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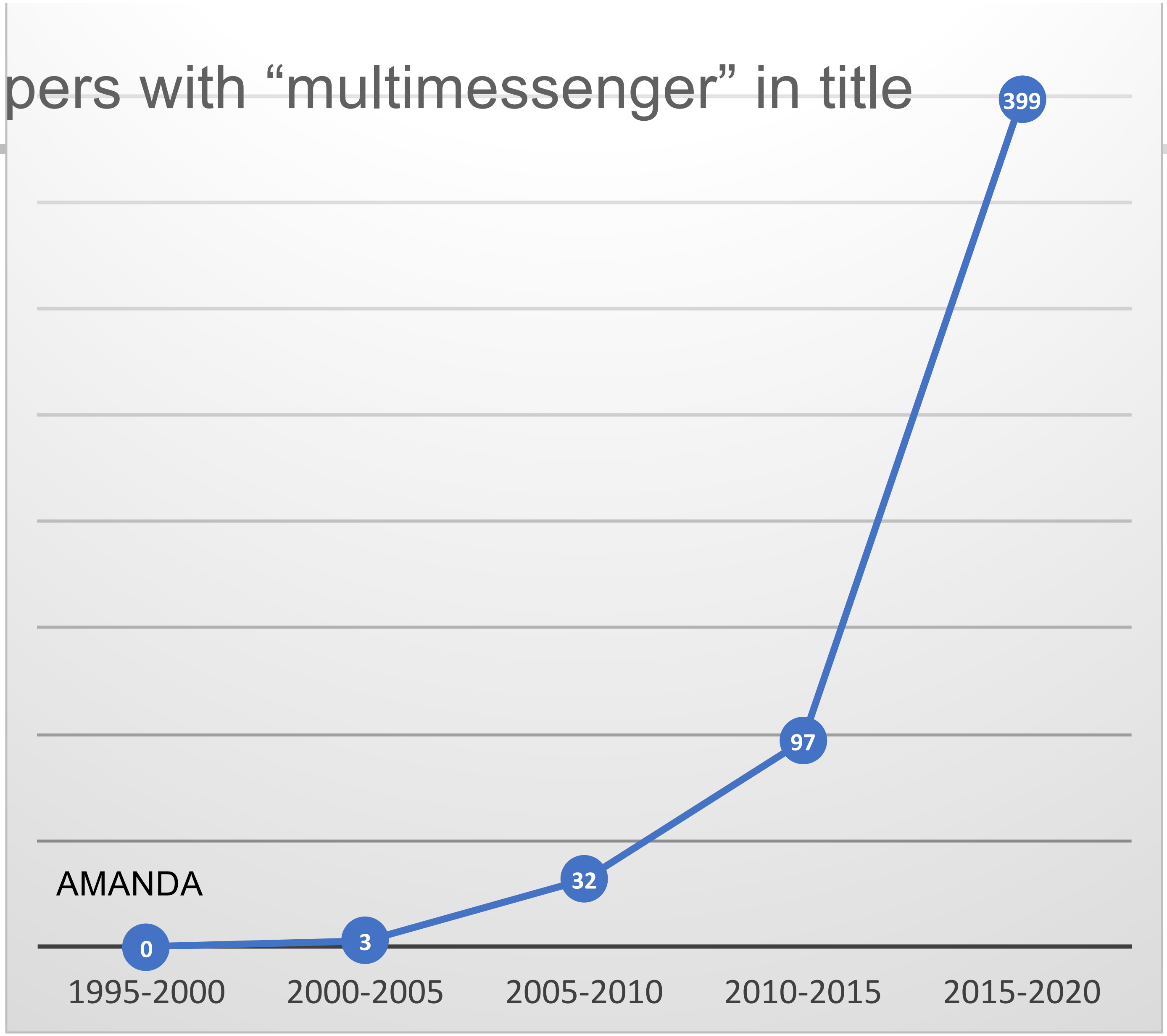
THE VARIABLE MULTI-MESSENGER SKY – OPPORTUNITIES, CHALLENGES, TOOLS

Number of papers with “multimessenger” in title



DUMAND

SN 1987A

Conferences & Schools 2022

- International conference PUMA22 “Probing the Universe with Multimessenger Astrophysics”
- PHAROS Conference 2022 “The Multi-Messenger Physics and Astrophysics of Neutron Stars”
- Kilonova: Multimessenger and Multiphysics, WE-Heraeus-Seminar
- Wilhelm and Else Heraeus seminar on Gravitational Wave and Multimessenger Astronomy
- 1st Astro-COLIBRI Multi-Messenger Astrophysics Workshop
- IAUS 375: The Multimessenger Chakra of Blazar Jets
- APS Session L14: Multimessenger Detection Strategies
- Multi-Messenger Astrophysics Workshop (MMAW)
- Third Gravi-Gamma Workshop: The Multimessenger View of the Black Hole Life Cycle.
- Workshop on Time Domain Astronomy/Multi-Messenger Astrophysics (TDAMM)
- Multi-Messenger Astronomy with Rubin Observatory
- …

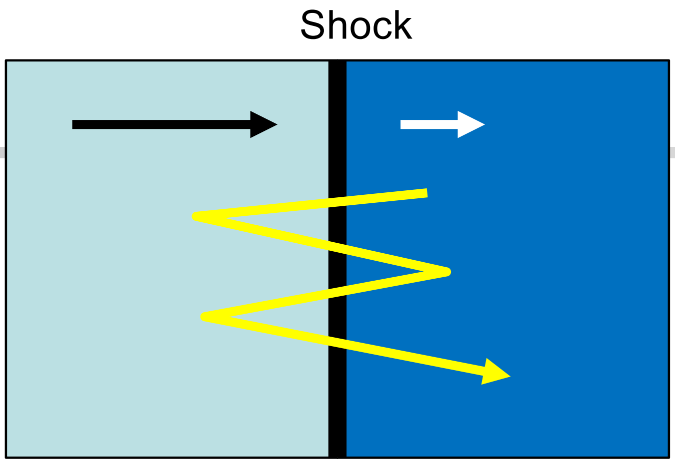
CAVEATS

(Following my own research interests)

Will focus on non-thermal astrophysics throughout this talk, and concentrate on aspects that are involve particle acceleration in astrophysical environments, and related radiative phenomena

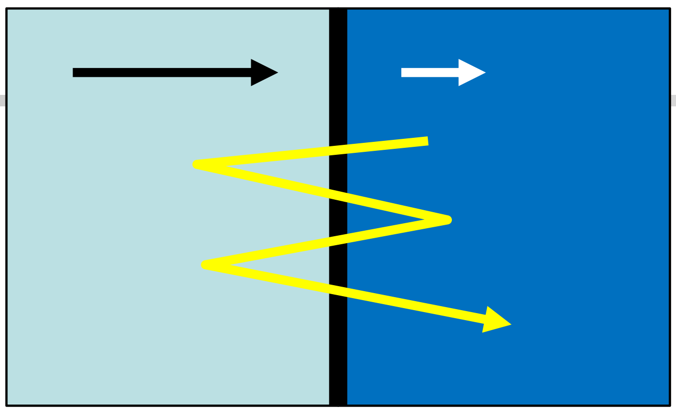
Particle acceleration

Fermi(-like) mechanisms

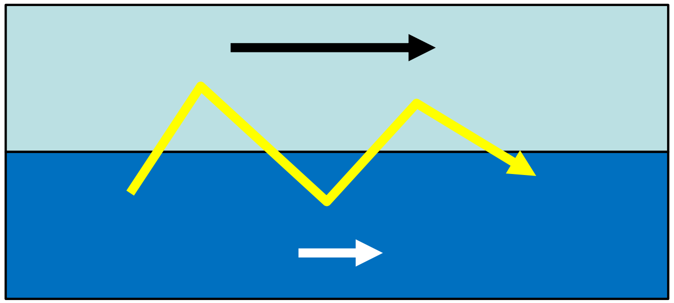


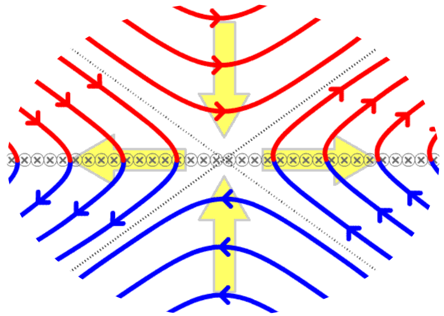
Particle acceleration

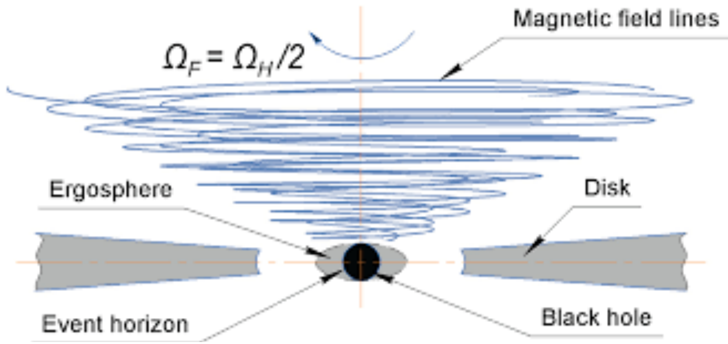
Fermi(-like) mechanisms

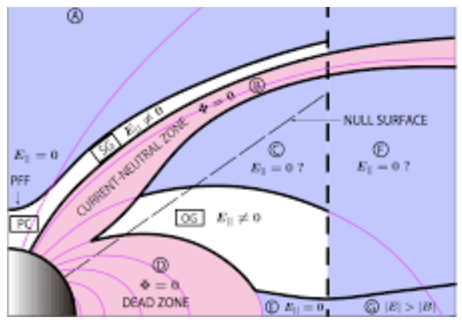


Other mechanisms







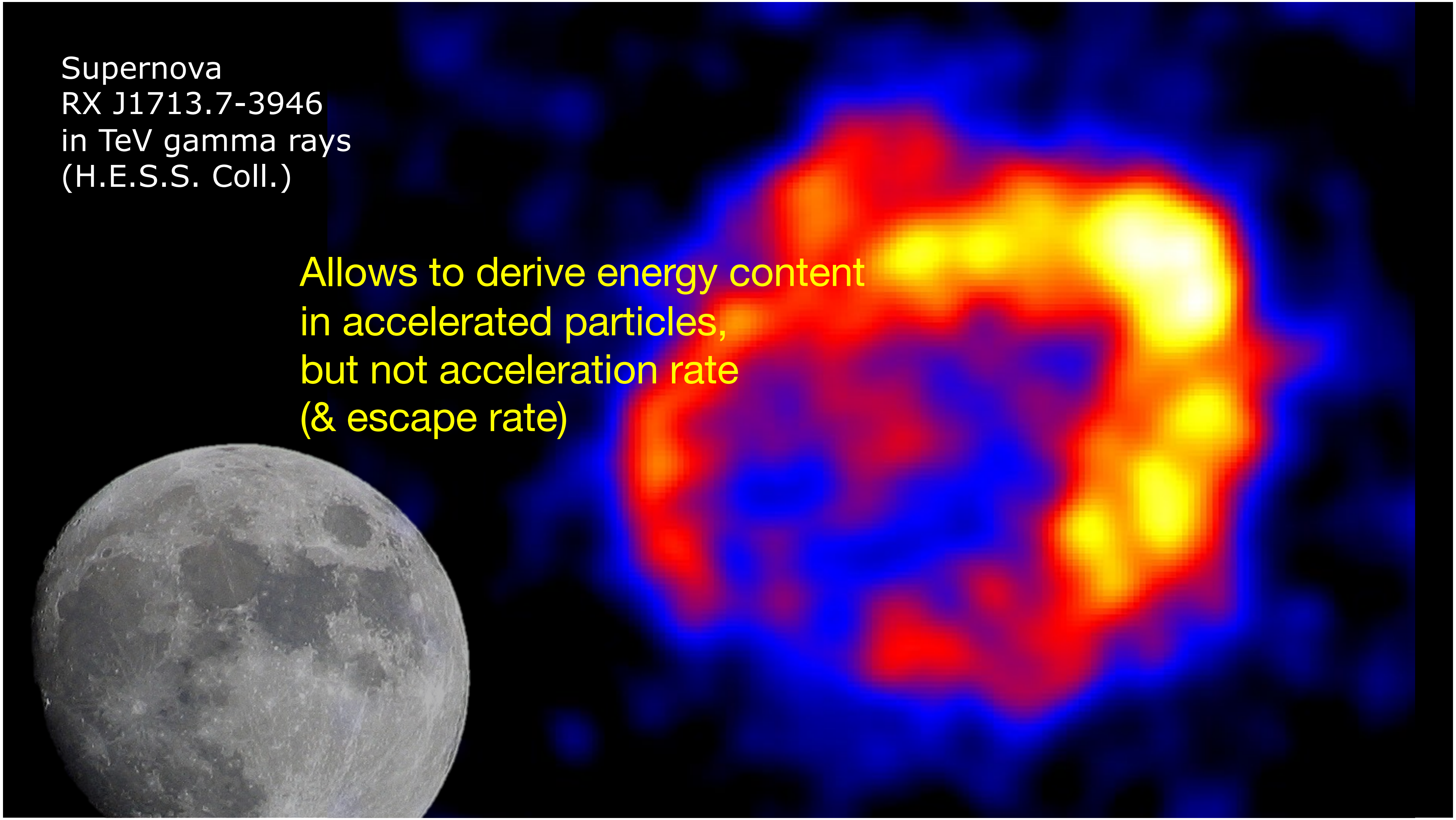


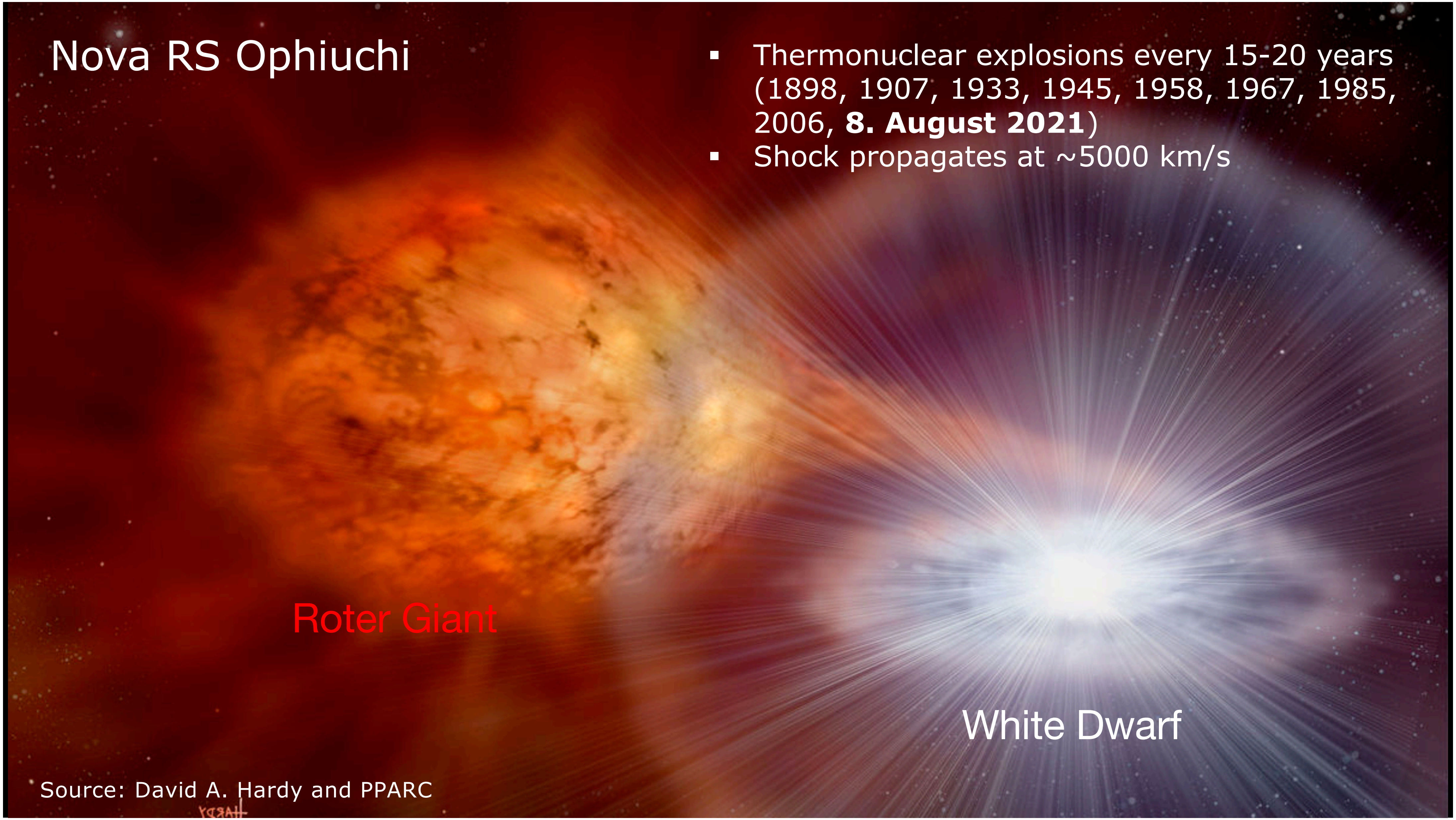
THE VARIABLE MULTI-MESSENGER SKY

The Variable Multimessenger Sky

Variability makes an additional dimension for probing astrophysical processes accessible, e.g.

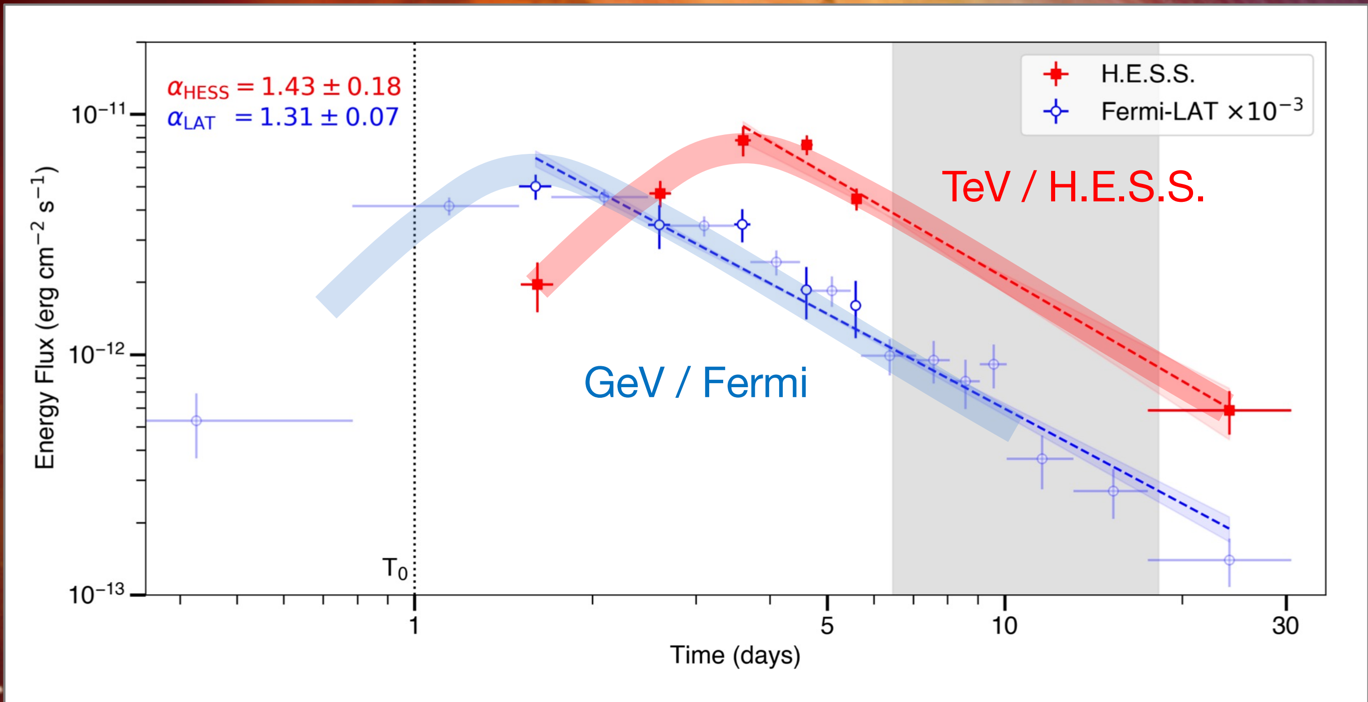
- Time scales for particle acceleration
- Time scales for particle cooling


Supernova
RX J1713.7-3946
in TeV gamma rays
(H.E.S.S. Coll.)
Allows to derive energy content
in accelerated particles,
but not acceleration rate
(& escape rate)


Nova RS Ophiuchi
Thermonuclear explosions every 15-20 years (1898, 1907, 1933, 1945, 1958, 1967, 1985, 2006, 8. August 2021)
Shock propagates at ~5000 km/s
Roter Giant
White Dwarf
Source: David A. Hardy and PPARC

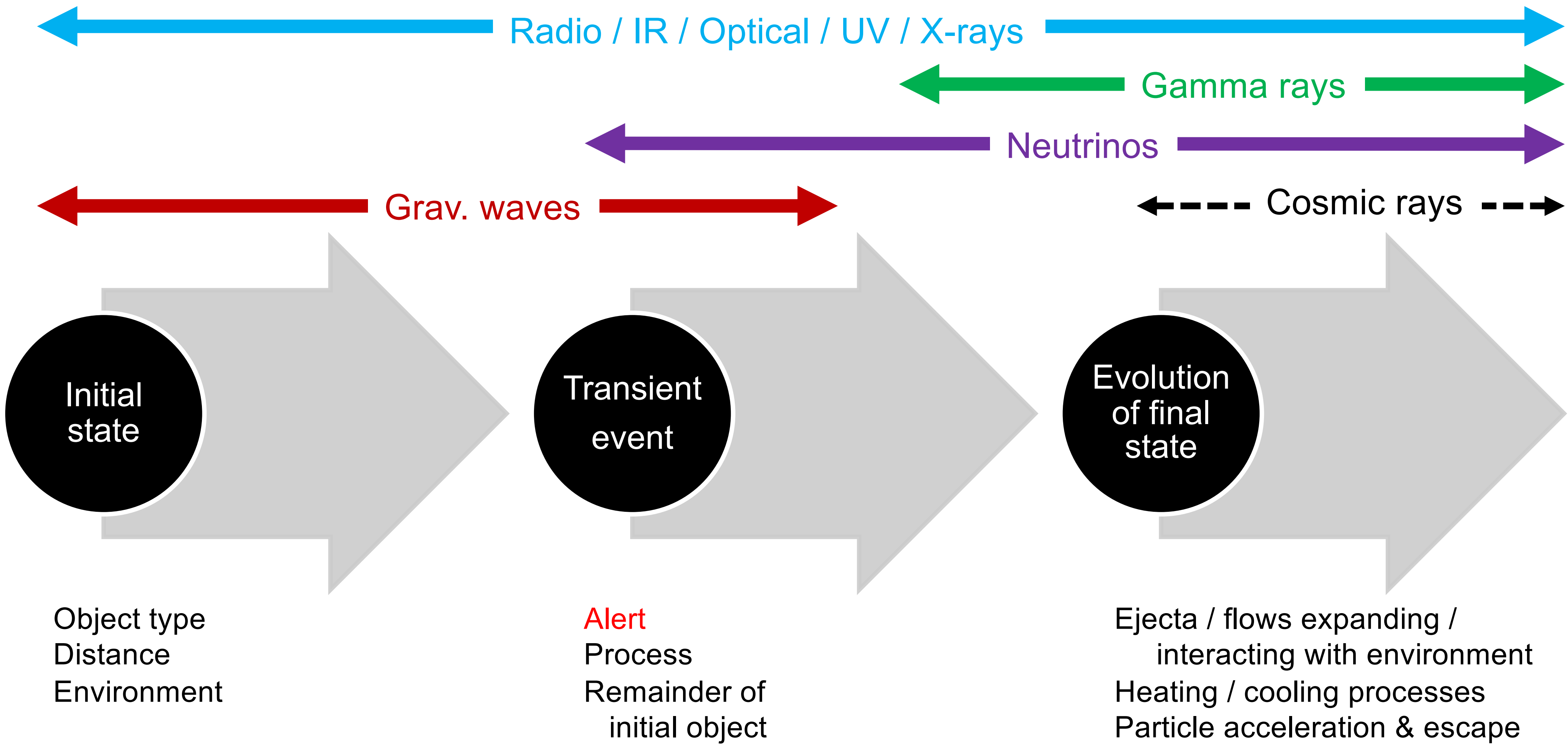
Nova RS Ophiuchi

H.E.S.S. ATEL #14844, Aug. 10
H.E.S.S. Science Mar. 2022
MAGIC Nature Astronomy 2022



THE VARIABLE **MULTI-MESSENGER** SKY

The Variable Multi-Messenger Sky



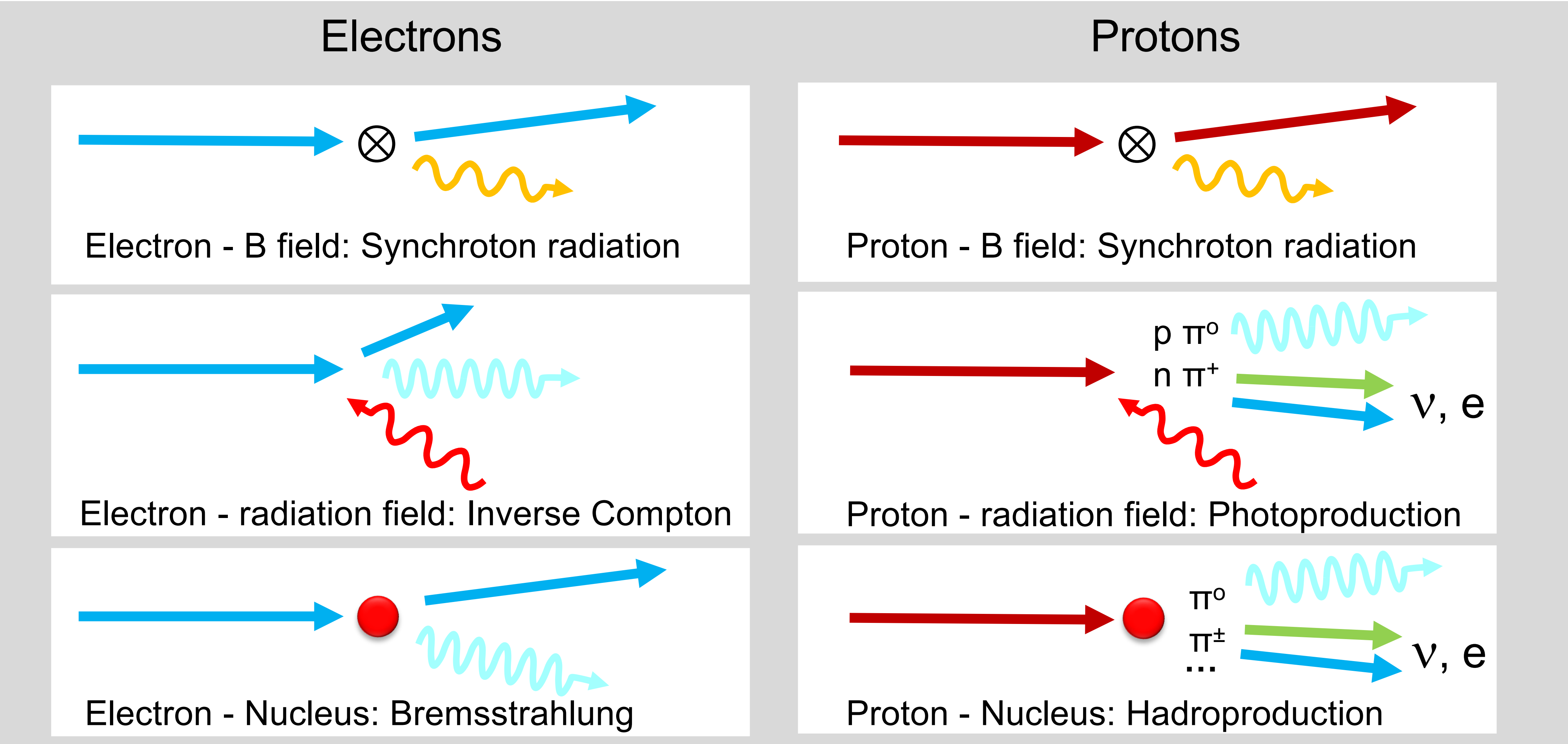
Messengers: Propagation and detection

Messenger	Statistics	Straight trajectory	Pointing resolution	Penetrating
EM			$\ll 1^o$	
Neutrino	Low x-section		$\sim 1^o$	
Proton, nuclei		B fields	B fields	
Grav. waves			$\sim 10^o$	

Adapted from Doug Cowen

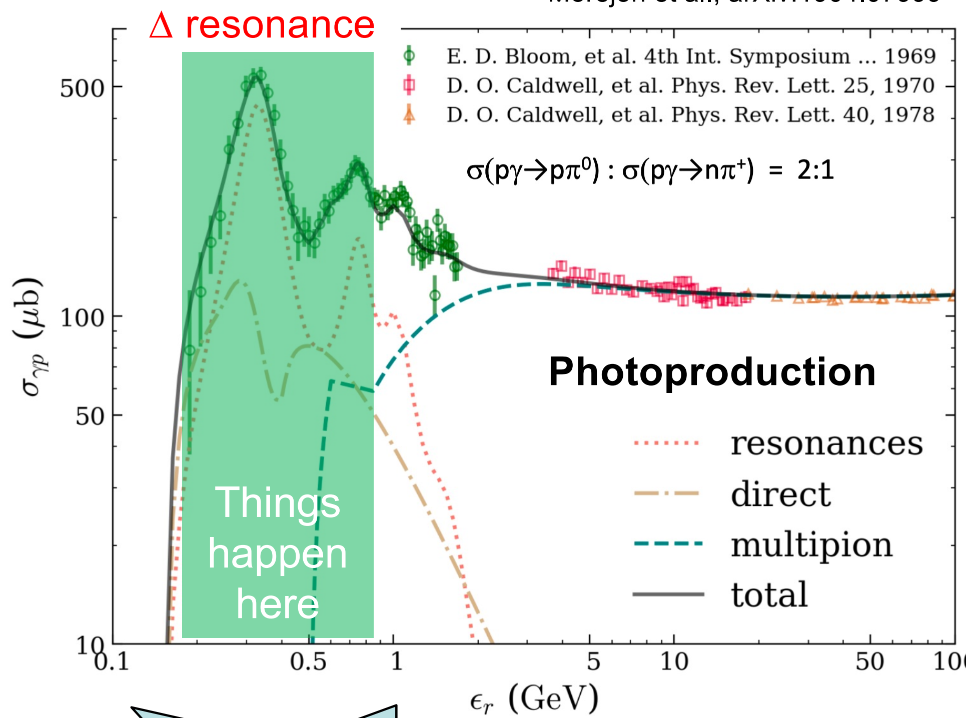
MESSENGERS: PRODUCTION (γ AND ν)

Nonthermal messenger production mechanisms



π^0 Production

Morejon et al., arXiv:1904.07999



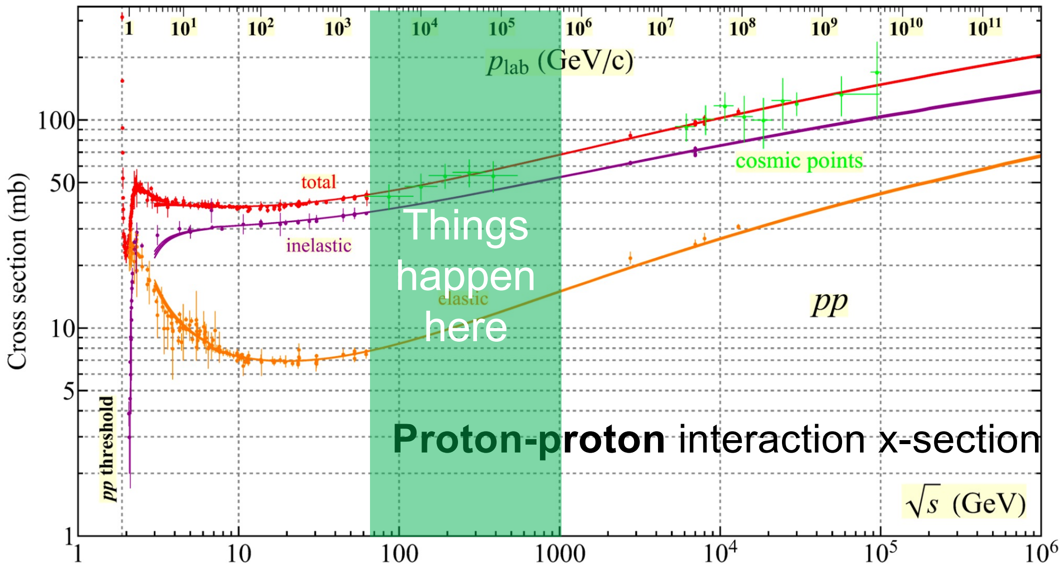
100 TeV proton on keV photon

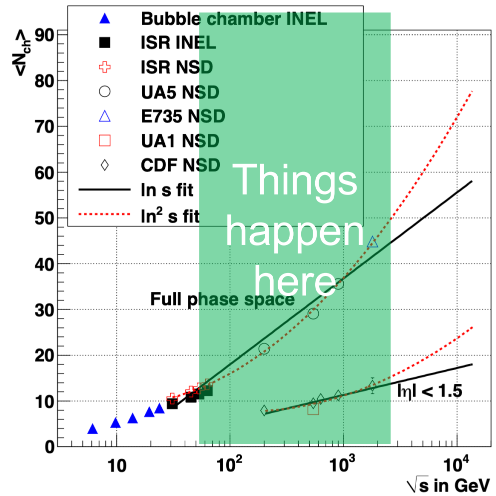
PeV proton on keV photon

Photon energy in proton rest frame

100 TeV proton

Particle Data Group





Charged particle multiplicity in proton-proton interactions

$\pi^0 : \pi^{\pm} = 1{:}2$

Dissertation
J.F. Große-Oetringhaus

π^0 Production

Proton-proton

$$\frac{p_\pi}{p_p} \approx \frac{1}{2} \cdot \frac{1}{n_\pi} \approx O(10^{-2})$$

Proton-photon

$$\frac{p_\pi}{p_p} \approx \frac{m_\pi}{m_p} \approx O(10^{-1})$$

Proton-proton has 100 x higher cross section than photon proton, but…

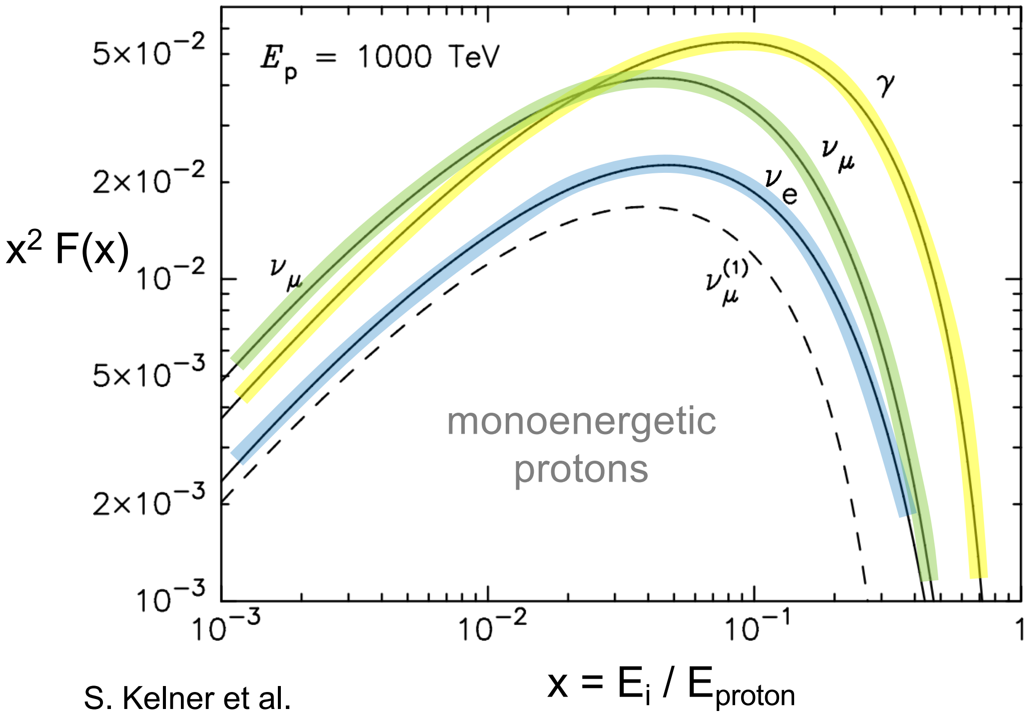
Typical AGN

$$\frac{n_{target-\gamma}}{n_{target-p}} \approx 10^{14}$$

M. Boettcher, Fermi Symposium 2022

Relations between messengers: Neutrinos and gamma rays

High-energy p-p interactions:
spectra of gammas (mostly from $\pi^0 \rightarrow \gamma\gamma$ decays)
and neutrinos (mostly from $\pi^\pm \rightarrow \mu^\pm\nu$ decays)



S. Kelner et al.
astro-ph/0606058

Both for
proton-proton interactions or
proton-radiation (photoproduction)

$$E_\nu^2 \frac{dN_\nu}{dE_\nu}(E_\nu) \approx K\, E_\gamma^2 \frac{dN_\gamma}{dE_\gamma}(E_\gamma = 2E_\nu)$$

K = 0.7 -1.5 depending on production process

MESSENGERS: PROPAGATION (γ)

$\gamma\gamma$ Absorption

Electron energy ε_0
Photon energy ω_0

$(\text{CMS Energy})^2 \simeq \varepsilon_0\, \omega_0\, (1-\cos\theta)$

Absorption cross section peaks near threshold (2 m_e), hence for

$E_\gamma[\text{eV}] \sim 10^{12}/E_{target}[\text{eV}]$

Absoption length:

10^7 target photons/cm^3 over 1 pc

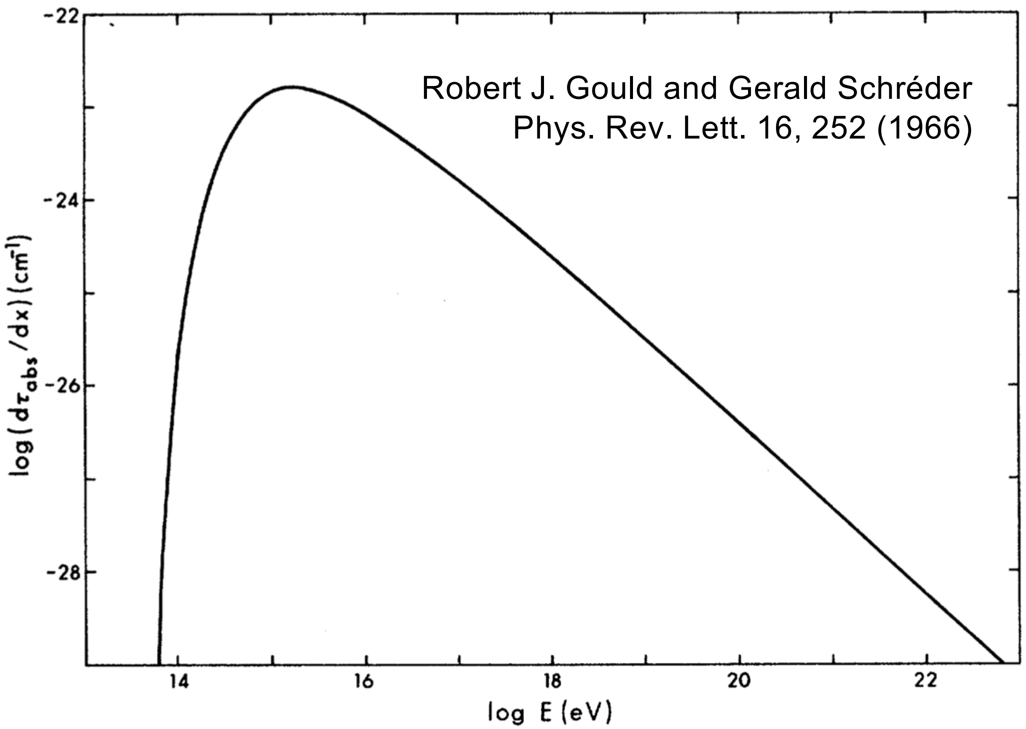
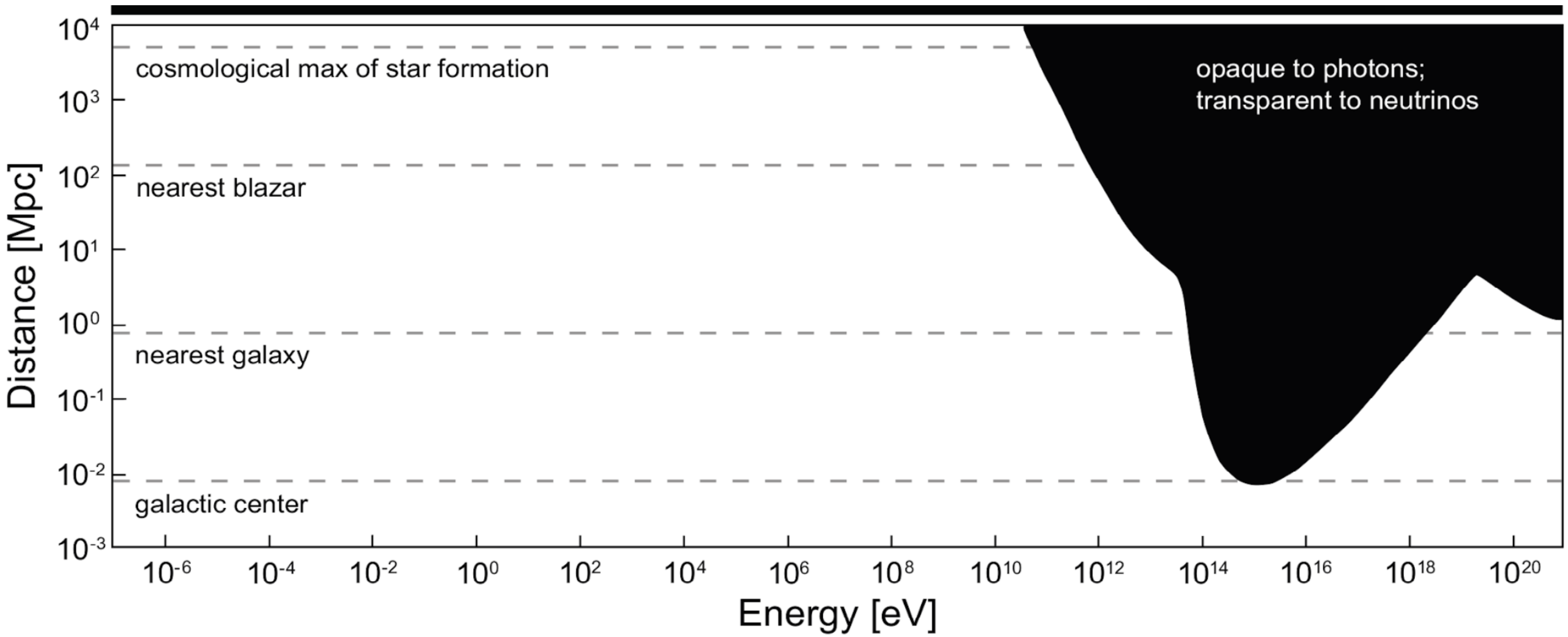


FIG. 1. Absorption probability per unit path length as a function of energy by means of the process $\gamma + \gamma' \rightarrow e^+ + e^-$ for high-energy photons traversing a black-body photon gas at 3.5°K. The absorption probability for interaction with a black-body photon gas at other temperatures may be computed with the help of this curve and Eq. (1).

Gamma ray range vs energy

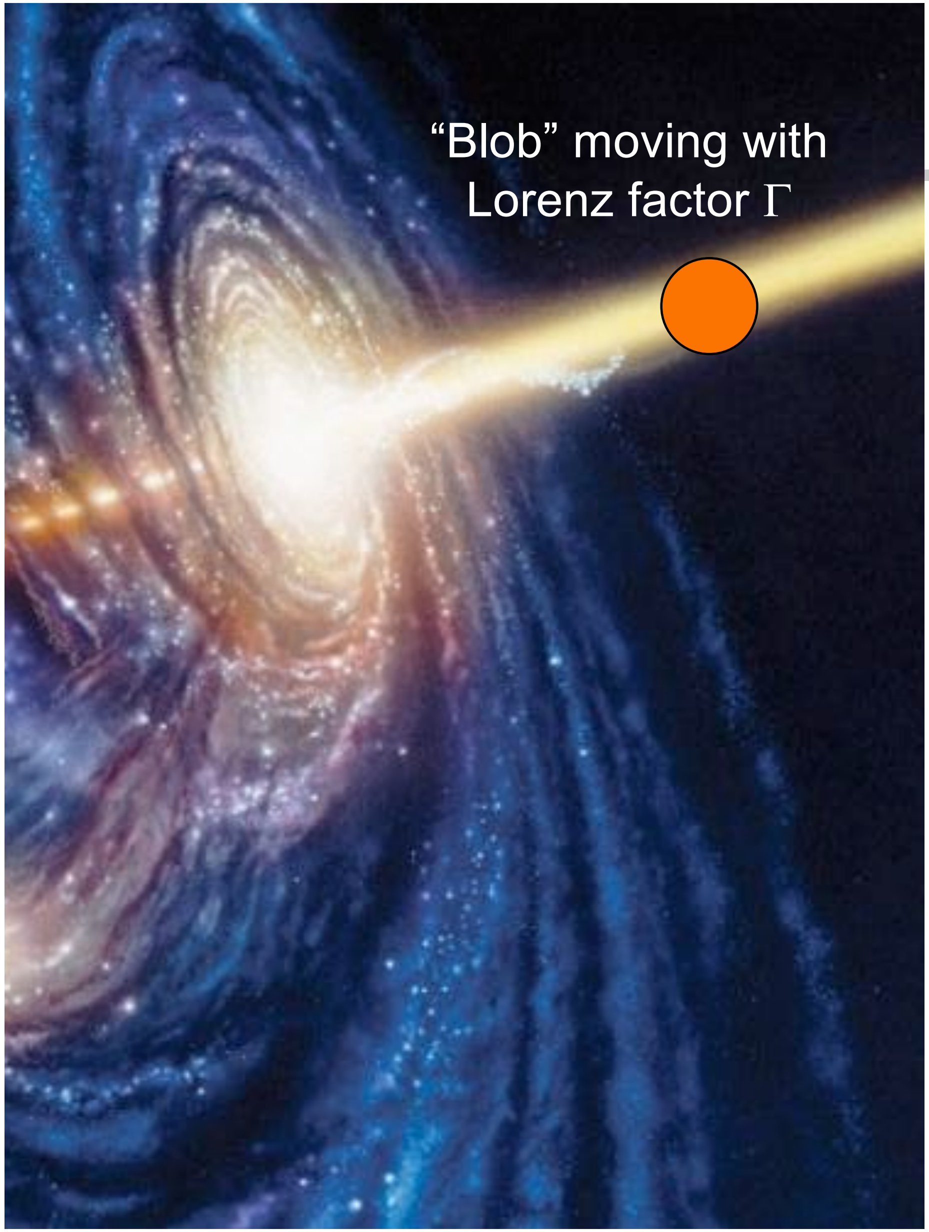


M. G. Aartsen et al.,
arxiv:2008.04323

Photon attenuation

using the above simple approximations

	Typ. photon energy	Photon density	System length scale	Peak absorption	Optical depth
Galaxy, CMB	0.0002 eV	0.26 eV/cm^3	10 kpc	$5x10^{15}$ eV	1.3
Galaxy, FIR	0.01 eV	0.3 eV/cm^3	10 kpc	$1x10^{14}$ eV	0.03
Galaxy, VIS	1 eV	0.3 eV/cm^3	10 kpc	$1x10^{12}$ eV	0.0003
Starburst galaxy, FIR	0.004 eV	1000 eV/cm^3	0.2 kpc	$3x10^{14}$ eV	5
Starburst galaxy, VIS	1 eV	1000 eV/cm^3	0.2 kpc	$1x10^{12}$ eV	0.02
AGN, Blob frame					< 1



Optical depth of blob ~ $R_* L_*$

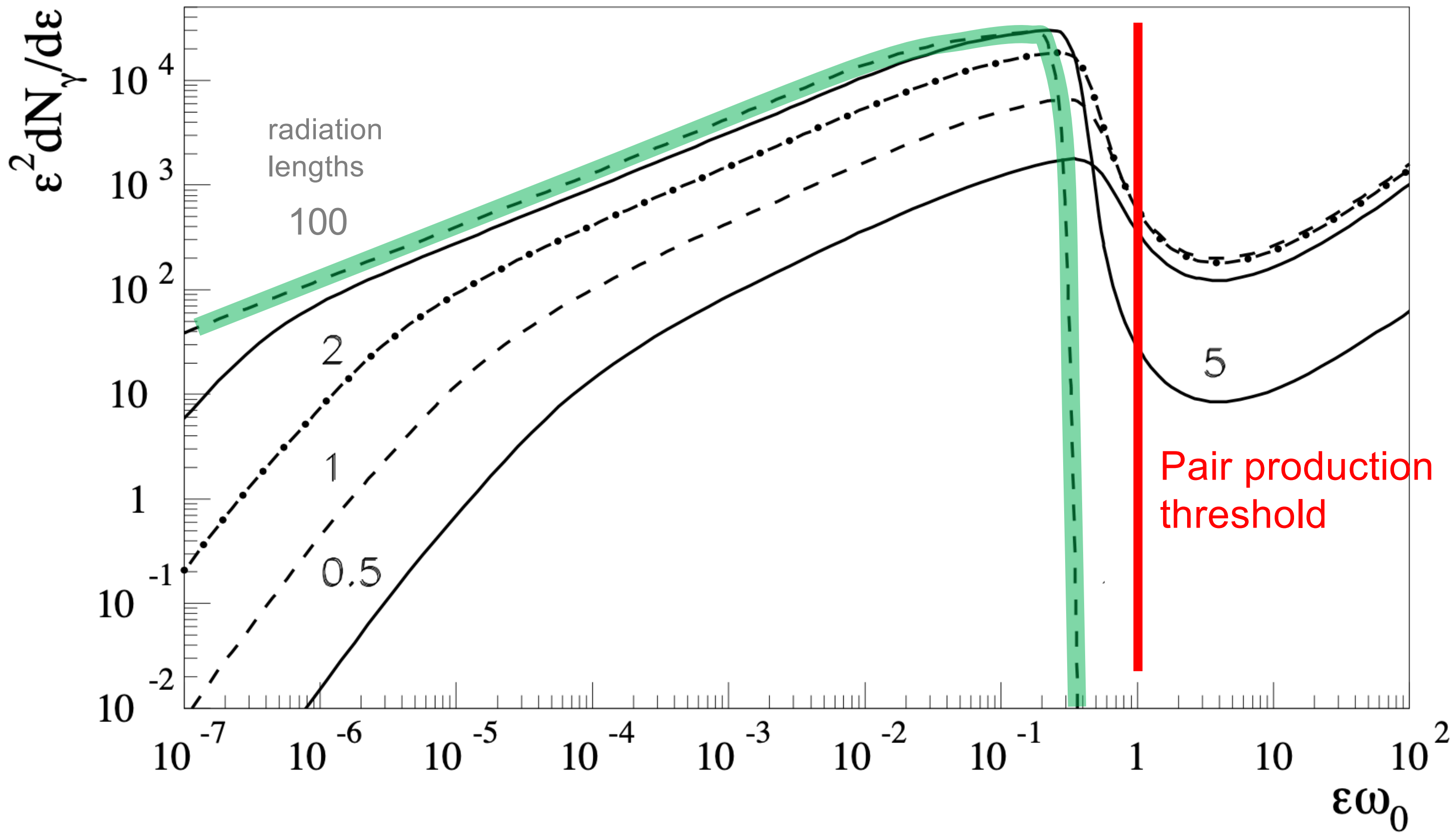
Size of blob:
Defined by observed variability, $R_* \sim c\,\Delta t\,\Gamma$

Density and energy of target photons in blob:
from observed optical / UV / X-ray flux F,
$E_* = E_{Lab}/\Gamma$; $L_* \sim F/\Gamma^3$

→ Optical depth of blob for gamma rays:
strong function of Γ
→ Select Γ large enough that depth < 1

Photon-induced cascades in (Planckian) radiation fields

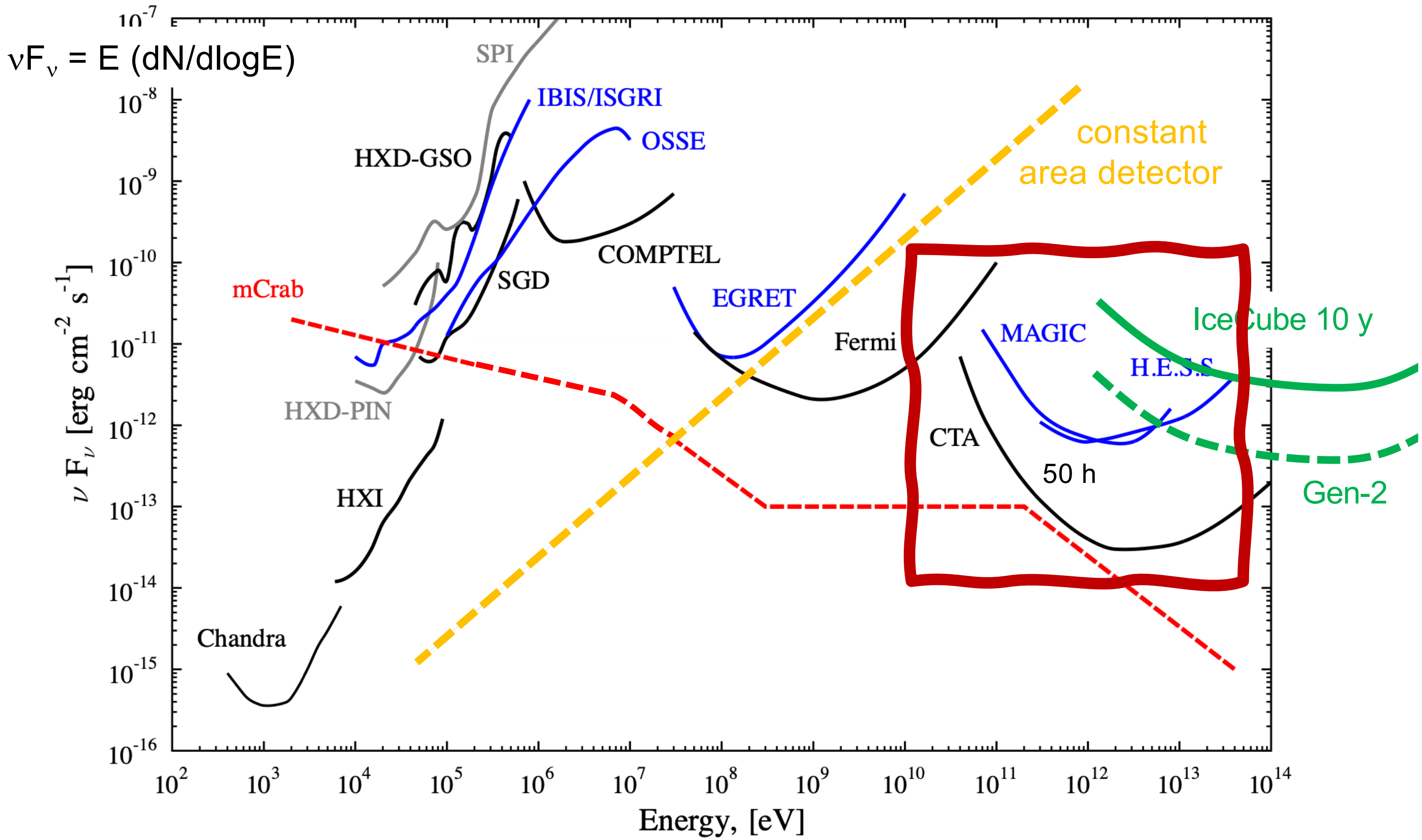
F.A. Aharonian, A.V. Plyasheshnikov
astro-ph/0208504



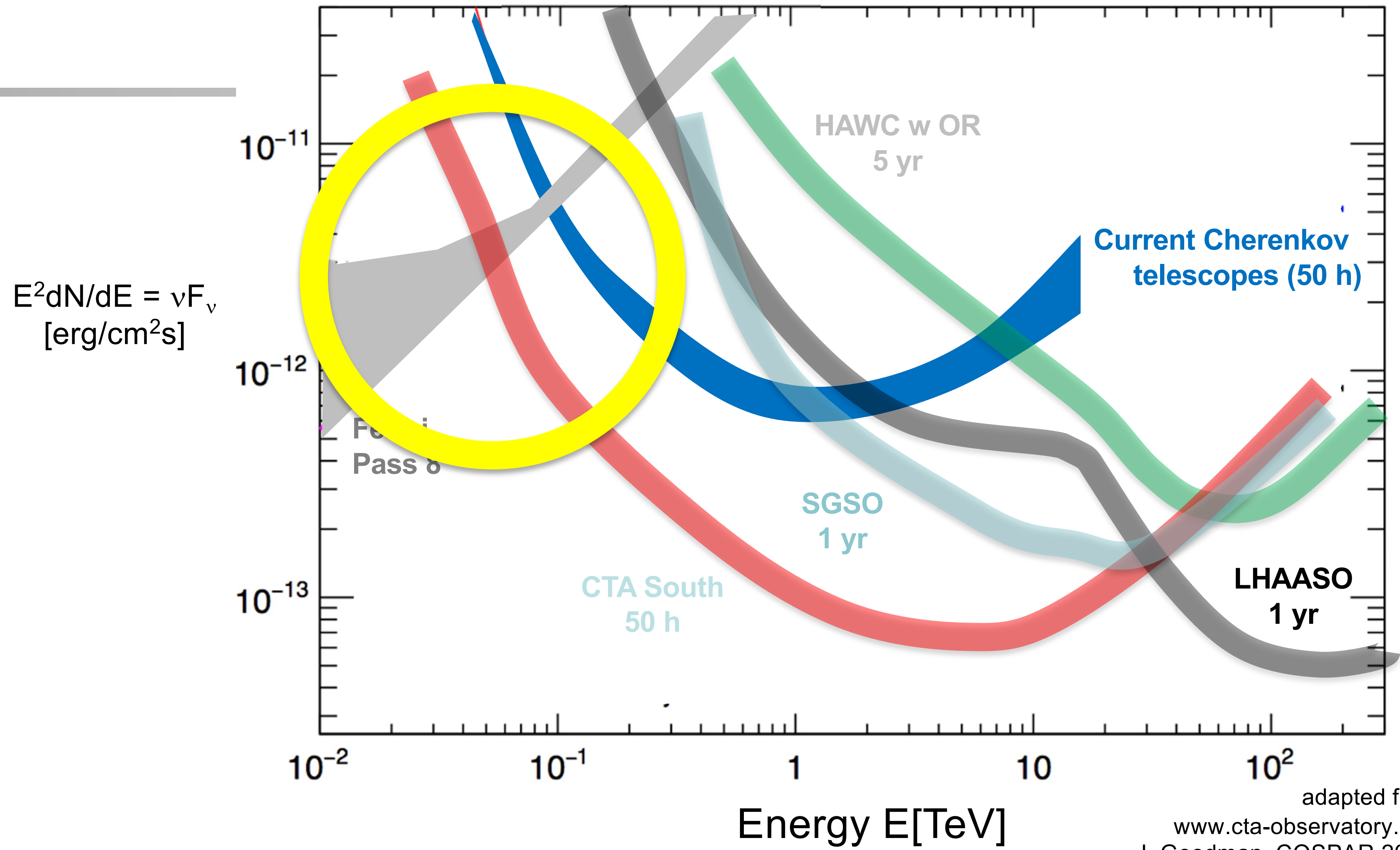
MESSENGERS: DETECTION

Messengers: Detection sensitivity for point sources

Warning:
widely different definitions of sensitivity (ΔE band), exposure time (tens of h to decades); shown is a practical sensitivity for steady sources



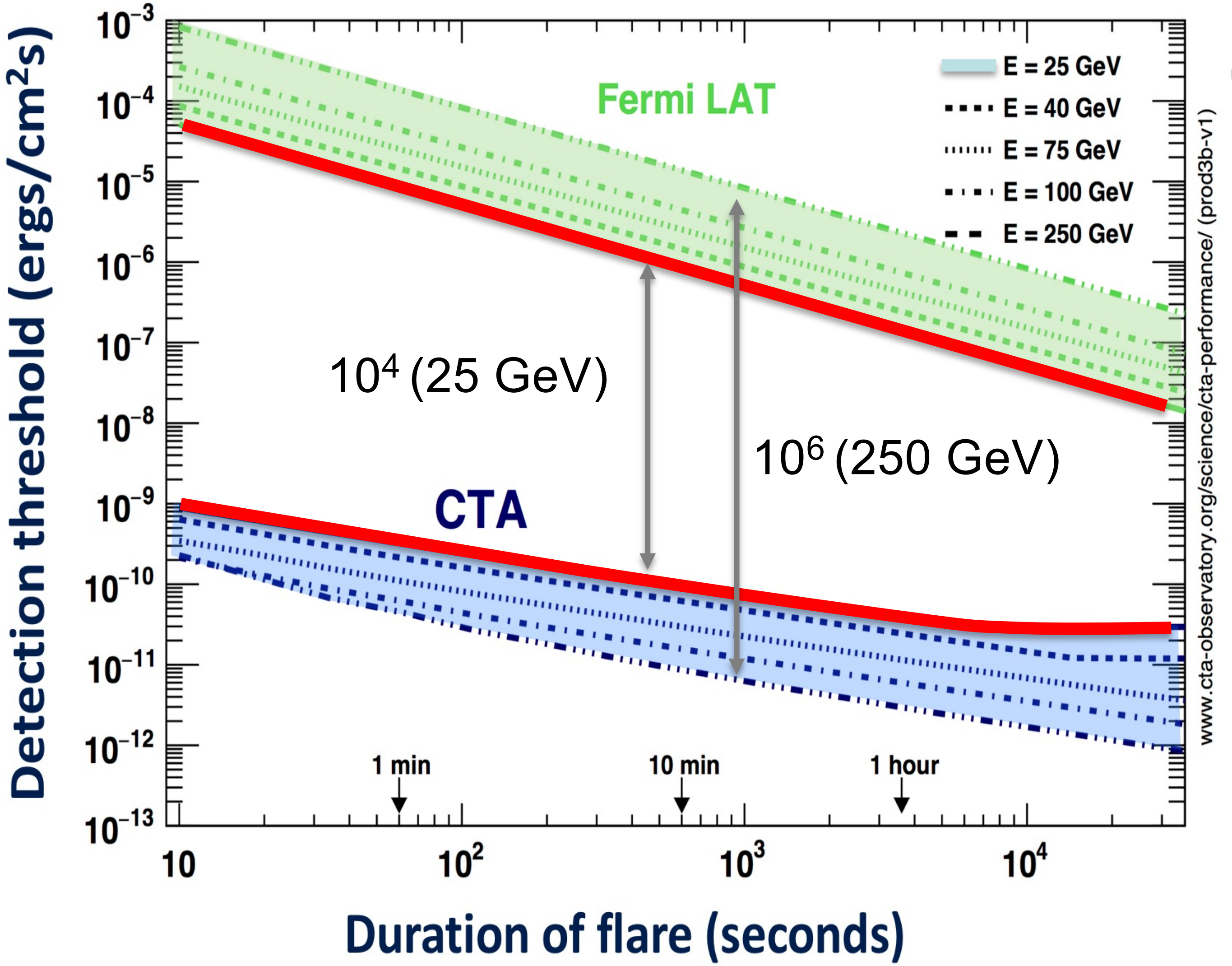
A M Krassilchtchikov et al.
Journal of Physics: Conference Series
1400 (2019) 022031



adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018

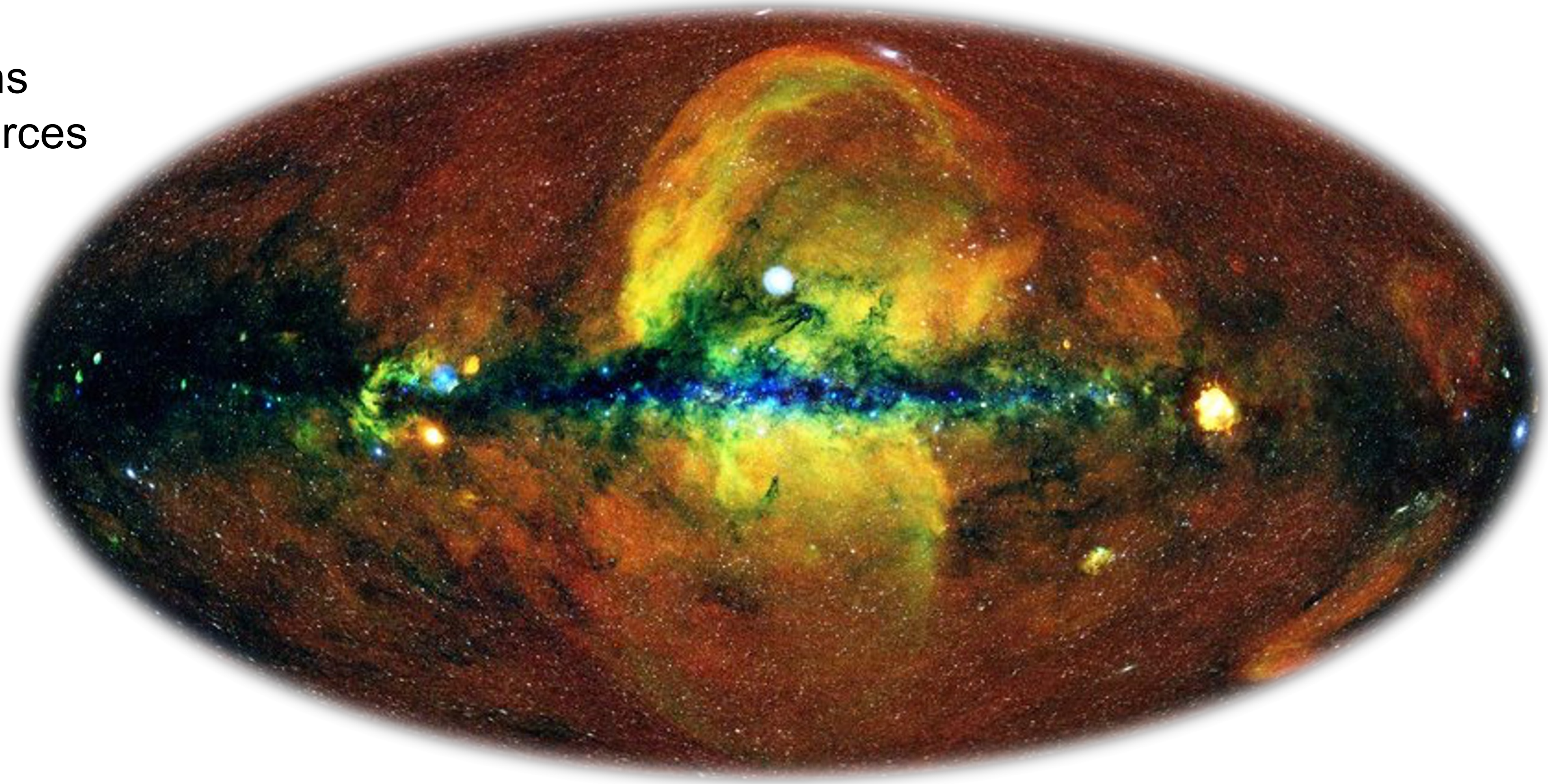
Flare sensitivity at fixed time scale:
Area matters!

CTA
versus
Fermi-LAT



keV sky

millions
of sources

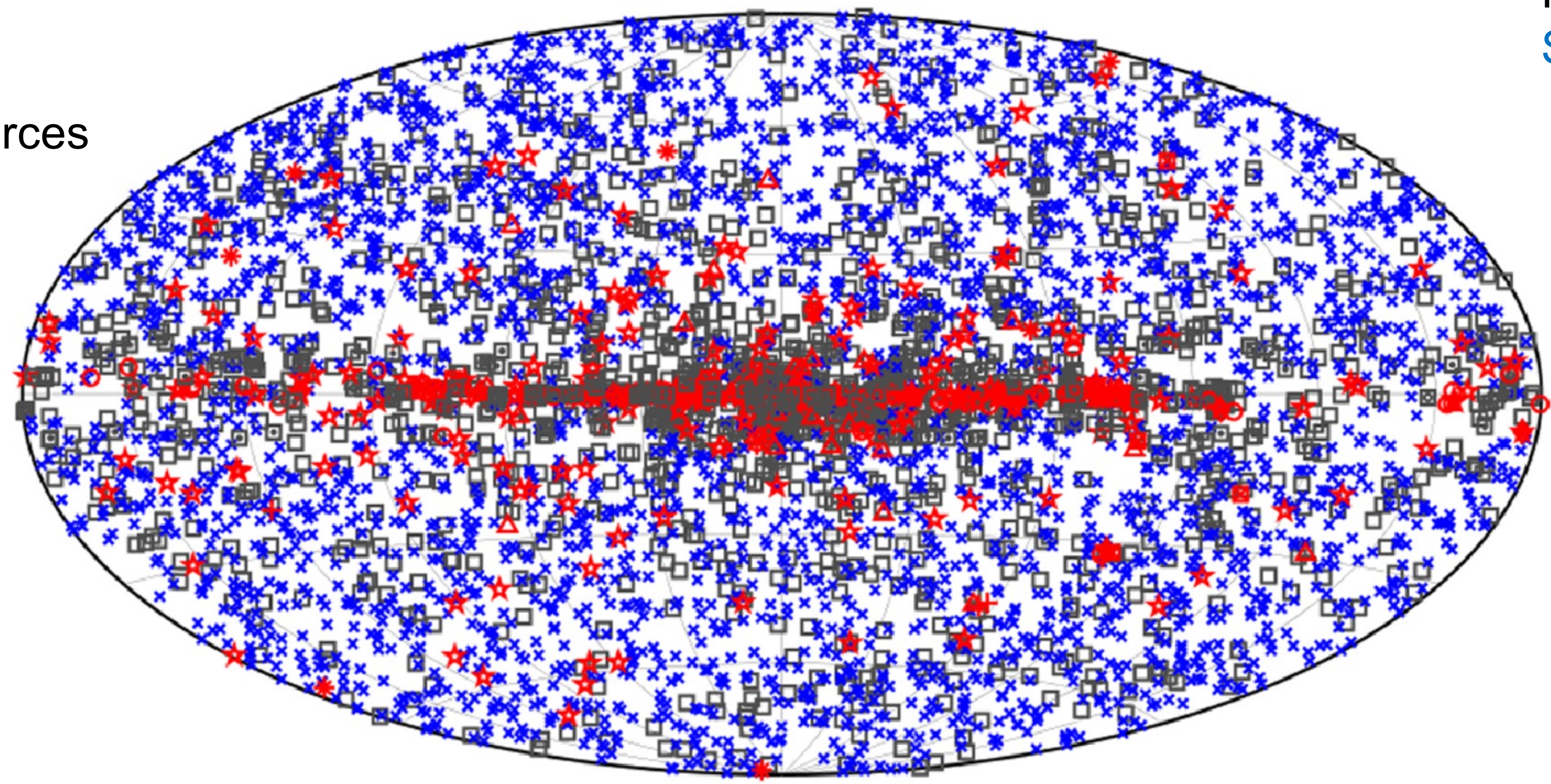


eROSITA
Sky map

GeV Sky

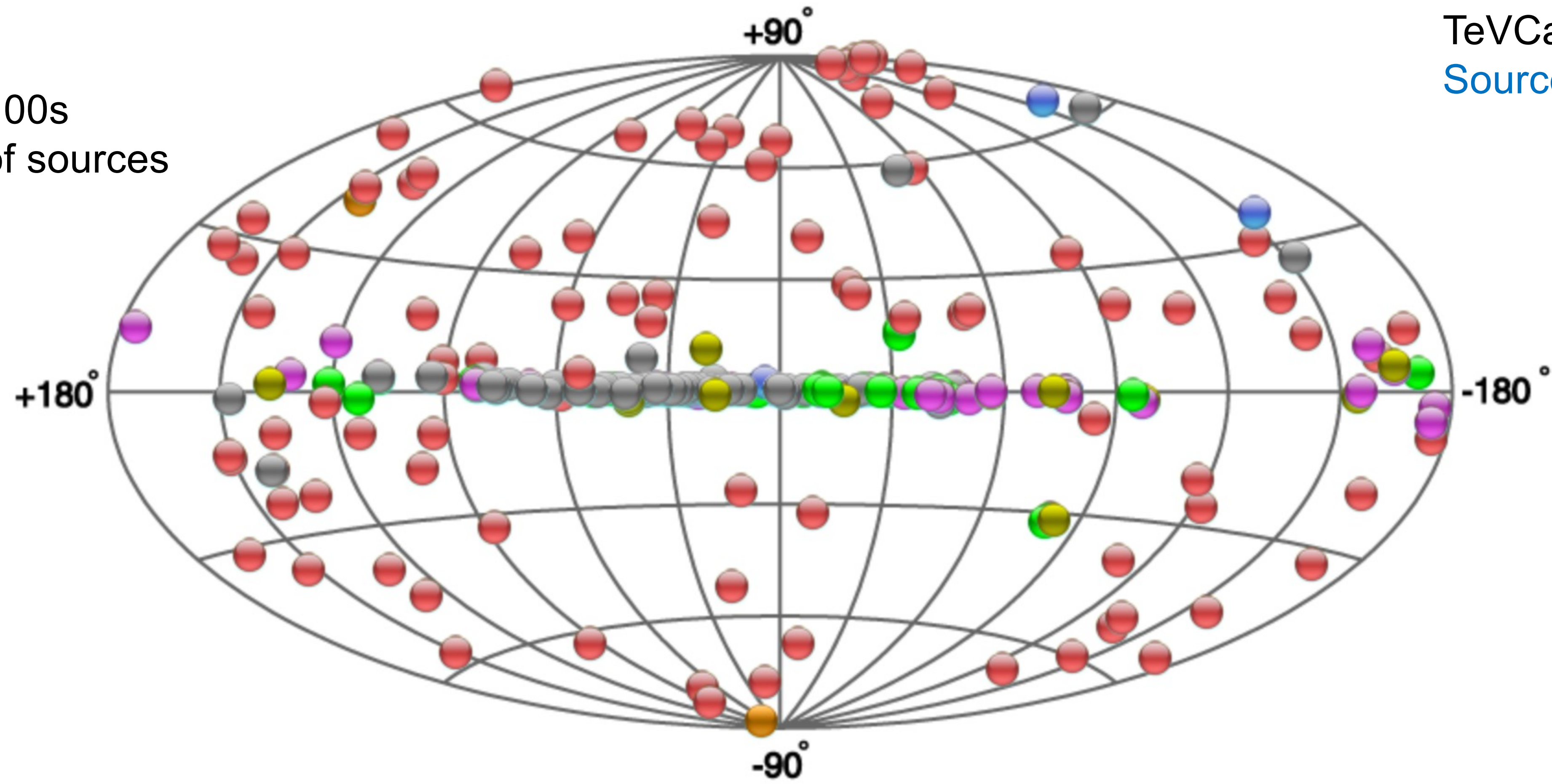
1000s
of sources

Fermi LAT
Source map



TeV Sky

100s
of sources

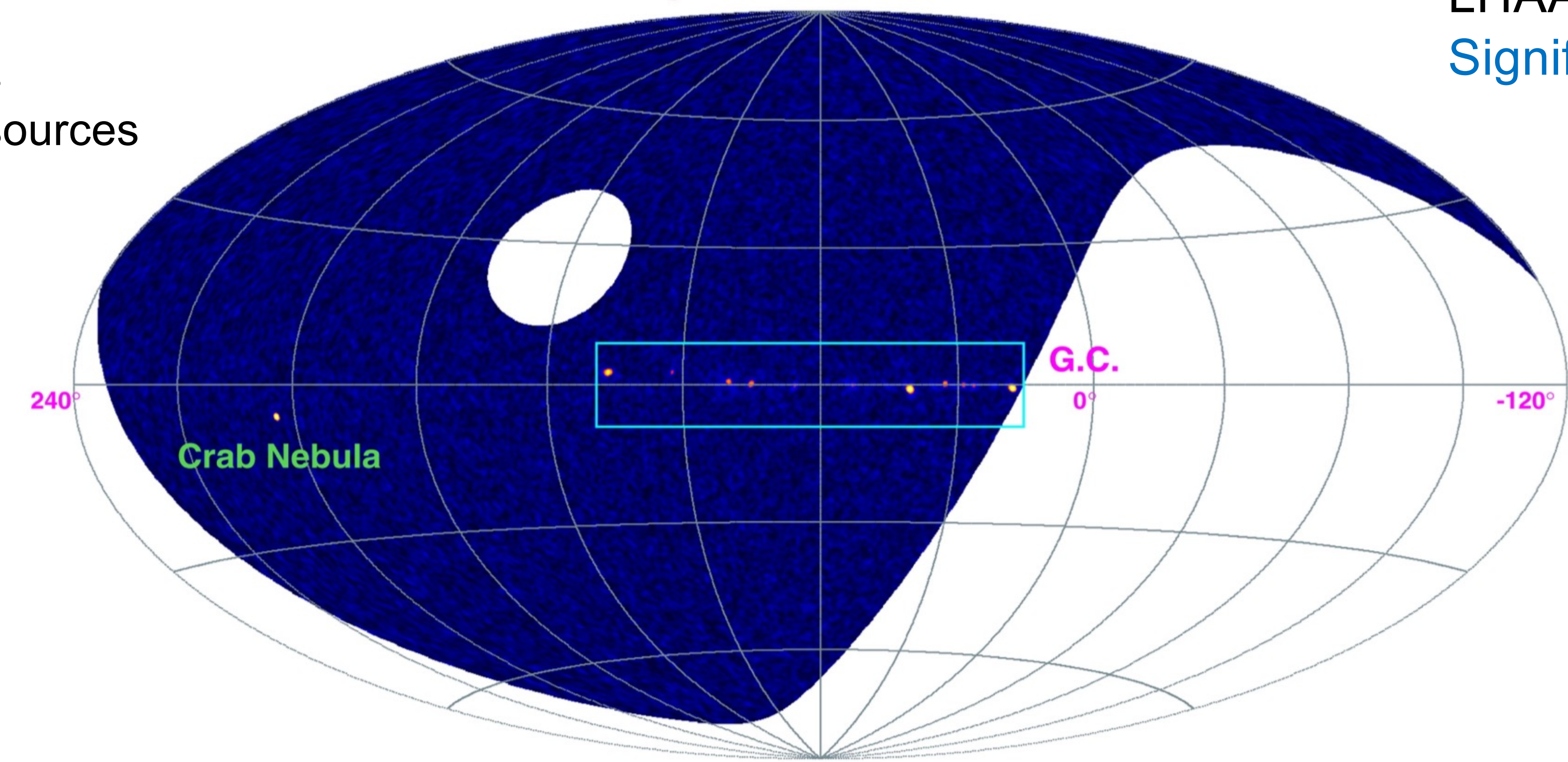


TeVCat
Source map

PeV Sky

10s
of sources

LHAASO,
Significance map



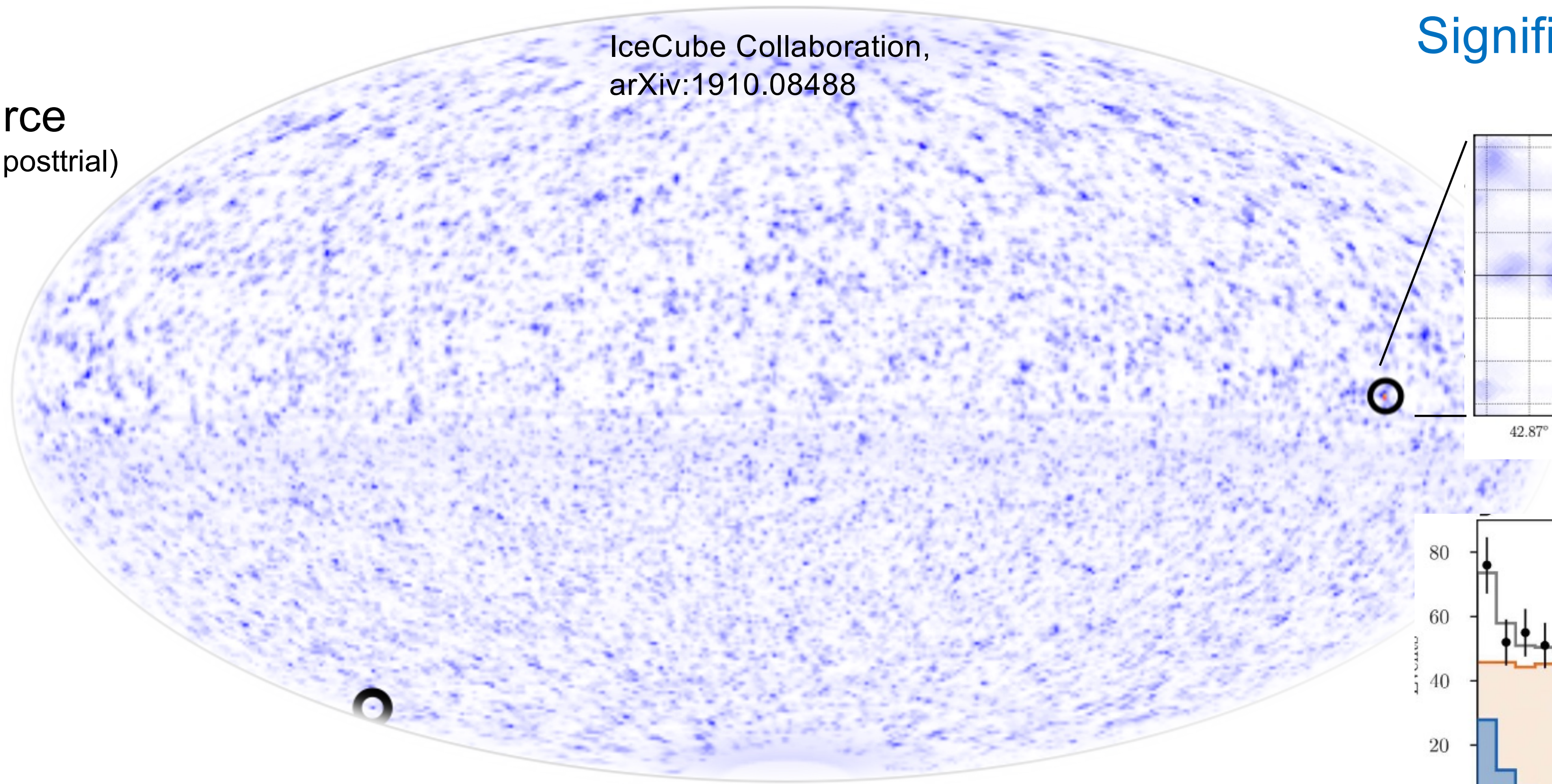
TeV/PeV Neutrino sky

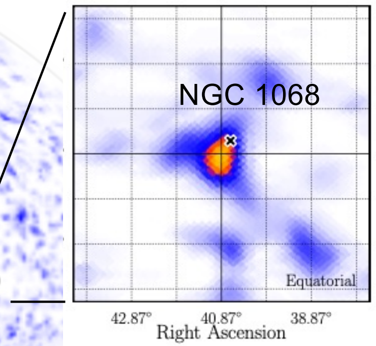
IceCube

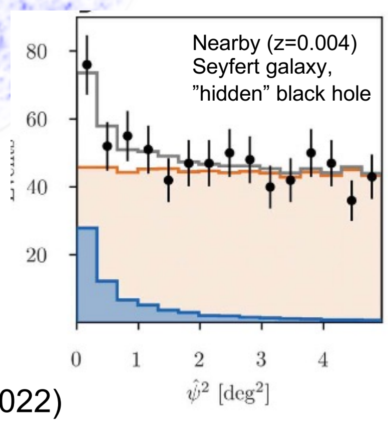
Significance map

1 source

(2 – 4 σ posttrial)

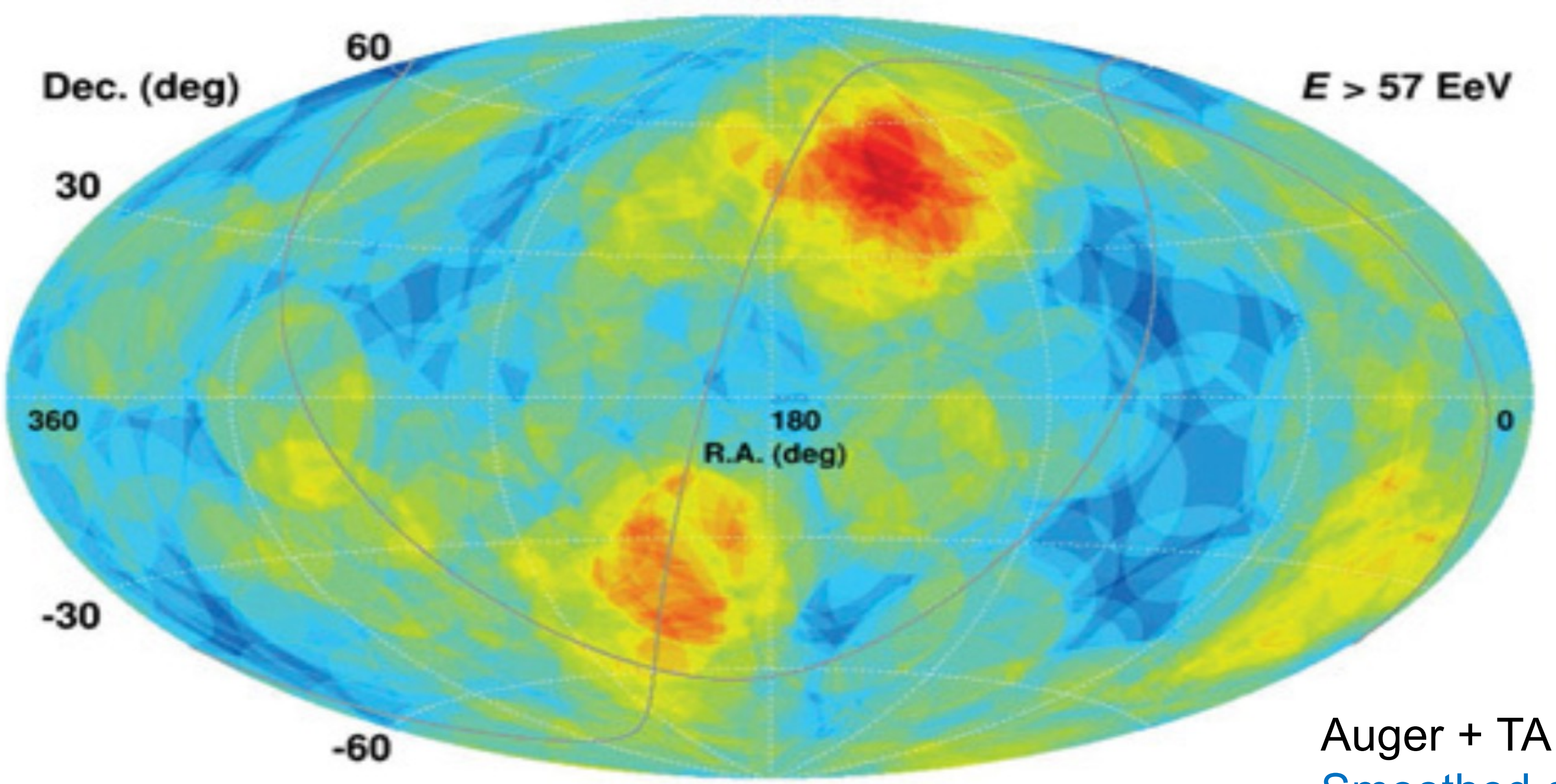






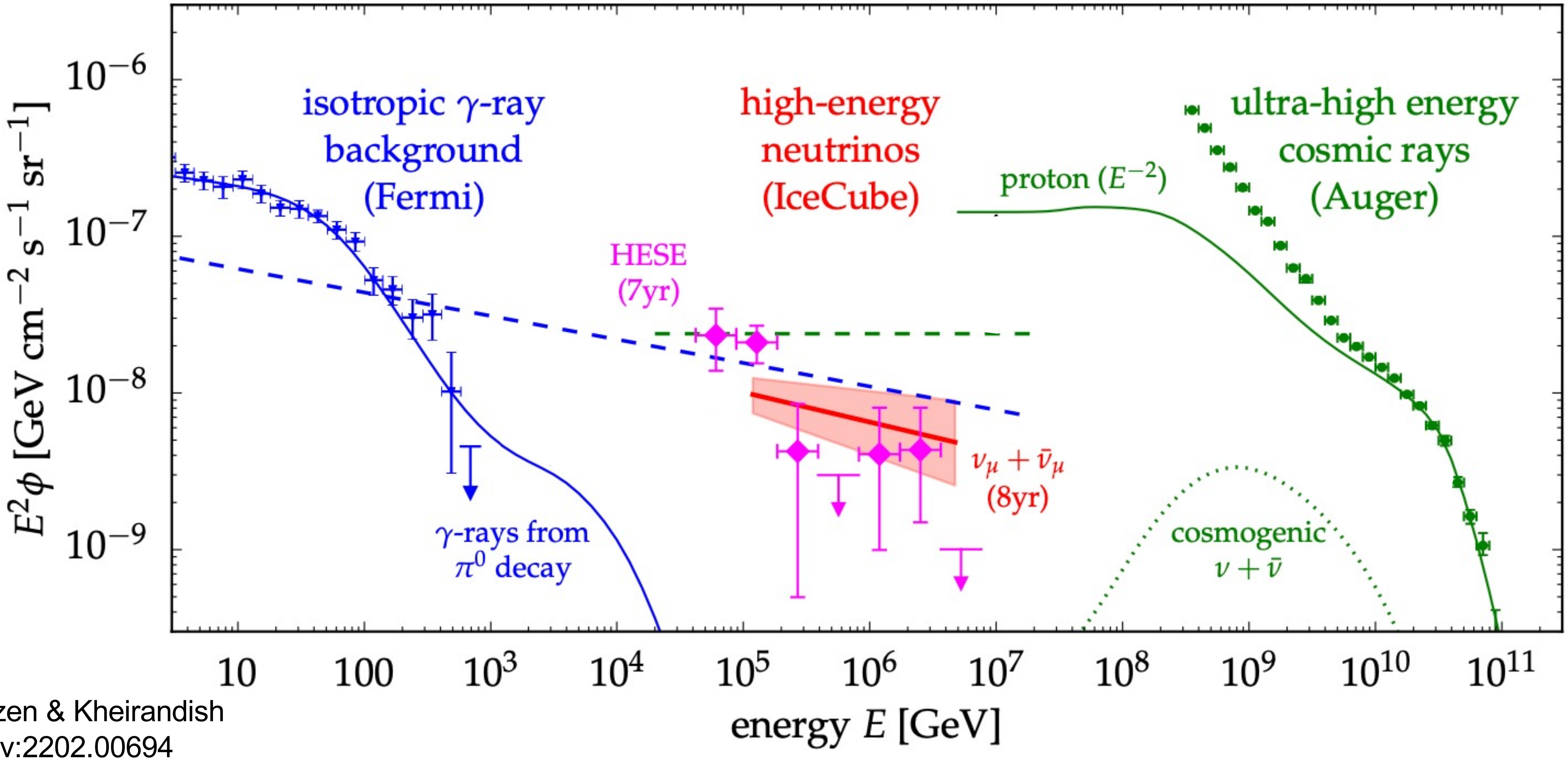
IceCube Collaboration,
Science378, 538–543 (2022)

100 EeV Cosmic Ray Sky



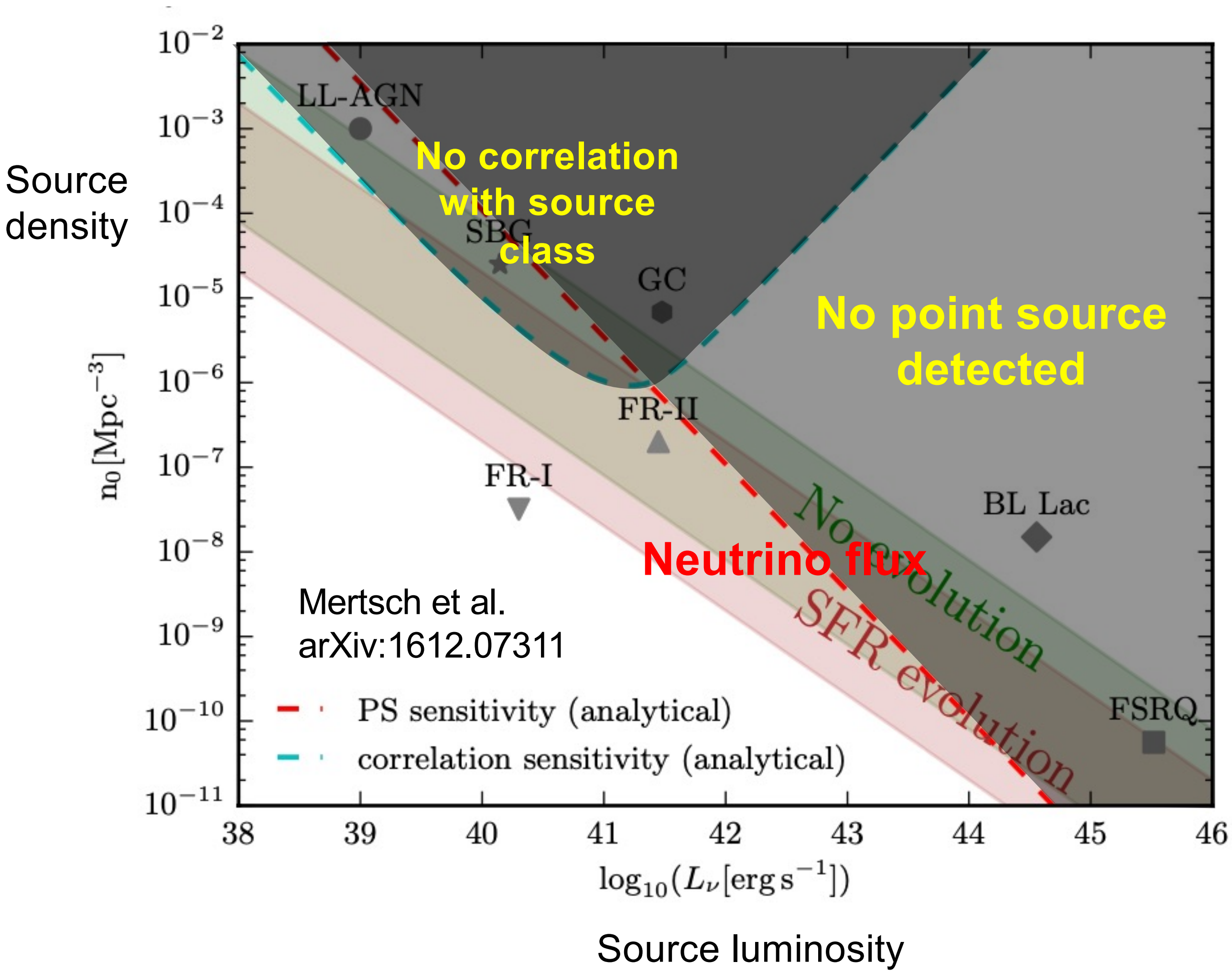
Auger + TA
Smoothed event map
(2017)

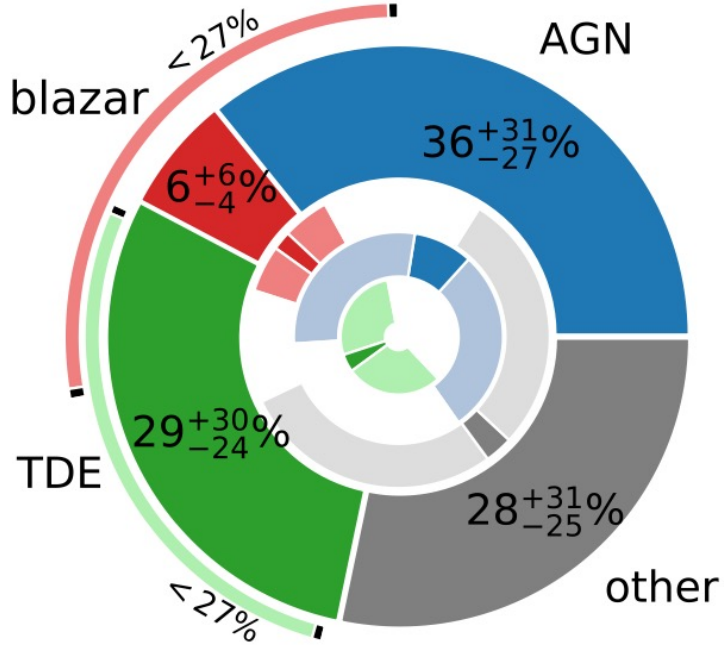
High energy cosmic neutrinos



Halzen & Kheirandish
arXiv:2202.00694

Sources of high-energy cosmic neutrinos

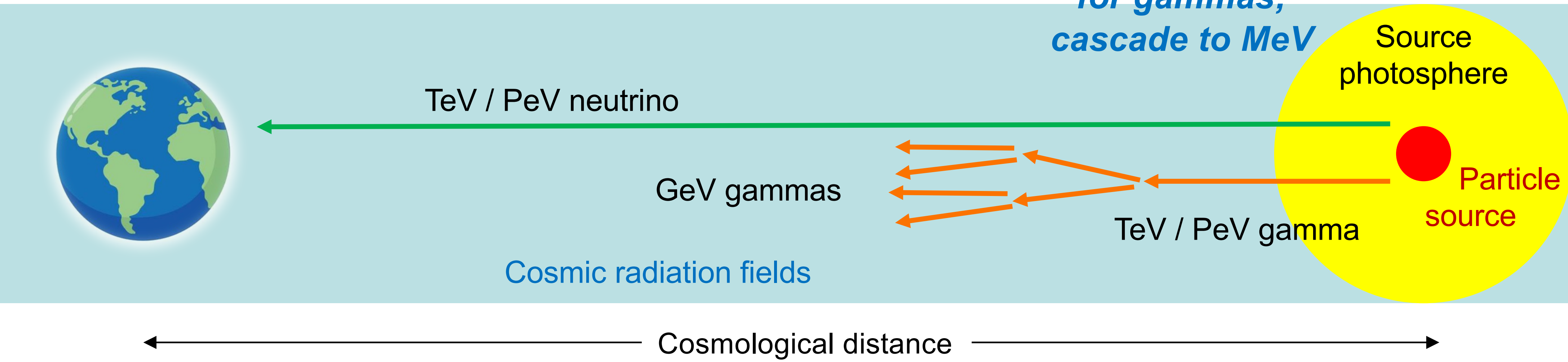


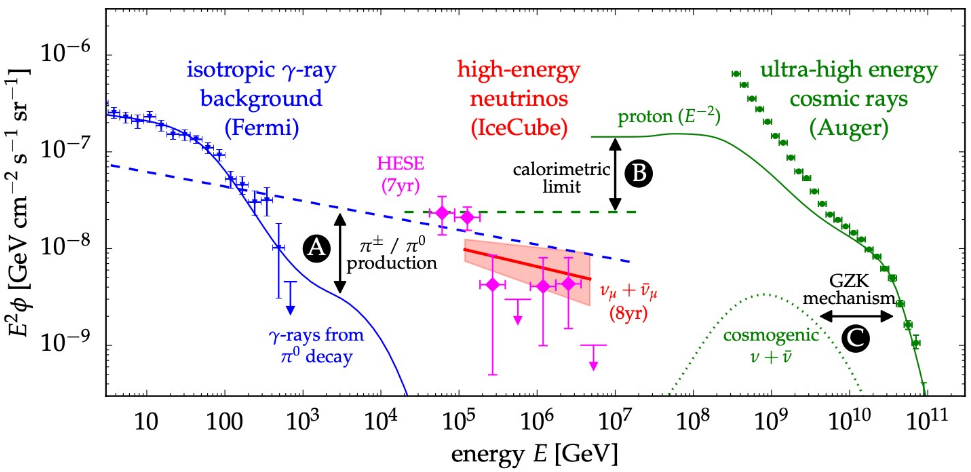


Bartos et al, ApJ 921 (2021) 45

Hidden neutrino sources

Photoproduction: source opaque for gammas; cascade to MeV





Propagation: Cascade gammas tend to overshoot diffuse gamma-ray background

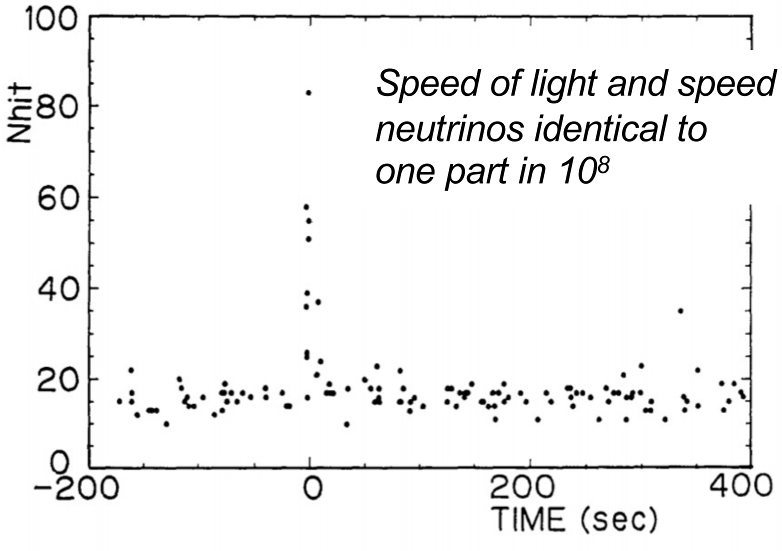
(Capamena et al., arXiv:2002:07192)

➡ ***TeV / PeV gamma rays do not escape from (typical) sources***

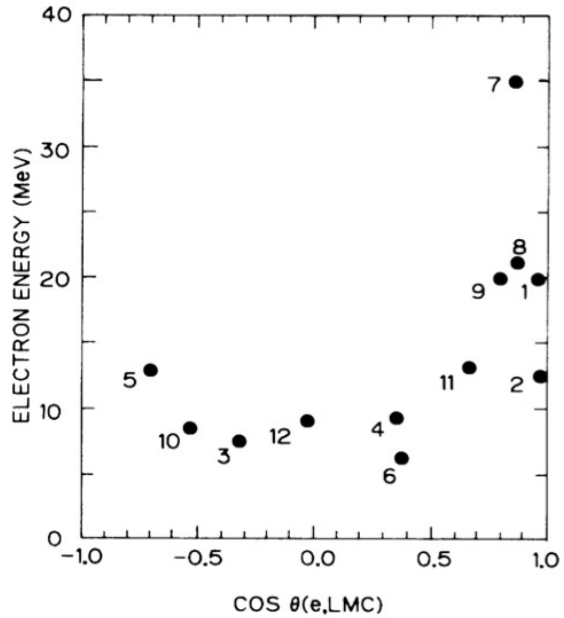
MM HIGHLIGHTS

SN 1987 A

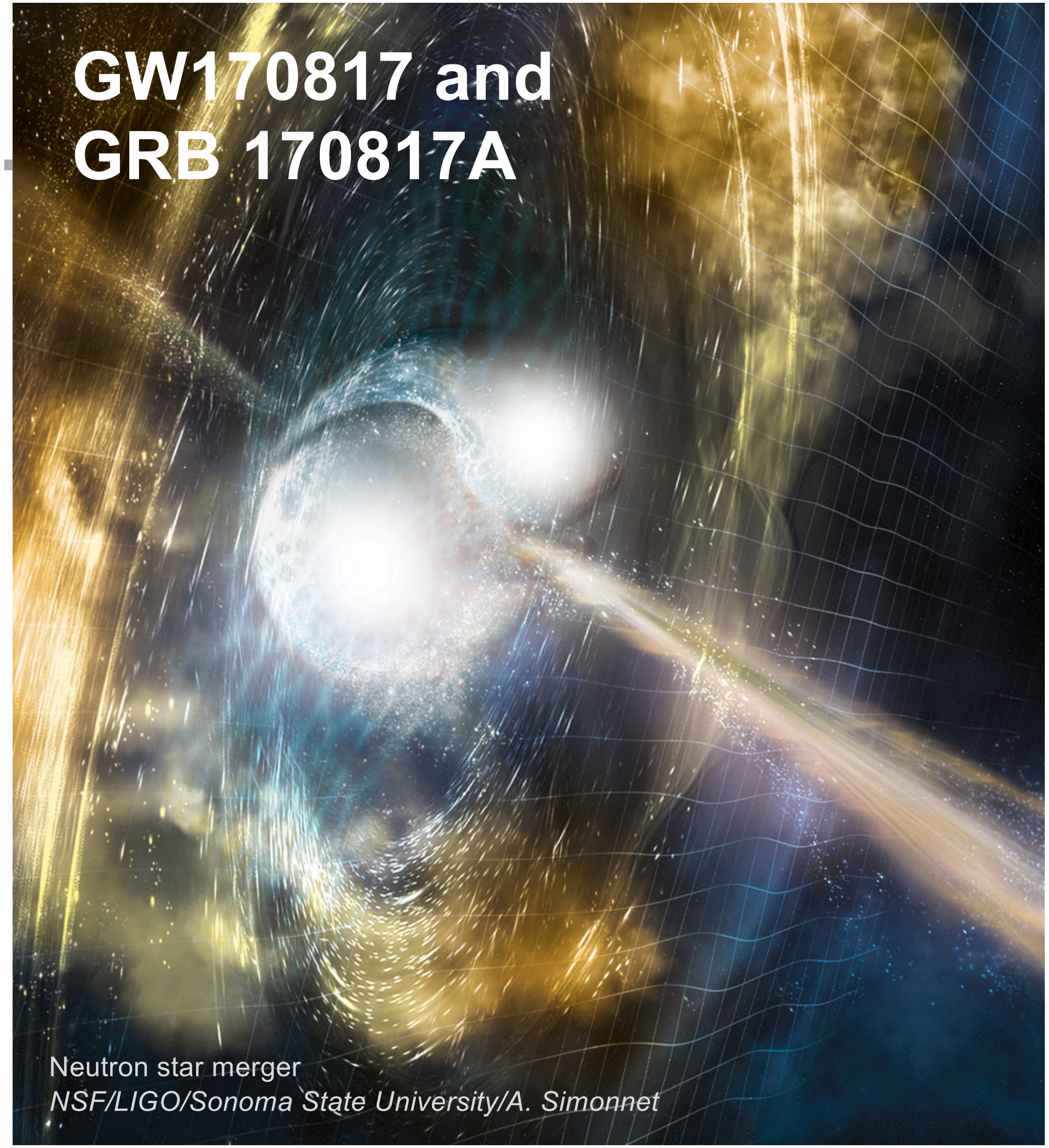
Anglo-Australian Observatory

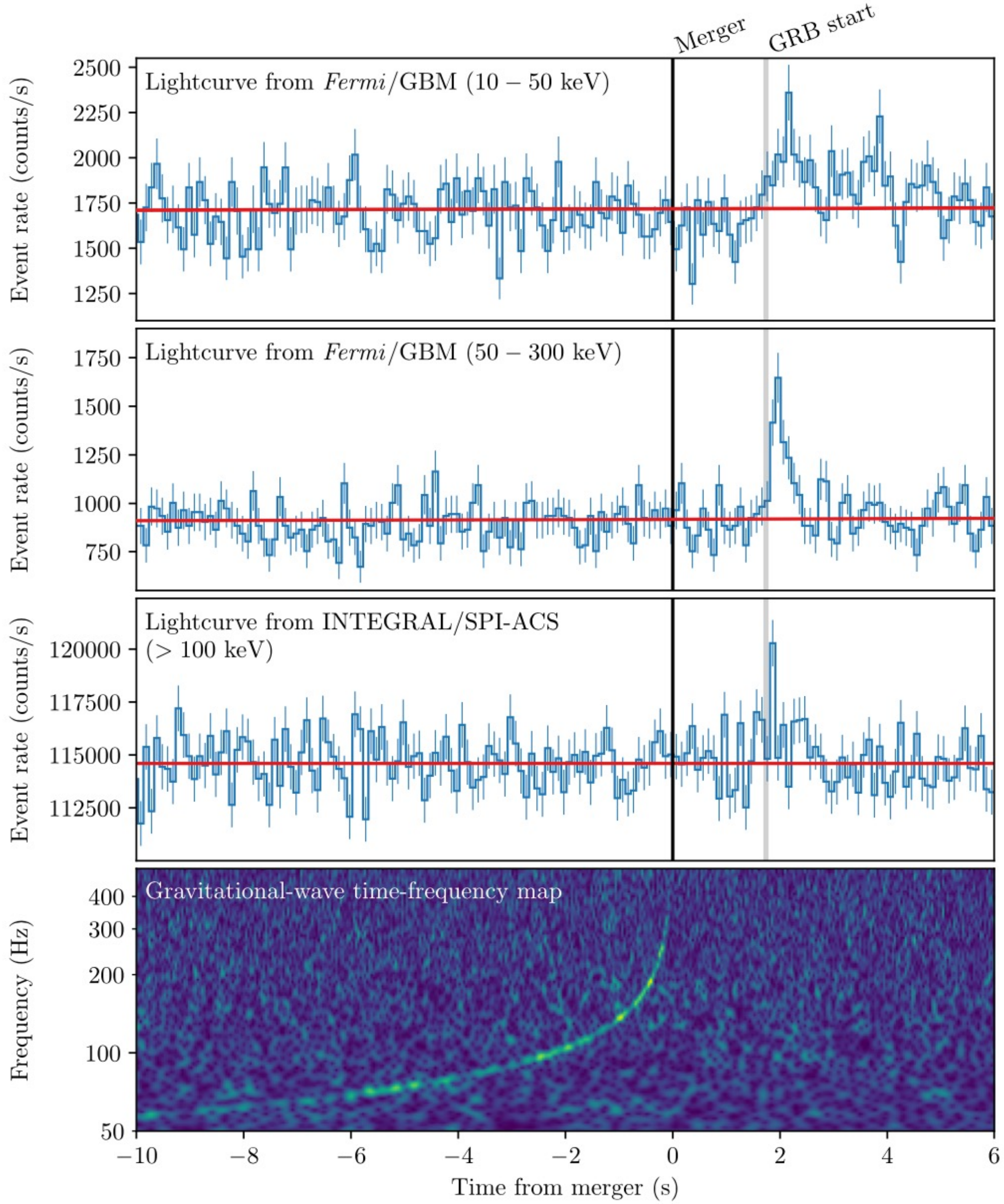


Speed of light and speed of neutrinos identical to one part in 10^8



Kamiokande II
Phys. Rev. Lett. 58 (1987) 1490


GW170817 and
GRB 170817A
Neutron star merger
NSF/LIGO/Sonoma State University/A. Simonnet


Merger
GRB start
Lightcurve from Fermi/GBM (10 – 50 keV)
Lightcurve from Fermi/GBM (50 – 300 keV)
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Gravitational-wave time-frequency map
Event rate (counts/s)
Frequency (Hz)
Time from merger (s)
2500
2250
2000
1750
1500
1250
1000
750
120000
117500
115000
112500
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6

GW170817 and GRB 170817A: Propagation

The observation of GW170817 and its electromagnetic counterpart implies that gravitational waves travel at the speed of light, with deviations smaller than a few ×10-15

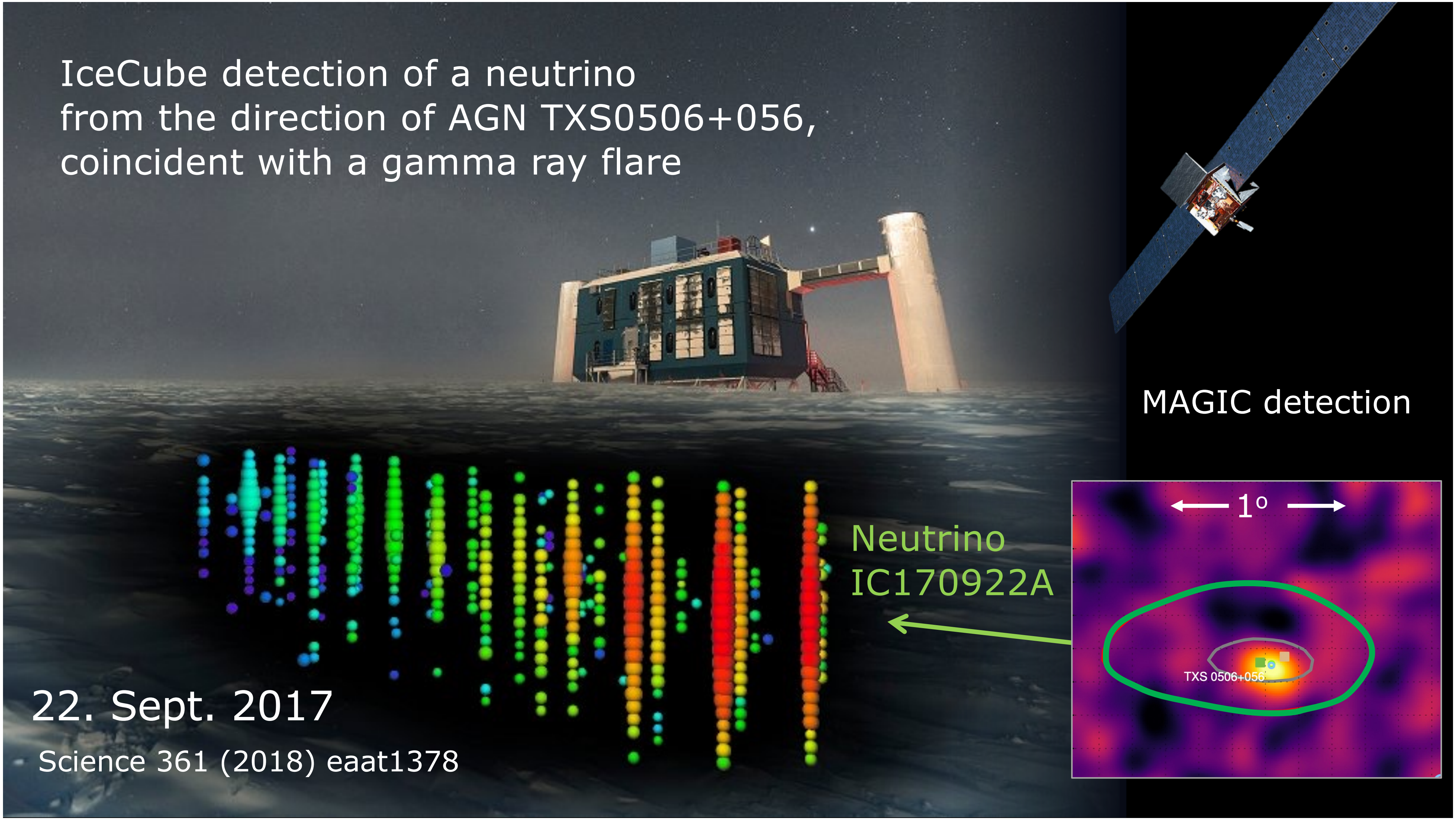
Constraining mass of the graviton with GW170817 (e.g. arXiv:2205:15432)

Improved constraints on H_0 Improved constraints on H0 (e.g. arXiv:1710.06426)

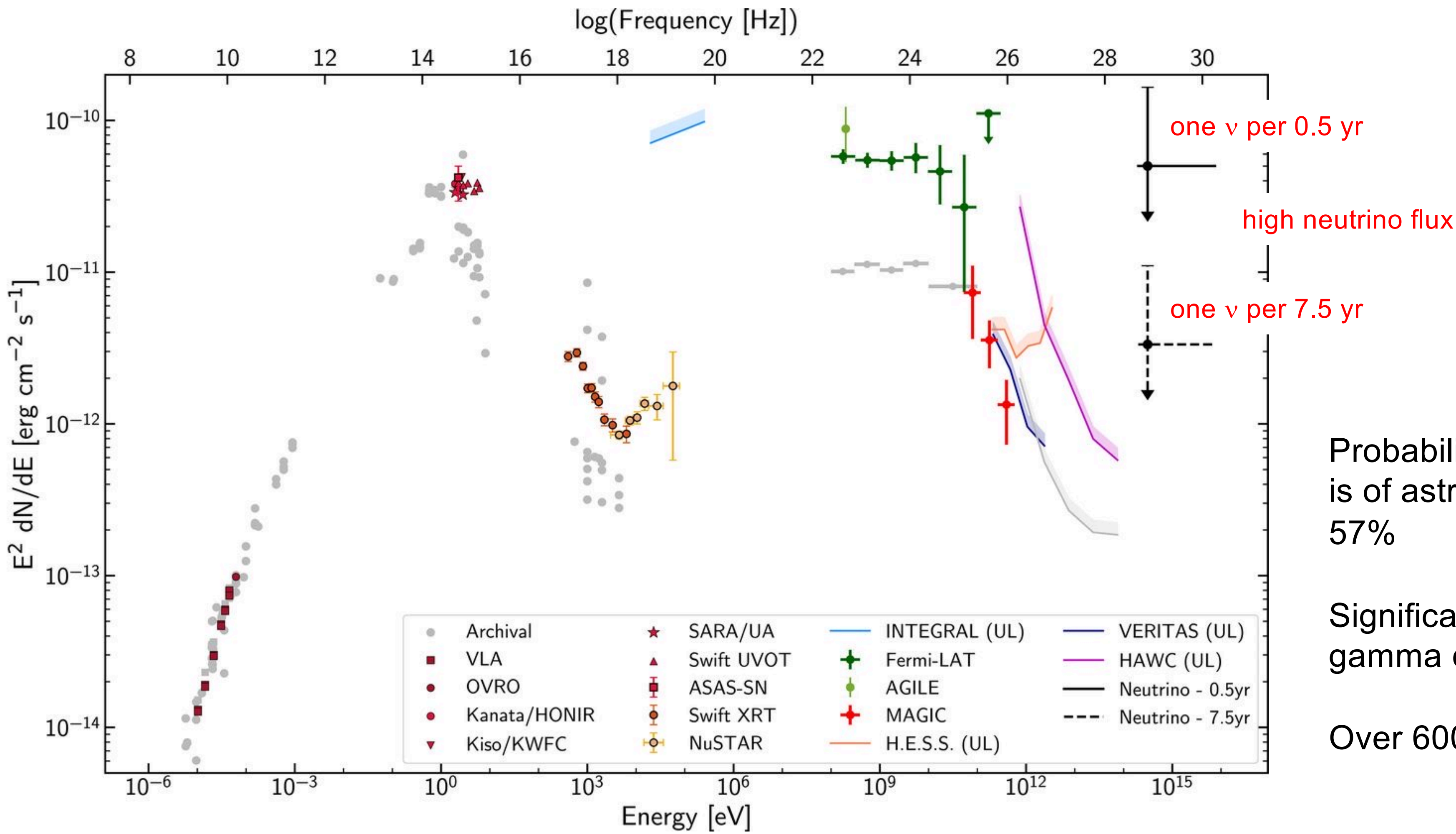
Tests of the weak equivalence principle from GW170817 (e.g. arXiv:1710.05860)

Limits on the number of spacetime dimensions from GW170817 (e.g. arXiv:1801.08160)

Implications for Dark Energy (e.g. arXiv:1710.0591)


IceCube detection of a neutrino
from the direction of AGN TXS0506+056,
coincident with a gamma ray flare
MAGIC detection
1°
Neutrino
IC170922A
TXS 0506+056
22. Sept. 2017
Science 361 (2018) eaat1378

TXS 0506+056



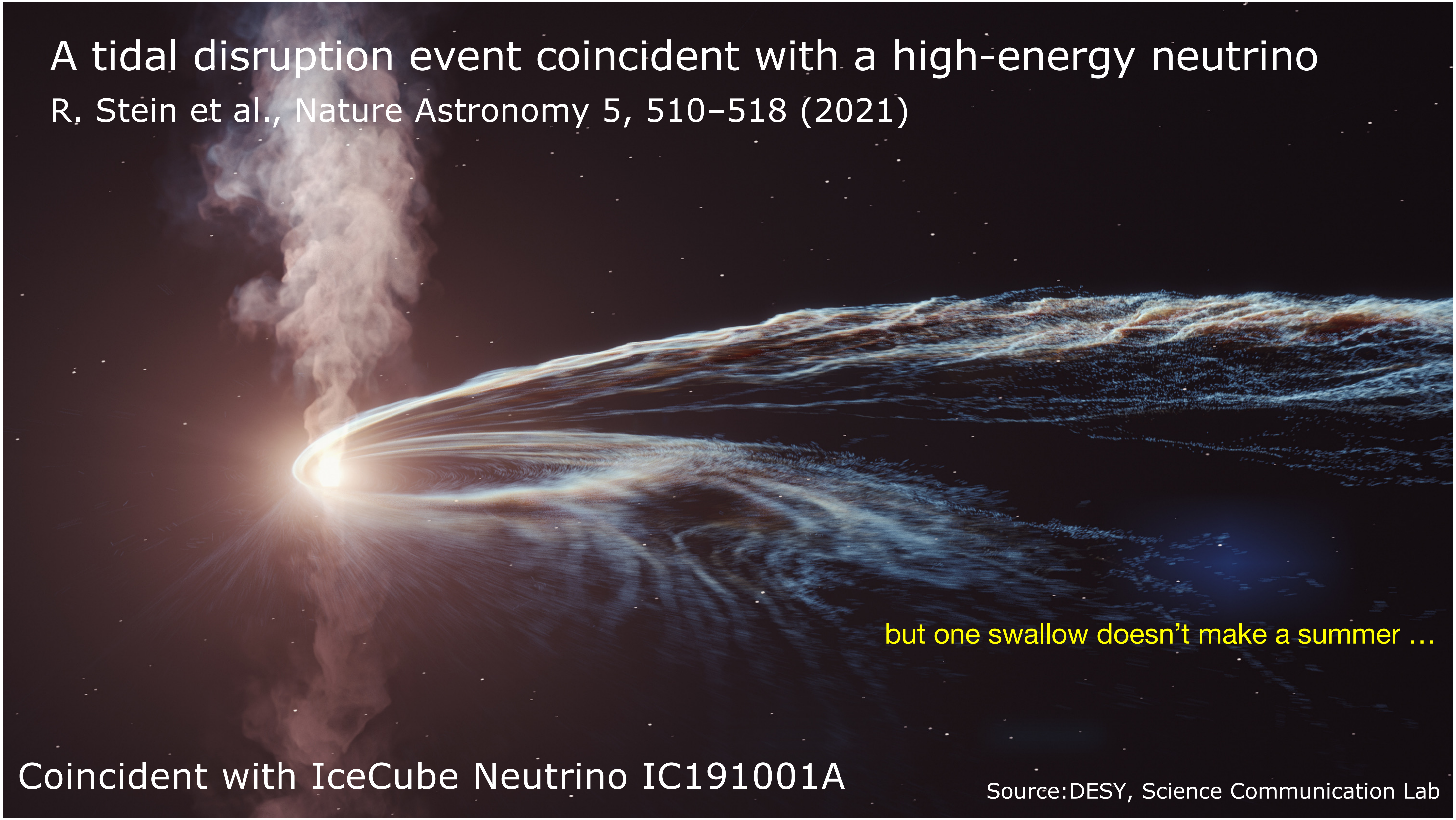
Probability that neutrino is of astrophysical origin: 57%

Significance of neutrino-gamma correlation: 3σ

Over 600 citations

A tidal disruption event coincident with a high-energy neutrino

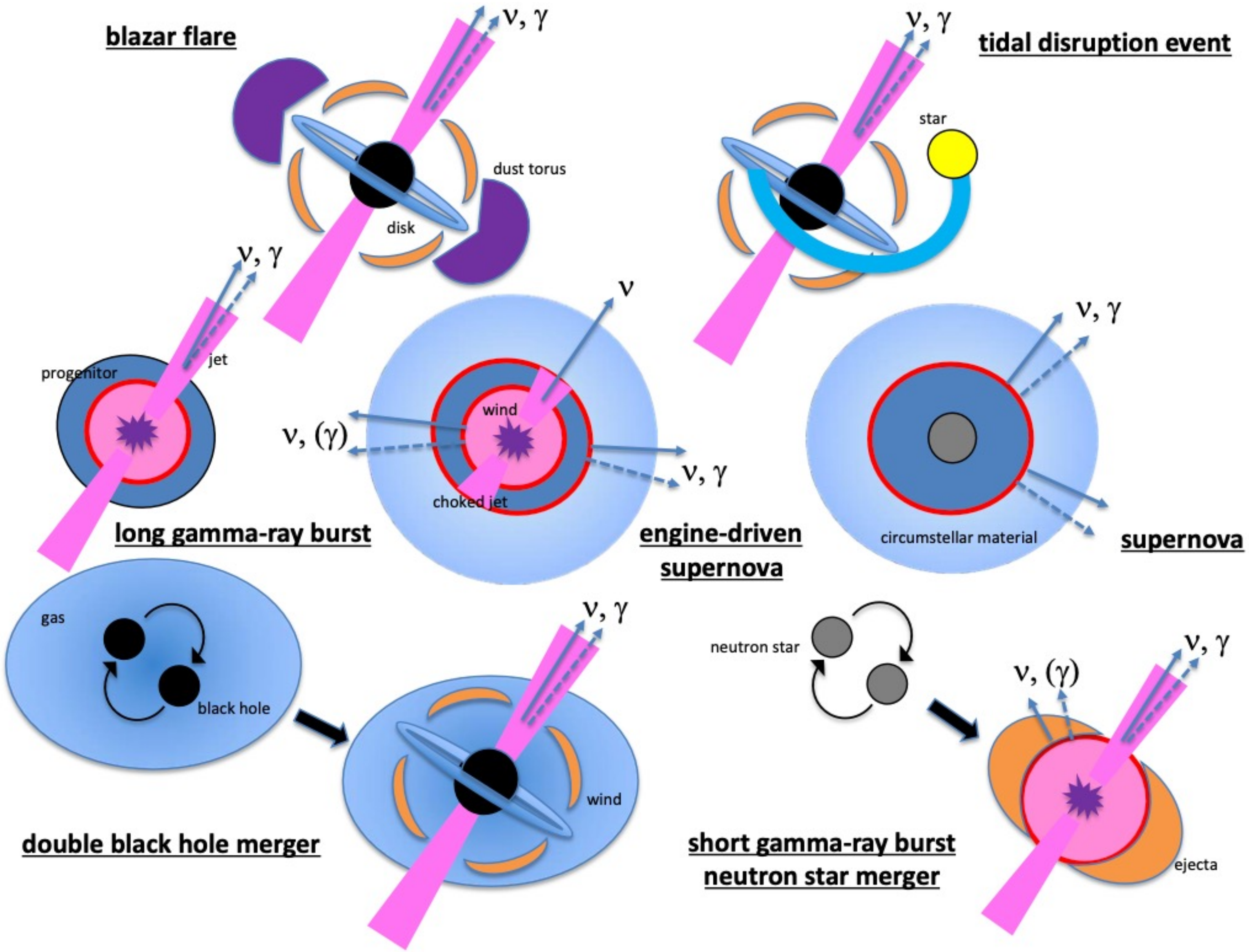
R. Stein et al., Nature Astronomy 5, 510–518 (2021)



but one swallow doesn't make a summer ...

Coincident with IceCube Neutrino IC191001A

Source:DESY, Science Communication Lab



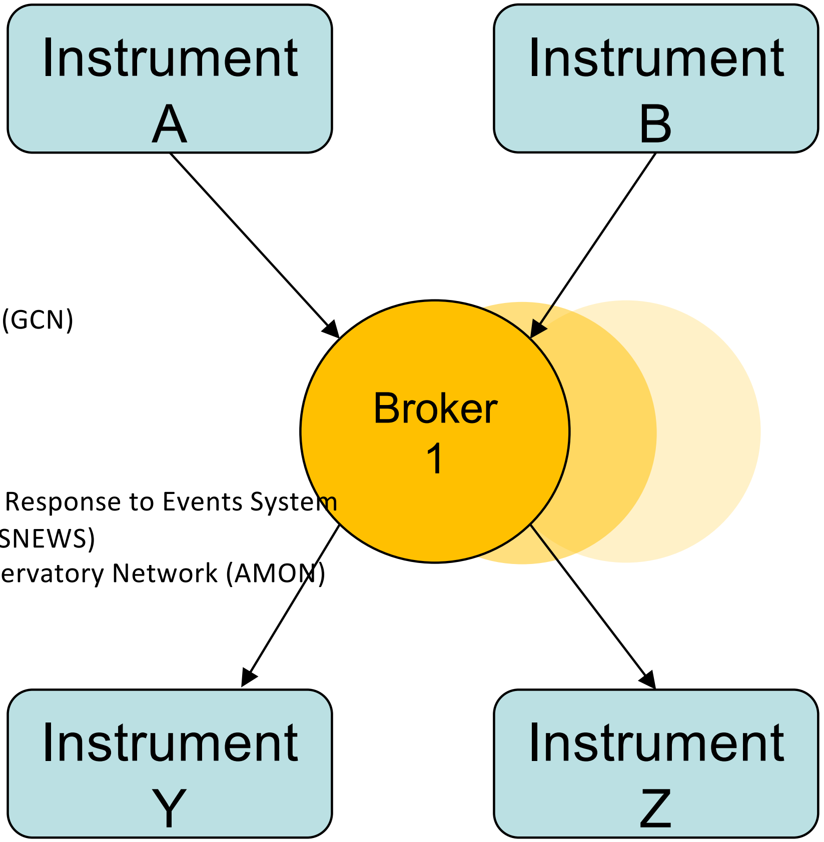
Schematic picture of various high-energy multi-messenger transients.

K. Murase, I. Bartos
Ann. Rev. Nucl. Part. Sci. 2019
arXiv:1907.12506

+ novae, …

THE AGE OF BROKERS

ALERT BROKERS

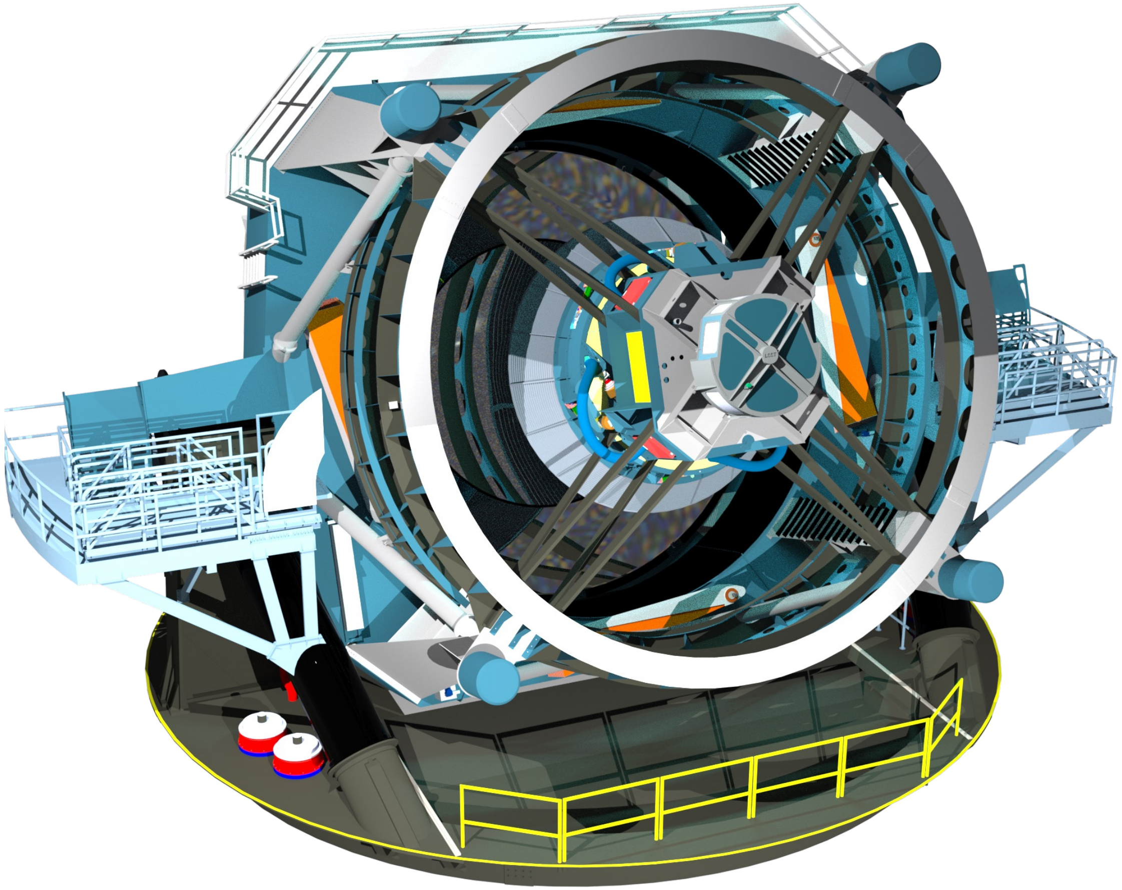


Gamma-Ray Coordinates Network (GCN)
Transient Name Server (TNS)
Astronomers' Telegram (ATEL)
VOEvent
Supernova Exchange (SNEx)
Arizona-NOAO Transient Alert and Response to Events System
Supernova Early Warning System (SNEWS)
Astrophysical Multimessenger Observatory Network (AMON)
…

Functions of brokers:

- (Re-)Distribution of alerts
- Format translation
- Classification and selective distribution of alerts from a given instrument
- Identification of coincidences between alerts
- Providing context for alerts (MWL/MM data base)

Extreme case: LSST



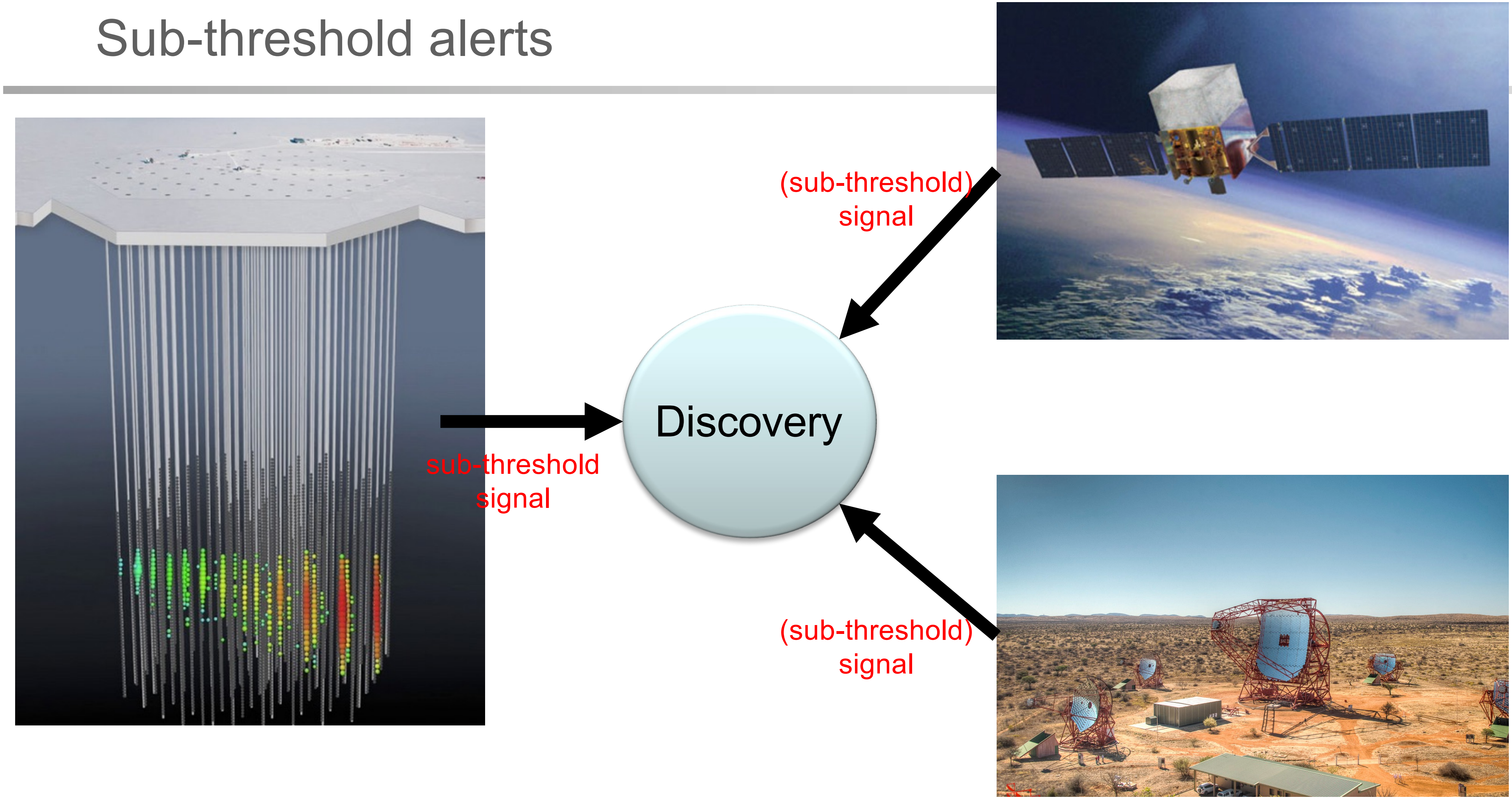
Up to 10^7 alerts per night (LSST DMTN-102)

Multiple brokers
for LSST alert stream,
e.g. FINK
(arXiv:2009.10185)

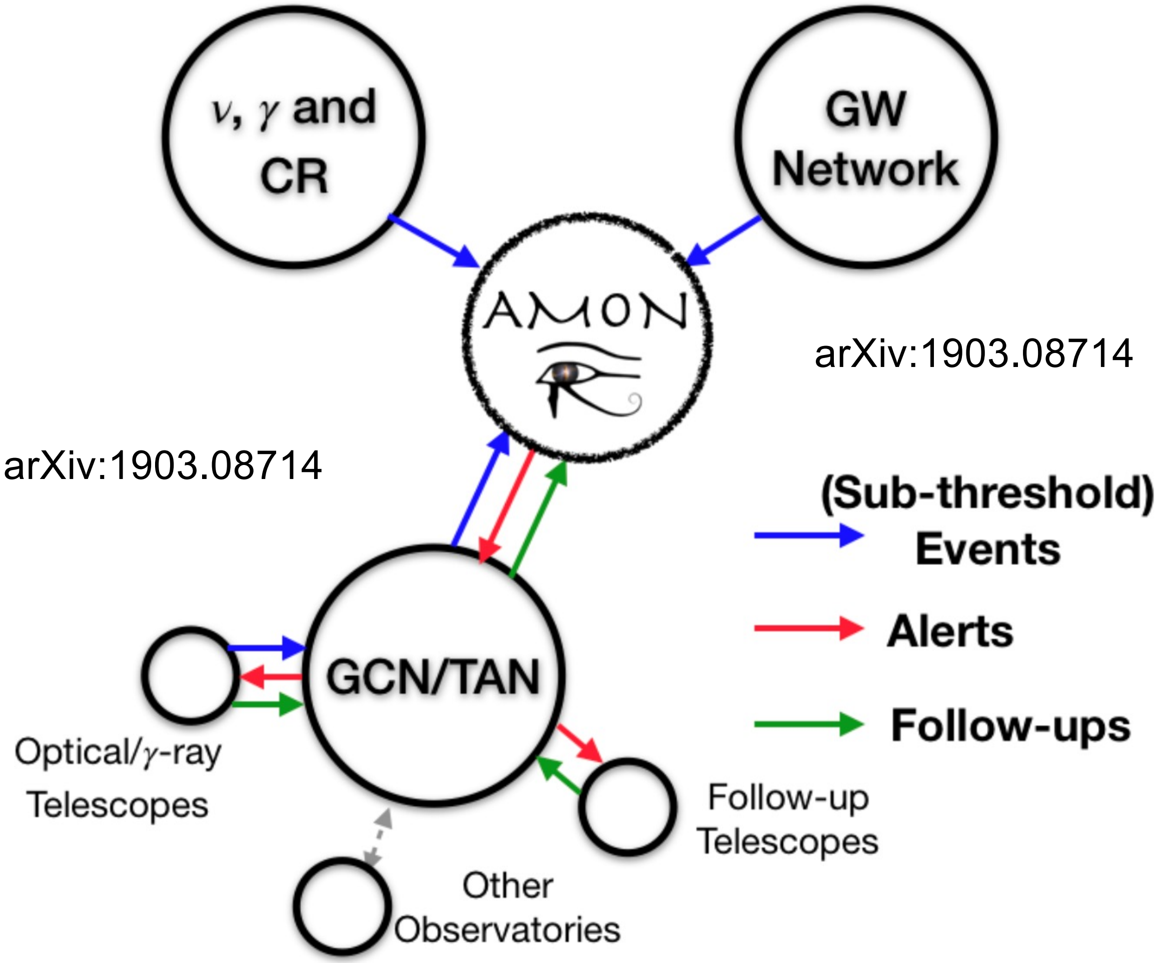
- Ingest the LSST alert stream
- Annotate alerts
  - Ingest continuously updated catalogues
  - Multi-wavelength and multi-messenger event cross-matches
  - Classify alerts within minutes
  - Early light-curve classification
  - Provide classification for a subset of science cases using deep learning and adaptive learning techniques
- Filter

Redistribute

Sub-threshold alerts

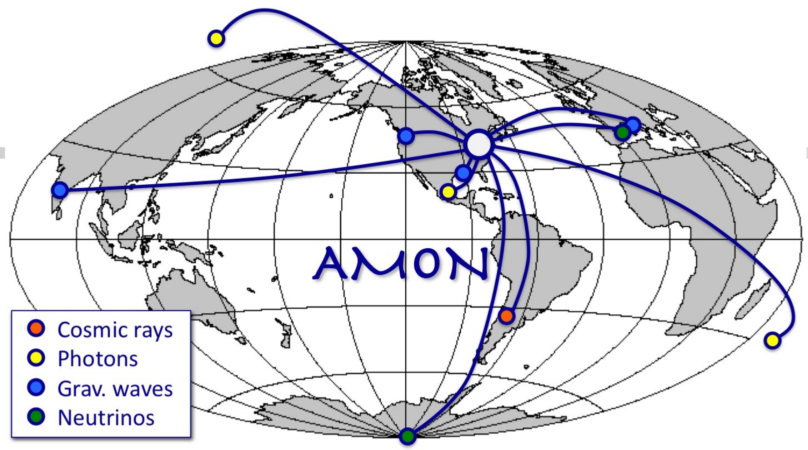


Sub-threshold alerts (e.g. AMON)



arXiv:1903.08714

arXiv:1903.08714



Perform coincidence searches of sub-threshold events of different observatories in real-time, and distribute prompt alerts to follow-up observatories.

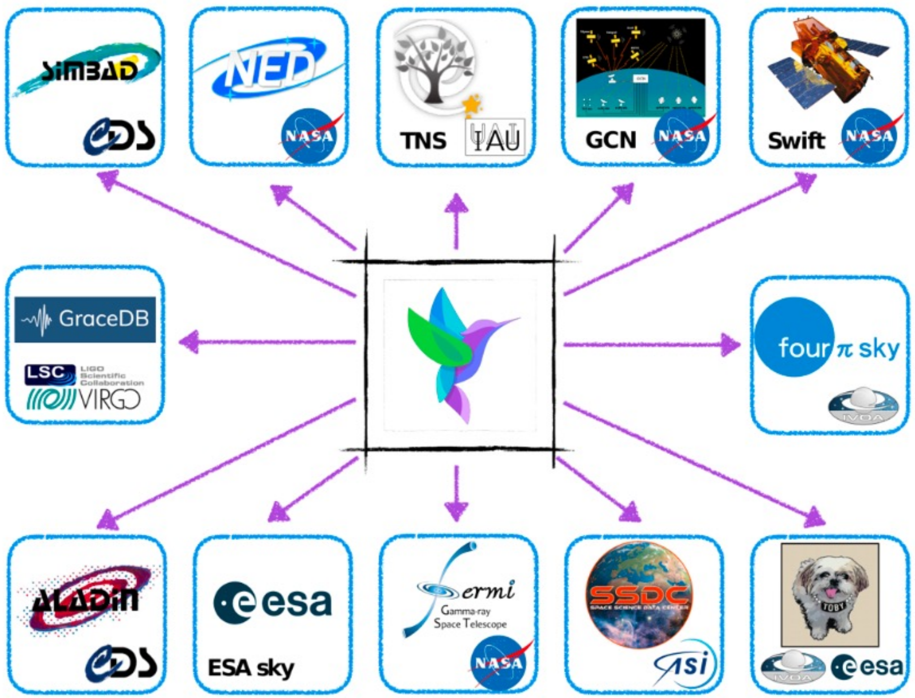
Receive events and broadcast them, through the Gamma- Ray Coordinates Network/Transient Astronomy Network (GCN/TAN.

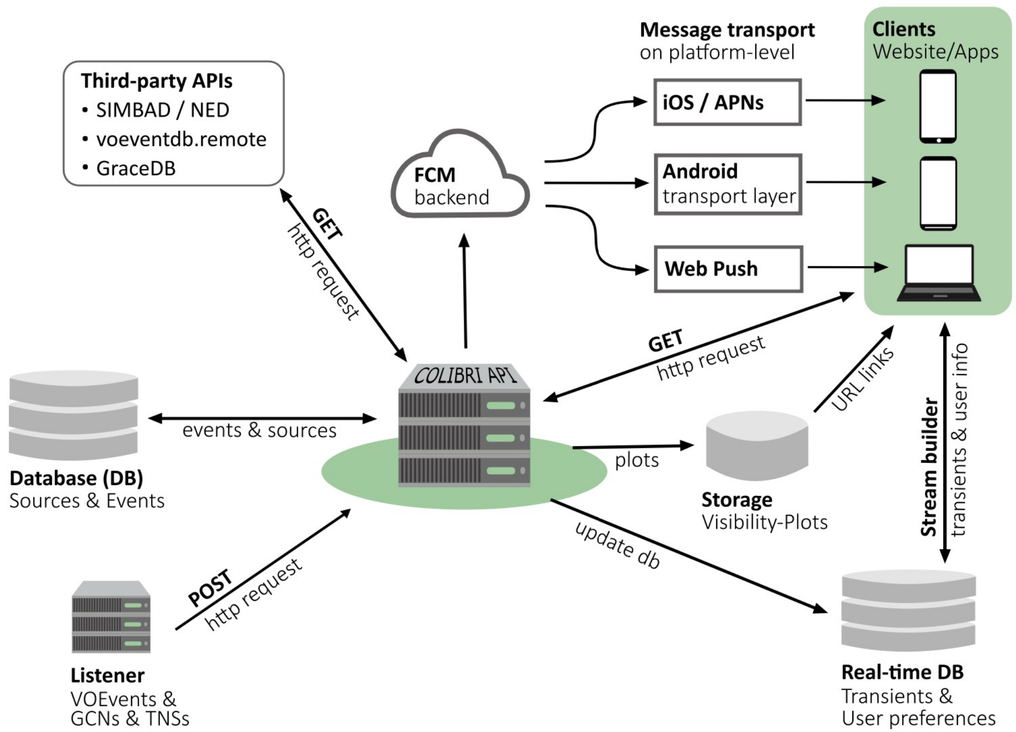
Store events into its database to perform archival coincidence searches.

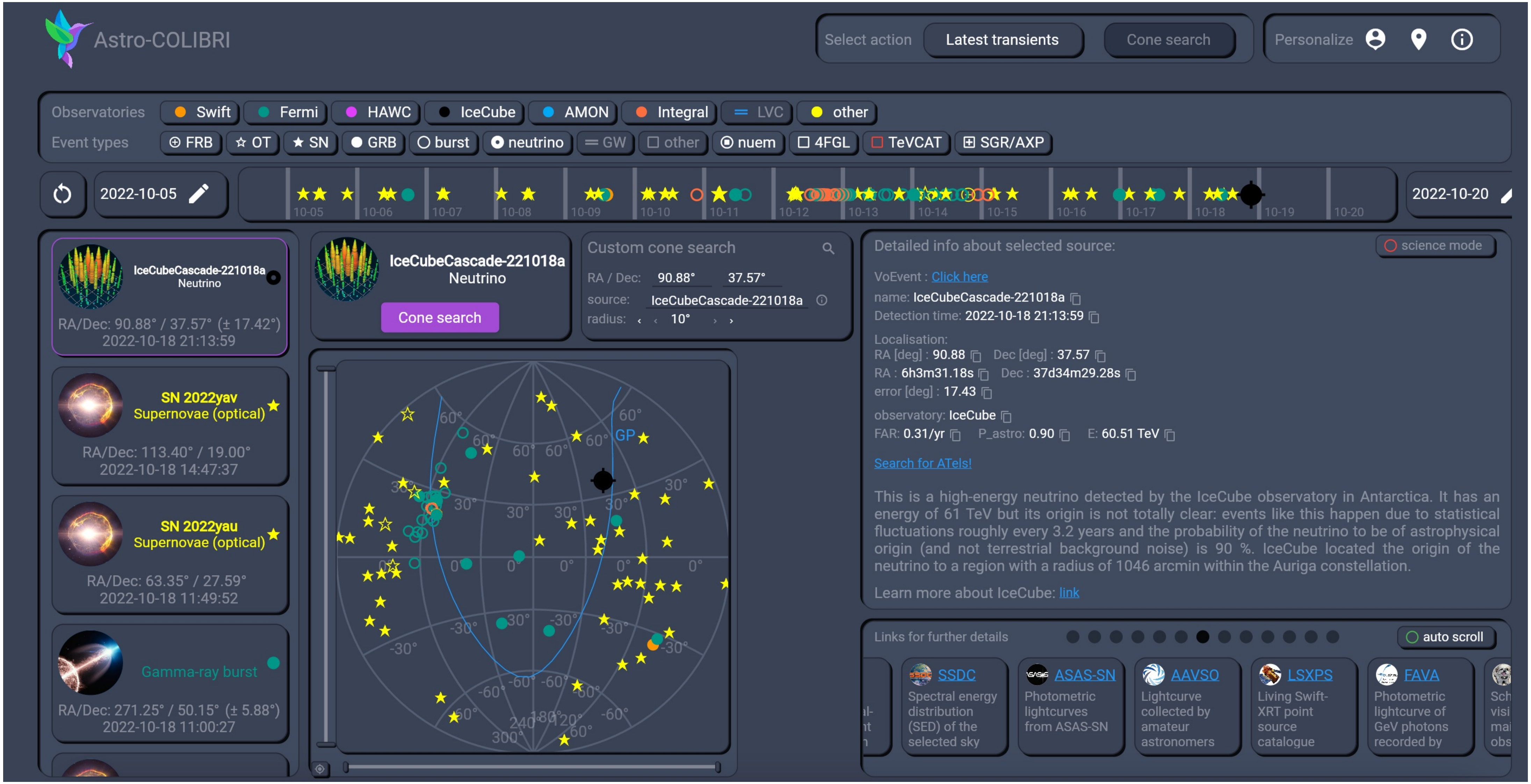
DATA RECOVERY & ANALYSIS FRAMEWORKS

EXAMPLE: ASTRO COLIBRI

arXiv:2109.01672







Astro-COLIBRI
Select action
Latest transients
Cone search
Personalize
Observatories
Swift
Fermi
HAWC
IceCube
AMON
Integral
LVC
other
Event types
FRB
OT
SN
GRB
burst
neutrino
GW
other
nuem
4FGL
TeVCAT
SGR/AXP
2022-10-05
2022-10-20
IceCubeCascade-221018a
Neutrino
RA/Dec: 90.88° / 37.57° (± 17.42°)
2022-10-18 21:13:59
SN 2022yav
Supernovae (optical)
RA/Dec: 113.40° / 19.00°
2022-10-18 14:47:37
SN 2022yau
Supernovae (optical)
RA/Dec: 63.35° / 27.59°
2022-10-18 11:49:52
Gamma-ray burst
RA/Dec: 271.25° / 50.15° (± 5.88°)
2022-10-18 11:00:27
IceCubeCascade-221018a
Neutrino
Cone search
Custom cone search
RA / Dec: 90.88° 37.57°
source: IceCubeCascade-221018a
radius: 10°
Detailed info about selected source:
science mode
VoEvent : Click here
name: IceCubeCascade-221018a
Detection time: 2022-10-18 21:13:59
Localisation:
RA [deg] : 90.88 Dec [deg] : 37.57
RA : 6h3m31.18s Dec : 37d34m29.28s
error [deg] : 17.43
observatory: IceCube
FAR: 0.31/yr P_astro: 0.90 E: 60.51 TeV
Search for ATels!
This is a high-energy neutrino detected by the IceCube observatory in Antarctica. It has an energy of 61 TeV but its origin is not totally clear: events like this happen due to statistical fluctuations roughly every 3.2 years and the probability of the neutrino to be of astrophysical origin (and not terrestrial background noise) is 90 %. IceCube located the origin of the neutrino to a region with a radius of 1046 arcmin within the Auriga constellation.
Learn more about IceCube: link
Links for further details
auto scroll
SSDC
Spectral energy distribution (SED) of the selected sky
ASAS-SN
Photometric lightcurves from ASAS-SN
AAVSO
Lightcurve collected by amateur astronomers
LXPS
Living Swift-XRT point source catalogue
FAVA
Photometric lightcurve of GeV photons recorded by

arXiv:1807.04780v1

Multi-messenger Astrophysics: Harnessing the Data Revolution

Gabrielle Allen[1], Warren Anderson[2], Erik Blaufuss[3], Joshua S. Bloom[4], Patrick Brady[2], Sarah Burke-Spolaor[5,6], S. Bradley Cenko[7,8], Andrew Connolly[9], Peter Couvares[10], Derek Fox[11], Avishay Gal-Yam[12], Suvi Gezari[13,8], Alyssa Goodman[14], Darren Grant[15], Paul Groot[16], James Guillochon[17], Chad Hanna[18], David W. Hogg[19,20], Kelly Holley-Bockelmann[21], D. Andrew Howell[22,23], David Kaplan[2], Erik Katsavounidis[24], Marek Kowalski[25,26], Luis Lehner[27], Daniel Muthukrishna[28], Gautham Narayan[29], J.E.G. Peek[29,30], Abhijit Saha[29], Peter Shawhan[3,8], and Ignacio Taboada[31]

"We argue, therefore, that the time is ripe for the community to conceive and propose an Institute for Multi-Messenger Astrophysics that would coordinate its resources in a sustained and strategic fashion to efficiently address these challenges …"

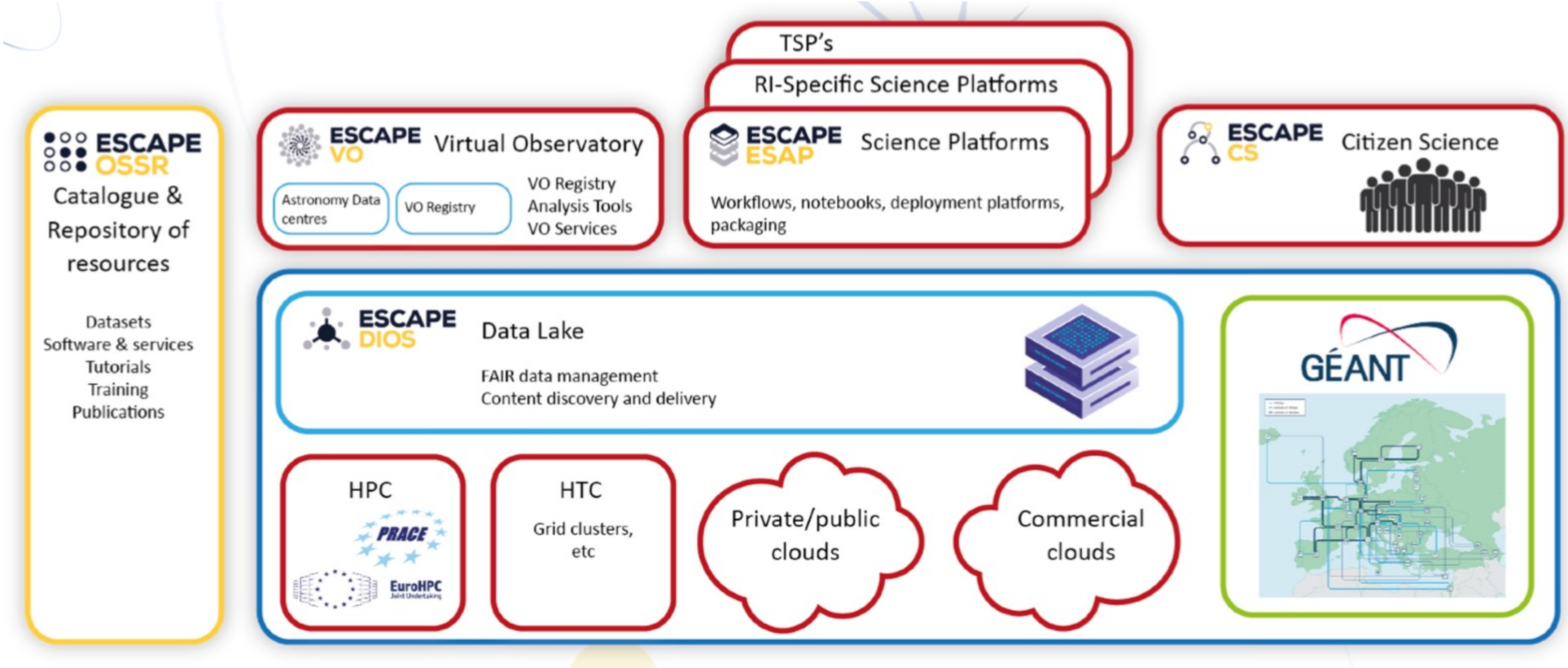
ESCAPE

European Science Cluster of Astronomy & Particle physics ESFRI research Infrastructures

ESAP
The ESCAPE ESFRI Science Analysis Platform

John D. Swinbank — swinbank@astron.nl

ESCAPE - The European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement n° 824064.


ESCAPE OSSR
Catalogue & Repository of resources
Datasets
Software & services
Tutorials
Training
Publications
ESCAPE VO
Virtual Observatory
Astronomy Data centres
VO Registry
VO Registry
Analysis Tools
VO Services
TSP's
RI-Specific Science Platforms
ESCAPE ESAP
Science Platforms
Workflows, notebooks, deployment platforms, packaging
ESCAPE CS
Citizen Science
ESCAPE DIOS
Data Lake
FAIR data management
Content discovery and delivery
GÉANT
HPC
PRACE
EuroHPC
HTC
Grid clusters, etc
Private/public clouds
Commercial clouds

Transients 2020
3 – 7 February 2020 • Cape Town
Program
Participants
Kavli-IAU Workshop
International co-ordination of multi-messenger transient observations in the 2020s and beyond
FIND OUT MORE
NASA/CXC/M. Weiss

International Coordination of Multi-Messenger Transient Observations in the 2020s and Beyond

Kavli-IAU White Paper

arXiv:2007.05546

S. Bradley Cenko[1] (co-chair), Patricia A. Whitelock[2] (co-chair), Laura Cadonati[3], Valerie Connaughton[4], Roger Davies[5], Rob Fender[5], Paul J. Groot[6], Mansi M. Kasliwal[7], Tara Murphy[8], Samaya Nissanke[9], Alberto Sesana[10], Shigeru Yoshida[11] and Binbin Zhang[12]

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[2] South African Astronomical Observatory, P.O. Box 9, Observatory, 7935 Cape Town, South Africa; Department of Astronomy, University of Cape Town, 7701 Rondebosch, South Africa
[3] Georgia Institute of Technology, USA

Bottlenecks identified:

1. Transient Alerts and Communication
2. Data Policies
3. Follow-Up Spectroscopy
4. Telescope Coordination
5. International Funding and Collaboration
6. Target-of-Opportunity Implementation
7. Theoretical and Computational Resources
8. Diversity, Equity, Inclusion and Workforce Development

Transient alerts and communication

- **Upgrades to the GCN** system. **Automated name server** to correlate events found by different facilities and/or at different wavelengths; increased **machine-readability** for GCN Circulars; and a means to query results based on source, position, and/or time
- Similar **notification capabilities for X-ray** (e.g., SRG/eROSITA, Einstein Probe) and **radio** (e.g., MeerKAT, ASKAP, SKA) transients
- **Standards** are critical for heterogeneous nodes in the transient/multi-messenger ecosystem to communicate efficiently and effectively. Recommend that the transient/multi-messenger community work with the International Virtual Observatory Alliance (IVOA) to build its standards.
- Establish with journals **uniform standards for data reportin**g on transient and multi-messenger sources

Data policies

Open Access to data & importance of limited data proprietary periods for the effective follow-up of transients and other time-critical observations

Data should be **FAIR** (findable, accessible, interoperable, and reusable). Good archives and supporting software are thus essential; e.g. high-level data products in a queryable database

Large projects in the USA and Europe should pay particular care towards supporting **open data policies**, to serve as examples for developing facilities in other countries

OPPORTUNITIES

- using the maximum available information to understand high-energy processes

BUT ALSO MUCH HYPE …

and (to quote an ESO director)
“most of the information about the Universe still reaches us in form of photons”

CHALLENGES

- Bringing quite different communities together
- Coordination, MoUs, …
- Trigger distribution and trigger selection
- Finding & combining data
- Efficient analysis tools
- Theory & simulation tools
- Papers & authorship