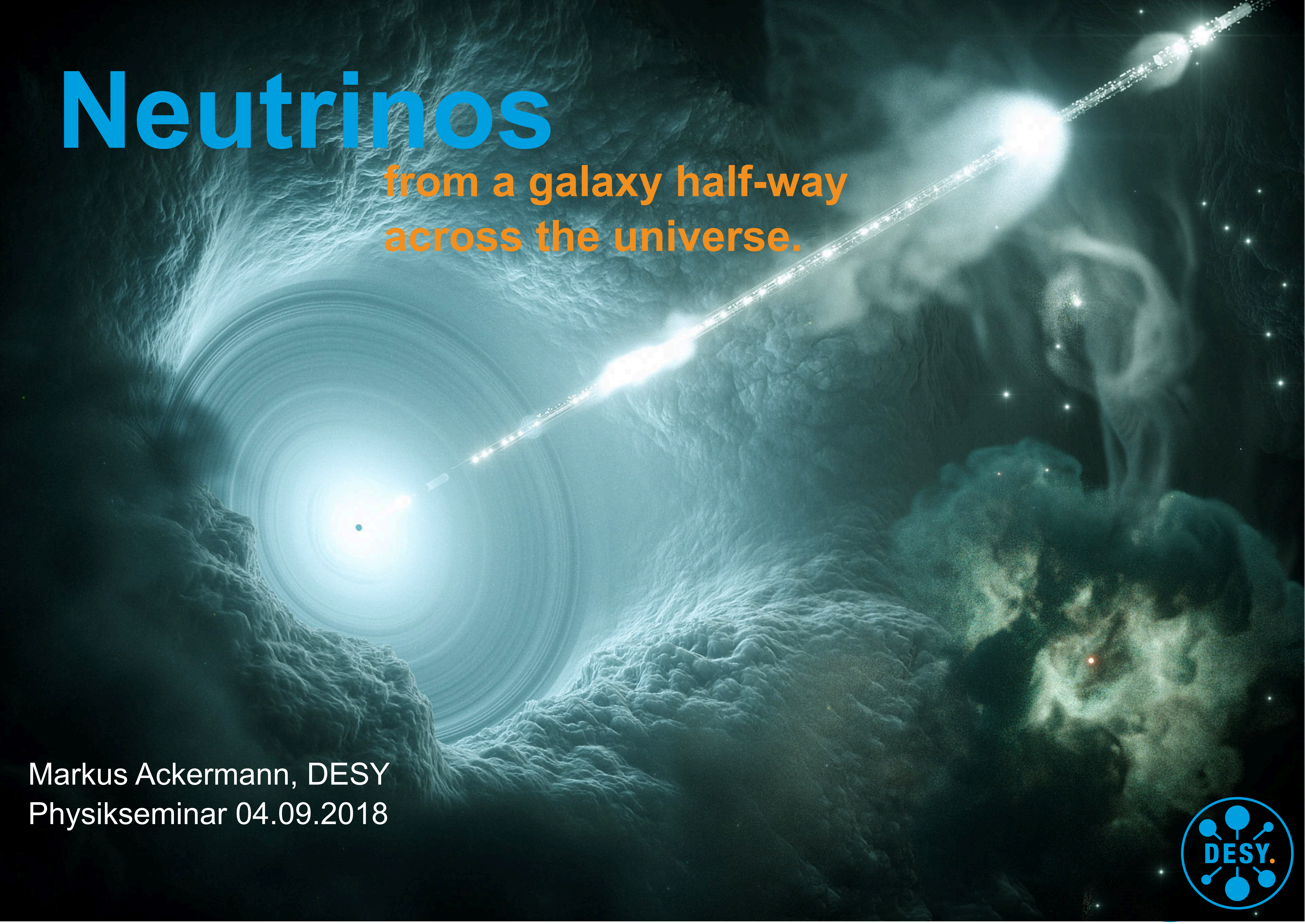


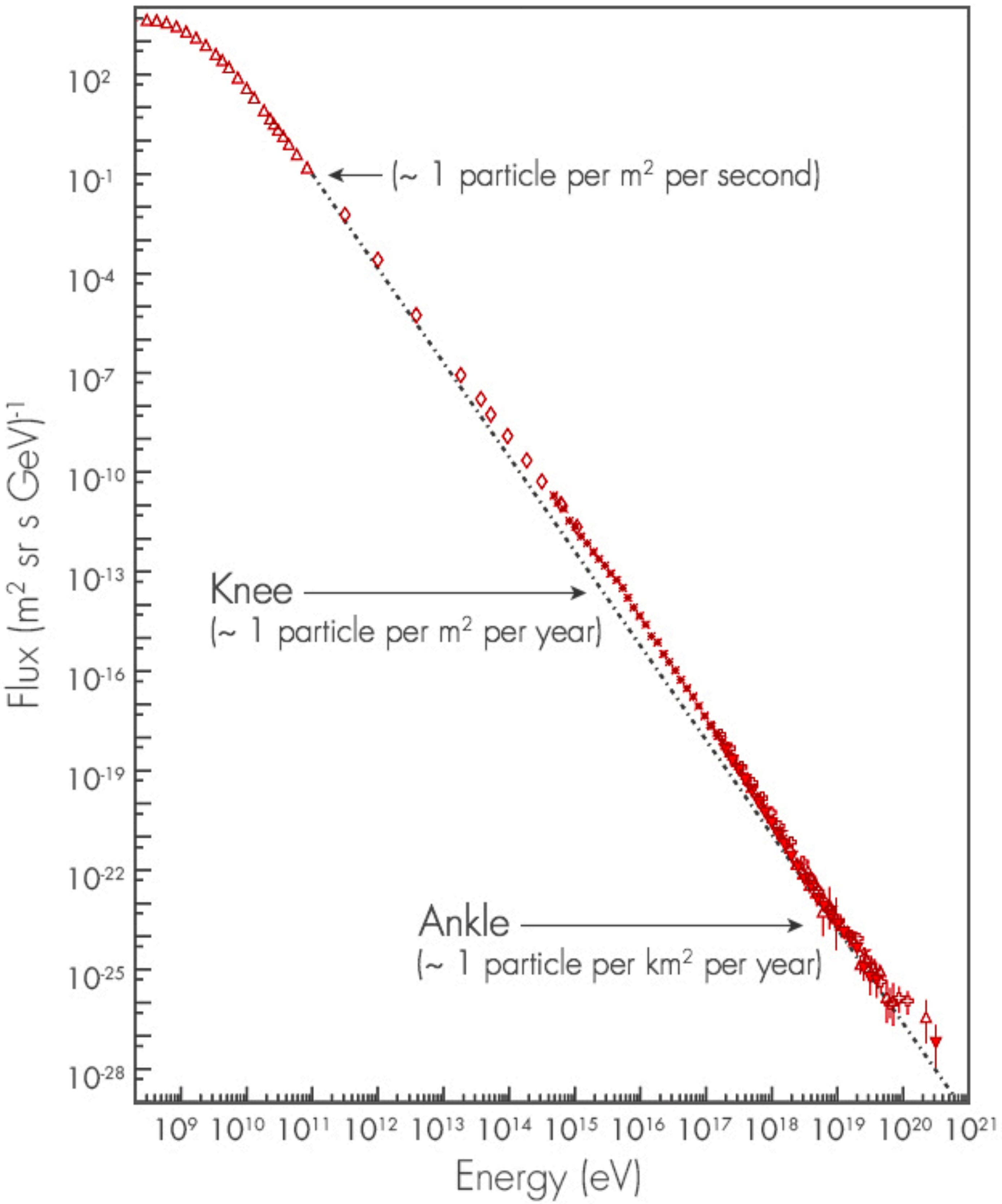
Neutrinos

from a galaxy half-way across the universe.

Markus Ackermann, DESY
Physikseminar 04.09.2018

Cosmic accelerators

- Particle accelerators in our cosmos reach energies far beyond man-made devices
- Gravitational/rotational energy driven plasma accelerators



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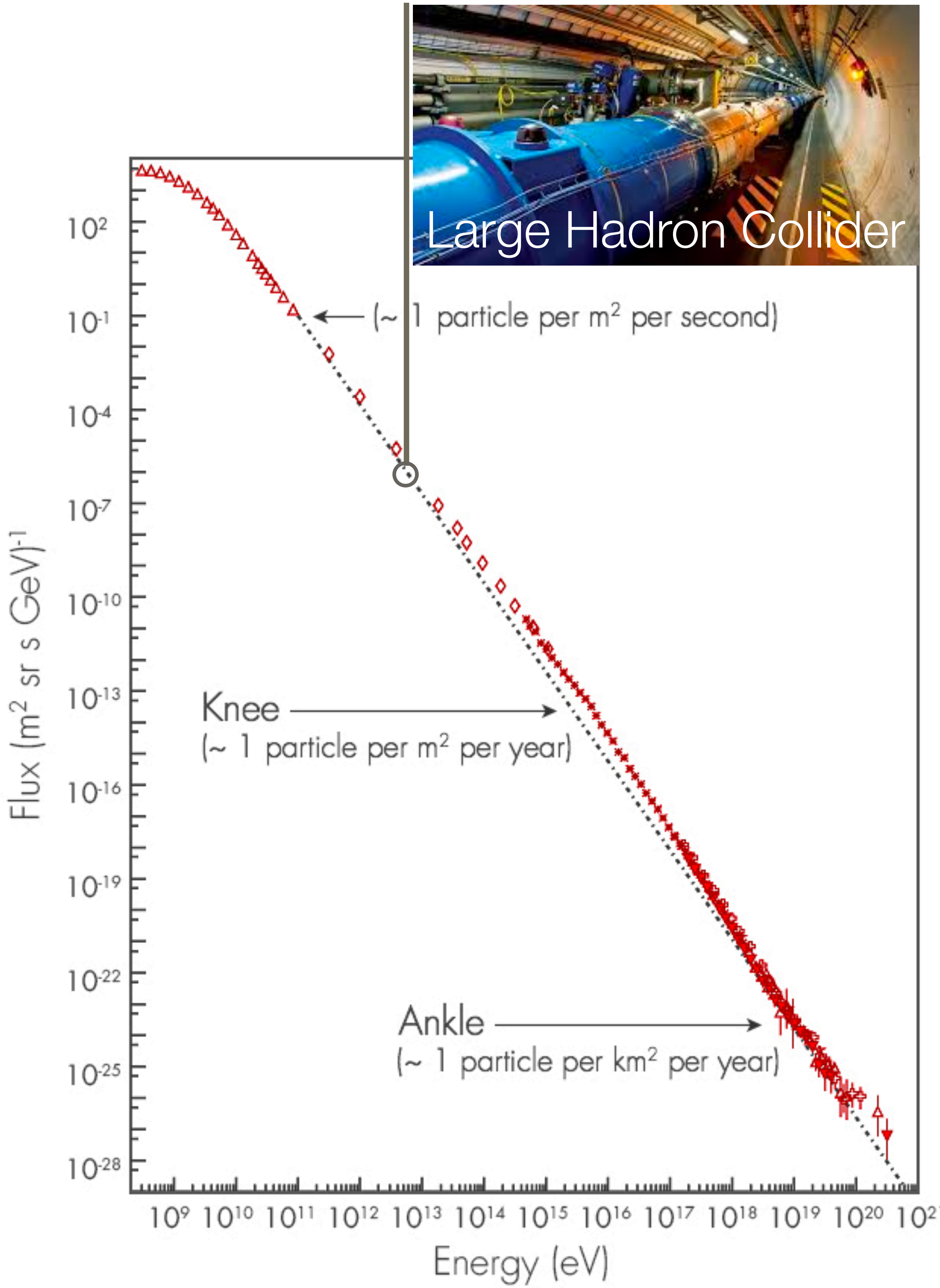

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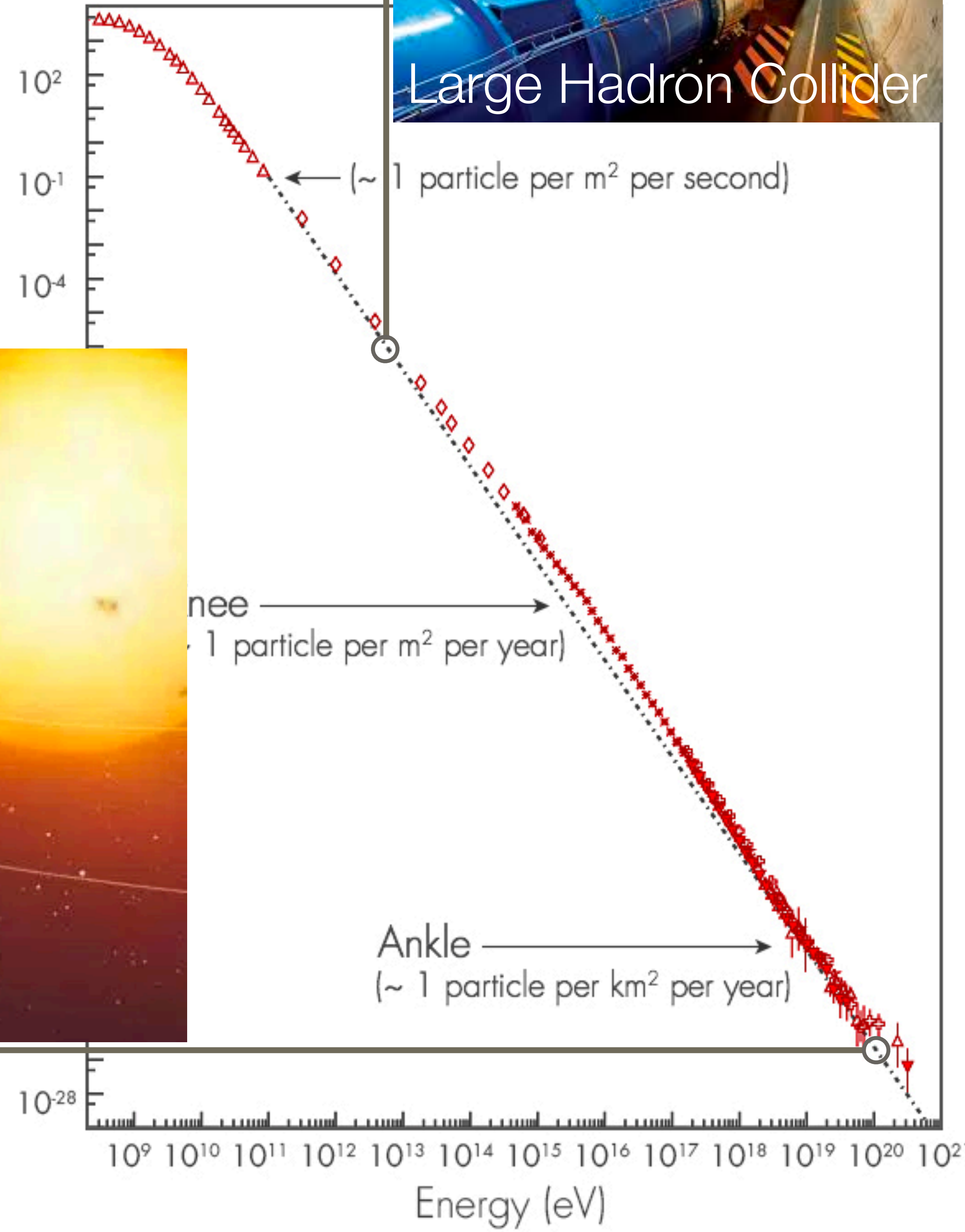
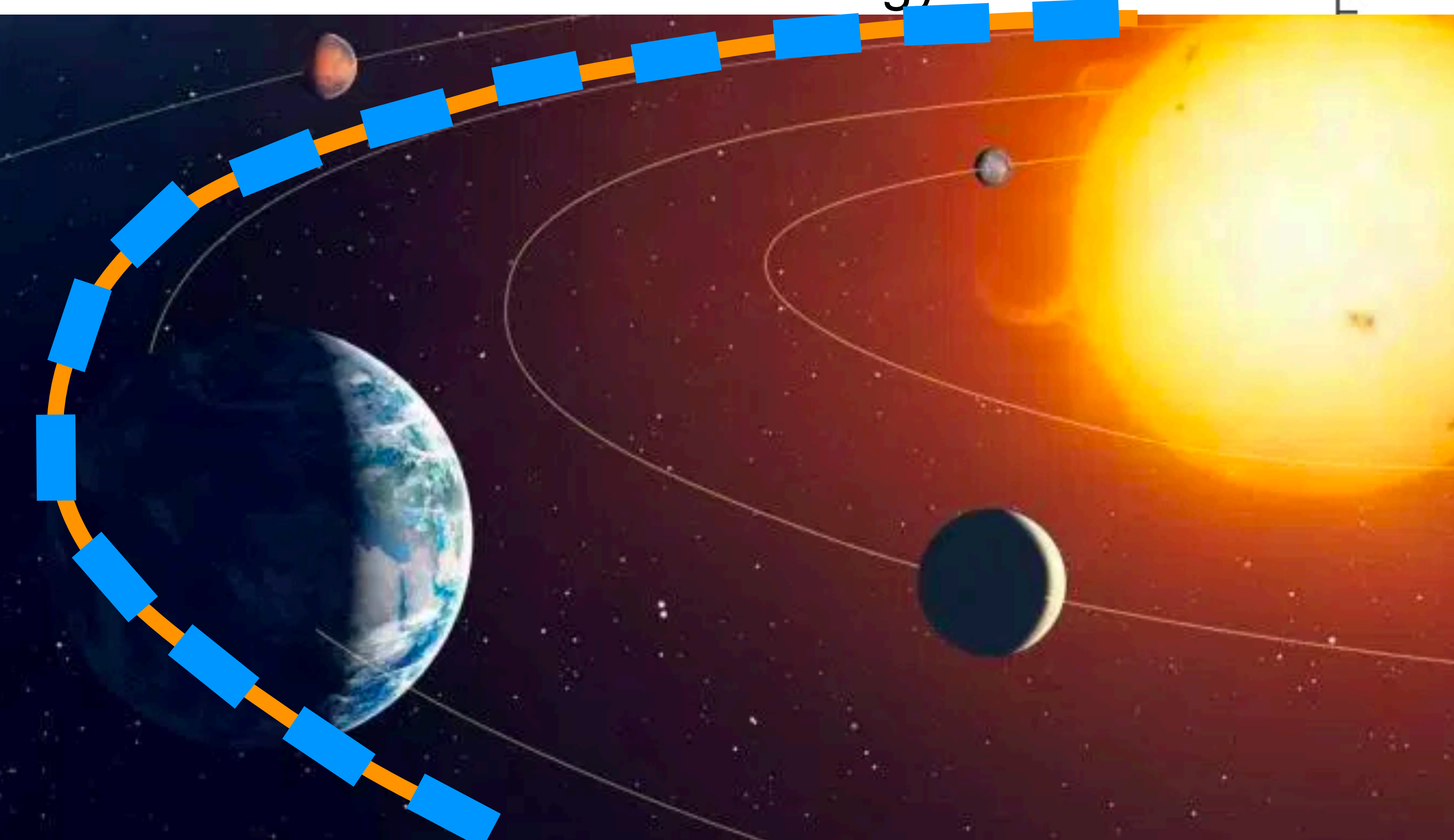
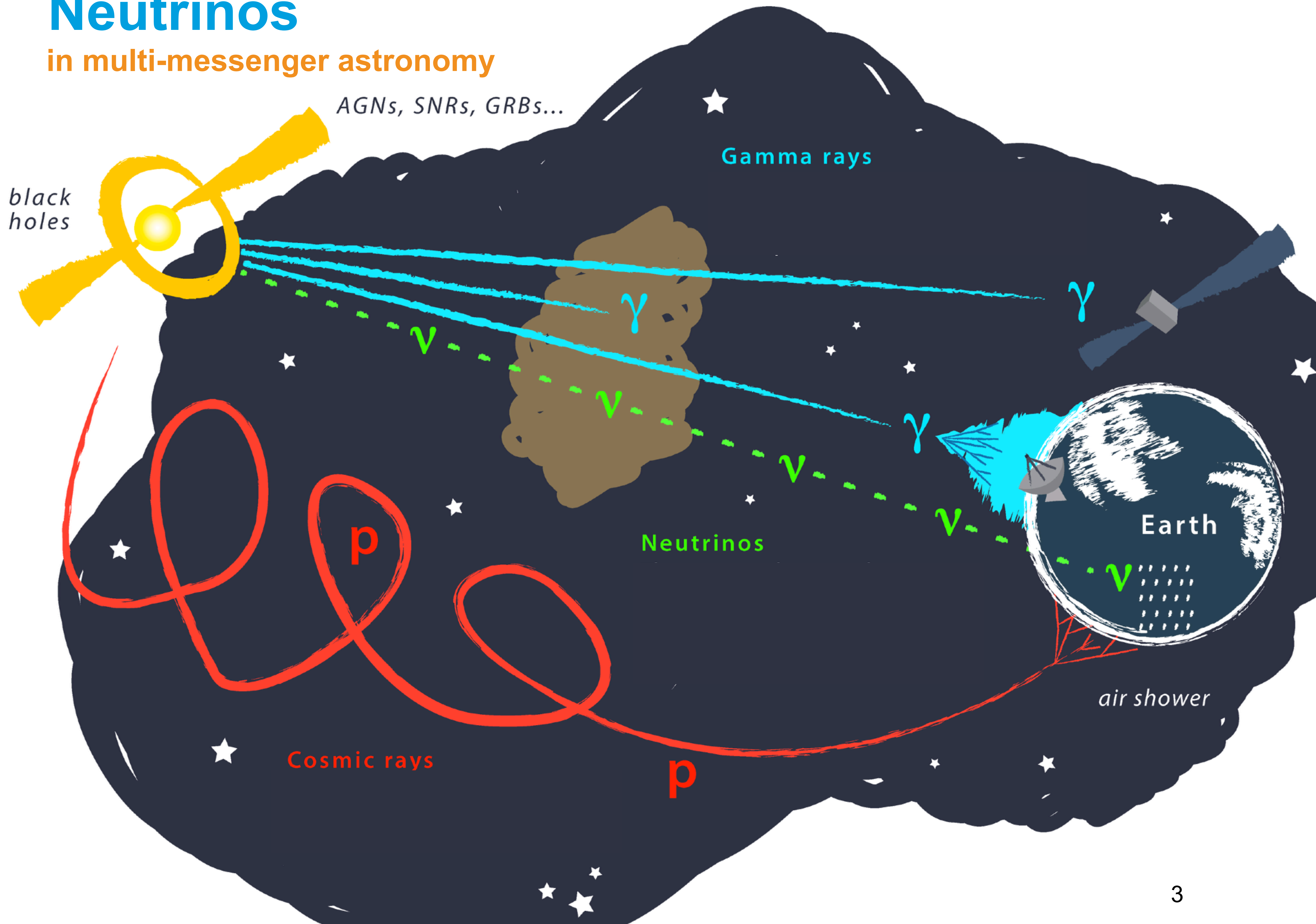




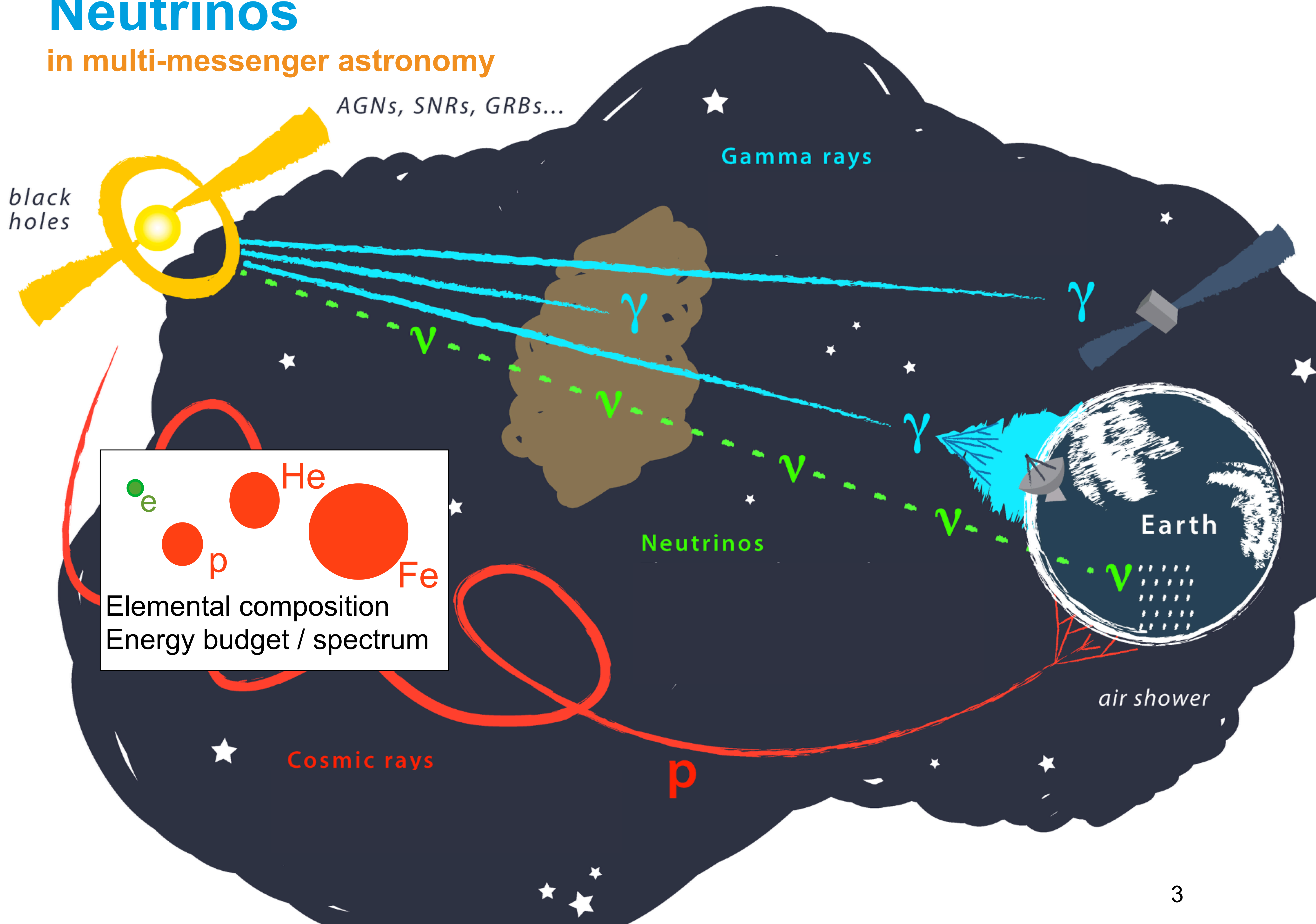
Neutrinos

in multi-messenger astronomy



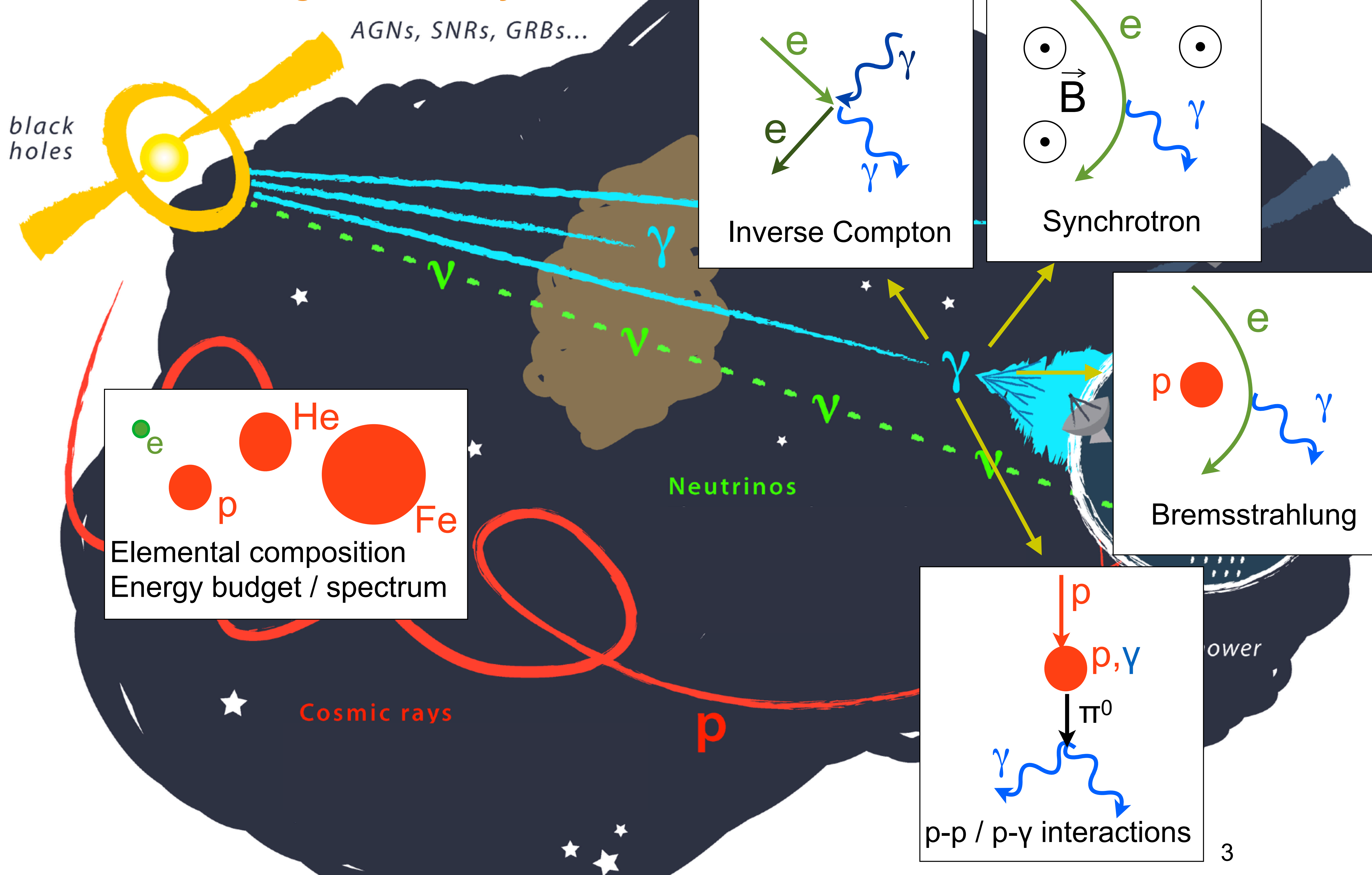
Neutrinos

in multi-messenger astronomy



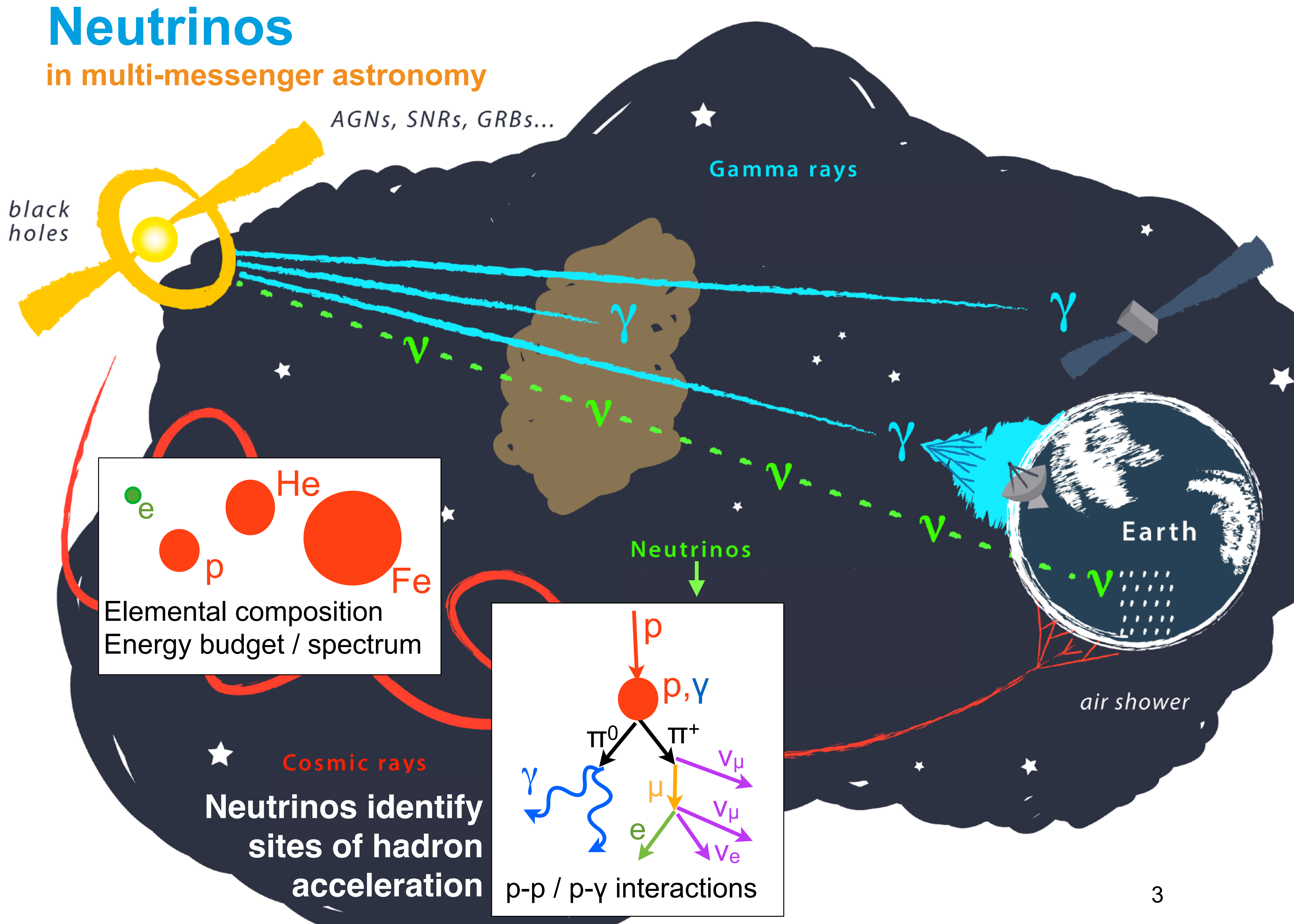
Neutrinos

in multi-messenger astronomy



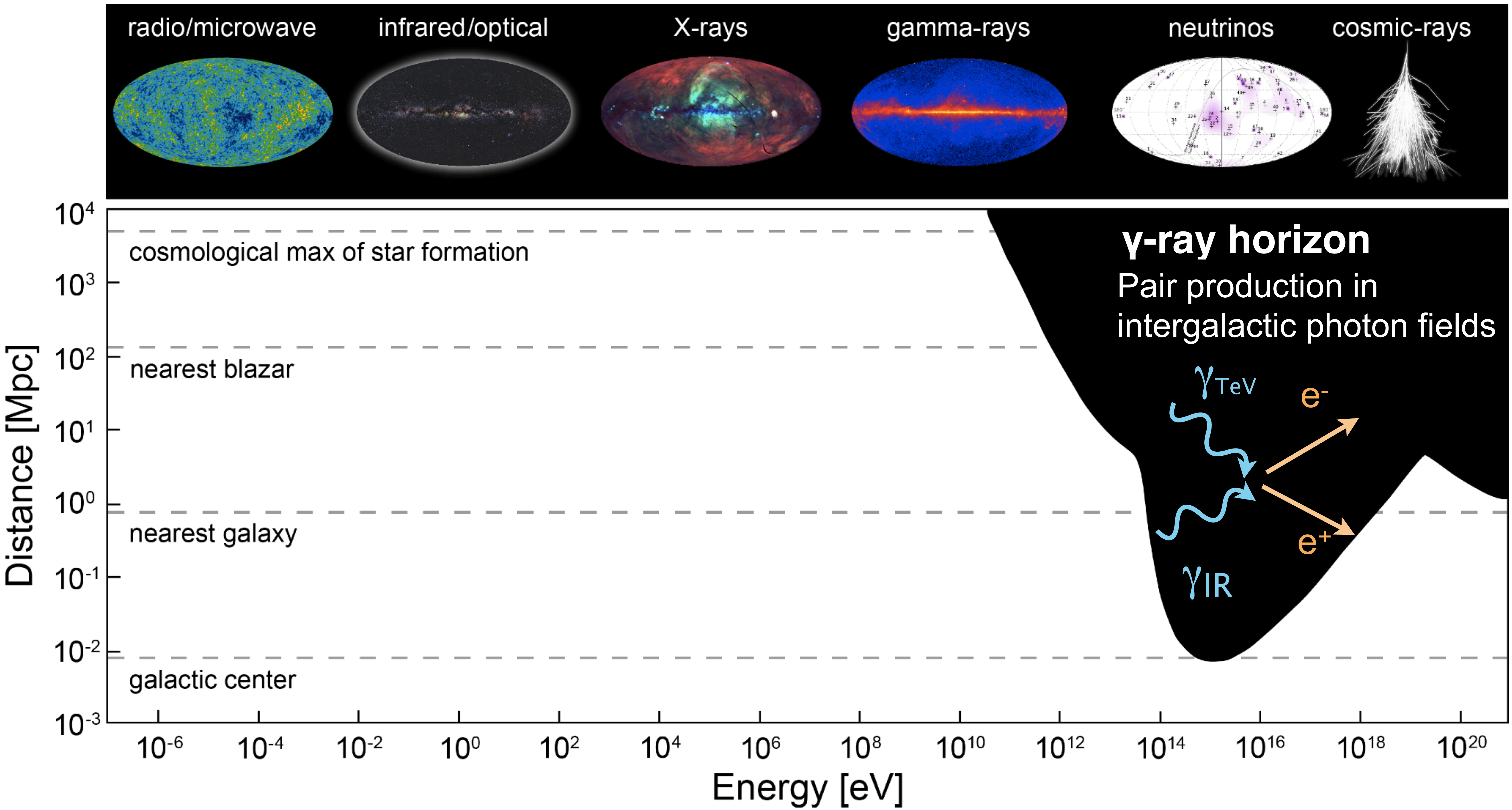
Neutrinos

in multi-messenger astronomy



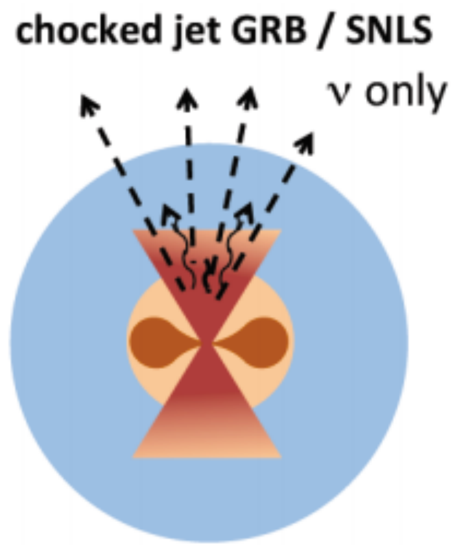
Neutrinos identify sites of hadron acceleration

PeV astronomy with neutrinos

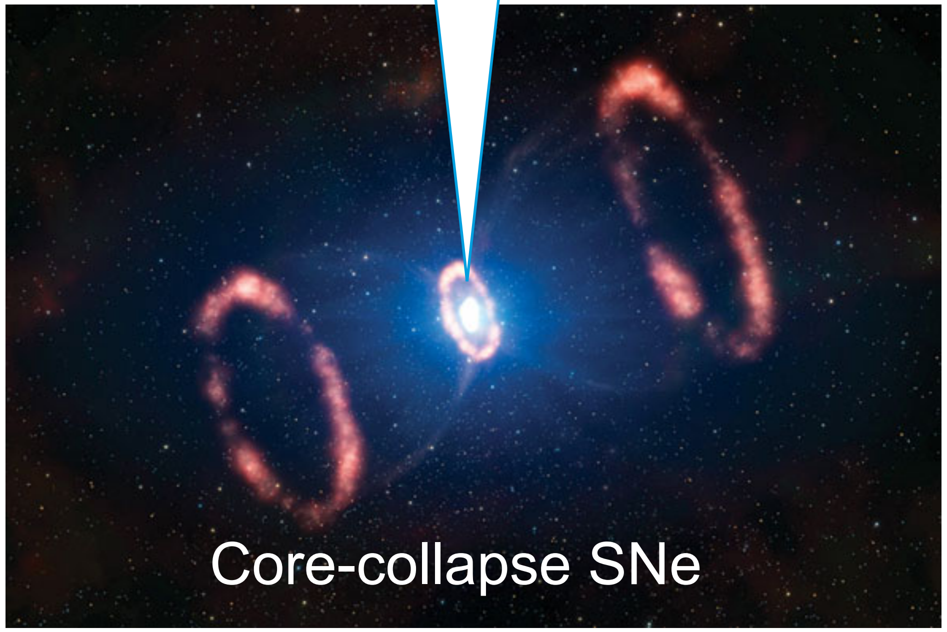


- Neutrinos allow us to **peek beyond** the gamma-ray horizon…

Environments opaque to EM radiation



Ando & Beacom, PRL 95 (2005)



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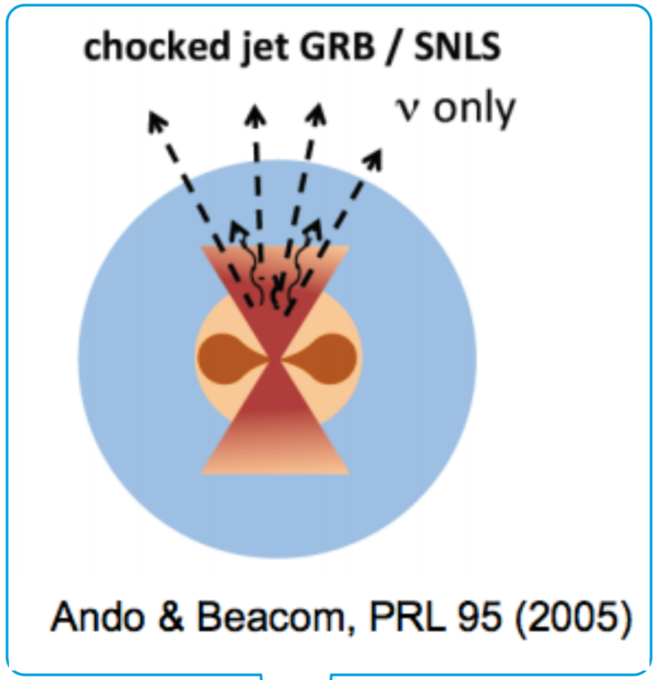

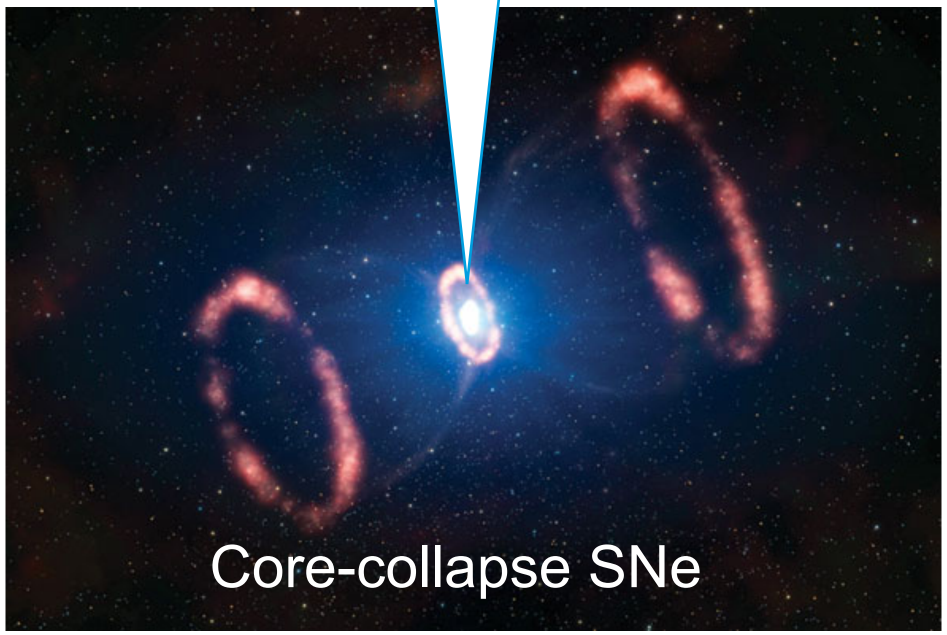

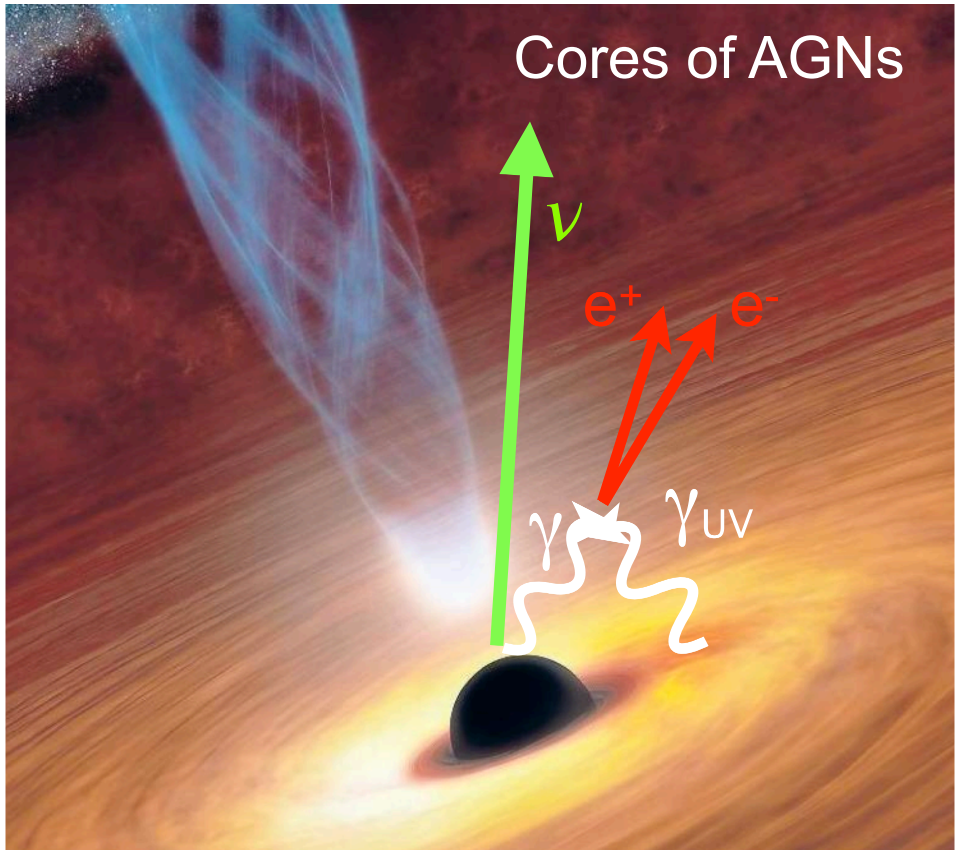

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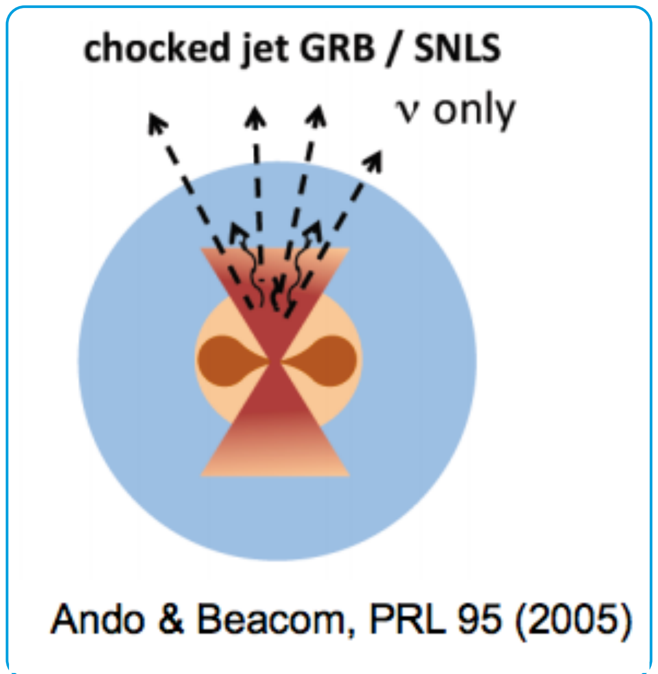
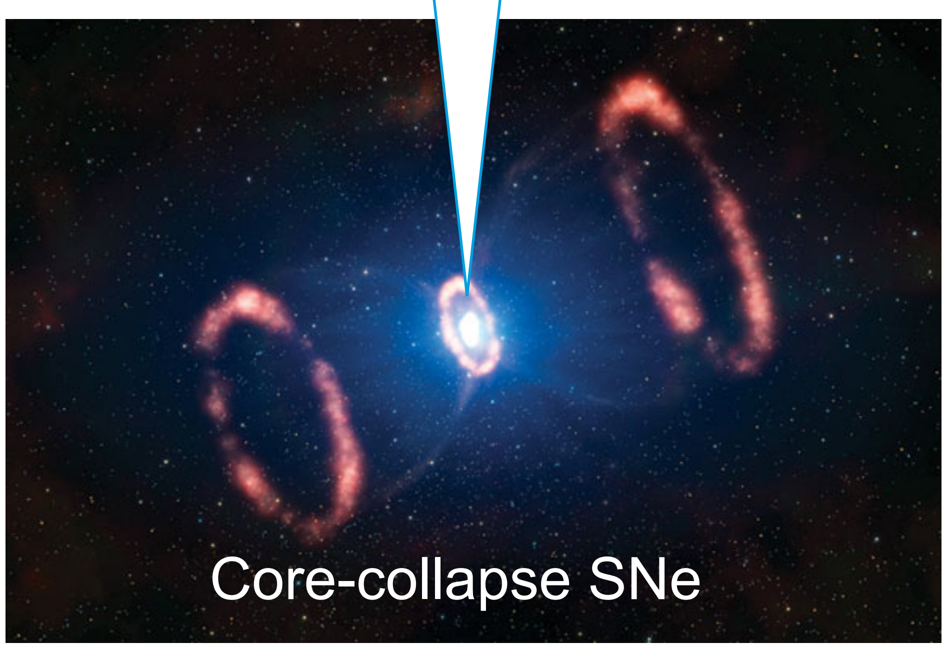
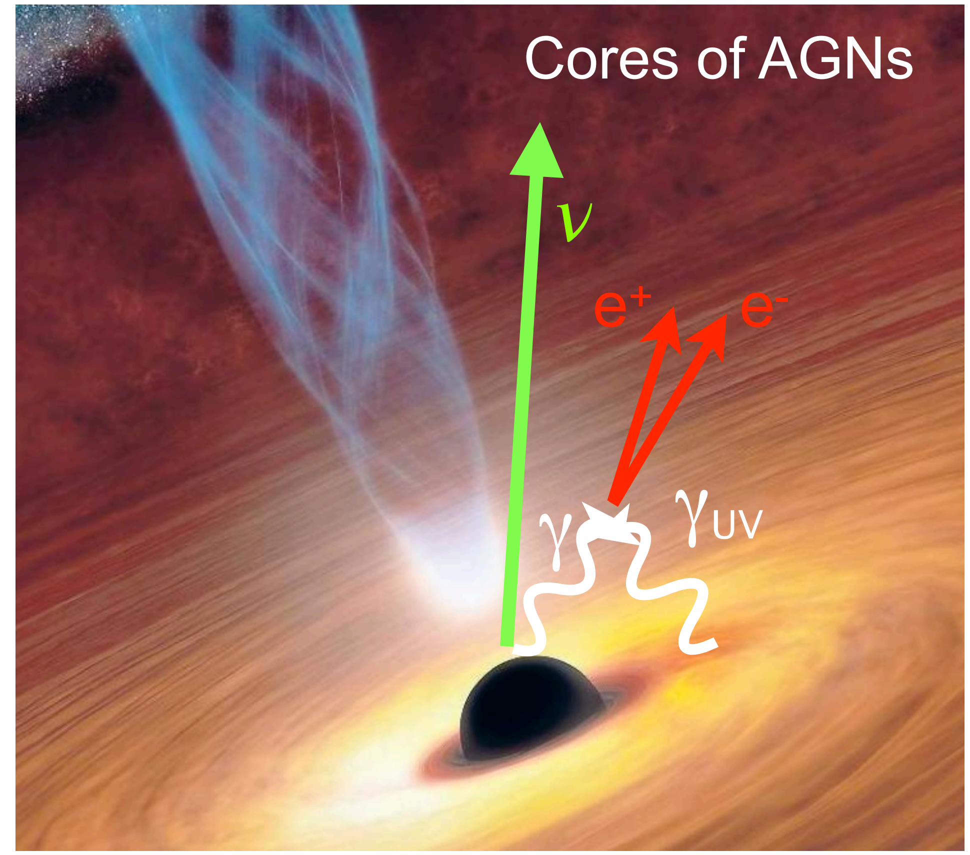
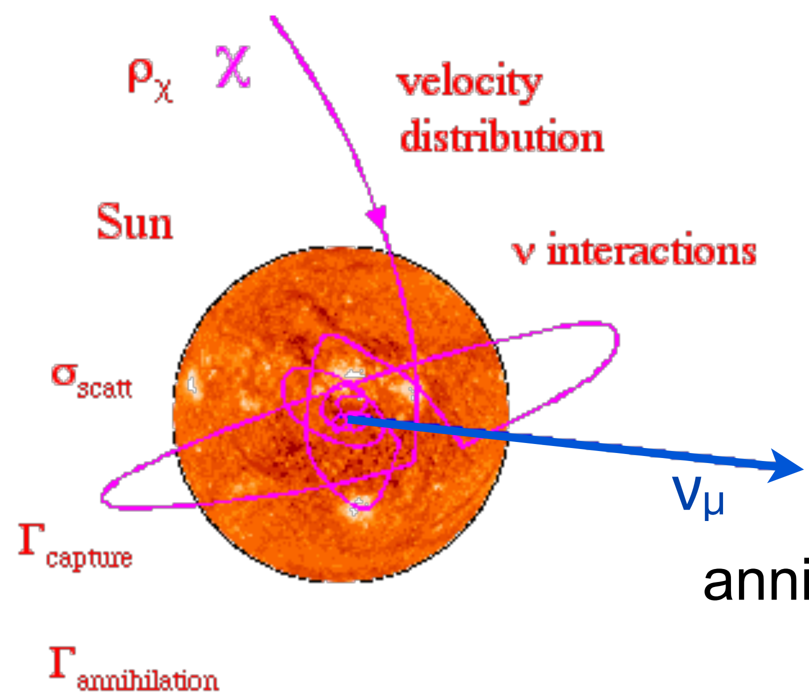


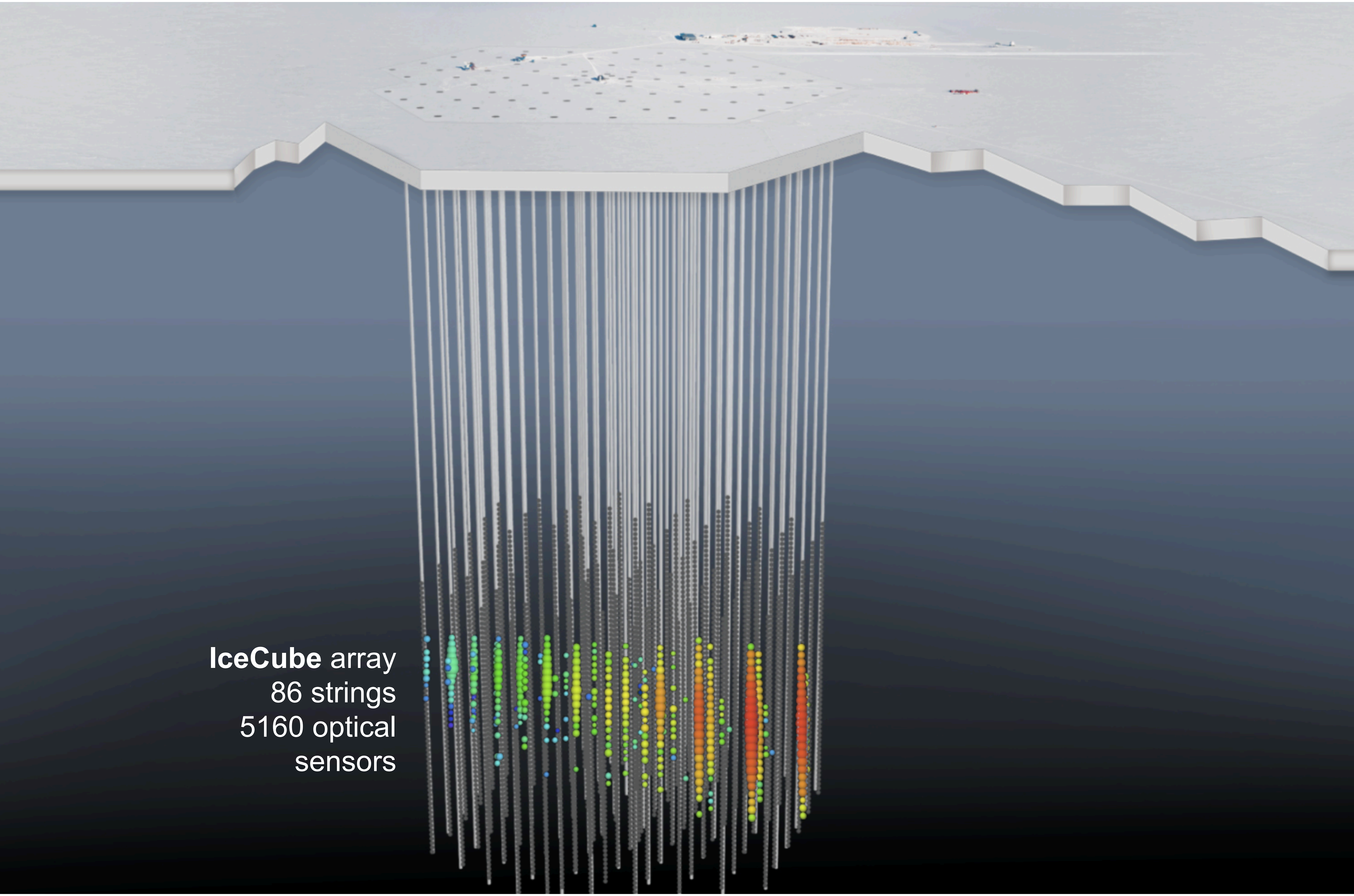




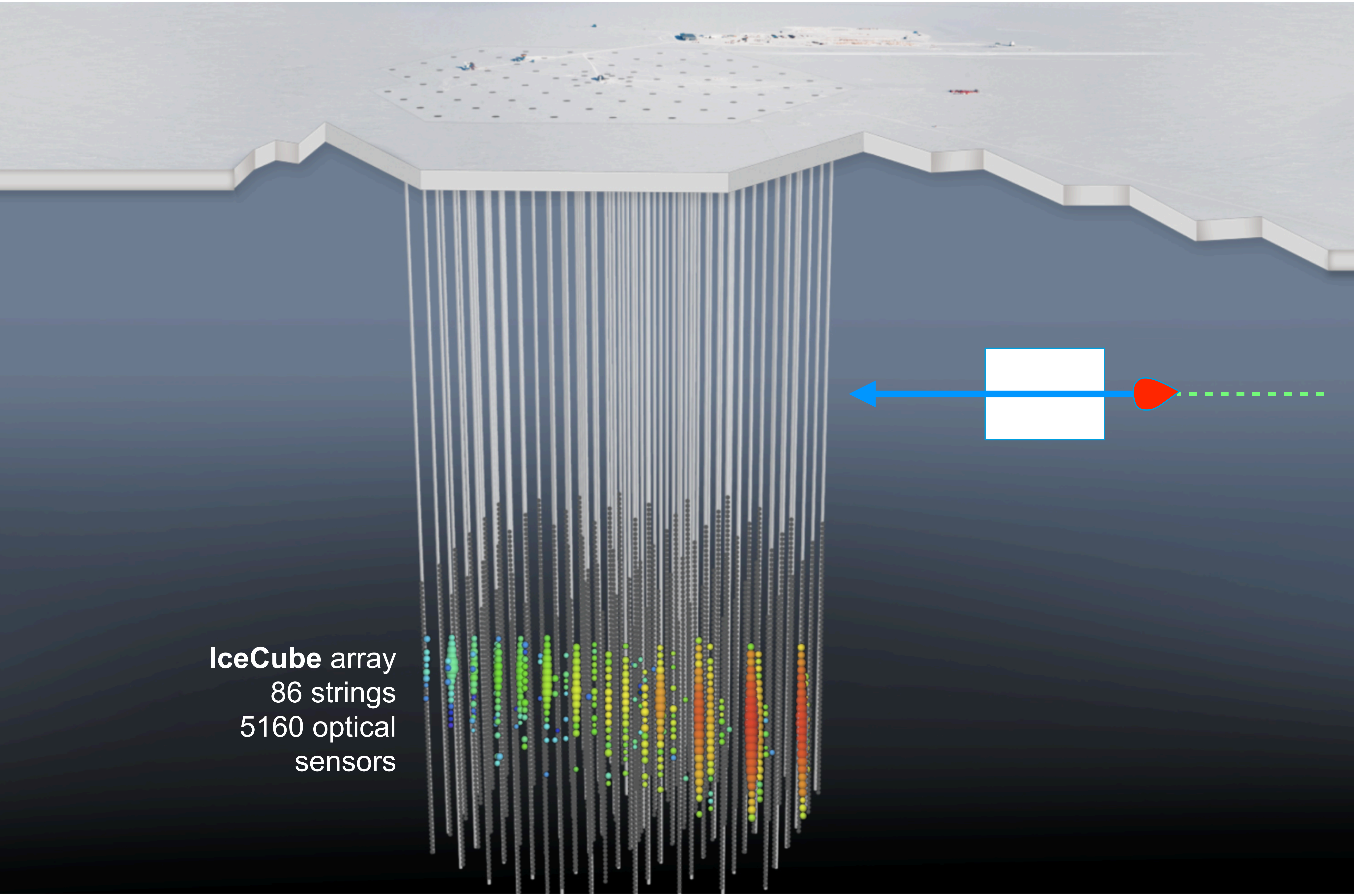


Dark Matter annihilation in the sun

Neutrino telescopes: IceCube

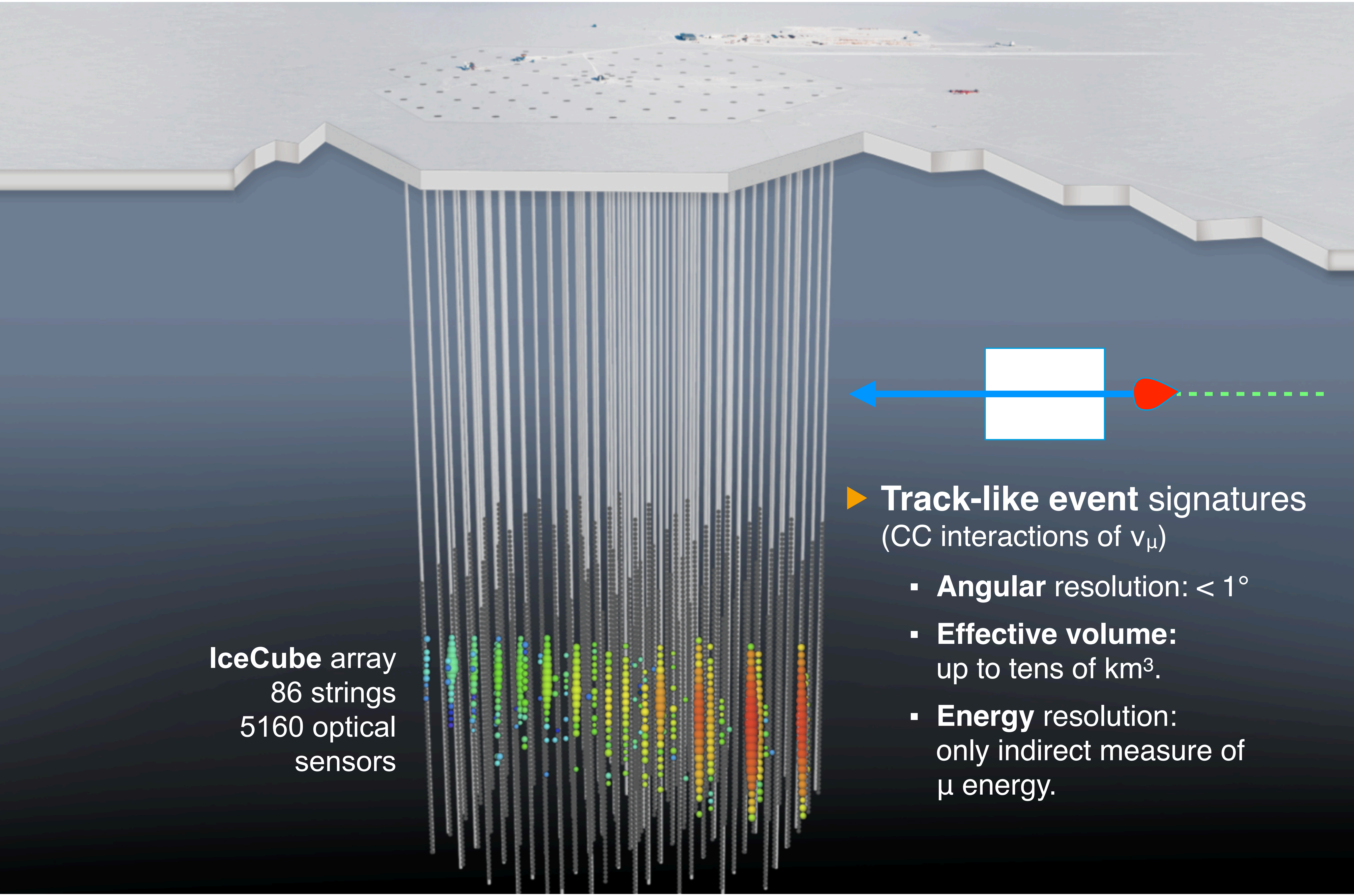


Neutrino telescopes: IceCube



IceCube array
86 strings
5160 optical
sensors

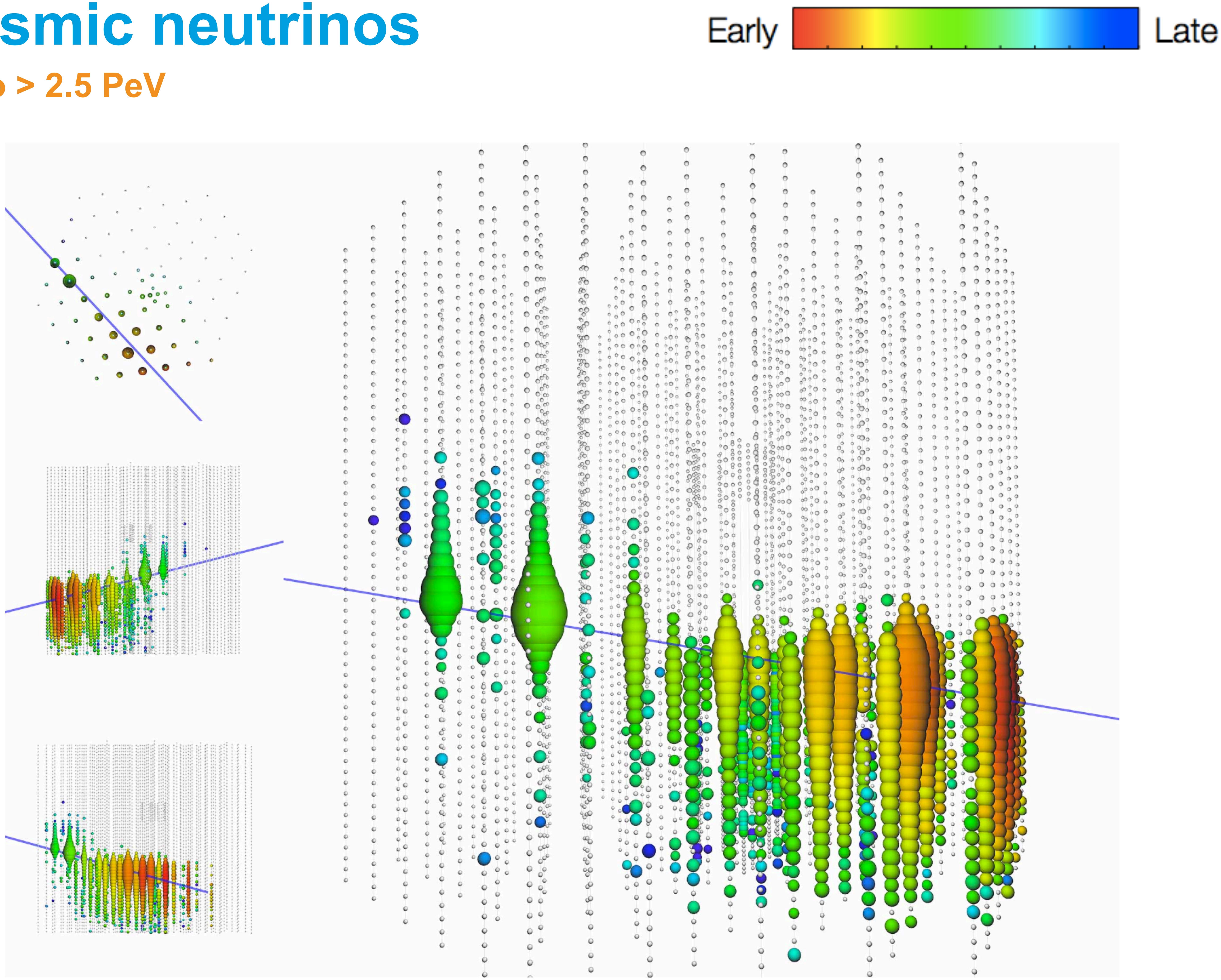
Neutrino telescopes: IceCube



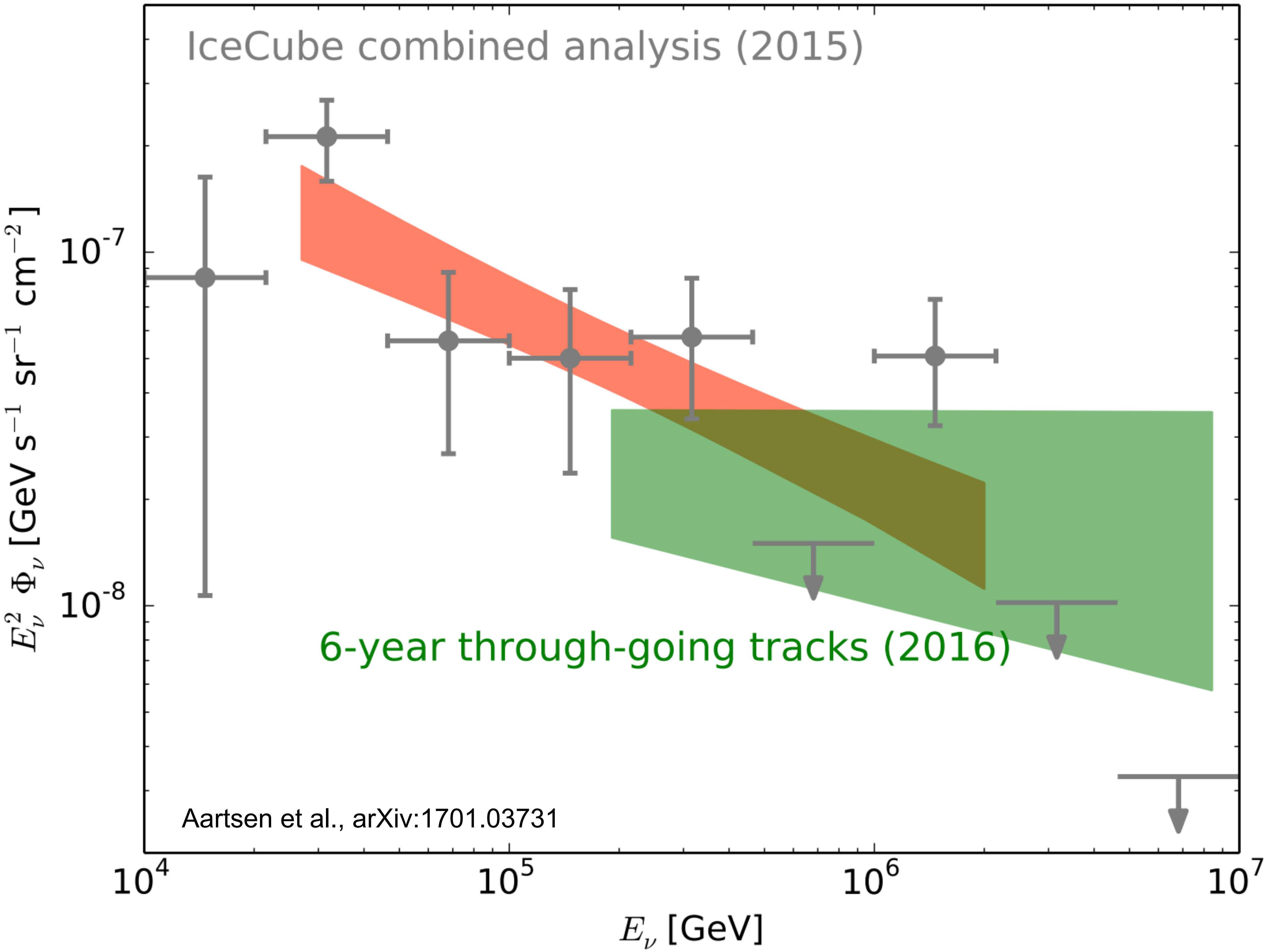
- **Track-like event** signatures
  (CC interactions of ν_μ)
  - **Angular** resolution: < 1°
  - **Effective volume:**
    up to tens of km^3.
  - **Energy** resolution:
    only indirect measure of
    μ energy.

Cosmic neutrinos

Up to > 2.5 PeV

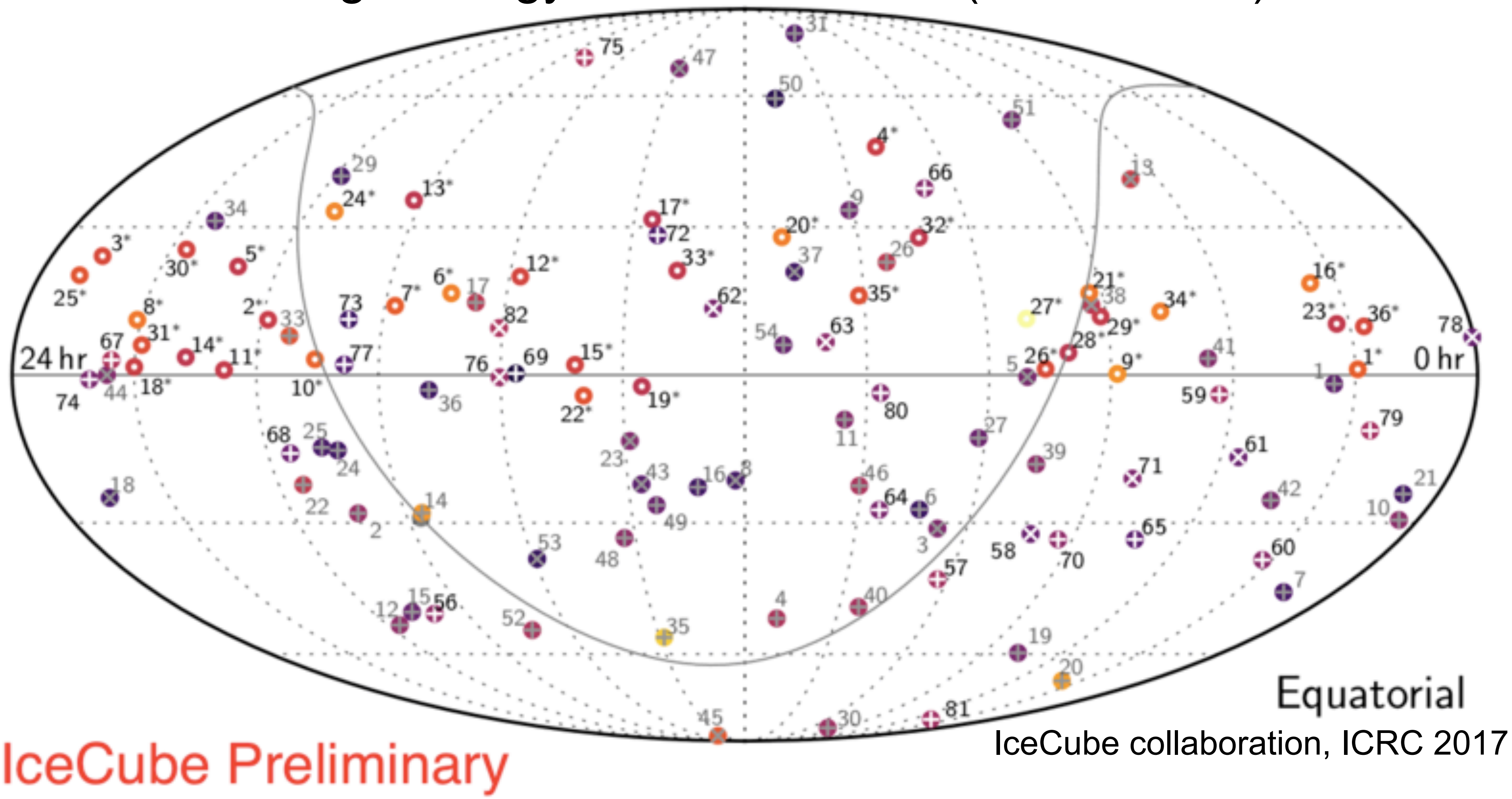


The cosmic neutrino spectrum



IceCube high-energy neutrinos

IceCube high-energy events > 30 TeV (2010 - 2016)

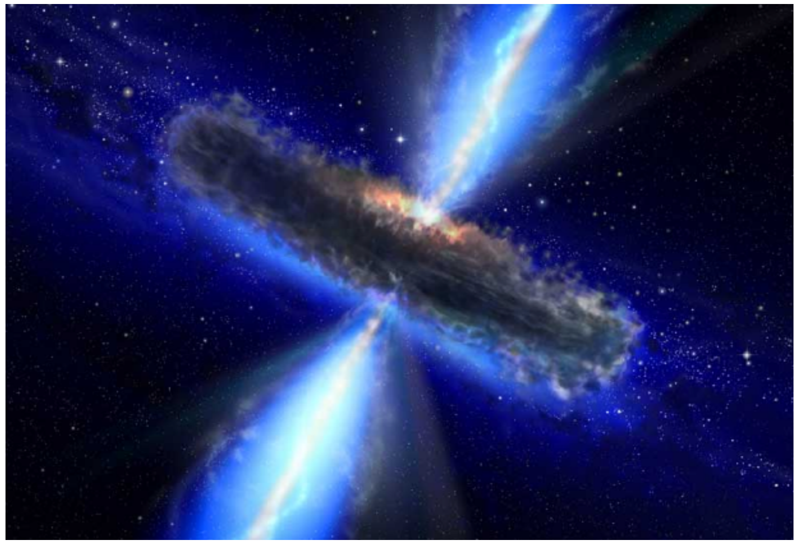


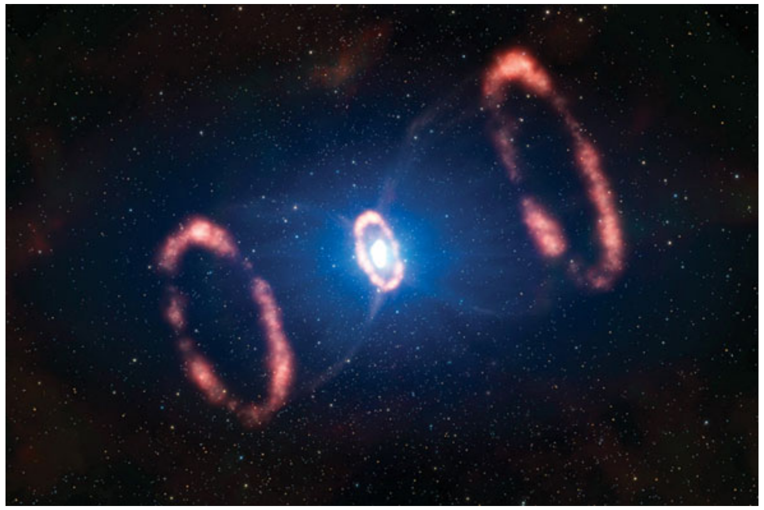
IceCube collaboration, ICRC 2017

- **Compatible** with an **isotropic** distribution
  - points to extragalactic origin of cosmic neutrinos
- **No significant clustering** of high-energy events

What is the origin of the astrophysical neutrinos?

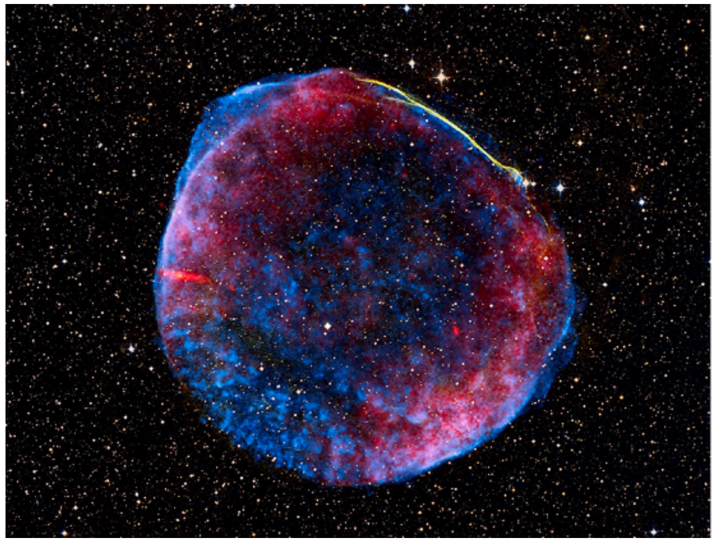
Active Galaxies ?





SNe ?

Where are the cosmic particle accelerators and how do they work ?

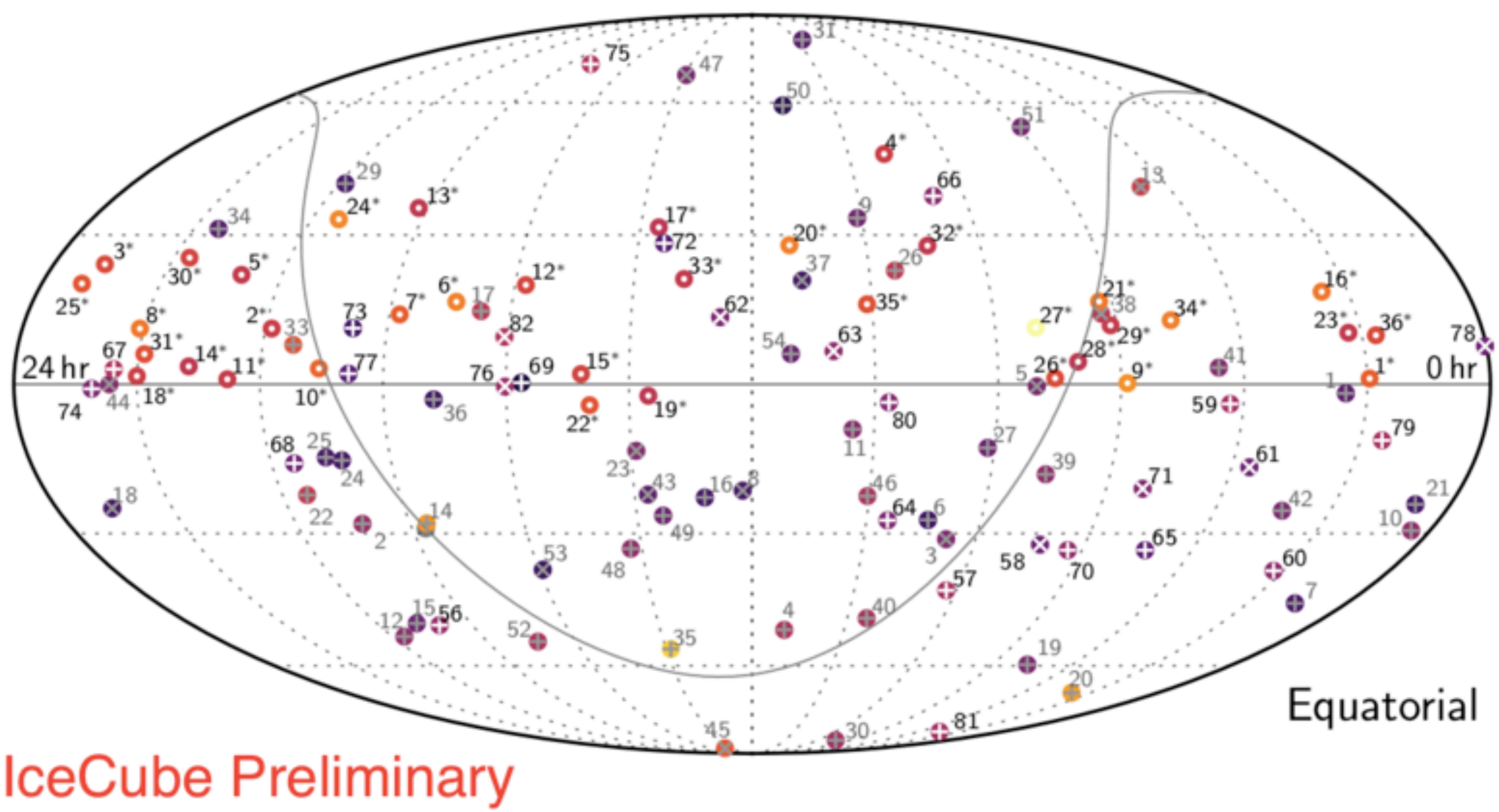


Supernova remnants ?

GRBs ?

A new strategy

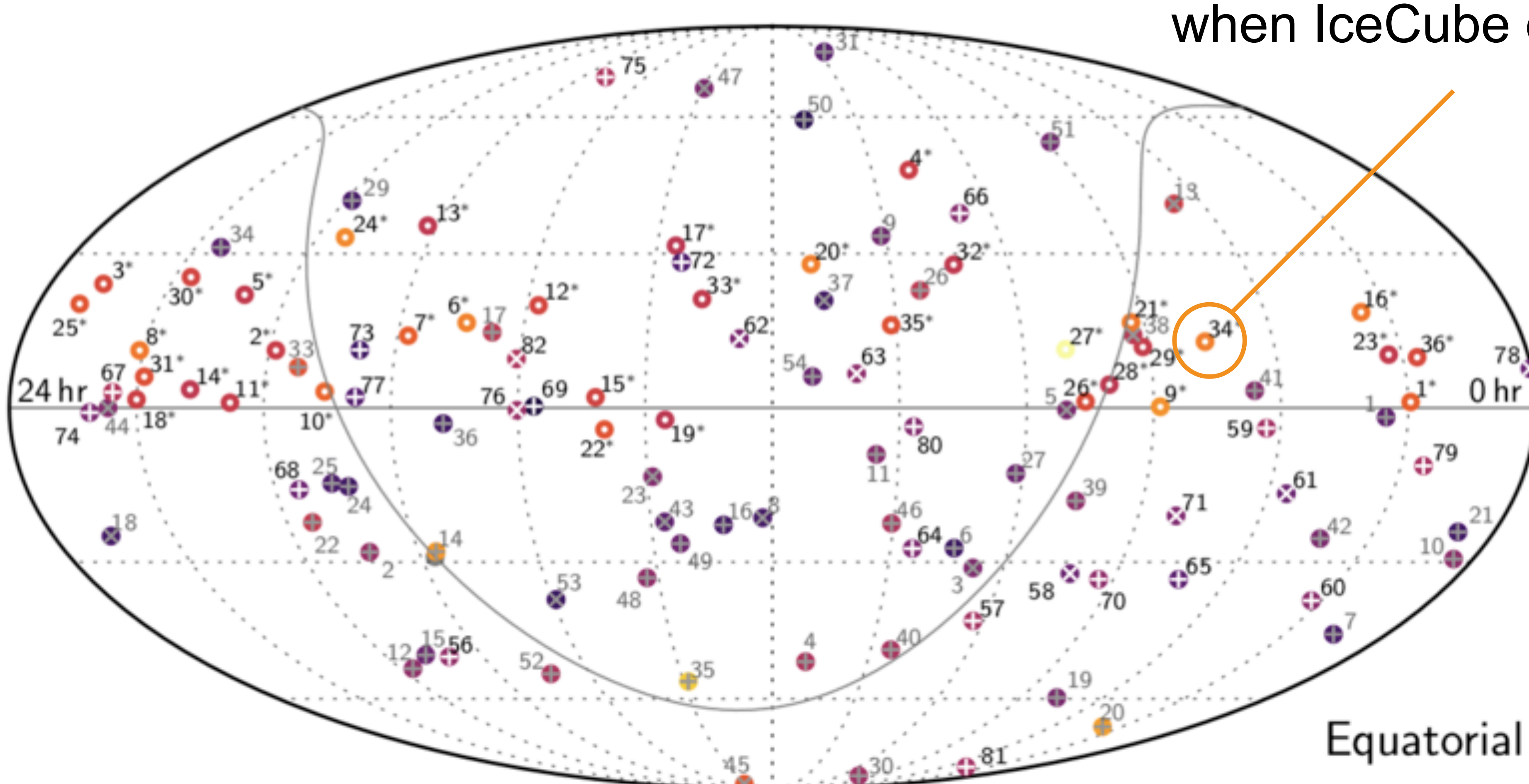
Real-time follow-up of high-energy events



A new strategy

Real-time follow-up of high-energy events

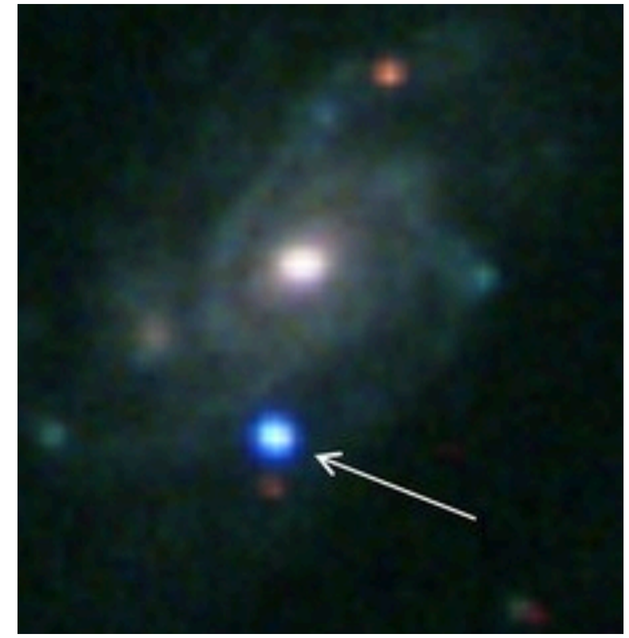
What happened in this direction in the sky when IceCube detected this neutrino ?



IceCube Preliminary

A new strategy

Real-time follow-up of high-energy events



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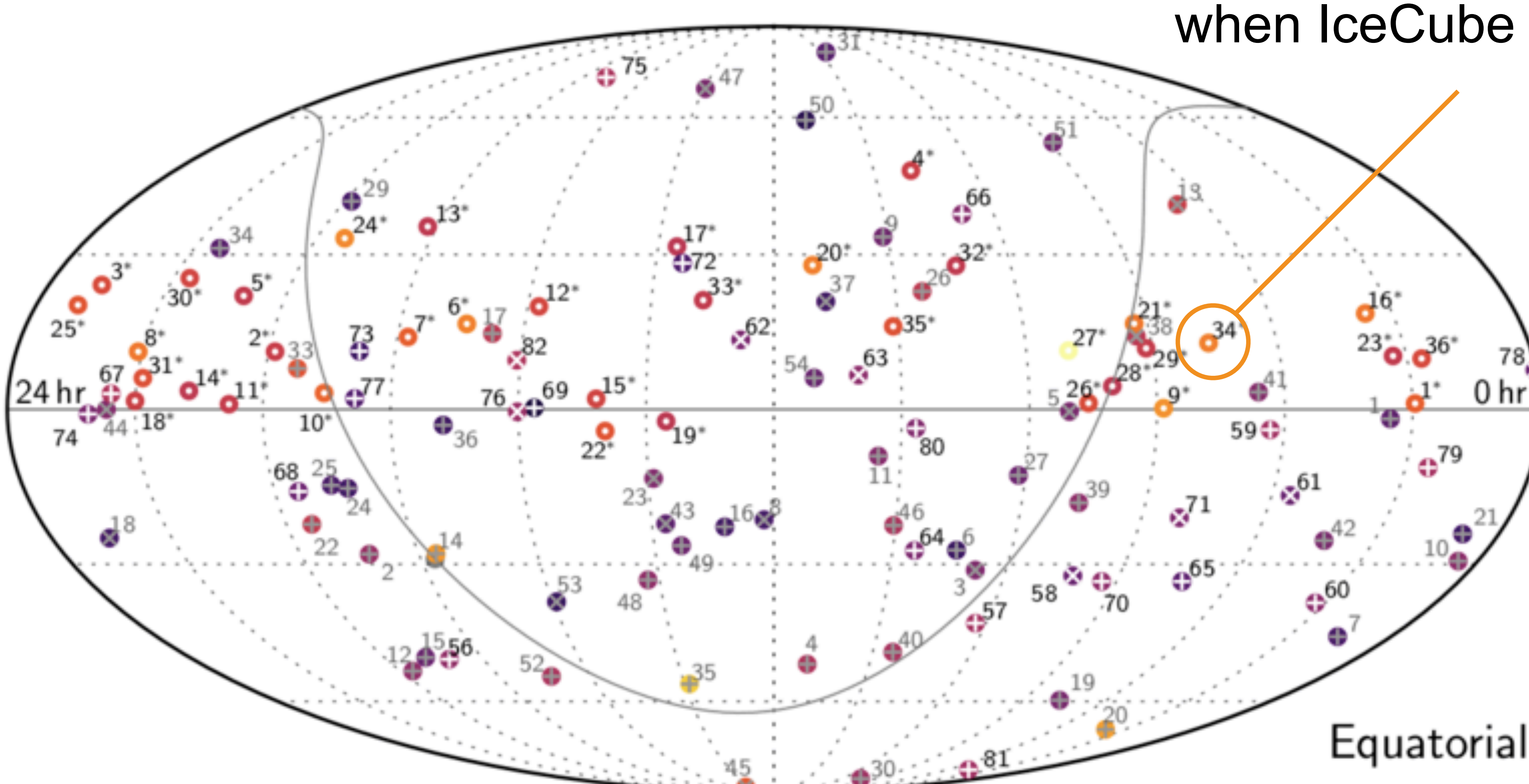

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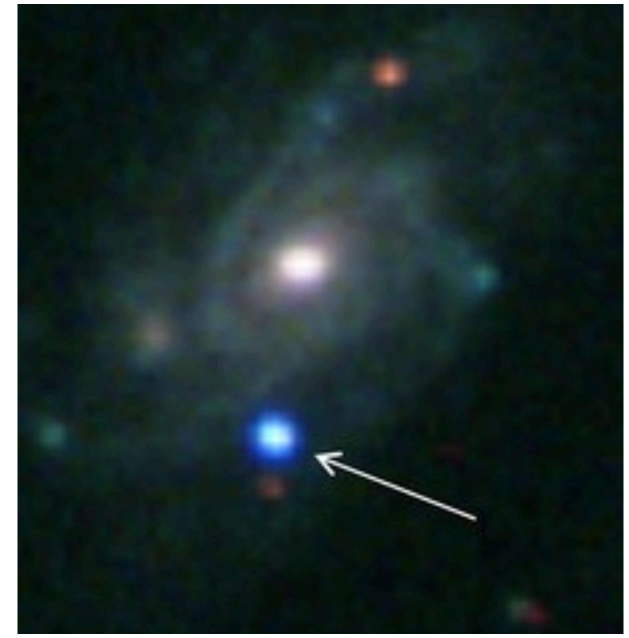

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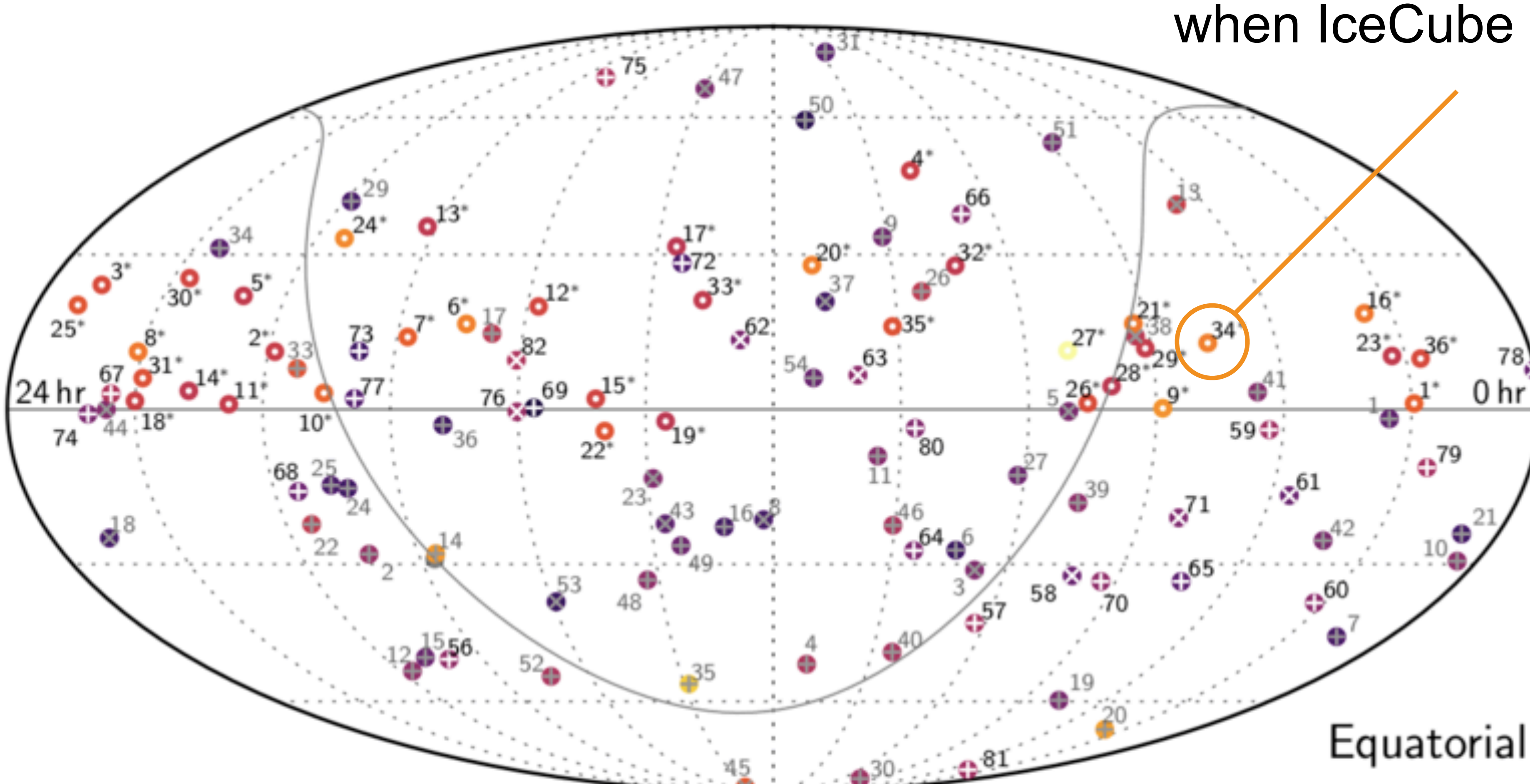

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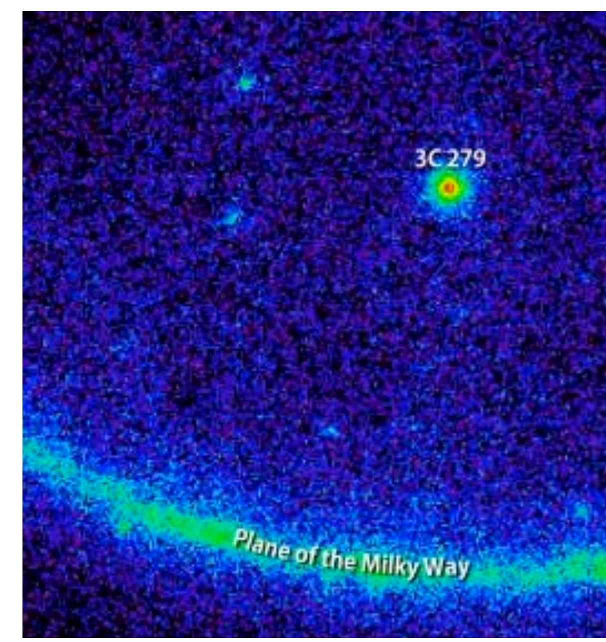


An active galaxy flared ?

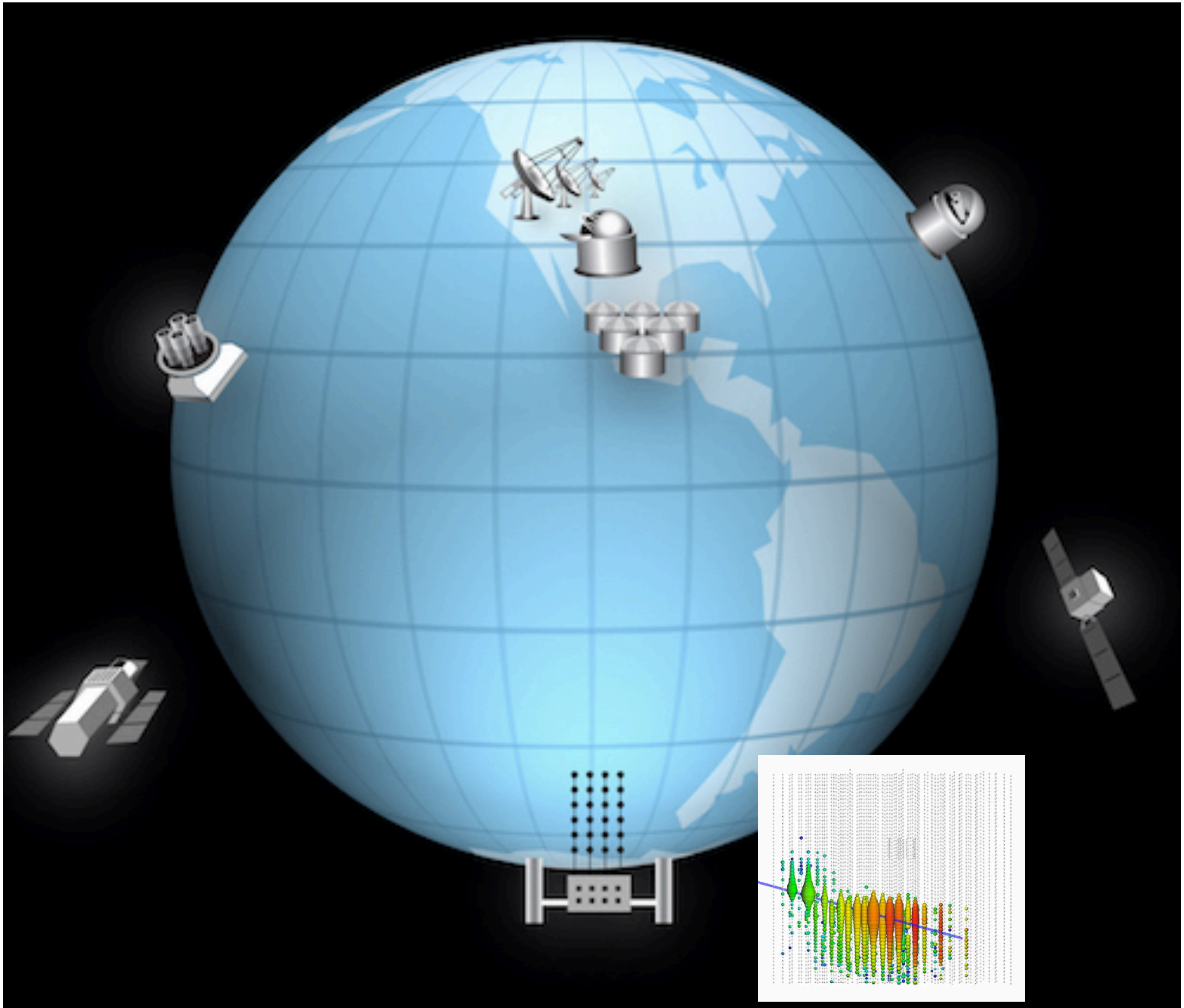
A new strategy

Real-time follow-up of high-energy events

- IceCube observes an interesting event
  - High-energy neutrinos
  - Cluster of neutrinos
- Information is sent out to partner observatories or made public
- Average response time: ~ 30 s
- High-energy event alerts since 2016

A new strategy

Real-time follow-up of high-energy events



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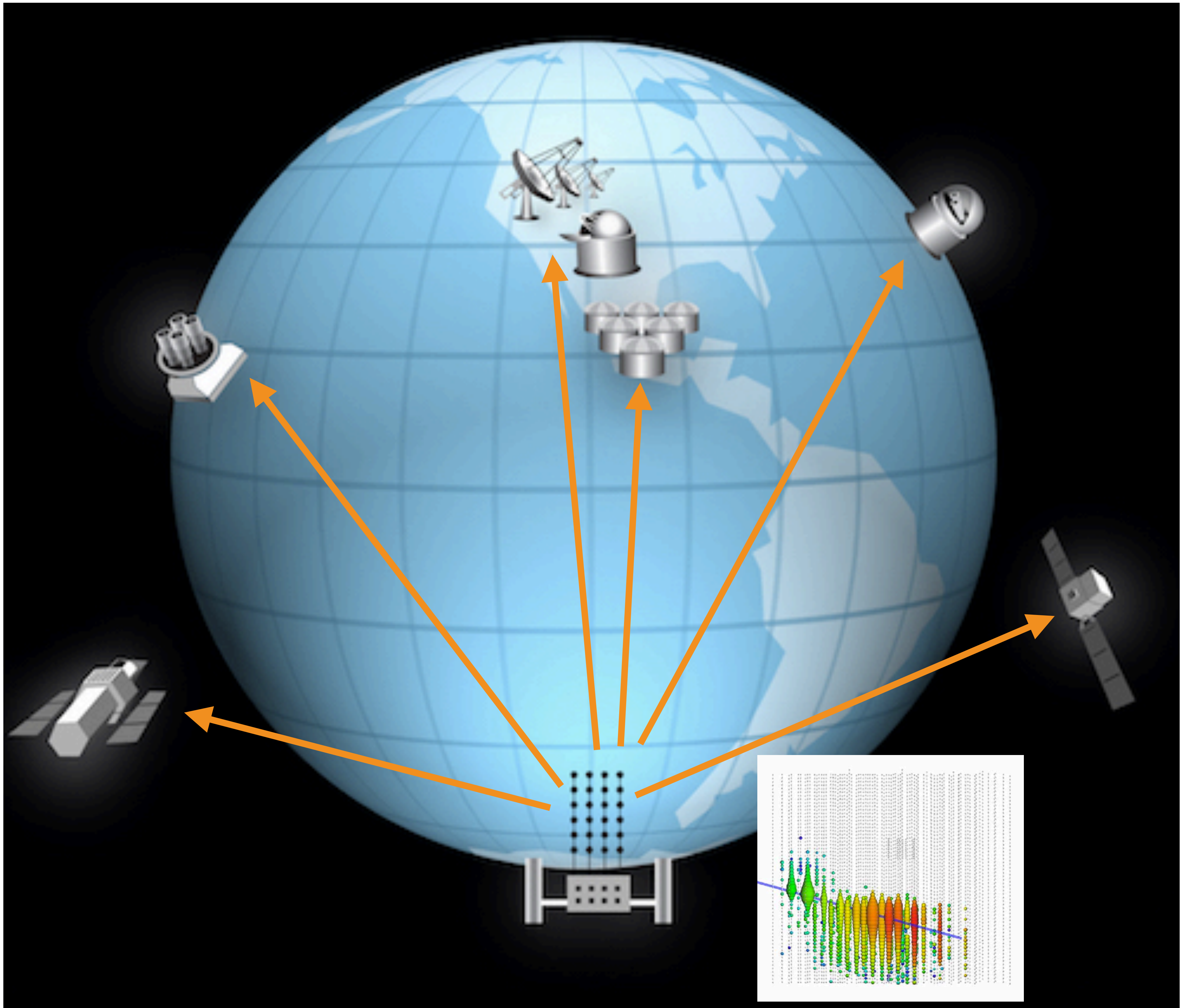

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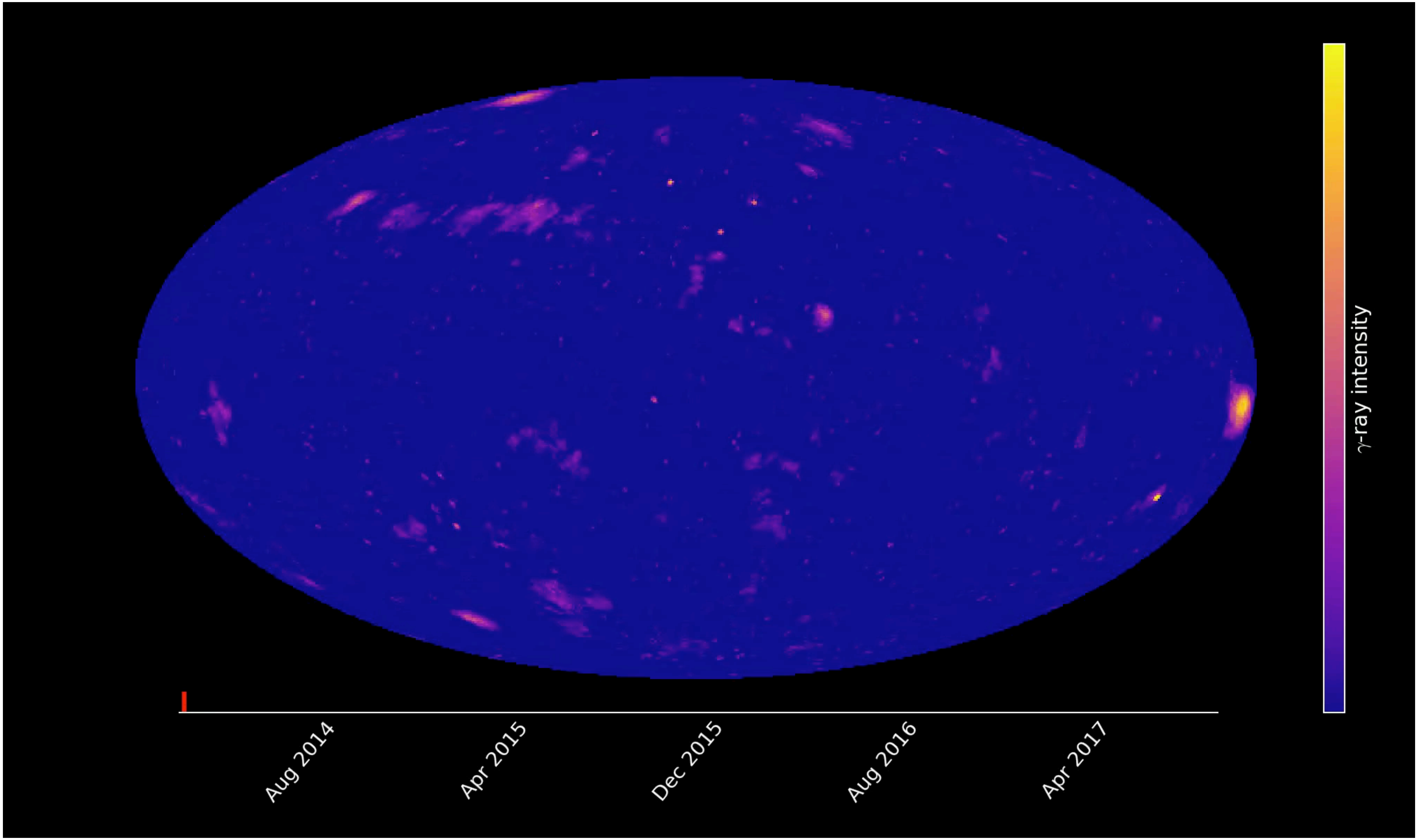
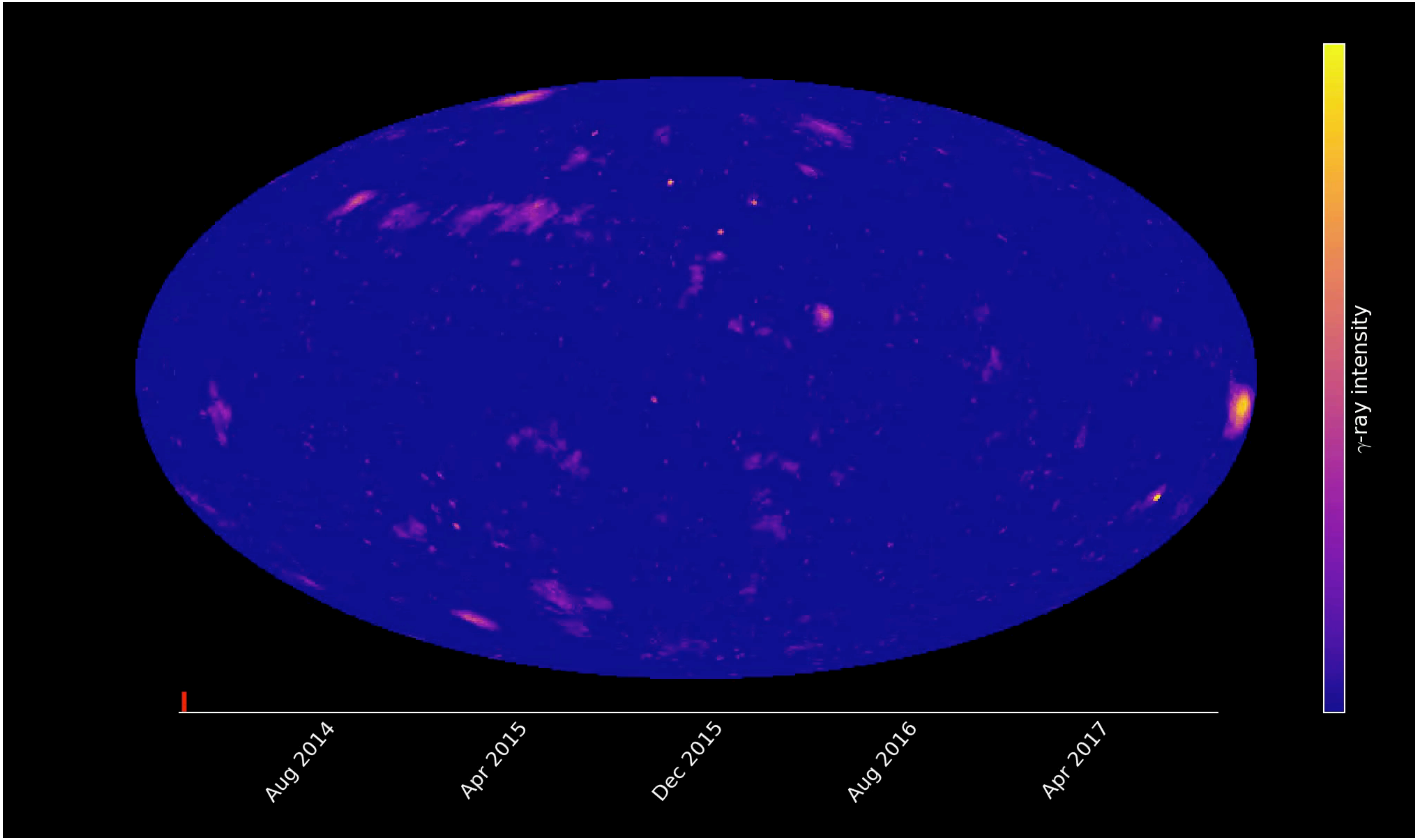
High-energy alerts

and the variable gamma-ray sky

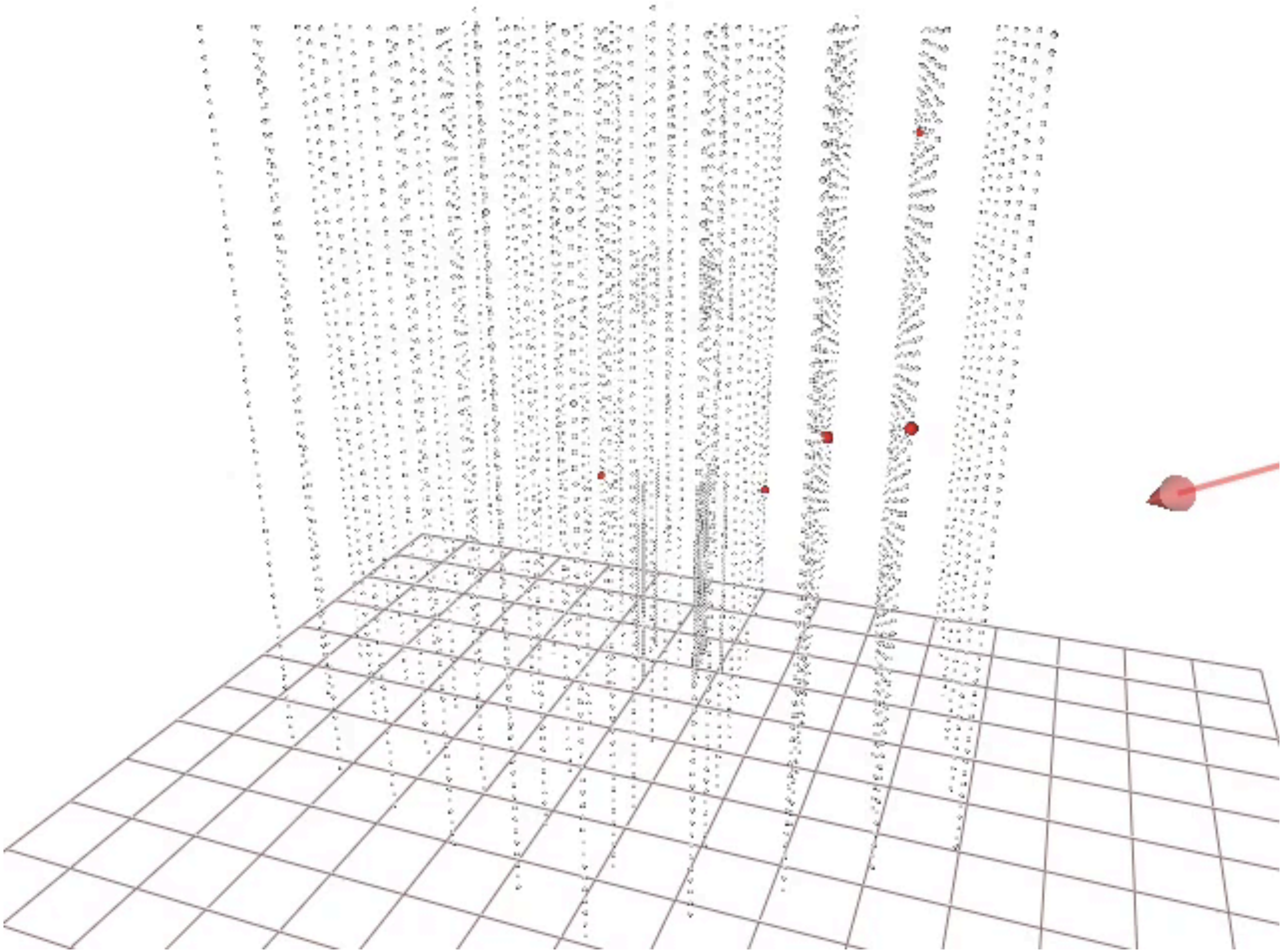


High-energy alerts

and the variable gamma-ray sky



The high-energy neutrino IC 170922A



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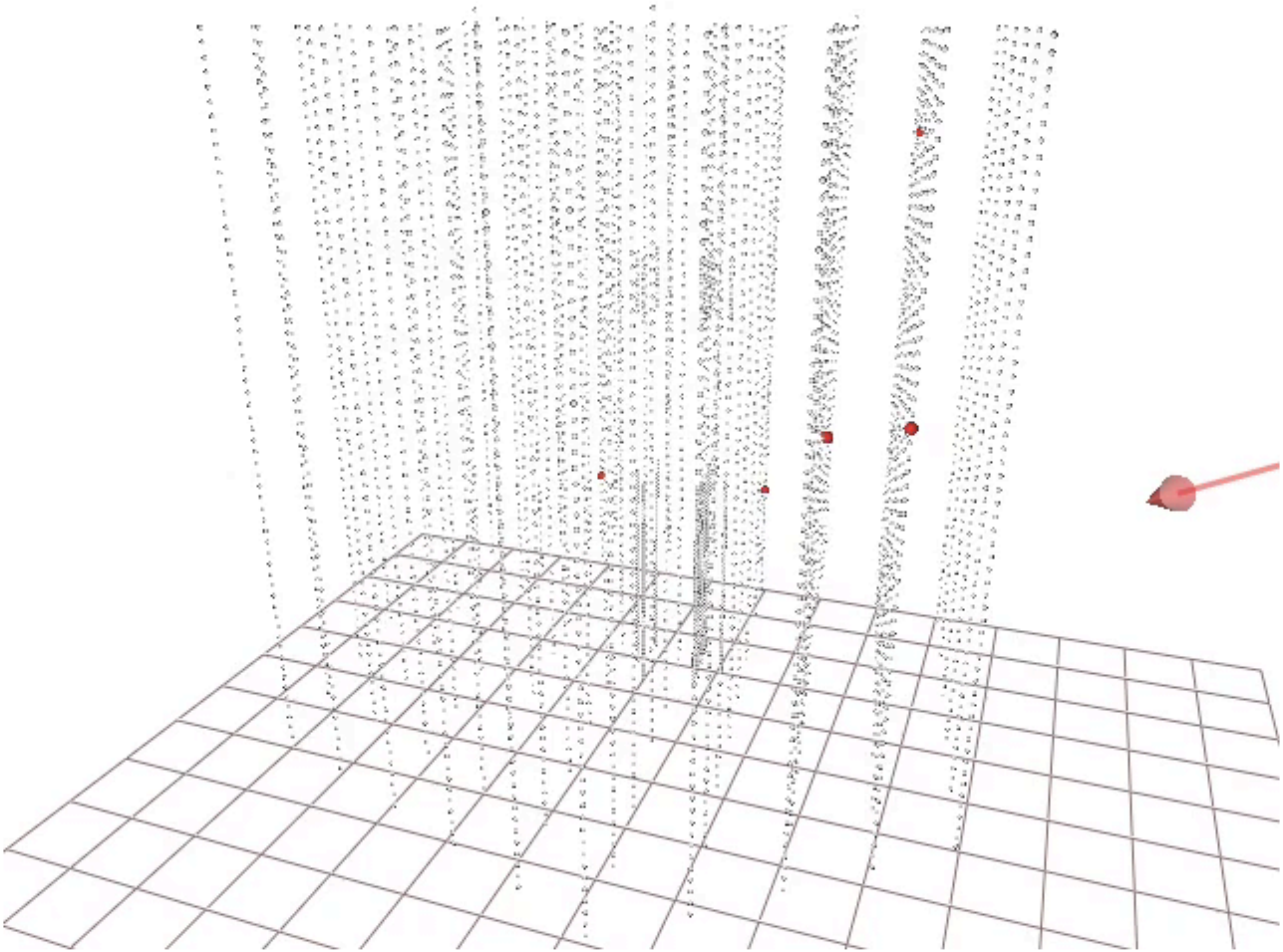

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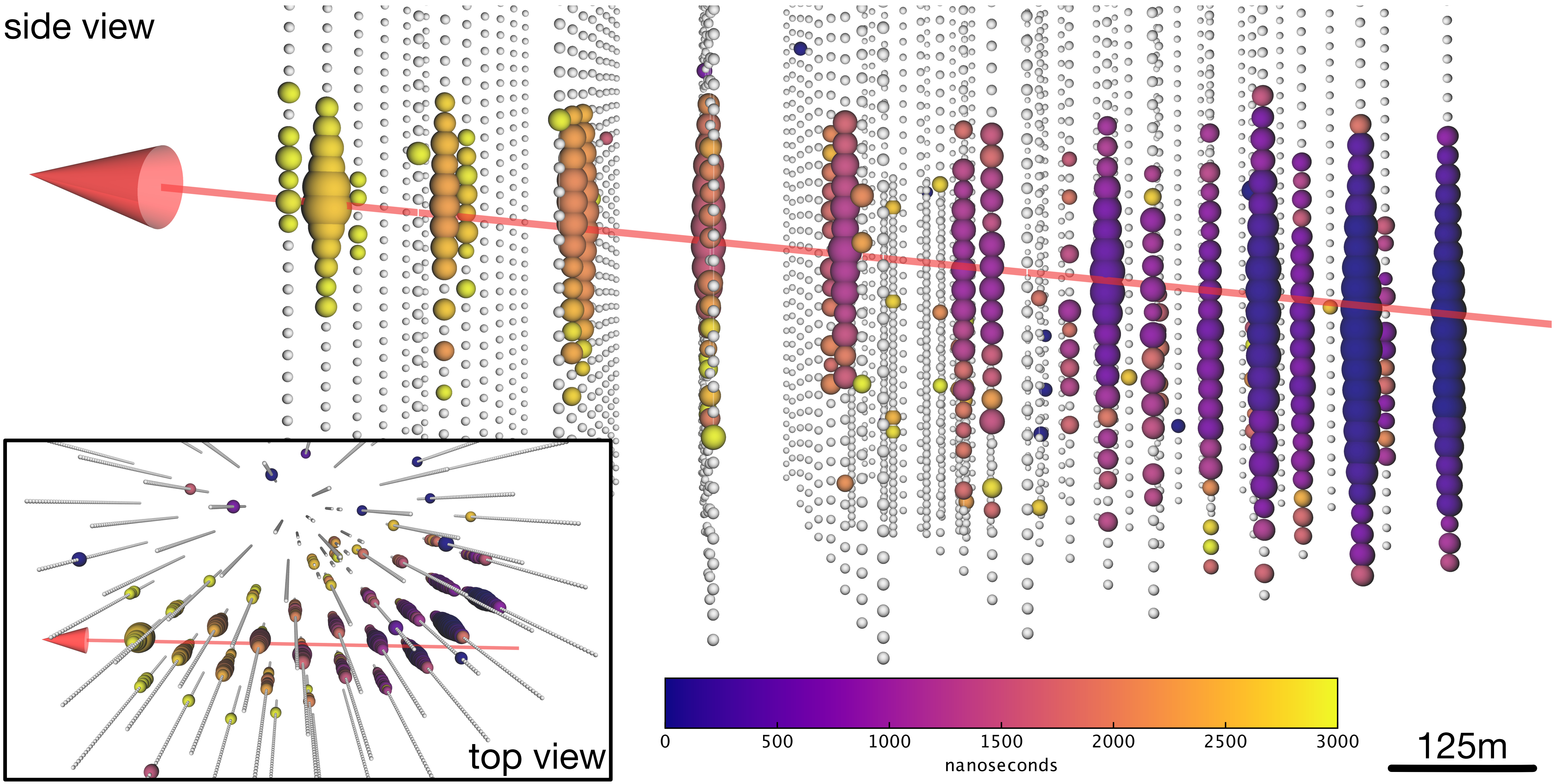

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

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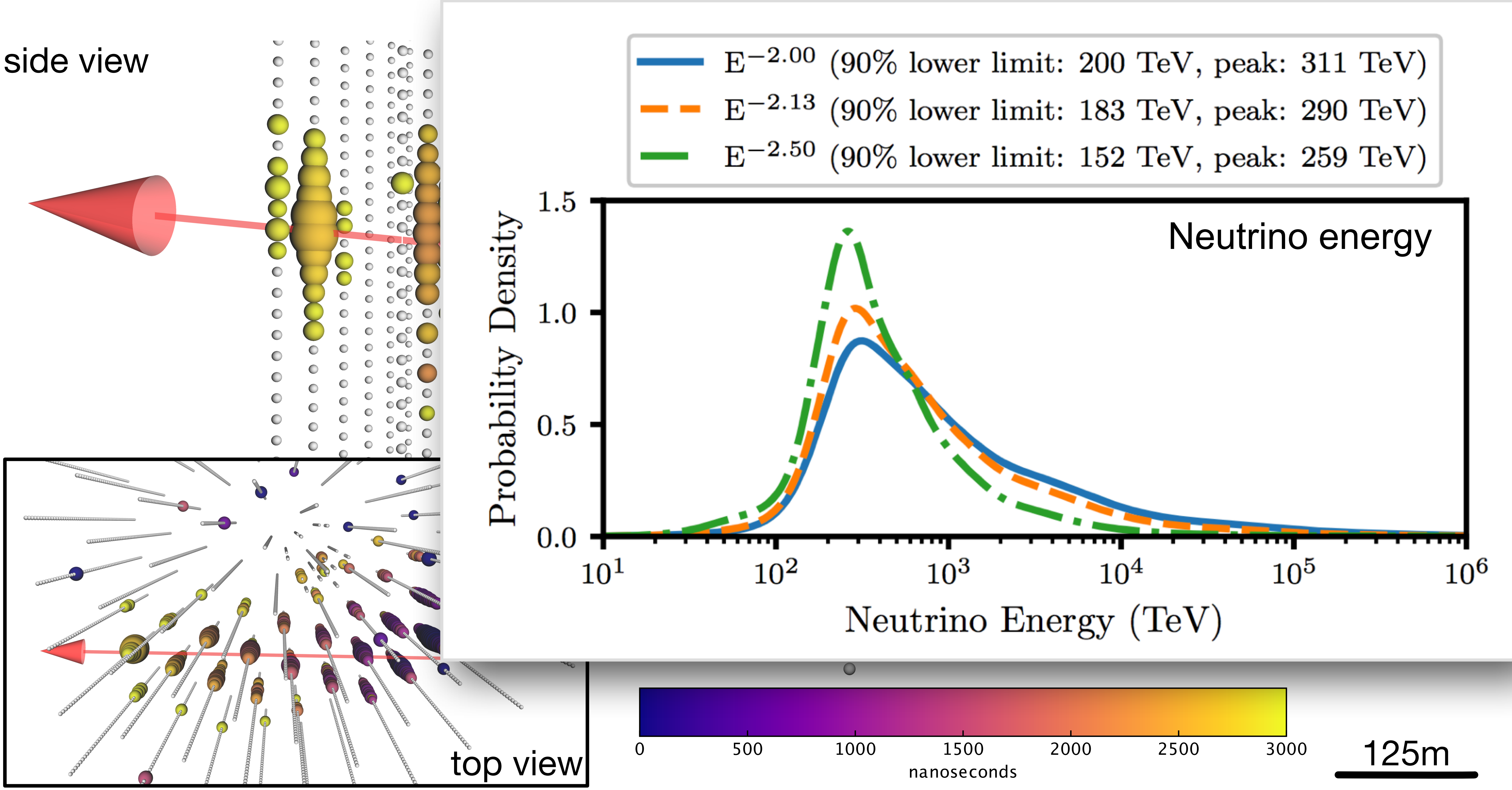
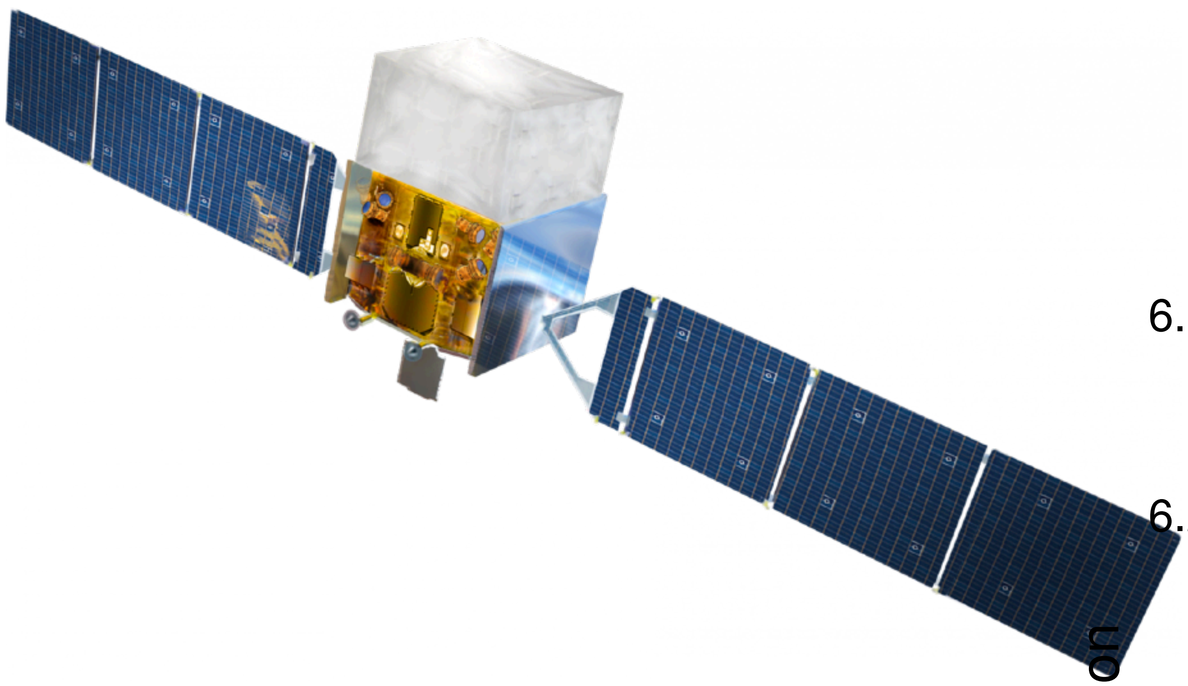


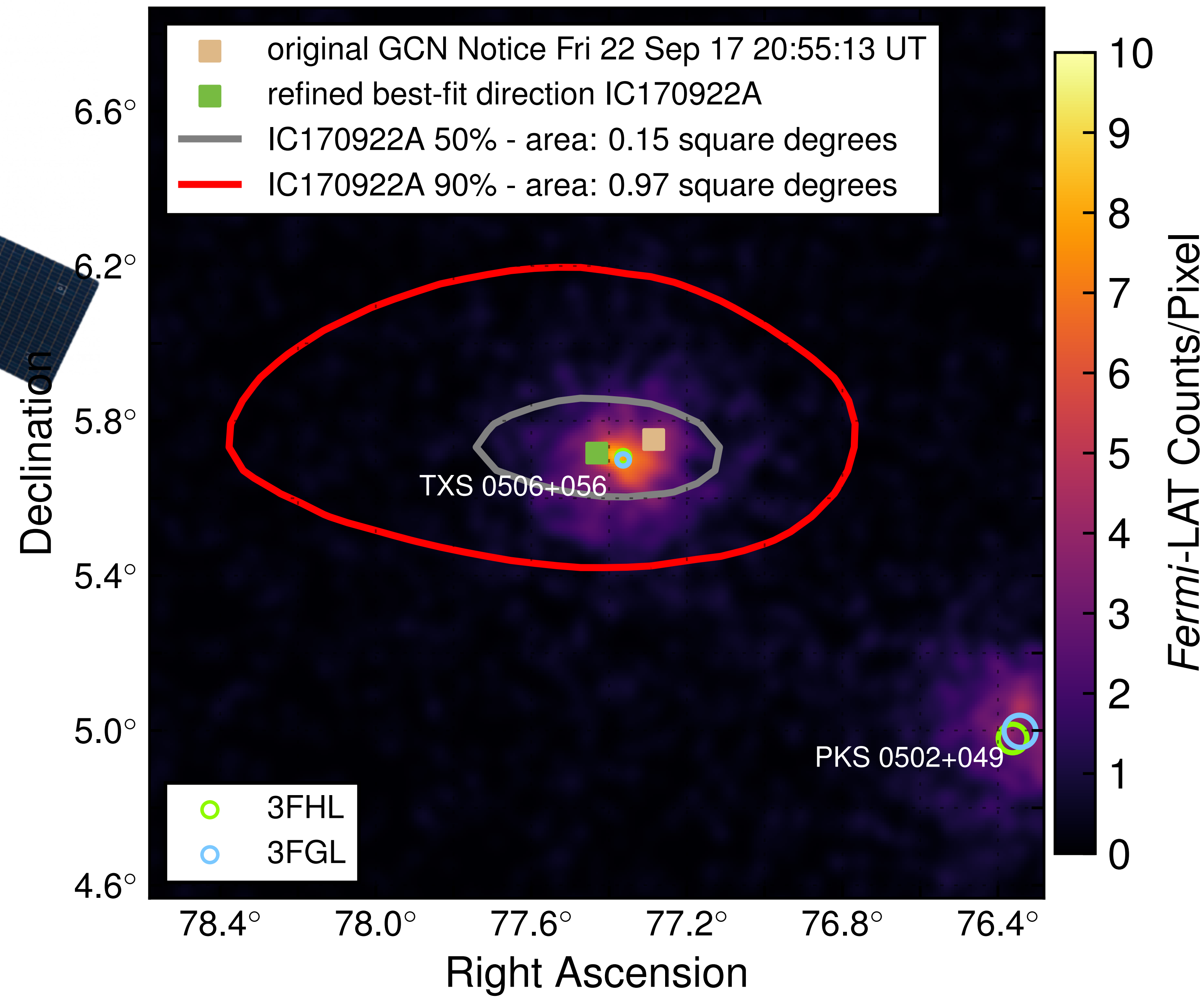
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

Fermi LAT observations

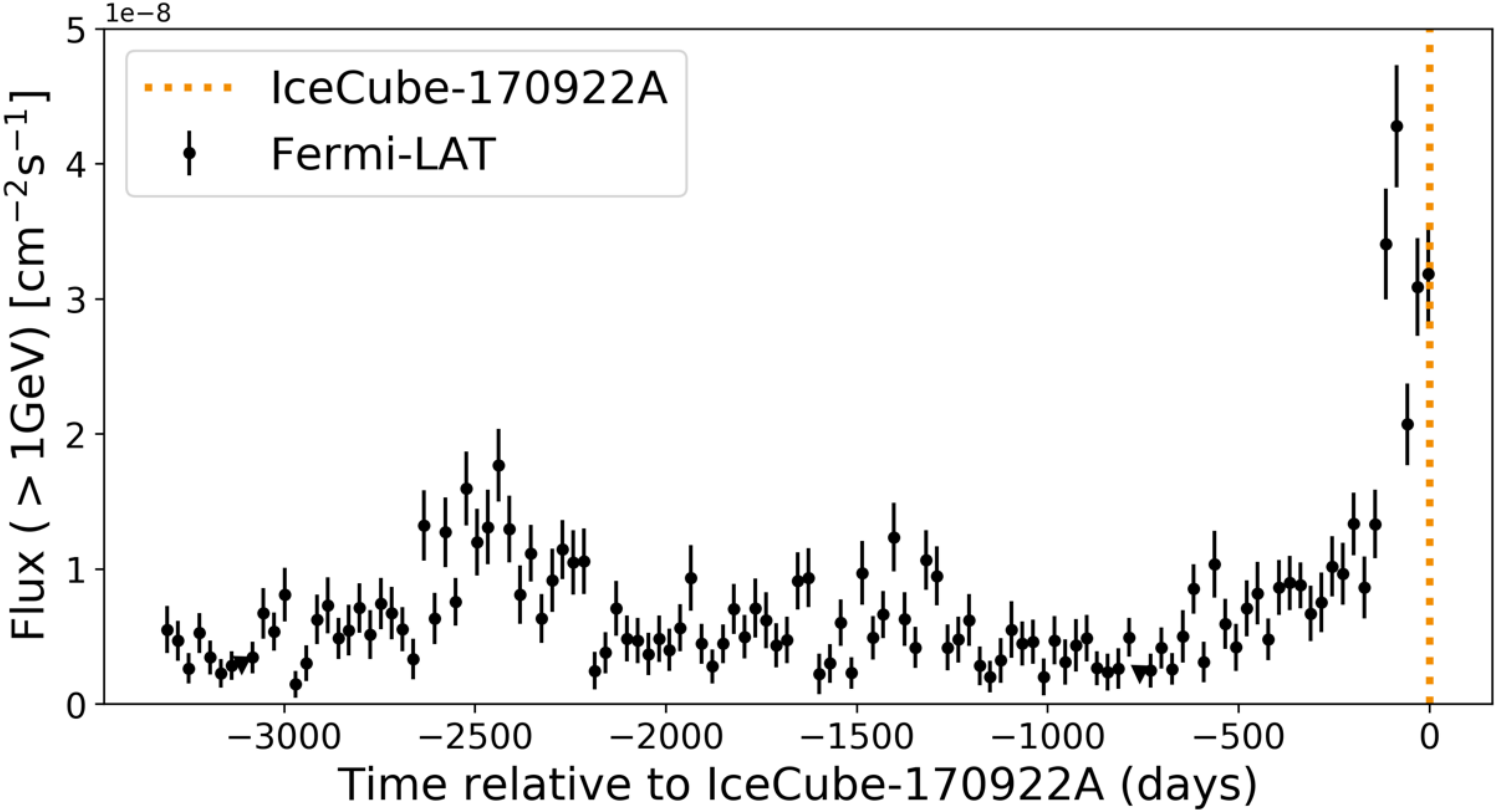
The gamma-ray blazar TXS0506+056



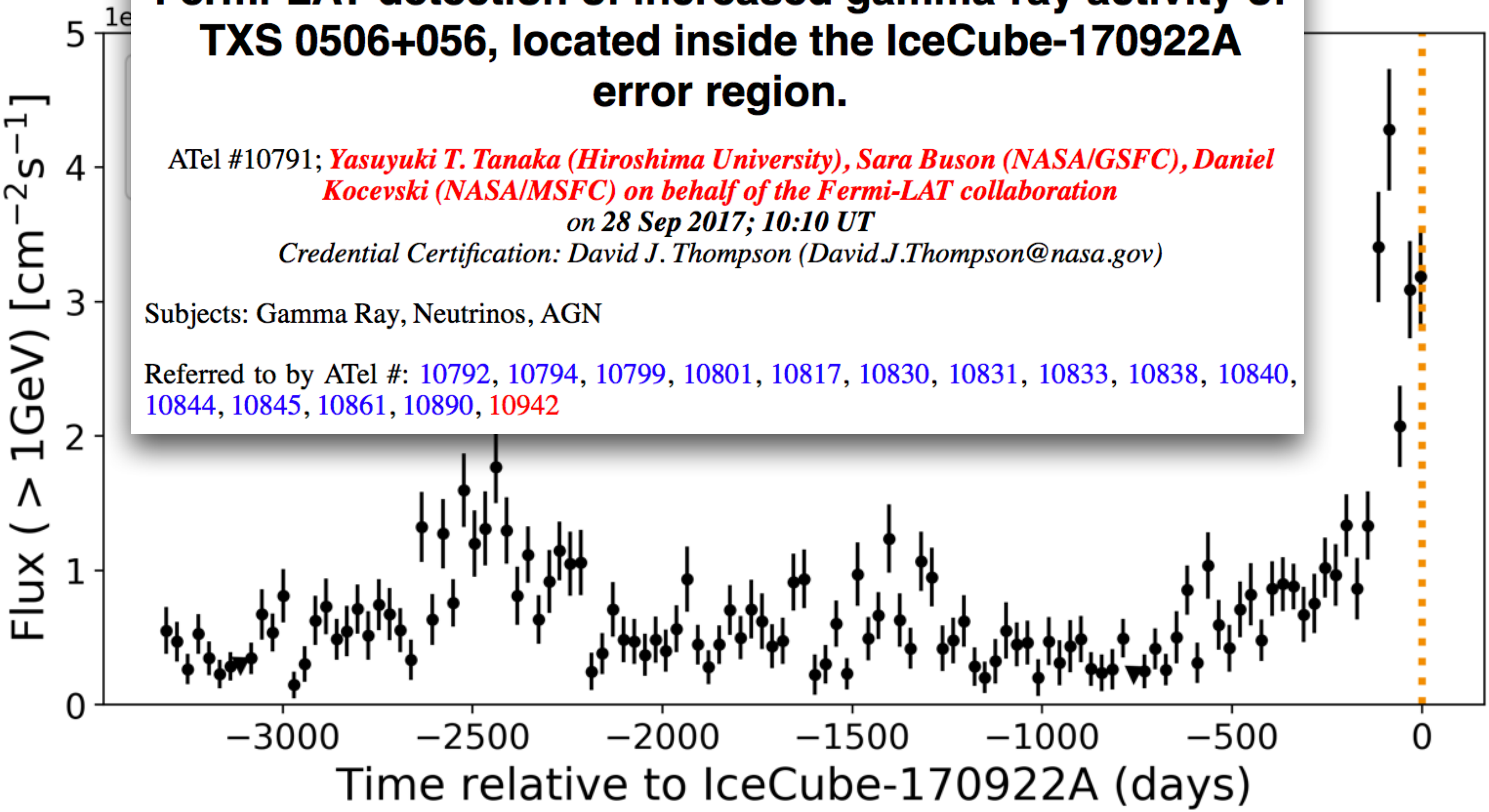
- Ferrmi LAT surveys the gamma-ray sky between 100 MeV and 300 GeV
- A full image of the sky every 3 hours since 2008



Fermi LAT observations



Fermi LAT observations



Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

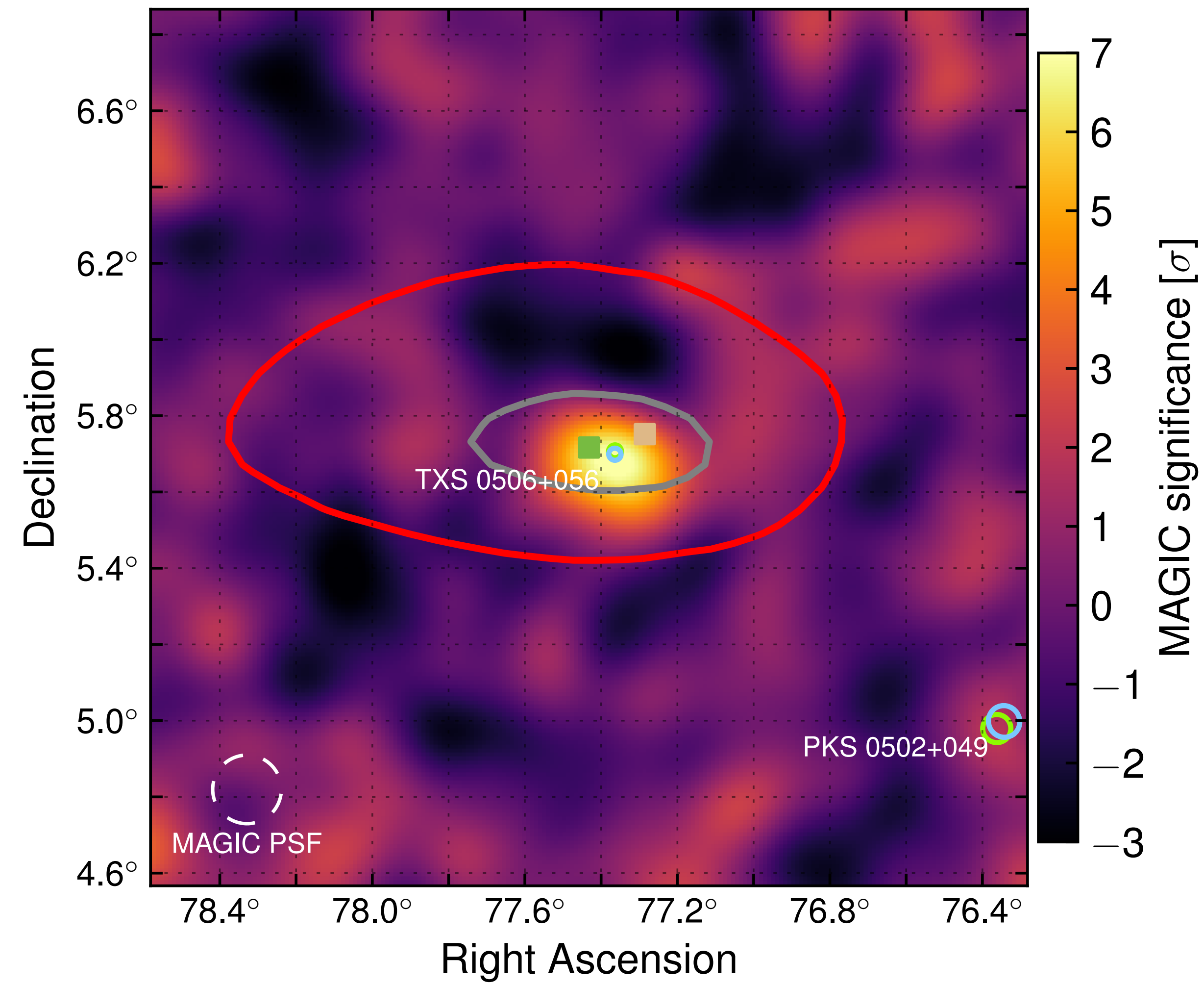
ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

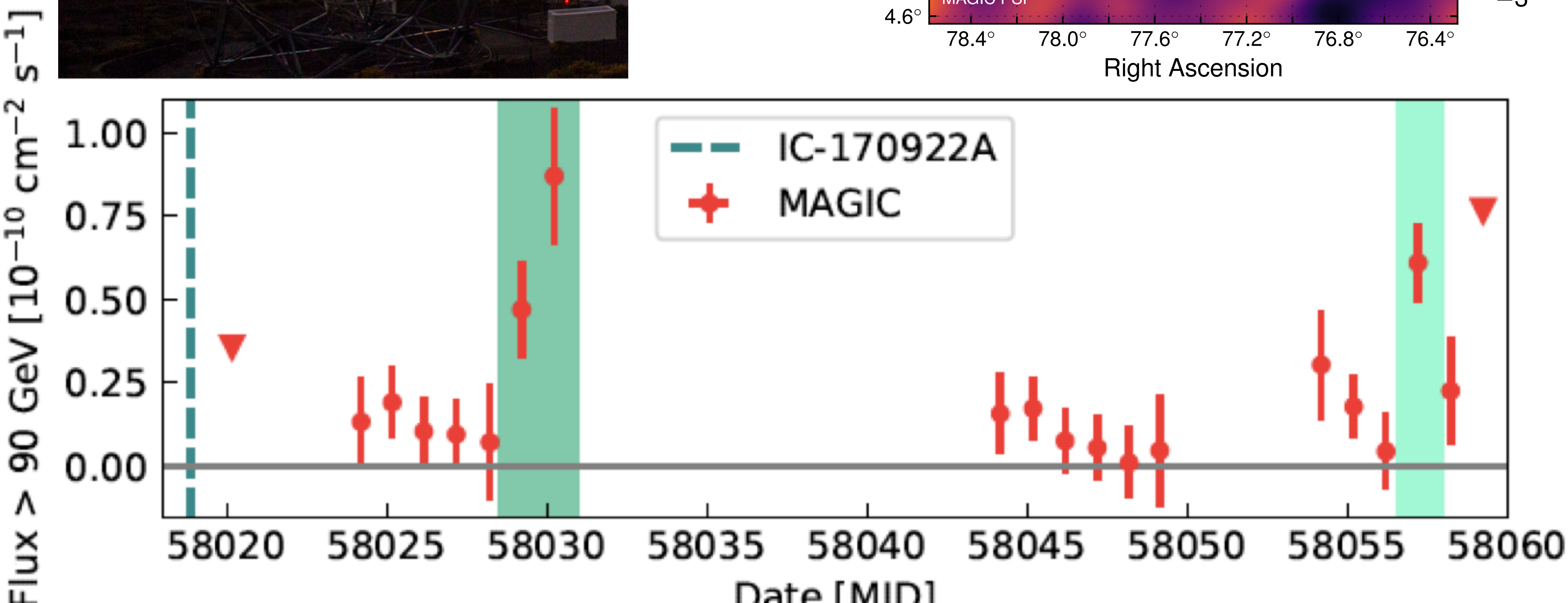
Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942

MAGIC observations

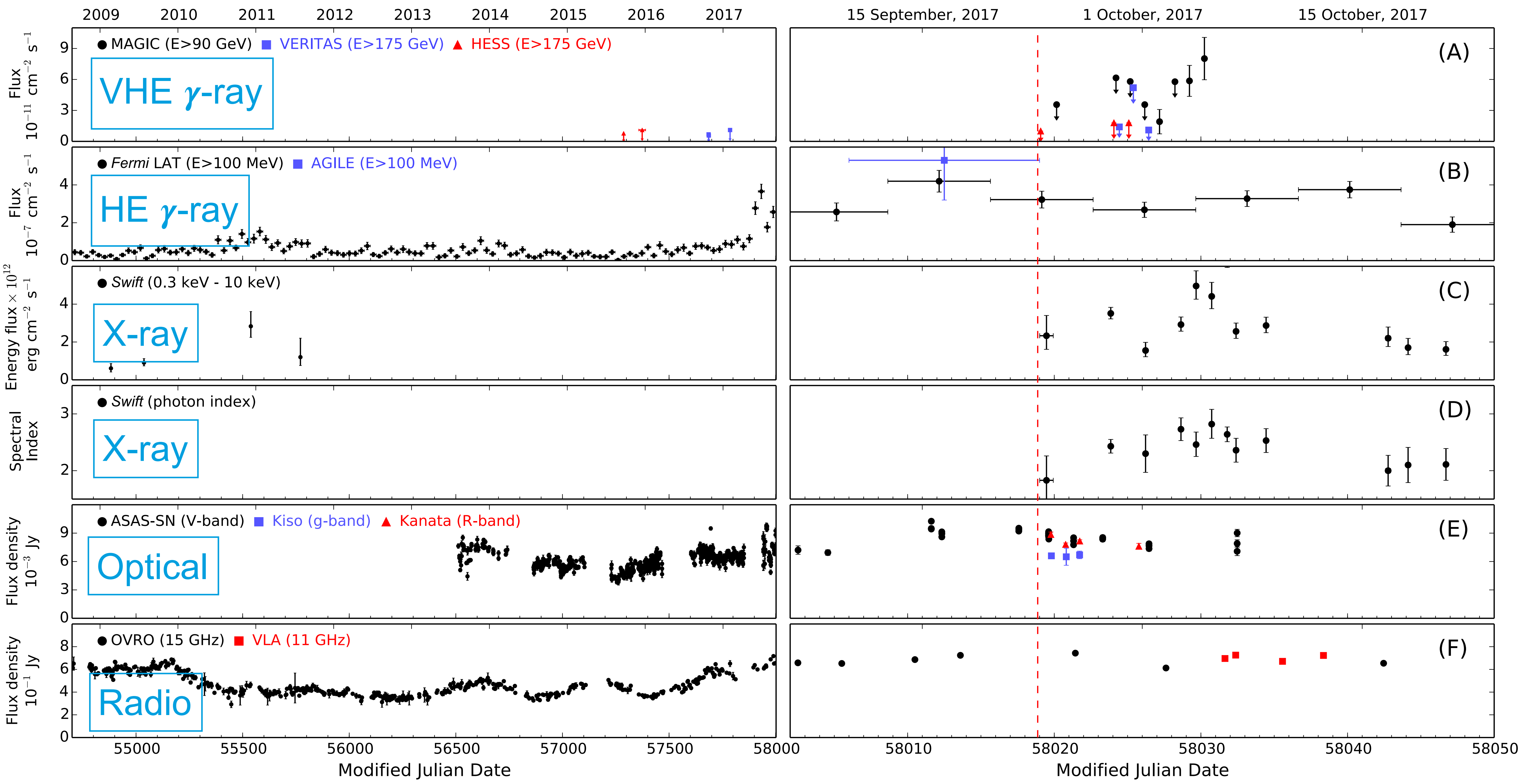
above 90 GeV in energy





The light curve of TXS0506+056

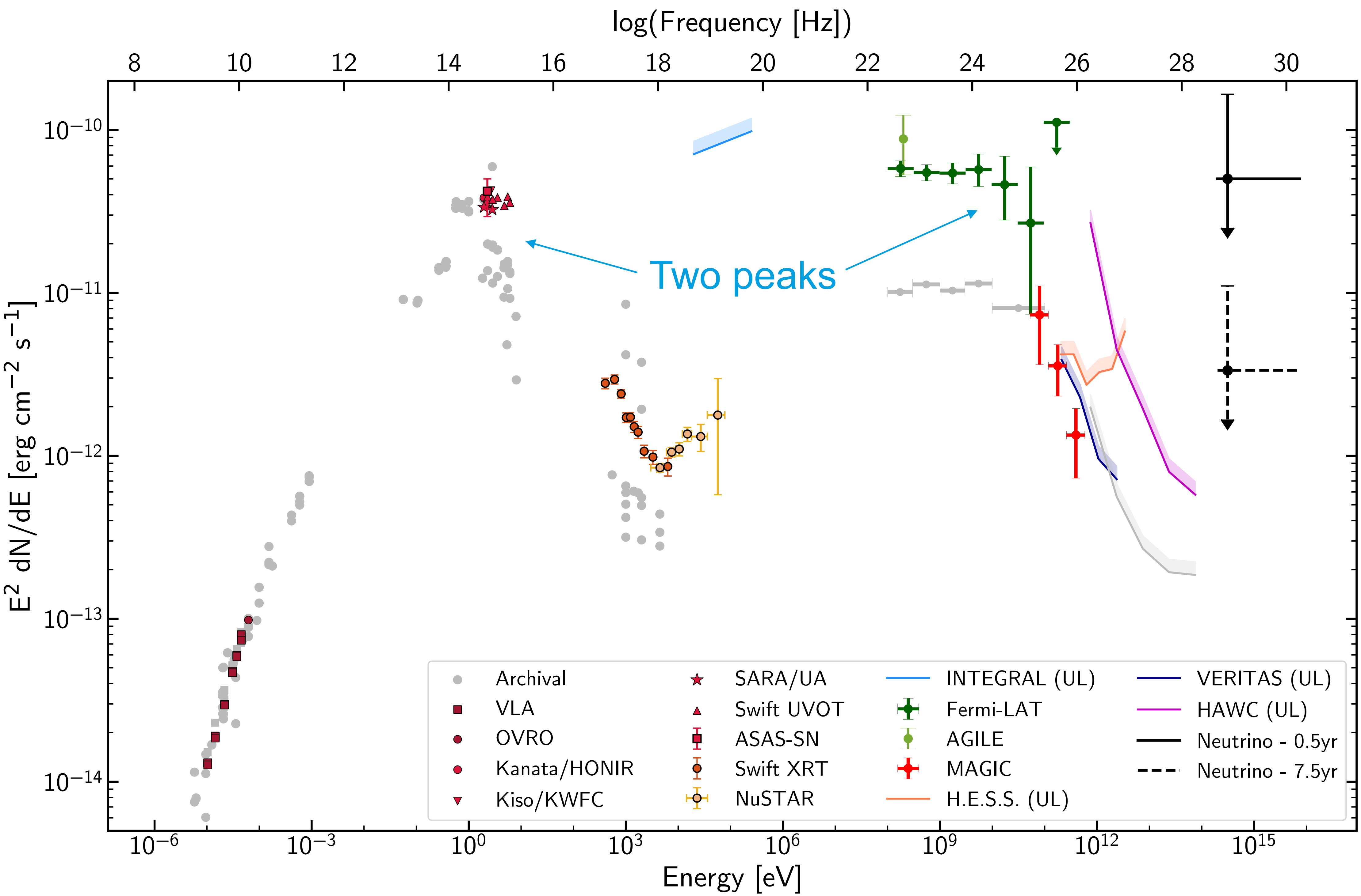
From radio to VHE gamma rays



IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

The spectral energy distribution (SED)

Observed radiation power as a function of frequency / energy

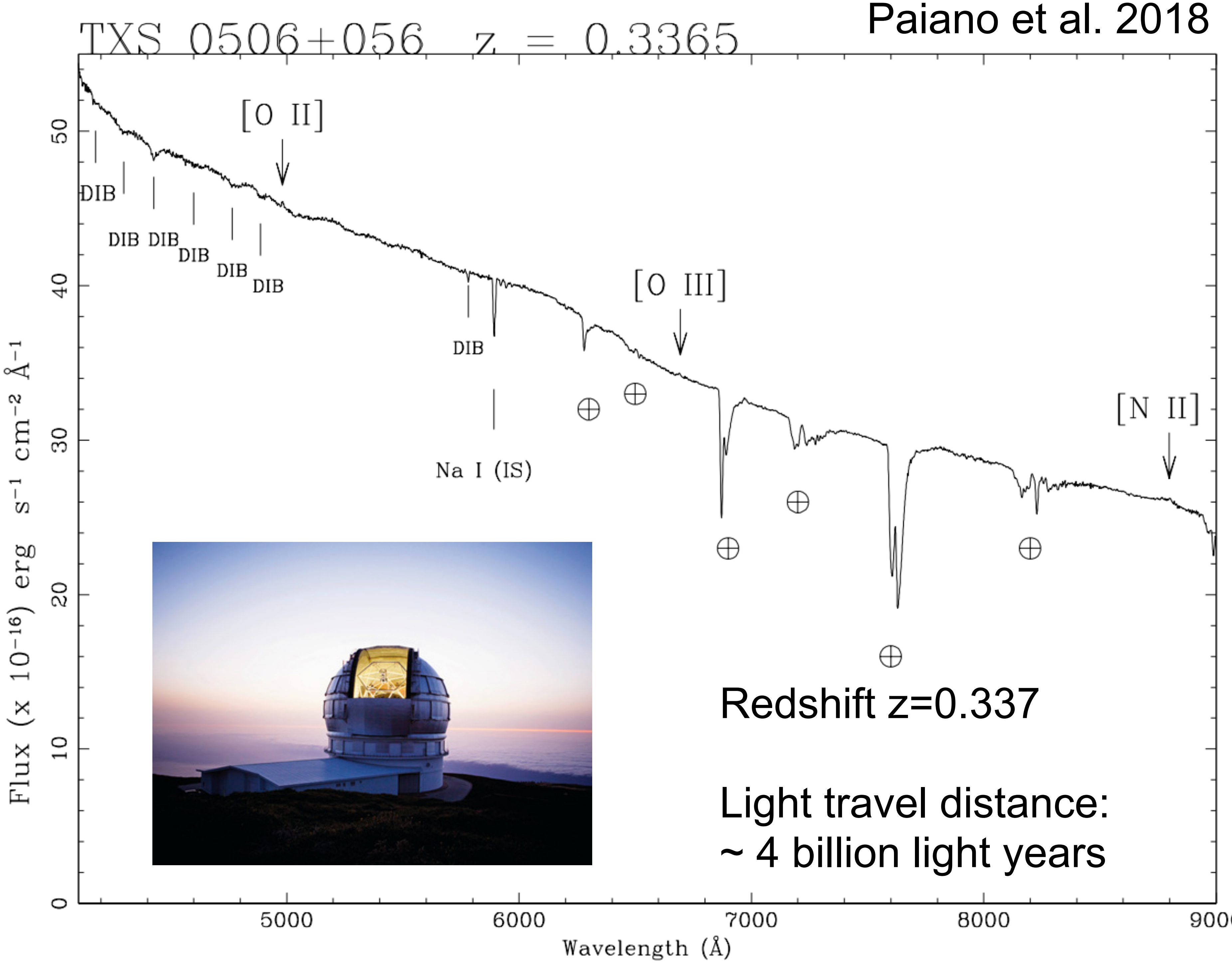


IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

And importantly a distance.

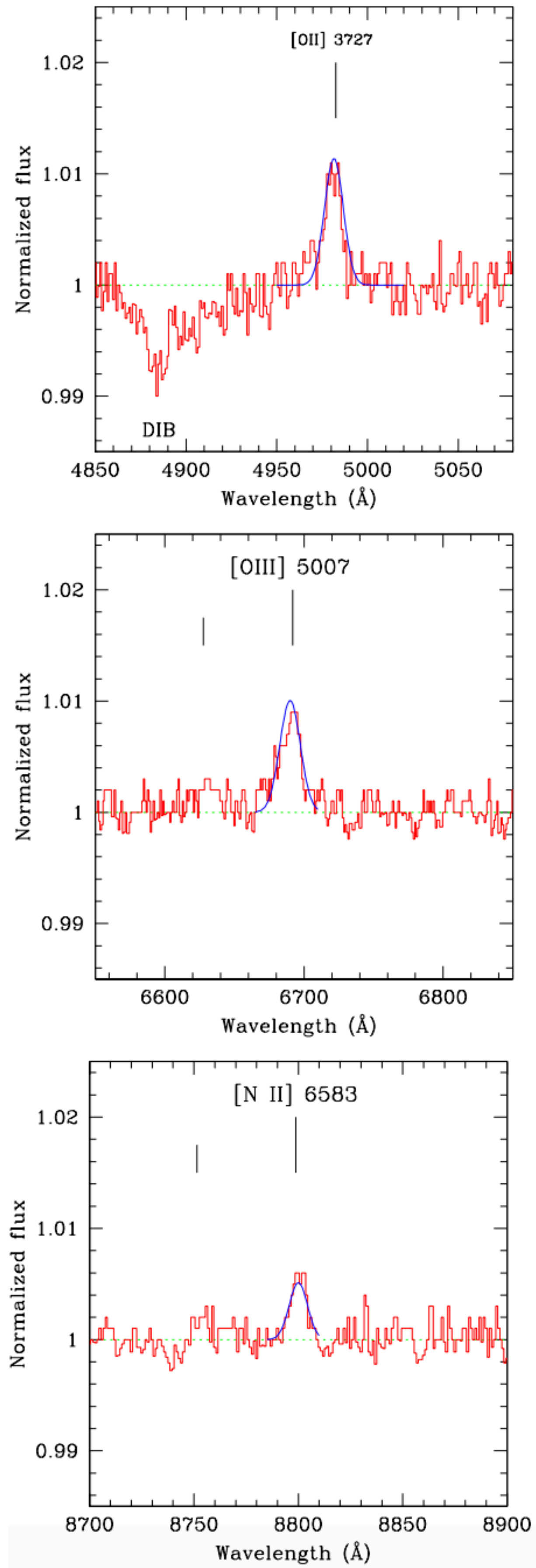
From the 10.4m Gran Telescopio Canarias

Paiano et al. 2018

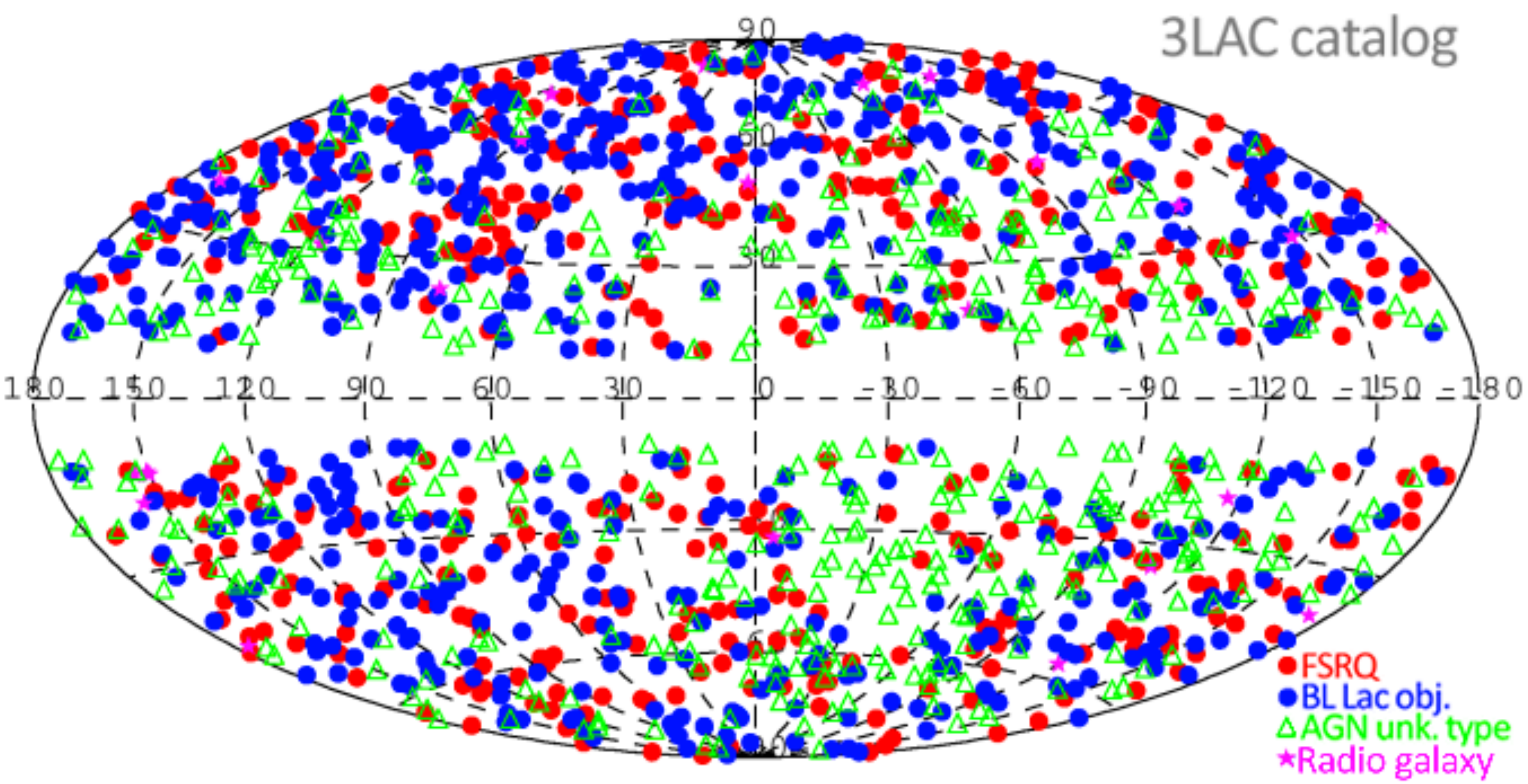


Redshift z=0.337

Light travel distance:
~ 4 billion light years



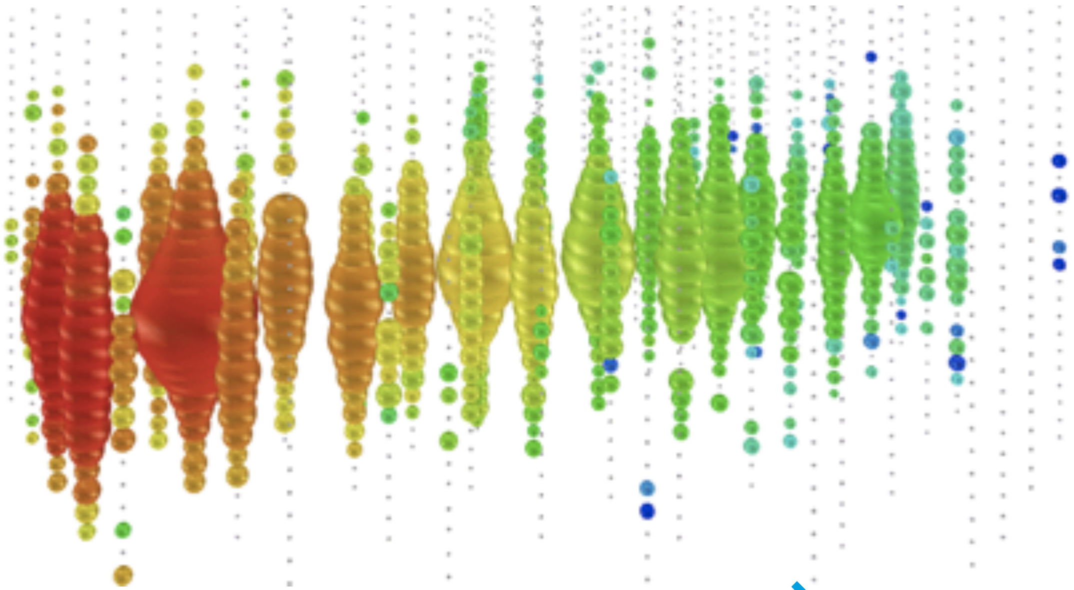
How likely does this happen by chance ?

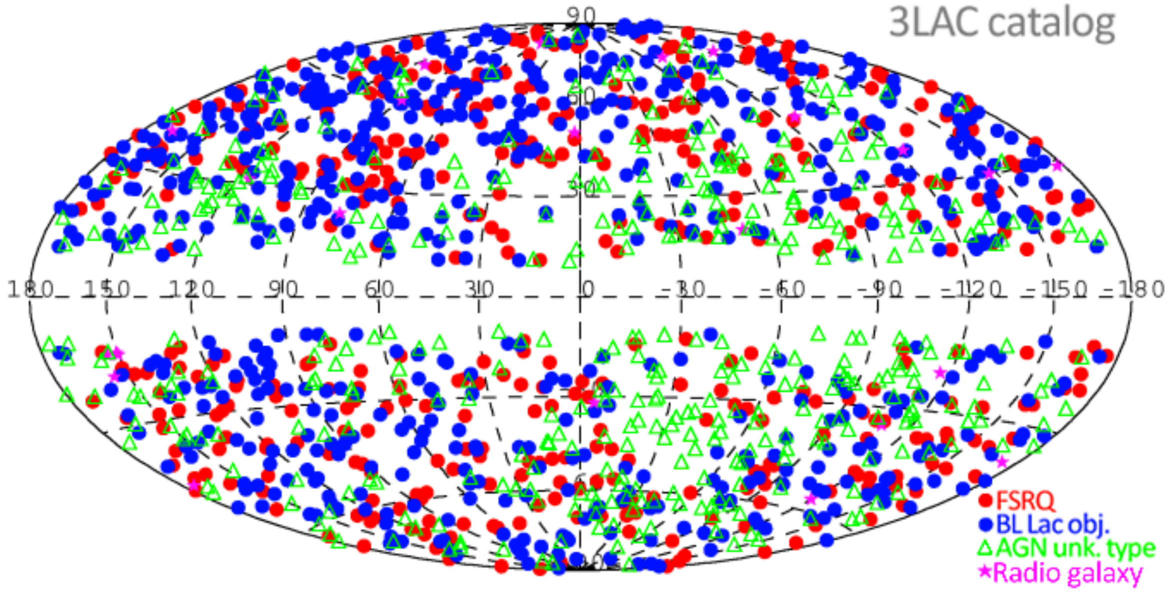


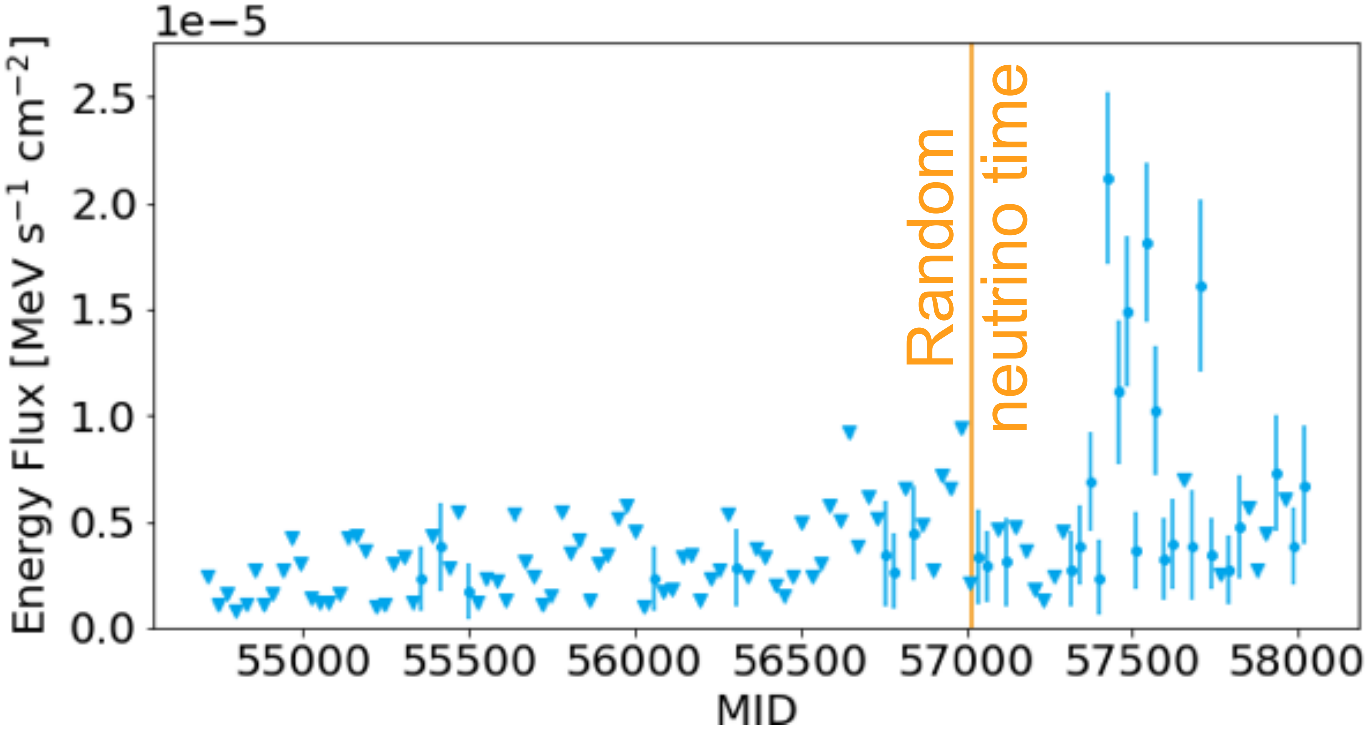
- 1563 gamma-ray blazars identified by Fermi LAT (3LAC catalog)
- TXS 0506+056 is one of the brightest sources during its outburst
- Correlation between gamma-ray and neutrino brightness expected

How likely does this happen by chance ?

An a-posteriori test with pseudo-experiments



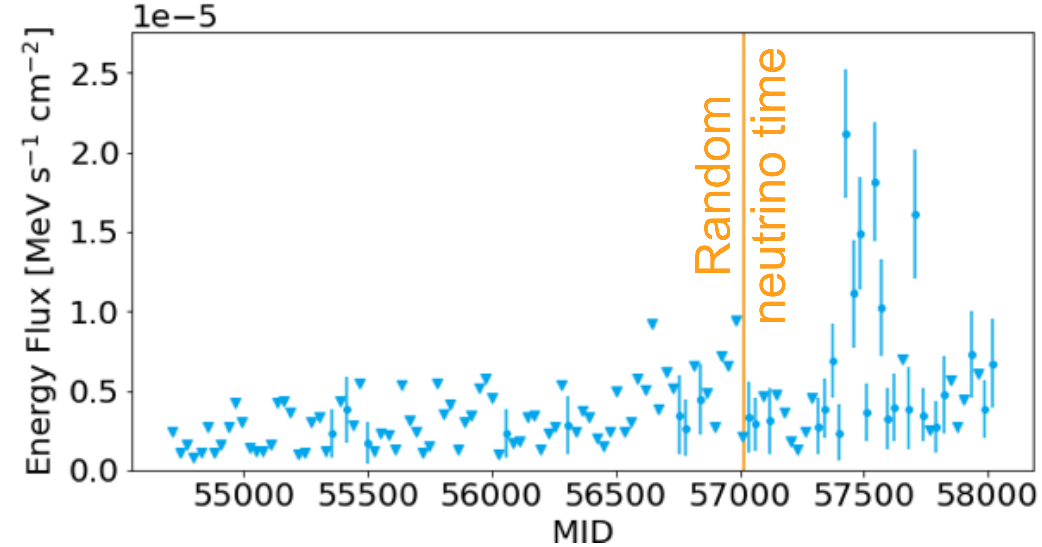


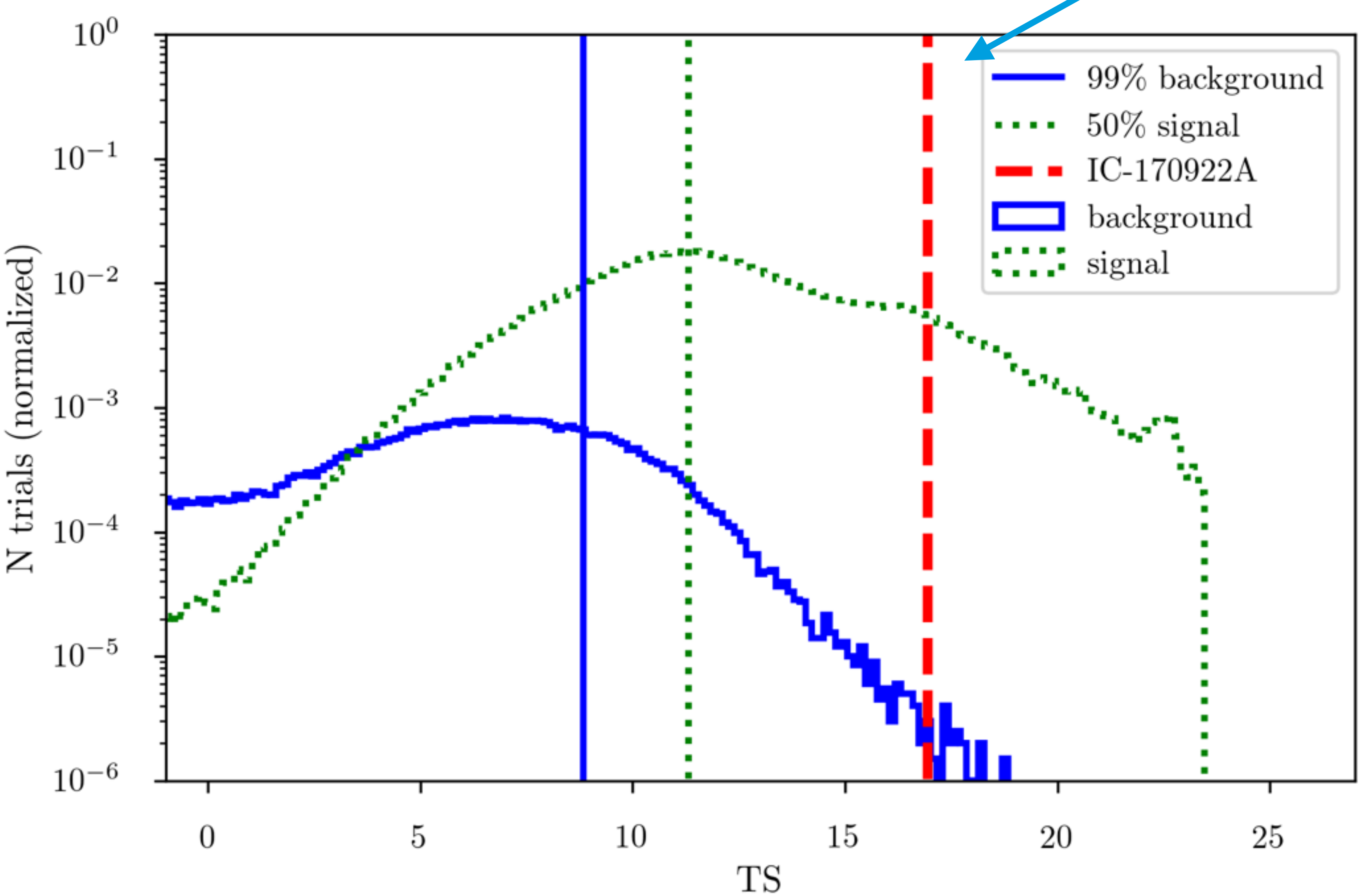


How likely does this happen by chance ?

The test statistic

- Test statistic based on:
  - Distance between neutrinos and blazars
  - Location on the sky
  - Observed brightness in gamma rays at the time of the neutrino



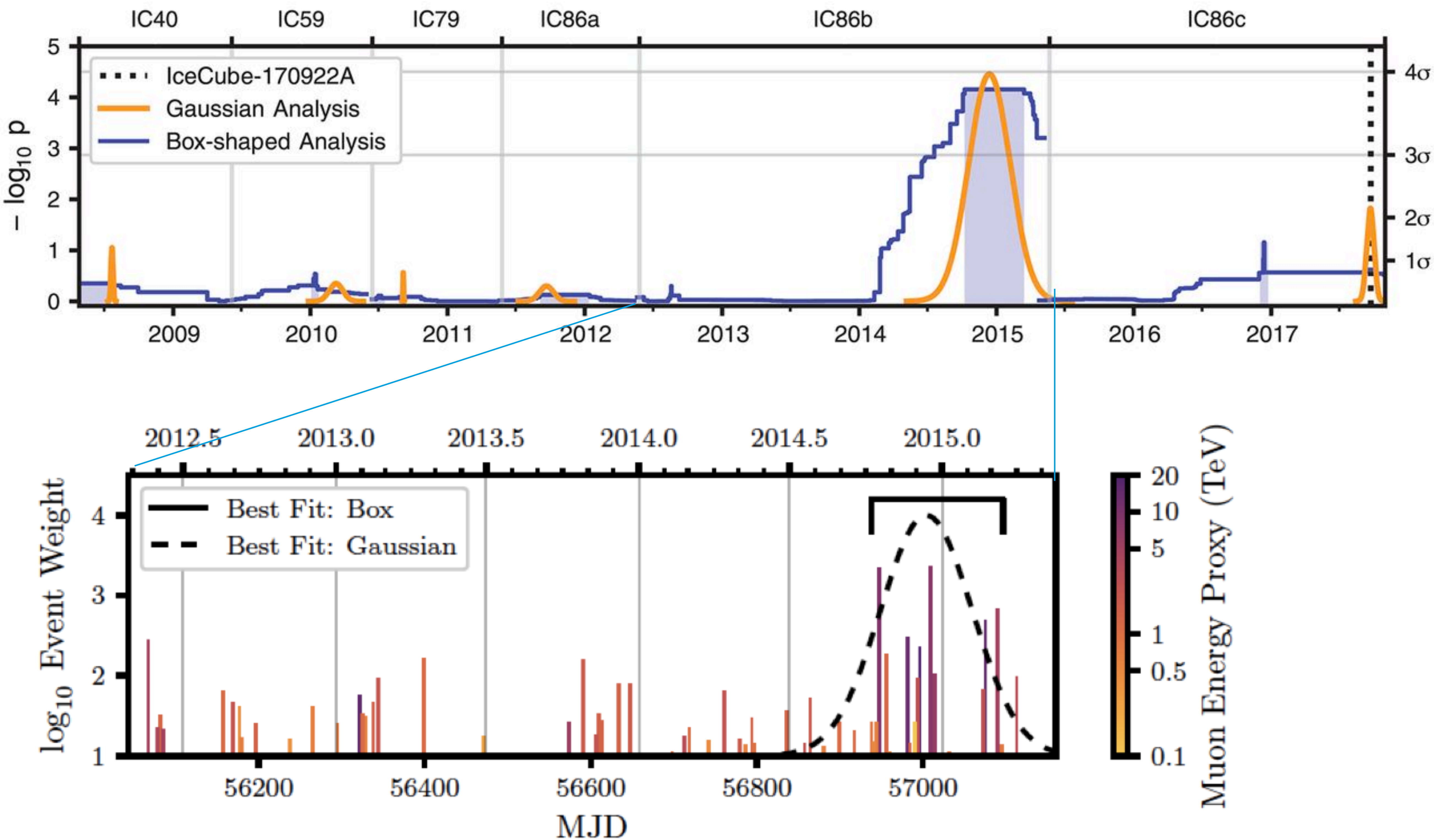


Significance
after correction for trial factor / look-elsewhere effect**:**

~ 3 σ

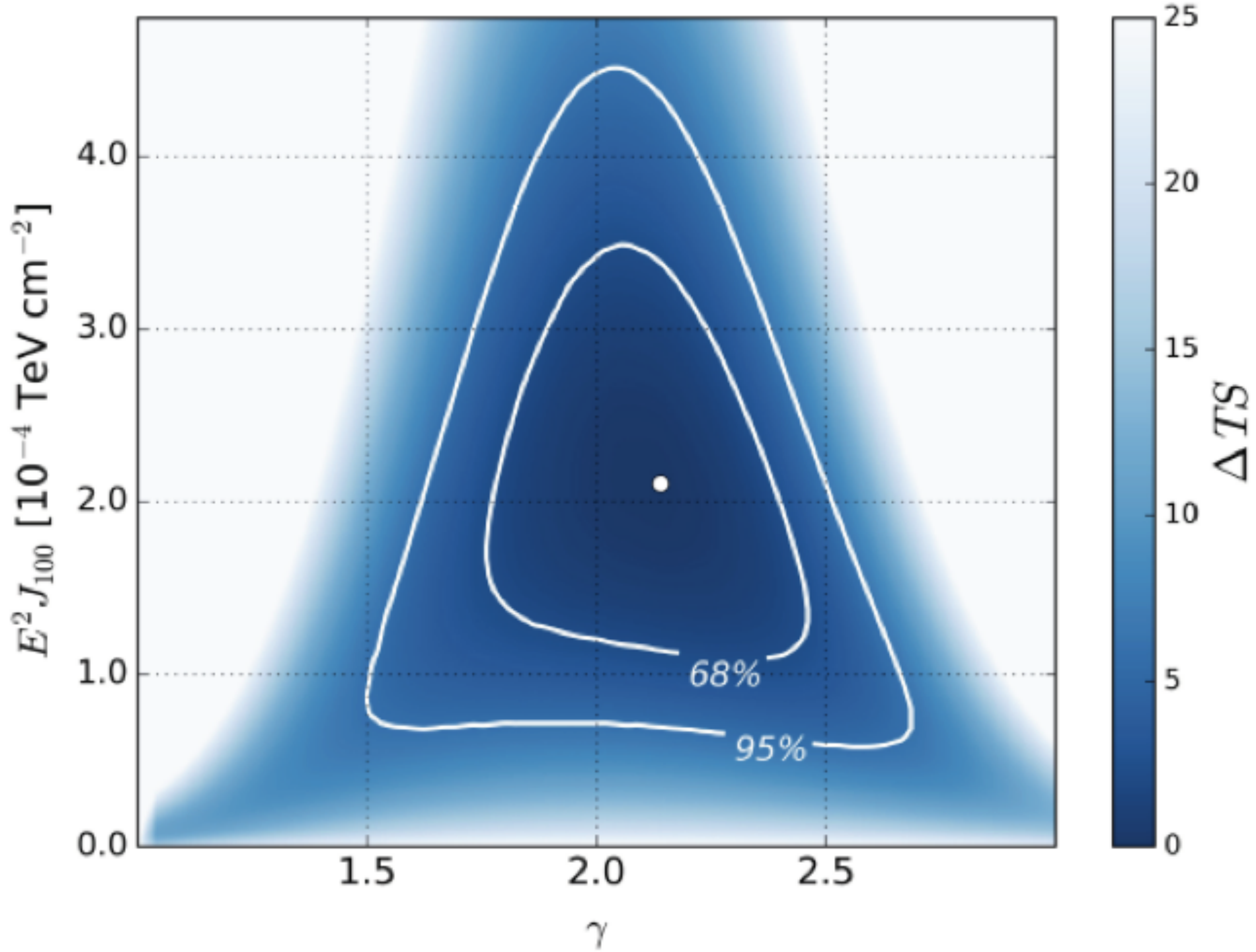
Looking back at IceCube's full dataset

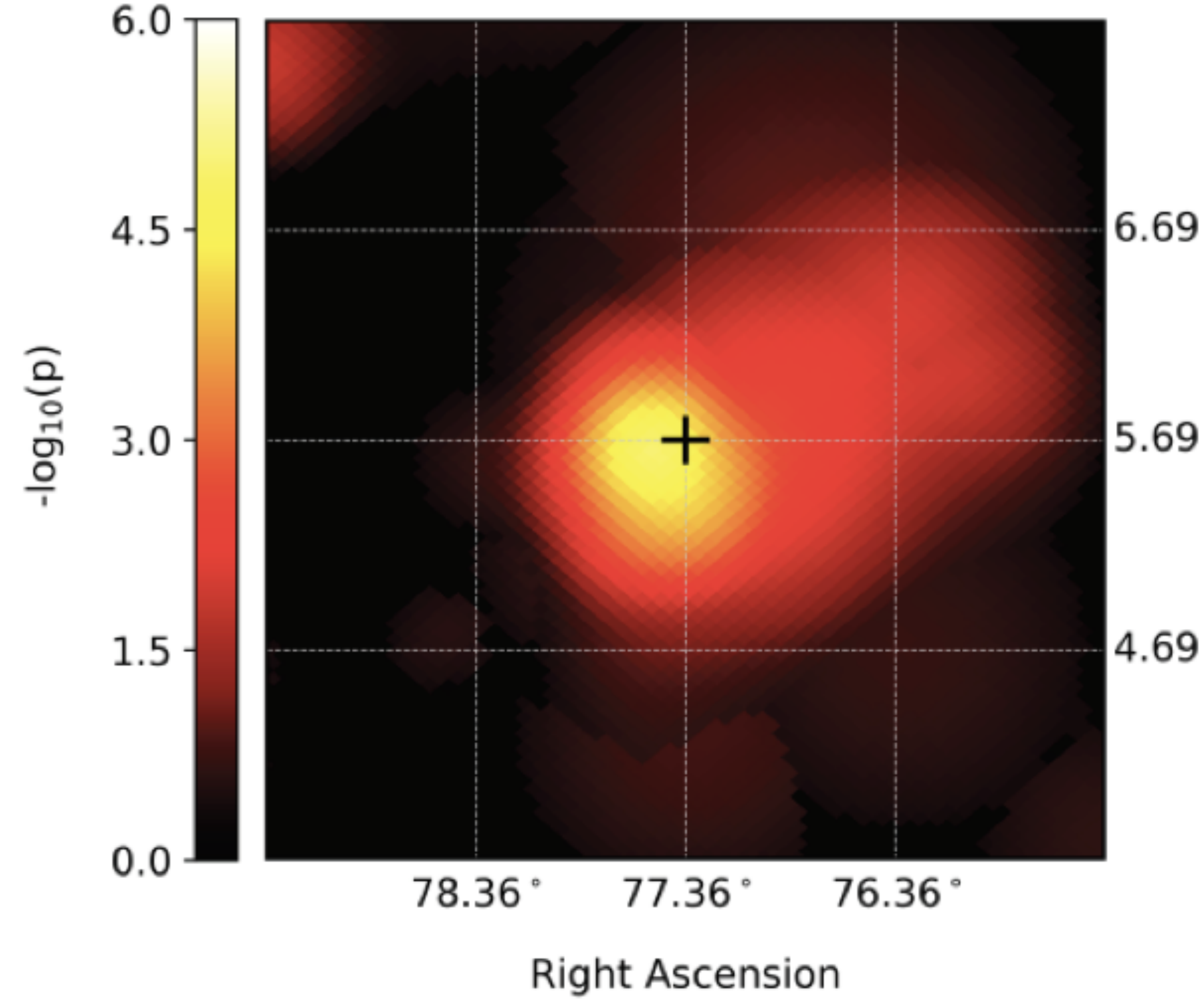
for TXS 0506+056



Looking back at IceCube's full dataset

for TXS 0506+056



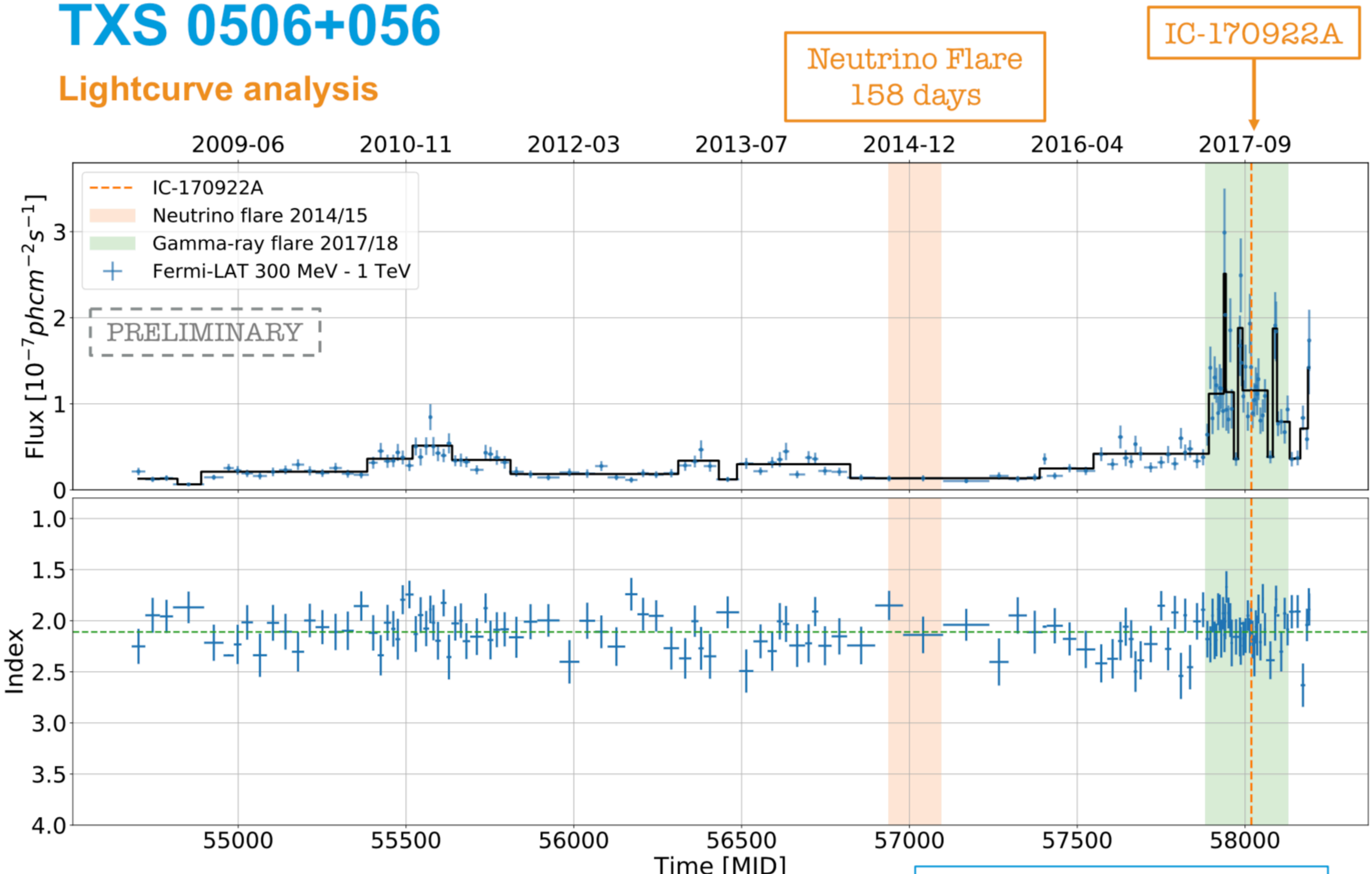


13±5 above the background of atmospheric neutrinos, 3.5σ

Neutrino luminosity (averaged over 158 days): $(1.2^{+0.6}_{-0.4}) \times 10^{47}$ erg s^{-1}

TXS 0506+056

Lightcurve analysis



Garrappa+ (in preparation)

No enhanced gamma-ray emission during the 2014/15 neutrino flare

A double feature in Science

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*†

Science 361 (2018) no. 6398, eaat1378

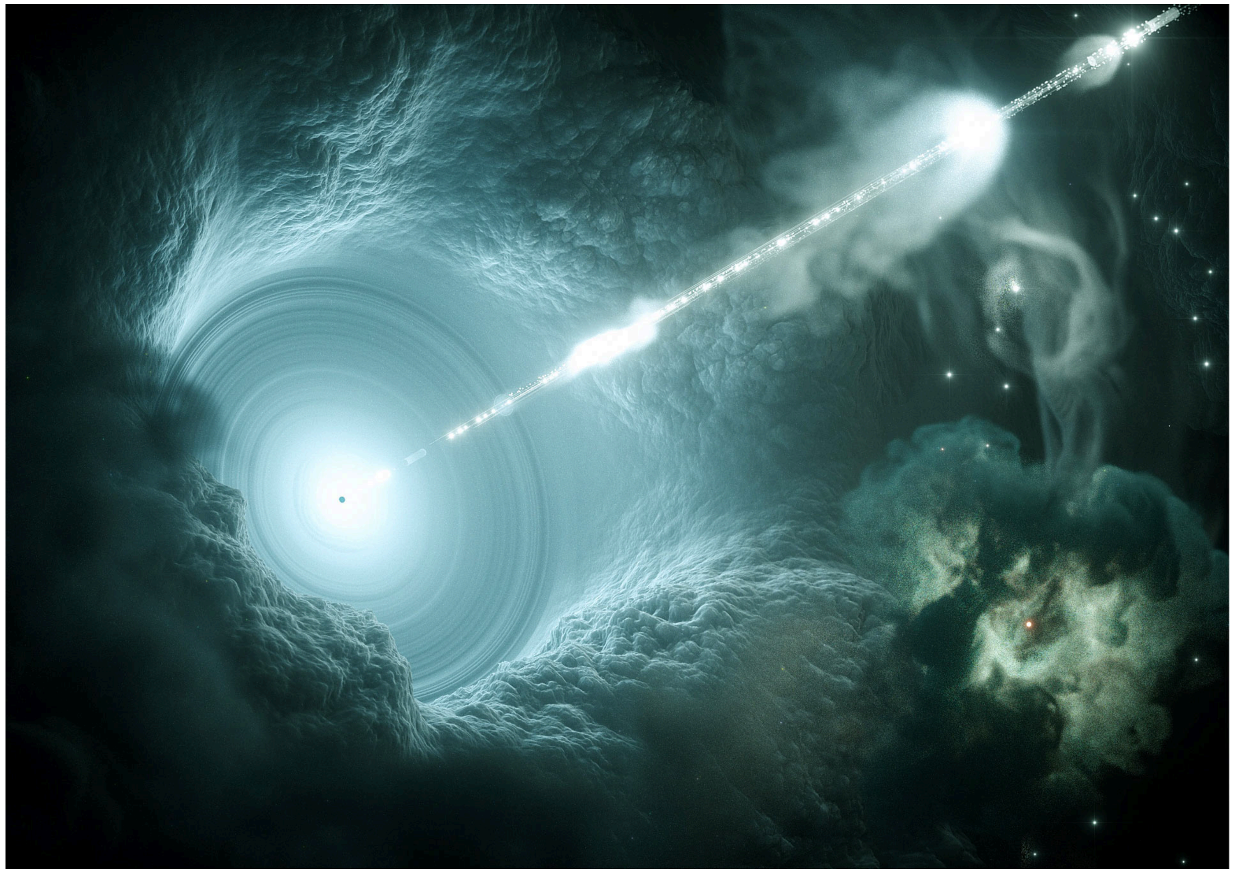
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†

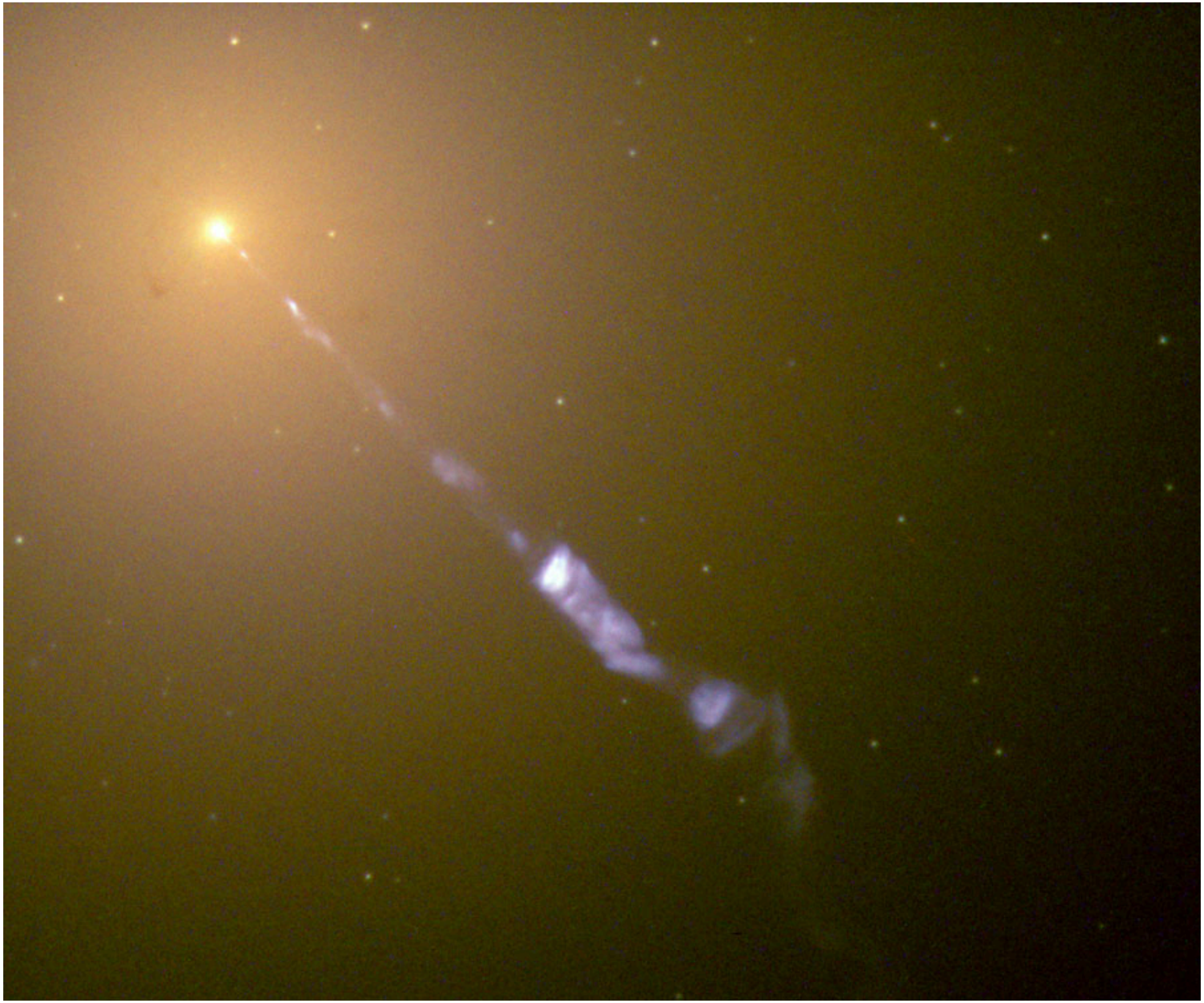
Science 361 (2018) no. 6398, 147-151

Do we understand what we see ?

- Did we expect Blazars to be cosmic-ray accelerators ?
- Have we found the first source of ultra-high-energy cosmic rays
- Do we learn something about the acceleration processes and environments in these objects ?
- Is this all consistent ?



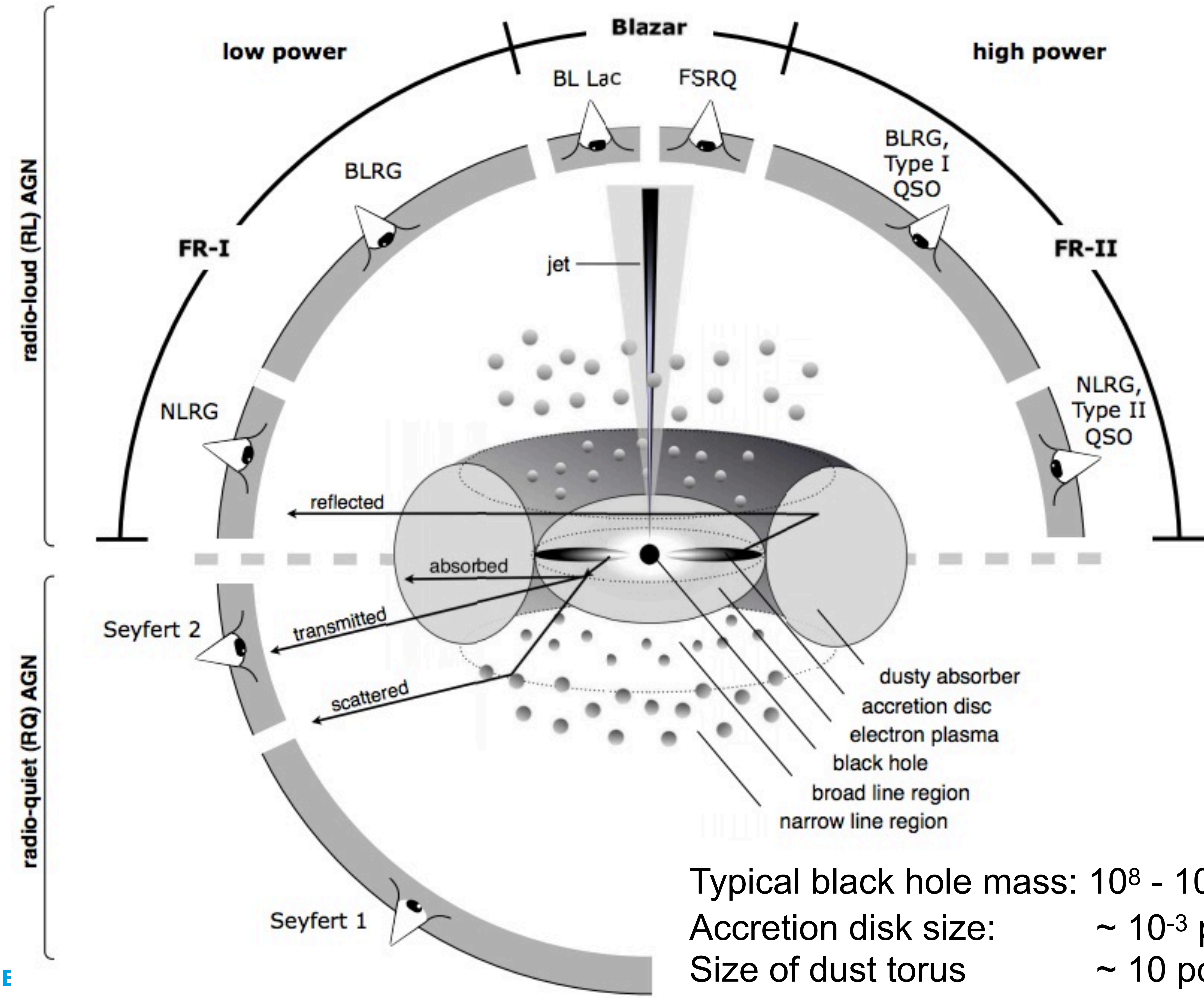
A short introduction to active galaxies and Blazars



M87
seen from Hubble Space Telescope

Distance:
~ 50 million light years

The AGN model



Typical black hole mass: 10^8 - 10^{10} $M_\odot$

Accretion disk size: ~ 10^{-3} pc

Size of dust torus ~ 10 pc

The AGN

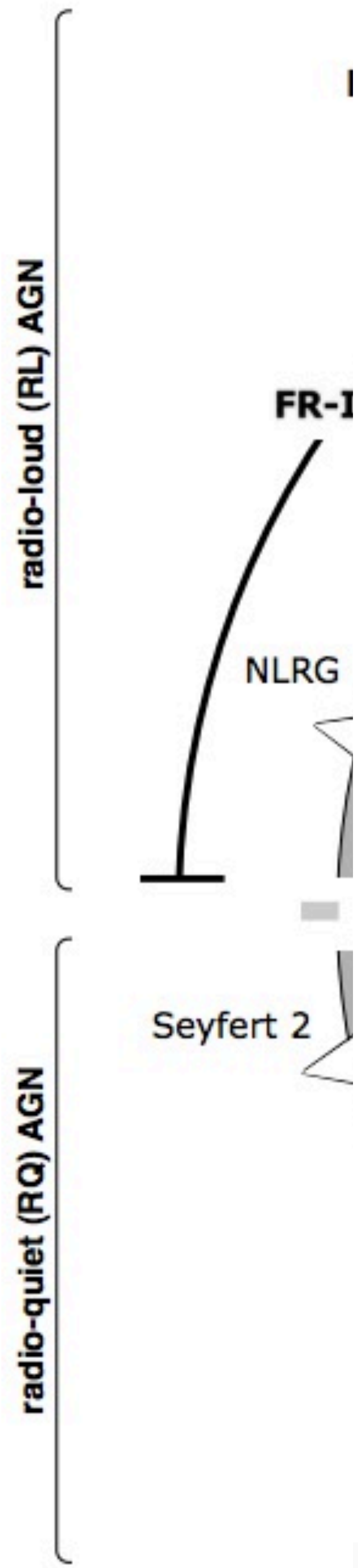


Table 1 The AGN zoo: list of AGN classes.

Class/Acronym	Meaning	Main properties/reference
Quasar	Quasi-stellar radio source (originally)	Radio detection no longer required
Sey1	Seyfert 1	FWHM $\gtrsim 1,000$ km s^{-1}
Sey2	Seyfert 2	FWHM $\lesssim 1,000$ km s^{-1}
QSO	Quasi-stellar object	Quasar-like, non-radio source
QSO2	Quasi-stellar object 2	High power Sey2
RQ AGN	Radio-quiet AGN	see ref. 1
RL AGN	Radio-loud AGN	see ref. 1
Jetted AGN		with strong relativistic jets; see ref. 1
Non-jetted AGN		without strong relativistic jets; see ref. 1
Type 1		Sey1 and quasars
Type 2		Sey2 and QSO2
FR I	Fanaroff-Riley class I radio source	radio core-brightened (ref. 2)
FR II	Fanaroff-Riley class II radio source	radio edge-brightened (ref. 2)
BL Lac	BL Lacertae object	see ref. 3
Blazar	BL Lac and quasar	BL Lacs and FSRQs
BAL	Broad absorption line (quasar)	ref. 4
BLO	Broad-line object	FWHM $\gtrsim 1,000$ km s^{-1}
BLAGN	Broad-line AGN	FWHM $\gtrsim 1,000$ km s^{-1}
BLRG	Broad-line radio galaxy	RL Sey1
CDQ	Core-dominated quasar	RL AGN, $f_{core} \geq f_{ext}$ (same as FSRQ)
CSS	Compact steep spectrum radio source	core dominated, $\alpha_r > 0.5$
CT	Compton-thick	$N_H \geq 1.5 \times 10^{24}$ cm^{-2}
FR 0	Fanaroff-Riley class 0 radio source	ref. 5
FSRQ	Flat-spectrum radio quasar	RL AGN, $\alpha_r \leq 0.5$
GPS	Gigahertz-peaked radio source	see ref. 6
HBL/HSP	High-energy cutoff BL Lac/blazar	$\nu_{synch\ peak} \geq 10^{15}$ Hz (ref. 7)
HEG	High-excitation galaxy	ref. 8
HPQ	High polarization quasar	$P_{opt} \geq 3\%$ (same as FSRQ)
Jet-mode		$L_{kin} \gg L_{rad}$ (same as LERG); see ref. 9
IBL/ISP	Intermediate-energy cutoff BL Lac/blazar	$10^{14} \leq \nu_{synch\ peak} \leq 10^{15}$ Hz (ref. 7)
LINER	Low-ionization nuclear emission-line regions	see ref. 9
LLAGN	Low-luminosity AGN	see ref. 10
LBL/LSP	Low-energy cutoff BL Lac/blazar	$\nu_{synch\ peak} < 10^{14}$ Hz (ref. 7)
LDQ	Lobe-dominated quasar	RL AGN, $f_{core} < f_{ext}$
LEG	Low-excitation galaxy	ref. 8
LPQ	Low polarization quasar	$P_{opt} < 3\%$
NLAGN	Narrow-line AGN	FWHM $\lesssim 1,000$ km s^{-1}
NLRG	Narrow-line radio galaxy	RL Sey2
NLS1	Narrow-line Seyfert 1	ref. 11
OVV	Optically violently variable (quasar)	(same as FSRQ)
Population A		ref. 12
Population B		ref. 12
Radiative-mode		Seyferts and quasars; see ref. 9
RBL	Radio-selected BL Lac	BL Lac selected in the radio band
Sey1.5	Seyfert 1.5	ref. 13
Sey1.8	Seyfert 1.8	ref. 13
Sey1.9	Seyfert 1.9	ref. 13
SSRQ	Steep-spectrum radio quasar	RL AGN, $\alpha_r > 0.5$
USS	Ultra-steep spectrum source	RL AGN, $\alpha_r > 1.0$
XBL	X-ray-selected BL Lac	BL Lac selected in the X-ray band
XBONG	X-ray bright optically normal galaxy	AGN only in the X-ray band/weak lined AGN

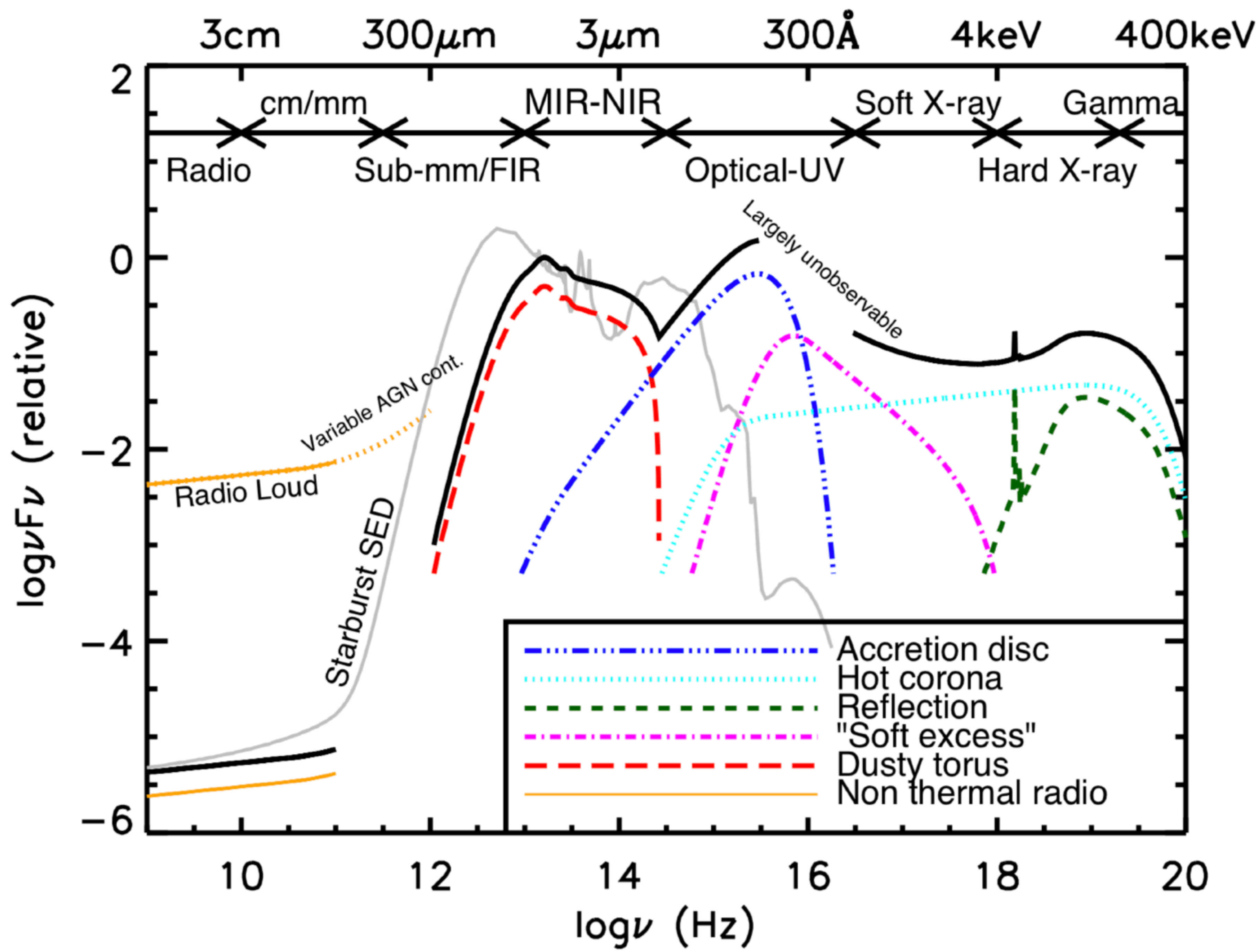
- 10^{10} M$_\odot$

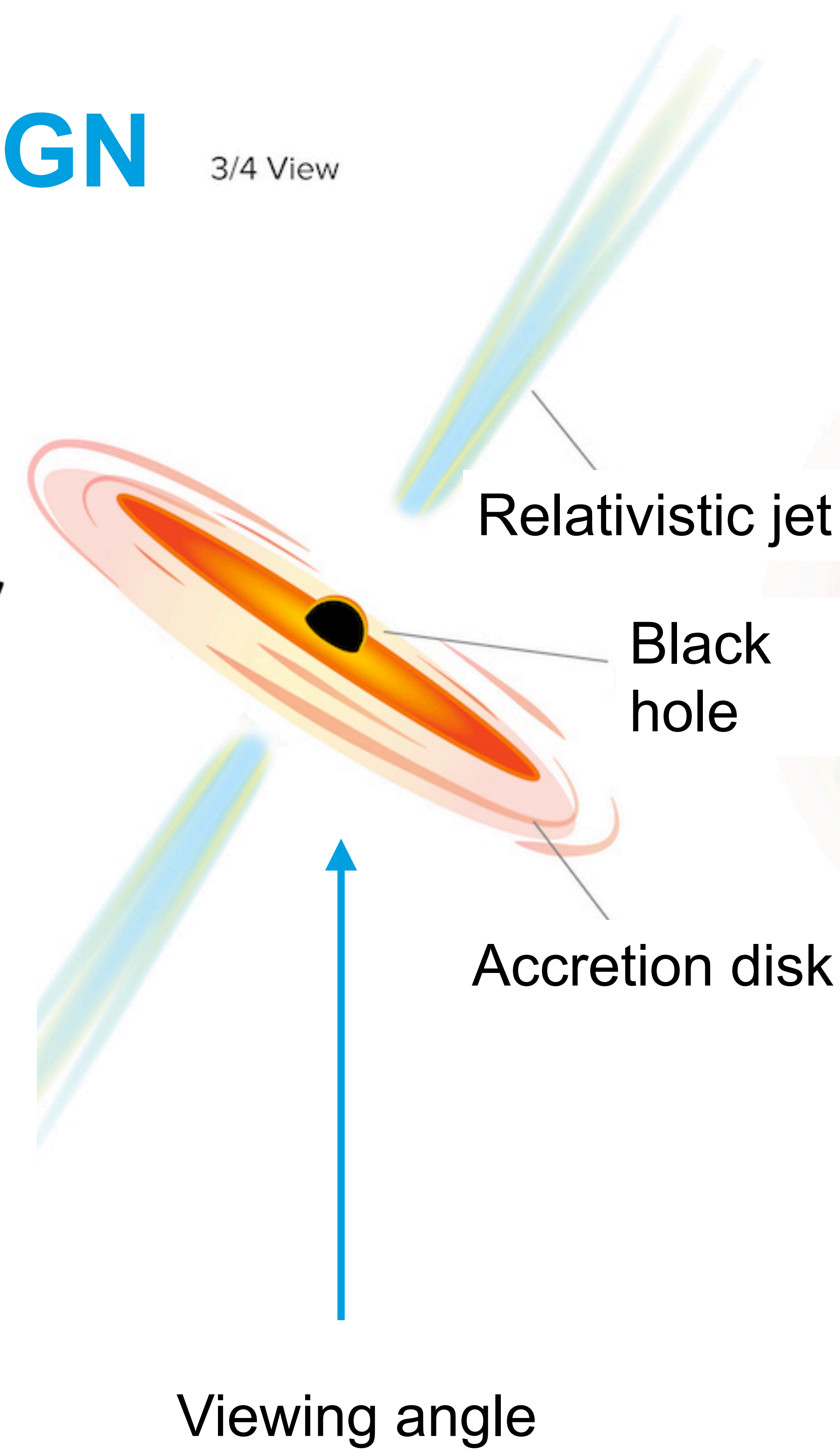
0^{-3} pc

0 pc

Multi-wavelength spectrum of AGN

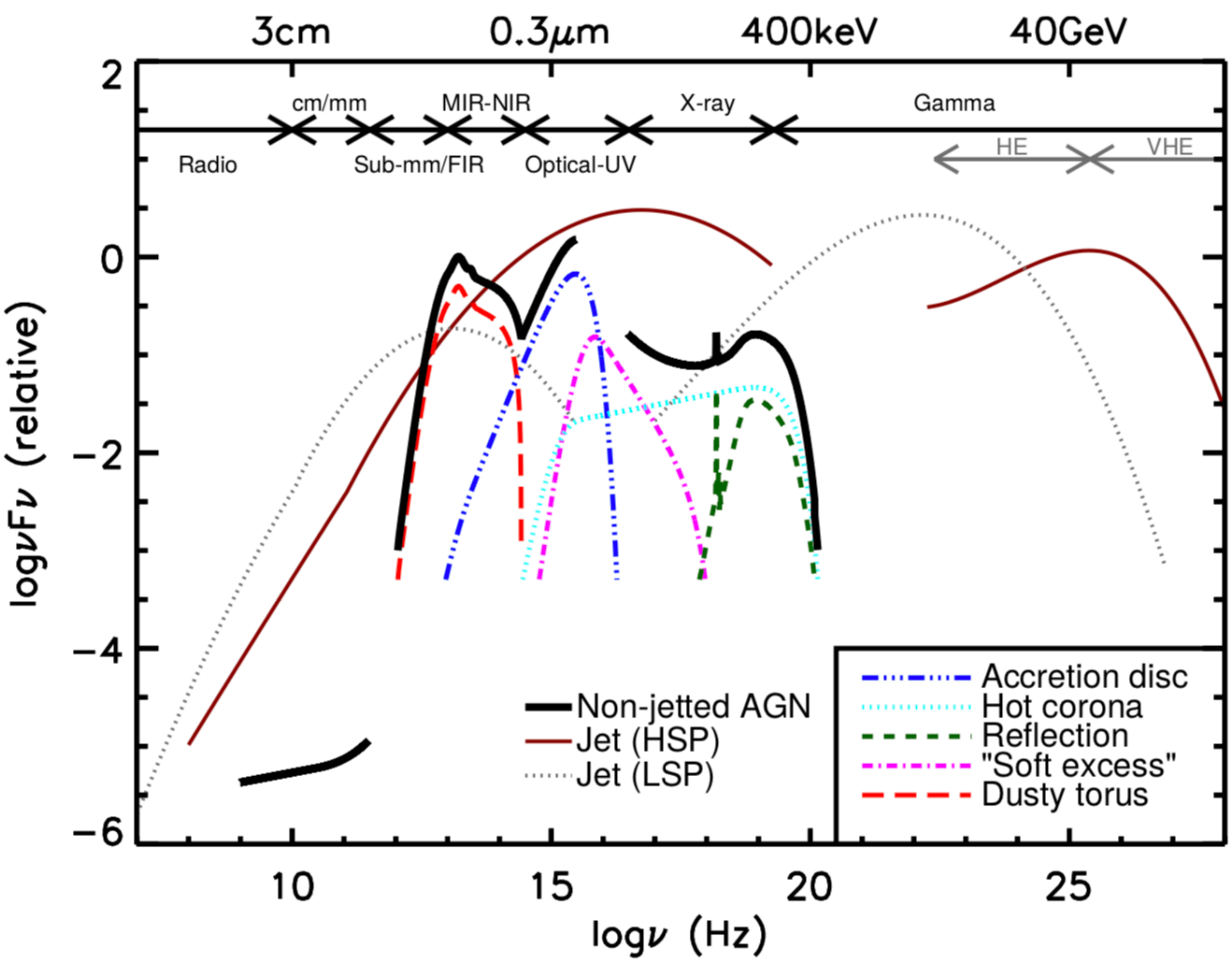
AGN spectra distinctively different from other Galaxies

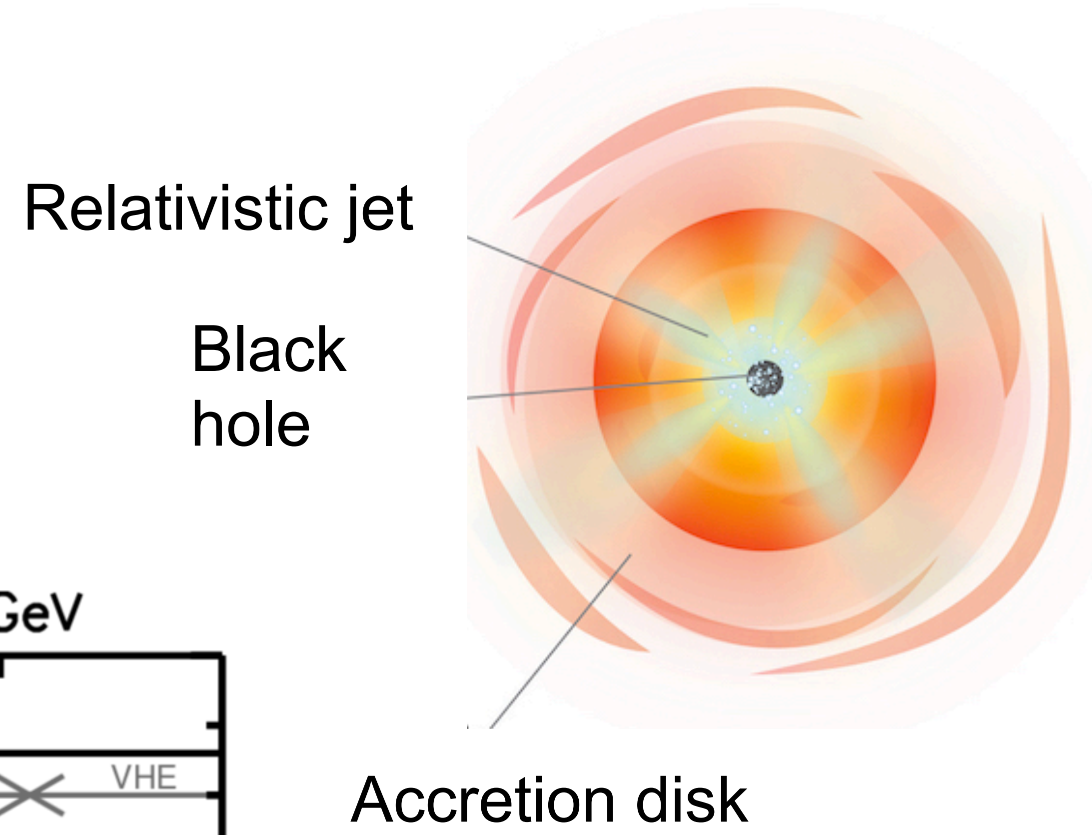




From AGN to Blazars

Non-thermal emission from the jet dominates the SED at almost all wavelengths

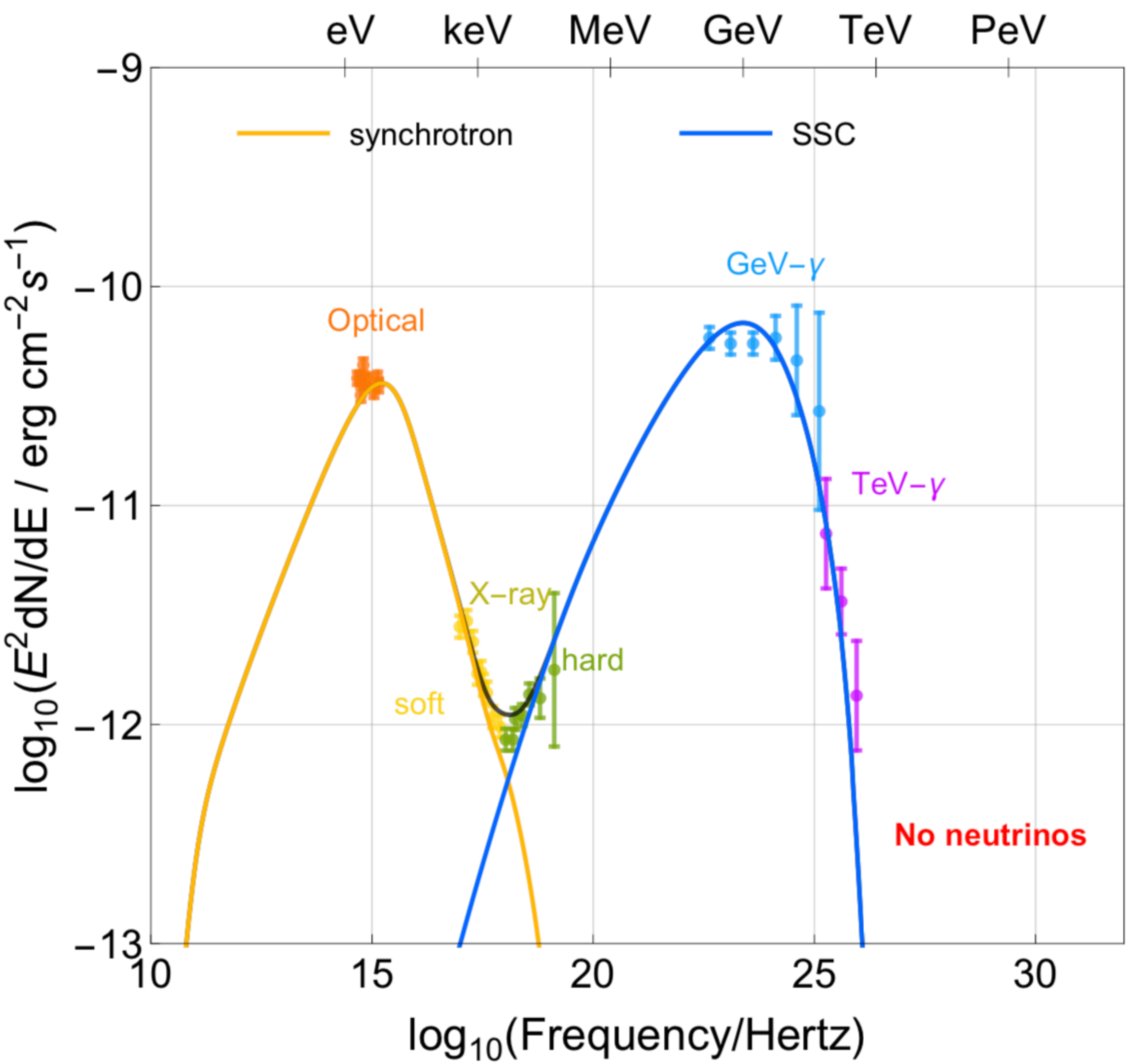




Viewing angle nearly aligned with jet axis

Typical Blazar spectral energy distribution

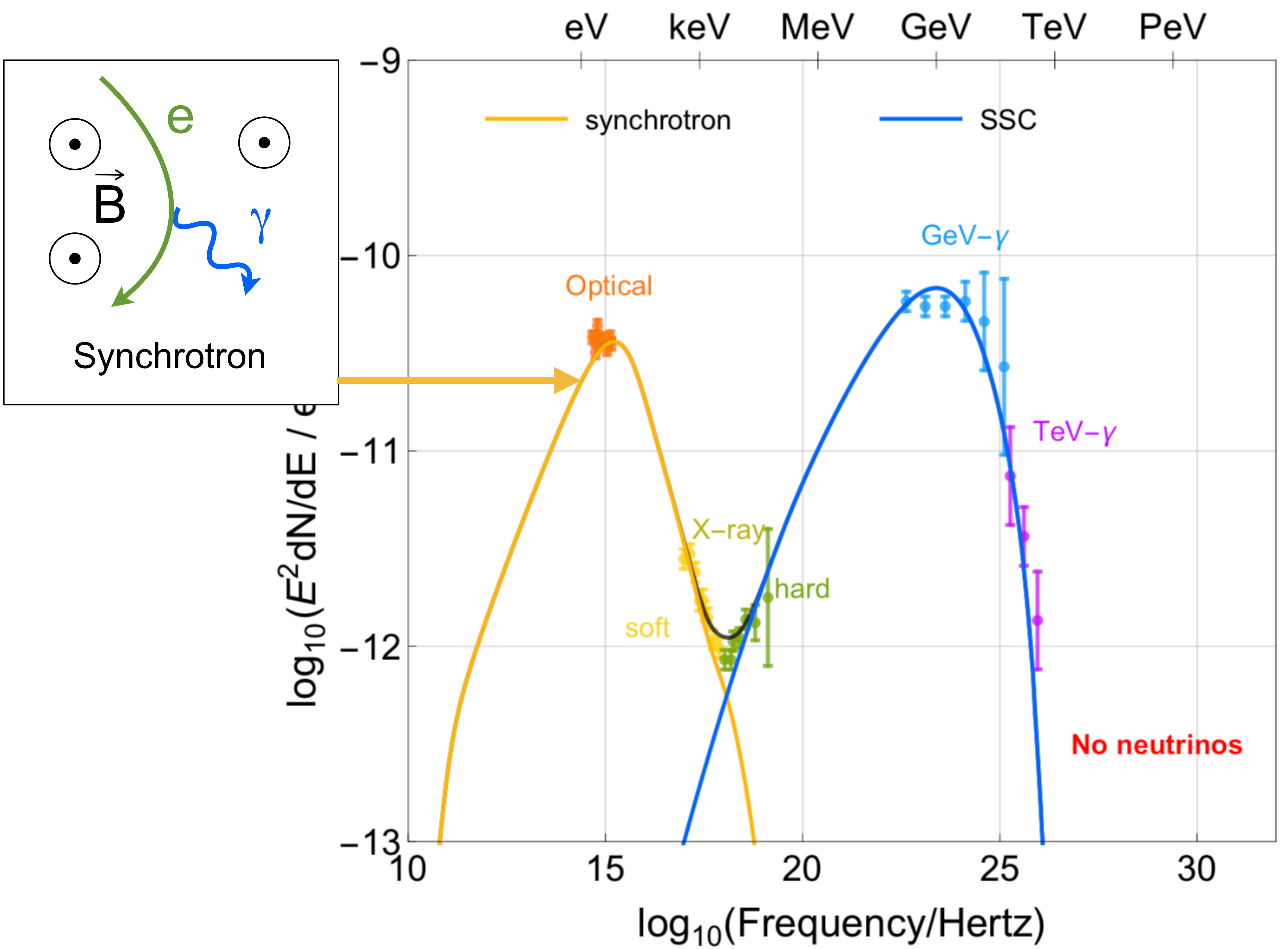
From Gao et al., 2018



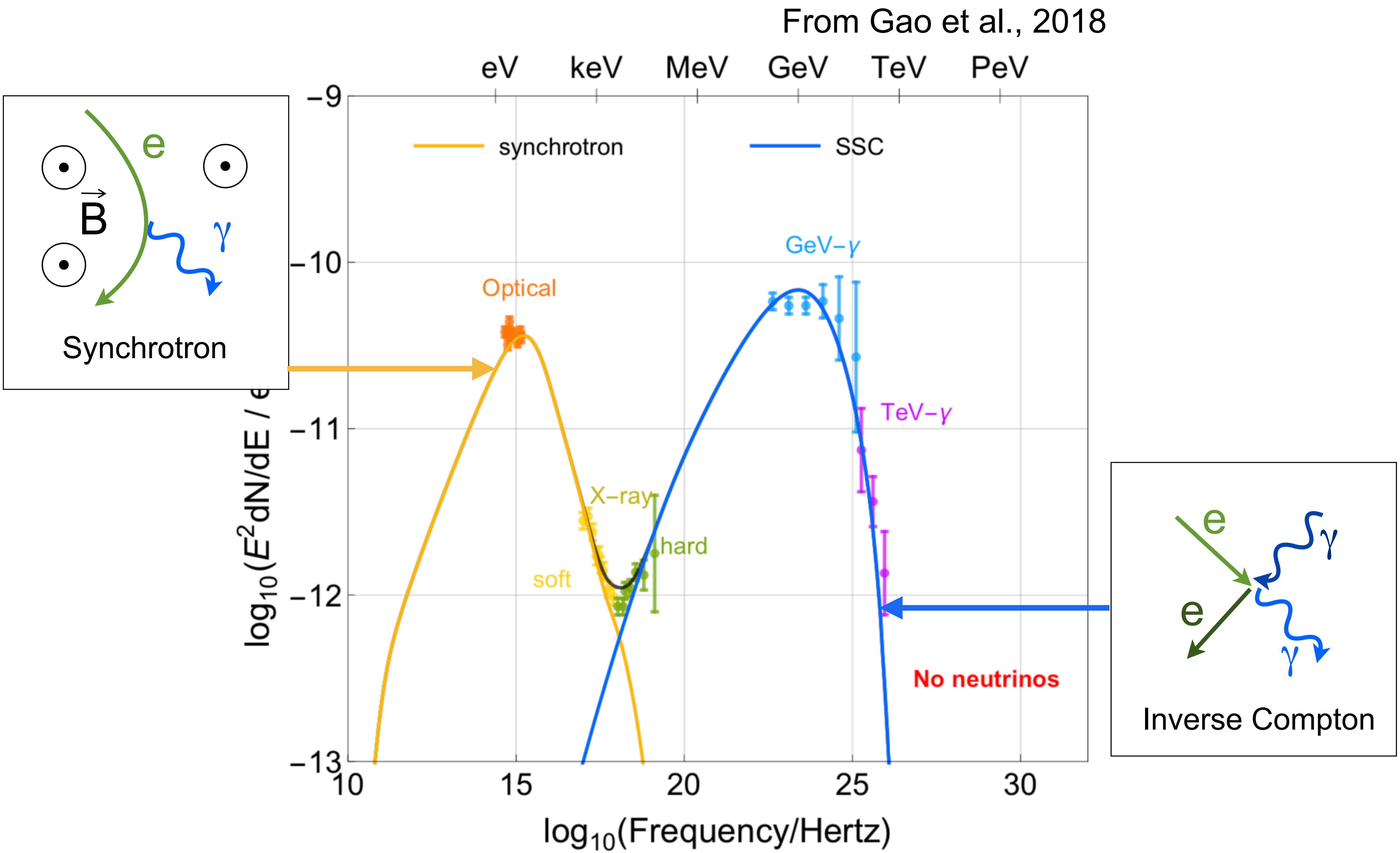
DESY.

Typical Blazar spectral energy distribution

From Gao et al., 2018

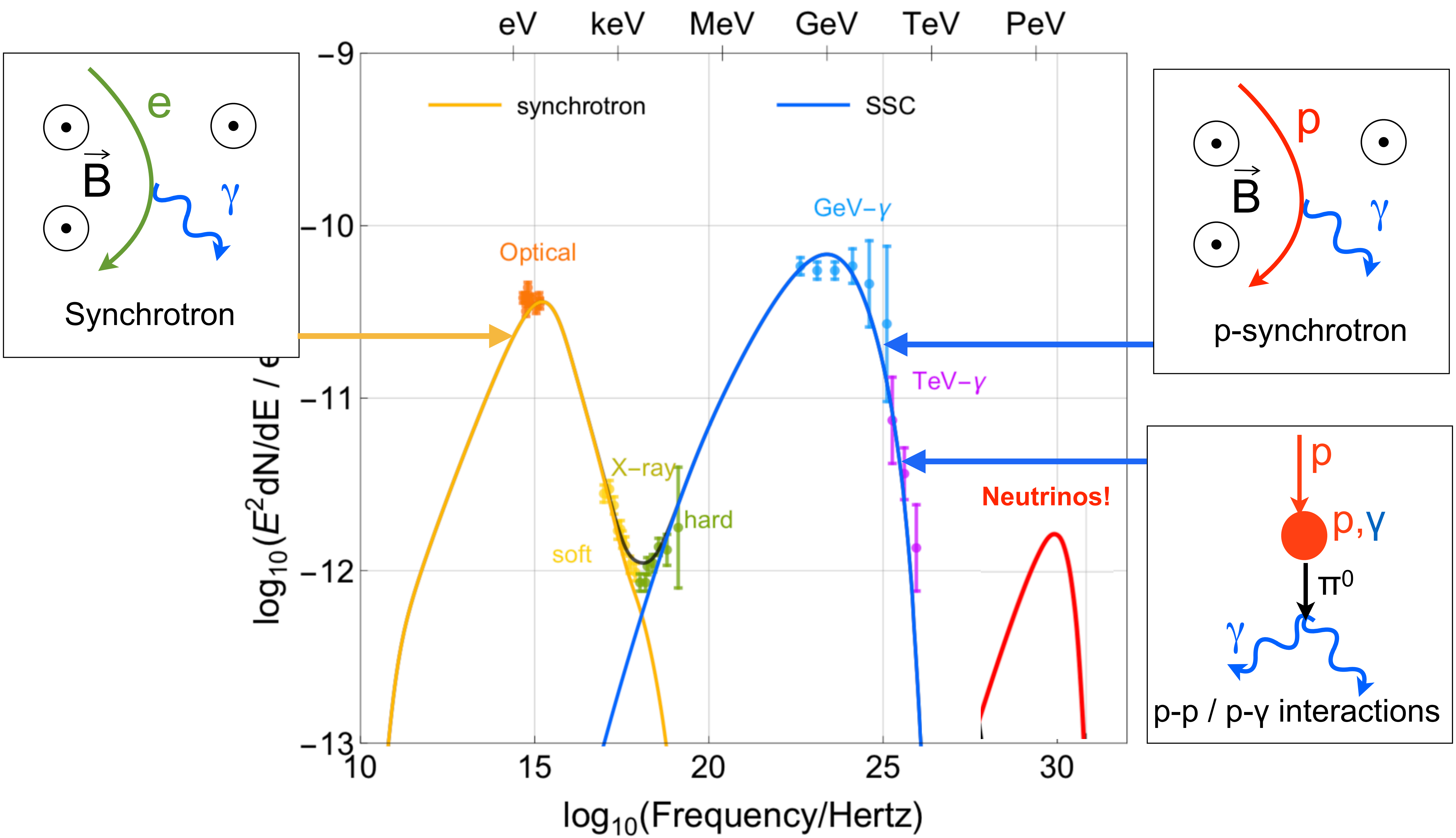


Typical Blazar spectral energy distribution



Typical Blazar spectral energy distribution

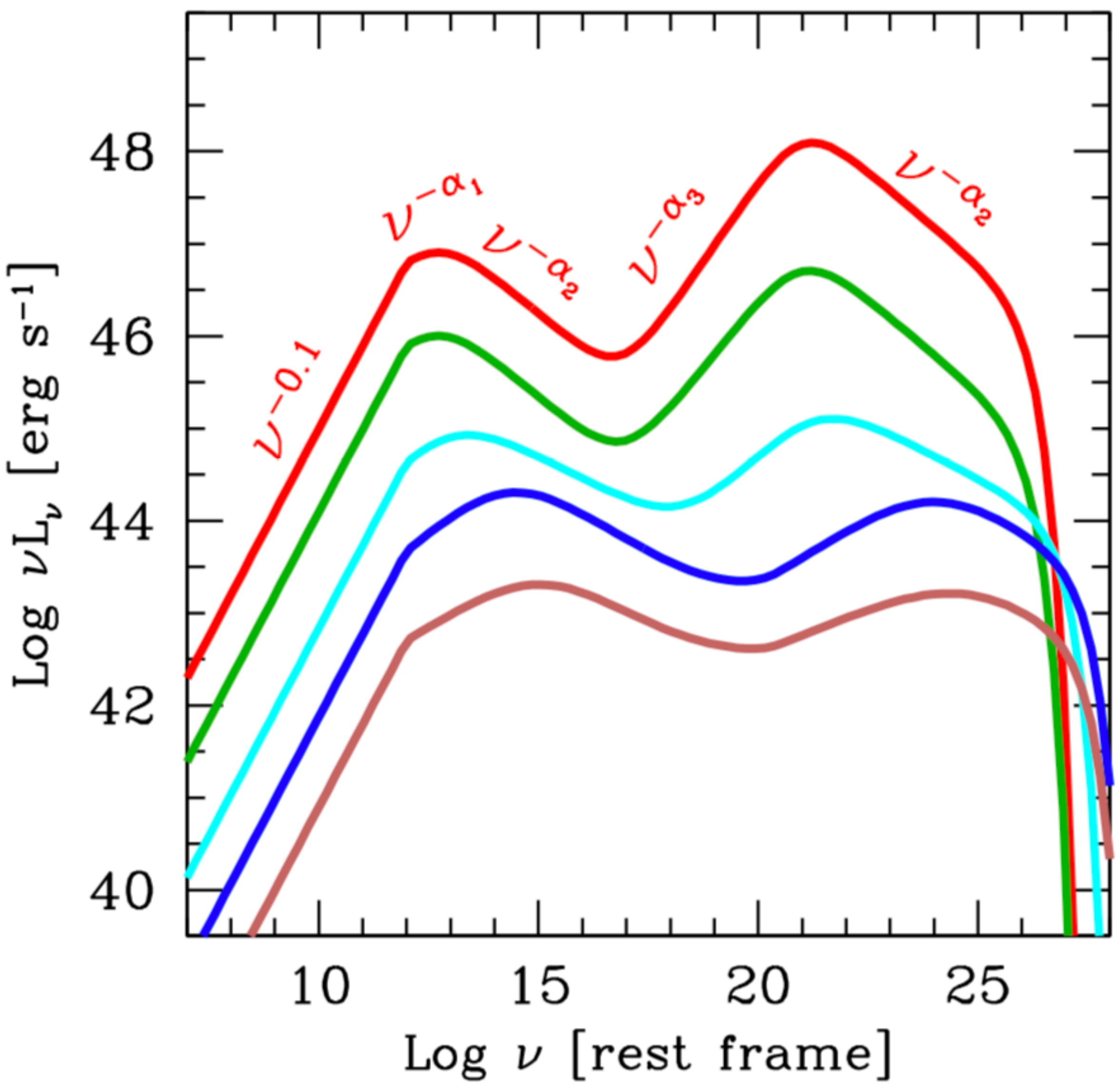
From Gao et al., 2018

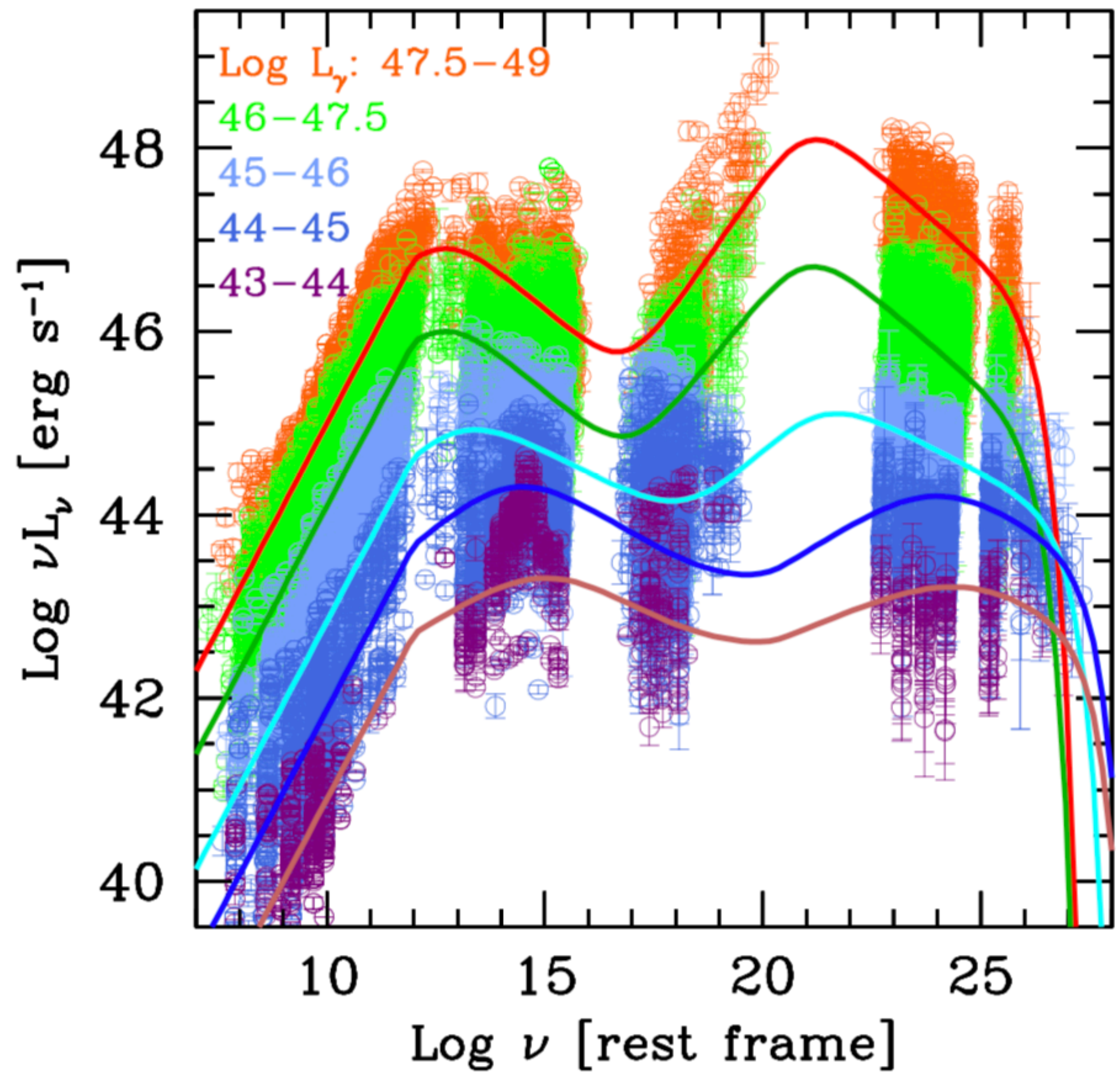


The Blazar sequence

FSRQ & BLLac

Higher luminosity, lower peak frequencies



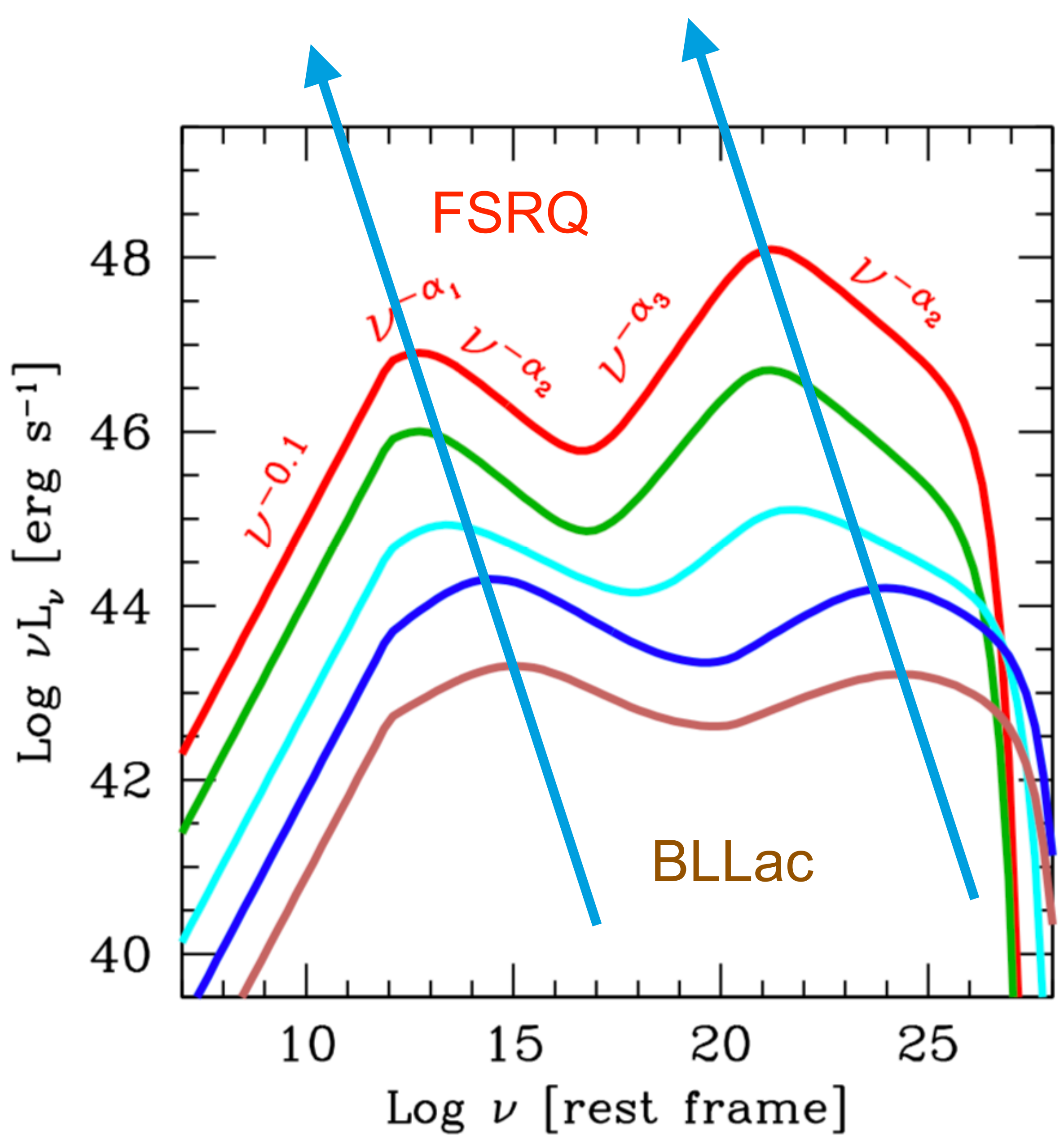


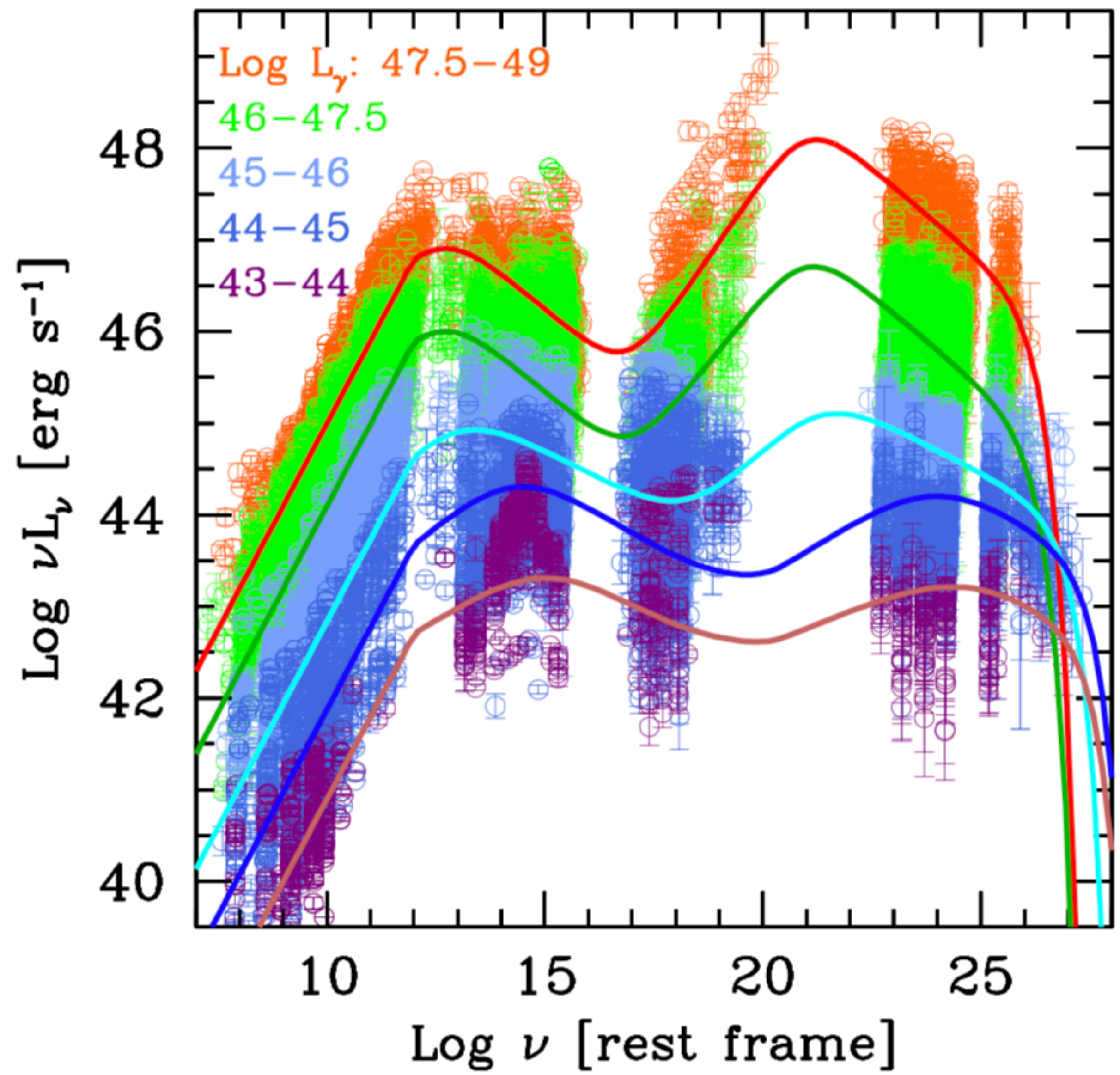
Ghisellini, Galaxies, 2016

The Blazar sequence

FSRQ & BLLac

Higher luminosity, lower peak frequencies





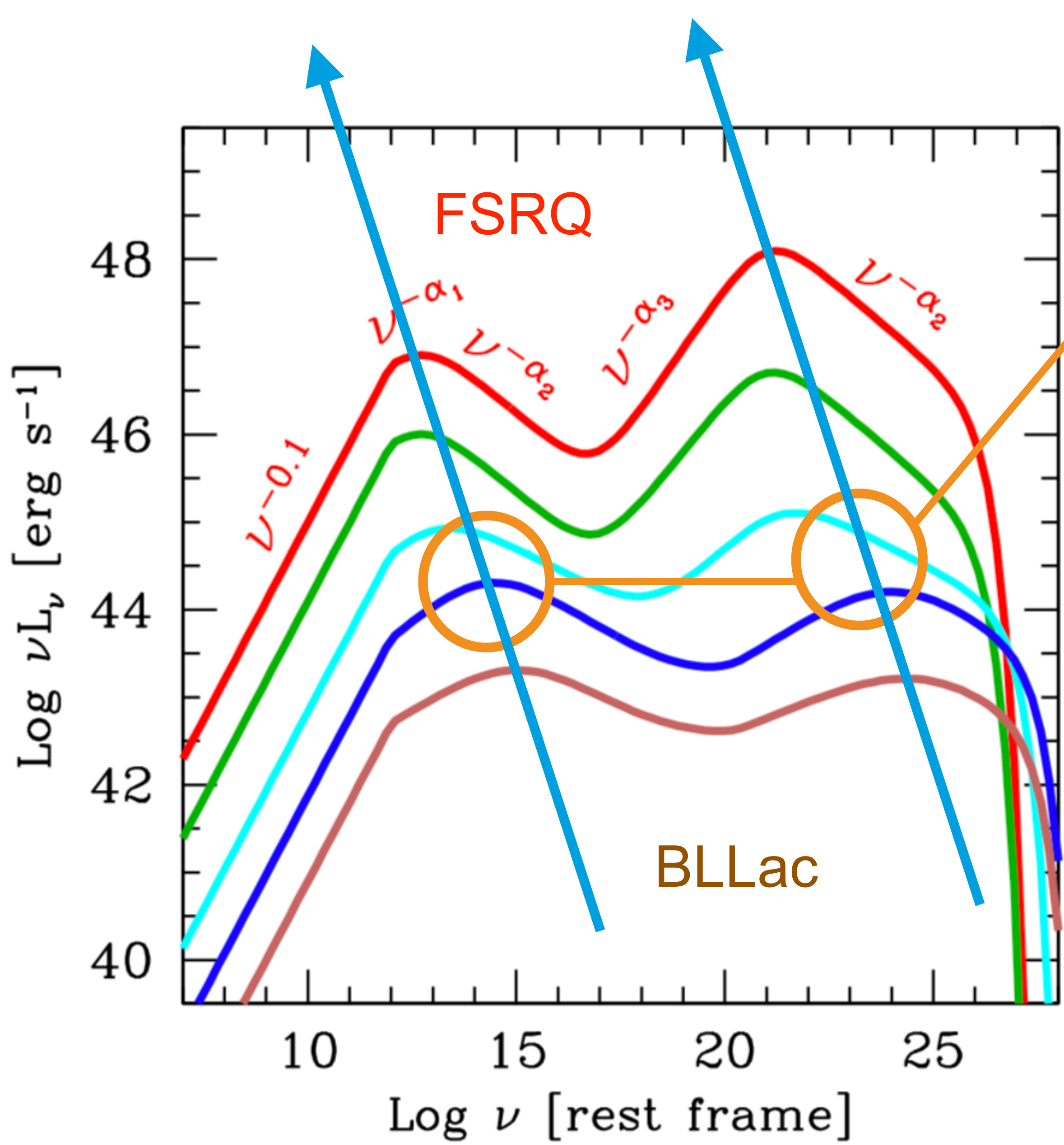
Ghisellini, Galaxies, 2016

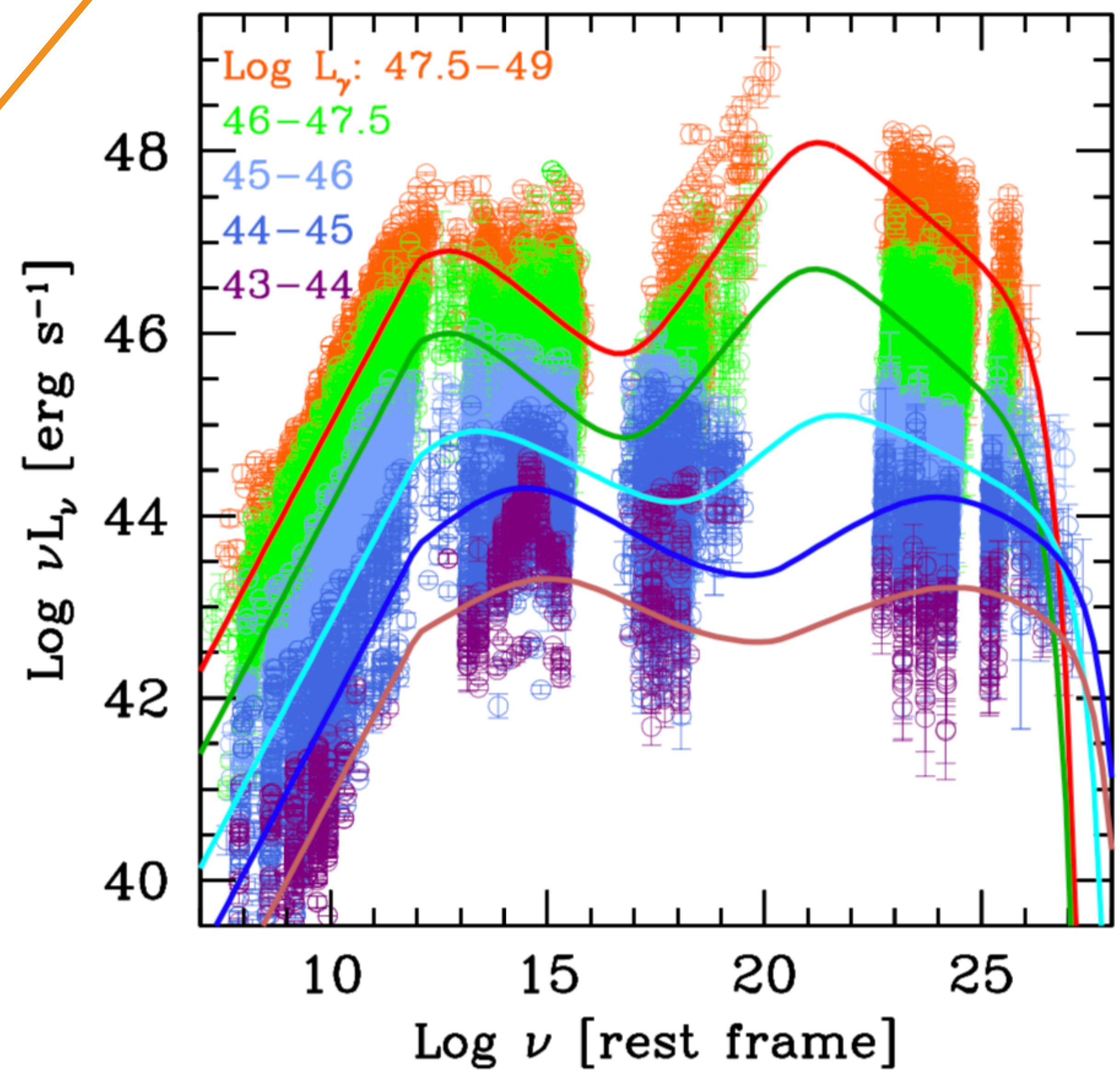
The Blazar sequence

FSRQ & BLLac

TXS0506+056

Higher luminosity, lower peak frequencies





Ghisellini, Galaxies, 2016

The jet

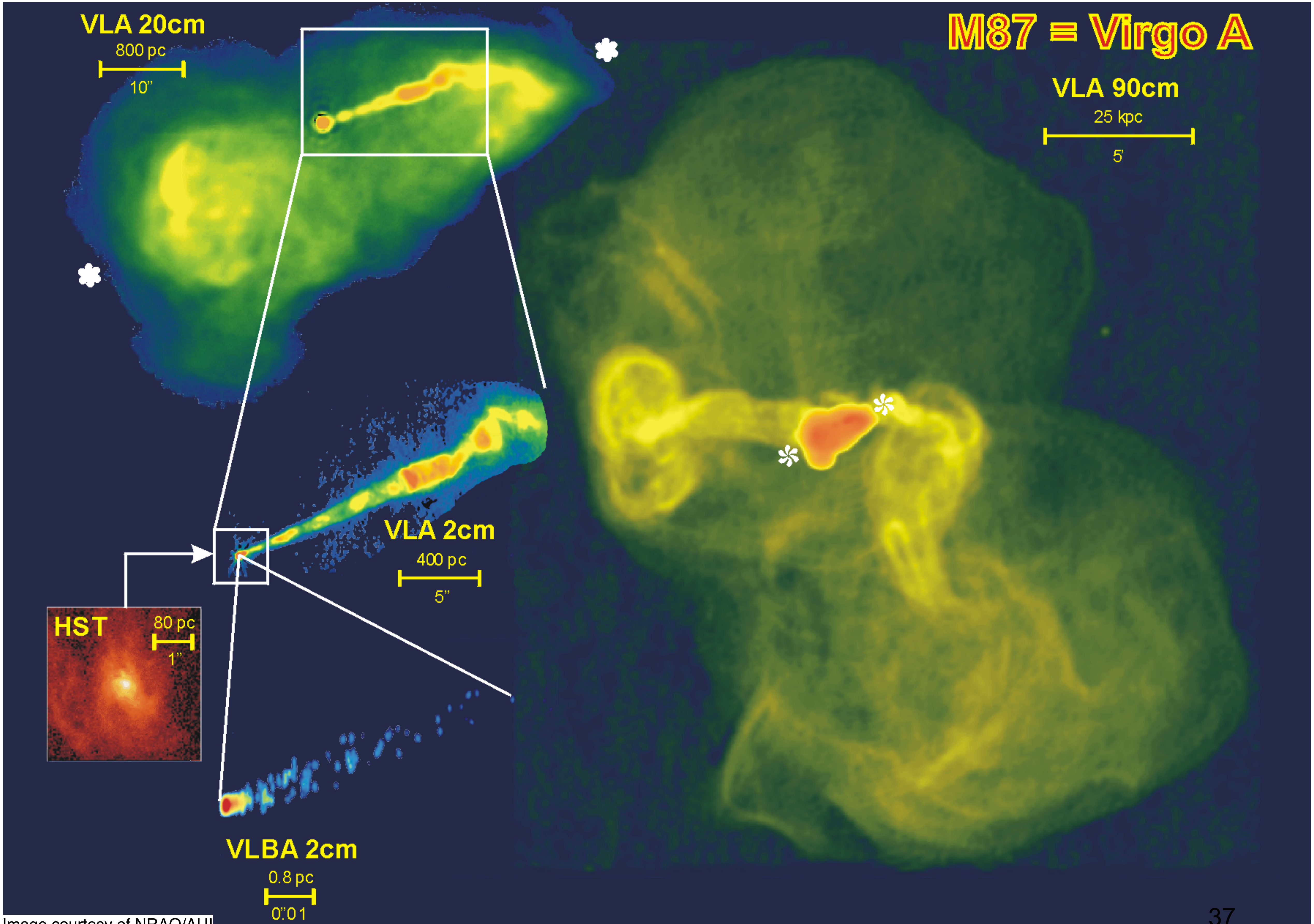


Image courtesy of NRAO/AUI

The jet

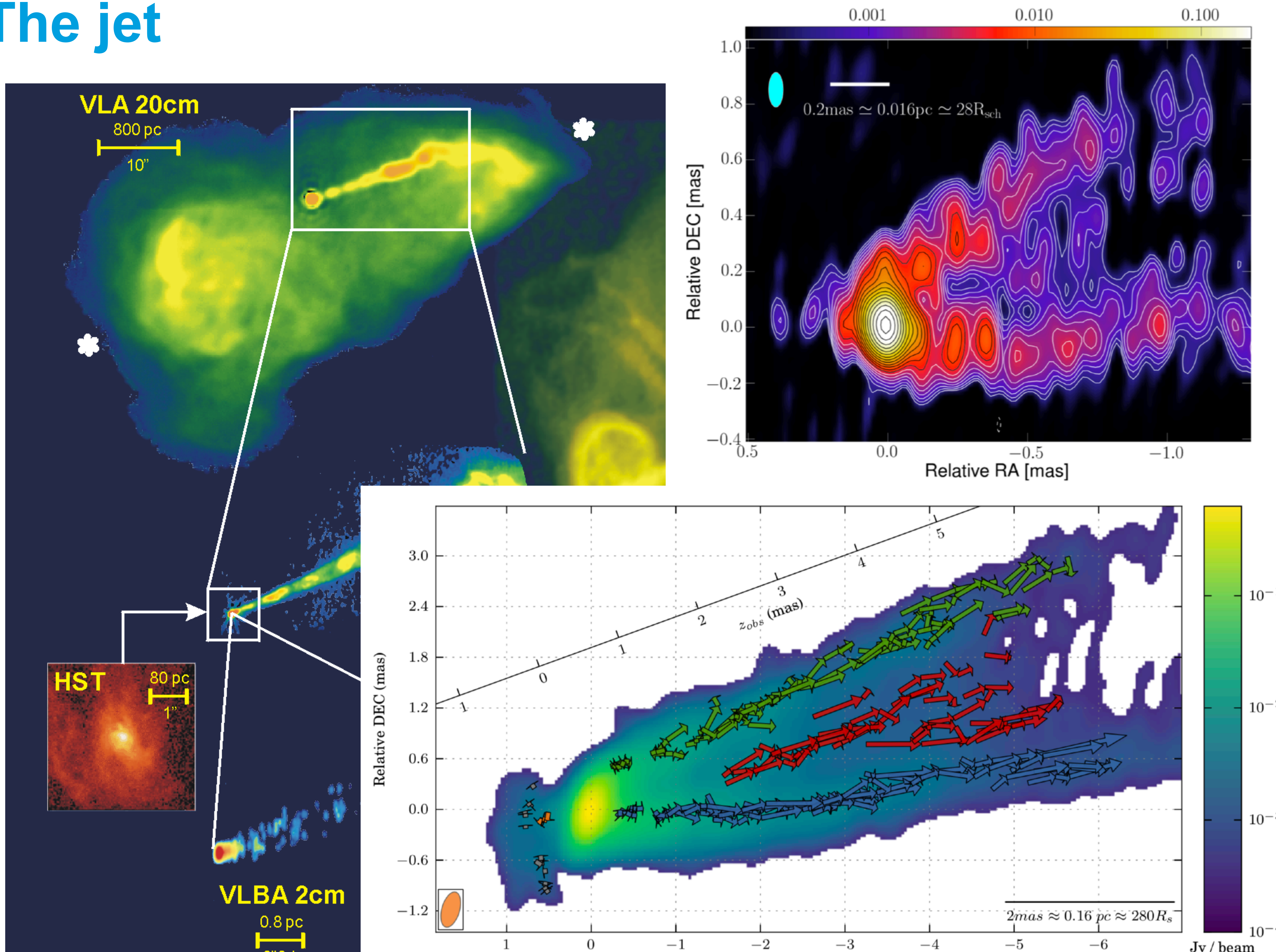
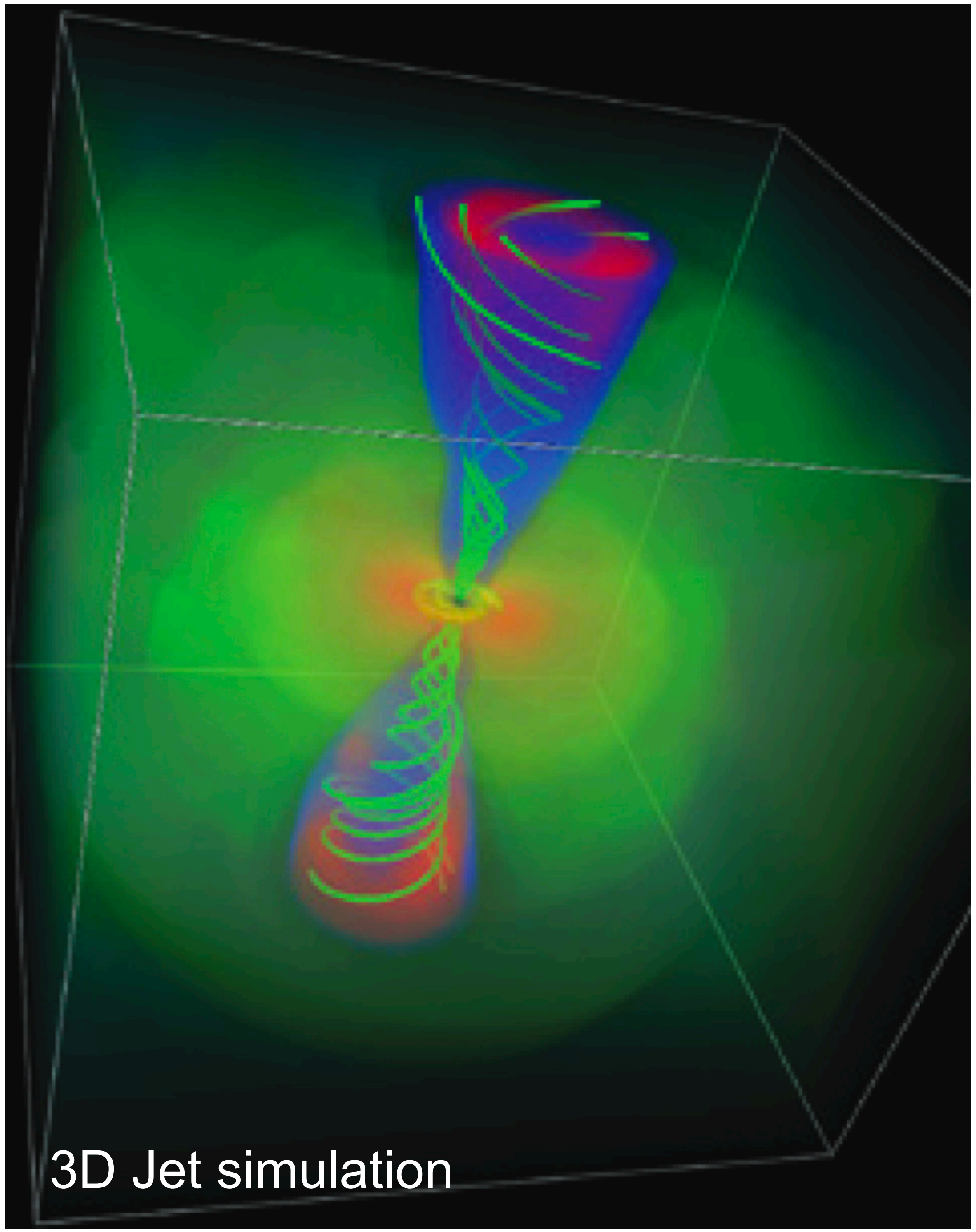


Image courtesy of NRAO/AUI

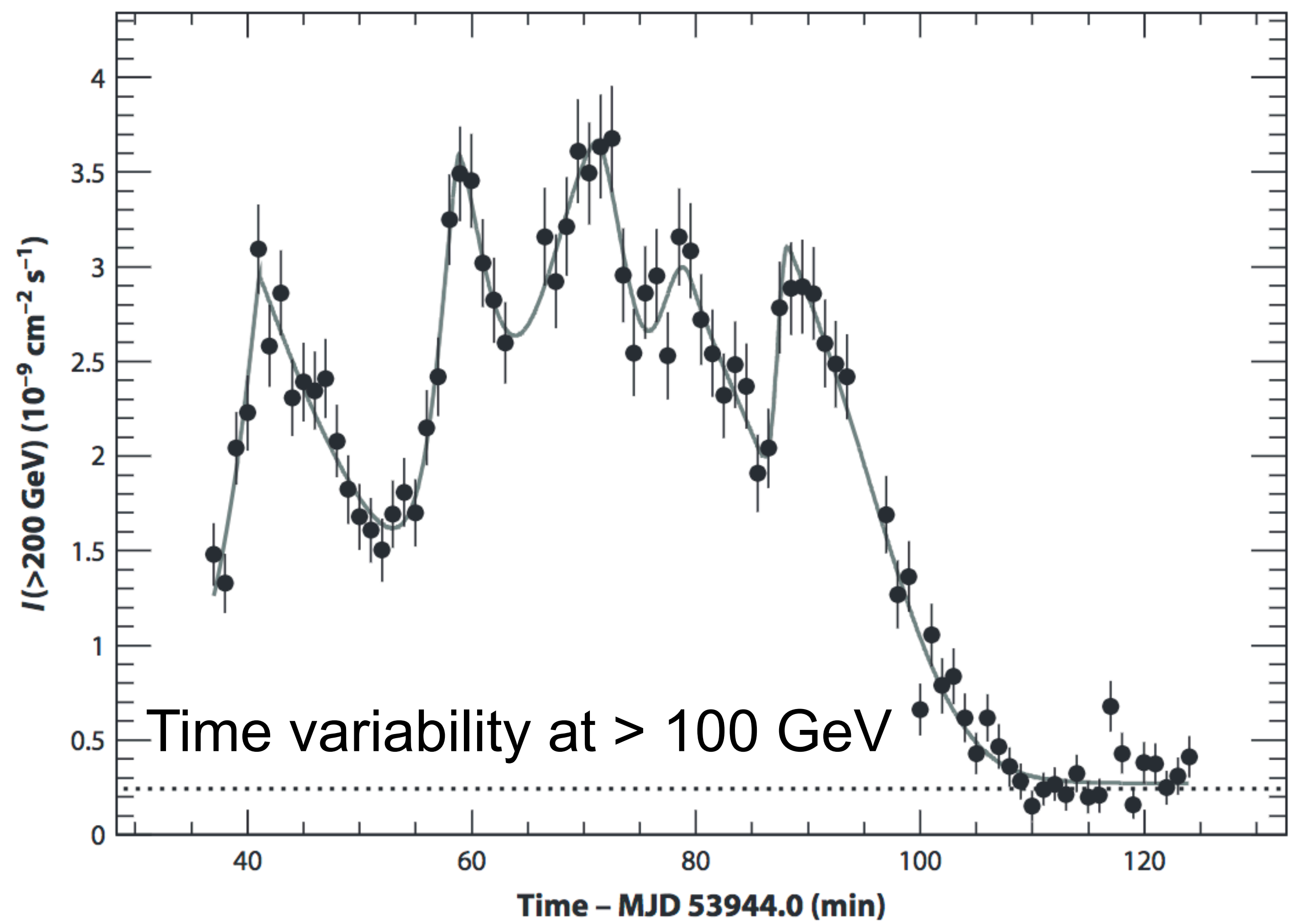
The jet continued

Constraints from variability and opacity



- Jet launch mechanism and conditions not well known
- Fueled by gravitational energy from accretion /rotational energy from BH
- Magnetically dominated at the base converted into kinetic energy
- Energy dissipation region likely at pc scale
- Fast variability, compact emission region

HESS collaboration(2007)

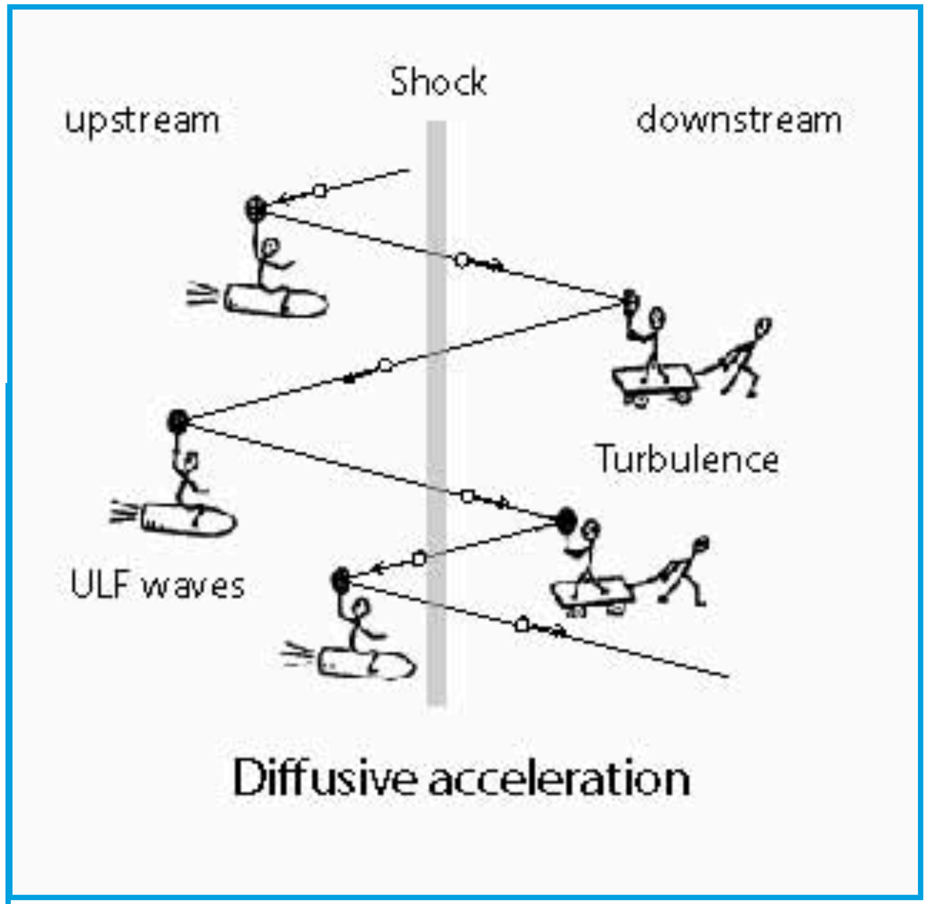


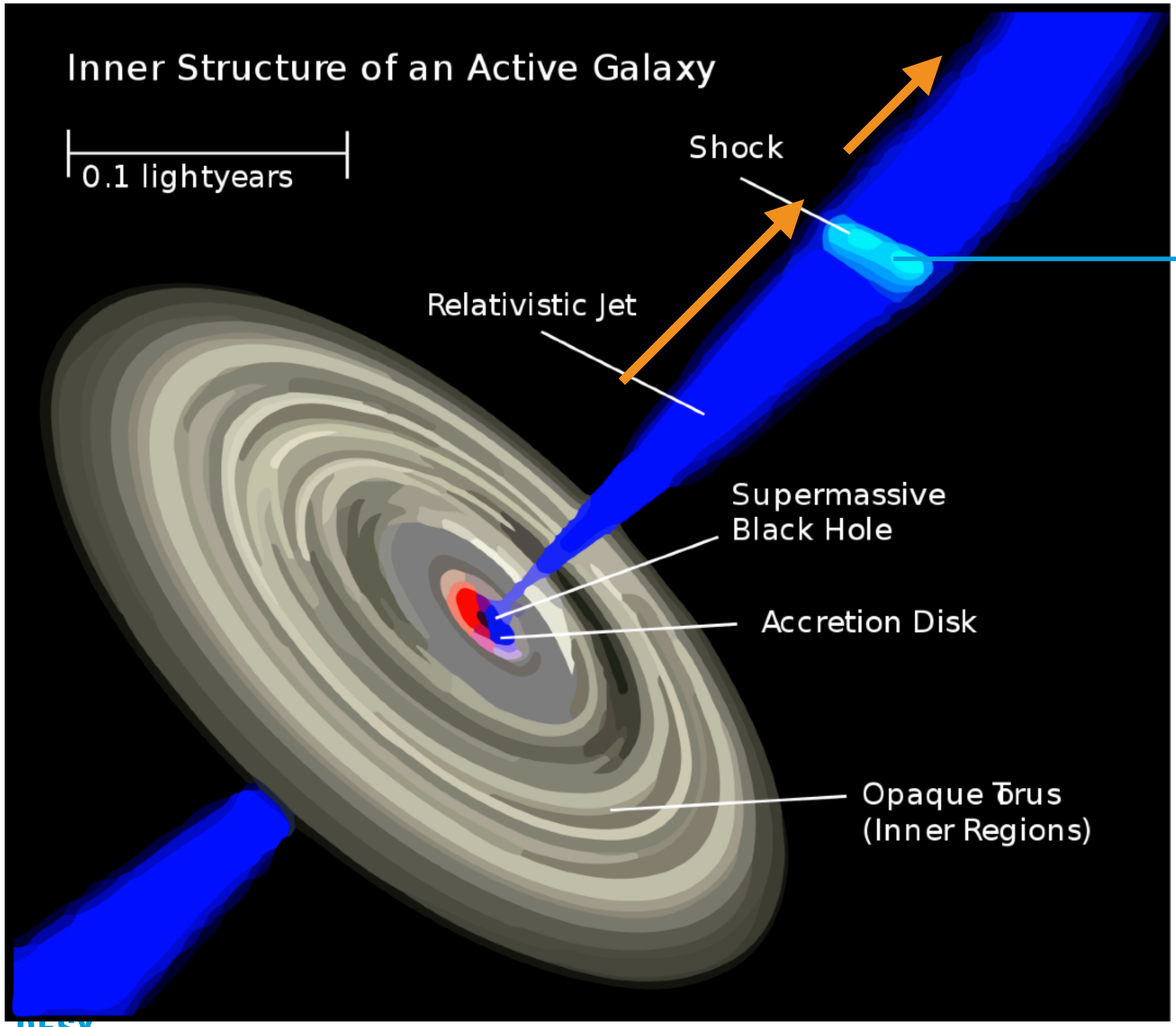
Particle acceleration in jets

Shock acceleration and magnetic reconnection

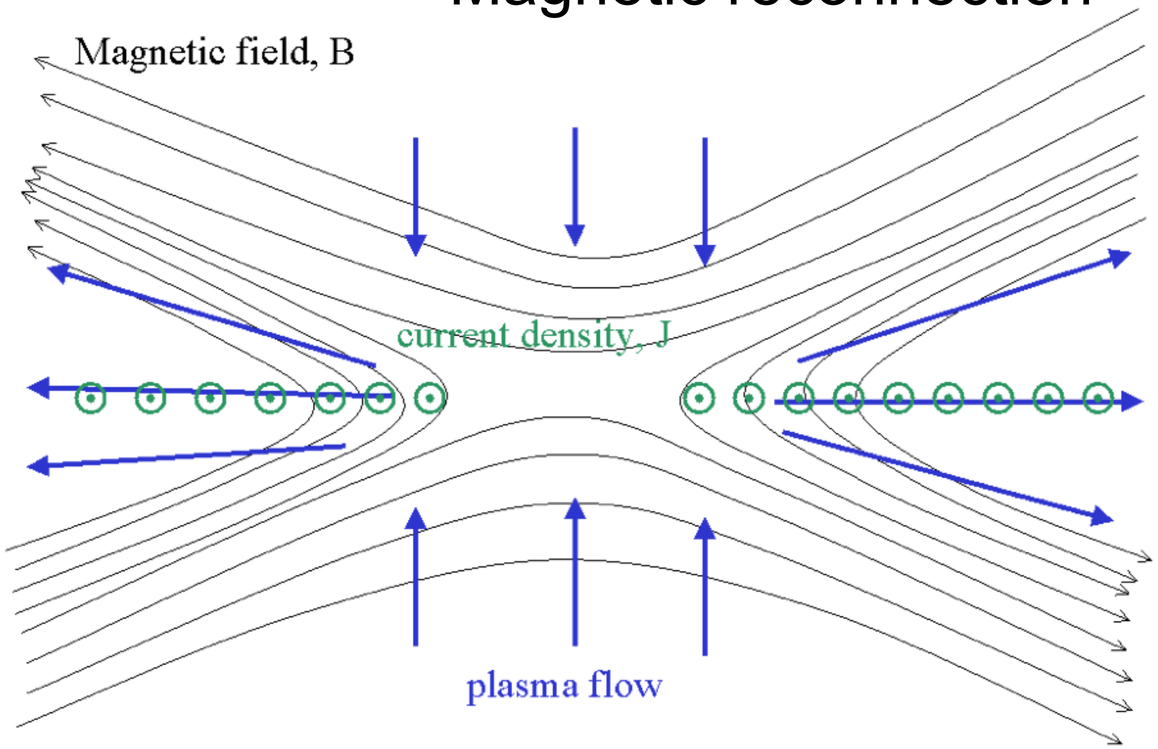
Acceleration mechanism not clear.

Shock / stochastic acceleration ? magnetic reconnection ? a combination of all ?



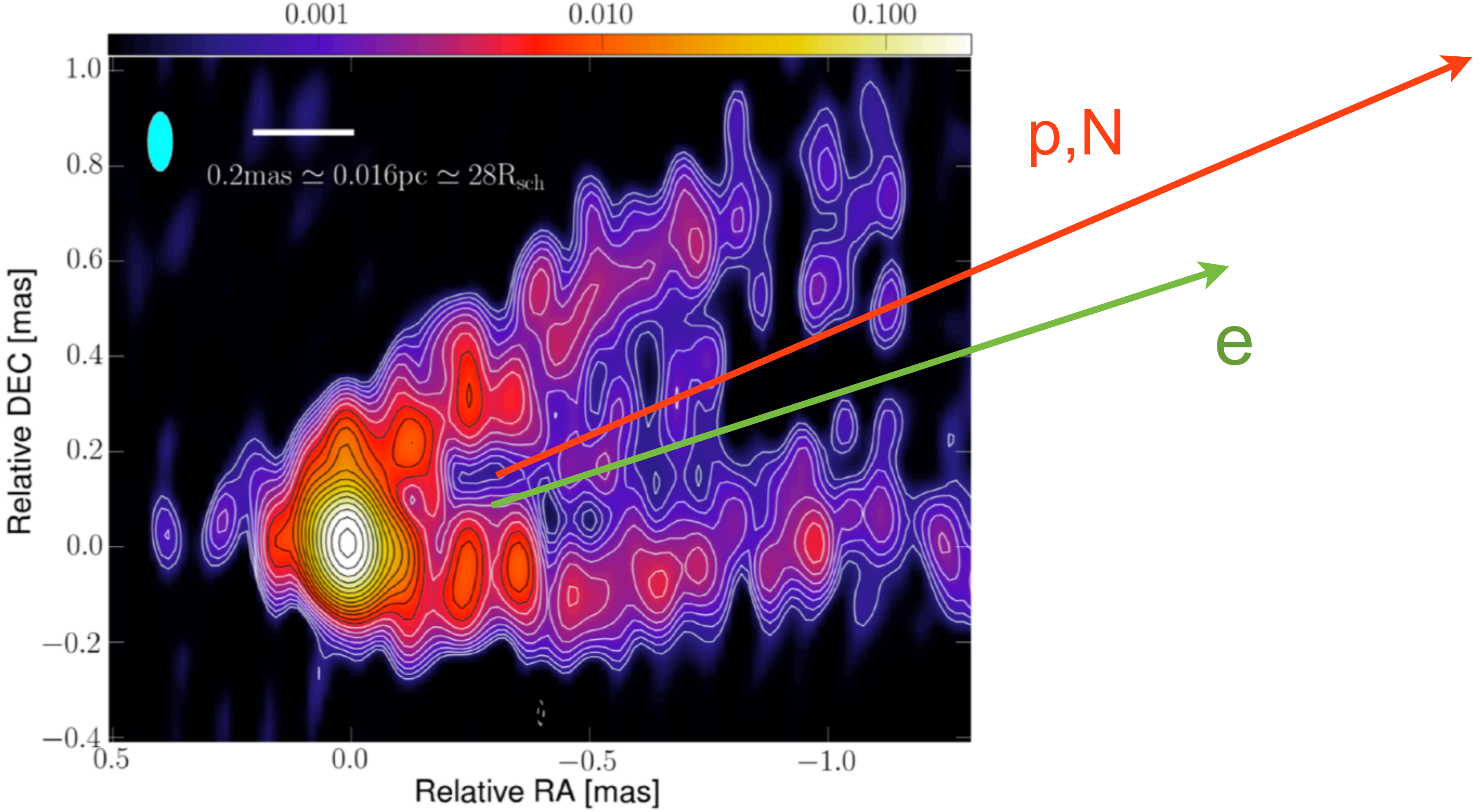


Magnetic reconnection



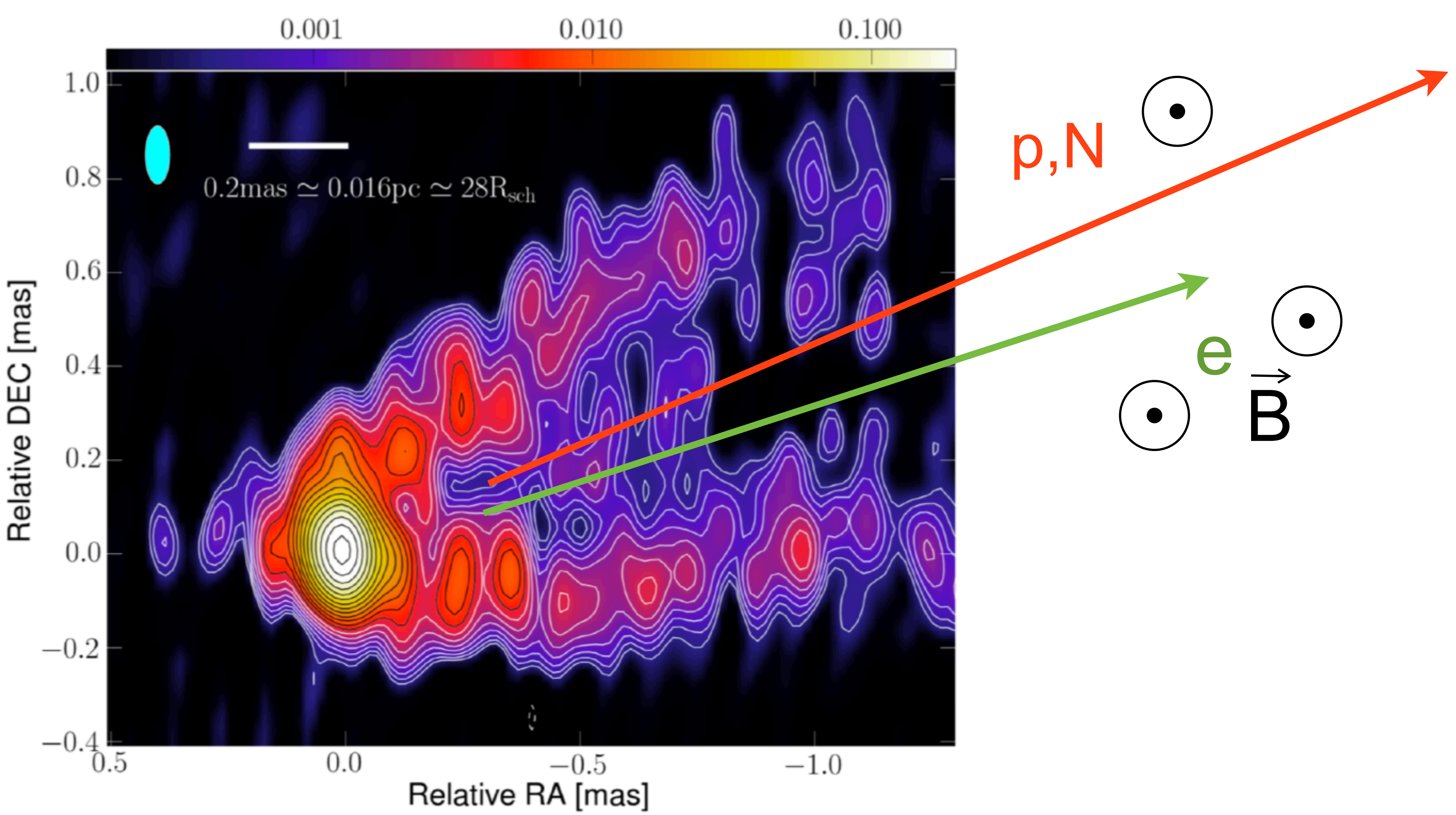
From protons and nuclei

To photons and neutrinos



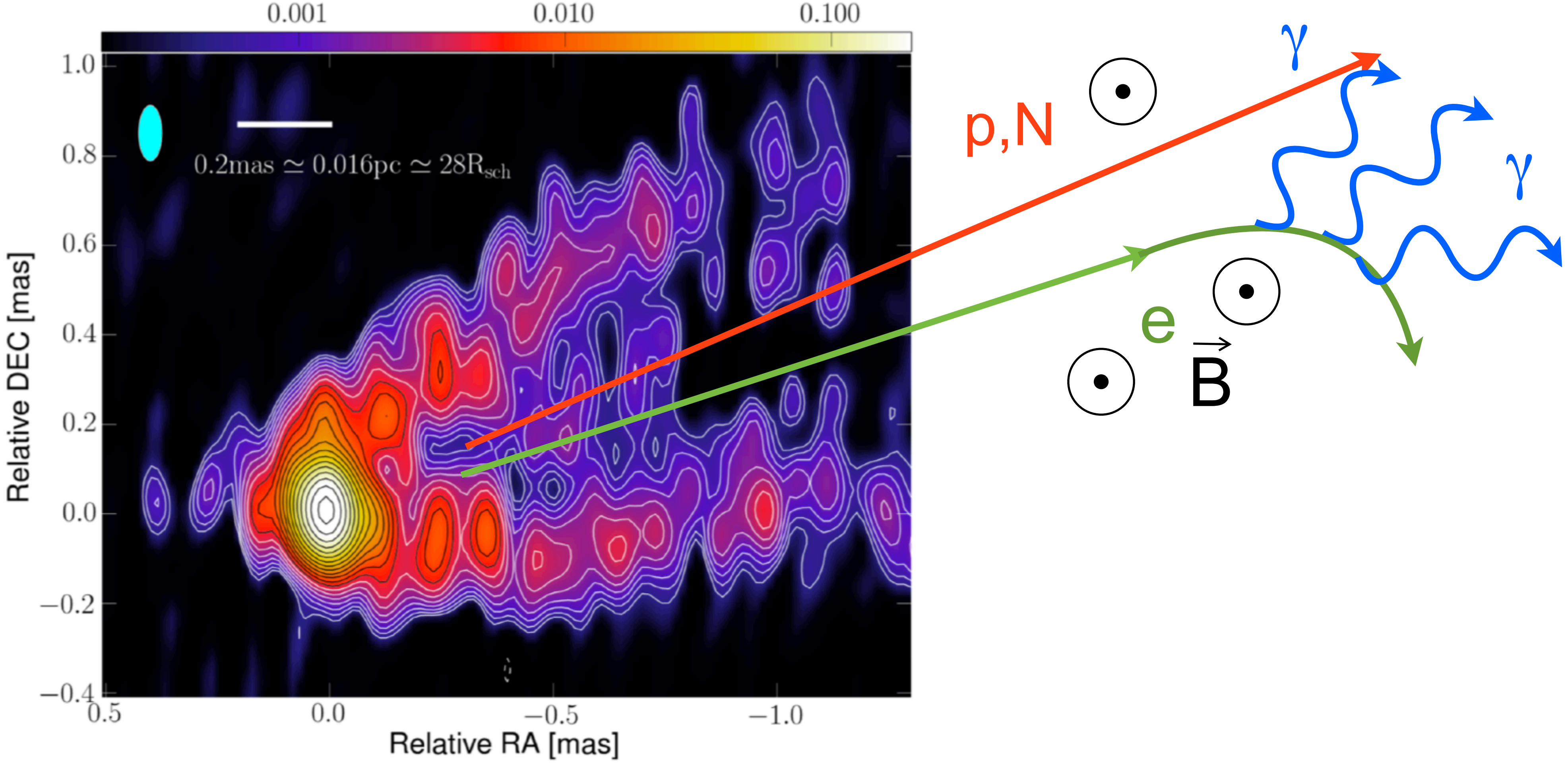
From protons and nuclei

To photons and neutrinos



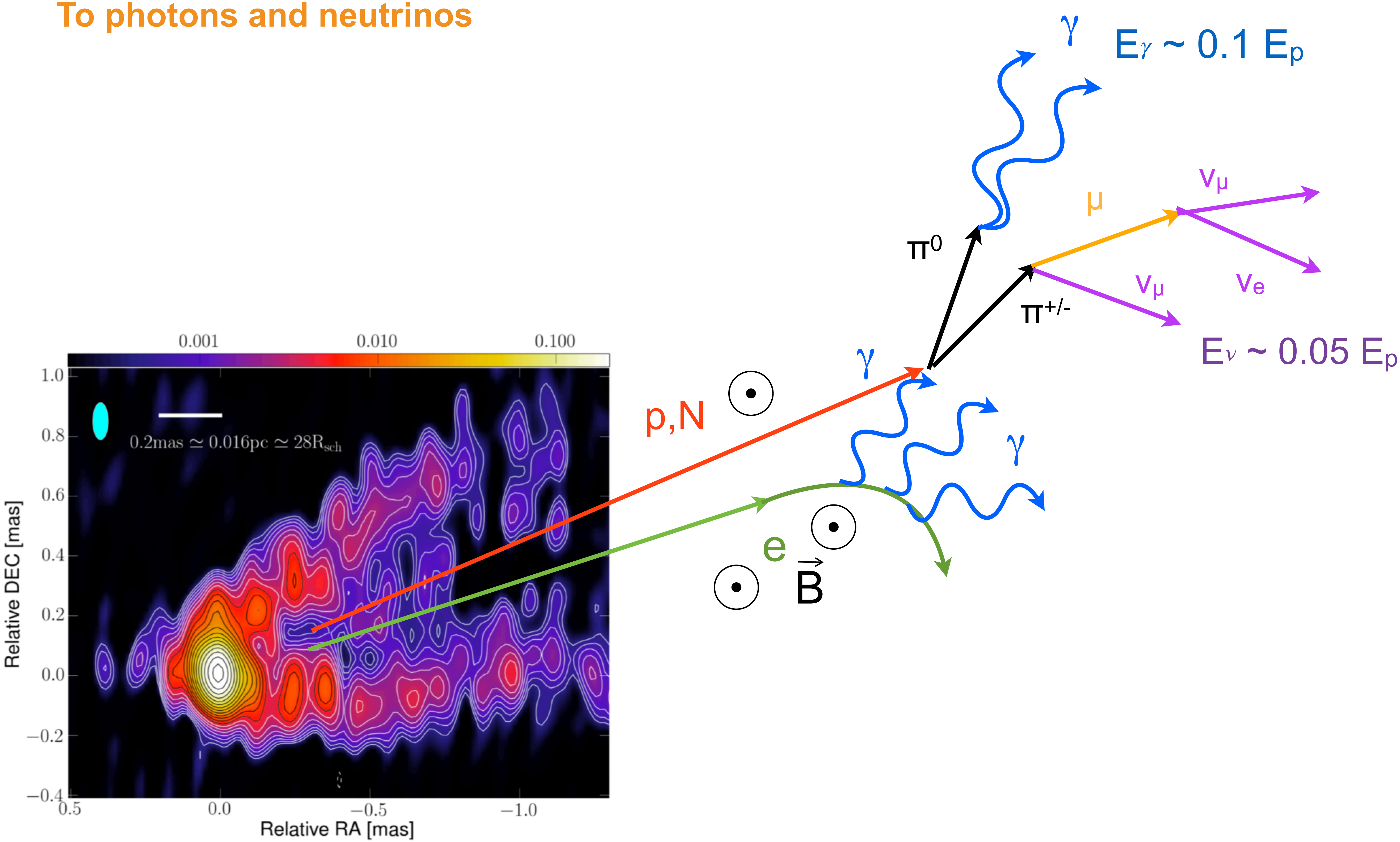
From protons and nuclei

To photons and neutrinos



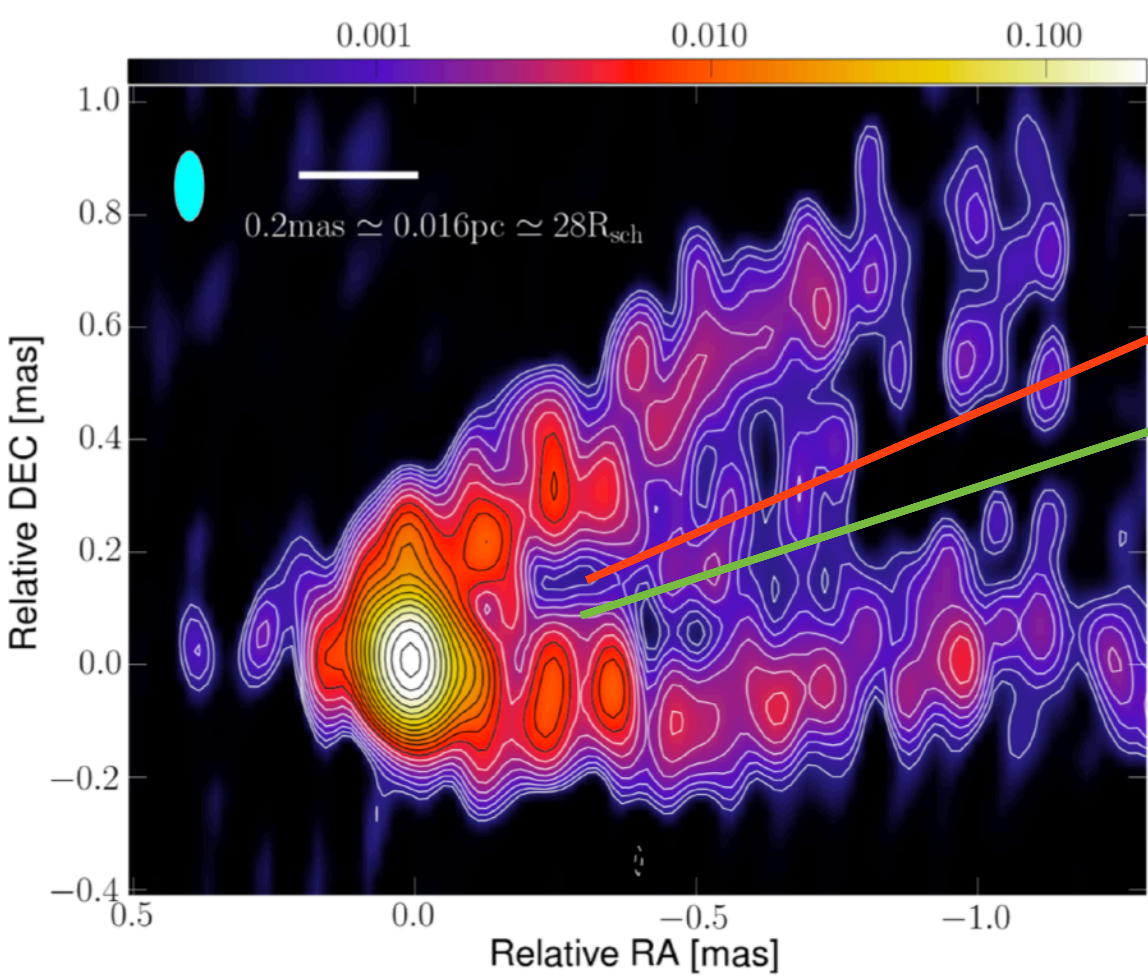
From protons and nuclei

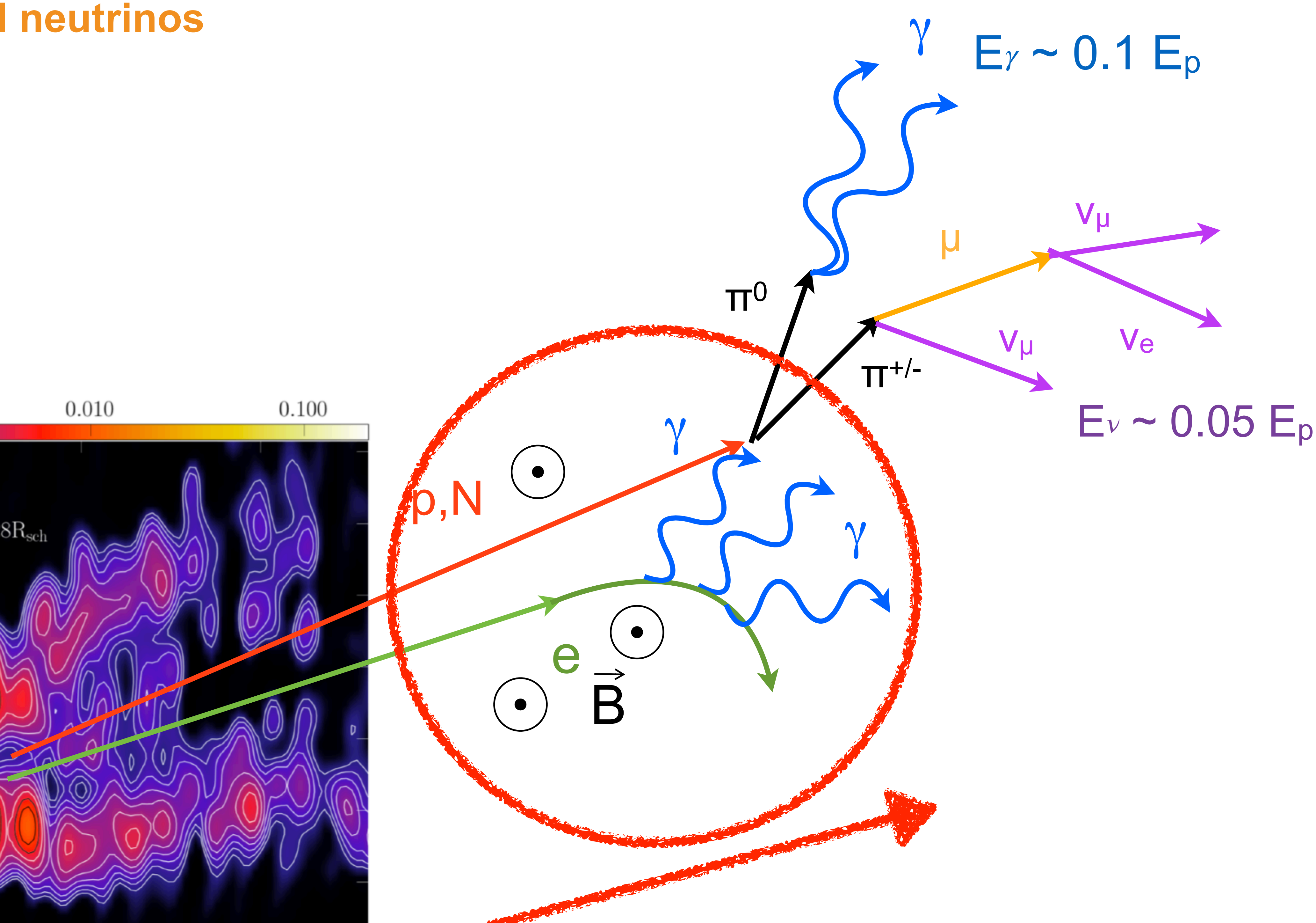
To photons and neutrinos



From protons and nuclei

To photons and neutrinos



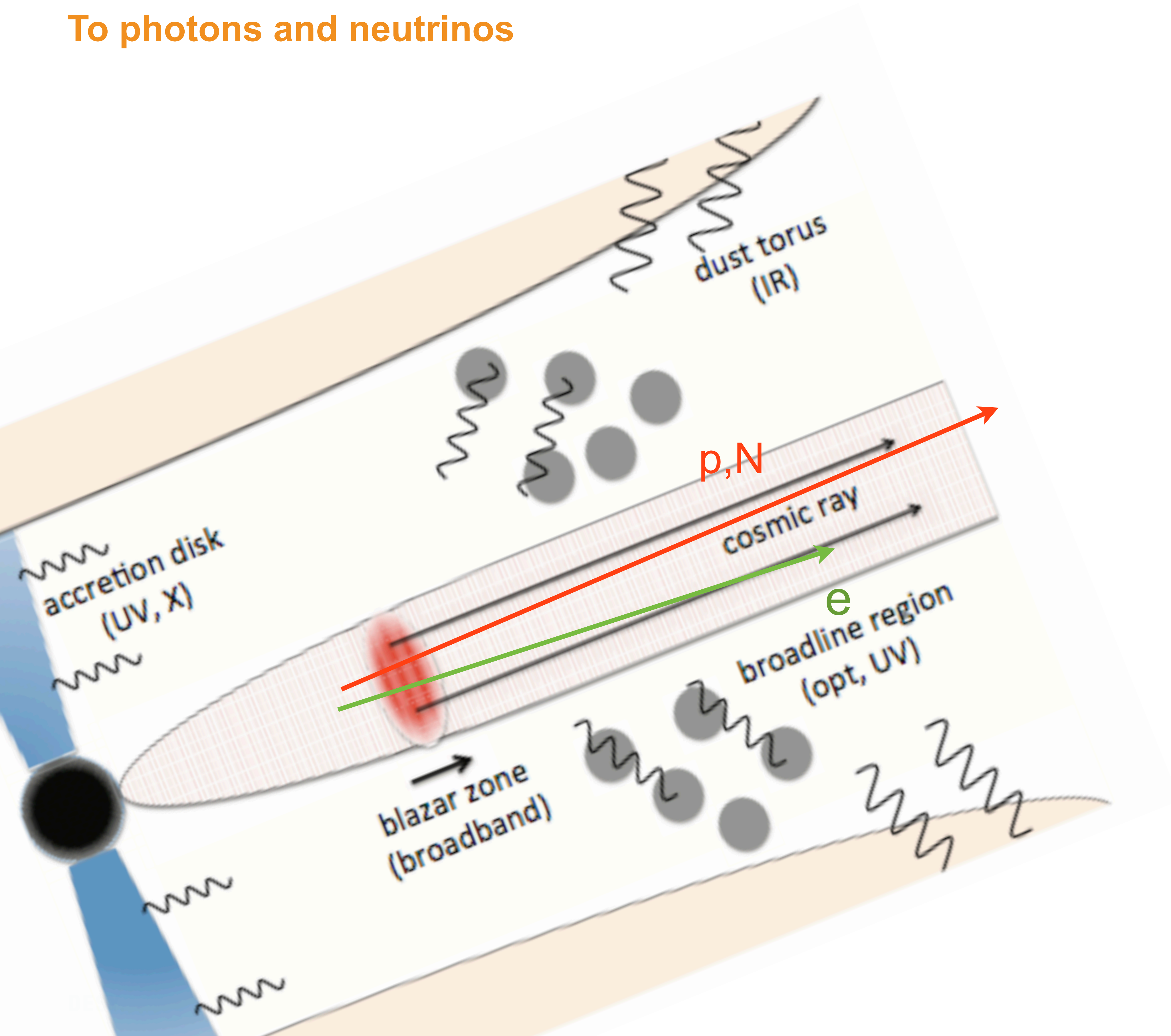


Relativistic jet with Γ ~ 5 — 40

Rel. Doppler factor: $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$

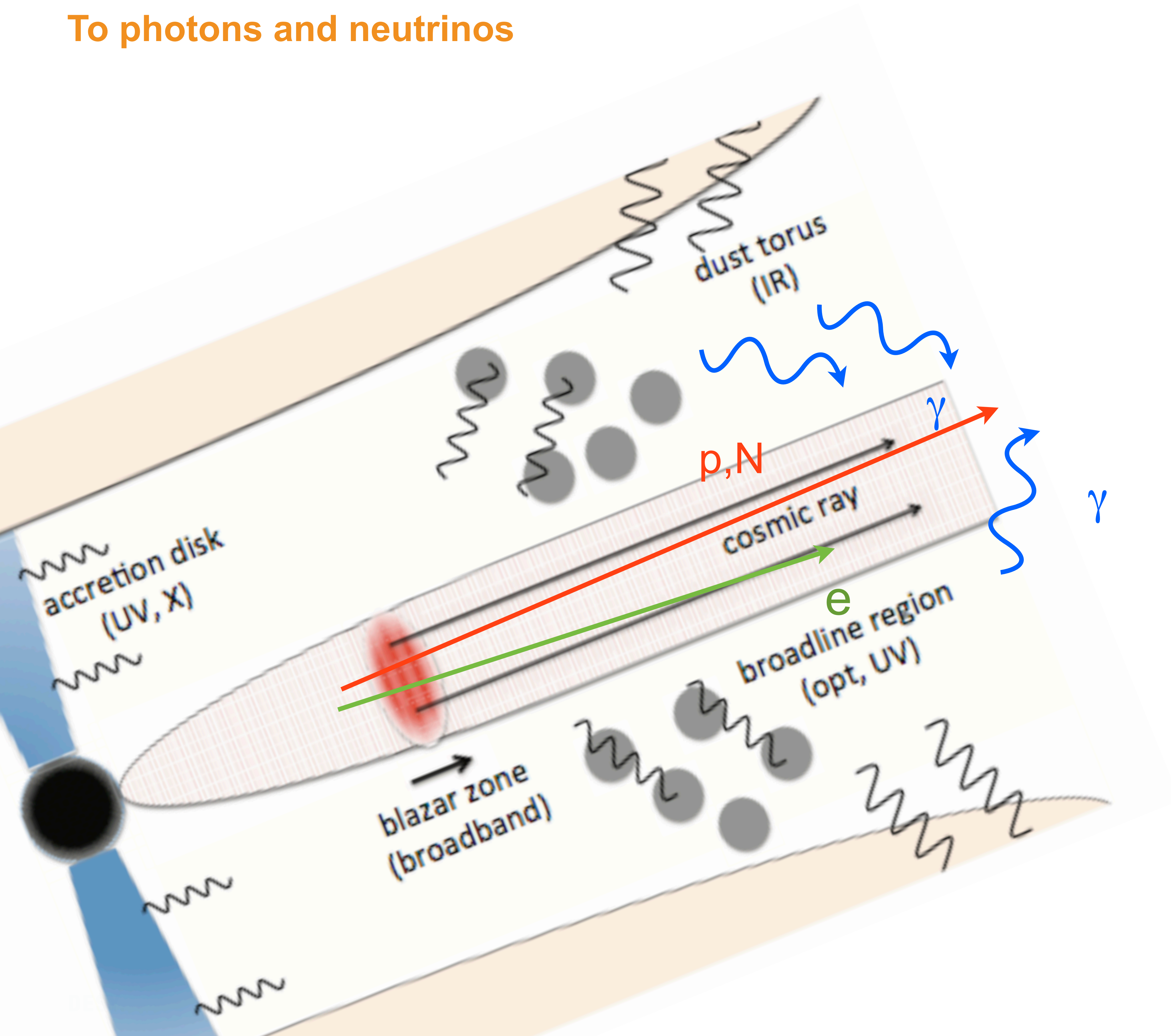
From protons and nuclei

To photons and neutrinos



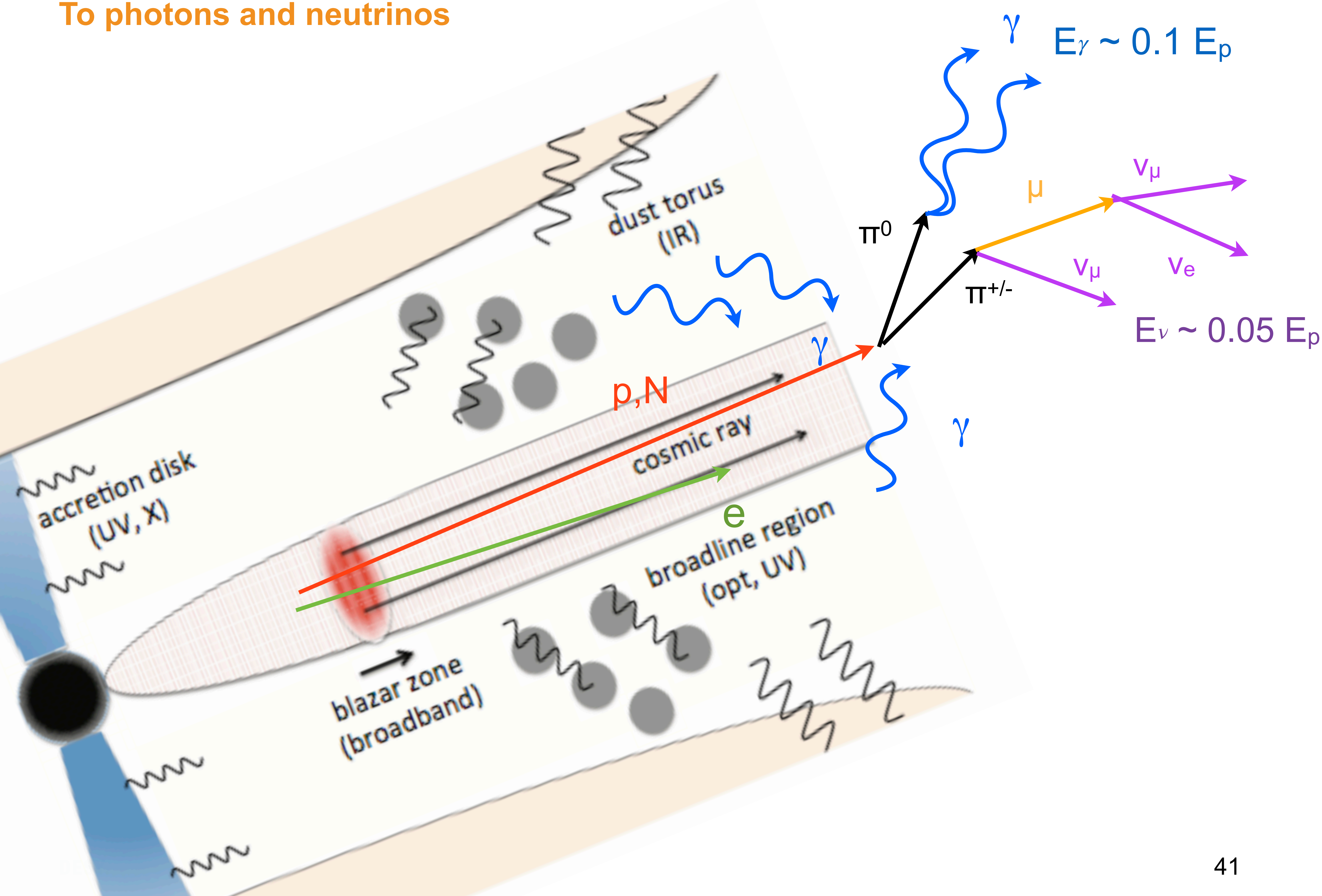
From protons and nuclei

To photons and neutrinos



From protons and nuclei

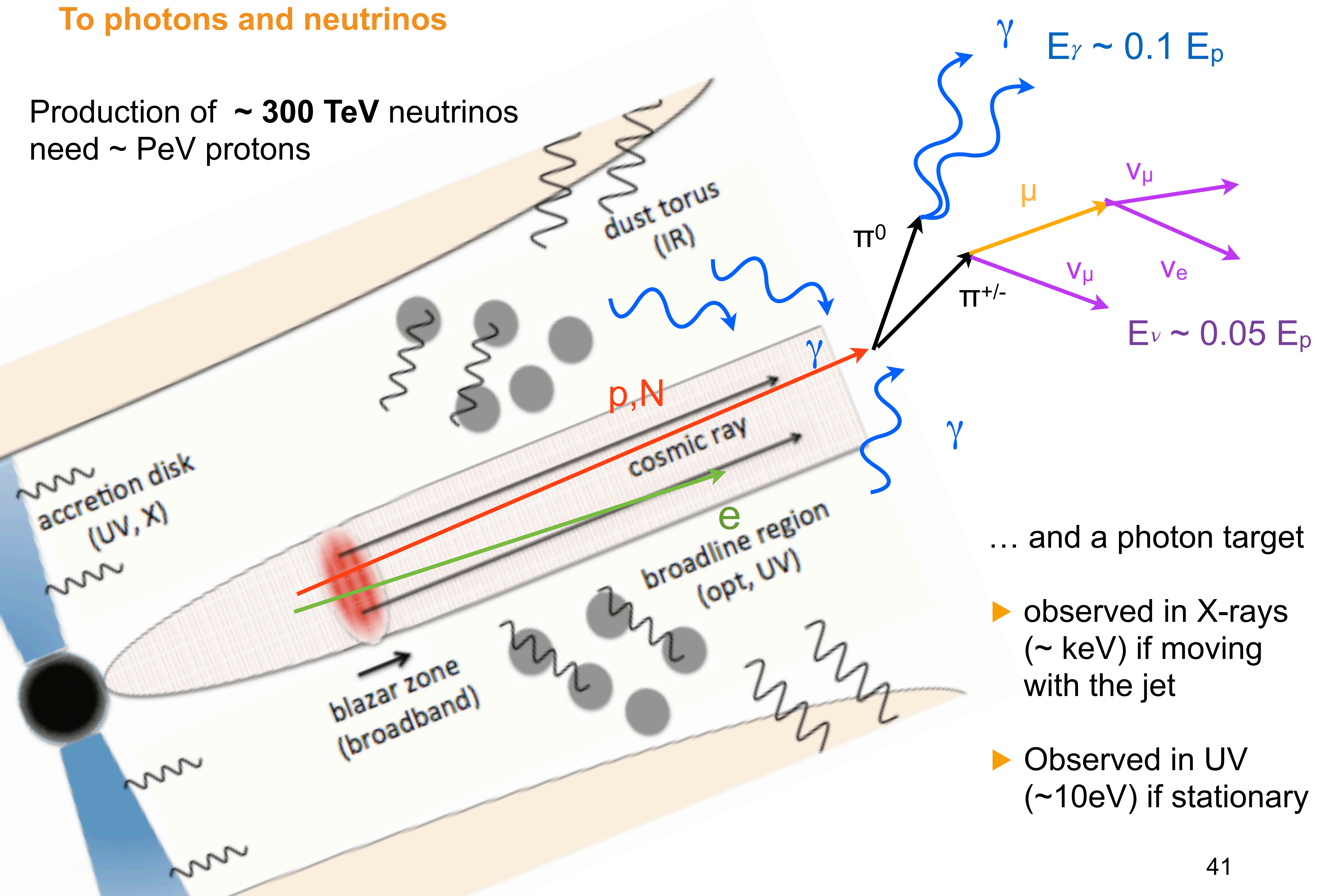
To photons and neutrinos



From protons and nuclei

To photons and neutrinos

Production of **~ 300 TeV** neutrinos need ~ PeV protons



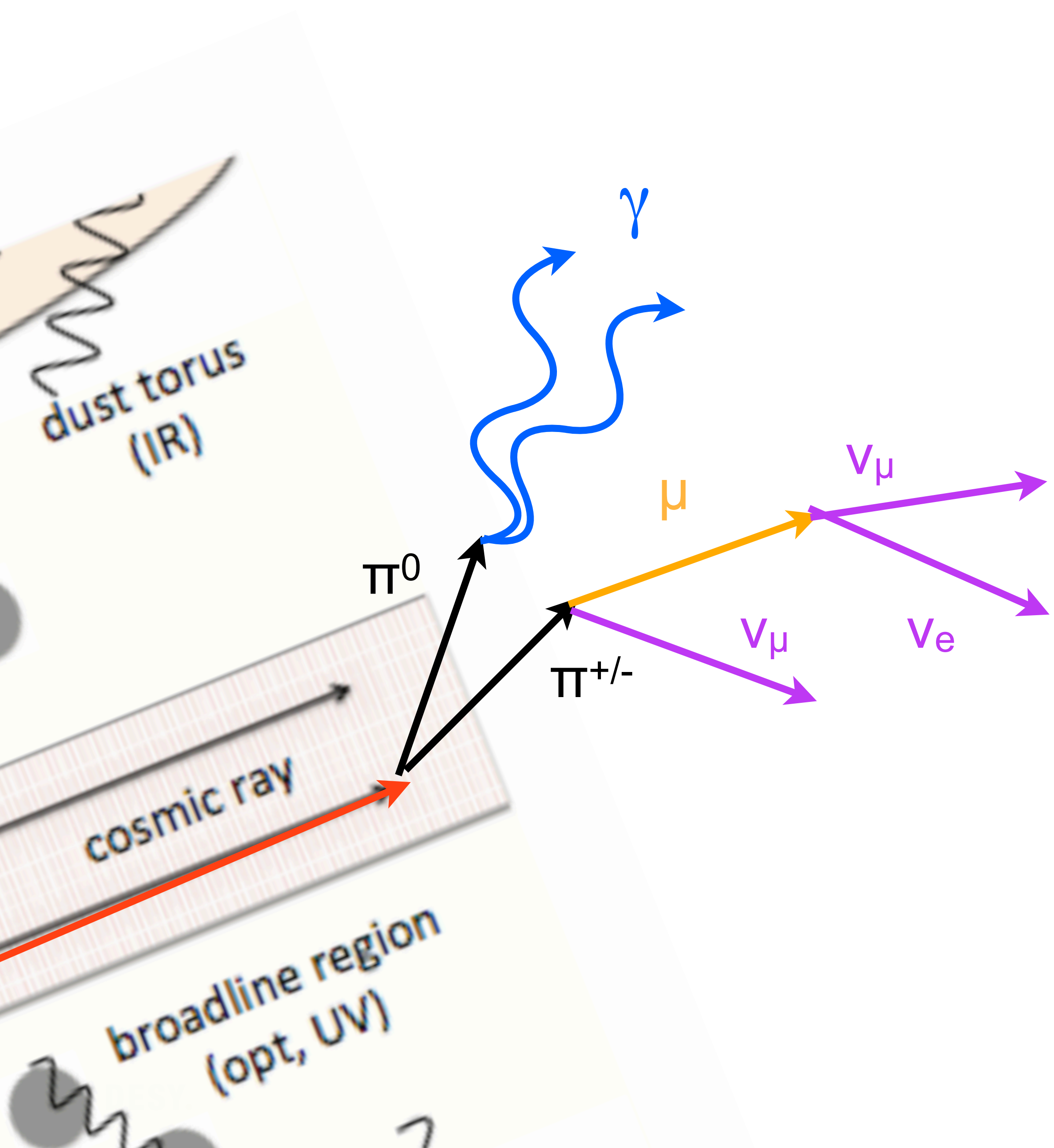
… and a photon target

- observed in X-rays (~ keV) if moving with the jet
- Observed in UV (~10eV) if stationary

From protons and nuclei

To photons and neutrinos

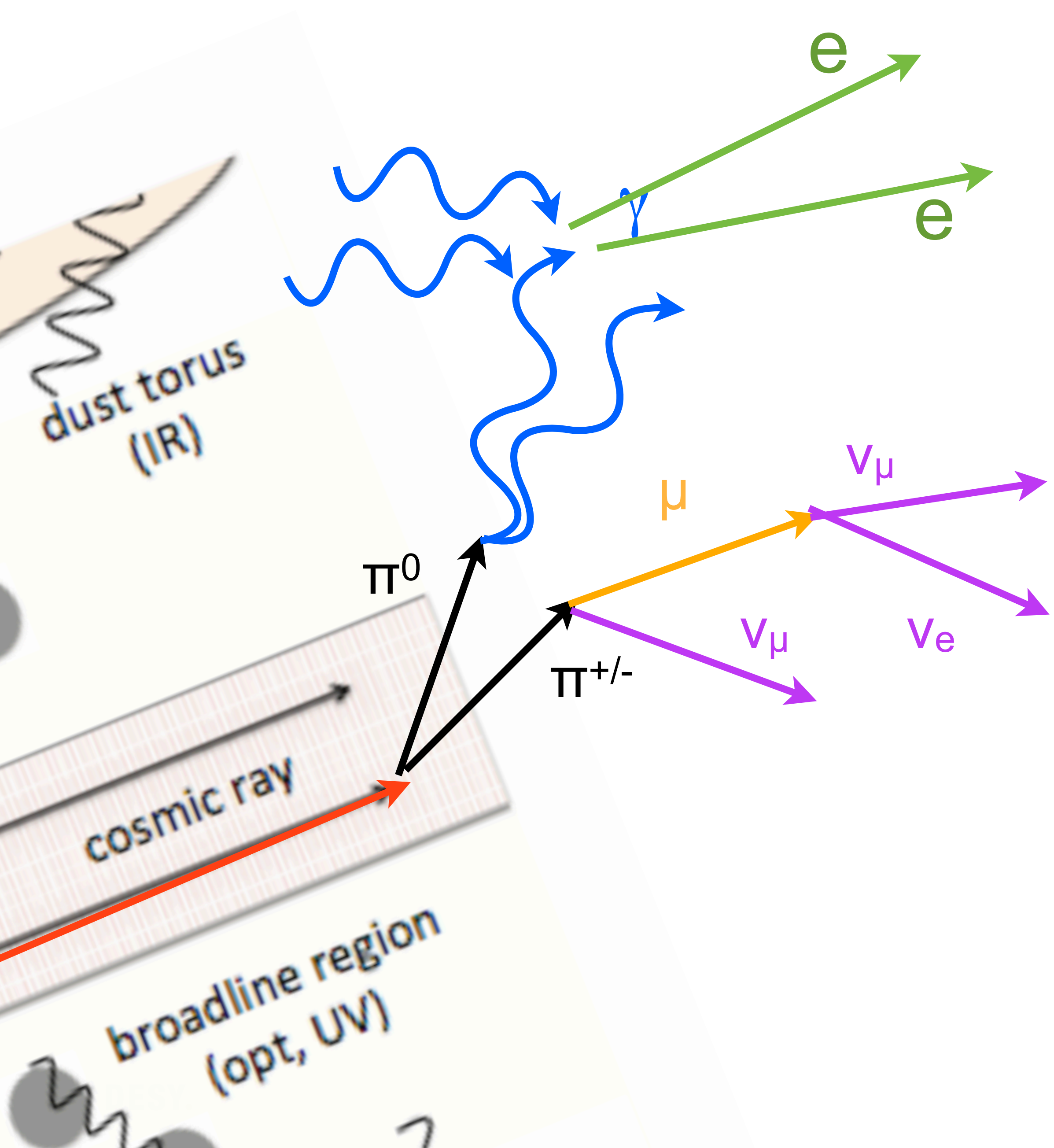
$\sigma_{\gamma\gamma} \gg \sigma_{p\gamma}$



From protons and nuclei

To photons and neutrinos

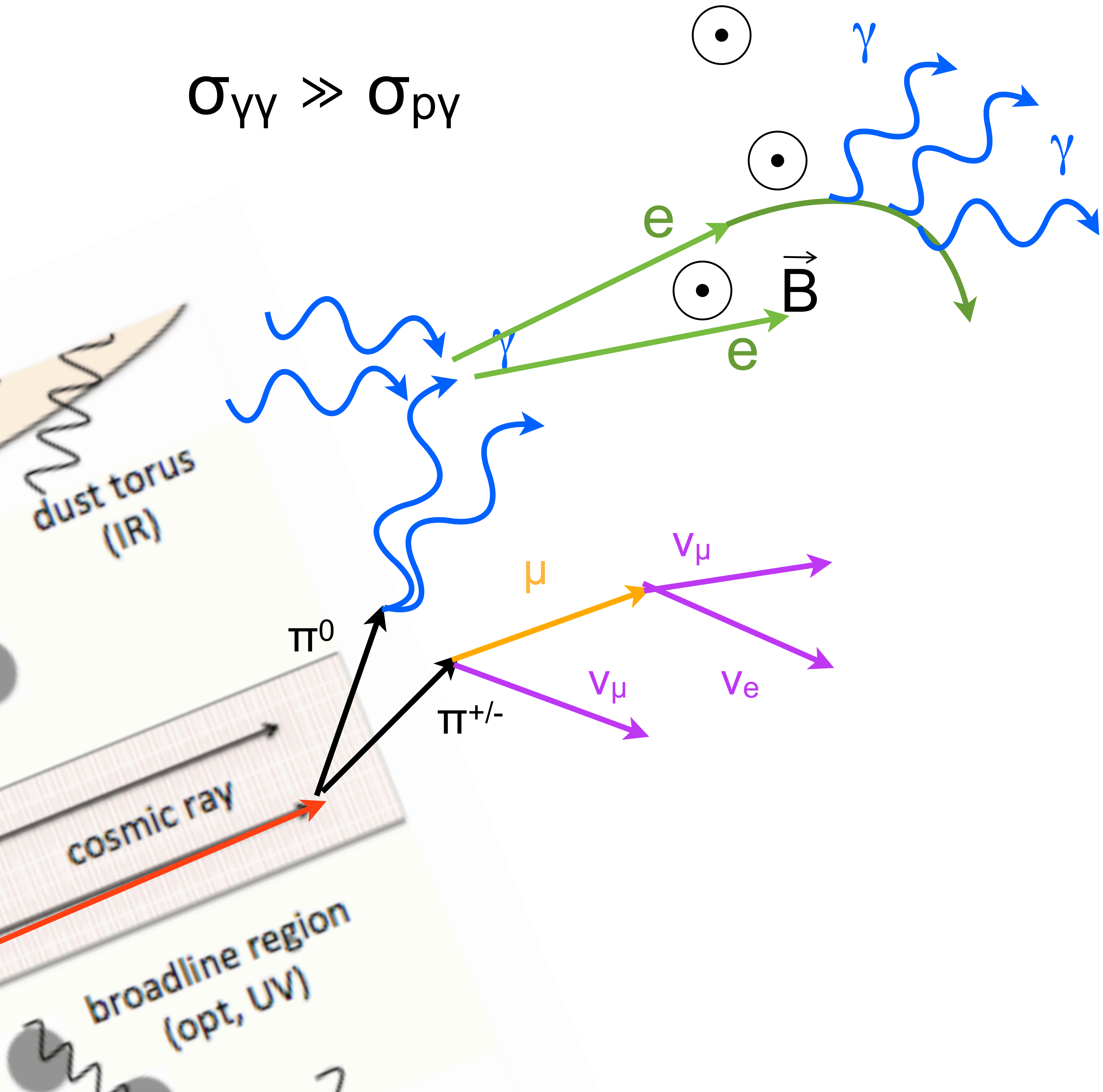
$\sigma_{\gamma\gamma} \gg \sigma_{p\gamma}$



From protons and nuclei

To photons and neutrinos

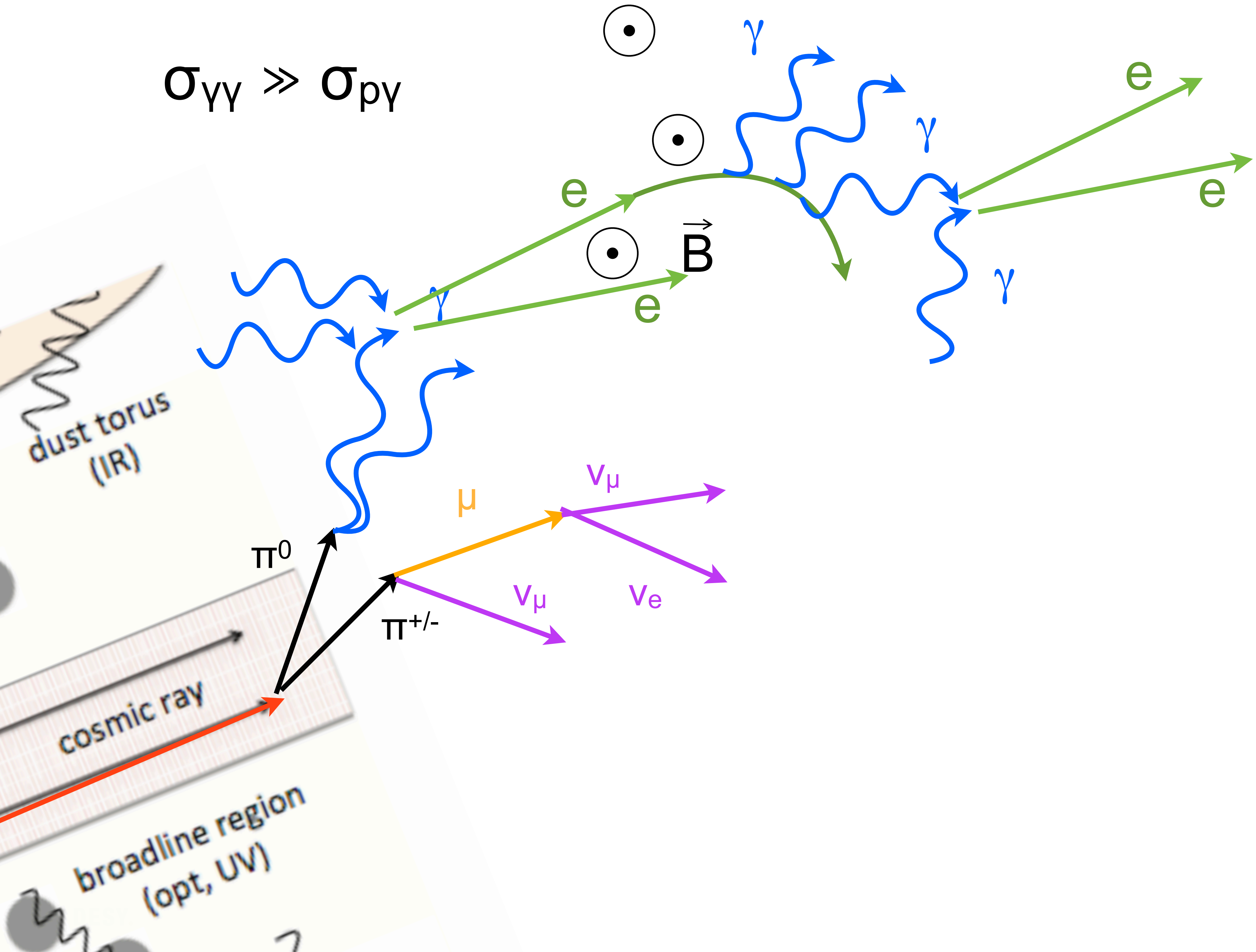
$\sigma_{\gamma\gamma} \gg \sigma_{p\gamma}$



From protons and nuclei

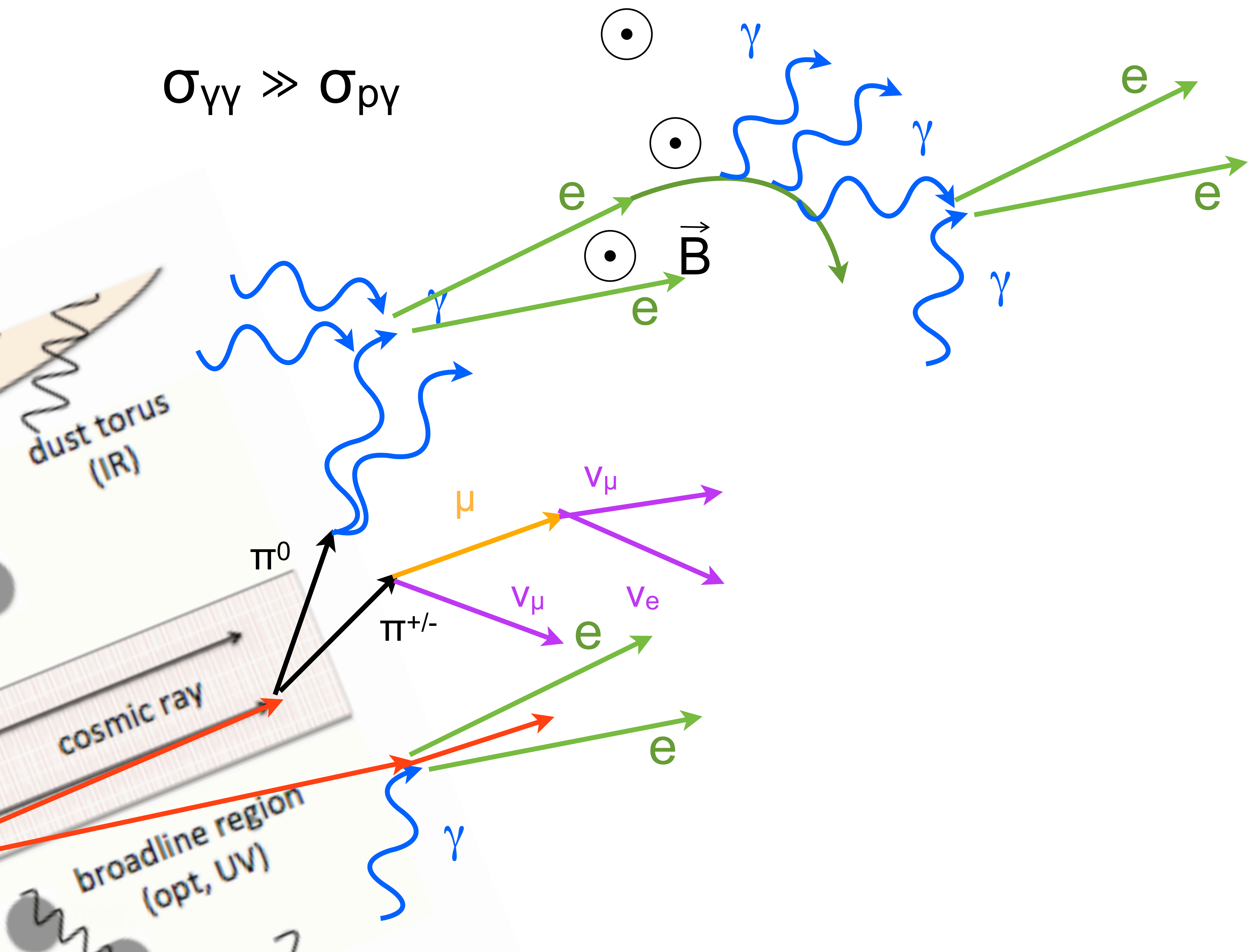
To photons and neutrinos

$\sigma_{\gamma\gamma} \gg \sigma_{p\gamma}$



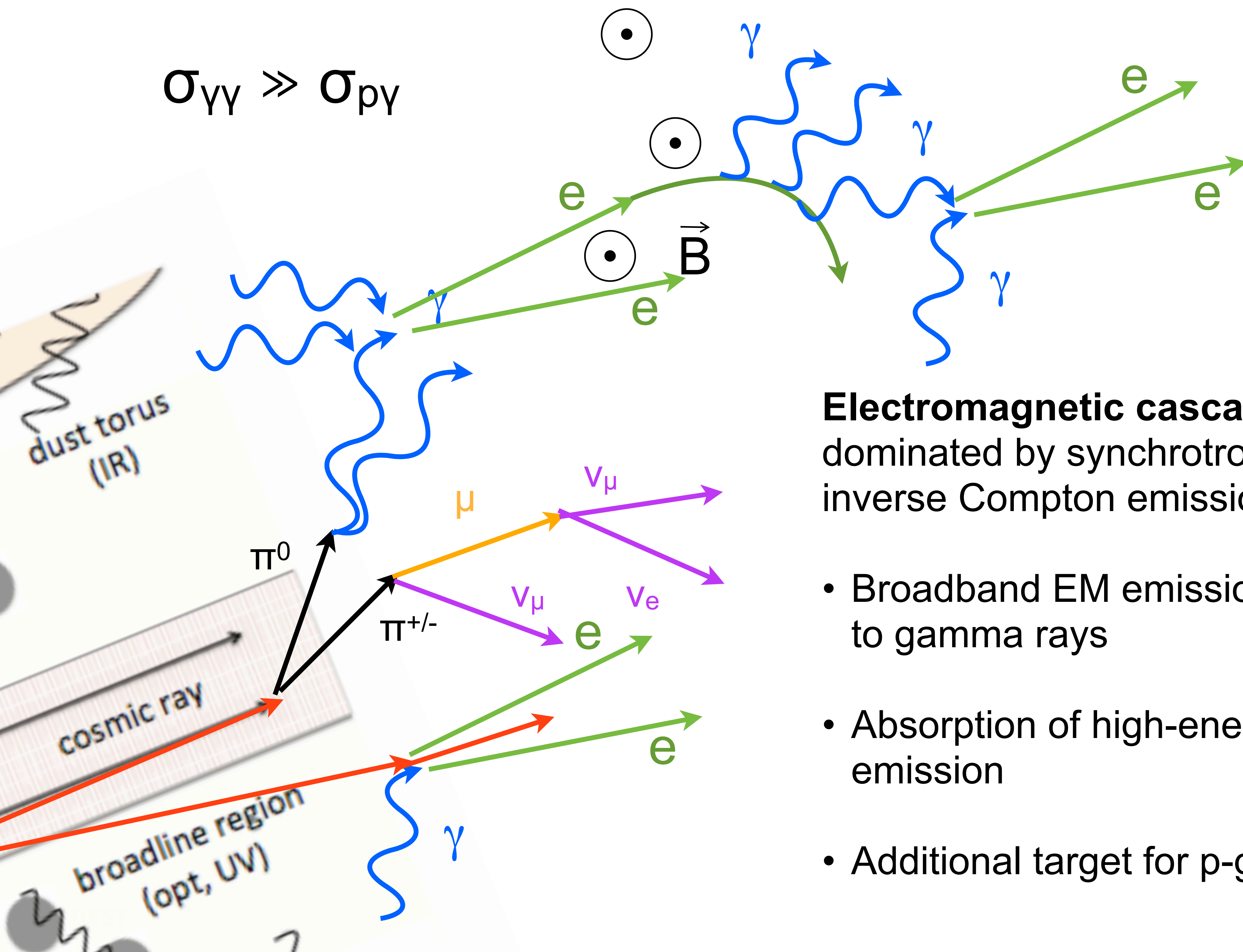
From protons and nuclei

To photons and neutrinos



From protons and nuclei

To photons and neutrinos



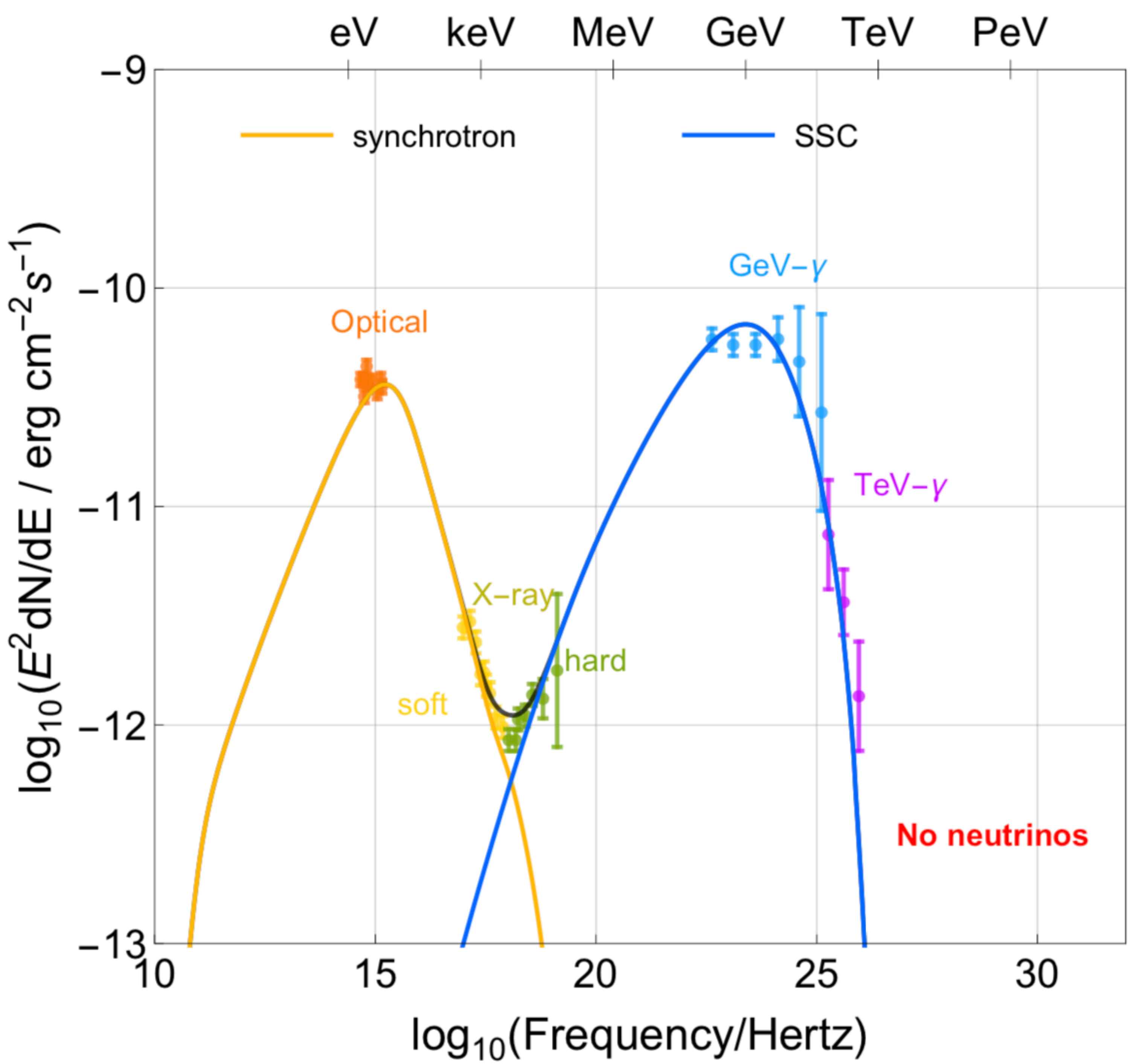
Electromagnetic cascade dominated by synchrotron or inverse Compton emission

- Broadband EM emission from radio to gamma rays
- Absorption of high-energy gamma-ray emission
- Additional target for p-gamma interactions

Modeling the Blazar emission

SSC, EC, hadronic lepto-hadronic, etc.

Parameter	Description
z	Redshift
B' (G)	Magnetic field
R'_{blob} (cm)	Blob size
Γ_{bulk}	Doppler factor
$L'_{e,\mathrm{inj}}$ (erg/s)	Electron injection luminosity
$\alpha_{e,1}$	Electron lower spectral index
$\alpha_{e,2}$	Electron upper spectral index
$\gamma'_{e,\mathrm{min}}$	Min. electron Lorentz factor
$\gamma'_{e,\mathrm{br}}$	Electron break Lorentz factor
$\gamma'_{e,\mathrm{max}}$	Max. electron Lorentz factor
$L'_{p,\mathrm{inj}}$ (erg/s)	Proton injection luminosity
$\gamma'_{p,\mathrm{min}}$	Min. proton Lorentz factor
$\gamma'_{p,\mathrm{max}}$	Max. proton Lorentz factor
α_p	Proton spectral index
η_{esc}	escape velocity of $e^{\pm}$ and p
Results	
L_{Edd} (erg/s)	Eddington luminosity *
$L_{\mathrm{jet}}/L_{\mathrm{Edd}}$	jet physical luminosity (in L_{Edd})
$E_{\nu,\mathrm{peak}}$, TeV	peak energy of neutrino spectrum
N_ν/yr	Expected neutrino rate in IceCube



From Gao et al., 2018

A simple model without protons…..

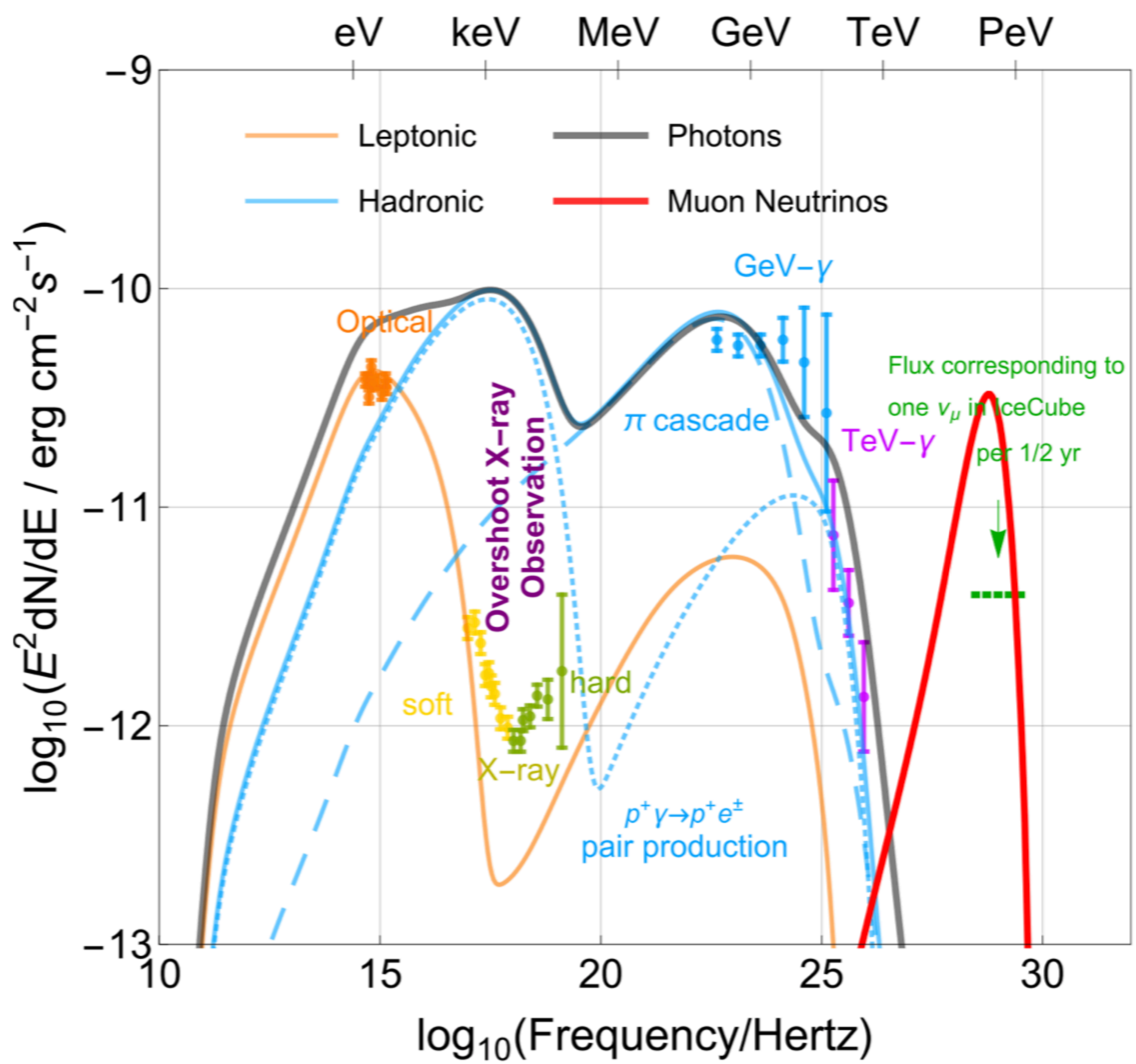
Modeling the Blazar emission

SSC, EC, hadronic lepto-hadronic, etc.

From Gao et al., 2018

Adding protons / neutrinos is not so simple…..

- Electromagnetic cascade would overshoot x-ray observations

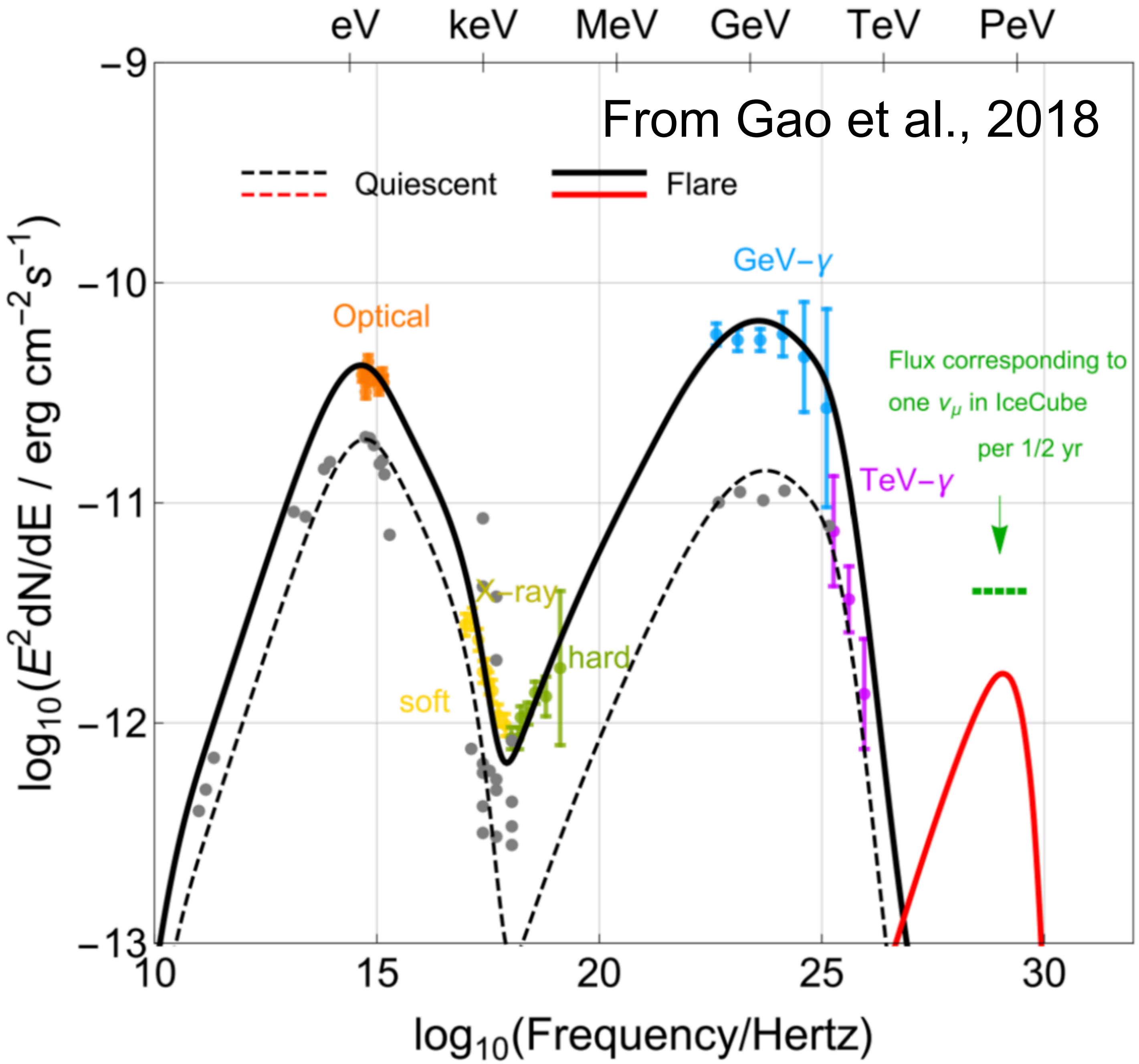


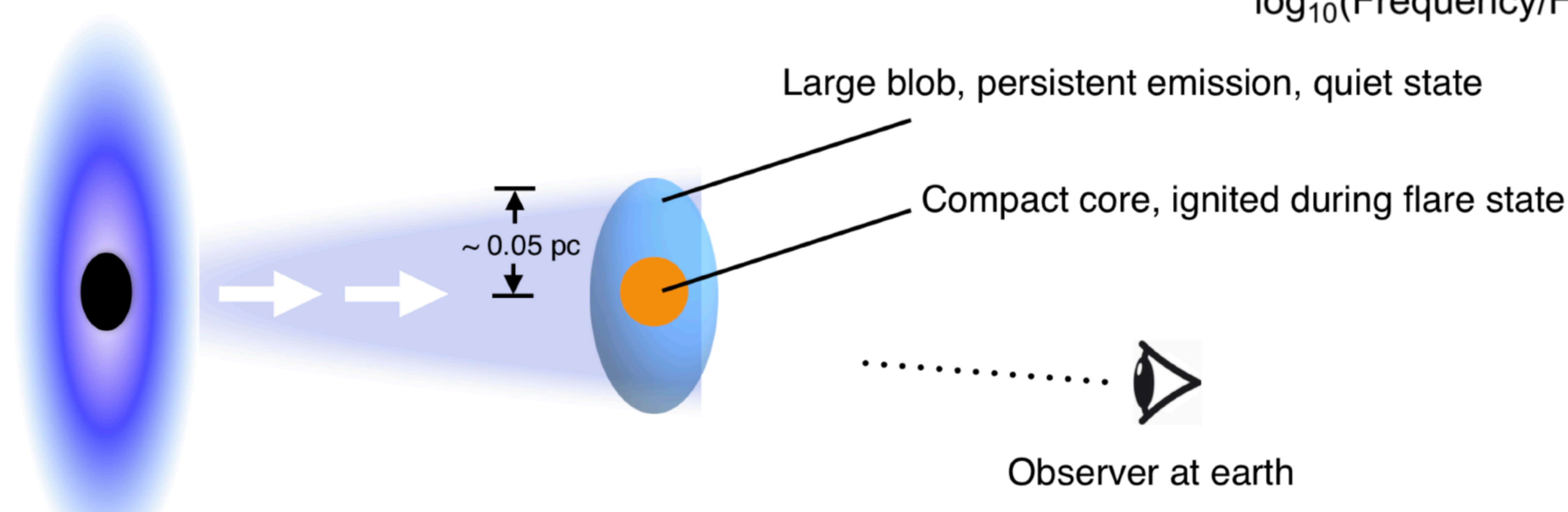
Two emission zones

X-rays as the key window

Adding protons / neutrinos is not so simple…..

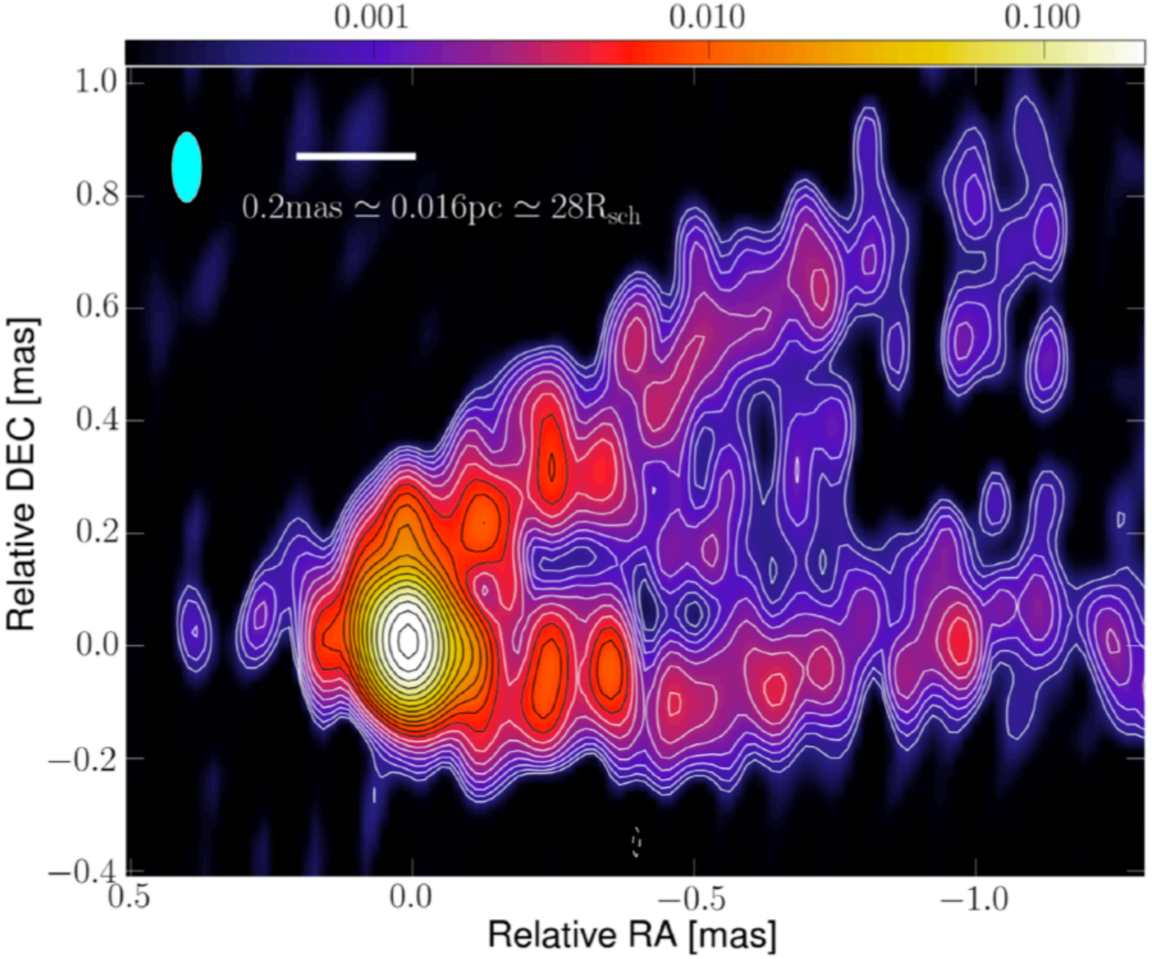
- Two emission zones help to reconcile observations





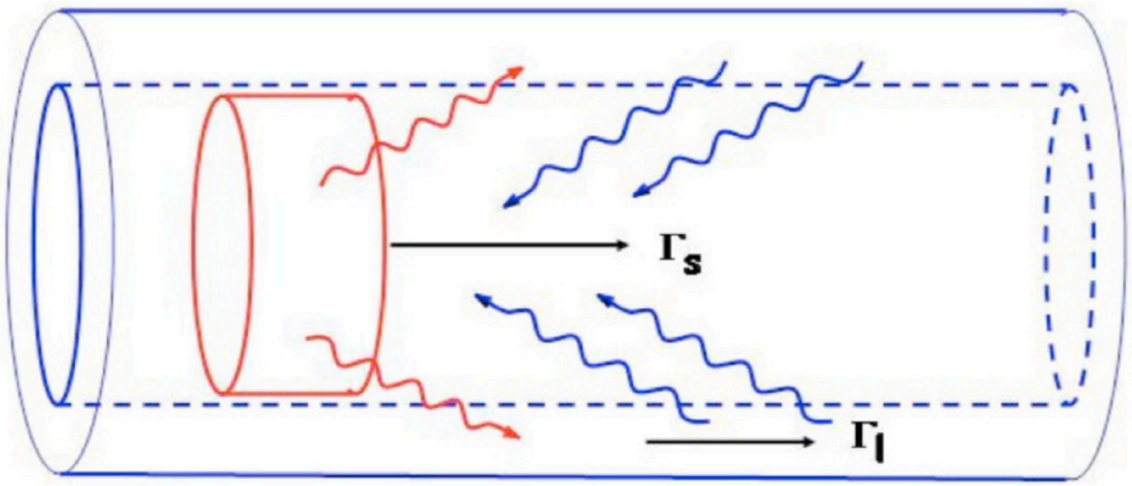
A structured jet ?

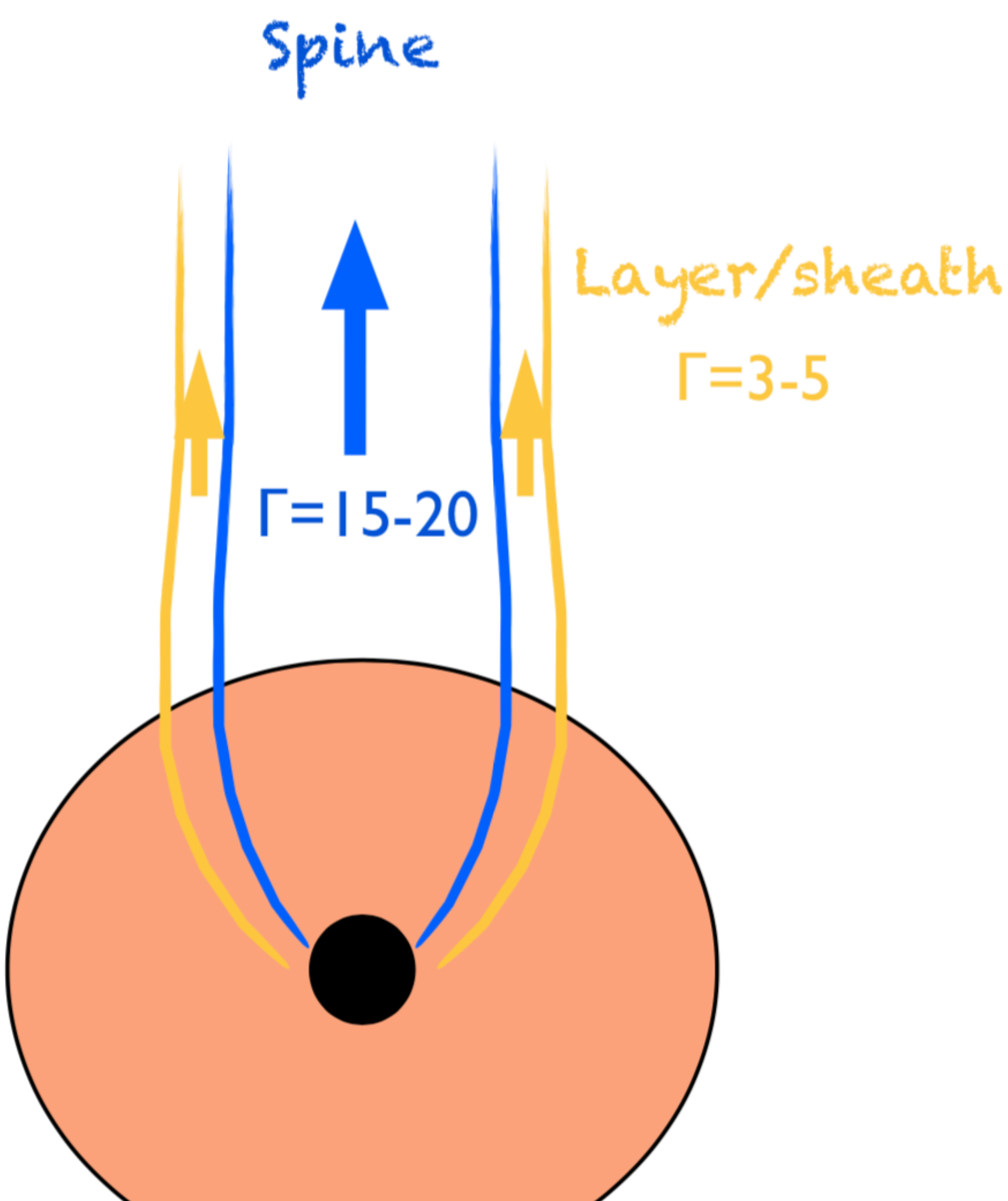
An elegant two emission zone model



$$\Gamma_{\rm rel} = \Gamma_{\rm s}\Gamma_{\rm l}(1-\beta_{\rm s}\beta_{\rm l})$$

$$U' \simeq U\Gamma_{\rm rel}^2$$

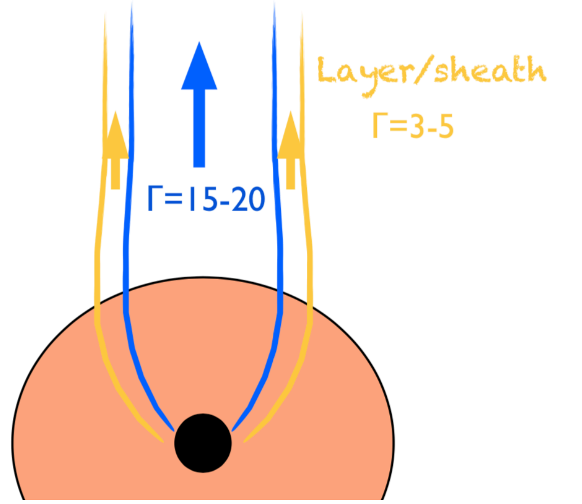


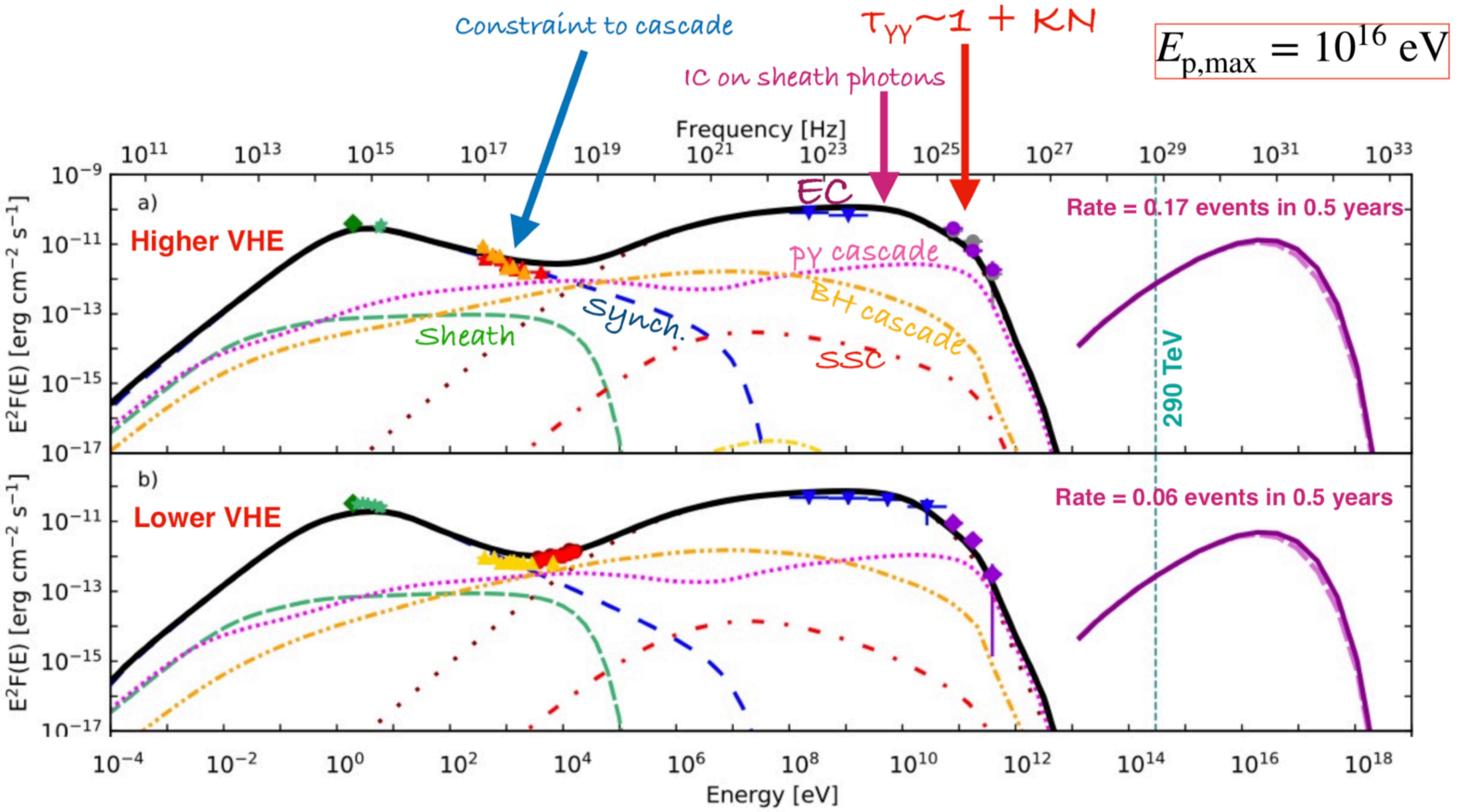


A structured jet ?

An elegant two emission zone model

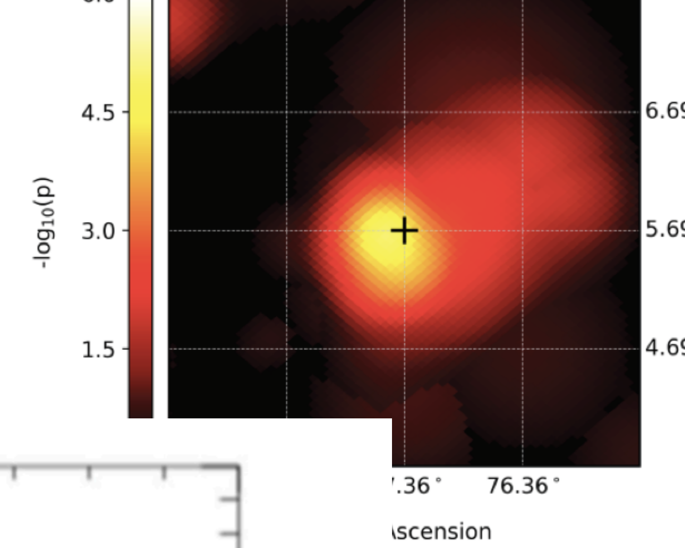
F. Taveccio, TeVPA 2018

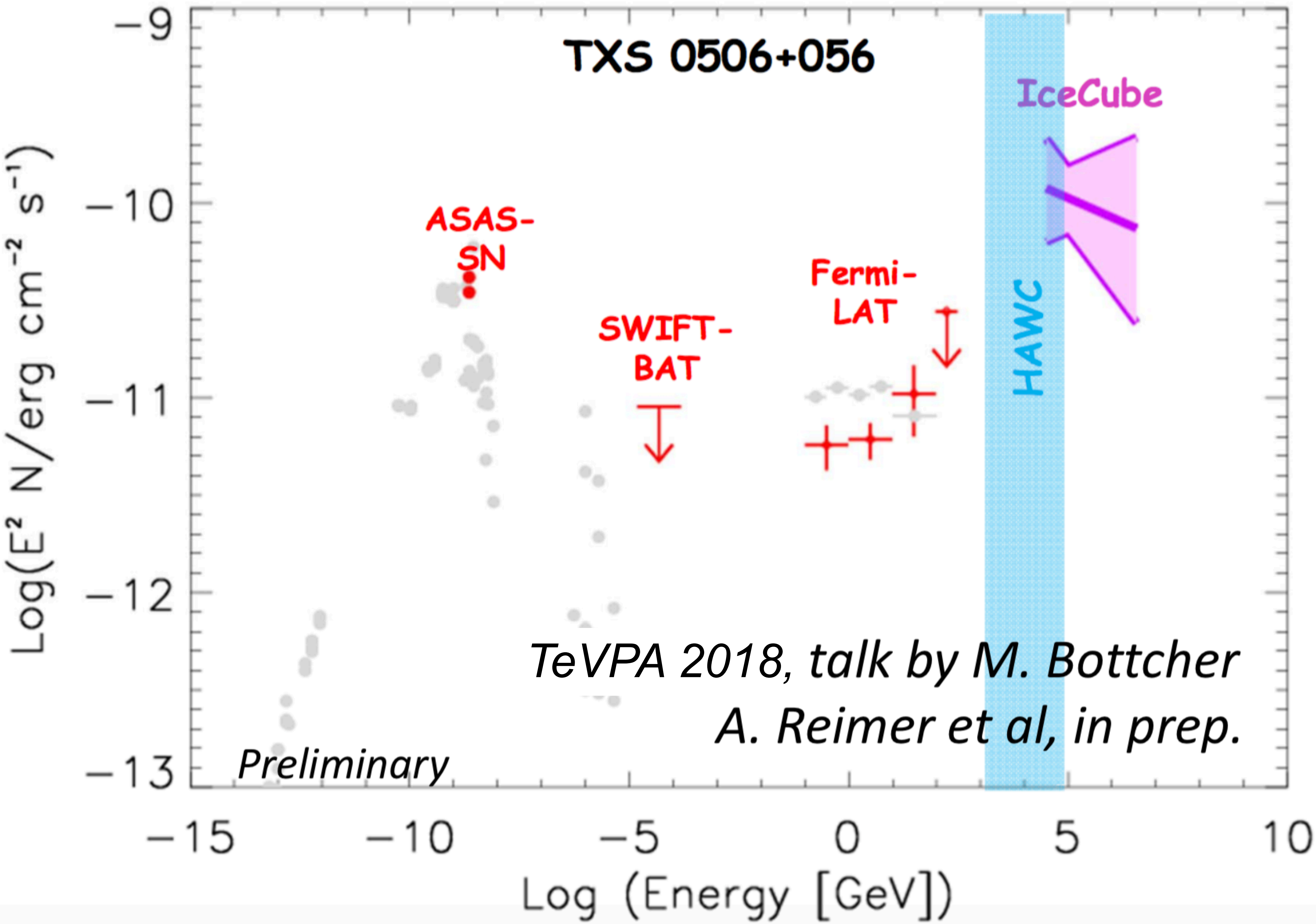




The case of the 2014/2015 flare

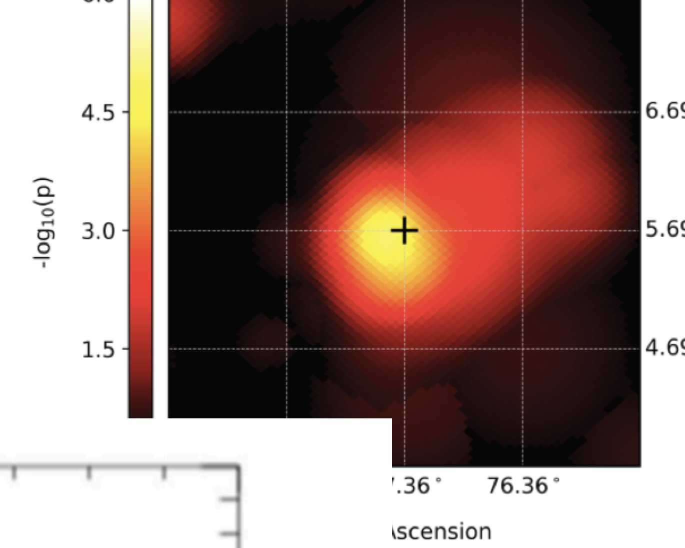
How does it fit into the picture ?

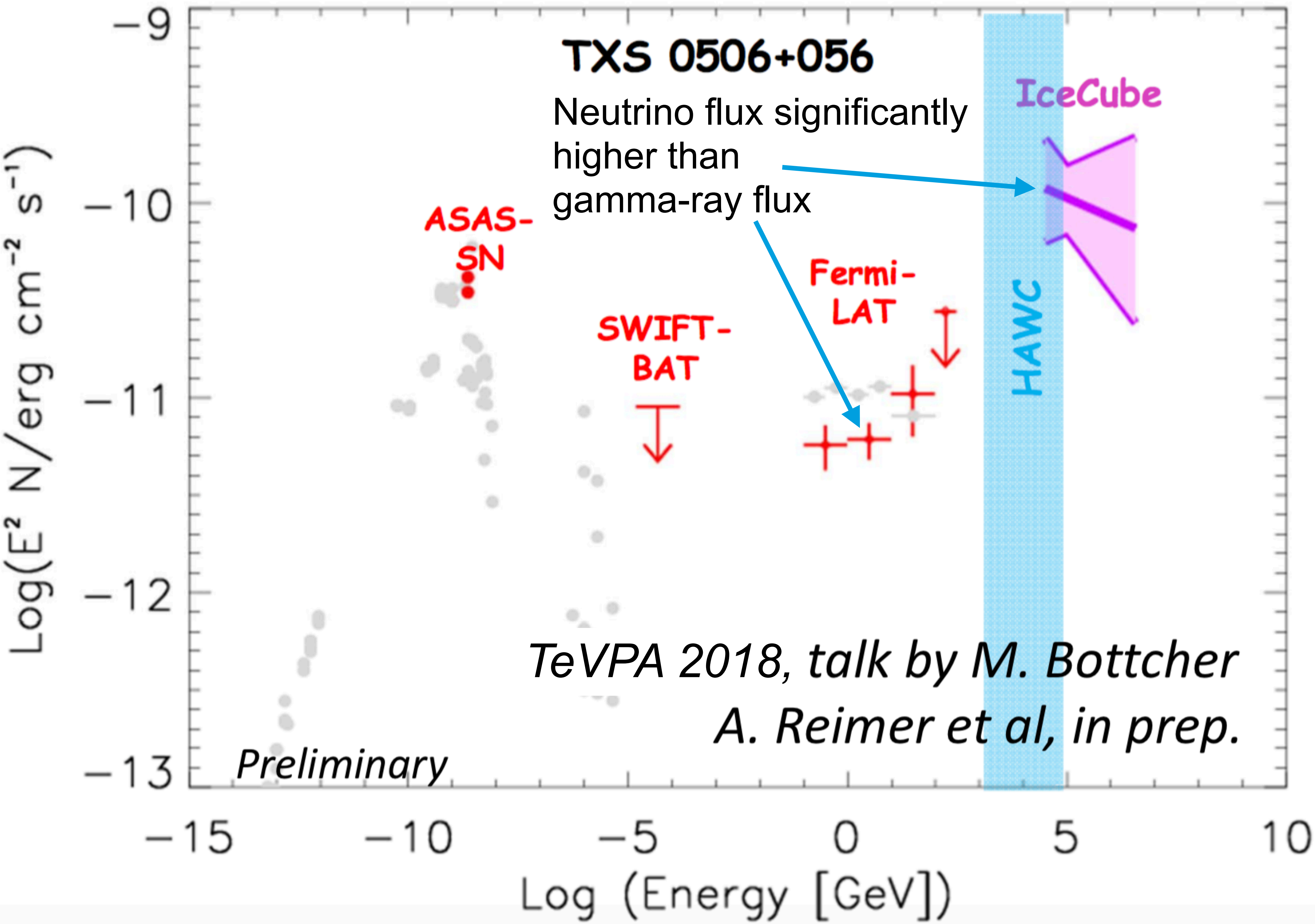




The case of the 2014/2015 flare

How does it fit into the picture ?

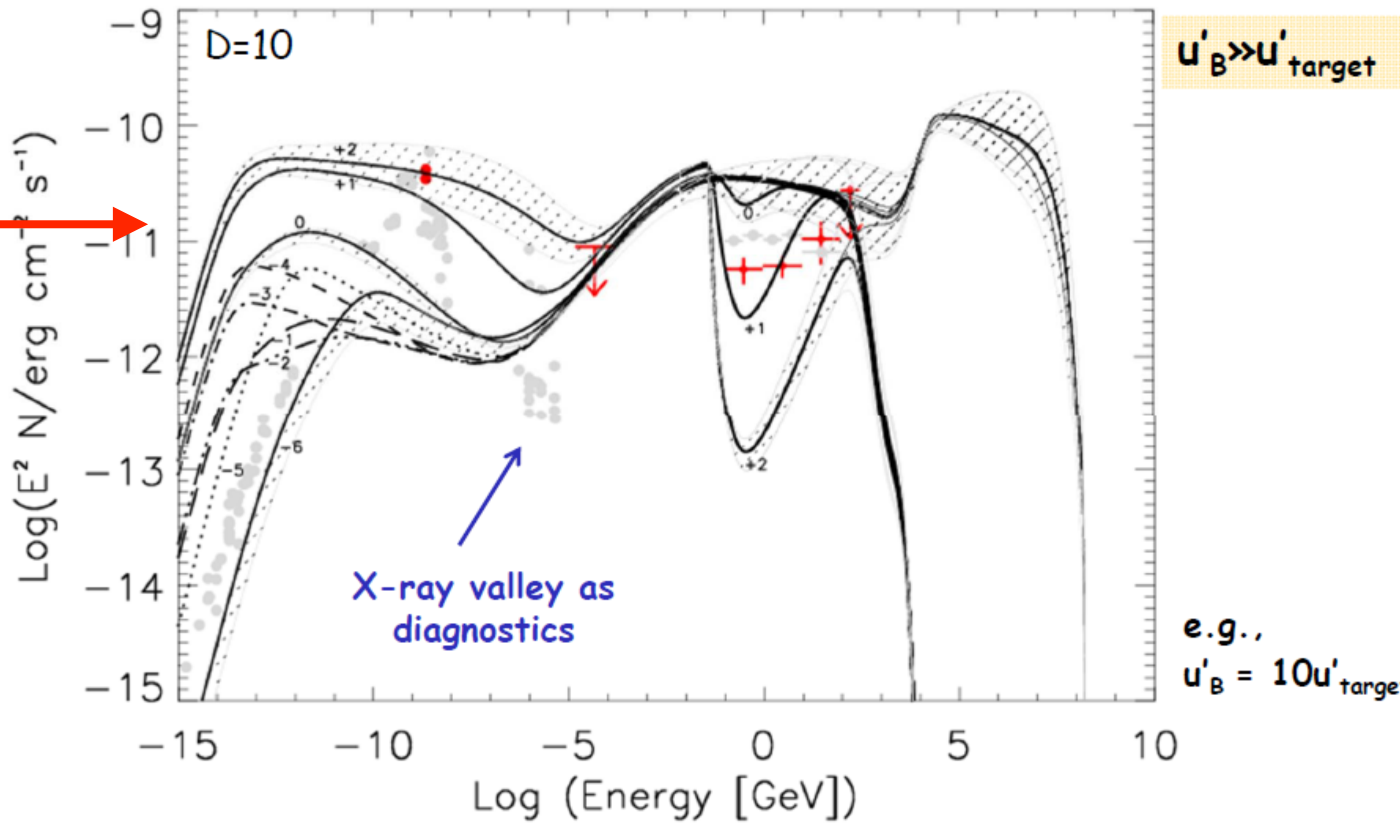




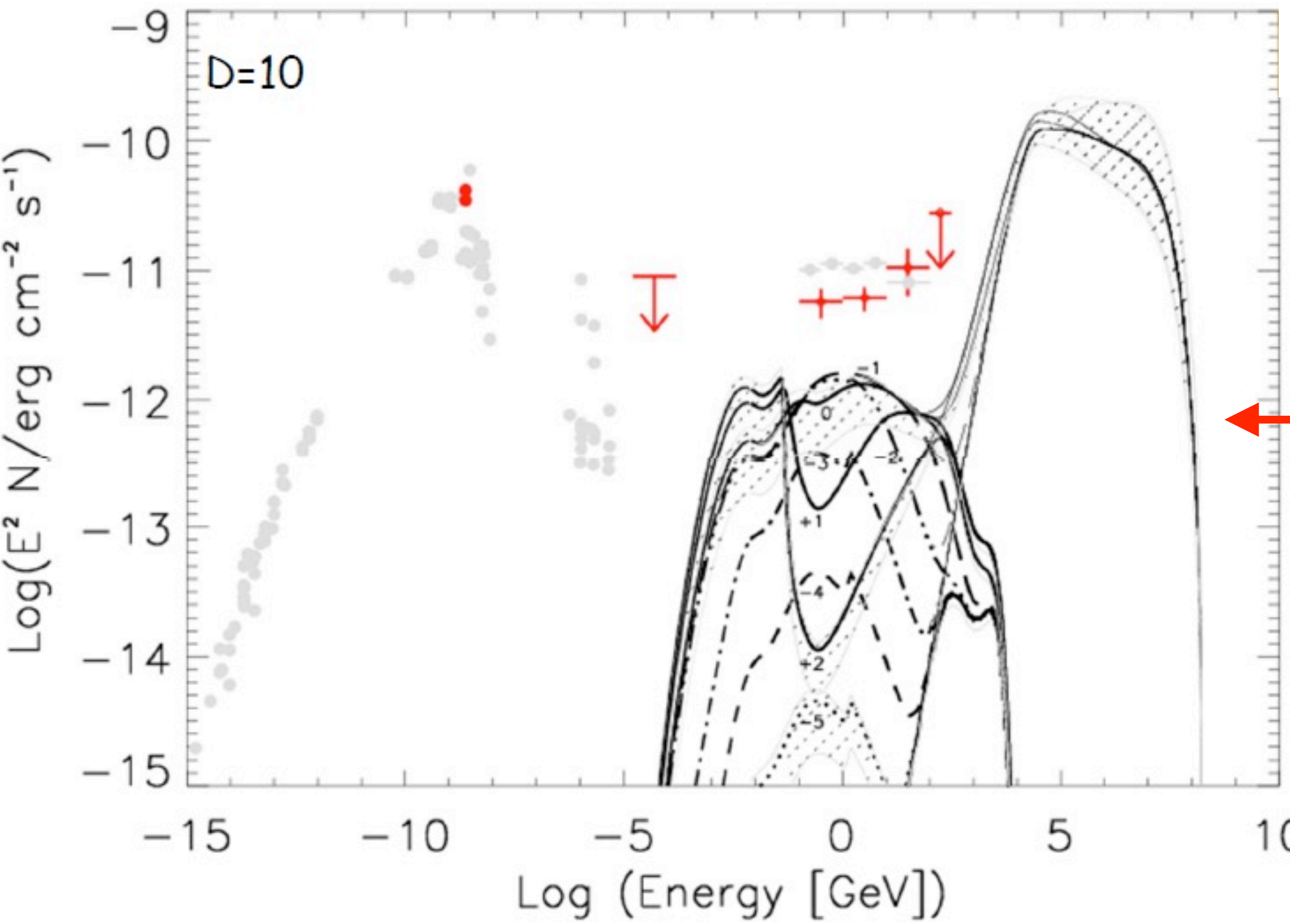
The case of the 2014/2015 flare

How does it fit into the picture ?

Overshoots x-ray or gamma-rays



Inverse Compton dominates
EM cascade formation



Synchrotron dominates
EM cascade formation

No correlation with gamma-rays

M. Boettcher, TeVPA 2018

Another interesting case ?

Counterpart for HESE 63

Starting event observed in 2014
(before real-time analysis
was online)

IC-141209A

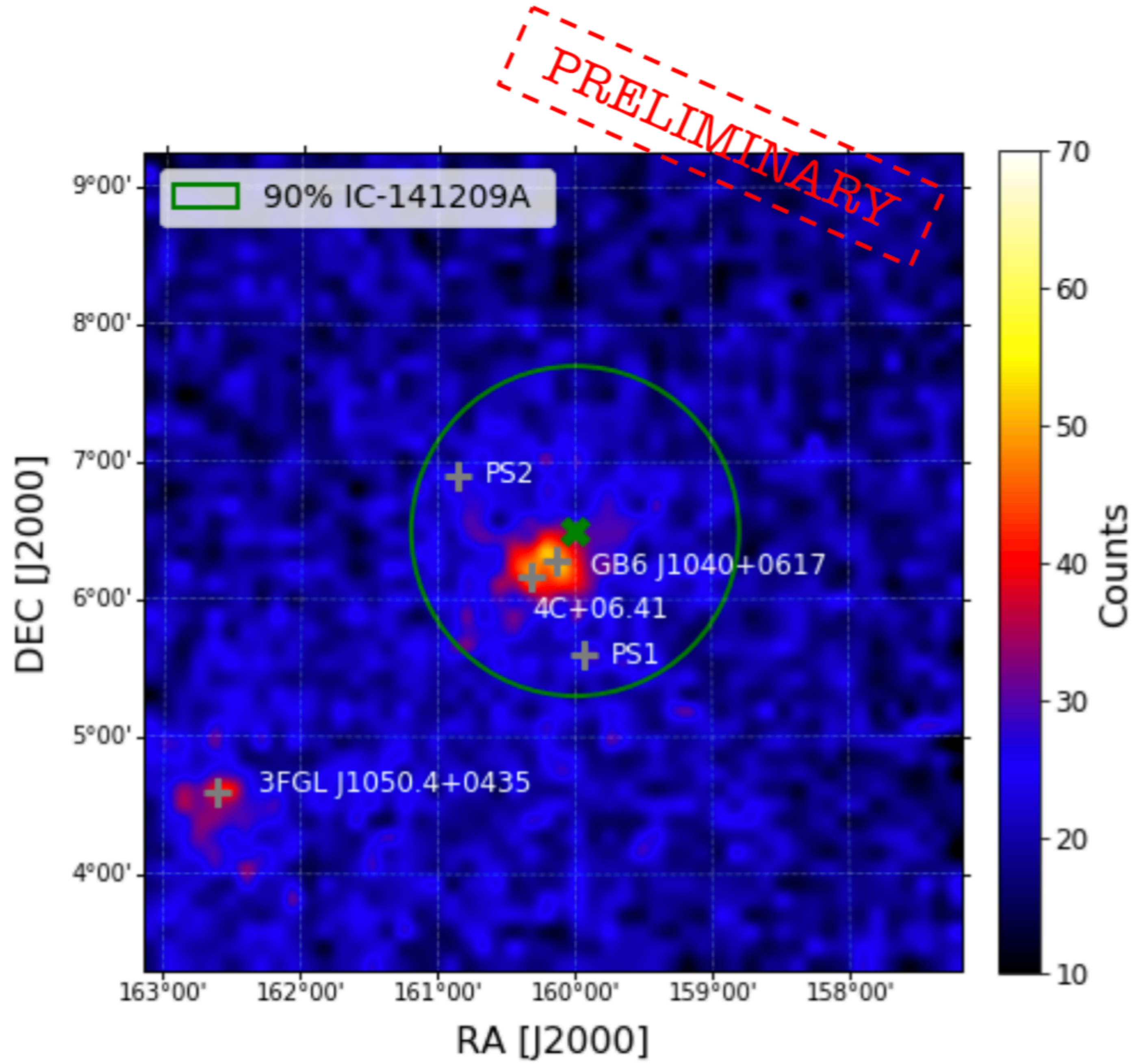
- MJD 57000.14
- (Ra , Dec) = (160.0°, 6.5°)
- Ang. Err. (90%) : 1.2°

GB6 J1040+0617

- BL Lac, LSP
- 3FGL J1040.4+0615
- z = 0.7351± 0.0045 *
- Dist. from IC-141209A: 0.27°

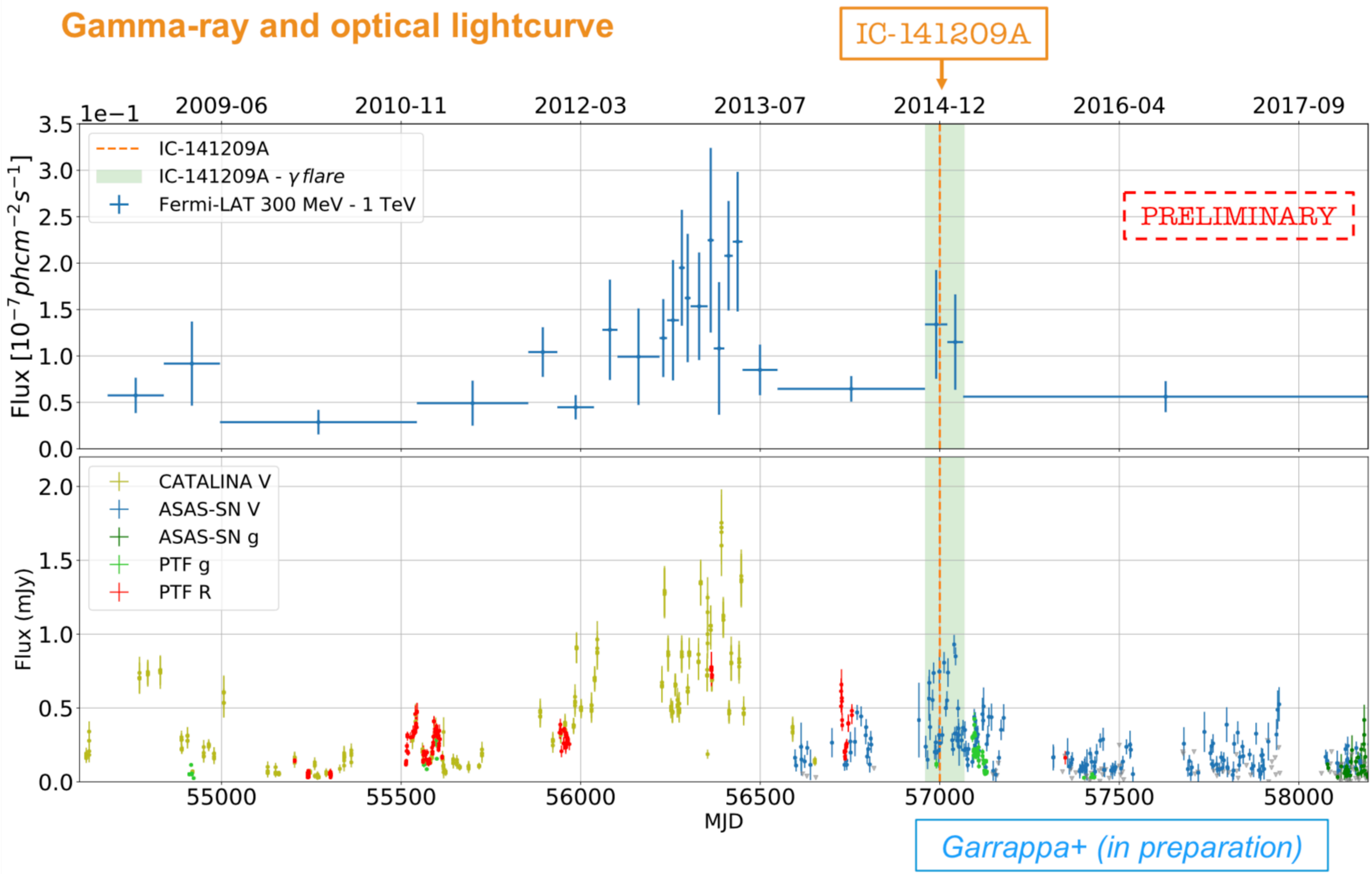
ROI

- 4C+06.41 (QSO)
- Two additional sources (PS1 and PS2) found using 9.6 years of data
- PS2 also included in FL8Y as FL8Y J1043.3+0651
- Very dim, can be excluded as possible counterparts.



Garrappa+ (in preparation)

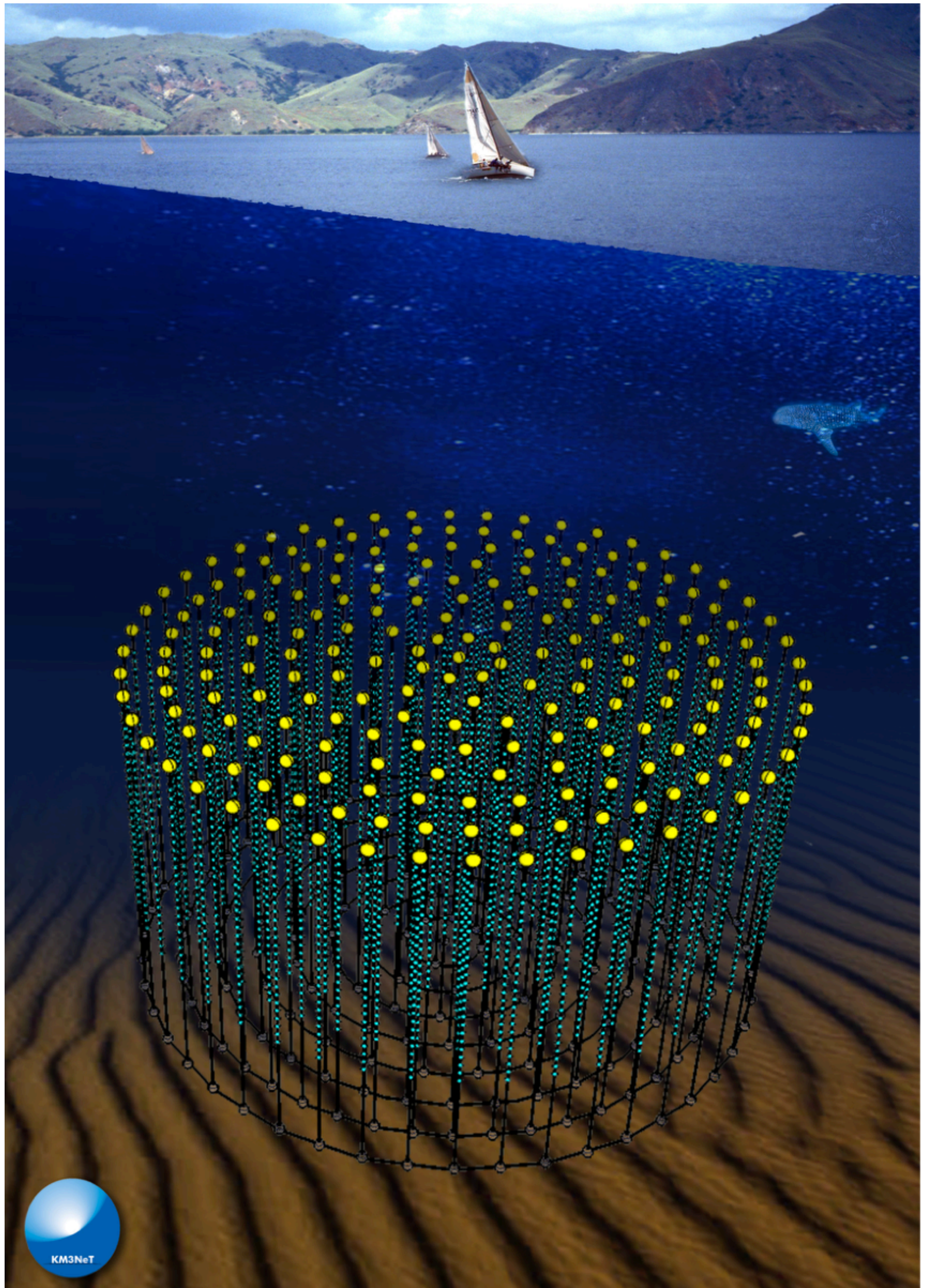
Another interesting case ?

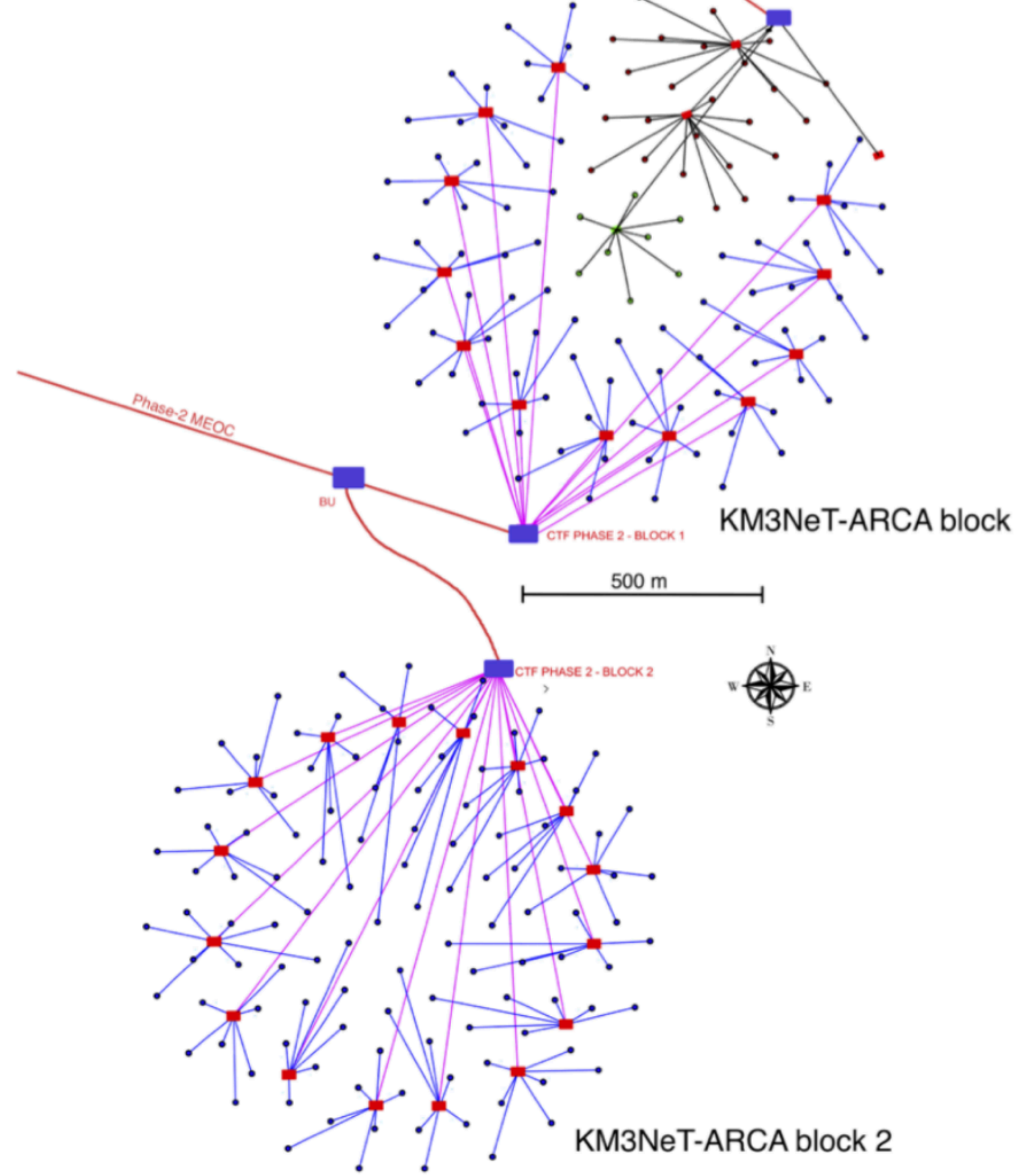


S.Garappa, TeVPA 2018

Where to go from here ?

The next generation of neutrino telescopes



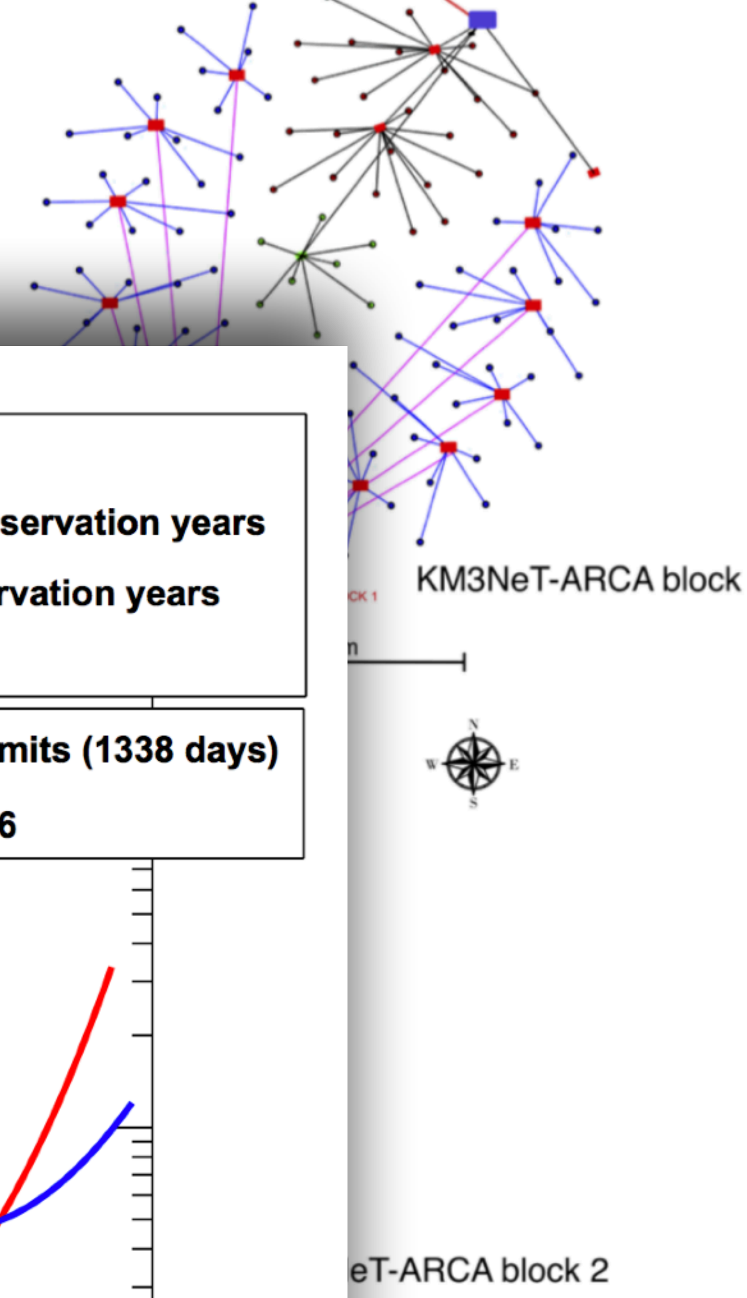


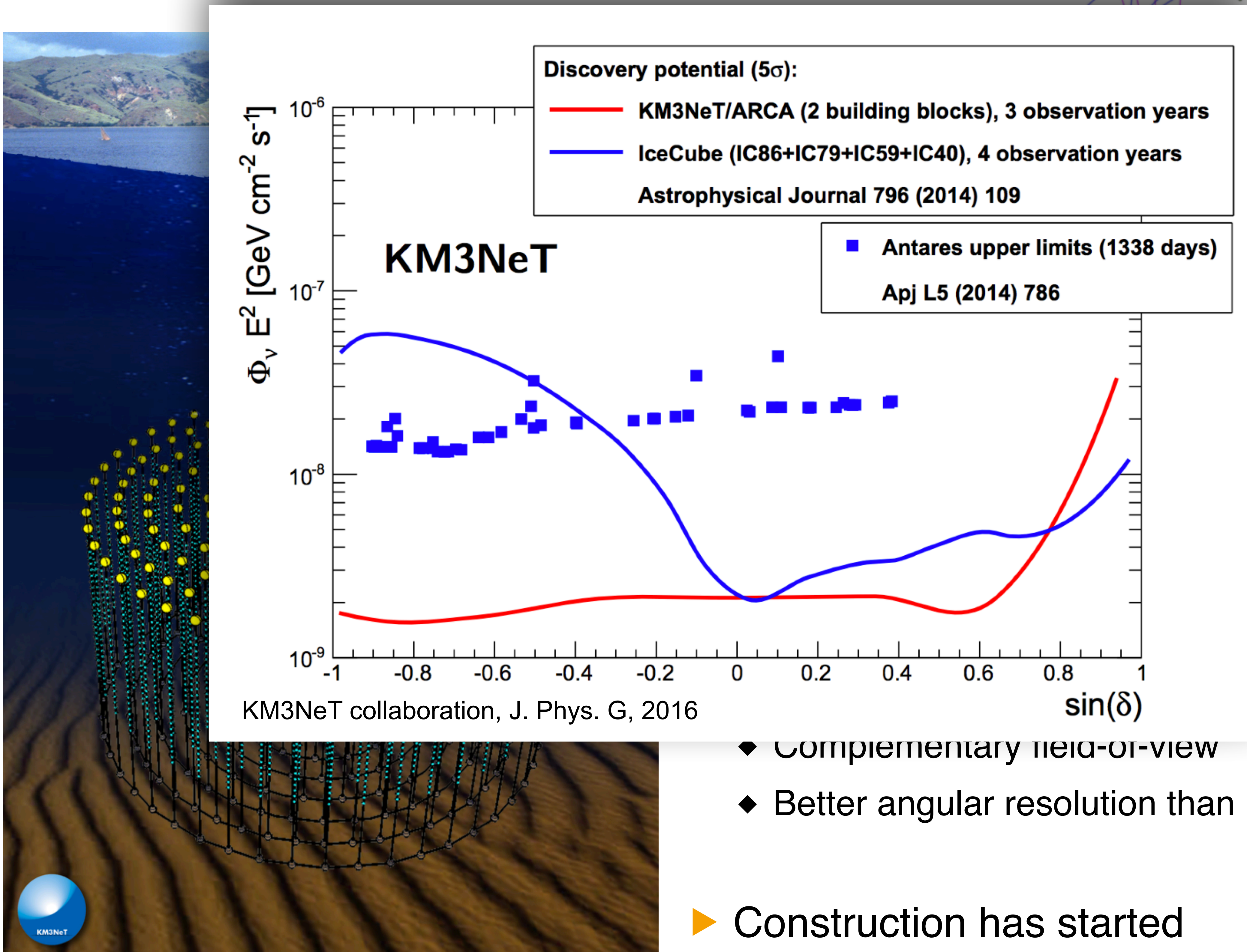
- **KM3NeT - ARCA**
  - Similar instrumented volume to IceCube
  - Complementary field-of-view
  - Better angular resolution than IceCube

- Construction has started

Where to go from here ?

The next generation of neutrino telescopes





IceCube

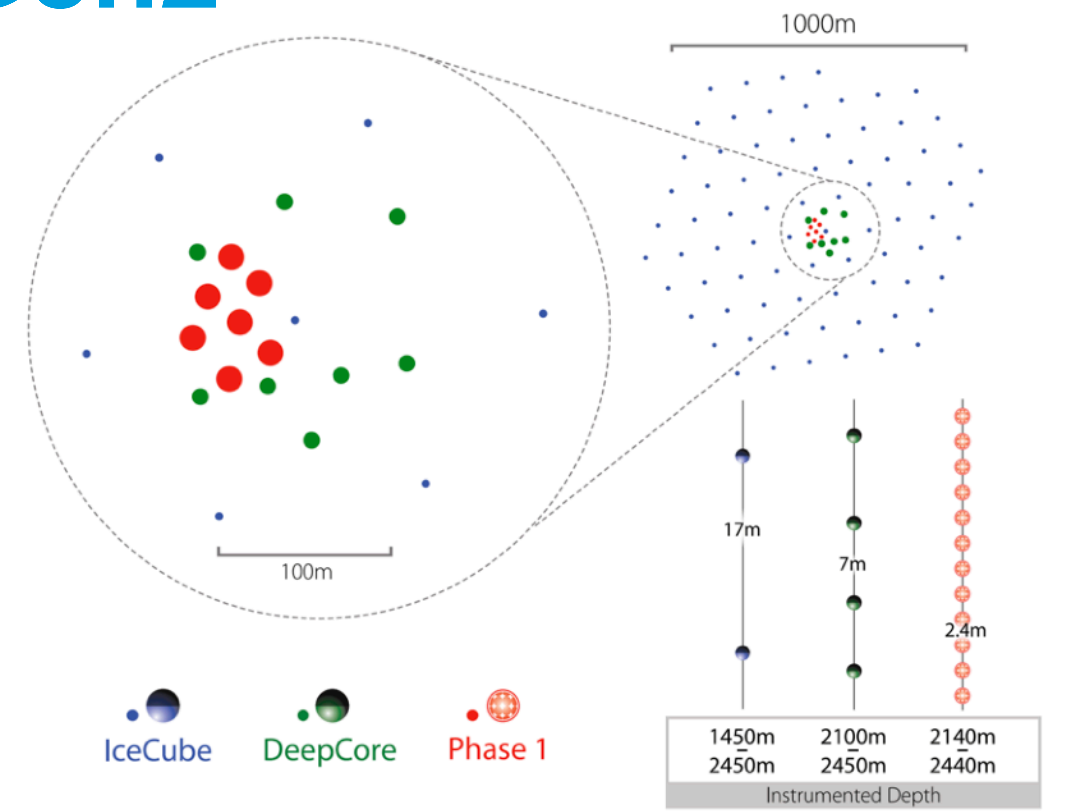
- Complementary field-of-view
- Better angular resolution than IceCube

- Construction has started

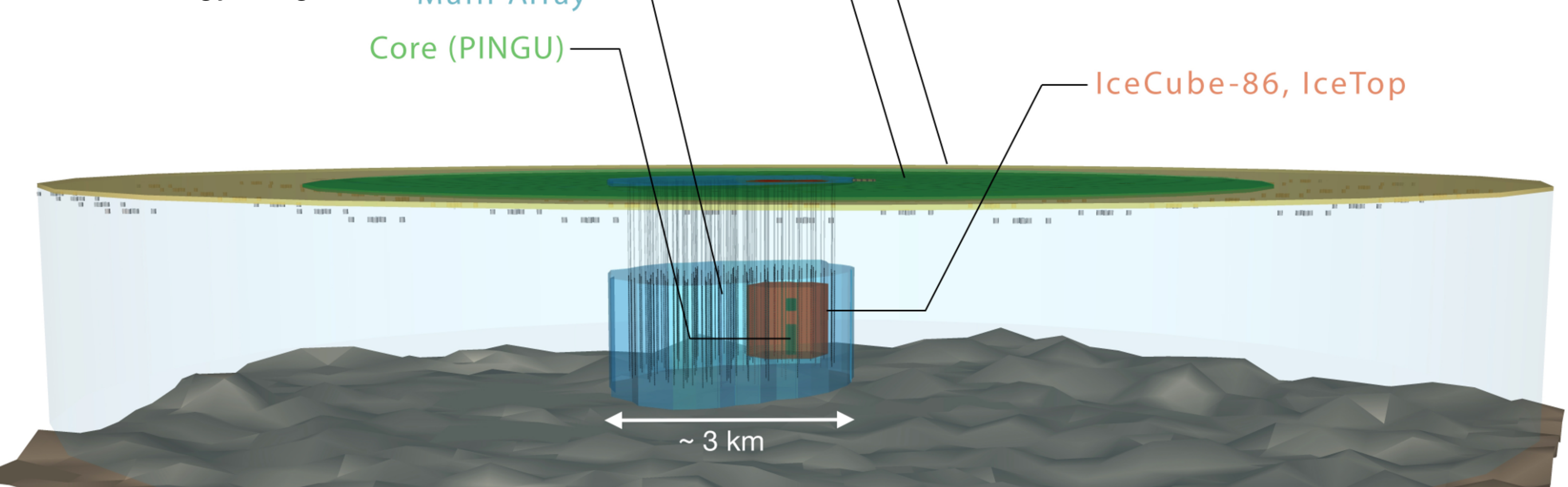
From IceCube to IceCube-Gen2

- **IceCube Upgrade**
  - 7 new strings in center of IceCube
  - New calibration devices

- Future IceCube-Gen2 will allow **precision studies** of cosmic neutrinos.
  - 5 x better source sensitivity
  - 10 x higher statistics
  - GeV to EeV energy range



Proposed first step: IceCube Upgrade



Summary

- A HE neutrino was found in Sep 2017, arriving from the direction of the flaring gamma-ray Blazar TXS 0506+056
- This is unlikely to be a chance coincidence
- The evidence is strengthened by finding a second excess of neutrinos from the same direction in an ~ 6 month time window between 2014 and 2015
- The interpretation is challenging, multi-zone emission models are needed to describe electromagnetic and neutrino emission.
- A single high-energy neutrino already impacts our understanding of Blazar physics