



Fermi

Gamma-ray Space Telescope



GeV to TeV Connections

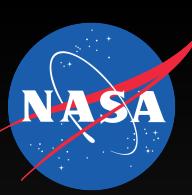
Regina Caputo
NASA/GSFC

Multimessenger Data Analysis in the
Era of CTA

24 June 2019

Sesto





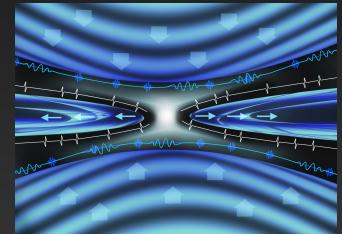
Gamma-ray Production



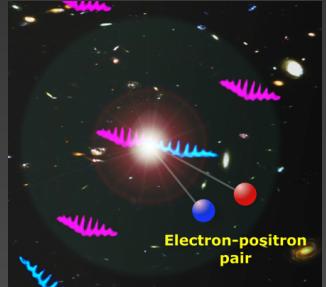
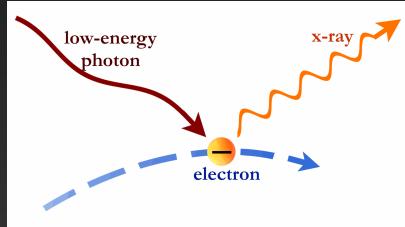
Energy source: **extreme events & systems**



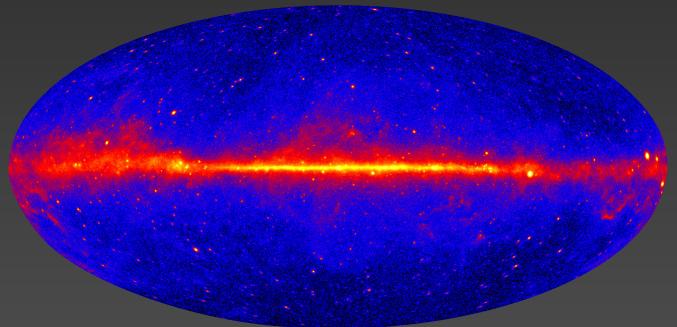
Acceleration mechanisms: **extreme fields**



Gamma-ray production mechanism: **cosmic rays and targets**

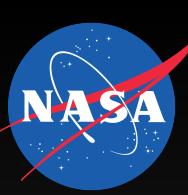


Absorption/propagation:
foregrounds

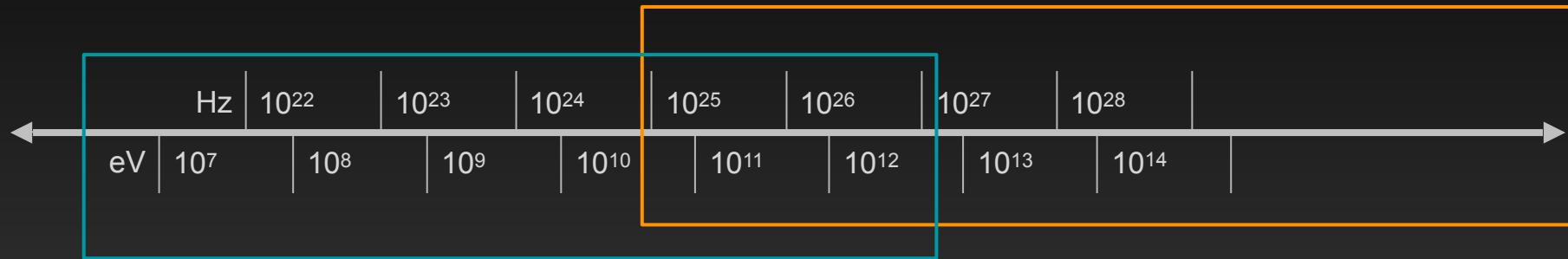


Gamma-ray sky

Same processes produce gamma-rays
from MeV to >TeV energies

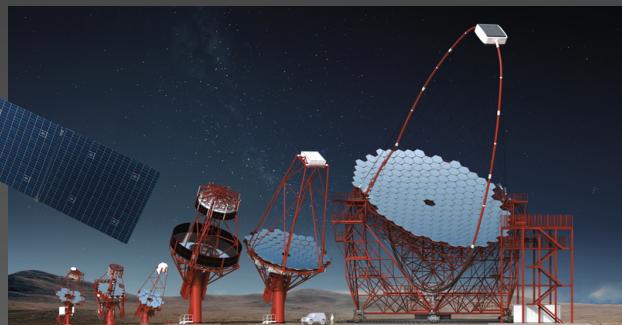
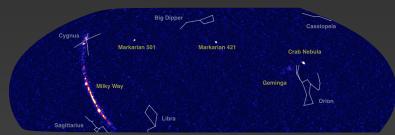
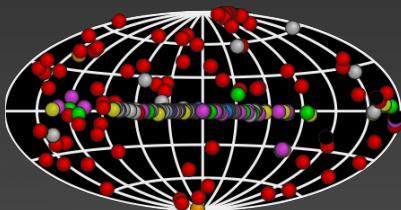
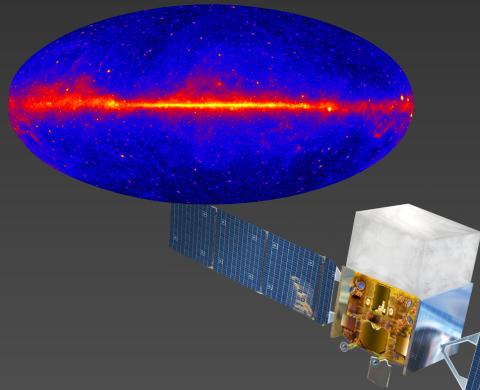


Non-thermal Gamma-ray Emission



High Energy Gamma-rays
(aka GeV or HE)

Very High Energy Gamma-rays
(aka TeV or VHE)



The *Fermi* Observatory



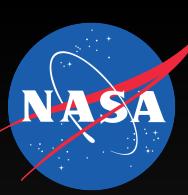
Gamma-ray Burst Monitor (GBM):

8 keV to 40 MeV
entire unocculted sky

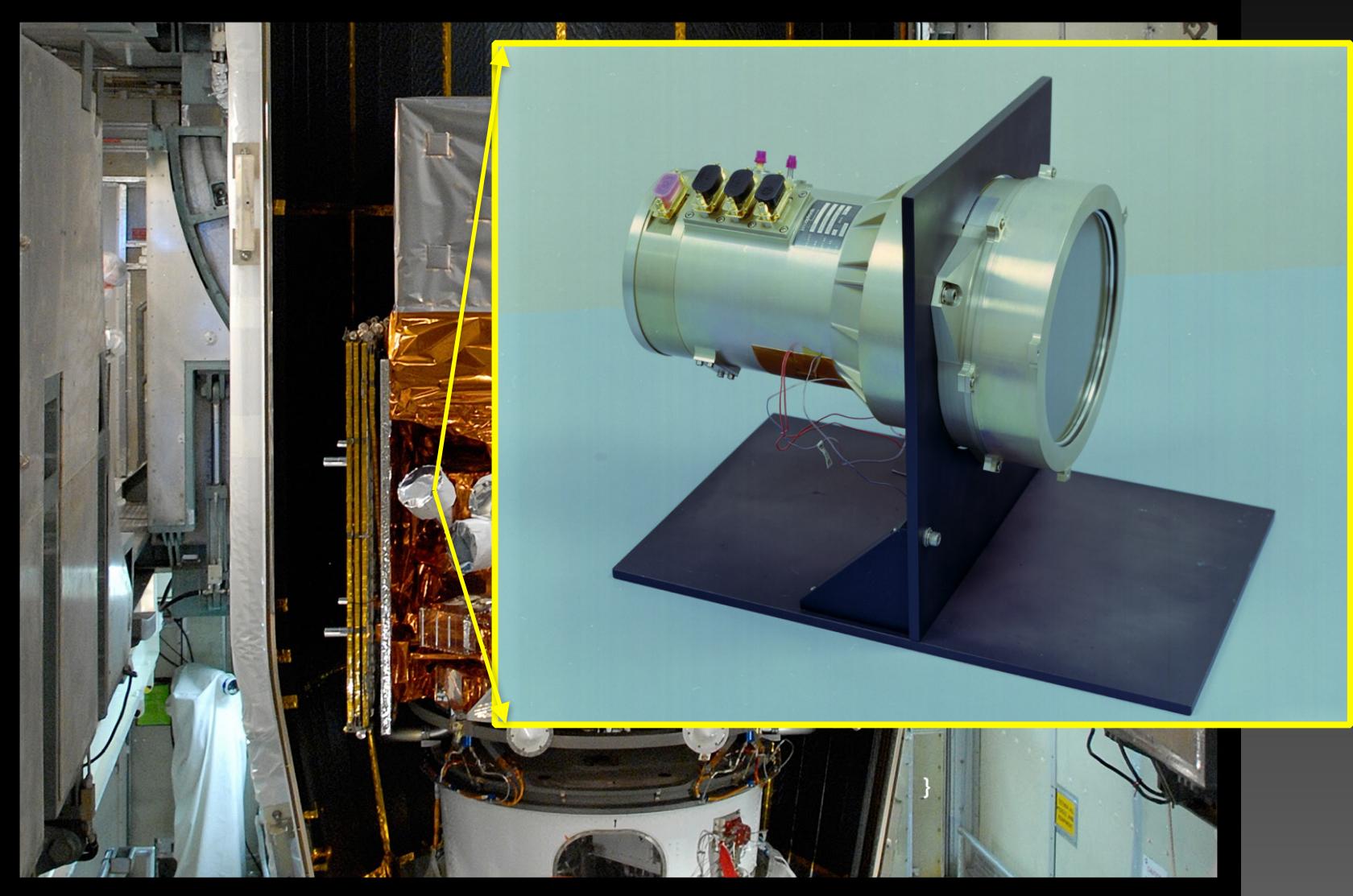
Large Area Telescope (LAT):

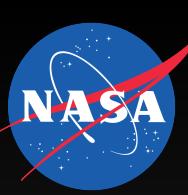
20 MeV to >1 TeV
20% of the sky, entire sky
every 3 hours

Complementarity with targeted/pointed observations:
Full sky, broad energy range, and public data

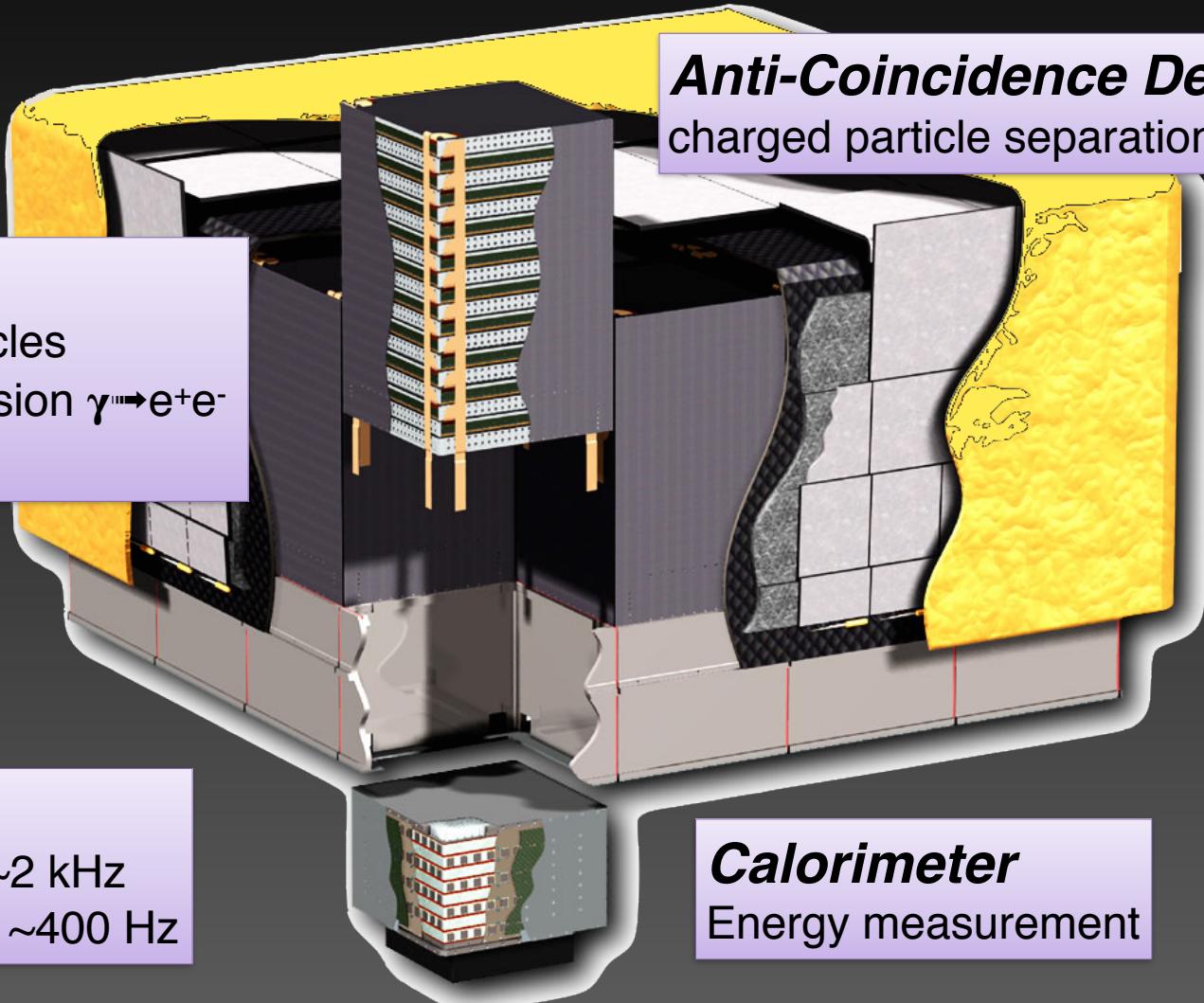


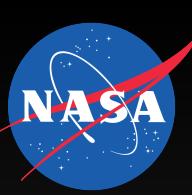
Fermi Gamma-ray Burst Monitor (GBM)





Fermi Large Area Telescope (LAT)





Fermi-LAT γ -ray sky

Extragalactic Sources

Active Galactic Nuclei
Starburst Galaxies...

+ Supernova Remnants
+ Pulsar Wind Nebulae
+ Globular Clusters
+ ...

Galactic Sources

Local Sources

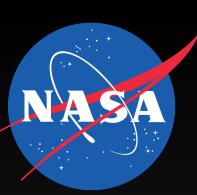
Solar Flares +
Terrestrial Gamma-ray Flashes

Pulsars

>5000 sources

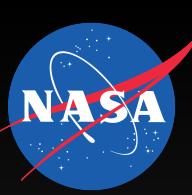
>1 GeV,
9 year map

Exotic and Transient Astrophysics



Fermi-LAT Catalogs

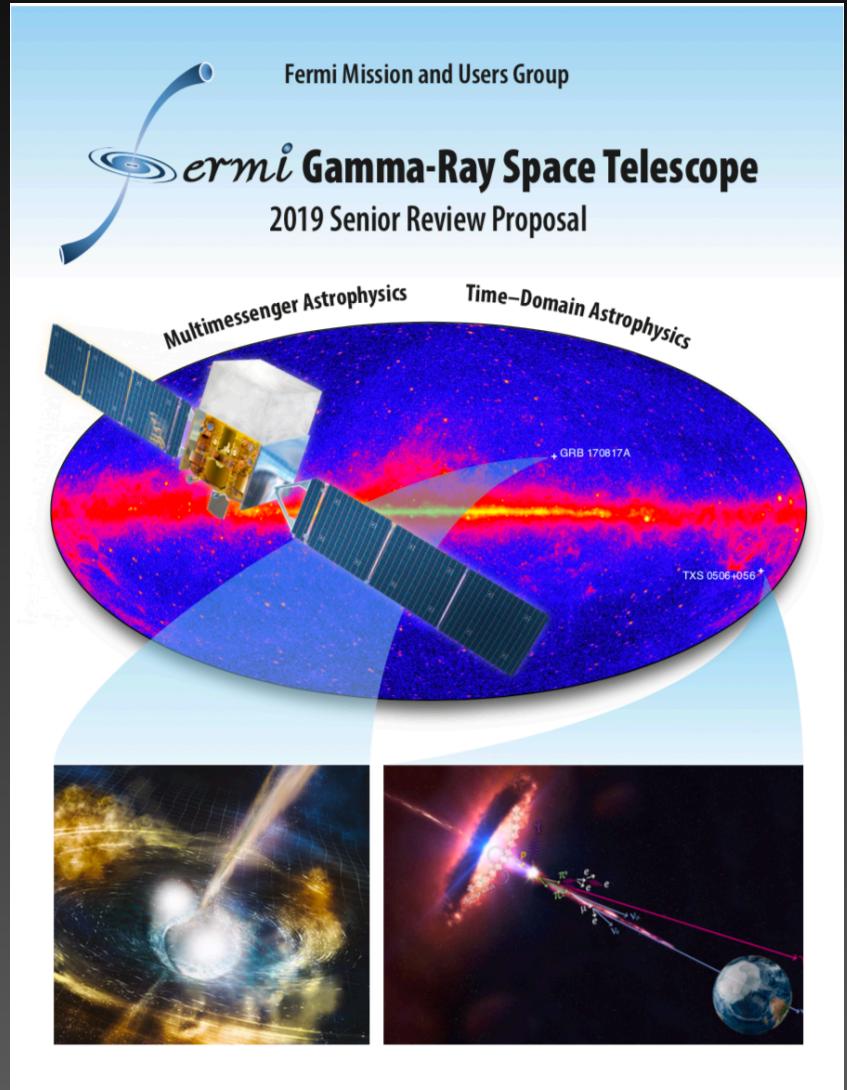
- 4th Fermi PointSource Catalog (4FGL)
- 2nd GRB Catalog
- 2nd LAT AGN Catalog (2LAC)
- 3rd Pulsar Catalog
- 3rd Fermi High Energy Catalog (3FHL)
- 1st Fermi-LAT Low Energy Catalog (1FLE)
- Fermi-LAT Extended Source Catalogs (FEGS,FHES)
- ...<https://fermi.gsfc.nasa.gov/ssc/data/access/lat/>
- In the works: Solar Flare Catalog, 3LAC, transient

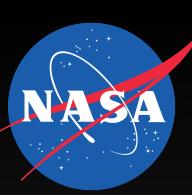


Fermi Senior Review

Fermi Primary Mission Objectives:

- Detect additional sGRB-GW counterparts (Disentangle emission structure, dynamics and viewing geometry of NS mergers)
- Use sGRB-GW time delays as probes of cosmology, fundamental physics and neutron star physics
- Resolve emission mechanisms in blazers by finding gamma-ray flares in coincidence with high-energy neutrinos

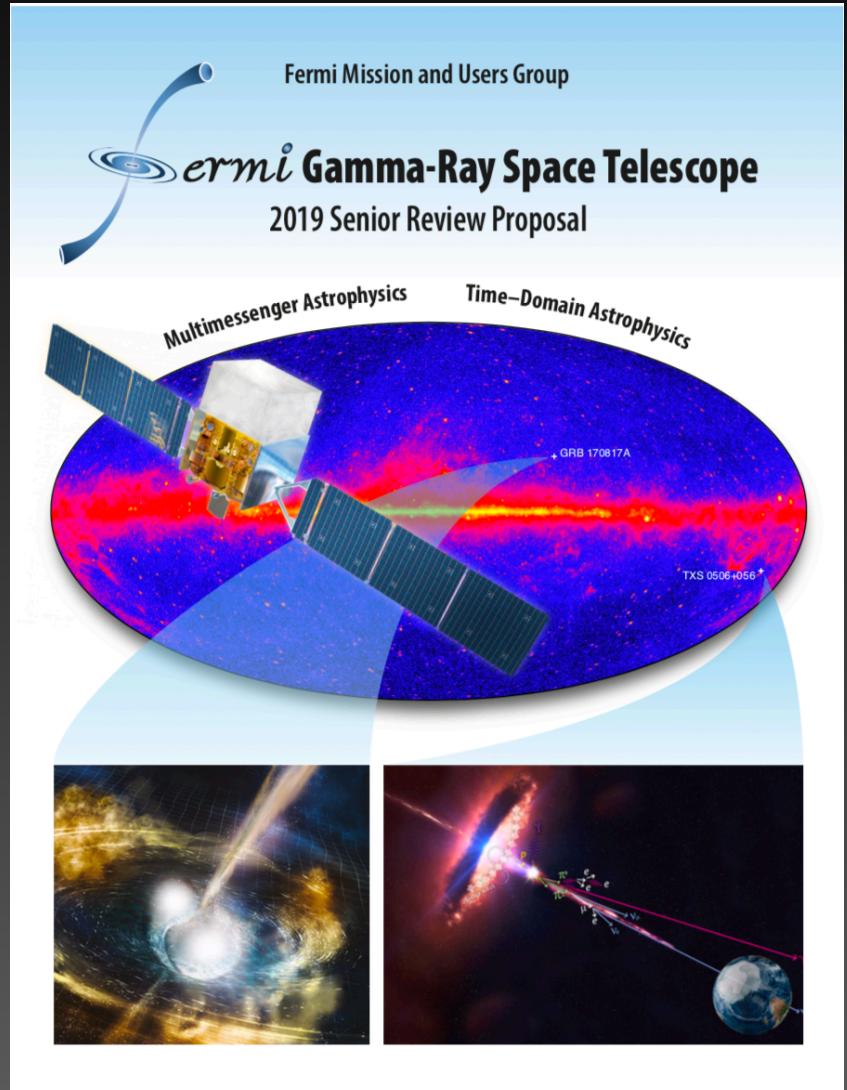


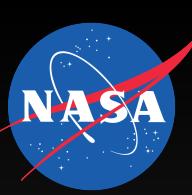


Fermi Senior Review

Fermi Primary Mission Objectives:

- Resolve physical processes in gamma-ray novae and other galactic binaries by measuring simultaneous multiwavelength light curves.
- Explore and interpret the growing diversity of gamma-ray pulsar systems - including adding new MSPs to PTAs
- Identify new temporal behavior only measurable with long baselines such as binary SMBHs.





CTA Key Science Programs

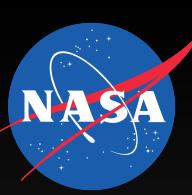
CTA key science programs (KSP)
overlap completely with Fermi science

CTA Science book mentions Fermi 108 times

The full sky capability and
overlapping energy range make
Fermi-LAT and CTA unique observing
partners

>10 GeV,
3FHL map

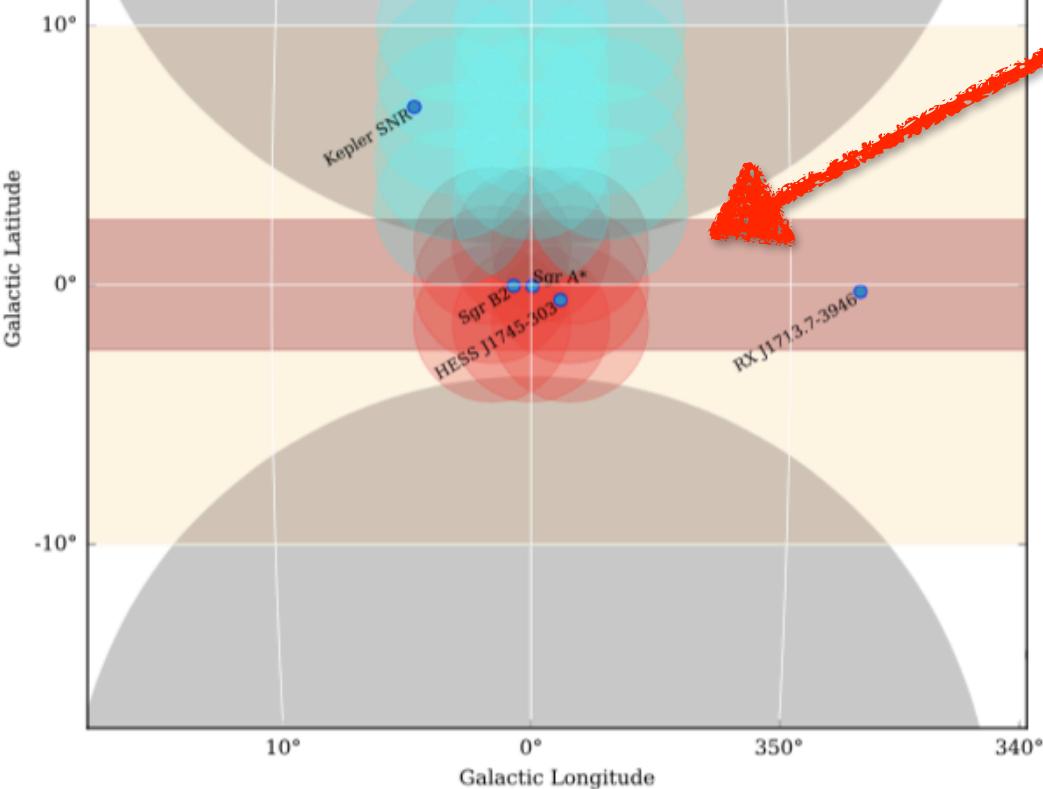
**L. Tibaldo counted



Galactic Program

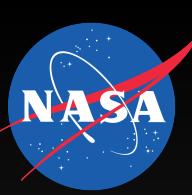
Connection between the central engine and the Fermi bubbles

Optical Bulge
Scale Height
Fermi Bubbles
Central Survey
Extended Survey



Galactic Center Observations

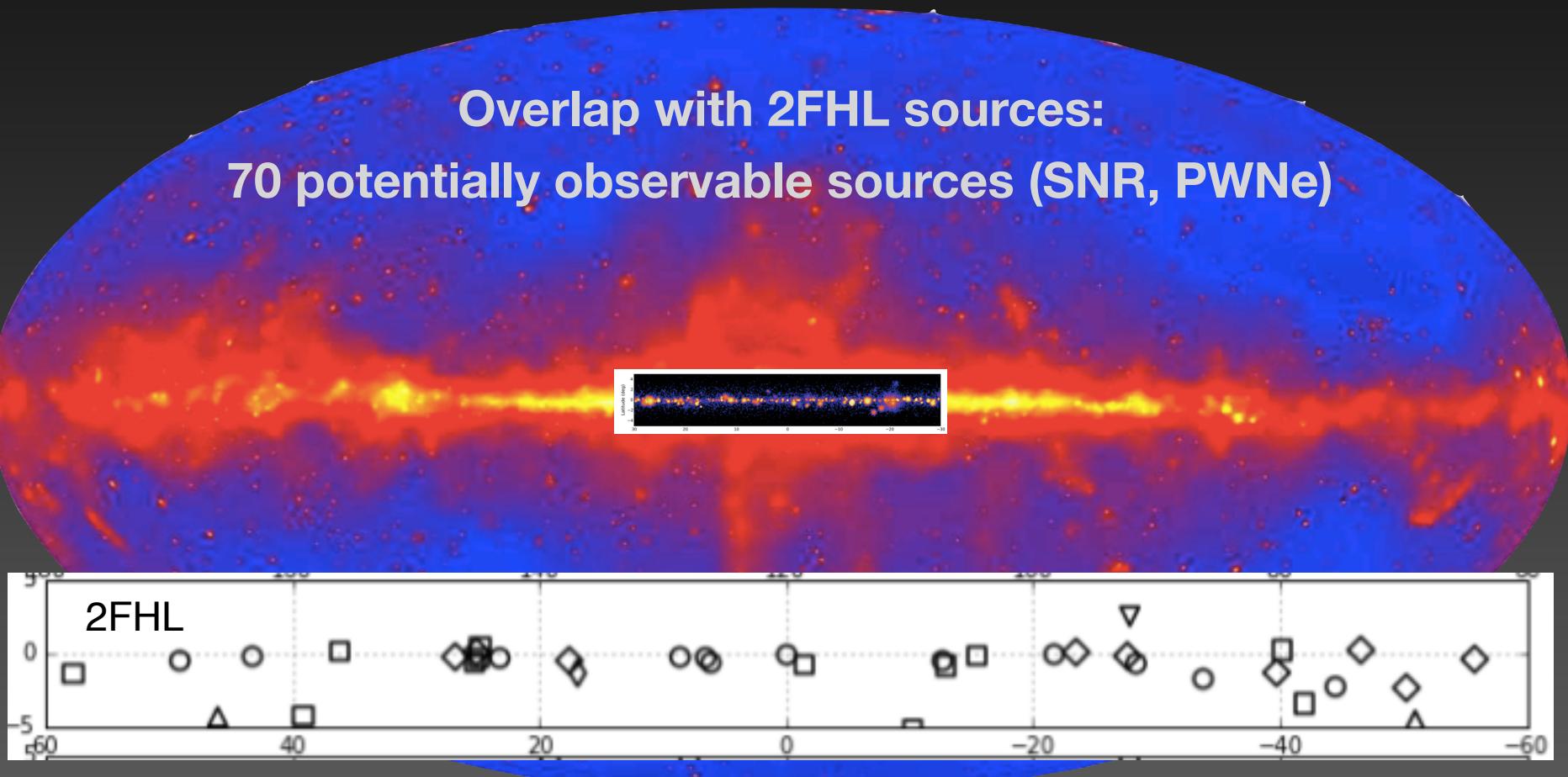
High energy diffuse emission complementary to Fermi-LAT observations
 <100 GeV

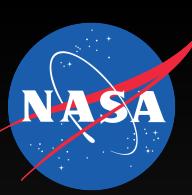


Galactic Program

Galactic Plane Survey

Overlap with 2FHL sources:
70 potentially observable sources (SNR, PWNe)

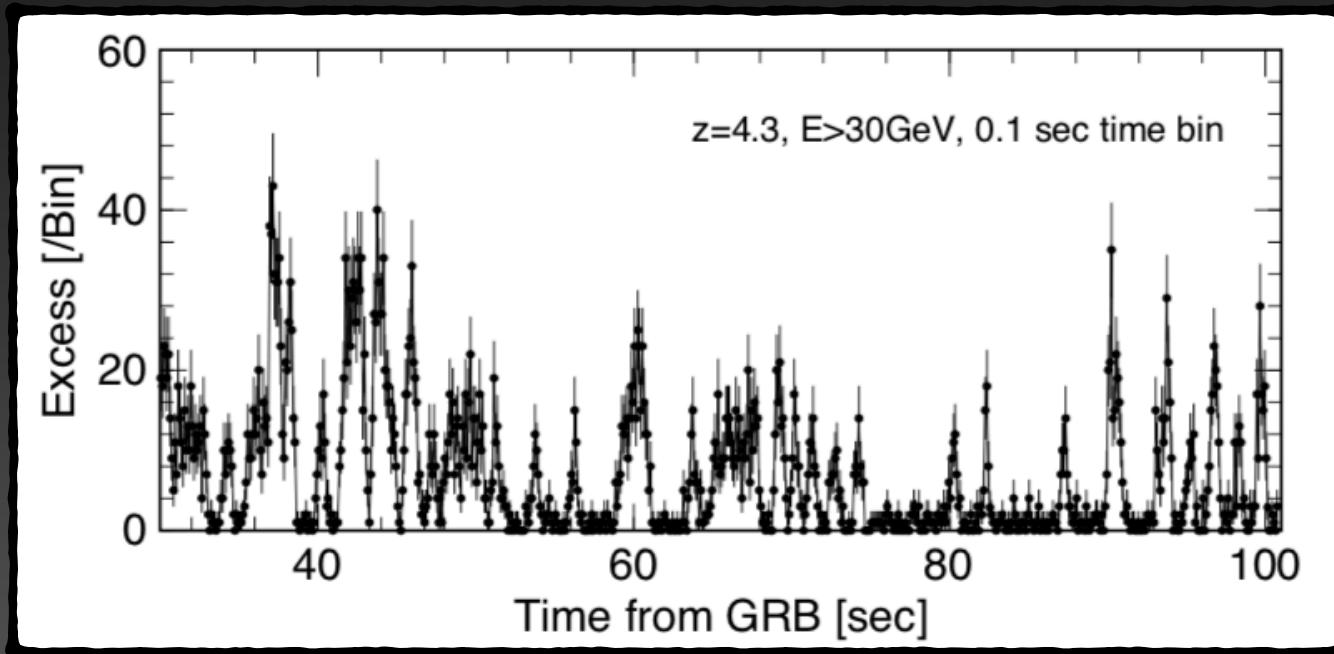




Transient Program

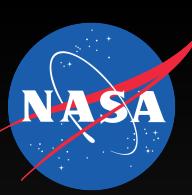
Gamma-ray Bursts

Fermi-LAT observations illustrate potential for CTA detections

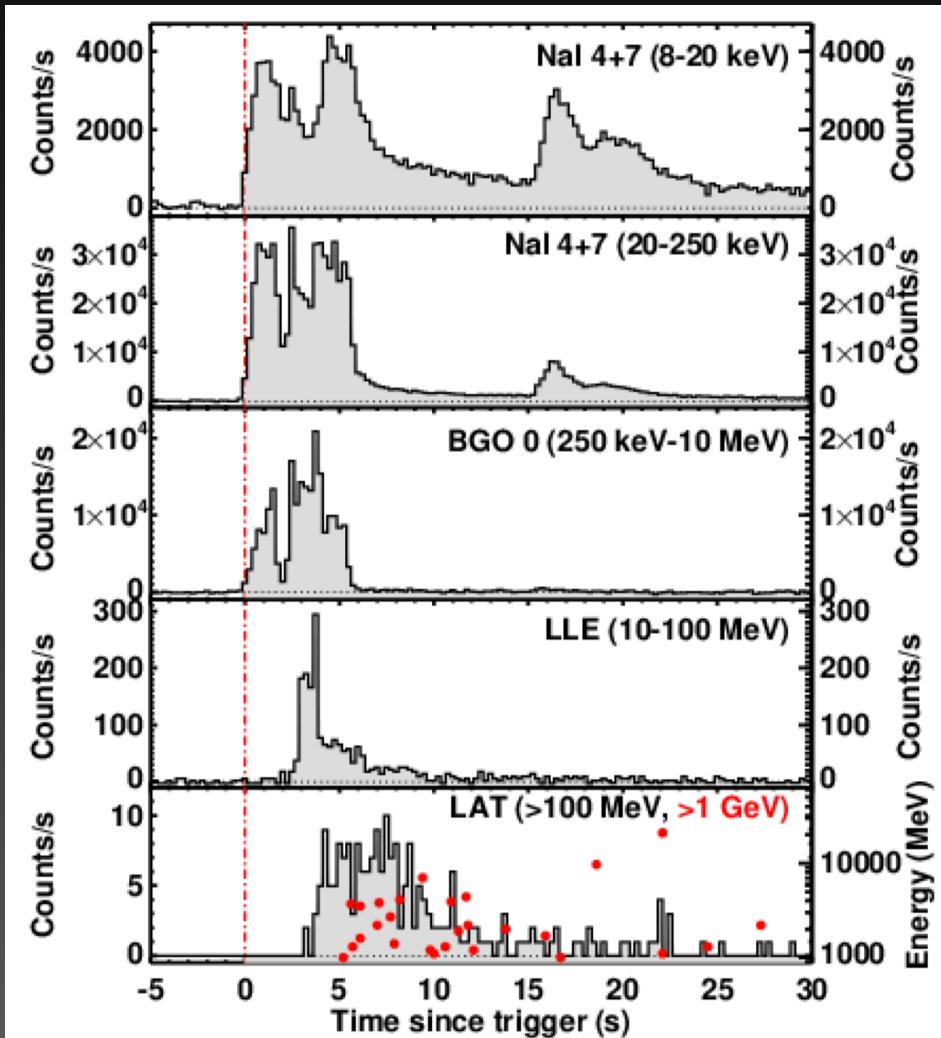


Simulated CTA light curve of GRB 080916C

Extrapolation from Fermi-LAT light curve above 0.1 GeV



GRB190114c



First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; **Razmik Mirzoyan on behalf of the MAGIC Collaboration**
on 15 Jan 2019; 01:03 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

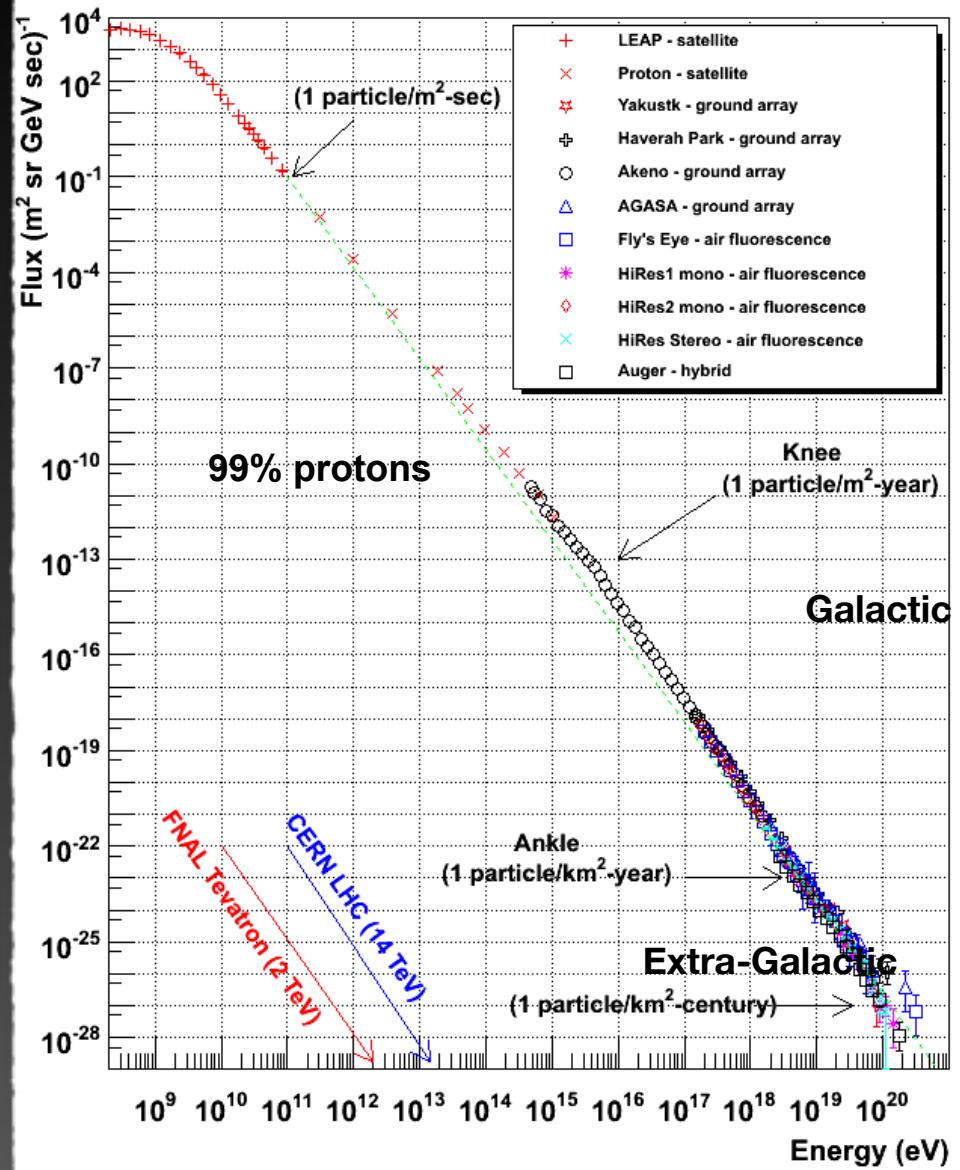
Referred to by ATel #: 12395

[Tweet](#)

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al., GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300 GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.



Cosmic Ray Spectra of Various Experiments

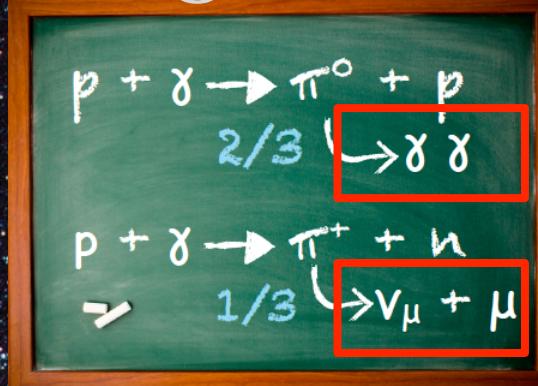


Multimessenger Program

What is creating
these ultra-high
energy particles?

Multimessenger Program

Neutrinos are
the smoking gun
signature for
hadronic
acceleration.



Fermi Gamma-ray
Space Telescope



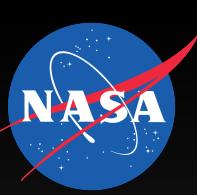
Proton

Photon

Neutrino

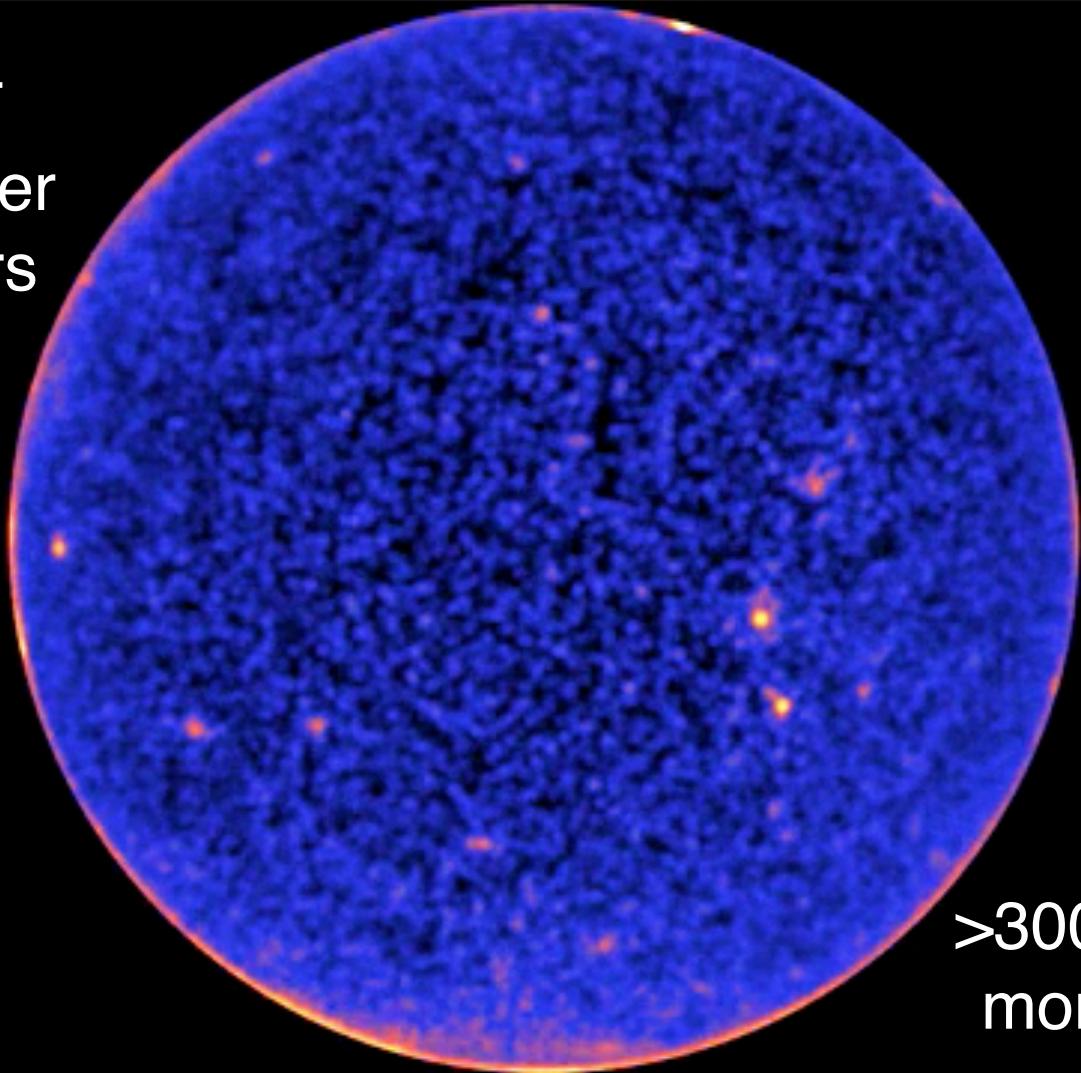
IACTs

Goal:
Find neutrinos coming
from an extra-galactic
source

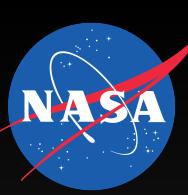


Variable *Fermi*-LAT γ -ray sky

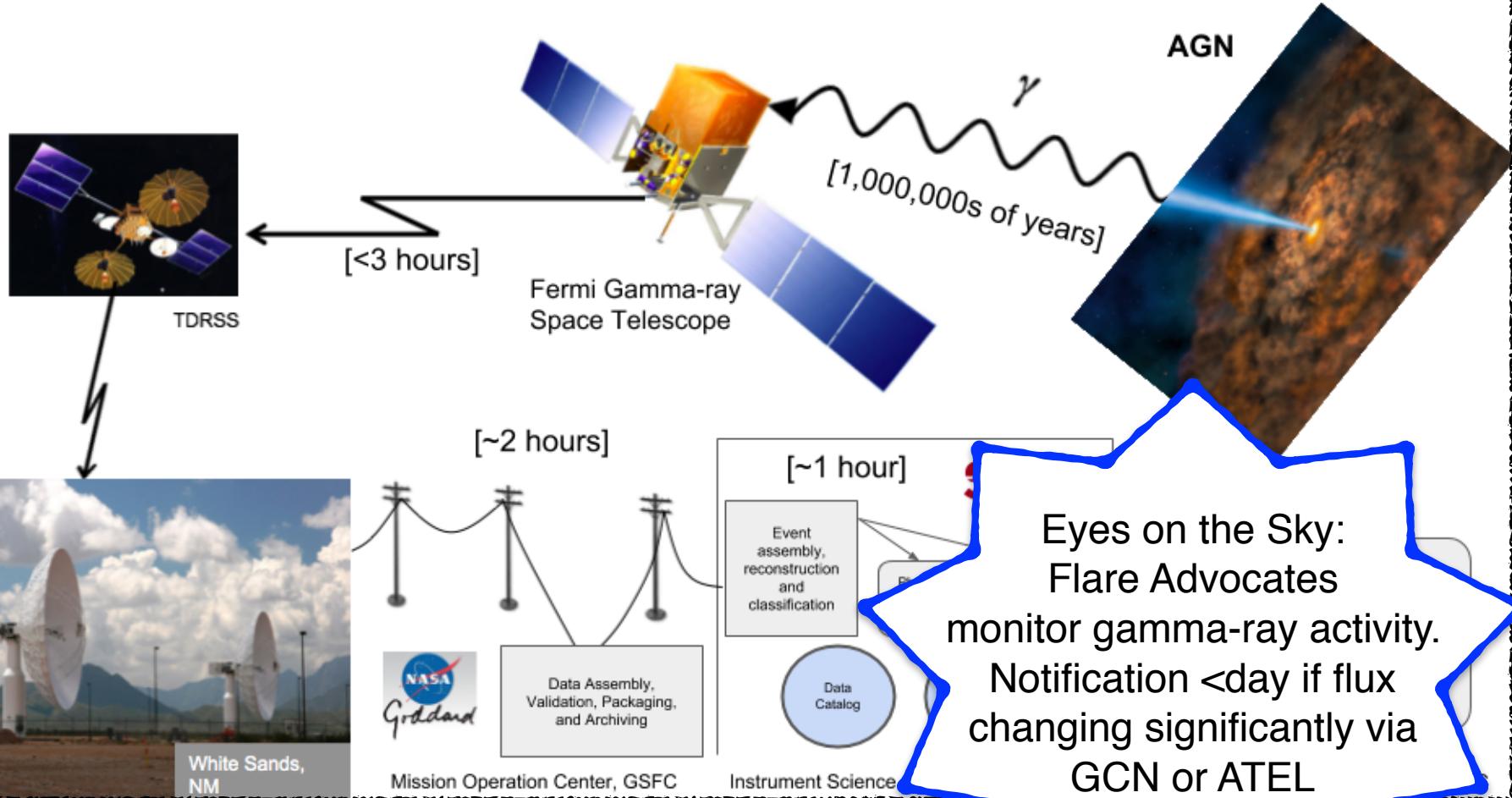
Fermi-LAT
observes over
2000 blazars

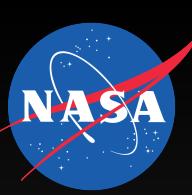


>300 MeV over 3
months in 2008

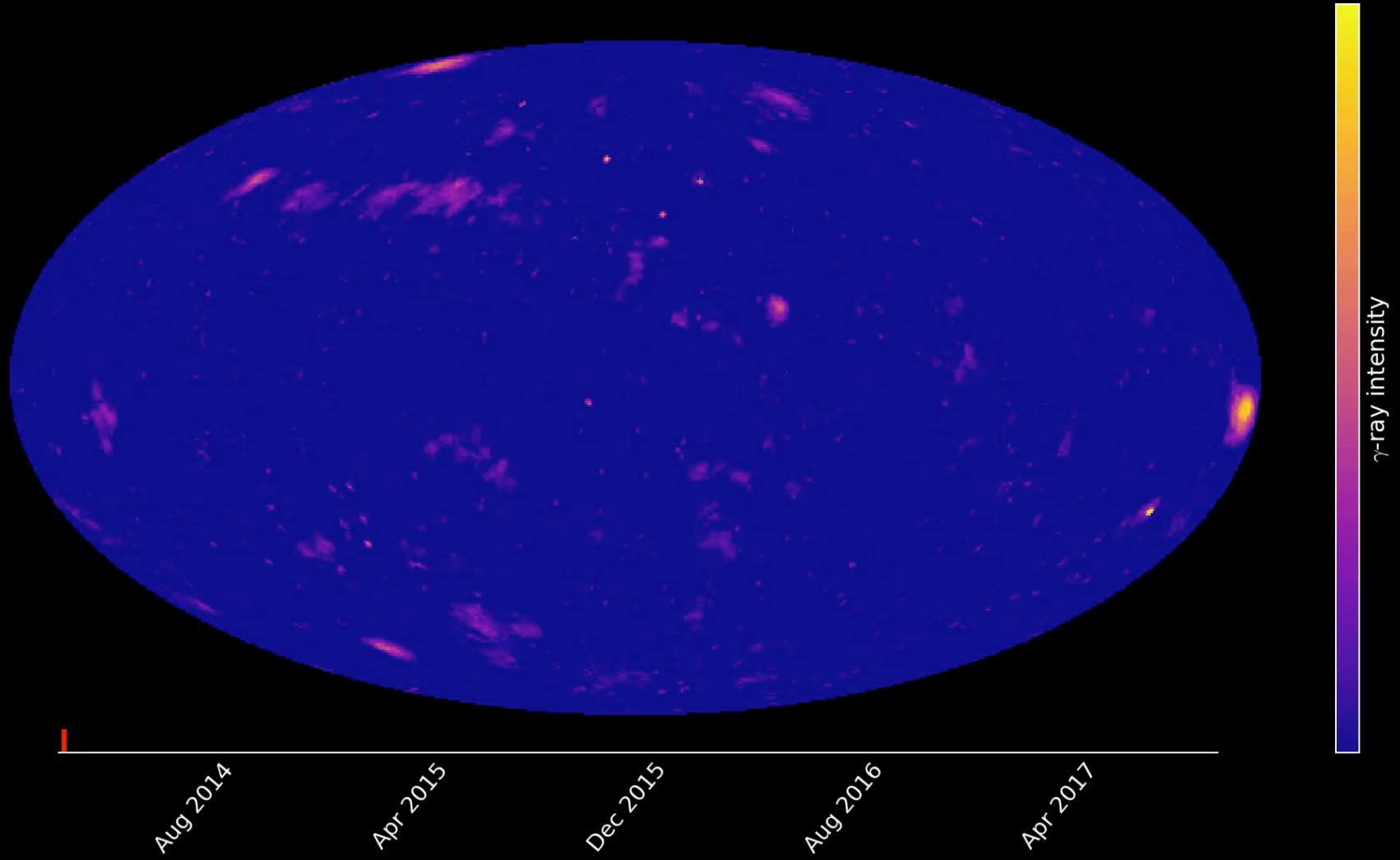


Variable *Fermi*-LAT γ -ray sky





IceCube starts issuing Transient Alerts





GCN Circular:
21916

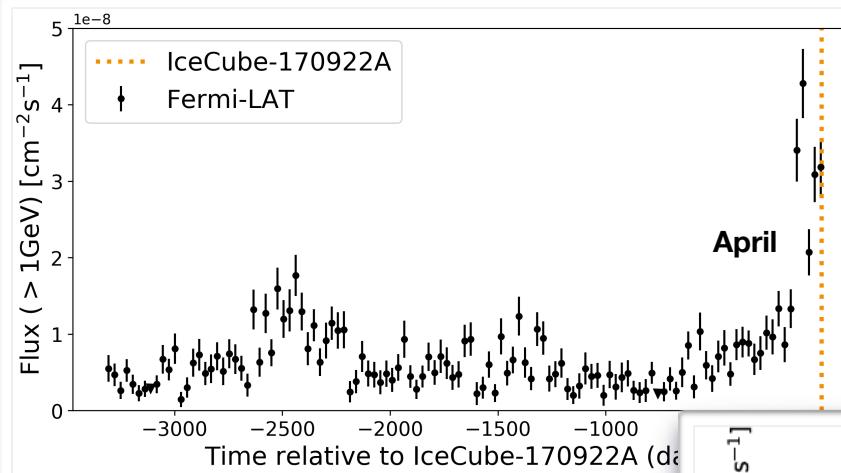


IceCube

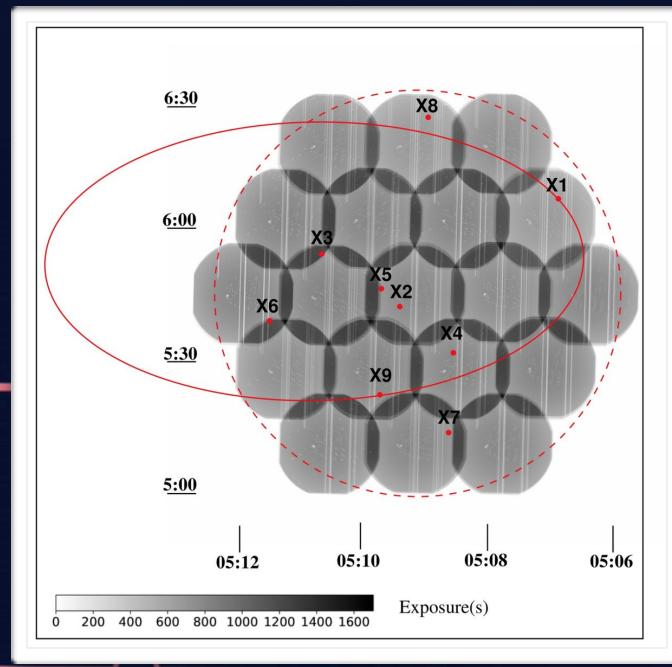
GCN Circular:
21930



Swift



Kanata, NuSTAR
October 12



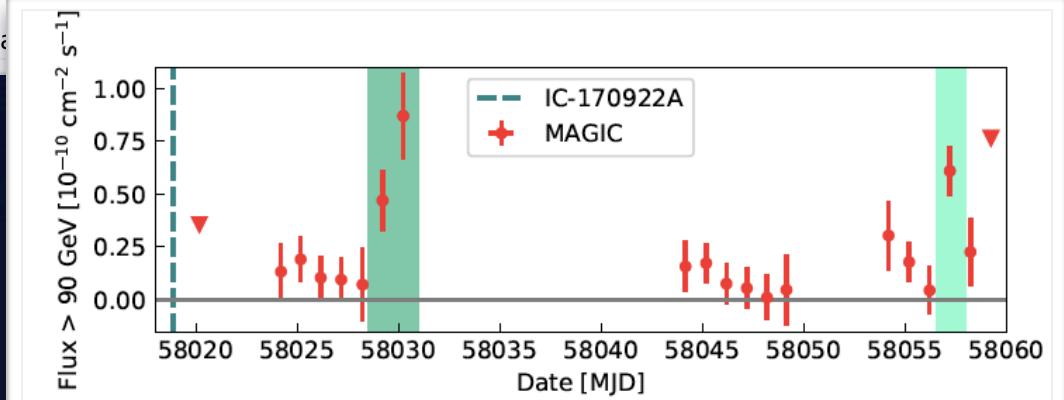
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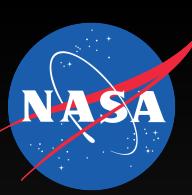


MAGIC
October 4

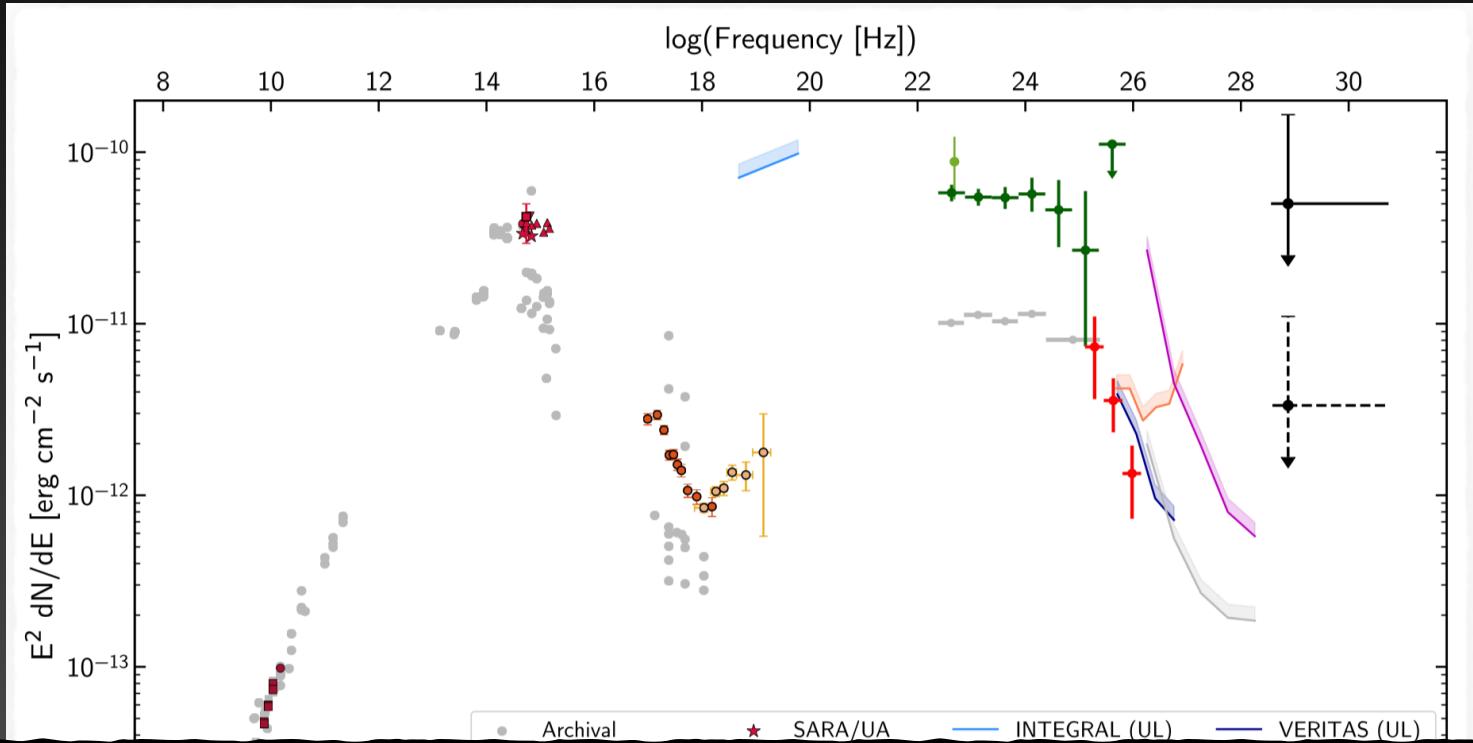
ATel: 10817

Liverpool, AGILE
September 29

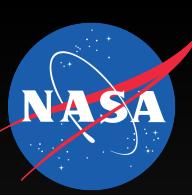




Spectra of TXS 0506+56 across wavelengths and messengers

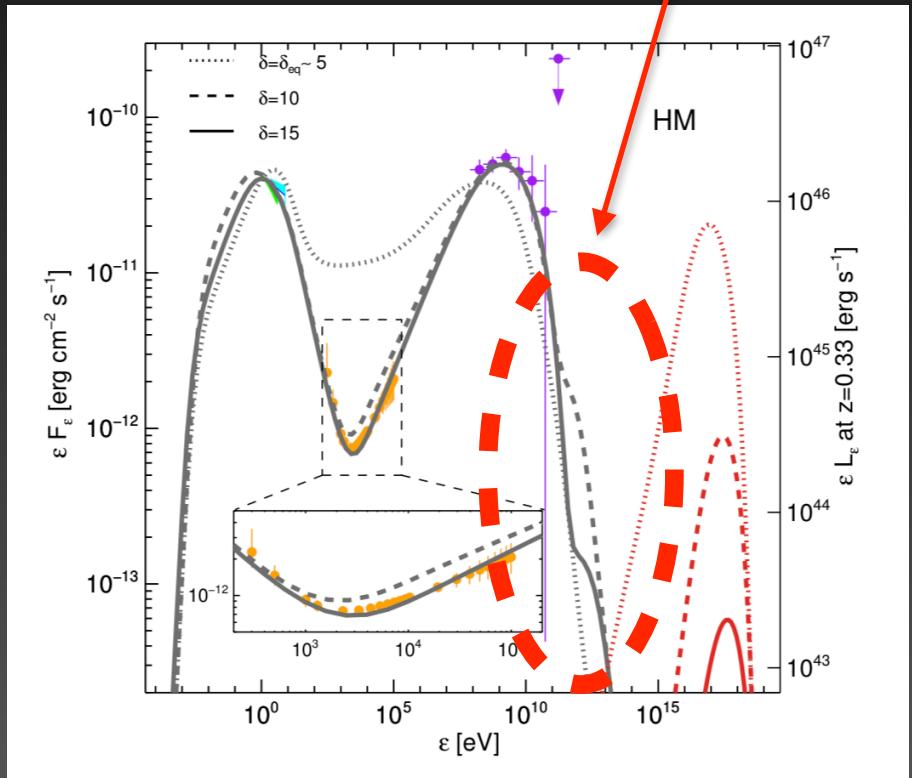


Joint detection of TXS 0506+56 with Fermi-LAT and MAGIC in the flaring state made evidence of hadronic production in the particle jet possible

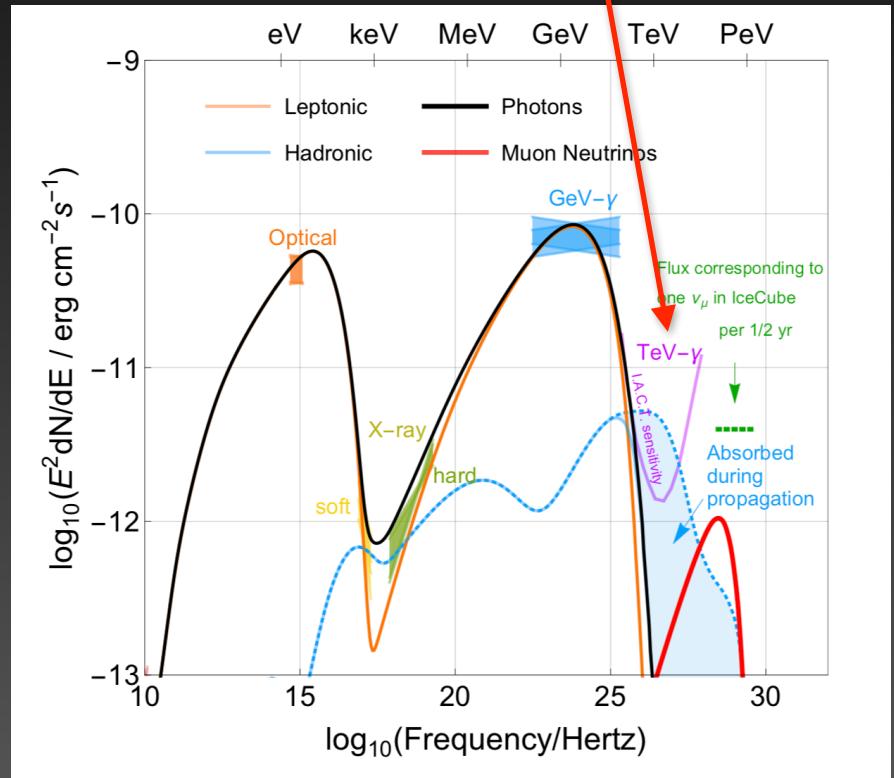


Leptonic, Hadronic... Both?

CTA can give insight on particle jet composition



Keivani et al. (2018)

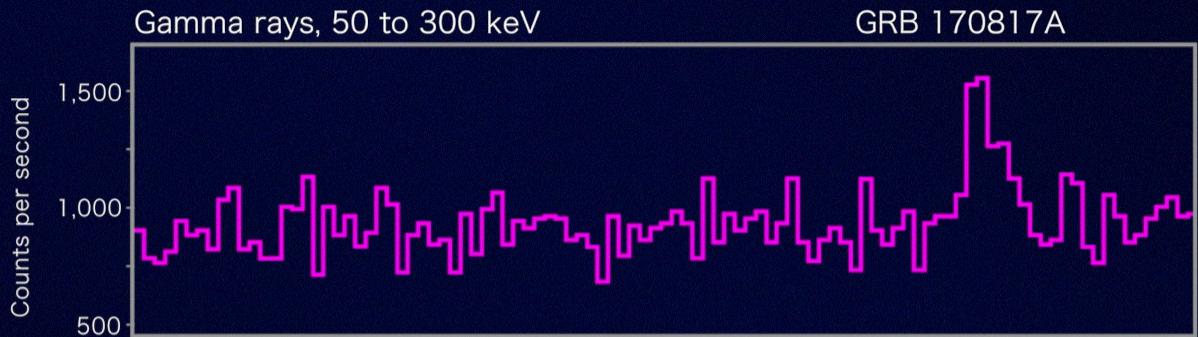


Gao et al. (2018)

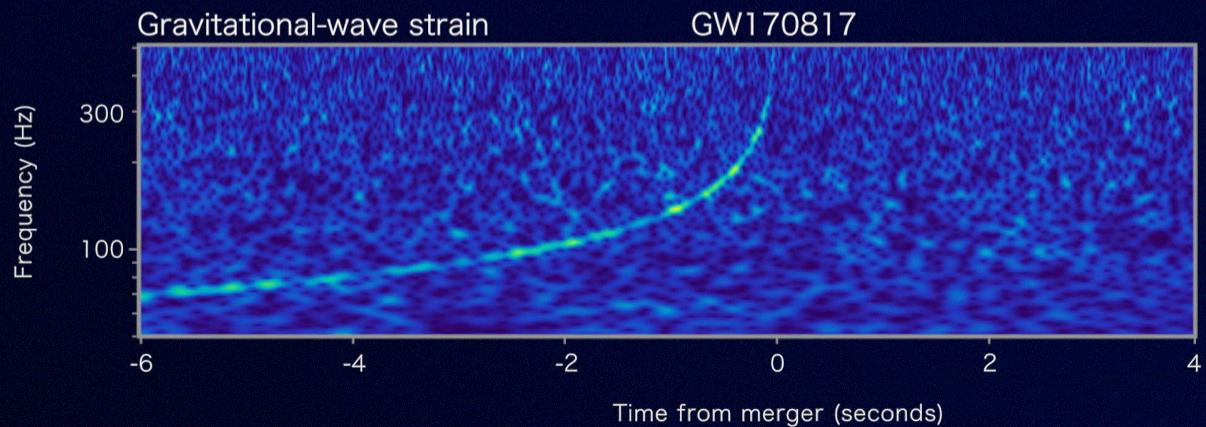


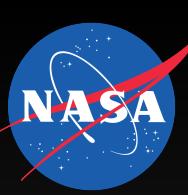
17 August 2017

Fermi



LIGO



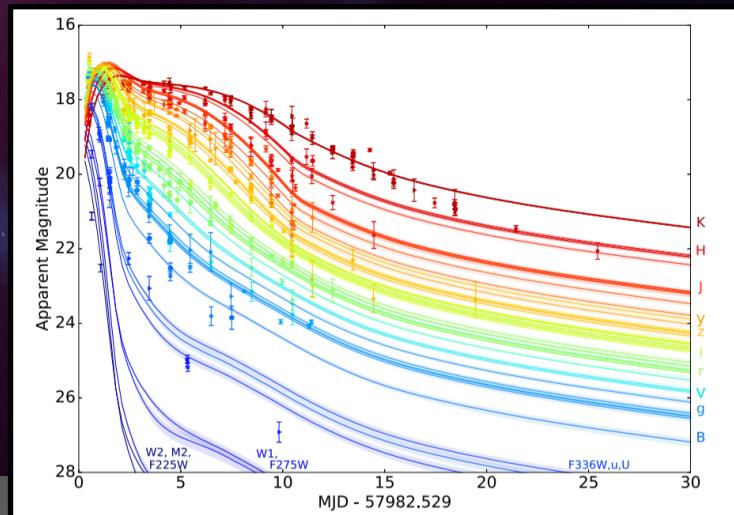
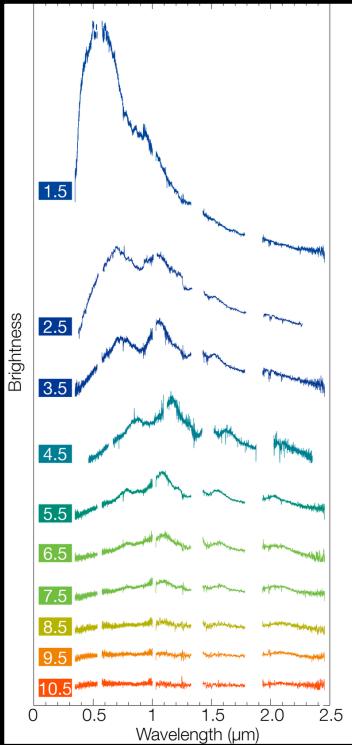


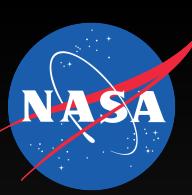
The Multimessenger Age

The unbound neutron star material undergoes r-process nucleosynthesis, expands, decays, and emits thermal radiation as a kilonova

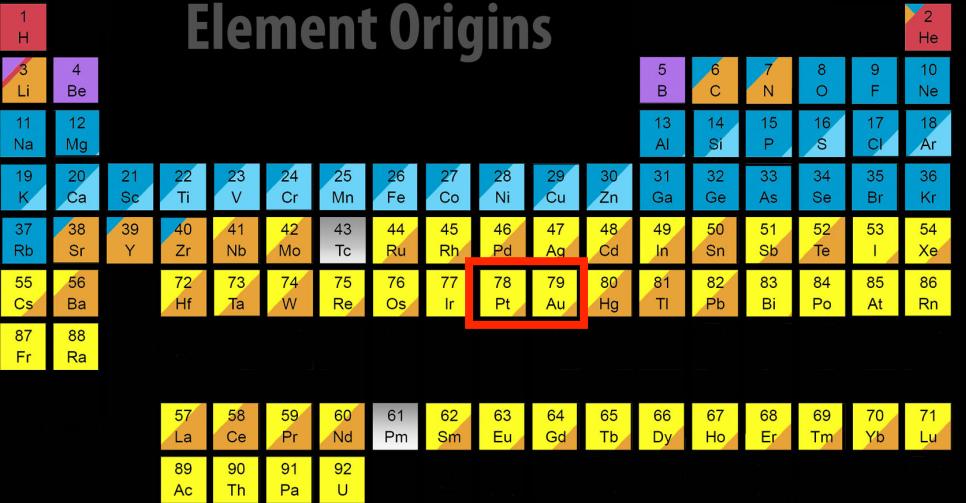
$t = \text{hours}$
to weeks

The kilonova emission evolves from UV → Optical → IR on a timescale of hours to weeks and reveals the details of the early merger and the ejecta velocity, mass, and composition





What did we learn?

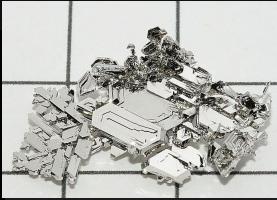
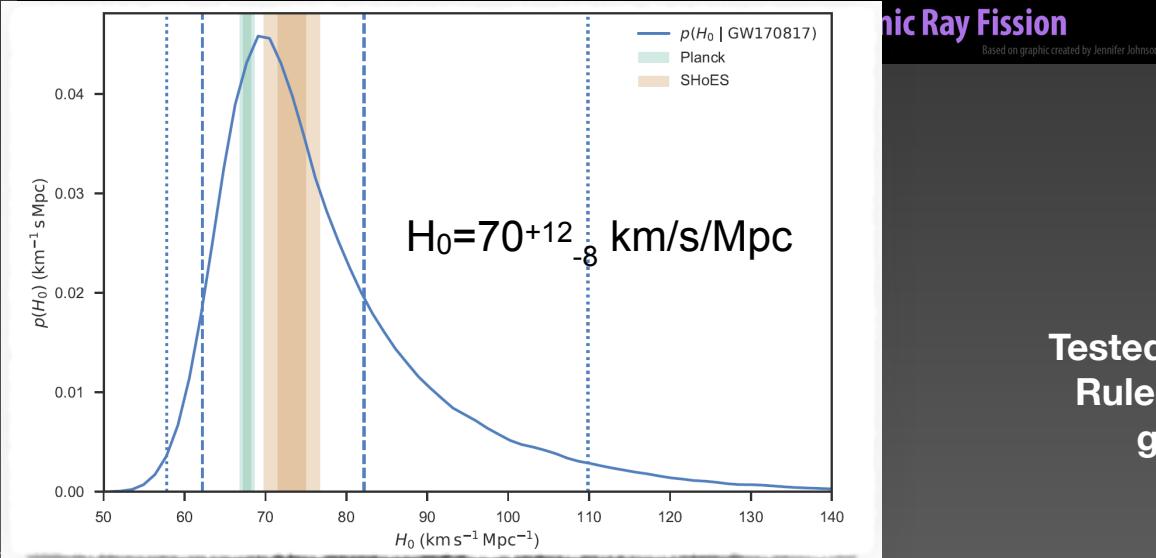


Merging Neutron Stars

Exploding Massive Stars

Big Bang
Nucleosynthesis
and Ray Fission

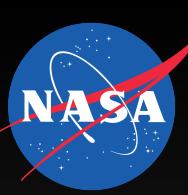
Based on graphic created by Jennifer Johnson



Speed of Gravity

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\text{EM}}} \leqslant +7 \times 10^{-16}$$

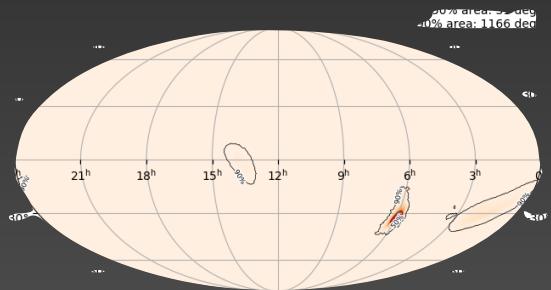
Tested Equivalence Principle of Gravity:
Ruled out many theories of modified gravity to explain dark matter



LIGO/Virgo: O3 BEGINS

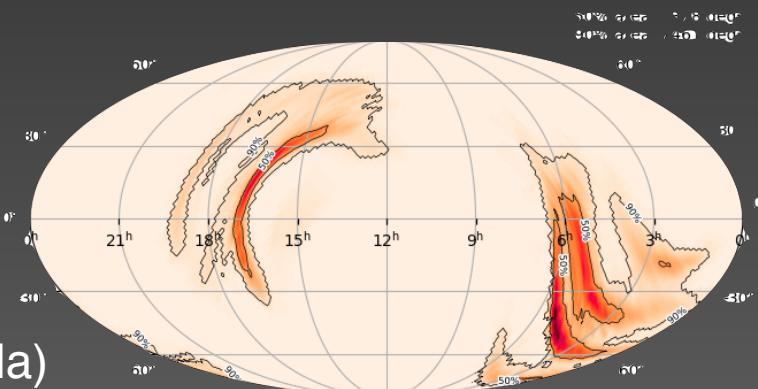
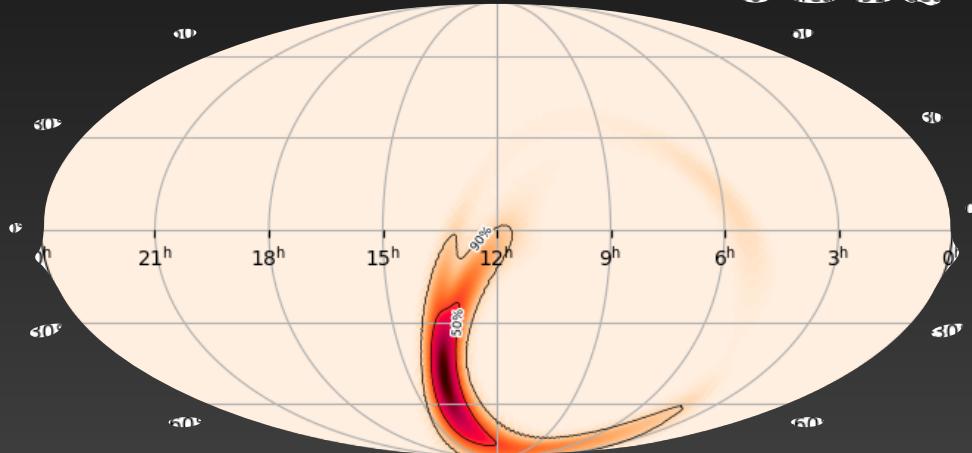
Start of O3: April 1
>10 mergers

BNS merger S190510g

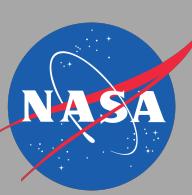


Continual GWs:
Measurements of pulsar glitches (Vela)

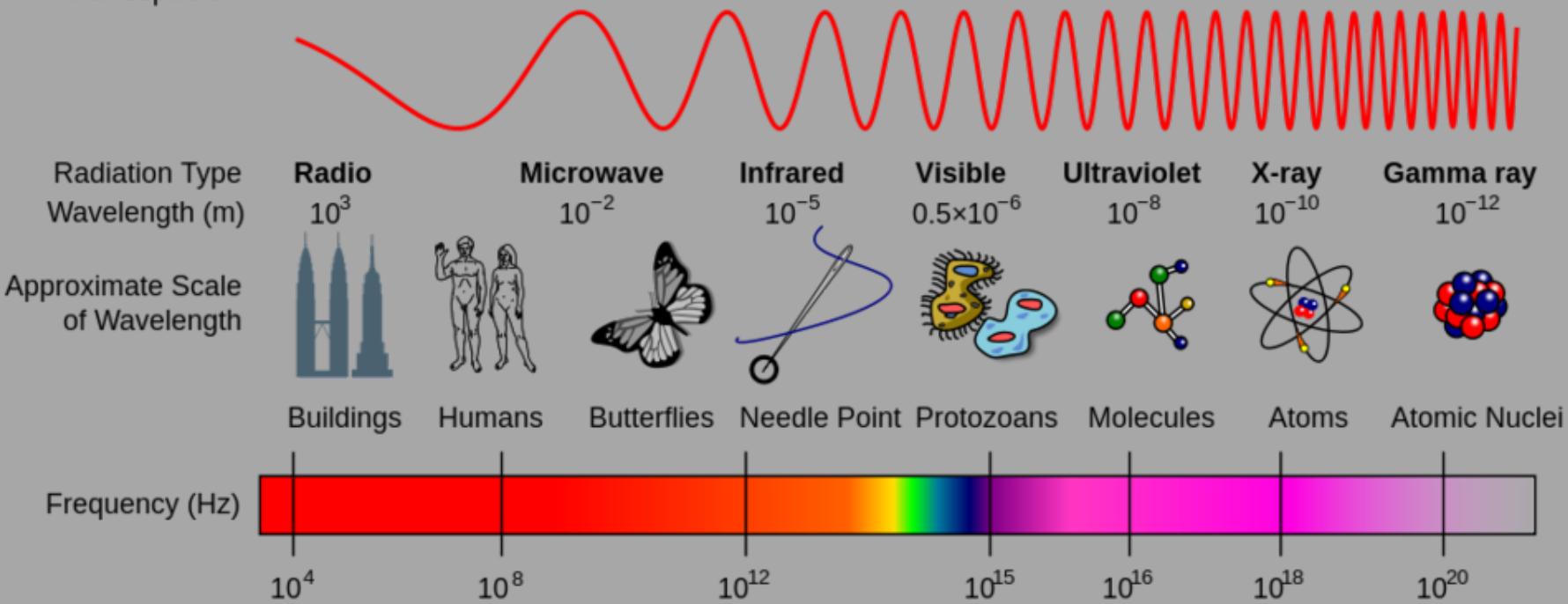
BBH merger S190421ar



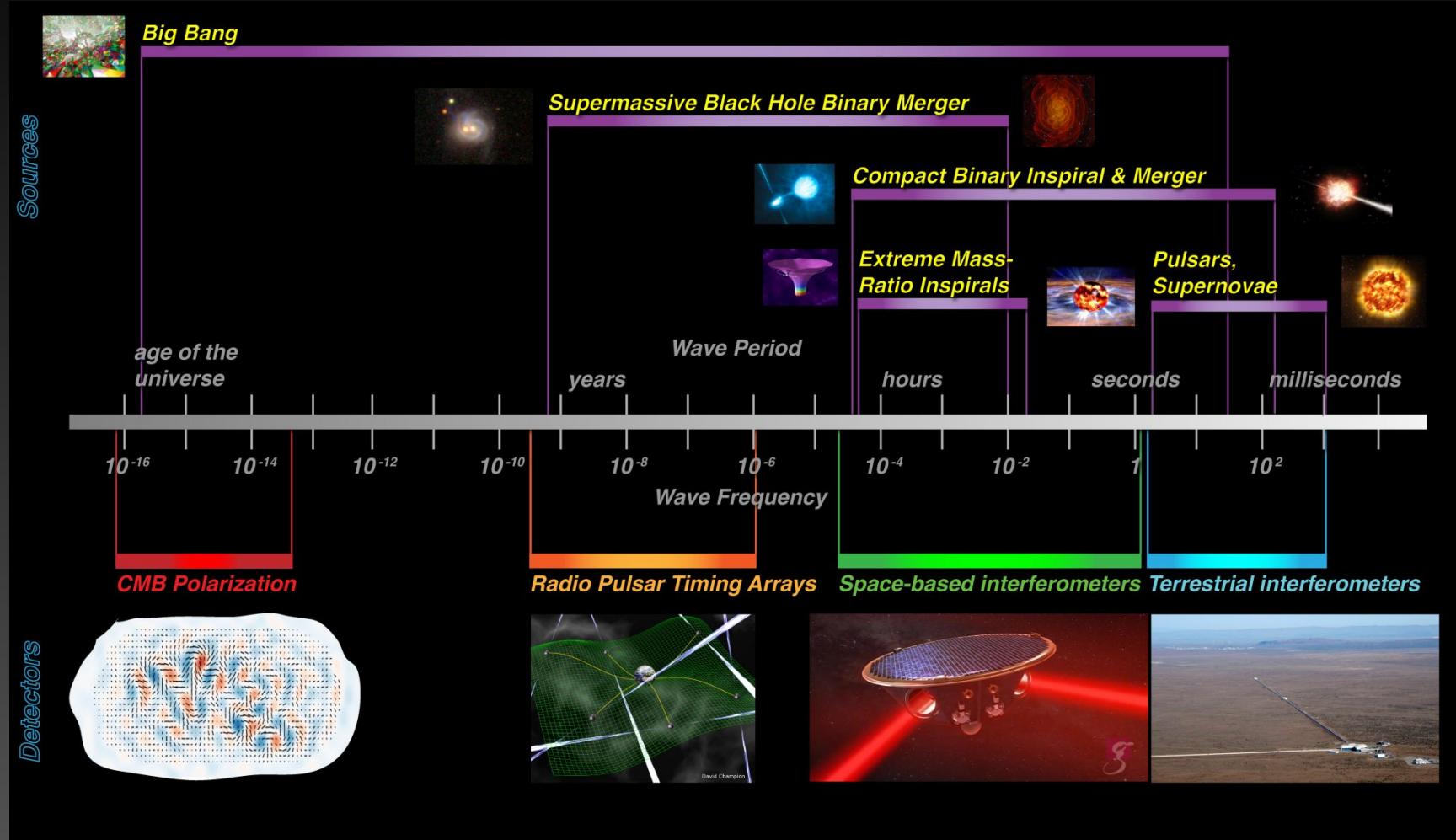
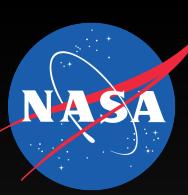
BNS merger S190425z



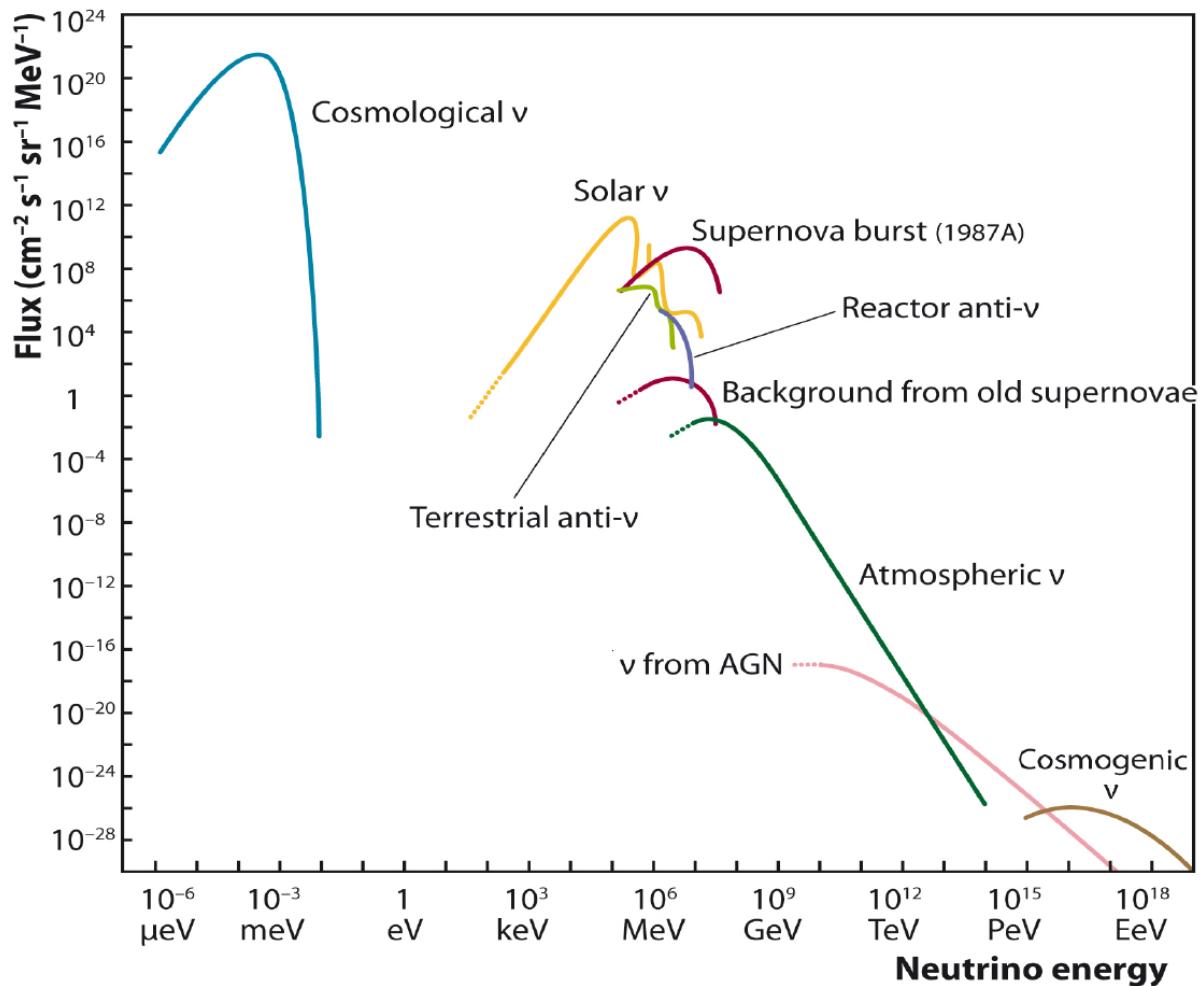
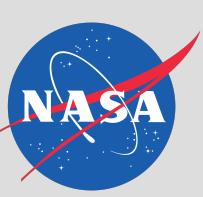
Penetrates Earth's Atmosphere?



Electromagnetic Spectrum

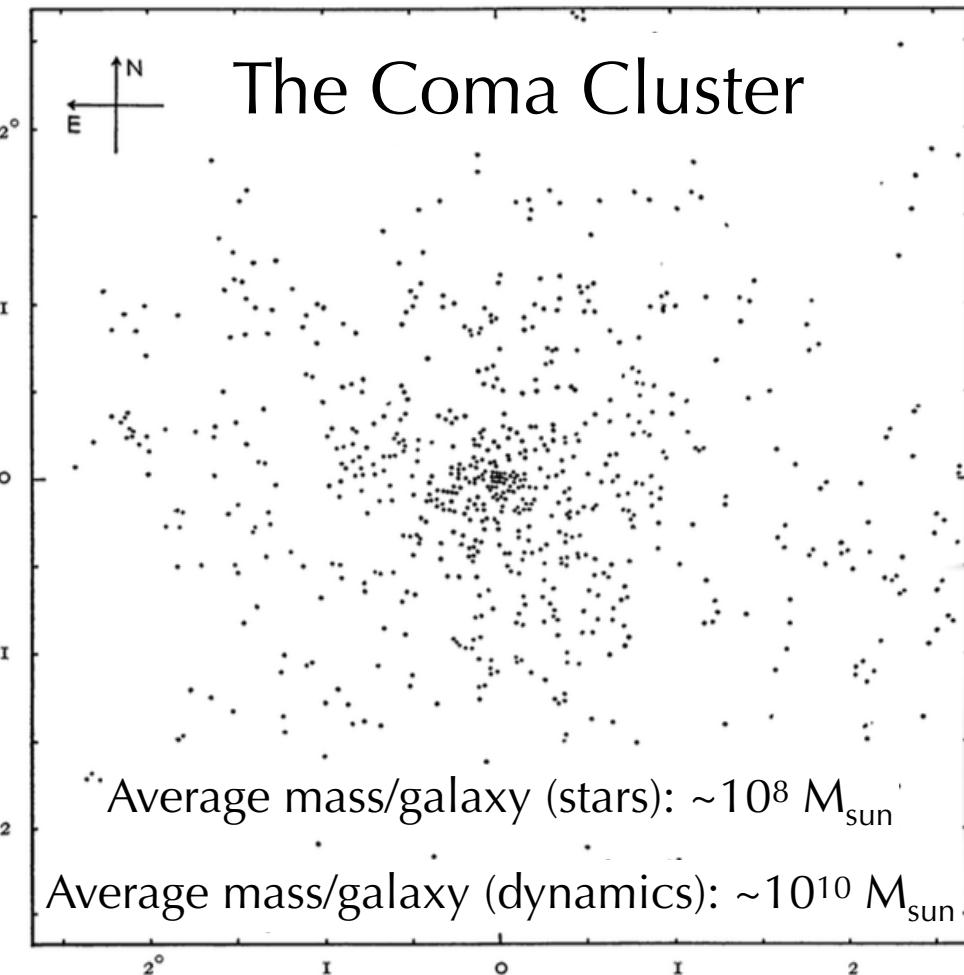


Gravitational Wave Spectrum



Neutrino Spectrum

Mystery of Missing Mass

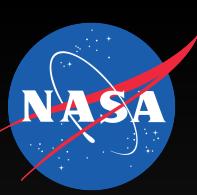


1930s- Zwicky, others

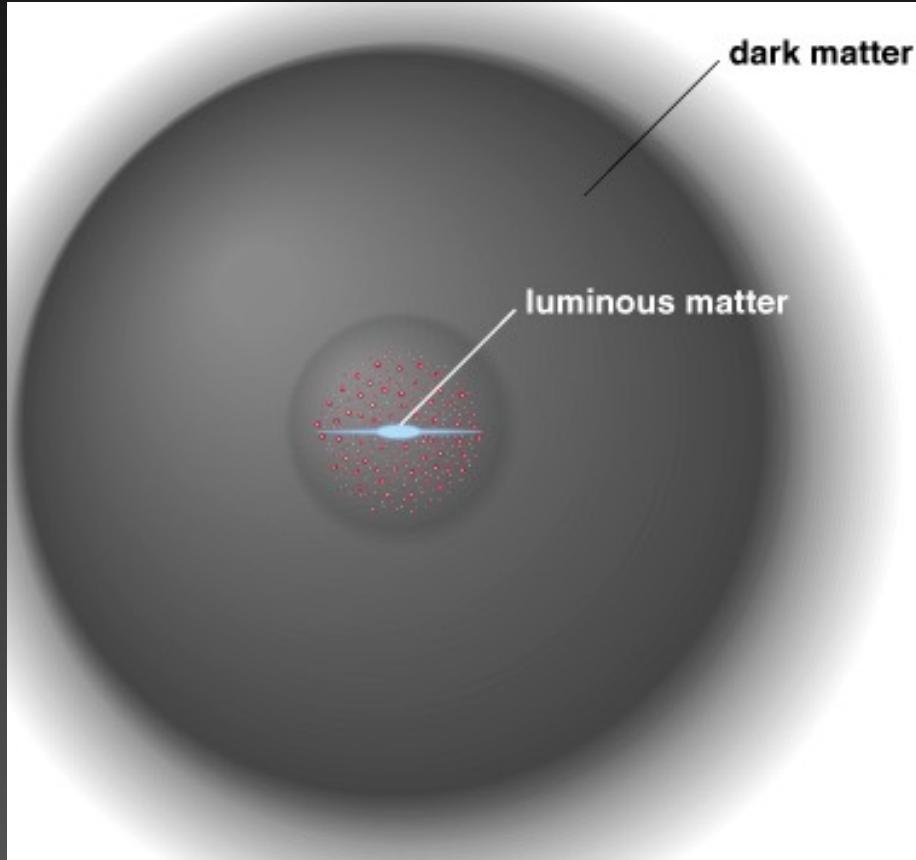
Coma cluster of galaxies:
only small % mass from
luminous matter



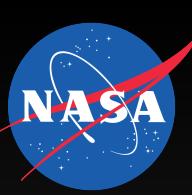
Dunkle Materie



Mystery of Missing Mass



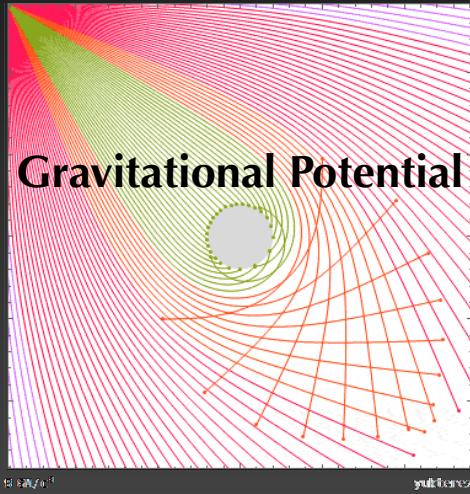
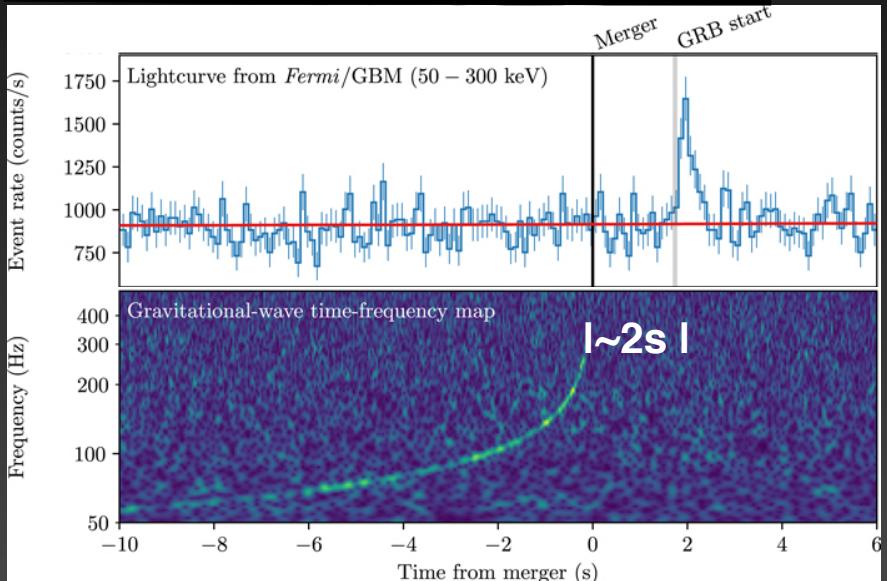
1970s- Rubin, Ford,
Thonnard
Galactic Rotation Curves



Modified Gravity?

GW170817/GRB170817A

Test of Weak Equivalence principle

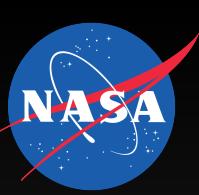


ApJ, 848:L13, 2017

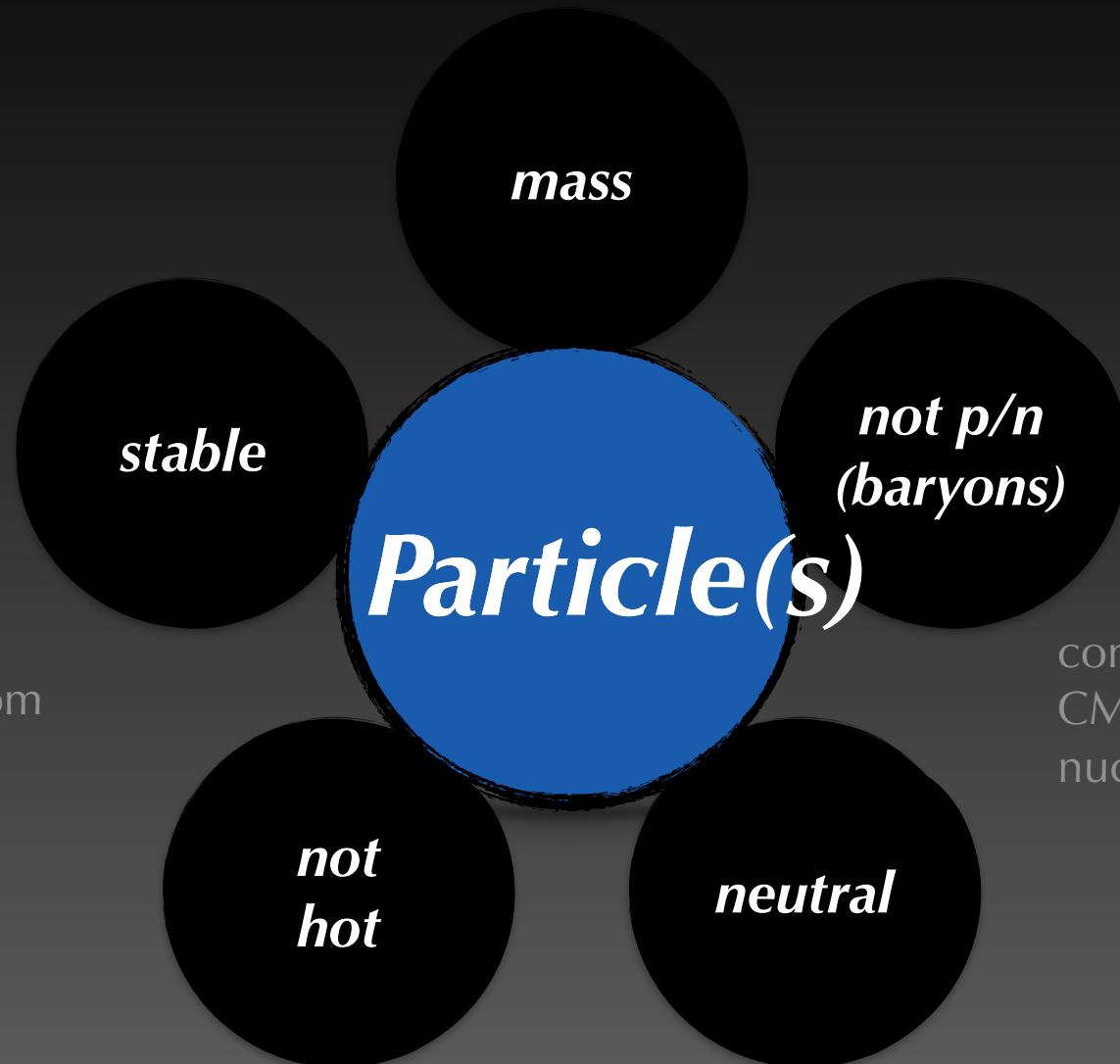
Boran et al., PRD 97, 041501 (2018),

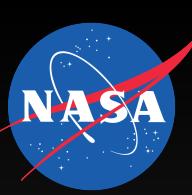
Gravitons and photons travel in space-time in the same way

*SN1987a found the same thing for neutrinos and photons



What do we know?



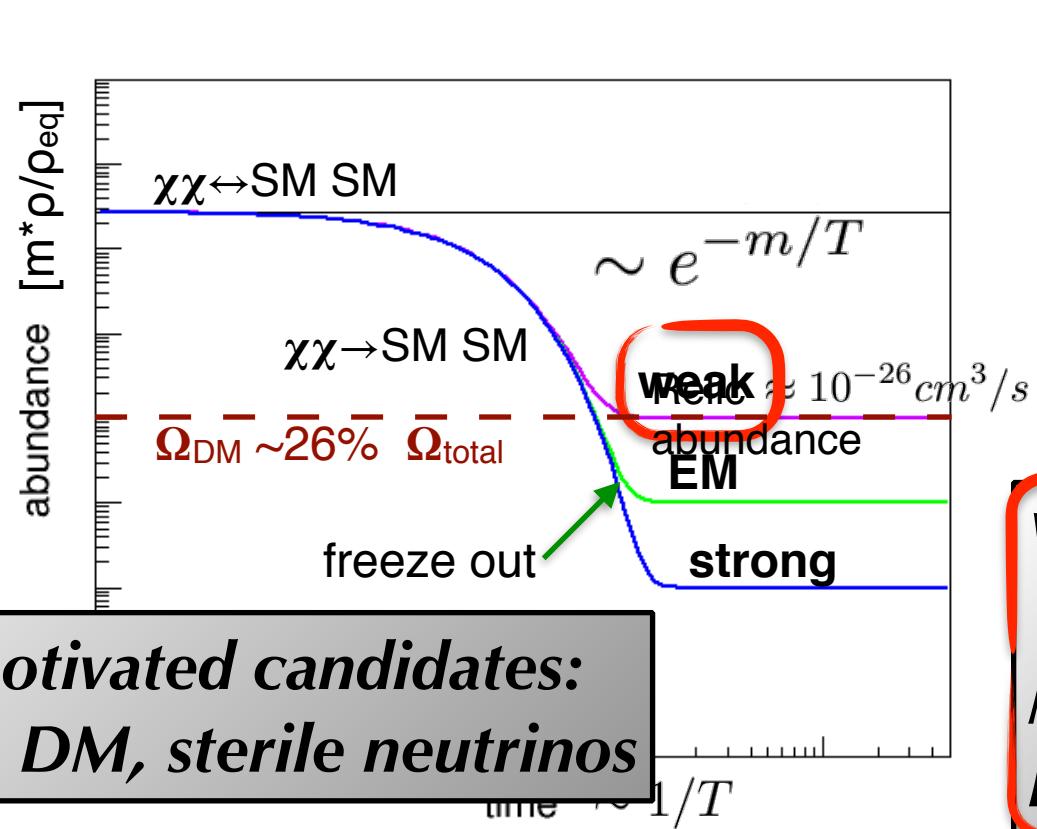


Portrait of a Candidate

Cosm | *The WIMP Coincidence* | ics

DM = χ

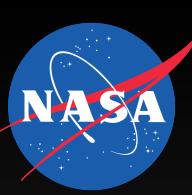
Weak (σ): 10^{-36} cm^2
velocity (v) @
freeze out: 10^5 km/s
 $\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{s}$



*Other well motivated candidates:
axions, asym. DM, sterile neutrinos*

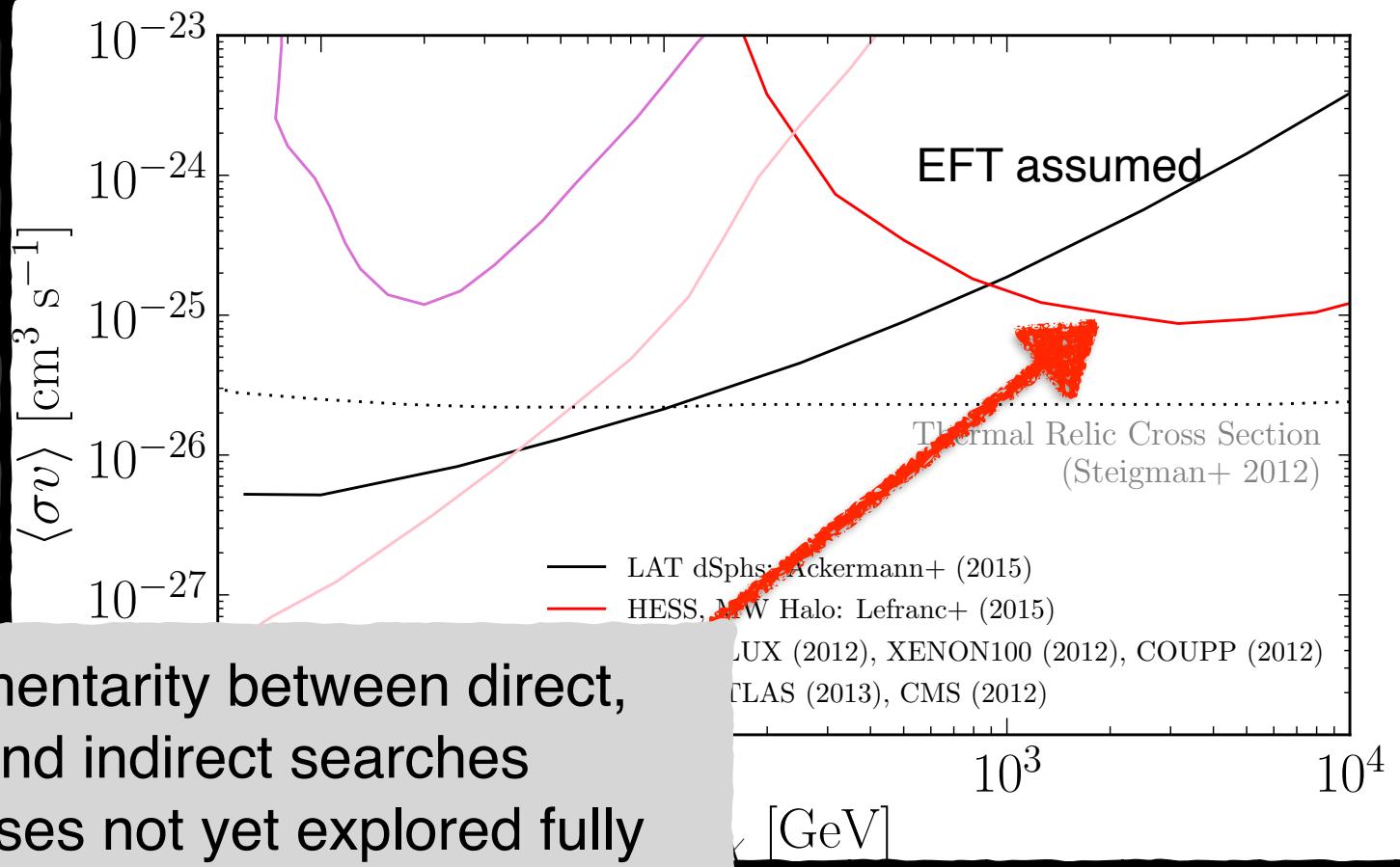
Abundance
 $\langle\sigma v\rangle n_{eq} \sim H$
 $\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{s}$

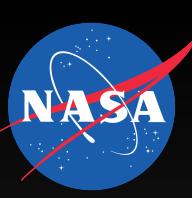
Weakly
Interacting
Massive
Particles



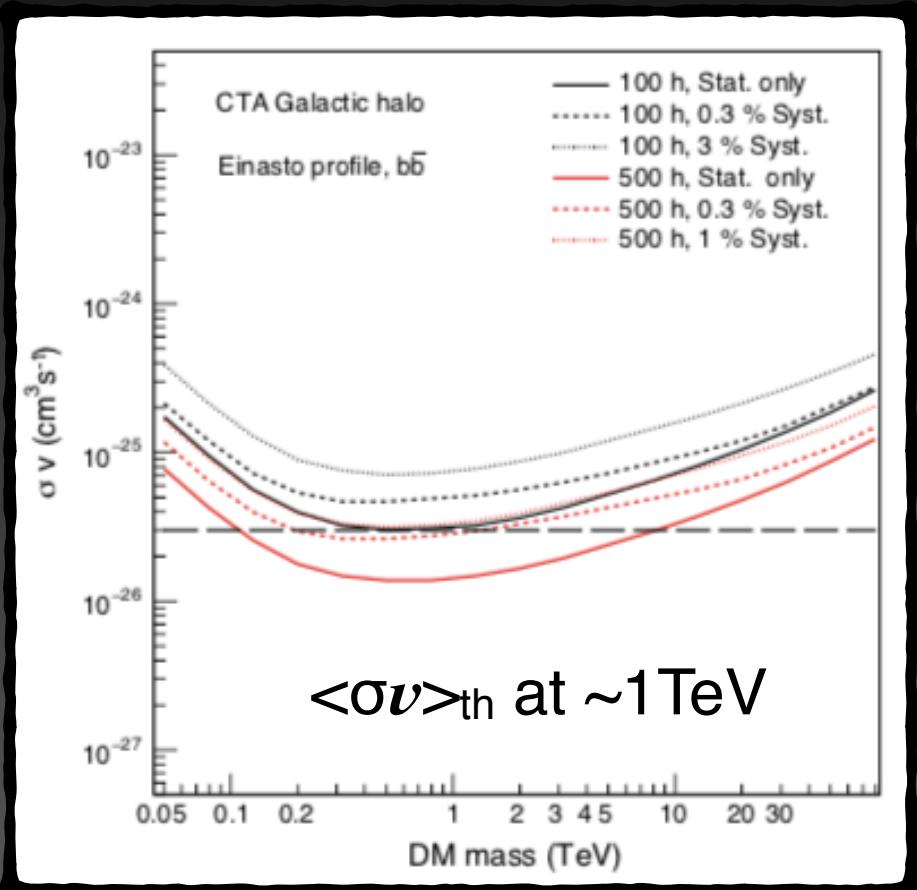
Dark Matter Program

Searches
for thermal
WIMPs



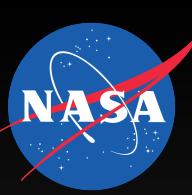


TeV Dark Matter



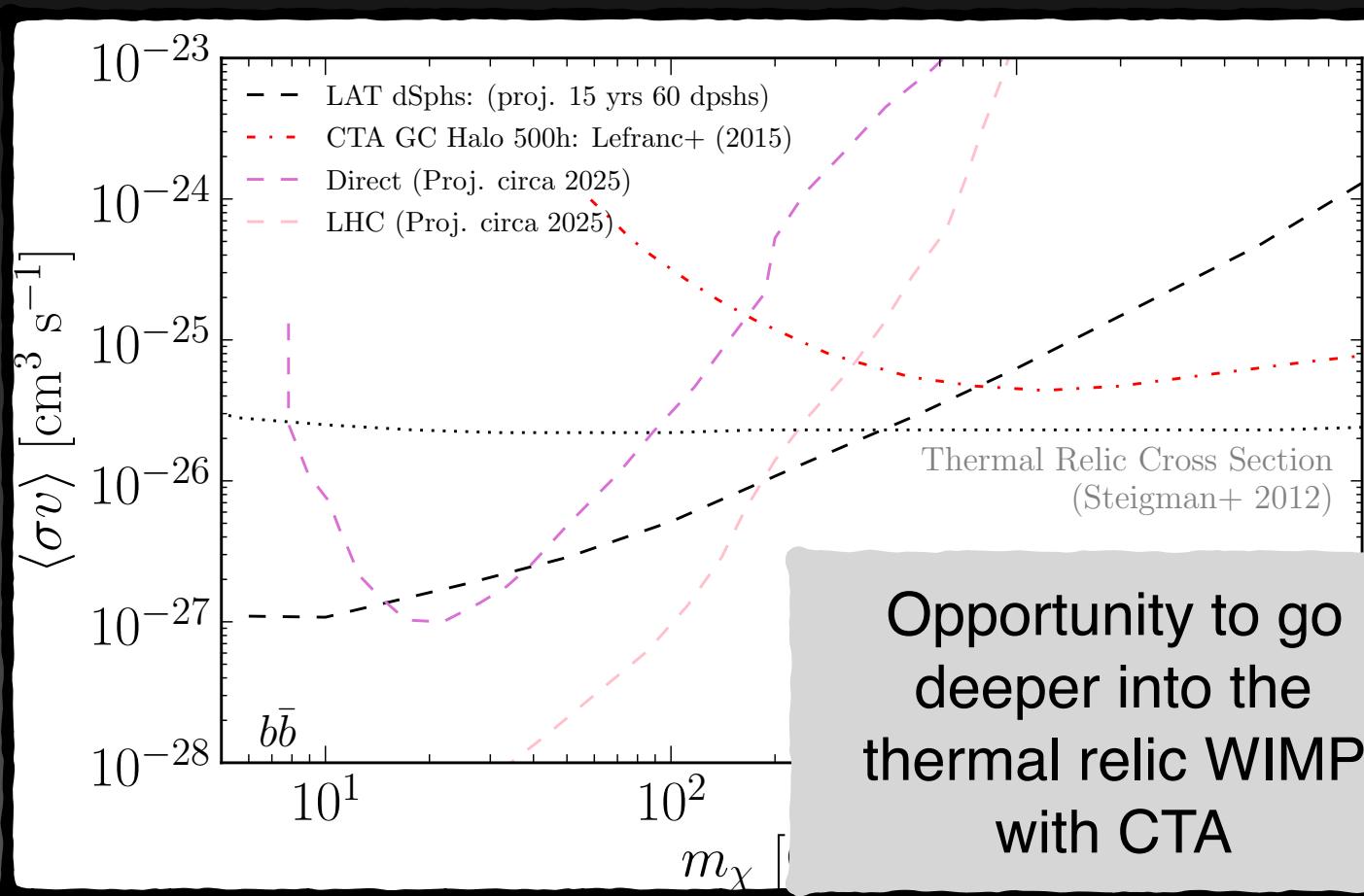
Ongoing analyses to incorporate CTA observational strategy, better IRFs and more accurate diffuse emission

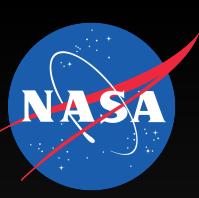
arXiv:1709.07997



Dark Matter Program

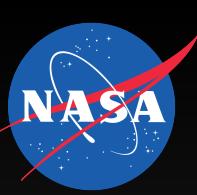
Future
sensitivities
for thermal
WIMPs





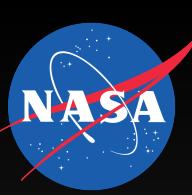
Fermi Tools

- Fermipy
 - Open-source python framework
 - High-level interface to Fermitools
 - Available on GitHub
 - See talk by F. De Palma Tuesday
- 3ML
 - Open-source python framework for multi-wavelength/multi-messenger analysis
 - Available on GitHub
 - See talk by N. Omodei Tuesday
- GSPEC
 - Python based GUI for analyzing Fermi GBM data
 - Seamless interface to XPEC

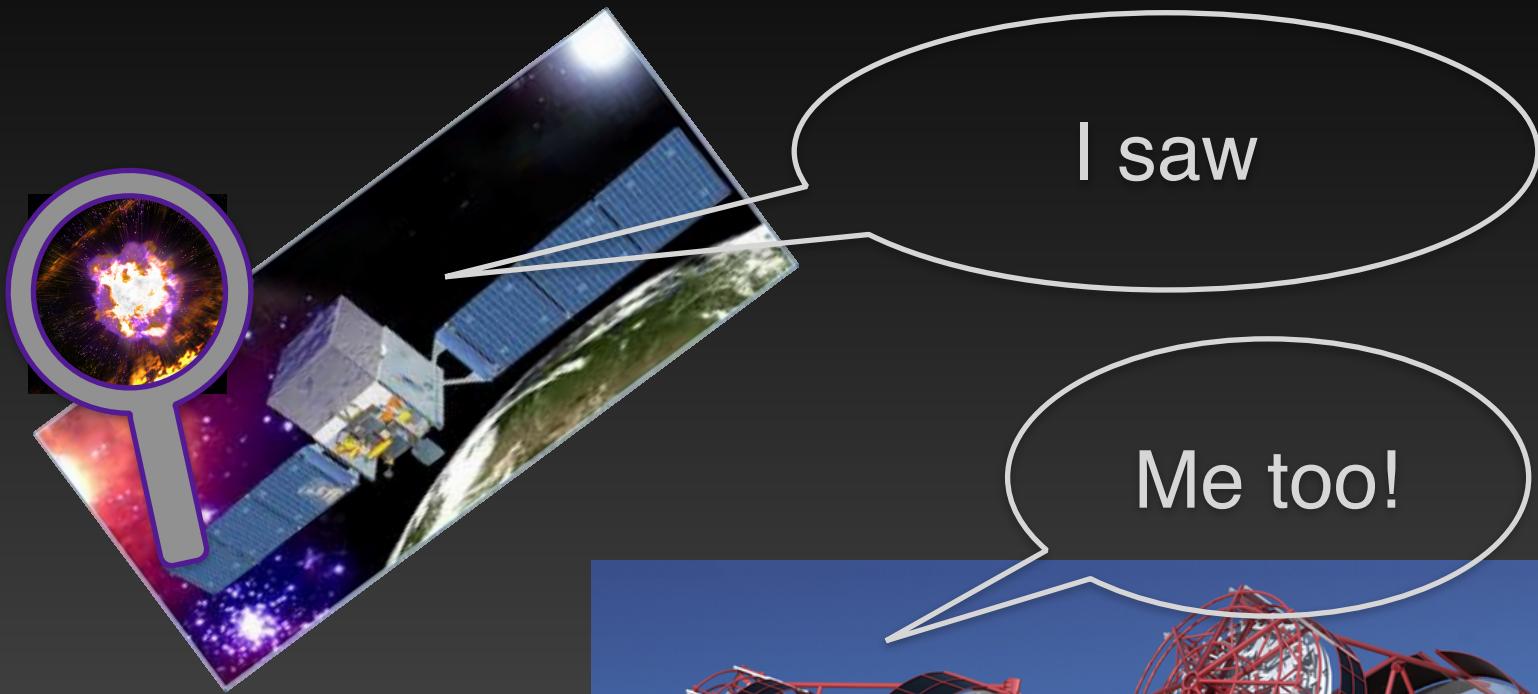


Summary

- Quick tour of *some* of the Fermi/CTA Synergies
 - GeV to TeV... with some keV/MeV sprinkled in
 - Impossible to overstate the depth of connection between CTA and Fermi science
 - Unprecedented understanding of fundamental processes producing the most extreme events



In Conclusion...



Fermi & CTA:
Better together

