Multi-messenger astronomy

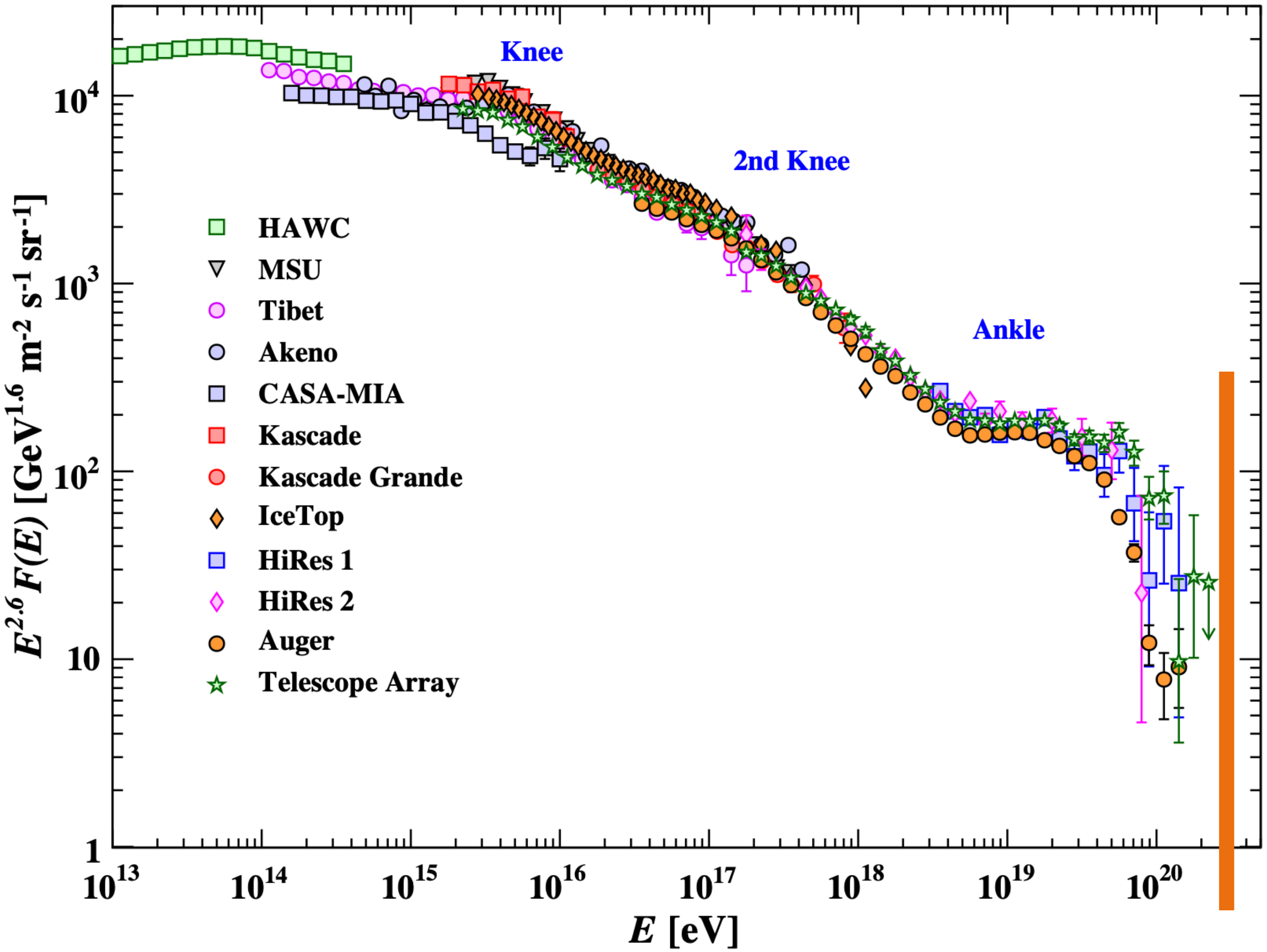
Overview of experimental and observational aspects

David Berge (DESY & Humboldt-University Berlin)

Spåtind 2023

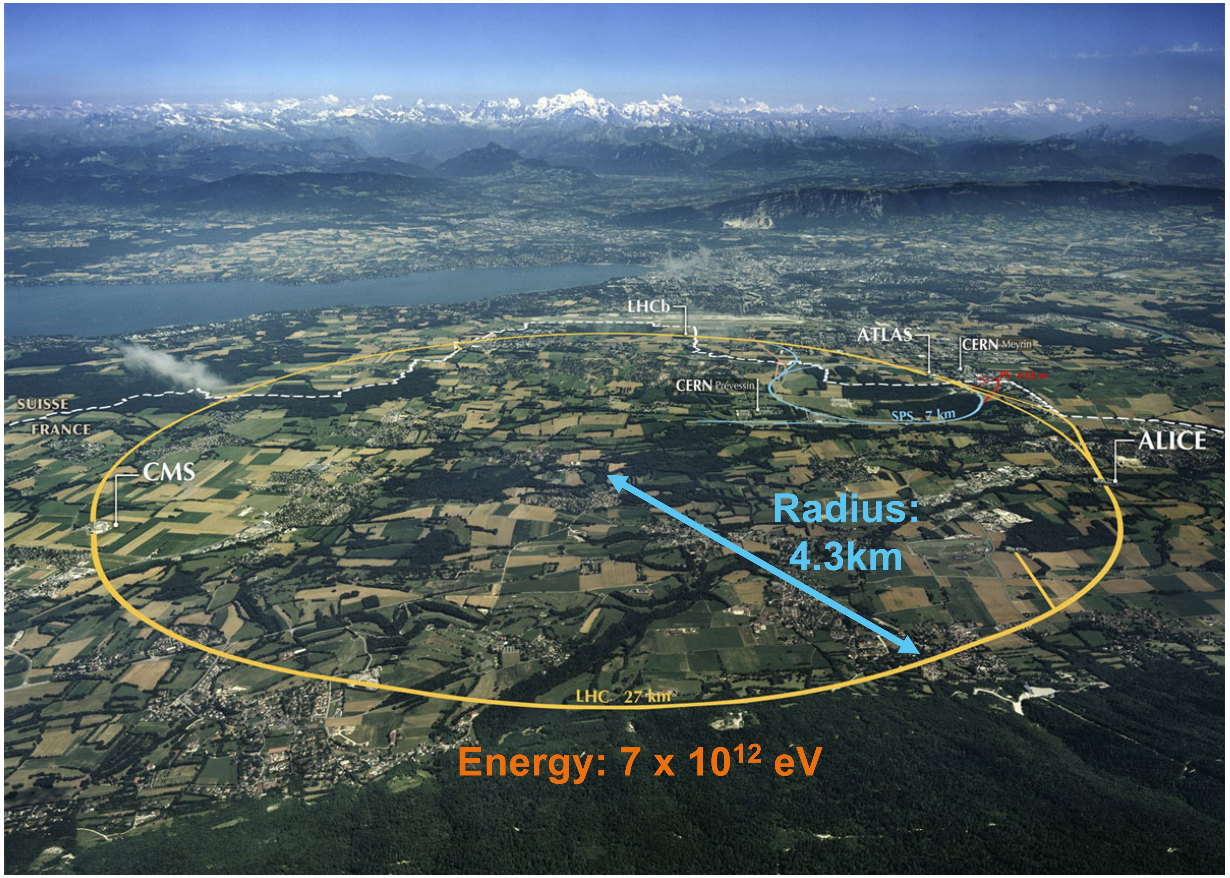
HELMHOLTZ

1. Why bother?

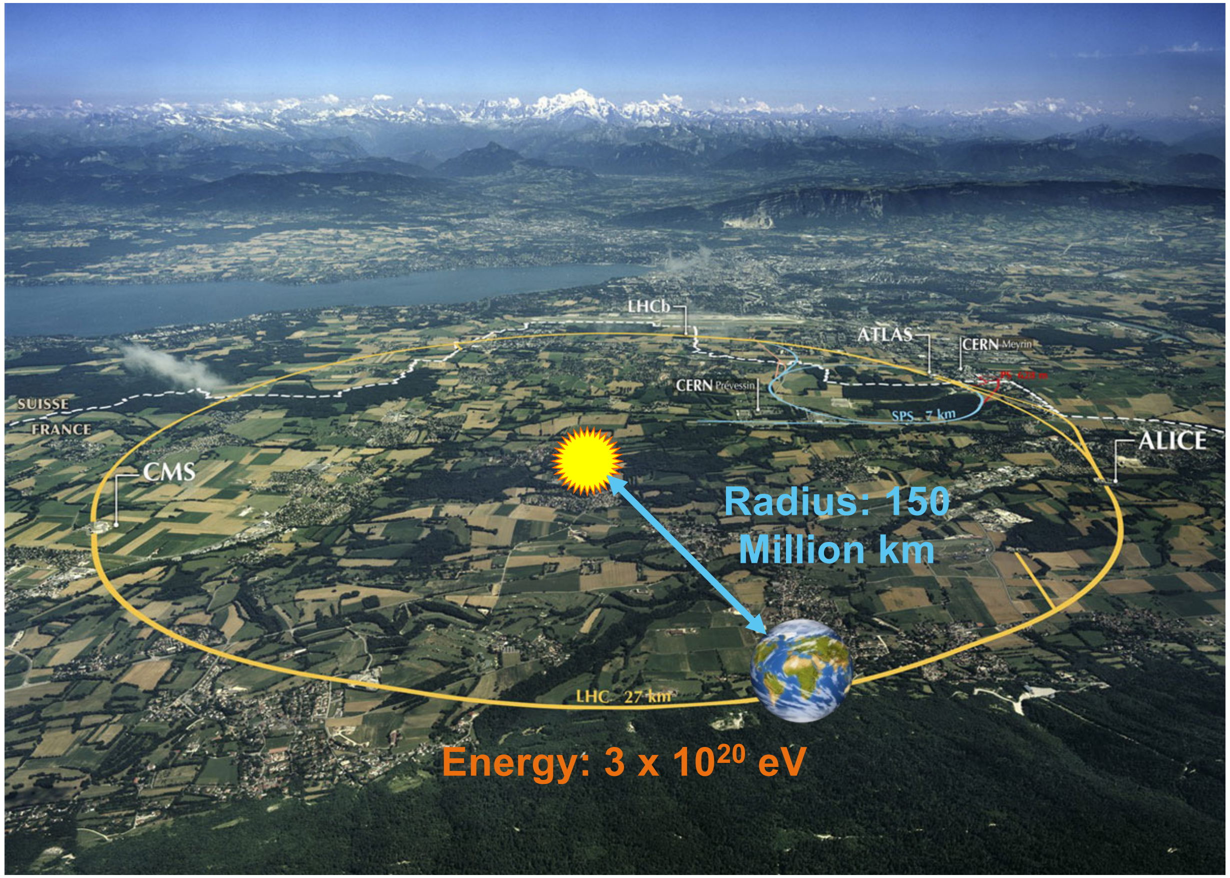


Tanabashi et al (PDG, PRD 98, 2019)

Large Hadron Collider at Earth

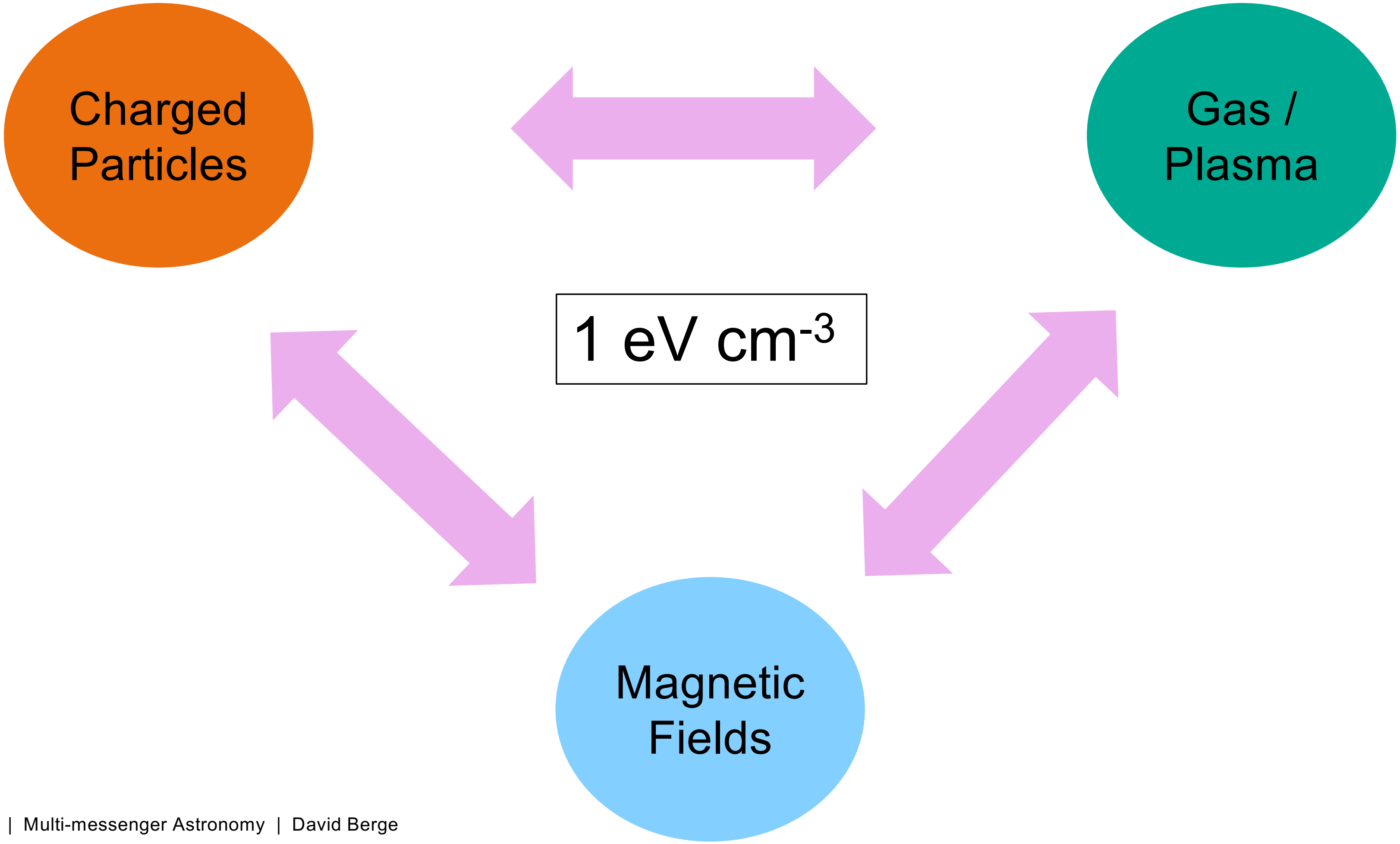


Cosmic Hadron Collider in the Universe?

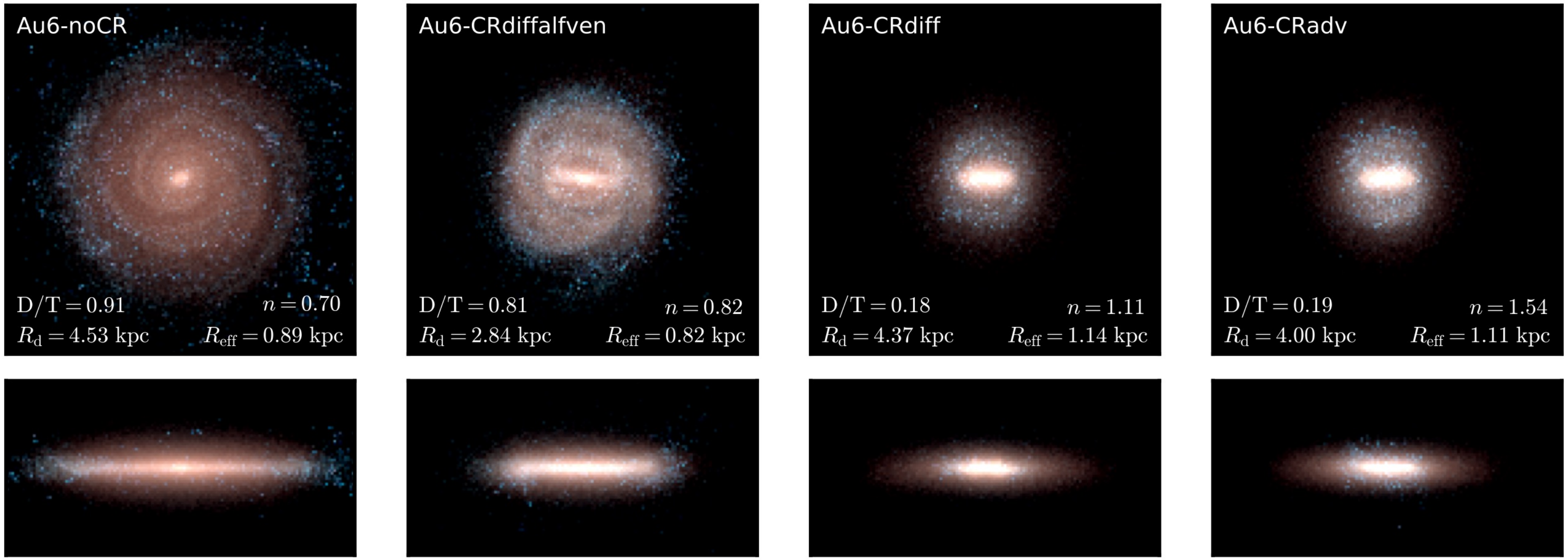


2. Why bother?

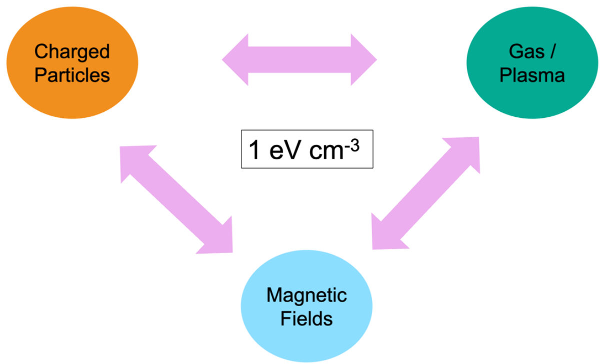
The same energy density in particles, magnetic fields, gas / plasma



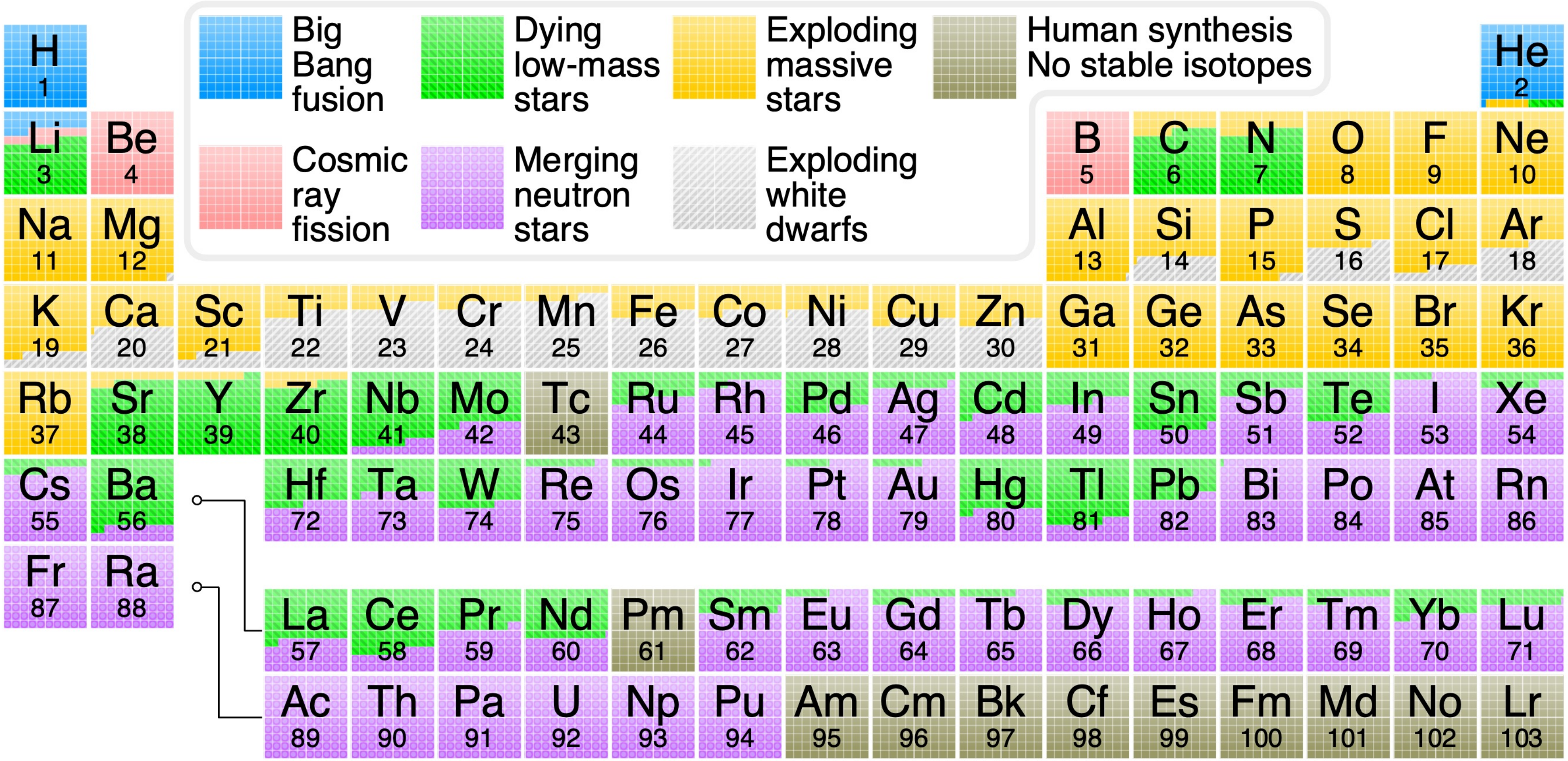
2. Why bother?



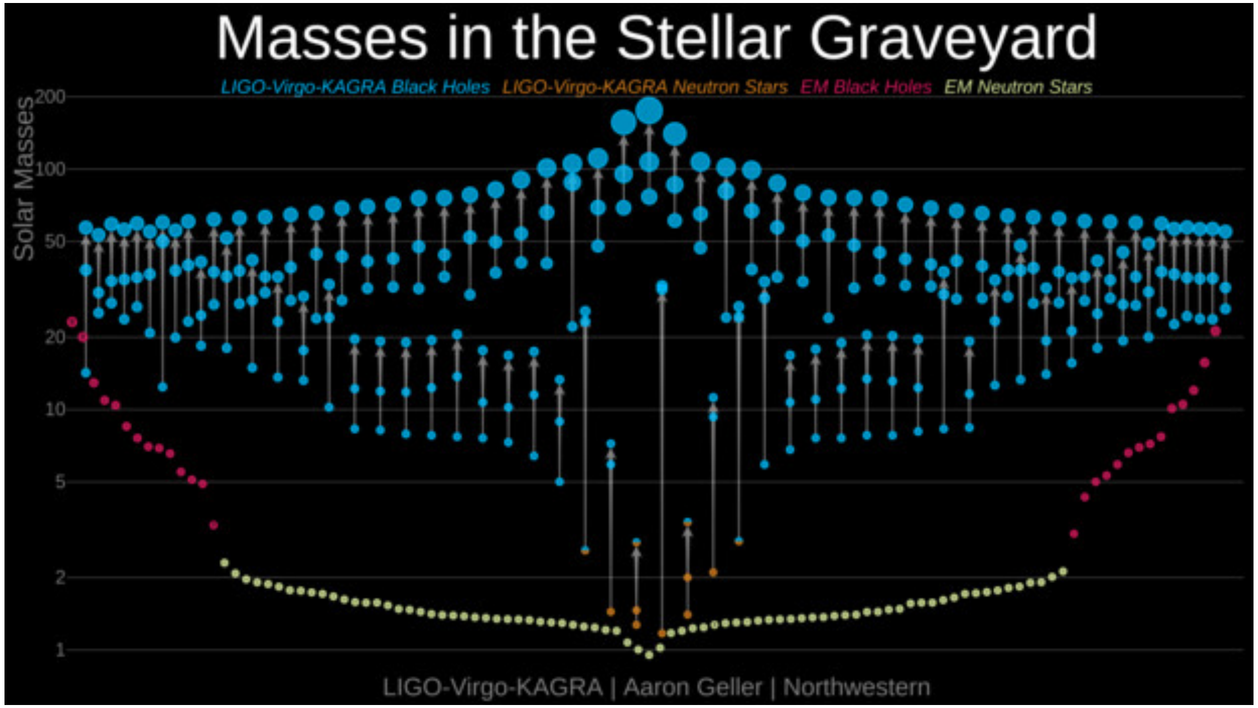
Buck et al (MNRAS 2019)



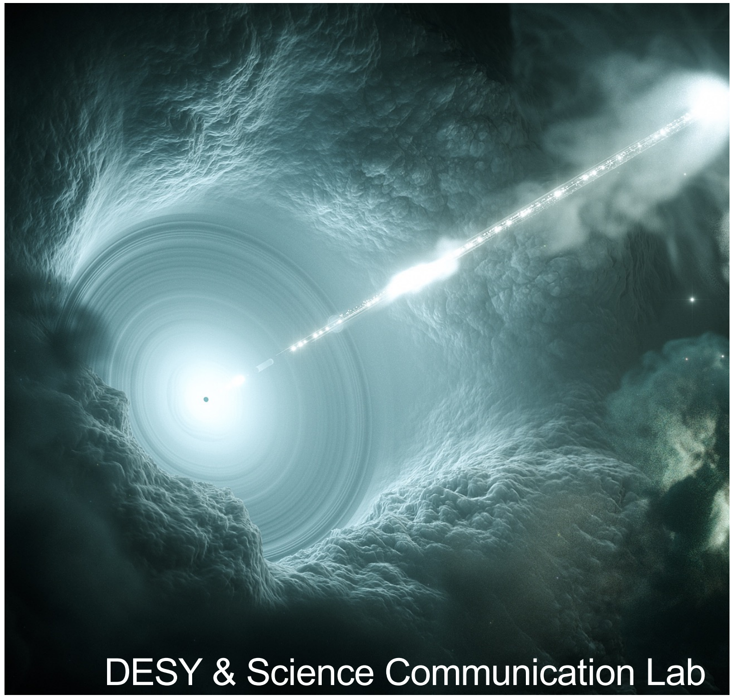
3. Why bother?


Big Bang fusion
Dying low-mass stars
Exploding massive stars
Human synthesis No stable isotopes
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Ac 89
Th 90
Pa 91
U 92
Np 93
Pu 94
Am 95
Cm 96
Bk 97
Cf 98
Es 99
Fm 100
Md 101
No 102
Lr 103

4. Why bother?



Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



DESY & Science Communication Lab

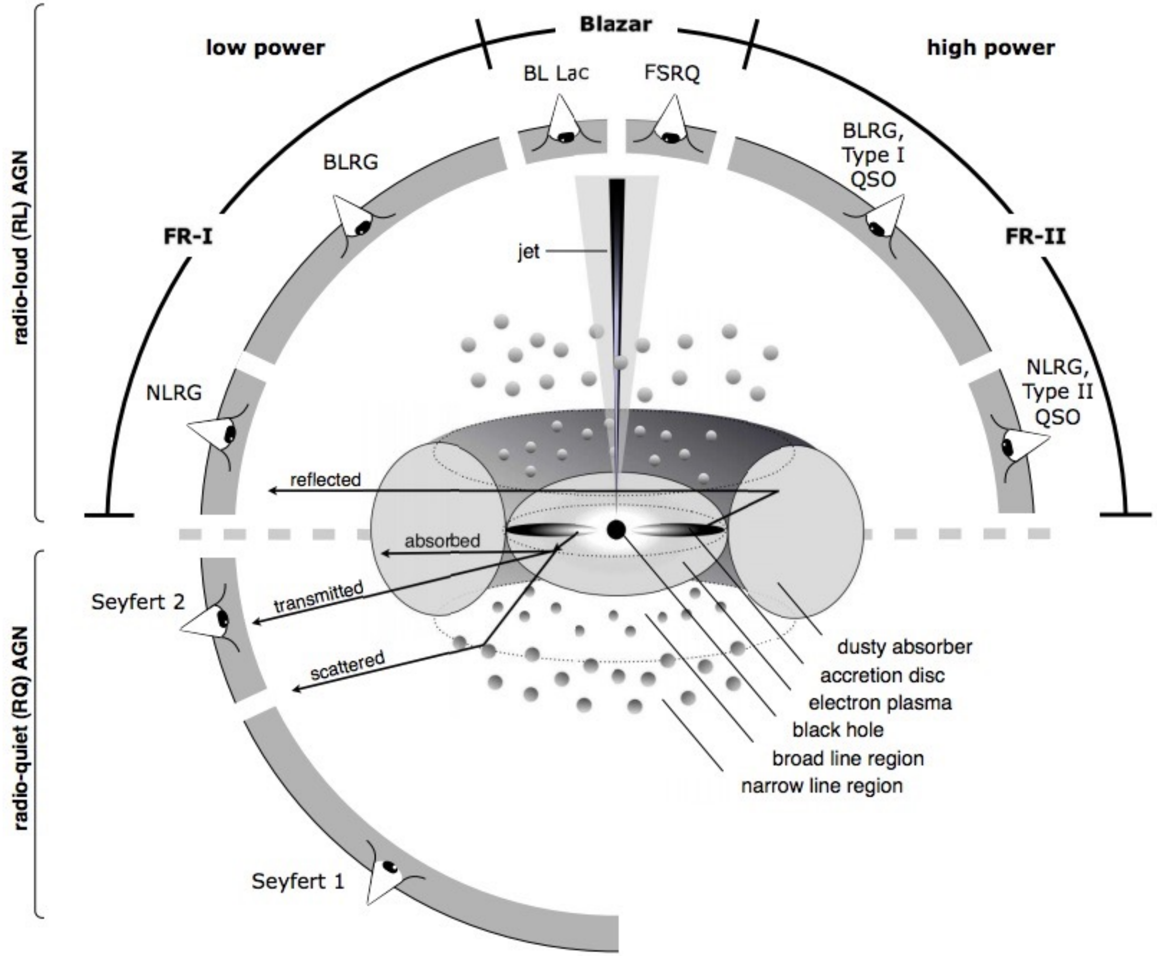
One main science driver of multi-messenger astronomy:

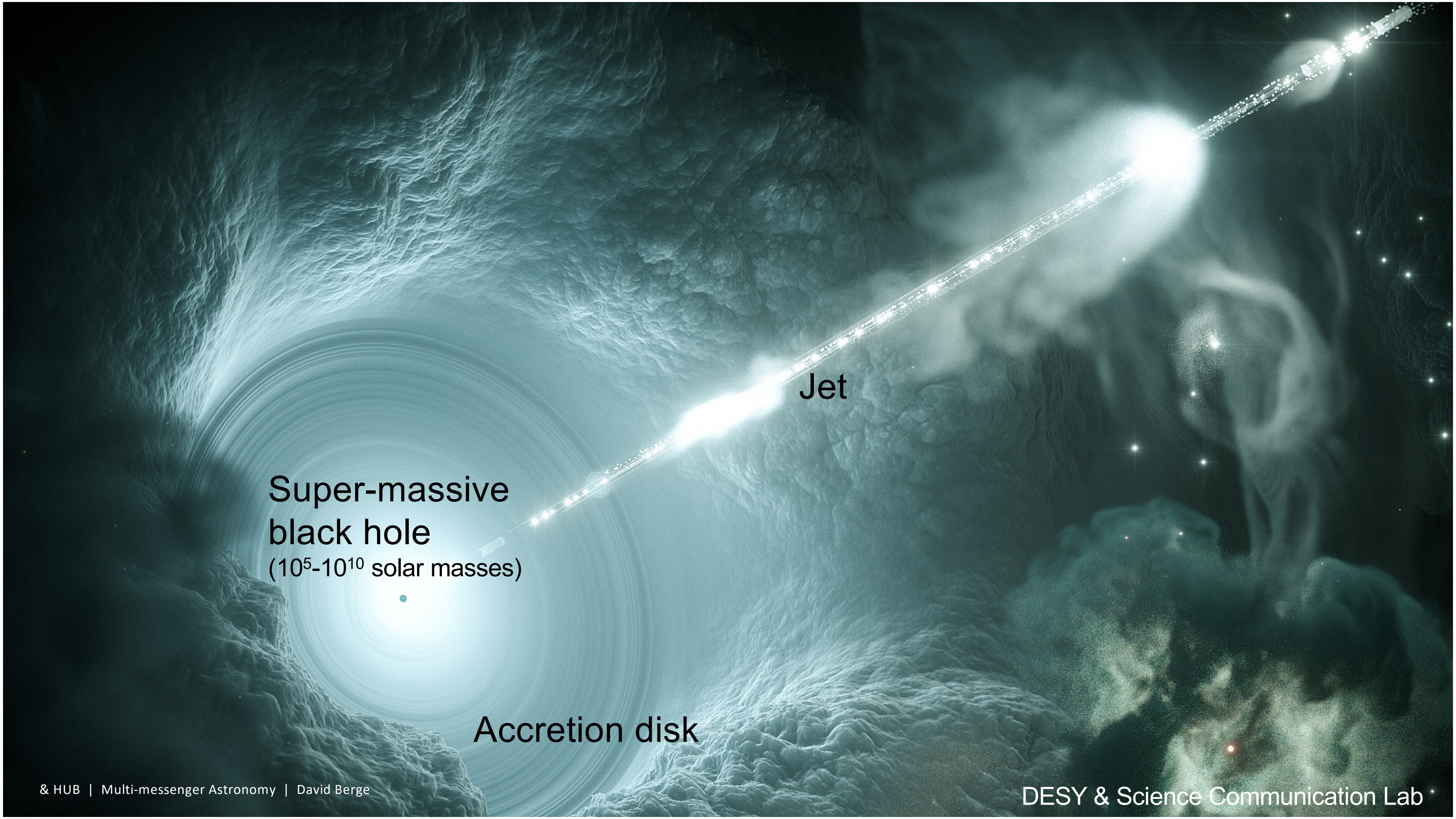
Where and how are cosmic rays accelerated?

Active Galactic Nuclei

… are particle accelerators!

M87, Hubble



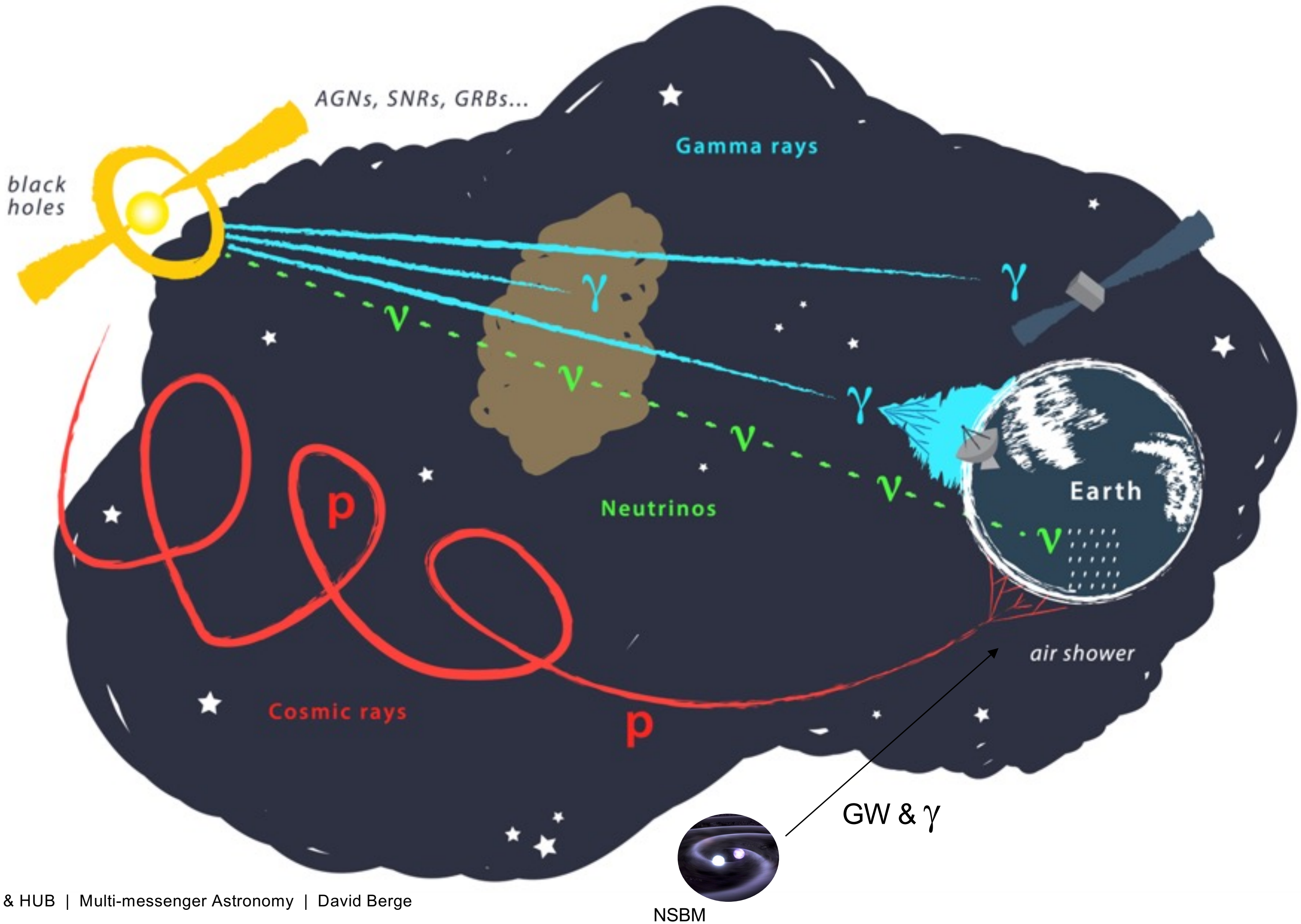

Jet
Super-massive
black hole
(10^5-10^{10} solar masses)
Accretion disk
DESY & Science Communication Lab

Shock waves following explosive events

… are particle accelerators!

DESY/H.E.S.S., Science Communication Lab
https://www.desy.de/news/news_search/index_eng.html?openDirectAnchor=2249

DESY, Science Communication Lab
https://www.desy.de/news/news_search/index_eng.html?openDirectAnchor=2080



Glossary

AGN: Active Galactic Nucleus

Seyfert galaxy, blazar: types of AGN

SNR: Supernova Remnant

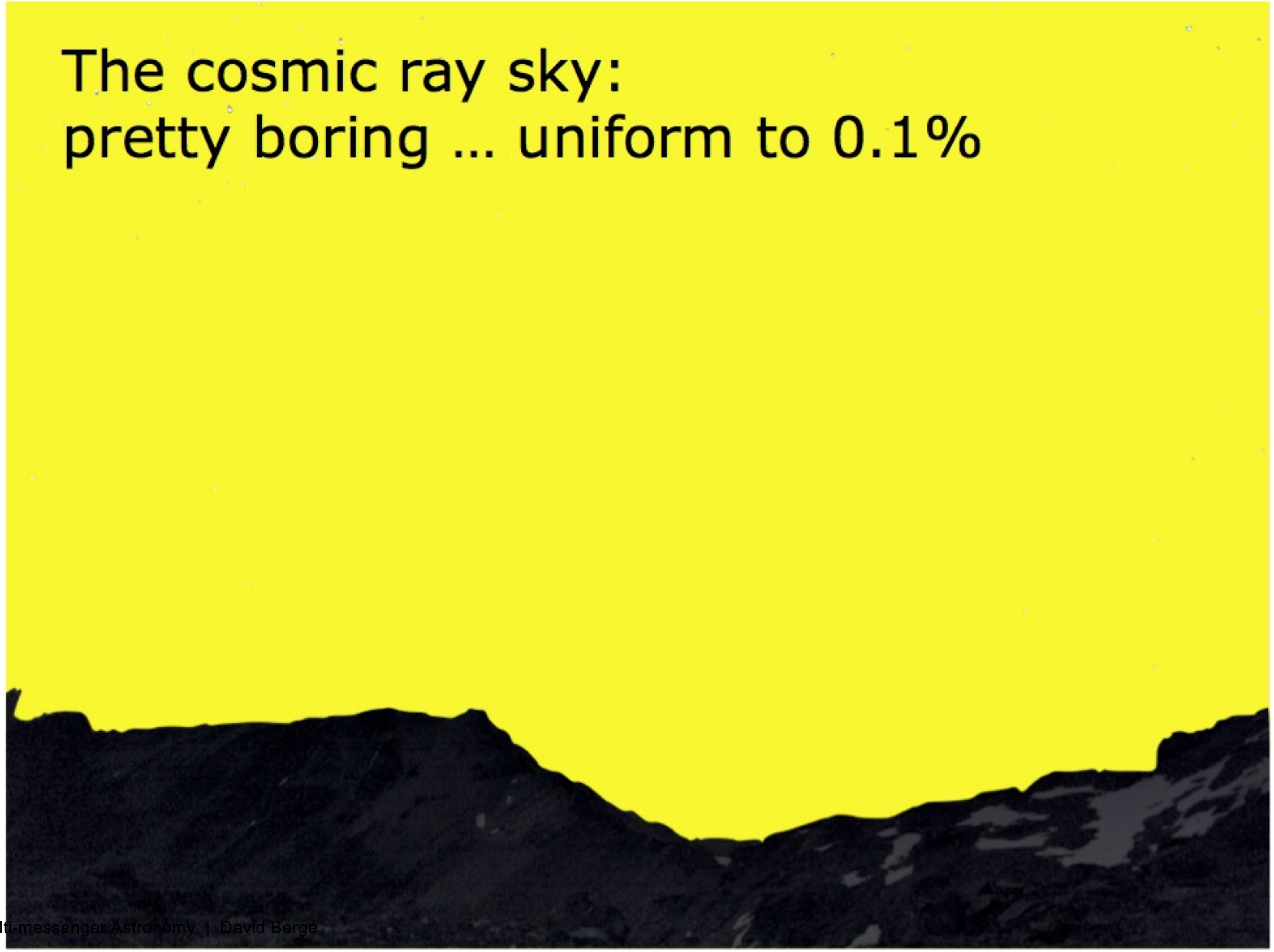
GRB: Gamma-ray Burst (short and long)

TDE: Tidal Disruption Event

NSBM: Neutron star binary merger

NGC: New General Catalogue


The cosmic sky:
fascinating


The cosmic ray sky:
pretty boring … uniform to 0.1%

Cosmic production of γ, ν, GW

“Non-thermal” Production Processes: Cosmic Beam Dumps

Cosmic ray

pp

$p\gamma$ $\rightarrow$

target

$$\left\{ \begin{array}{l} \ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \ldots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \\ \ldots + \pi^0 \rightarrow \gamma\gamma \end{array} \right.$$

"Non-thermal" Production Processes

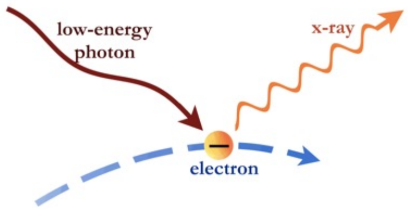
Cosmic ray
pp
$p\gamma$ $\rightarrow$
target

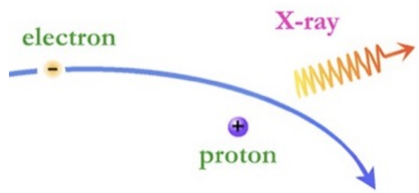
$$\ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

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

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

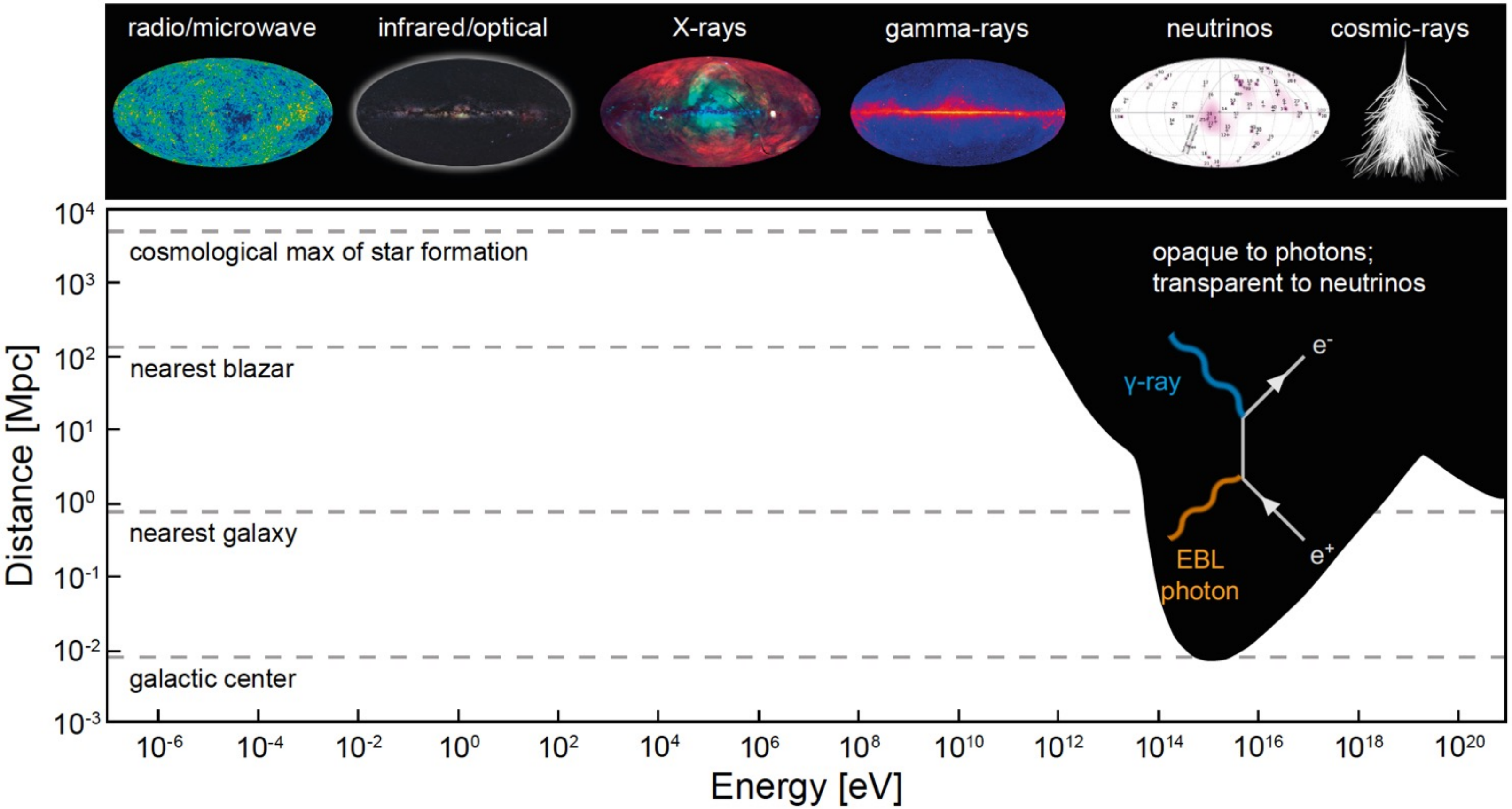
Gamma-rays are not exclusively produced in hadronic processes



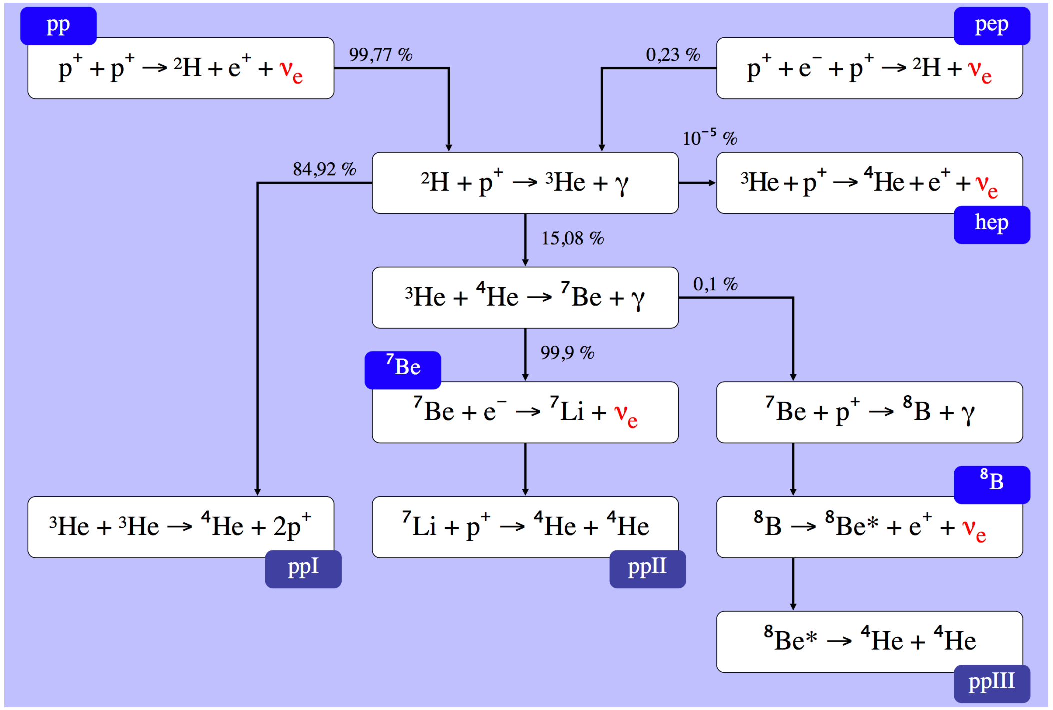


Neutrino measurements key to nailing down proton accelerators!

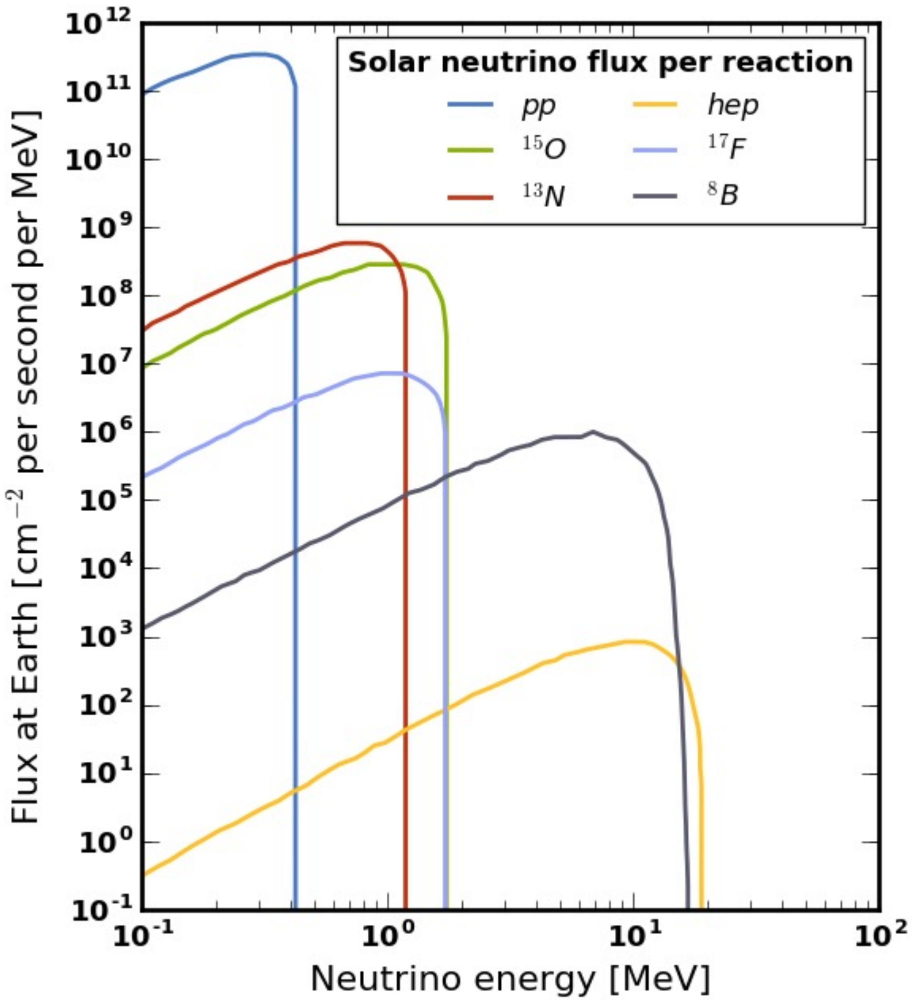
How to image the high-energy universe



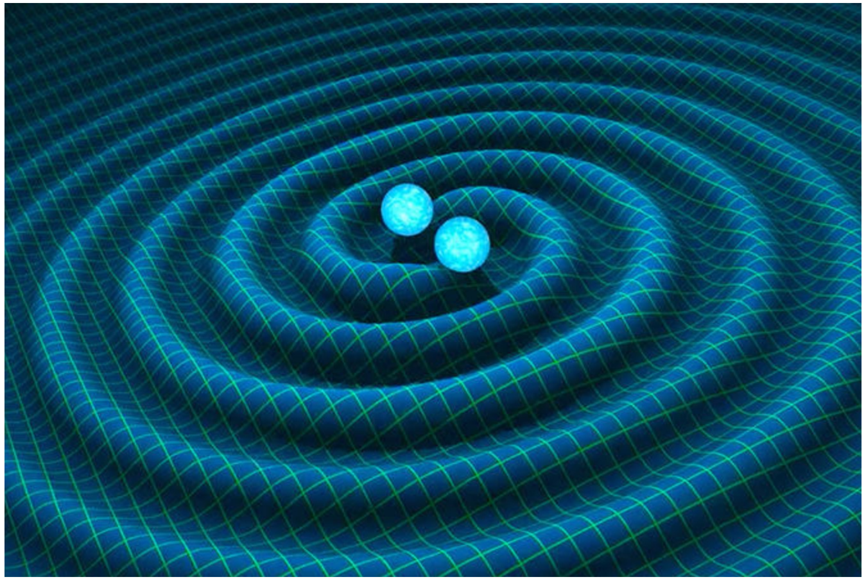
But also: solar neutrinos…

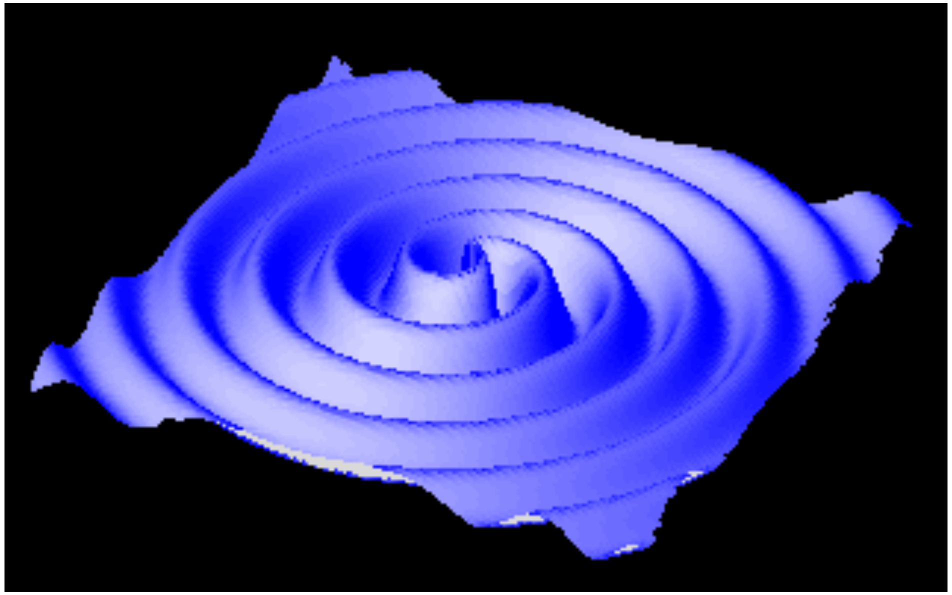


wikipedia



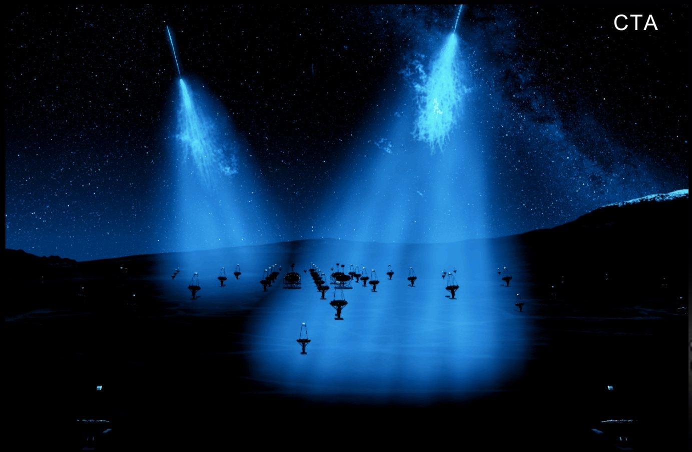
Gravitational Waves



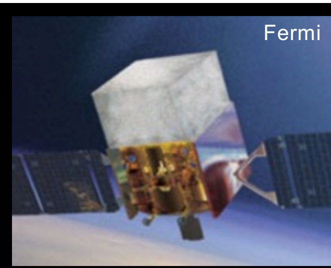


Our Tools for MM Astronomy

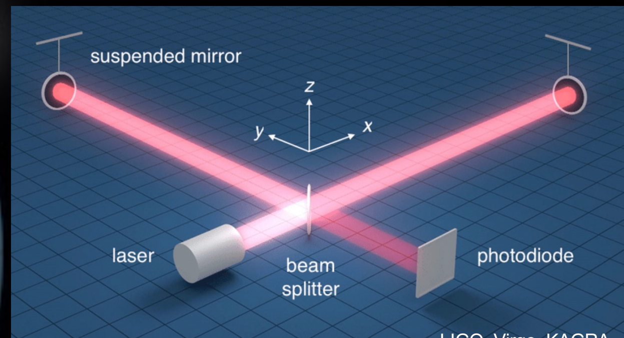
Calorimeters, trackers, interferometers…



H.E.S.S., MAGIC, VERITAS, HAWC, LHAASO…, e.g. https://www.annualreviews.org/doi/abs/10.1146/annurev-nucl-102014-022036

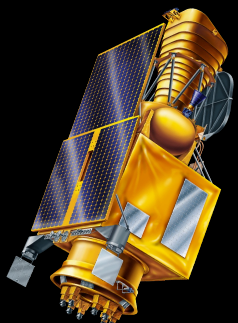


Fermi, Integral, AGILE, etc: Compton scattering, pair production

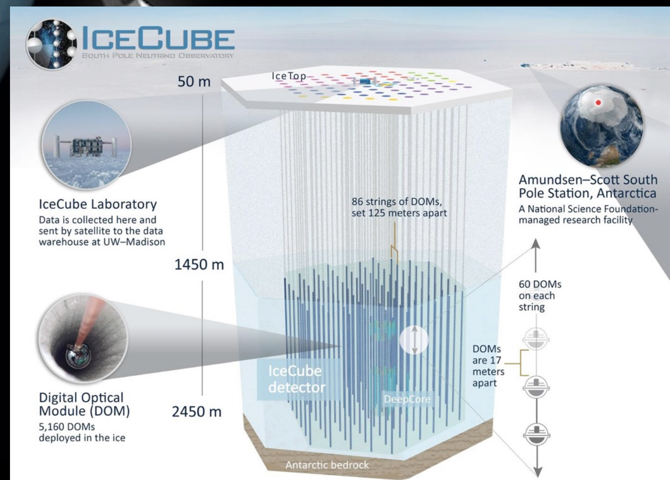


LIGO, Virgo, KAGRA

Large field survey instruments (radio to X-rays): ZTF, LSST, ULTRASAT, etc etc



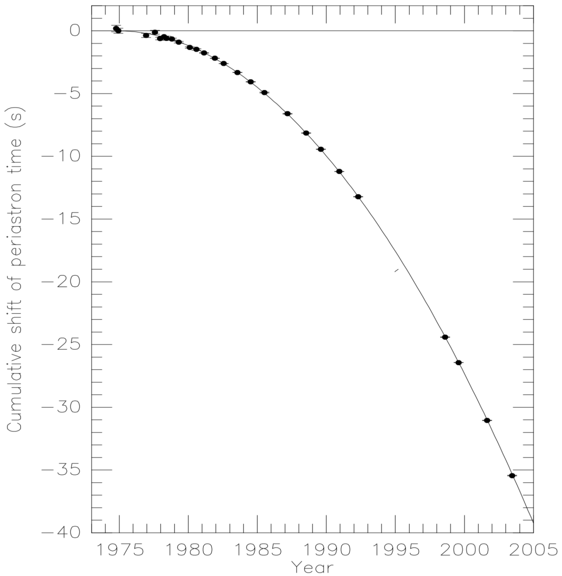
ULTRASAT



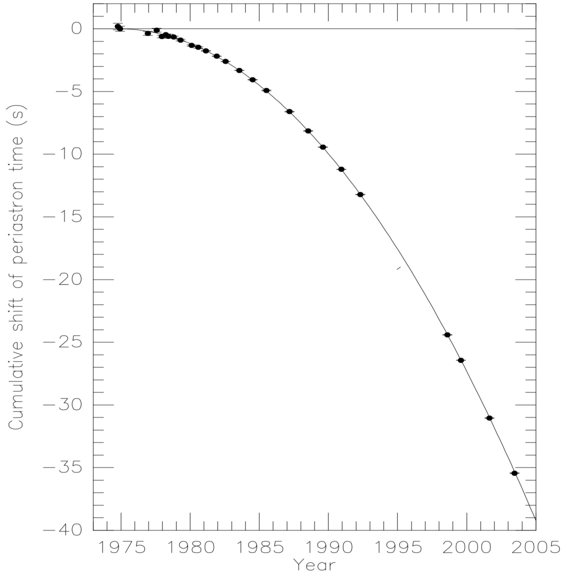
IceCube Coll., JINST 12 P03012 (2017)

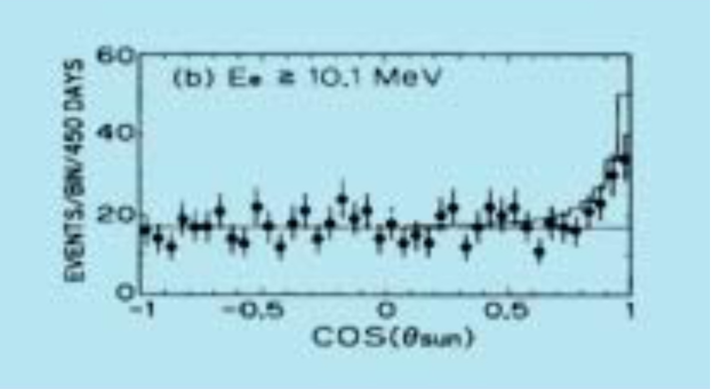
Multi-Messenger Astronomy – History Quiz

History Quiz

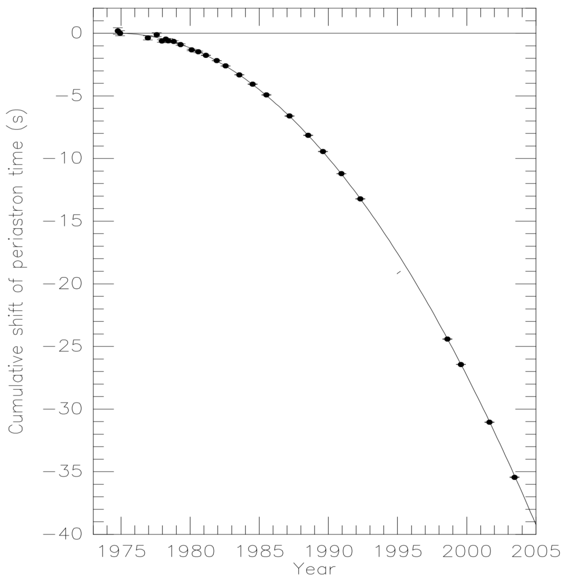


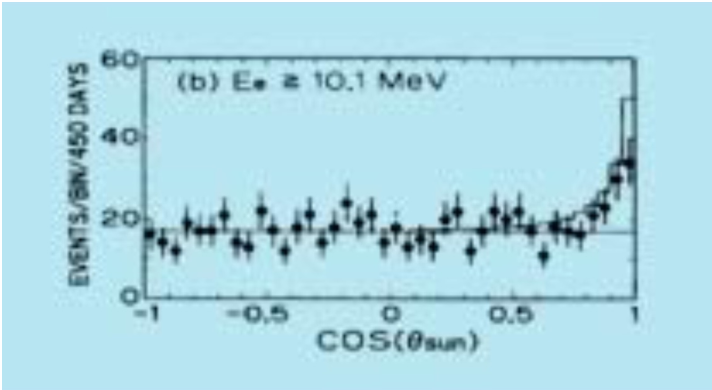
History Quiz

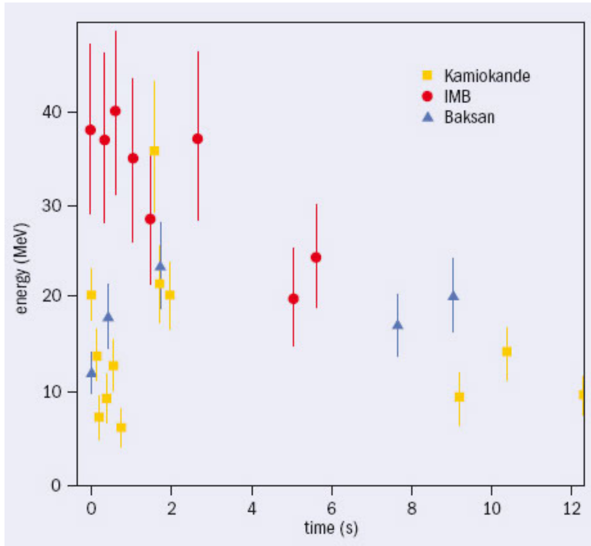




History Quiz

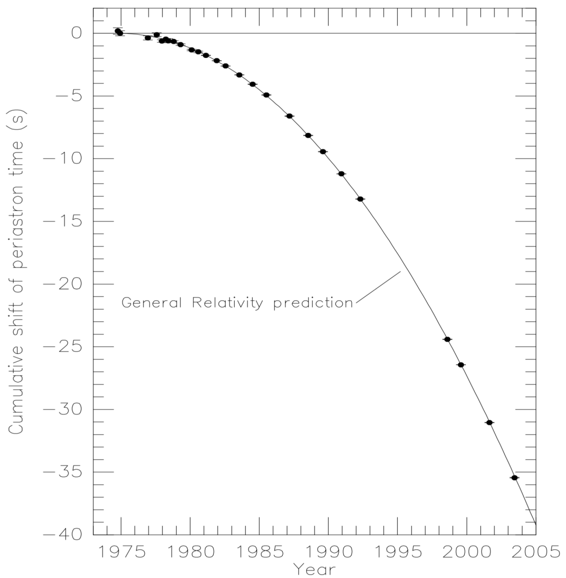


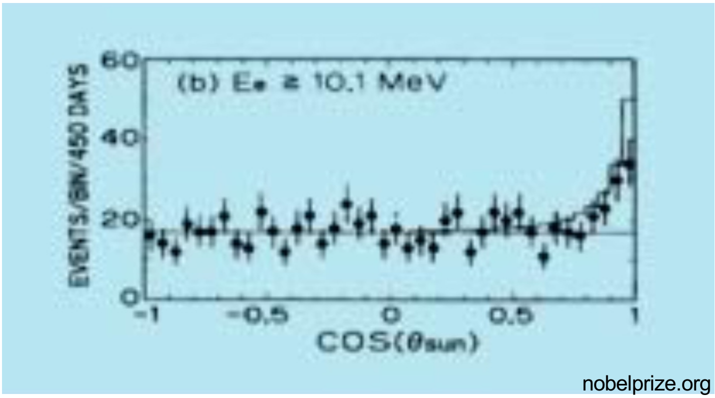


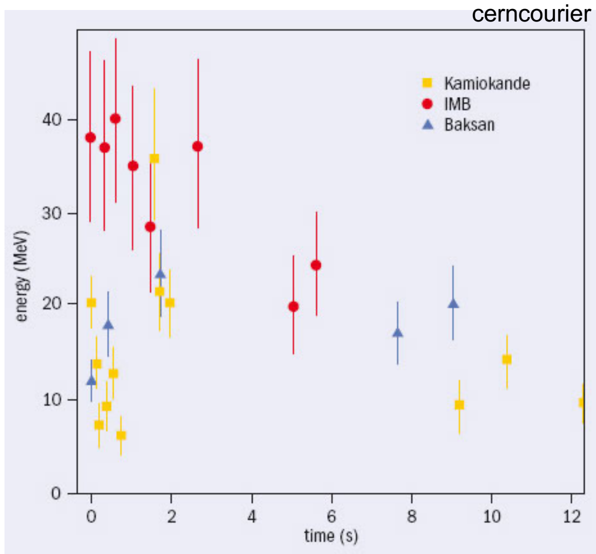


History Quiz

Weisberg&Taylor 2004







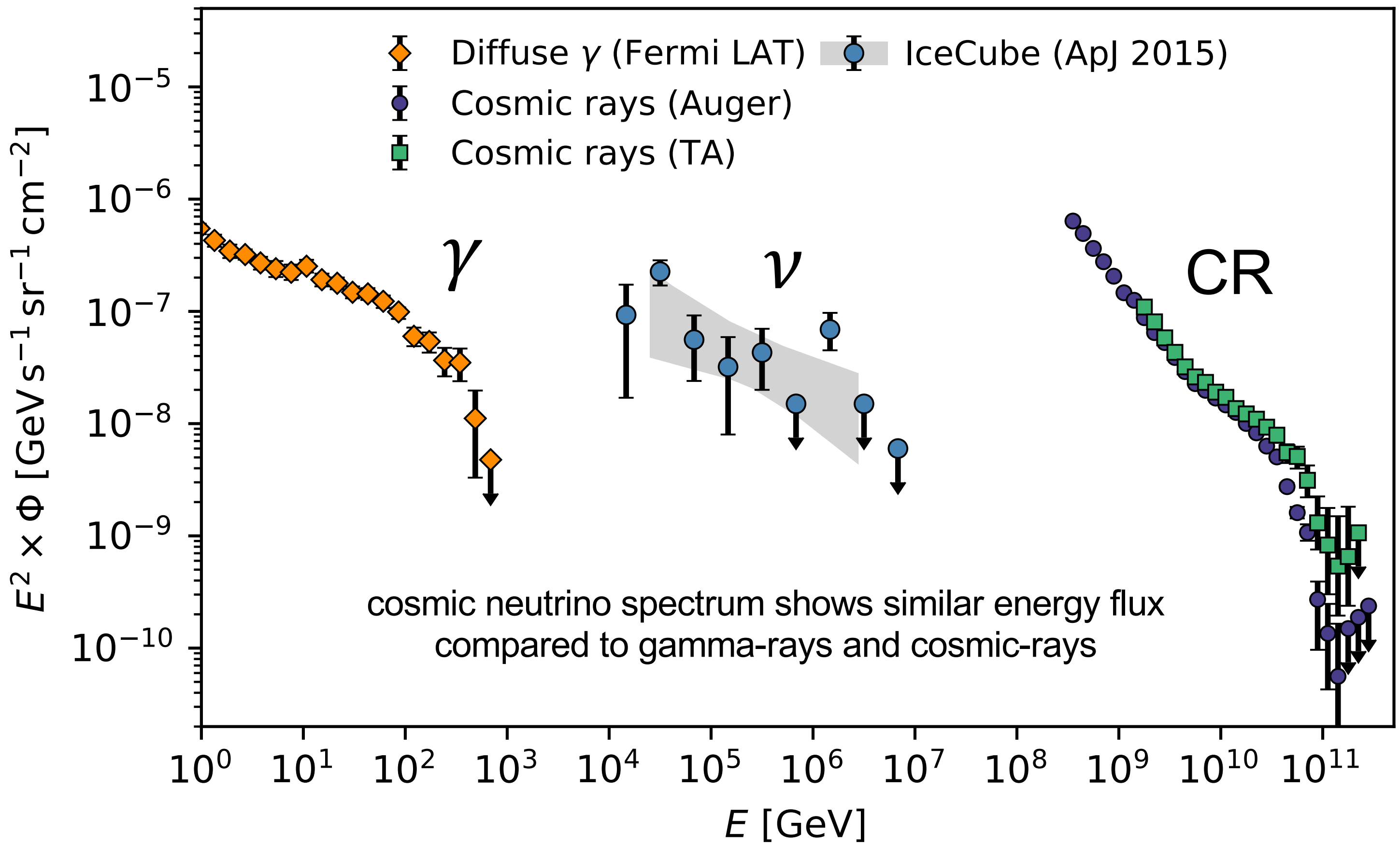
Hulse-Taylor binary, 59-ms pulsar orbits around neutron star, pulses shifted by 3s every 7.75 hrs, orbital decay (change of periastron) due to emission of GW's!

Neutrinos from the Sun (Davis Jr, Homestake mine)!

Neutrinos from SN1987a, a supernova in the Large Magellanic Cloud, our cosmic neighbourhood.
12 neutrinos in 12s by Kamiokande, out of 10^{16} passing through the detector, and 10^{58} emitted during the stellar collapse!

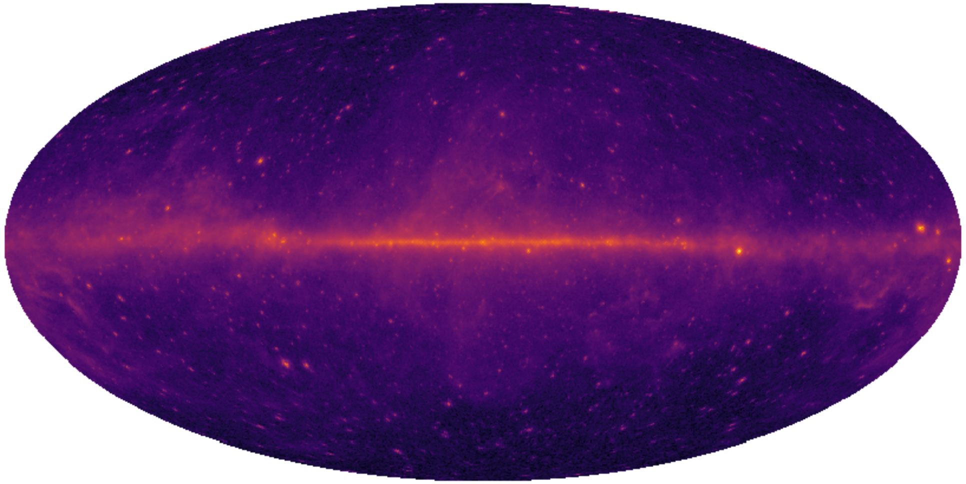
Science Highlights

All-sky Energy Flux Spectra



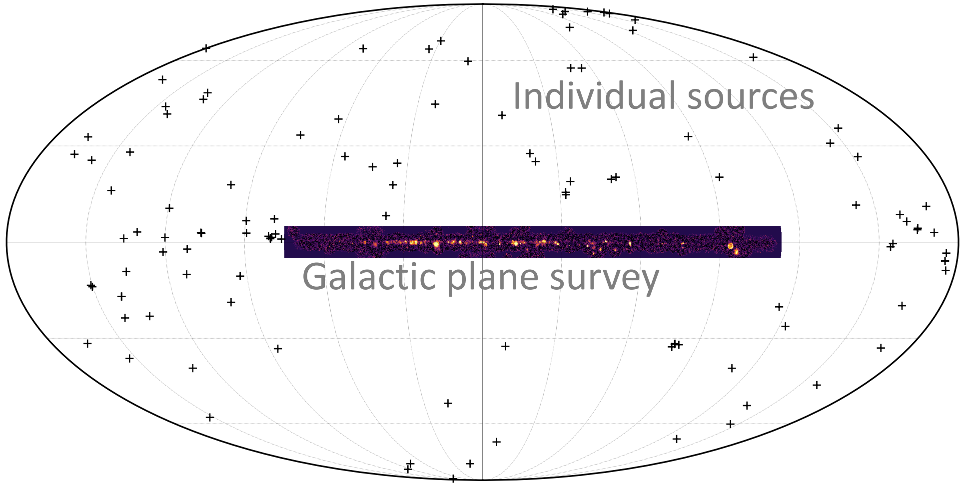
Fermi-LAT, R.Bühler

Gamma-ray sky, 1 - 100 GeV

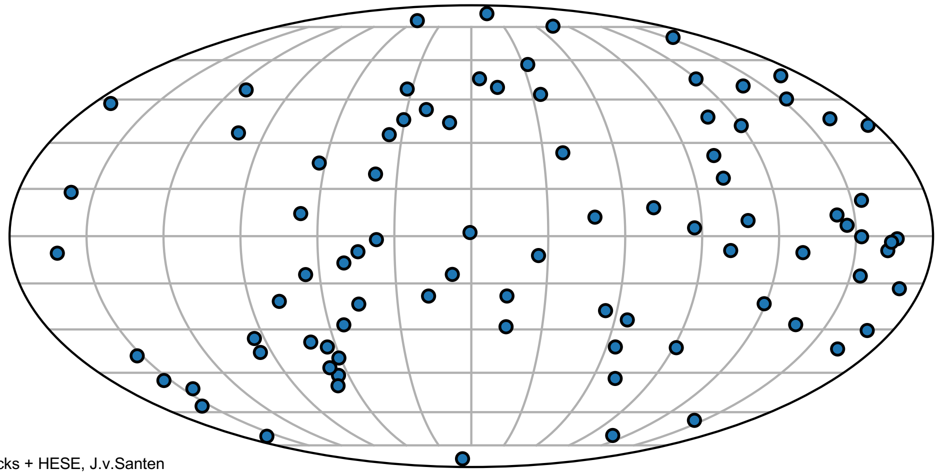


All IACTs, M.Nievas-Rosillo

Gamma-ray sky, 0.1 - 10 TeV

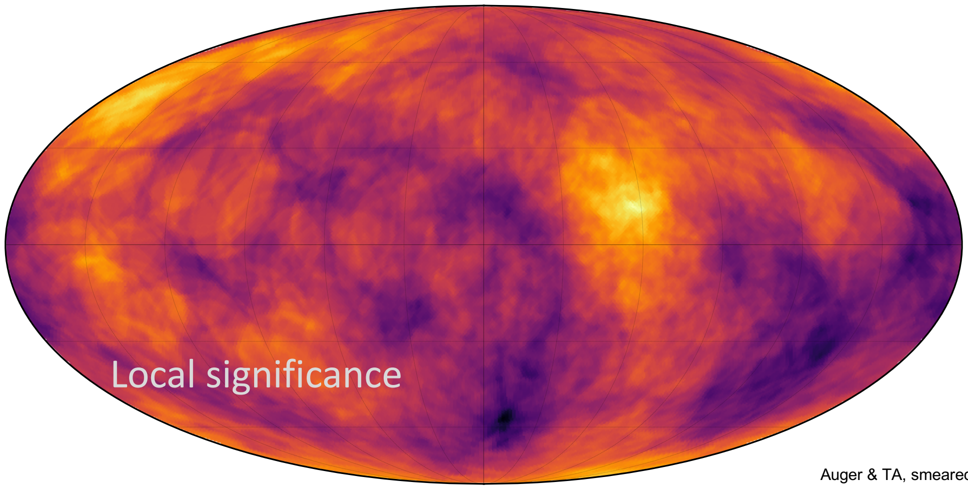


Neutrino sky, > 200 TeV



IceCube tracks + HESE, J.v.Santen

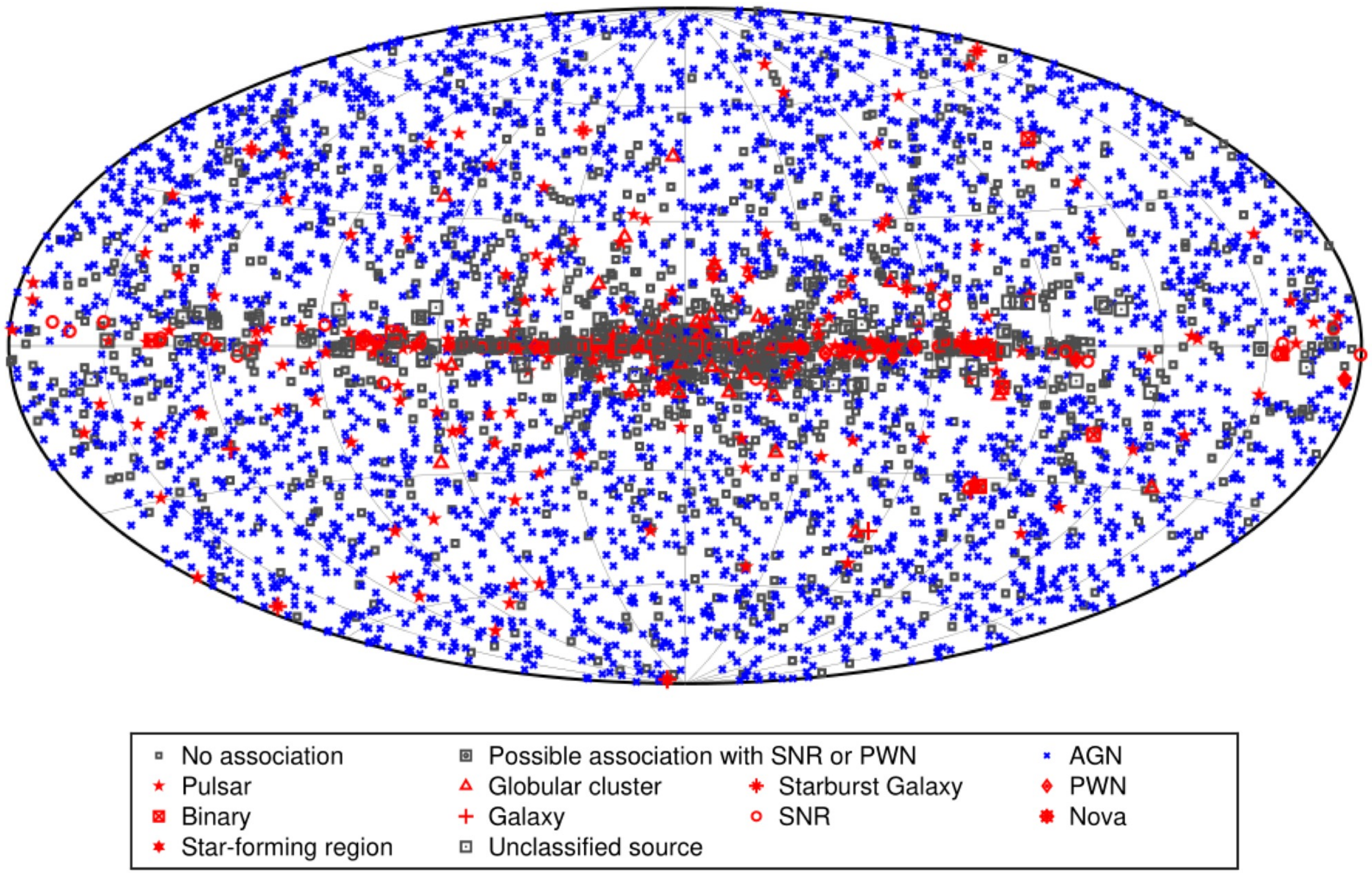
Cosmic-ray sky, > 40 EeV



Auger & TA, smeared, M.Unger

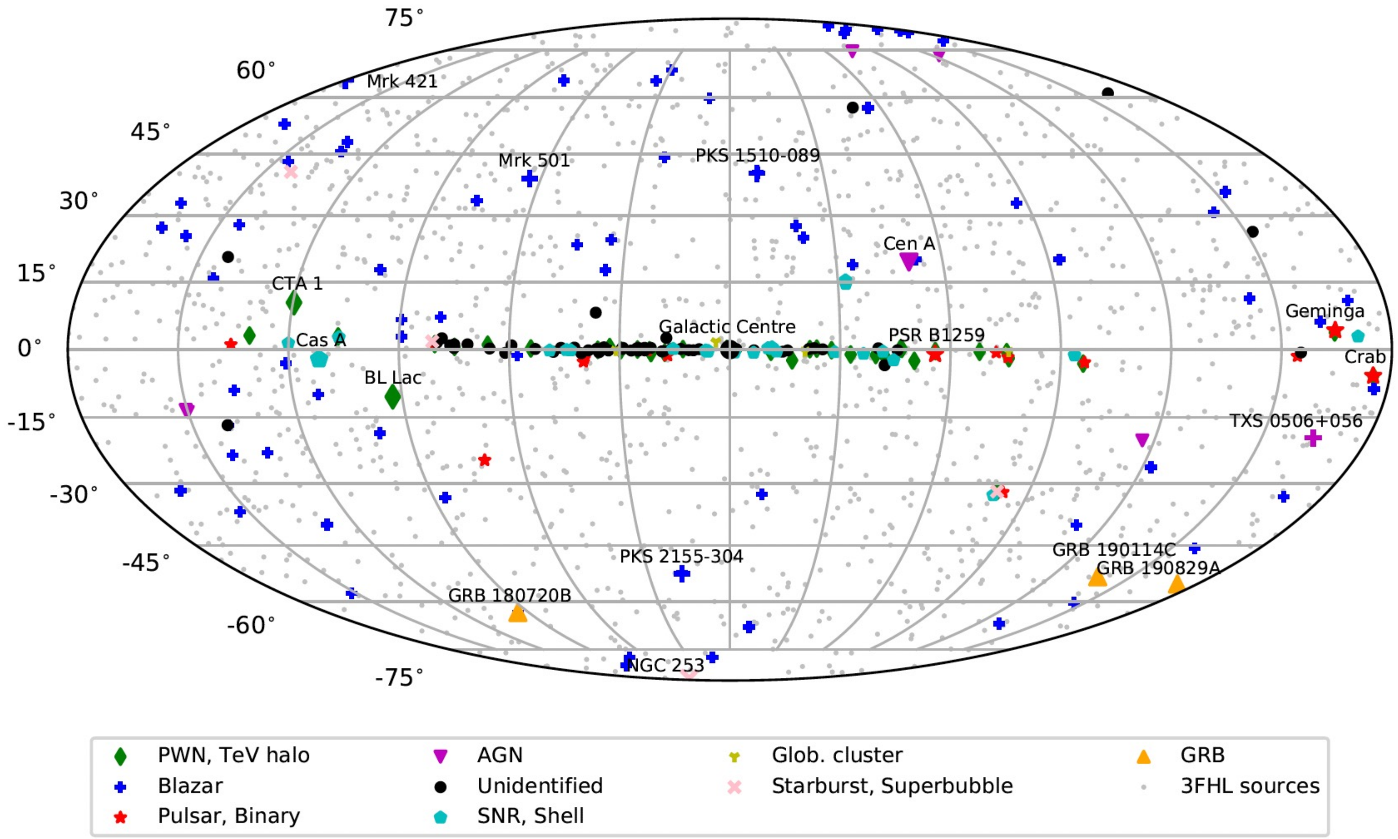
Gamma-ray sources

Overview HESS plane scan



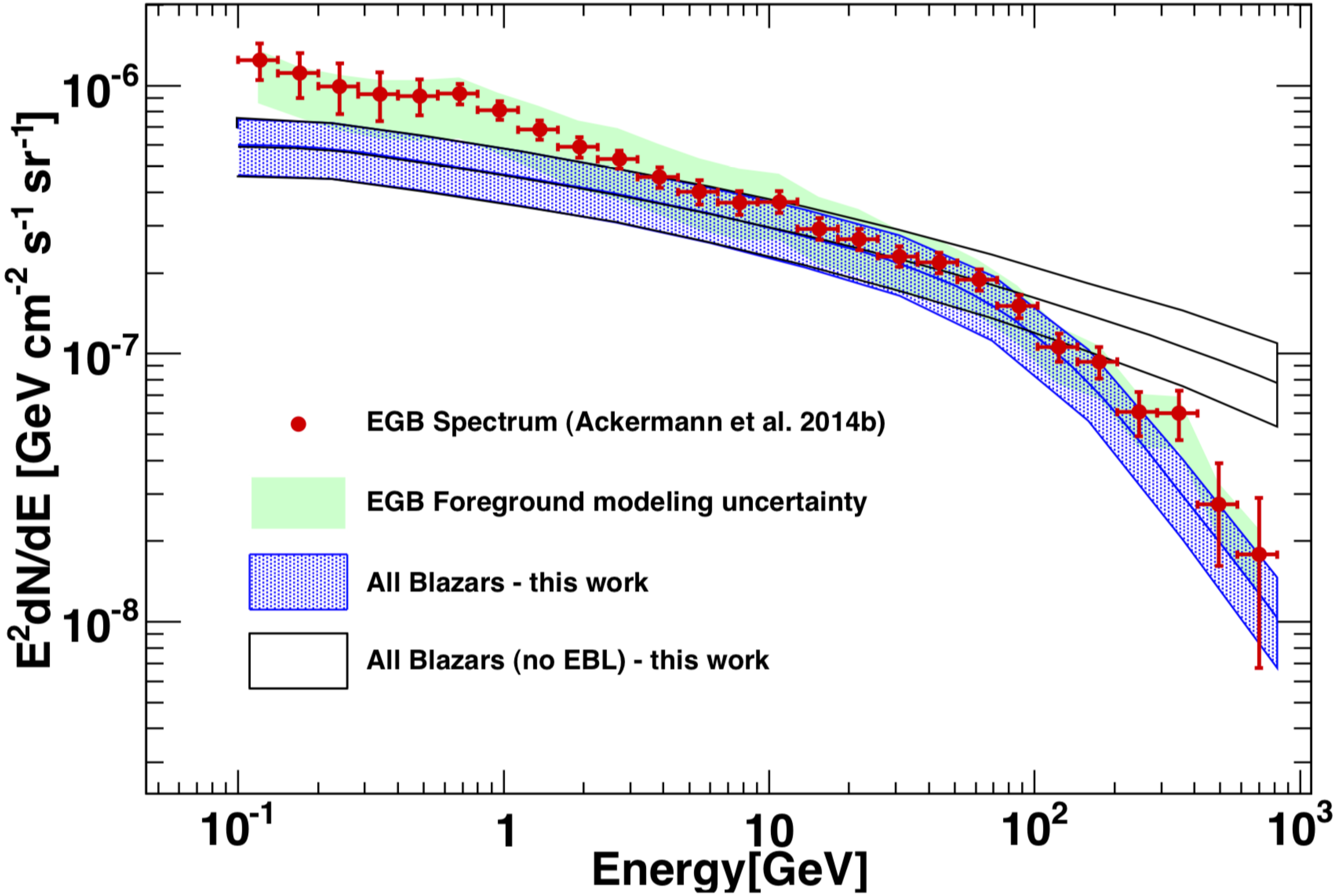
Fermi-LAT, 8 years, 5000 sources (2/3 blazars), ApJS 247, 2020

Gamma-ray sources



Hinton & Ruiz-Velasco, TAUP 2019

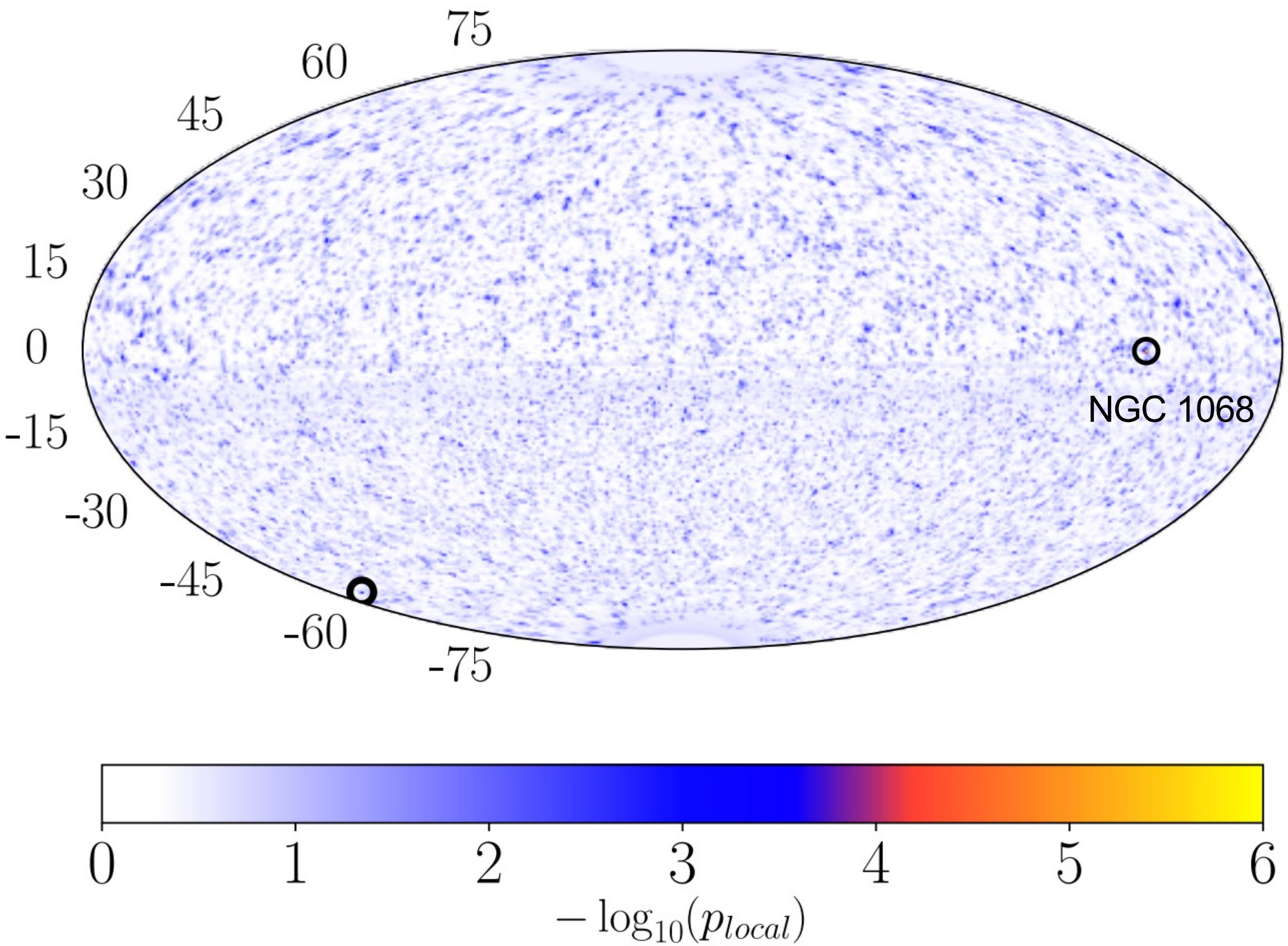
The Extragalactic Gamma-ray Background



[Ajello+, ApJL, 2015)]

What are the Neutrino sources?

1. Search for hotspots and probe bright gamma-ray sources ('stacking' analyses)
2. Look for EM counterparts of individual high-energy neutrinos of high signalness

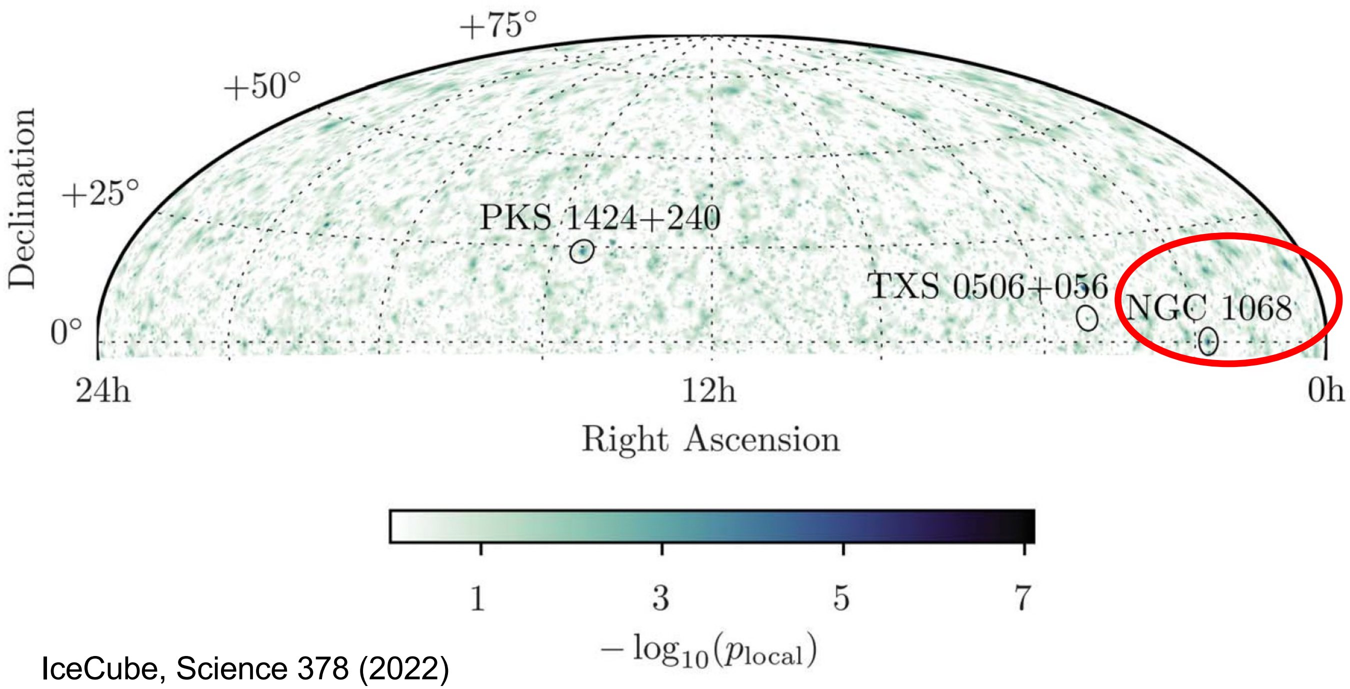


IceCube, PRL 124 (2020)

Strategy 1: Search for neutrinos from pre-defined source list

- 110 sources based on **gamma-ray properties** and weighted with neutrino search sensitivity
  - **8 starburst galaxies** detected by Fermi-LAT
  - **98** brightest Fermi-LAT **blazars** (above 1 GeV)
  - **12 galactic sources based on VHE gamma-ray** measurements
- → **Discovery of NGC 1068**

Neutrino hottest spot: NGC 1068

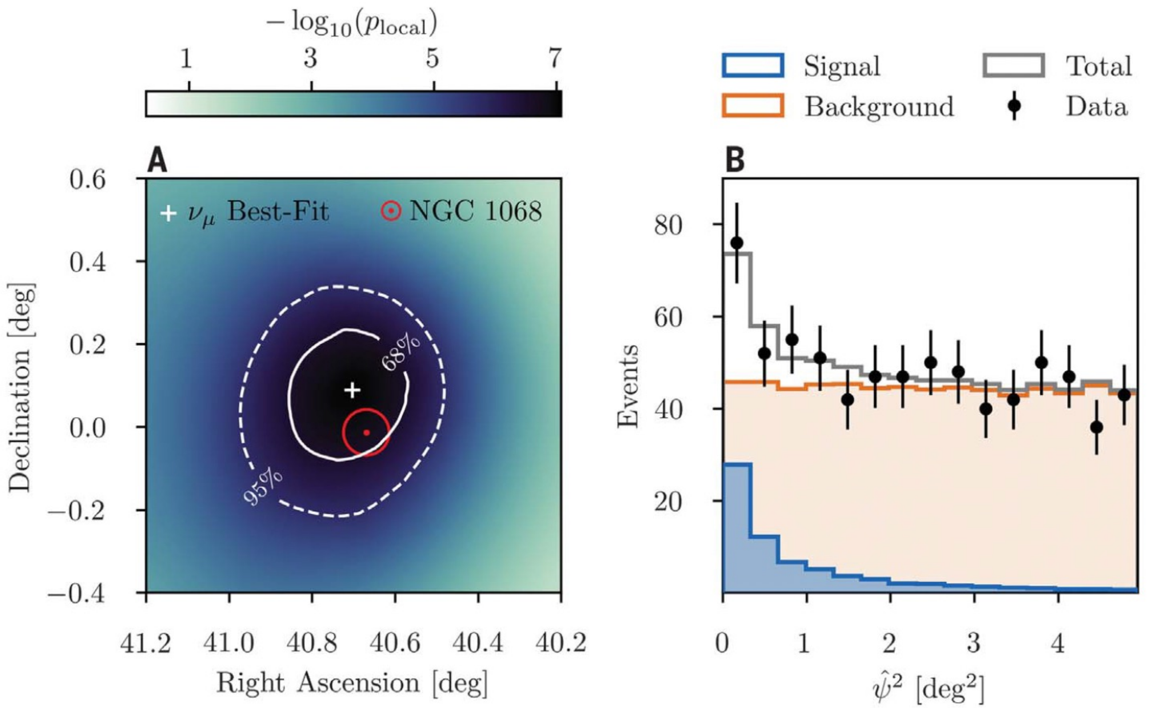


IceCube, Science 378 (2022)

Hubble image NGC 1068, prototypical Seyfert 2 galaxy

79 Neutrinos, 4.2 sigma post trials, the first Neutrino point source!

Neutrino hottest spot: NGC 1068

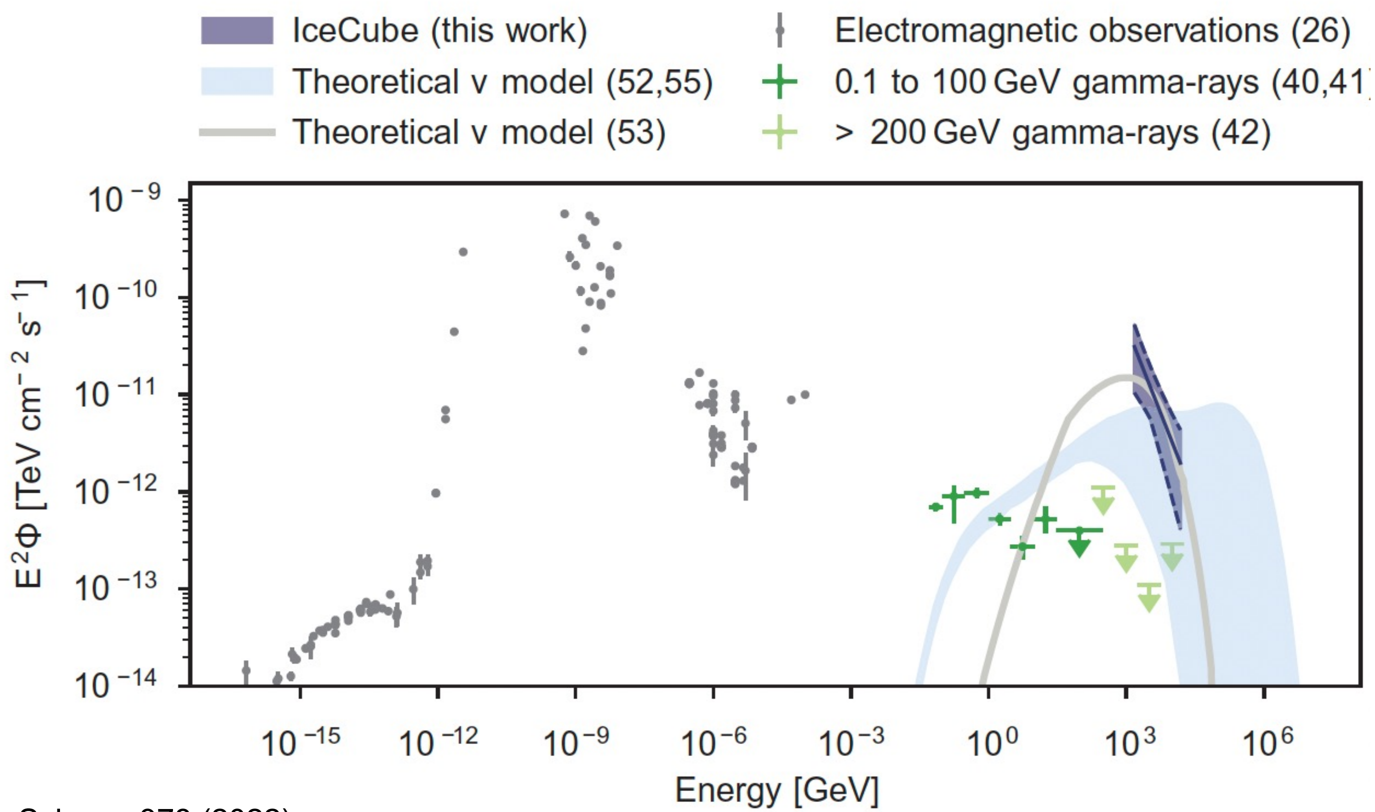


IceCube, Science 378 (2022)

79 Neutrinos, 4.2 sigma post trials, the first Neutrino point source!

Neutrino hottest spot: NGC 1068

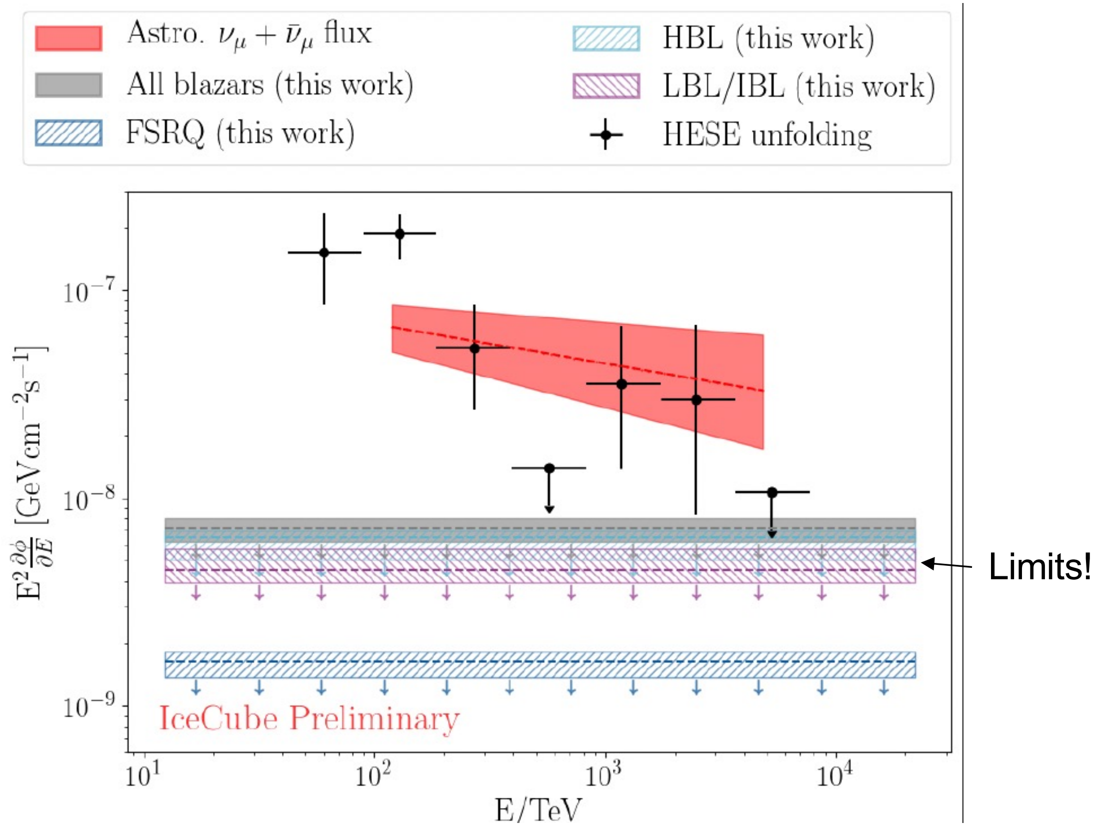
Need to find ways to hide corresponding gamma-ray emission…



IceCube, Science 378 (2022)

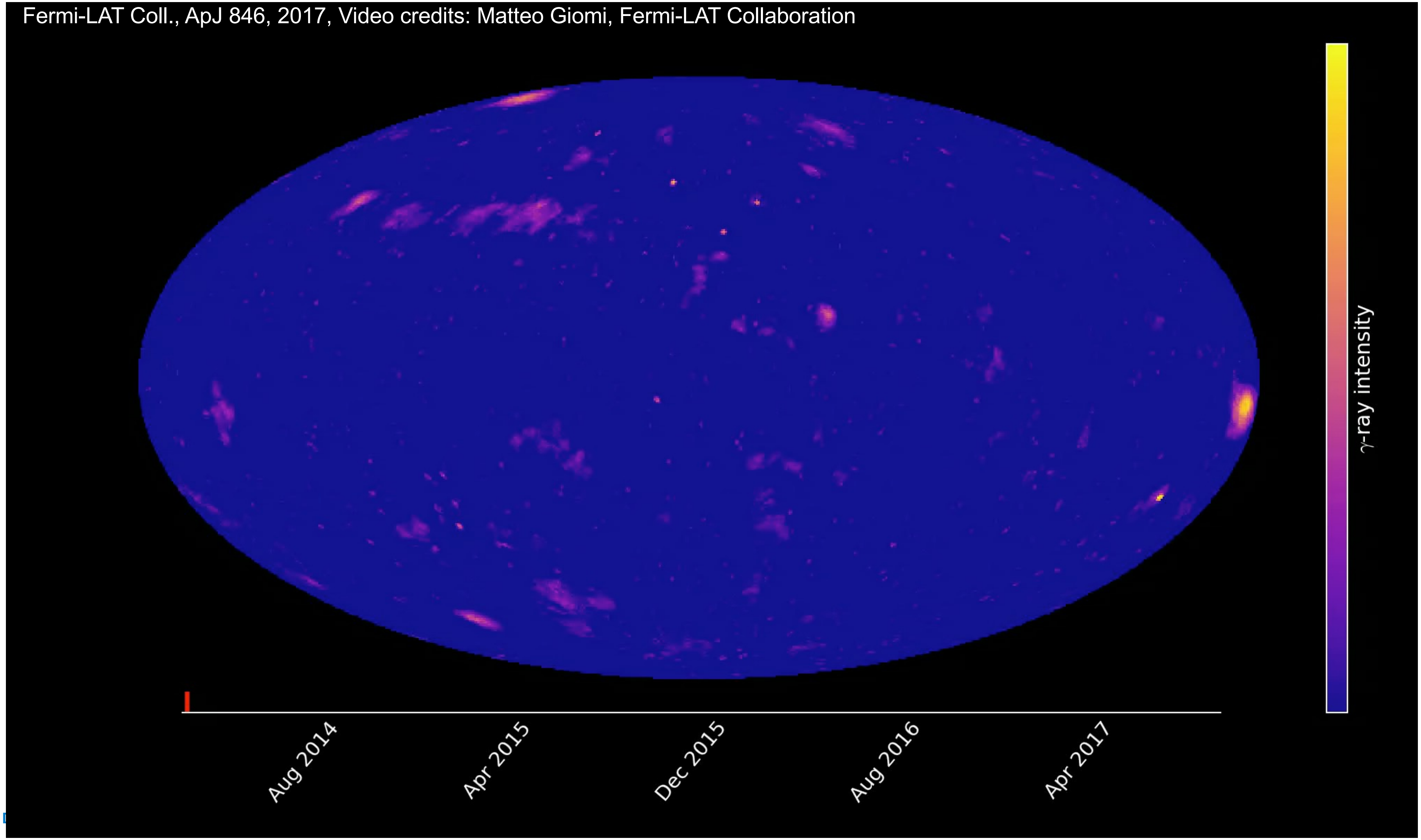
Stacking analysis of all 110 pre-defined sources

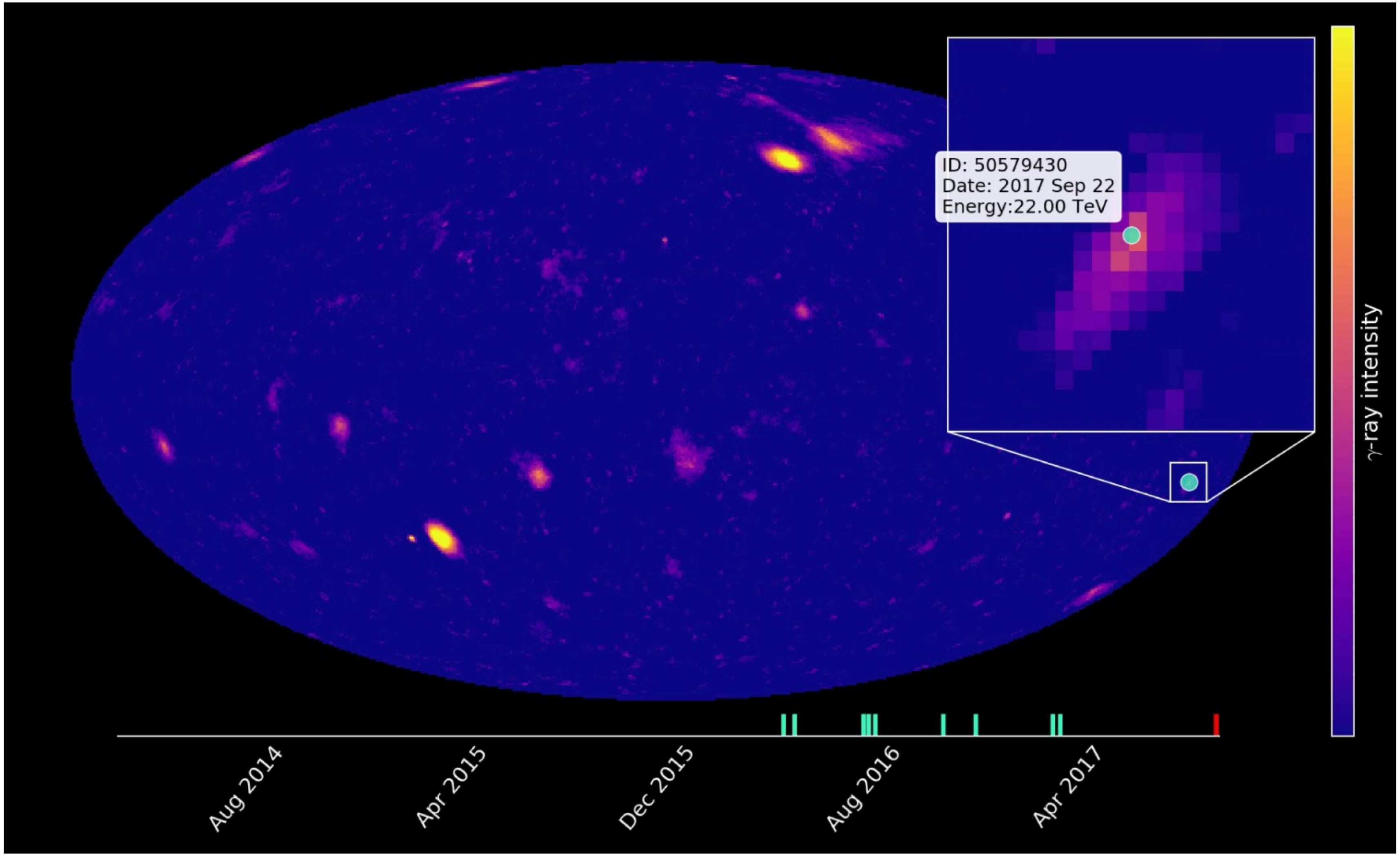
Fermi blazars < 10% of diffuse neutrinos



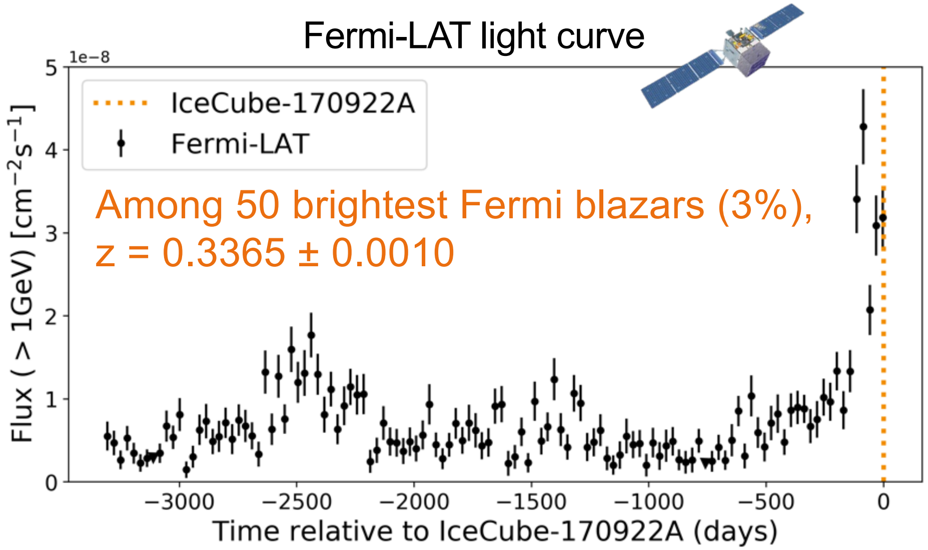
IceCube ApJ 835, 2017

2. Strategy: look for Neutrino – gamma-ray transients

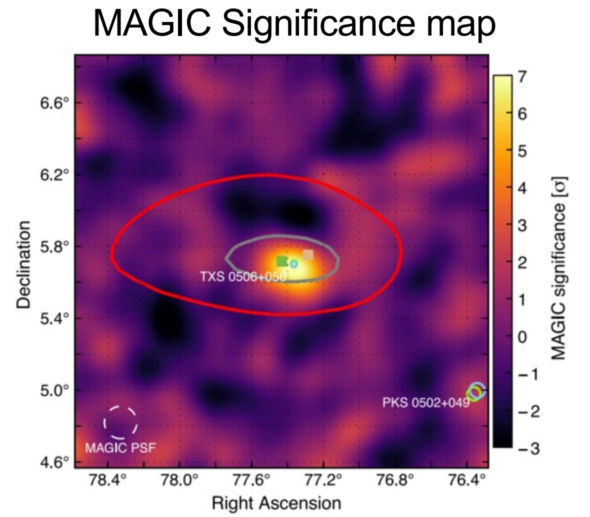

Fermi-LAT Coll., ApJ 846, 2017, Video credits: Matteo Giomi, Fermi-LAT Collaboration
γ-ray intensity
Aug 2014
Apr 2015
Dec 2015
Aug 2016
Apr 2017


ID: 50579430
Date: 2017 Sep 22
Energy:22.00 TeV
γ-ray intensity
Aug 2014
Apr 2015
Dec 2015
Aug 2016
Apr 2017

Blazar TXS 0506+056



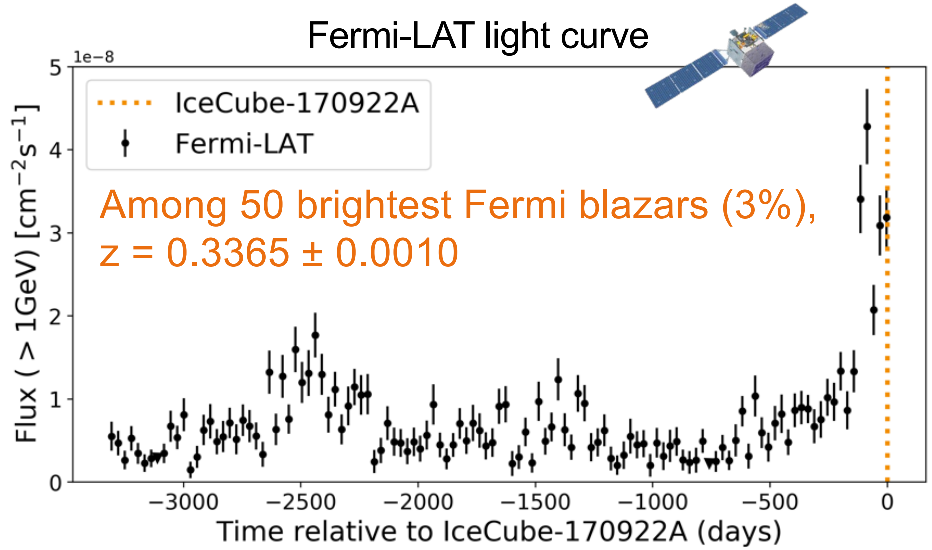
Among 50 brightest Fermi blazars (3%),
z = 0.3365 ± 0.0010

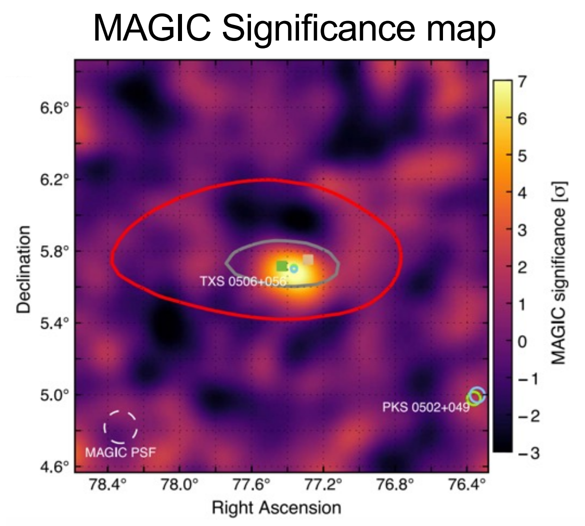


300 TeV neutrino coincident with gamma-ray flare (3σ significance)

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

Blazar TXS 0506+056

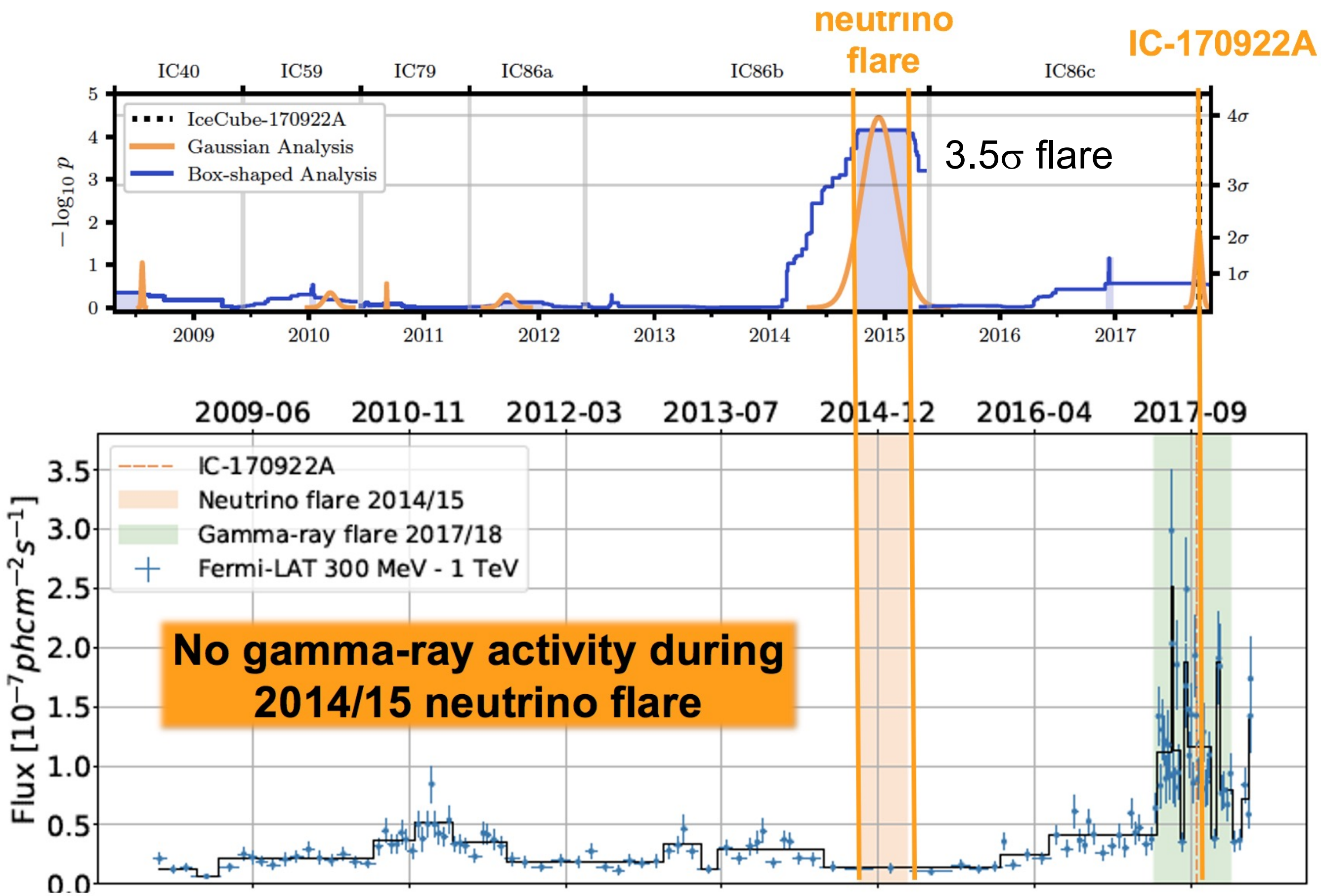




- Signalness of 290 TeV neutrino: 56.5%
- Chance coincidence ‘disfavoured’ at 3 σ level
- This blazar among the 30 brightest gamma-ray blazars in the sky

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

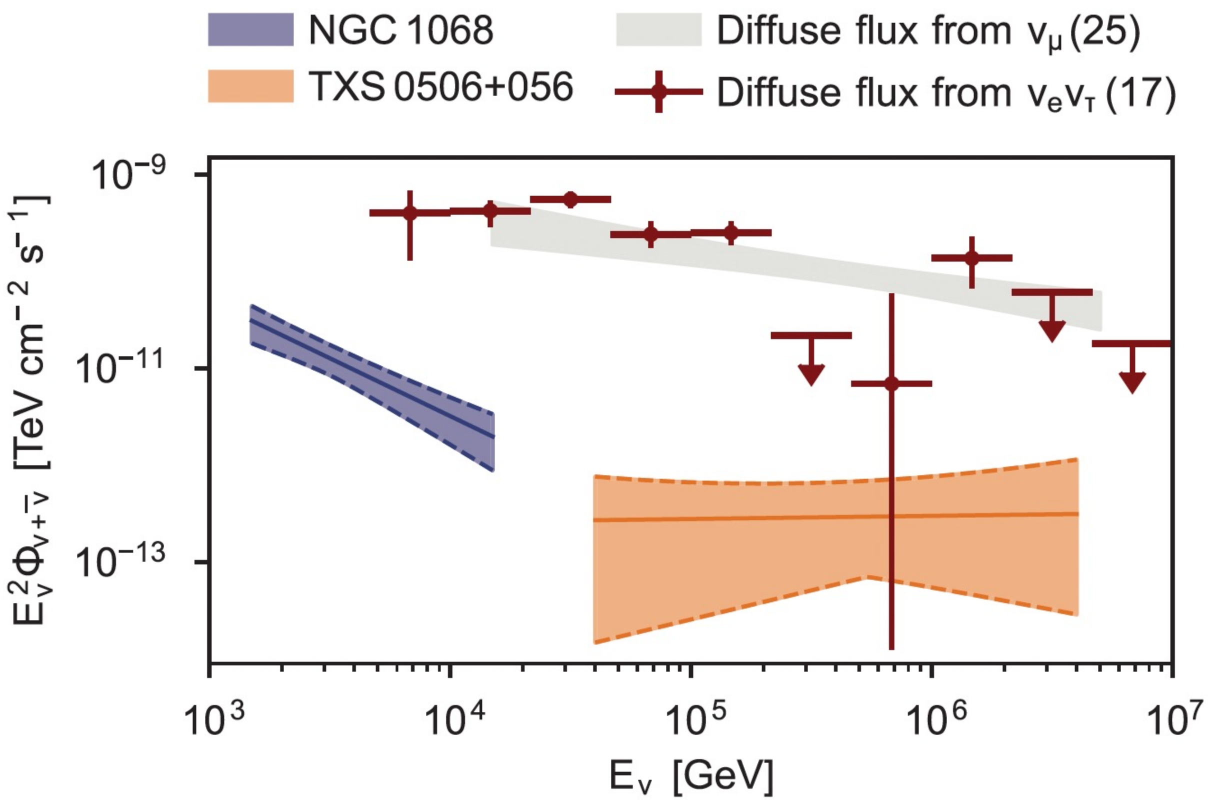
Archival search revealed another Neutrino flare w/o gammas…



Challenge for models, need more of these!

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

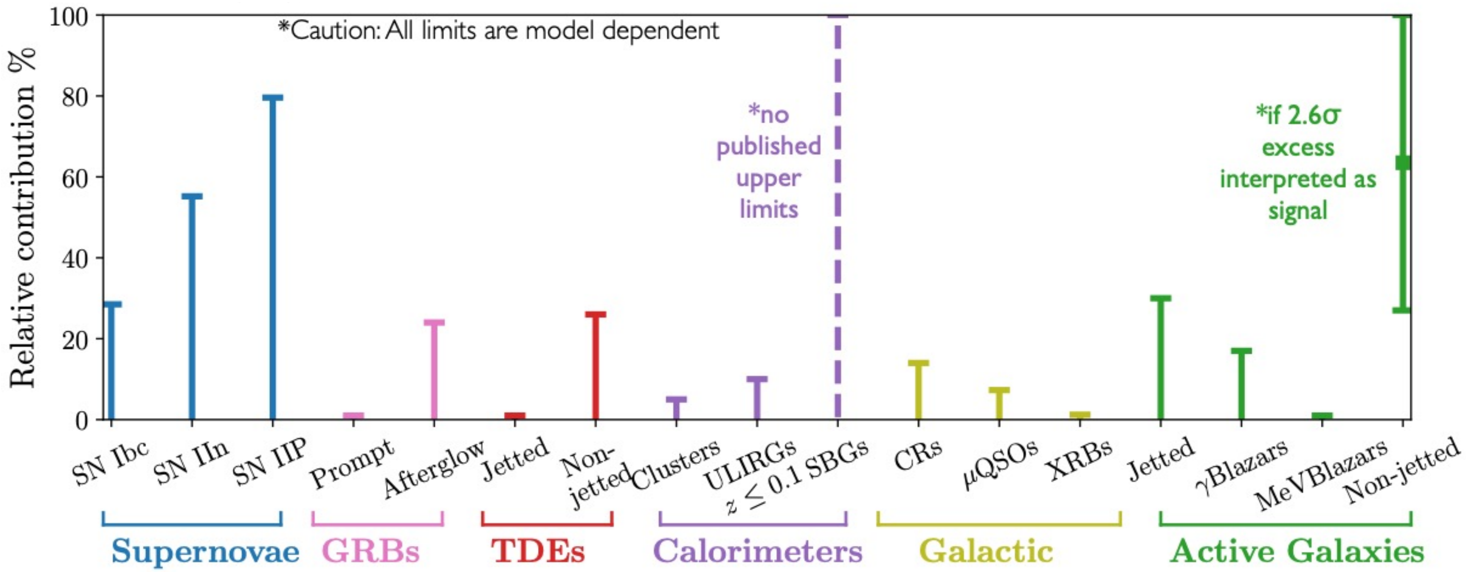
First two potential extrasolar Neutrino sources not dominant



IceCube, Science 378 (2022)

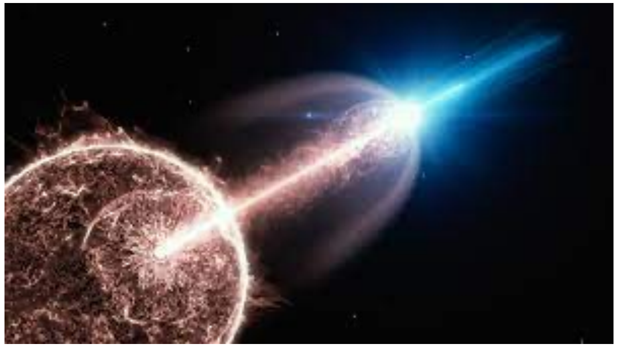
Summary of Stacking Limits

So far no dominant source class for diffuse neutrinos identified



F. Oikonomou PoS ICRC2021 (2022) 030, arXiv:2201.05623

Science highlight: explosives…



DESY, Science Communication Lab

Gamma Ray Bursts

Why interesting?

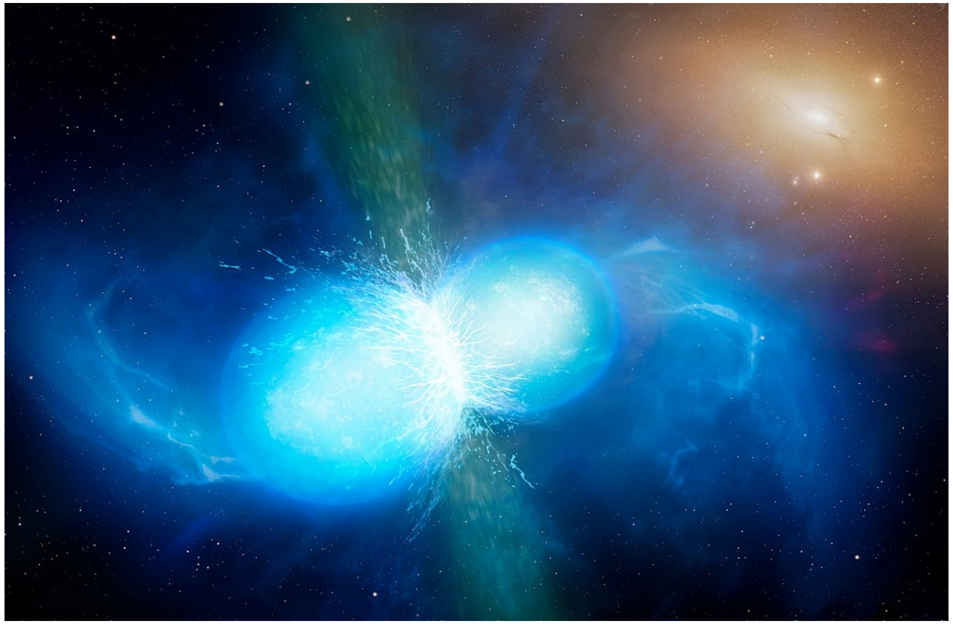
- Up to 10^{55} erg (10^{48} Joule) in seconds to minutes released
  - 1 solar mass = 1.8×10^{54} erg

- Potential sources of highest energy cosmic rays
- Potential sources of heavy elements
- Among the farthest known light sources (can use as beacon to measure cosmic light fields via absorption)
- **Multi-messenger Question: Are GRBs accelerating hadrons?**

Gamma Ray Bursts

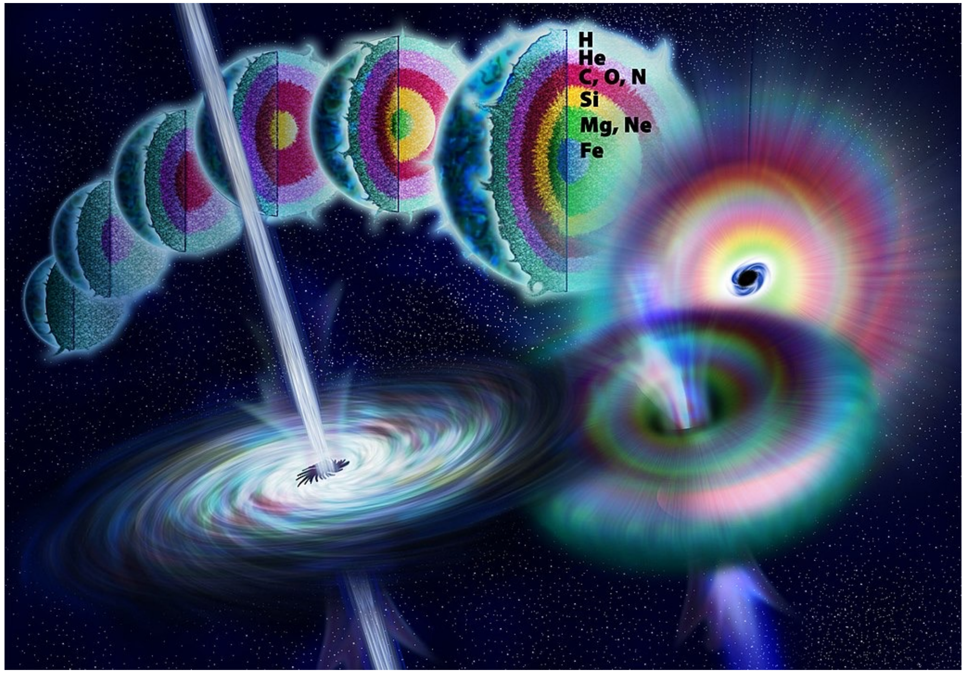
Short and long gamma-ray bursts

Short GRBs: prompt phase (few sec) + afterglow



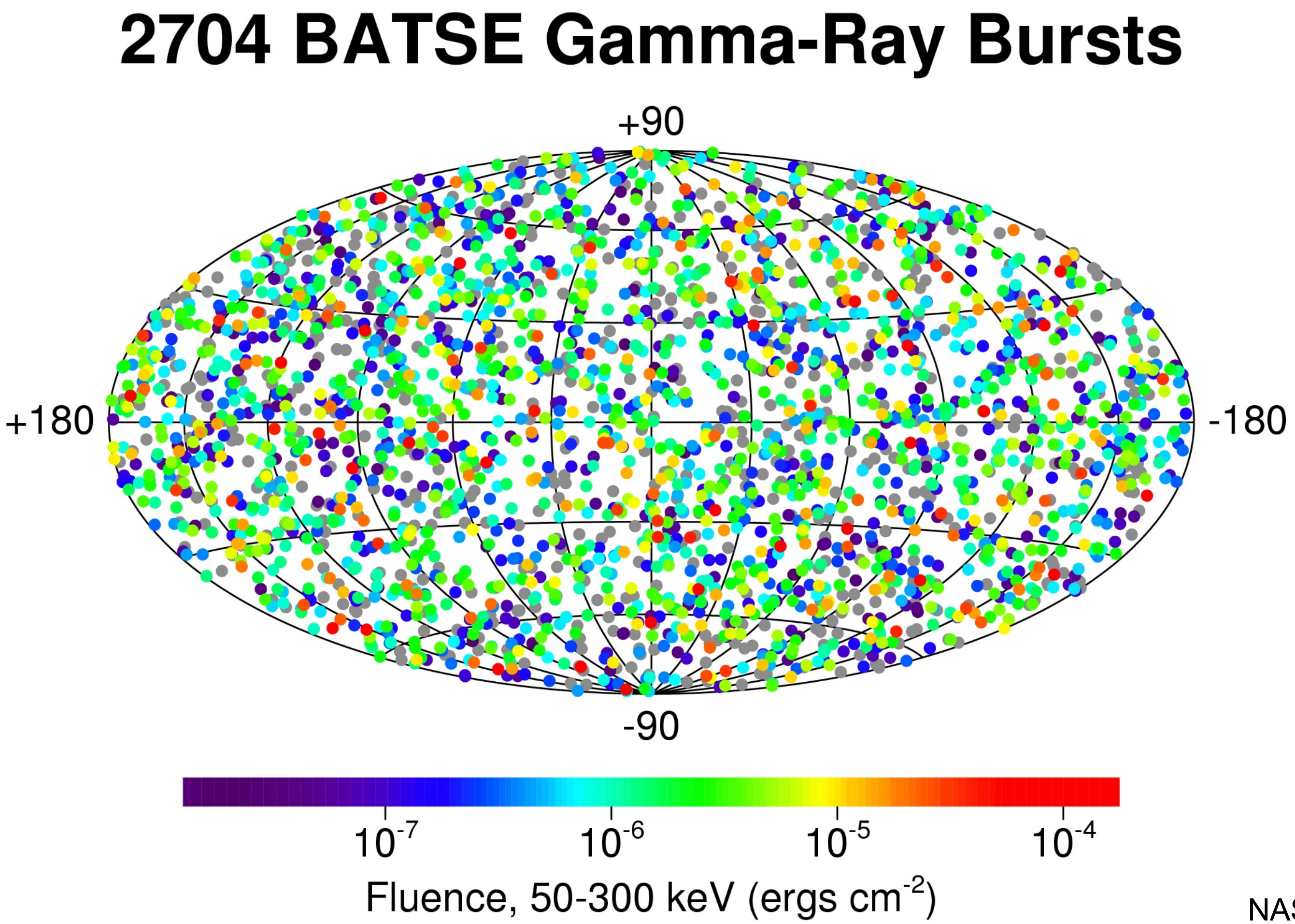
Neutron-star merger event / ESO

Long GRBs: prompt phase (sec - min) + afterglow



Collapse of massive star / NSF

Gamma Ray Bursts



NASA

Isotropic locations

Up to 10^{55} erg

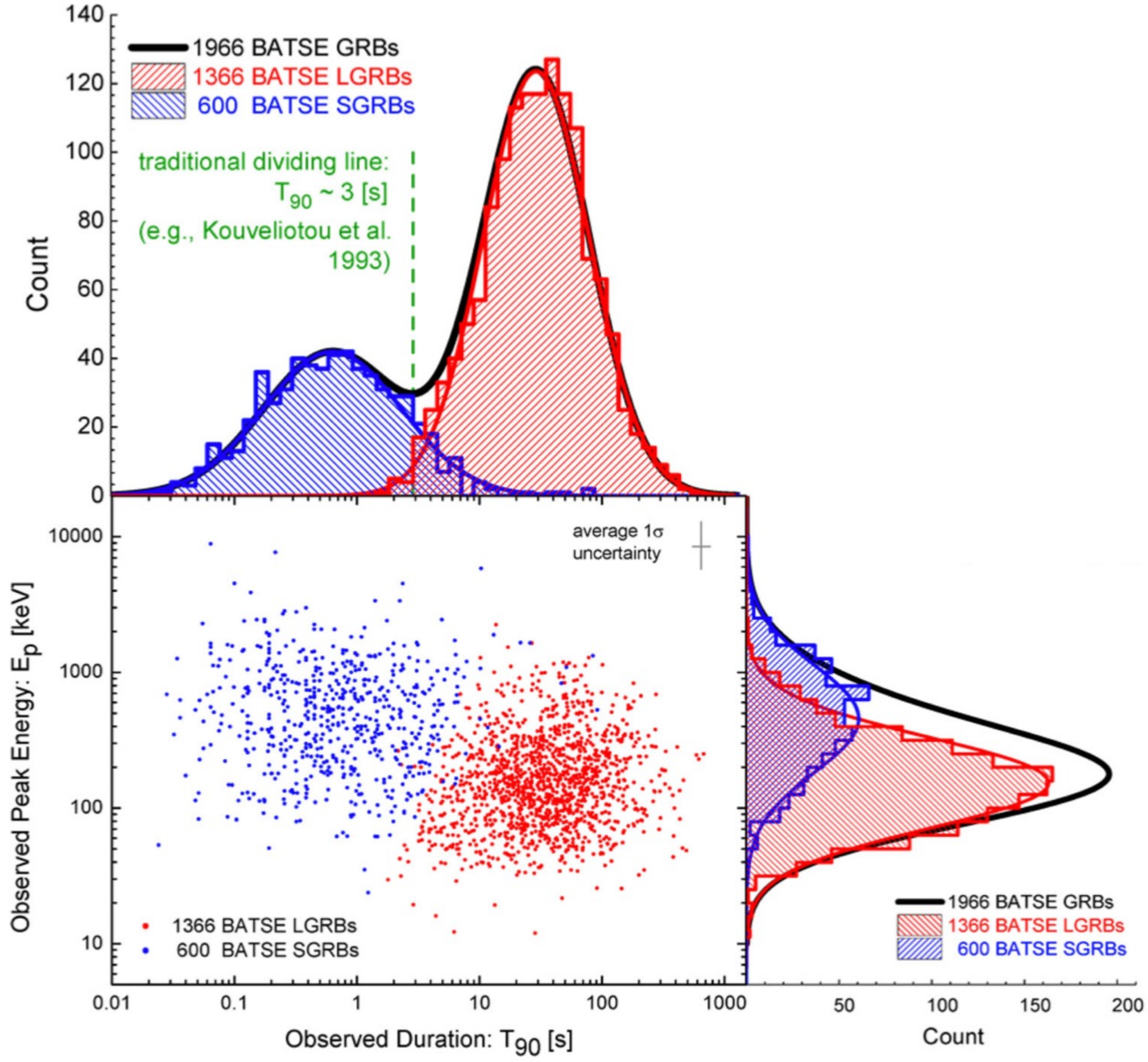
Prompt and afterglow emission

Gamma Ray Bursts

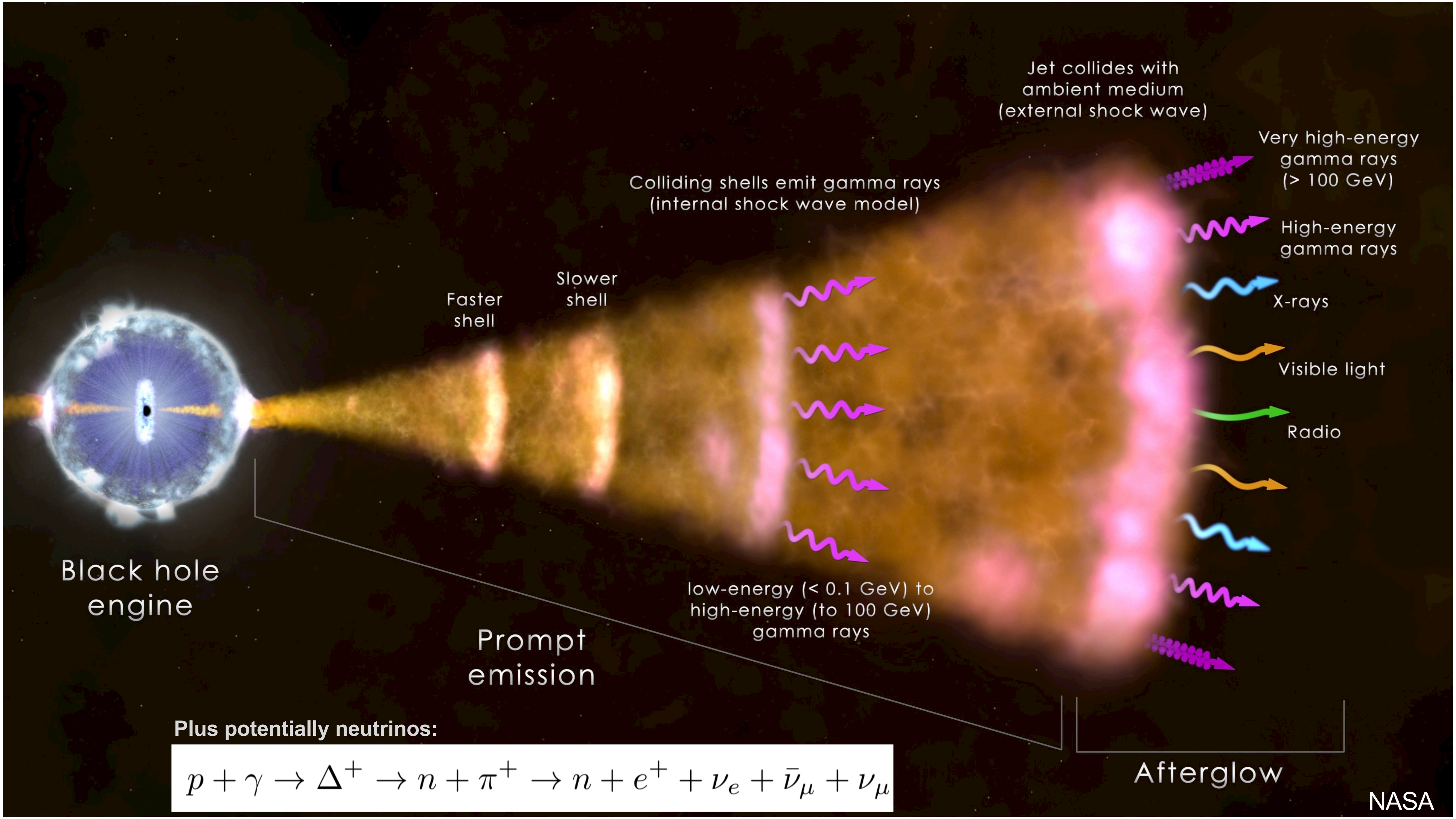
Short and long gamma-ray bursts

- Long GRBs
  - Cosmological distances
  - In star-forming galaxies
  - Some associated with SNe
  - → collapse of massive stars

- Short GRBs
  - Smaller redshifts / less luminous
  - Not in star forming regions
  - → old compact objects, NS-NS or NS-BH mergers

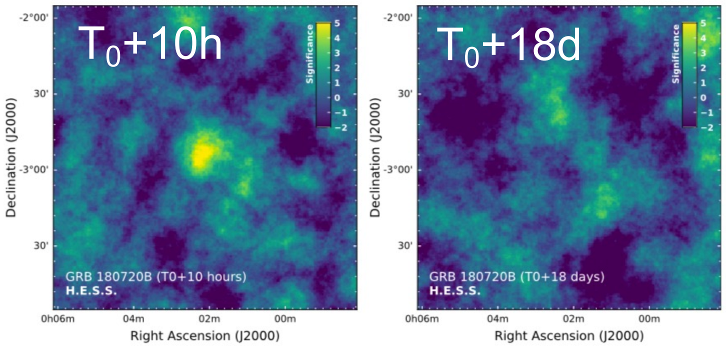


Shahmoradi & Nemiroff (MNRAS, 2015)


Jet collides with
ambient medium
(external shock wave)
Very high-energy
gamma rays
(> 100 GeV)
Colliding shells emit gamma rays
(internal shock wave model)
High-energy
gamma rays
Faster
shell
Slower
shell
X-rays
Visible light
Radio
Black hole
engine
low-energy (< 0.1 GeV) to
high-energy (to 100 GeV)
gamma rays
Prompt
emission
Plus potentially neutrinos:
$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$
Afterglow
NASA

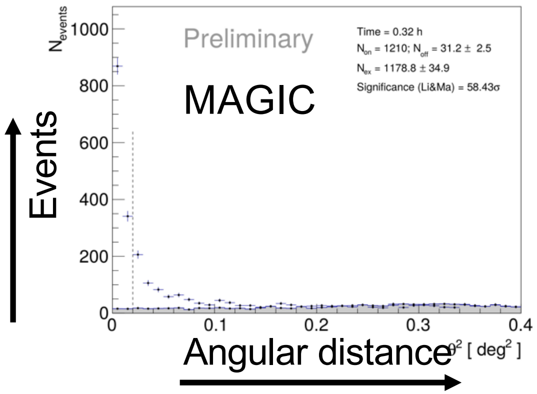
Long GRBs at TeV energies

When? 20 July 2018
Where? 6 billion light-years away
What? 100 GeV photons at T_0+10h



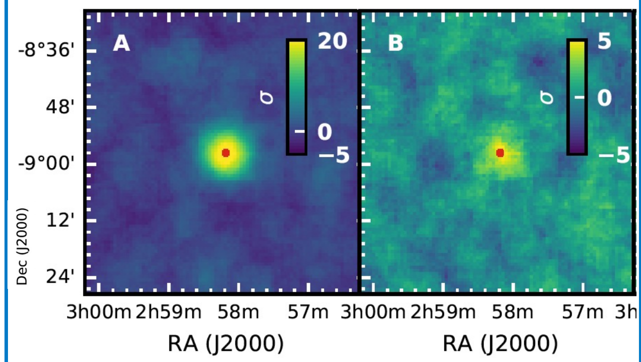
GRB 180720B, H.E.S.S. Nature (2019)

When? 14 January 2019
Where? 4 billion light-years away
What? 1 TeV photons at T_0+1min



GRB 190114C, MAGIC Nature (2019)

When? 29 August 2019
Where? 1 billion light-years away
What? 1 TeV photons at T_0+50h!



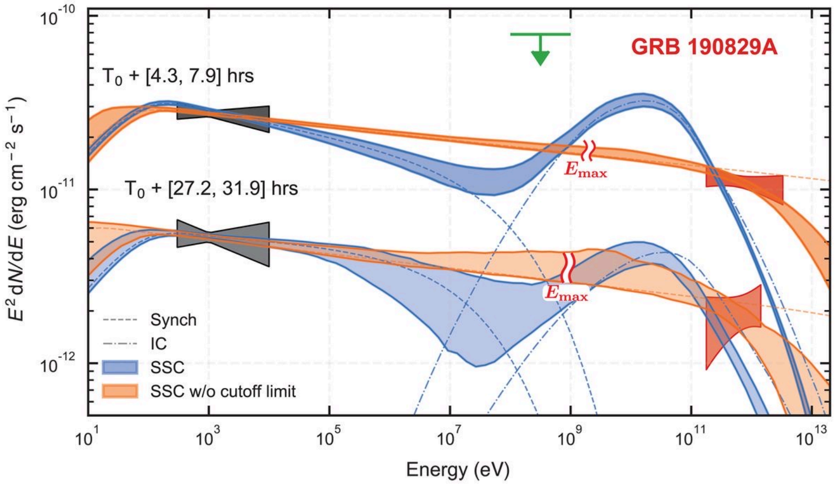
GRB 190829A, H.E.S.S. Science (2021)

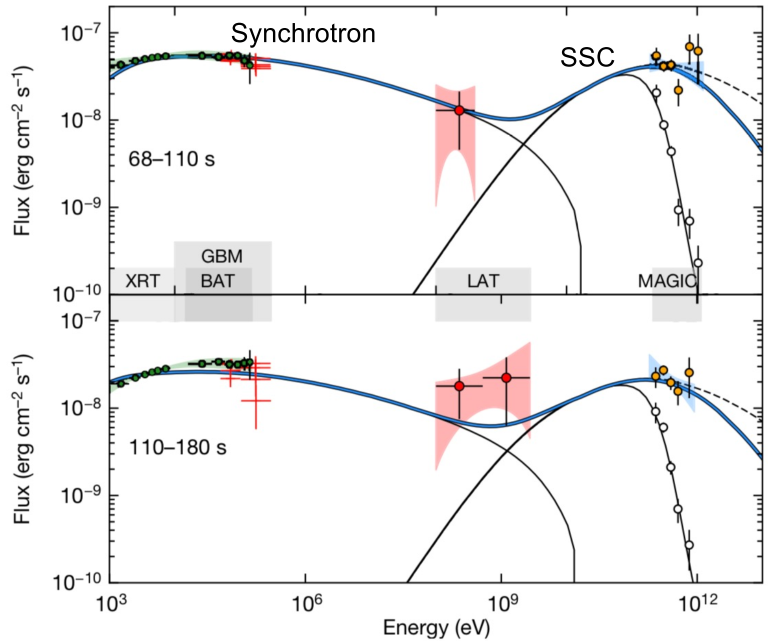
… plus a very recent nearby beast (221009A), brightest ever in X-rays, LHAASO TeV measurement expected soon, https://en.wikipedia.org/wiki/GRB_221009A

TeV emission from GRBs, implications

GRB 190114C, MAGIC Nature (2019)

GRB 190829, H.E.S.S. Science (2021)



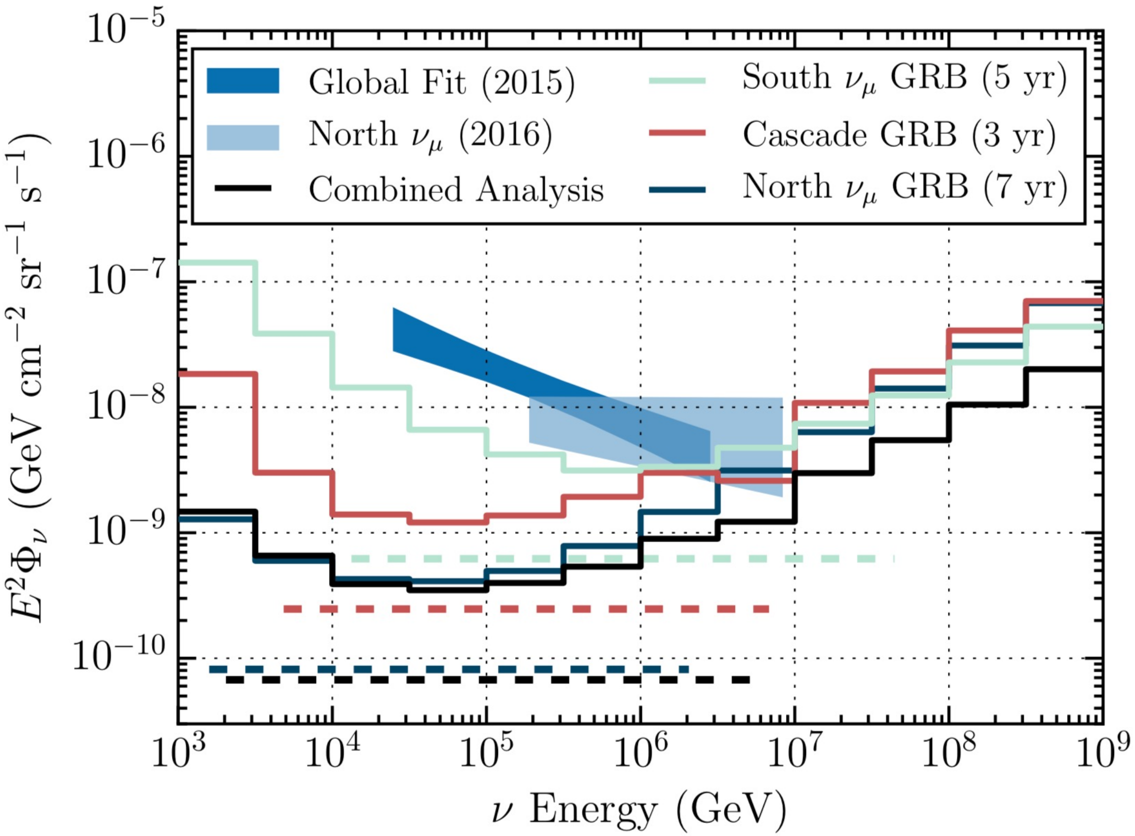


- Surprisingly large TeV energy fraction (50/50 for the January 2019 GRB)
- Leptonic emission (from timescales + X-ray correlation)
- Models for high-energy emission mechanisms under debate

IceCube GRB Neutrino Searches

Any neutrino measured coincident with a GRB?

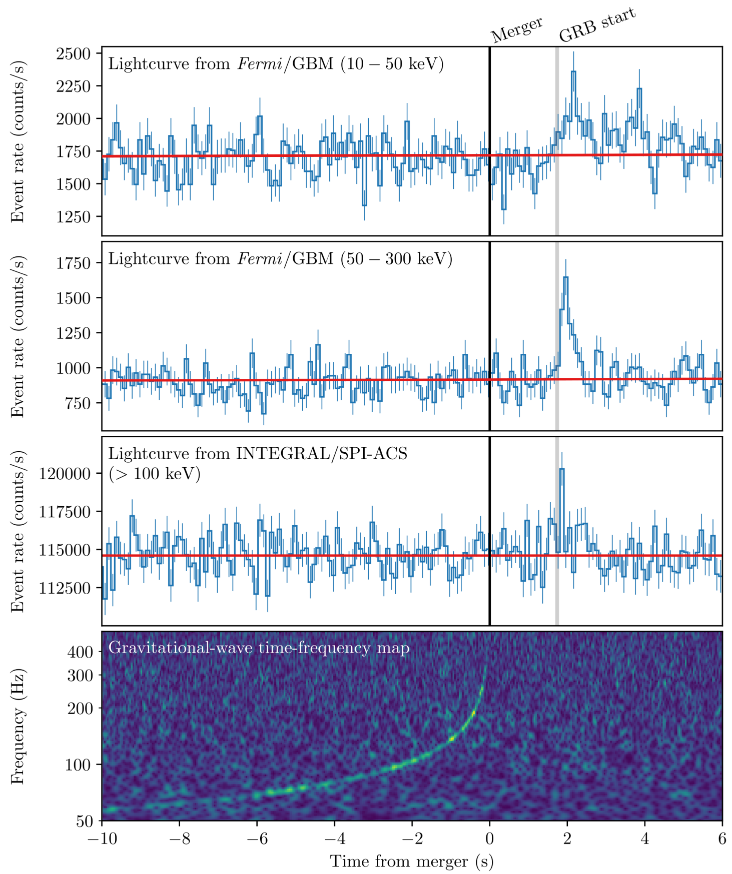
- No correlation found
- Measured GRBs are not significantly contributing to the IceCube diffuse neutrino flux
- Constraining scenarios in which GRBs are the main sources of highest-energy cosmic rays **during their prompt phase**
  - Maybe they aren't UHECR sources
  - Maybe 'prompt phase' search to short
  - Maybe they are but protons produce no neutrinos at source (somewhat constrainable through EM signals)

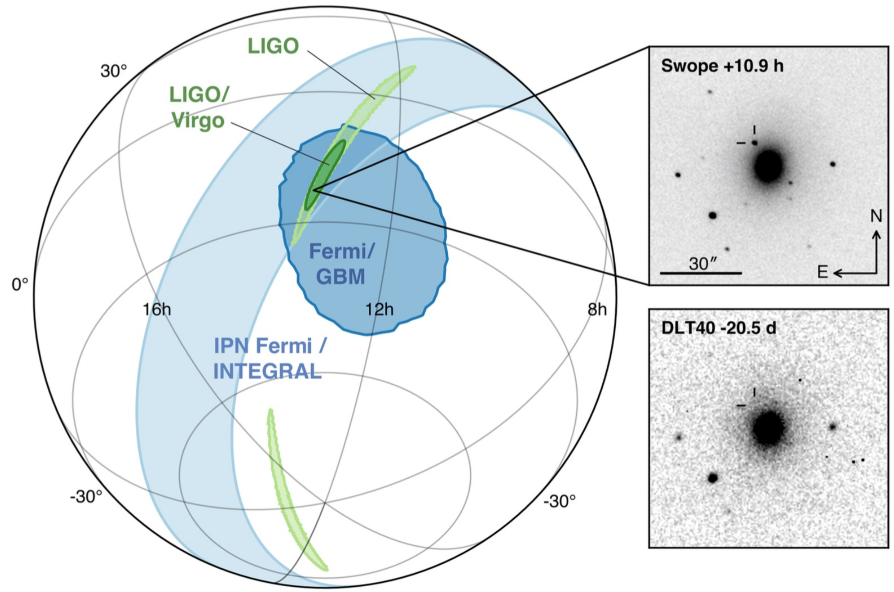


IceCube (ApJ, 2017)

Neutron Star Merger Event GW170817

Short GRBs are Neutron Star mergers and produce 'kilonovae'

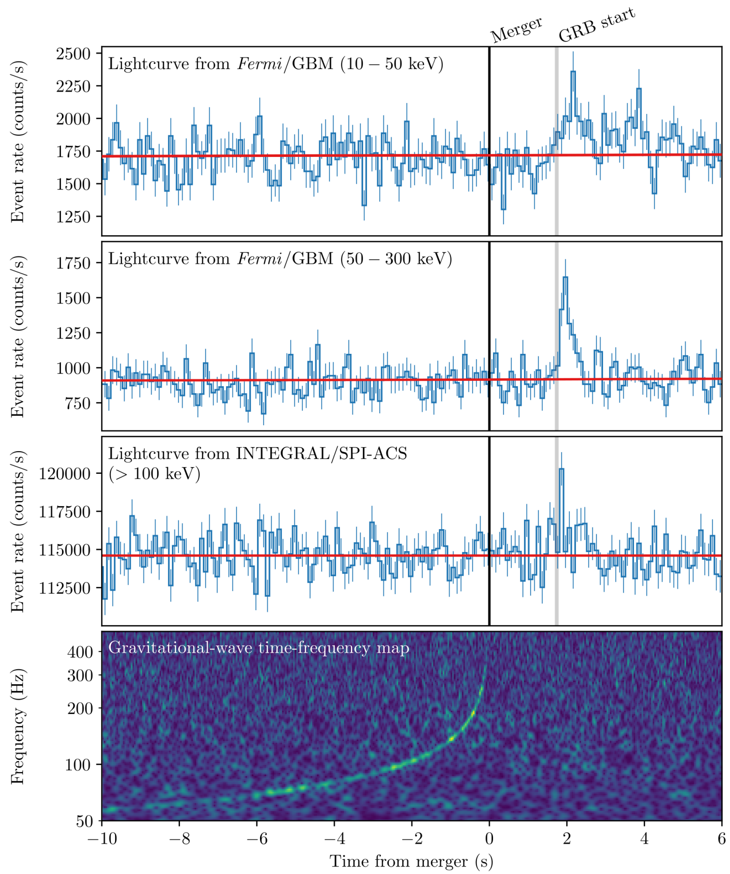




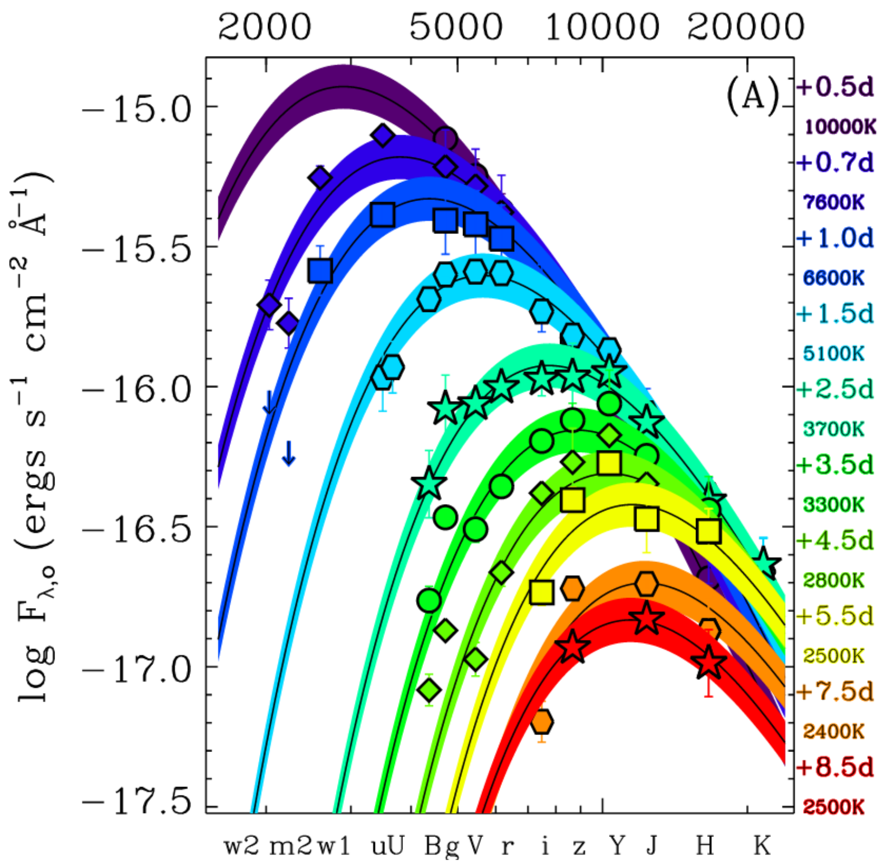
Abbott et al 2017

Neutron Star Merger Event GW170817

Short GRBs are Neutron Star mergers and produce ‘kilonovae’ → synthesis of heavy elements!

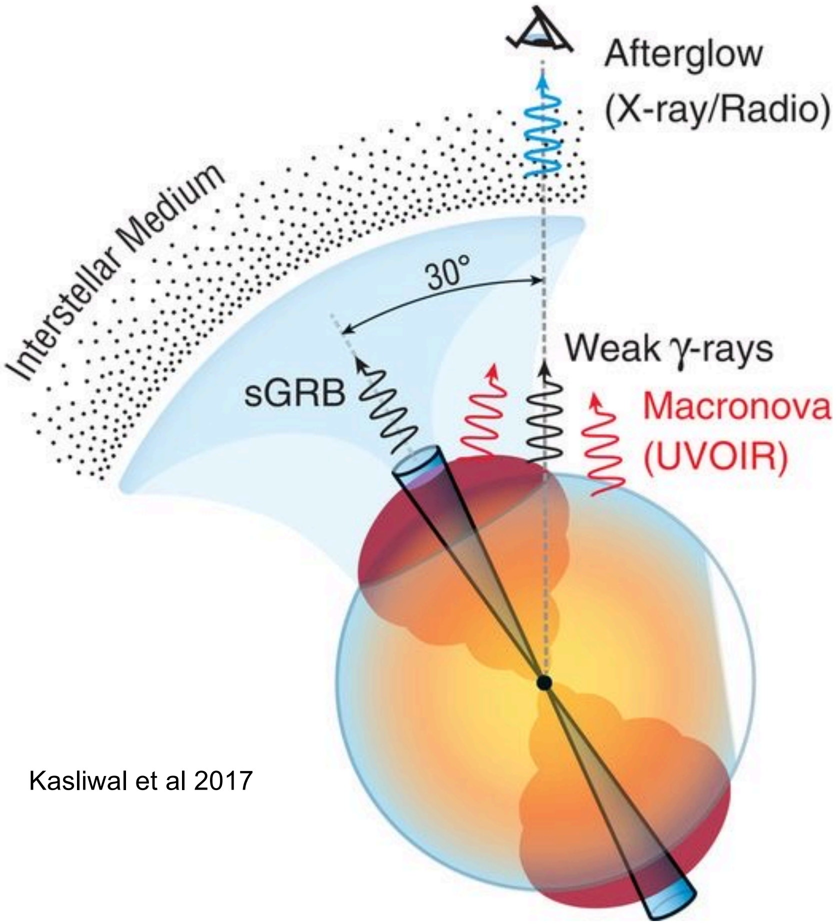


Abbott et al 2017



Credit: Drout et al, Science 2017

Neutron Star Merger Cartoon

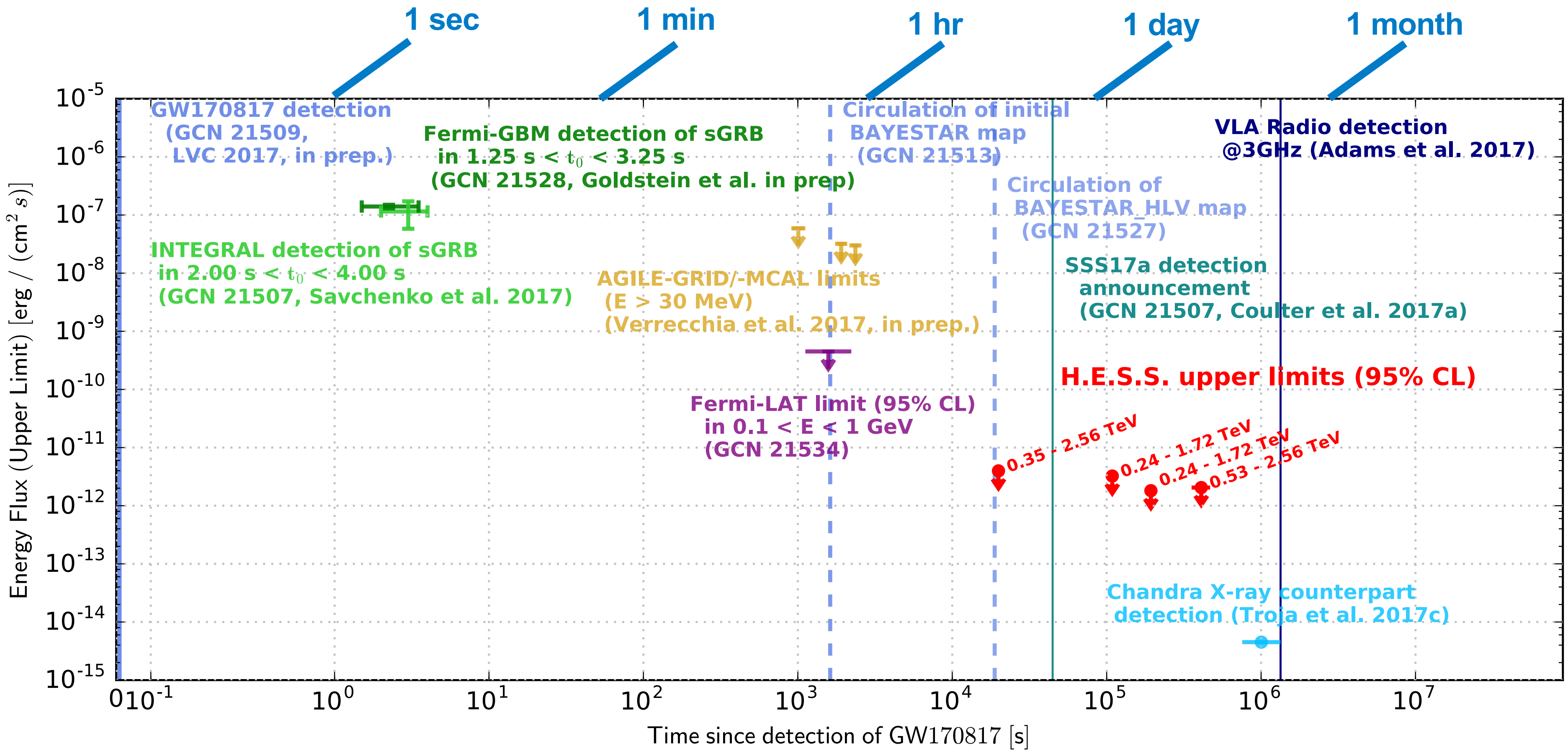


Kasliwal et al 2017

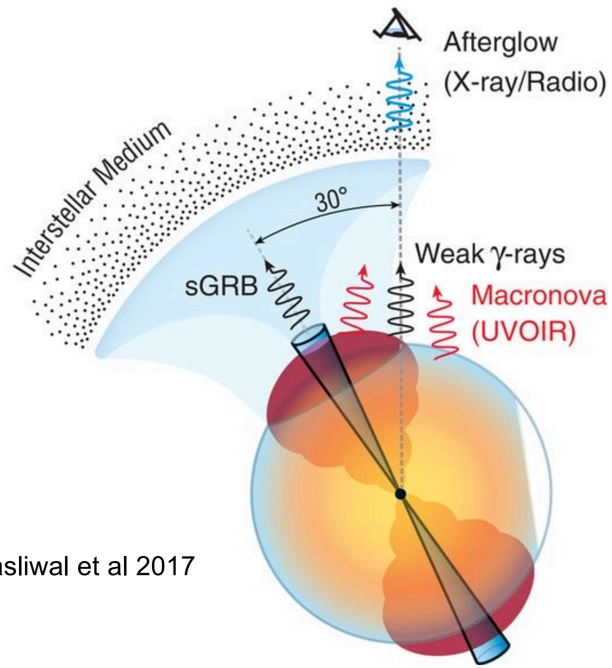
The EM follow-up of GW170817

Kilonova discovered within days

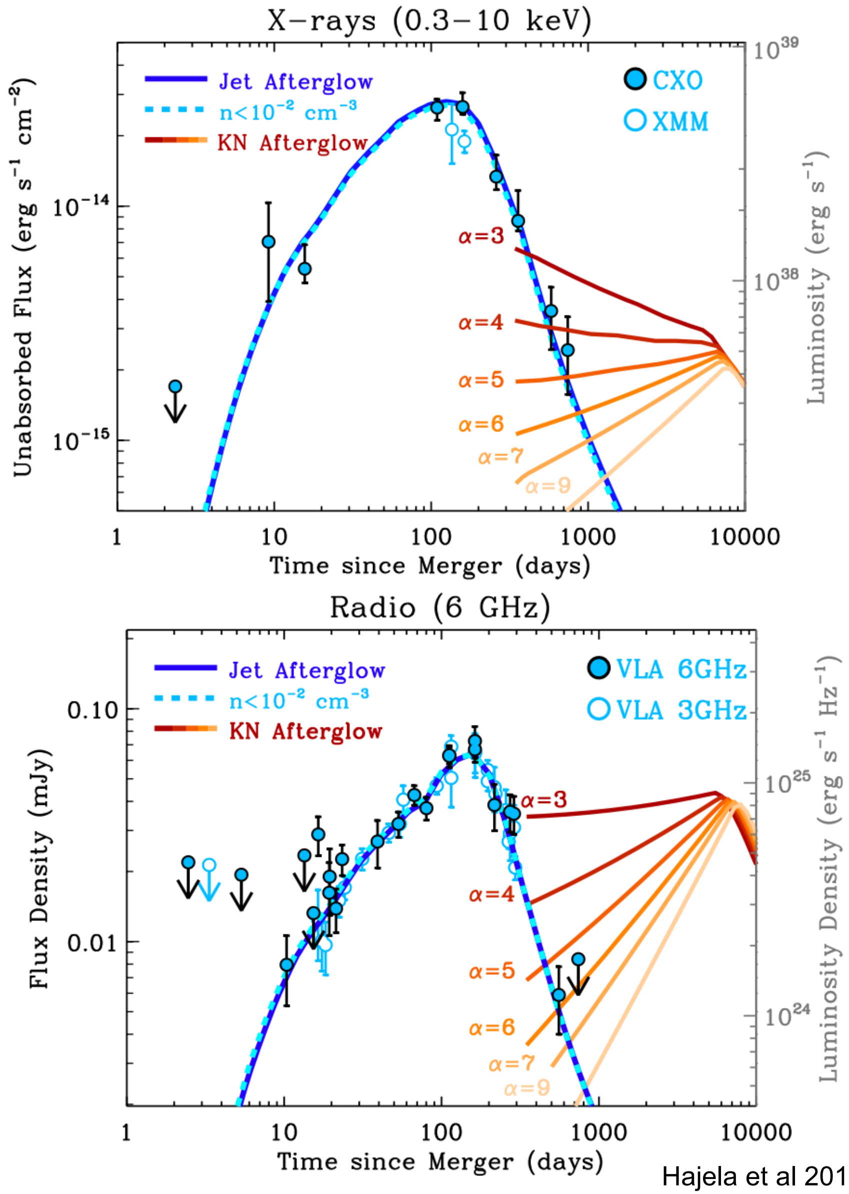
Onset of non-thermal afterglow soon after



Prompt and afterglow emission



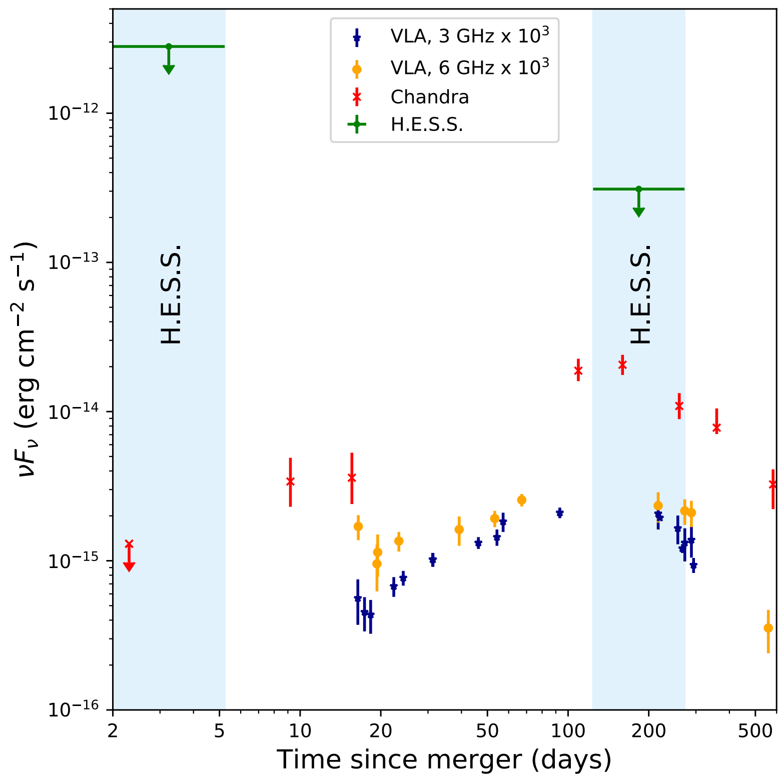
Kasliwal et al 2017



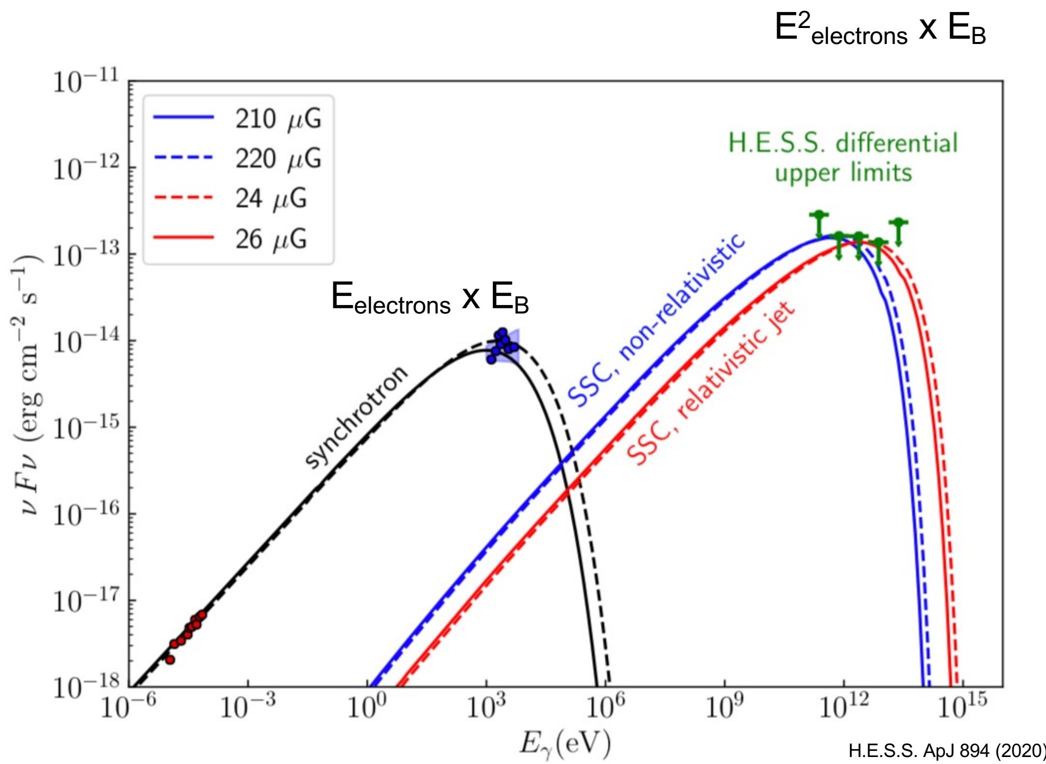
Hajela et al 2019

H.E.S.S. observations

0.2 – 5 days and 124 – 272 days after event



Abdalla et al 2020



H.E.S.S. ApJ 894 (2020)

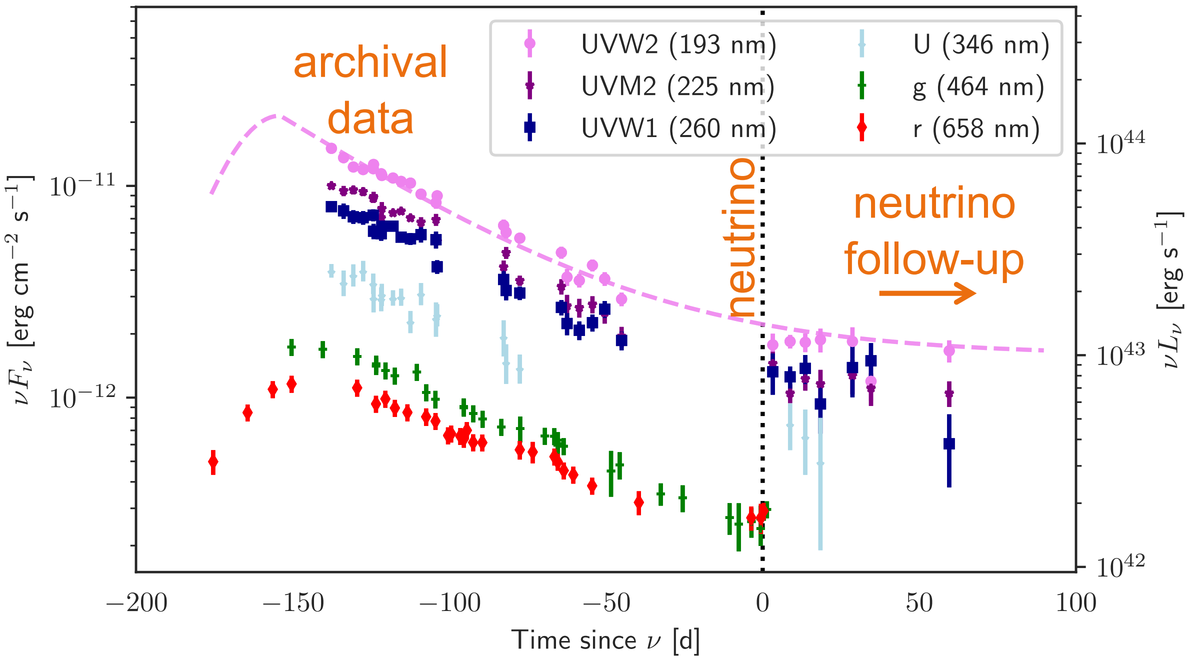
Synchrotron Self Compton process
TeV observations break degeneracy
→ probe magnetic field!

Tidal Disruption Event

PRL 2022, https://physics.aps.org/articles/v15/77,
https://www.desy.de/news/news_search/index_eng.html?openDirectAnchor=2030

Evidence for neutrino emission

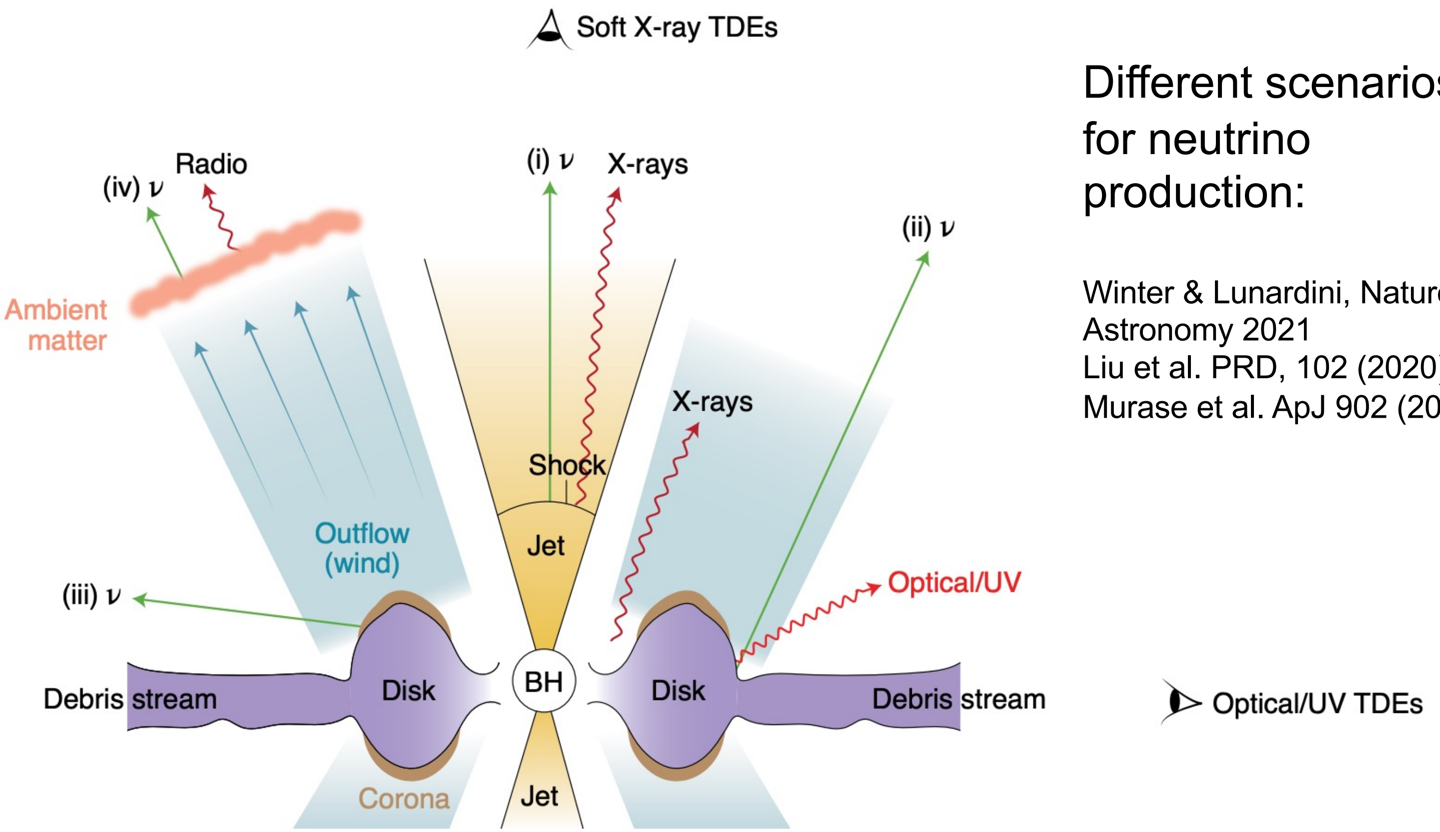
R. Stein et al., Nature Astronomy 2021, S. Reusch et al. PRL 2022, S. Van Velzen et al. arXiv:2111.09391



Distance: z = 0.05 (d = 230 Mpc), no gamma rays

- First hint of neutrino production in TDEs
- Two more candidates identified (3.7 sigma)

Neutrino Production in TDEs

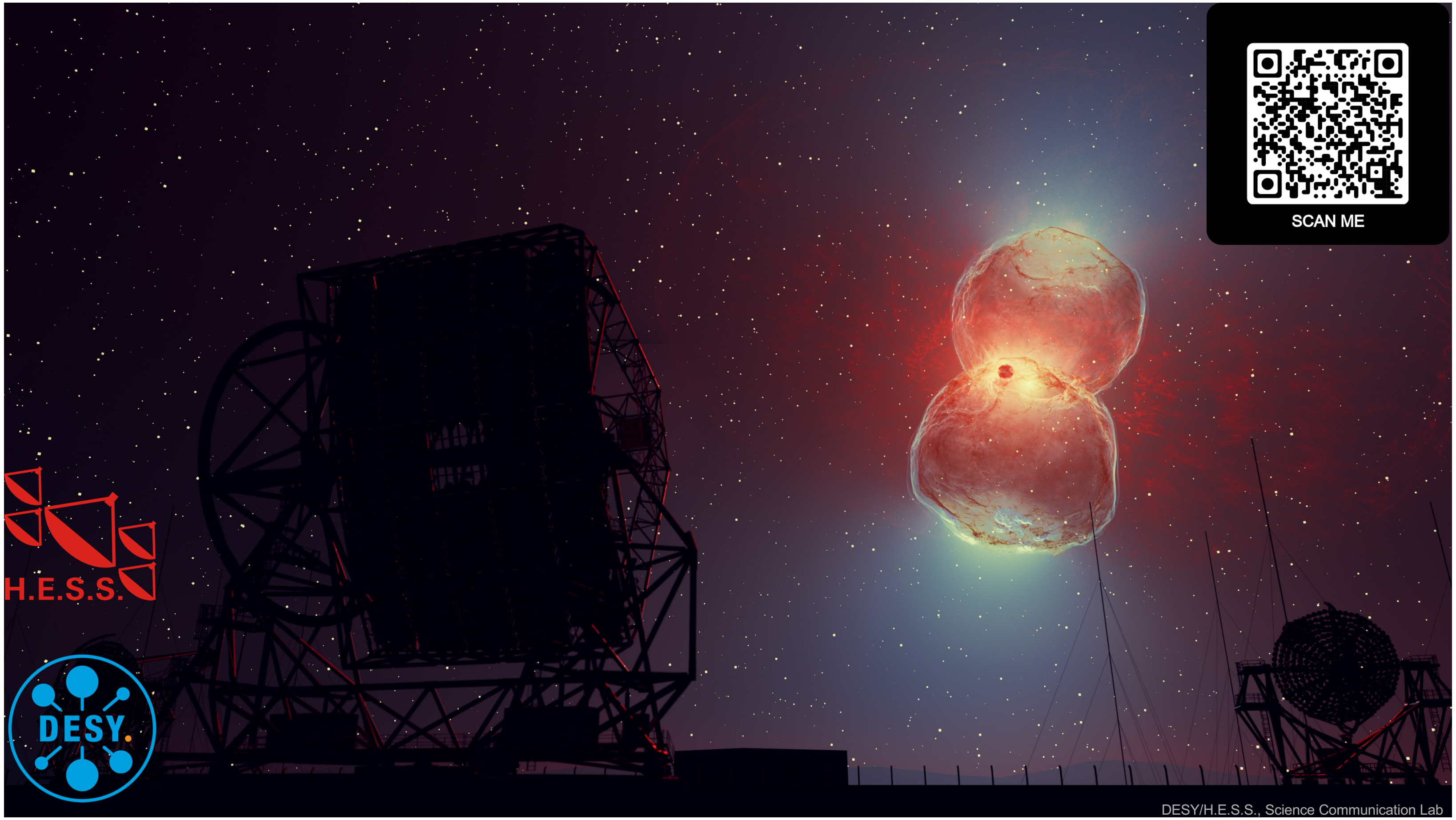


Different scenarios for neutrino production:

Winter & Lunardini, Nature Astronomy 2021
Liu et al. PRD, 102 (2020)
Murase et al. ApJ 902 (2020)

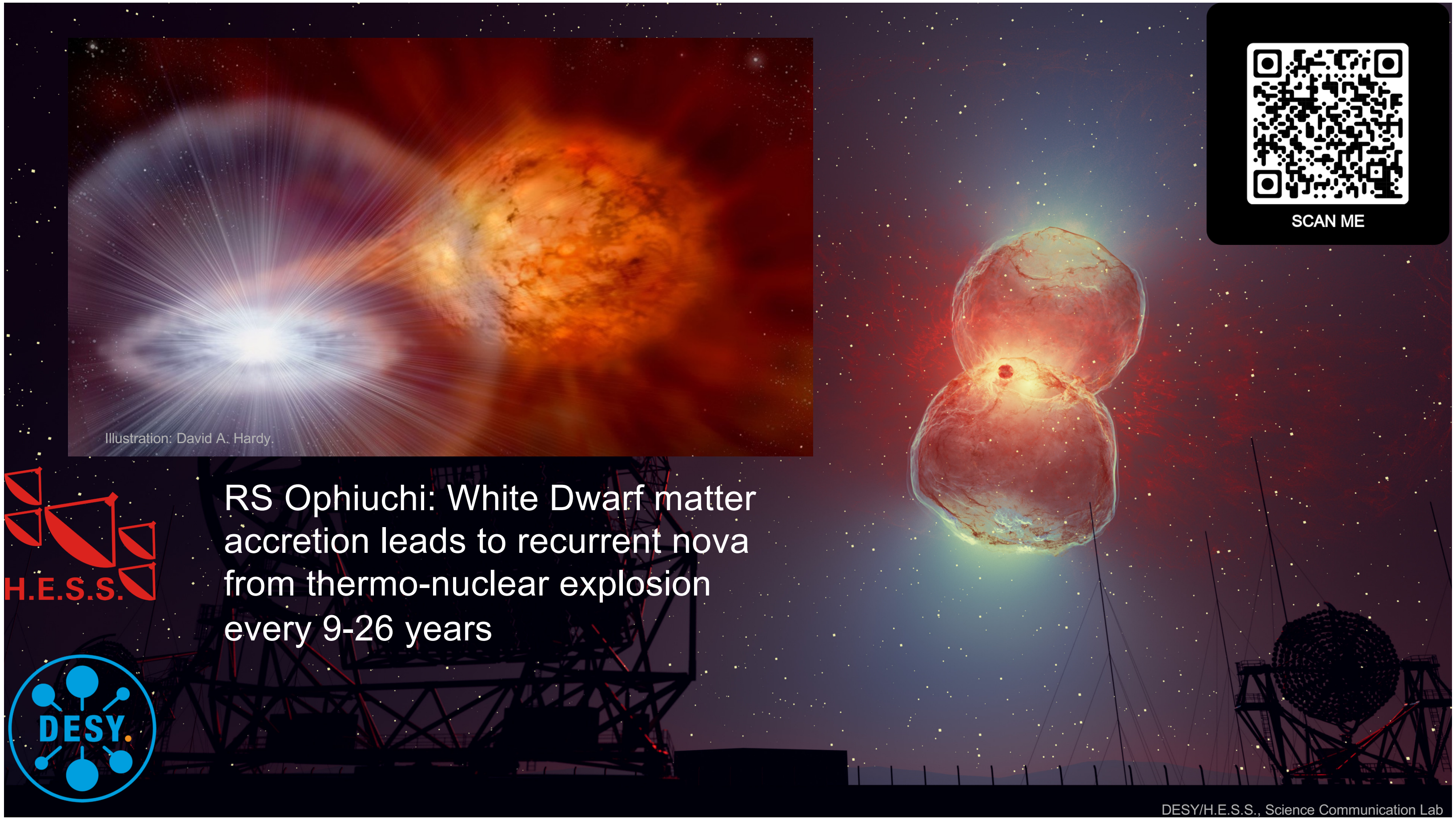
Hayasaki, Nature Astronomy 2021

Recurrent Nova RS Oph in TeV gamma rays



H. E. S. S. Collaboration et al., Science 376, 6588, 77-80, 2022

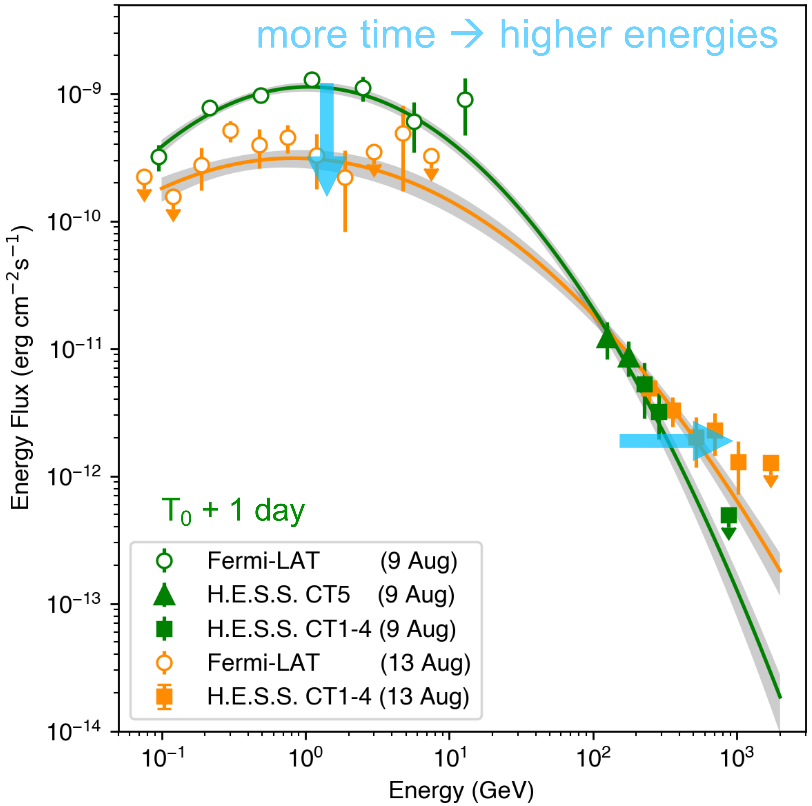
Recurrent Nova RS Oph in TeV gamma rays



H. E. S. S. Collaboration et al., Science 376, 6588, 77-80, 2022

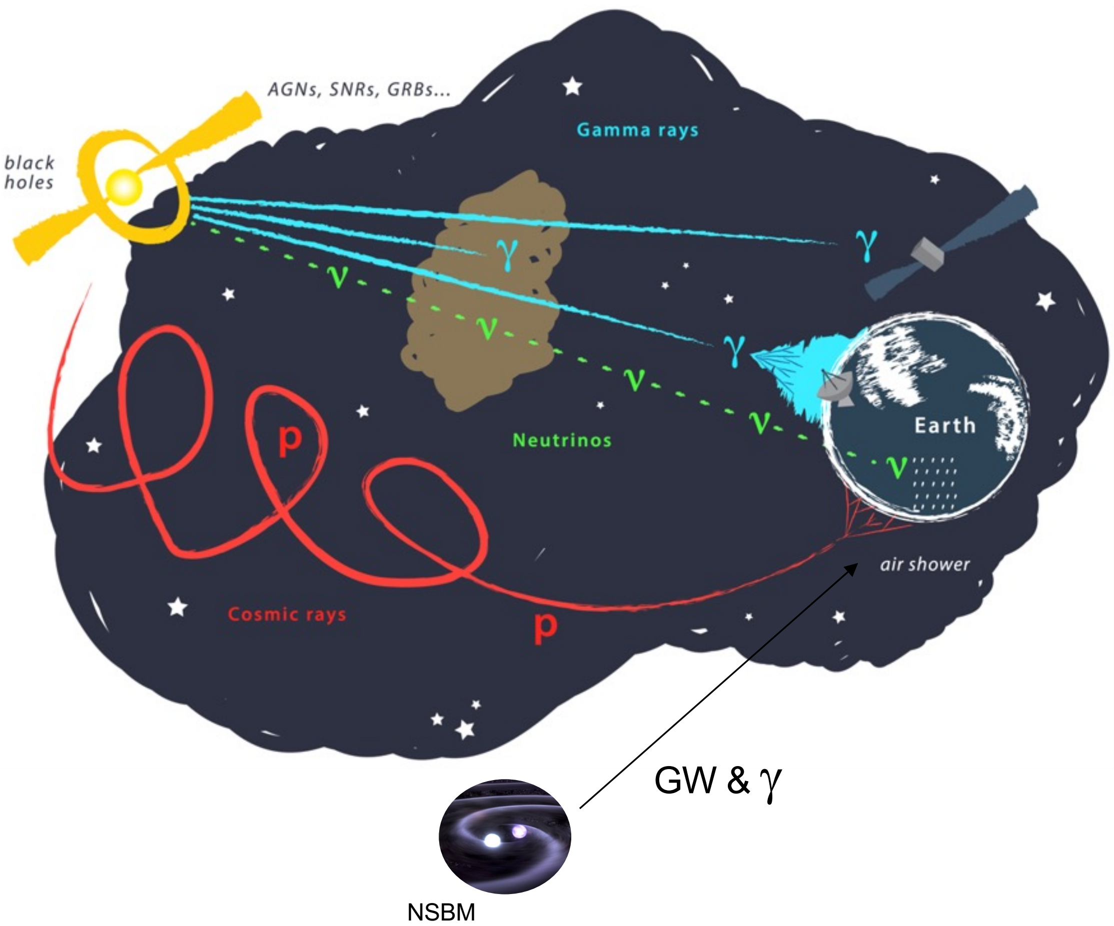
Efficient particle acceleration

- Discovery of VHE gamma rays (> 100 GeV) in 2021
- Gamma ray spectral evolution with time points to cosmic hadron (not lepton) accelerator
- Particle acceleration at theoretical limit in astrophysical shocks, support for supernova remnant paradigm of cosmic rays



H. E. S. S. Collaboration et al., Science 376, 6588, 77-80, 2022

How to improve in future

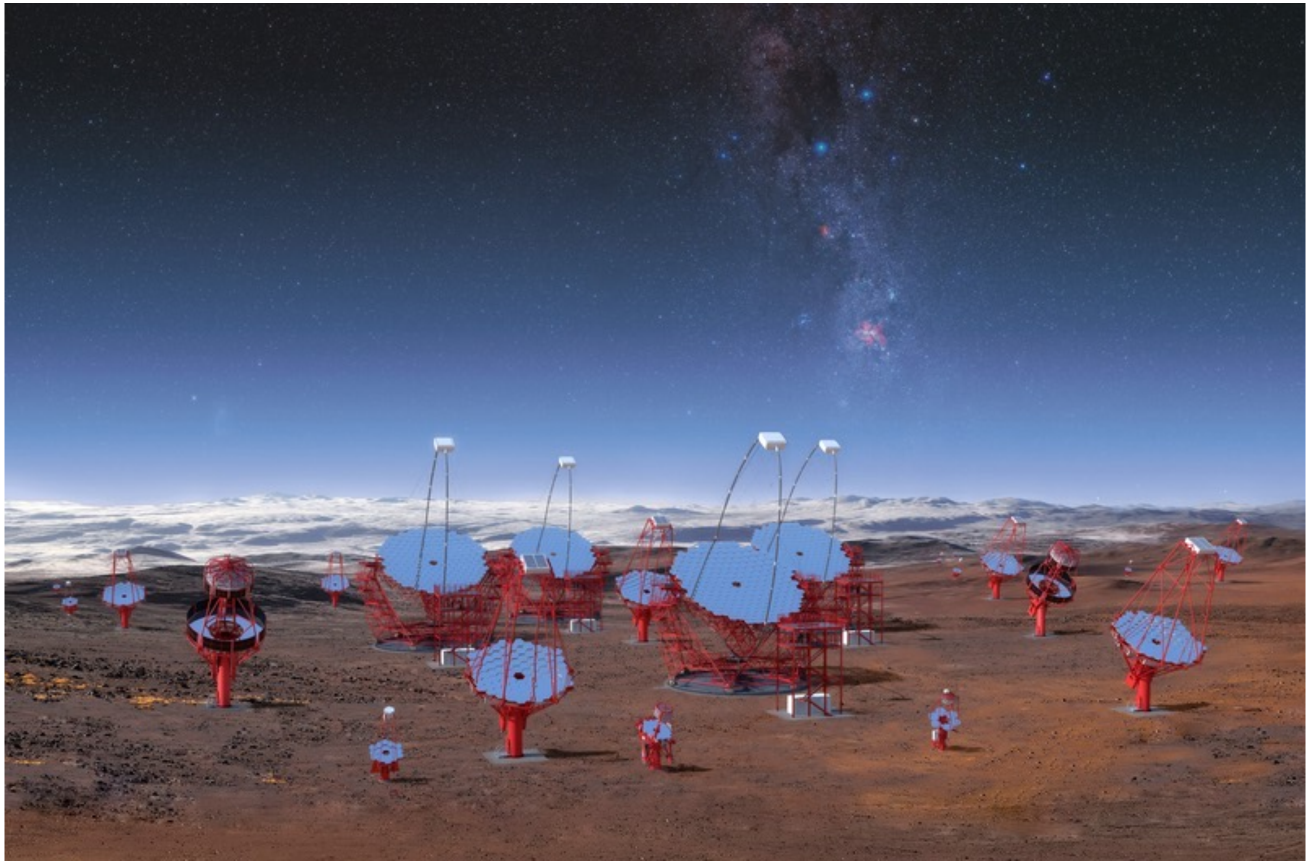


Important future projects (secured / planned):

- **CTA**
- **LSST**
- **ULTRASAT**
- Einstein Probe (X-rays satellite)
- SVOM (GRB monitor)
- **IceCube Gen-2**
- Einstein Telescope
- LISA
- MeV – GeV satellite (ASTROGAM, AMEGO-X)
- keV flagship satellite (Athena)
- … and probably more that I am forgetting now

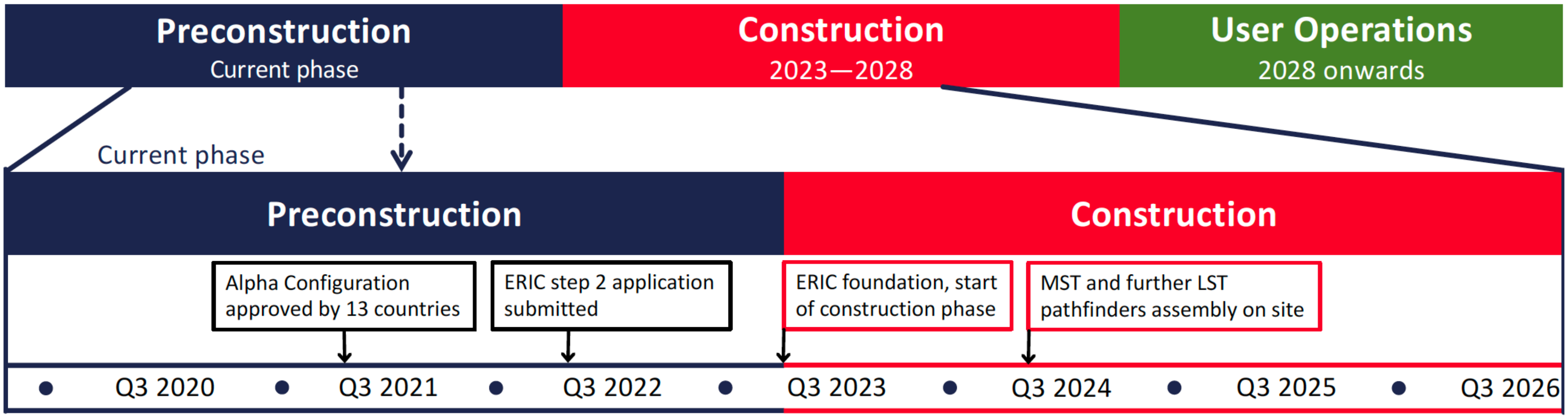
CTA

- Open gamma-ray observatory
  - Transition from particle physics style collaborations to open observatory…
- Two telescope locations:
  - 13 telescopes La Palma (CTAO North)
  - 58 telescopes Paranal, Chile (CTAO South)
- Headquarters Bologna, Science Data Management Center at DESY in Zeuthen

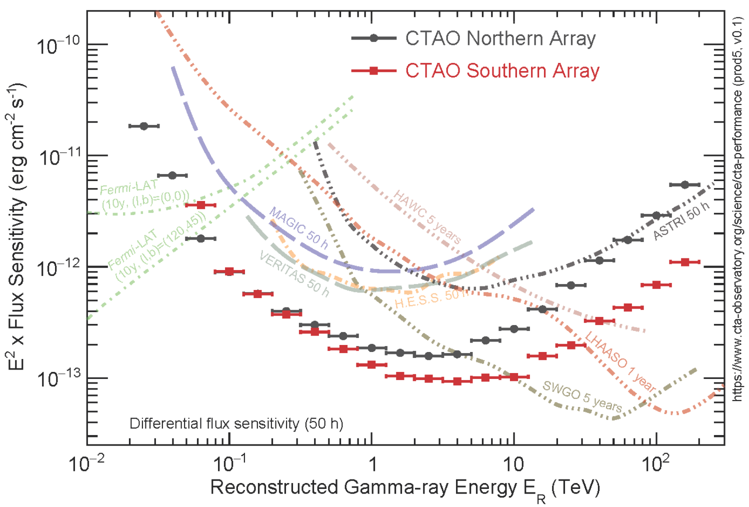


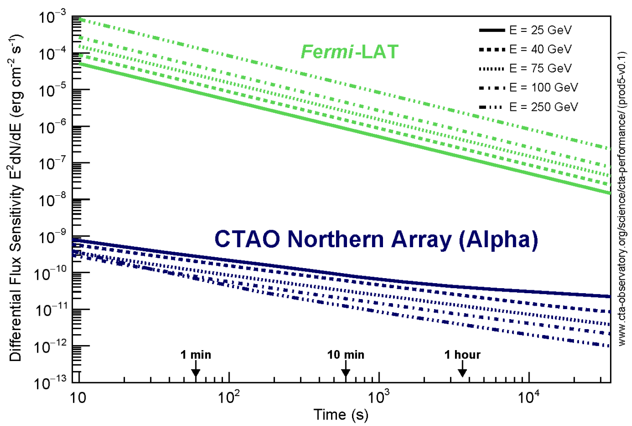
‘good things take time’

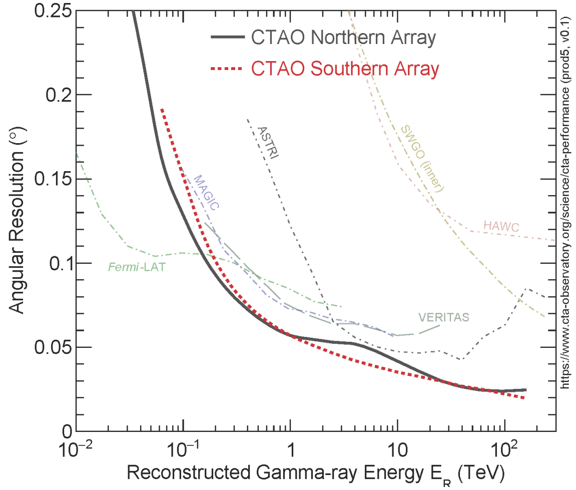
… founding an ERIC is not a swift process!

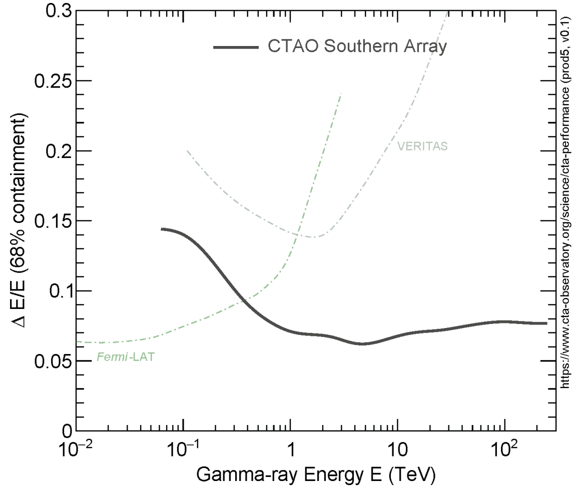


CTA Performance







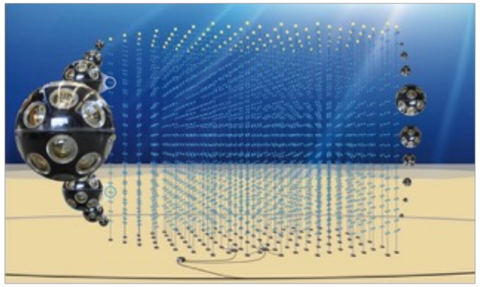


Next Generation Neutrino Telescopes

Neutrino sources
on the southern sky

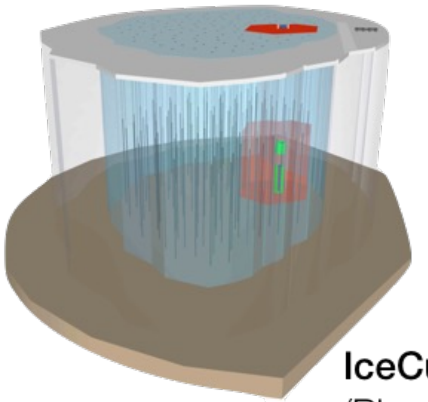
Today's neutrino telescopes

Neutrinos at
EeV energies



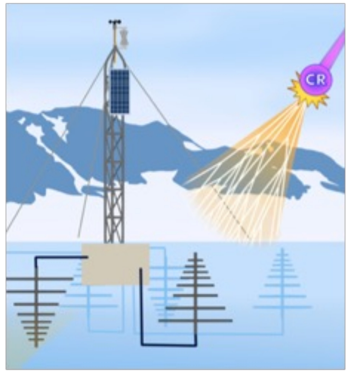
KM3NeT / Baikal-GVD
(construction started)

5x better sensitivity
in the TeV-PeV
energy range



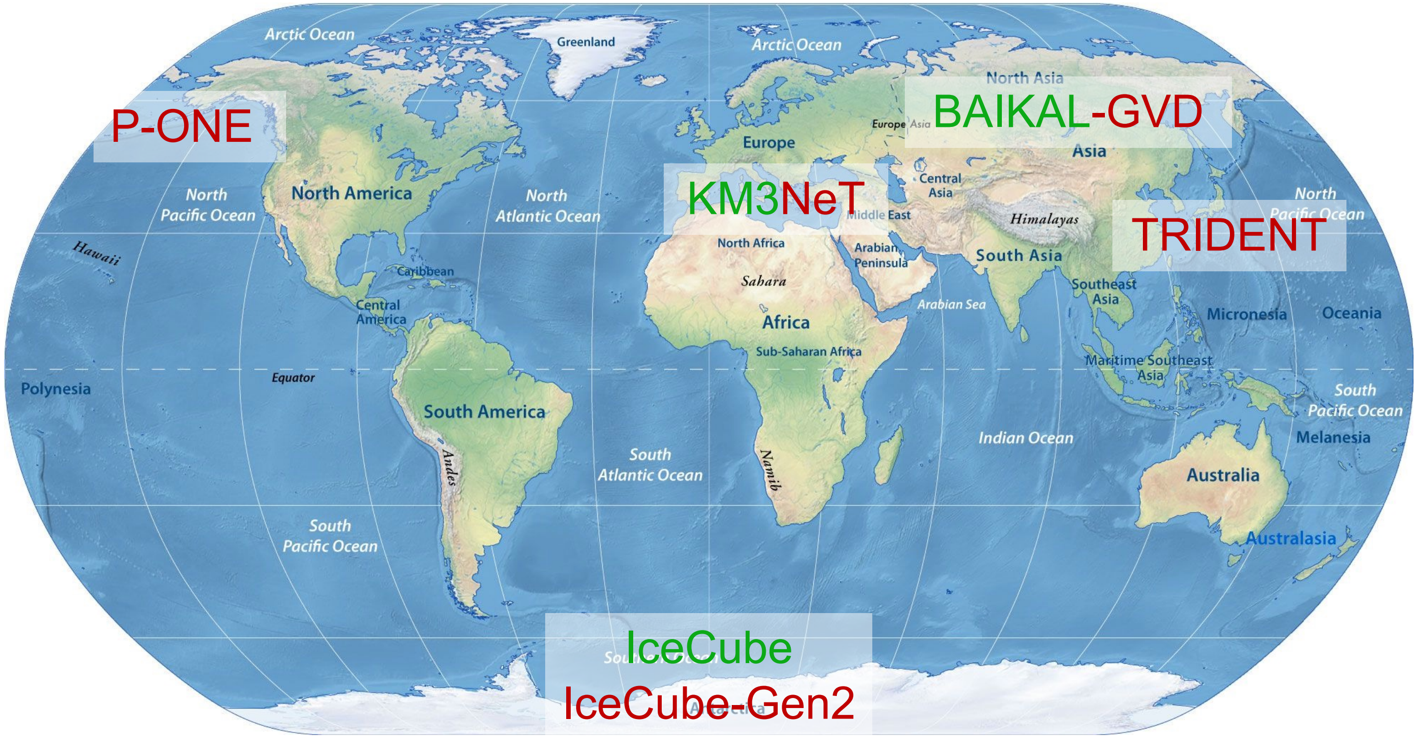
IceCube-Gen2
(Phase 1 started)

If funded today construction period
>= 2025 for operation >= 2032…



ARA/ARIANNA, RNO, Gen2-Radio
(proposals in)

Next Generation Neutrino Telescopes



Operating

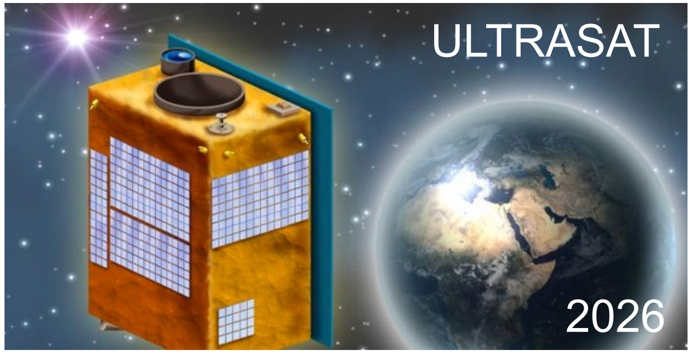
Planned / under construction

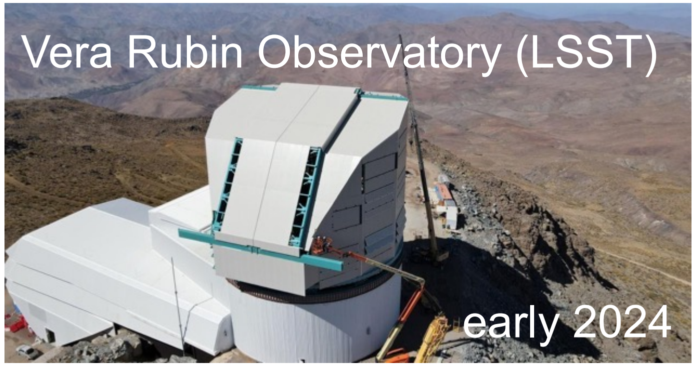
At very-high energies:

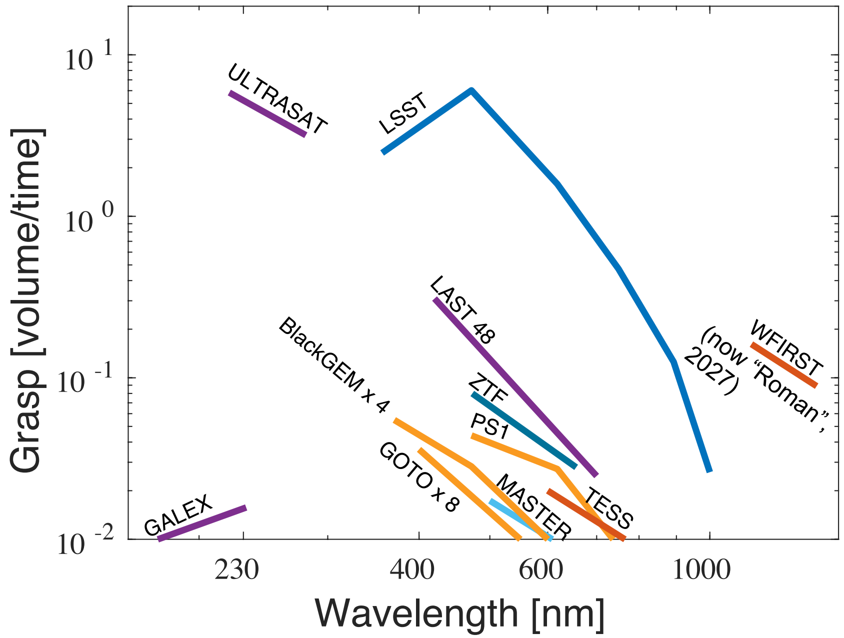
PAO, RNO-G, GRAND,

POEMMA, …

New Instrument to identify Counterparts

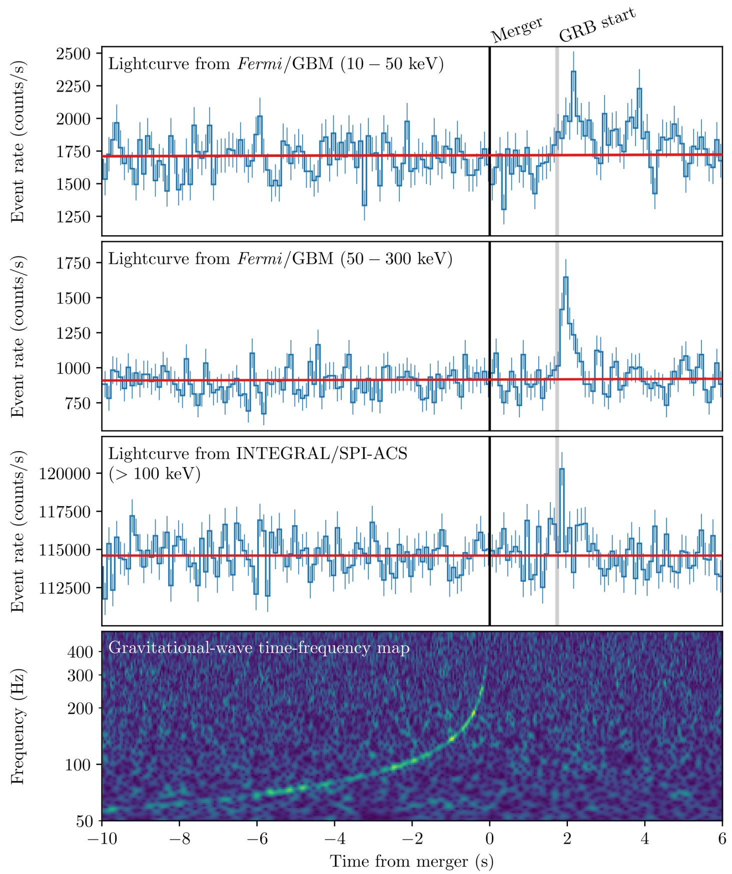




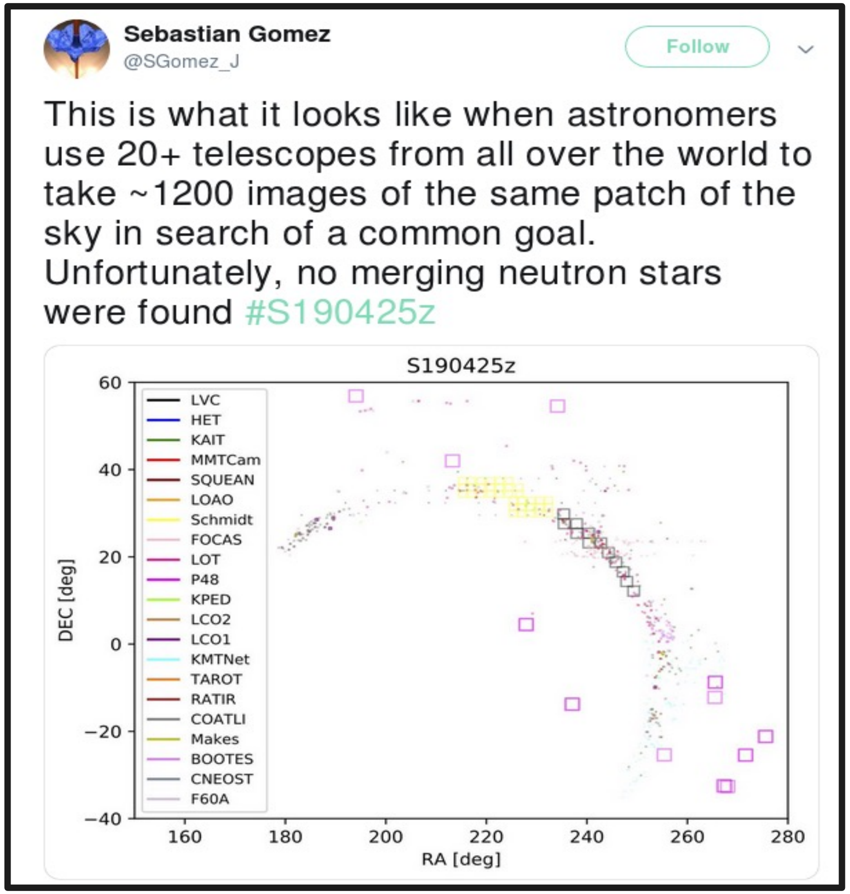


Neutron Star Merger Event GW170817

Short GRBs are Neutron Star mergers and produce ‘kilonovae’



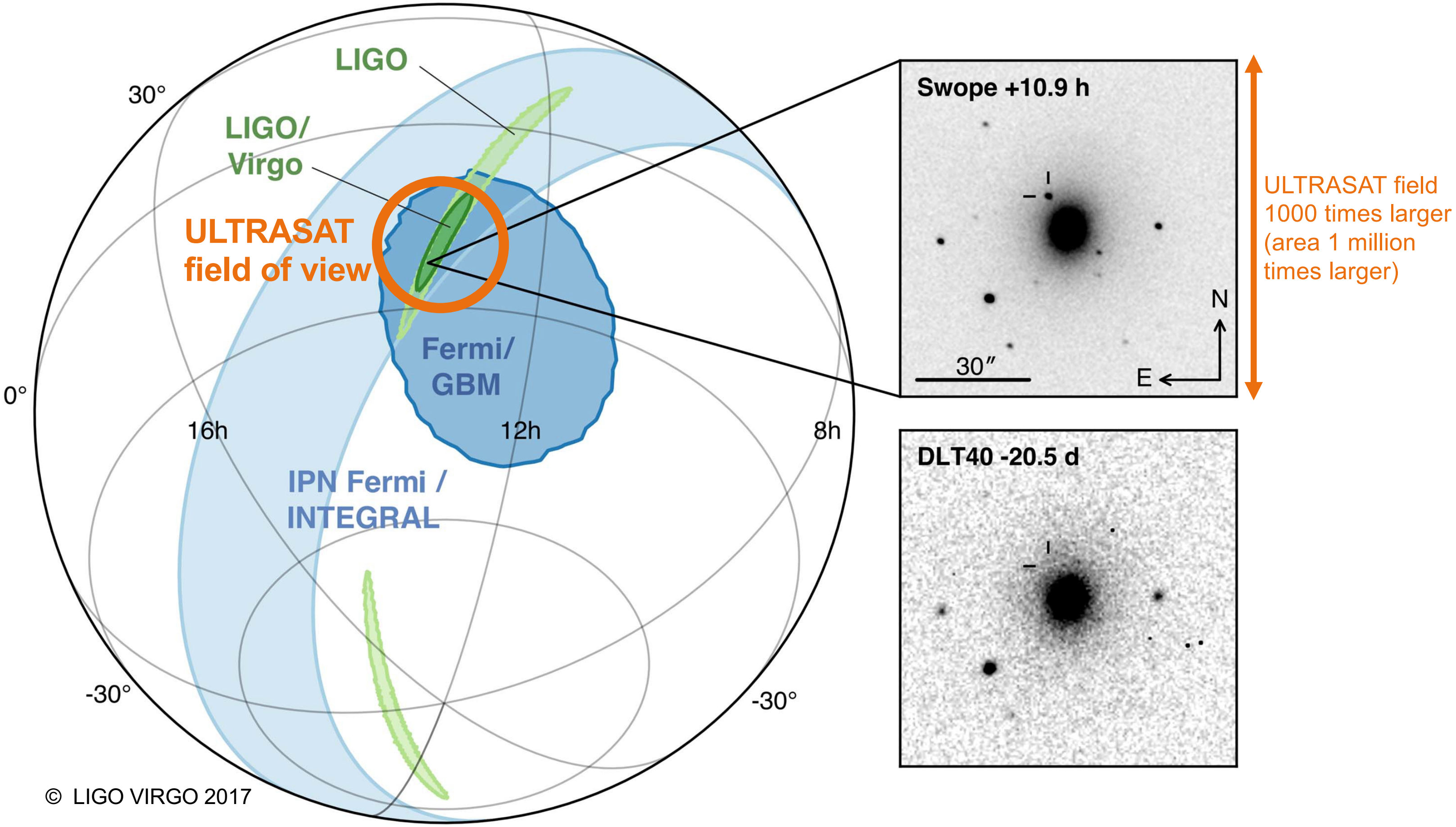
Abbott et al 2017



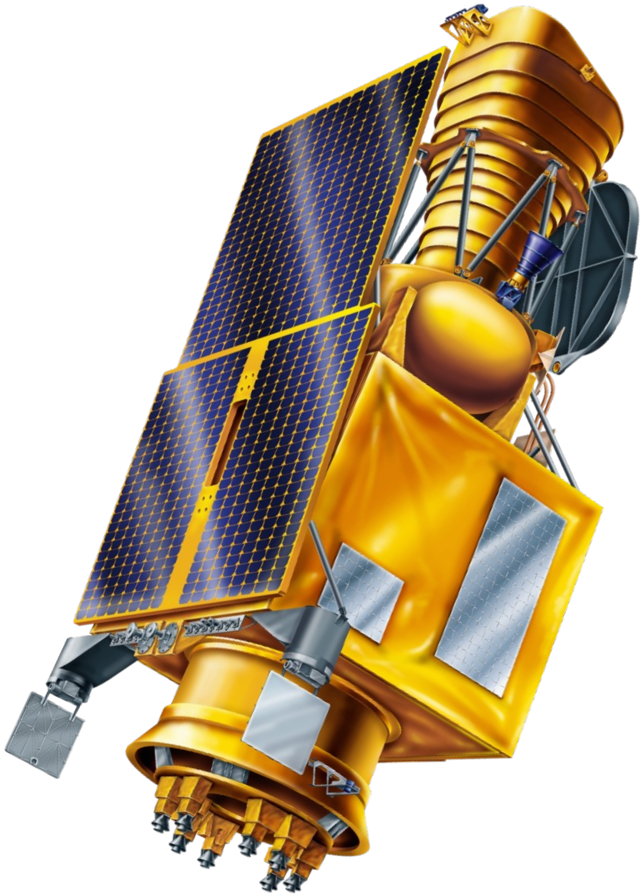
Large field-of-view telescopes are key to finding these GRBs / kilonovae!

ULTRASAT – A Discovery Machine in the UV

The 'large field of view' revolution



ULTRASAT



Key Features

- Very large, 200 deg^2, field of view.
- High UV (230-290nm) sensitivity:

  1.5×10^{-3} ph/cm^2 s (900s, 5σ)

Key Capabilities

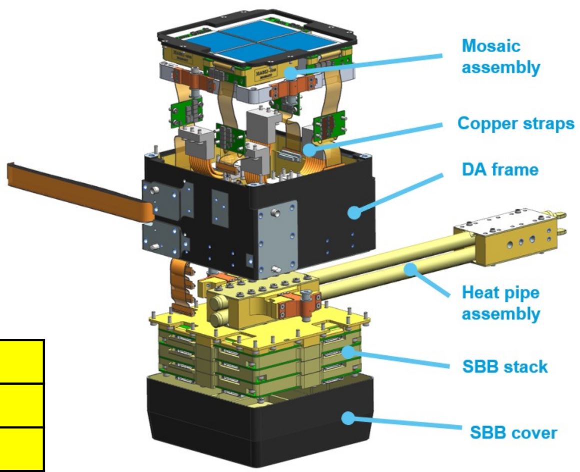
- Monitor an unprecedentedly large volume of the Universe.
- Real-time alerts to ground/space-based telescopes (GEO orbit) to initiate world-wide follow-ups.
- Instantaneous >50% of the sky in <15 min for >3 hr.

Key Science

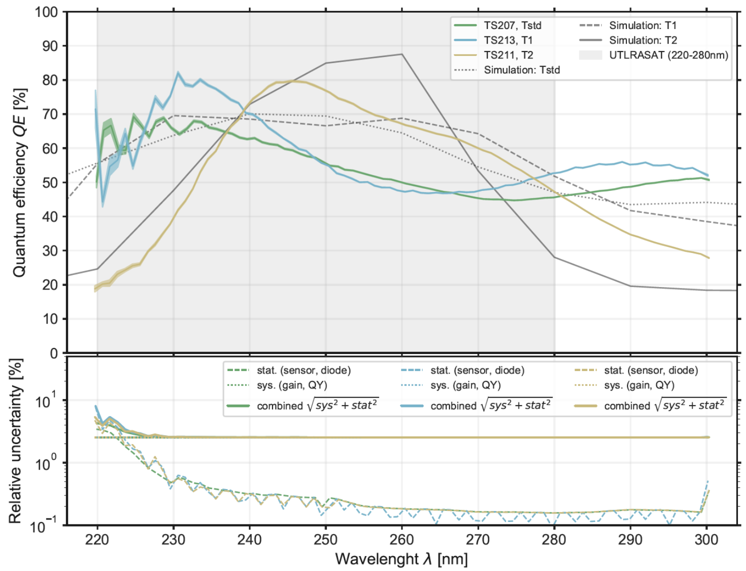
- Supernovae
- GW follow-up (NS-NS, NS-BH)
- GRB
- AGN
- Stars

ULTRASAT

DESY Contribution: UV camera

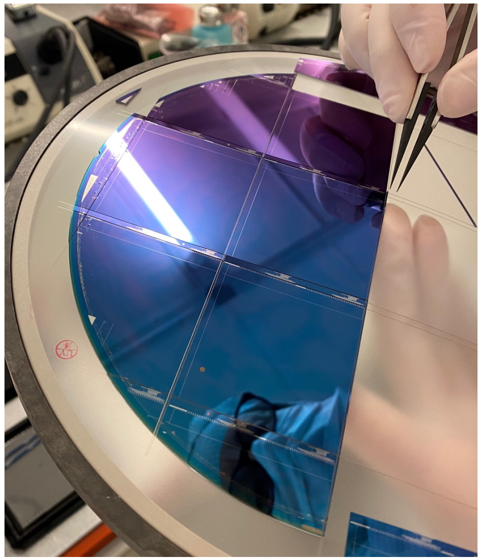


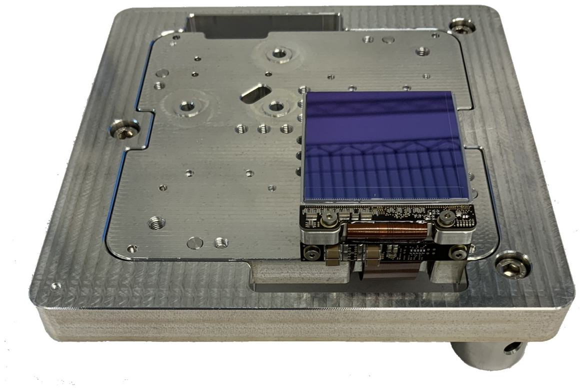
SPIE 2021, https://arxiv.org/abs/2108.02521



Sensor main Specs.

Photosensitive surface	90x90 mm
Pixel size	9.5 µm
Operation waveband	230-290nm
Mean QE in Operation band	>60%
Operation temperature	200±5 °K
Dark current @ 200 °K	<0.03 e-/sec
Readout mode	Rolling shutter
Readout time	<25 sec
Readout noise @ High-gain	<3.5 e-/pixel
Electronic cross-Talk	<0.01%
Pixel sampling scheme	HDR capability
Low-gain Well capacity	140-155 Ke-
High-gain Well capacity	16-21 Ke-
Bits per Pixel – total (data only)	14 (13)





Multi-messenger astronomy

- A blooming field with a golden decade ahead of us thanks to new observatories coming online
- The origin of cosmic rays was a key driver of this field, and aspects of this question will remain with us for some time
- Time domain astronomy (aka real-time multi-messenger astronomy) is just opening up and is recognised as a key priority in Europe and the US