Gamma-ray astronomy

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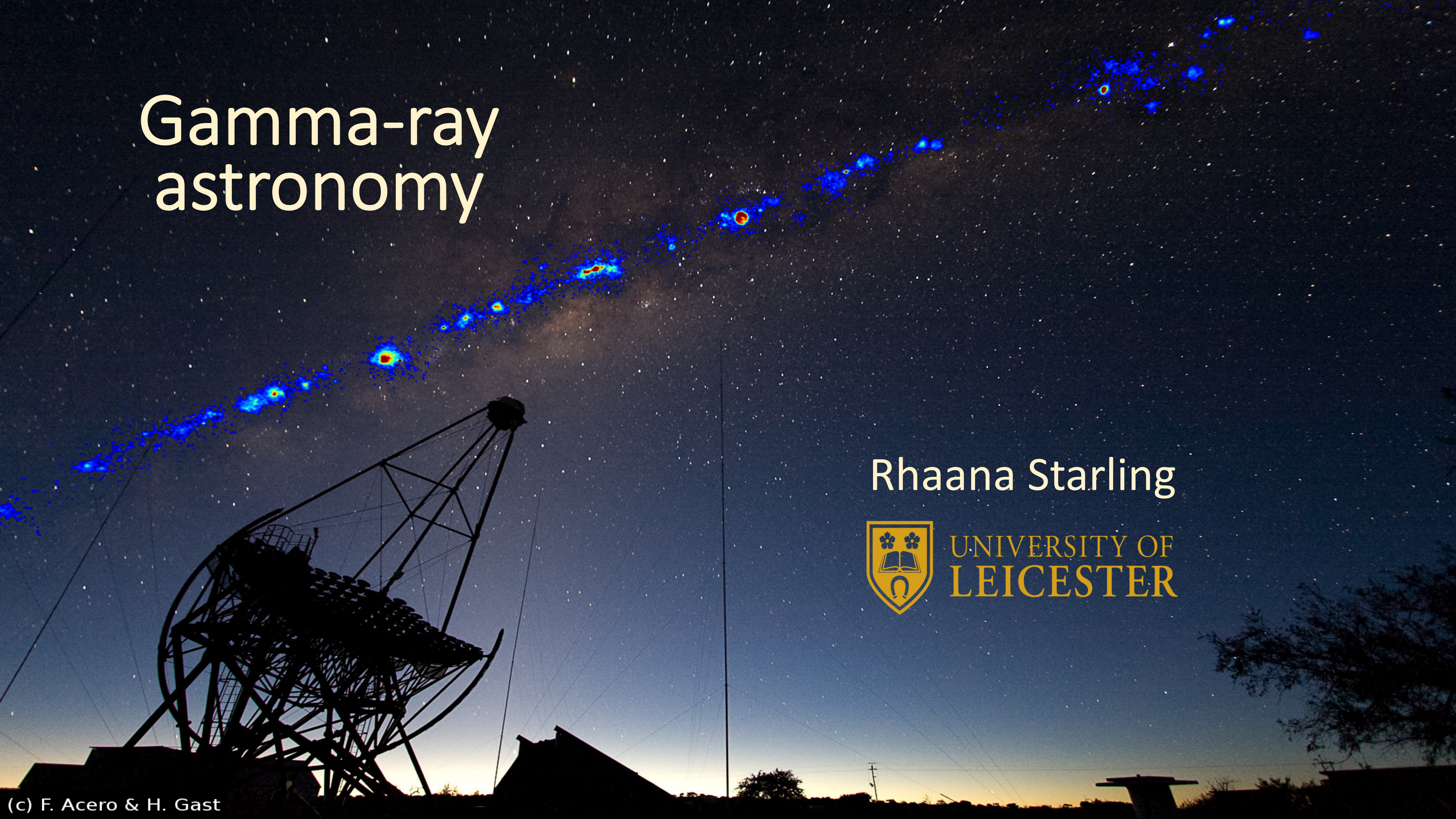
UNIVERSITY OF LEICESTER

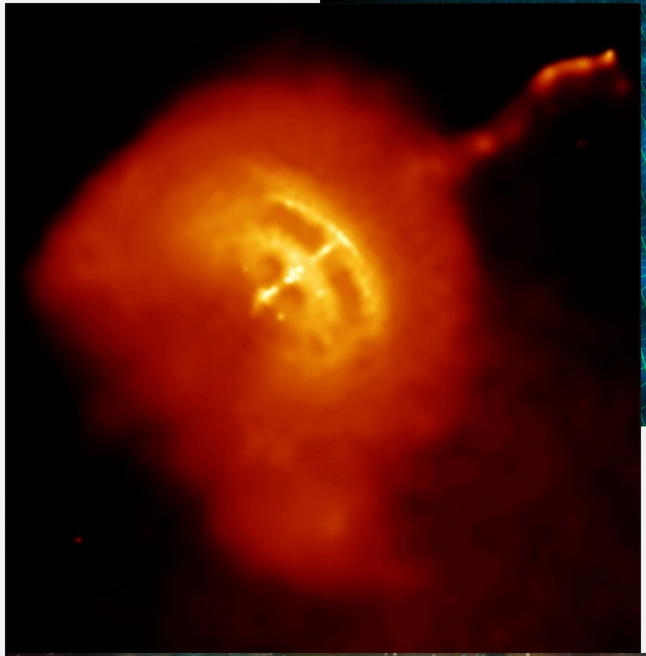


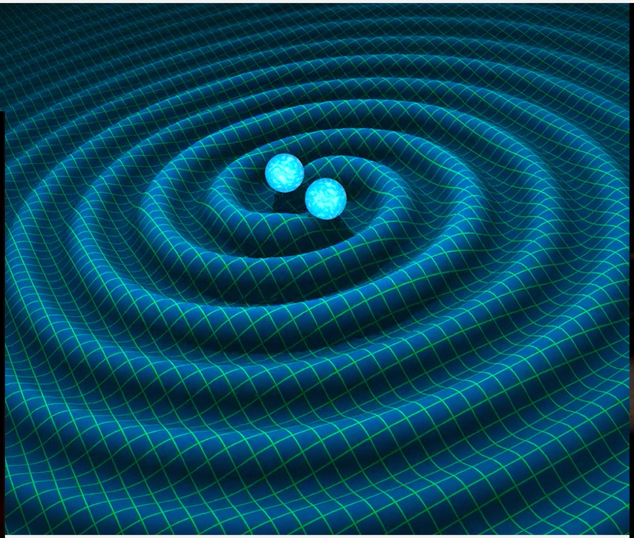
(c) F. Acero & H. Gast

Gamma-ray astronomy – a quick tour

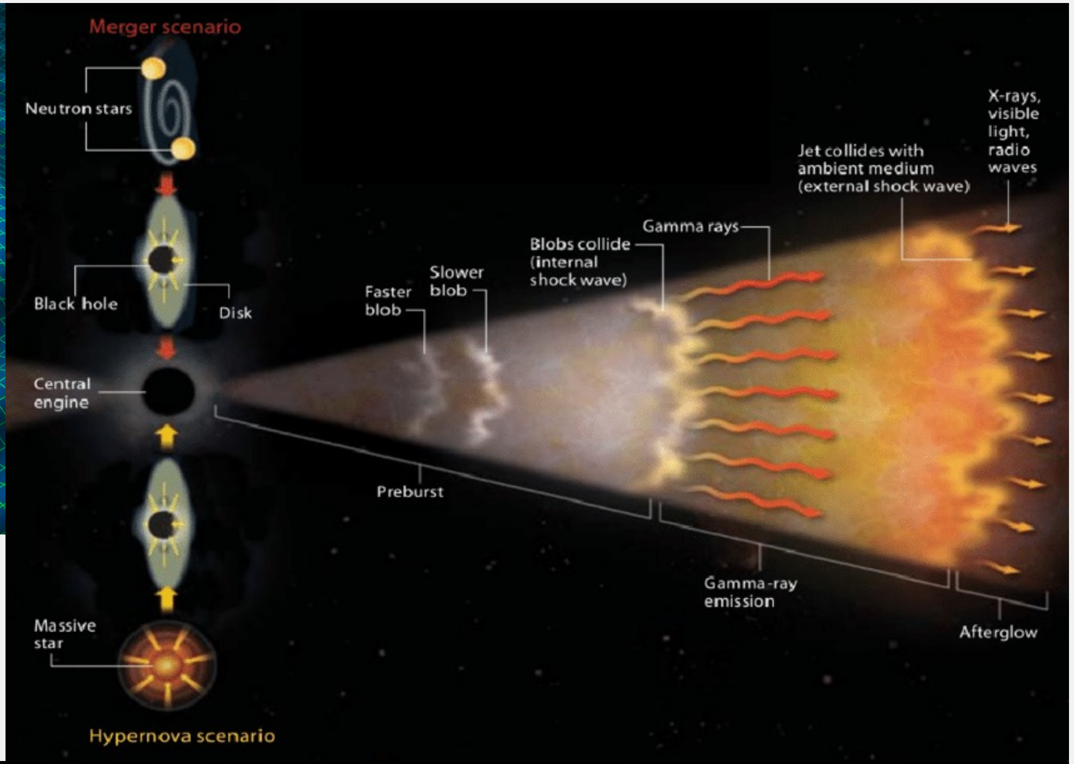
- Astrophysical gamma-ray production: sites and mechanisms
- Detection GeV – MeV – TeV, ground and space
- Absorption of extragalactic signals
- Blazars: synchrotron, inverse Compton and neutrinos
- Gamma-ray bursts: synchrotron, inverse Compton and gravitational waves
- Radioactive decay gamma-rays
- Positron annihilation gamma-rays
- Future outlook: the Cherenkov Telescope Array

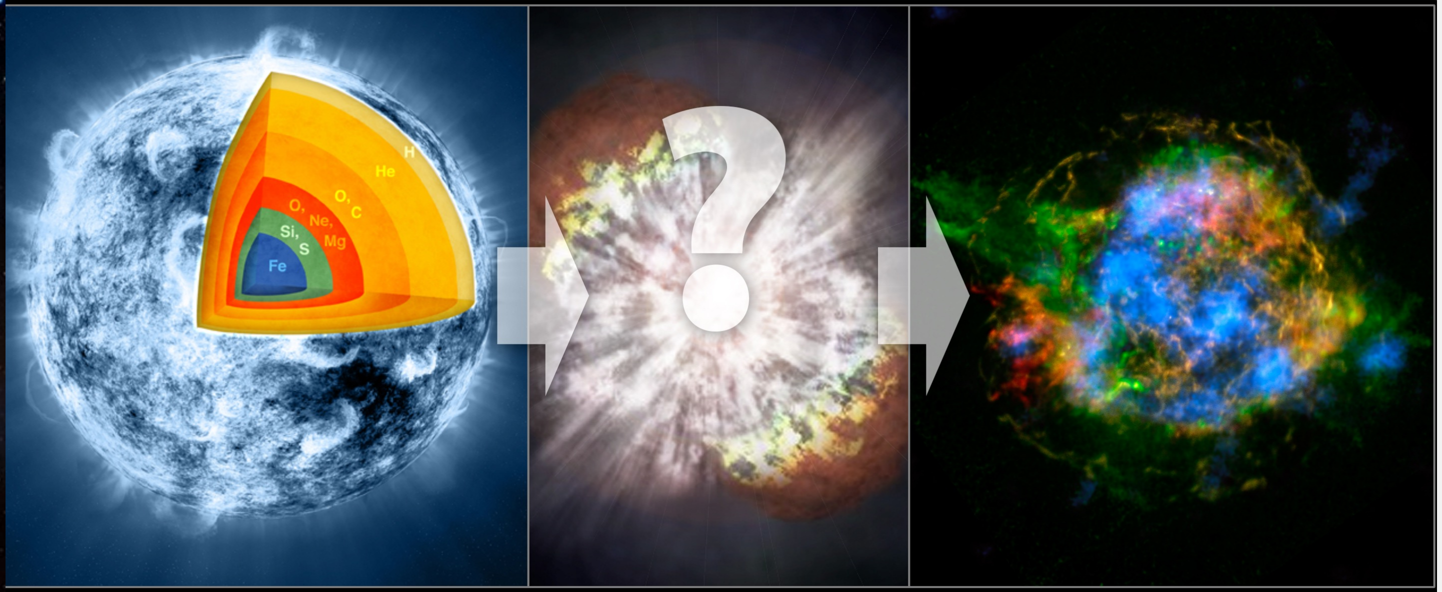
Credits:
NASA/ESA/LIGO/
CXC/HESS

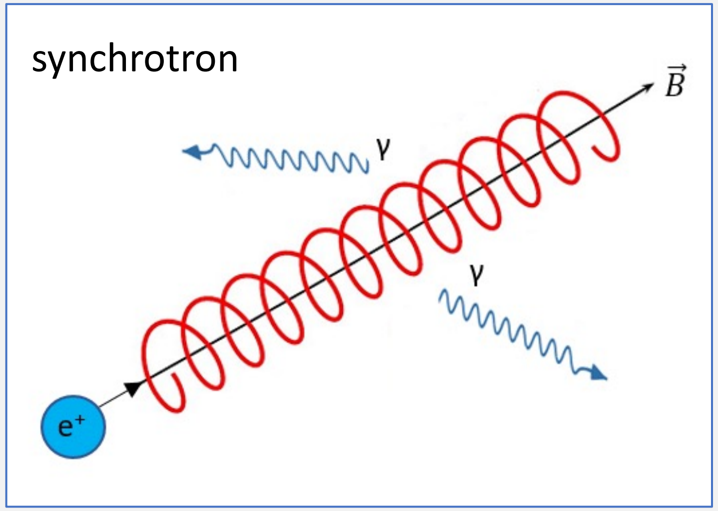


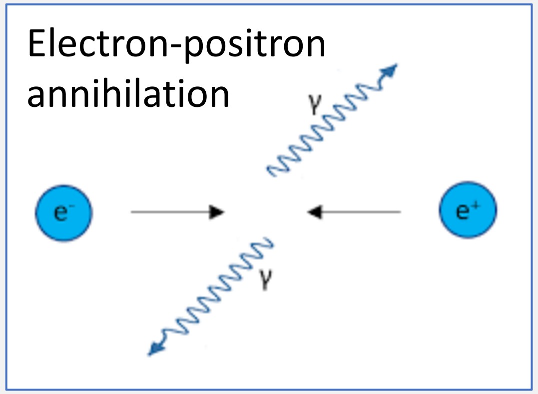


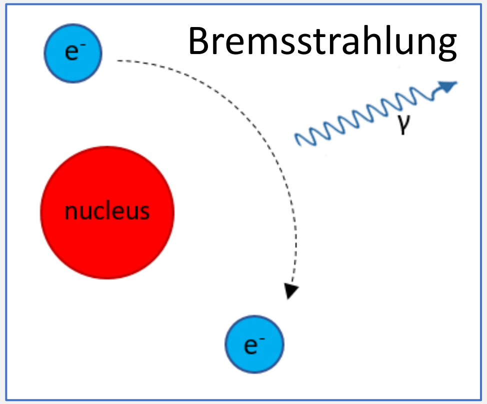
Cosmic particle accelerators across the Universe



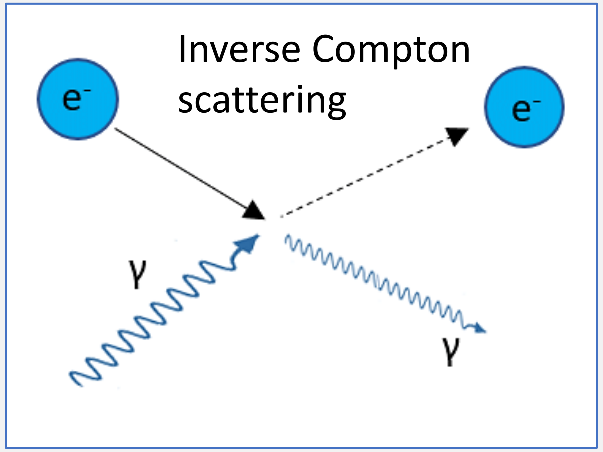


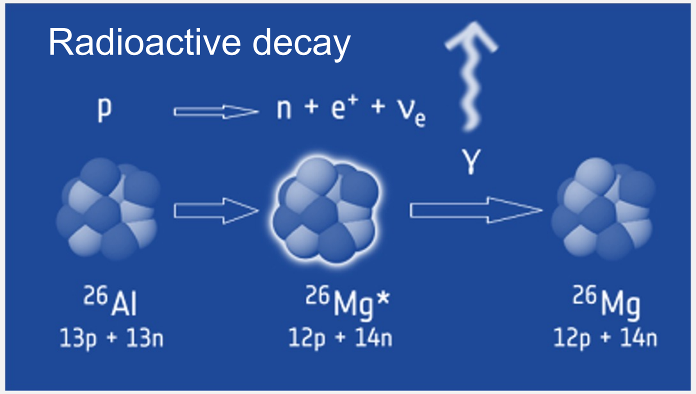






Probing different gamma-ray production processes





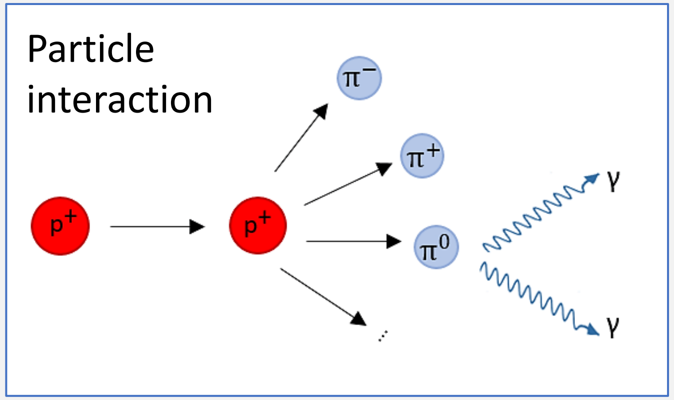
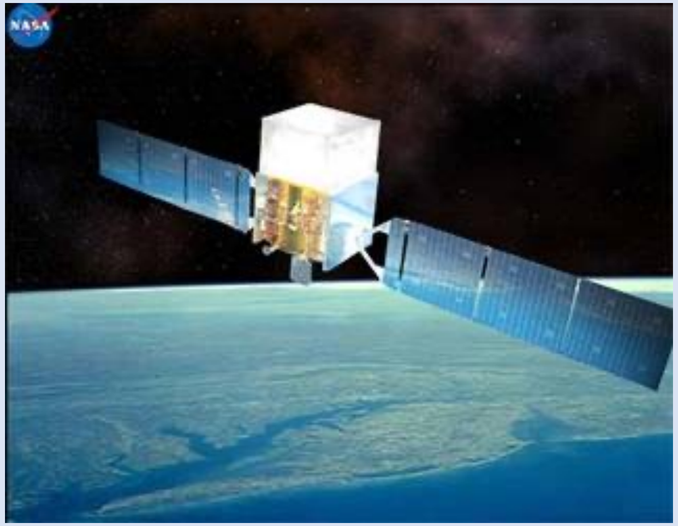


Image credits:
Pecimotika 2018 / ESA

Detection methods

Space

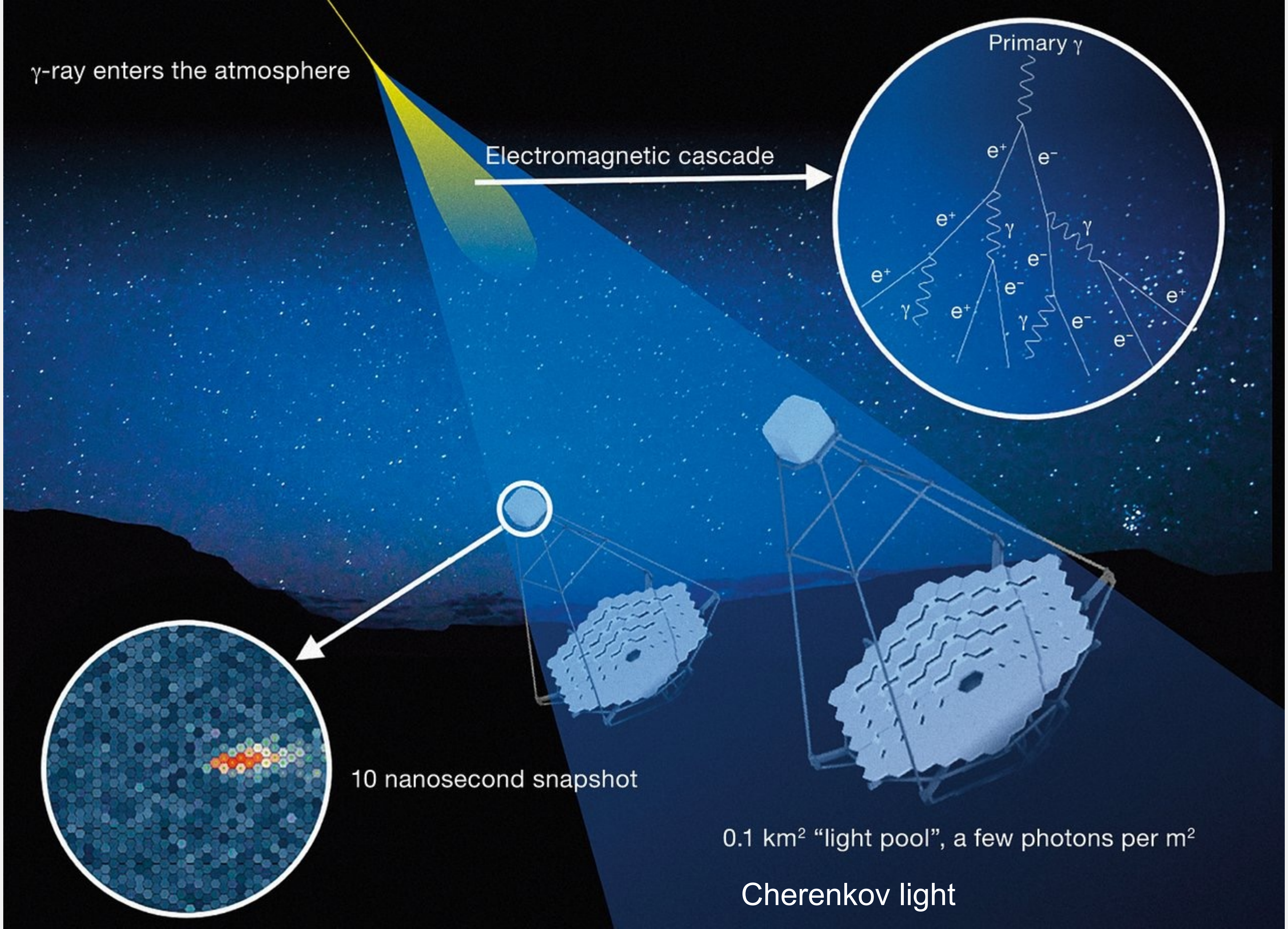
- GeV - MeV
- Pair conversion
- eg CGRO (1991-2000), AGILE, Fermi-LAT



Ground

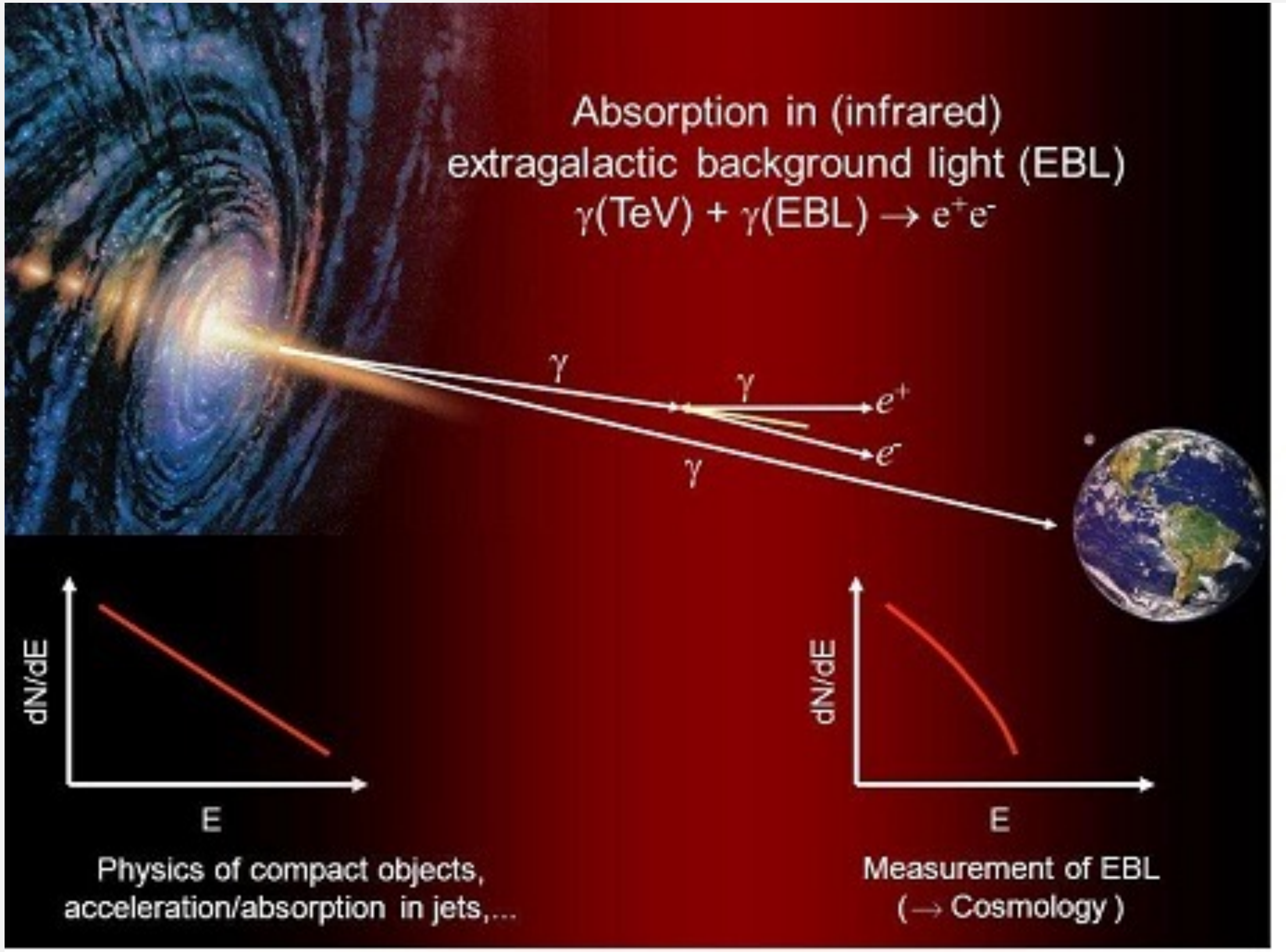
- GeV – TeV
- Imaging atmospheric cherenkov
- eg H.E.S.S., MAGIC, VERITAS, CTA
- >10 TeV
- water cherenkov
- eg HAWC, LHAASO

IACT



Credit:
CTA project

Challenges for distant sources



Credit: HAGAR project, R Martin Raue 2011

Early Universe = longer path length

interaction with photons along the path → absorbed

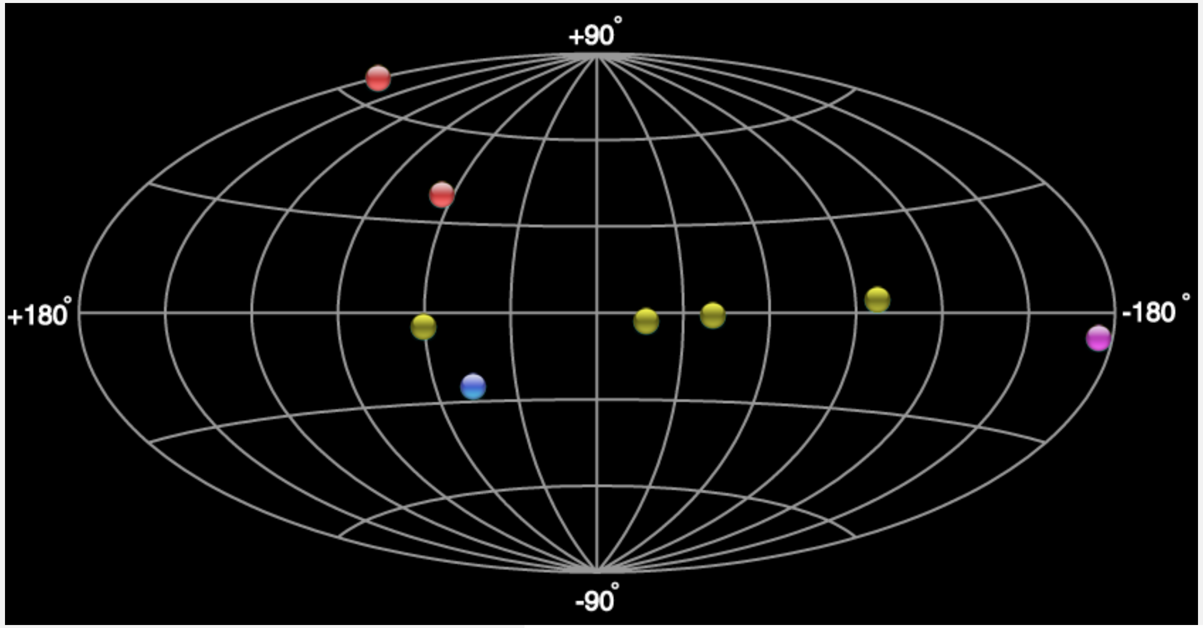
"extragalactic background light" reduces radiation received

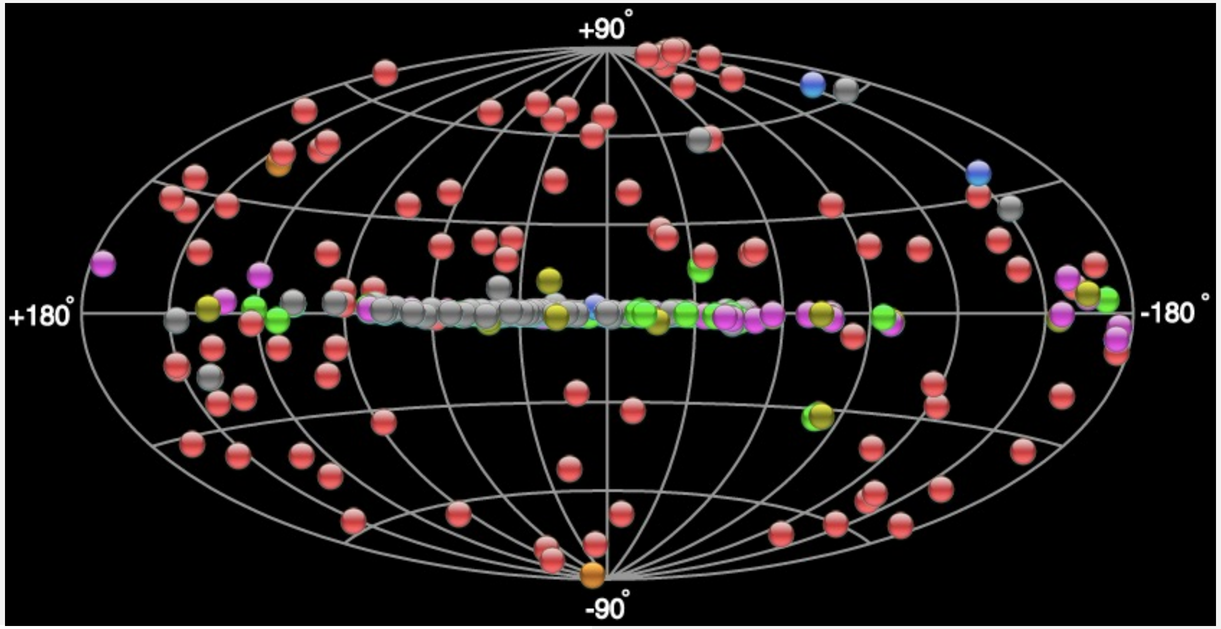
Limits volume of Universe probed

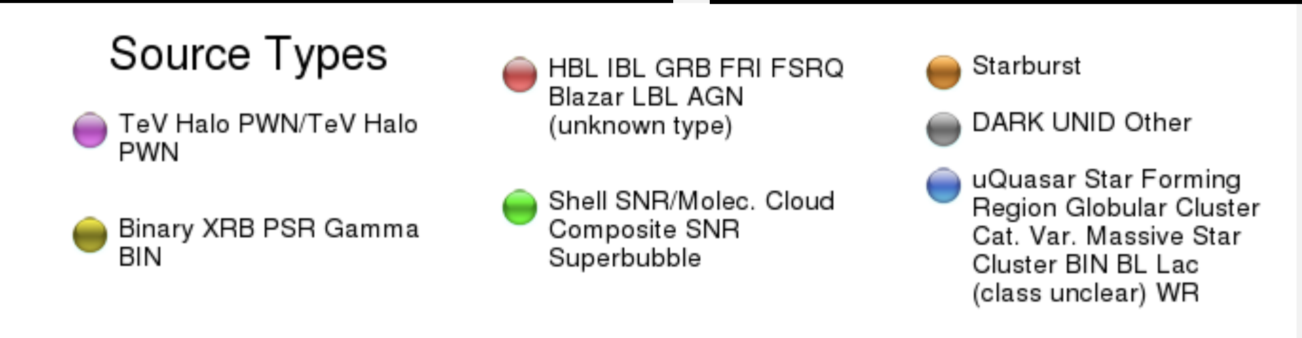
Detections > 100 GeV

TeVCat 1996 → TeVCat March 2022

8 sources → 251 sources







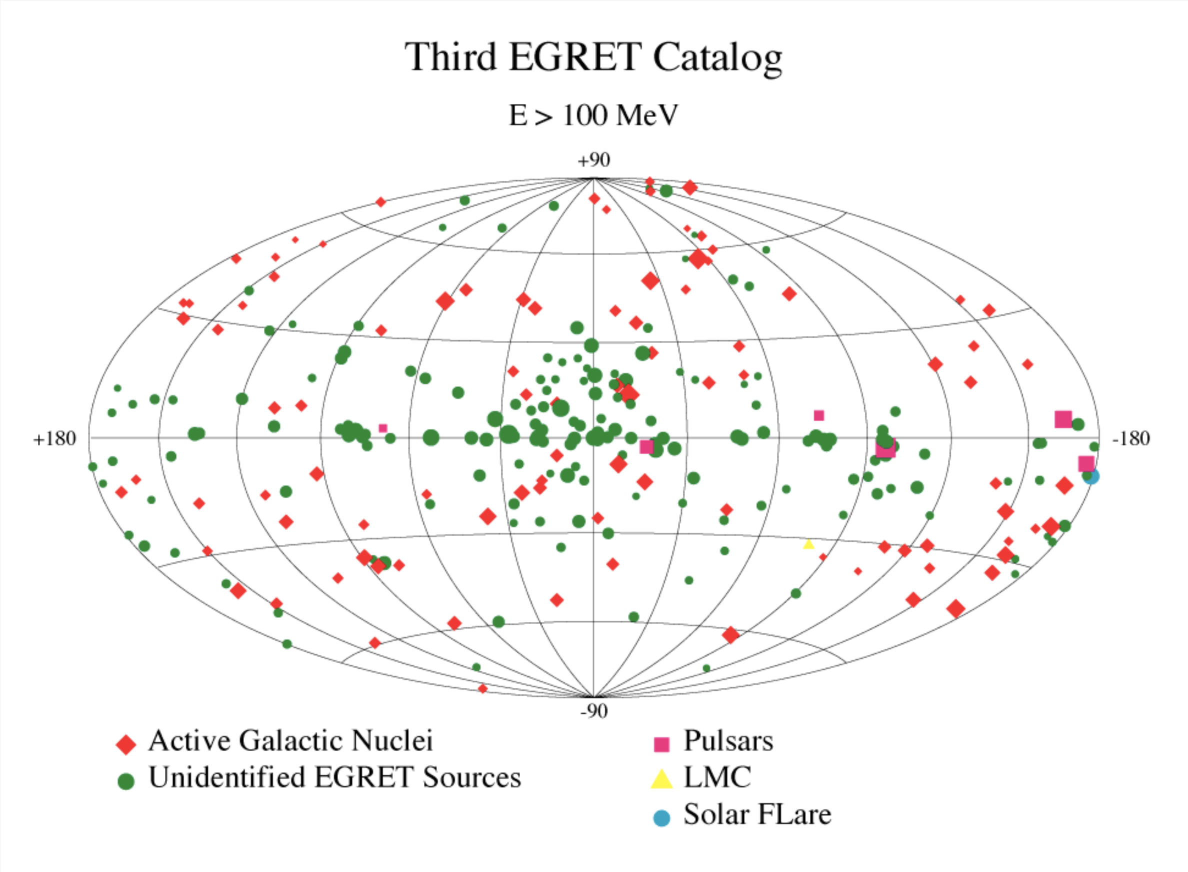
Detections > 100 MeV

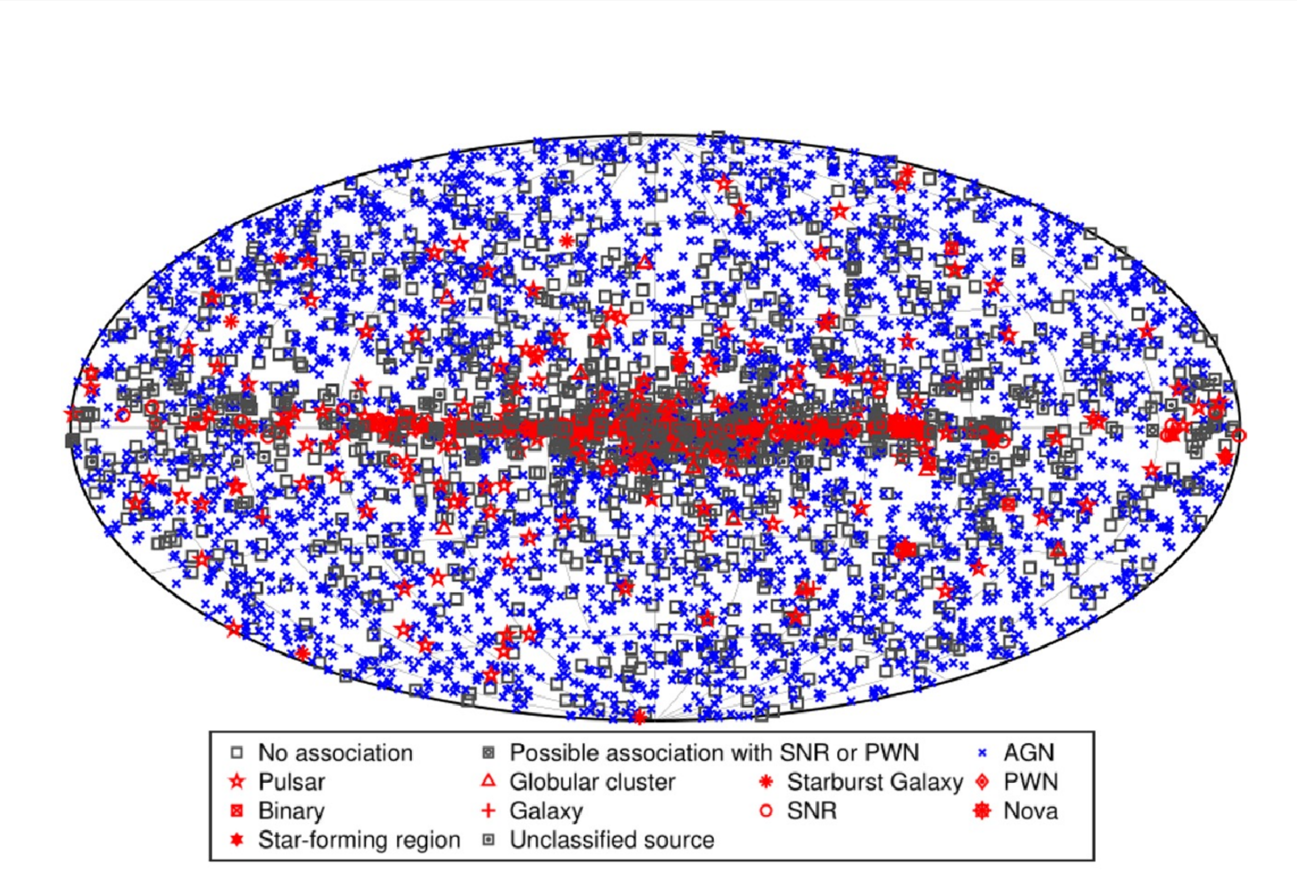
EGRET (1991-96) Hartman et al. 1999

271 sources

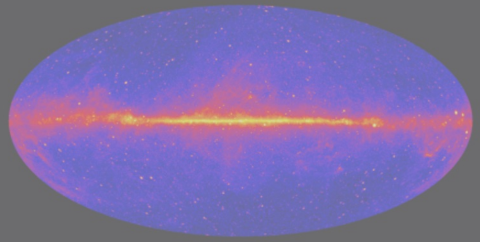
Fermi LAT (2008-18) 4FGL Abdollahi et al. 2020

5065 sources

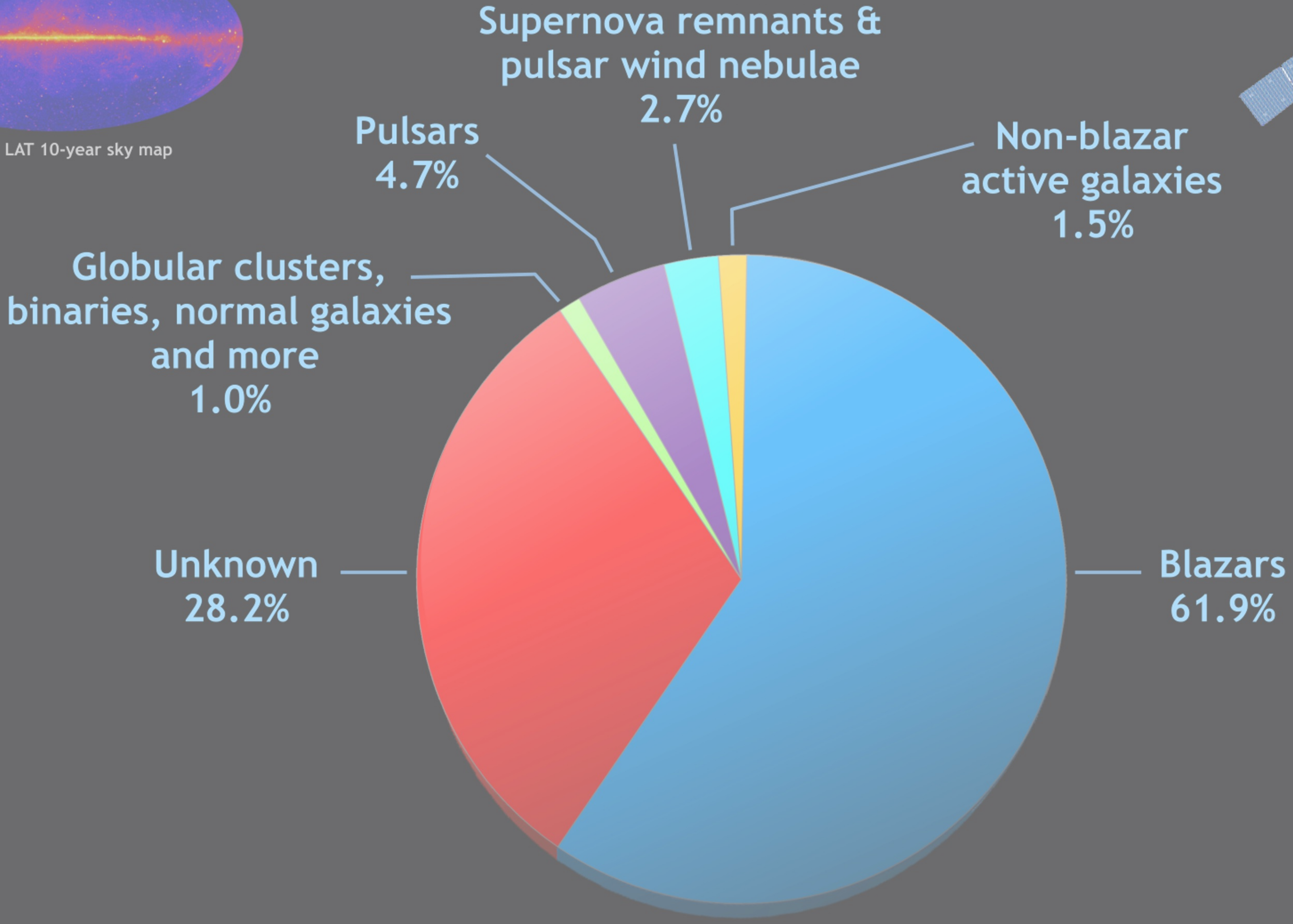




The Fourth Fermi LAT Catalog



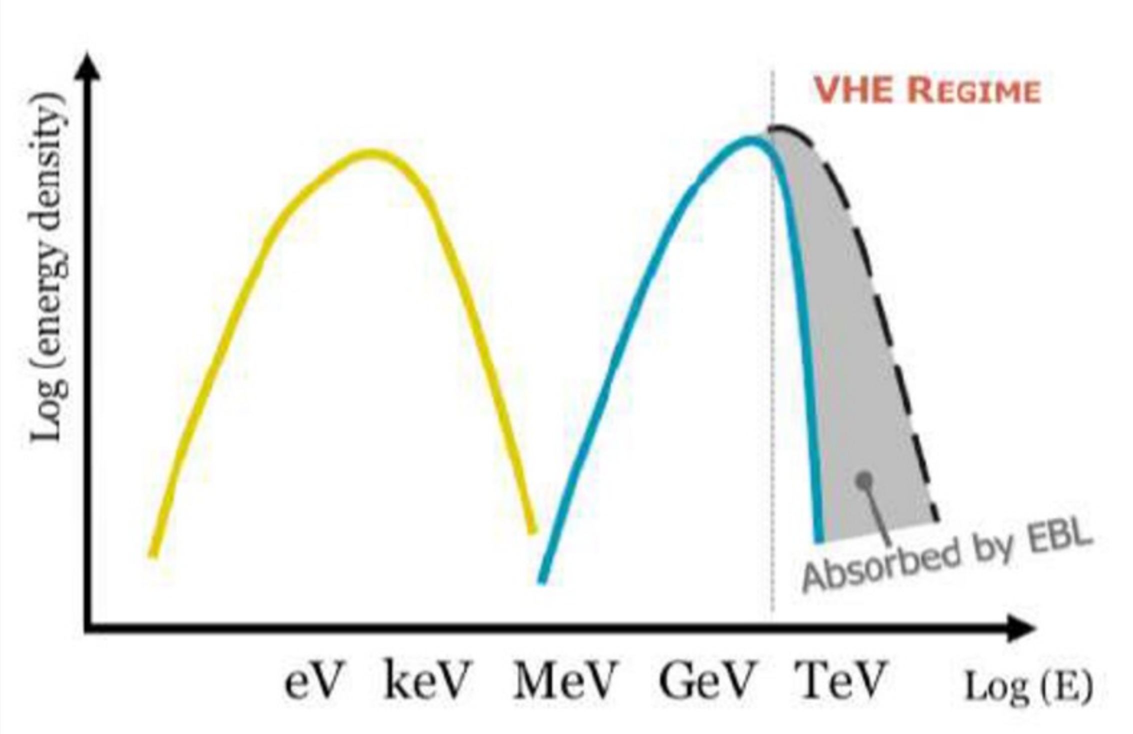
Fermi LAT 10-year sky map



Blazars: most numerous GeV source type

Staring down the jet of an active galaxy
Rotating black hole powers relativistic jets

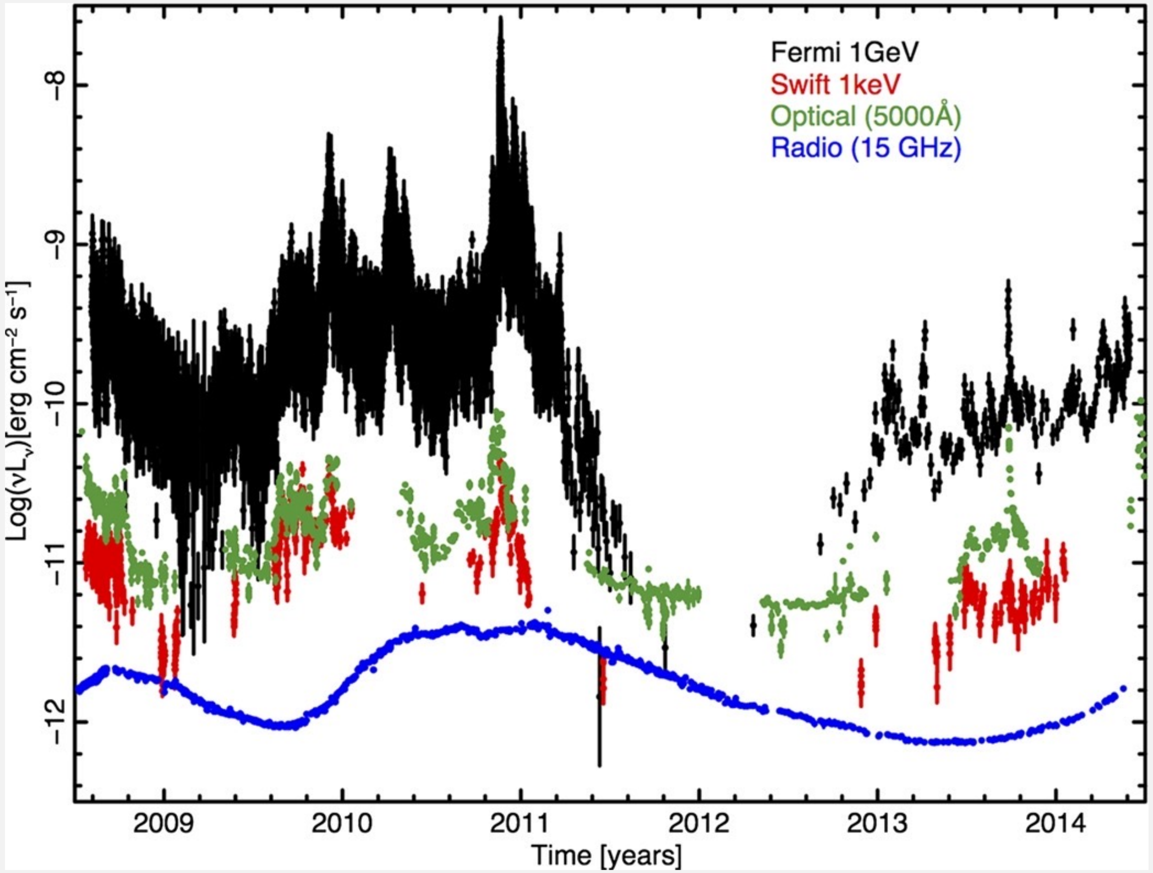
Credit: HESS Project/MPI

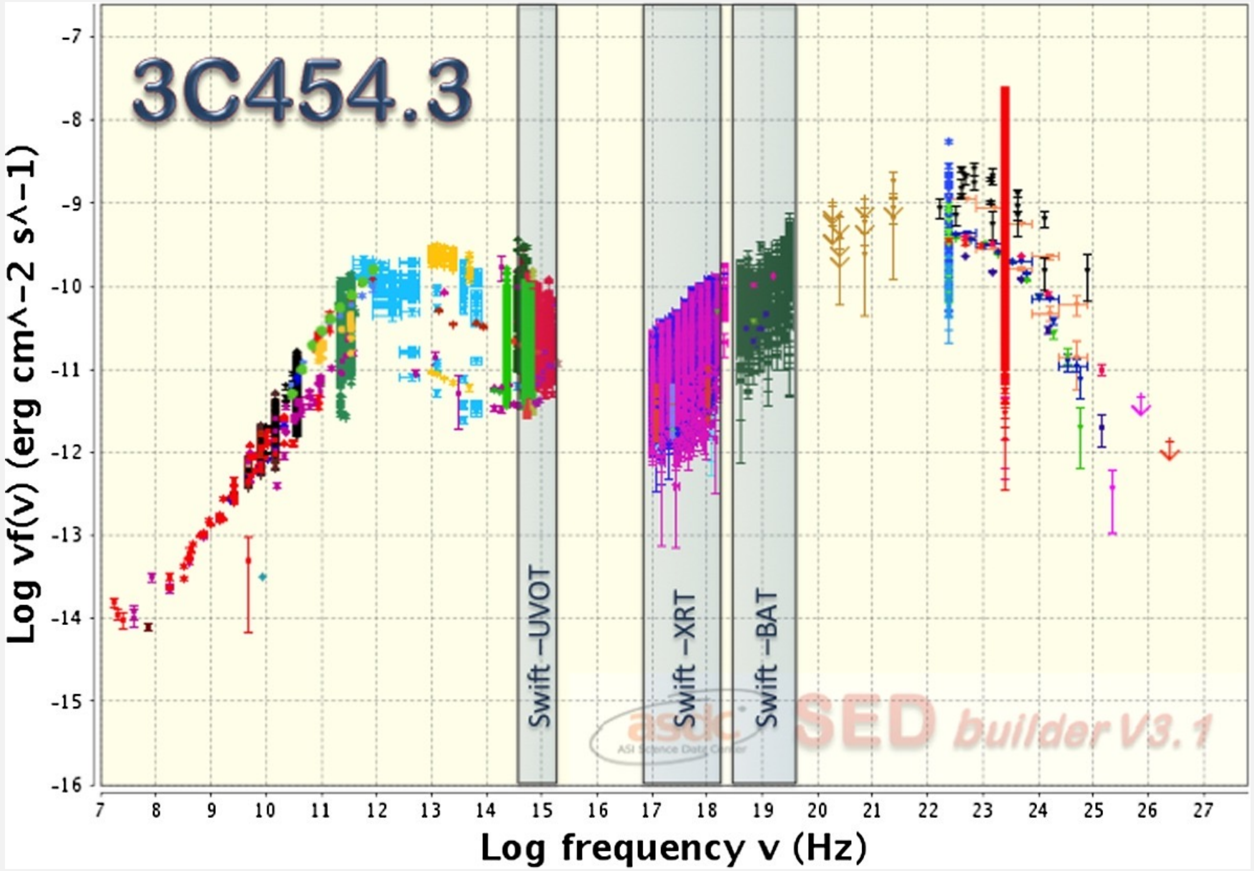


Prandini et al. 2011

Blazars: most numerous GeV source type

Highly variable – blazar flares





Giommi et al. 2015

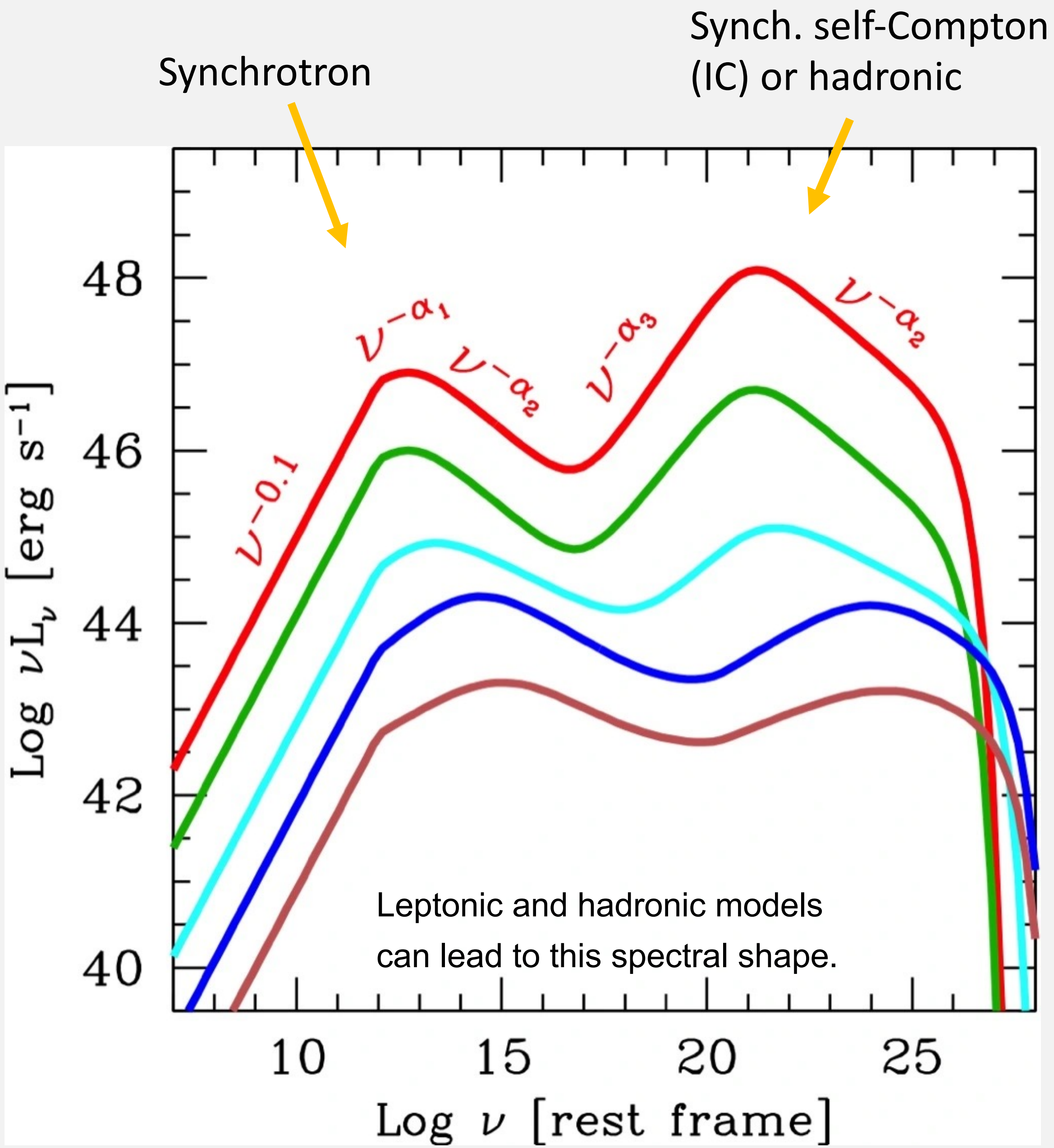
Blazar sequence

family of blazar-types, differing peak frequencies, luminosities

What drives this?

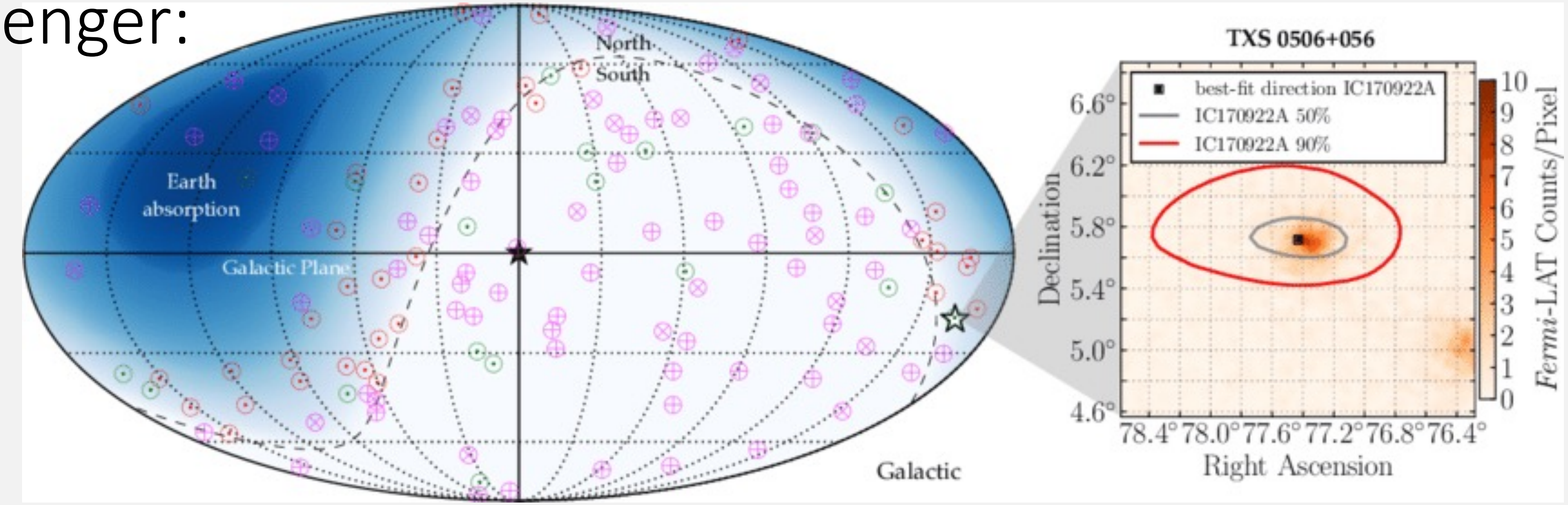
Black hole mass dependency + complex set of other factors?

Jet launching,
particle acceleration,
energy dissipation mechanisms
all unclear



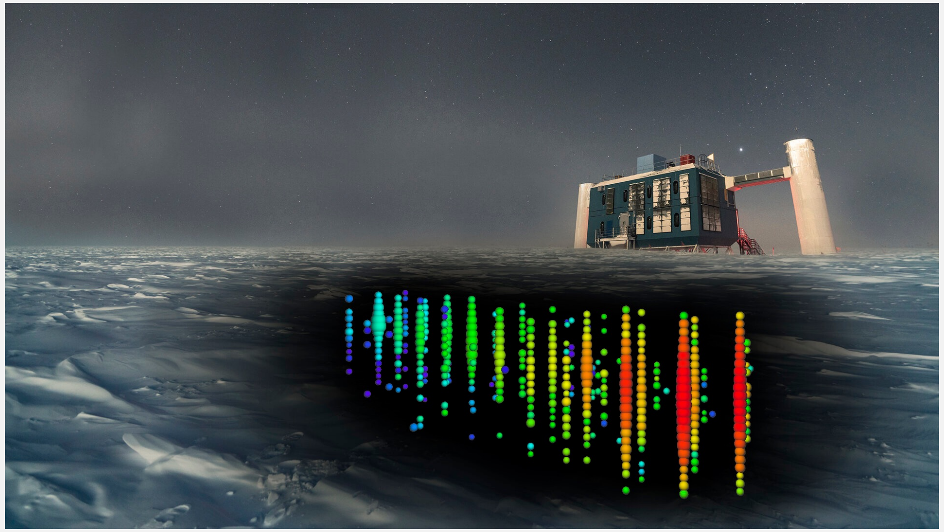
Ghisellini et al 2016

Multi-messenger: neutrinos



First neutrino signal localised to an extragalactic source: a flaring TeV blazar

Gamma-rays also expected in process:
- not seen with 2014-15 neutrino signal
- seen with lower 2017 neutrino signal

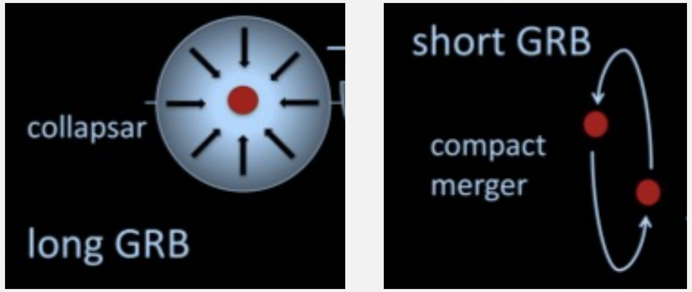


Credit: IceCube project / Aartsen et al. 2019.
See also papers in 2018 Science 361

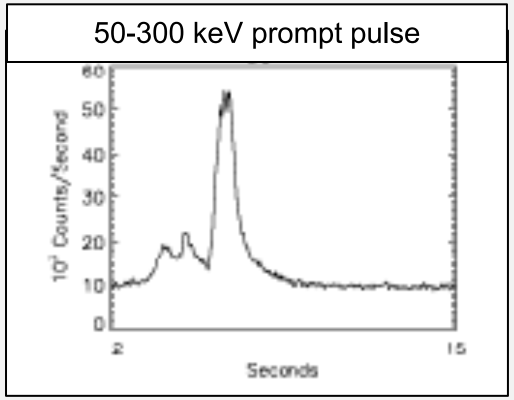
The rapidly-evolving sky: transients

Sources only seen once, fade rapidly

Many are **gamma-ray bursts** – endpoints of massive stars or compact binary mergers →



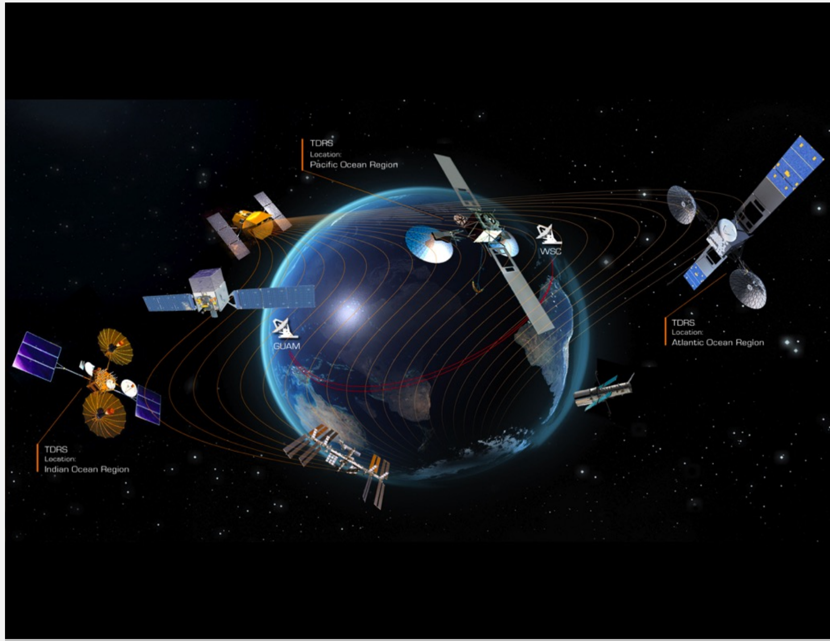
A. Gomboc



CGRO/BATSE
J.T. Bonnell/NASA/GSFC

Observational challenges

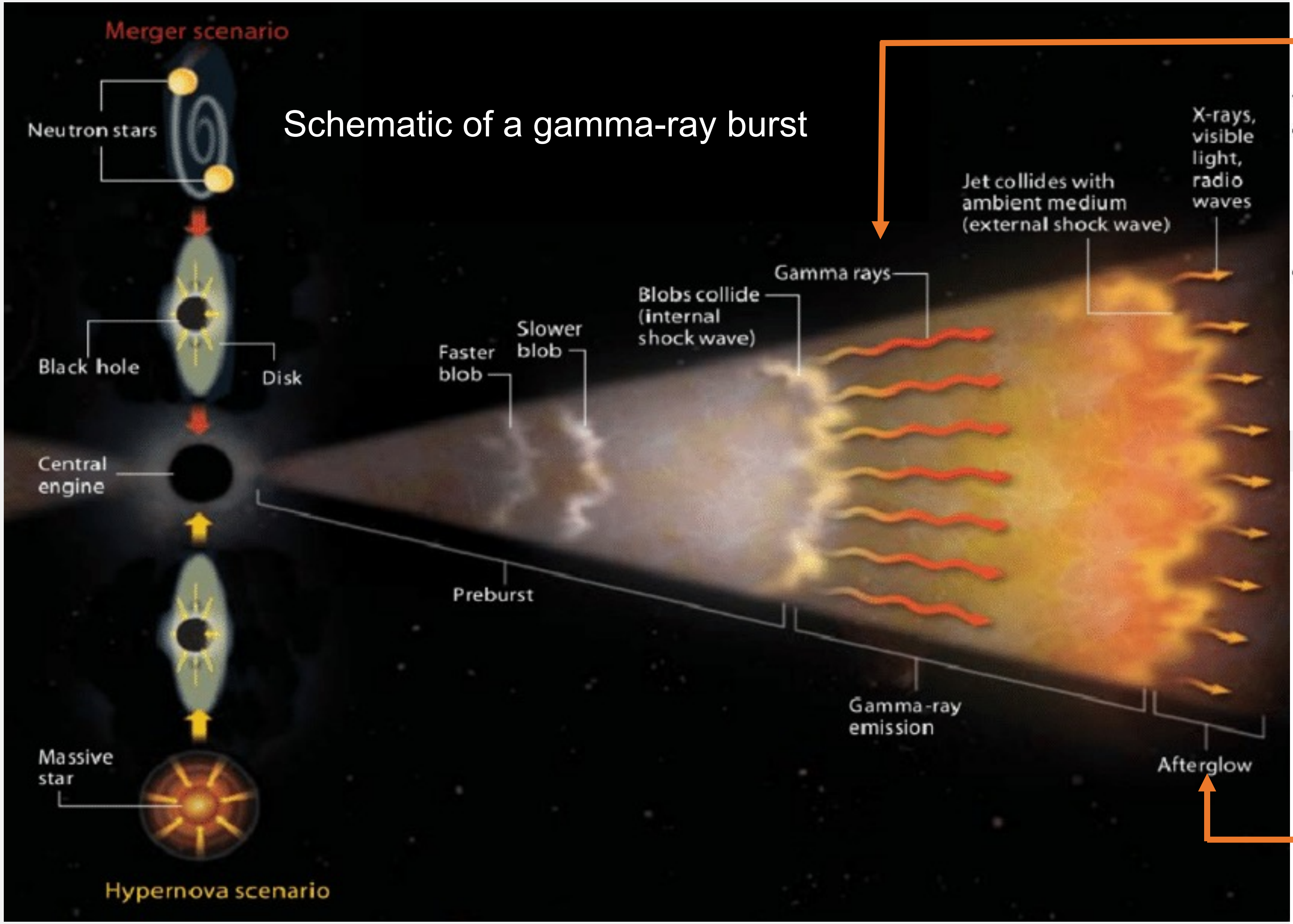
- Need for speed: reaction to new real-time discoveries
- Global, broadband coverage (gamma-ray to radio, incl. optical spectra)



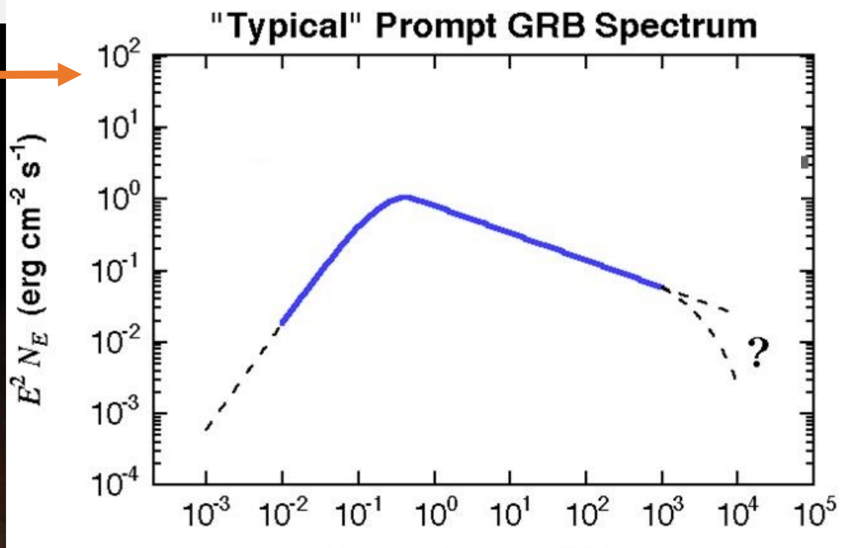
TDRSS network of satellites relays detections to ground in real-time. Credit Fermi/NASA/GSFC

Redshifts via optical/IR spectroscopy essential for luminosity/energy determination. Below: ESO Very Large Telescope

Schematic of a gamma-ray burst

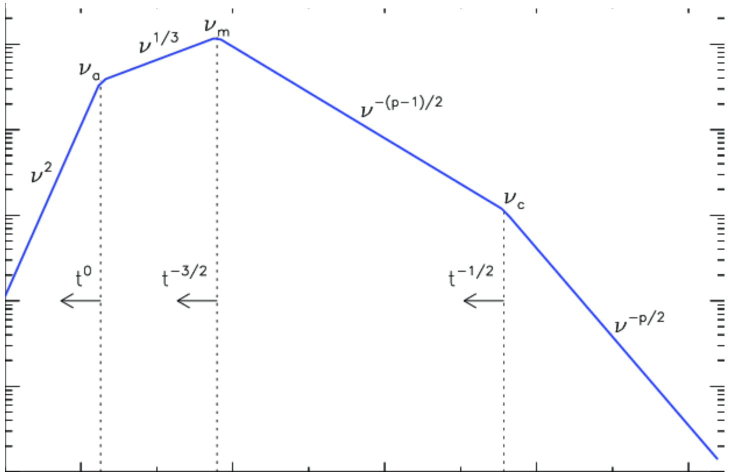


Credit: NASA



Credit: FSSC

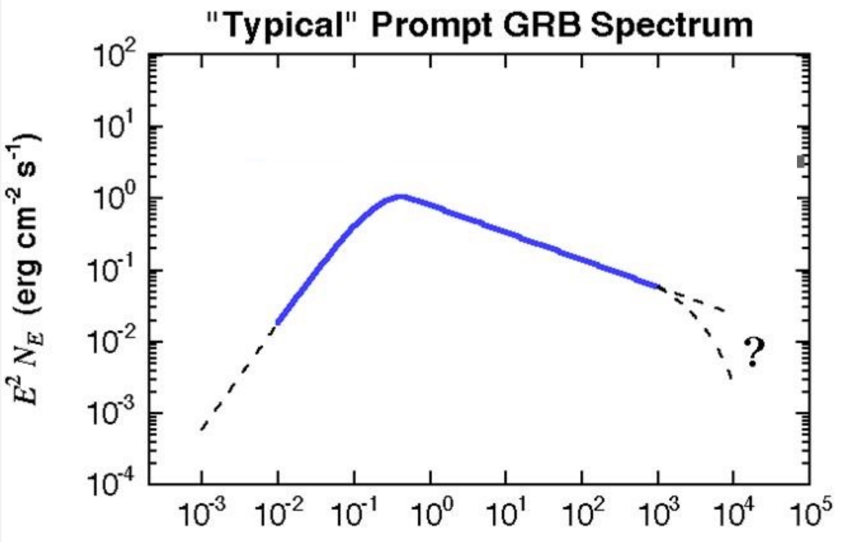
Afterglow shock front: synchrotron



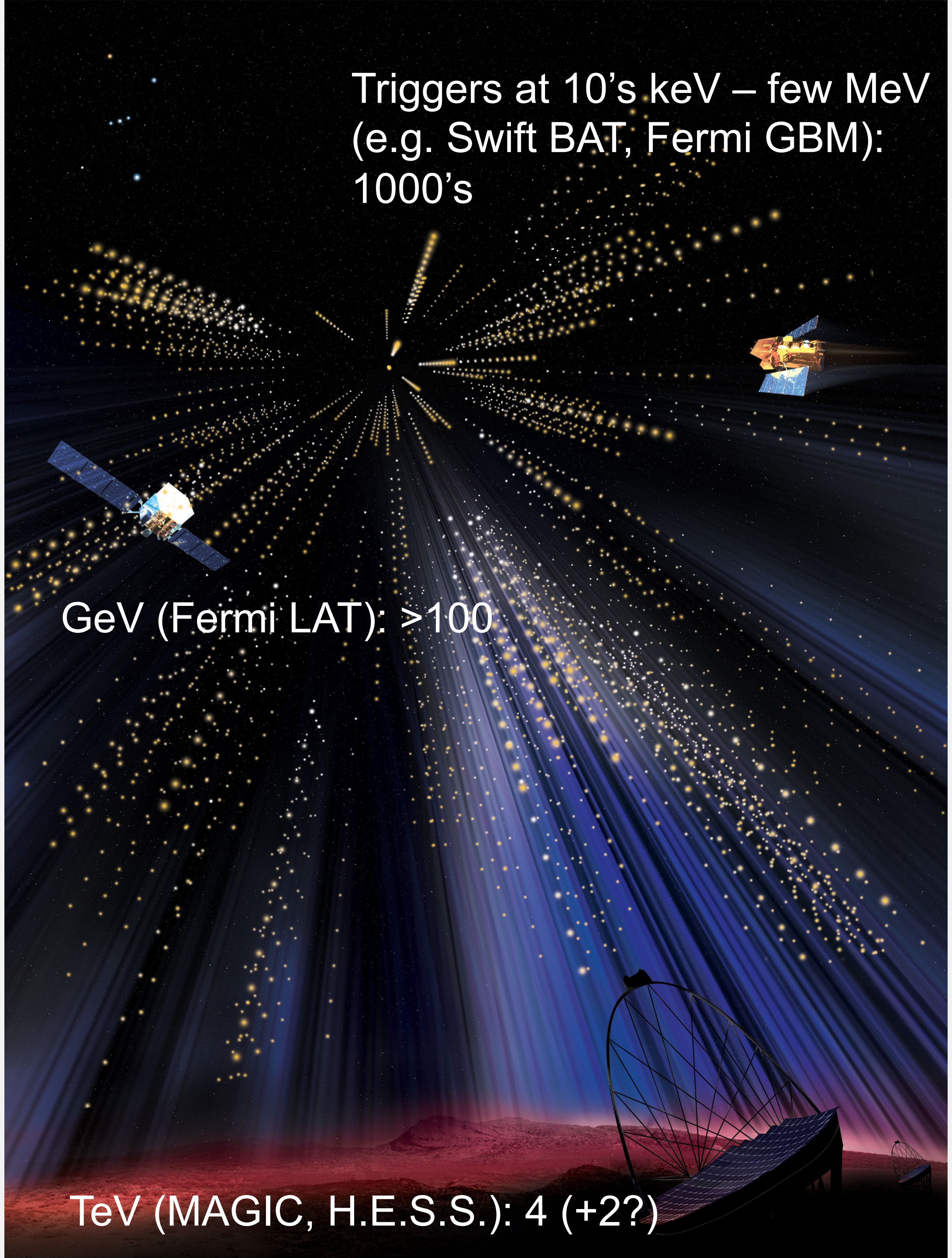
Credit: De Ugarte Postigo et al. 2012 / Sari et al. 1998

Do gamma-ray bursts produce very high energy photons?

Yes! But quite not what we expected…



Credit: FSSC

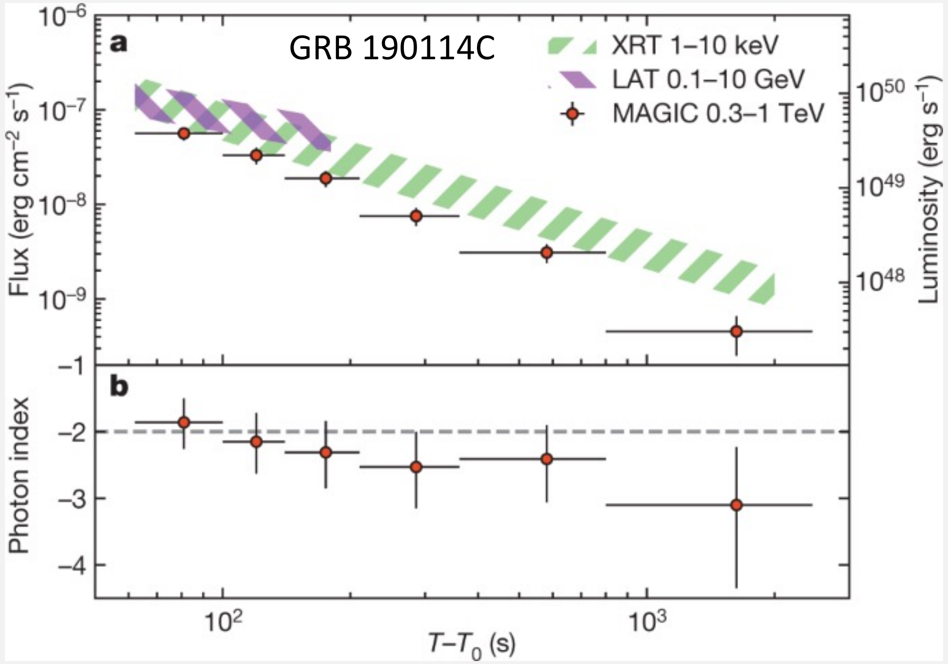


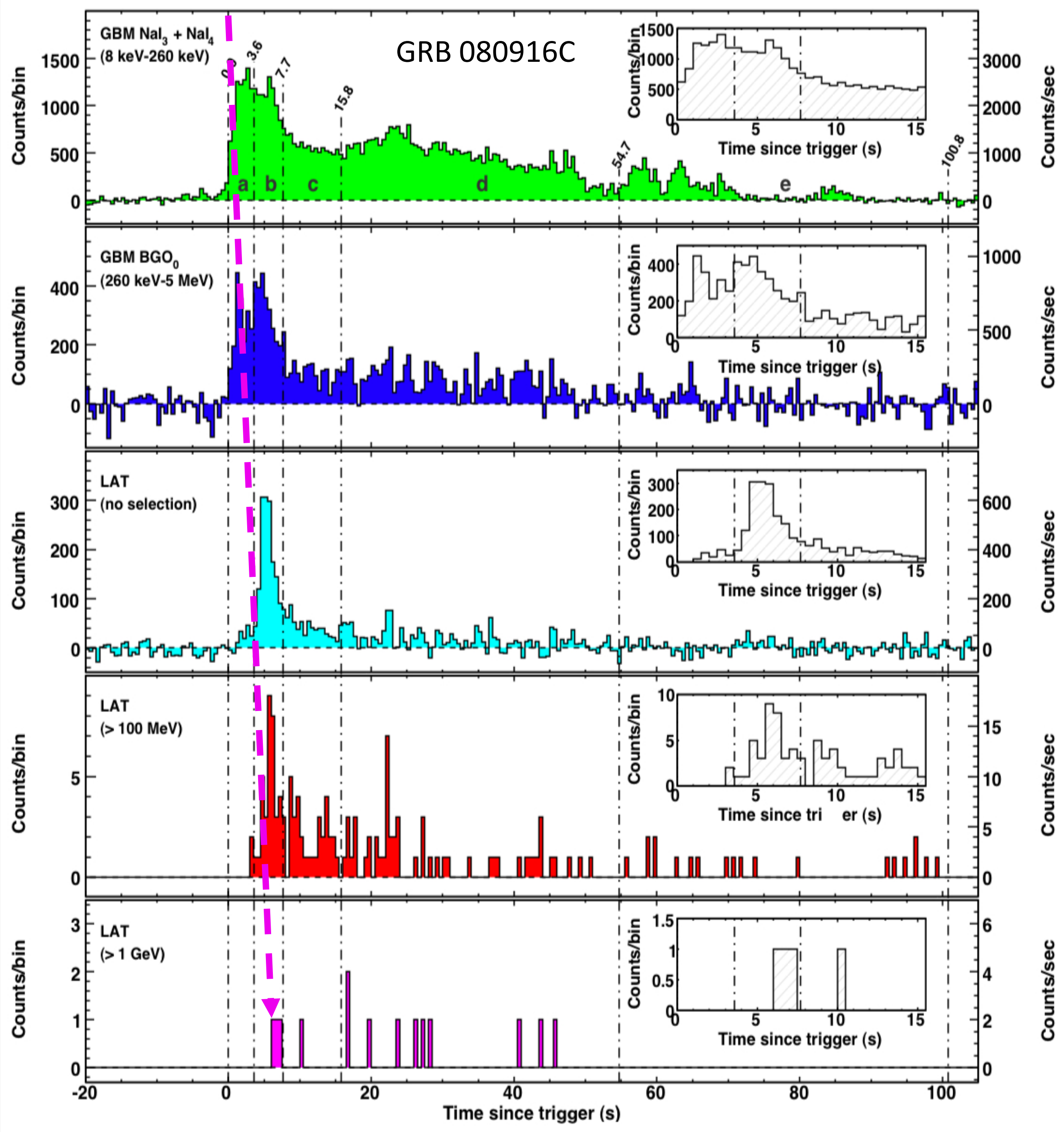
Credit: NASA/GSFC / Aurora Simonnet Sonoma State U.

Do gamma-ray bursts produce very high energy photons?

GeV-TeV emission

- follows similar temporal decay to X-ray
- delayed onset, like the afterglow





Credits above: MAGIC Collab. 2019; Right: Bouvier et al. 2010

Do gamma-ray bursts produce very high energy photons?

GeV, TeV

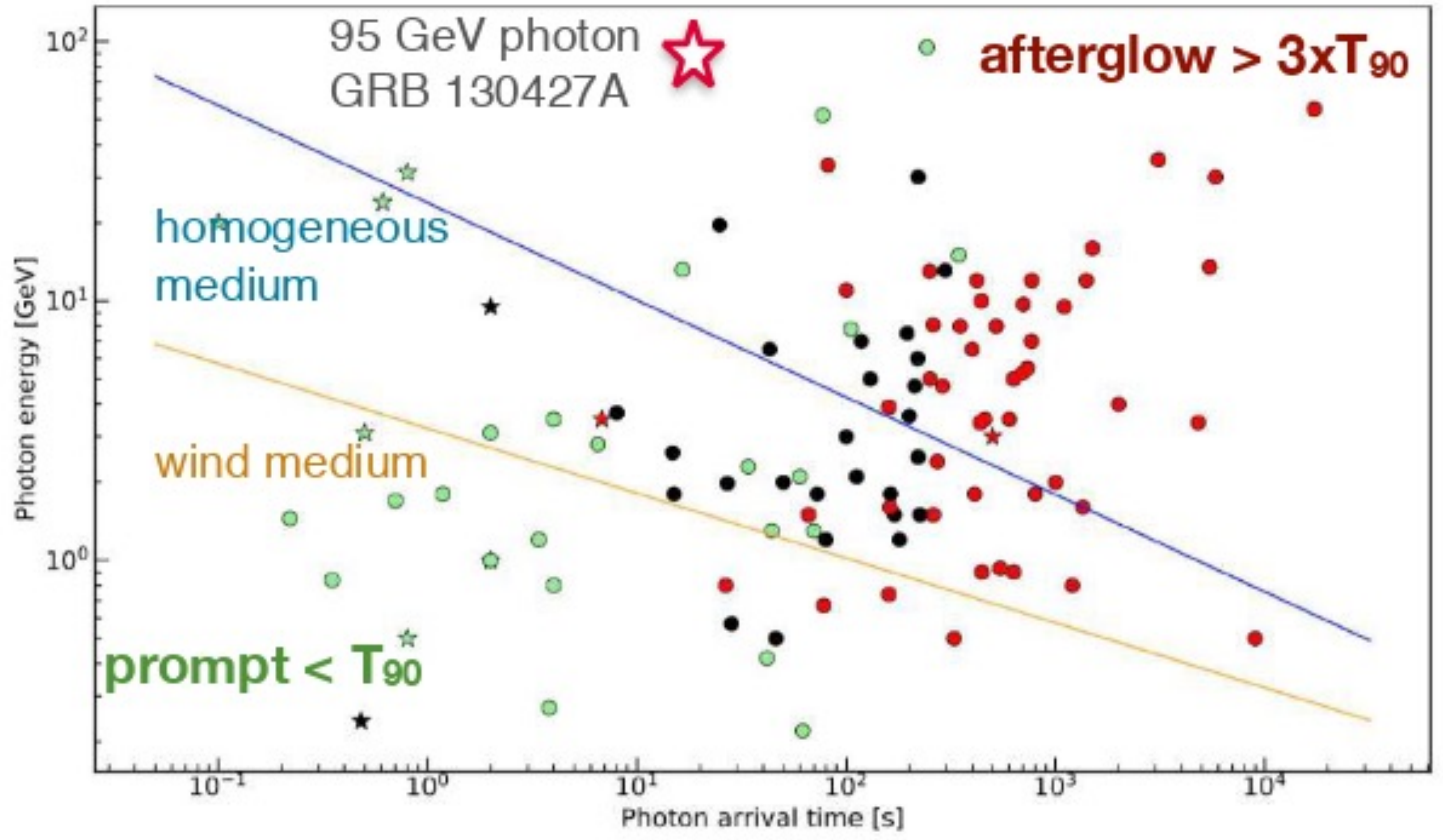
- similar temporal properties
- different spectral shapes

→ same region as afterglow forward shock, different physics?

At high energies expect:
Synchrotron radiative losses < acceleration time (burn-off limit)

~~synchrotron~~

Photon energies vs arrival times for GRB 190114C

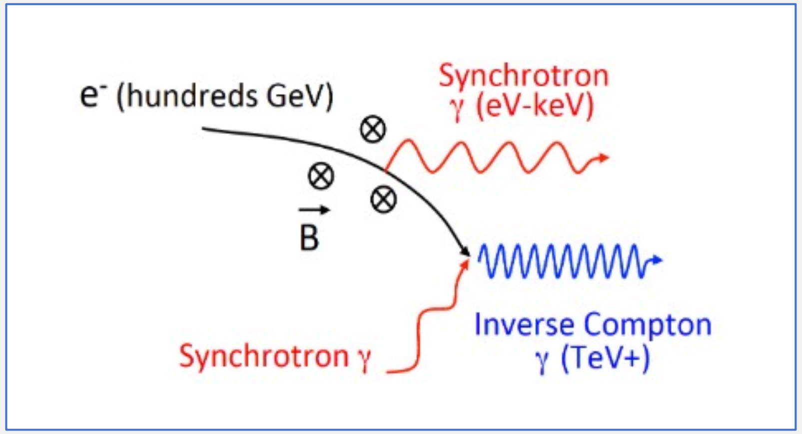


Credit: taken from a 2020 IAU Workshop talk by Ulisses Barres de Almeida, see also Nava 2018

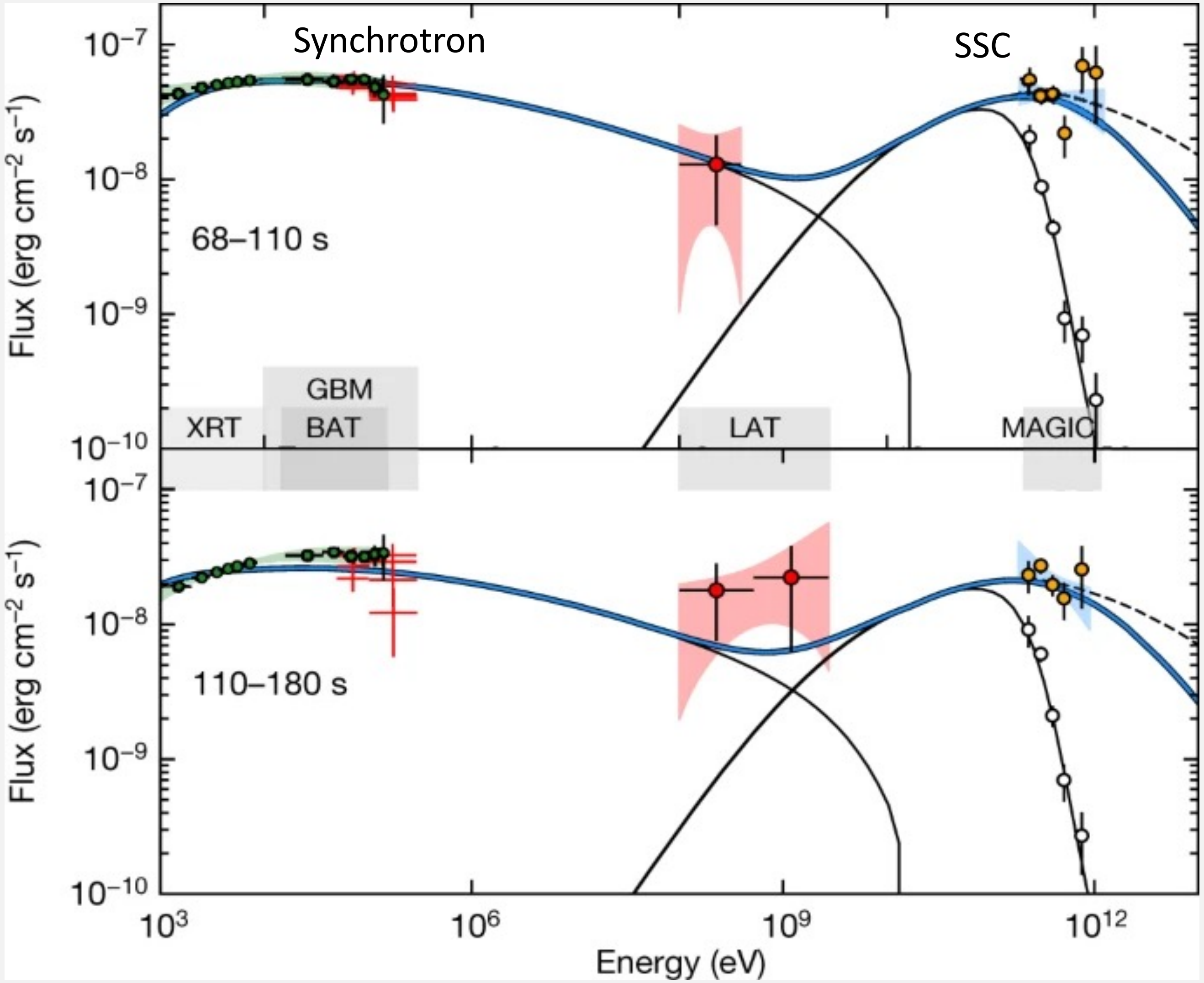
New high energy component?

Gamma-ray photons from synchrotron can interact with accelerated electrons: synchrotron self-Compton process (inverse Compton) → energetic gamma-rays

may be common and detectable at TeV for many nearby GRBs

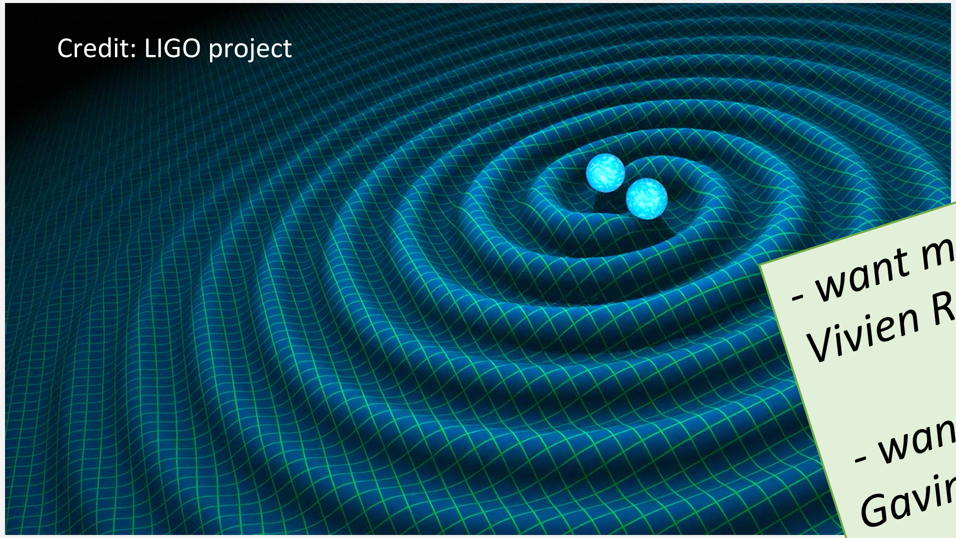


Credit: Introduction to particle and astroparticle physics
De Angelis & Pimenta



Swift + Fermi + MAGIC spectral energy distributions at two epochs for GRB 190114C with Synchrotron + SSC model overlaid
Credit: MAGIC Collab. 2019, Nat 575, 459,.

Multi-messenger: Gravitational waves



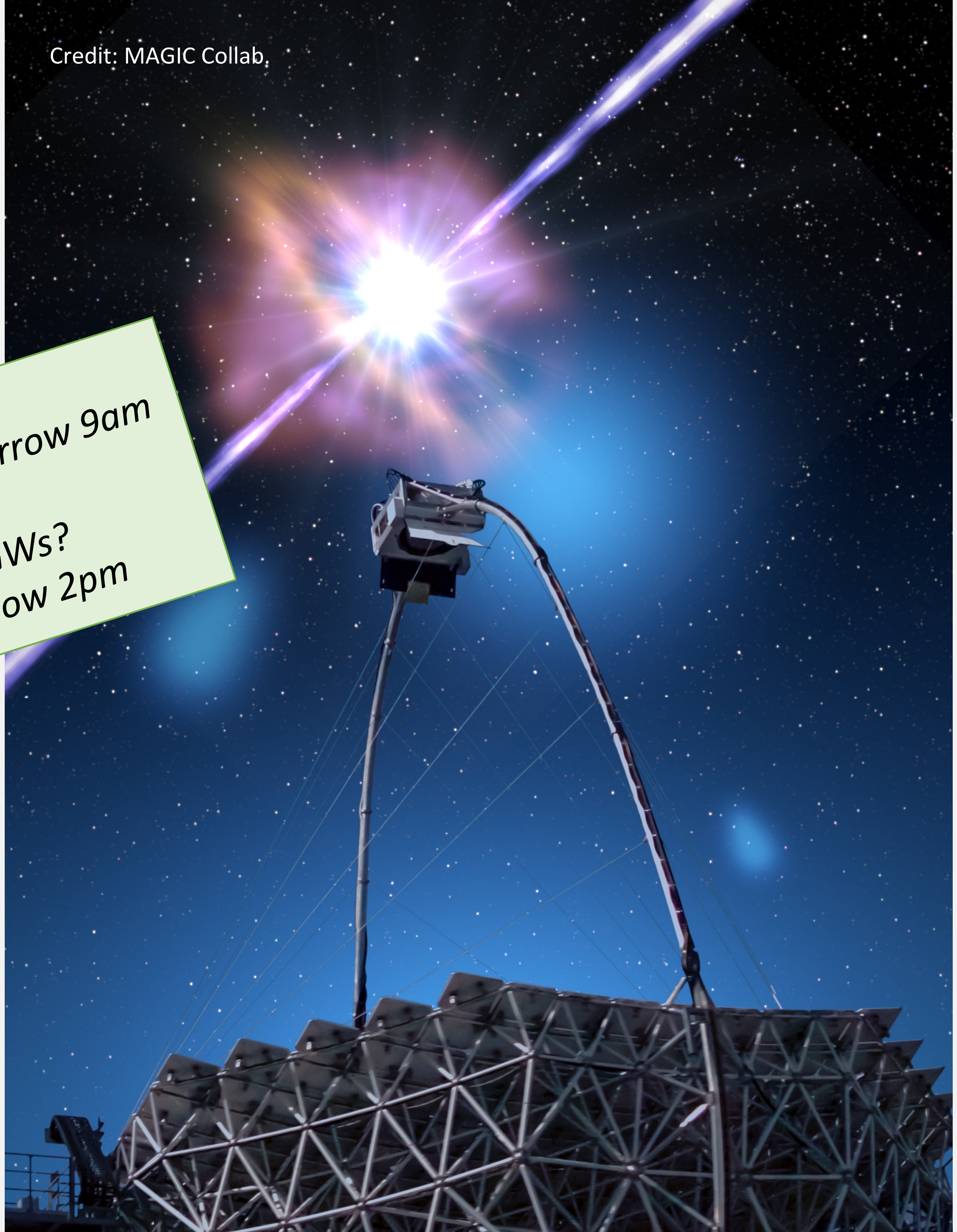
- want more GWs?
Vivien Raymond, tomorrow 9am

- want more GRBs/GWs?
Gavin Lamb, tomorrow 2pm

Short-duration gamma-ray bursts are known to originate from compact binary mergers.

Associated with detectable gravitational waves

One tentative detection at TeV

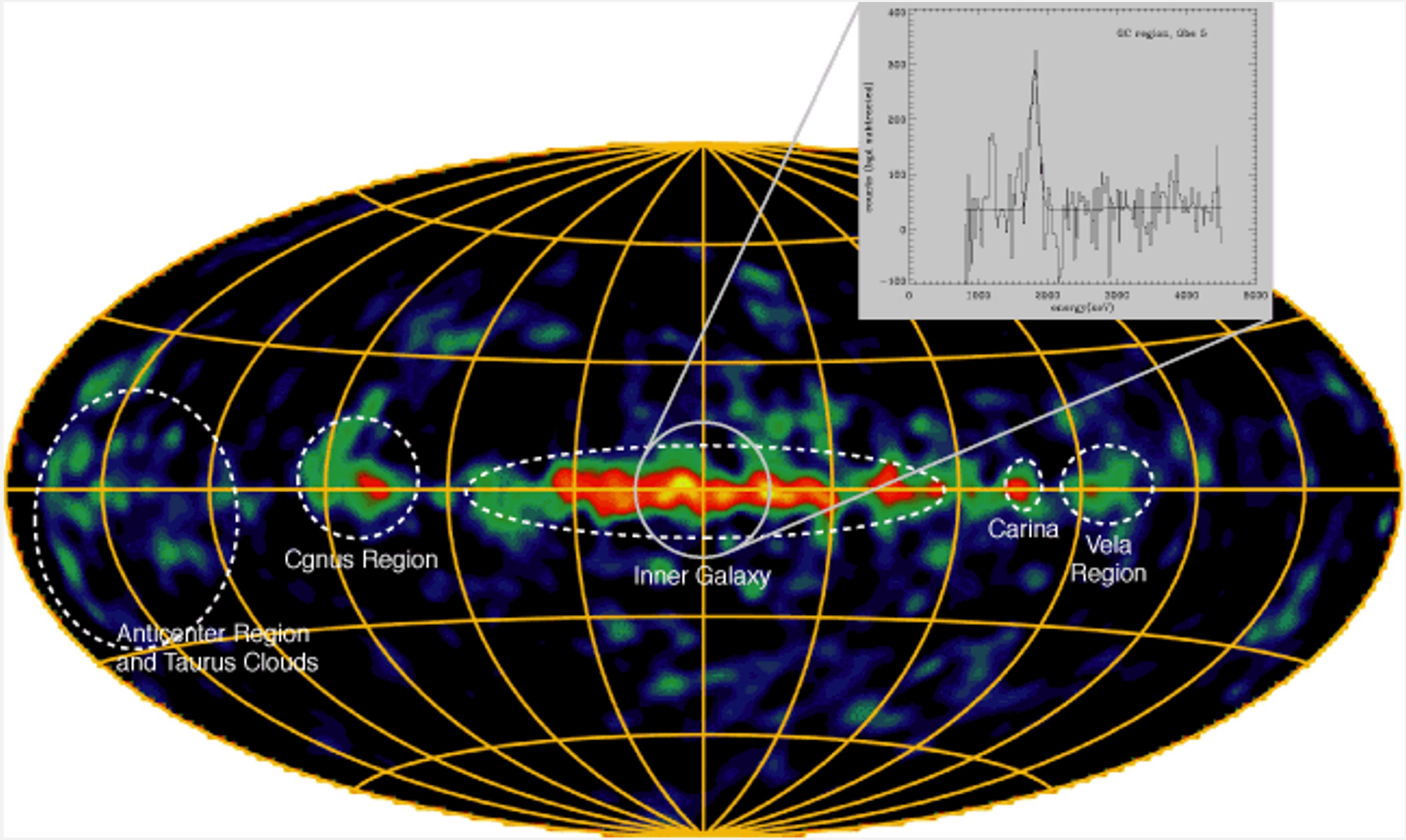


Gamma-rays from radioactive decay

^{26}Al all-sky map at 1.8 MeV, CGRO/COMPTEL

Long half-life: shows nucleosynthesis over millions of years.

Traces our own galaxy
- star formation
    - core-collapse supernovae
    - winds of massive stars



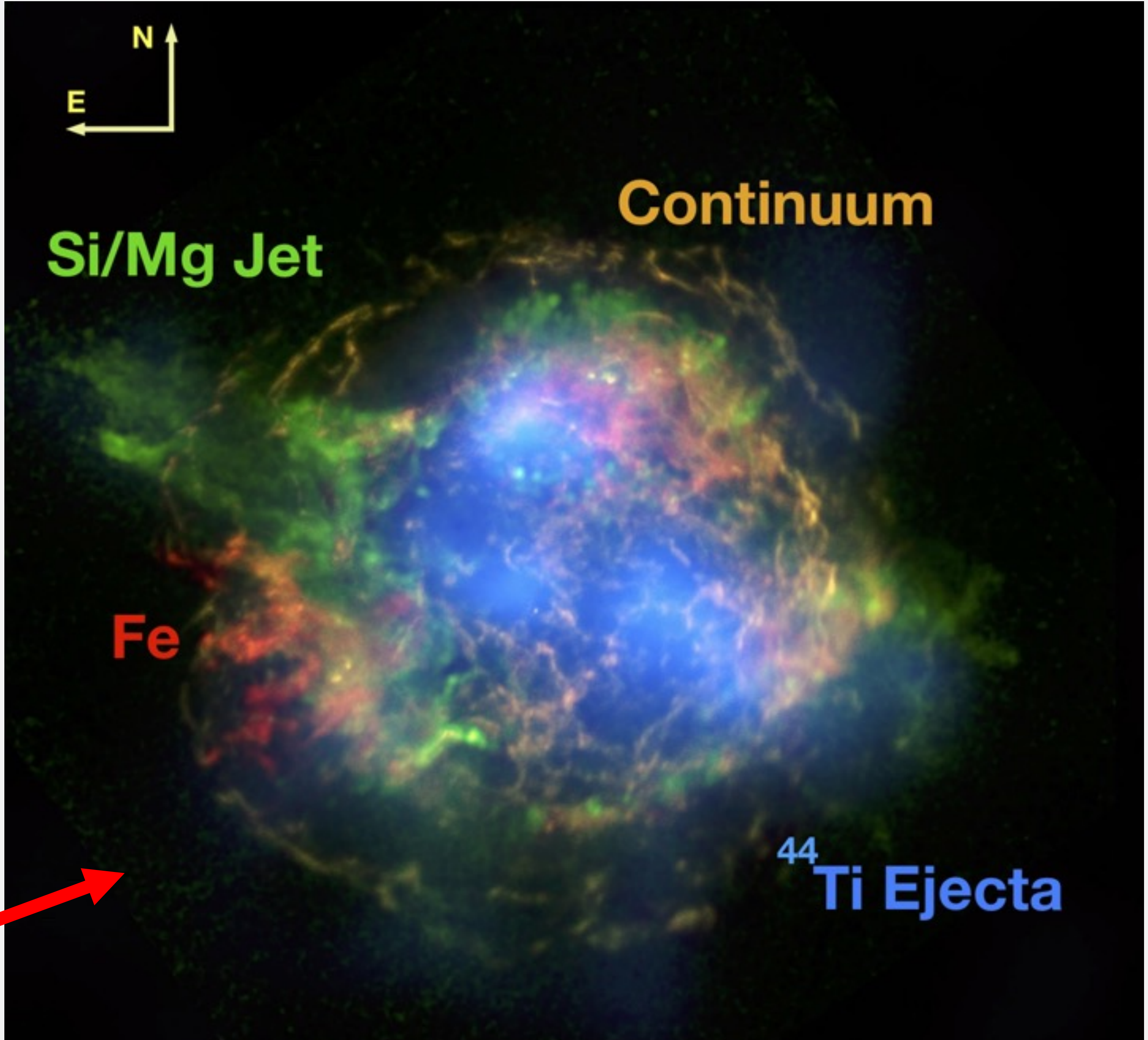
Credits: Oberlack et al. 1997 / Knodlseder et al. 1999 / CGRO / ESA

Gamma-rays from radioactive decay

COSI mission to measure ^{26}Al, ^{60}Fe

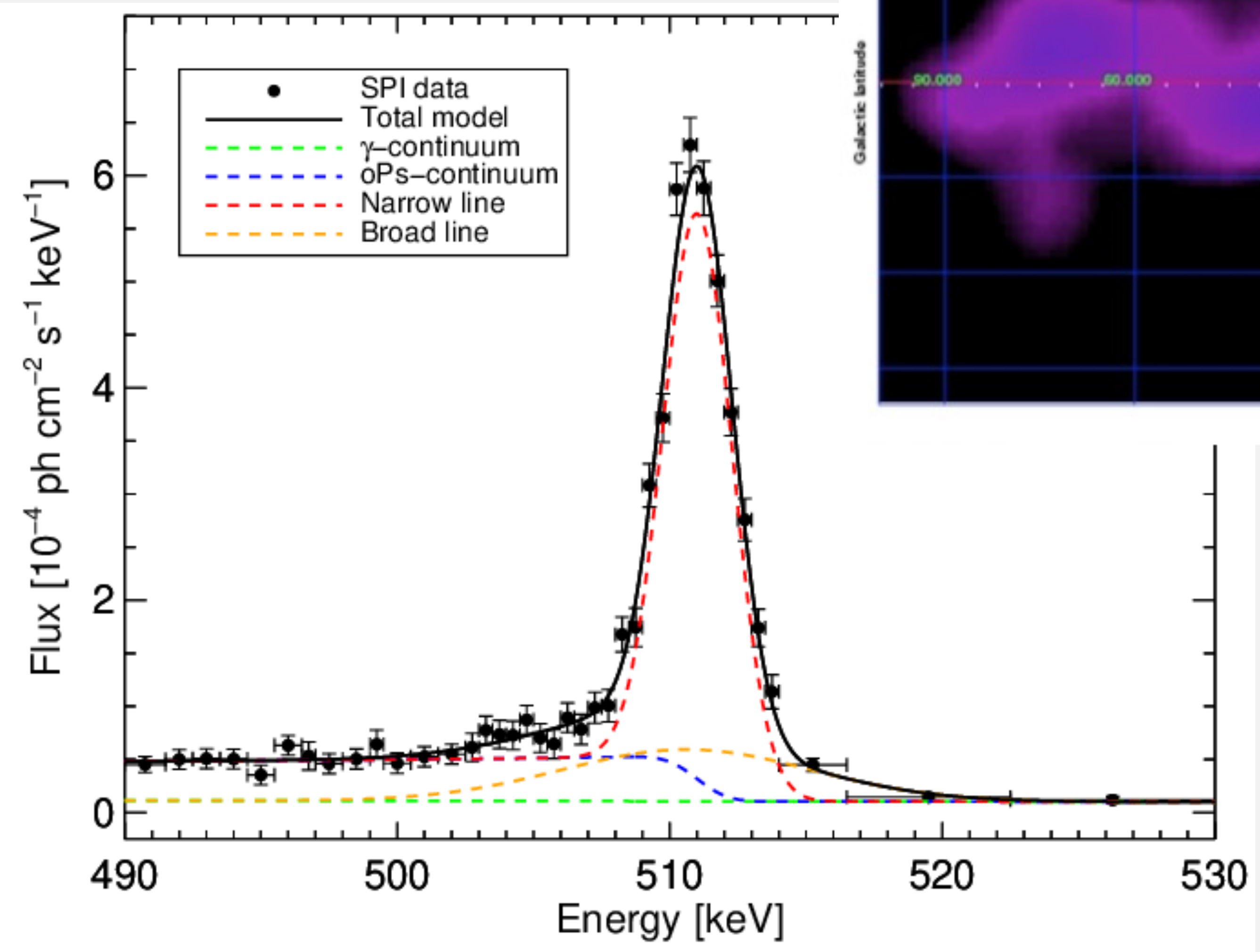
Also ^{44}Ti from β-decay at 1.16 MeV: shorter half-life (60y) traces younger supernova remnant material

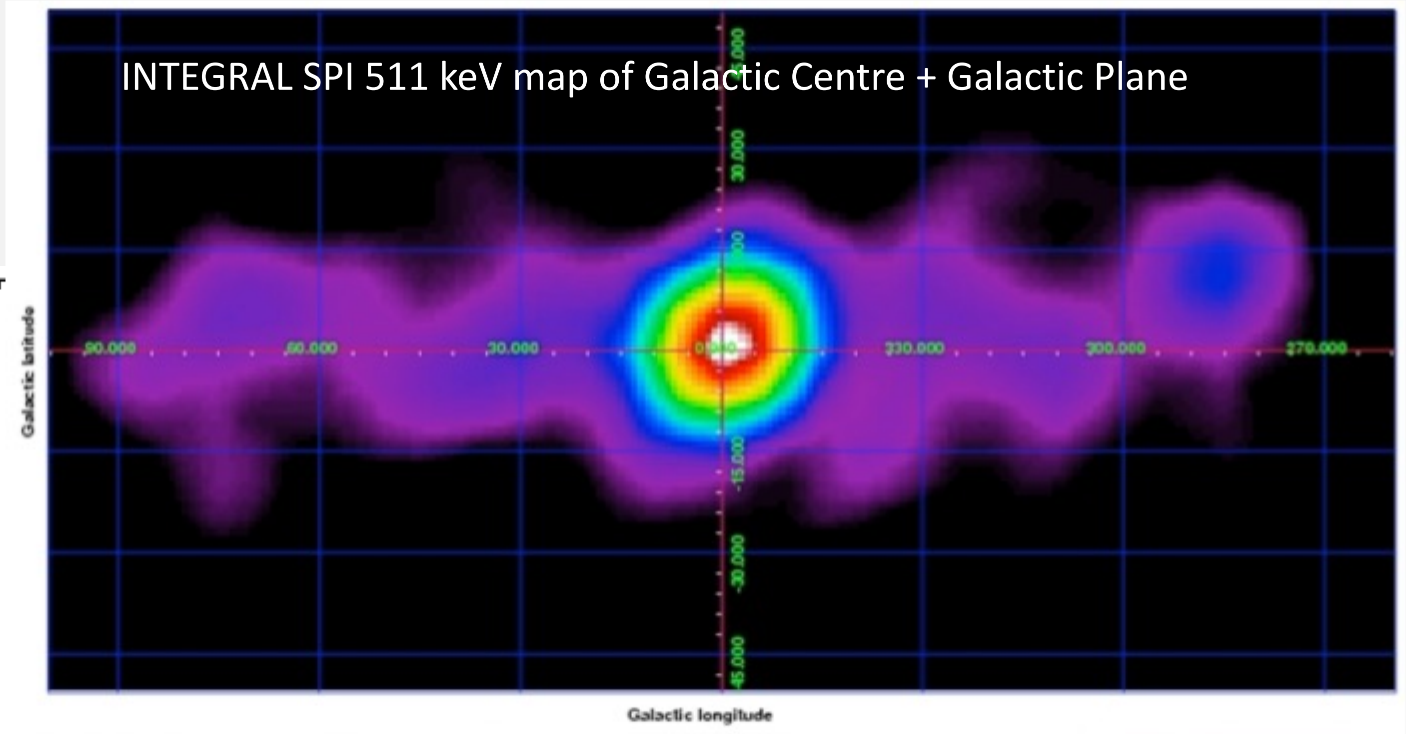
Couple with hard X-ray data to map ejecta history



Cassiopeia A supernova remnant in X-rays with NuSTAR
Credit: Grefenstette et al. 2017

Positron annihilation

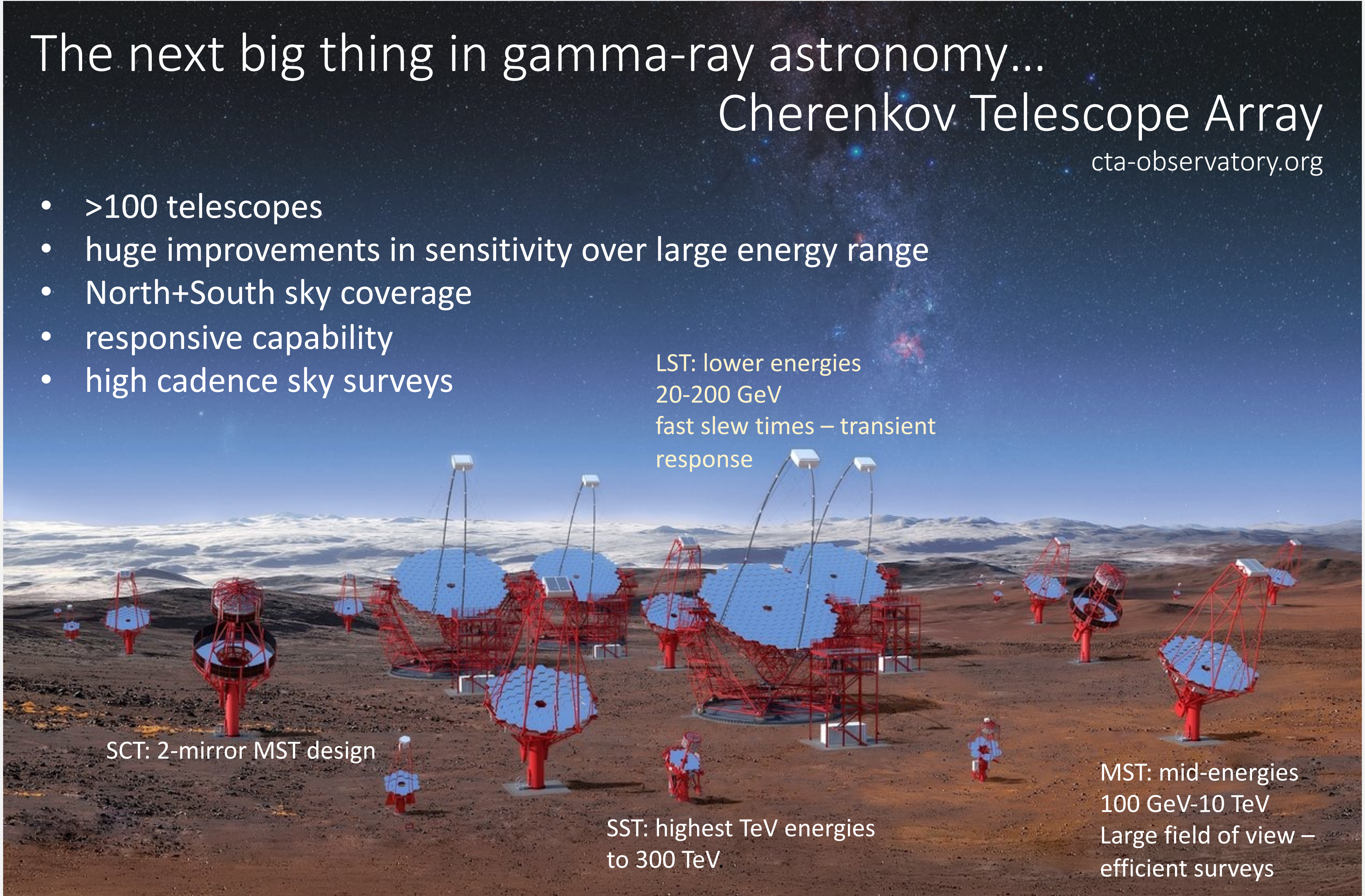




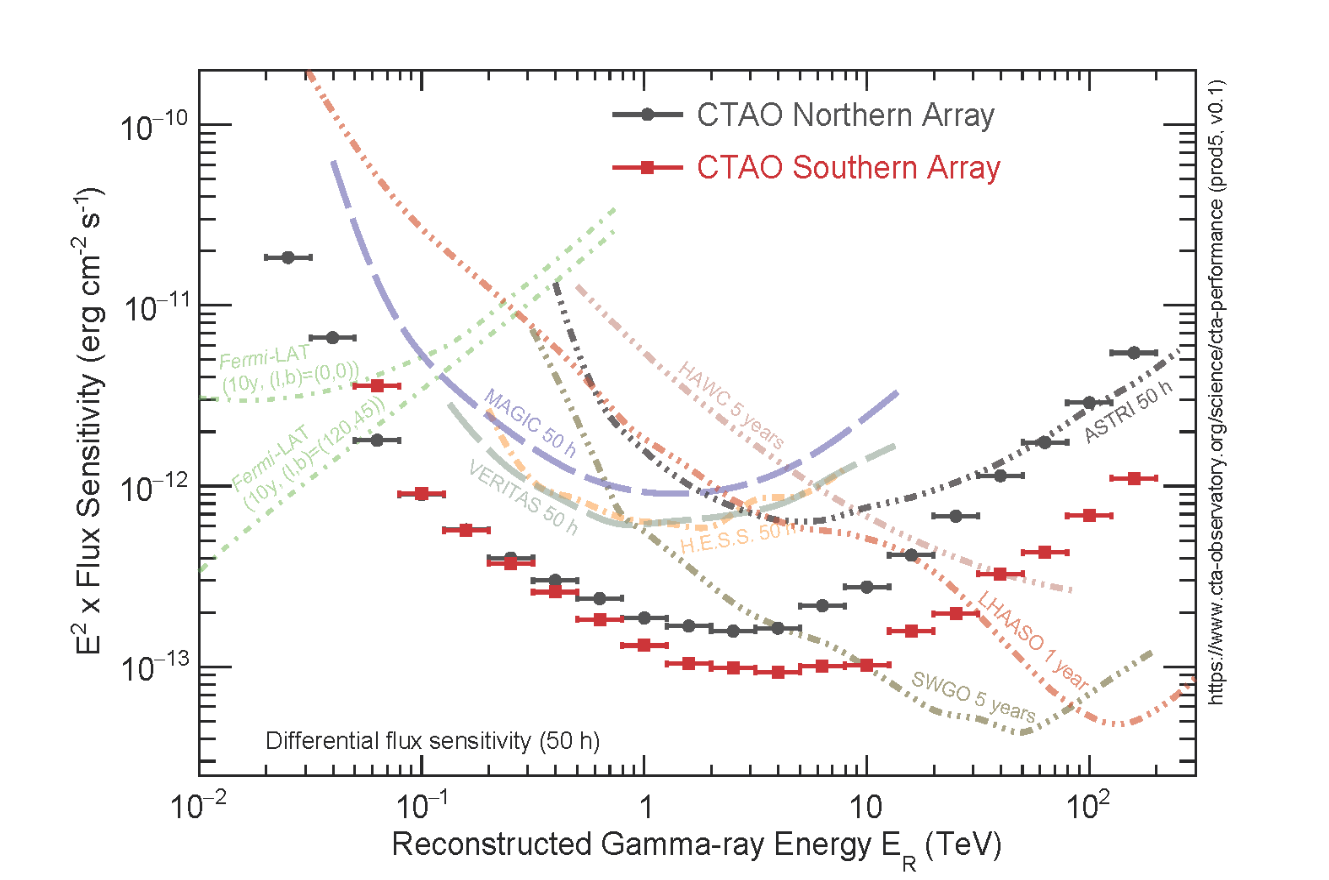
Focussed on Galactic Plane and Centre.
Origin of positrons unknown…

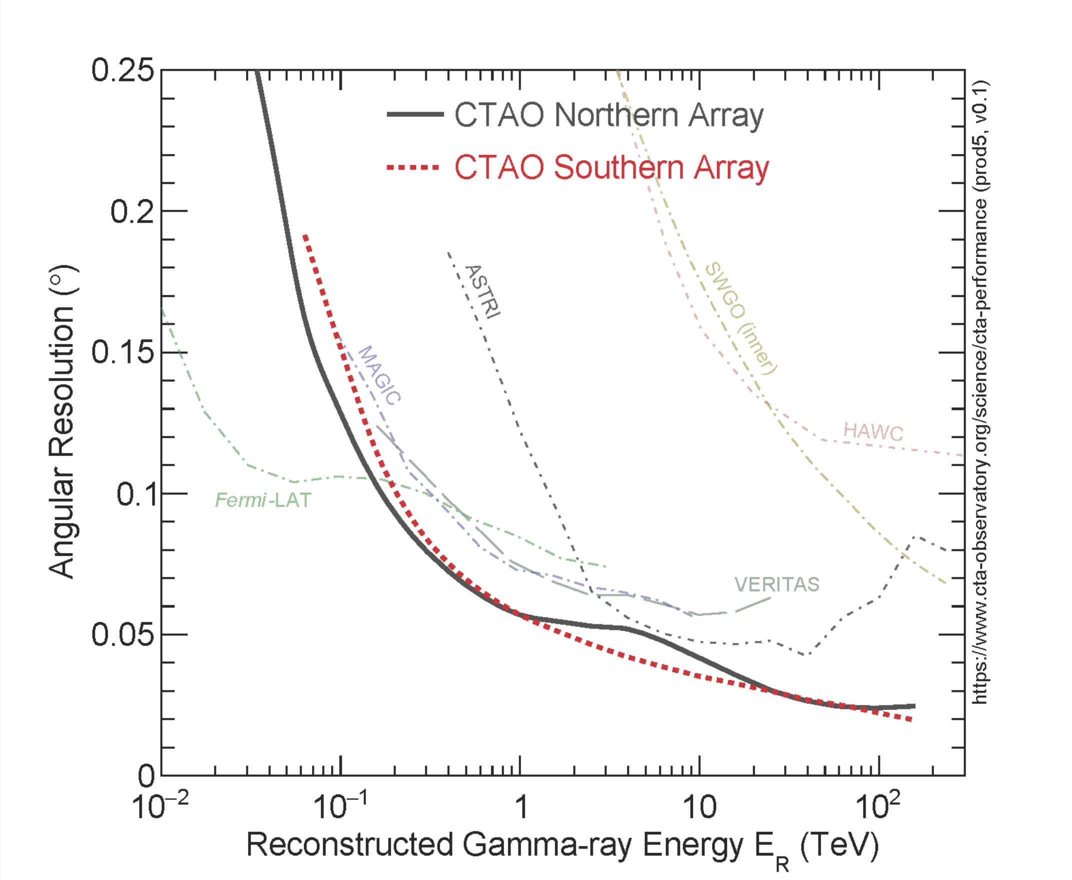
Radioactive decay in stars?
Black-hole-driven sources?
Pulsars or magnetars?
Dark matter physics?

Credits: Siegert et al. 2019 / Knodlseder et al. 2005 / CGRO / Bouchet et al. 2010 / ESA INTEGRAL-SPI


The next big thing in gamma-ray astronomy…
Cherenkov Telescope Array
cta-observatory.org
• >100 telescopes
• huge improvements in sensitivity over large energy range
• North+South sky coverage
• responsive capability
• high cadence sky surveys
LST: lower energies
20-200 GeV
fast slew times – transient
response
SCT: 2-mirror MST design
SST: highest TeV energies
to 300 TeV
MST: mid-energies
100 GeV-10 TeV
Large field of view –
efficient surveys

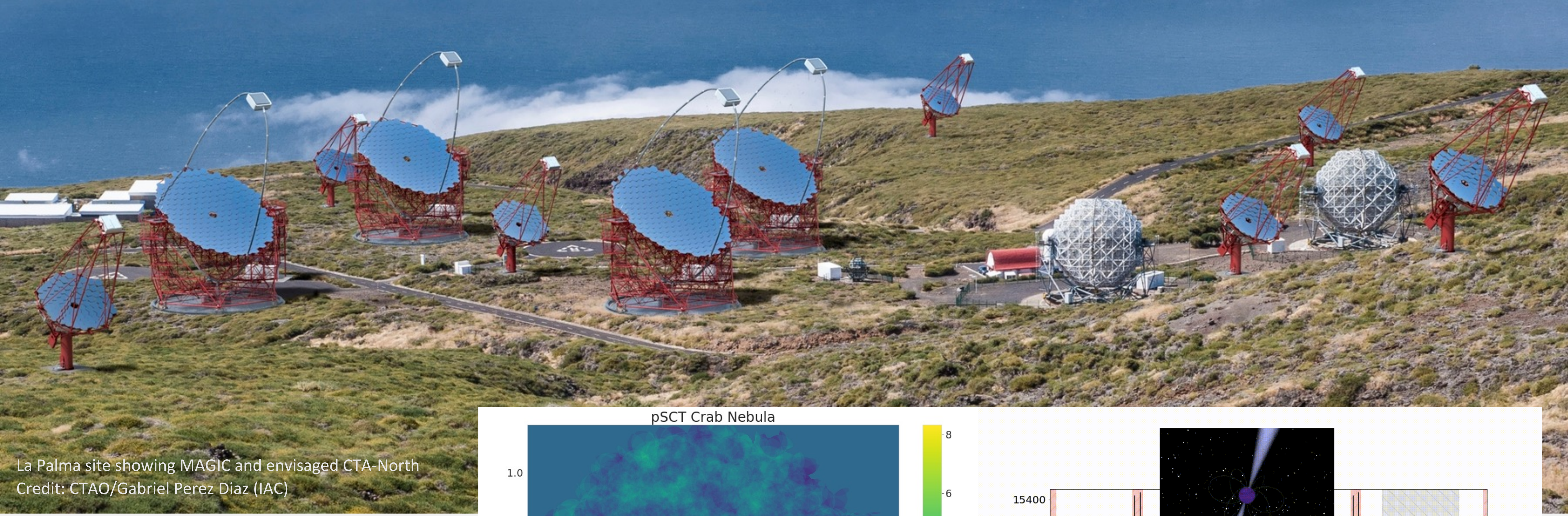
CTA performance





Expected to expand the number of known astrophysical gamma-ray sources by x10

More details at cta-observatory.org

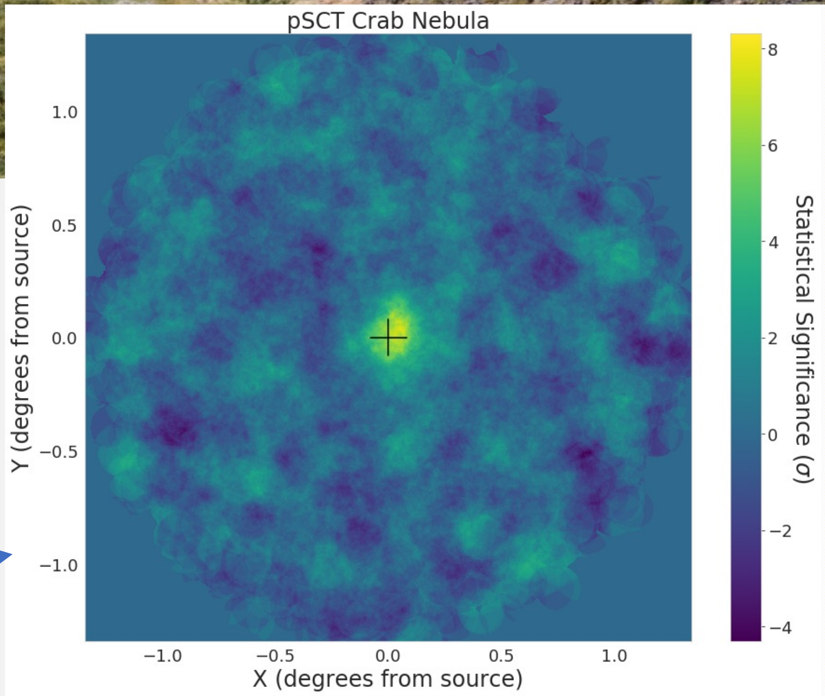


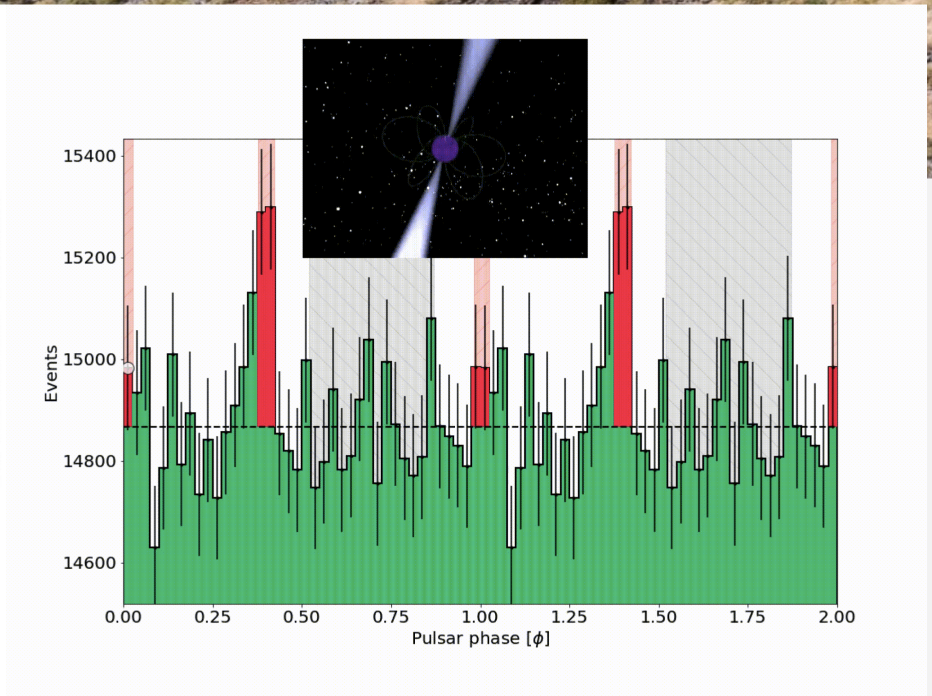
La Palma site showing MAGIC and envisaged CTA-North
Credit: CTAO/Gabriel Perez Diaz (IAC)

First-light detections!

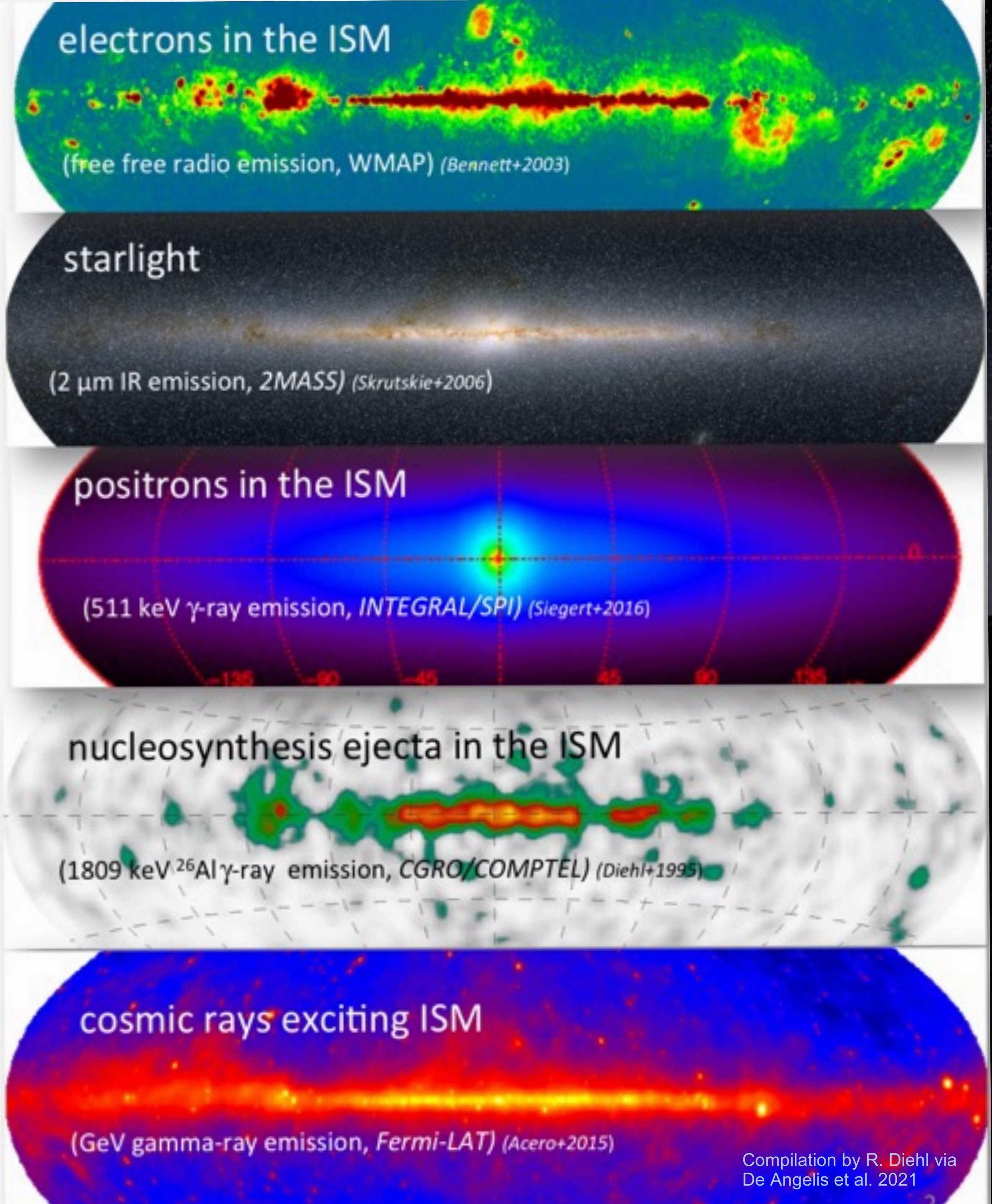
Large- medium- and small-sized telescope prototypes

Crab pulsar





Credits: CTA / SCT Consortium / LST Collaboration/ Michael Gallis, see also Lombardi et al. 2020



Compilation by R. Diehl via De Angelis et al. 2021

Contact me:
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14 UK institutions in CTA: roles in instrumentation (SST CHEC camera), software, computing resources, science
2 UK institutions in H.E.S.S.