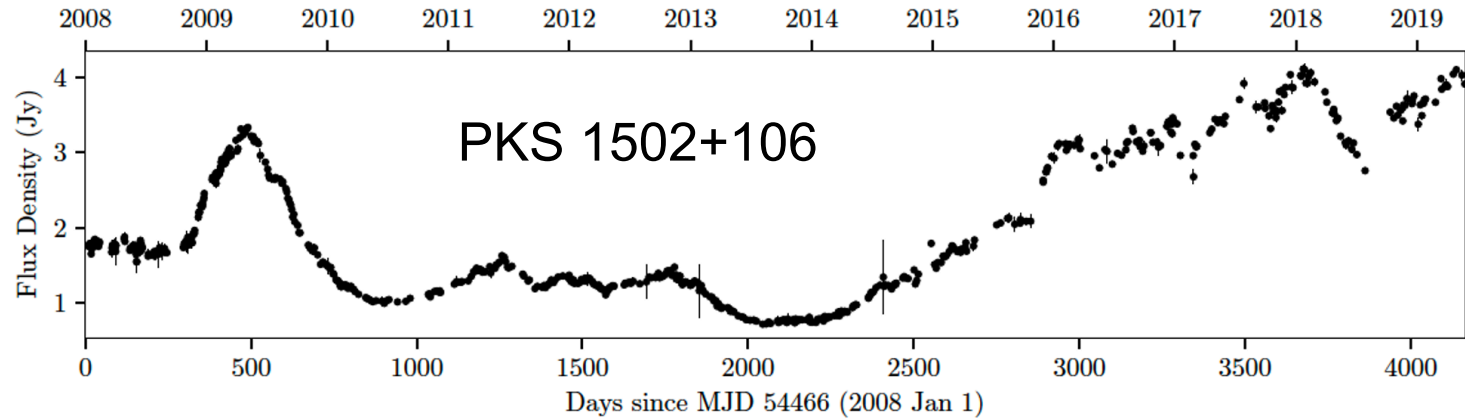
[Tweet](#)

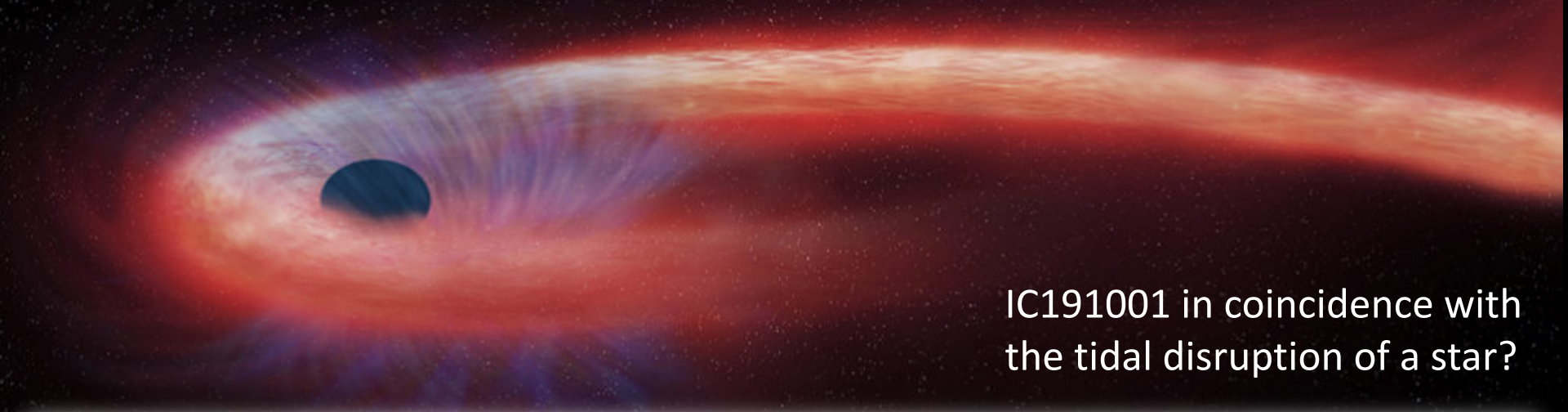
On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (ATel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event [IceCube-170922A](#).

Related

- 12996 [Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz](#)
- 12985 [IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations](#)
- 12983 [Optical fluxes of candidate neutrino blazar PKS 1502+106](#)
- 12981 [ASKAP observations of blazars possibly associated with neutrino events IC190730A and IC190704A](#)
- 12974 [Optical follow-up of IceCube-190730A with ZTF](#)
- 12971 [IceCube-190730A: MASTER alert observations and analysis](#)
- 12967 [IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106](#)
- 12926 [VLA observations reveal increasing brightness of 1WHSP J104516.2+275133, a potential source of IC190704A](#)

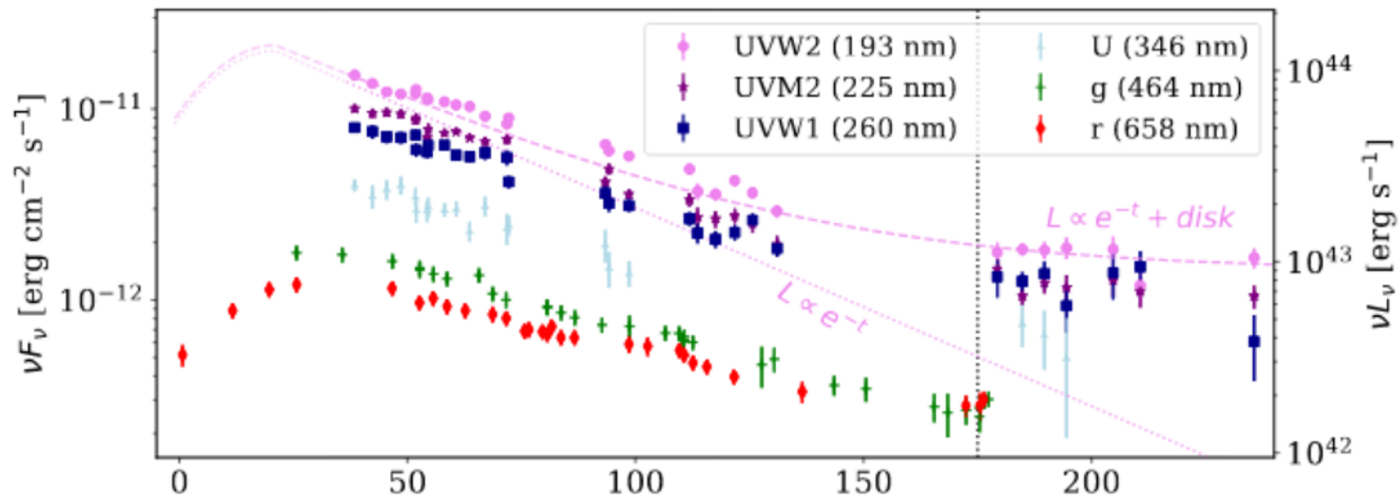
the two highest energy IceCube alerts are coincident with radio flares





IC191001 in coincidence with the tidal disruption of a star?

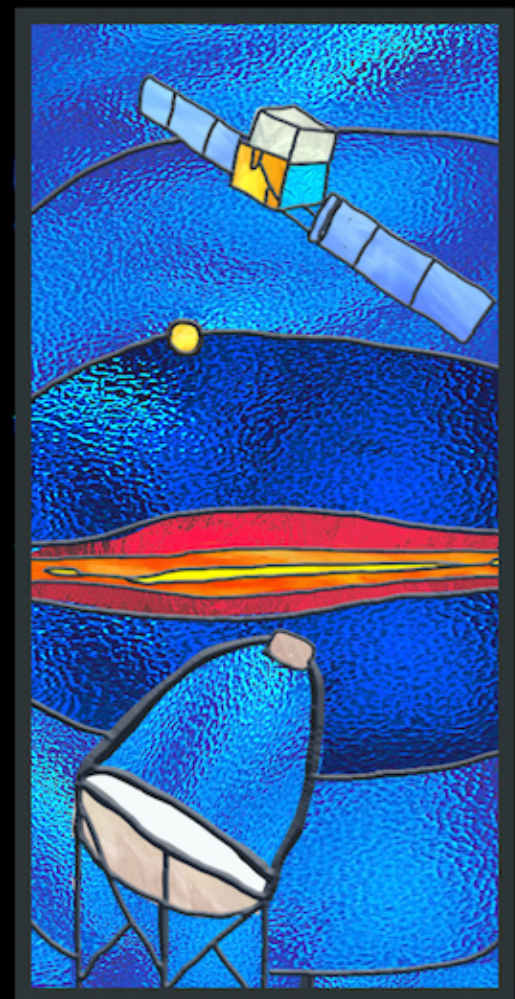
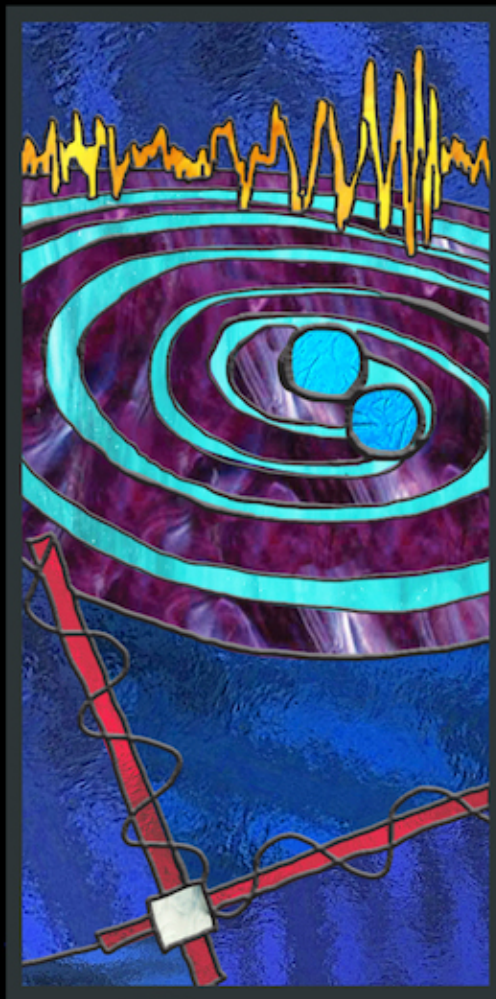
IC191001 close to luminous TDE of the Zwicky Transit Factory



Discovered in April 2019 by ZTF, lots of data! Neutrino arrived ~ 175 days post-discovery.

Relatively early/bright plateau, consistent with accretion disk formation.

As for most TDEs, well-described by thermal emission ($T \sim 10^{4.6}$ K, $R \sim 10^{14.5}$ cm, $L_{\text{peak}} \sim 10^{44.5}$ erg s $^{-1}$)



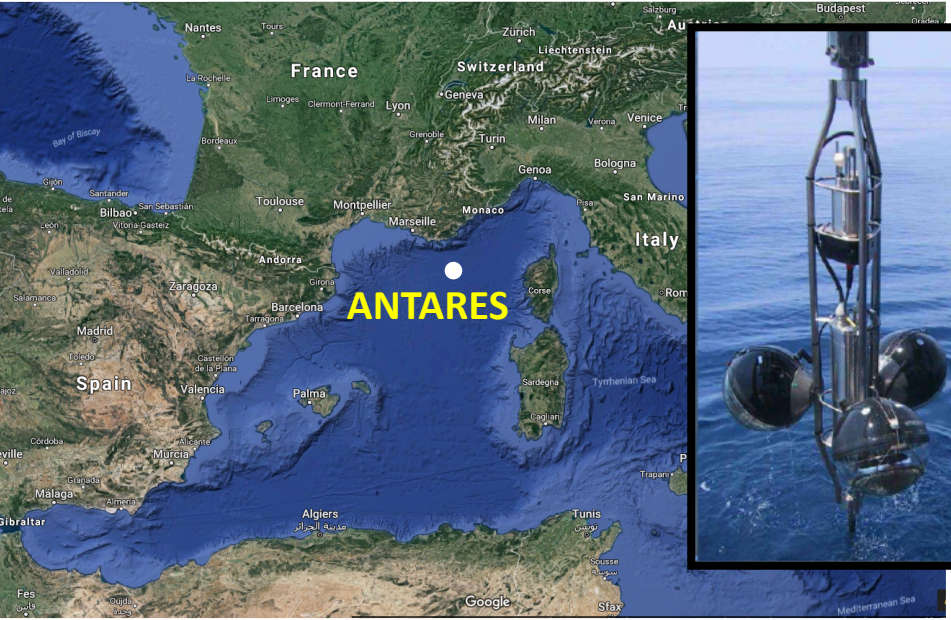
next attraction: gravitational waves + neutrinos?

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

Neutrinos in the Era of Multimessenger Astronomy

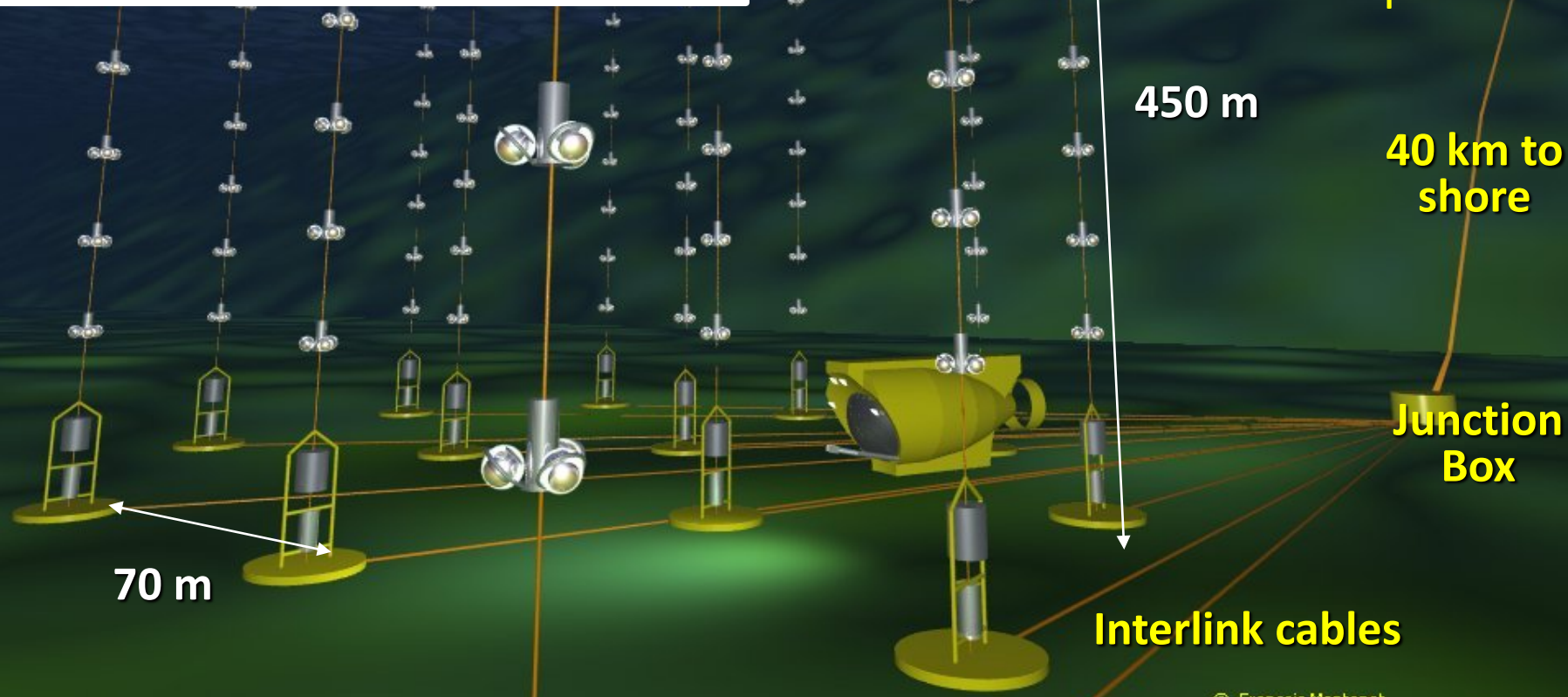
francis halzen

- cosmic neutrinos: many independent observations
 - muon neutrinos through the Earth
 - starting neutrinos: all flavors
- the first high-energy cosmic ray accelerator: a rotating supermassive black hole
- from discovery to astronomy: next-generation instruments: x 5~10 (PeV) and x100 (EeV)
- also, a beam for PeV neutrino physics



ANTARES

Running since 2007
885 10" PMTs
12 lines
25 storeys/line
3 PMTs / storey
2500 m deep



450 m

40 km to shore

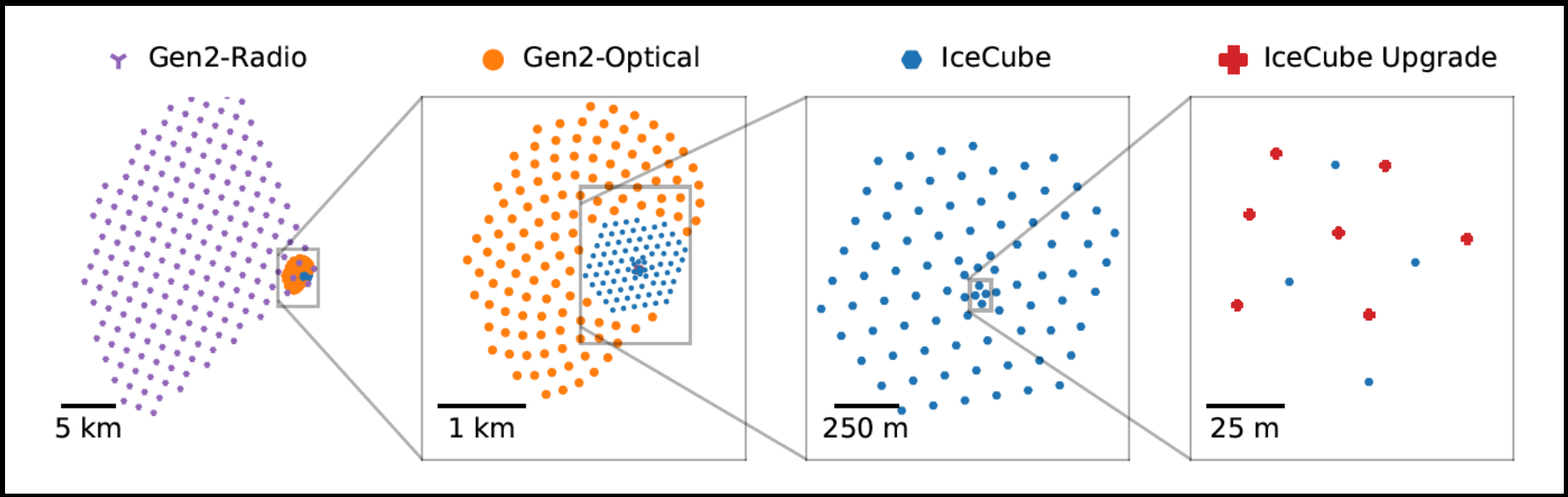
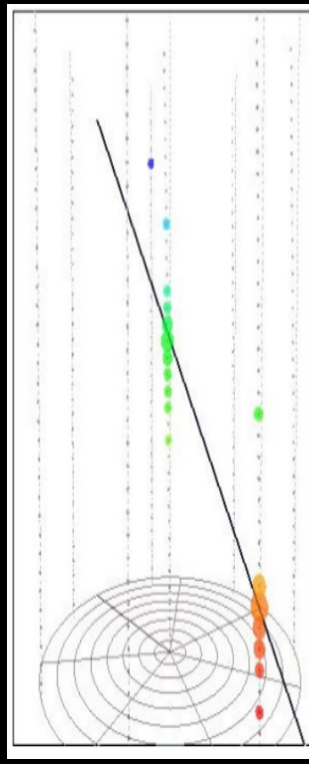
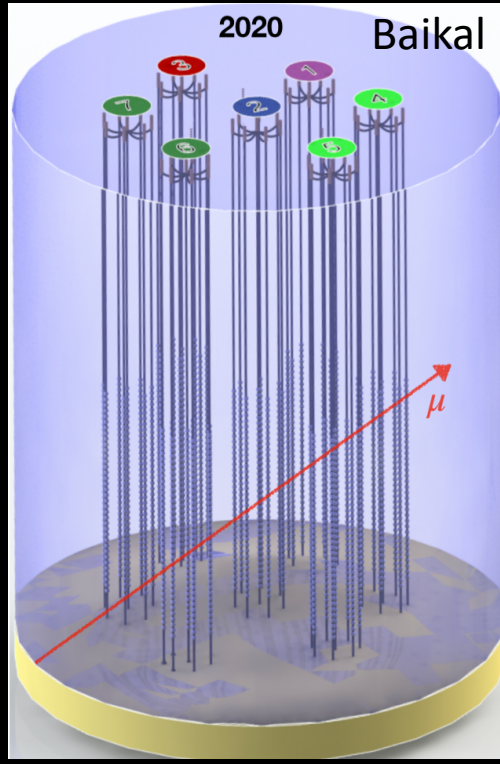
Junction Box

70 m

Interlink cables

Lake Baikal experiment reaches 0.35 km³

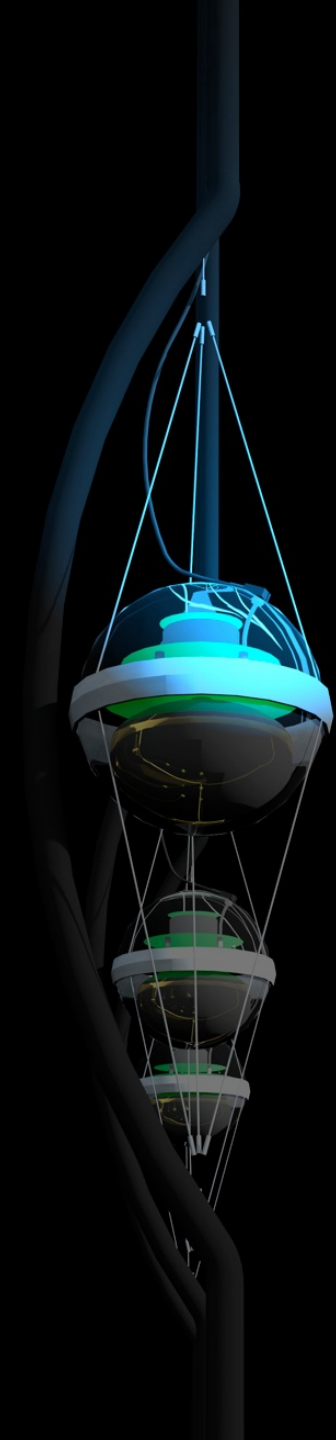




Neutrinos in the Era of Multimessenger Astronomy

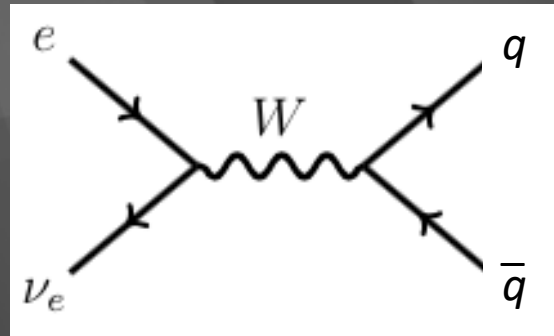
francis halzen

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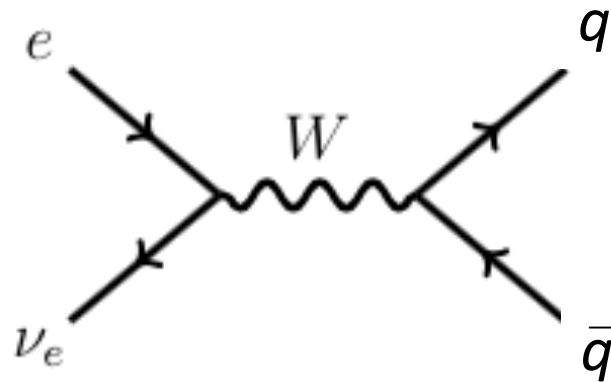
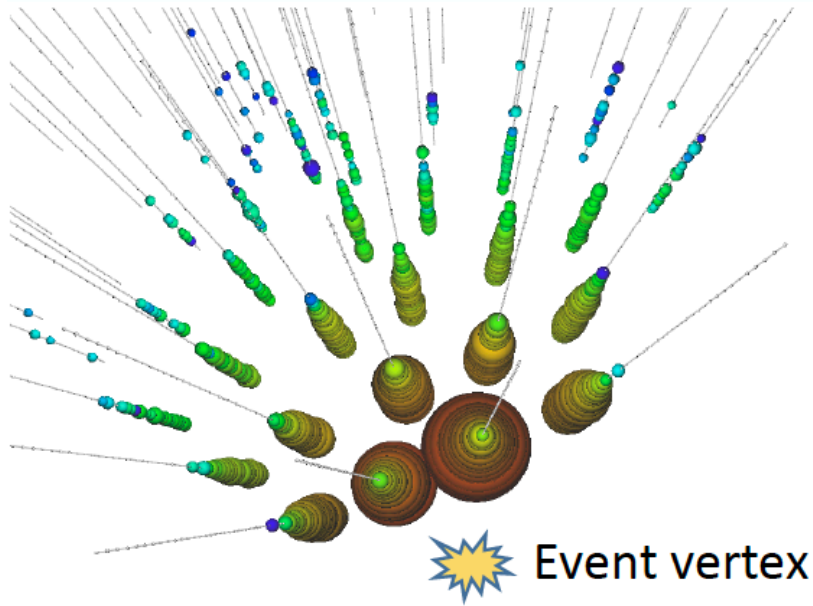


the first Glashow resonance event:

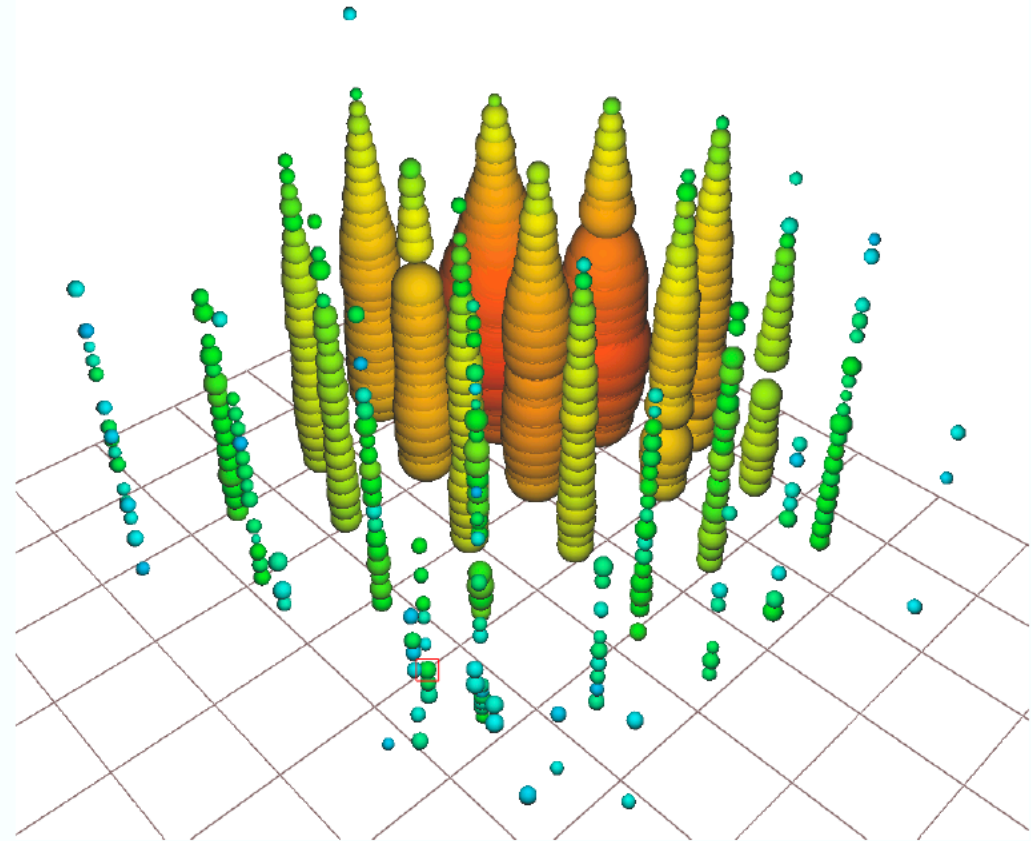
anti- ν_e + atomic electron \rightarrow real W at 6.3 PeV



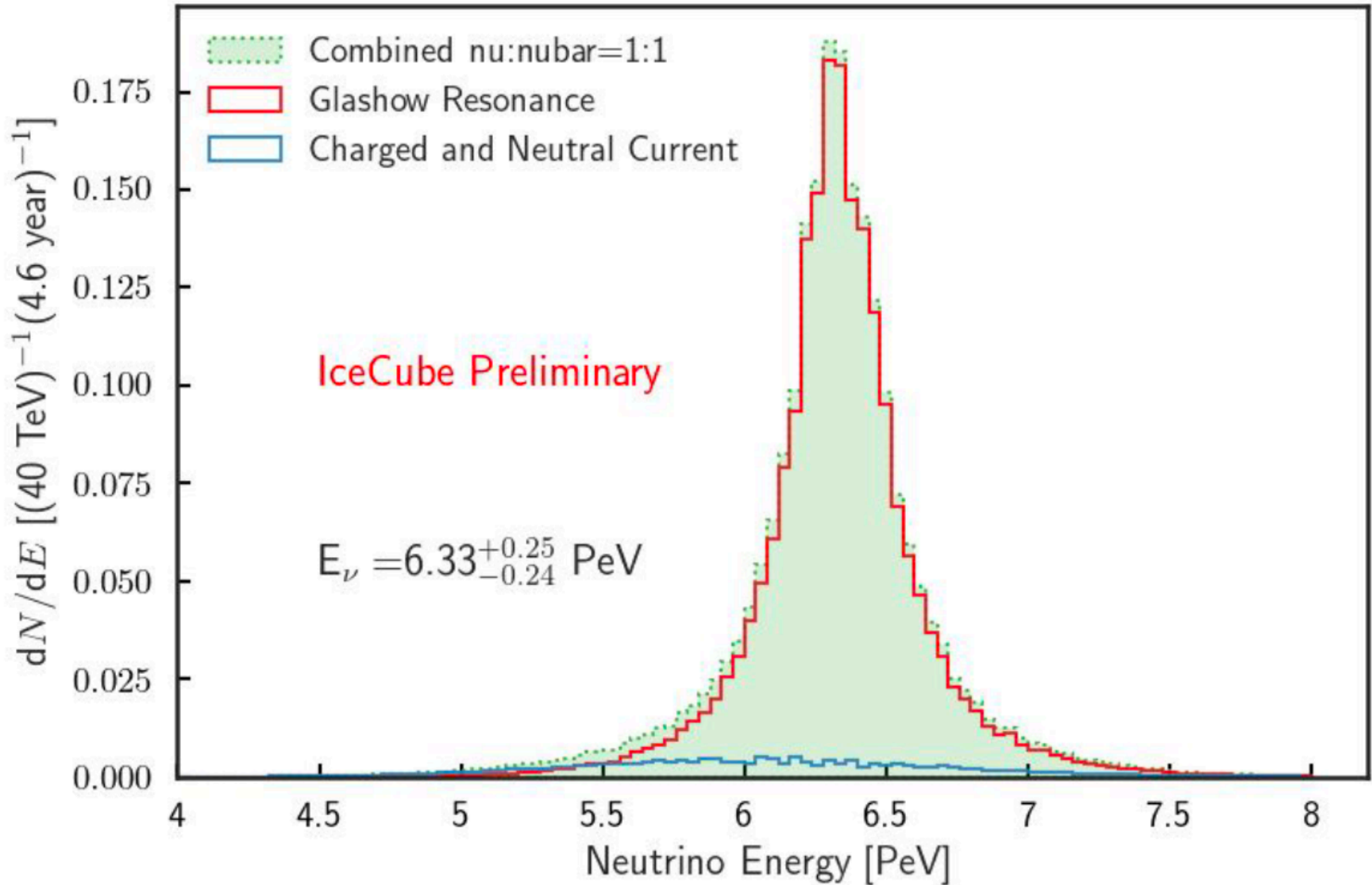
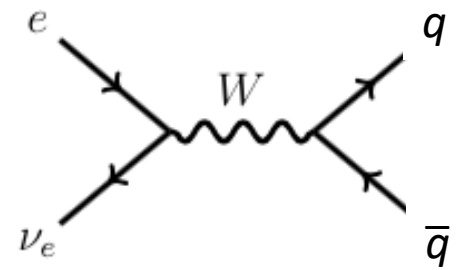
partially contained event with energy 6.3 PeV



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

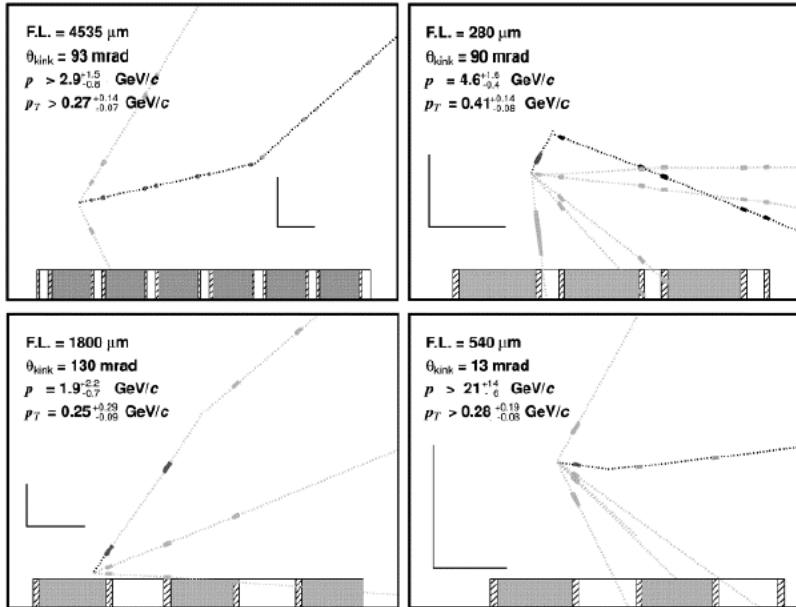


- energy measurement understood
- identification of anti-electron neutrinos



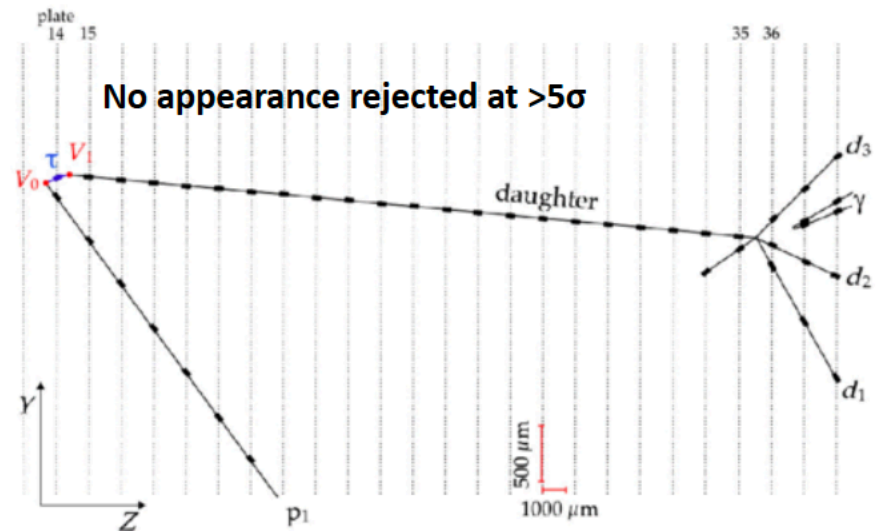
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion



DONUT Phys. Lett. B, [Volume 504, Issue 3](#), 12 April 2001, Pages 218-224

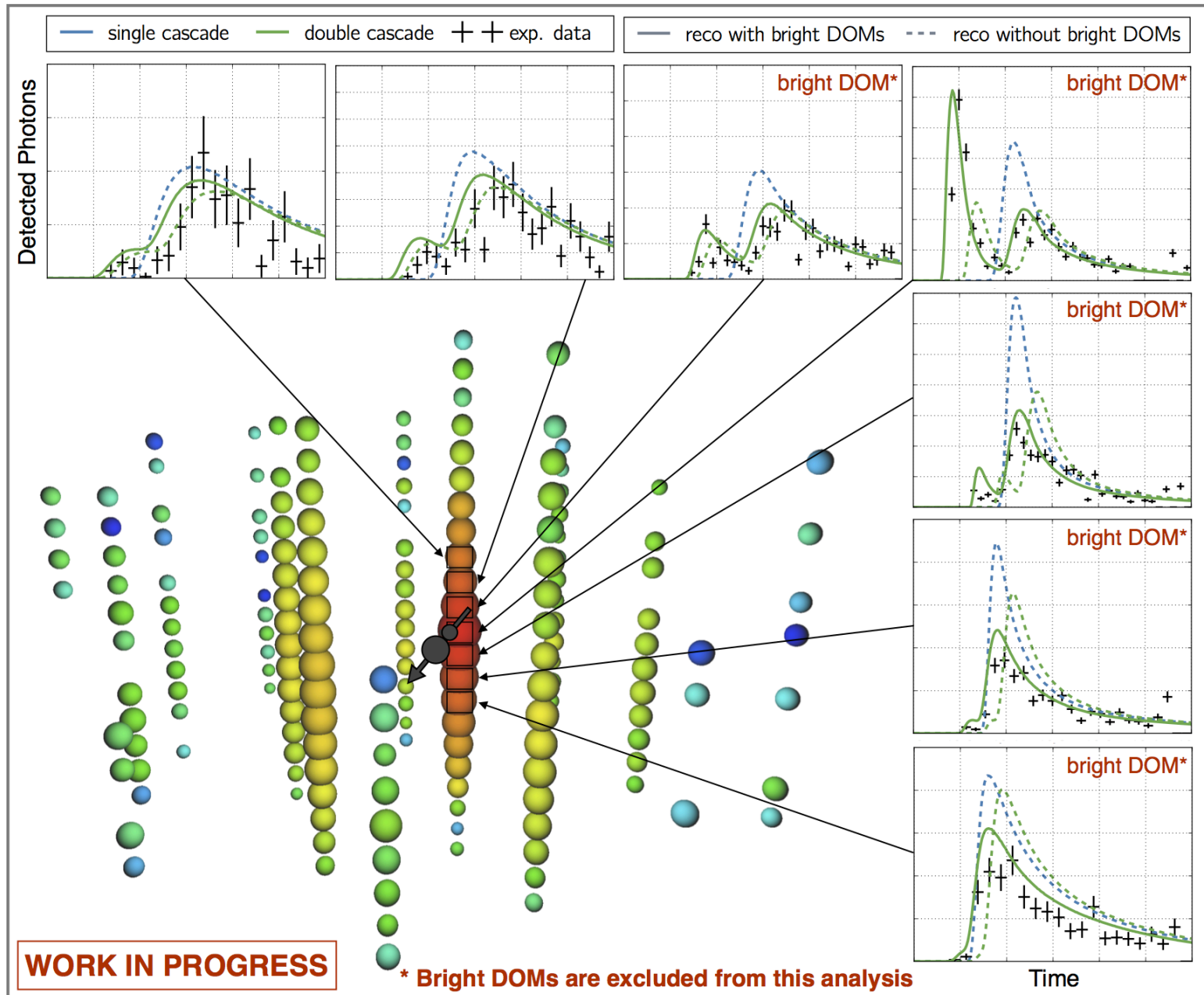
OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion



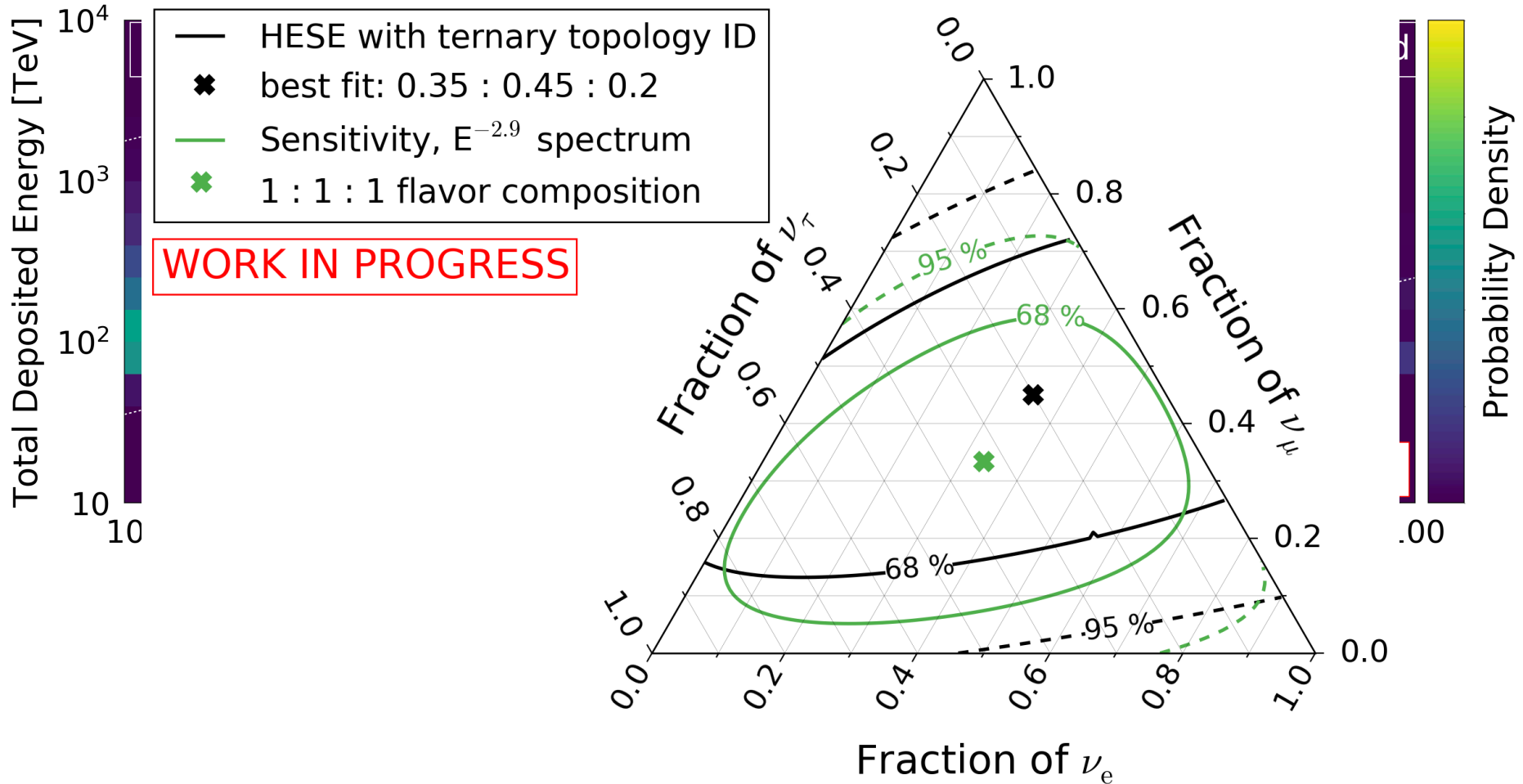
OPERA Phys. Rev. Lett. 115, 121802 (2015)

$$\text{tau decay length} = \gamma c \tau = 50\text{m per PeV}$$

a cosmic tau neutrino: livetime 17m



high-energy starting events – 7.5 yr



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



neutrino astronomy 2020

- it exists
- more neutrinos, better neutrinos
- closing in on cosmic ray sources

THE ICECUBE COLLABORATION



THE ICECUBE COLLABORATION



AUSTRALIA 1

UNITED KINGDOM 1

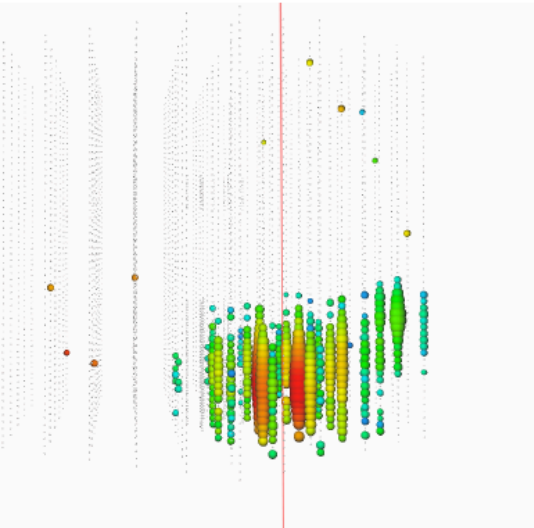
UNITED STATES 25



overflow sides

IC200107A: The “DNN-starting-track Neutrino”

DNN (HESE V3)



High-charge HESE event, did not qualify as alert
(see SplineMPE direction...)

Good starting track, confirmed by Theo's DNN

Signalness ~65% (Not reported).

Posted in [GCN circular](#).

Coincident with “extreme blazar”.

Followed Up In 7 GCNs + 3 ATEs + 3 Papers:

ZTF

(Non-detection)

Fermi GBM

(Non-detection)

Integral

(Non-detection)

HAWC

(Non-detection)

Fermi-LAT

(Nothing coincident,
no new sources)

Swift

(ATEL, ATEL)
(Coincident Extreme
Blazar, flaring)

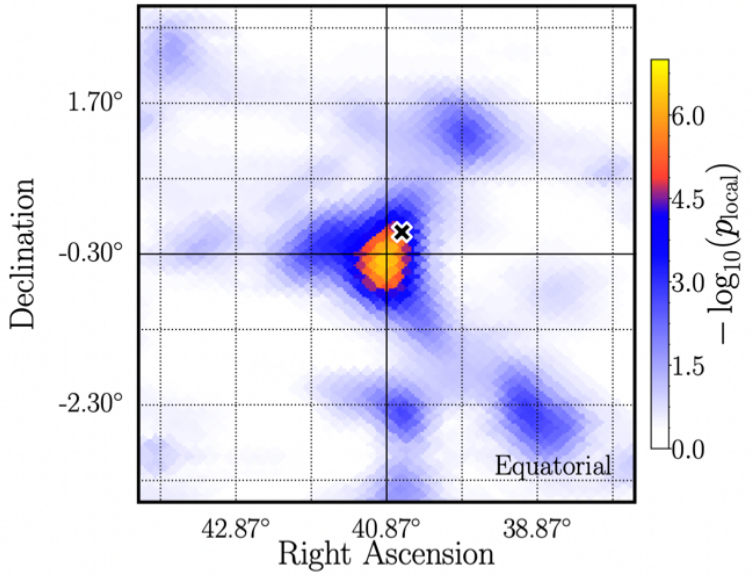
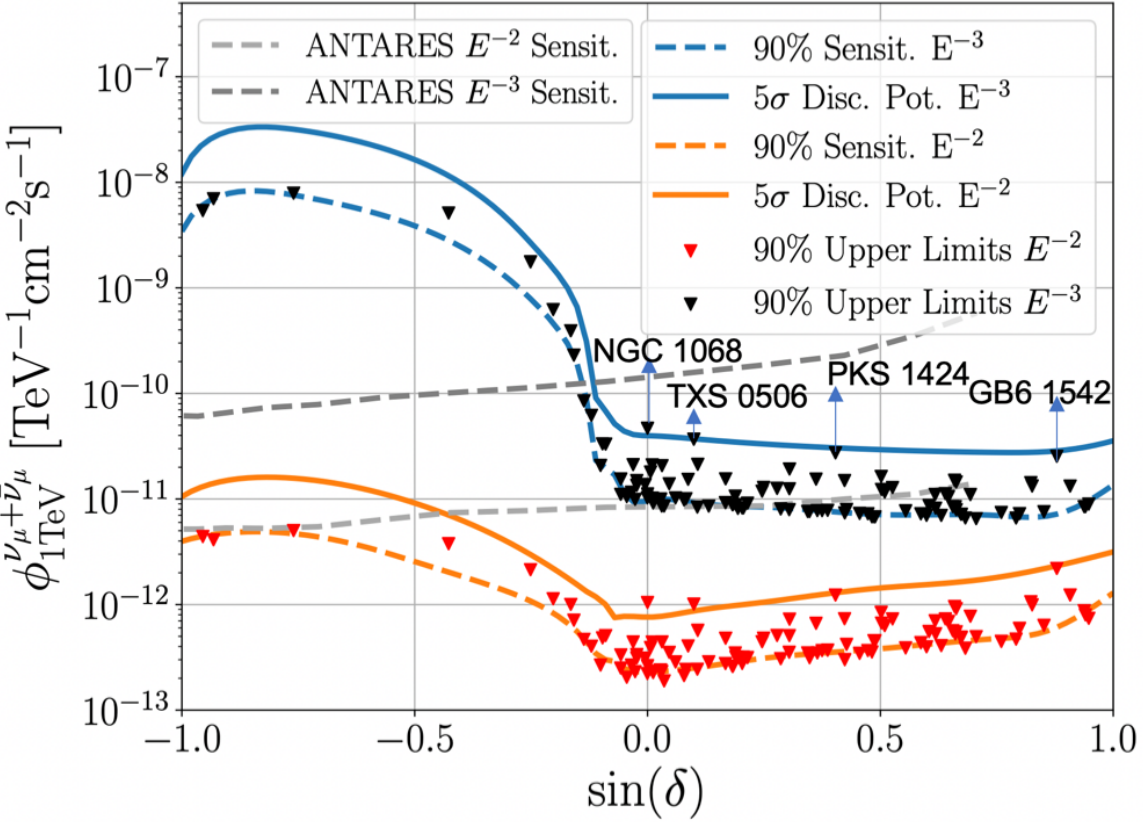
IceCube (FRA)

($p_2 = 0.04$)

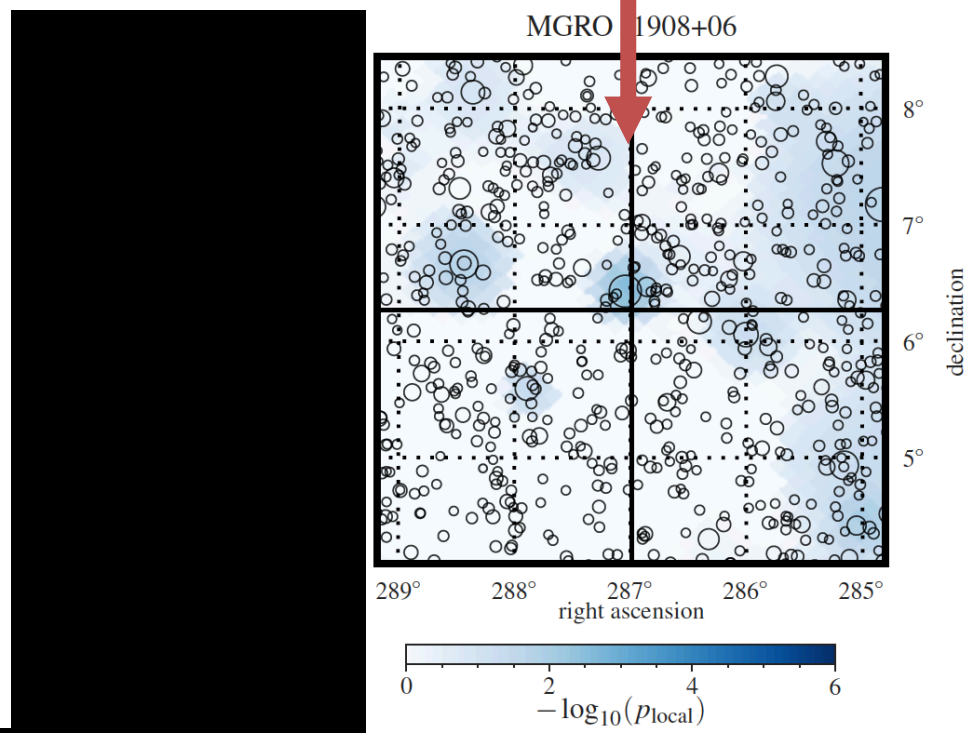
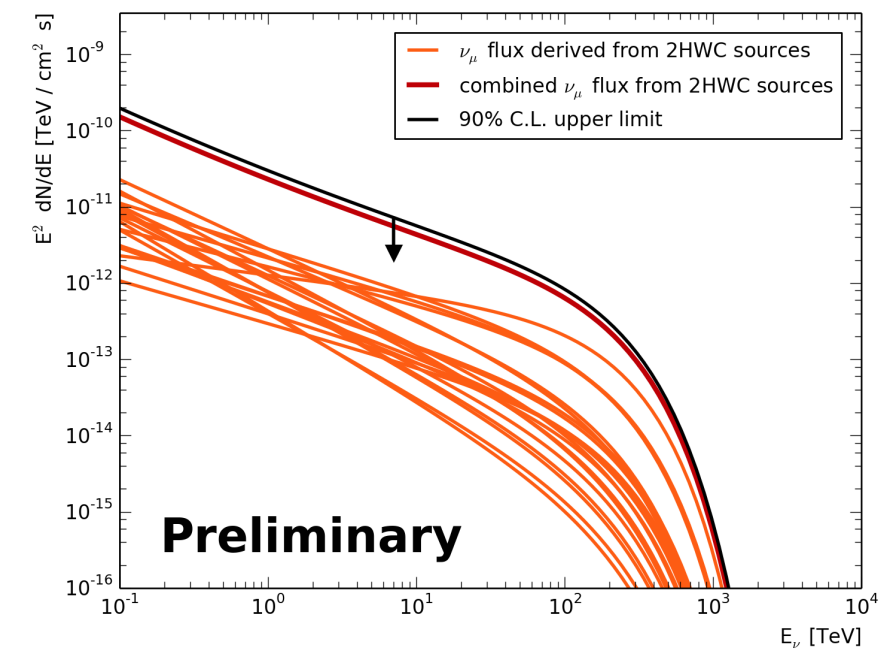
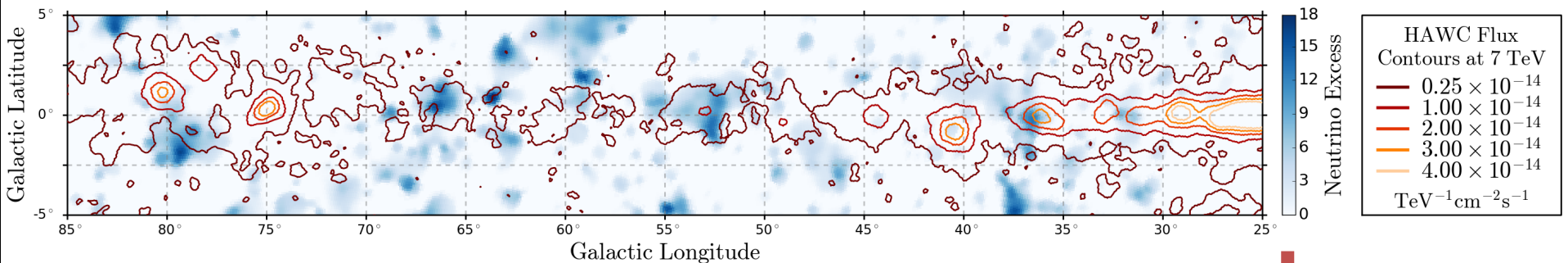
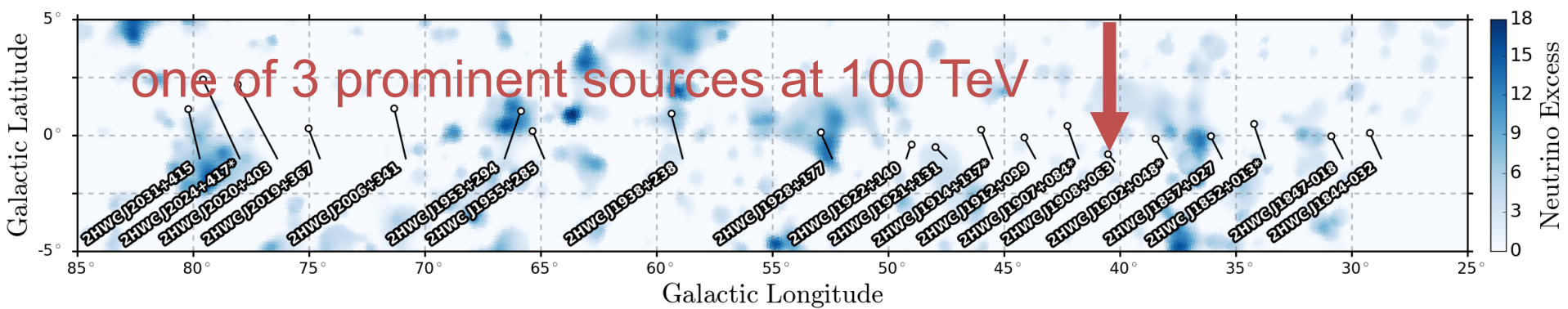
LBT

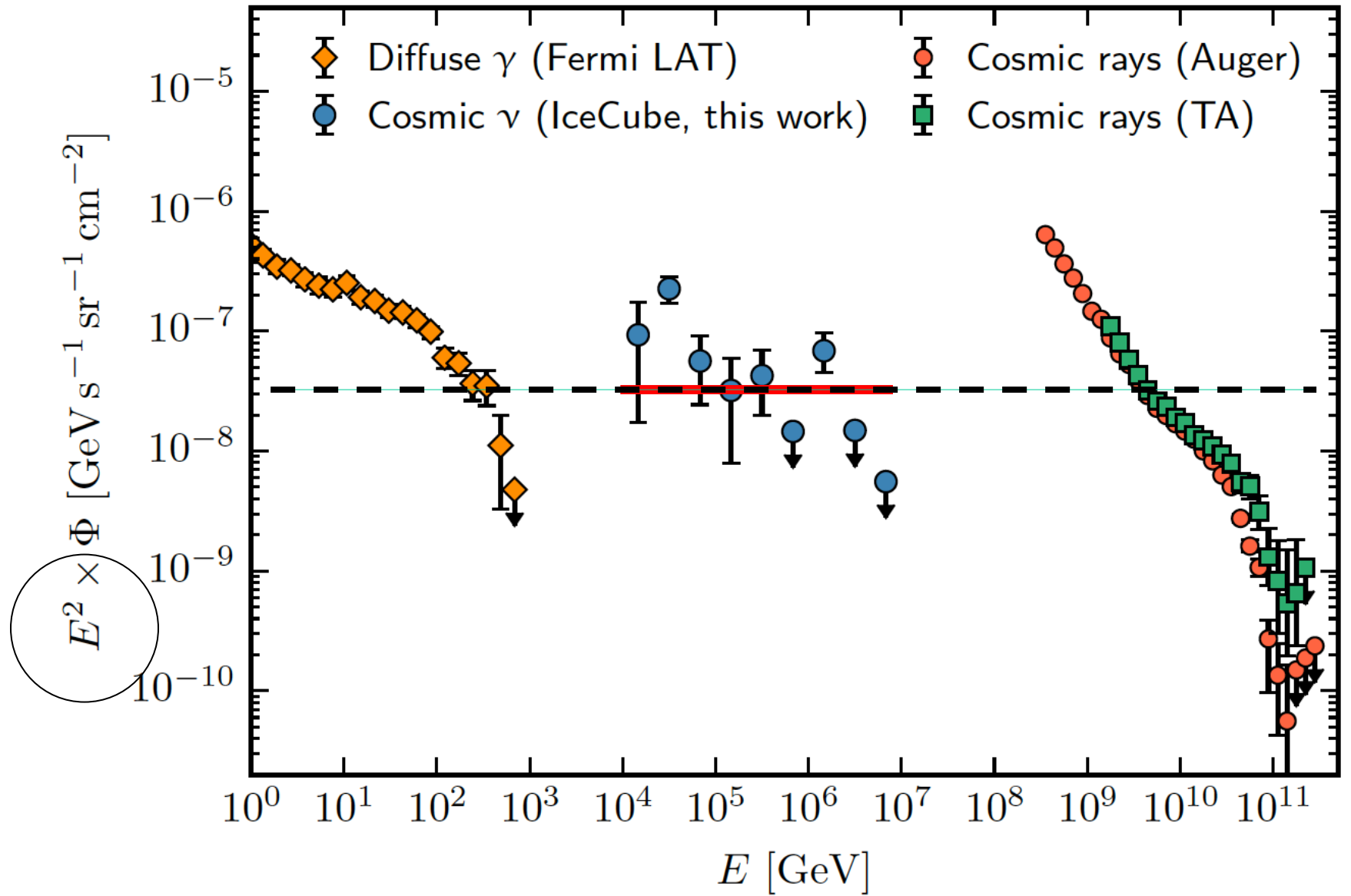
(Redshift)

10 years of IceCube data: evidence for non-uniform skymap, mostly resulting from 4 source candidates

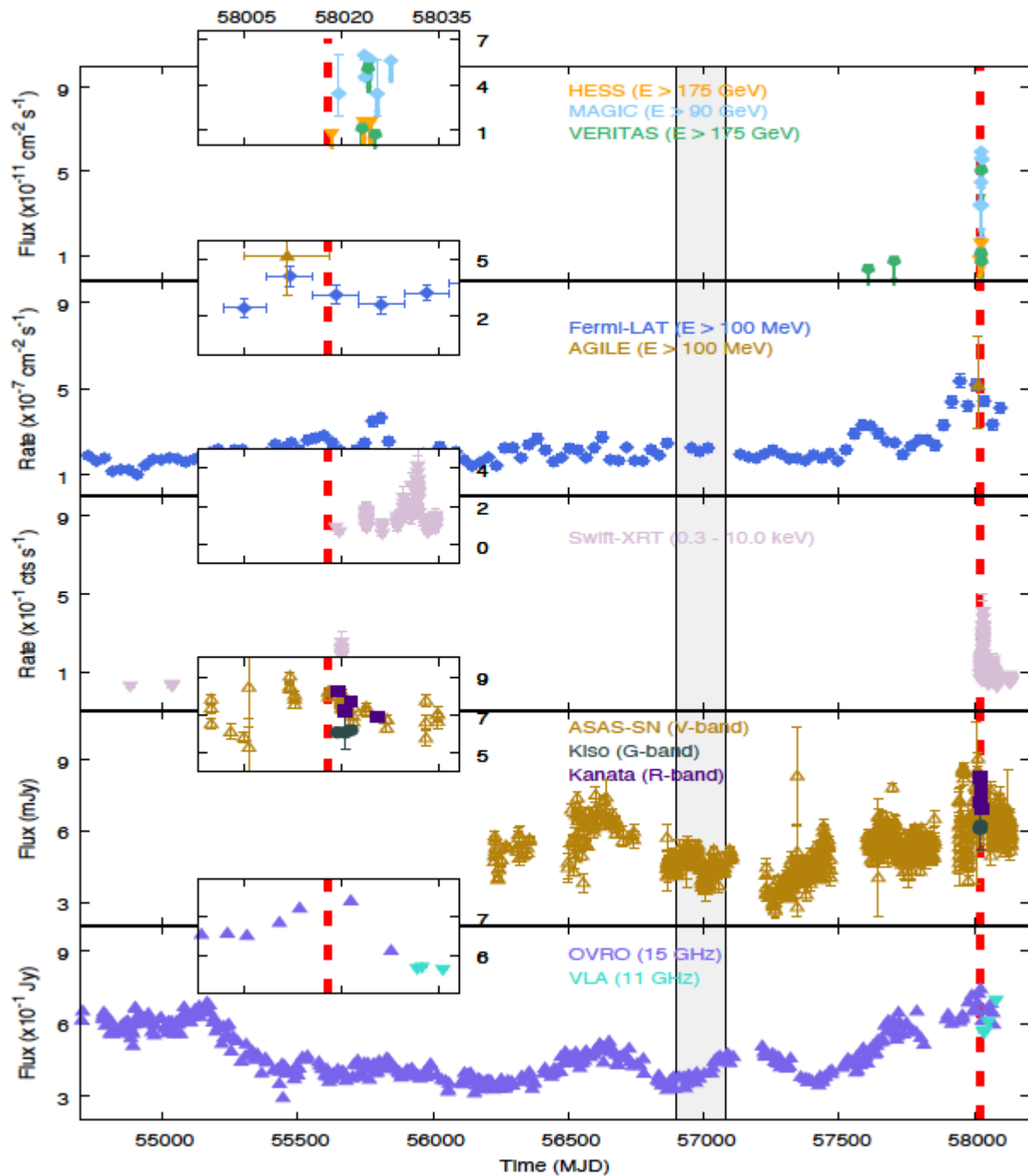


why not seen before?





energy in the Universe in gamma rays, neutrinos and cosmic rays



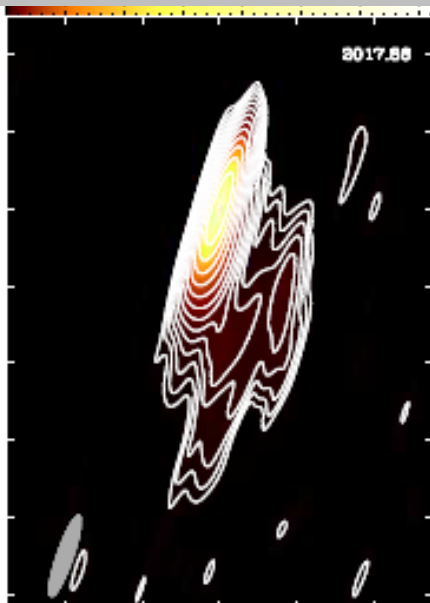
TXS 0506+056

“beyond 5 mas the core loses its tight collimation...”

jet found a target after ~tens of pc

jet star interaction?

theory confirms observation?



1912.01743v1 [astro-ph.GA] 3 Dec 2019

LETTER TO THE EDITOR

Apparent superluminal core expansion and limb brightening in the candidate neutrino blazar TXS 0506+056

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⁶ Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16801, USA

⁷ National Aeronautics and Space Administration/Goddard Space Flight Center, Greenbelt, MD 20771, USA

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Submitted: November 28, 2019; Accepted: December 3, 2019

ABSTRACT

Context. IceCube has reported a very-high-energy neutrino (IceCube-170922A) in a region containing the blazar TXS 0506+056. Correlated gamma-ray activity has led to the first high-probability association of a high-energy neutrino with an extragalactic source. This blazar has been found to be in a radio outburst during the neutrino event.

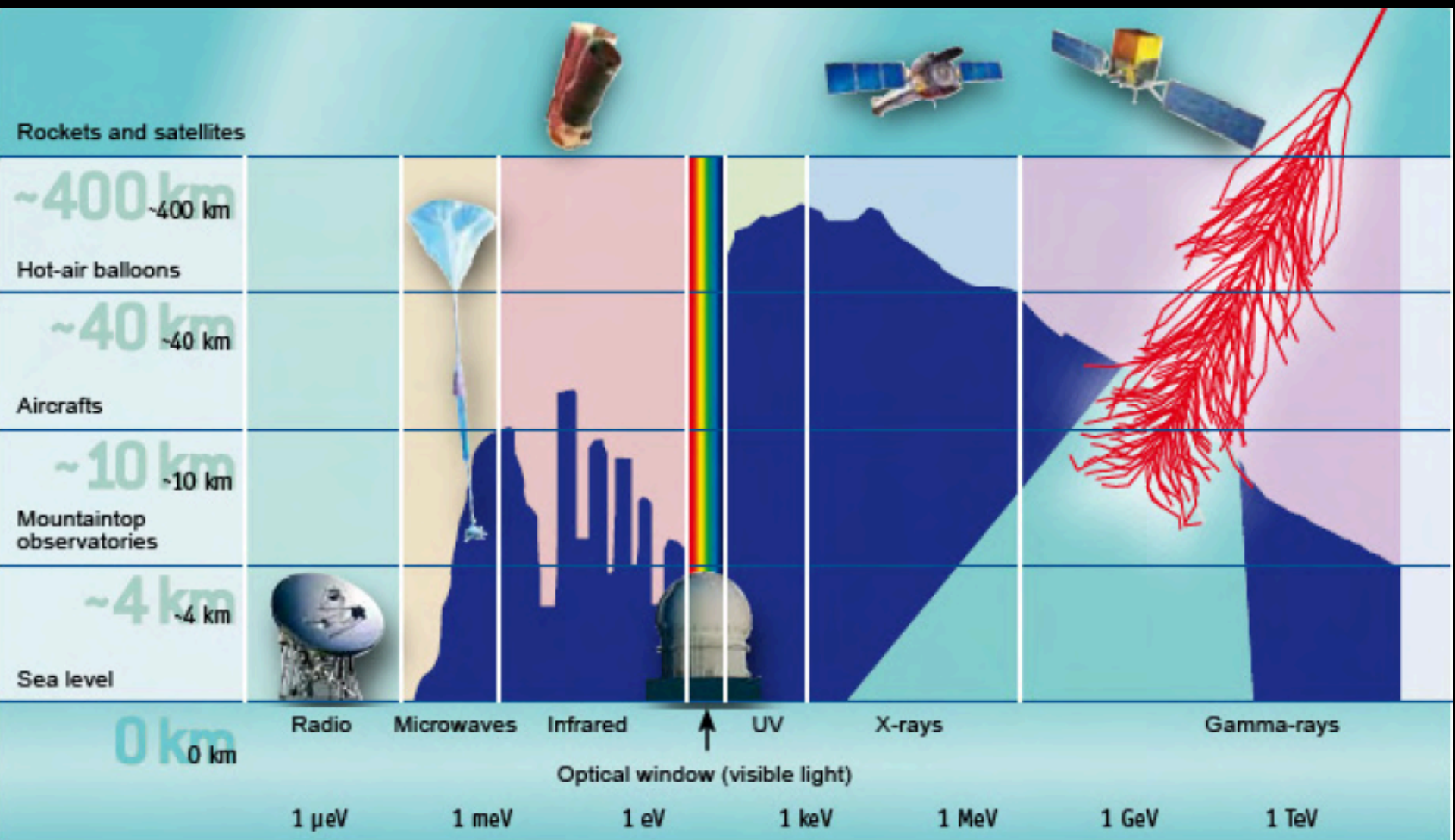
Aims. Our goal is to probe the sub-millisecond properties of the radio jet right after the neutrino detection and during the further evolution of the radio outburst.

Methods. We have performed target-of-opportunity very-long-baseline interferometry imaging observations at 43 GHz frequency, corresponding to 7 mm in wavelength, with the Very Long Baseline Array two and eight months, respectively, after the neutrino event.

Results. We produced two images of the radio jet of TXS 0506+056 at 43 GHz with angular resolutions of (0.2×1.1) mas and (0.2×0.5) mas, respectively. The source shows a compact, high brightness temperature core (albeit not approaching the equipartition limit, Readhead 1994) and a bright and originally very collimated inner jet. Beyond about 0.5 mas from the mm-VLBI core, the jet loses this tight collimation and expands rapidly. During the months after the neutrino event associated with this source, the overall flux density is rising. This flux density increase happens solely within the core. Notably, the core expands in size with apparent superluminal velocity during these six months so that the brightness temperature drops by a factor of three in spite of the strong flux density increase.

Conclusions. The radio jet of TXS 0506+056 shows strong signs of deceleration and/or a spine-sheath structure within the inner 1 mas (corresponding to about 70 pc to 140 pc in deprojected distance) from the mm-VLBI core. This structure is consistent with theoretical models that attribute the neutrino and gamma-ray production in TXS 0506+056 to interactions of electrons and protons in the highly-relativistic jet spine with external photons originating from a slower-moving jet region. Proton loading due to jet-star interactions in the inner host galaxy is suggested as the possible cause of deceleration.

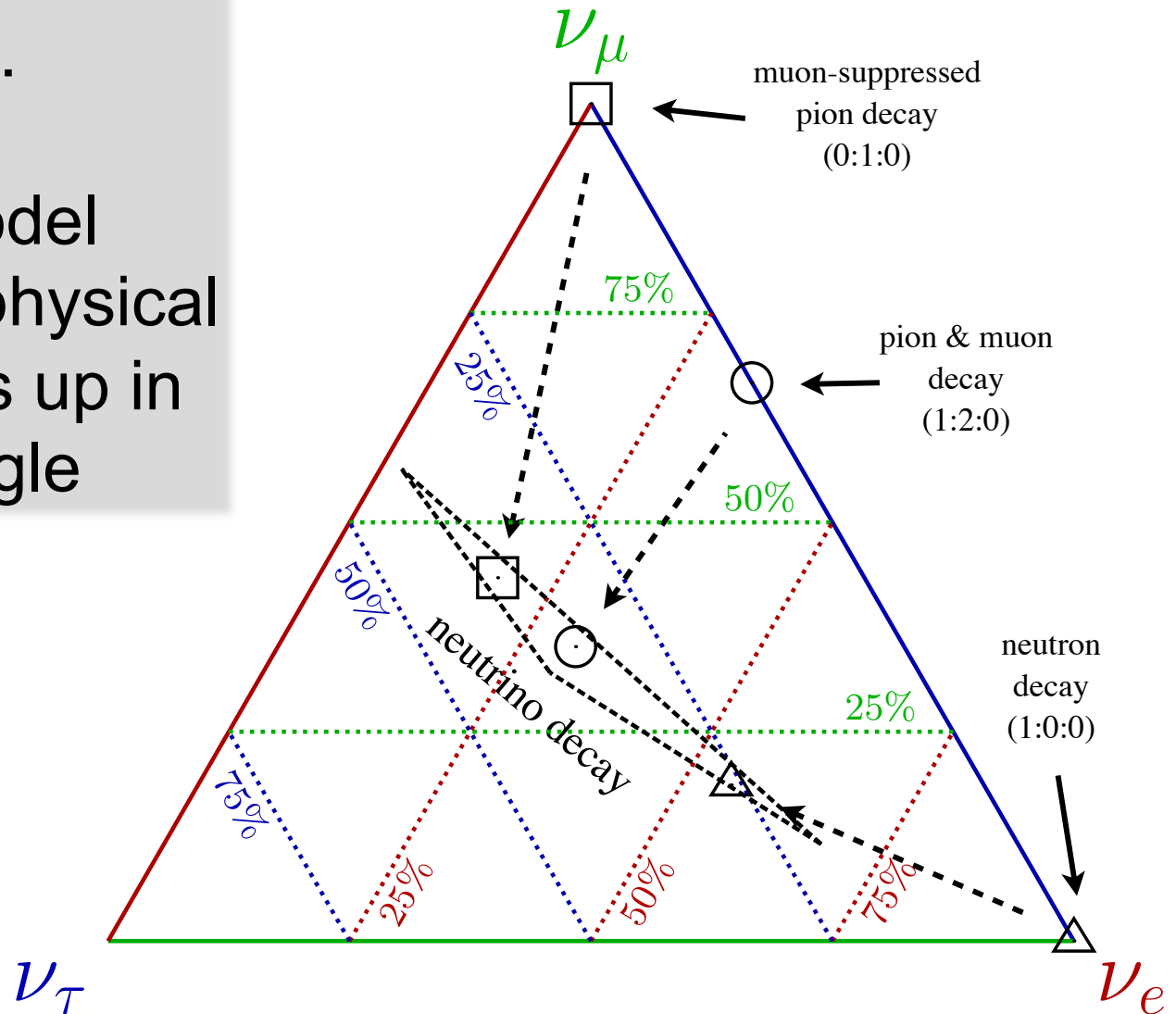
Key words. Radiation mechanisms: non-thermal – Neutrinos – Techniques: interferometric – Radio continuum: galaxies – Galaxies: quasars: individual: TXS 0506+056



new physics ?

if not...

every model
for the astrophysical
source ends up in
the triangle



upgrade/Gen2

- neutrino oscillation at PeV energy
- test of the 3-neutrino scenario
- neutrino physics BSM

