HE AND VHE GAMMA-RAY OBSERVATIONS IN THE MULTI-WAVELENGTH AND MULTI-MESSENGER CONTEXT

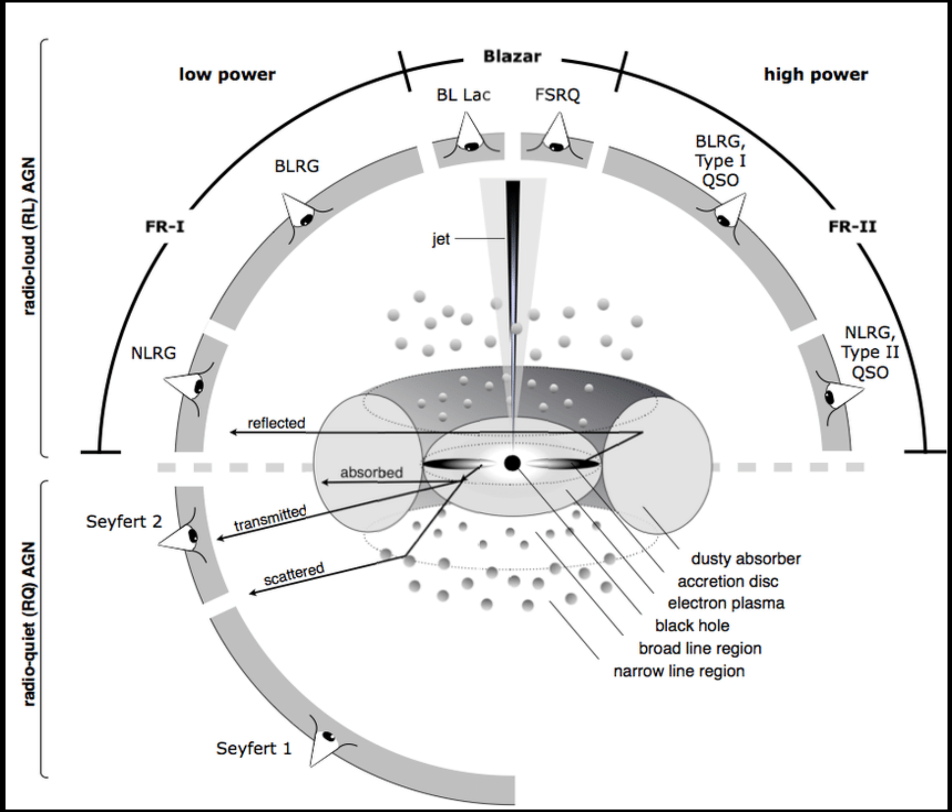
Congresso della Sezione INFN e del Dipartimento di Fisica di Bari

21-22 giugno 2021

Serena Loporchio – serena.loporchio@ba.infn.it

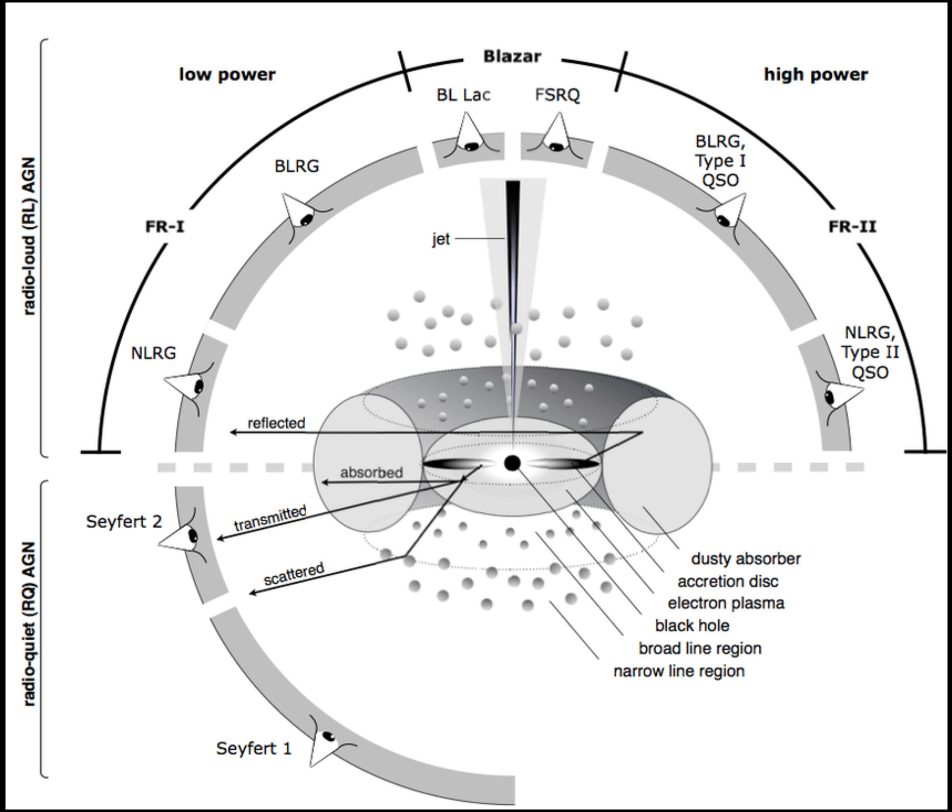
AGN: ACTIVE GALACTIC NUCLEI

- Galaxies with HE emission from the nucleus which cannot be explained as thermal radiation
- SMBH accreting + disk of hot plasma rotating
- Can be radio-loud or radio-quiet



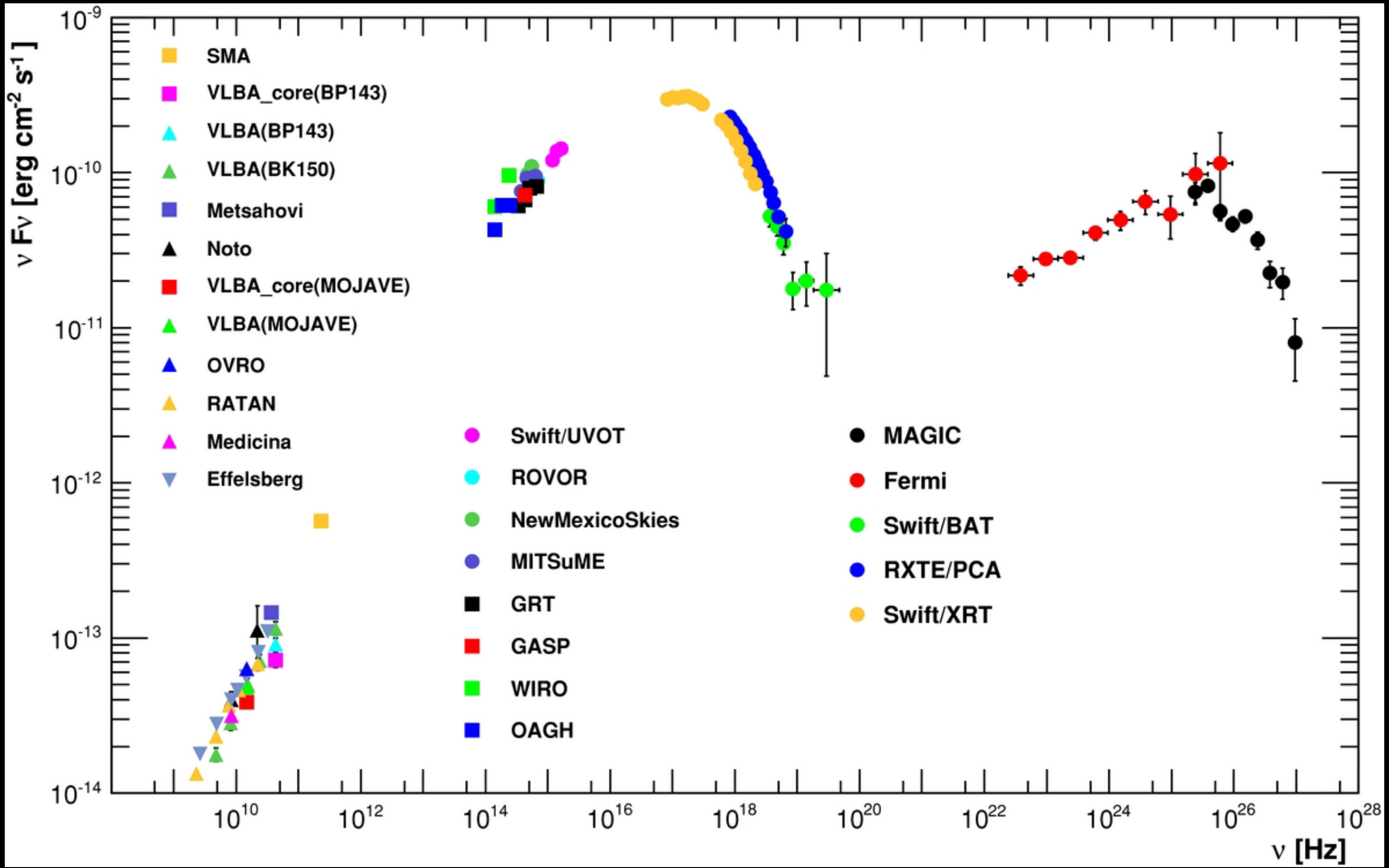
AGN: ACTIVE GALACTIC NUCLEI

- Galaxies with HE emission from the nucleus which cannot be explained as thermal radiation
- SMBH accreting + disk of hot plasma rotating
- Can be radio-loud or radio-quiet
  - Loudness in radio band → production of collimated jets (several kpc)
  - Jets are the only components of AGN able to produce VHE emission
  - Blazars: close alignment between jets and line of sight



SPECTRAL ENERGY DISTRIBUTION

Markarian 421
HBL
z=0.031
Discovered in 1992



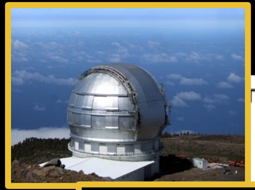
A. A. Abdo et al 2011 ApJ 736 131

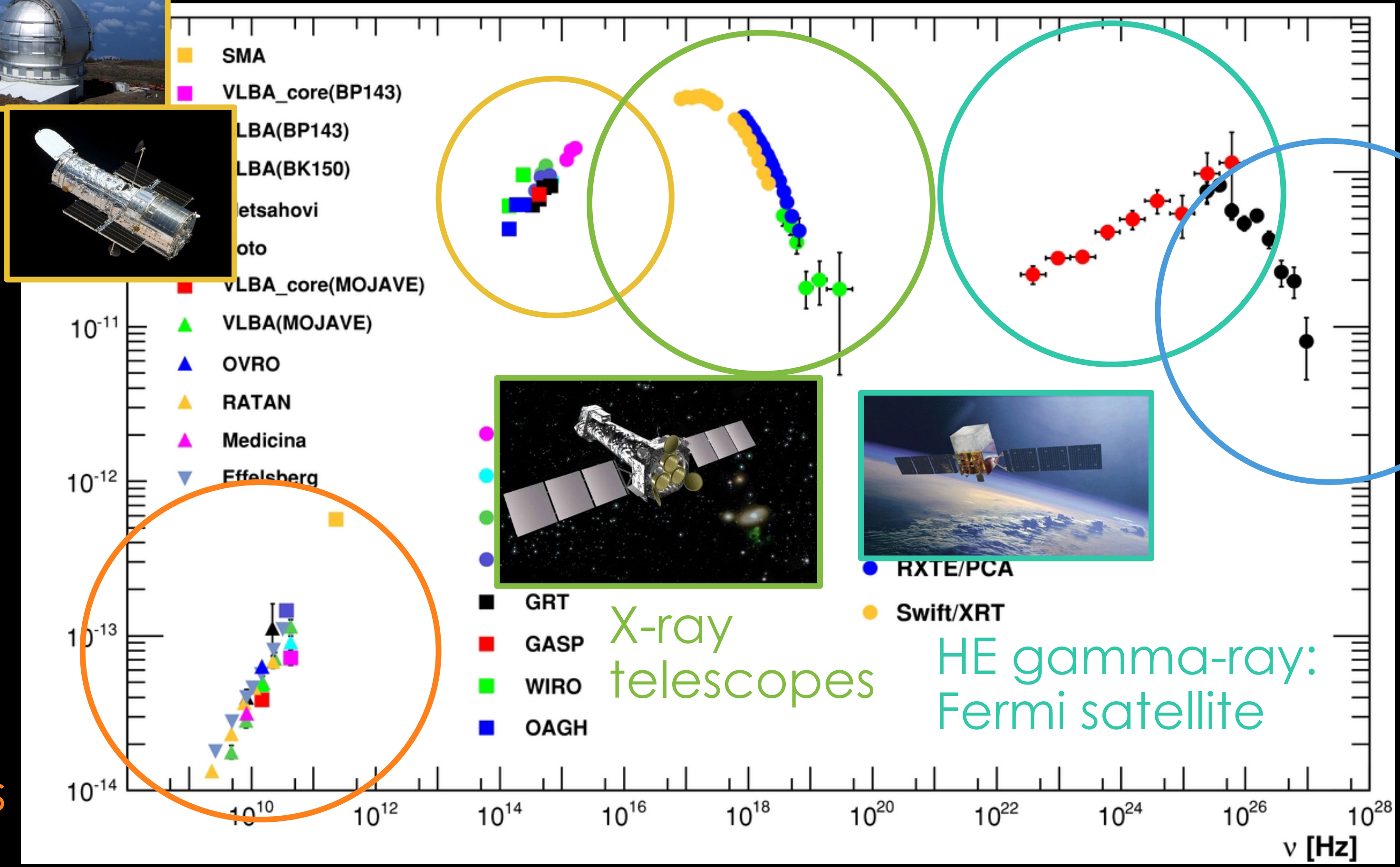
Synergy between instruments and community is crucial!

We learn something different from each component!

SPECTRAL ENERGY DISTRIBUTION

Optical telescopes and satellites





X-ray telescopes

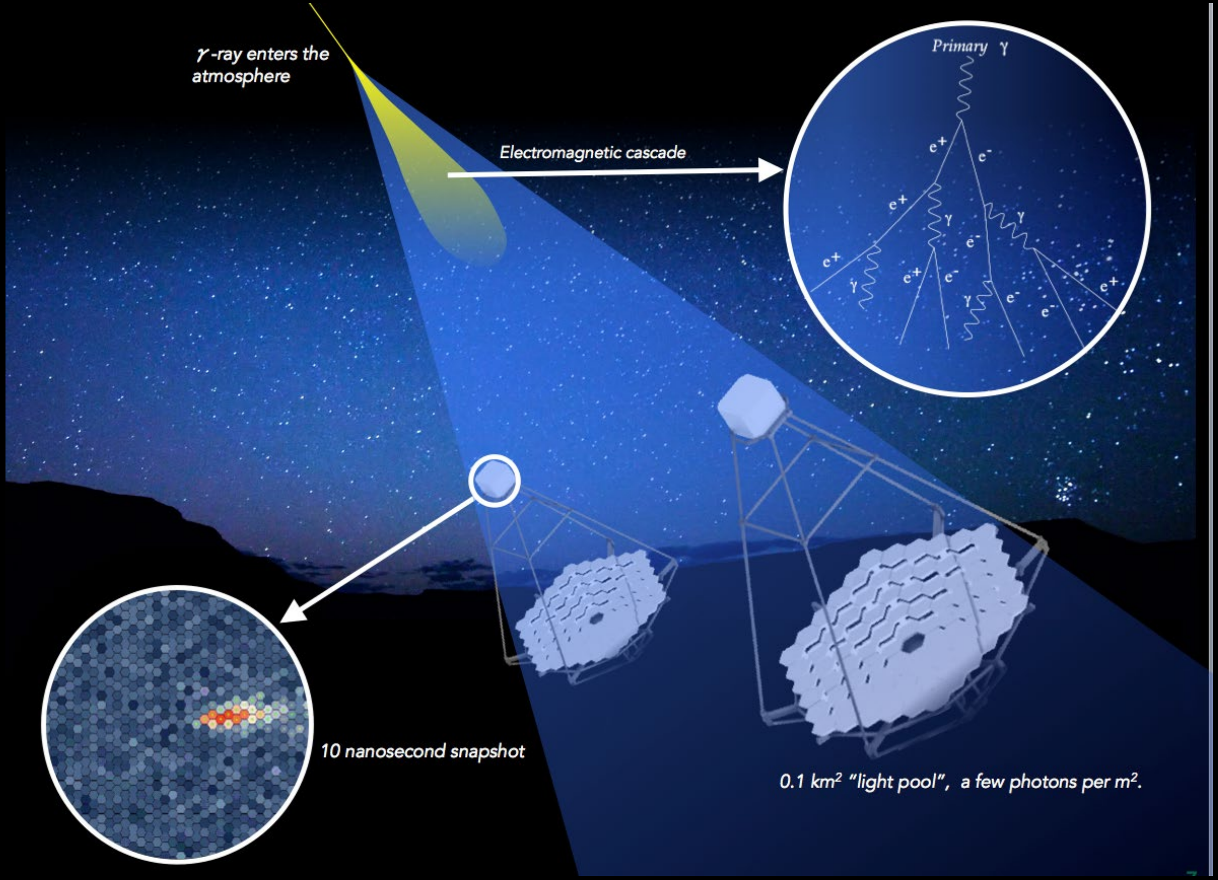
HE gamma-ray: Fermi satellite

Radio telescopes

VHE gamma-ray: Cherenkov telescopes

A. A. Abdo et al 2011 ApJ 736 131

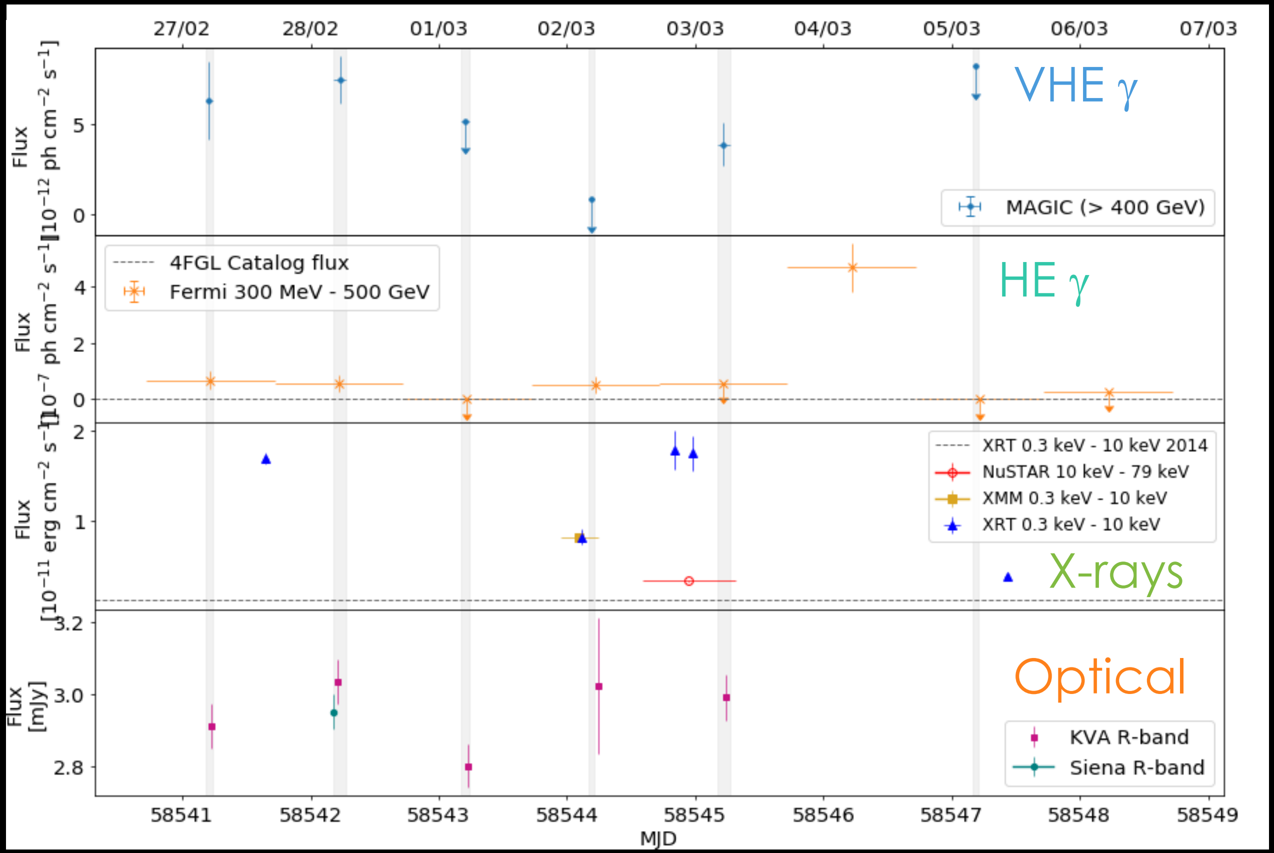
VHE GAMMA-RAY DETECTION: CHERENKOV TELESCOPES



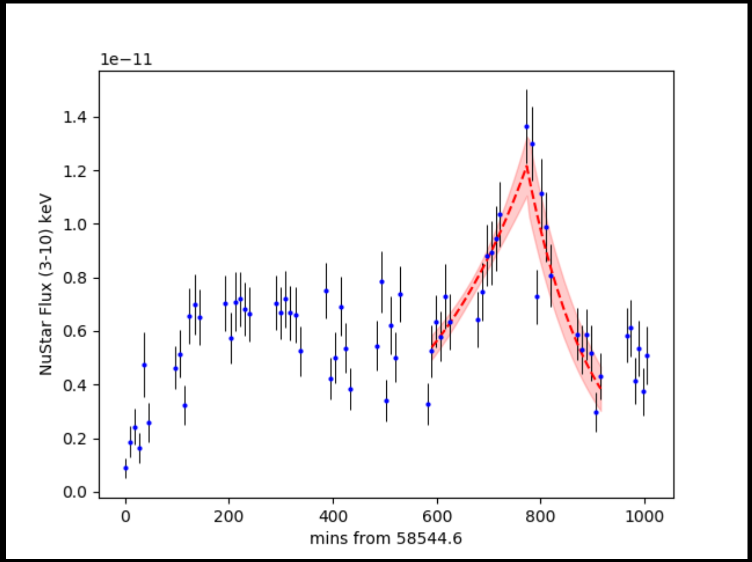
- System of stereo telescopes to detect VHE gamma rays thanks to their interaction with the atmosphere
- Image reconstruction → nature of primary, energy and direction
- From tens of GeV to tens of TeV
- 3 instruments (at the moment):
  - MAGIC, H.E.S.S. and VERITAS
- Future: CTA

TXS 1515-273 X-RAY VARIABILITY

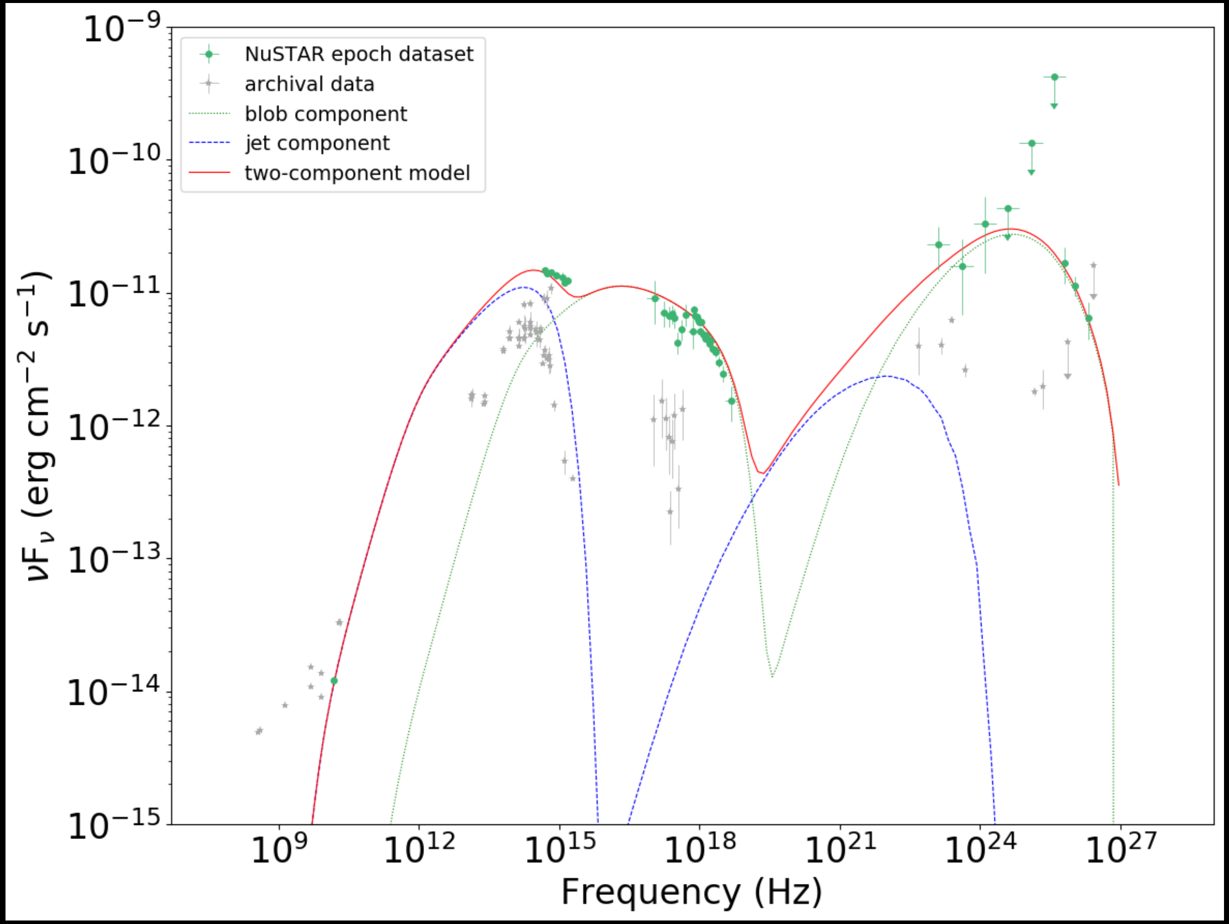
TXS 1515-273
HBL
z=0.1281
Discovered in 2019



- MWL light curve of BL Lac object TXS 1515-273 during observational campaign in 2019
- Rapid variability in the X-rays



TXS 1515-273 SED MODELING



- SED modelling with leptonic models
- Parameters constrained from different observations

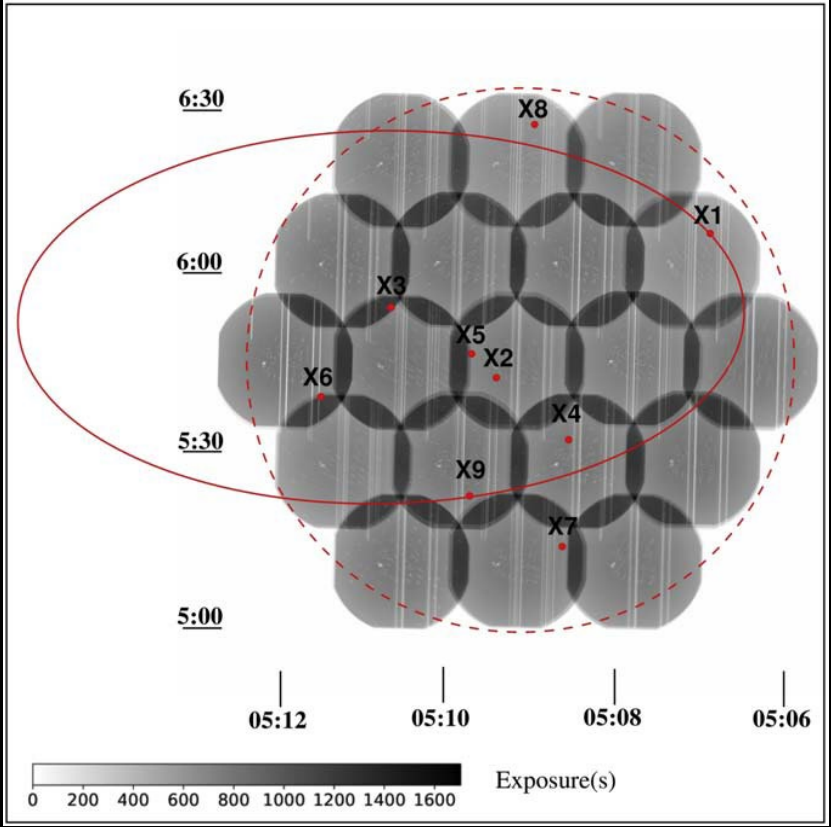
- Synchrotron emission + IC on same electron population → Synchrotron Self Compton

Hadronic models?

Blazars are proposed as UHECR accelerators

A MULTI-MESSENGER CASE: TXS 0506+056

- TXS 0506 is a bright gamma-ray emitting blazar
- Special interest for the hadronic scenario
- September 22, 2017: neutrino with E = 290 TeV detected by IC in
  - AMON_ICECUBE_EHE alert 50579430 distributed via AMON & GCN after 43s
  - Multiple observatories pointed at its location after the IC trigger
  - Spatial and temporal coincidence with enhanced gamma emission
- Evidence of hadronic emission in blazars



A. Keivani et al., ApJ 864:84 (2018).

A MULTI-MESSENGER CASE: TXS 0506+056

amma-ray emitting

e hadronic scenario

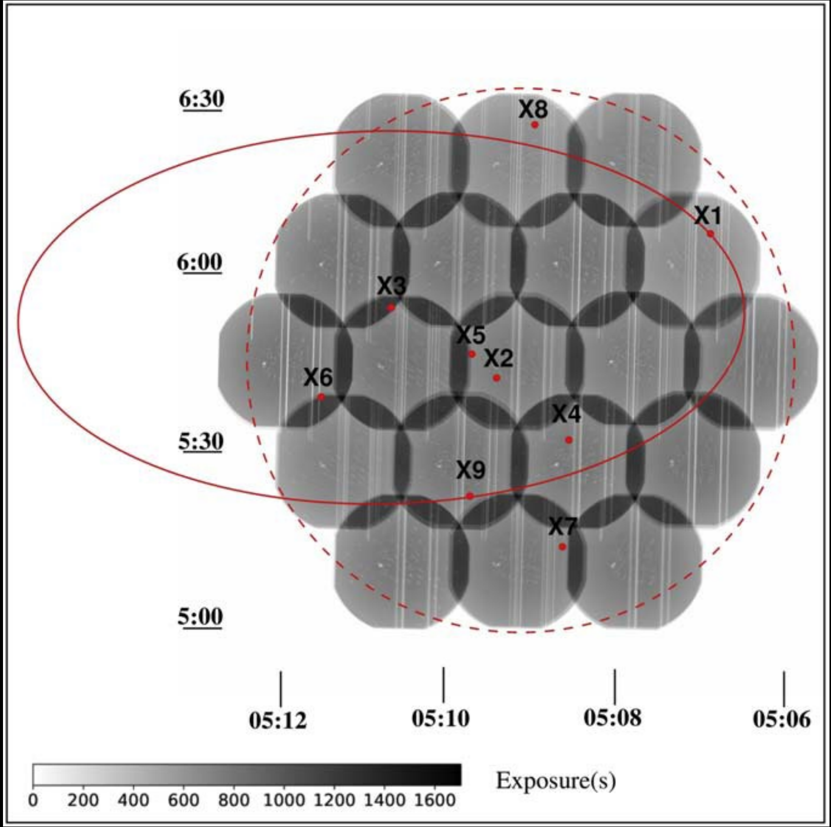
neutrino with E = 290
n

IE alert 50579430
N & GCN after 43s

es pointed at its
C trigger

- Spatial and temporal coincidence with enhanced gamma emission

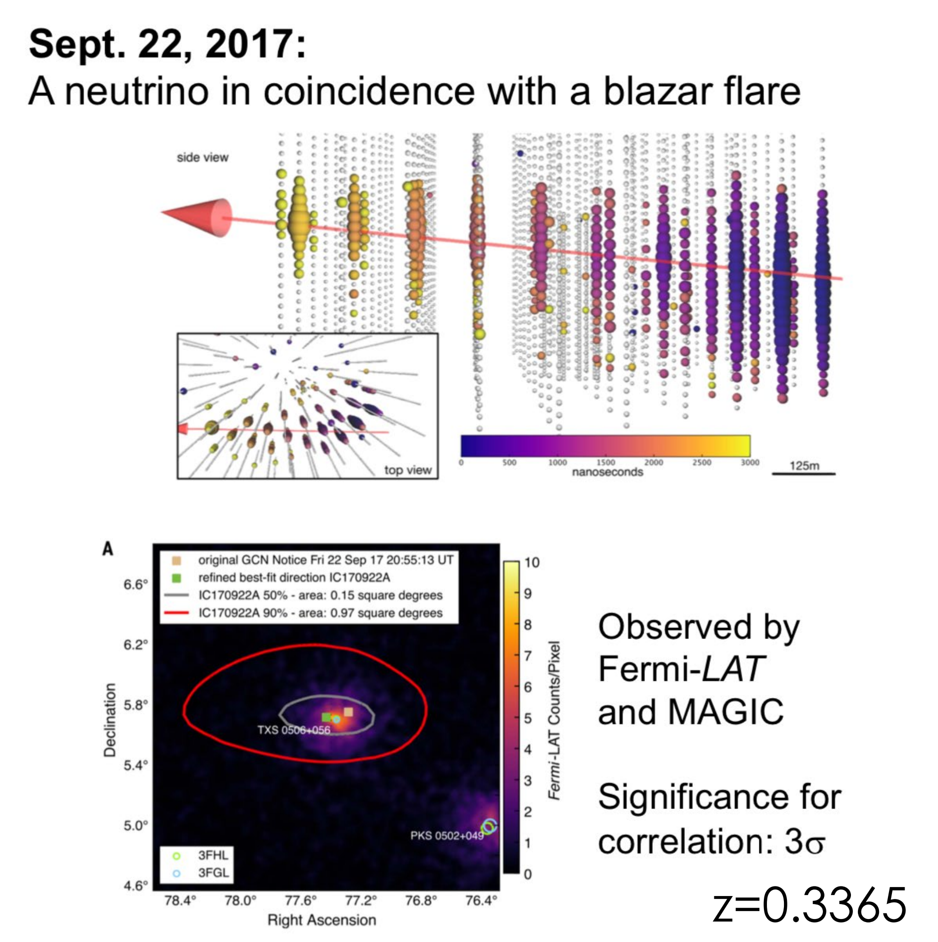
- Evidence of hadronic emission in blazars



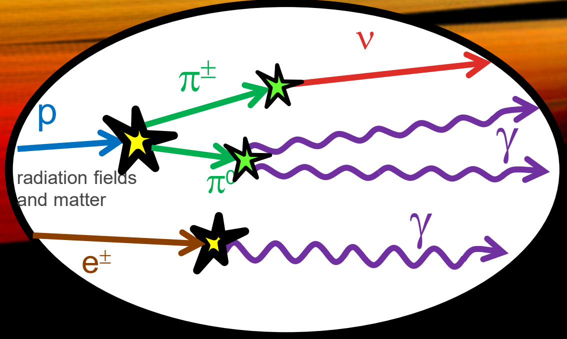
A. Keivani et al., ApJ 864:84 (2018).

NEUTRINOS FROM TXS 0506+056 (ICECUBE)

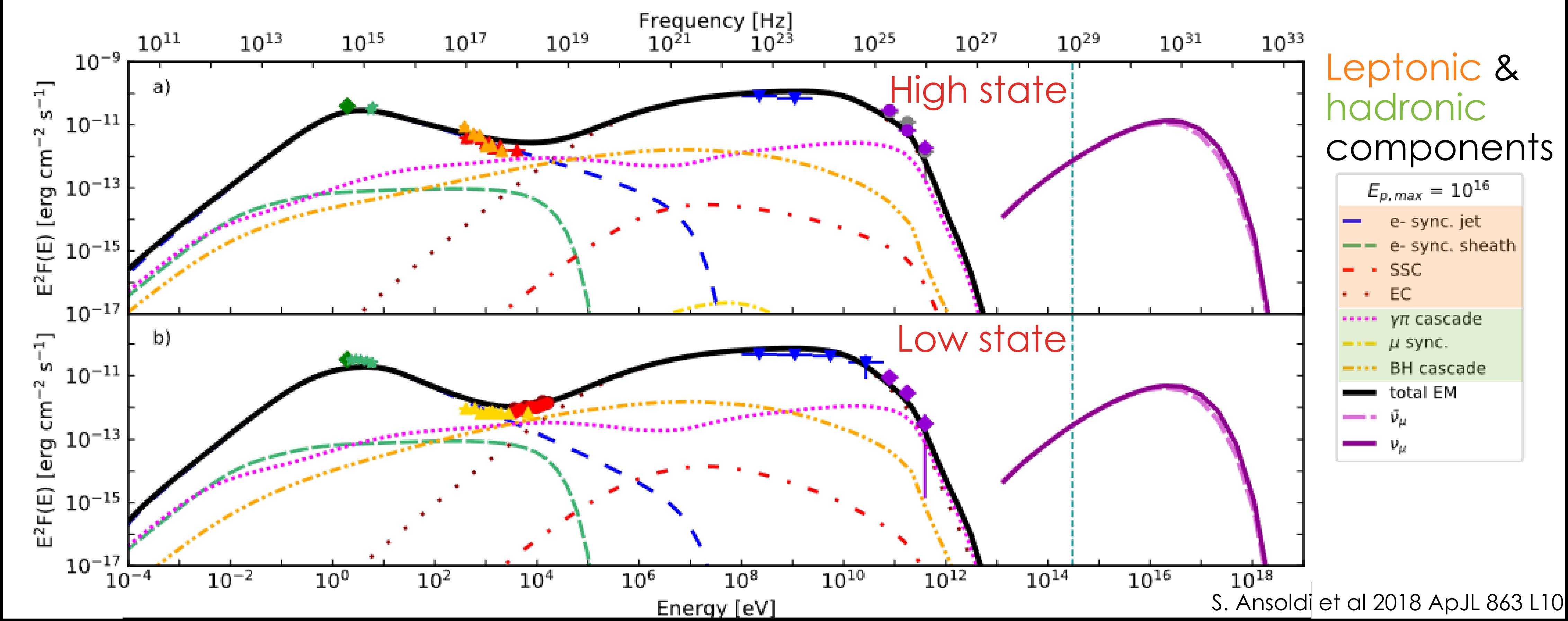
IceCube Collaboration et al., Science 361 (2018).



- Electromagnetic follow-up campaign of the event IceCube-170922A → the event came from the direction of a known AGN blazar, TXS 0506+056.
- Found to be flaring at multiple wavelengths.
- IceCube conclusion: **evidence** of a HE ν from a blazar

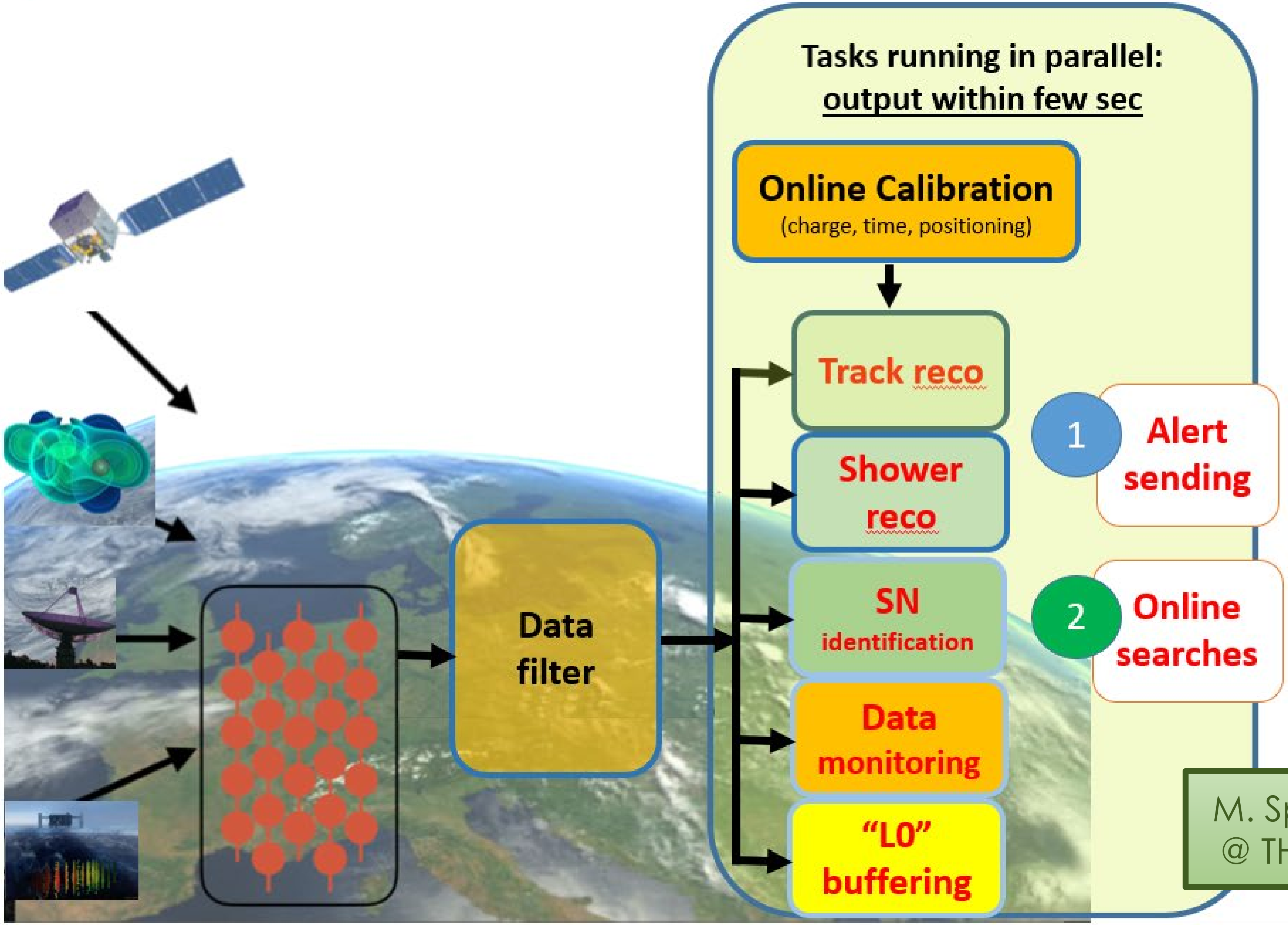


HADRONIC MODELS AND NEUTRINO PRODUCTION IN AGNS



S. Ansoldi et al 2018 ApJL 863 L10

KM3NeT online alert system

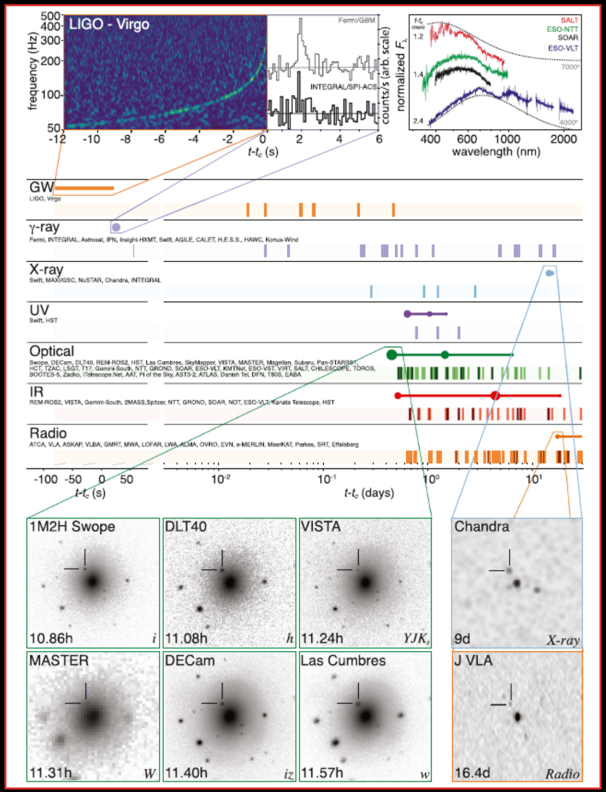


M. Spurio: Neutrino telescopes, @ THESEUS CONFERENCE 2021

MULTI-MESSENGER DOESN'T GO ON HOLIDAY!

- 17 August 2017: Fermi-GBM detects GRB170817A at 12:41:06 UTC
- GCN is issued at 12:41:20 UTC
- 6 minutes later a GW is detected, consistent with a BNS merger at 12:41:04 UTC, less than 2s BEFORE the GRB.
- 70 observatories → extensive observing campaign in all e.m. spectrum
- Bright optical transient detected less than 11h after the merger
- X-ray and radio counterpart

B. P. Abbott et al 2017 ApJL 848 L12

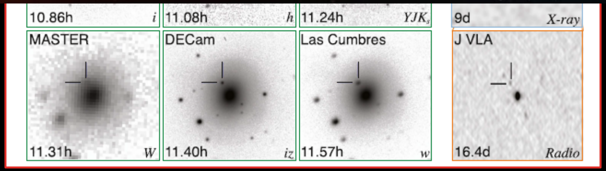


MULTI-MESSENGER DOESN'T GO ON HOLIDAY!

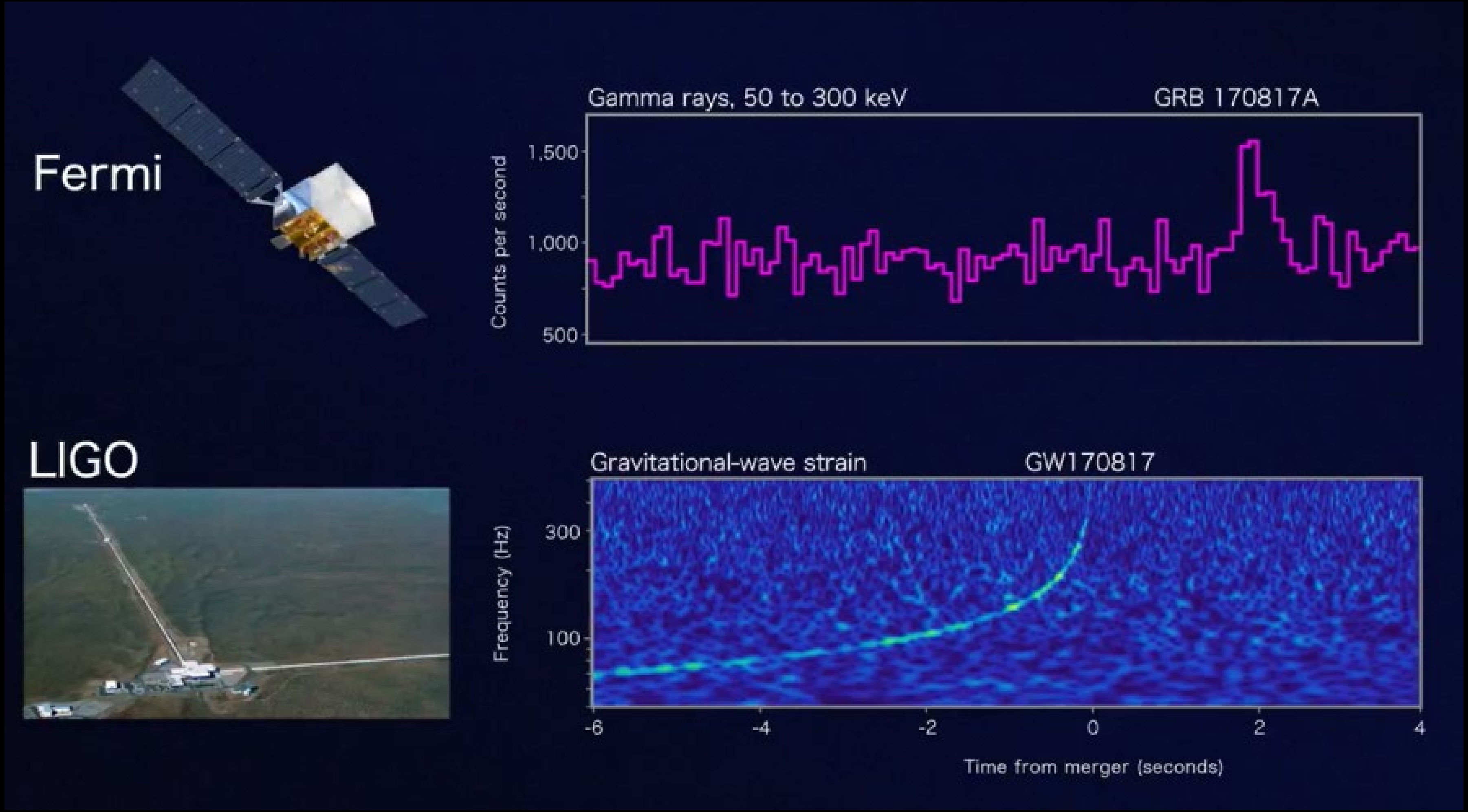
B. P. Abbott et al 2017 ApJL 848 L12

- 70 observatories → extensive observing c
  in all e.m. spectrum
- Bright optical transient detected less tha
  the merger
- X-ray and radio counterpart

Breakthrough of the Year by Science!



GAMMA-RAY AND GW: MULTI-MESSENGER FROM GRBS



GAMMA-RAY AND GW: MULTI-MESSENGER FROM GRBS

NS-NS merging
Host galaxy NGC 4993
~ 40 Mpc

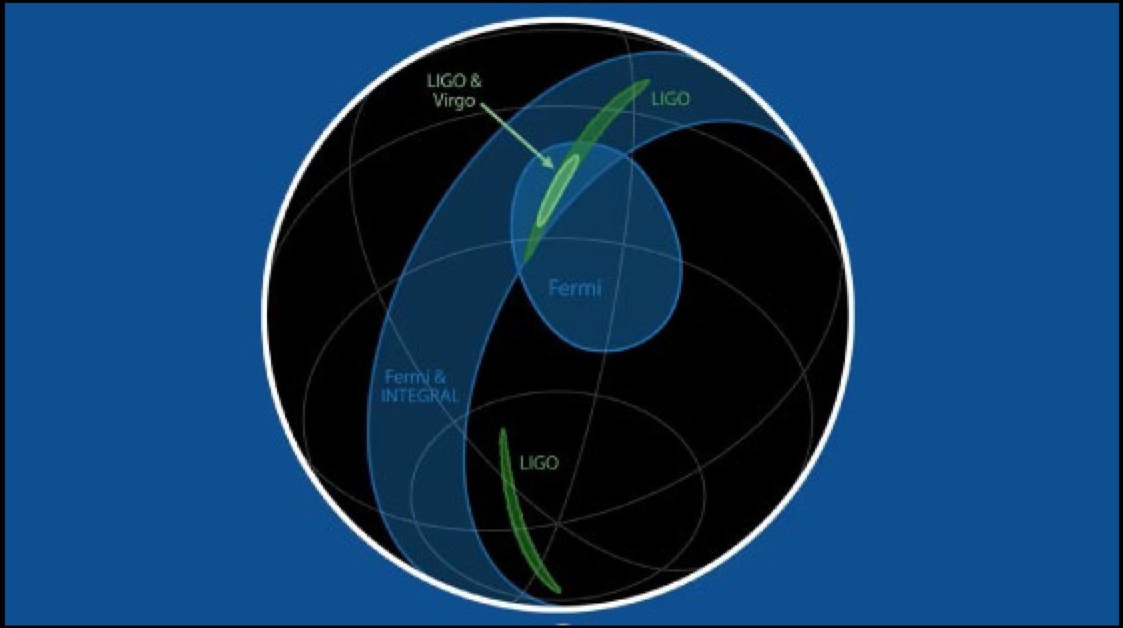
- Transient GW signal from a binary neutron star merger: GW170817 + GRB170817A
- Huge regions of the sky
- The first multi-messenger paper

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

OPEN ACCESS

Multi-messenger Observations of a Binary Neutron Star Merger

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



GAMMA-RAY AND GW: MULTI-MESSENGER FROM GRBS

NS-NS merging
Host galaxy NGC 4993
~ 40 Mpc

- Transient GW signal from a binary neutron star merger: GW170817 + GRB170817A
- Huge regions of the sky
- The first multi-messenger paper

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

OPEN ACCESS

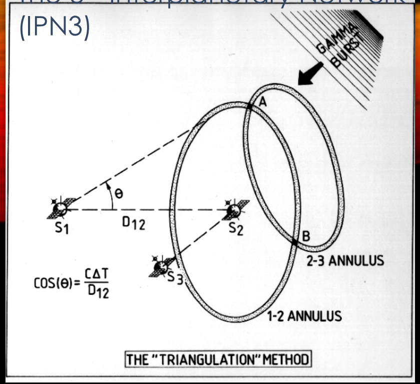
CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger

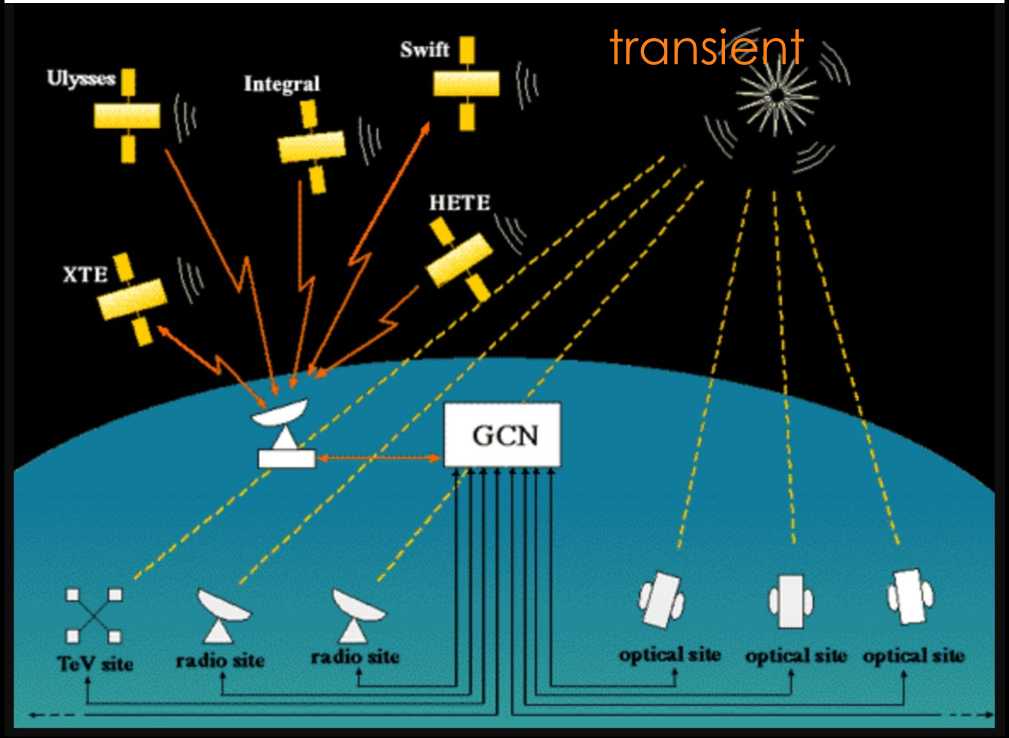
LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration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

SYNERGY IS THE KEY!

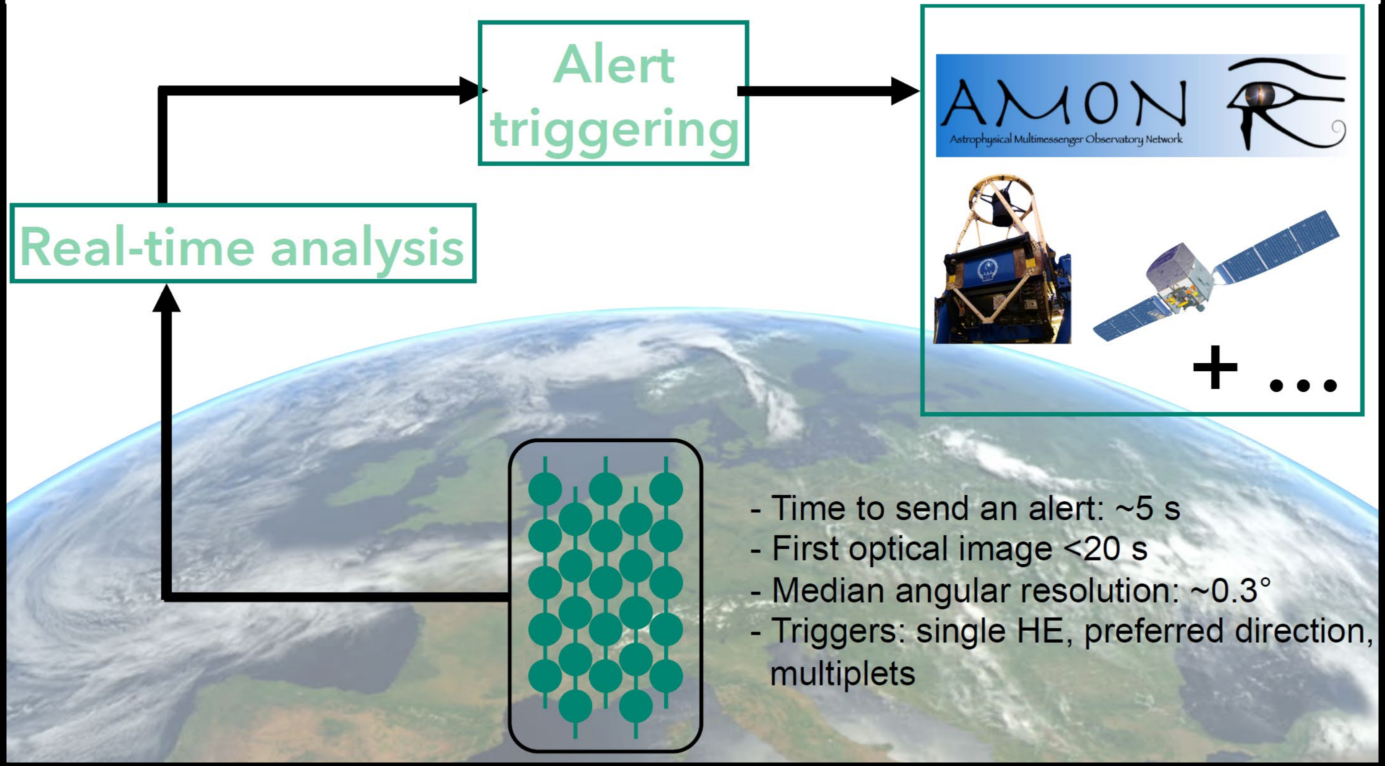
The 3rd Interplanetary Network (IPN3)



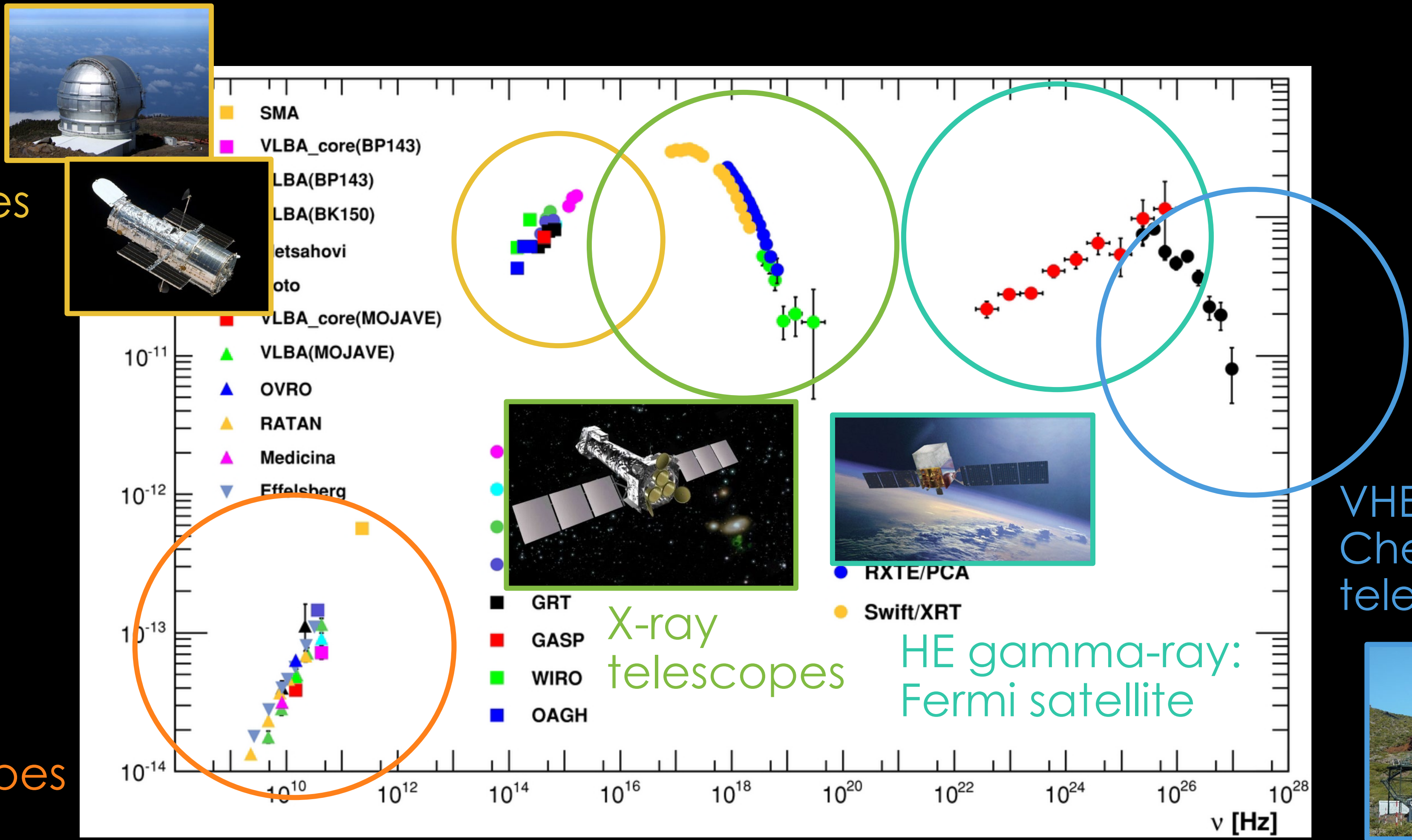
The Gamma-ray Coordinates Network (GCN)



Astrophysical Multimessenger Observatory Network (AMON)



Optical telescopes and satellites

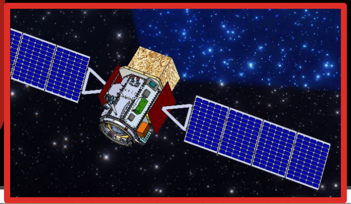


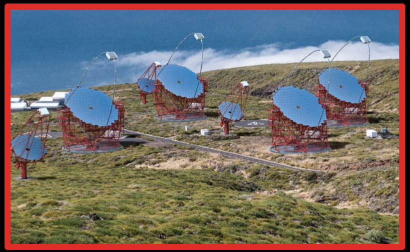
Radio telescopes

VHE gamma-ray: Cherenkov telescopes

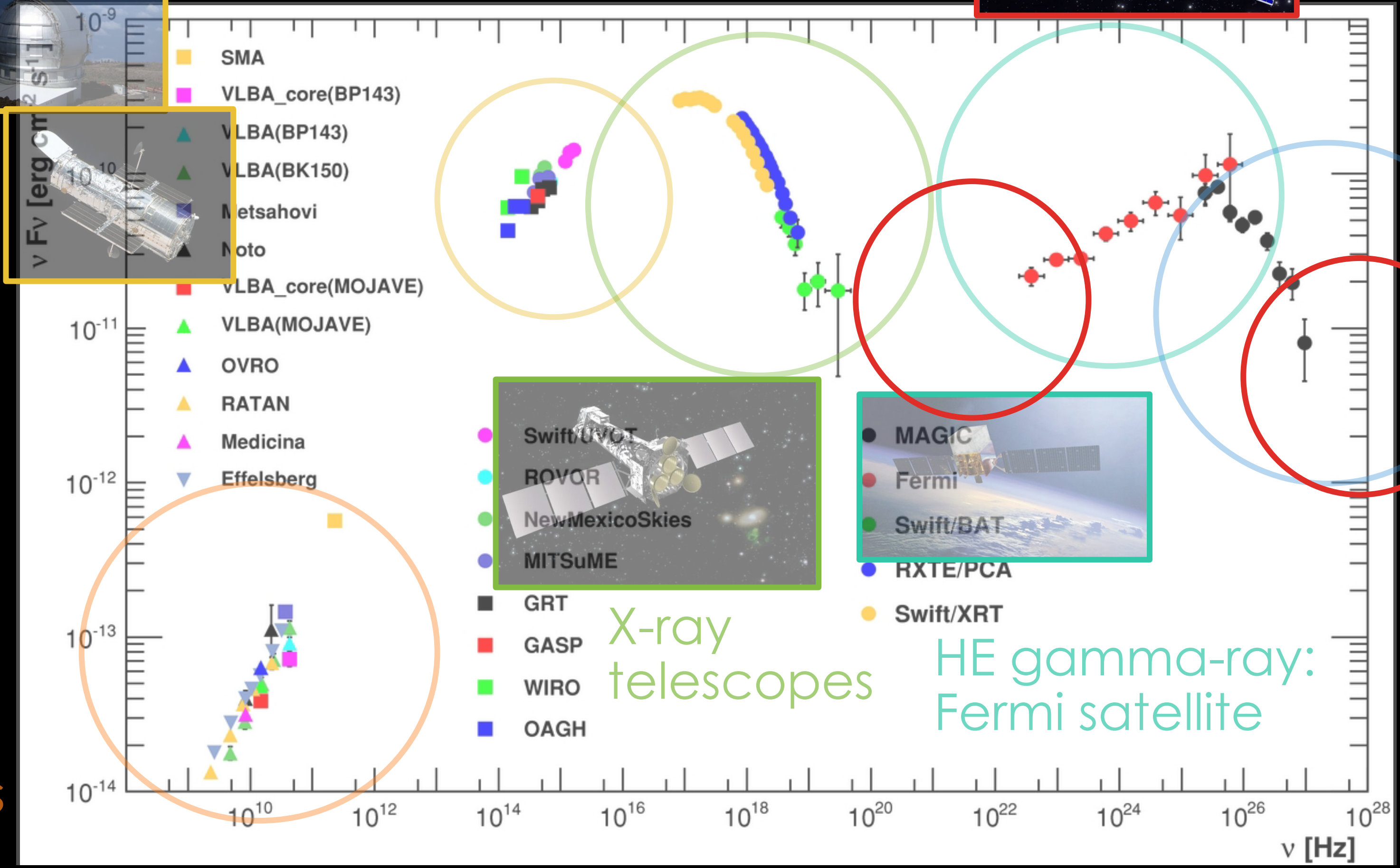
A. A. Abdo et al 2011 ApJ 736 131

New satellites for MeV energy range: APT, AMEGO





Optical telescopes and satellites

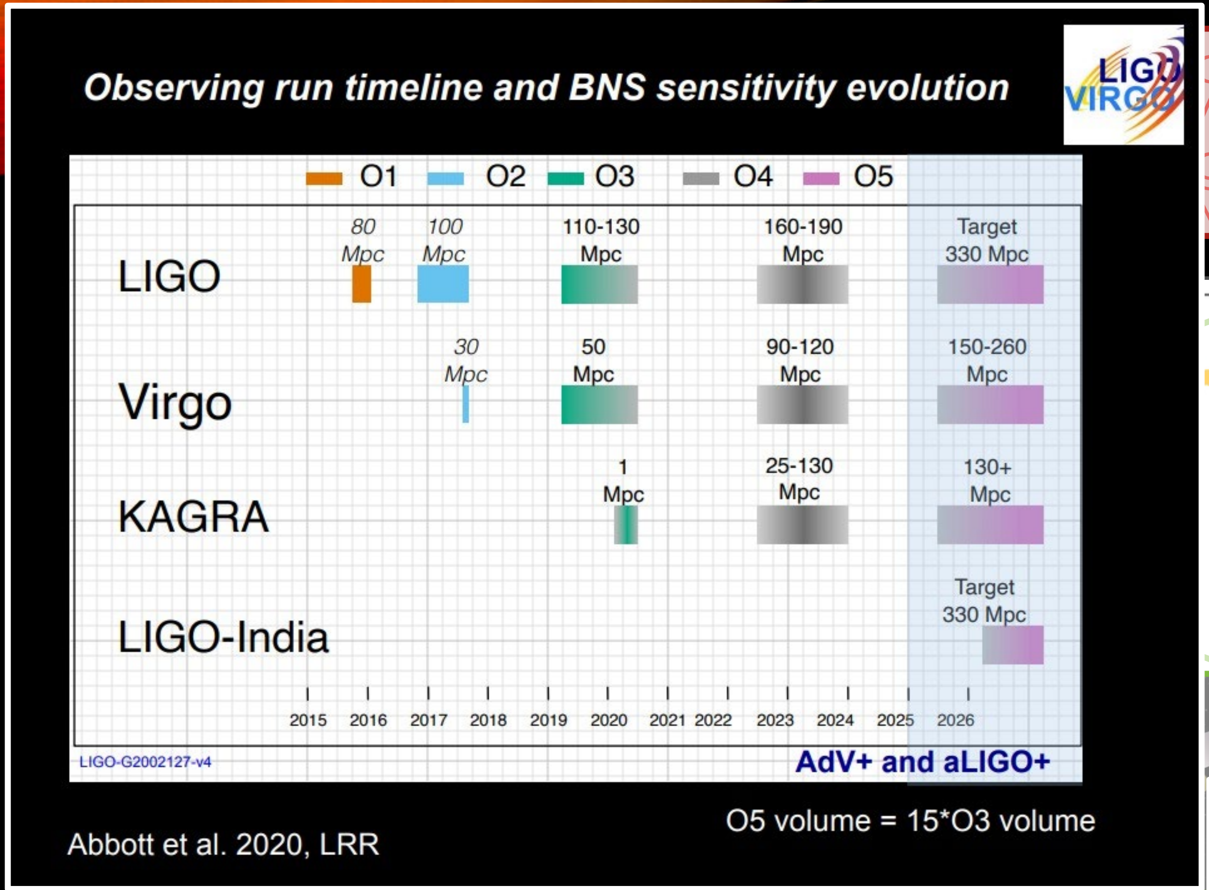


Future of Cherenkov: CTA

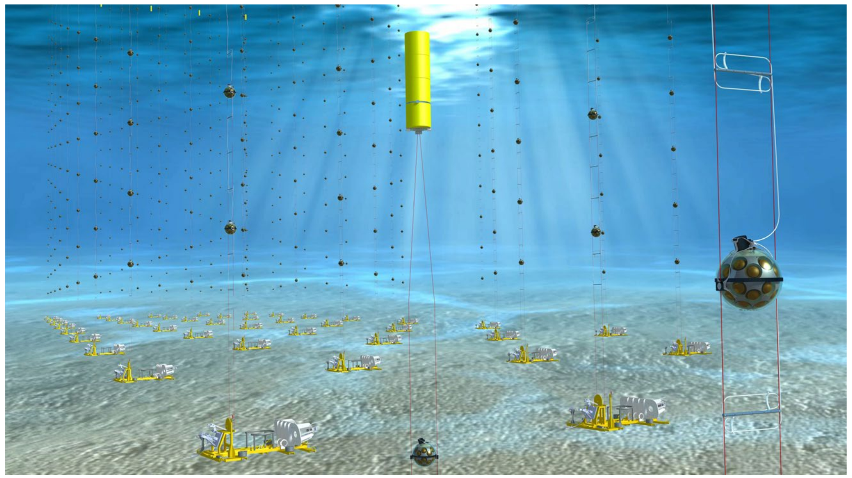
VHE gamma-ray: Cherenkov telescopes

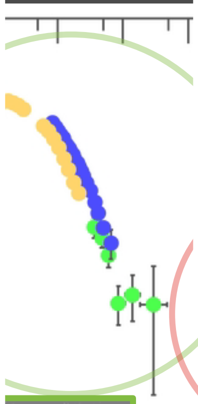
Radio telescopes

A. A. Abdo et al 2011 ApJ 736 131

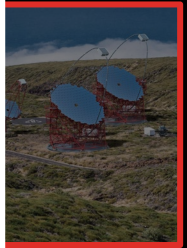


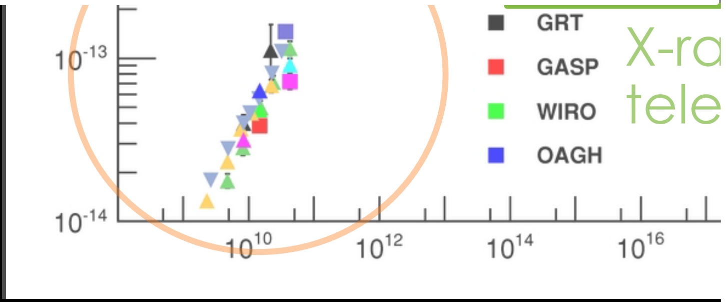
atellites for
energy
ge: APT,
MEGO



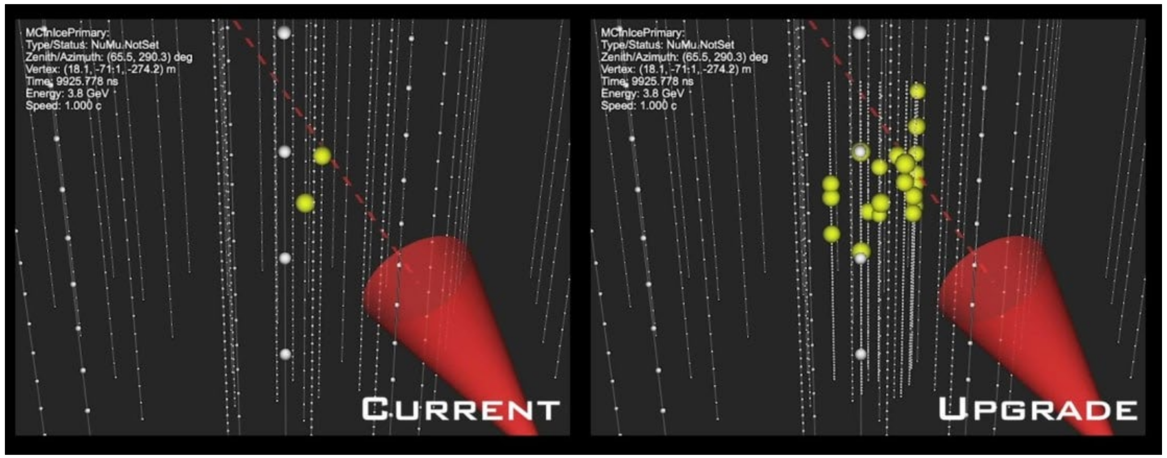


e of
nkov:
CTA





X-ra
tele

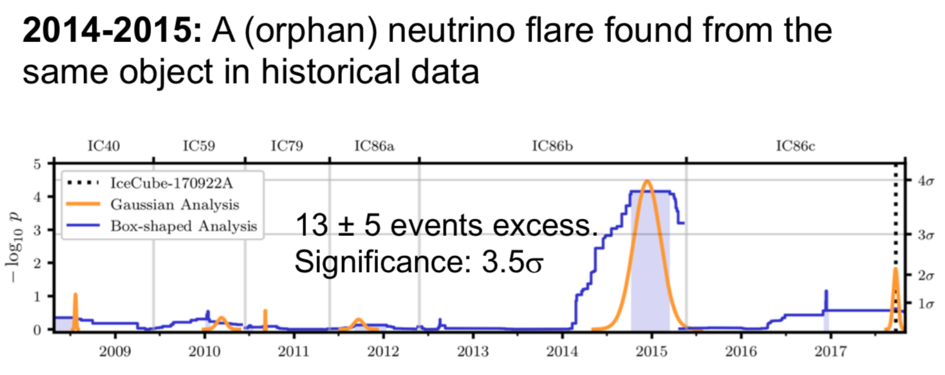


Radio
telescopes

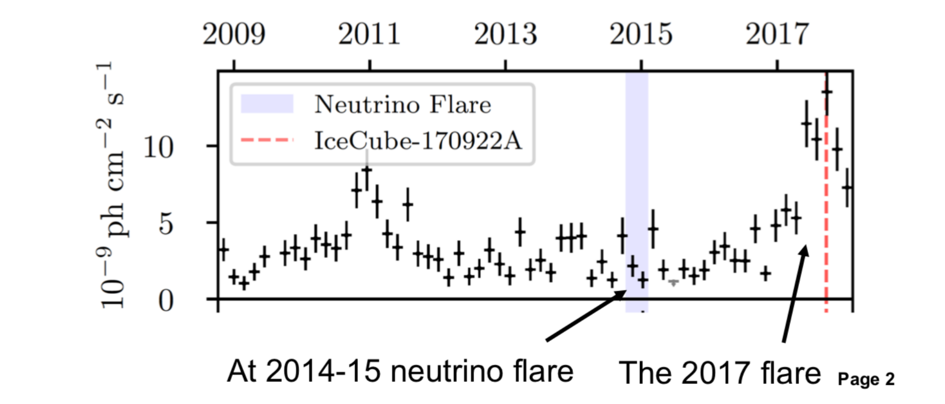
THANK YOU FOR YOUR ATTENTION!

NEUTRINOS FROM THE BLAZAR TXS 0506+056 (ICECUBE)

IceCube Collaboration et al., Science 361 (2018).



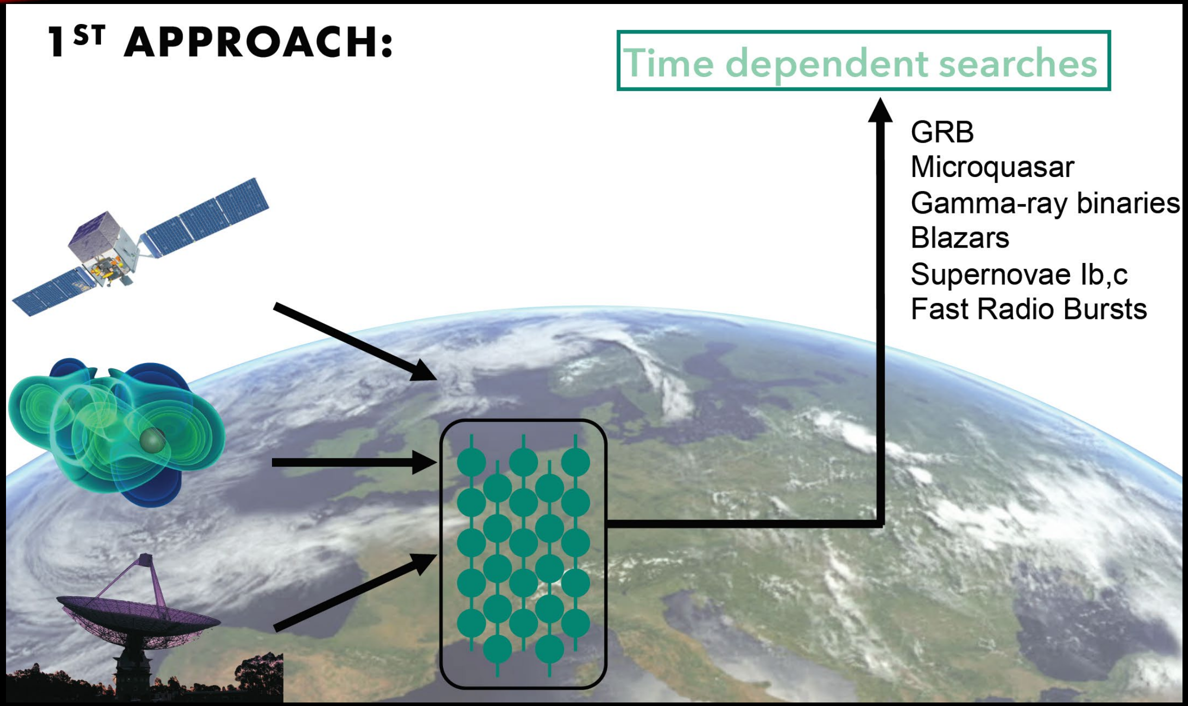
P. Padovani et al., MNRAS, 480 (2018) 192

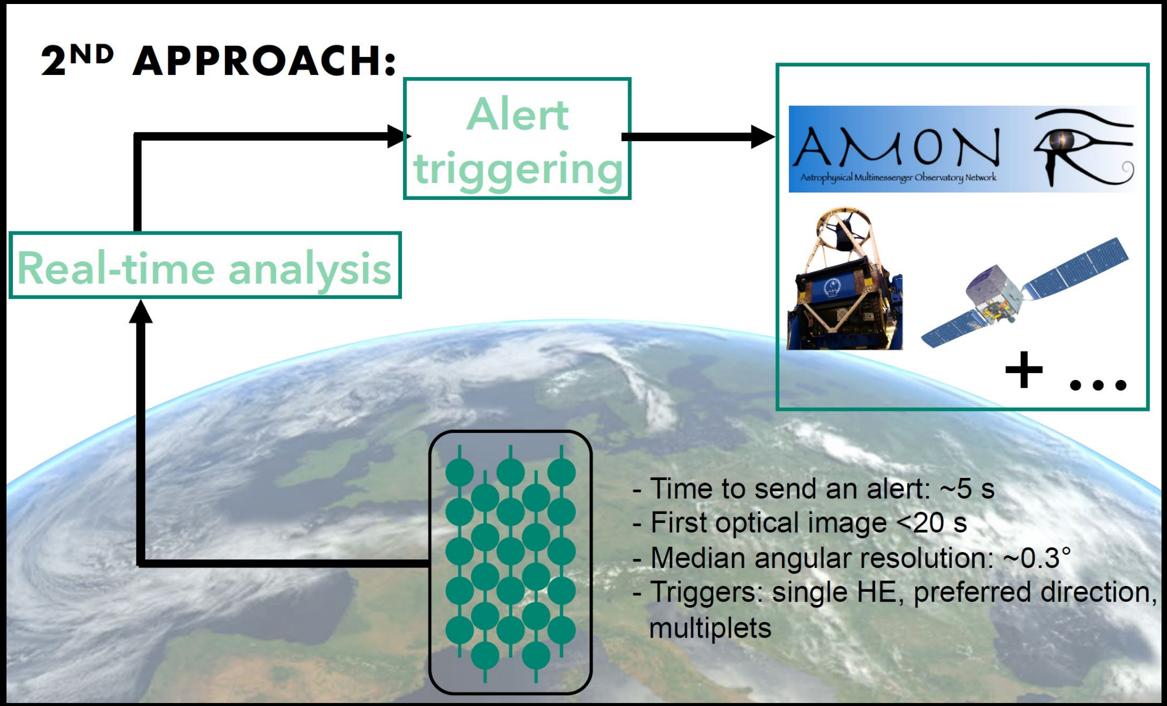


- A further analysis of archival IceCube data revealed that this blazar was emitting neutrinos before
- Excess of 13±5 events found in 2014-2015 data
- During this period, there was no significant EM flaring activity
- IceCube conclusion: **Compelling evidence** of a HE ν from a blazar

THE MULTI MESSENGER NETWORK

M. Spurio: Neutrino telescopes, @ THESEUS CONFERENCE 2021

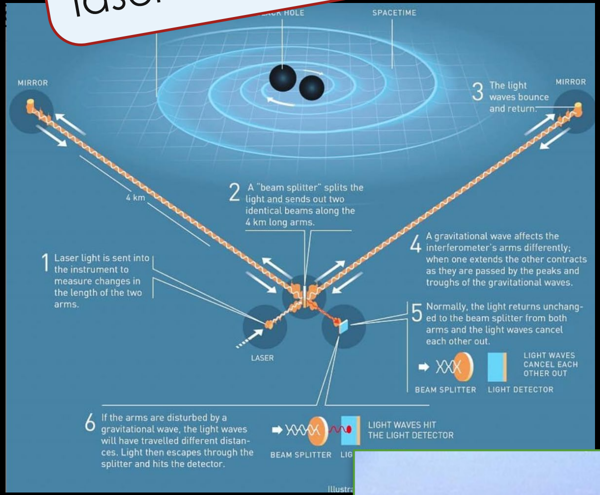




M. Spurio: Neutrino telescopes, @ THESEUS CONFERENCE 2021

A NEW WINDOW INTO THE UNIVERSE

1970s: **Early work** on GW detection by laser interferometers



Operational
Under construction
Planned

2000s: **First** Science Runs
Since 2015:
Advanced Detectors

4 km

3 km

Credit: LIGO–Virgo

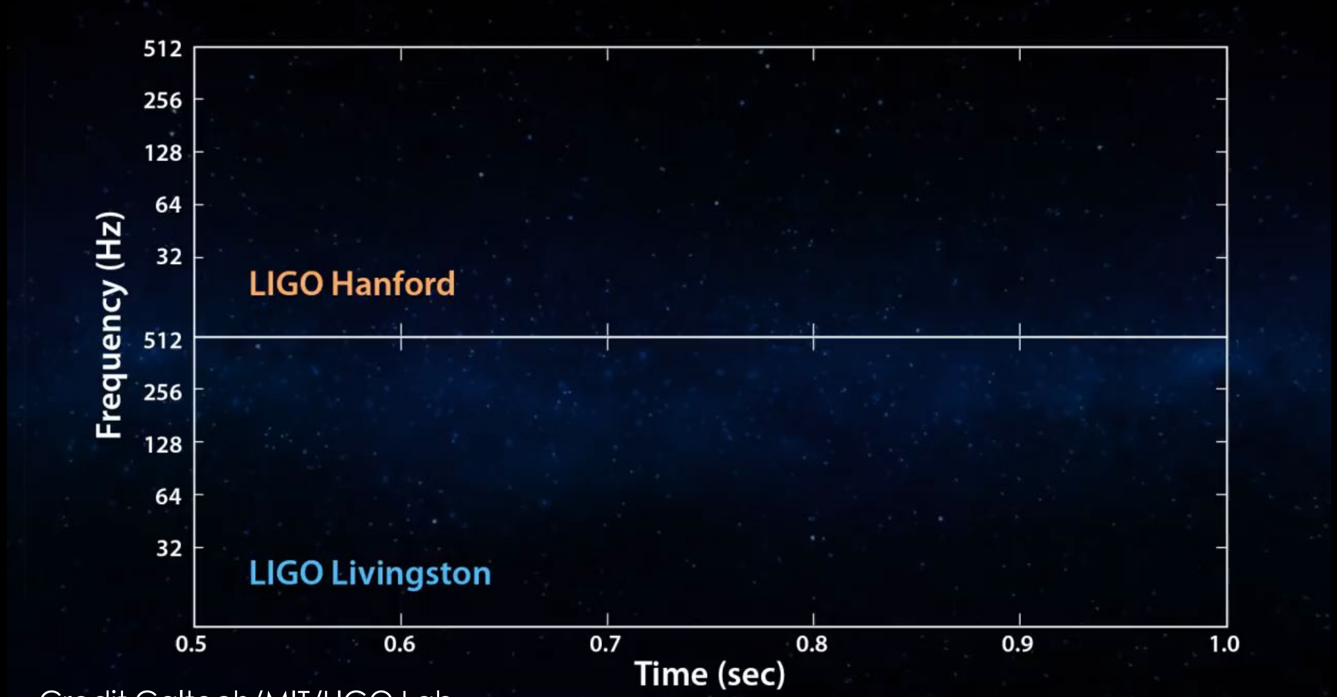
THE BEGINNING OF THE GW ERA!

PRL 116, 061102 (2016)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 12 FEBRUARY 2016

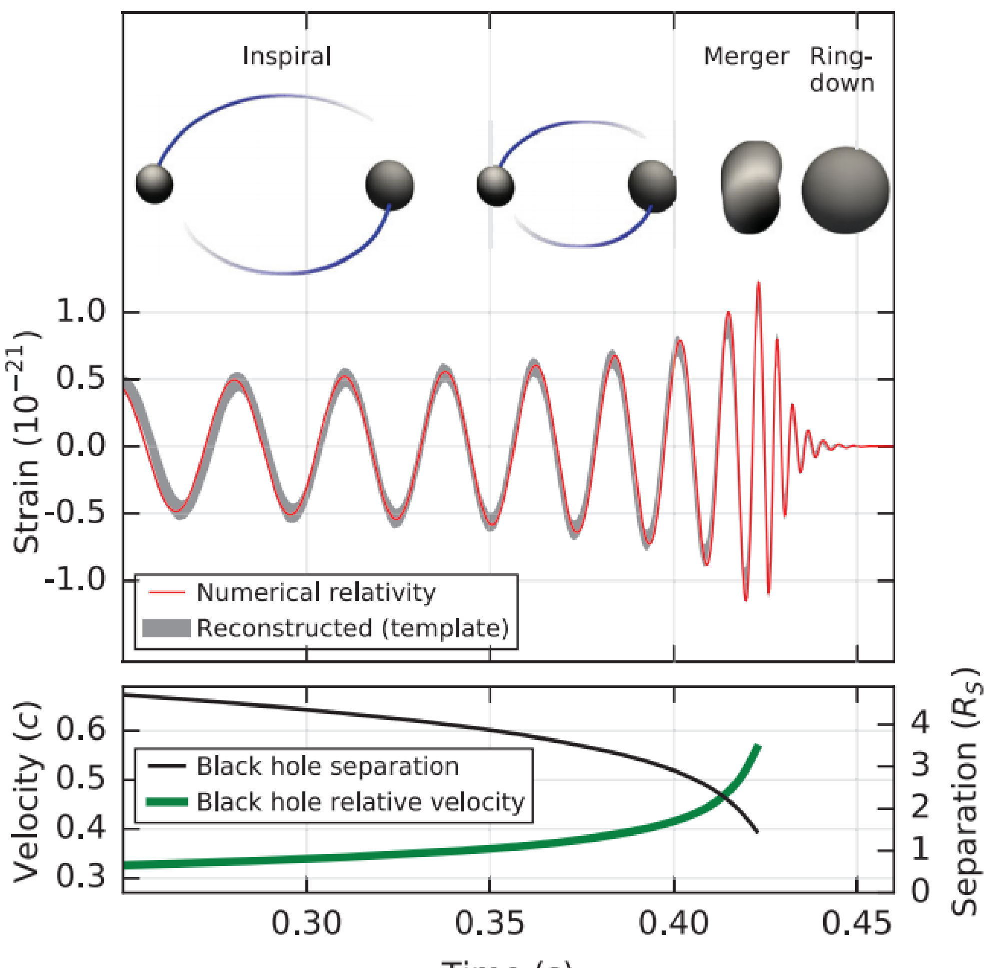
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

GW150914



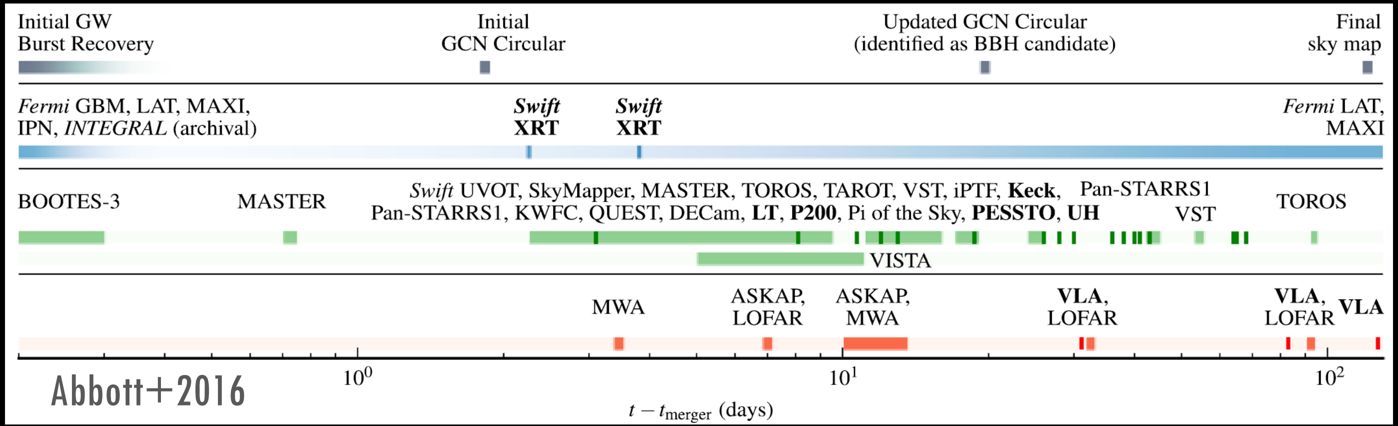
Credit Caltech/MIT/LIGO Lab

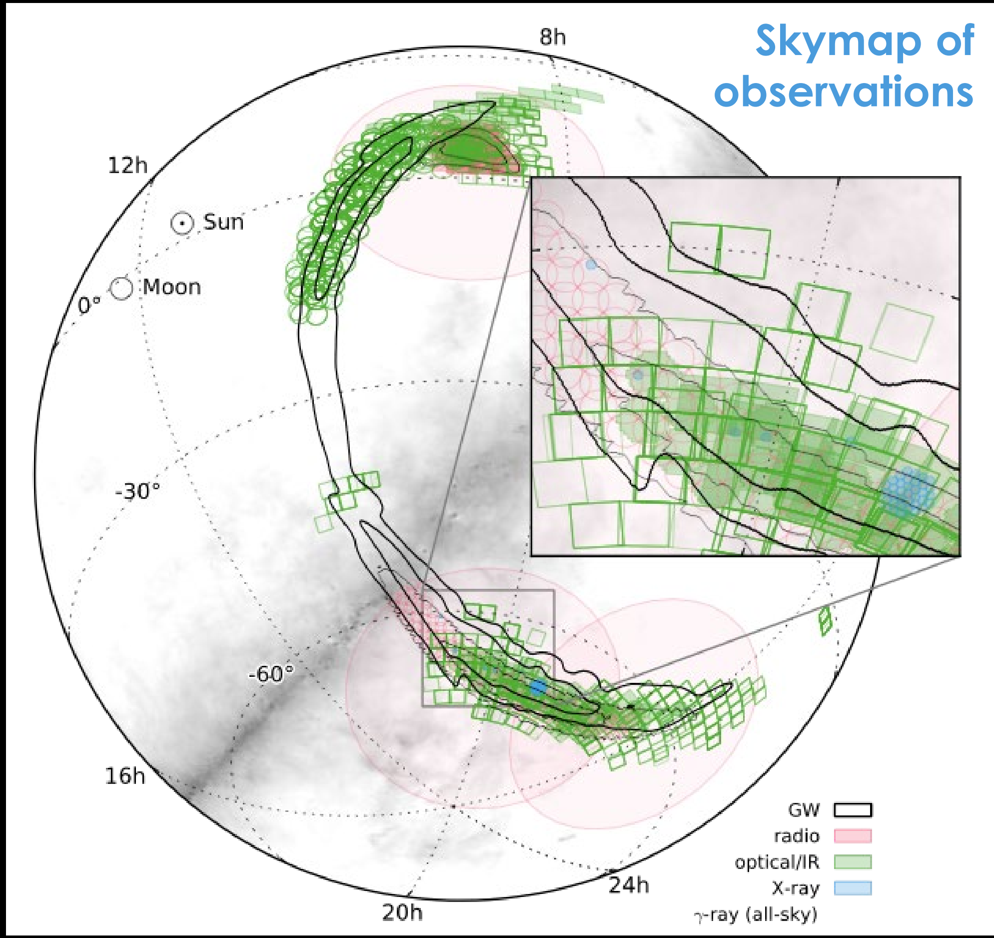


B.P. Abbott et al (2016) Phys. Rev. Lett. 116, 061102

THE EM FOLLOW-UP OF GW150914

- No coincident triggers from space-based observatories → Offline searches
- Follow-up observations reported by 25 teams via private GCN circulars: NO counterpart detected!



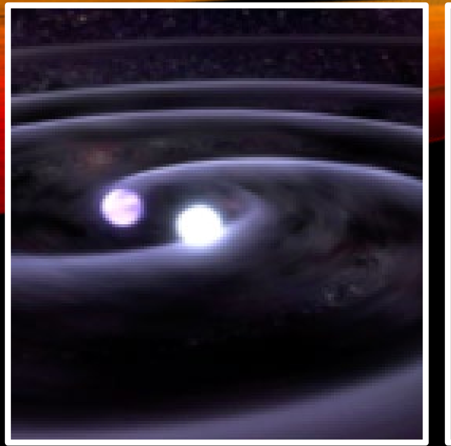


B.P. Abbott et al (2016) Phys. Rev. Lett. 116, 061102

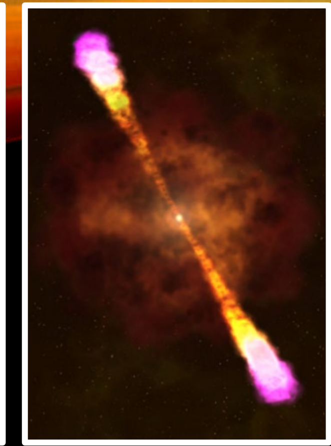
  - Event nature (BBH merger) → Little expectation of a detectable EM signature

→ But: Milestone achieved! First broadband EM counterpart search campaign!

  - Proving broad capabilities of the transient astronomy community and their observing strategies



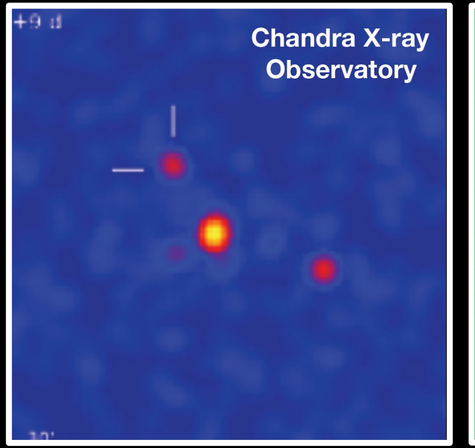
NS merger



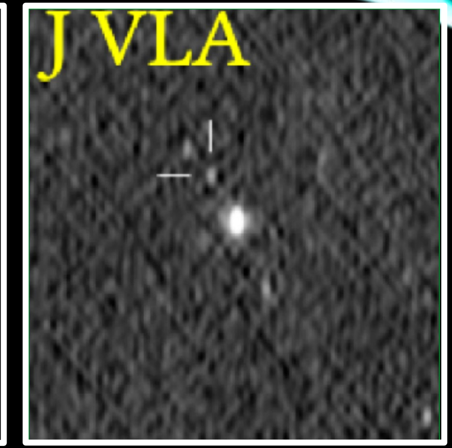
Short GRB

```
///////////////////////////////////
TITLE:            GCN/FERMI NOTICE
NOTICE_DATE:      Thu 17 Aug 17 12:41:20 UT
NOTICE_TYPE:      Fermi-GBM Alert
RECORD_NUM:       1
TRIGGER_NUM:      524666471
GRB_DATE:         17982 TJD;    229 DOY;    17/08/17
GRB_TIME:         45666.47 SOD {12:41:06.47} UT
TRIGGER_SIGNIF:   4.8 [sigma]
TRIGGER_DUR:      0.256 [sec]
E_RANGE:          3-4 [chan]    47-291 [keV]
ALGORITHM:        8
```

GBM GCN Notice



X-ray afterglow



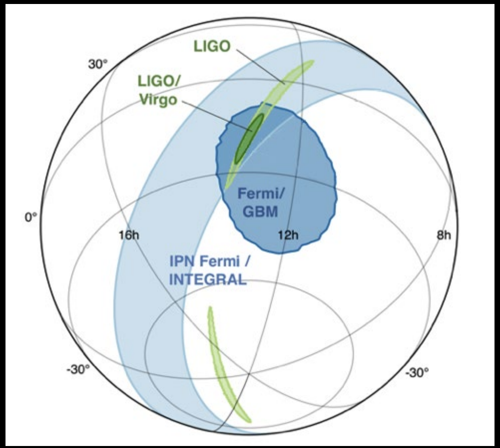
Radio

T_0 +1.7s +16s +45min +6hrs +11 hrs +9 days +16 days

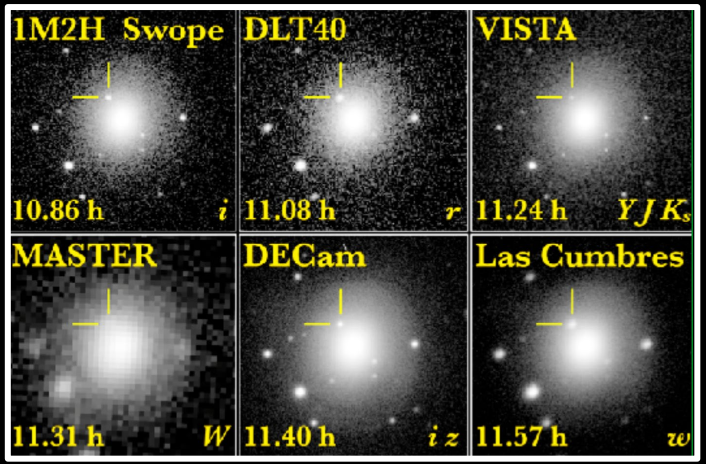
LVC GCN Circular

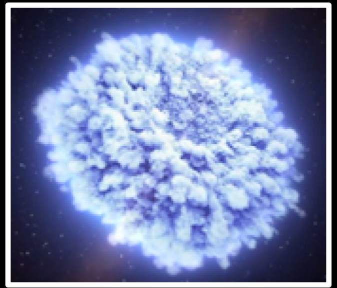
```
///////////////////////////////////
TITLE:   GCN CIRCULAR
NUMBER:  21505
SUBJECT: LIGO/Virgo G298048: Fermi GBM trigger
524666471/170817529: LIGO/Virgo Identification of a possible
gravitational-wave counterpart
DATE:    17/08/17 13:21:42 GMT
FROM:    Reed Clasey Essick at MIT  <ressick@mit.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration
report:
The online CBC pipeline (gstlal) has made a preliminary identifi-
cation of a GW candidate associated with the time of Fermi GBM
trigger 524666471/170817529 at gps time 1187008884.47 (Thu Aug 17
12:41:06 GMT 2017) with RA=186.62deg Dec=-48.84deg and an error
radius of 17.45deg.
The candidate is consistent with a neutron star binary
coalescence with False Alarm Rate of ~1/10,000 years.
```

LHV sky localization



UV/Optical/NIR Kilonova





40 Mpc away!

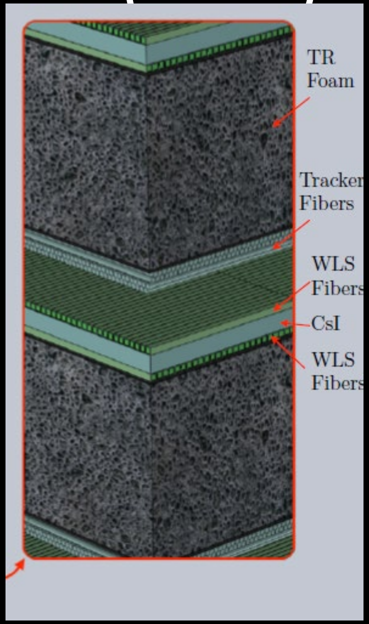
LIGO/Virgo O1 - O3a

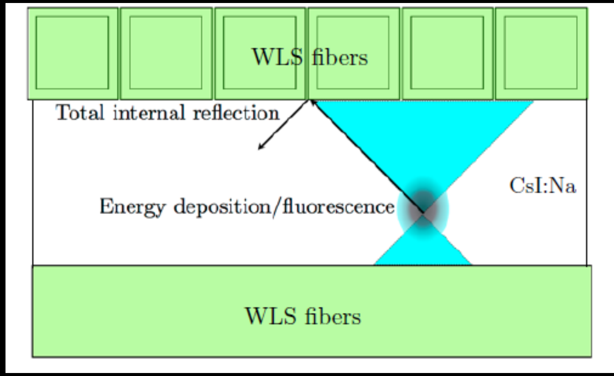
Time: -0.30 seconds

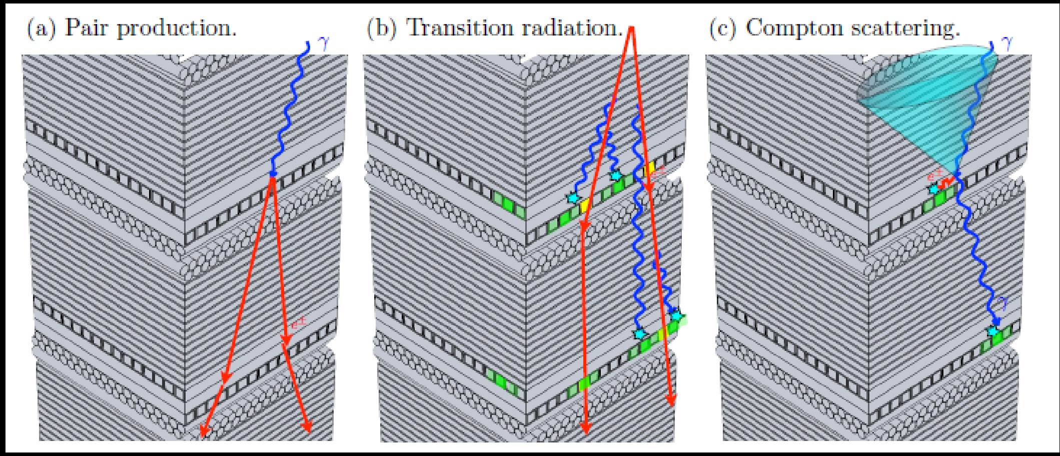
NICHOLAS AND LEE BEGOVICH GW PAC
Center for Gravitational-Wave Physics and Astronomy

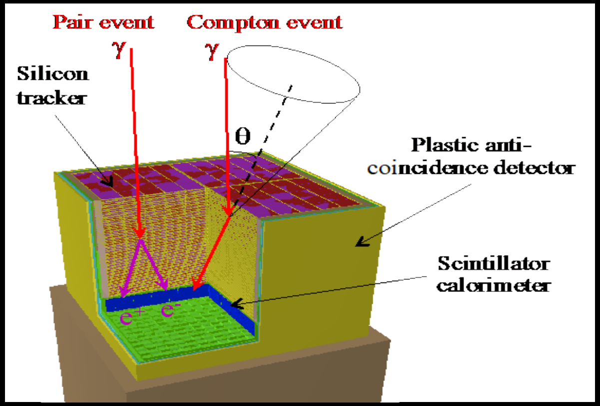
THE ADVANCED PARTICLE-ASTROPHYSICS TELESCOPE (APT) – ASTRO2020

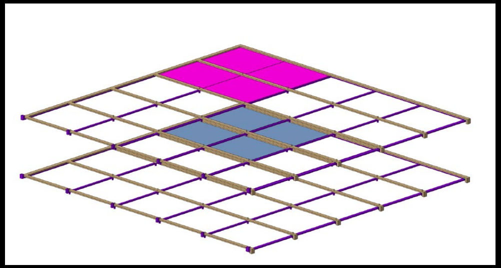
- The APT detector design (3m x 3m x 2.5m):
  - mission concept for a space-based gamma-ray and cosmic-ray explorer
  - 20 layers of 5mm thick CsI(Na) with crossed wavelength shifting fiber (WLS fiber) readout
  - 20 x - y scintillating optical fiber tracker (SOFT) layers using interleaved 1.5mm round scintillating fibers
  - With the addition of foam radiators, the CsI detectors could detect the transition radiation X-rays from very-high-energy light cosmic rays
  - Top-bottom symmetry doubles FoV (in L2 orbit)
  - Read out on the sides with SiPM photodetectors and analog-pipeline waveform digitizers



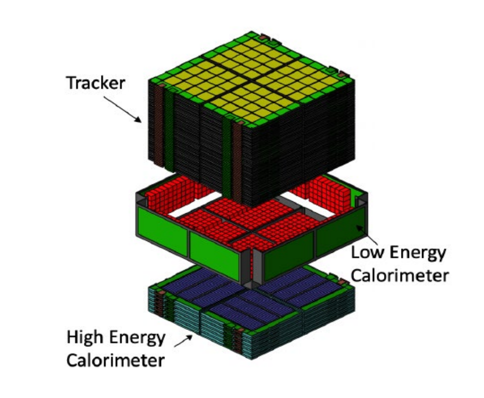


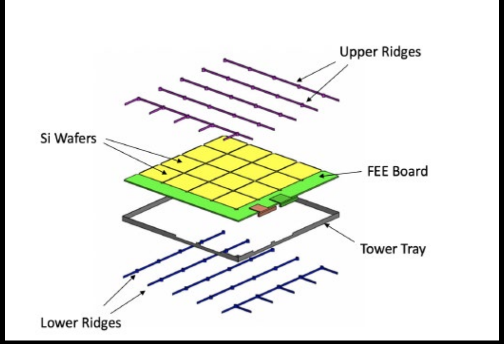






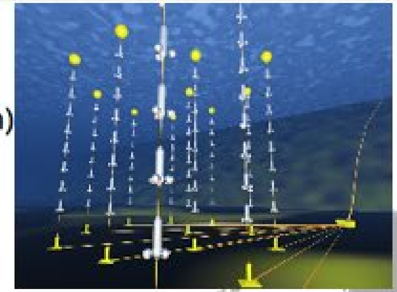
- MeV-GeV satellite
- ASTROGAM:
  - nearly 56 m^2 of double-sided Si strip detectors (DSSDs)
  - 4 towers, 56 layers of 5×5 DSSDs
    - 5600 DSSDs
  - Each DSSD wafer has a cross section of 9.5×9.5 cm^2, a thickness of 500 μm and a pitch of 240 μm (384 strips per side)
  - Strips of the DSSDs are wire-bonded to form 5×5 2-D ladders
- AMEGO
  - 4 towers, 60 layers of 4×4 DSSDs
    - 4800 DSSDs
  - DSSD wafers 9.5 cm wide, 500 μm thick and pitch of 500 μm (190 strips per side)
  - Strips of the DSSDs are wire-bonded to form 4×4 2-D ladders

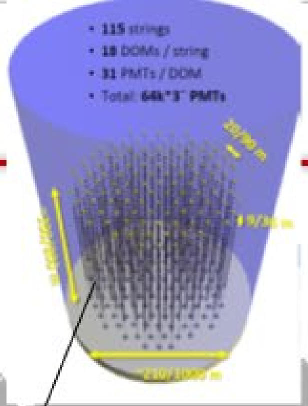




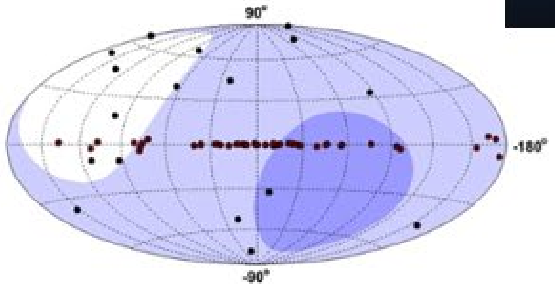
Neutrino telescopes. Where …

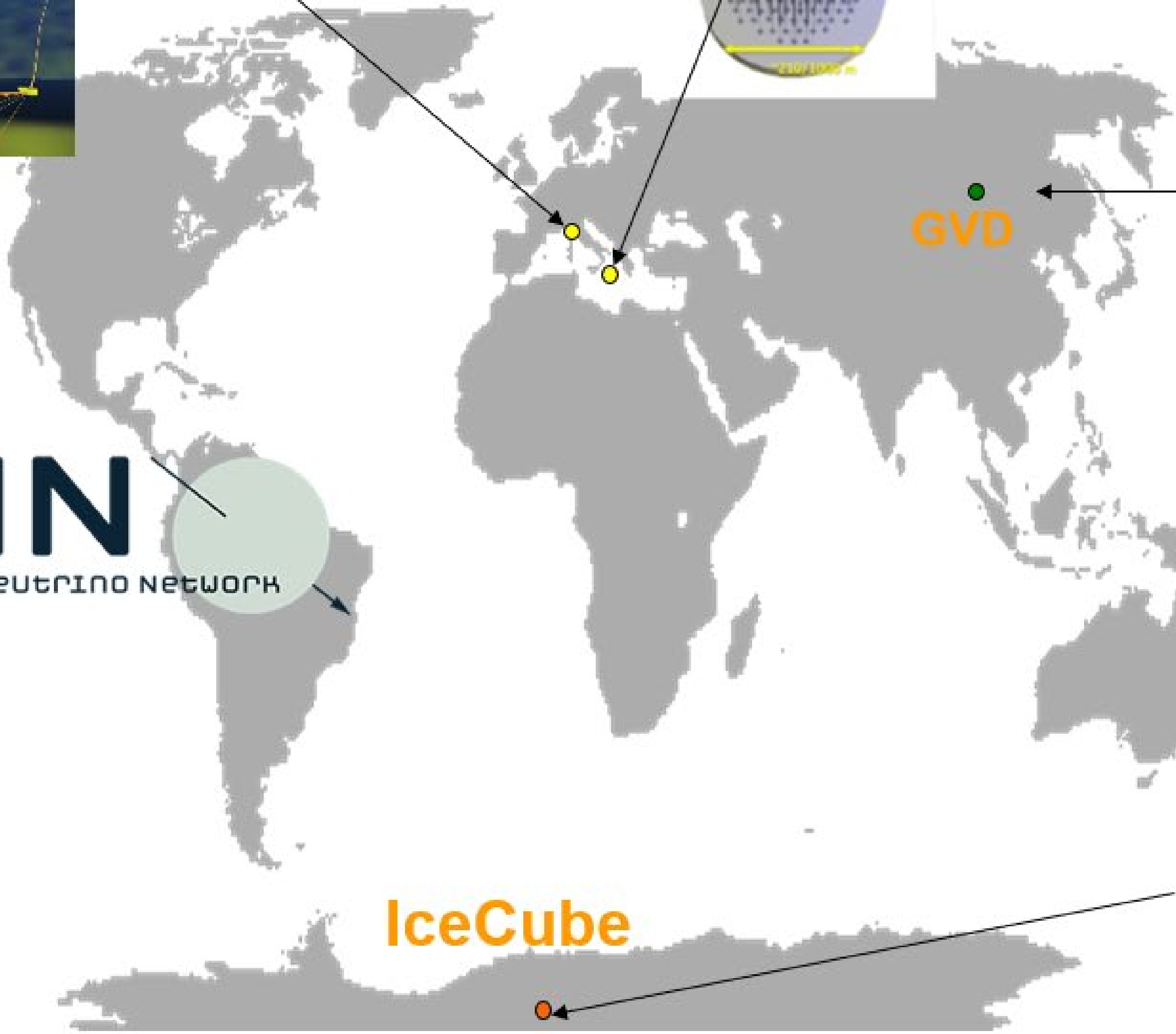
M. Spurio: Neutrino telescopes, @ THESEUS CONFERENCE 2021

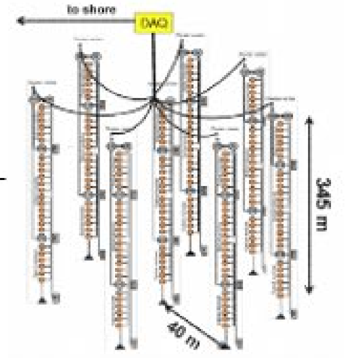




Visibility ANTARES (Mediterranean)
- 75%
- 25% – 75%
- 25%

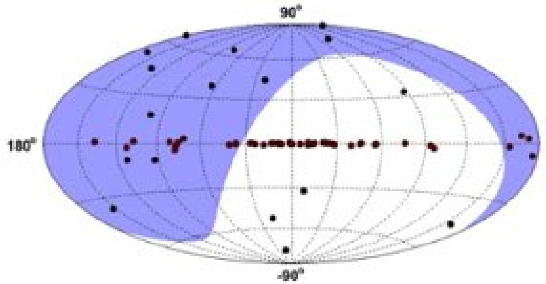


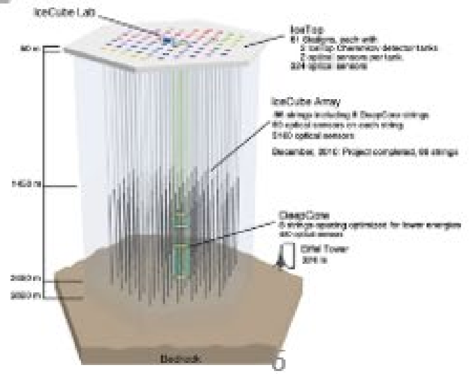




GNN
The Global Neutrino Network

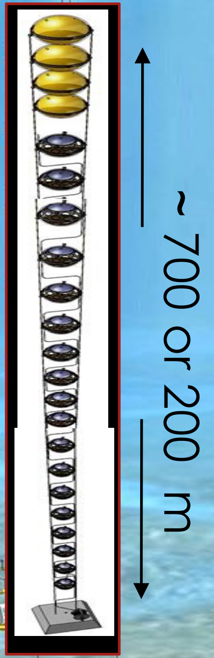
Visibility IceCube (South Pole)
- 100%
- 0%

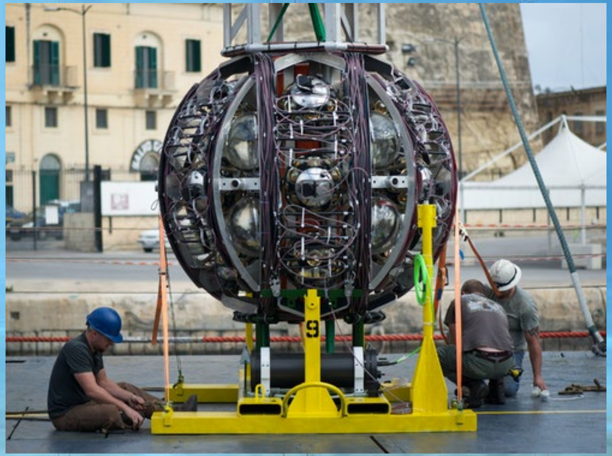




New telescopes in water: KM3NeT

M. Spurio: Neutrino telescopes, @ THESEUS CONFERENCE 2021





Digital Optical Module (DOM)
- Multi-PMT : 31 x 3” PMTs
- Gbit/s on optical fiber
- Positioning & timing

Detection Unit (DU)
- 18 DOMs
- Low-drag design

- Rapid deployment
- Multiple strings/sea campaign
- Autonomous/ROV unfurling
- Reusable

Current IACT facilities

Energy range: from tens of GeV to tens of TeV, overlapping with satellites

MAGIC
La Palma – 2200 m asl
2 x 17 m Ø
Since 2003 (1), 2009 (2)

VERITAS
Arizona – 1270 m asl
4 x 12 m Ø
Since 2007

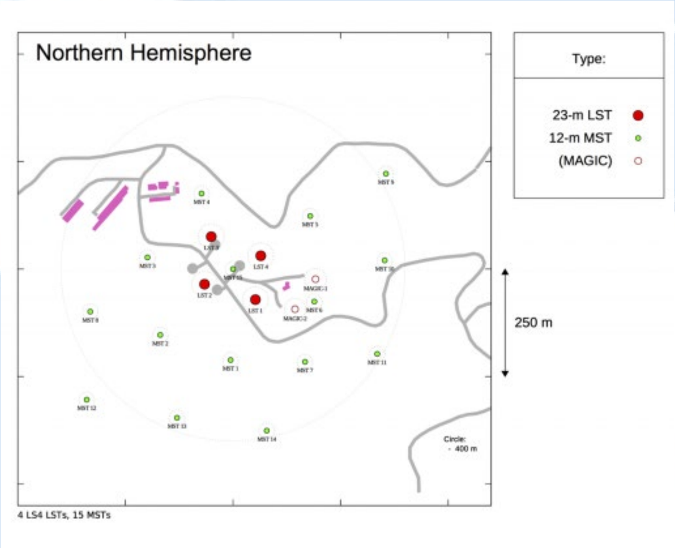
H.E.S.S.
Namibia – 1800 m asl
4 x 12 m Ø + 1 x 28 m Ø
Since 2003 (4), 2012 (5)

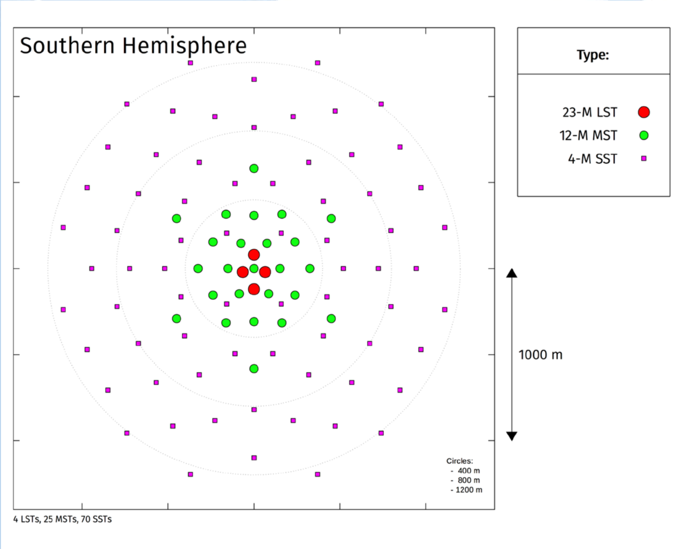
cta cherenkov telescope array

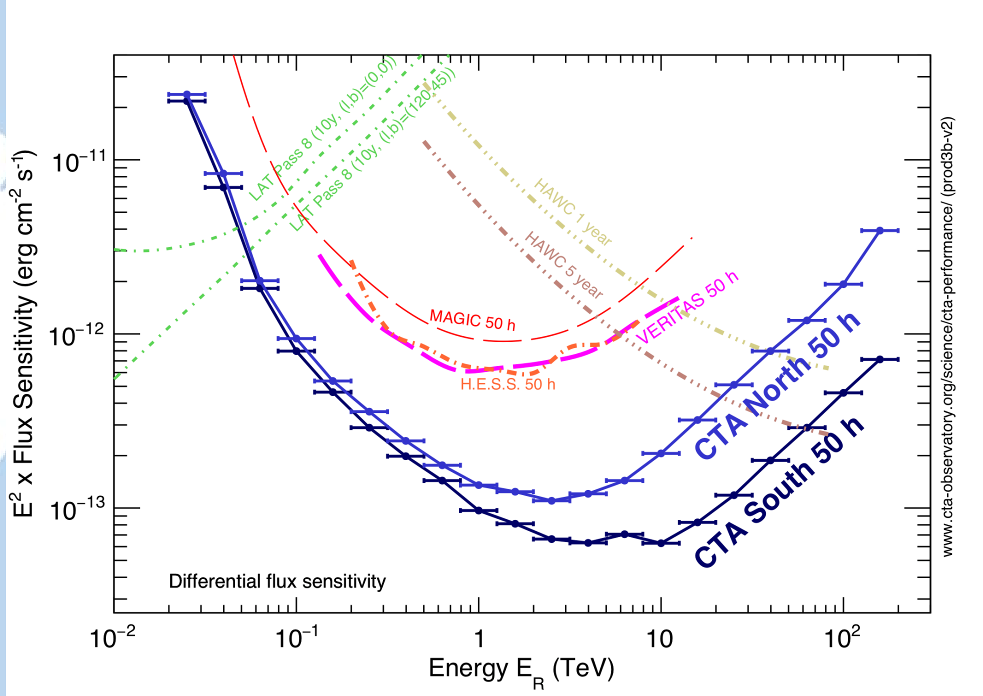
<u>North Site</u>: La Palma
<u>South Site</u>: Chile

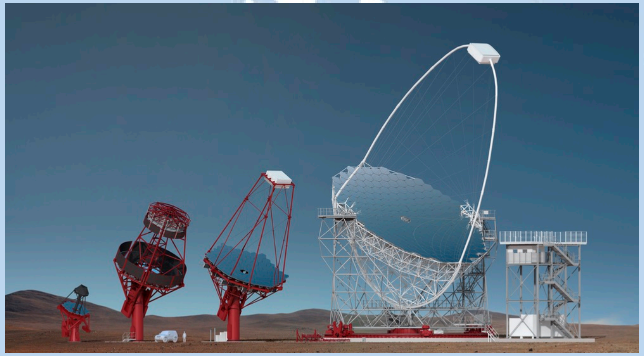
Cherenkov Telescope Array

- about100 telescopes
- increased detection area
- improved sensitivity
- 3 telescope sizes.









Energy range: from tens of GeV to hundreds of TeV

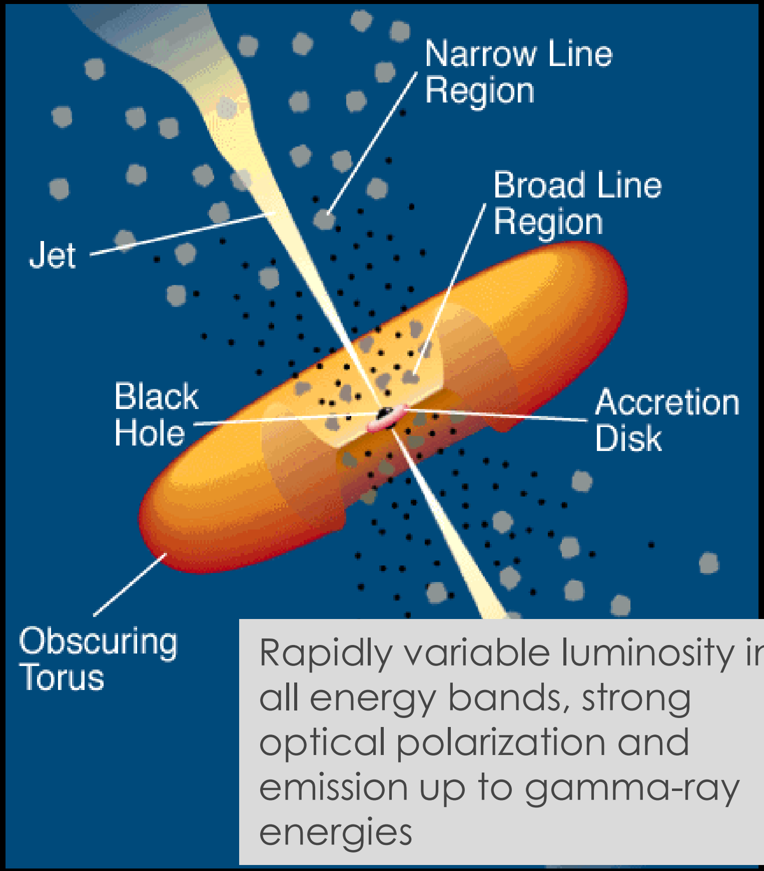
HADRONIC MODELS

- Proton blazar model
- Low energy emission from synchrotron radiation from electrons
- High energy emission from interaction between energetic protons in the jet (production of e+/e-, pions)
- Production of gamma rays at higher energies w.r.t. leptonic processes, but more extreme conditions (strong B)
- These processes are slower → difficult to explain fast variability
- Also it is difficult to explain the correlation between X-rays and gamma rays

→ lepto/hadronic models: hadronic emission responsible for luminosity, leptonic for variabilty

RADIO-LOUD AGN CLASSIFICATION

- Radio galaxies: AGN seen from large angles. Central BH, accretion disk and BLR are hidden by the torus
- Blazars: closely aligned AGN, the jets emission hides the thermal emission from the rest of the galaxy
  - FSRQ: two bump continuum in the spectrum and strong evidence of BLR and NLR in addition to thermal component
  - BL Lacs: two bump continuum but no evidence for emission or absorption line
  - Classified in LSP, ISP and HSP according to the location of the synchrotron peak ($<10^{14}$ Hz, 10^{14} Hz – 10^{15} Hz, $>10^{15}$ Hz)



Rapidly variable luminosity in all energy bands, strong optical polarization and emission up to gamma-ray energies

THE FERMI-LAT

- Tens of MeV – few hundreds of GeV
- Pair-conversion telescope
- Converter-tracker
  - 16 layers of high Z material (W) → conversion of gamma rays into e^-/e^+ pair
  - Conversion layers interleaved with planes of Si strip detectors to track the trajectories
  - Two layers of Si strip → 2D reconstruction
- Calorimeter
  - Reconstruction of the energy
  - 8 layers of CsI(Tl) + photo-diodes to readout the signal
- Segmented ACD
  - Plastic scintillator to act as veto for charged particles