The Multi-Messenger Astronomy Era: Status and Potential

11th Cosmic Ray International Seminar

Johannes Knapp, DESY Zeuthen

Energy scale:

radio IR Visible light UV X rays γ rays

meV ... eV ... keV ... MeV ... GeV ... TeV ... PeV ... EeV ... ZeV

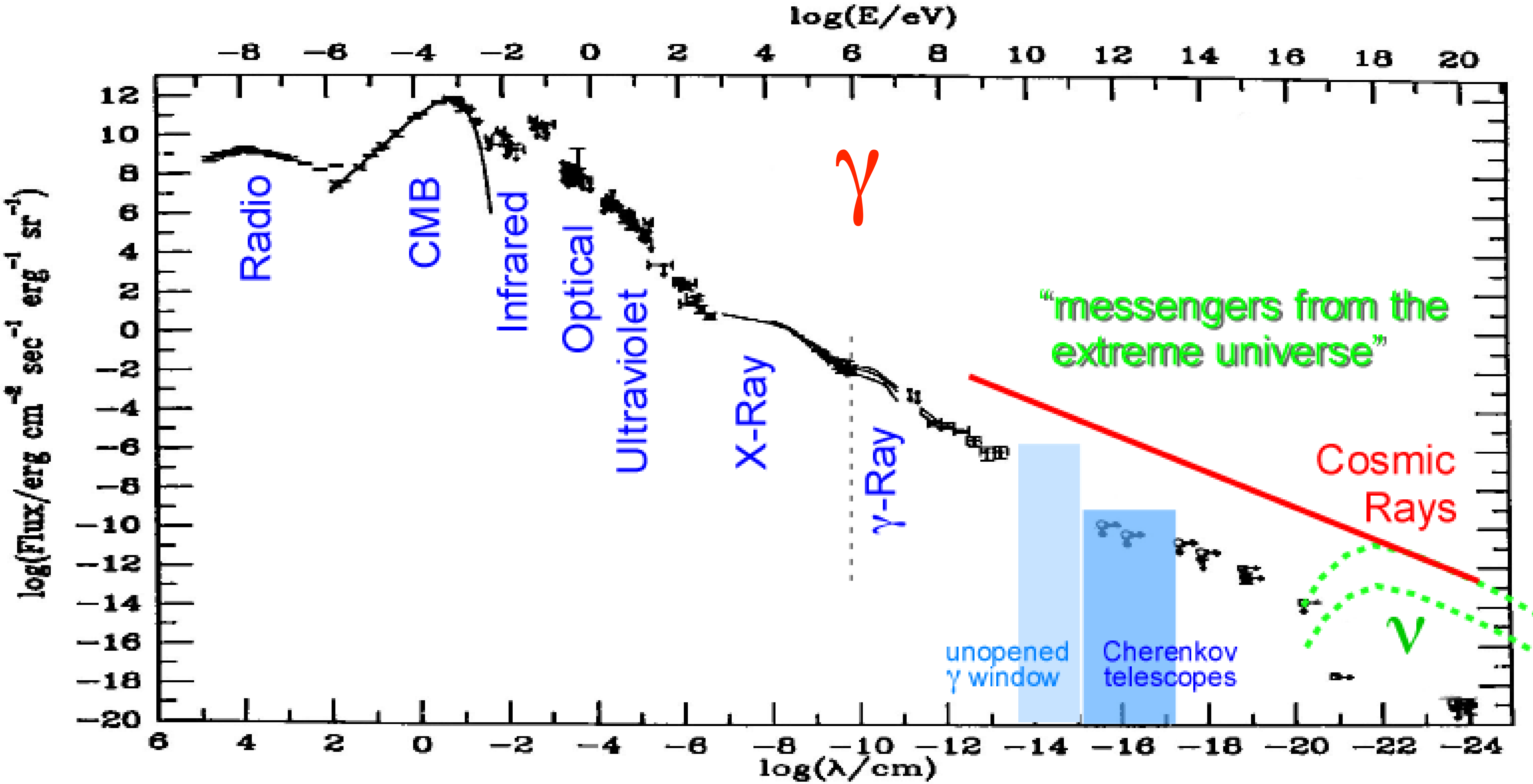
10^{-3} ... 1 ... 10^{3} ... 10^{6} ... 10^{9} ... 10^{12} ... 10^{15} ... 10^{18} ... 10^{21} eV

Photons: astronomy

light: electromagnetic waves,
travels in straight lines, is easily detectable

the workhorse of astronomy.

Multi wavelength observations: popular since long time



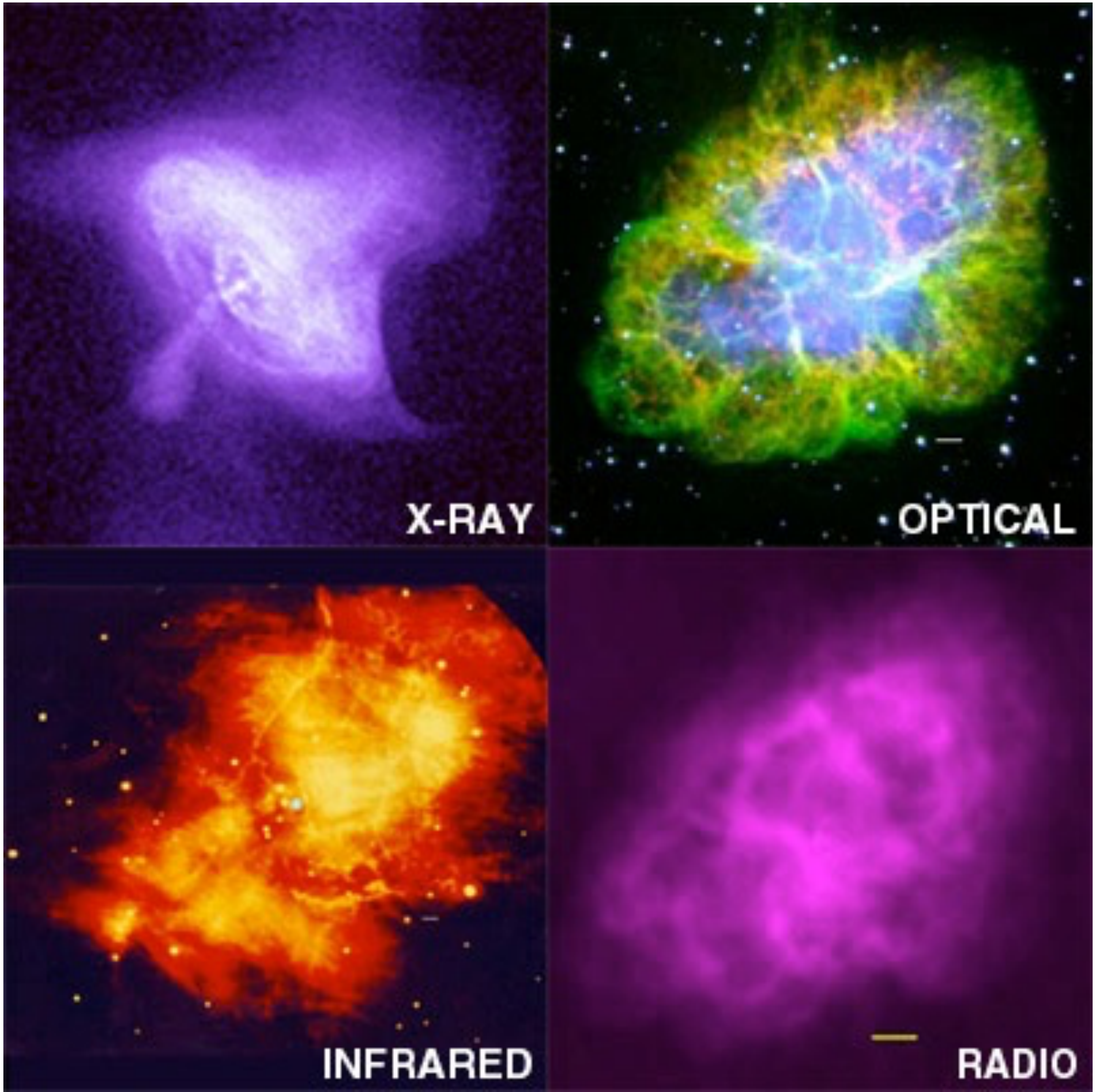
thermal

non-thermal

thermal / lines

non-thermal

Multi wavelength observations: popular since long time



Different wavelengths reveal very different & complementary features of a source.

Multi Wavelength approach

1830: IR
1930: radio
1962: X-rays
1961: gamma rays (MeV/GeV)
1989: gamma rays (> 100 GeV)

complementary &
true multi-wavelength

What other messengers allow for astronomy?

γ,ν

UHECRs (??)
(if not deflected too much)

Gravitational Waves

Particles:
- acquire high energies,
- carry it to us,
- interact in detector

Waves:
- amplitudes & phases

Early Multi-Messenger Events

Optical - Cosmic Rays

September 1, **1859**
The solar storm of 1859 or the "Carrington event".

most powerful flare ever (and the first one) to be observed
(by British astronomer Richard Carrington)

flare visible to a naked eye (in *white* ***light***)
stunning auroras down to tropical latitudes such as Cuba or Hawaii (**CRs**)

set telegraph systems on fire !! (magnetic storm)

The flare left a trace in Greenland ice (nitrates and beryllium-10)

Solar activity modulates brightness and enhances flaring behaviour.

1948: neutron monitors: cosmic ray fluxes from the Sun on the atmosphere

Optical - solar Neutrinos
(MeV)

1970-1990
Ray Davis (Experiment)
John Bahcall (Solar Model expectations)

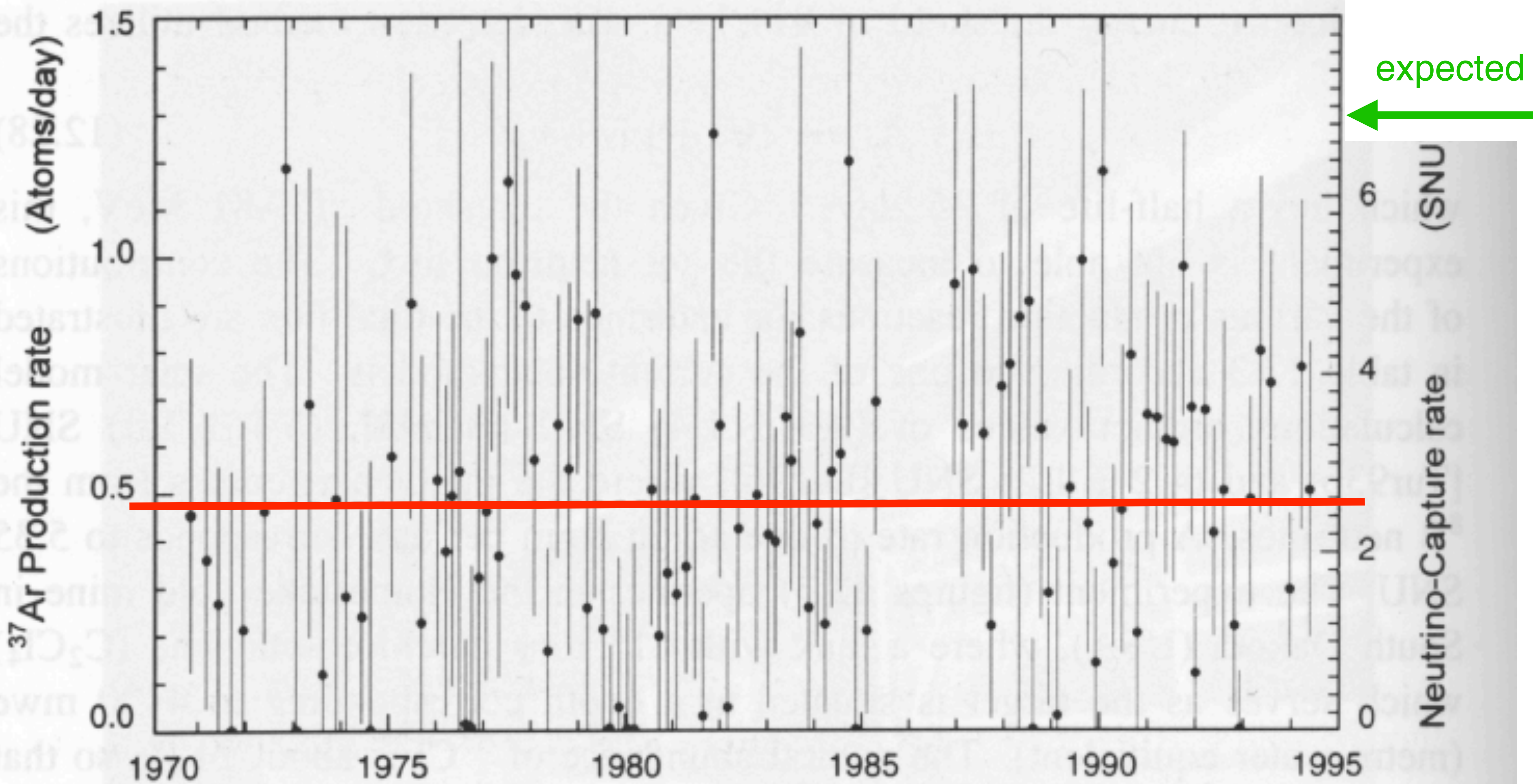
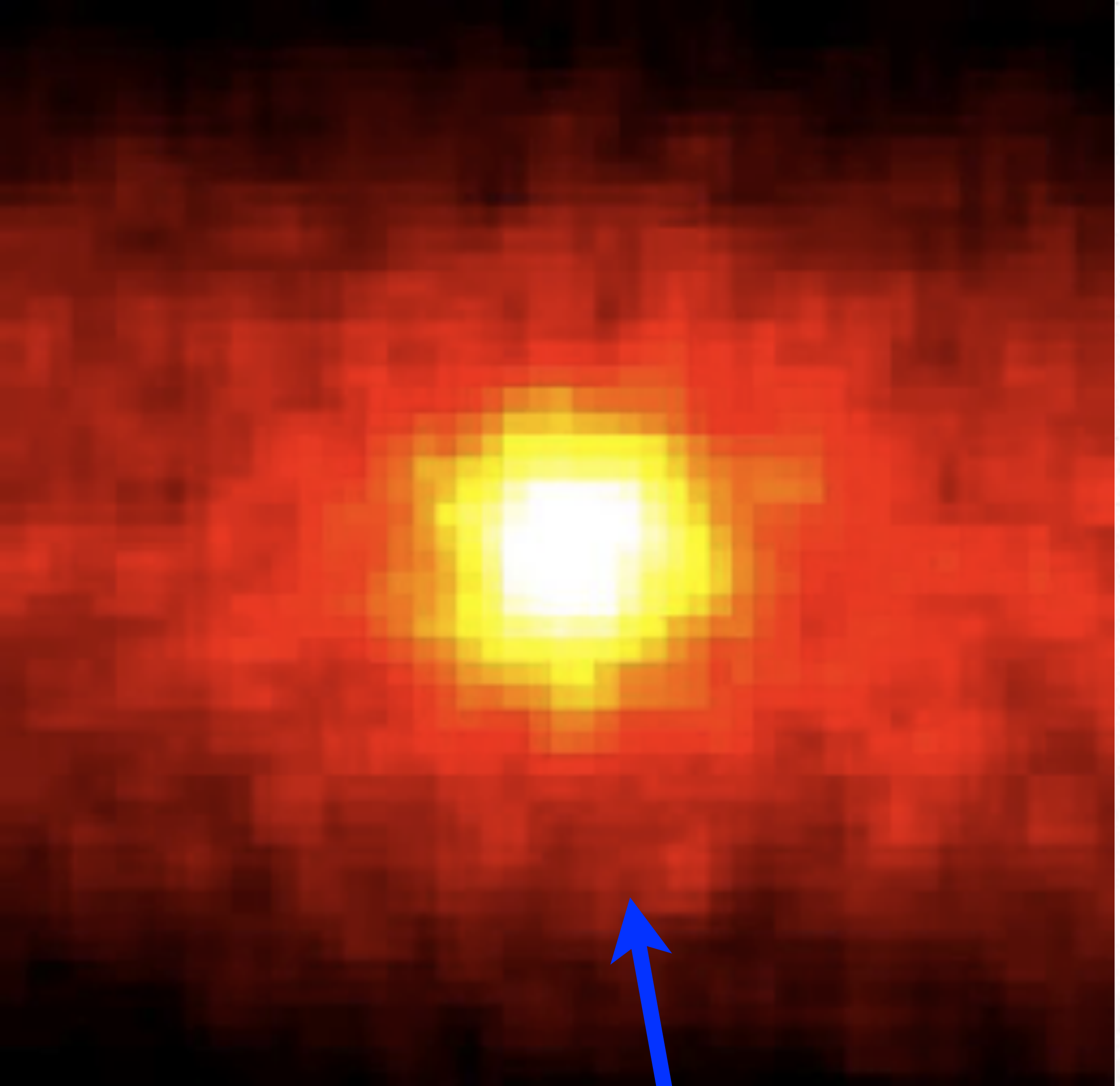


Figure 12.8. The neutrino flux measured from the Homestake ^{37}Cl detector since 1970. The average measured value (broken line) is significantly smaller than the predicted one. This discrepancy is the origin of the so-called solar neutrino problem (from [Dav96]).

(>0.8 MeV)

measured: 2.56 ± 0.22



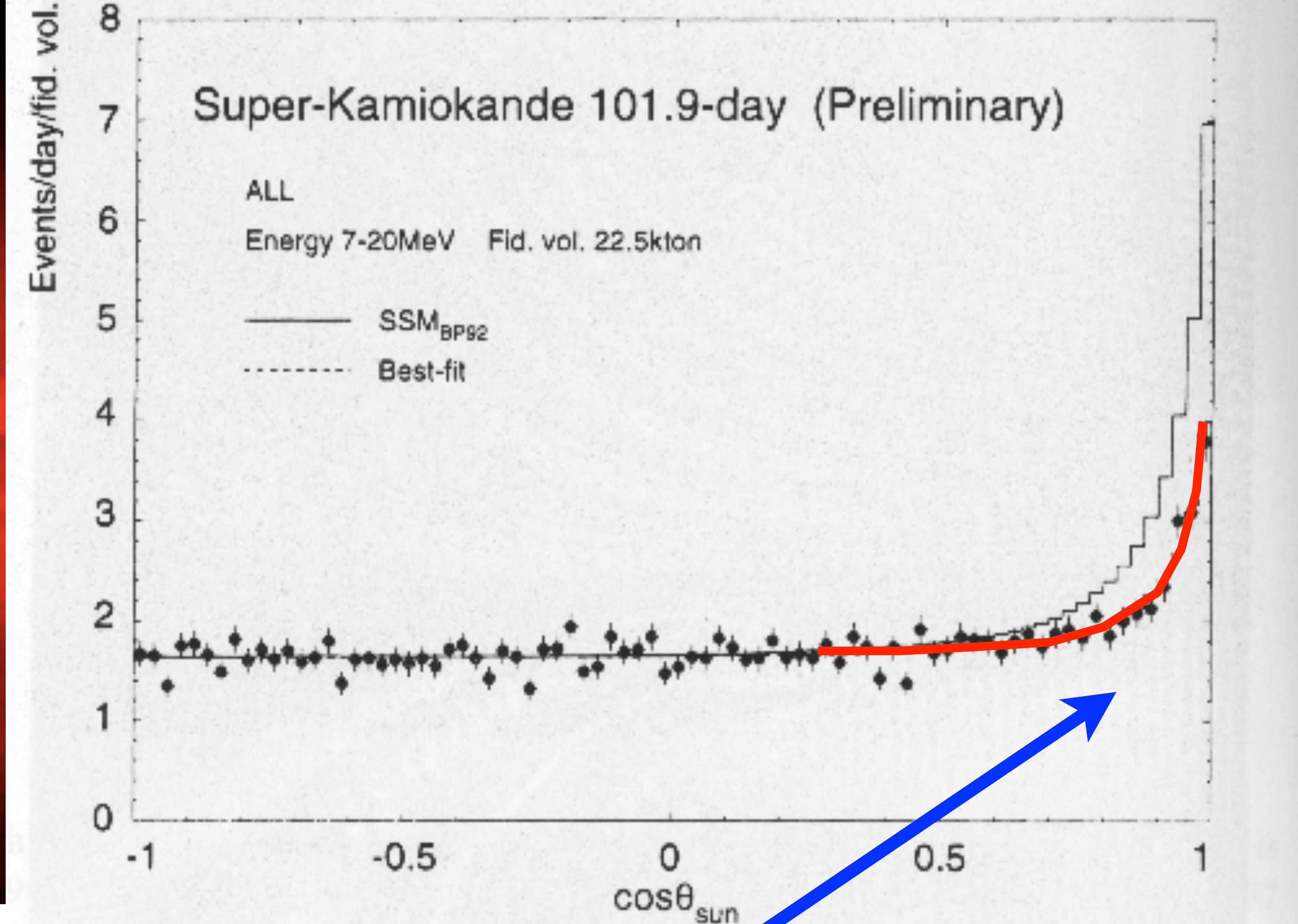
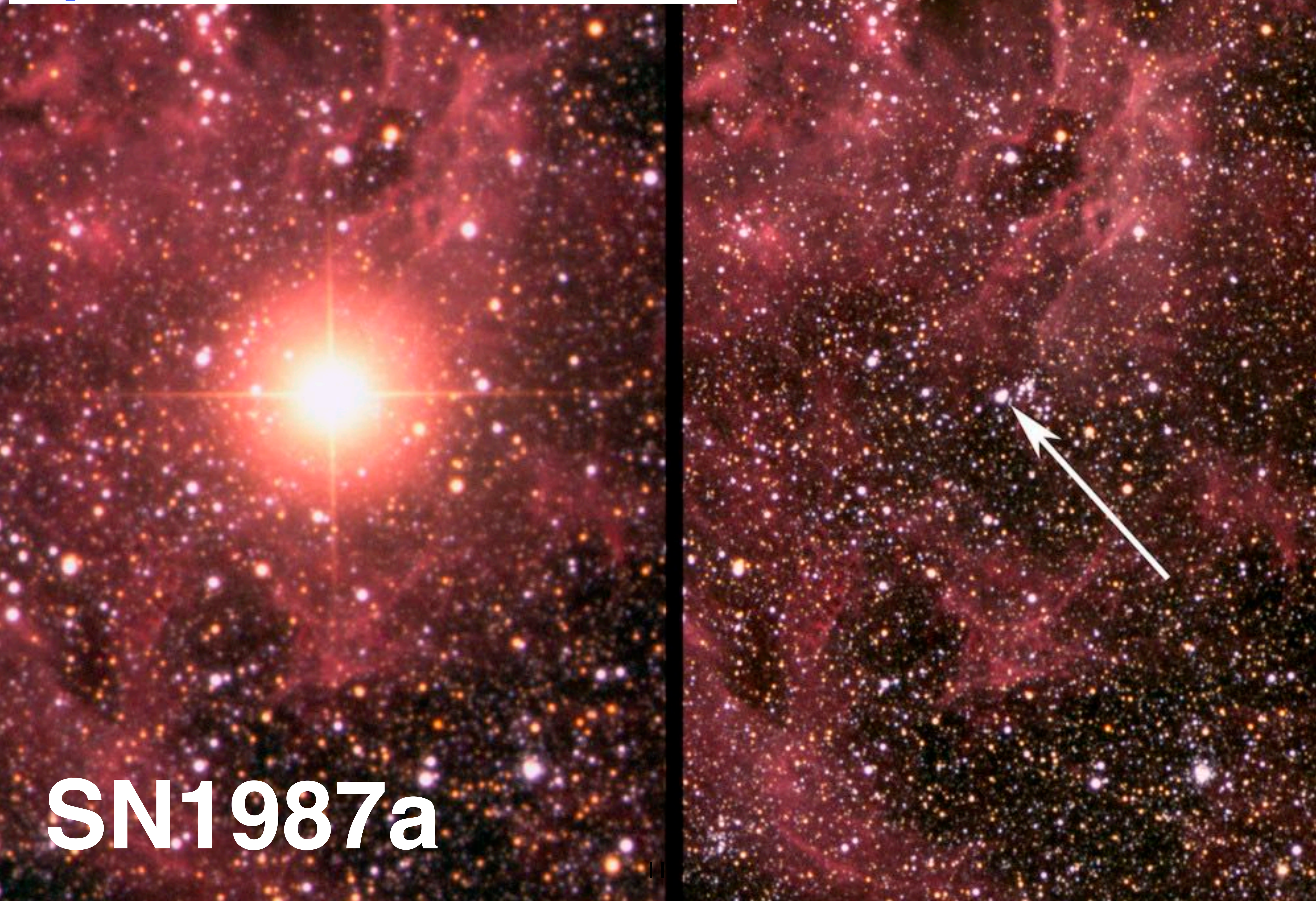


Figure 12.15. Angular distribution of the events in the Superkamiokande detector, relative to the direction of the Sun, after a measuring time of 102 days (from [Suz97]).

Kamiokande
Super-K

Neutrinos do come from the Sun, but also here a deficit (8 MeV)

Optical - SN Neutrinos



Kamiokande SN1987a

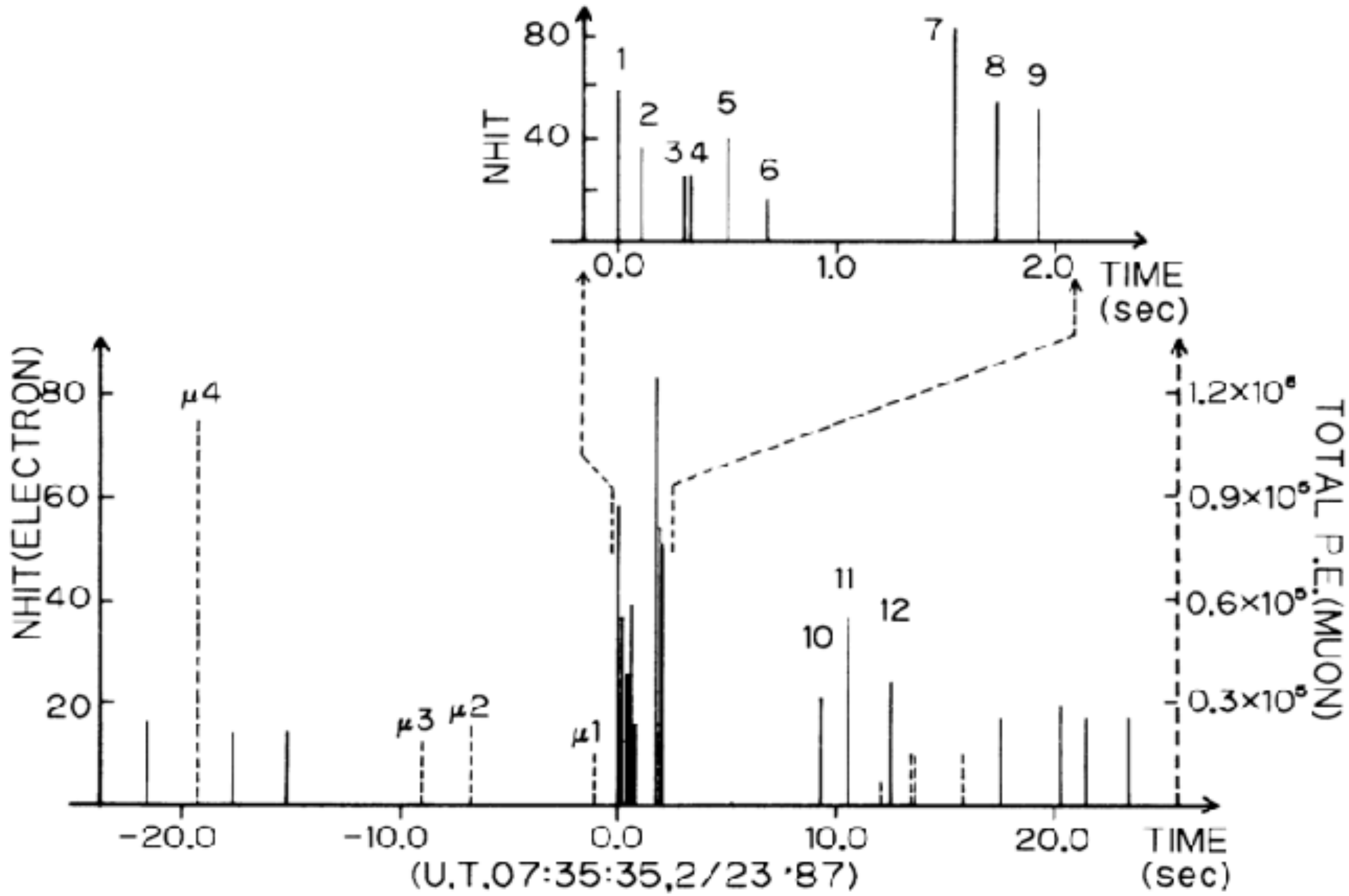


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's, N_{hit} (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events $\mu1-\mu4$ are muon events which precede the electron burst at time zero. The upper right figure is the 0–2-sec time interval on an expanded scale.

12 SN Neutrinos (MeV)
in 15 sec

Different messengers reveal very different & complementary features of a source, as well.

Multi Messenger approach

1962: UHECRs
1965: MeV Neutrinos
1995: TeV-PeV Neutrinos
2015: GWs

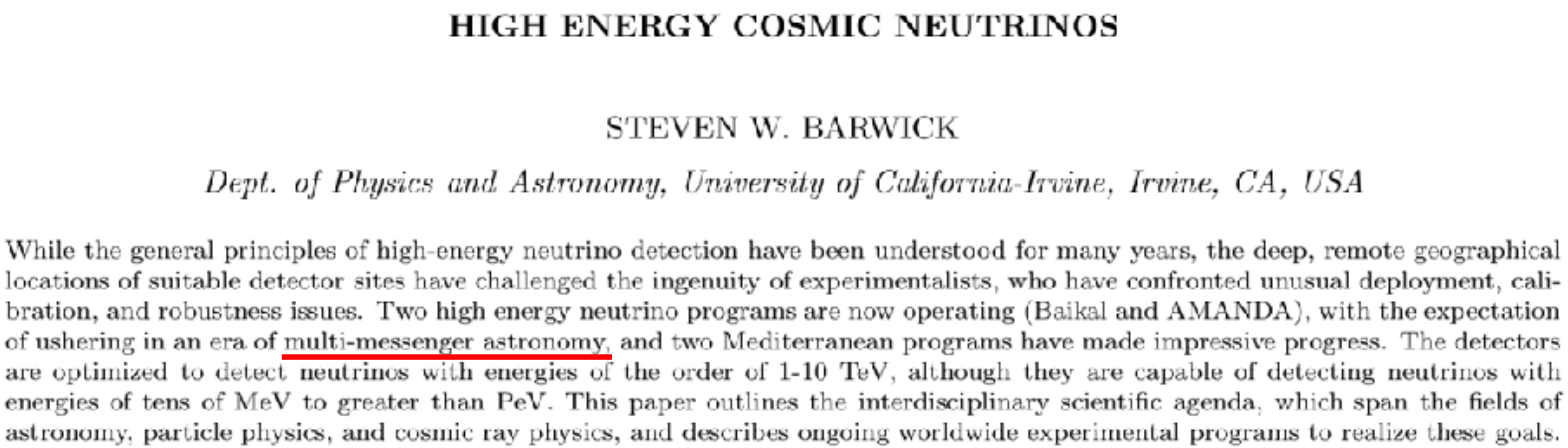
Multi-Messenger

– **Complementarity**
  see complementary information
  (different locations, time, …)

– **“True” multi-messenger:**
  see the **same sources**
  at the **same time**

First mention of "multi-messenger astronomy" in ADS

1999


HIGH ENERGY COSMIC NEUTRINOS

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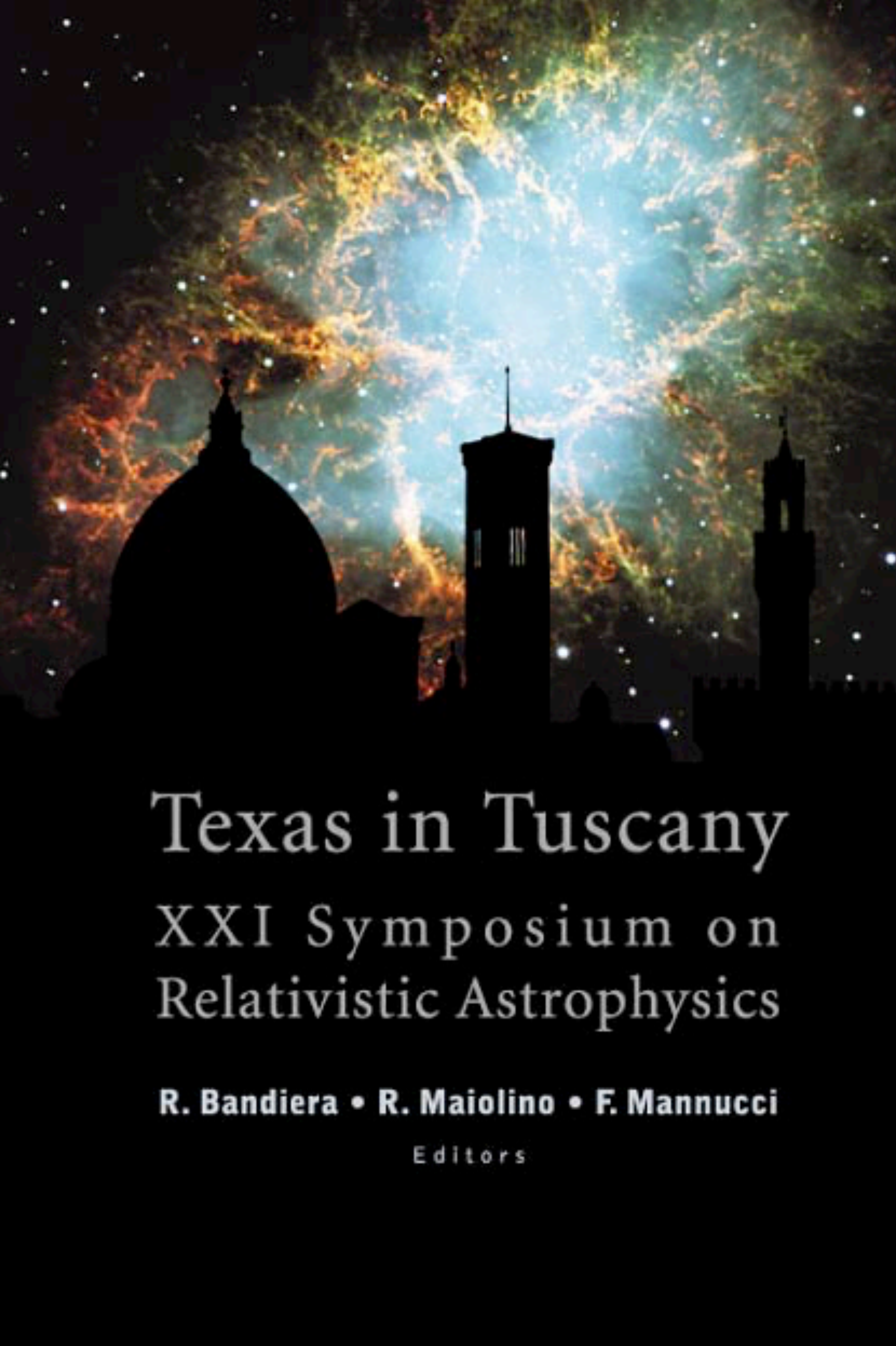
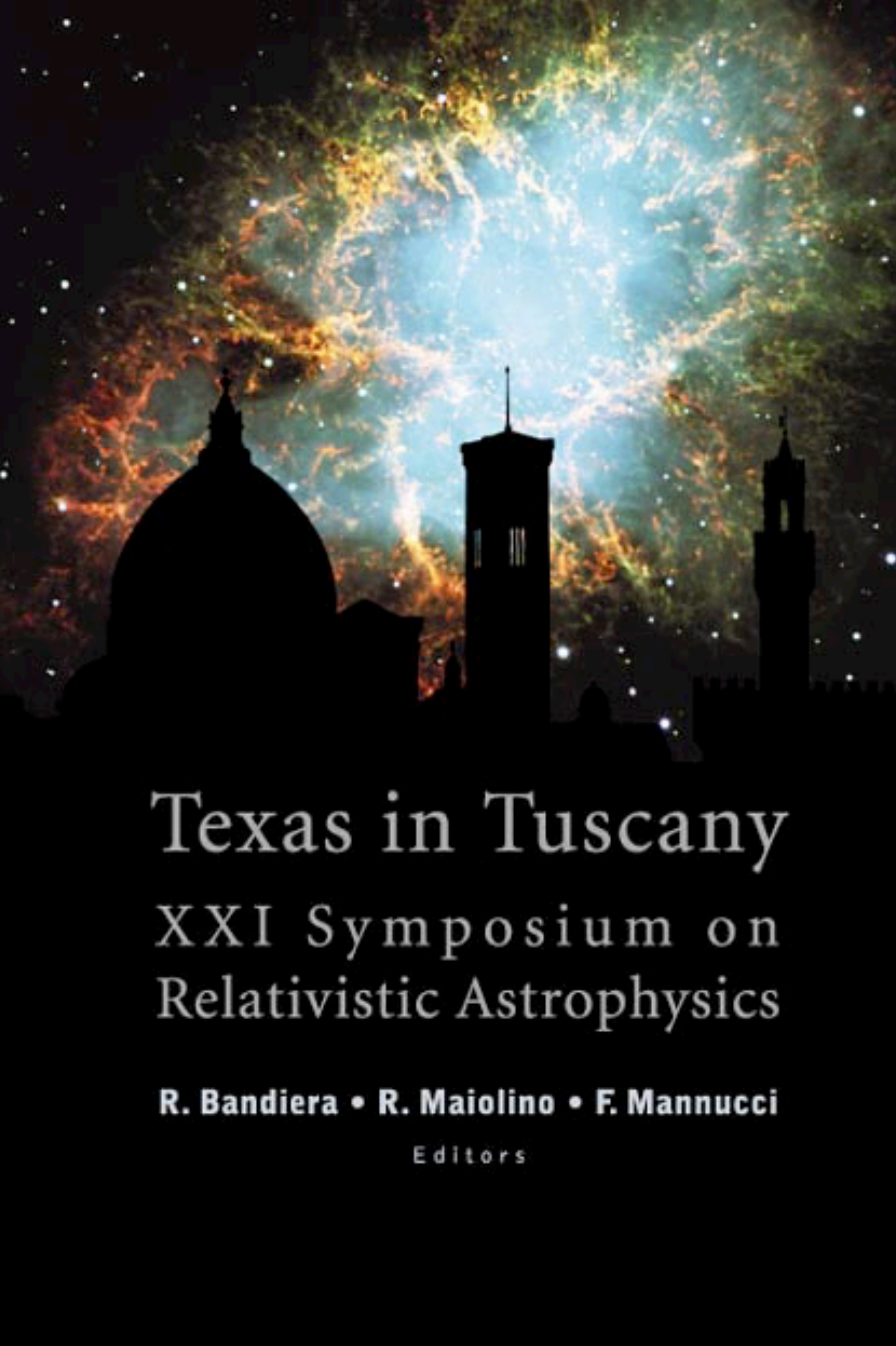
While the general principles of high-energy neutrino detection have been understood for many years, the deep, remote geographical locations of suitable detector sites have challenged the ingenuity of experimentalists, who have confronted unusual deployment, calibration, and robustness issues. Two high energy neutrino programs are now operating (Baikal and AMANDA), with the expectation of ushering in an era of multi-messenger astronomy, and two Mediterranean programs have made impressive progress. The detectors are optimized to detect neutrinos with energies of the order of 1-10 TeV, although they are capable of detecting neutrinos with energies of tens of MeV to greater than PeV. This paper outlines the interdisciplinary scientific agenda, which span the fields of astronomy, particle physics, and cosmic ray physics, and describes ongoing worldwide experimental programs to realize these goals.

... Just as multi-wavelength studies have provided unparalleled insight on many astronomical sources, multi-messenger studies by neutrino, gamma ray, and gravity wave detectors may be the Rosetta stone of cosmic accelerators.

astro-ph/9903467



Florence, Italy, December 2002



Francis Halzen:
"Multi-Messenger Astronomy:
cosmic rays, gamma rays, neutrinos"

Florence, Italy, December 2002

Multi-messenger astronomy: cosmic rays, gamma-rays, and neutrinos

Francis Halzen (Wisconsin U., Madison)

Feb 2003 - 15 pages

(2003)
DOI: 10.1142/9789812704009_0011
Presented at Conference: C02-12-09, p.117-131
Proceedings
MADPH-03-1320
e-Print: astro-ph/0302489 | PDF

Abstract (World Scientific)
Although cosmic rays were discovered a century ago, we do not know where or how they are accelerated. There is a realistic hope that the oldest problem in astronomy will be solved soon by ambitious experimentation: air shower arrays of 10,000 kilometer-square area, arrays of air Cerenkov telescopes and kilometer-scale neutrino observatories. Their predecessors are producing science. We will review the highlights: 1) Cosmic rays: the highest energy particles and the GZK cutoff, the search for cosmic accelerators and the Cygnus region, top-down mechanisms: photons versus protons? 2) TeV-energy gamma rays: blazars, how molecular clouds may have revealed proton beams, first hints of the diffuse infrared background? 3) Neutrinos: first results and proof of concept for technologies to construct kilometer-scale observatories.
Abstract (arXiv)

Keyword(s): INSPIRE: review: Florence 2002/12 | photon: cosmic radiation | cosmic radiation: acceleration | neutrino: cosmic radiation | GZK effect | blazar | cosmic radiation: particle source | p: cosmic radiation | numerical calculations: interpretation of experiments | bibliography

around 2000 … two truly remarkable decades ahead

UHECRs:

all still pretty much in their infancy

UHECRs on straight lines?
HIRES vs AGASA, GZK or not? Auger in construction

Gamma rays:

Whipple, HEGRA, … 14 sources seen since 1989
HESS, MAGIC in construction, VERITAS planned

Neutrinos:

Baikal, AMANDA, few strings,
first upward going tracks seen (atmospheric neutrinos)

Gravitational waves:

GEO600, LIGO in construction

in 2018

incredible progress

UHECRs:

Spectral cut-off seen (GZK ? **!**) Composition still unclear.
Anisotropy seen, but no clusters / sources

Gamma rays:

HESS, MAGIC; VERITAS, HAWC, Fermi, Agile, SWIFT, DAMPE …
Lots of results, many source types, transients, alerting,
sources: >210 (@ E>80 GeV) >3000 (@ E<100 GeV)

Neutrinos:

IceCube: Astrophysical neutrinos seen (to > PeV),
solar ν, atmospheric ν, ν oscillation

Nobel Prize 2002:
Davis, Koshiba
Nobel Prize 2015:
Kajita, McDonalds

Gravitational waves:

Adv. LIGO, VIRGO operational, several merger events seen

Nobel Prize 2017:
Weiss, Thorne, Barish

further improvements / extensions ongoing everywhere

Multi-Messenger looks more promising than ever.

Astro-Particles

energetic (elementary) **particles**
from space (Sun, Milky Way, distant galaxies)
bombard Earth continuously.

Energies from MeV .... >10^{20} eV

1 eV = 1.6 x10^{-19} J
10^{20} eV = 16 J

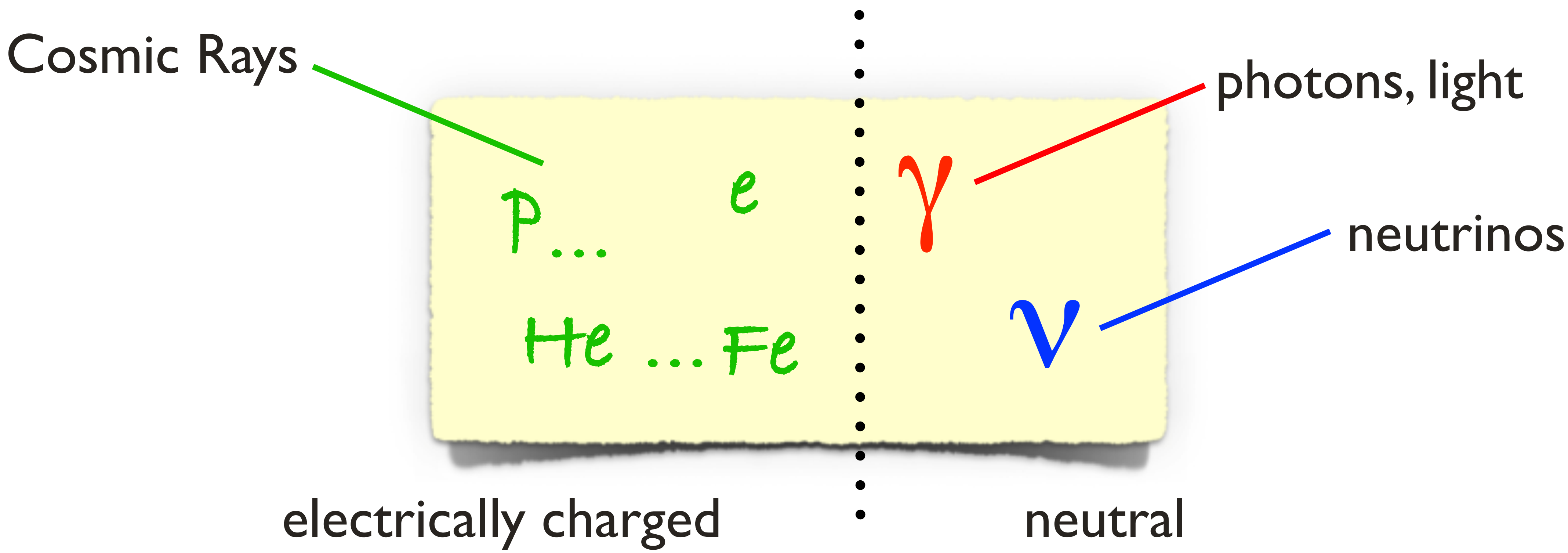
most relativistic particles in the Universe

Astrophysics with high energy photons and particles.

Particle physics with probes of astrophysical origin.

What are these cosmic particles?

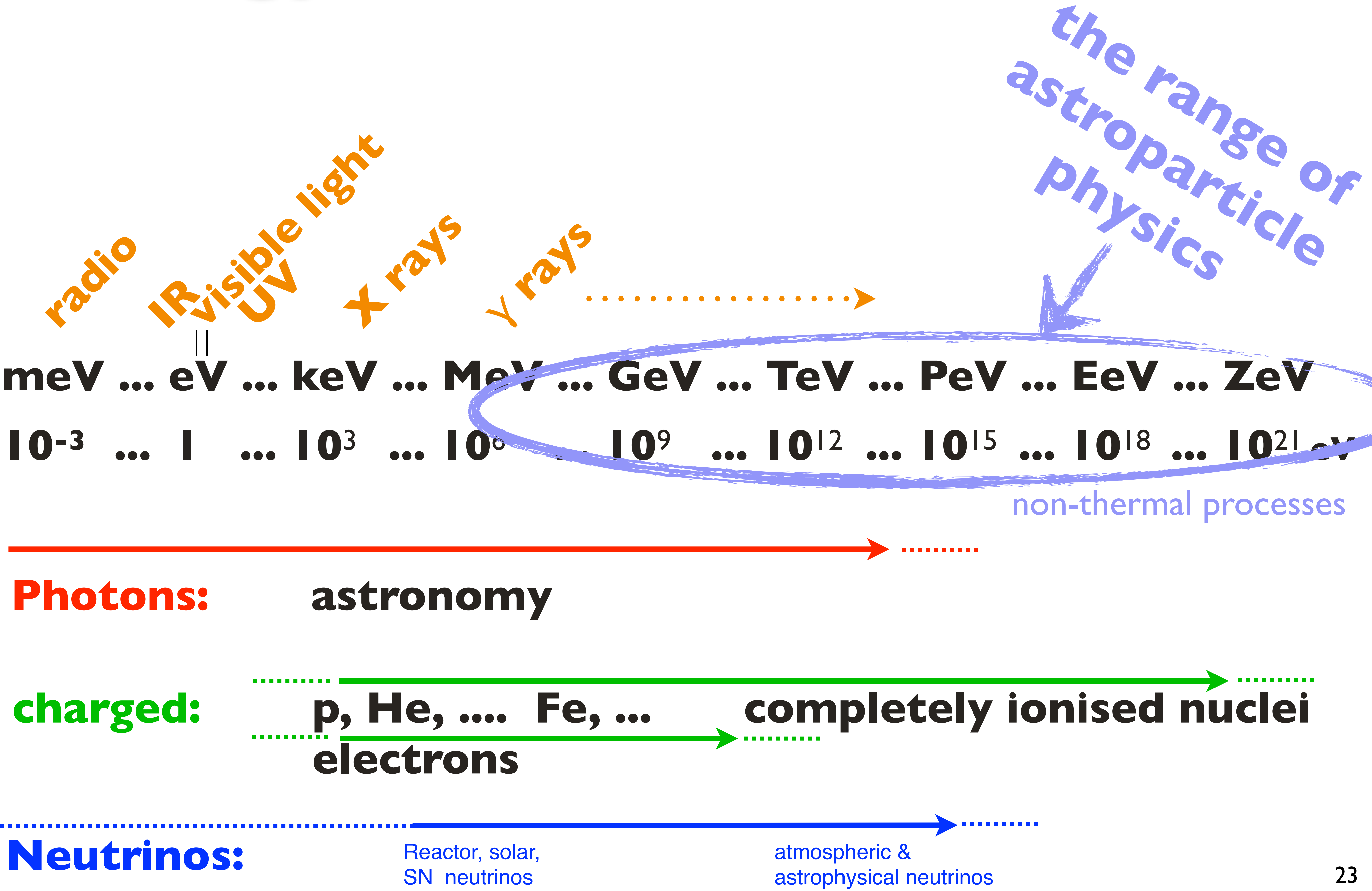
must be stable (to survive the travel to us)



+ can be accelerated in electric fields
– are deflected in magnetic fields

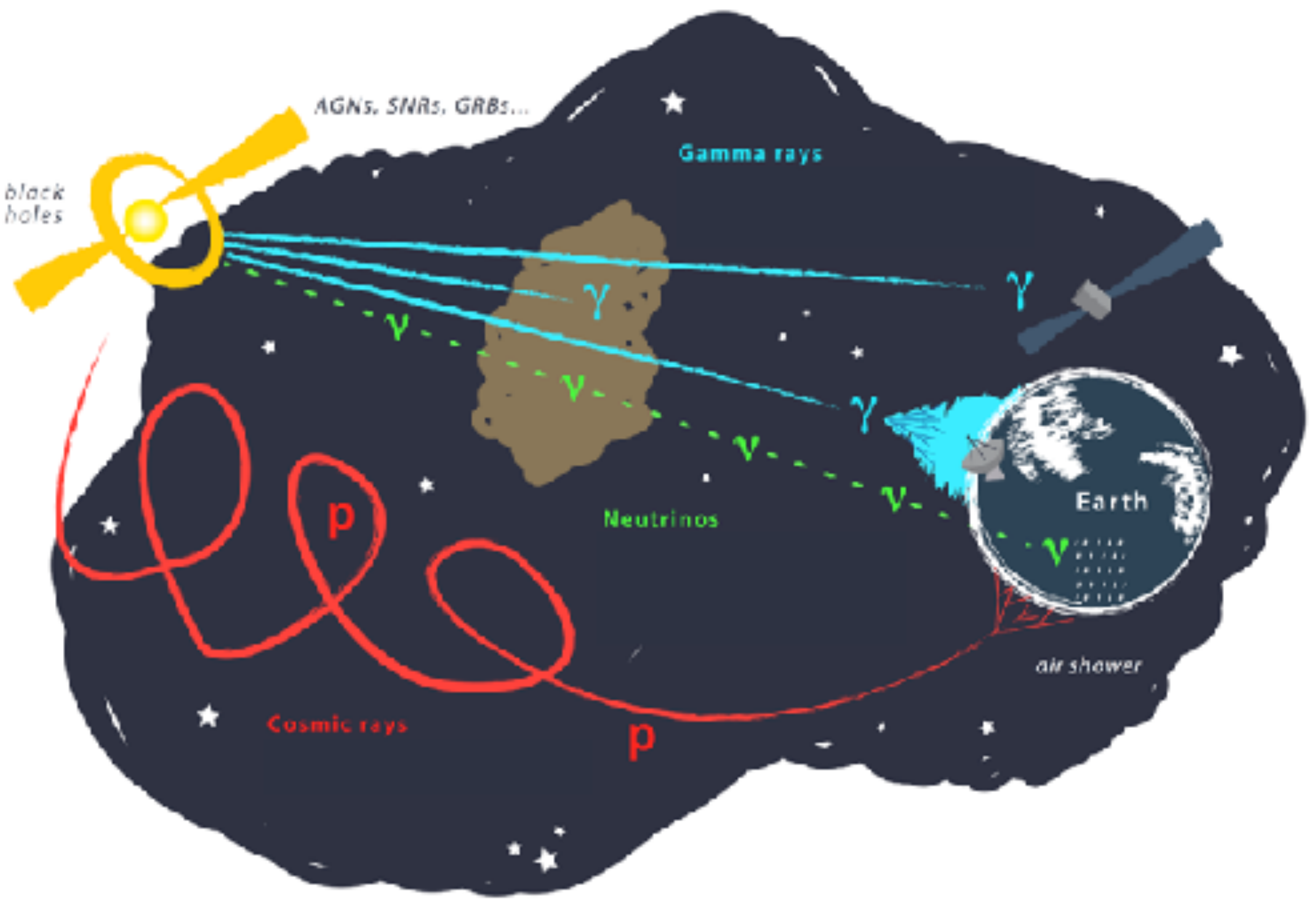
+ move in straight lines (good for astronomy)
– secondary particles

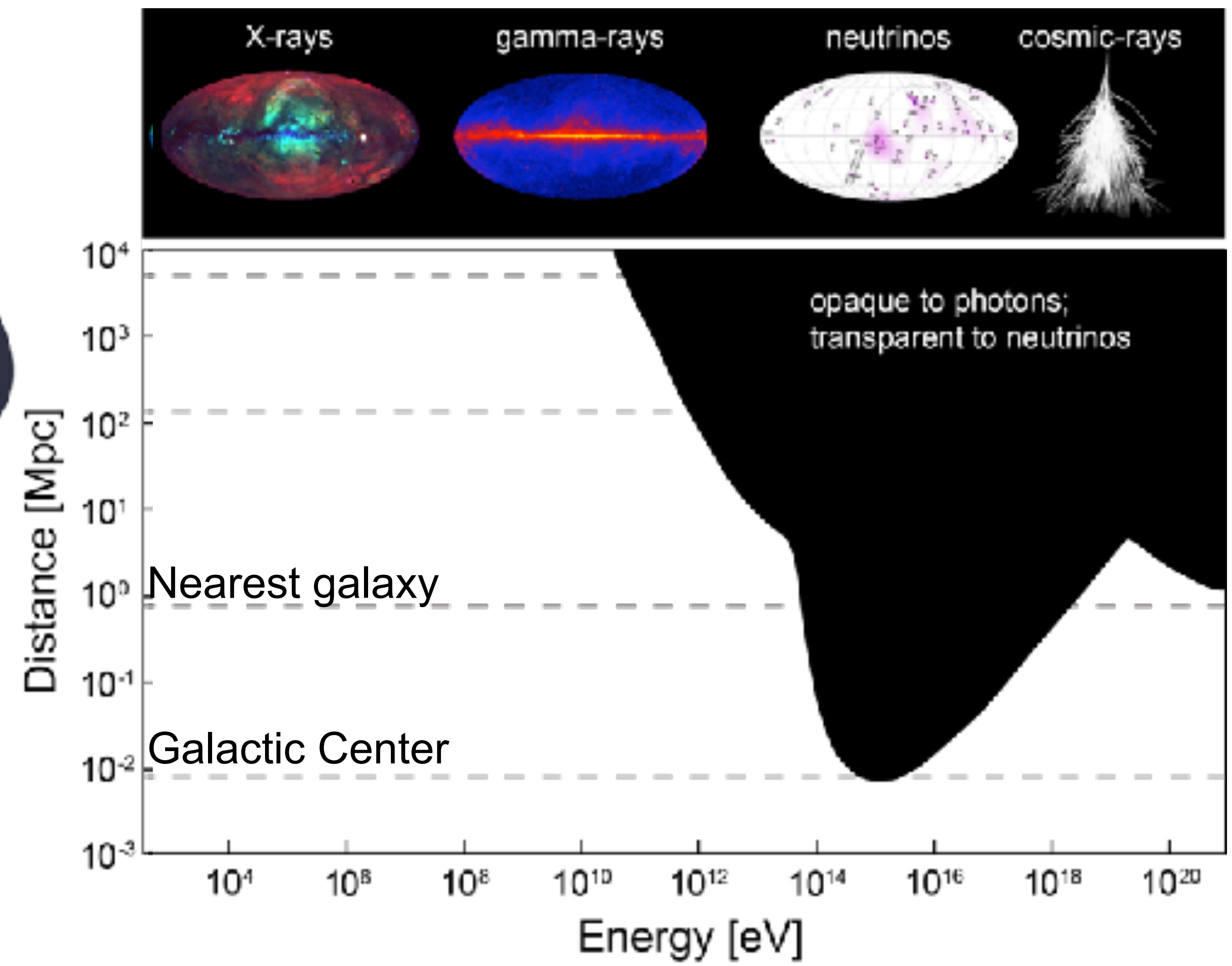
Energy scale:



The High-Energy Universe

Multi-Messenger Astronomy



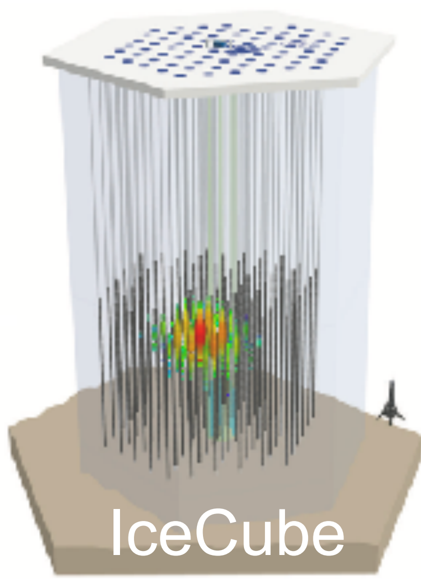


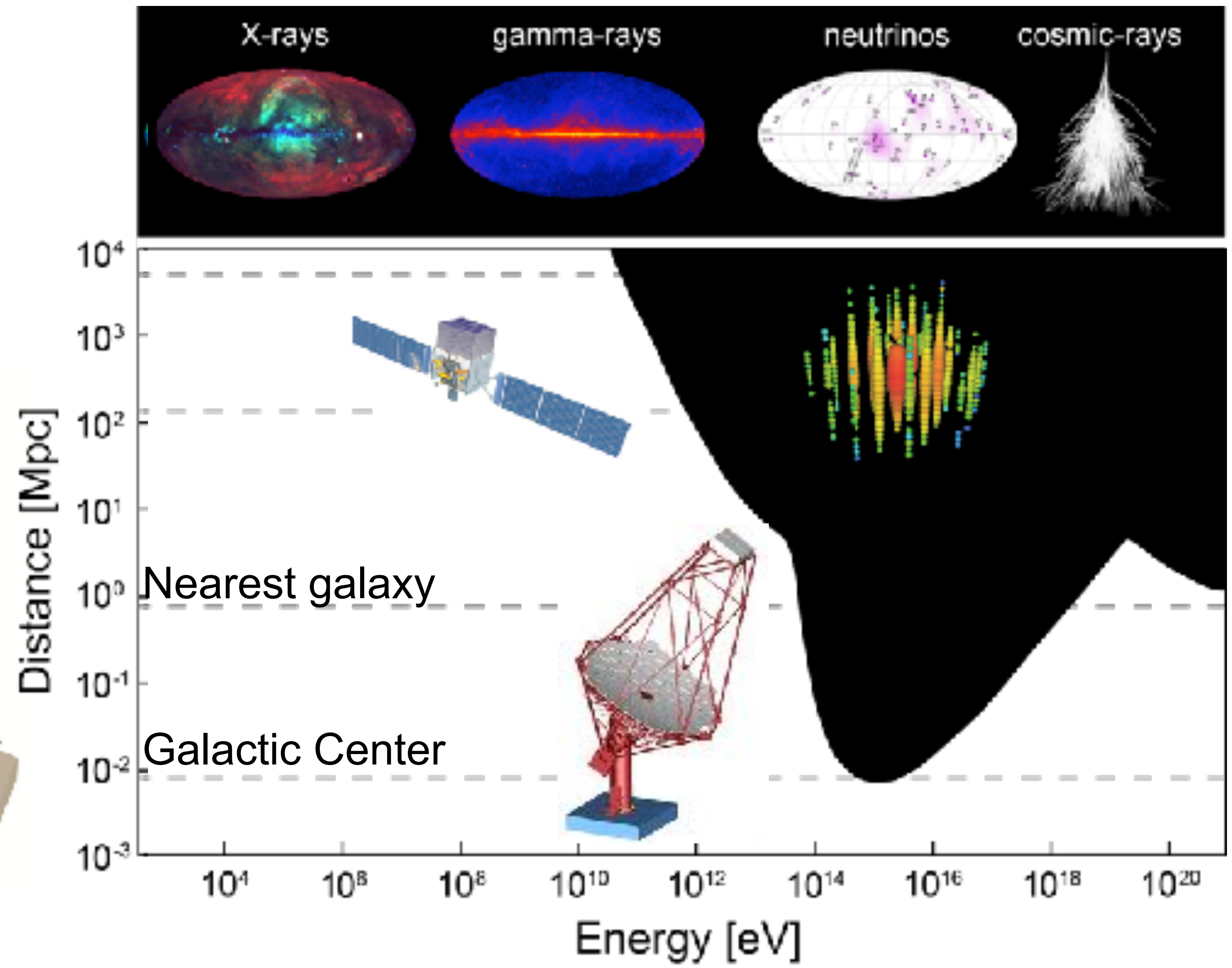
CRs: diffusion, average over many different sources & a long time.

γ,ν point back, one source at a time, time variability / coincidences

The High-Energy Universe
Multi-Messenger Astronomy

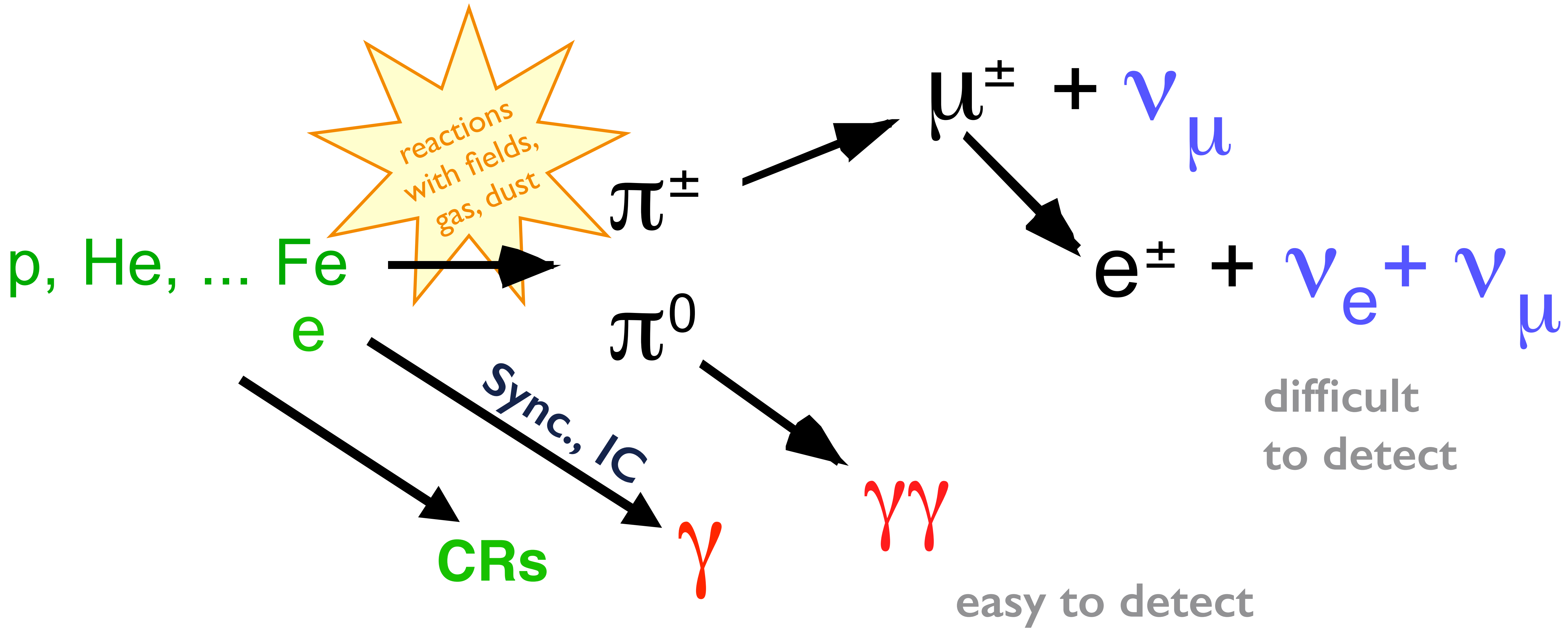
Gamma-ray astronomy
Neutrino astronomy
Theoretical astroparticle physics





same sources /
complementary source

Cosmic rays, gamma rays and neutrinos come likely from the same sources

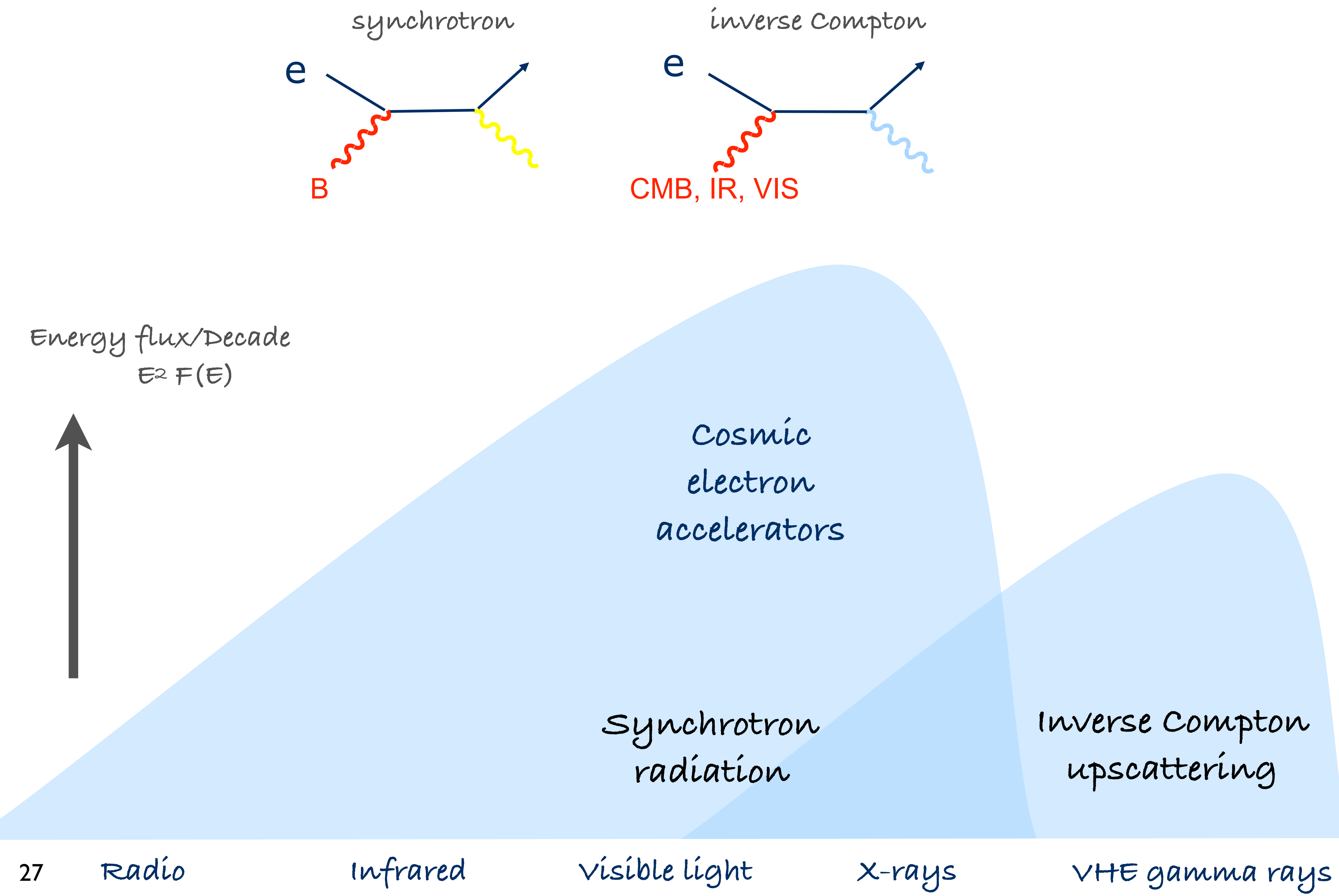


only charged particles can be accelerated in el.mag. fields

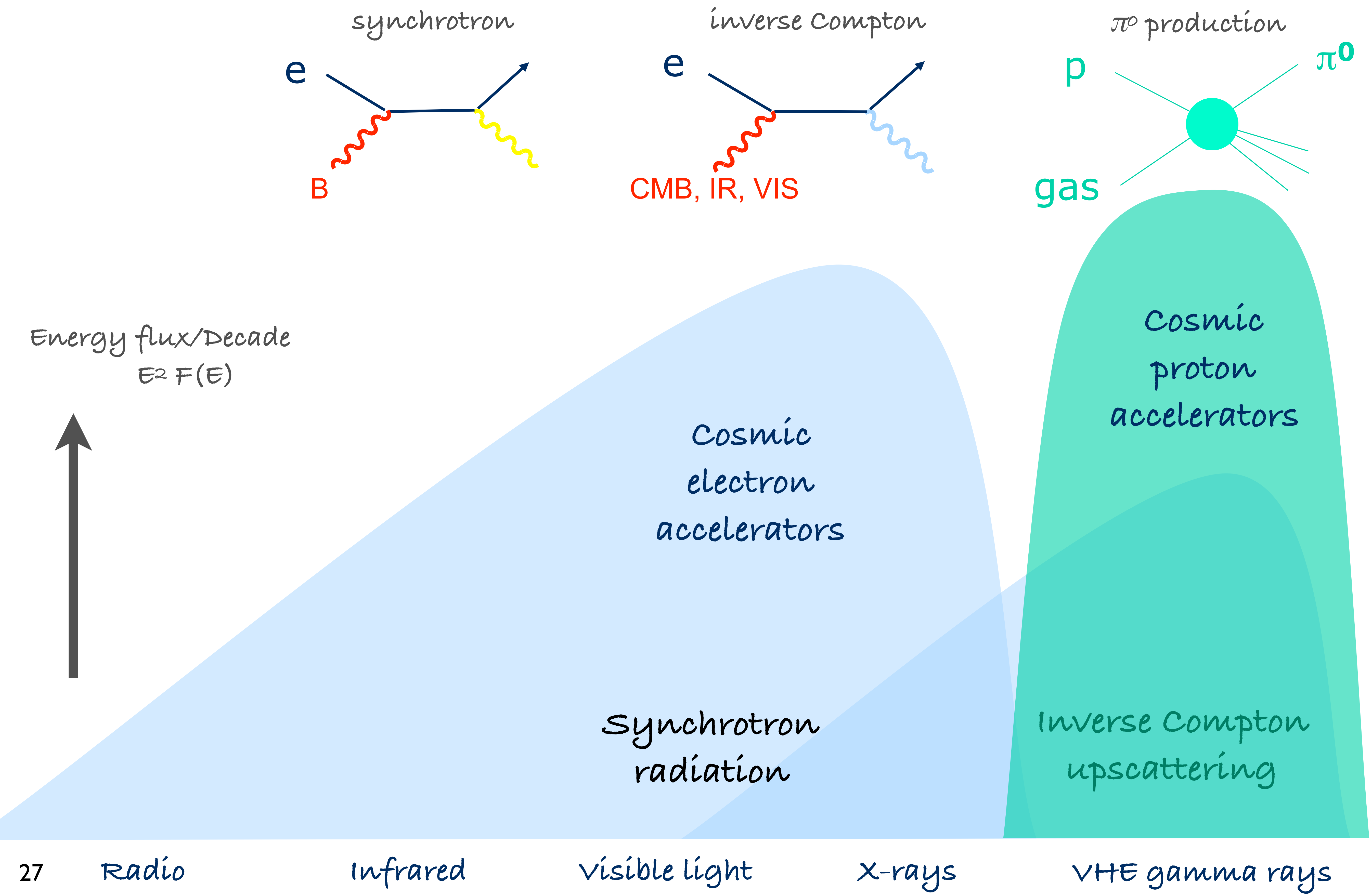
γ, ν

point back to sources
but serious backgrounds

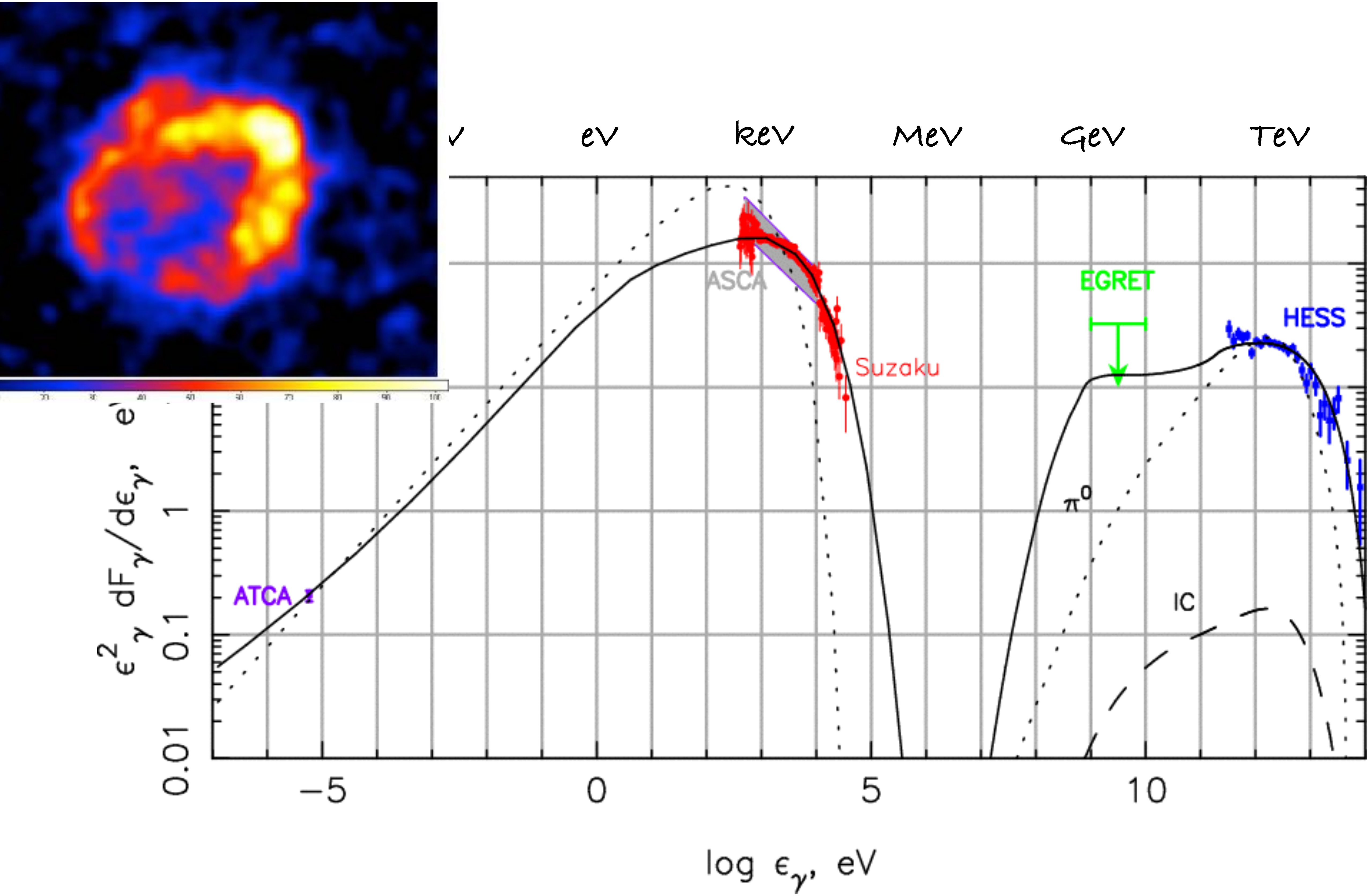
Gamma Ray Production



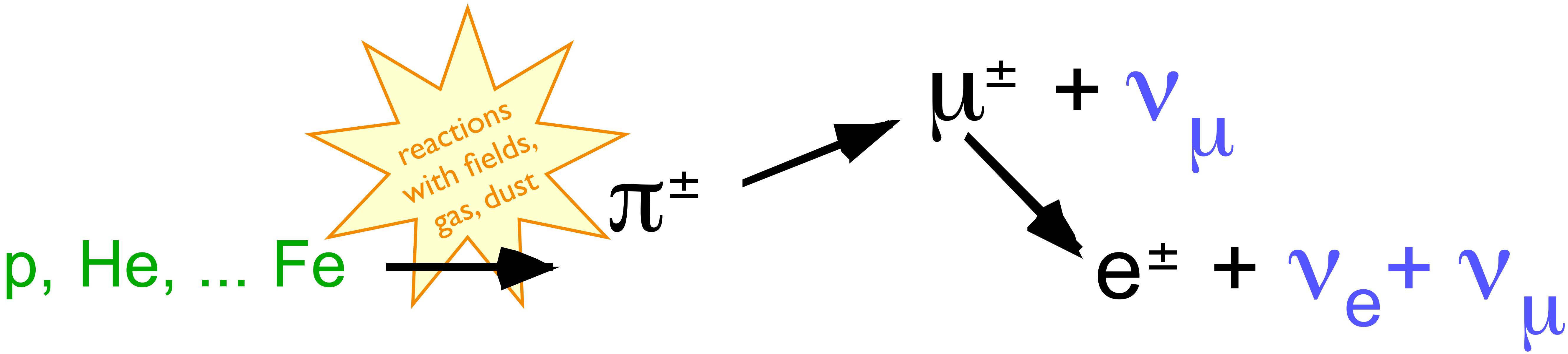
Gamma Ray Production



Supernova Remnant RX J1713.7-3946

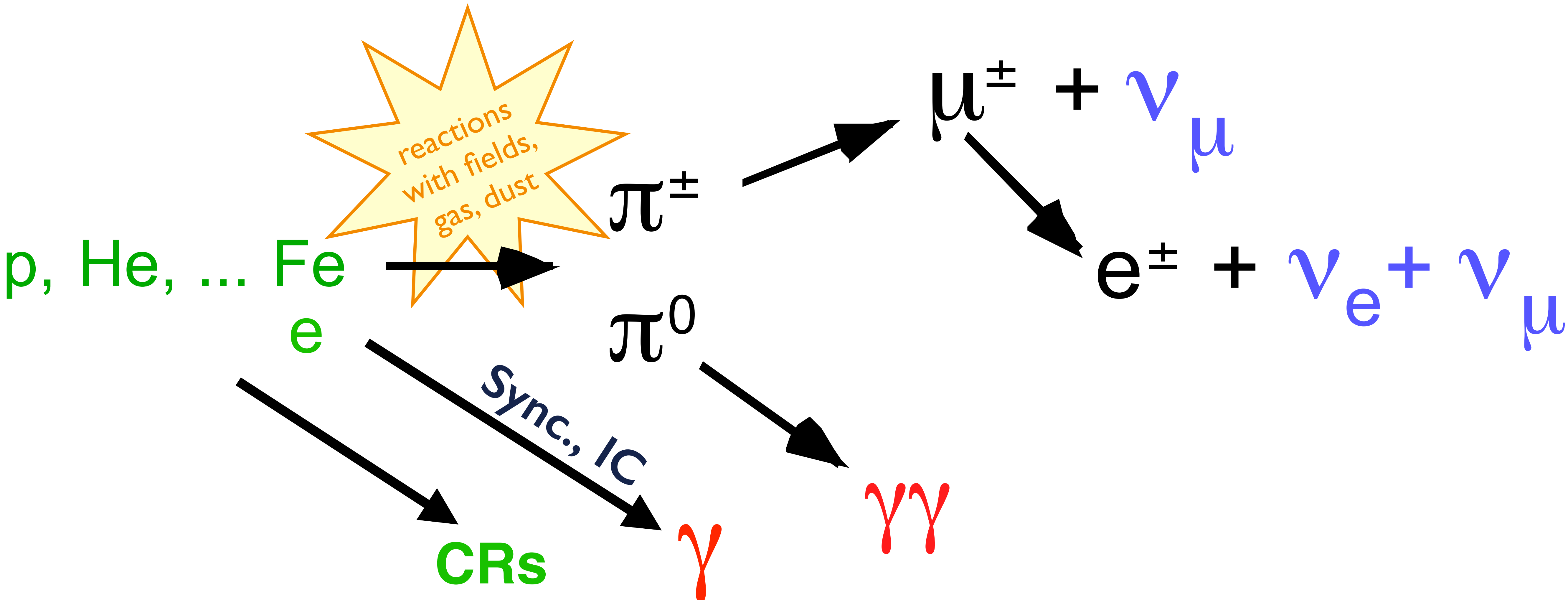


Neutrino Production (at astroparticle energies)



p more efficient than nuclei in producing HE neutrinos, as E/n is higher.

Cosmic rays, gamma rays and neutrinos come likely from the same sources



1. acceleration

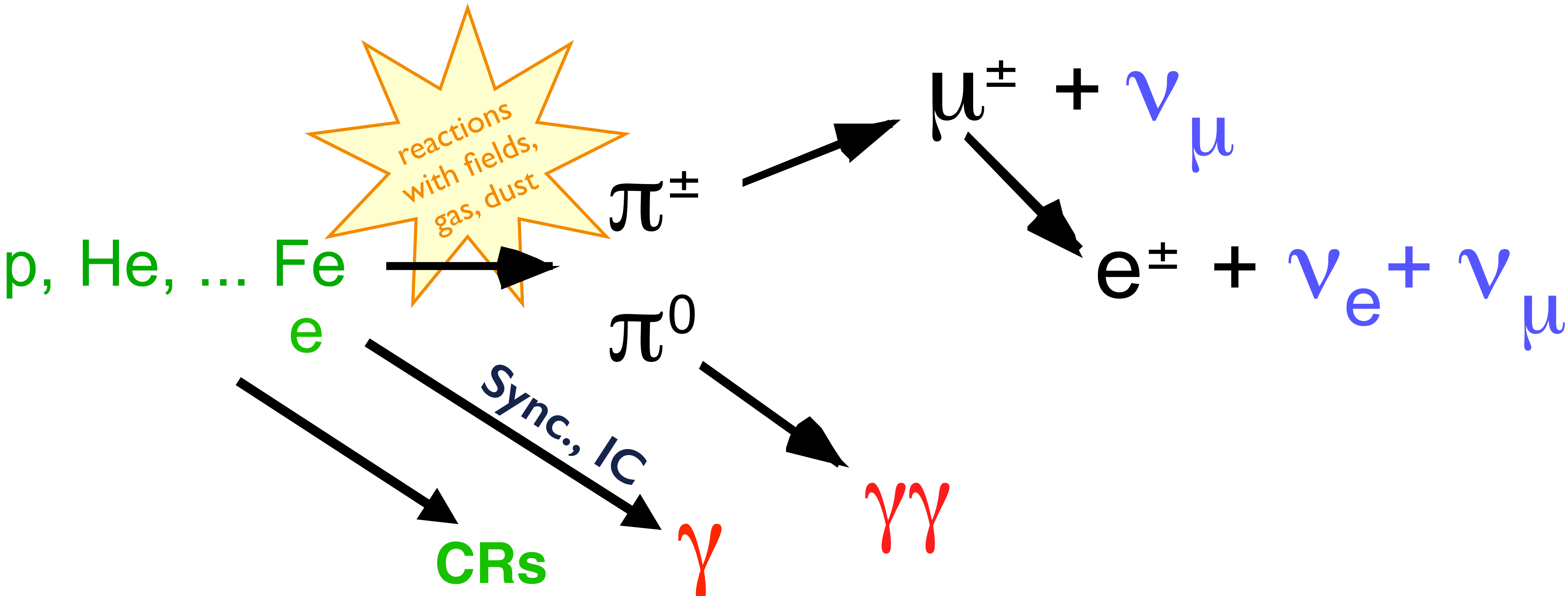
(gain > losses) –: e

–: CRs

Fermi acceleration

mag. field reconnection ??

Cosmic rays, gamma rays and neutrinos come likely from the same sources



1. acceleration
(gain > losses) –: e
–: CRs

2. interaction/escape

3. interaction/decay

4. propagation

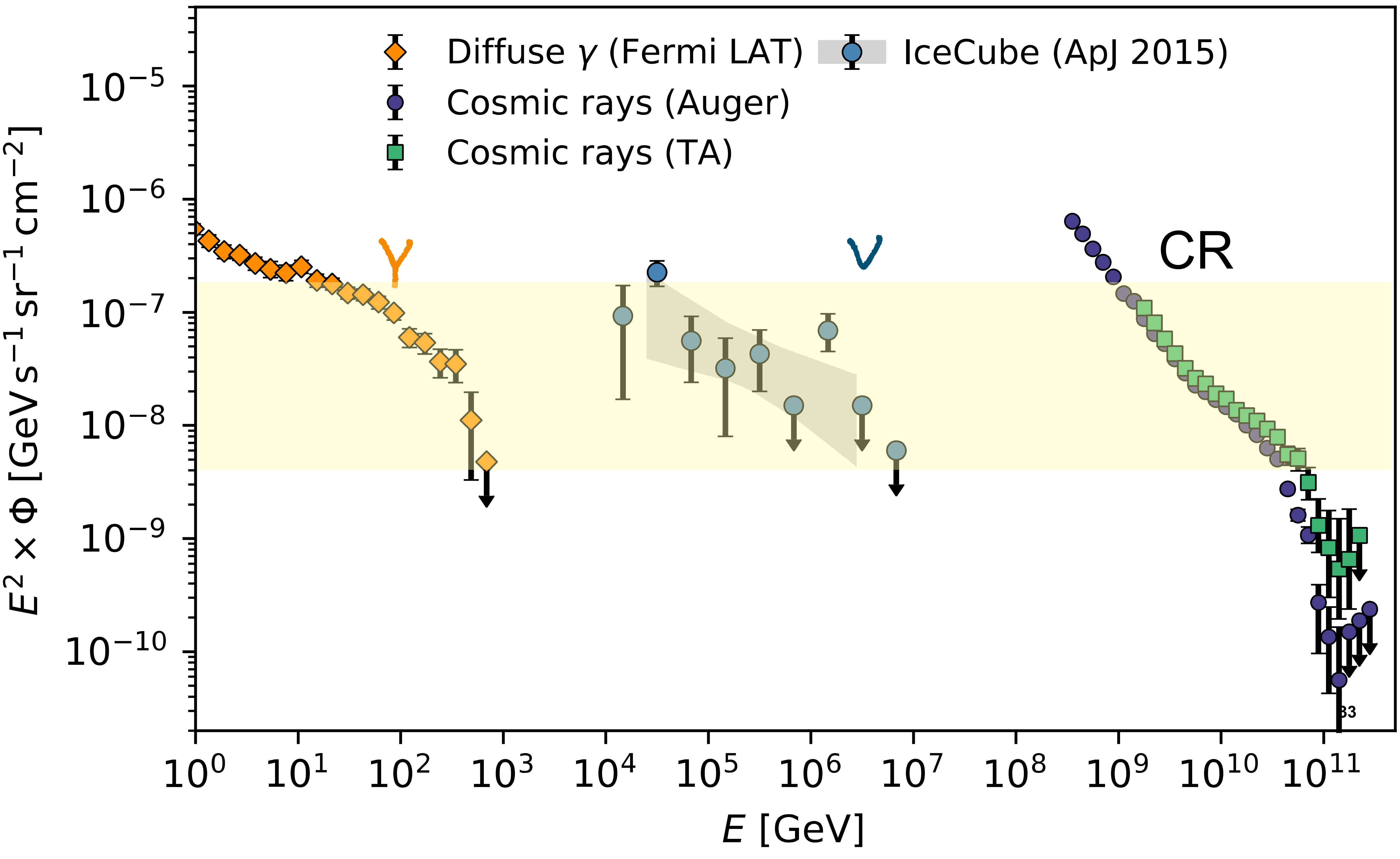
"multi-messenger astrophysics" … see all components together “multi-messenger astrophysics” … **promising**

see all components together?
direct link/proportionality between neutrino and γ-ray flux ? **Not necessarily**

What fraction goes in which branch ??
Depends on the **local environment**.

May be different from source to source.

CRs, ν, γ show similar energy fluxes



last few years: many papers / year on Multi-Messenger Astronomy,
conferences on Multi-messenger Astronomy
very popular ….

But, until recently, experimental ”true” Multi-Messenger analyses were not possible.

No sources seen in Cosmic Rays
spectrum up to 10^{20} eV, some structure,
unknown composition,
2018: anisotropy hinting at a source (Cen A) ???

No sources seen in neutrinos
largely diffuse sky plot, no clusters

No sources seen in grav. waves:
2015: GW150914 … , poor location
BH–BH mergers, no elmag emission expected.

Only important theoretical work on source models,
e.g. can blazers / GRBs be sources of Neutrinos?

Correlation of different messengers
Complement

Detect sources: good sensitivity for weaker sources,
source location, angular resolution, field of view
morphology, angular resolution,
spectral shape, energy resolution,
variability, time resolution … in different messengers

Variability, Transients, Coincidences ….

allow for efficient correlations
study of dynamics of acceleration/emission process
Transients make brighter sources, are easier to spot.

Steady sources, not so much to correlate
smooth spectra, … not so much to learn

Gamma rays

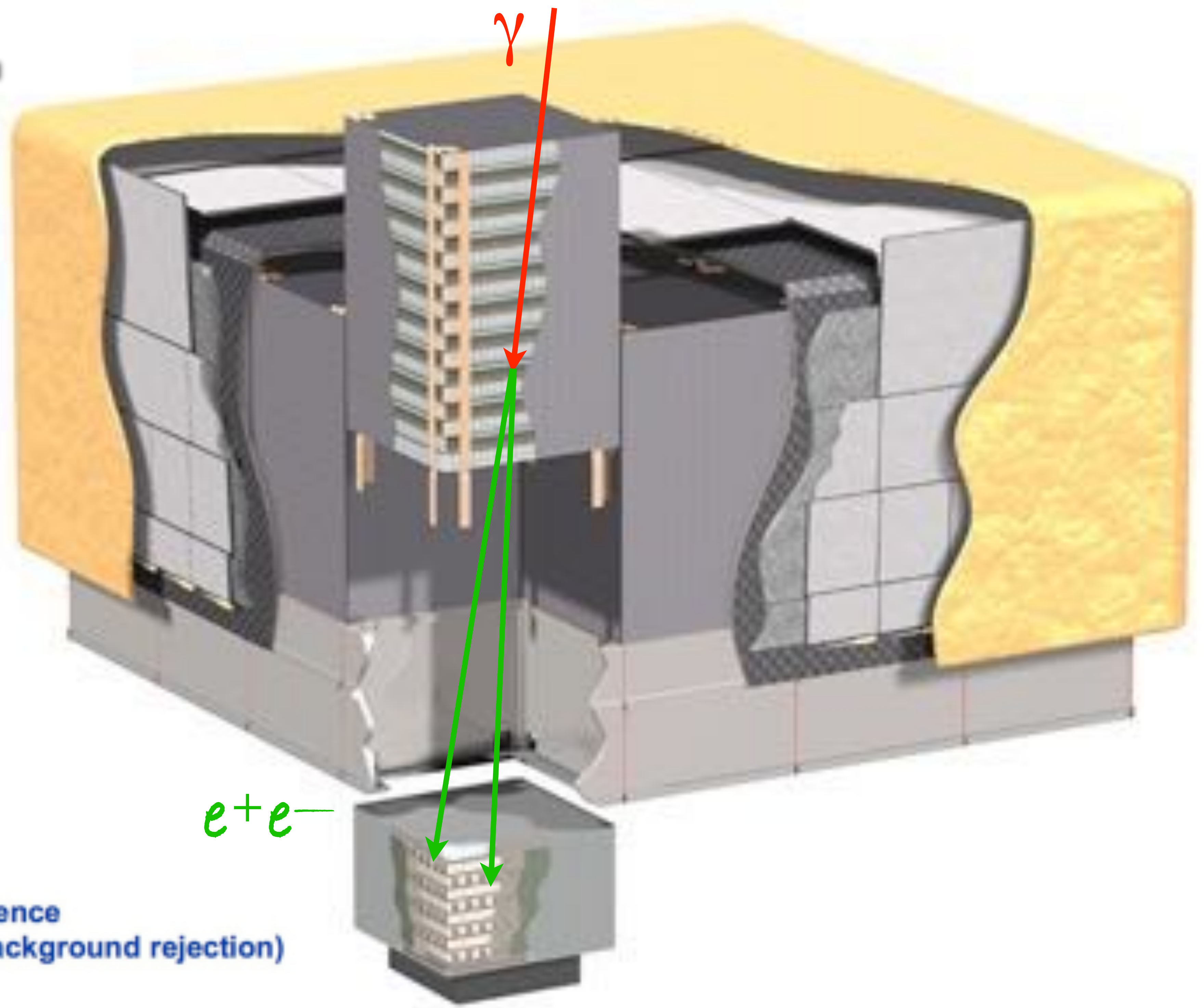
Cosmic accelerators and the sources of CRs ??

In past 2 decades, we have learned more on this
from gamma-ray measurements
than from CR measurements.

**Gamma rays are currently by far
the most "productive" messengers.**

Fermi - LAT

large angle
telescope

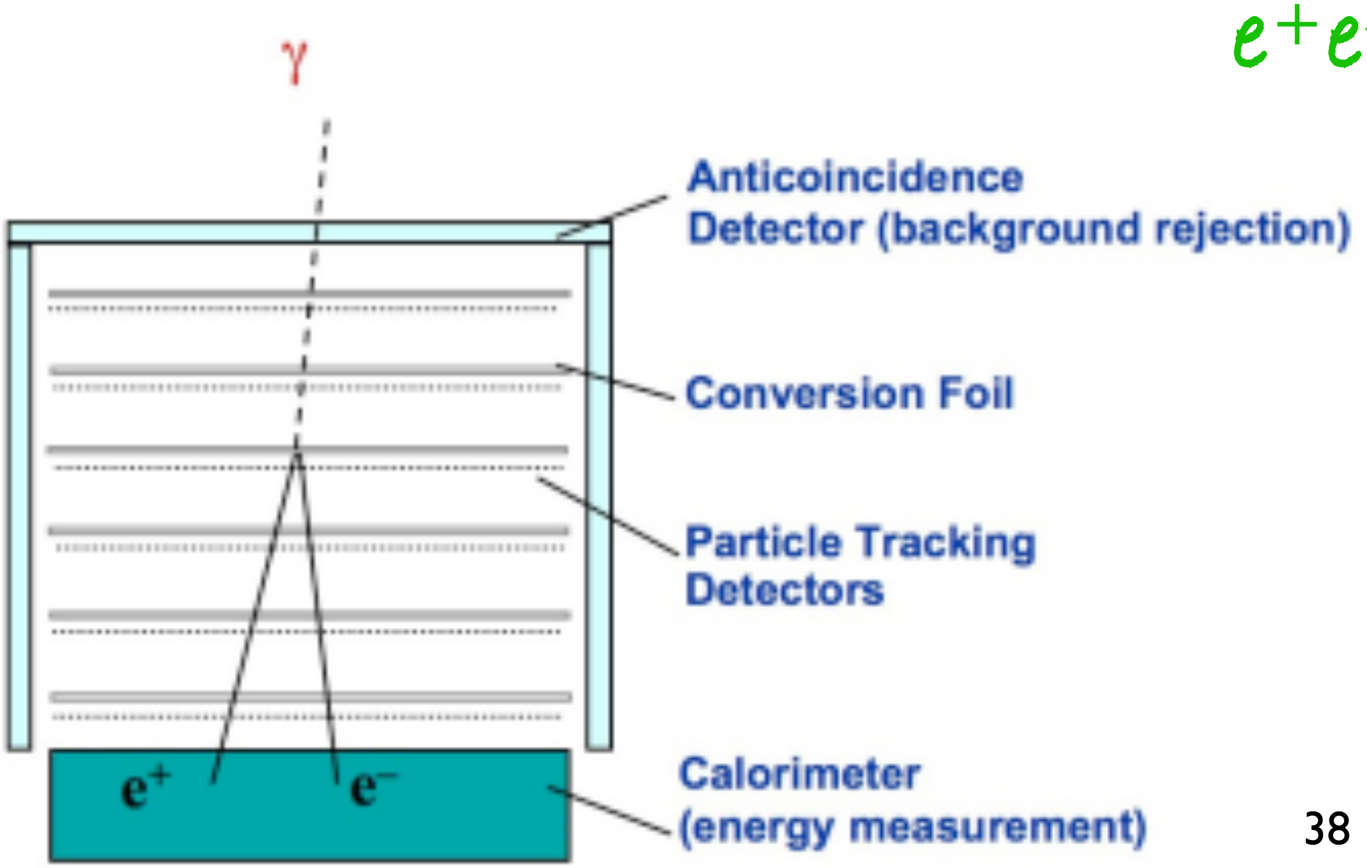


pair-conversion telescope with:

precision trackers
18 layers tungsten converters
and x, y silicon strip detectors.

calorimeter
96 CsI(Tl) crystals in an
8 layer hodoscope (depth: 8.6 X_0)

4x4 modules covered by
anti-coincidence shield



<100 MeV .... ~100 GeV

≈ 1 m² 2.5 sr

near-perfect rejection of charged primaries

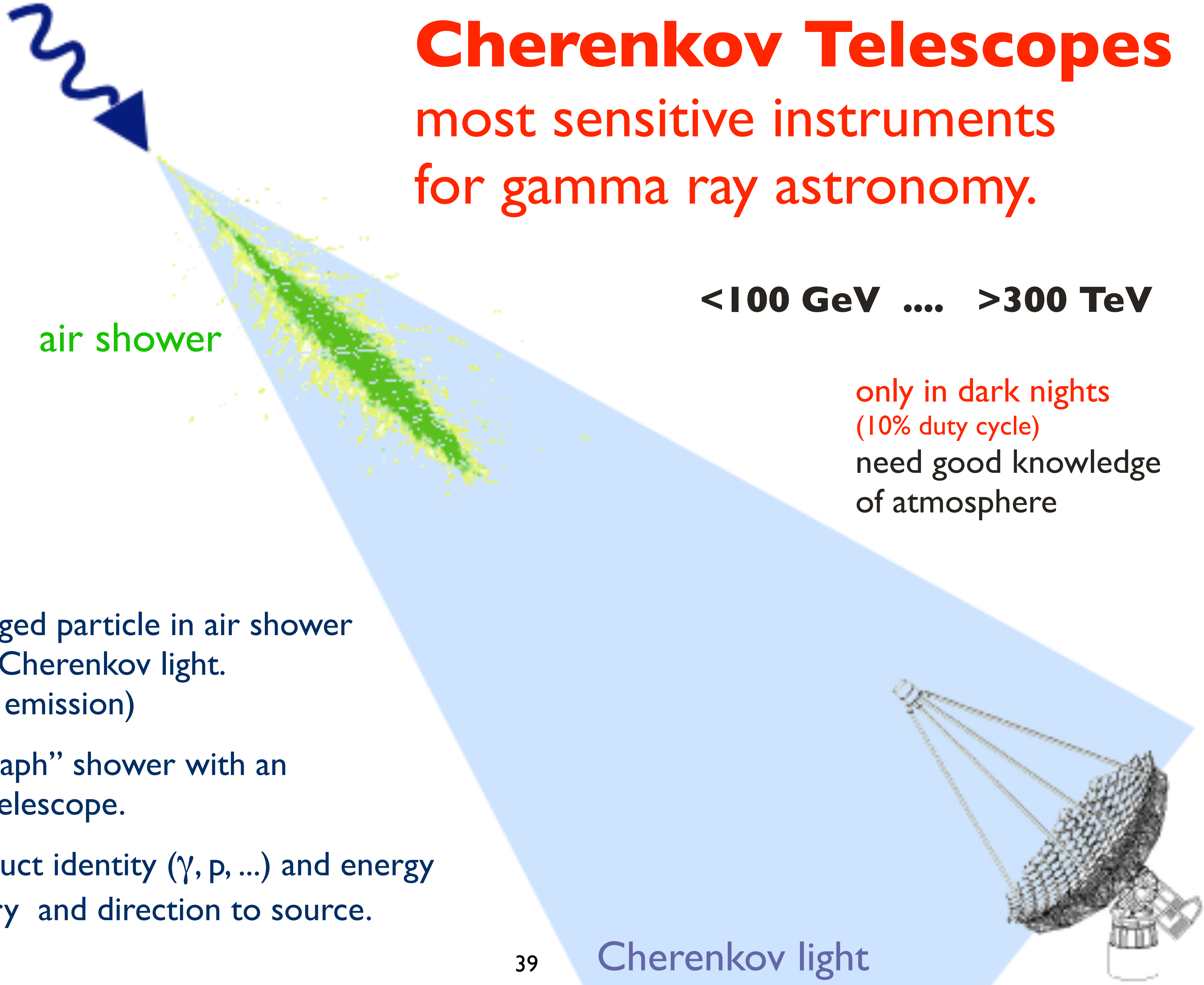
duty cycle: ≈100%

Cherenkov Telescopes

most sensitive instruments
for gamma ray astronomy.

<100 GeV .... >300 TeV

only in dark nights
(10% duty cycle)
need good knowledge
of atmosphere

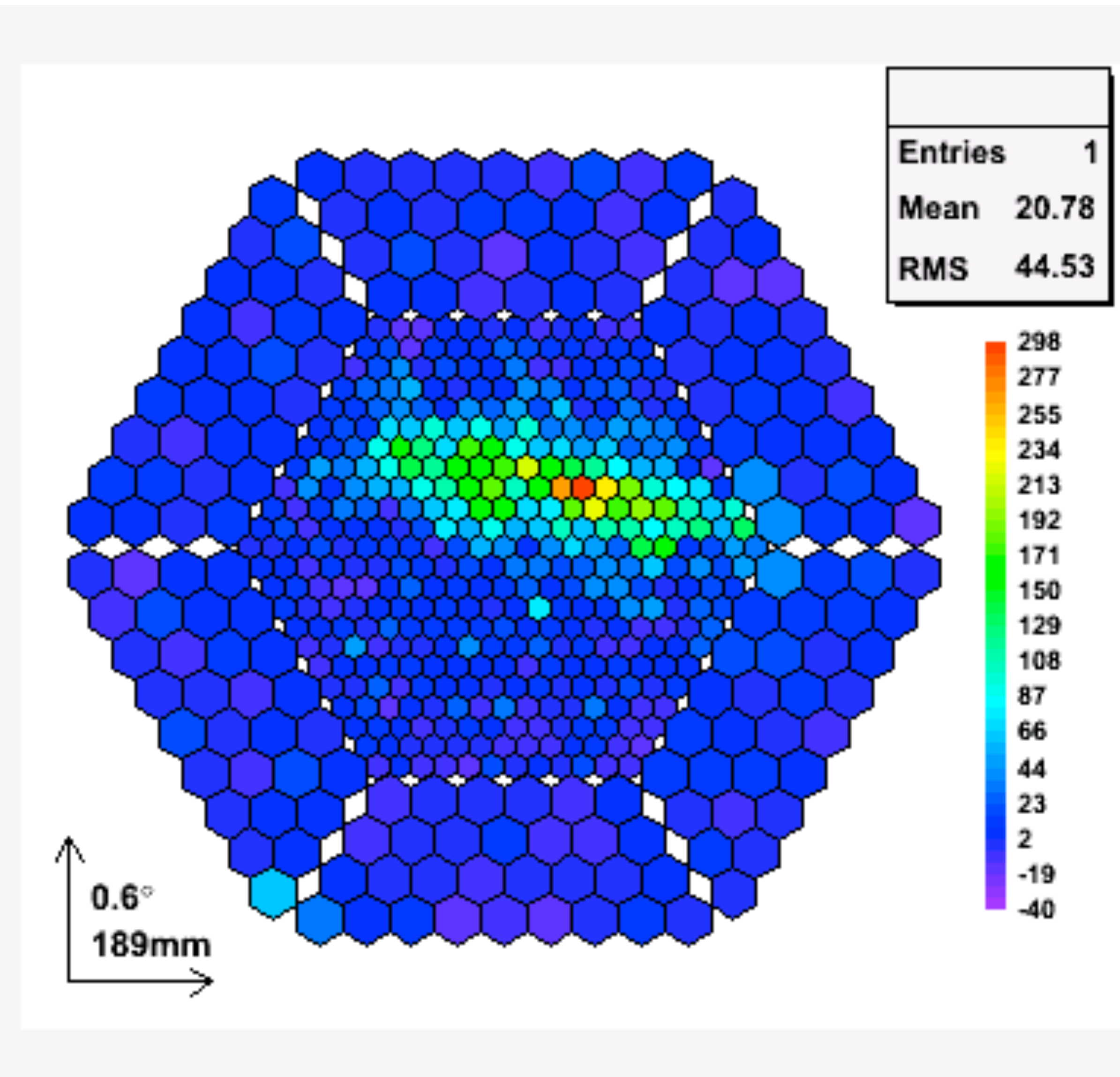


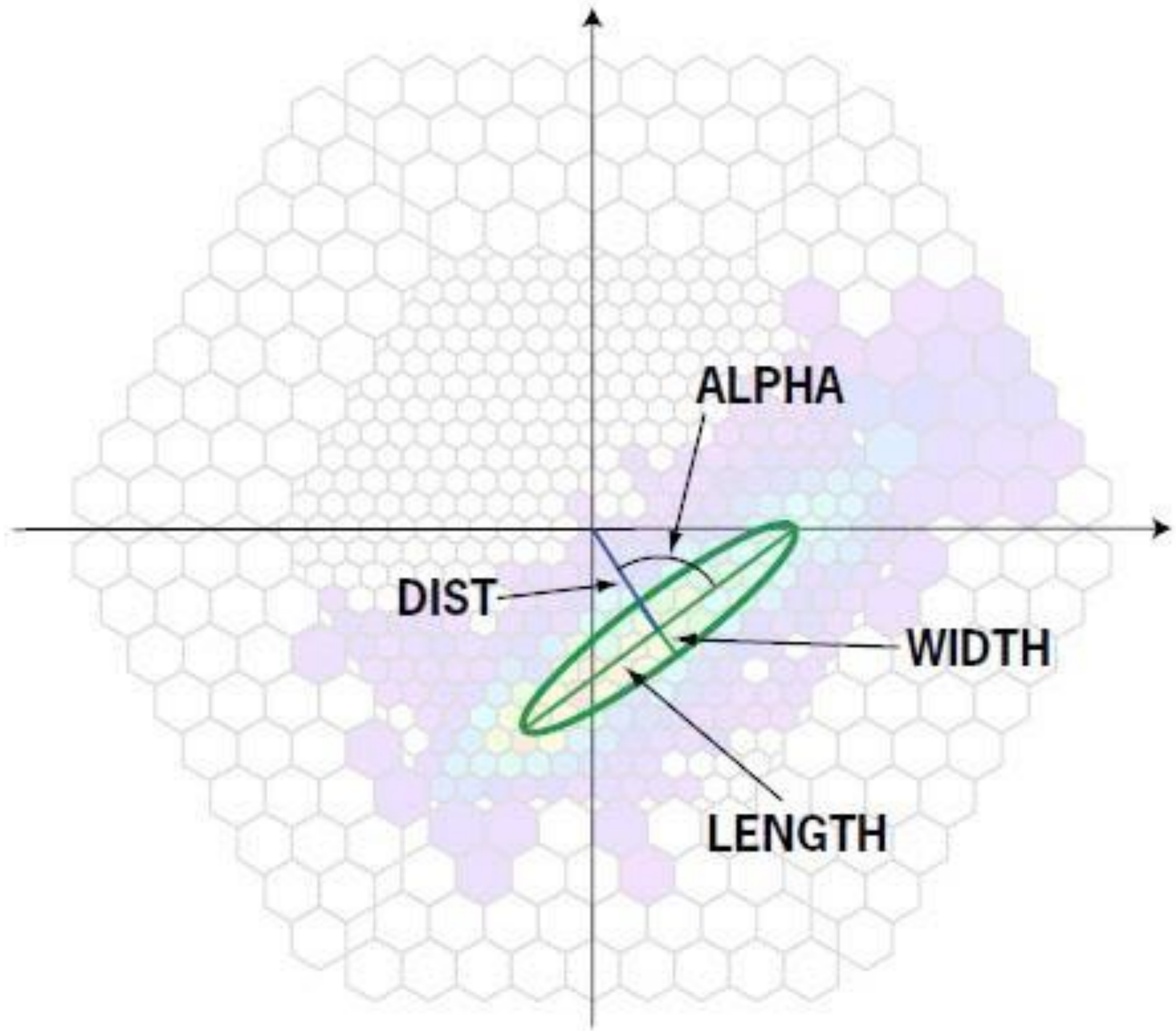
Fast charged particle in air shower produce Cherenkov light. (forward emission)

"Photograph" shower with an imaging telescope.

Reconstruct identity (γ, p, ...) and energy of primary and direction to source.

e.g. MAGIC camera

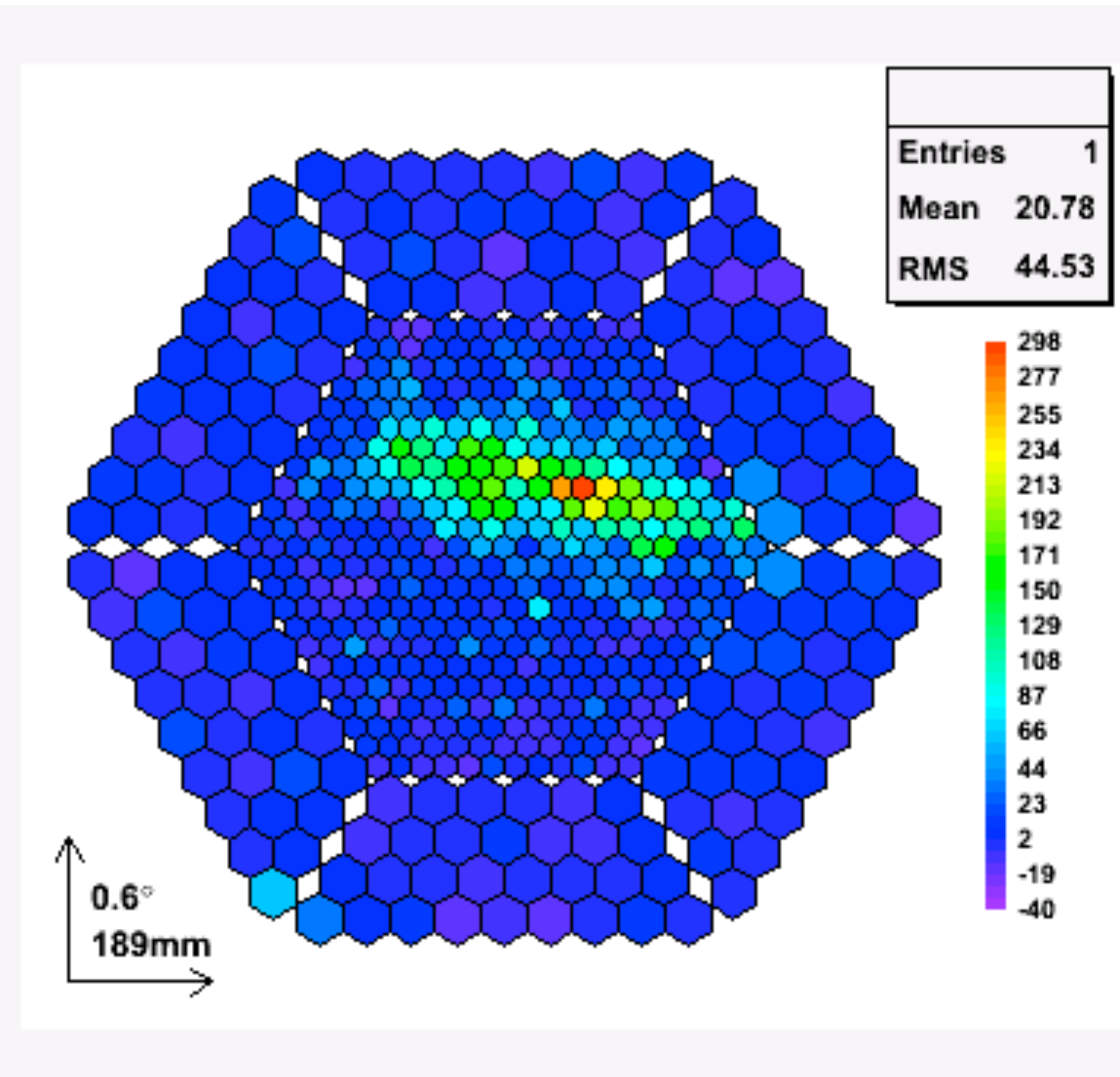


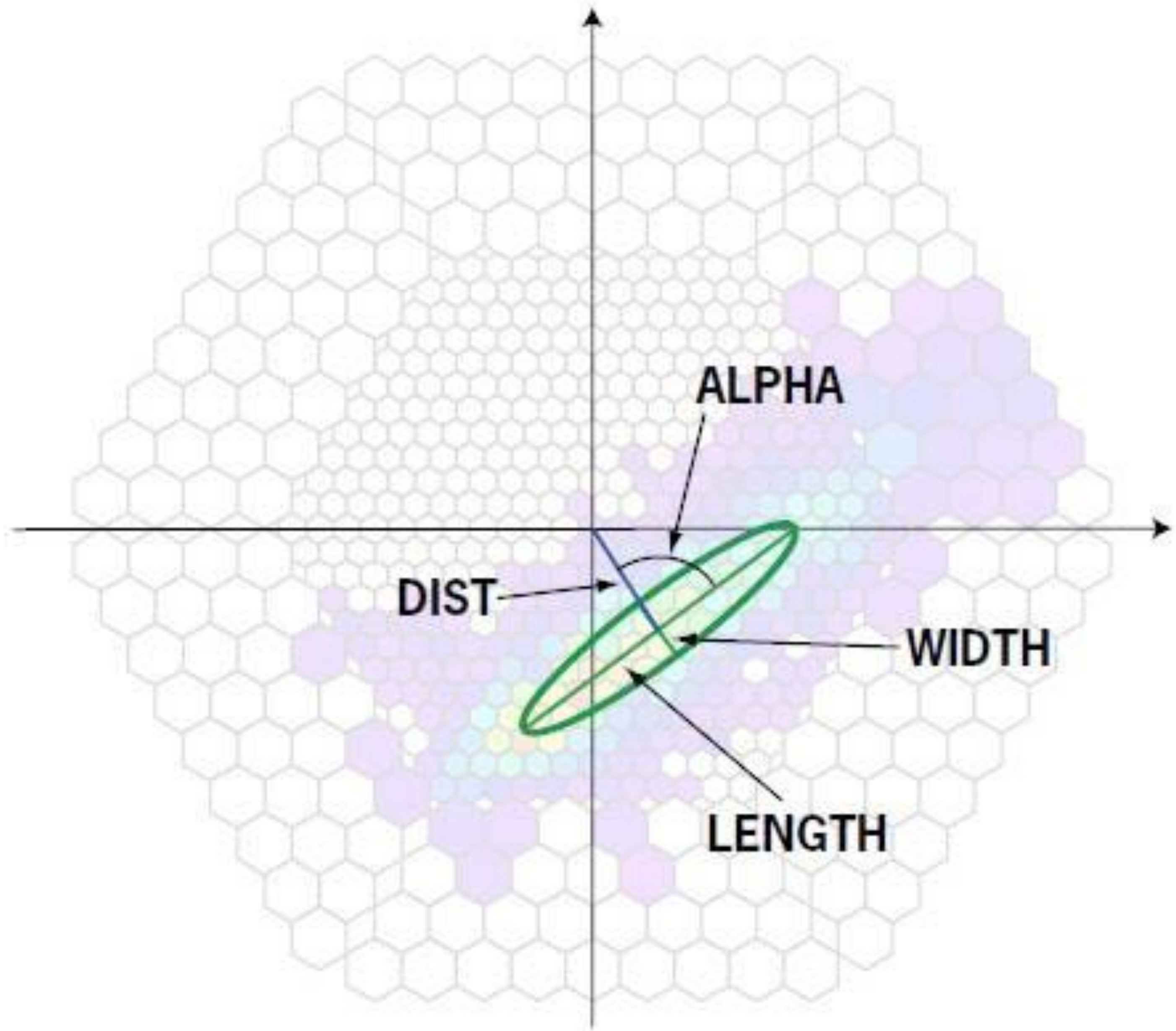


suppress the 10^4x higher hadronic background

image analysis:
form and orientation

e.g. MAGIC camera





suppress the 10^4x higher hadronic background

image analysis:
form and orientation

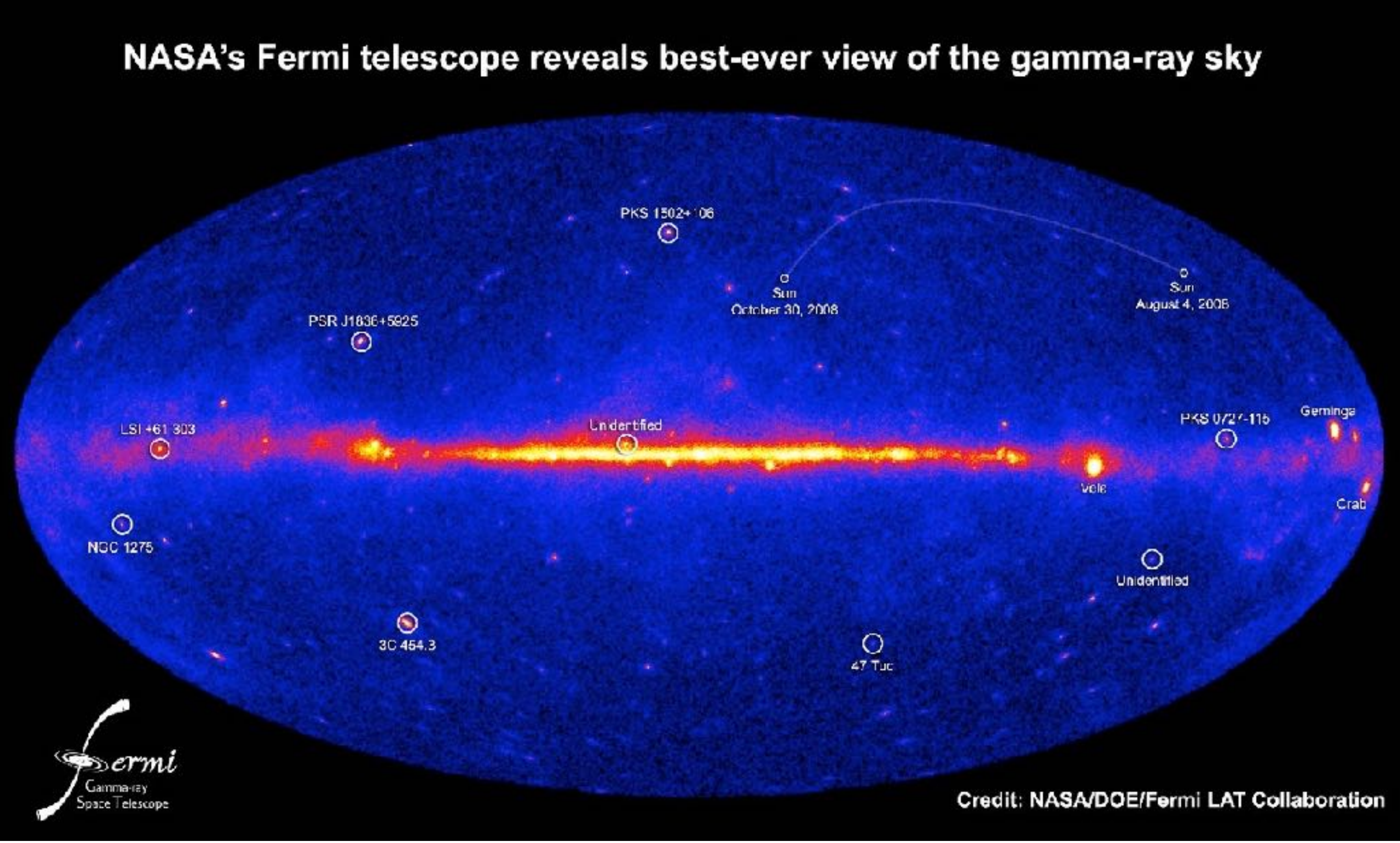
e.g. HESS Observatory (28-m Telescope added in 2012)

Namibia: 0.5 km^2

5 imaging Cherenkov telescopes

TeV-Gamma rays

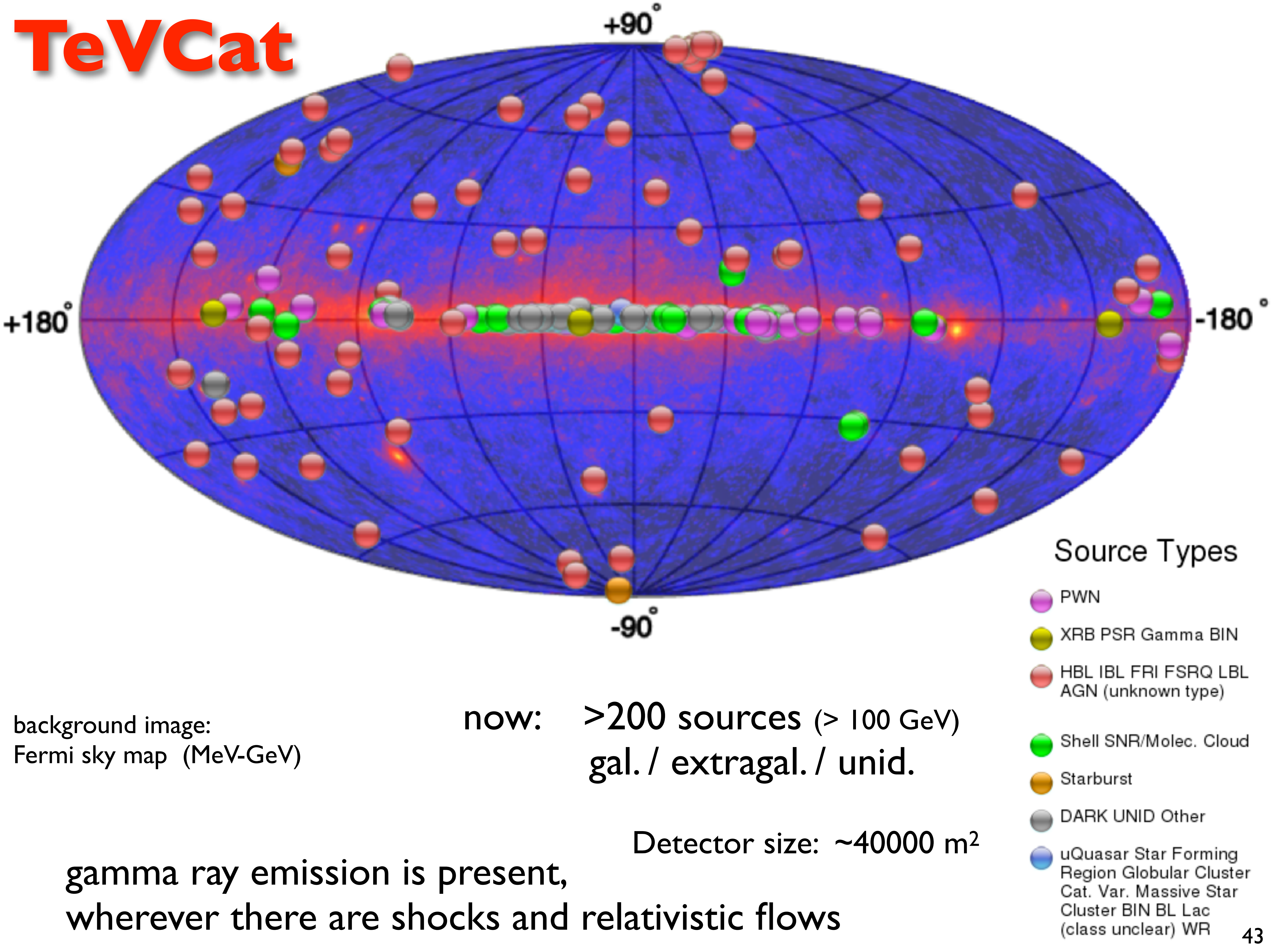
($E \approx 10^{11}$–10^{14} eV)



Satellite experiment: 100 MeV - 100 GeV
point sources, extended sources and diffuse emission, ...

≈3000 sources, **huge** number of gamma rays. Detector size: ~1 m^2

TeVCat



background image:
Fermi sky map (MeV-GeV)

now: >200 sources (> 100 GeV)
gal. / extragal. / unid.

Detector size: ~40000 m^2

gamma ray emission is present,
wherever there are shocks and relativistic flows

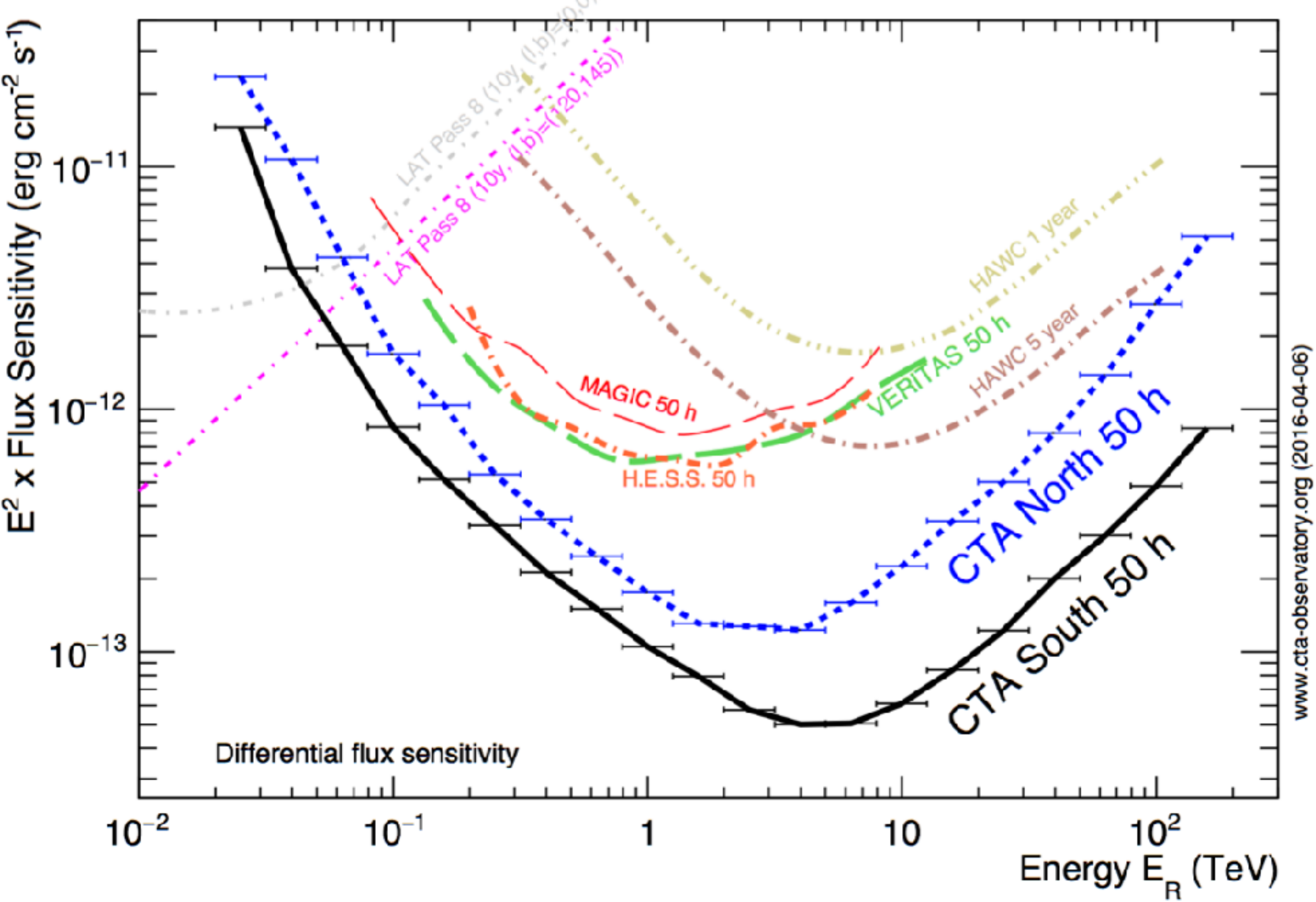
TeV astronomy highlights

from **HESS, MAGIC** and **VERITAS**
Descartes & Rossi Prize for HESS

Supernova remnants:	Nature	432 (2004) 75		
Microquasars:	Science	309 (2005) 746	Science	312 (2006) 1771
Pulsars:	Science	322 (2008) 1221	Science	334 (2011) 69
Galactic Centre:	Nature	439 (2006) 695	Nature	531 (2016) 476
Galactic Survey:	Science	307 (2005) 1839		
LMC:	Science	347 (2015) 406		
Black Holes:	Science	346 (2014) 1080		
Starbursts:	Nature	462 (2009) 770	Science	326 (2009) 1080
Active Galactic Nuclei:	Science	314 (2006) 1424	Science	325 (2009) 444
EBL:	Nature	440 (2006) 1018	Science	320 (2008) 752
Dark Matter:	PRL	96 (2006) 221102	PRL	106 (2011) 161301
	PRL	114 (2015) 081301	PRL	110 (2013) 41301
Lorentz Invariance:	PRL	101 (2008) 170402		
Cosmic Ray Electrons:	PRL	101 (2008) 261104		

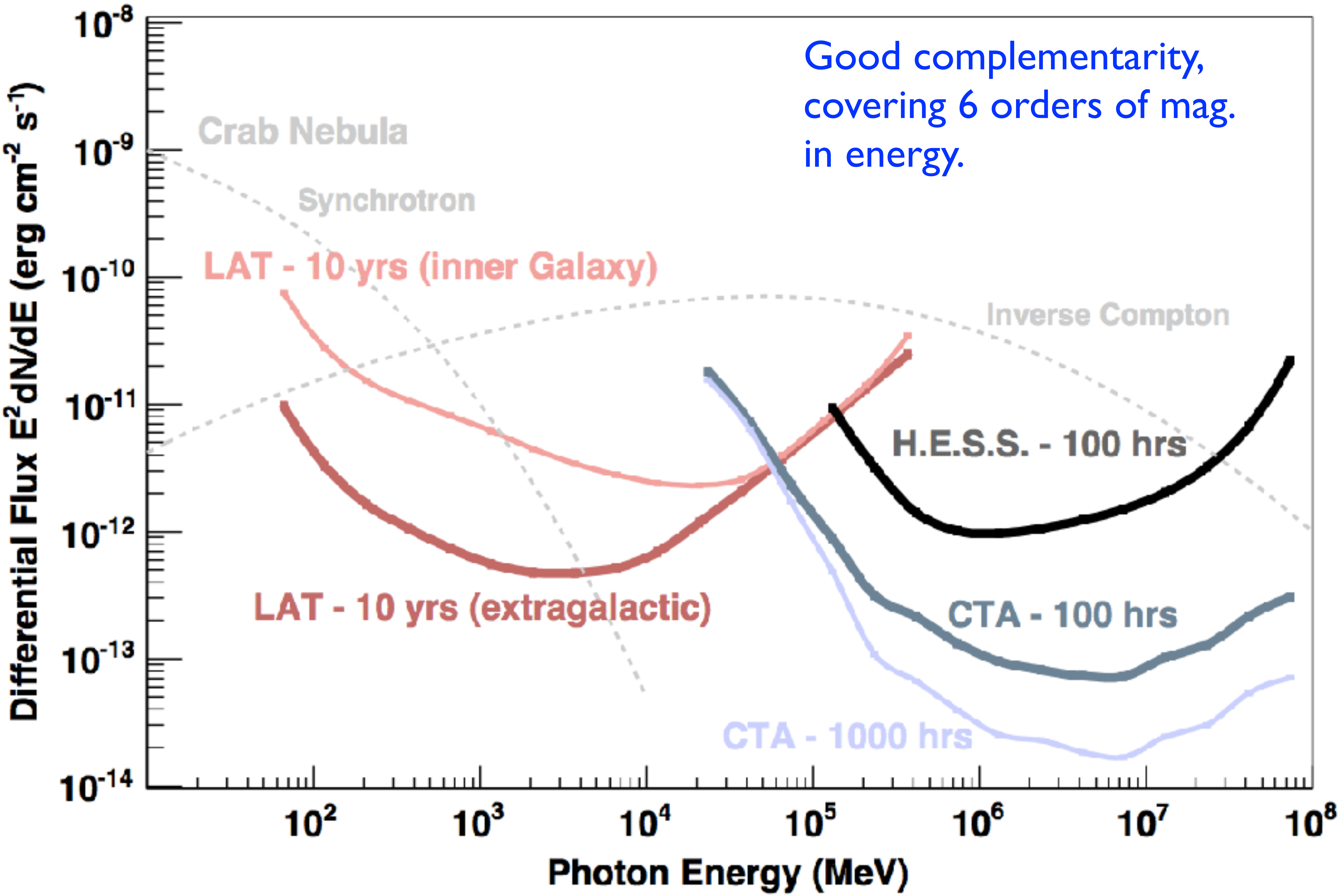
+ many papers in other journals
… a booming field.

Sensitivity to point sources



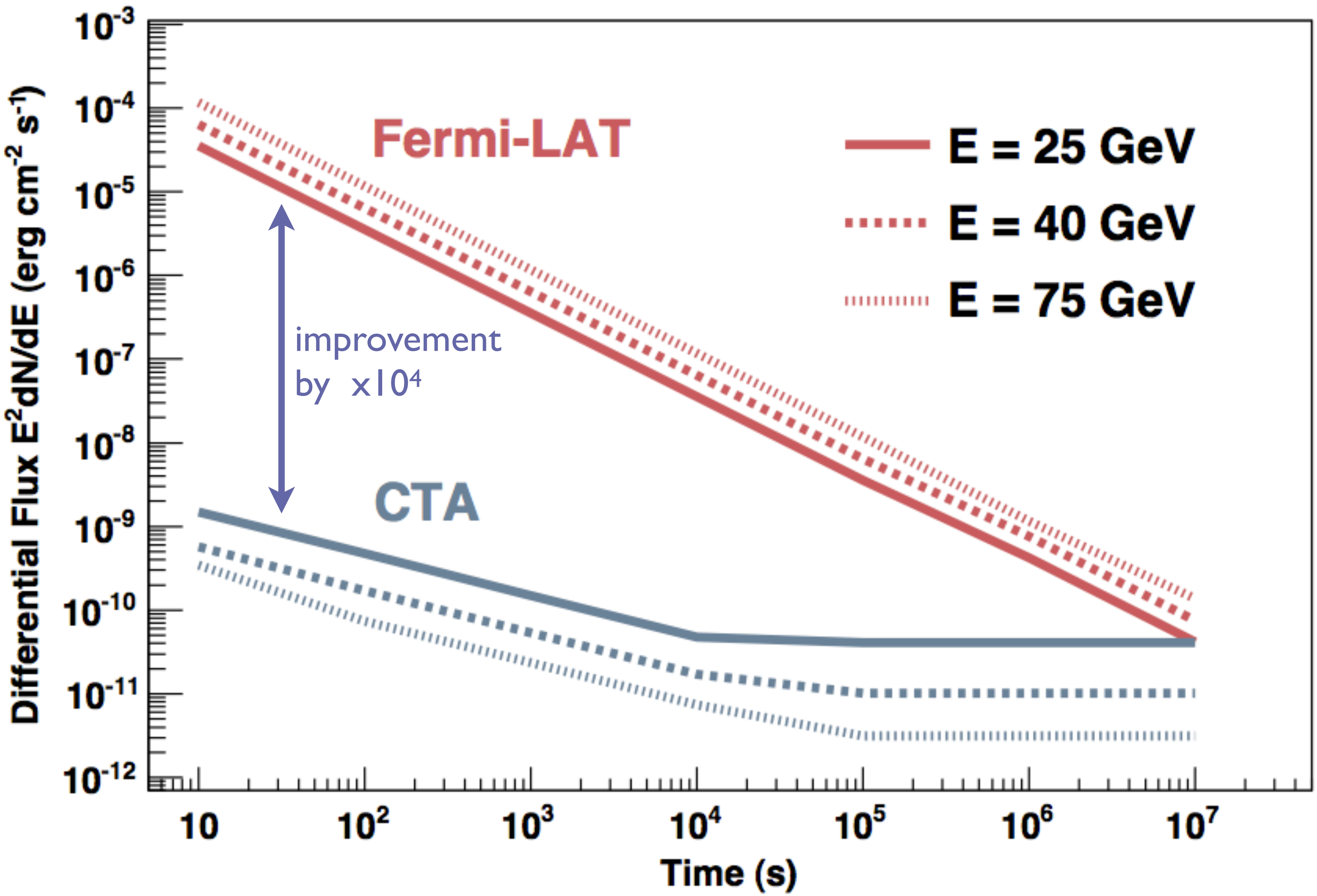
CTA and Fermi

(Steady sources)

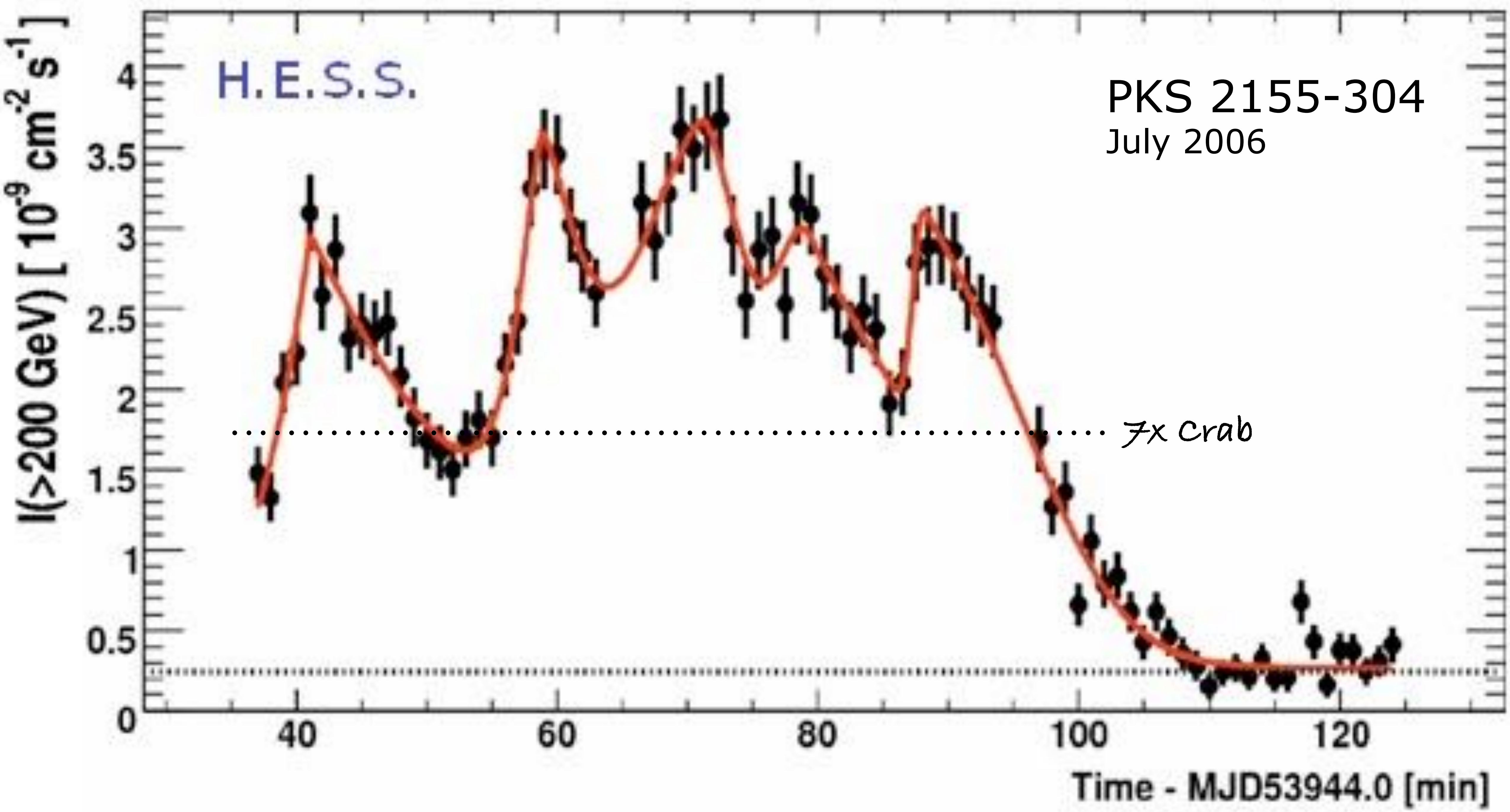


Variability and Short-Timescale Phenomena

(flares, GRBs, ... all sorts of transients)



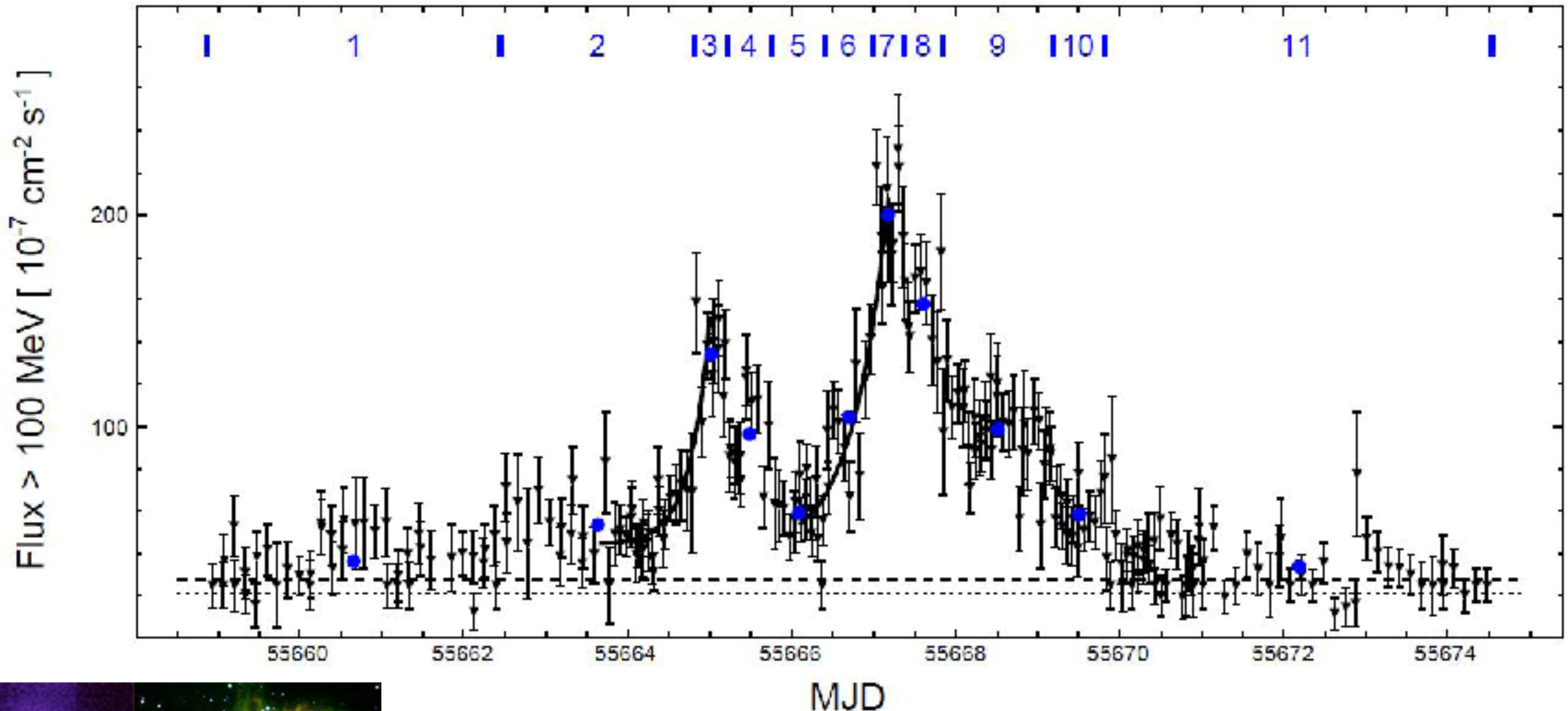
CTA … a transient machine: repointing fast enough?

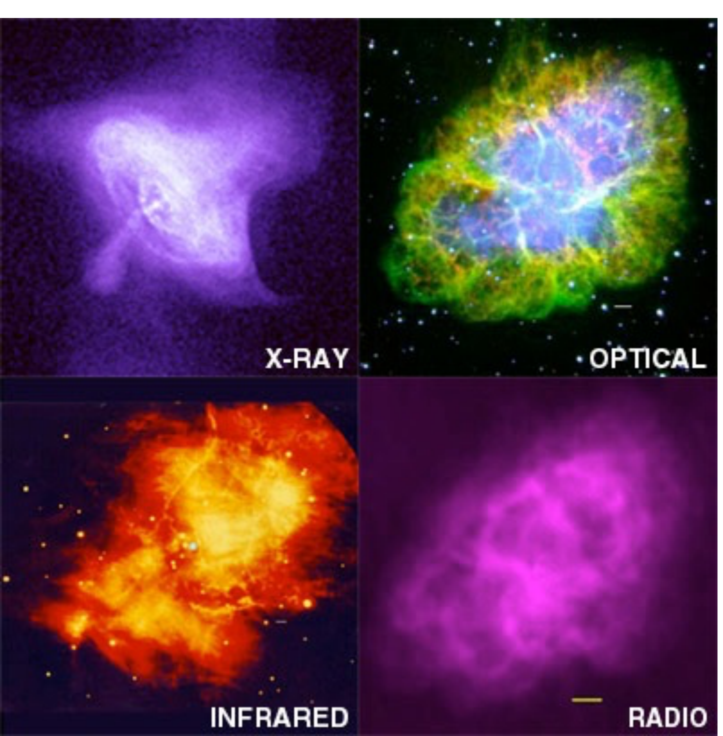


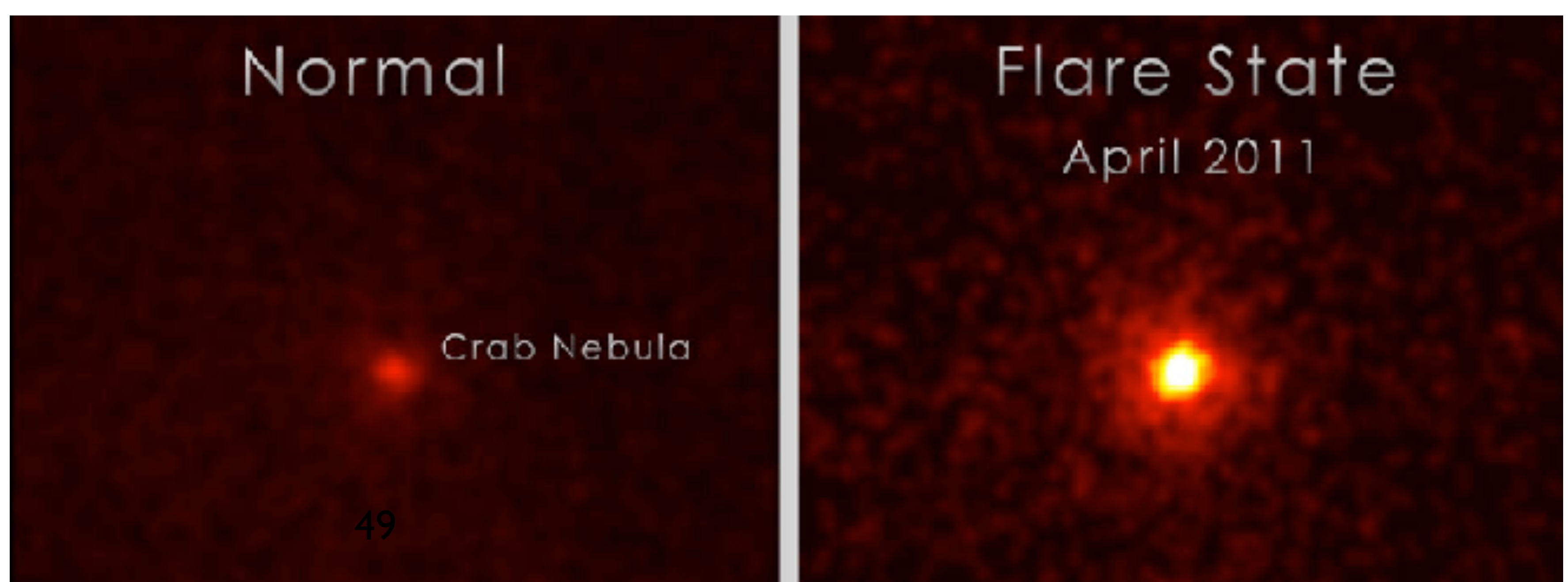
BL Lac object $z = 0.116$
bursts on minute scales
$\Gamma \geq 100$ are required

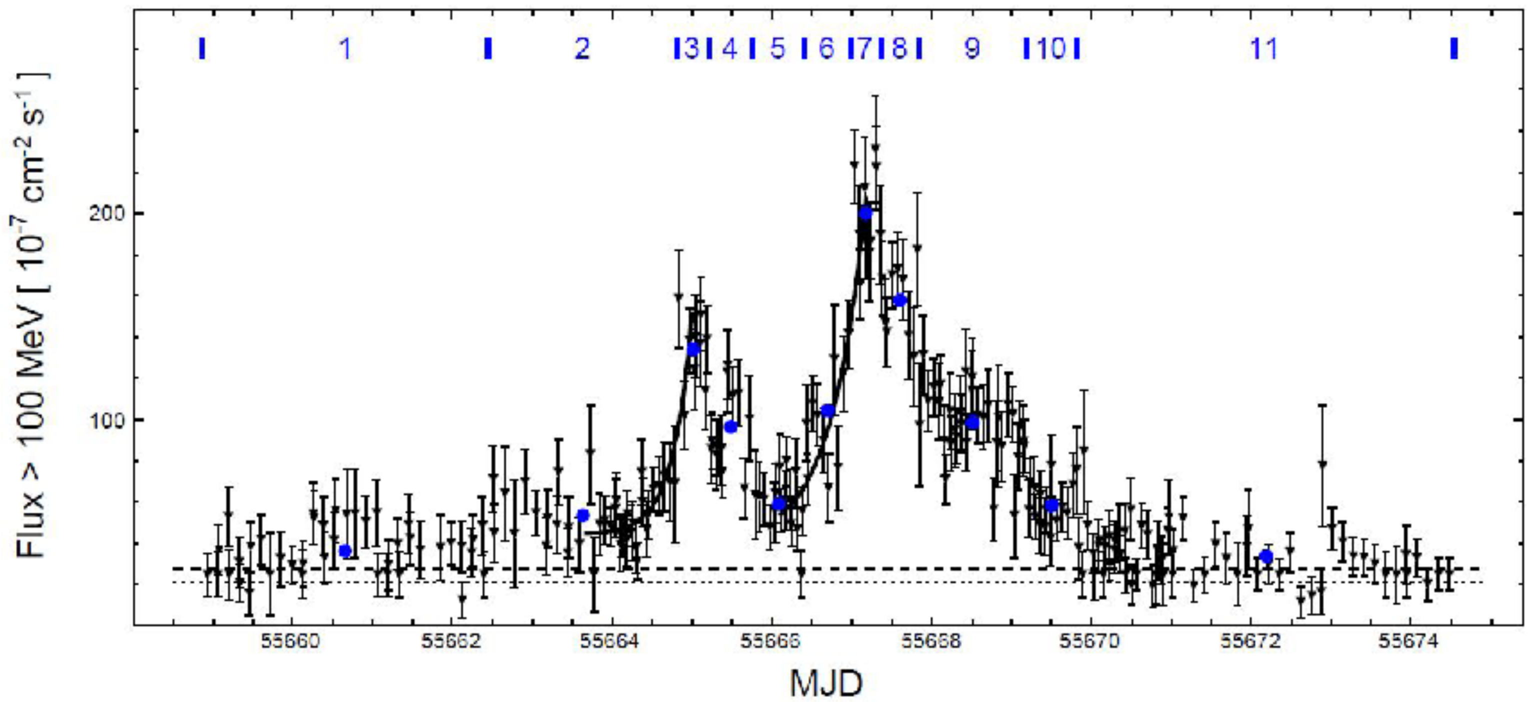
Major gamma-ray flare from Crab Nebula (April 2011)

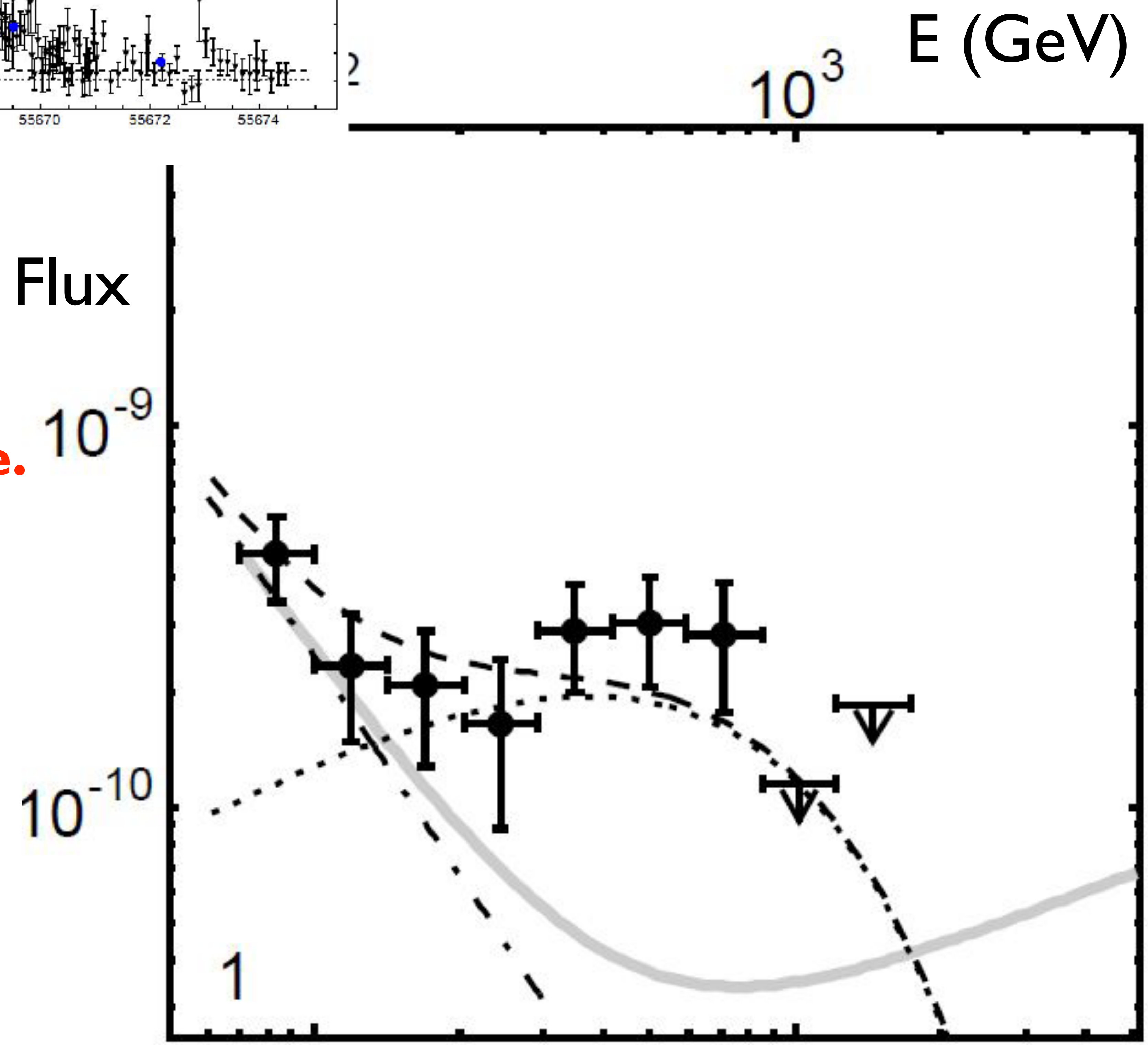
Crab was always seen as the "standard candle"



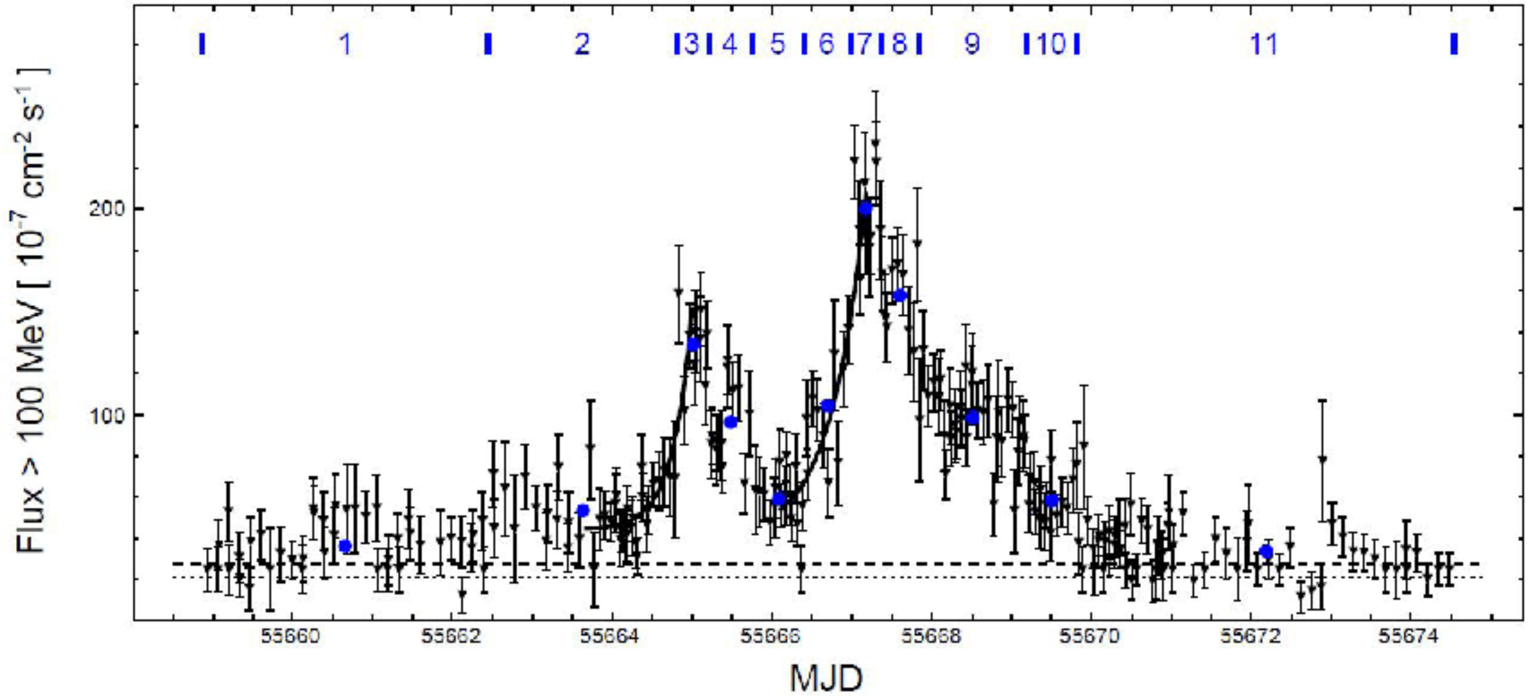








Spectrum varies with time.
Allows study of the
"dynamic processes"
of particle acceleration.



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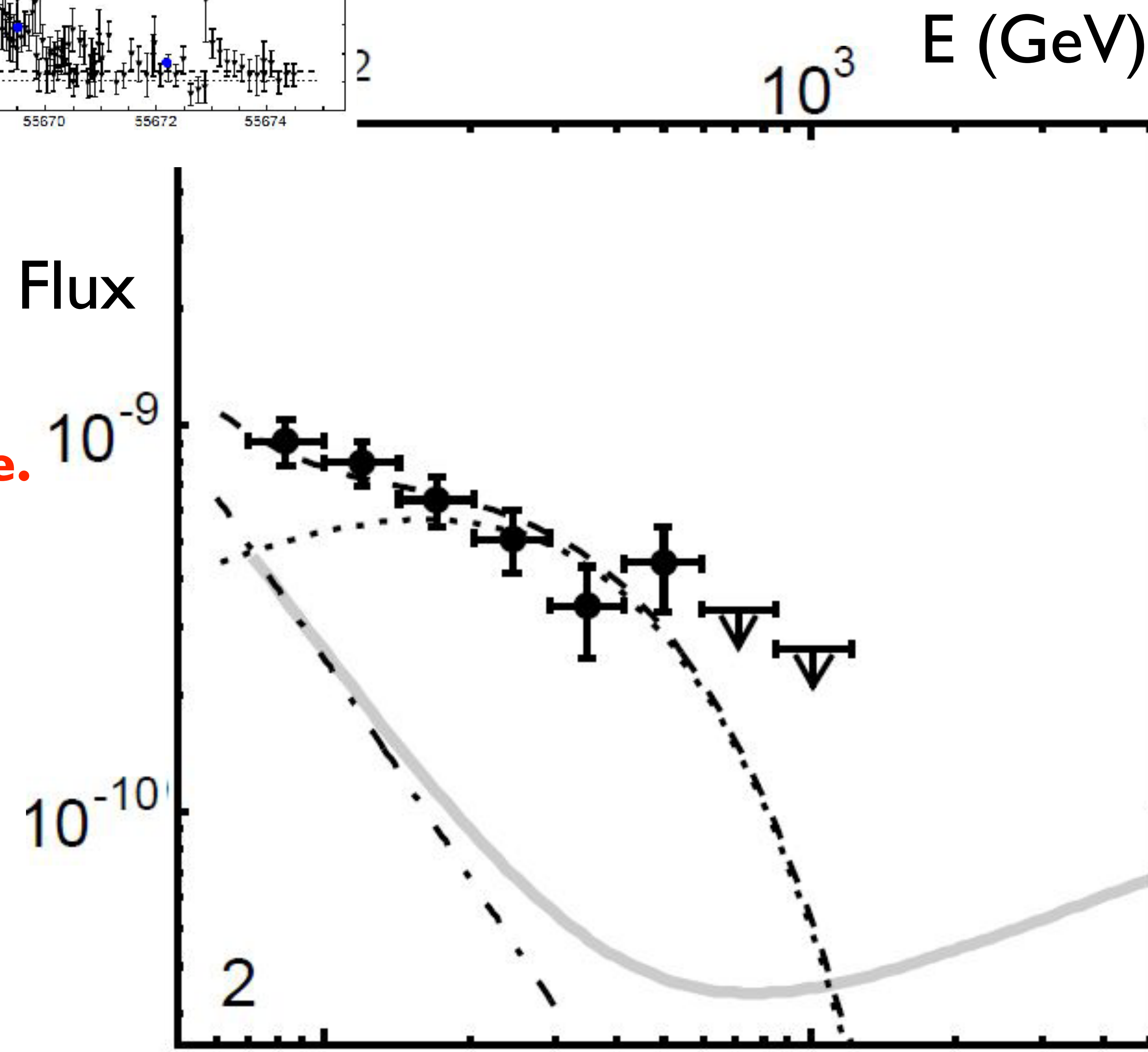

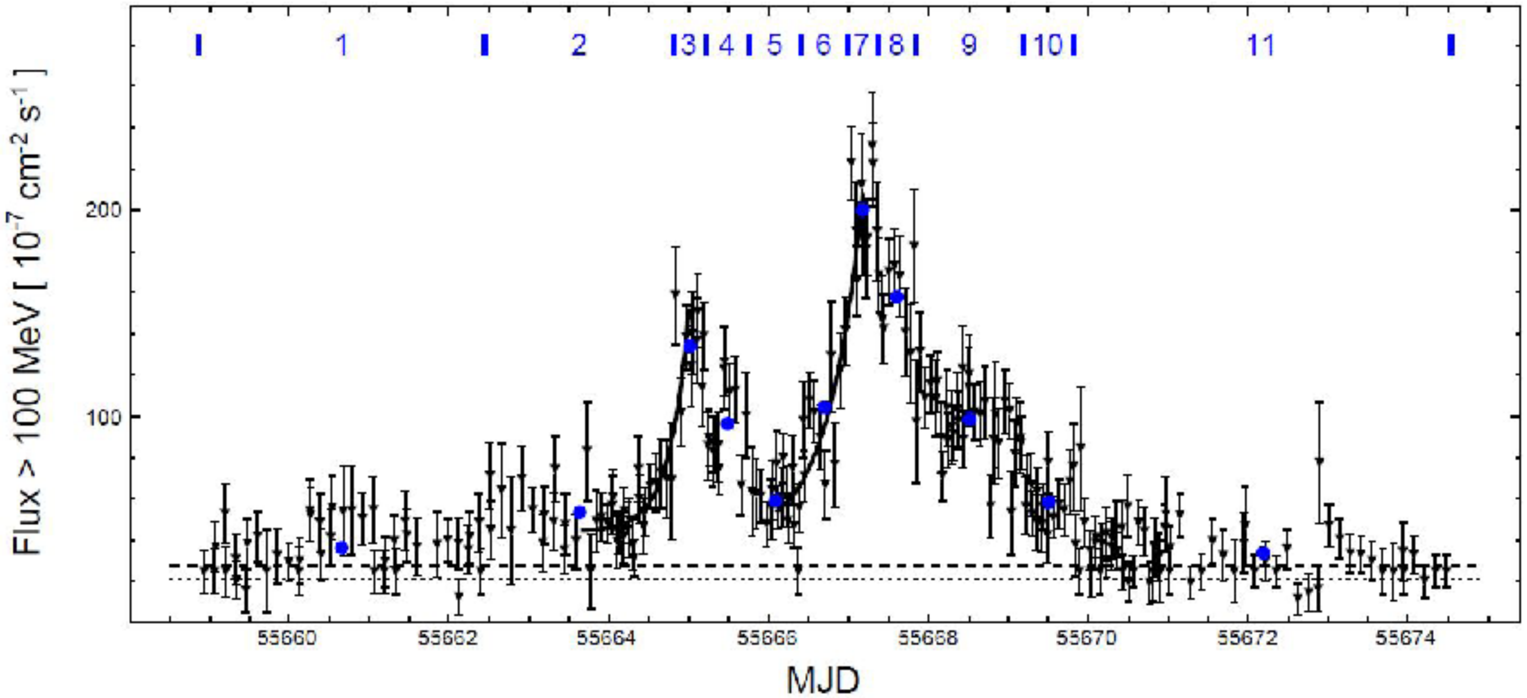

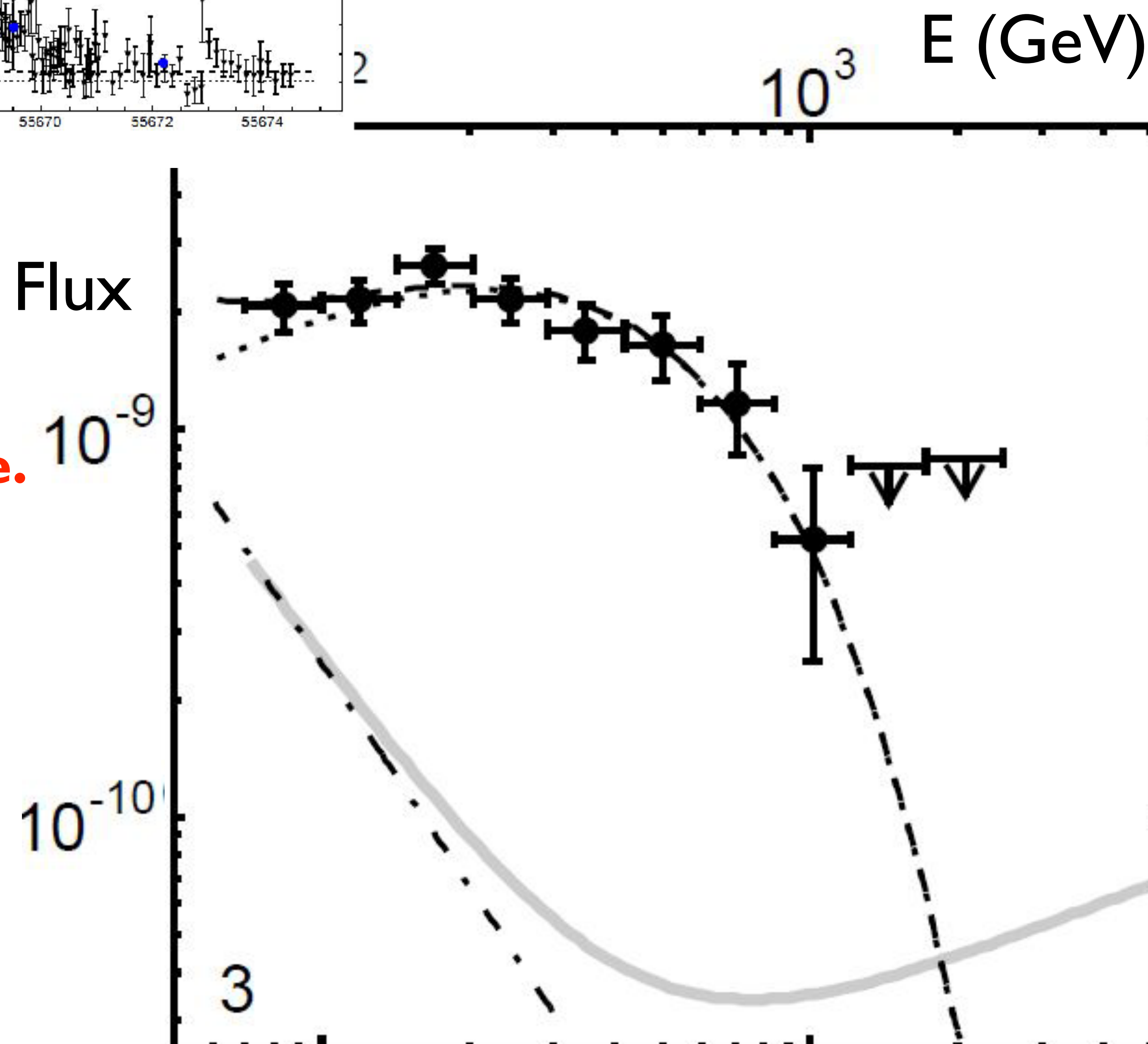

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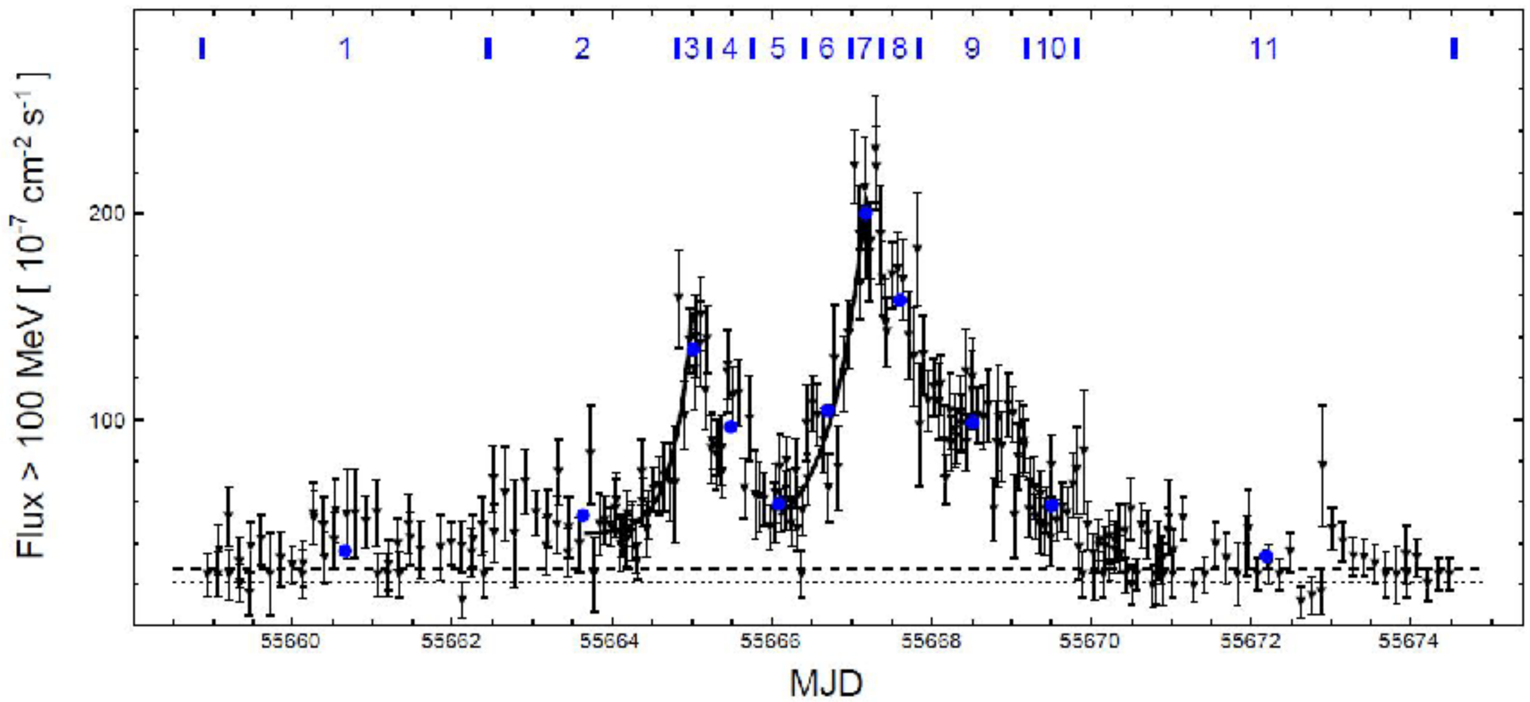

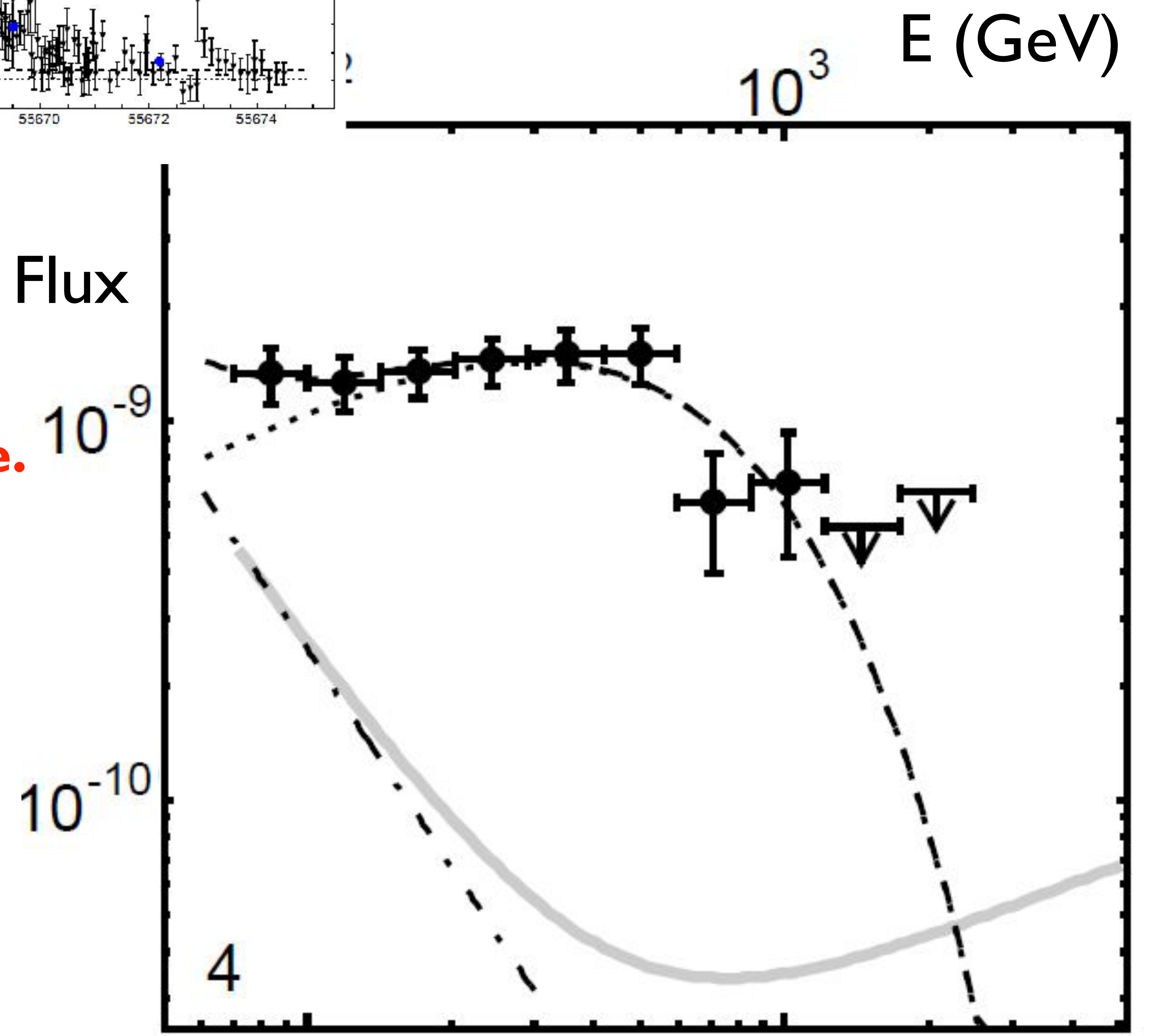

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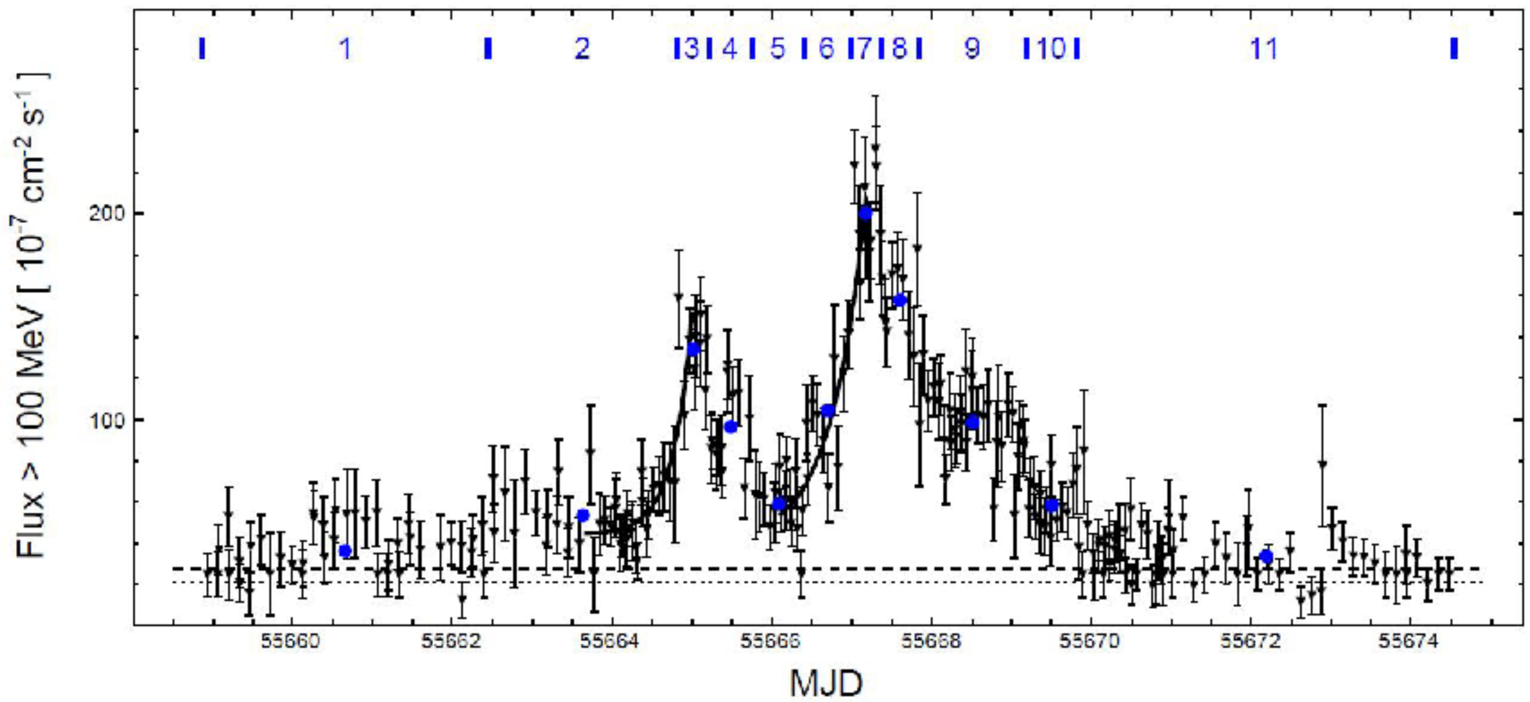

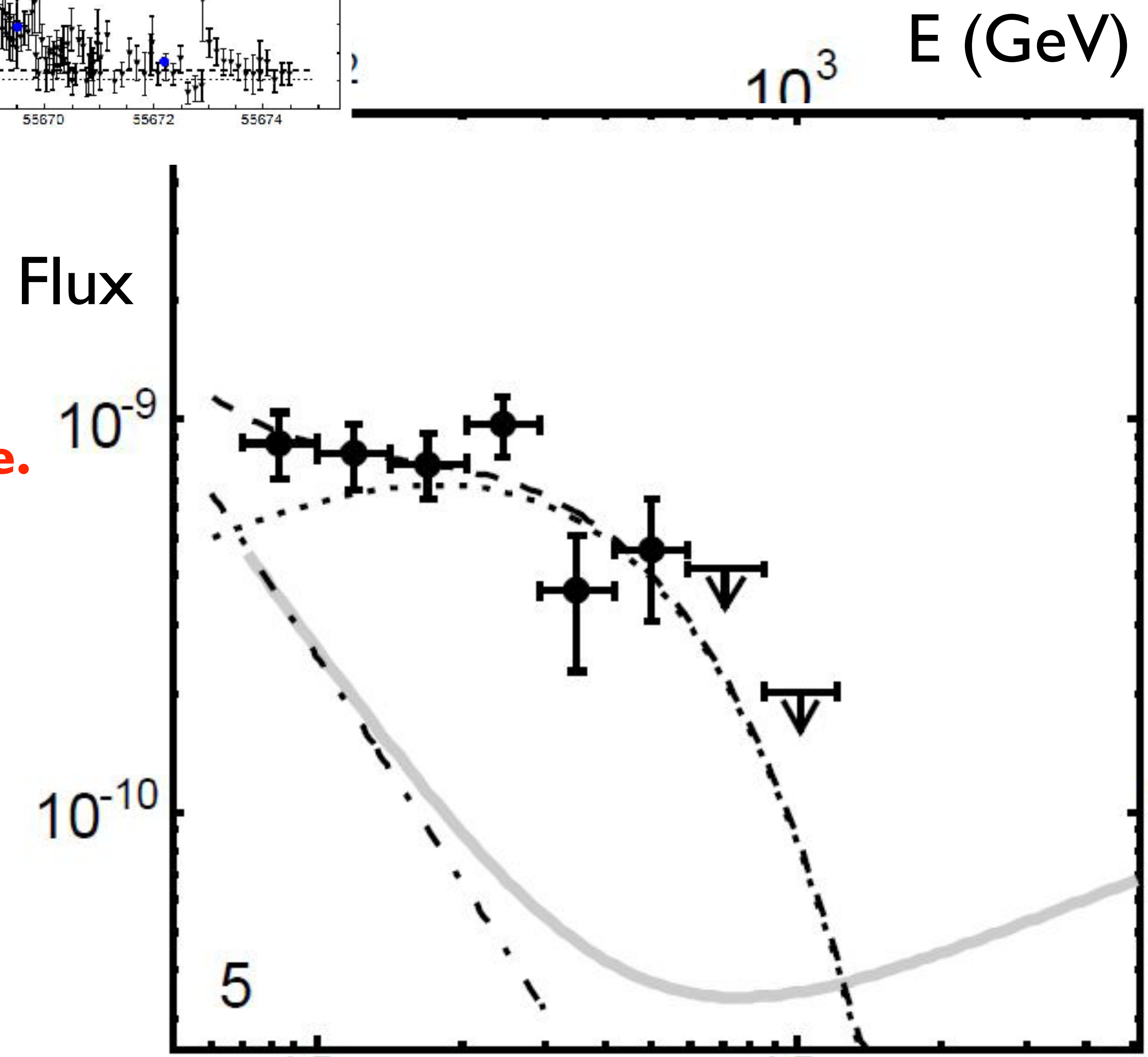

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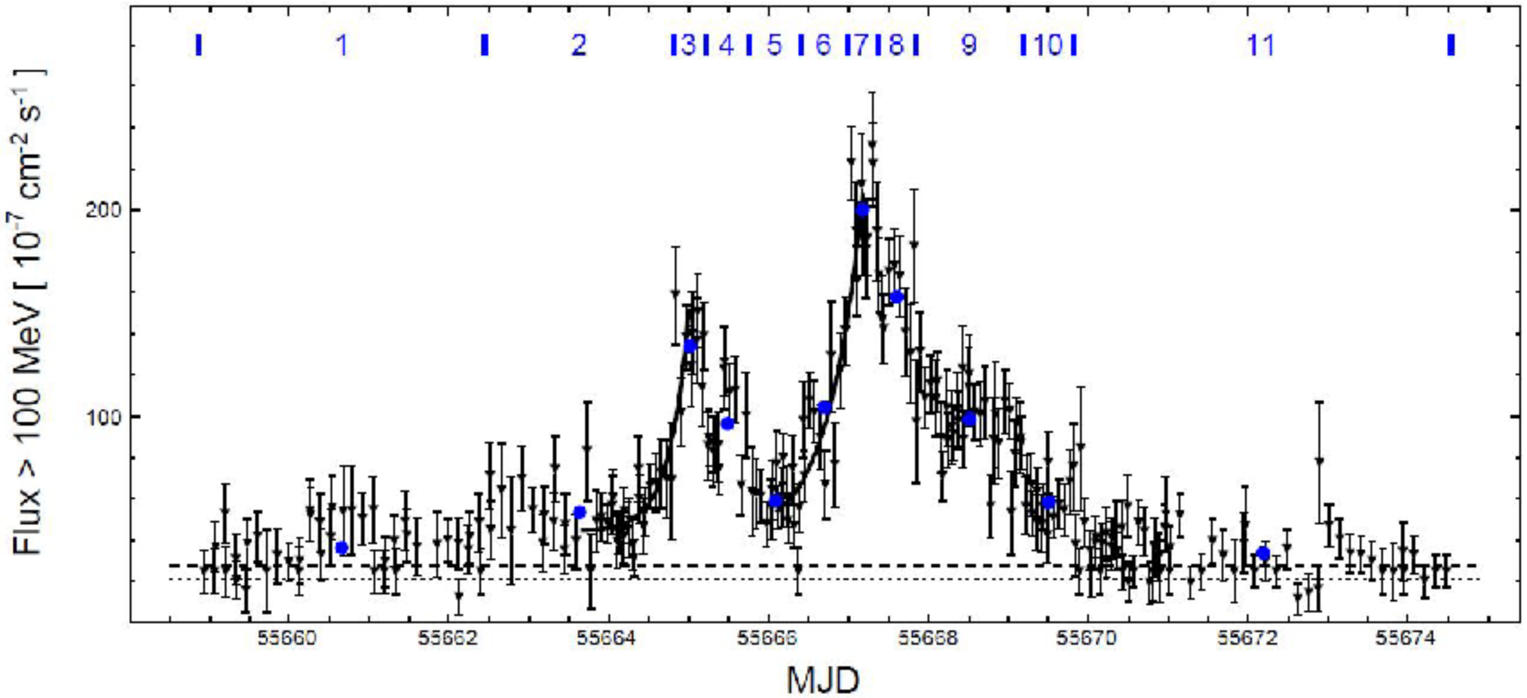

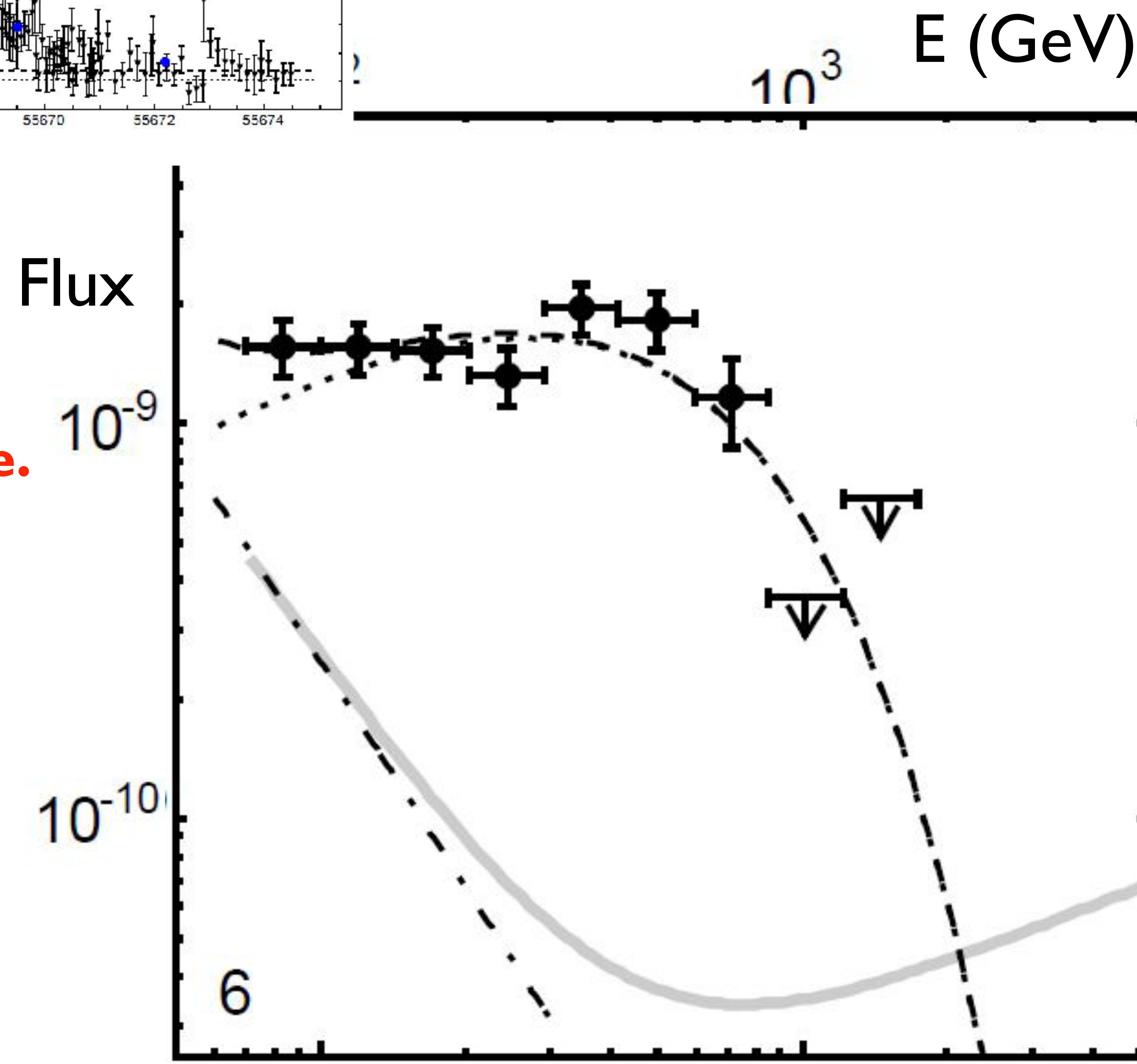

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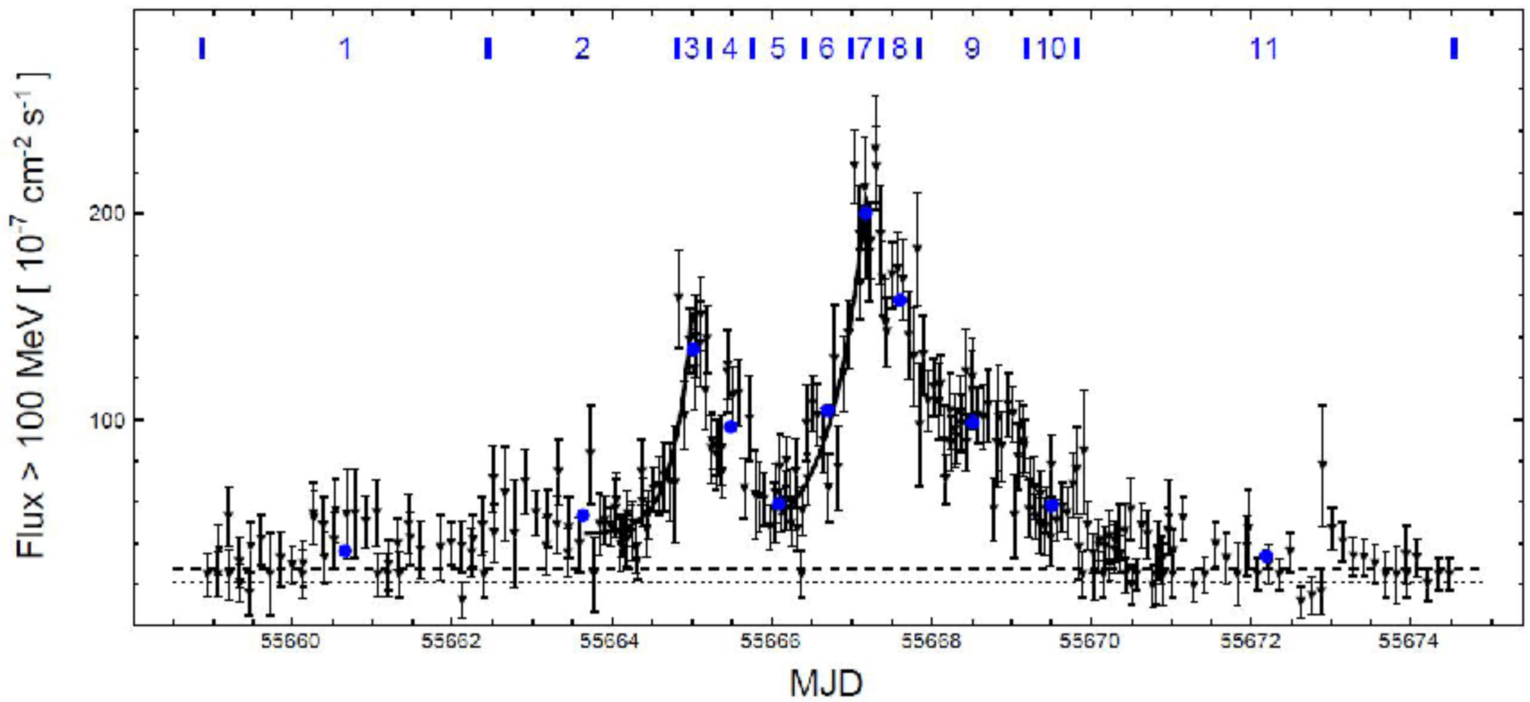

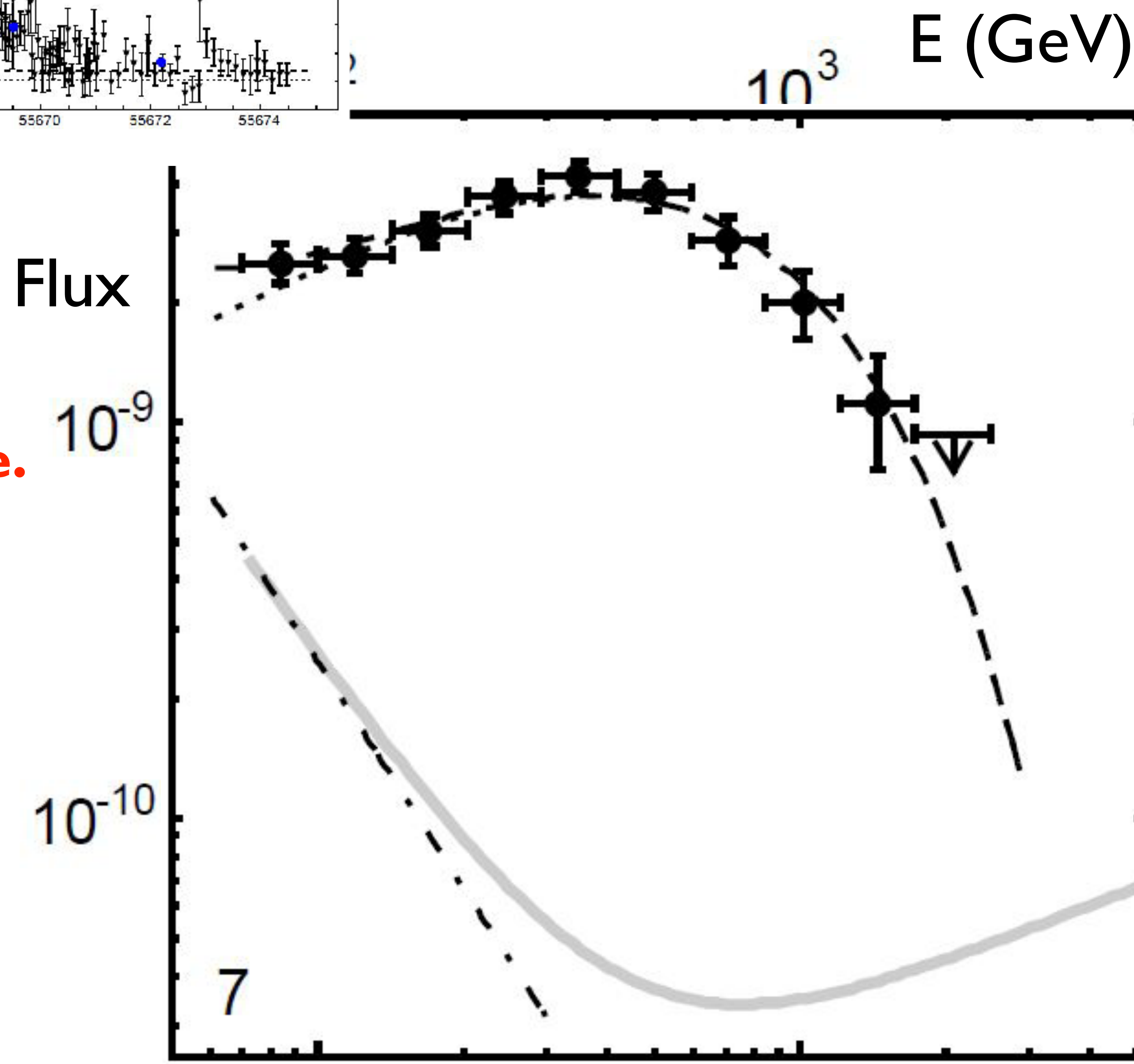

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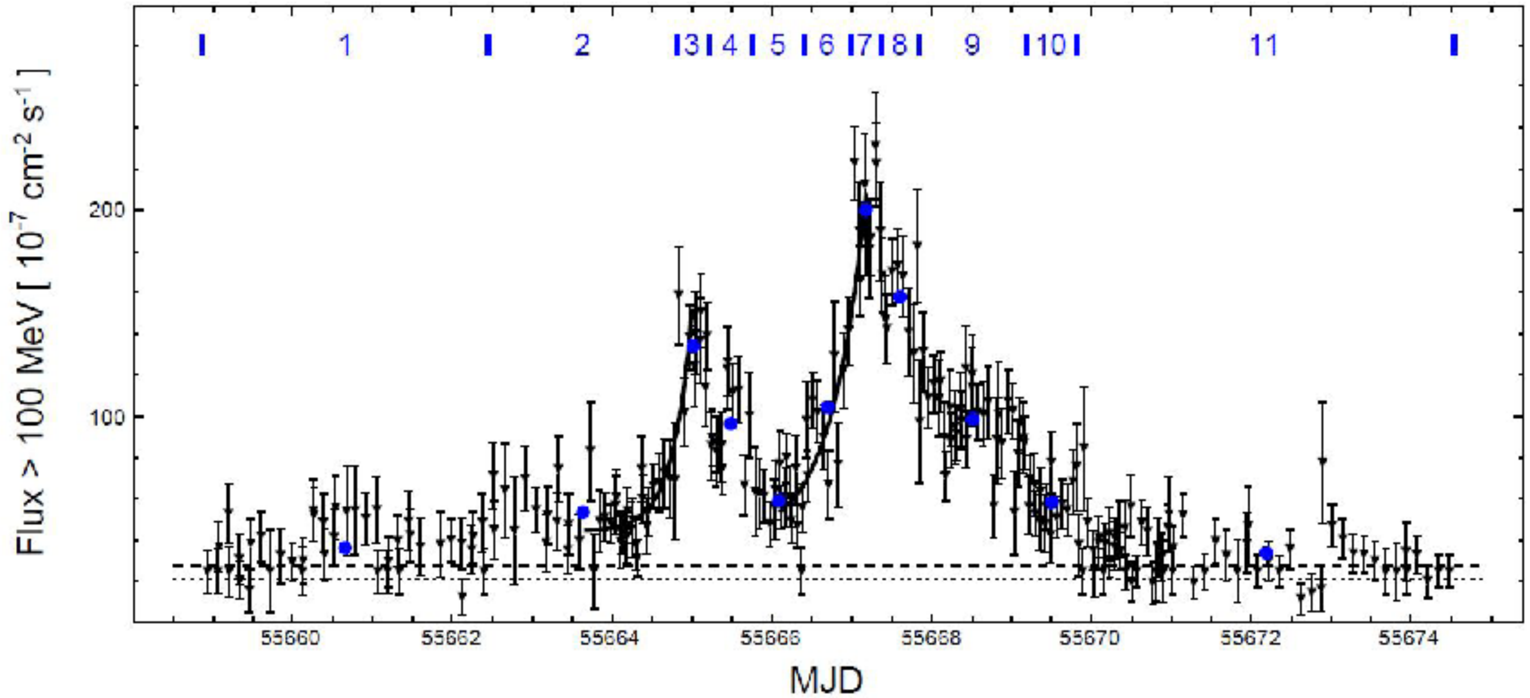

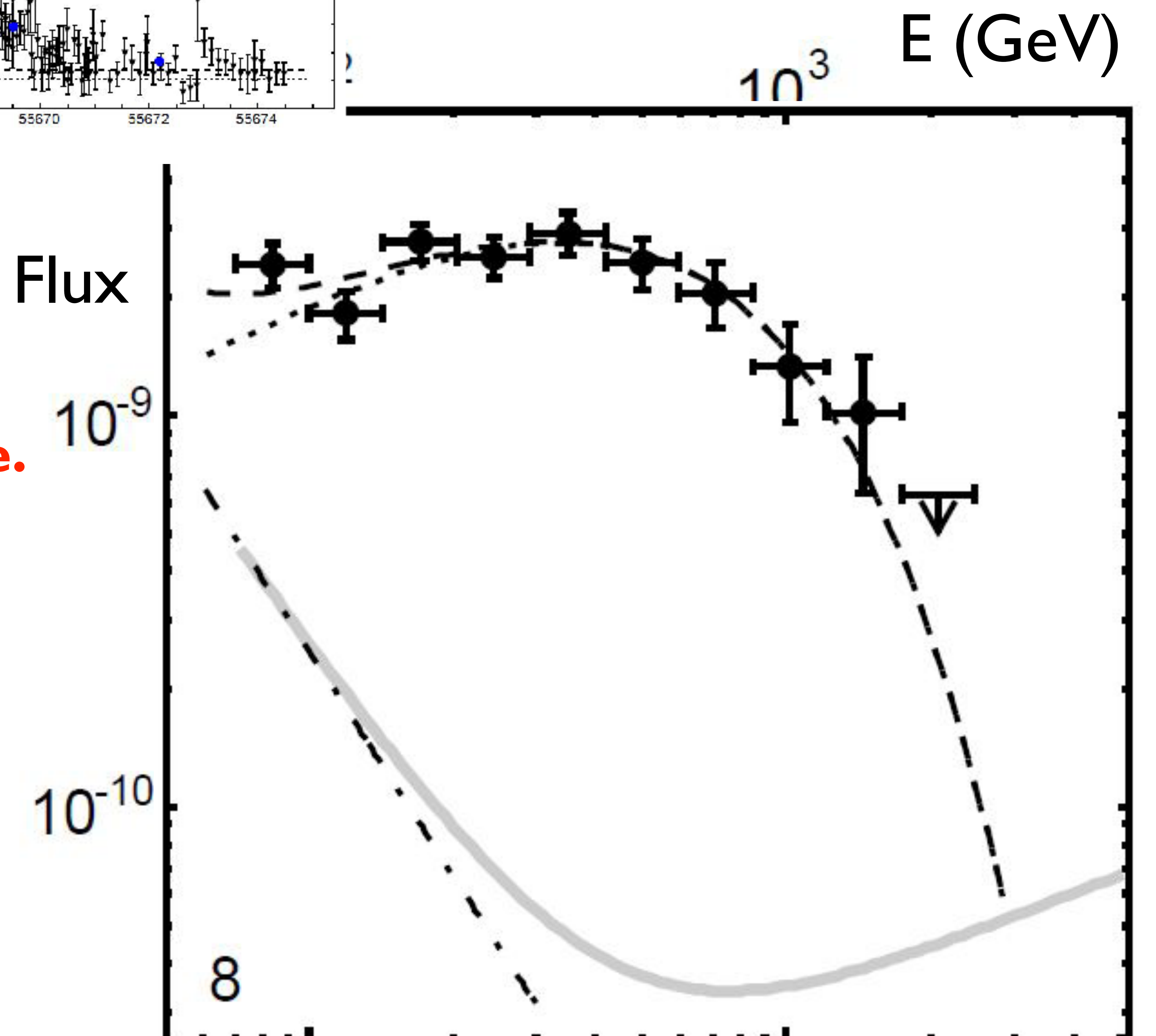

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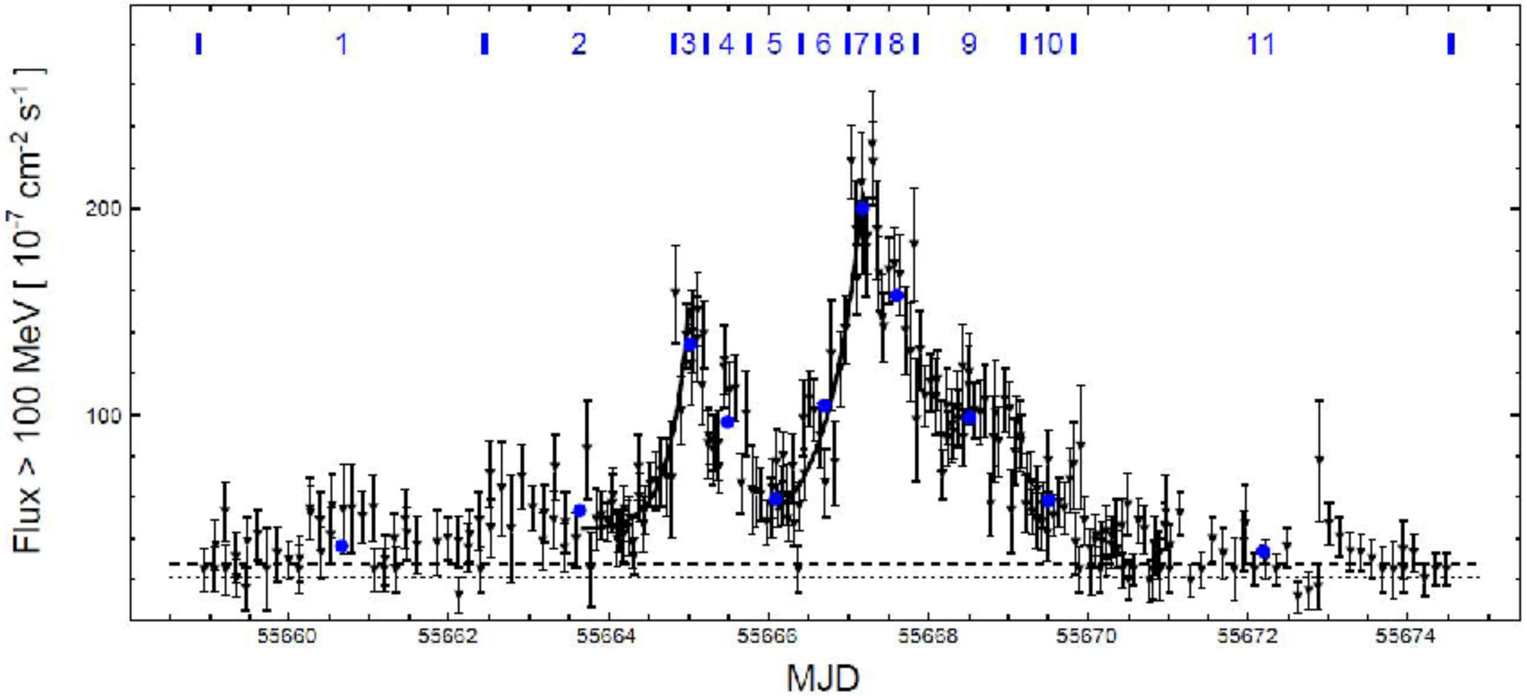

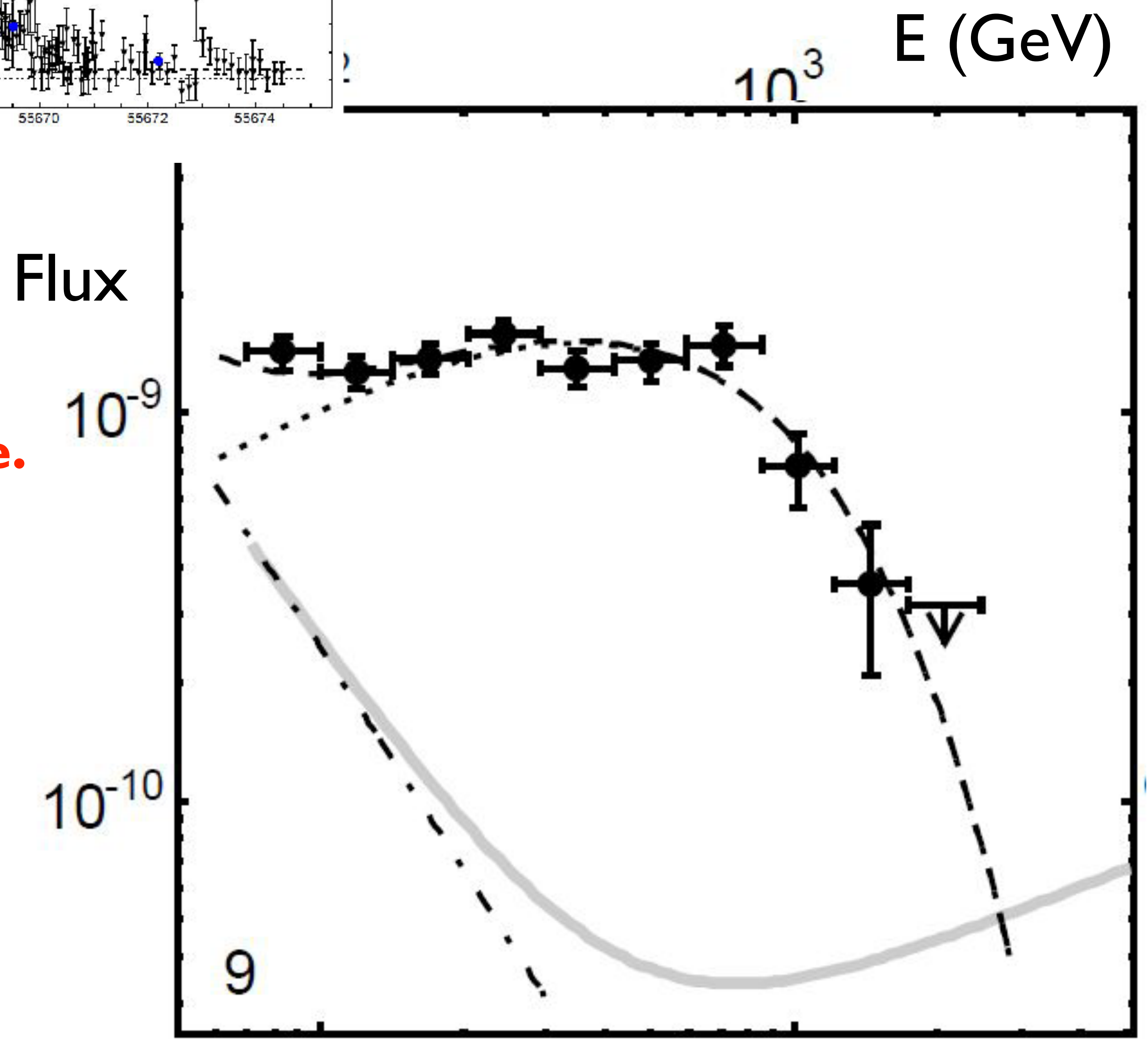

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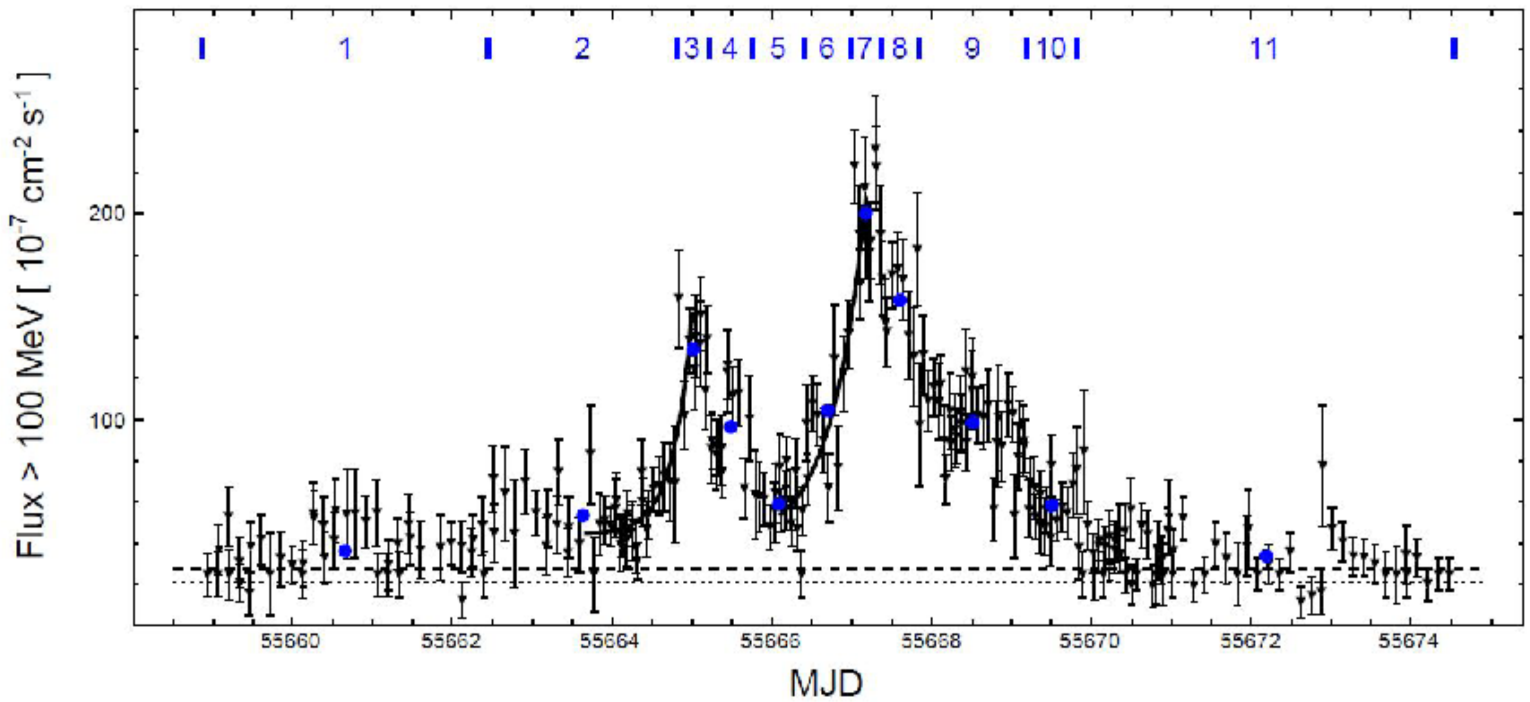

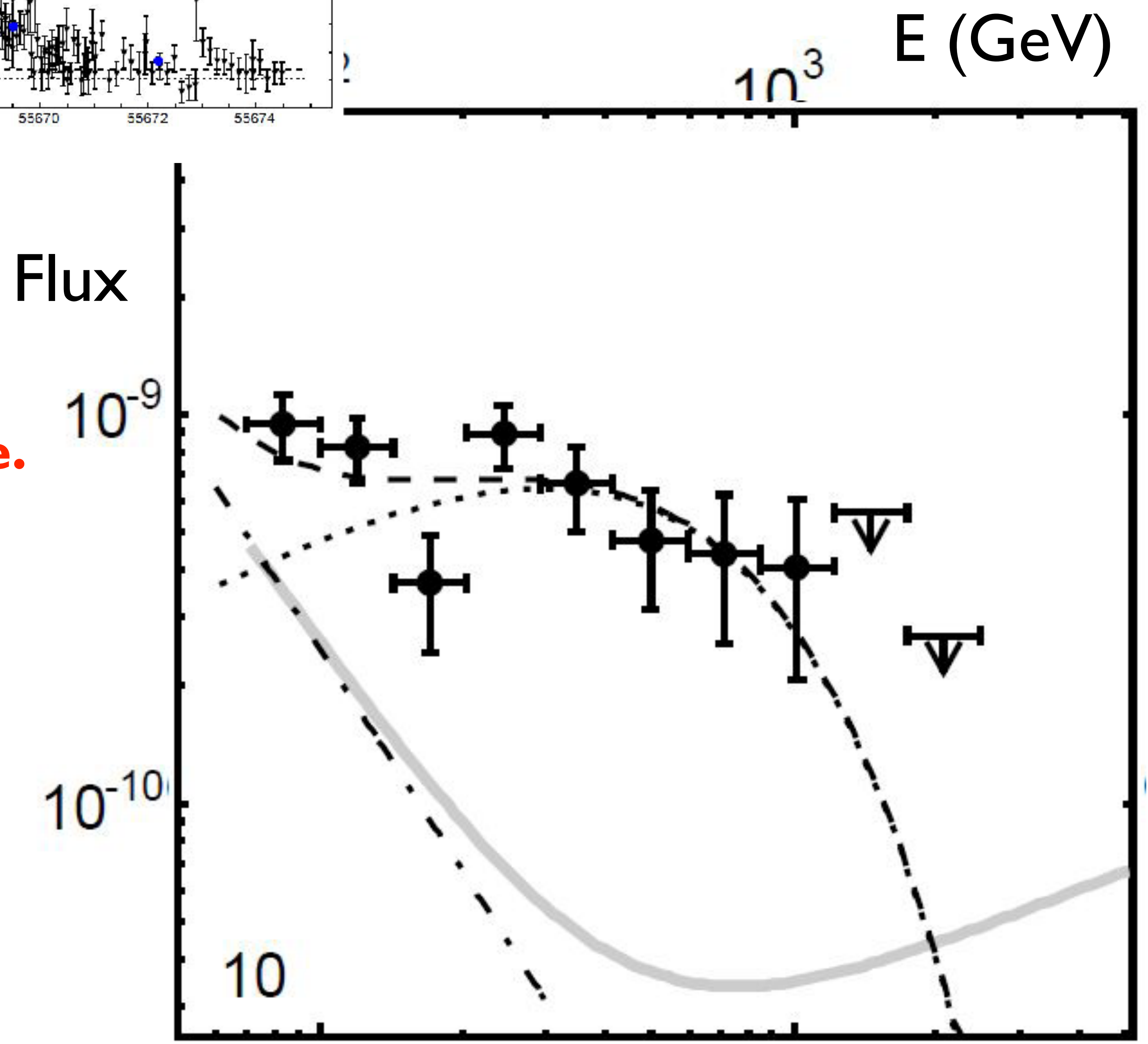

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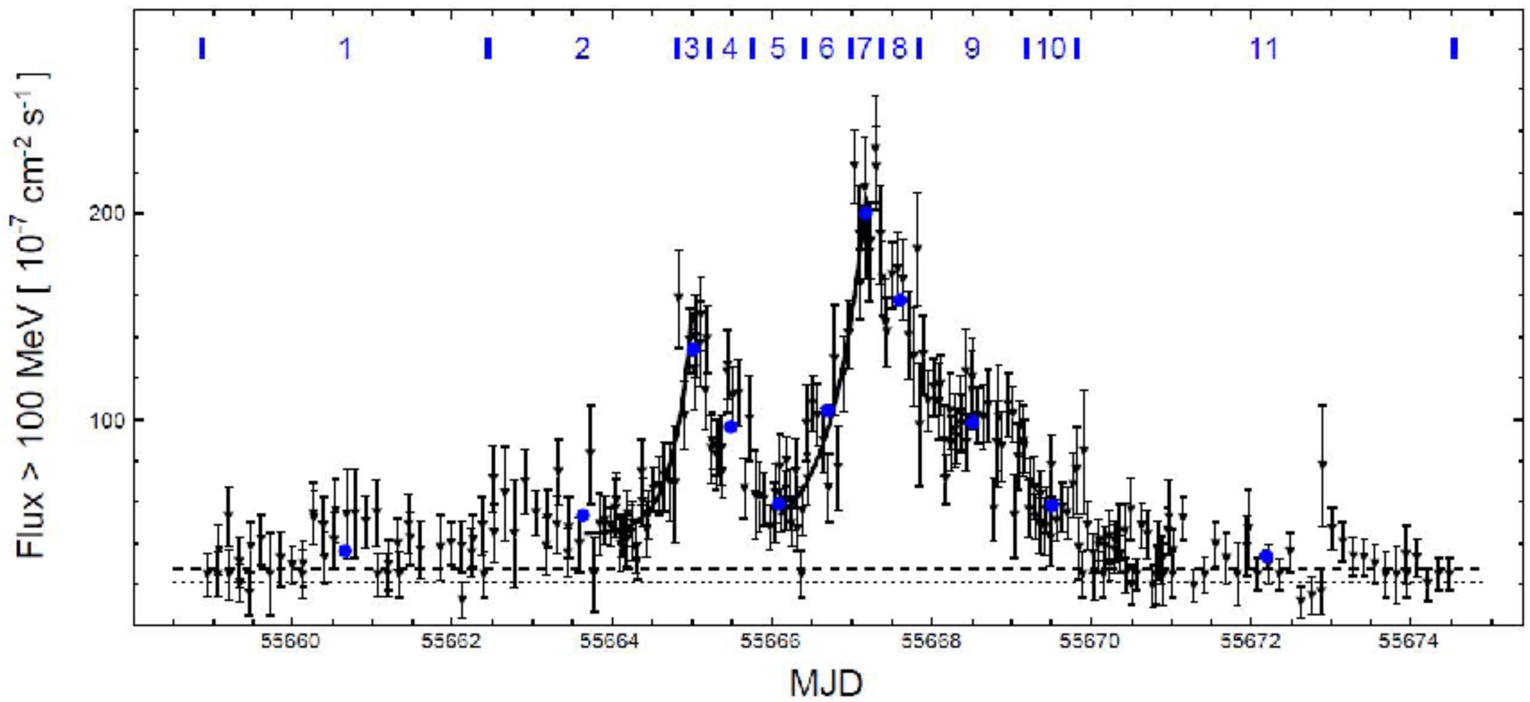
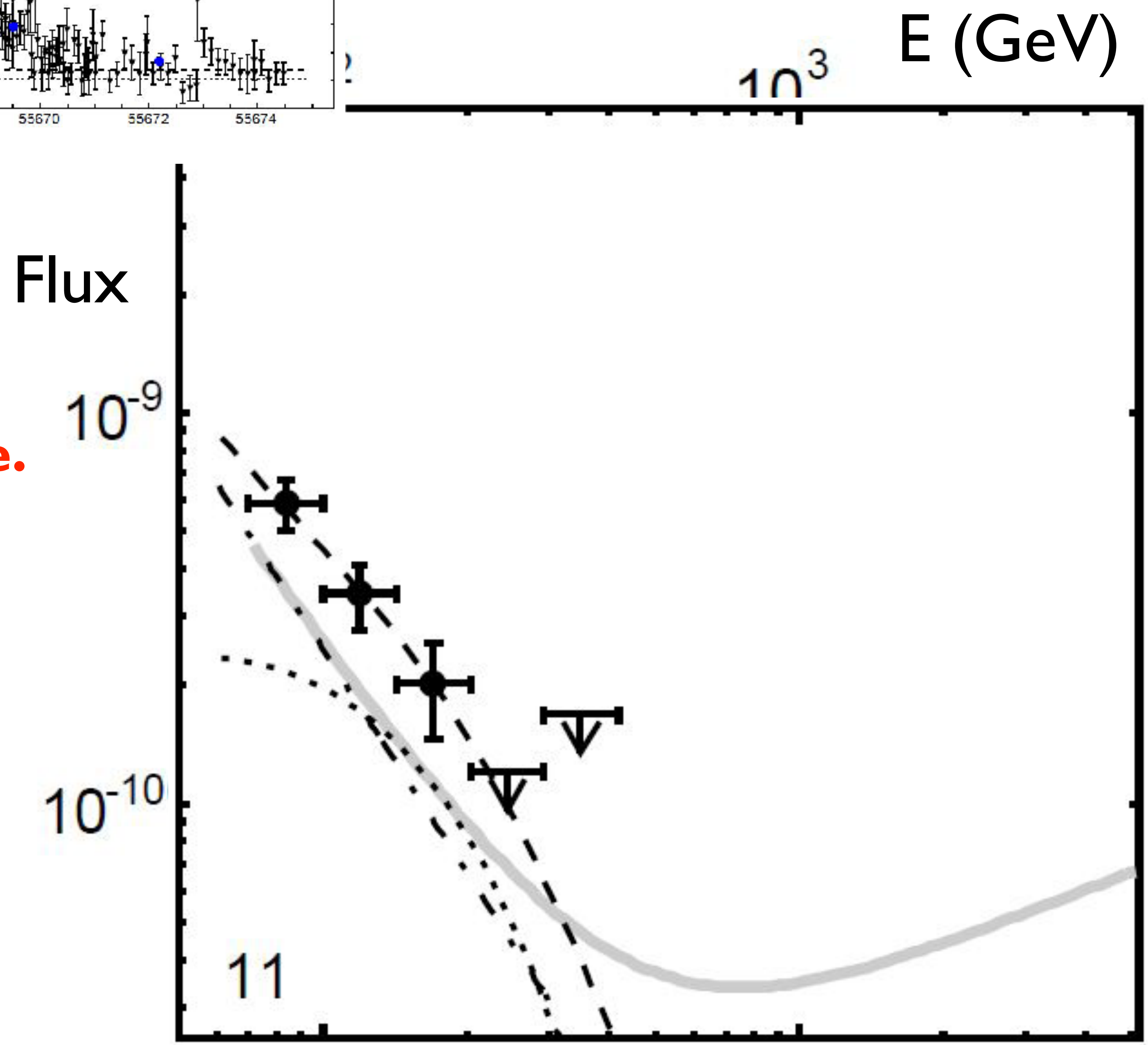




Spectrum varies with time.
Allows study of the
“dynamic processes”
of particle acceleration.

Transients are tremendously helpful:

enhanced fluxes
dynamic processes
correlations in multi-wavelength & multi-messenger studies

use **temporal coincidence**

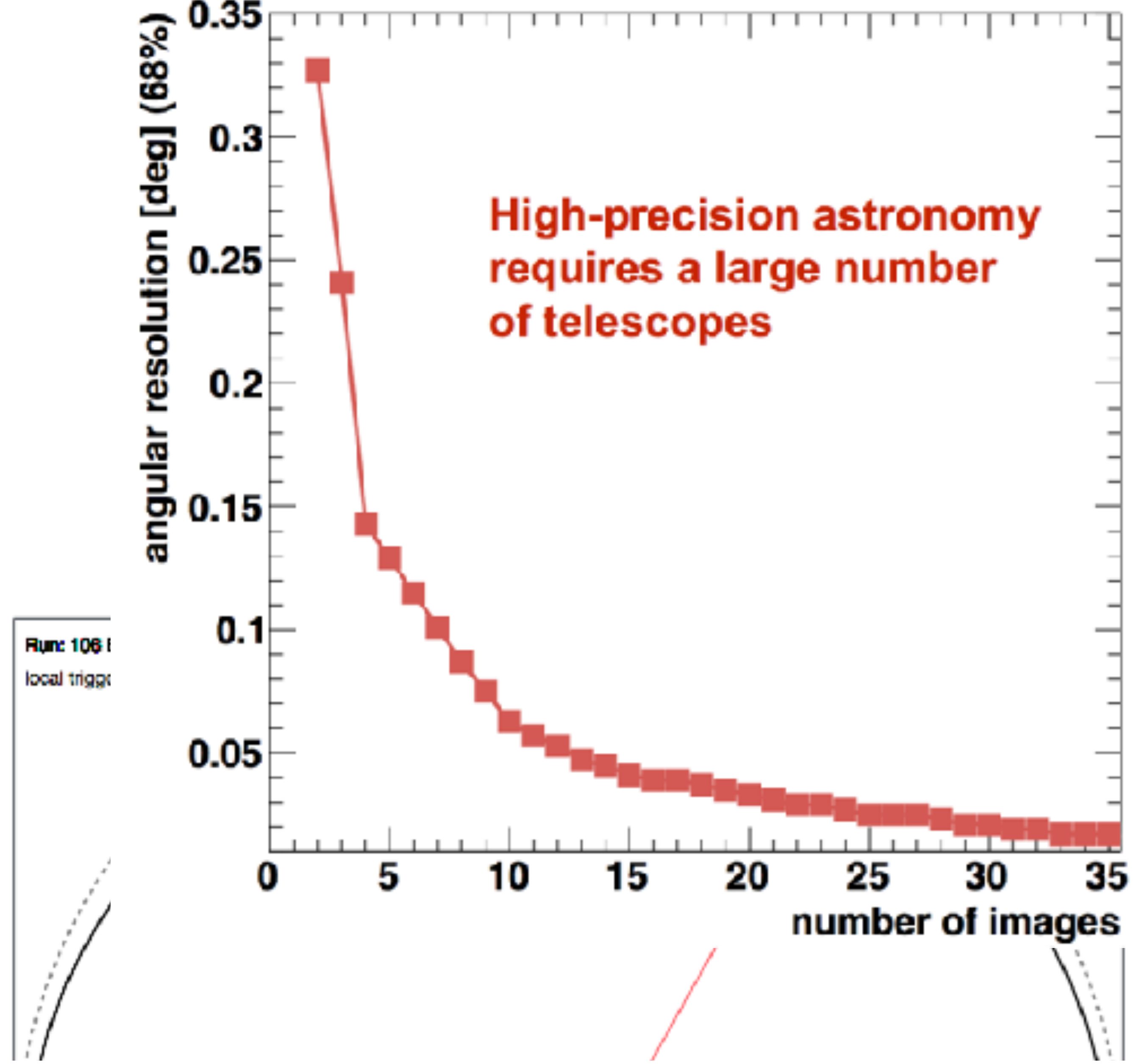
(on top of spatial coincidence)

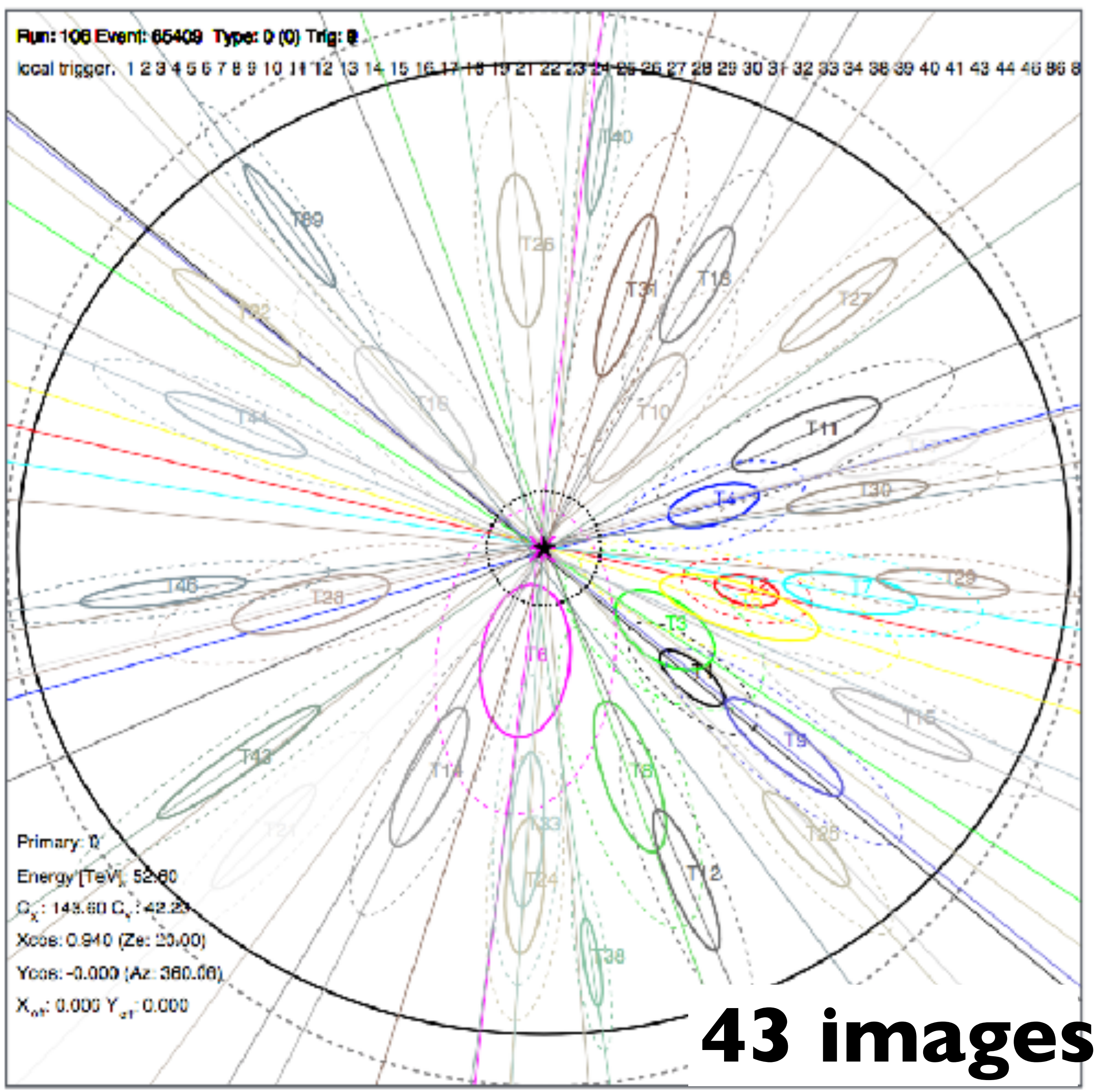
Mutual alerting very important

(see AMON talk by Miguel)

Angular Resolution:

< 0.1° for ≥ 5 images
or for E > 100 GeV (≥ 4 images)

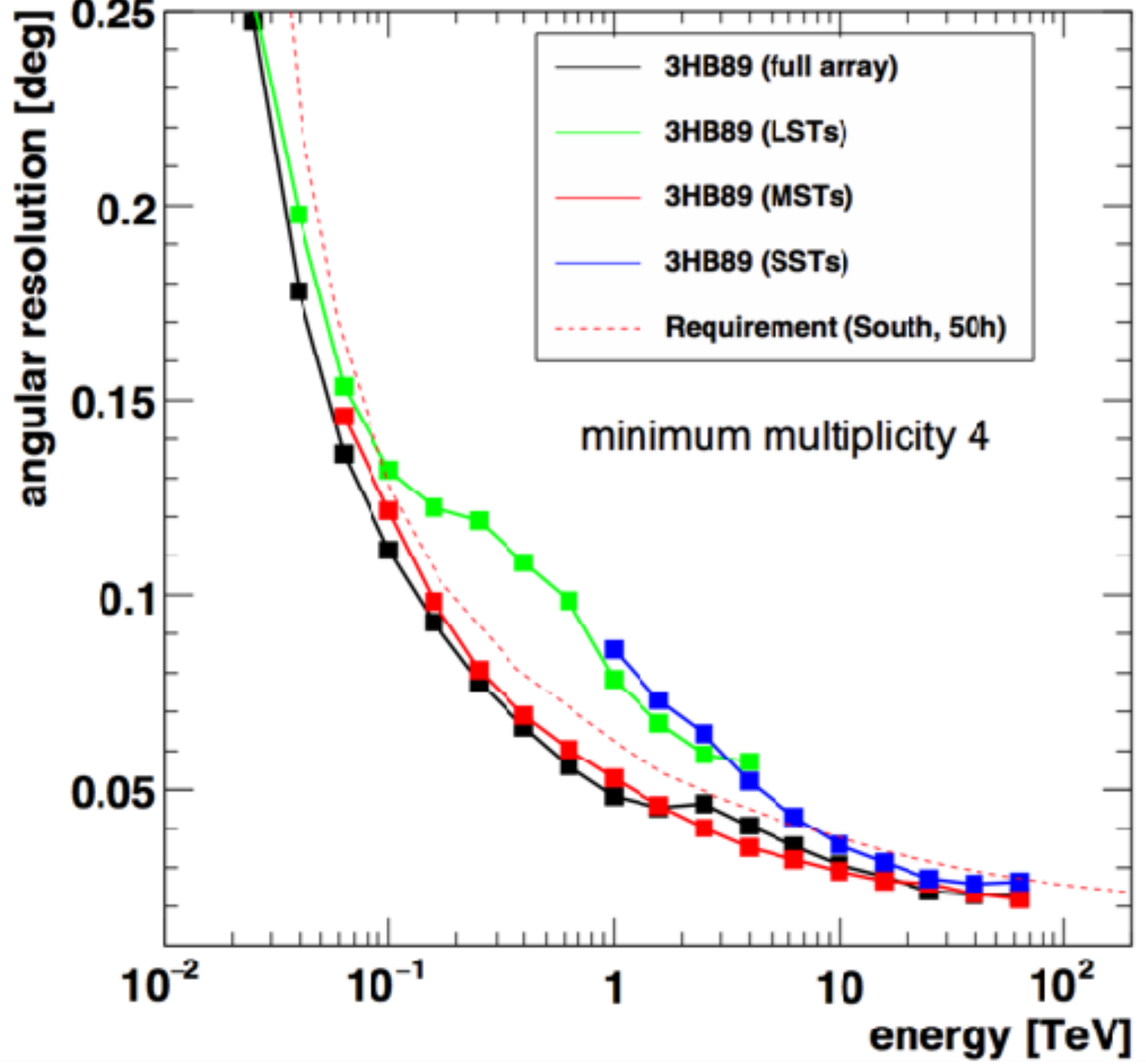


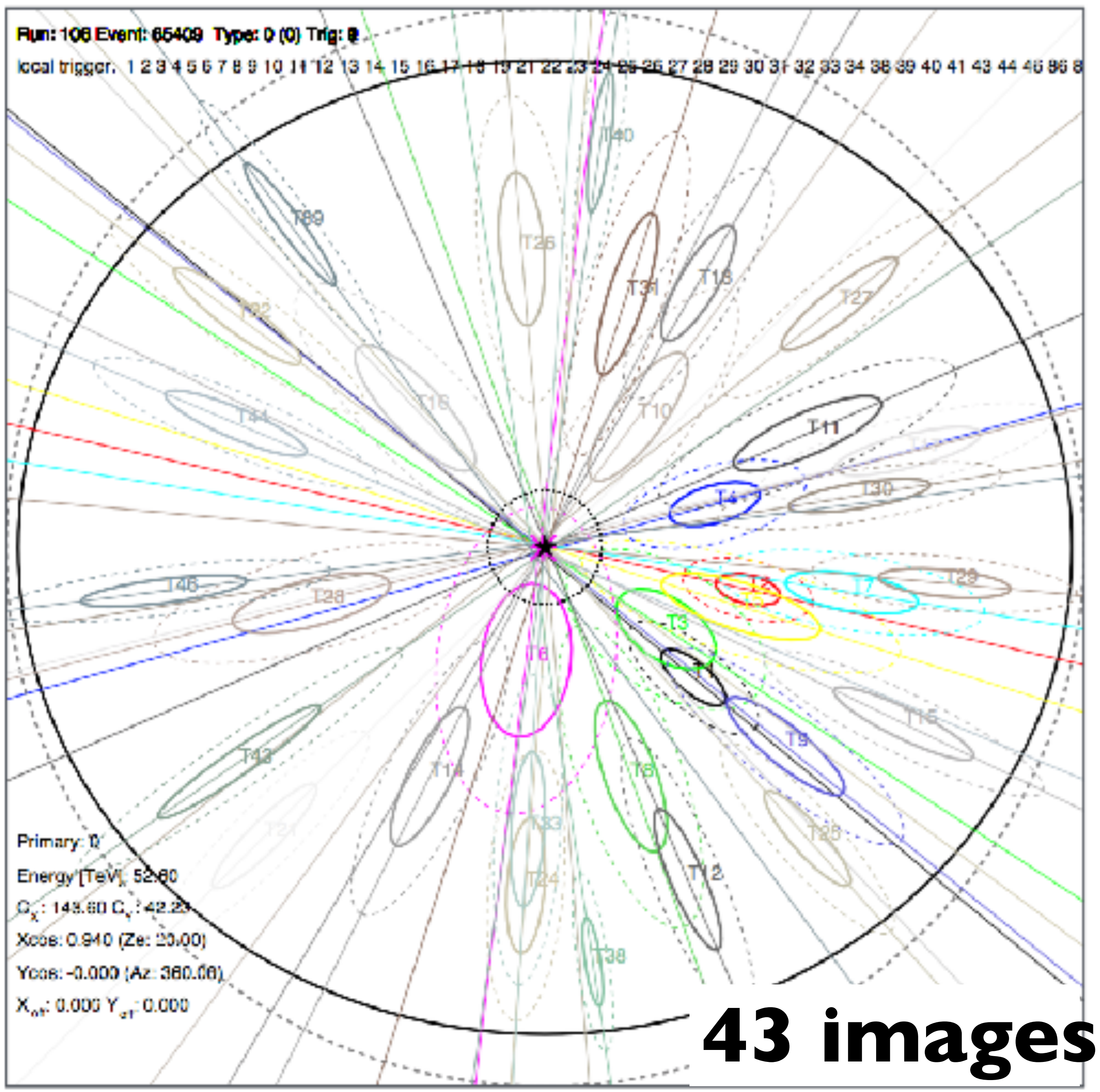


… for morphology studies of extended sources, avoiding source confusion

Angular Resolution:

< 0.1° for ≥ 5 images
or for E > 100 GeV (≥ 4 images)





43 images

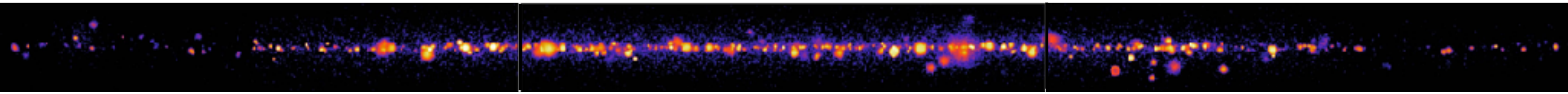
… for morphology studies of extended sources, avoiding source confusion

CTA prognosis: >1000 new sources

galactic disc

CTA prognosis:

~600 sources



GC

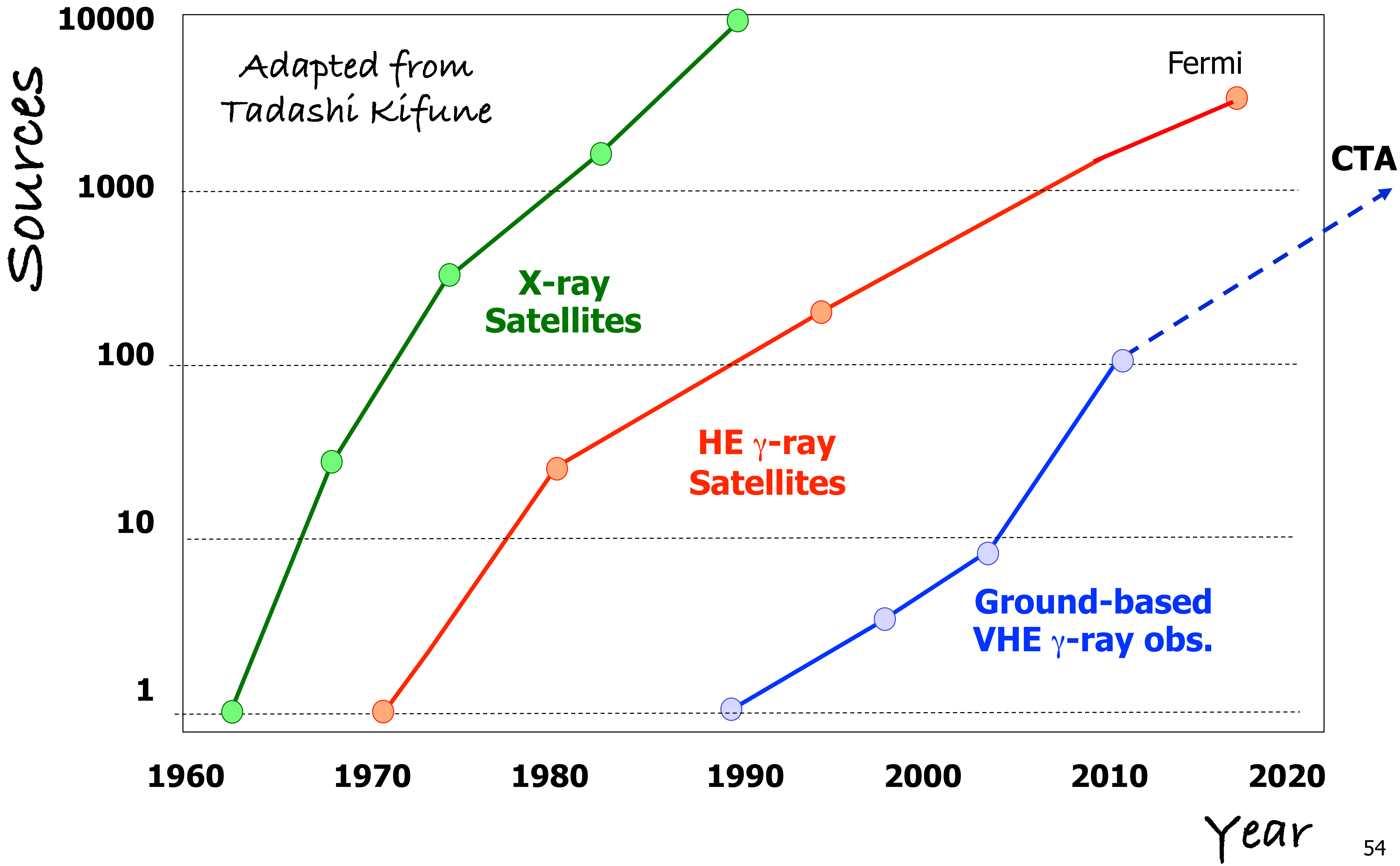
90

-90

galactic + extragalactic: ≥ 1000 sources

Source Number

Gamma-Ray Astronomy goes "mainstream"



Neutrinos

Neutrino Interaction Cross Section:

$\mathbf{10^{-42}\ cm^2}$ x E_ν / MeV

… a blessing and **a curse**

Large, natural volumes become part of the detectors:

ice shields,

oceans,

...

IceCube at the South Pole

1 km^3 5200 sensors,

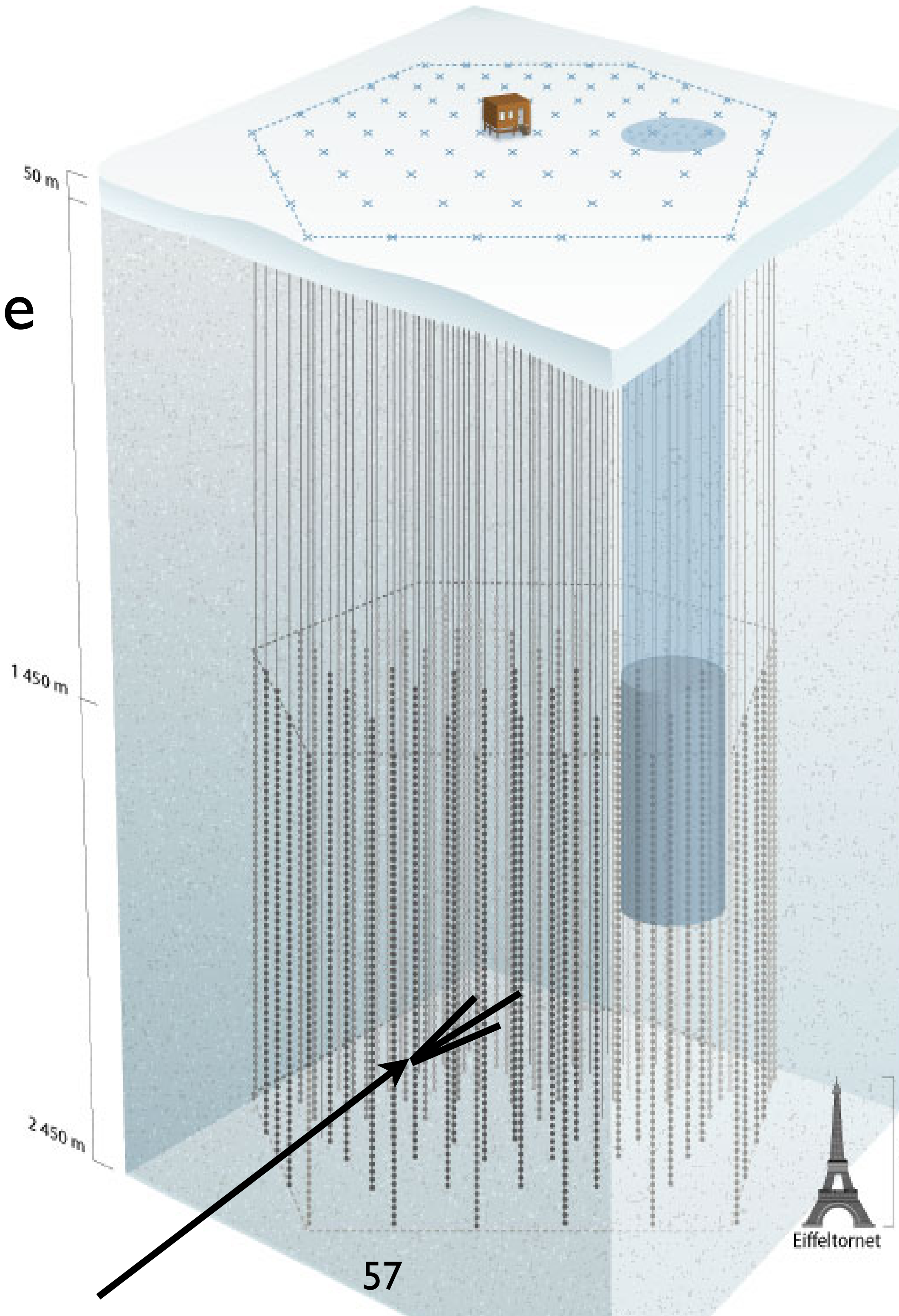
~2 km deep in ice

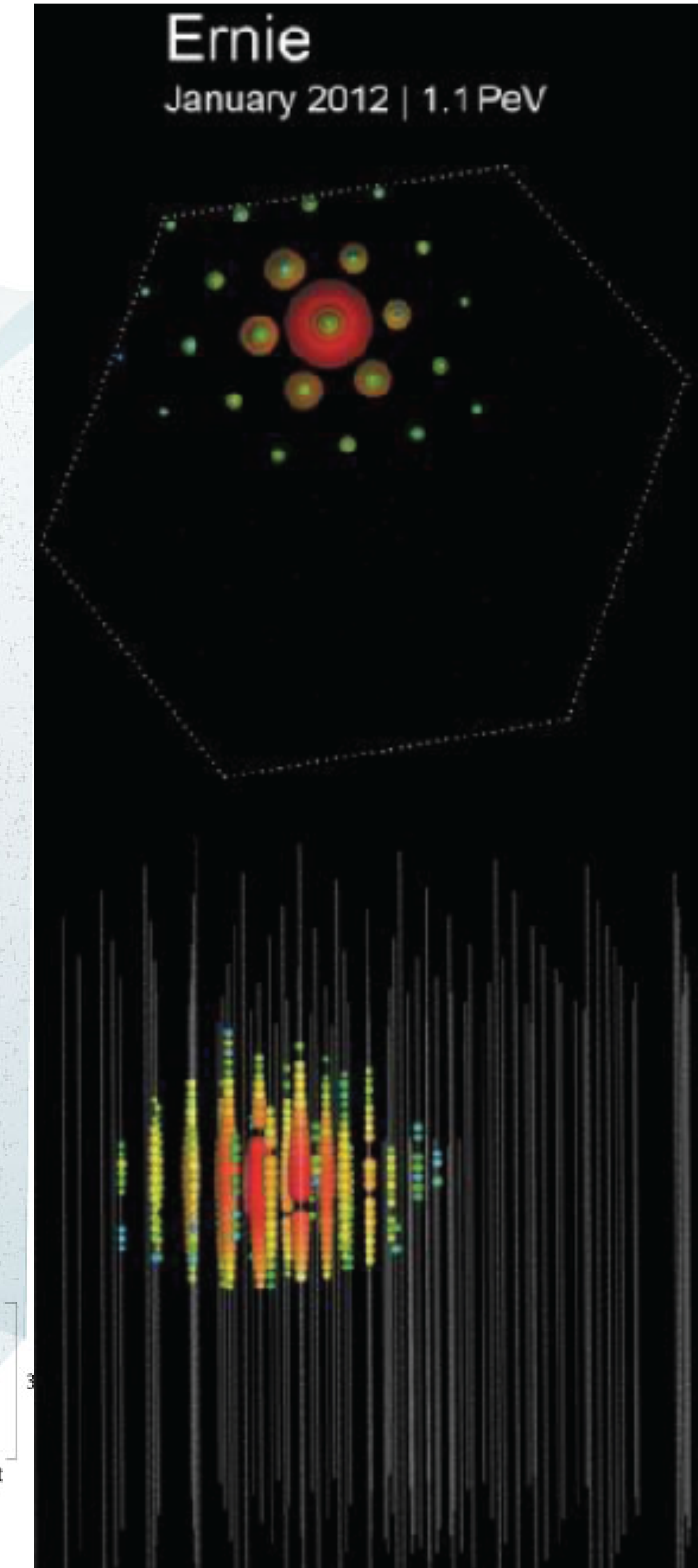
Detector size:

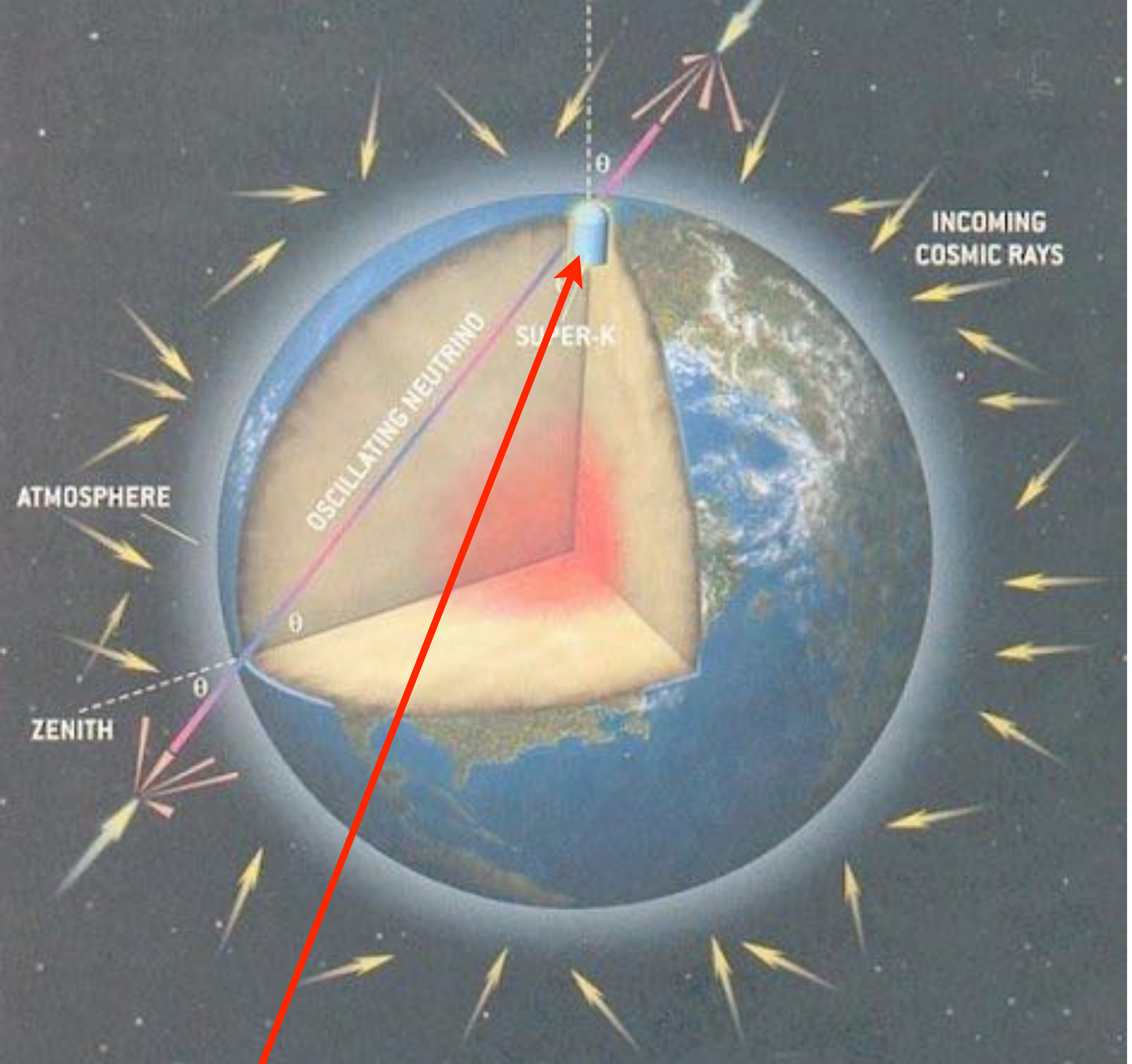
~1.000.000.000 m^3 ice

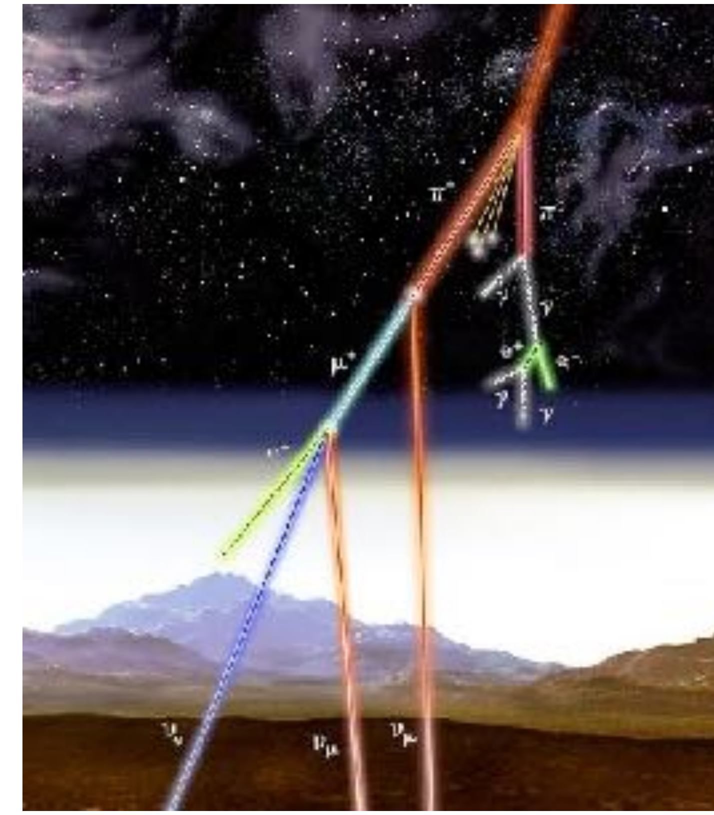
Neutrinos go through the earth.

($E \approx 10^{11}$–10^{15} eV)









astrophysical ν

How to tell apart astrophysical / atmospheric neutrinos?

At energies > 10^{15} eV astrophysical ν are expected to dominate the atmospheric ones.

"coincident appearance"
"excess of events"

atmospheric ν:

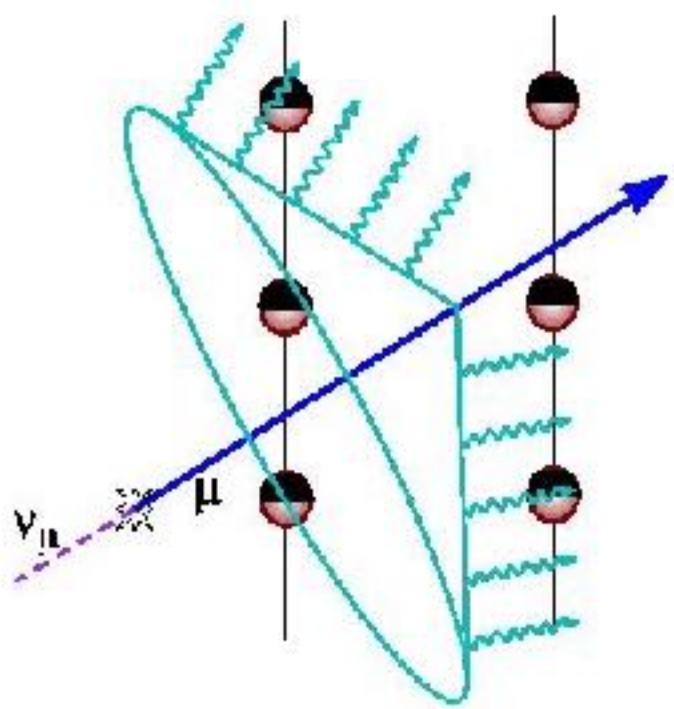
CR air showers produce many νs.
(diffuse background)

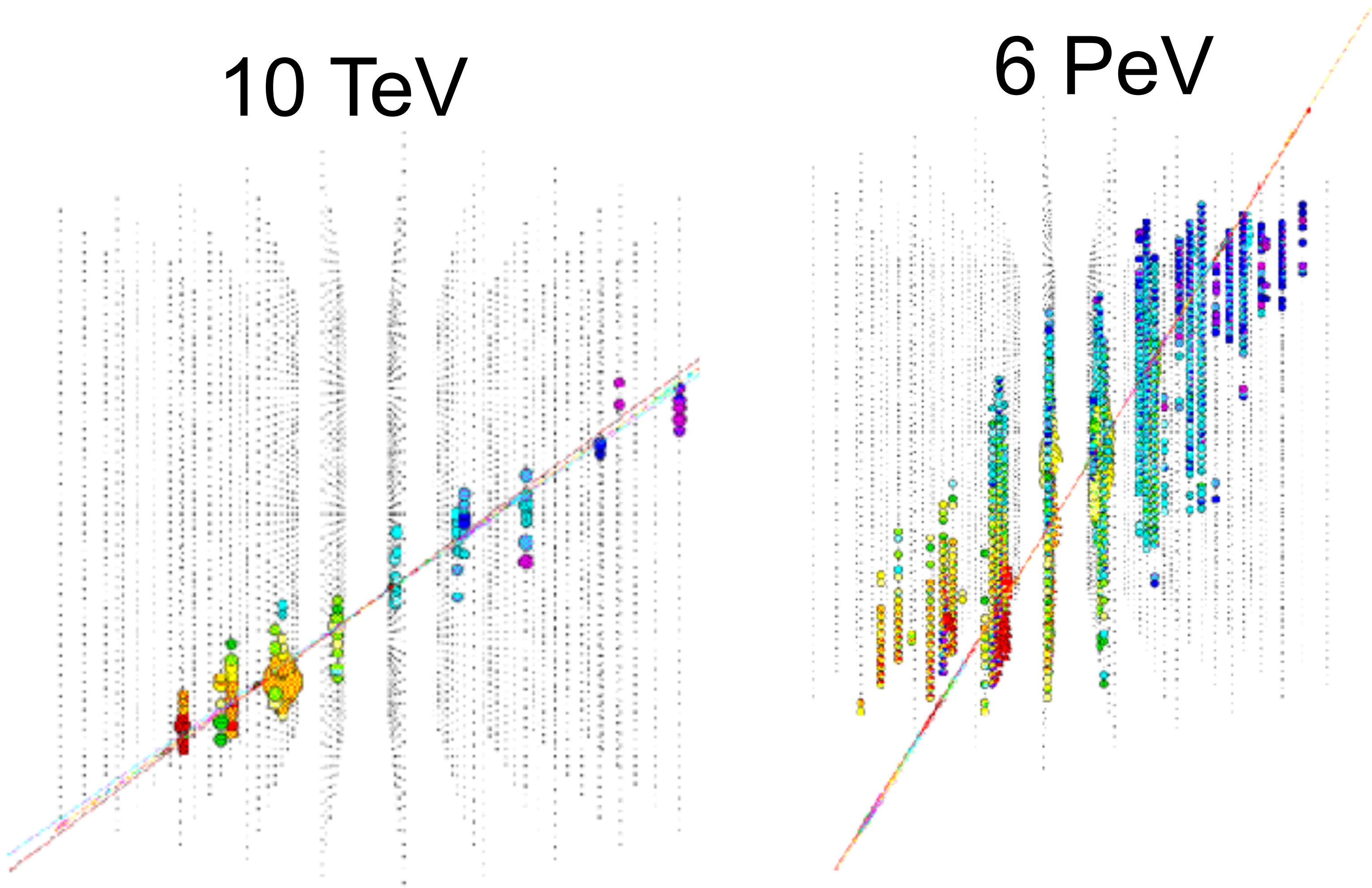
Neutrinos create charged particles
which in turn produce Cherenkov light.

Muon-tracks

good pointing (<1 degree)

large event rates due to long muon tracks



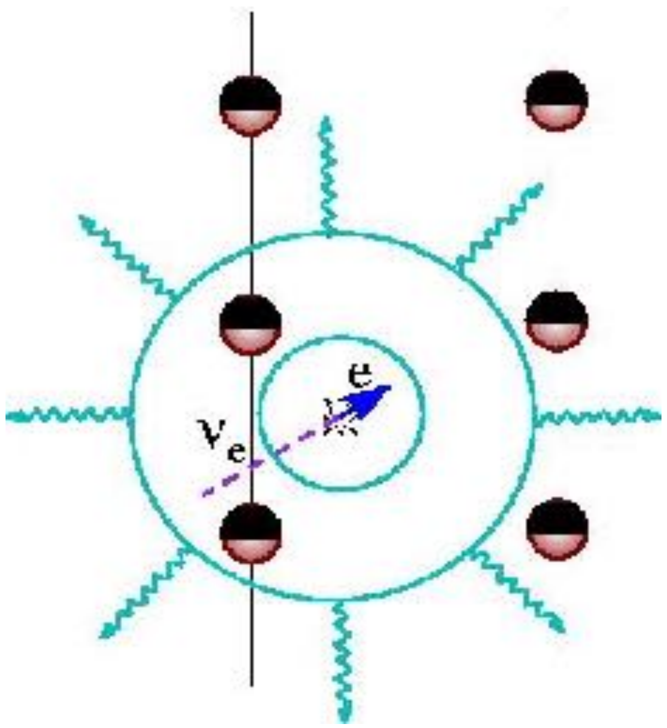


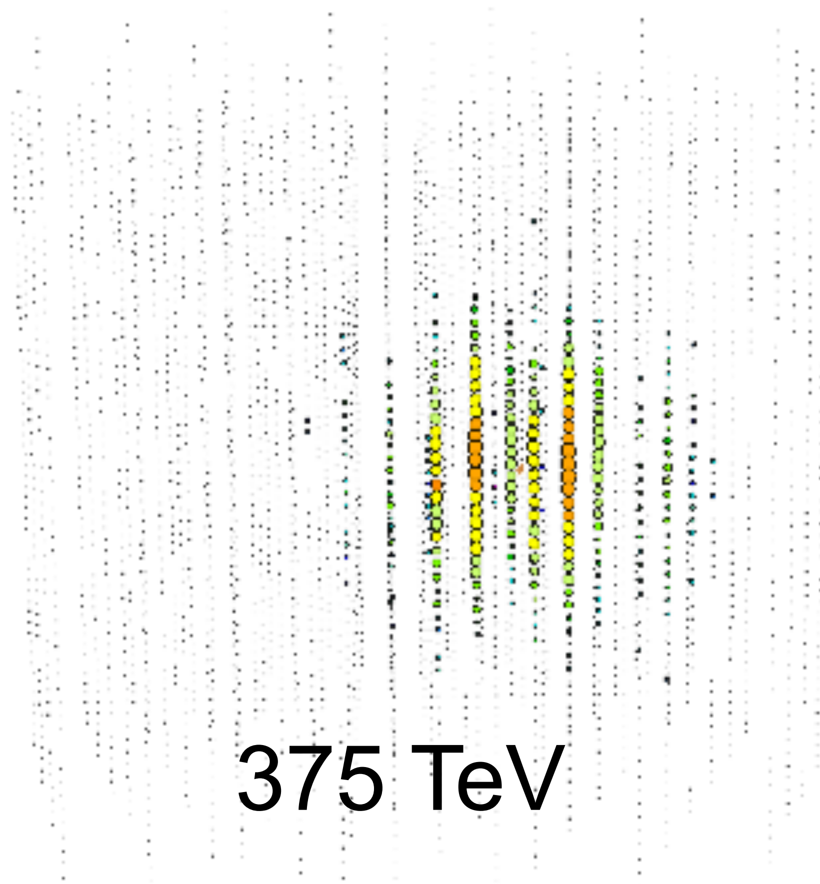
signature of ν_μ

Particle cascades

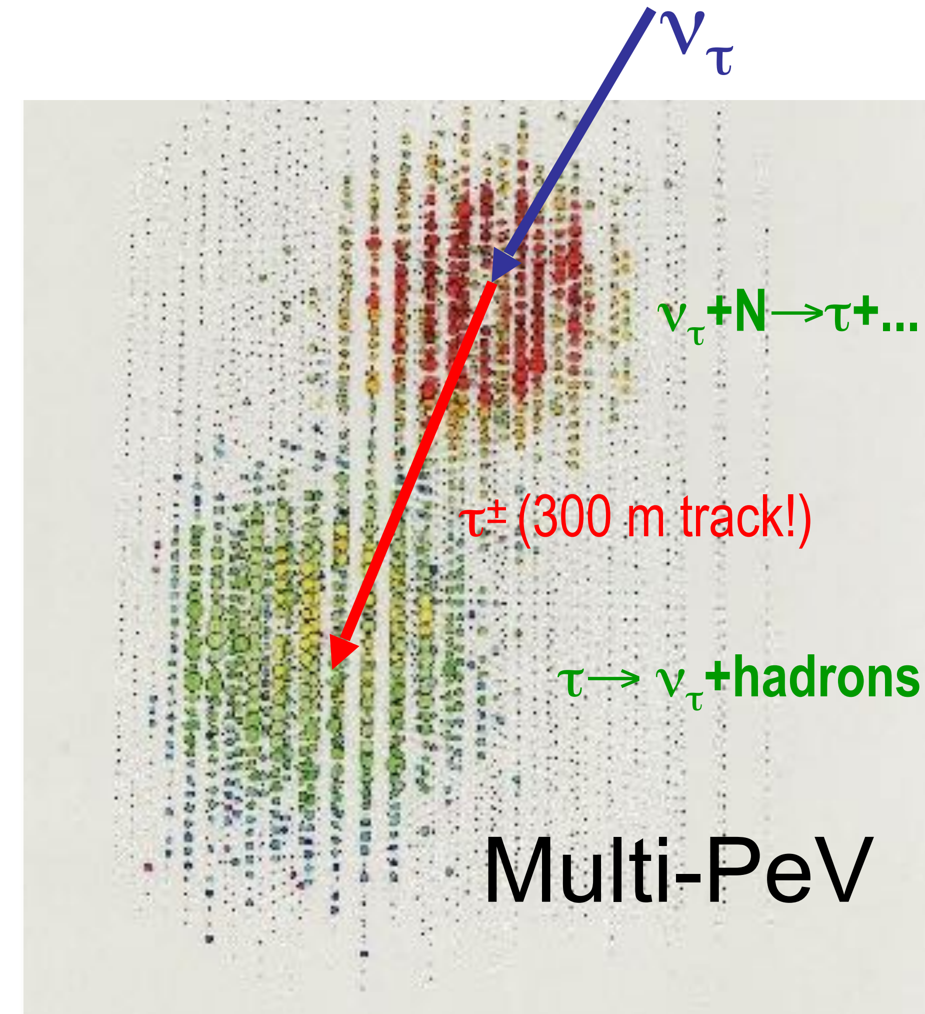
ν_e , ν_τ

good energy resolution,
little background





signature of ν_e

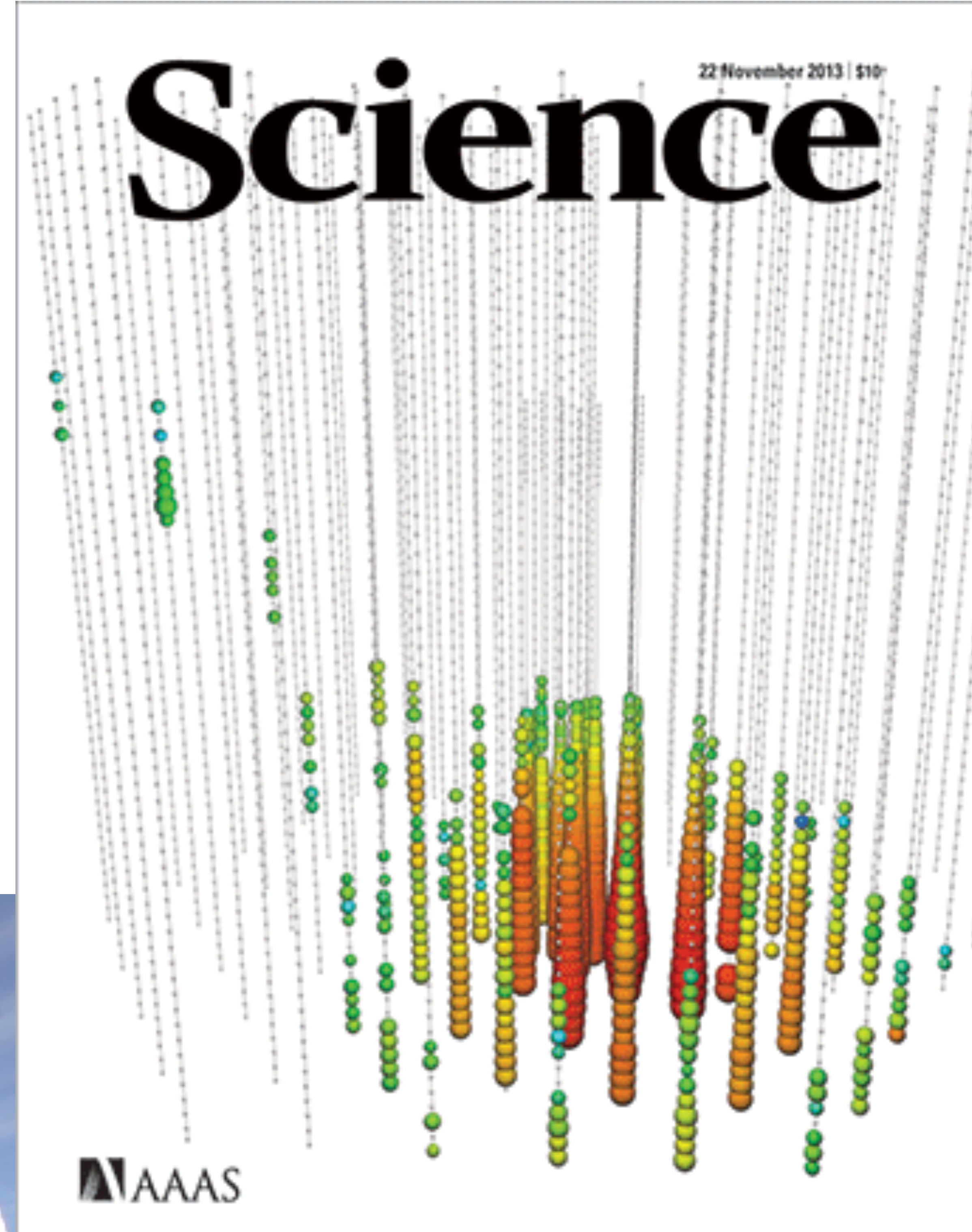


signature of ν_τ

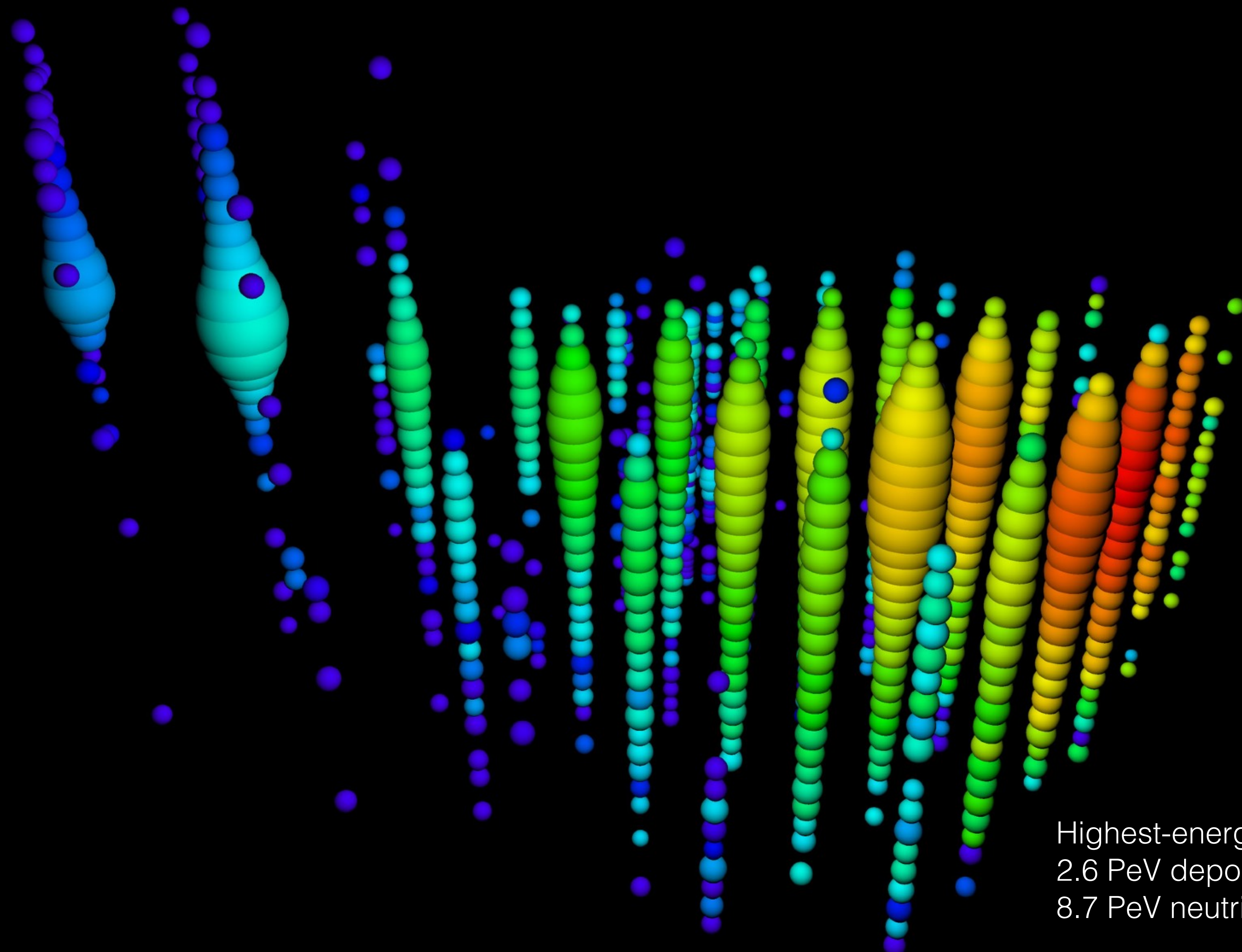
28 high-energy νs

Clear evidence for astrophysical origin

($>5\sigma$)



Nov 2013

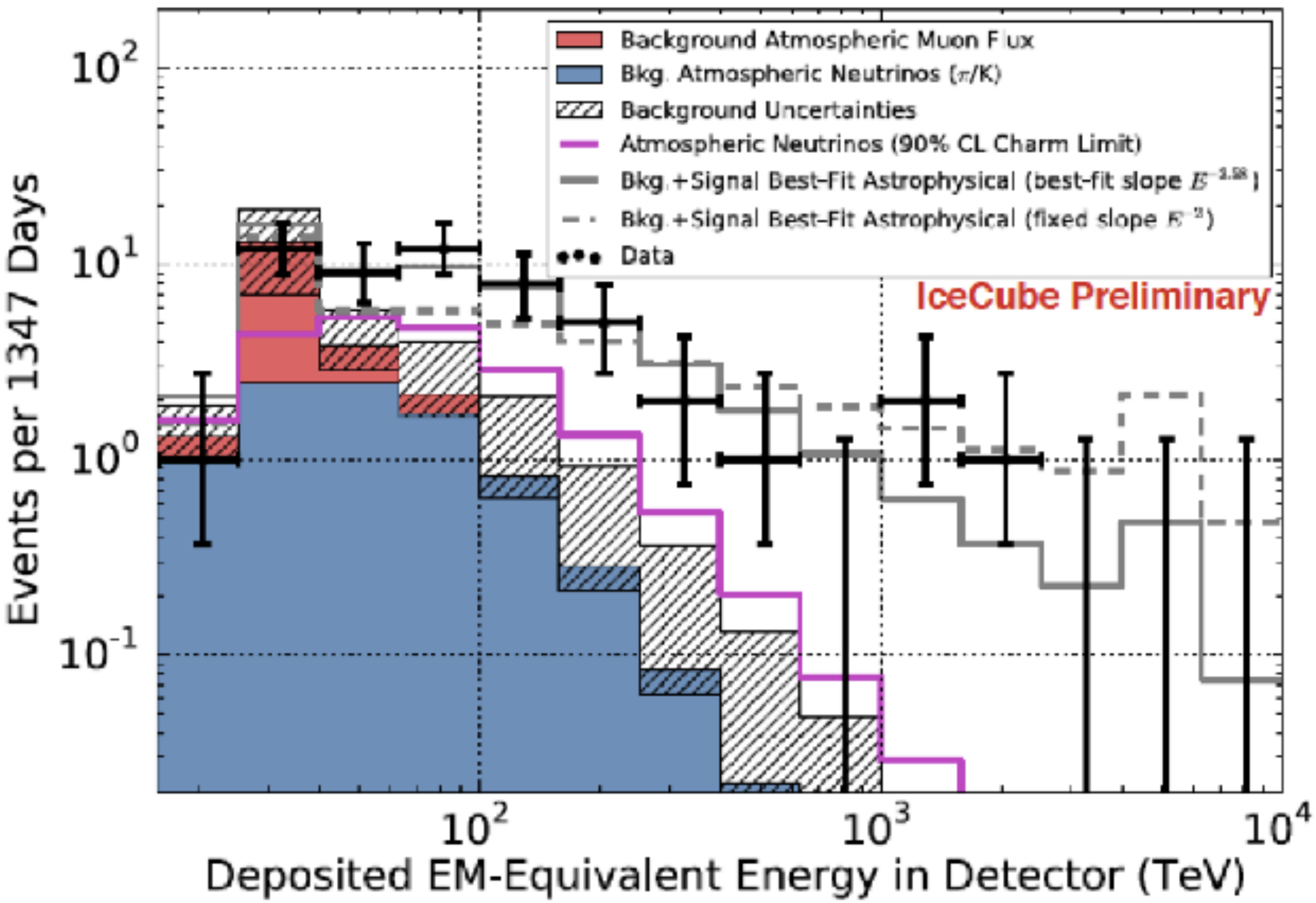


Highest-energy neutrino-induced muon
2.6 PeV deposited energy
8.7 PeV neutrino energy (median)

Astrophys.J. 833 (2016) no.1, 3

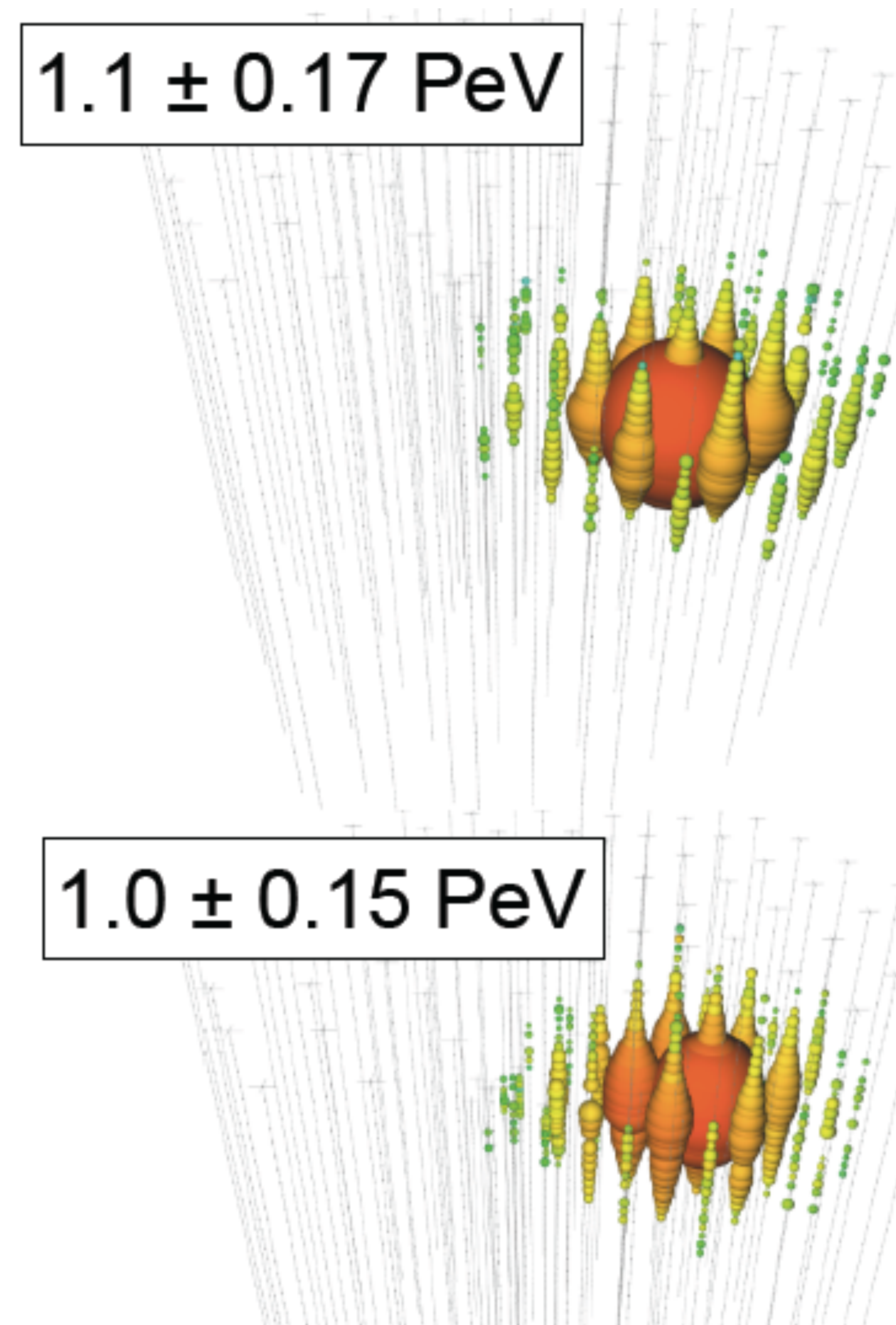
Spectrum

54 events observed,
20±6 expected from atmosphere

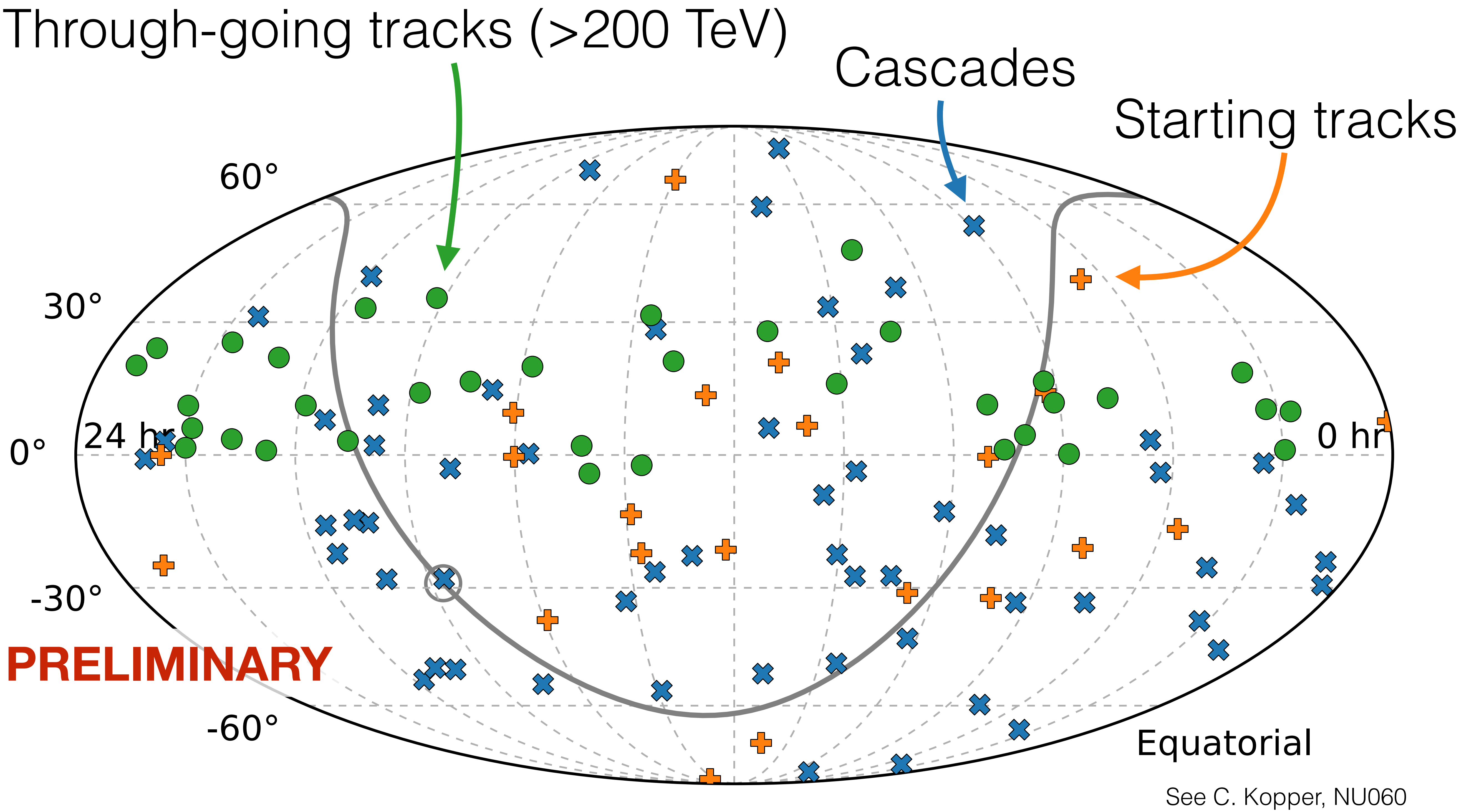


now: ~7 σ evidence for
extra-terrestrial ν

$E \geq 10^{15}$ eV



High-energy neutrinos on the sky



No evidence of clustering in high-energy neutrino directions (> 50% astrophysical).

~60 astro neutrinos, no sources (yet) … **must be largely extragalactic**

2013: The birth of Neutrino Astronomy

- **extra terrestrial**
- neutrino types
- neutrino properties
- studies on source classes

Possible Sources?

Blazars (AGN): bright/powerful in gamma rays
predicted to are neutrino sources

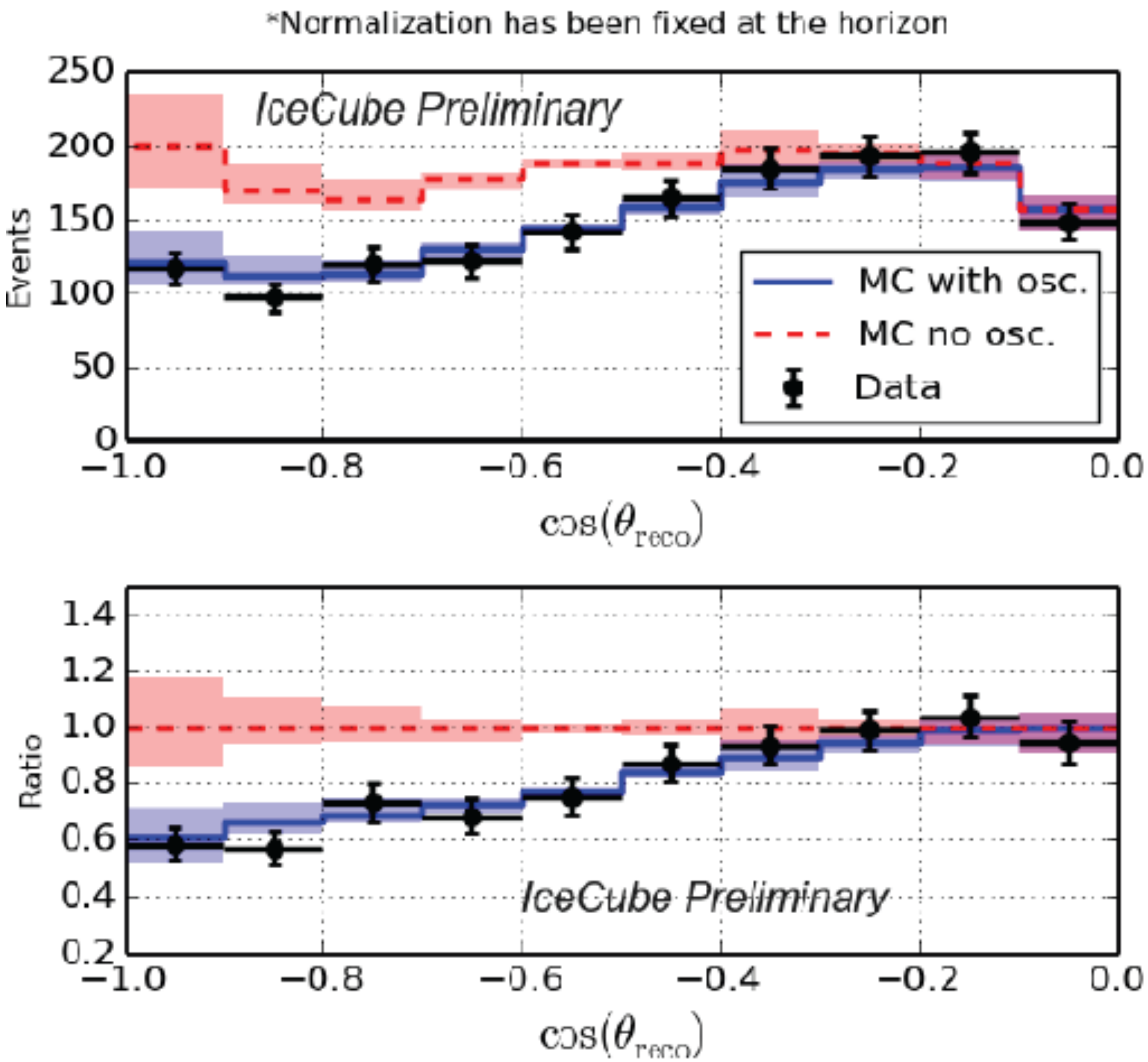
GRBs: very bright in gamma rays, transient

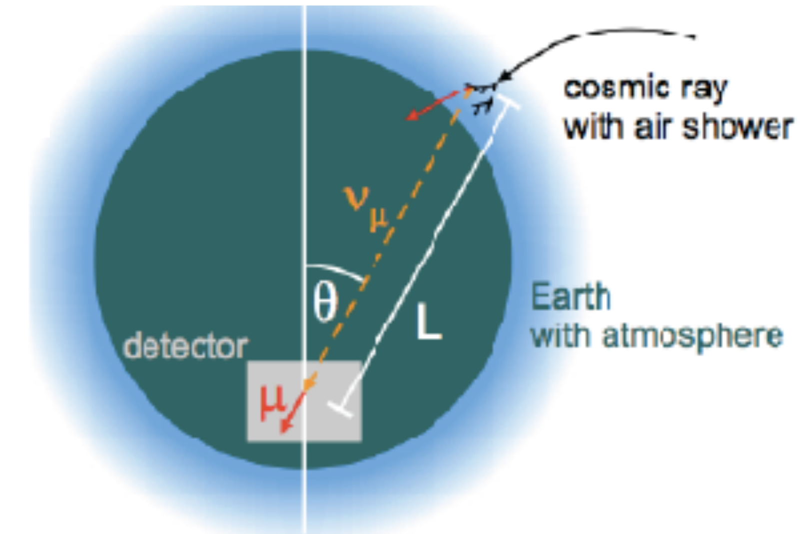
… but comparison of neutrino positions with Blazars / GRBs
rules them out as major sources.

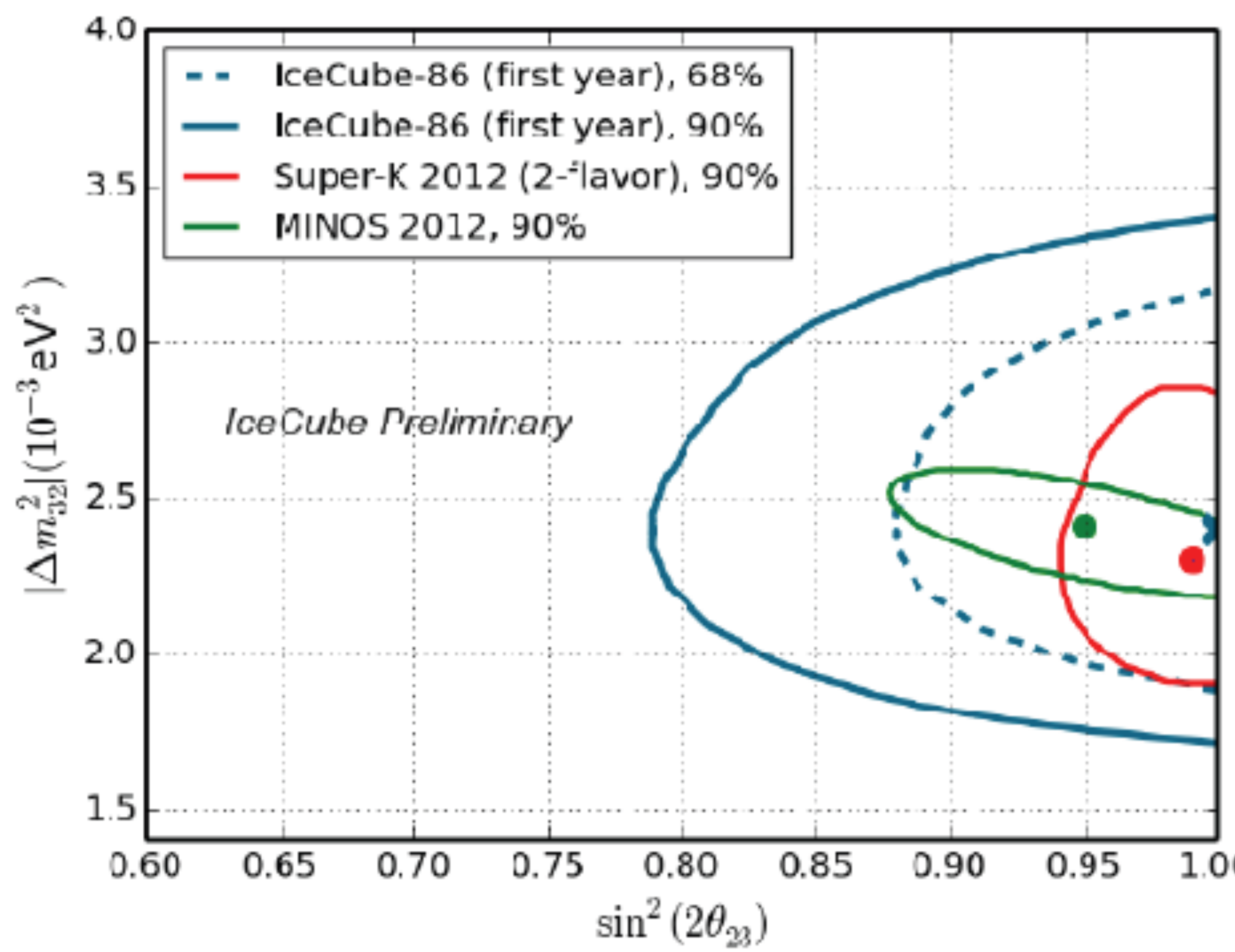
GRBs < 1% of IceCube neutrinos
Blazars < 27%

So, what are the sources of the high-energy neutrinos ???

Neutrino properties (oscillations)







Each astro neutrino points back at its source.
(track like events: <1 deg precision)

Why don't we see a "strongest source" with more than a few neutrinos?

Perhaps, there are very many sources,
but with so low fluxes that most give us
0 neutrinos,
few give us one neutrino,
none gives us more than one.

Neutrinos reach us from the whole universe.
There are very many sources….

Not much to learn on sources, if on has an isotropic sky and no more than 1 neutrino per source.

Need much better (100x ?) sensitivity
for more neutrinos
source identification

(without loss of quality)

Ice Cube gen2 ? Price cannot go up 100x (wrt. IceCube)
Is 10x improvement good enough?

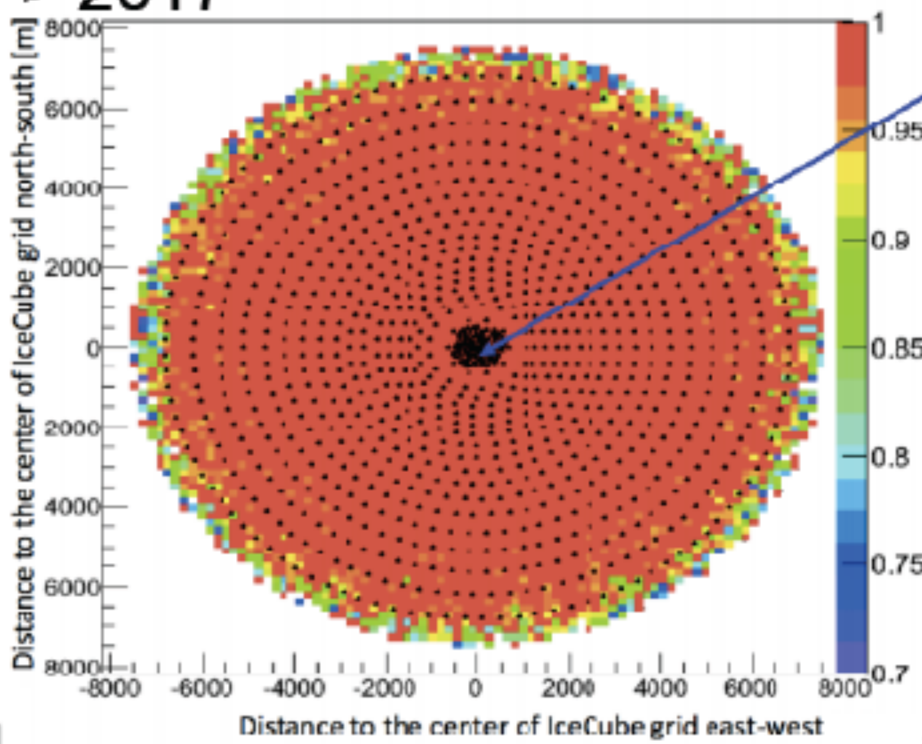
Beyond IceCube: Gen2

… a multi-purpose research infrastructure at the South Pole.

+ other…

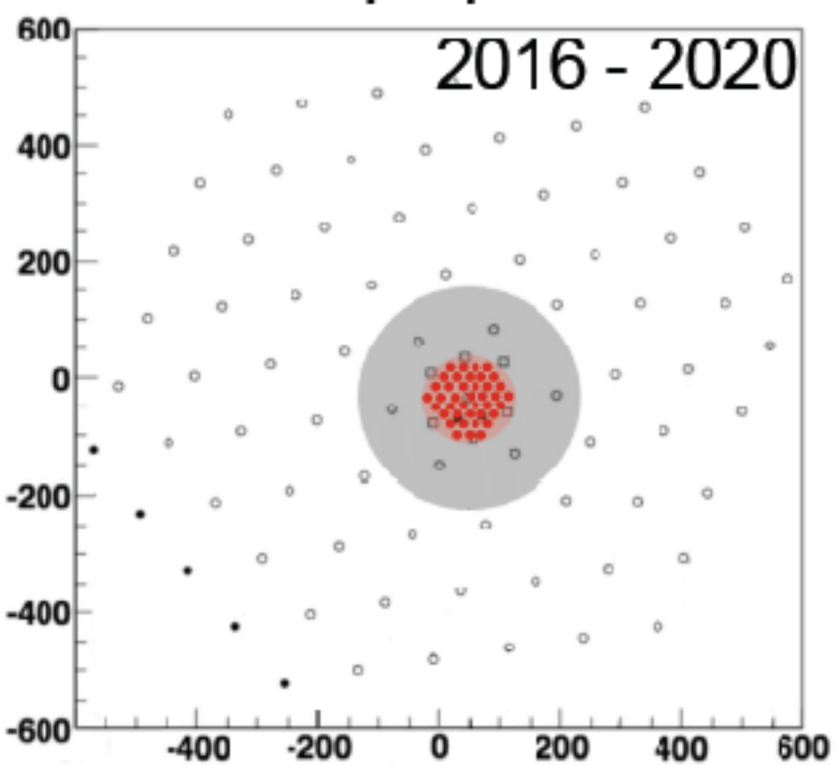
> 2017 Multi-km² Surface Detector

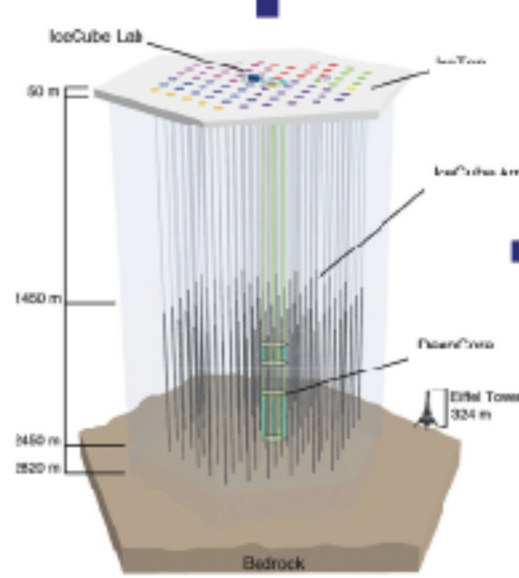
Atm. neutrino veto
CR physics



PINGU

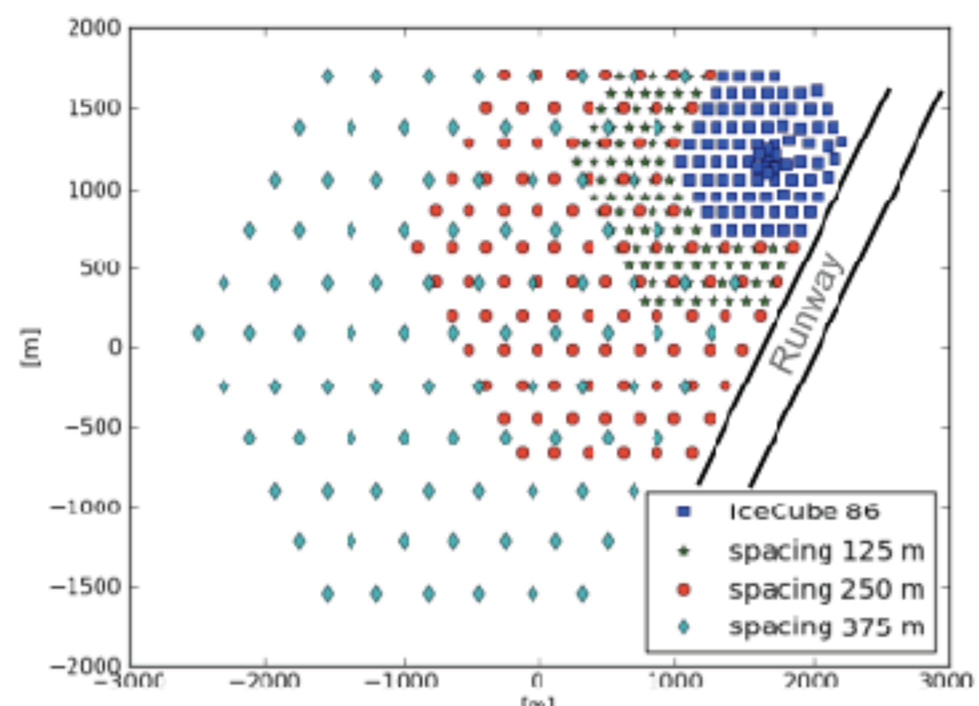
Neutrino properties





Multi-km³ Neutrino Telescope

Neutrino astronomy



>2020

Beyond IceCube: Gen2

… a multi-purpose research infrastructure at the South Pole.

> 2017 Multi-km² Surface Detector

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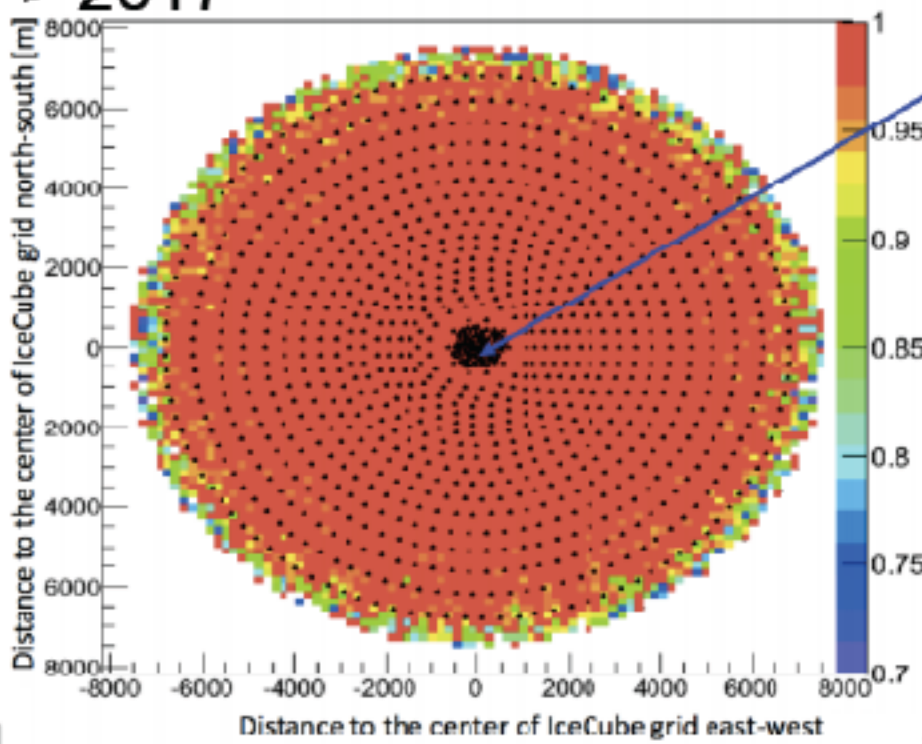
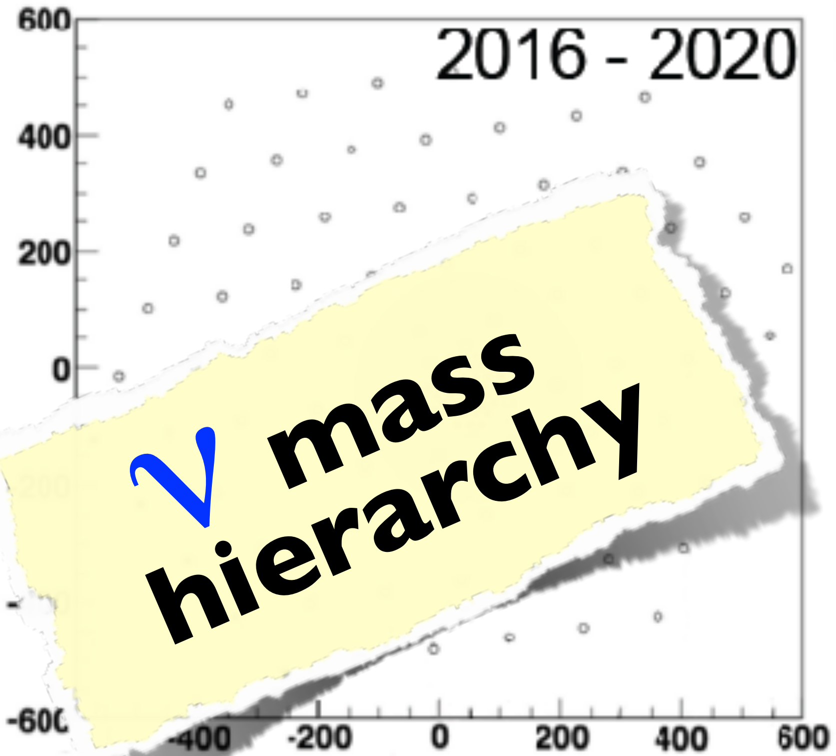
CR physics

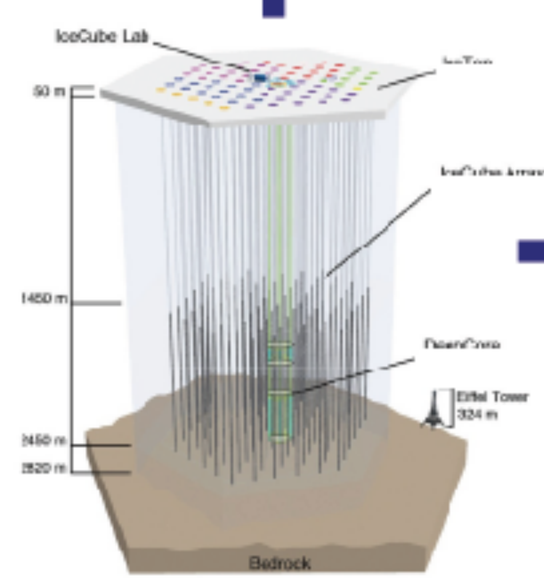


+ other…

PINGU

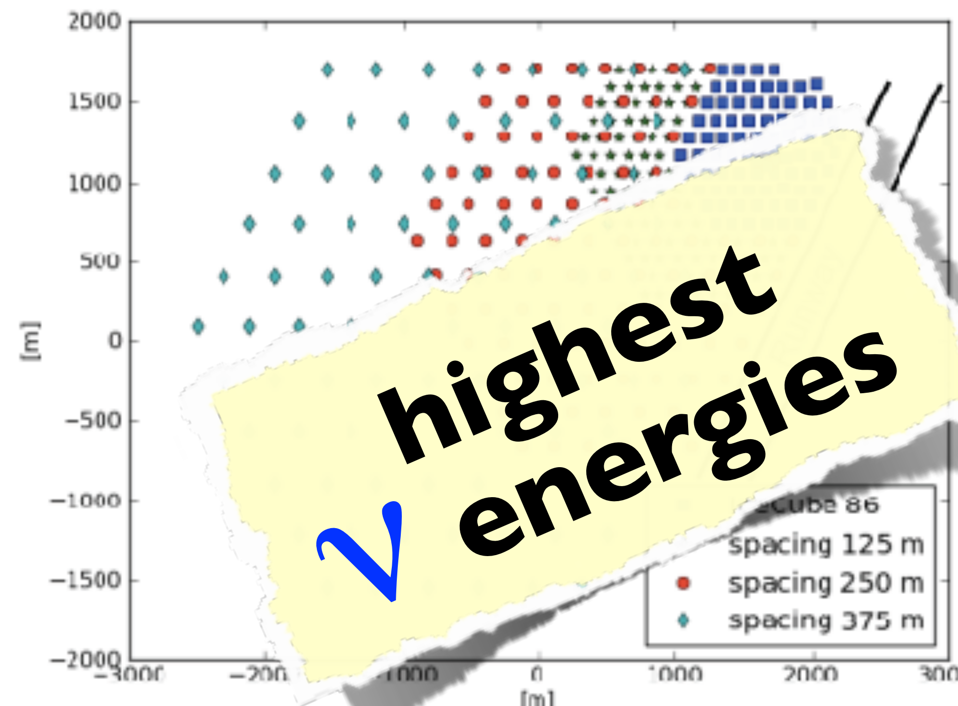
Neutrino properties





Multi-km³ Neutrino Telescope

Neutrino astronomy



>2020

Gravitational Waves

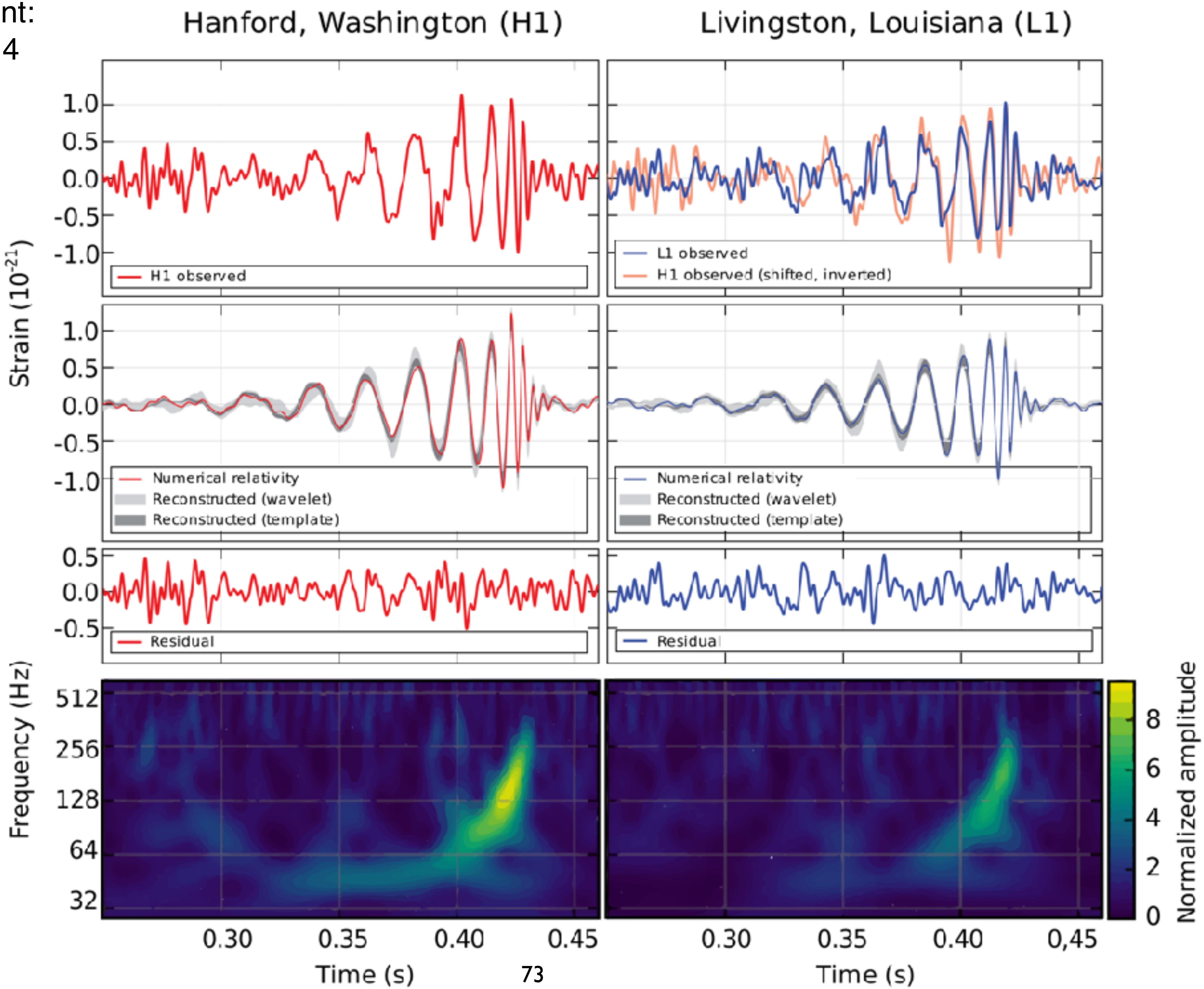
1918: Prediction of Gravitational Waves by Einstein

1970s: Indirect detection in binary pulsar (Hulse &Taylor)
Nobel Prize, 1995

intensive search with laser interferometers
GEO, LIGO, …

14 Sep 2015: Advanced LIGO
GW150914, first GW event
unambiguous detection

1.GW event:
GW150914



GW event	Detection time (UTC)	Date published	Location area[n 1] (deg^2)	Luminosity distance (Mpc)[n 2]	Energy radiated ($c^2 M_\odot$)[n 3]	Chirp mass ($M_\odot$)[n 4]	Primary		Secondary		Remnant			Notes
							Type	Mass ($M_\odot$)	Type	Mass ($M_\odot$)	Type	Mass ($M_\odot$)	Spin[n 5]	
GW150914	2015-09-14 09:50:45	2016-02-11	600; mostly to the south	440^{+160}_{-180}	$3.0^{+0.5}_{-0.5}$	$28.2^{+1.8}_{-1.7}$	BH [n 6]	$35.4^{+5.0}_{-3.4}$	BH [n 7]	$29.8^{+3.3}_{-4.3}$	BH	$62.2^{+3.7}_{-3.4}$	$0.68^{+0.05}_{-0.06}$	First GW detection; first BH merger observed; largest progenitor masses to date

BH–BH BH

35 + 30 = 62 + 3 solar masses

440 Mpc cosmological distance

600 sq.deg poor location

so much information in the GW signal:

frequency, amplitude, phase

a transient: 0.5 sec

GW event	Detection time (UTC)	Date published	Location area[n 1] (deg^2)	Luminosity distance (Mpc)[n 2]	Energy radiated ($c^2 M_\odot$)[n 3]	Chirp mass ($M_\odot$)[n 4]	Primary		Secondary		Remnant			Notes
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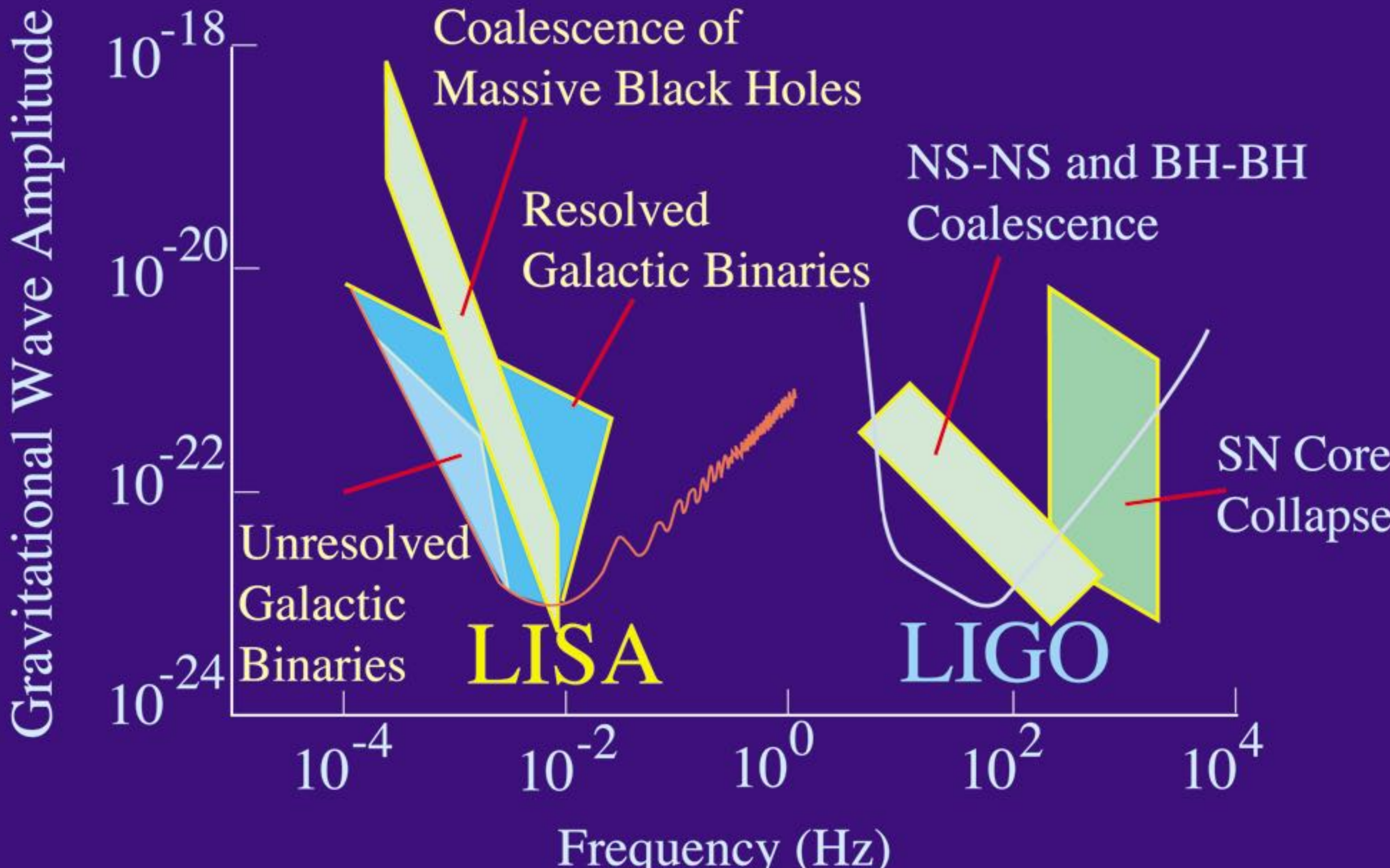
GW150914	2015-09-14 09:50:45	2016-02-11	600; mostly to the south	440^{+160}_{-180}	$3.0^{+0.5}_{-0.5}$	$28.2^{+1.8}_{-1.7}$	BH [n 6]	$35.4^{+5.0}_{-3.4}$	BH [n 7]	$29.8^{+3.3}_{-4.3}$	BH	$62.2^{+3.7}_{-3.4}$	$0.68^{+0.05}_{-0.06}$	First GW detection; first BH merger observed; largest progenitor masses to date
LVT151012 (fr)	2015-10-12 09:54:43	2016-06-15	1600	1000^{+500}_{-500}	$1.5^{+0.3}_{-0.4}$	$15.1^{+1.4}_{-1.1}$	BH	23^{+18}_{-6}	BH	13^{+4}_{-5}	BH	35^{+14}_{-4}	$0.66^{+0.09}_{-0.10}$	Not significant enough to confirm (~13% chance of being noise)
GW151226	2015-12-26 03:38:53	2016-06-15	850	440^{+180}_{-190}	$1.0^{+0.1}_{-0.2}$	$8.9^{+0.3}_{-0.3}$	BH	$14.2^{+8.3}_{-3.7}$	BH	$7.5^{+2.3}_{-2.3}$	BH	$20.8^{+6.1}_{-1.7}$	$0.74^{+0.06}_{-0.06}$	
GW170104	2017-01-04 10:11:58	2017-06-01	1200	880^{+450}_{-390}	$2.0^{+0.6}_{-0.7}$	$21.1^{+2.4}_{-2.7}$	BH	$31.2^{+8.4}_{-6.0}$	BH	$19.4^{+5.3}_{-5.9}$	BH	$48.7^{+5.7}_{-4.6}$	$0.64^{+0.09}_{-0.20}$	Farthest confirmed event to date
GW170608	2017-06-08 02:01:16	2017-11-16	520; to the north	340^{+140}_{-140}	$0.85^{+0.07}_{-0.17}$	$7.9^{+0.2}_{-0.2}$	BH	12^{+7}_{-2}	BH	7^{+2}_{-2}	BH	$18.0^{+4.8}_{-0.9}$	$0.69^{+0.04}_{-0.05}$	Smallest BH progenitor masses to date
GW170814	2017-08-14 10:30:43	2017-09-27	60; towards Eridanus	540^{+130}_{-210}	$2.7^{+0.4}_{-0.3}$	$24.1^{+1.4}_{-1.1}$	BH	$30.5^{+5.7}_{-3.0}$	BH	$25.3^{+2.8}_{-4.2}$	BH	$53.2^{+3.2}_{-2.5}$	$0.70^{+0.07}_{-0.05}$	First detection by three observatories; first measurement of polarization
GW170817	2017-08-17 12:41:04	2017-10-16	16 ~~28~~; NGC 4993	40^{+8}_{-14}	> 0.025	$1.188^{+0.004}_{-0.002}$	NS	1.36 - 1.60[n 8]	NS	1.17 - 1.36[n 9]	BH [n 10]	< $2.74^{+0.04}_{-0.01}$ [n 11]		First NS merger observed in GW; first detection of EM counterpart (GRB 170817A; AT 2017gfo); nearest event to date

Do BH-BH mergers emit anything apart from GWs? Likely not.

Neutron stars do have a skin of normal / neutron star matter, can eject material when collapsing.



continuous, steady transients

Gravitational Waves … a rather different messenger

merger events: (e.g. 2015 BH-BH merger)

huge energy release, transients, characteristic chirps,
at cosmological distances

binary events: (e.g. with LISA)

much less energy released, (nearly) steady emitters,
galactic binaries,
much less useful for MM studies

difficult to identify the precursor
follow-up on final state, unless there is elmag emission

2 great events:

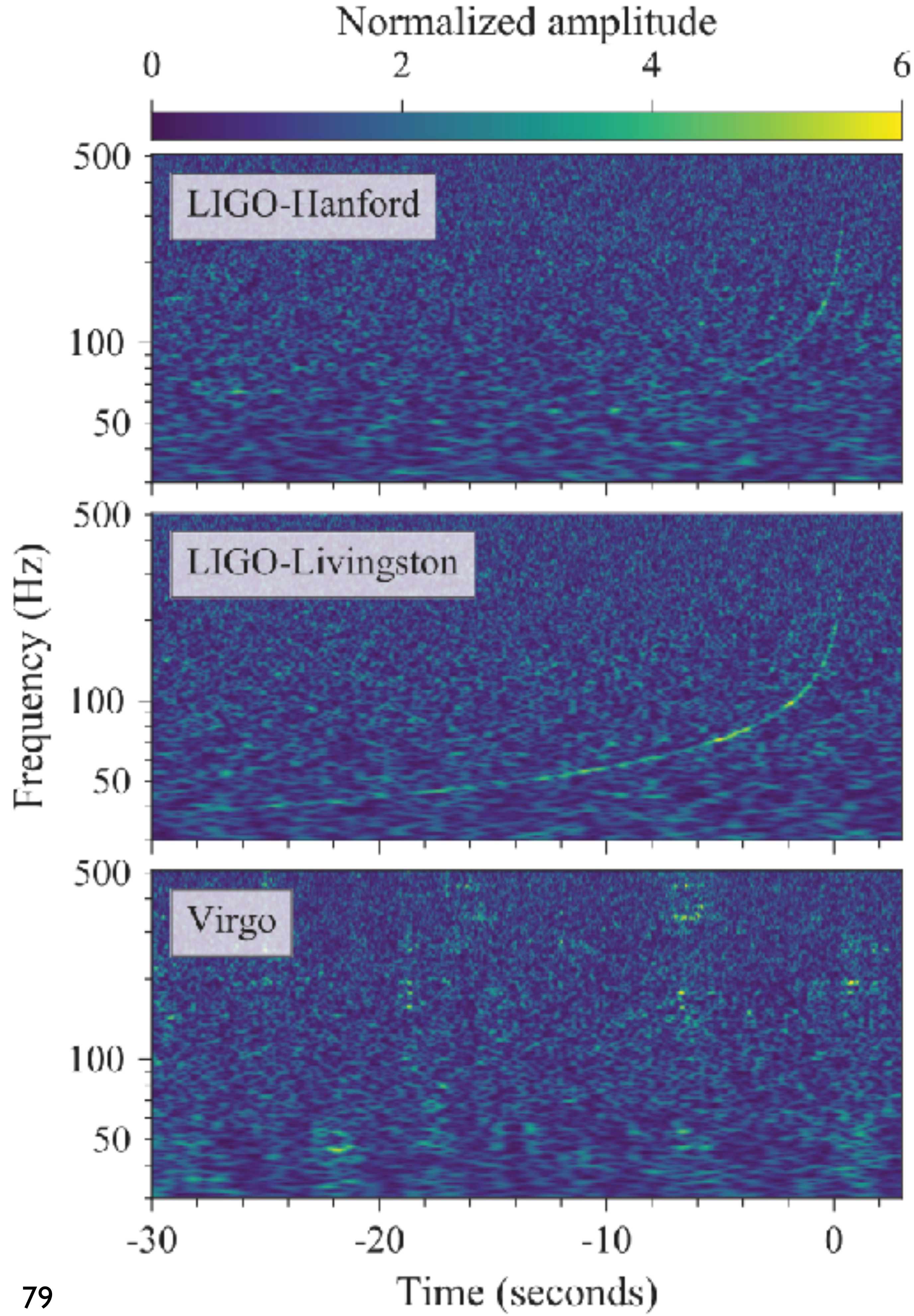
17 Aug 2017: **GW170817 / GRB 170817A**

17 Sep 2017: **IC170922a / TXS 0506+056**

The birth of “true”
multi-messenger astronomy ?

GW 170817 a NS-NS merger

GRB 170817A

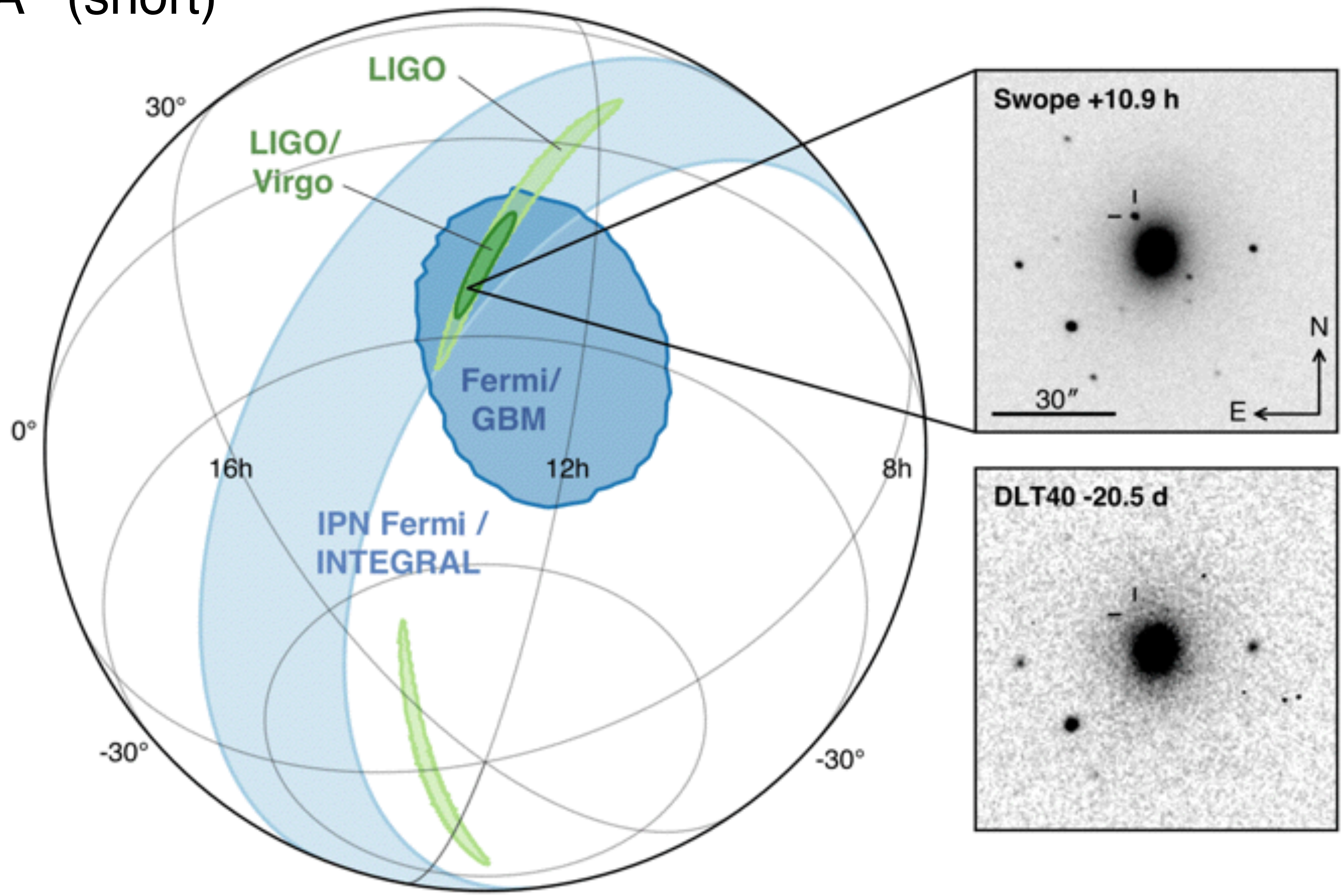


GW 170817

GRB 170817A   (short)

PRL 119, 161101 (2017)

ApJ Lett., 848:L12 (2017)



August 2017:   **merging neutron stars,   coincident with a short GRB**
first time: seen also by gamma ray telescopes,
good location determination
followed up by 70 !! observatories

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Abstract

On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of ~1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg^2 at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The component masses were later measured to be in the range 0.86 to 2.26 $M_{\odot}$. An extensive observing campaign was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a, now with the IAU identification of AT 2017gfo) in NGC 4993 (at ~40 Mpc) less than 11 hours after the merger by the One-Meter, Two Hemisphere (1M2H) team using the 1 m Swope Telescope. The optical transient was independently detected by multiple teams within an hour. Subsequent observations targeted the object and its environment. Early ultraviolet observations revealed a blue transient that faded within 48 hours. Optical and infrared observations showed a redward evolution over ~10 days. Following early non-detections, X-ray and radio emission were discovered at the transient's position ~9 and ~16 days, respectively, after the merger. Both the X-ray and radio emission likely arise from a physical process that is distinct from the one that generates the UV/optical/near-infrared emission. No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches. These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of *r*-process nuclei synthesized in the ejecta.

Key words: gravitational waves – stars: neutron

ApJ Lett., 848:L12 (2017)

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
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Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

That's the potential of multi wavelength / messenger observations !!

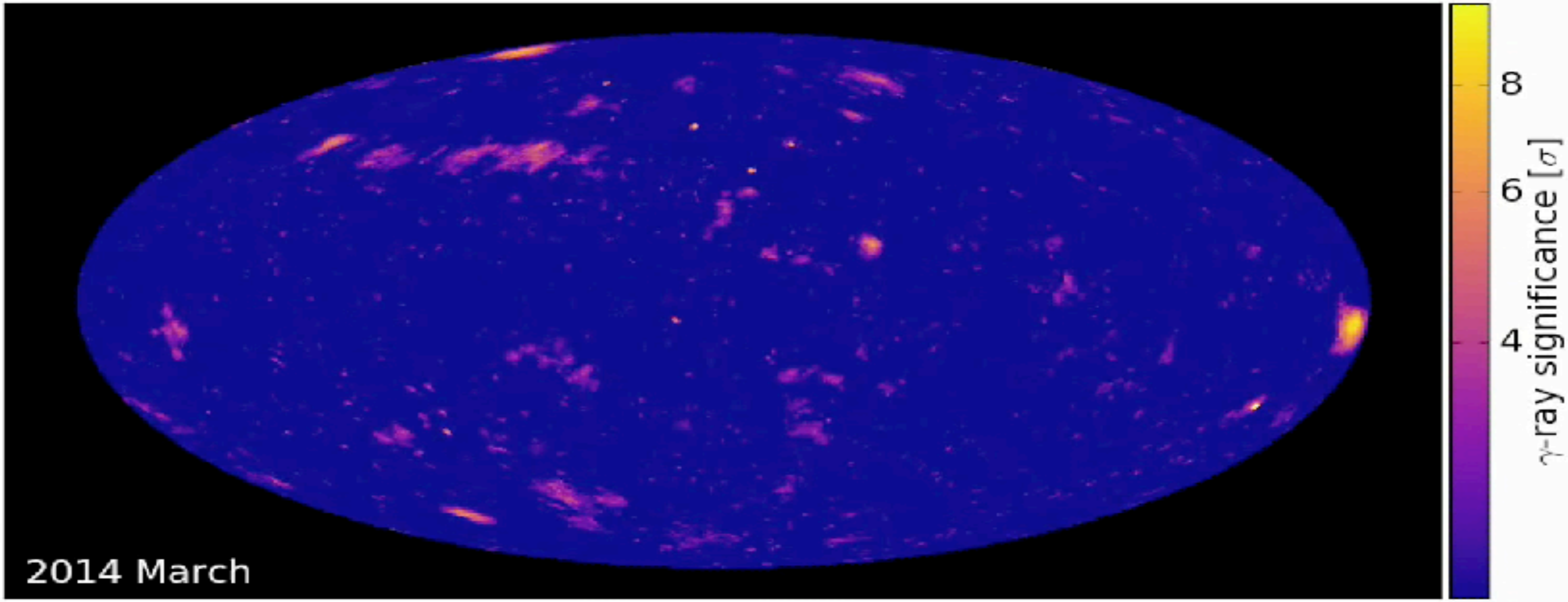
ABSTRACT

On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of ~1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg^2 at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The component masses were later measured to be in the range 0.86 to 2.26 $M_\odot$. An extensive observing campaign was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a, now with the IAU identification of AT 2017gfo) in NGC 4993 (at ~40 Mpc) less than 11 hours after the merger by the One-Meter, Two Hemisphere (1M2H) team using the 1 m Swope Telescope. The optical transient was independently detected by multiple teams within an hour. Subsequent observations targeted the object and its environment. Early ultraviolet observations revealed a blue transient that faded within 48 hours. Optical and infrared observations showed a redward evolution over ~10 days. Following early non-detections, X-ray and radio emission were discovered at the transient's position ~9 and ~16 days, respectively, after the merger. Both the X-ray and radio emission likely arise from a physical process that is distinct from the one that generates the UV/optical/near-infrared emission. No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches. These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of *r*-process nuclei synthesized in the ejecta.

Key words: gravitational waves – stars: neutron

ApJ Lett., 848:L12 (2017)

Still, much is learnt from every event recorded, whether el.mag. counterpart or not.

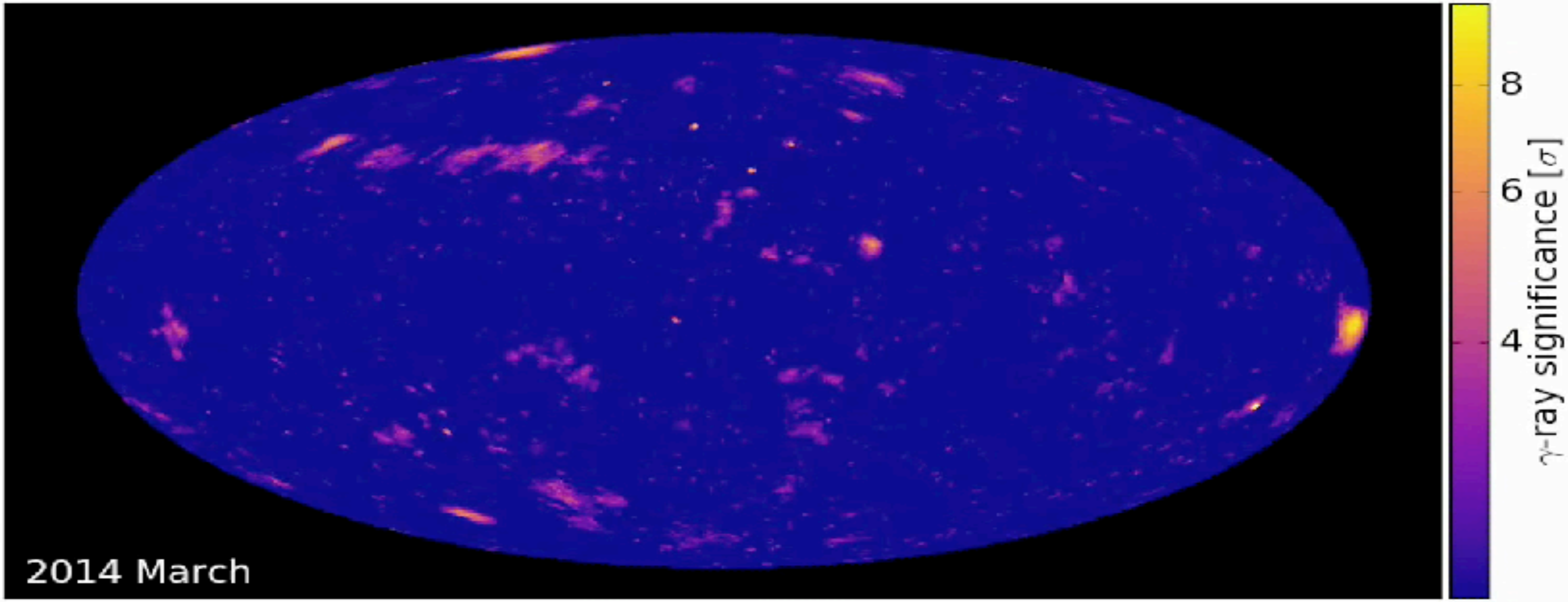


Fermi All-Sky Variability Analysis, M. Giomi,'17

Fermi LAT variability analysis + IceCube HE events

First PeV neutrino (IceCube 170922A)
seen coincident with a gamma ray flare
of the blazar TXS0506+056

+ others from radio to gamma energies



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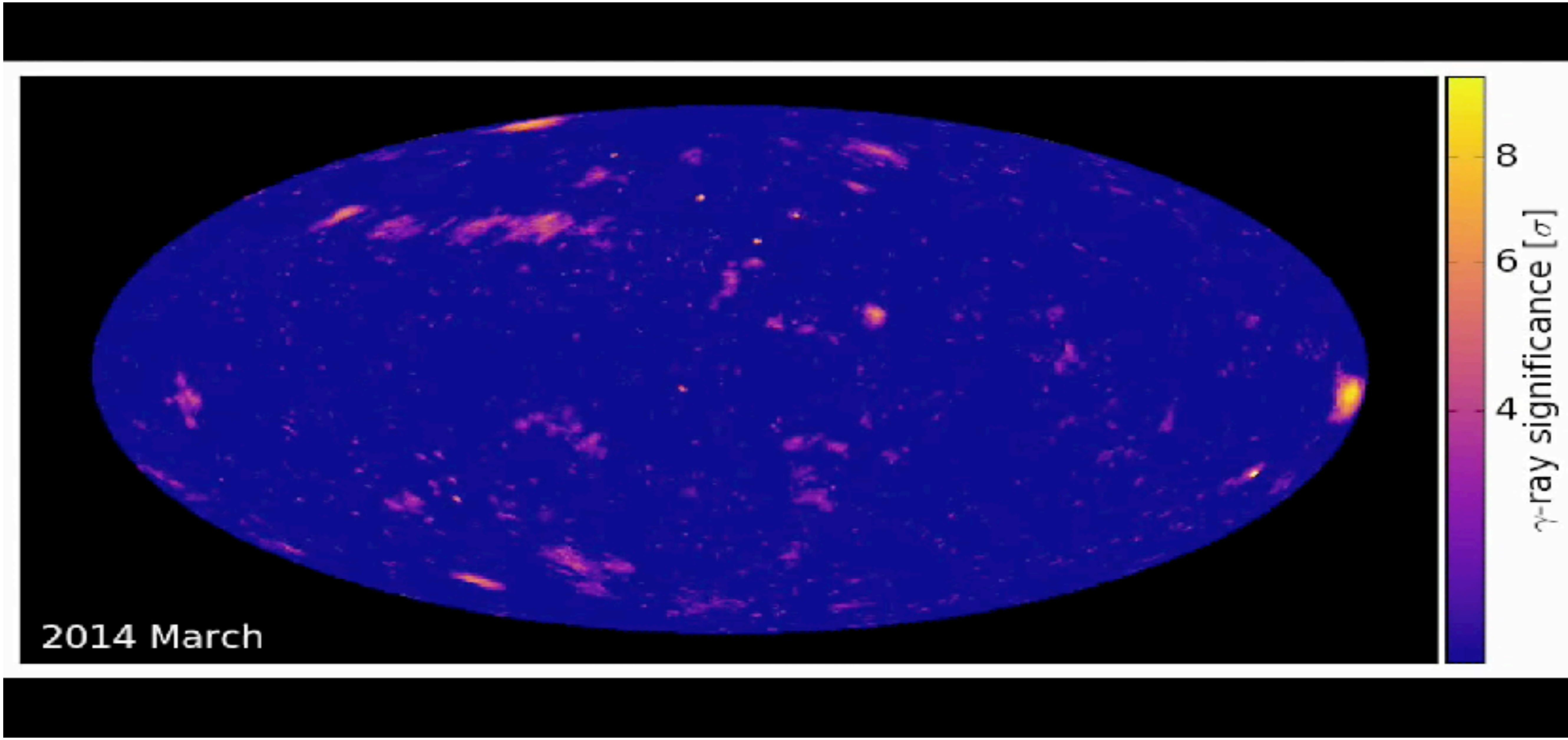

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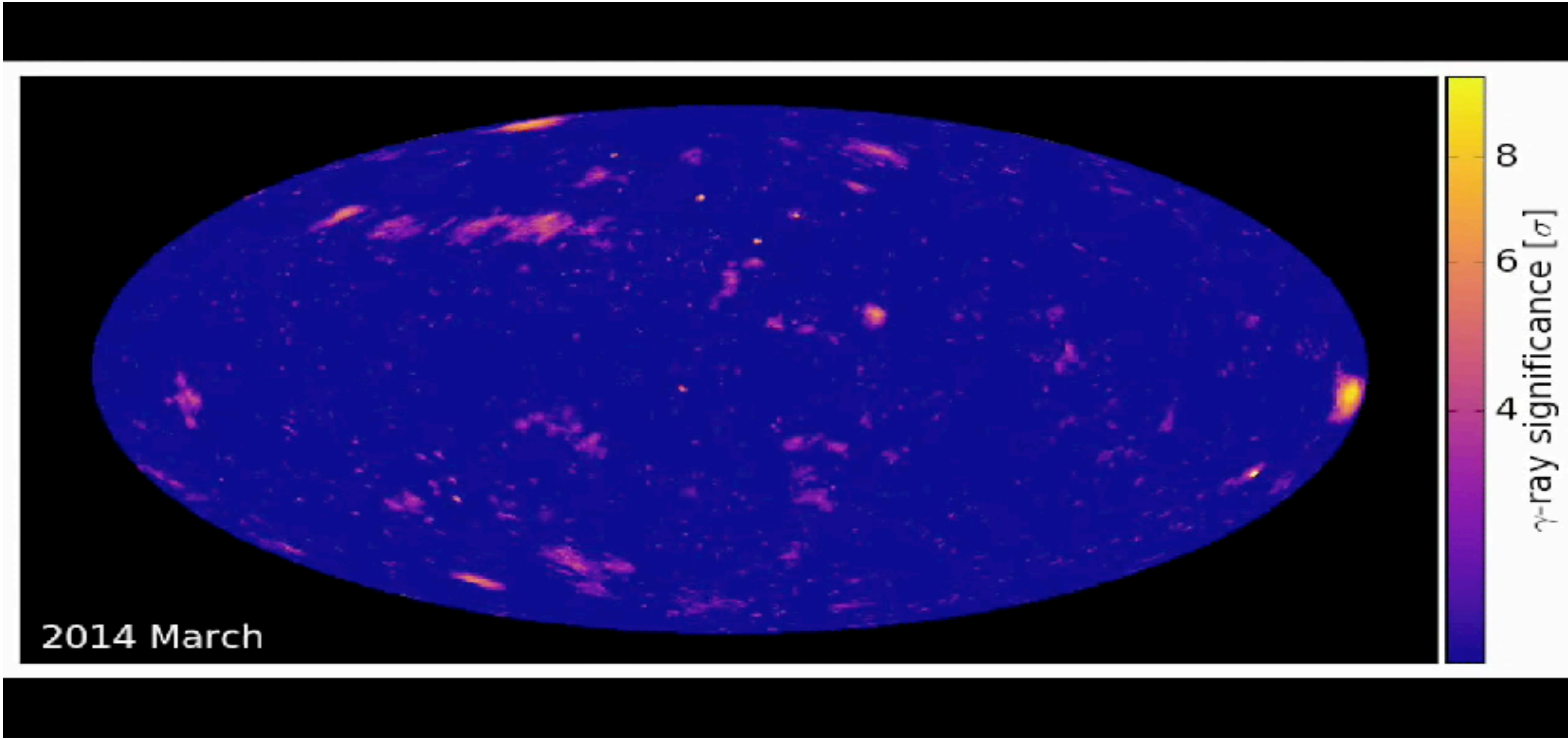

Fermi LAT variability analysis + IceCube HE events

First PeV neutrino (IceCube 170922A)
seen coincident with a gamma ray flare
of the blazar TXS0506+056

+ others from radio to gamma energies

EHE track-like event

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09:26 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of Maryland) report on behalf of the IceCube Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical origin. The event was identified by the Extremely High Energy (EHE) track event selection. The IceCube detector was in a normal operating state. EHE events typically have a neutrino interaction vertex that is outside the detector, produce a muon that traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg 90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu

EHE track-like event

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE:
FROM:

[Previous | Next | ADS]

Further Swift-XRT observations of IceCube 170922A

ATel #10792; *P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B. Fox (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), and F. E. Marshall (GSFC) report on behalf of the Swift-IceCube collaboration:*
on 28 Sep 2017; 11:57 UT
Credential Certification: Phil Evans (pae9@star.le.ac.uk)

Subjects: X-ray, Quasar, Variables

Referred to by ATel #: 10794, 10799, 10817, 10830, 10838, 10840, 10844, 10861

Fermi-LAT has reported a gamma-ray source (blazar), TXS 0506+056 (3FGL J0509.4+0541 / 3FHL J0509.4+0542) which is located inside the IceCube-170922A event error region (Kopper & Blaufuss, GCN #21916) and is flaring above 800 MeV (Tanaka et al., ATEL #10791). This source is also observed in our Swift-XRT follow-up of IceCube-170922A (Source 2, 1SXPS J050925.9+054134 in the 1SXPS catalogue), reported previously by Keivani et al. (GCN #21930).

We conducted a further 5 ks observation of this Source with Swift, beginning at 2017 Sep 27 at 18:52 UT (4.95 d after the neutrino event). In these data the X-ray source has brightened since we the original observations. The current spectral photon index (Γ) is 2.50 [+0.23, -0.12], similar to the historical value in 1SXPS: Γ = 2.32 [+0.33, -0.29] (http://www.swift.ac.uk/1SXPS/1SXPS%20J050925.9%2B054134; Evans et al. 2014). In our initial observations following the neutrino trigger, Γ was marginally harder but with large uncertainty: 1.9 [+0.8, -0.7]. The hardness ratio light curve of the observations taken since the neutrino trigger also shows evidence for spectral softening between the two epochs, suggesting that the source is undergoing spectral evolution.

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EHE track-like event

TITLE: GCN CIRCULAR
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Further Swift-XRT observations of IceCube 170922A

ATel #10792; *P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B. Fox (P*

Subjects: X

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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, 11419, 11430, 11489

We searched for Fermi-LAT sources inside the extremely high-energy (EHE) IceCube-170922A neutrino event error region (https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3, see also ATels 10773, 10787) with all-sky survey data from the Large Area Telescope (LAT), on board the Fermi Gamma-ray Space Telescope. We found that one Fermi-LAT source, TXS 0506+056 (3FGL J0509.4+0541 and also included in the 3FHL catalog, Ajello et al., arXiv:1702.00664, as 3FHL

EHE track-like event

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
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Further Swift-XRT observations of IceCube 170922A

ATel #10792; *P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B. Fox (P...*

Subjects: X...

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

ATel #10791; *Daniel...*

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Subjects: Gam...

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First-time detection of VHE gamma rays by MAGIC a direction consistent with the recent EHE neutri... event IceCube-170922A

5σ

>0.1 TeV

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration on 4 Oct 2017; 17:17 UT*

Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

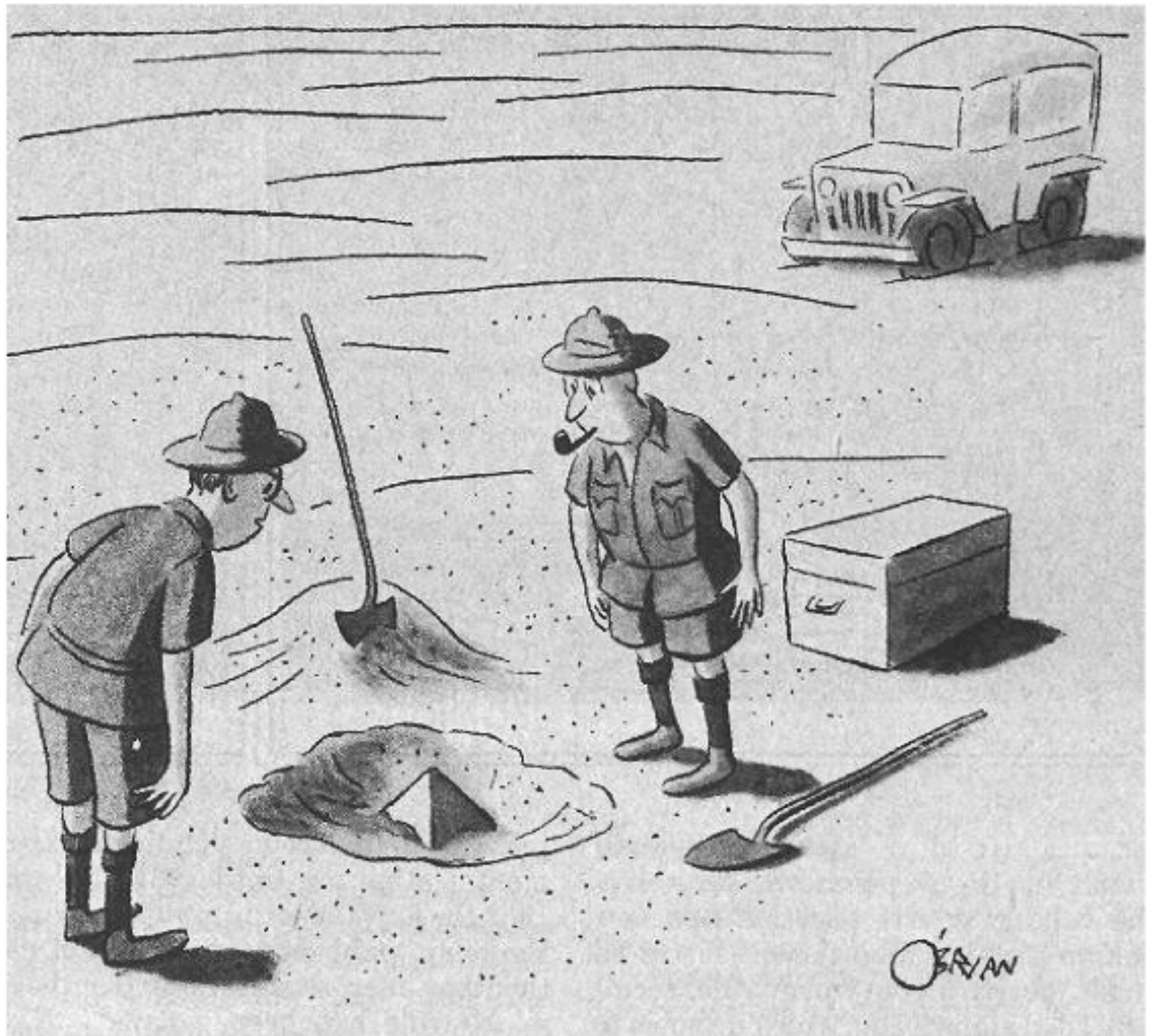
… a detailed joint analysis is to appear anytime soon in Science (still embargo).

The first “true” multi-messenger event in the $\gamma - \nu$ channel ?

Blazars **could be** HE neutrino sources! But at what level?

… but only **1 neutrino** & **many gamma rays** difficult to exploit in MM way.

…. but with only 1 event each, it is still early days.



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Two “true” MM events within a month !!

A huge boost to confidence and enthusiasm to all involved

Rather likely, more of those events will be seen in the very near future.

First mention of "multi-messenger astronomy" in ADS

1999

astro-ph/9903467

HIGH ENERGY COSMIC NEUTRINOS

STEVEN W. BARWICK

Dept. of Physics and Astronomy, University of California-Irvine, Irvine, CA, USA

While the general principles of high-energy neutrino detection have been understood for many years, the deep, remote geographical locations of suitable detector sites have challenged the ingenuity of experimentalists, who have confronted unusual deployment, calibration, and robustness issues. Two high energy neutrino programs are now operating (Baikal and AMANDA), with the expectation of ushering in an era of multi-messenger astronomy, and two Mediterranean programs have made impressive progress. The detectors are optimized to detect neutrinos with energies of the order of 1-10 TeV, although they are capable of detecting neutrinos with energies of tens of MeV to greater than PeV. This paper outlines the interdisciplinary scientific agenda, which span the fields of astronomy, particle physics, and cosmic ray physics, and describes ongoing worldwide experimental programs to realize these goals.

Conclusion

The late Fred Reines, Nobel Laureate and father of neutrino physics, was fond of saying that one should choose to work on physics topics worthy of a lifetime's study. The broad diversity of scientific capabilities and enormous potential of high energy neutrino astrophysics certainly qualifies.

…

[ν] If history is a guide, there will be surprises as well as these detectors begin to survey the great canvas of the unknown. …

First mention of "multi-messenger astronomy" in ADS

1999

astro-ph/9903467

HIGH ENERGY COSMIC NEUTRINOS

STEVEN W. BARWICK

Dept. of Physics and Astronomy, University of California-Irvine, Irvine, CA, USA

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…

[ν] If history is a guide, there will be surprises as well as these detectors begin to survey the great canvas of the unknown. …

…physics topics worthy of a lifetime's study:

neutrino astronomy
gamma ray astronomy
cosmic ray research
gravitational wave astronomy
…

and the multi messenger approach.

Steven Weinberg,
Four golden lessons
Nature 426 (2003) 389

(for young physicists)

“My advice is to go for the messes - that’s where the action is.”

Astroparticle Physics poses many puzzles.
Experimental findings and theoretical ideas
do not (yet) form a coherent and clear image.

…. and certainly, there is a lot of “action”

Summary:

- Astroparticle Physics is an exciting field.
- Highest energy phenomena are rare & difficult to detect

  ... but new experiments are getting better
  in detecting them and identifying their sources.
- Energetic CRs, gamma rays, neutrinos & gravity waves
  come from the most violent environments in the universe.
- Four new windows in Astronomy
- The Multi-Messenger approach is taking off.

  first transient observations of $\gamma - \nu$ and $\mathrm{gw} - \gamma$,
  many to follow / much to be learnt.

… a bright future ahead.