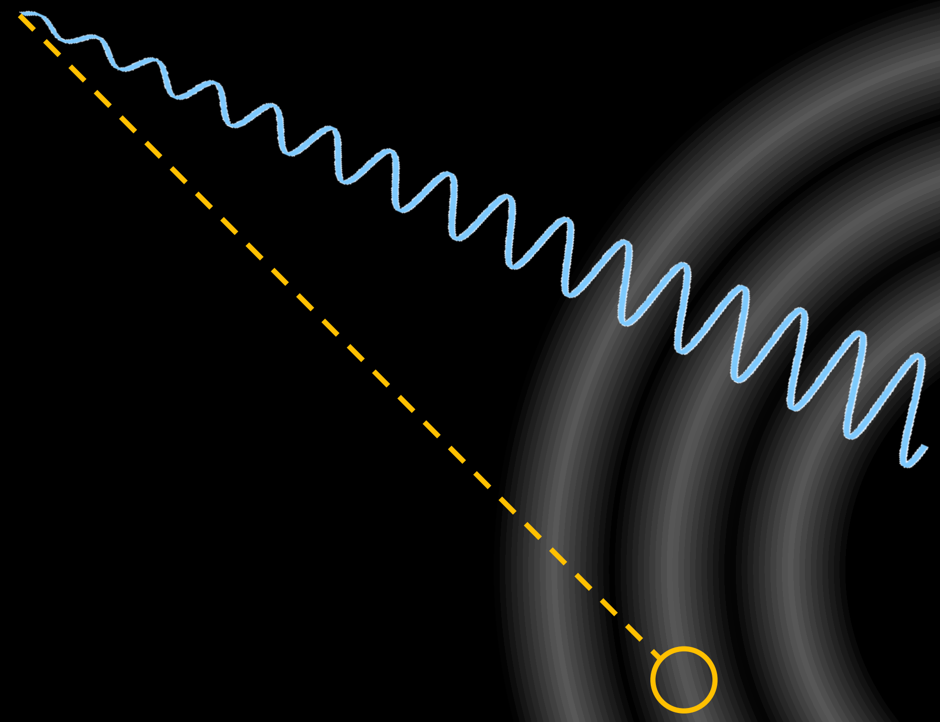


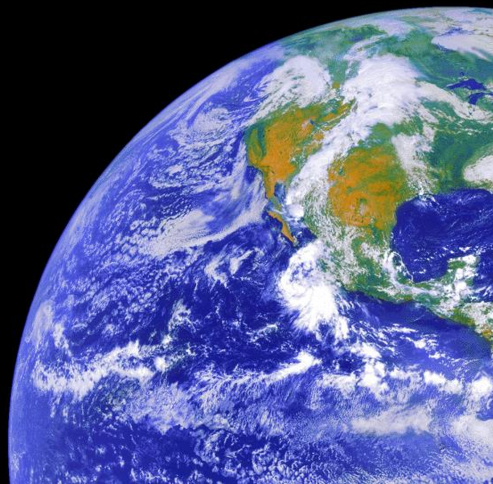
Multi-Messenger Astrophysics

(ICHEP2018 Highlights, and More)

Peter S. Shawhan
University of Maryland Dept. of Physics
and Joint Space-Science Institute

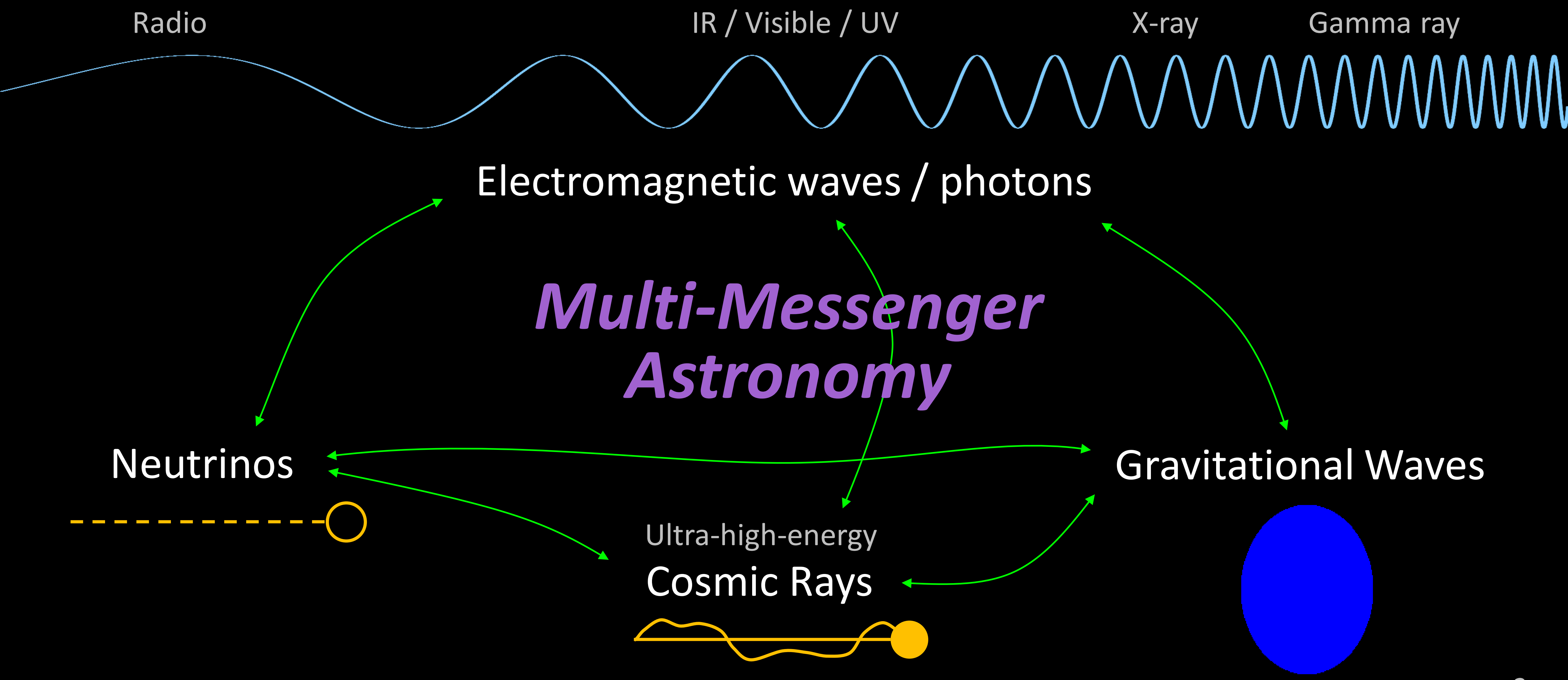
PHY-1710286

ICHEP2018 SEOUL
XXXIX INTERNATIONAL CONFERENCE ON high energy PHYSICS
JULY 4 - 11, 2018 COEX, SEOUL



GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

Astrophysical Messengers



Connection with Fundamental Forces

We detect these "messengers" through their different interactions with detectors or material (e.g. atmosphere, water, Earth)…

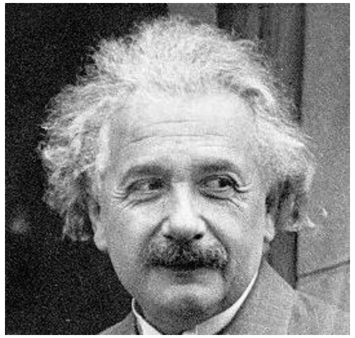
Electromagnetic waves / photons
→ Electromagnetic

Neutrinos
→ Weak

Ultra-high-energy
Cosmic Rays
→ Strong

Gravitational Waves
→ Gravity (?)

A consequence of Einstein's general theory of relativity (GR)



… which says that gravity is really an effect of "curvature" in the geometry of space-time, caused by the presence of any object with mass

- ► It's not actually a force!
- ► Things naturally move along "straight" paths in the curved spacetime

The Einstein field equations have static solutions describing the regular gravitational field, but also wave solutions which travel at the speed of light

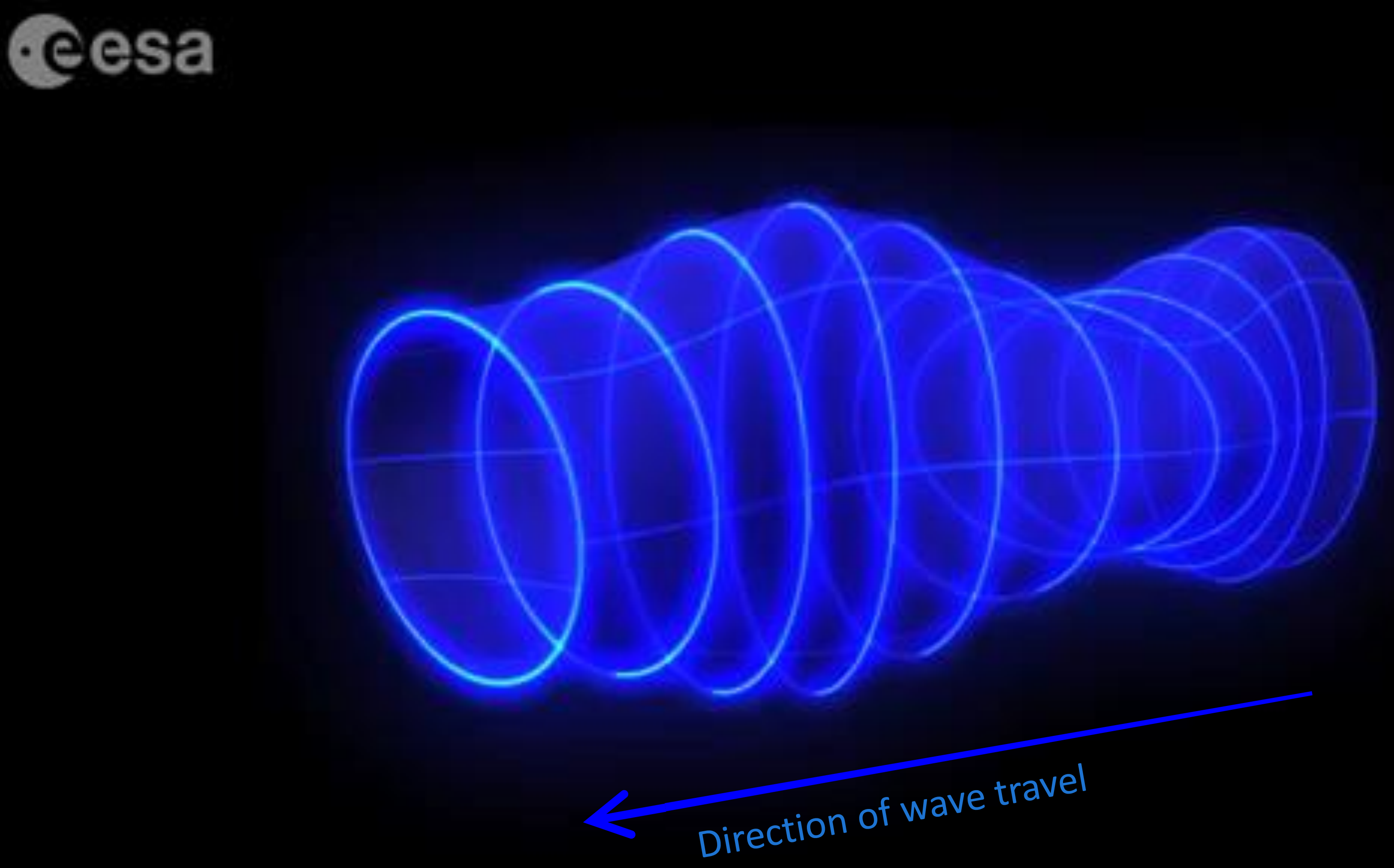
These waves are *perturbations of the spacetime metric* — the effective distance between points in space and time

$$g_{\mu\nu}$$

Looking at a fixed place in space while a gravitational wave travels past, the waves alternately **stretch** and *shrink* space and anything in it

➔The geometry of space-time is dynamic, not fixed!

A Gravitational Wave in Motion



Different Emissions from the Same Sources

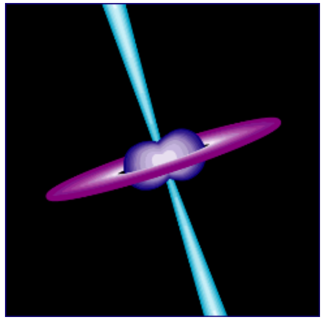
Can look at individual sources, or populations


Bill Saxton, NRAO/AUI/NSF

Stellar core collapse → gravitational waves? (if non-axisymmetric collapse)
→ low-energy neutrinos (from nuclear reactions)
[supernova] → UV/visible/IR light (from expanding envelope)
→ cosmic rays (shock acceleration in SN remnant)

High-energy cosmic rays interacting with ambient photons
→ high-energy neutrinos (Waxman & Bahcall 1998)

Relativistic jets — *generated by accretion around black hole or neutron star*
→ high-energy neutrinos (from hadronic interactions and decays)
[AGN, GRB] → EM emissions at a wide range of wavelengths
(synchrotron emission from particles in turbulent magnetic fields; inverse Compton scattering)

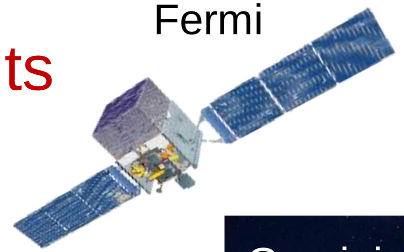

P.J.T. Leonard, NASA/GSFC

Neutron star binary merger → gravitational waves
→ relativistic jets (see above)
→ UV/visible/IR light (from heated ejecta)

And other sources…

Different Messengers Give Complementary Information

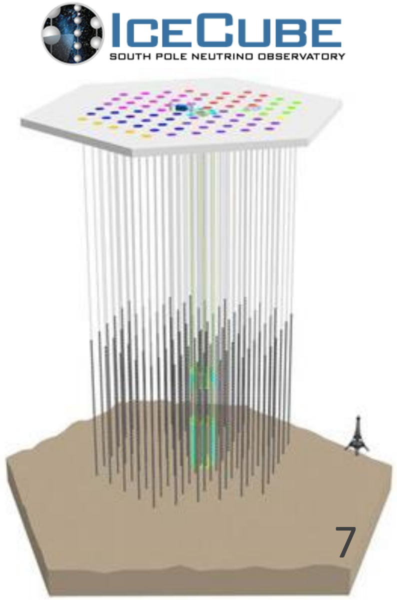
Fermi



Swift

Stéphane Courteau/Queen's U

Image courtesy of NRAO/AUI



We have a large variety of wide-field and pointed instruments

Different observational strengths:

- **Gamma ray**: timing, spectrum, particle acceleration signature
- **X-ray**: timing, good localization, low background
- **Visible/IR**: precise localization, spectroscopy (& redshift), thermal signature
- **Radio**: late-time synchrotron afterglow, precise localization
- **Neutrino**: timing, particle acceleration signature
- **Gravitational waves**: timing, distance, mass parameters

Different views of the event:

- **Core engine**: low-energy neutrinos, gravitational waves
- **Outflows**: high-energy neutrinos, gamma rays, X-rays, visible/IR, radio
- **Environment**: X-ray and radio afterglow

➔ ***Multi-Messenger Astrophysics***

Challenges for Multi-Messenger Astronomy

Comparable detectability?

Will a source be detectable with more than one messenger, given instrument sensitivities?

Coordination — observing a transient source at compatible times

GW and neutrino detectors normally store all useful data, but most EM instruments *point*

Wide-field EM instruments are more likely to have the source in view, but the most sensitive telescopes tend to be narrow-field and must be pointed in the right direction

Motivates real-time analysis and rapid sharing of information about candidate events (i.e., cross-facility triggering)

Follow-through

Rapid assessment of candidate events

Strategies for additional observations, such as spectroscopy, to fully characterize the event before it fades completely

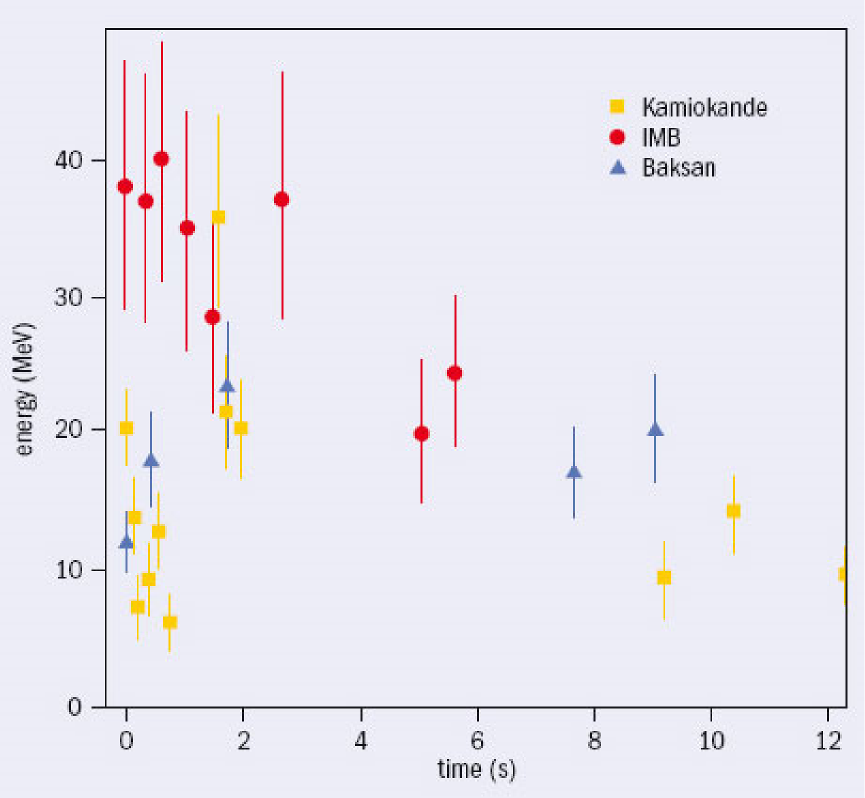
Interpretation of combined signals

May require sophisticated modeling of astrophysical processes

The First Multi-Messenger Astrophysics Event

Supernova 1987A !

Neutrino burst preceded appearance of the supernova light by a few hours



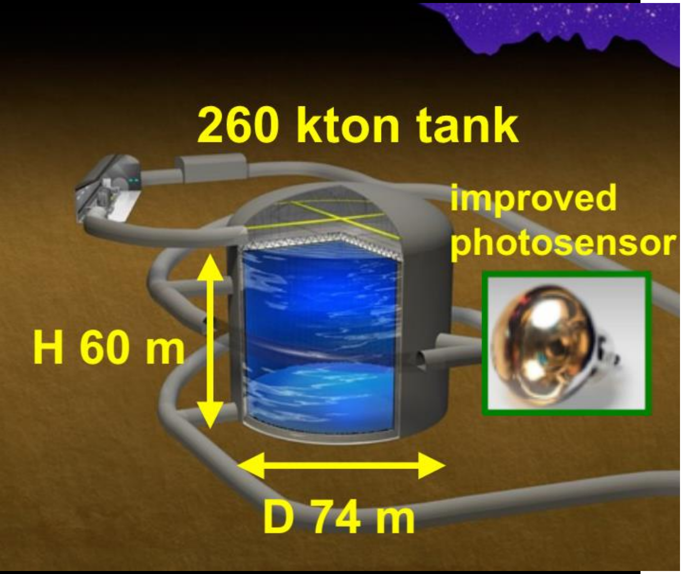
Credit: M. Nakahata (ICRR) / CERN Courier

Credit: ESA/Hubble, NASA

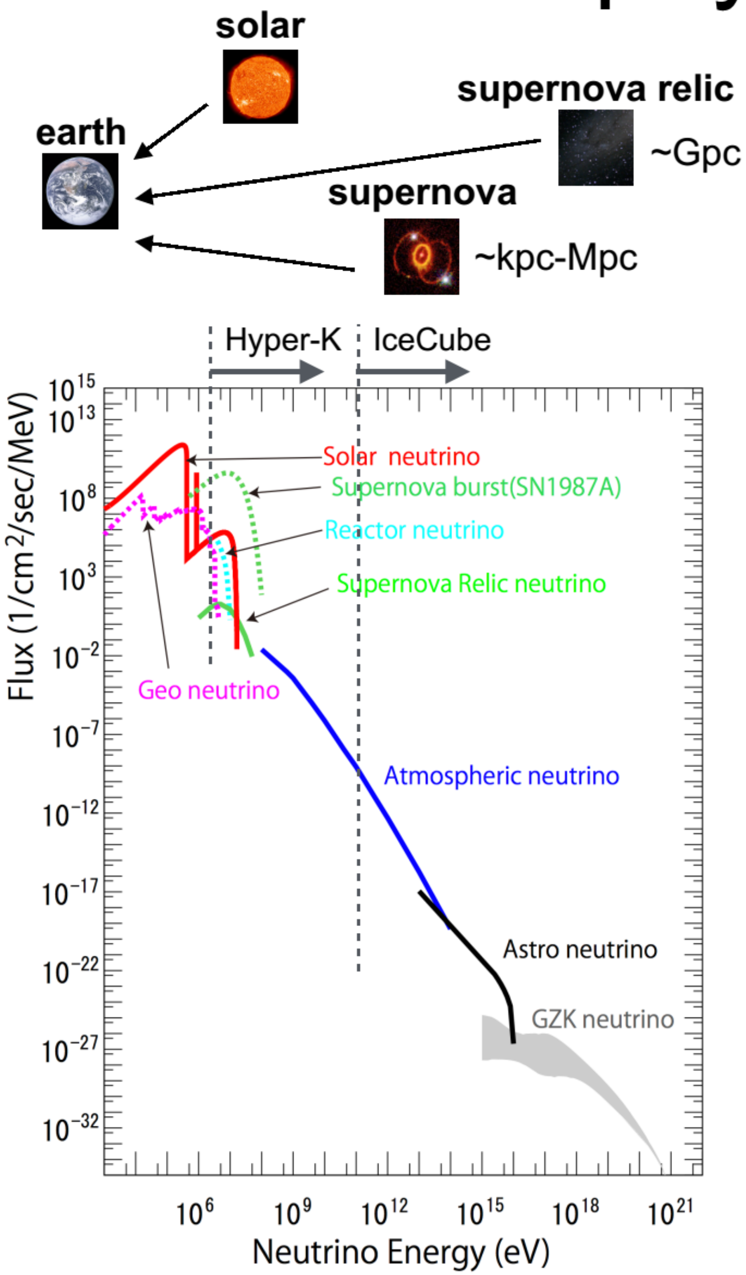
From Thursday:

I. Shimizu

"Astrophysical Neutrinos at Hyper-Kamiokande"



Astrophysical Neutrinos



Hyper-K (187 kton H_2O)

^{8}B solar neutrino	130 events / day
Supernova neutrino	~50,000 events / burst
Supernova relic neutrino	~18 events / year

highest statistics / directional information

DUNE (40 kton Ar)

Supernova neutrino	~3,000 events / burst

complementary with different mode

no directional information

JUNO (17 kton LS)

Supernova neutrino	~5,000 events / burst
Supernova relic neutrino	~3 events / year

no directional information

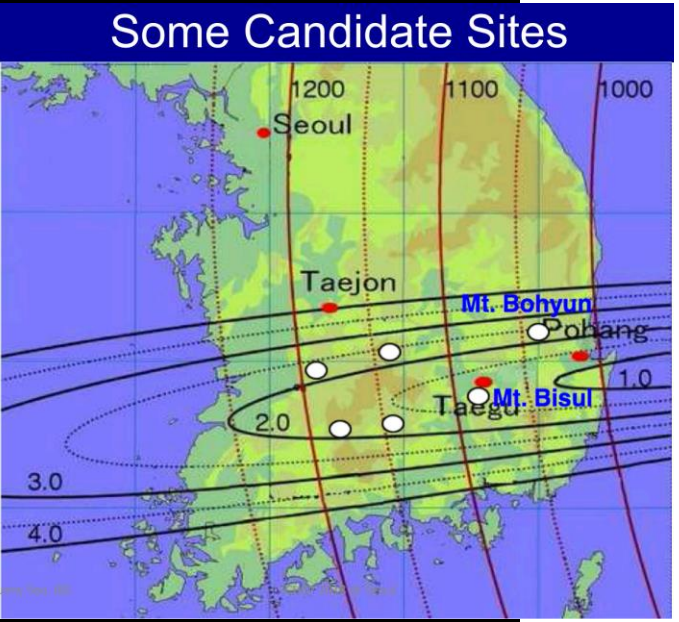
IceCube (2,400 kton H_2O)

Supernova neutrino	~300,000 events / burst

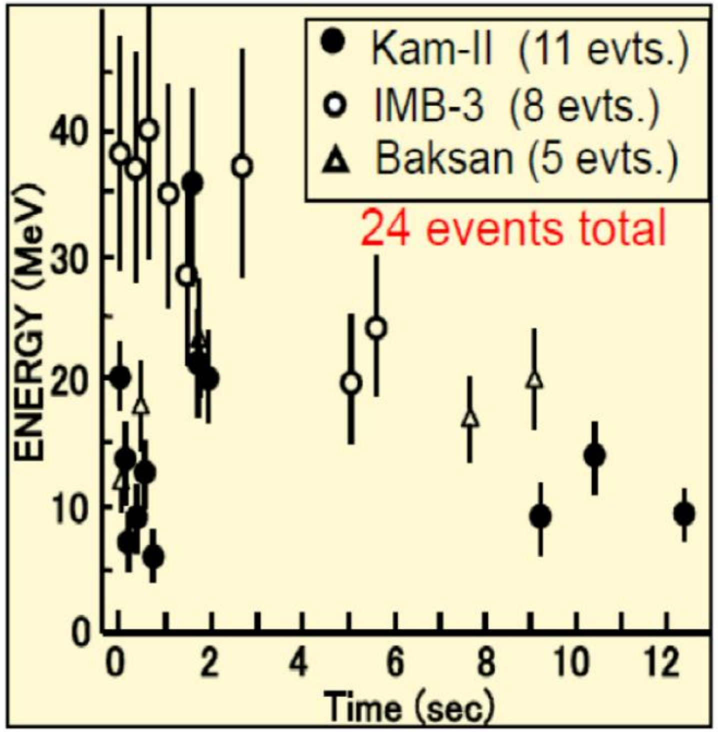
no energy / directional information

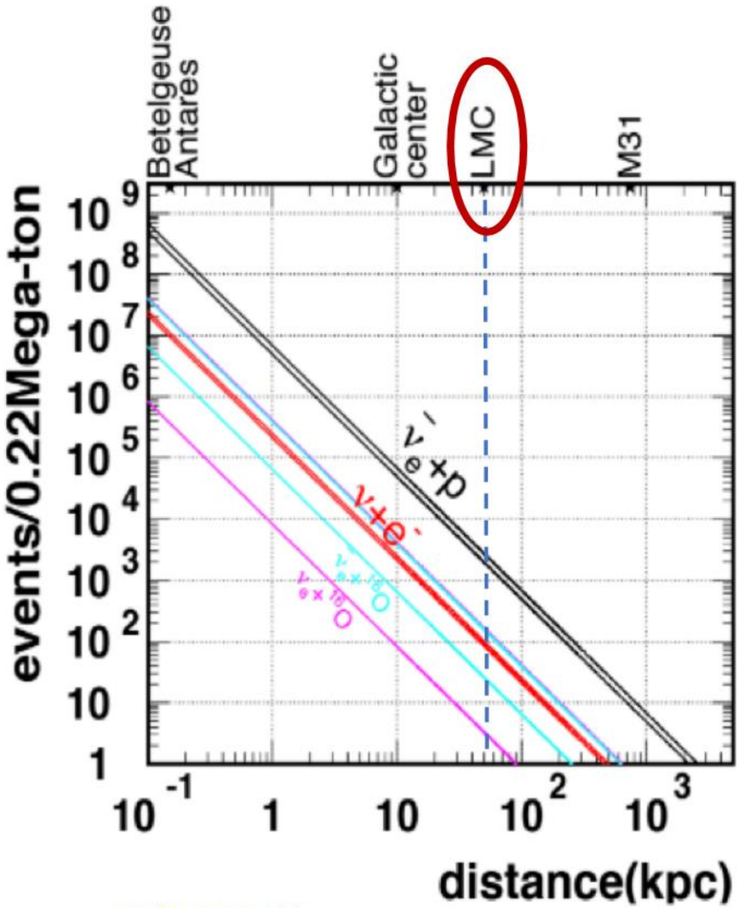
Supernova Burst Neutrinos

From Friday:
S. Seo
"Physics Potentials of the Hyper-K 2nd Detector in Korea"



SN1987A @LMC





11 events
@Kamiokande

O(1000) events
@Hyper-K/KNO

Astronomy & Astrophysics with High-Energy Neutrinos

Can be produced in relativistic jets or by shocks

IceCube has observed a diffuse flux of astrophysical neutrinos *[Aartsen et al. 2013, Science 342; 2014, PRL 113]*

- Above background of atmospheric neutrinos
- Have measured flavor ratio *[Aartsen et al. 2015, PRL 114]*

What are the sources?

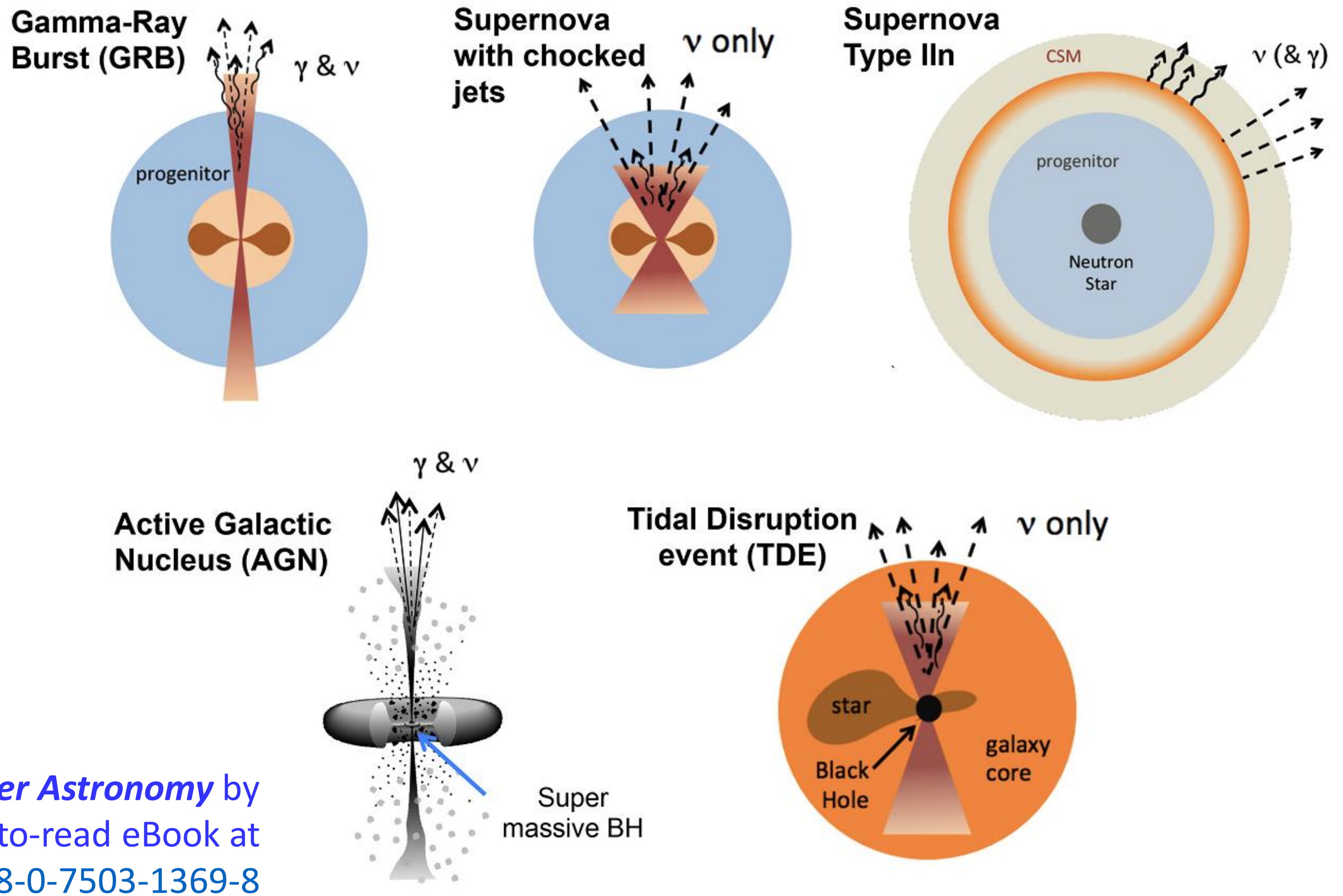


Figure from ***Multimessenger Astronomy*** by I. Bartos and M. Kowalski, a free-to-read eBook at http://iopscience.iop.org/book/978-0-7503-1369-8

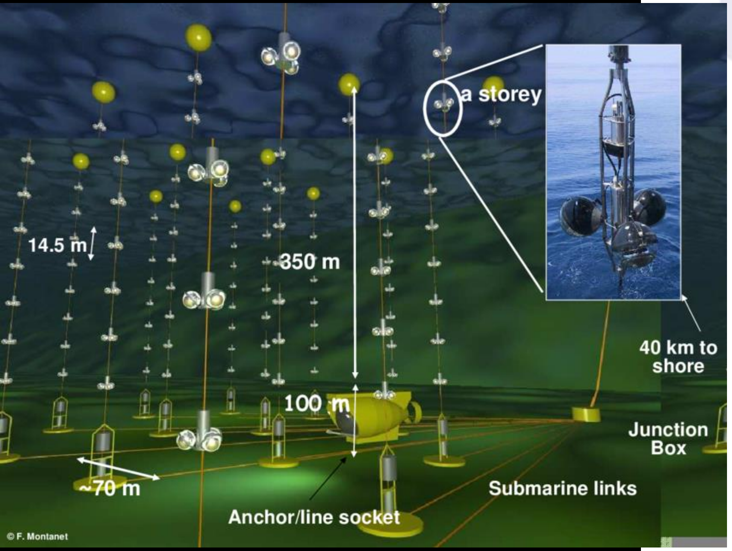
Figure 2. Scenarios for sources of neutrinos, with varying degrees of jet formation.

From Friday:

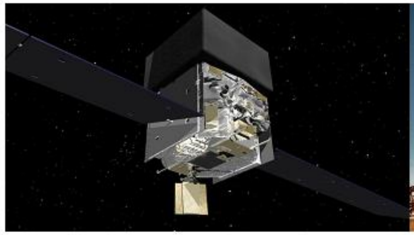
A. Creusot

"Latest results of the ANTARES detector and perspectives for KM3NeT/ARCA"

In the Mediterranean Sea



- space/time correlation
- alerts and follow-up



- radio: MWA, Parkes
- visible: TAROT, ZADKO, MASTER, SVOM-GWAC
- X-ray: Swift
- γ-ray: Integral
- GeV-ray: Fermi-LAT
- TeV-ray: HESS, HAWC
- GW: Ligo, VIRGO
- neutrino: IceCube

GRB - ANTARES

From Friday:

A. Creusot

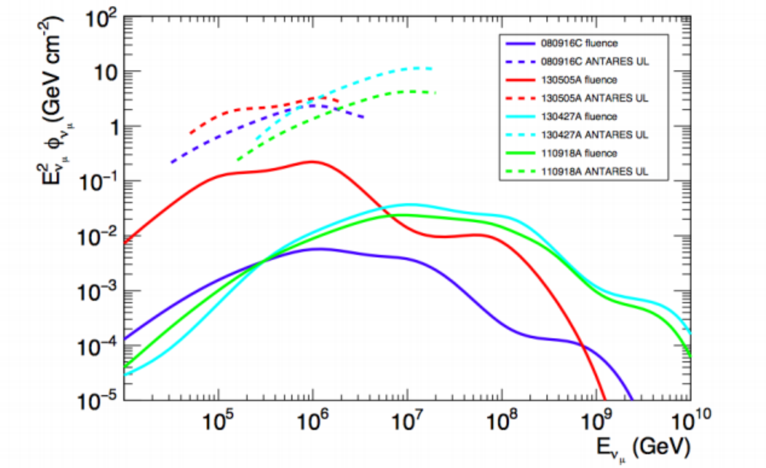
"Latest results of the ANTARES detector and perspectives for KM3NeT/ARCA"

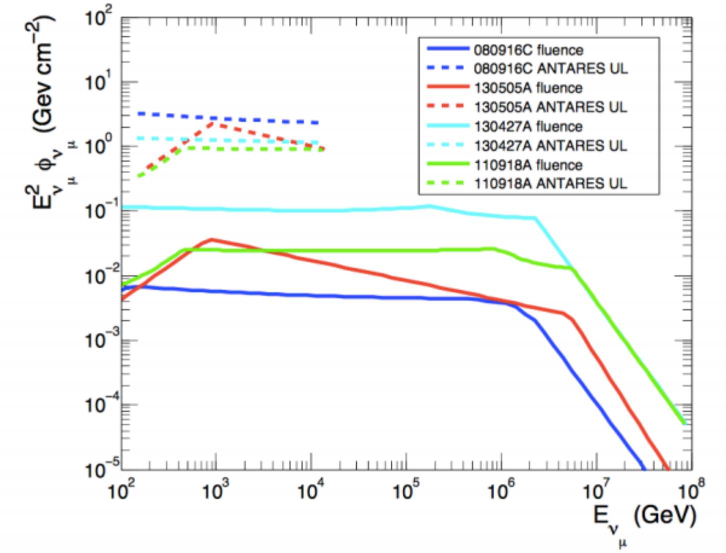
No neutrino events found coincident in time & space
➔ limits on emission

IceCube, too, has looked for neutrinos coincident with GRBs, with no statistically *significant correlation*
[Aartsen et al., ApJ 824]

- neutrino events in coincidence with observed GRB
- data 200 s after GRB trigger
- GRB 080916C, 110918A, 130427A and 130505A
- internal shock model (up)
- photospheric model (down)

MNRAS 469, 906-915 (2017)





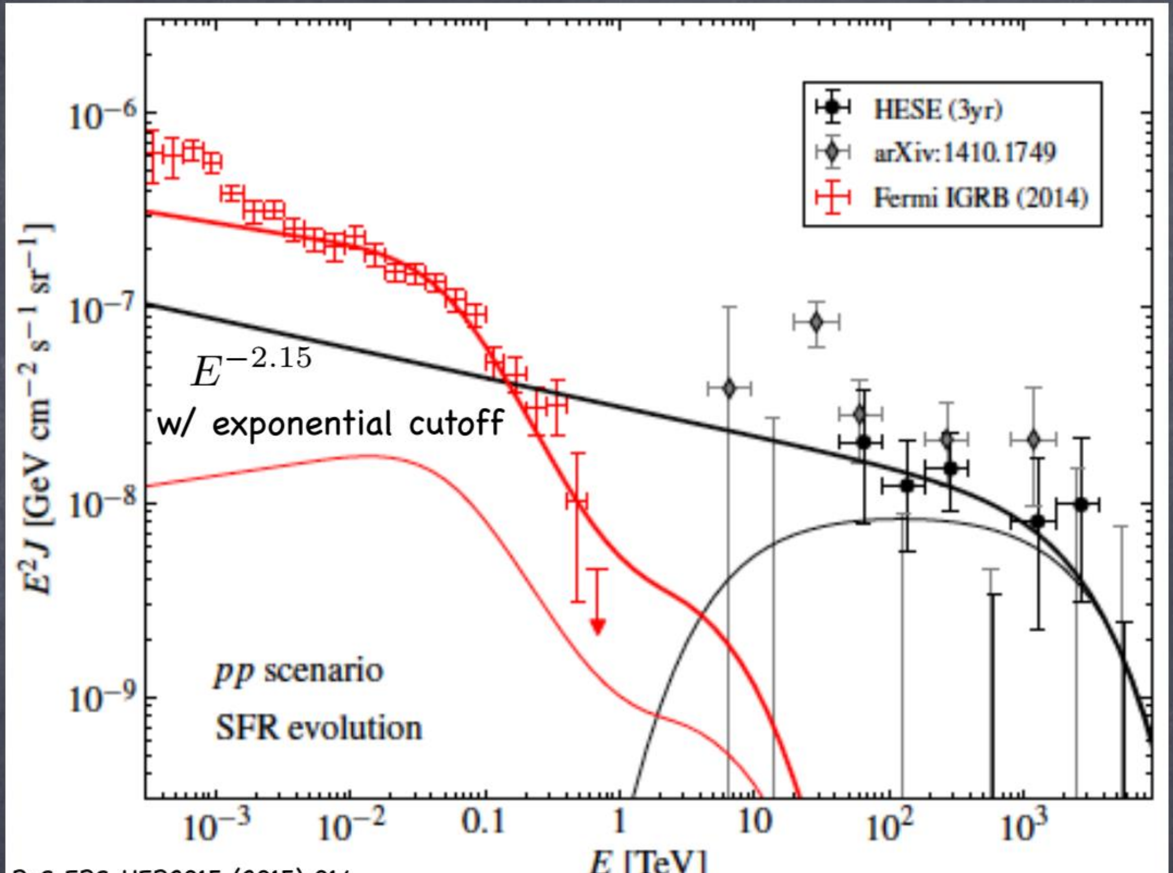
Connection with gamma rays

From Friday:

D. Marfatia

"IceCube's astrophysical neutrino spectrum from CPT violation"

Compare energy spectra for high-energy neutrinos and gamma rays to probe new physics models



PoS EPS-HEP2015 (2015) 014

- Neutrino spectra softer than shown are inconsistent with Fermi data
- Connection for $p\gamma$ sources weaker because target photons prevent gamma rays from leaving source

What about Active Galactic Nuclei?

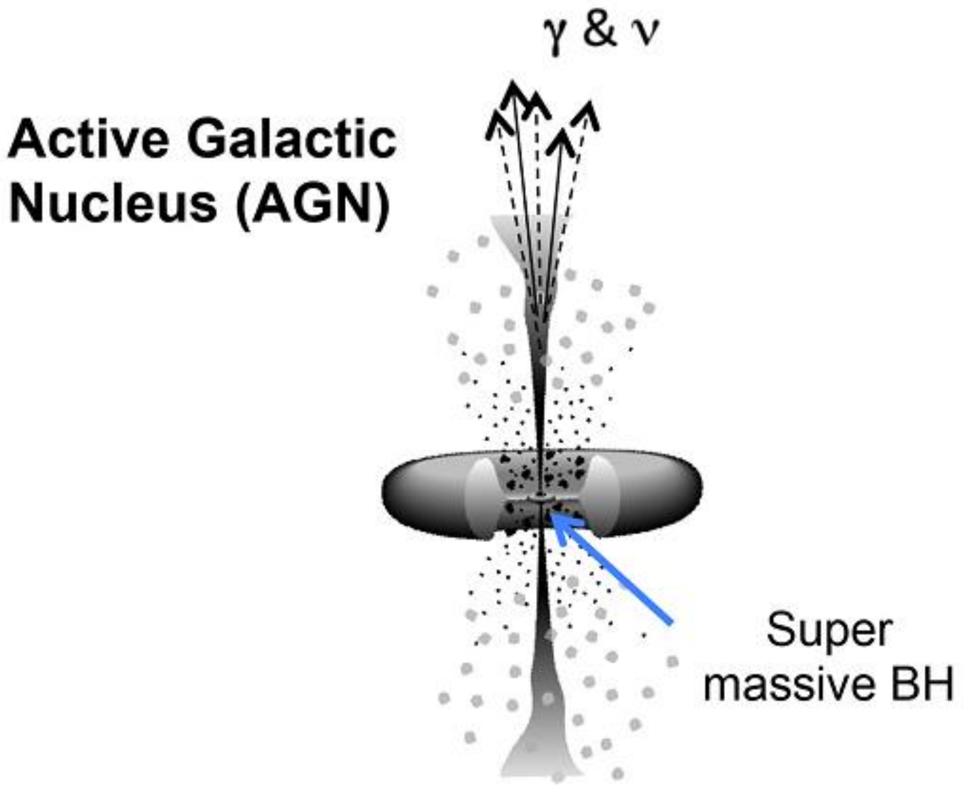
An AGN contains a supermassive black hole with an accretion disk which produces a relativistic jet

- By the Blandford-Znajek process (extracts energy from black hole spin via magnetic fields)
- Or possibly by the Penrose mechanism (extracts energy from frame dragging)

There are many classes of AGN depending on viewing angle, etc.

A ***blazar*** is an AGN oriented so that the jet points toward Earth

- Can see emissions over the whole EM spectrum, up to gamma rays
- Emissions may exhibit variability due to variations in accretion rate or other disk/jet changes



[Figure from Bartos & Kowalski]

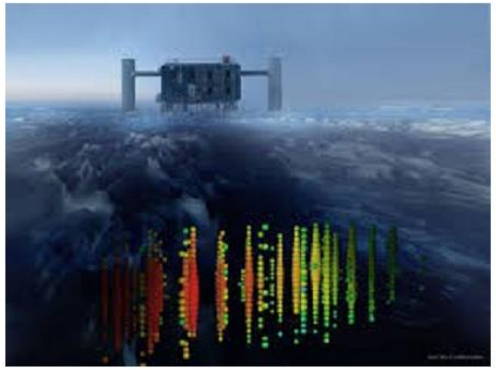
In September, IceCube detected an “extremely high energy” muon track pointing back near a known blazar

The blazar’s gamma-ray emission increased significantly around the same time!

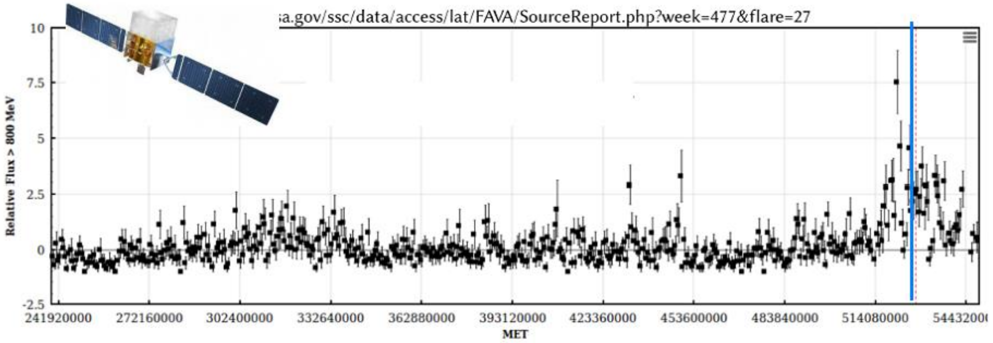
Awaiting paper with final analysis results…

Slide made by
Konstancja Satalecka

Alerts: IC-170922A

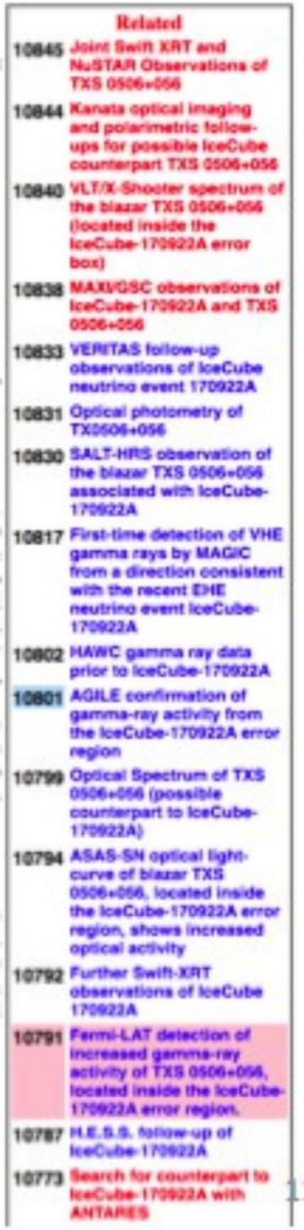


GCN #21916
Sep 22nd, 2017 @20:54:30.43 UTC
IceCube detects a high-energy muon track with a high probability of being of astrophysical origin (EHE)
RA: 77.43 deg (-0.80 deg/+1.30 deg, 90% PSF)
Dec: 5.72 deg (-0.40 deg/+0.70 deg, 90% PSF)
14 arcmin away from blazar TXS 0506+056!



ATel #10791
Sep 27th, 2017
Fermi/LAT detection of an **increased gamma-ray activity of TXS 0506+056**

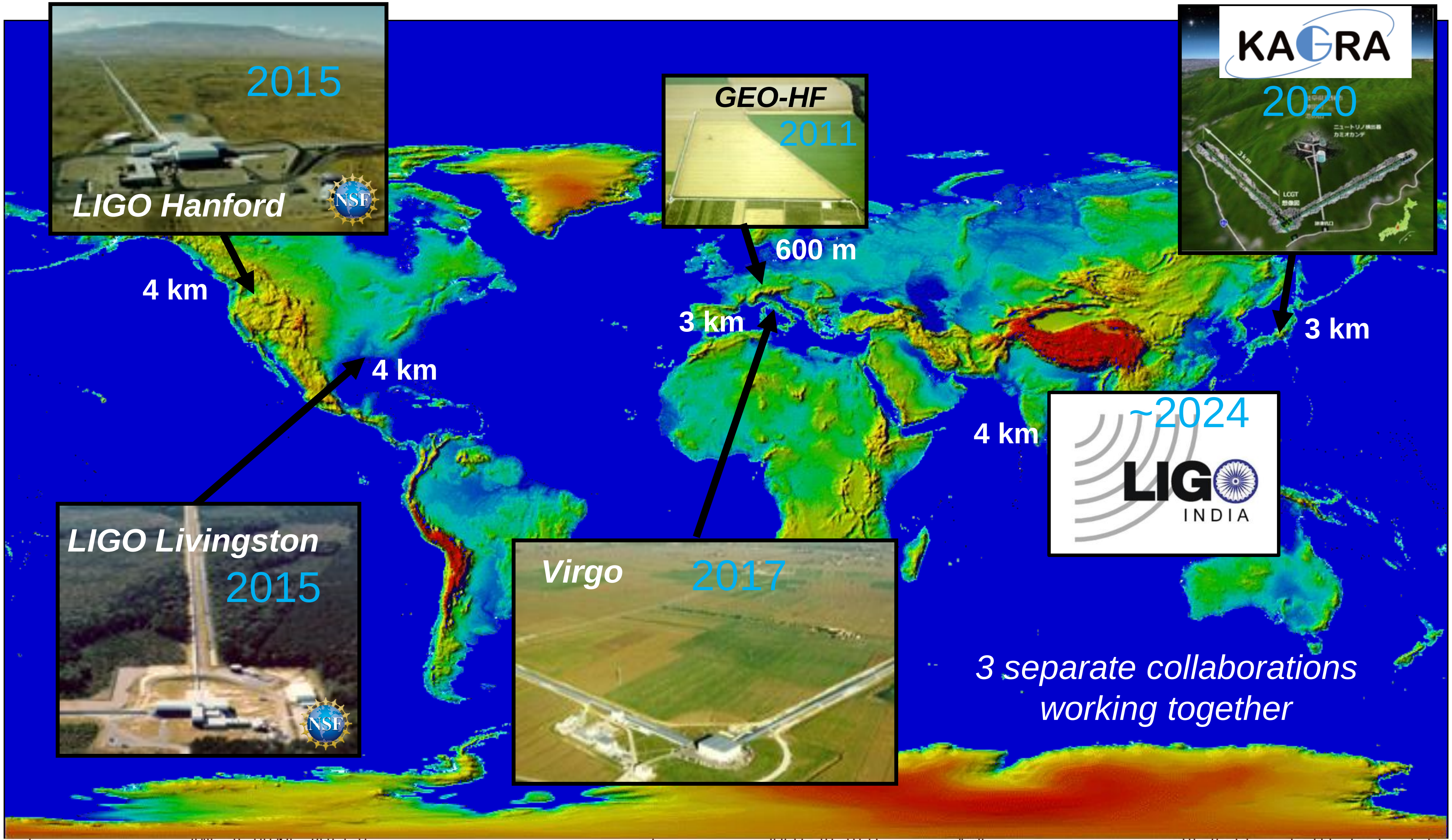
ATel #10817
Oct 4th, 2017
MAGIC: 12h of observations Sep 28th-Oct 3rd
Detection > 5 sigma > 100 GeV
First time detection of TXS 0506+056 in VHE gamma-rays



Related

10845 Joint Swift XRT and NuSTAR Observations of TXS 0506+056
10844 Kanata optical imaging and polarimetric follow-ups for possible IceCube counterpart TXS 0506+056
10840 VLT/X-Shooter spectrum of the blazar TXS 0506+056 (located inside the IceCube-170922A error box)
10838 MAXI/GSC observations of IceCube-170922A and TXS 0506+056
10833 VERITAS follow-up observations of IceCube neutrino event 170922A
10831 Optical photometry of TX0506+056
10830 SALT-HRS observation of the blazar TXS 0506+056 associated with IceCube-170922A
10817 First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A
10802 HAWC gamma ray data prior to IceCube-170922A
10801 AGILE confirmation of gamma-ray activity from the IceCube-170922A error region
10799 Optical Spectrum of TXS 0506+056 (possible counterpart to IceCube-170922A)
10794 ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity
10792 Further Swift-XRT observations of IceCube 170922A
10791 Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.
10787 H.E.S.S. follow-up of IceCube-170922A
10773 Search for counterpart to IceCube-170922A with ANTARES

The Expanding Network of *Advanced* GW Detectors

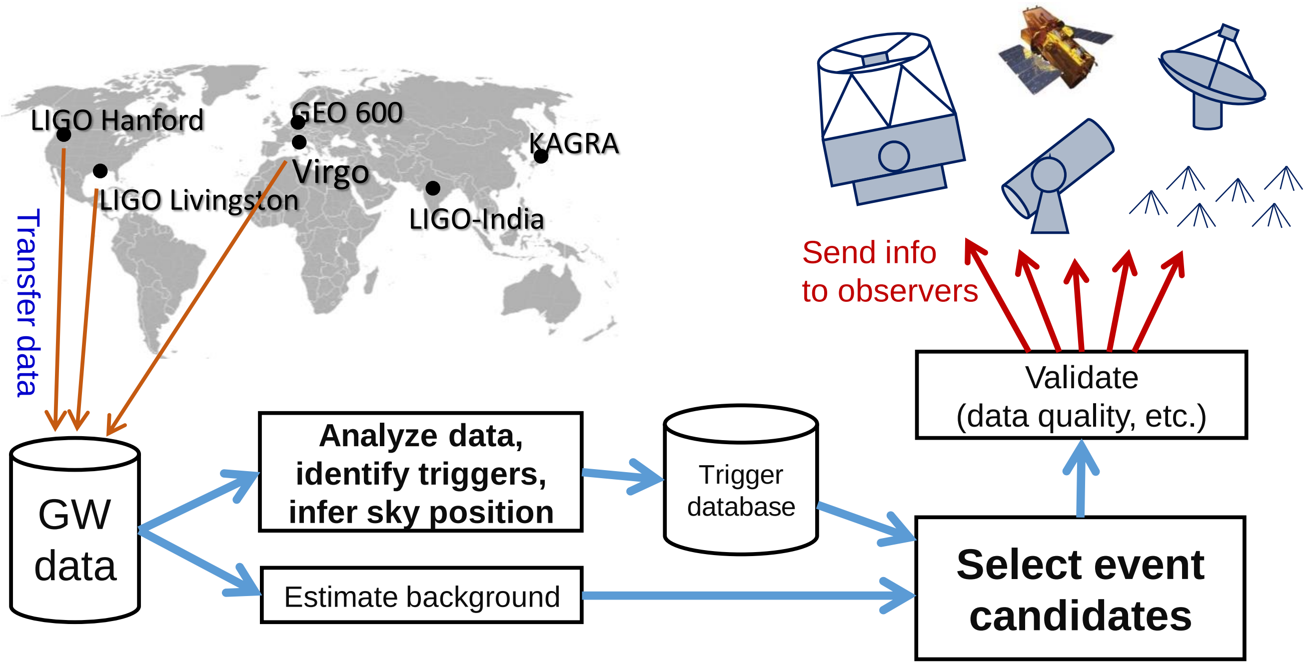


Multi-Messenger Searches with Gravitational Waves

LIGO/Virgo have done many *externally triggered* GW searches
(deep analysis of GW data around the time and/or sky position of reported EM event)
and have collaborated on *joint* searches (compare sets of candidate events)

Many types of objects:

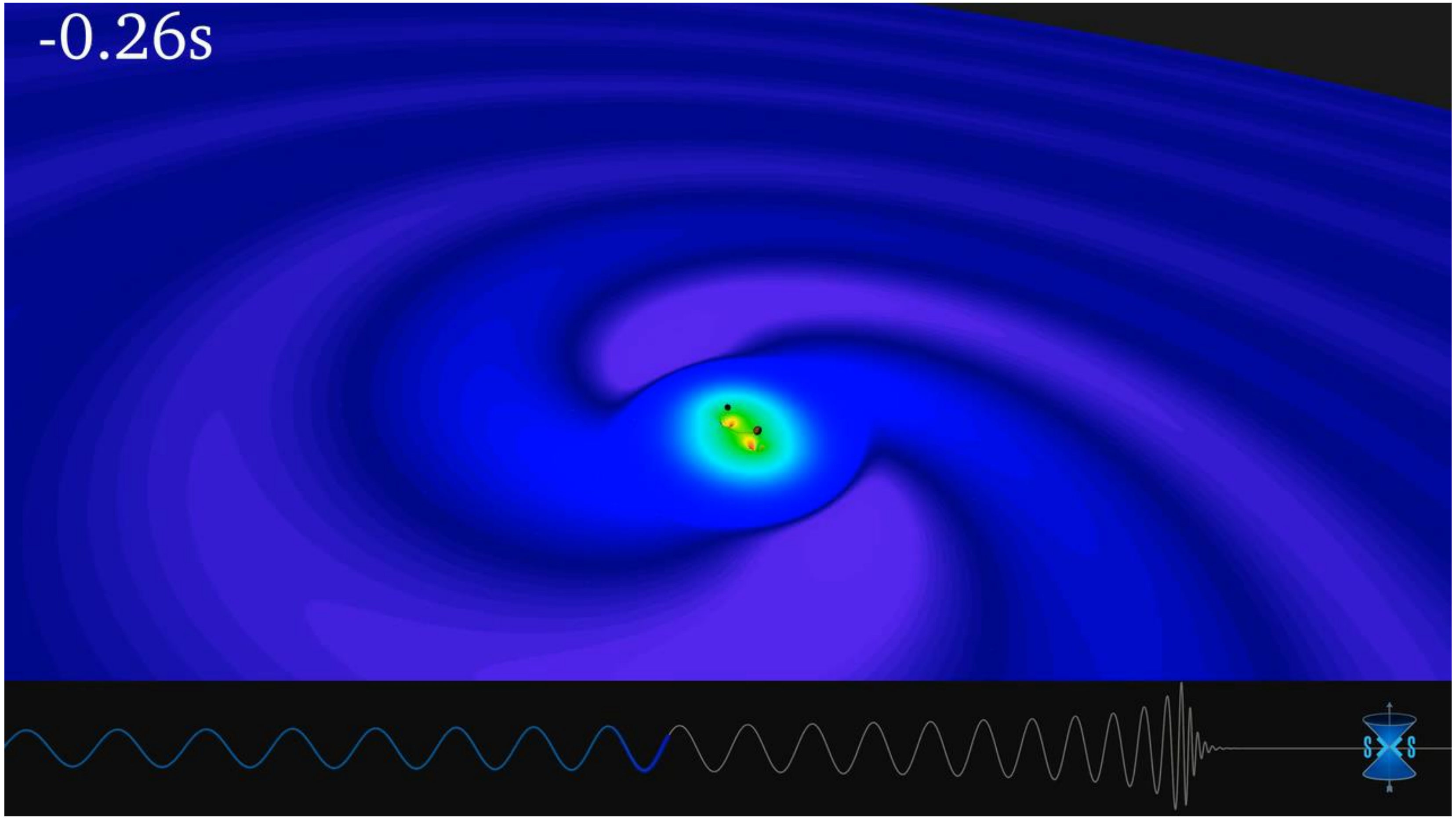
- GRBs
- Known pulsars (CW signal)
- SGR/magnetar flares
- Pulsar glitch (Vela)
- High-energy neutrinos
- Radio transients
- Supernovae



Also initiated an *EM follow-up program*, distributing GW event candidate alerts to observers to enable them to search for counterparts

Low-Latency Searches

Search data from the gravitational-wave detectors for signals expected from compact binary coalescence, as well as generic GW transient signals



From Thursday:

N. Arnaud

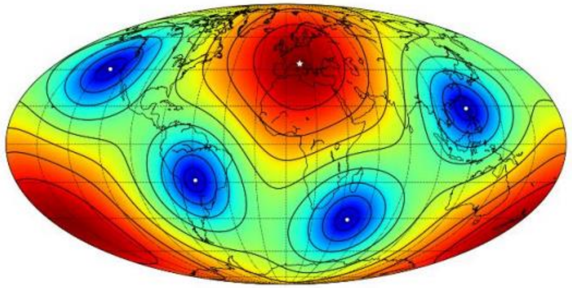
“In between the Observation Runs 2 and 3, a status report on the Advanced LIGO and Advanced Virgo GW detectors”

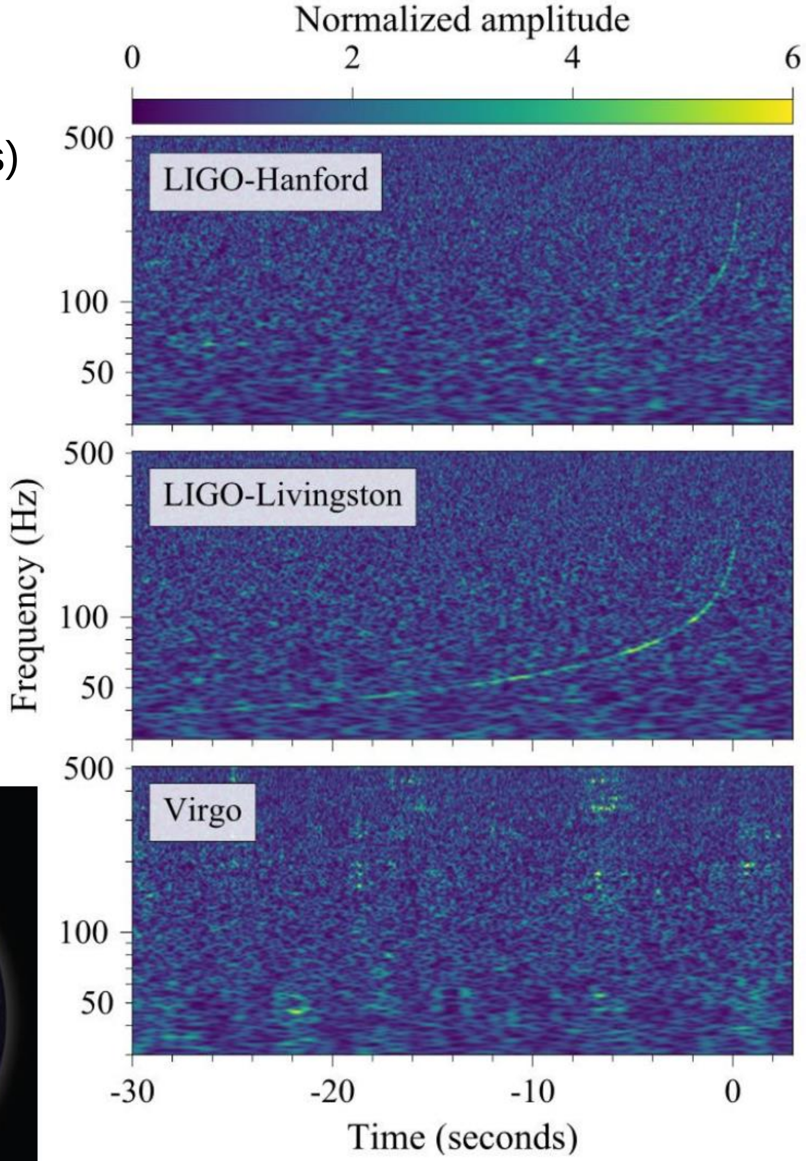
Normally the sky localization would be available within minutes, but had to work around a glitch in the LIGO-Livingston data

GW170817: first binary neutron star merger

- Strong signal in both LIGO detectors
  (consistent with masses of known neutron stars)
- No signal in Virgo
  - Worse sensitivity
  - Source location close to a blind spot
    → Antenna pattern effect

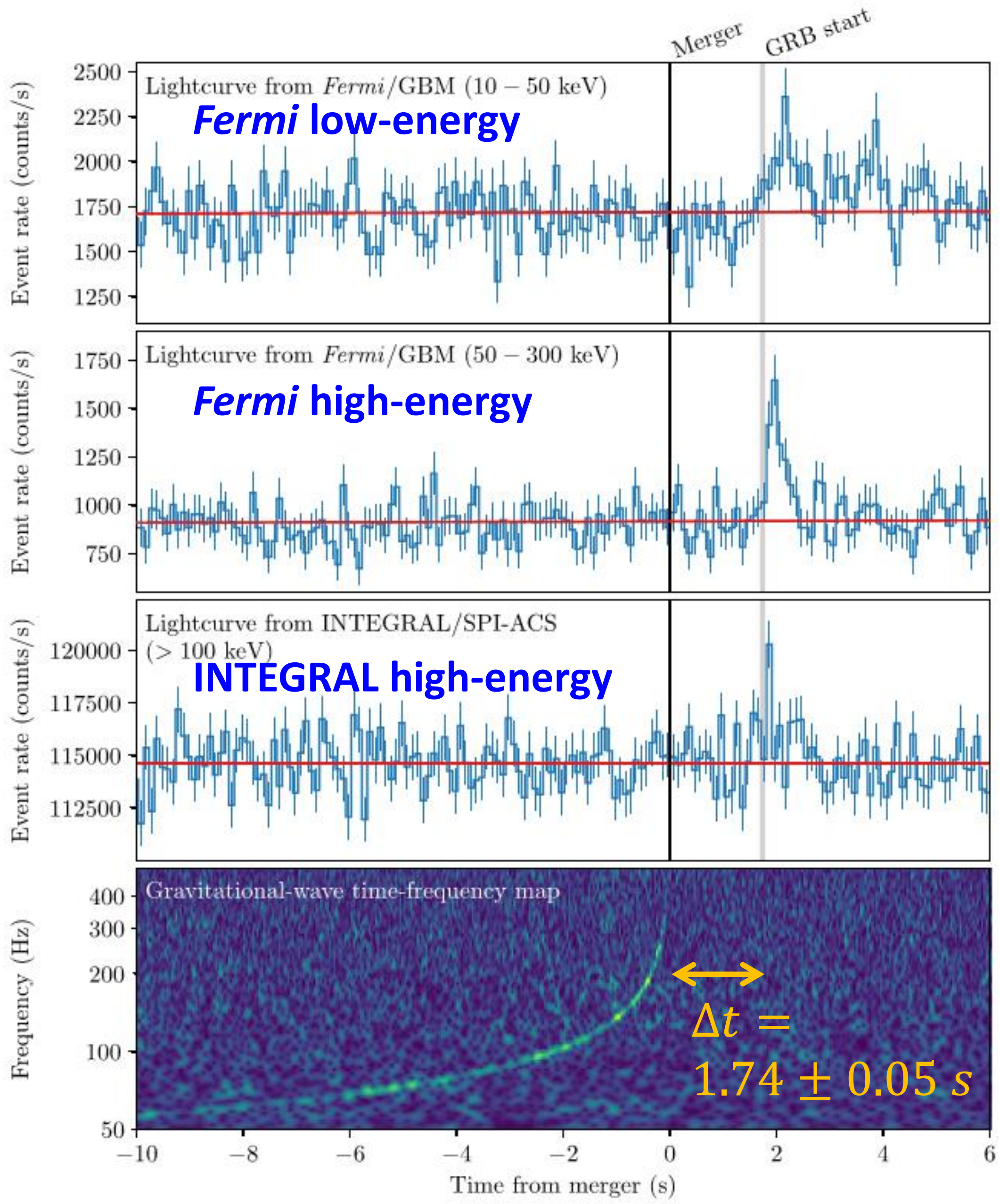
→ Accurate sky localization (30 square deg.)
  - Latency of about 5 hours
  - Consistent with Fermi and Fermi-Integral localizations





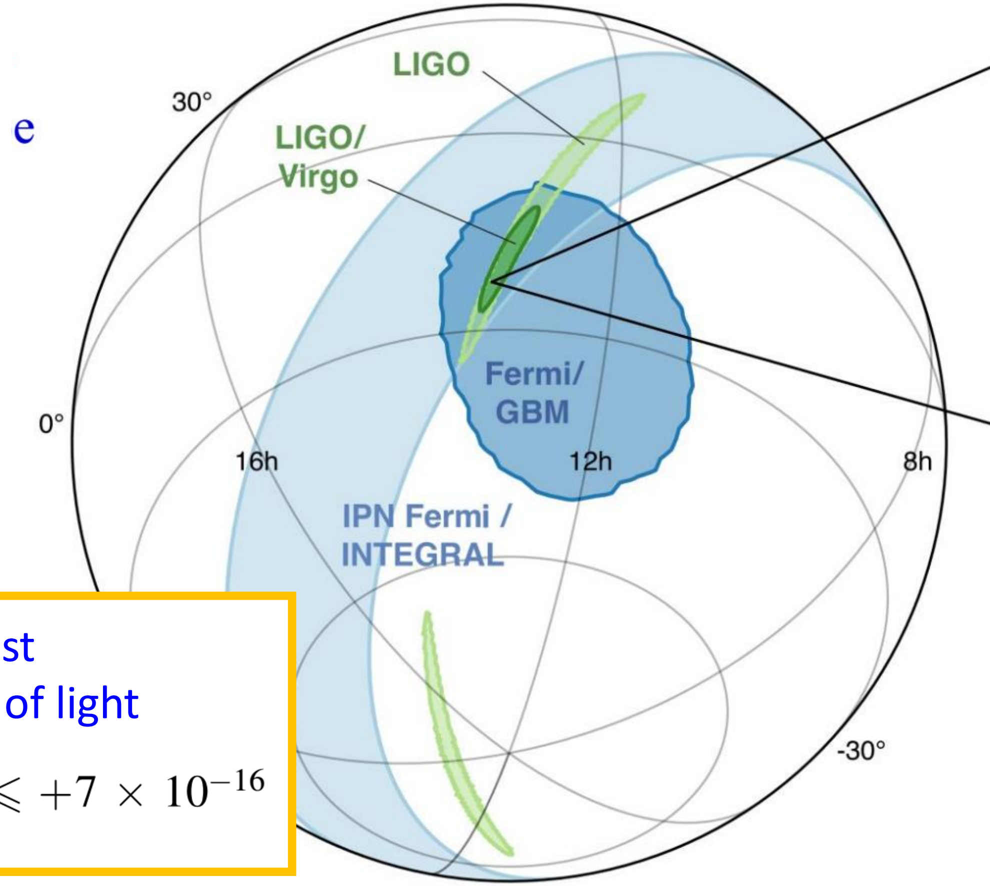
GW170817 sky localizations

Adapted from slide by N. Arnaud



[LIGO, Virgo, Fermi-GBM and INTEGRAL 2017, ApJL 848, L13]

- Green: LIGO and LIGO + Virgo
- Blue : information from gamma ray burst satellites



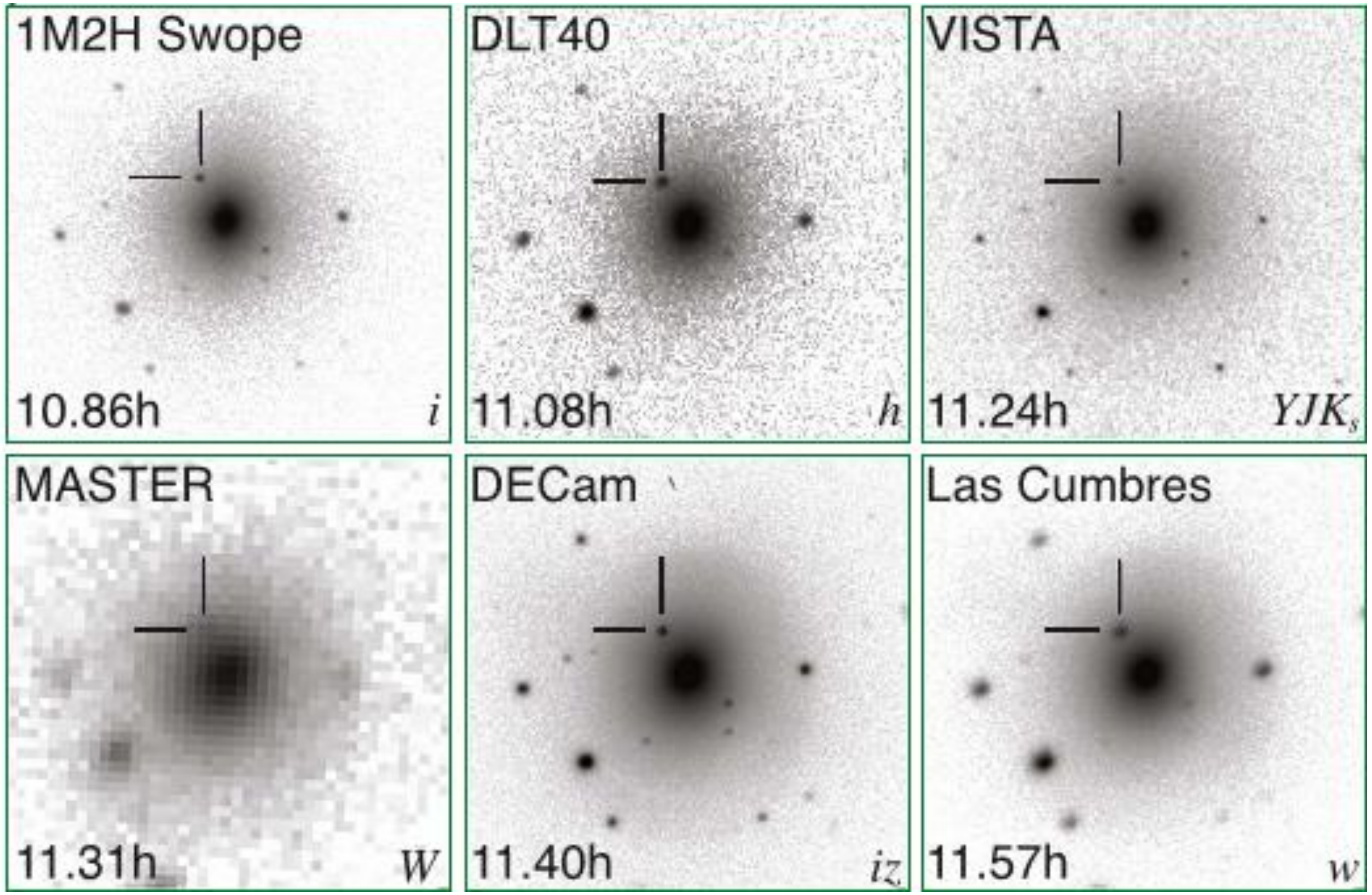
➔ Speed of GWs is just about equal to speed of light

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

Astronomers found the optical counterpart!

Independently found by 6 teams within a span of 45 minutes, in the galaxy

NGC 4993



GRB 170817A

GW170817

SSS17a

DLT17ck

MASTER J130948.10-232253.3

→ AT 2017gfo

[Abbott and many others 2017, ApJL 848, L12]

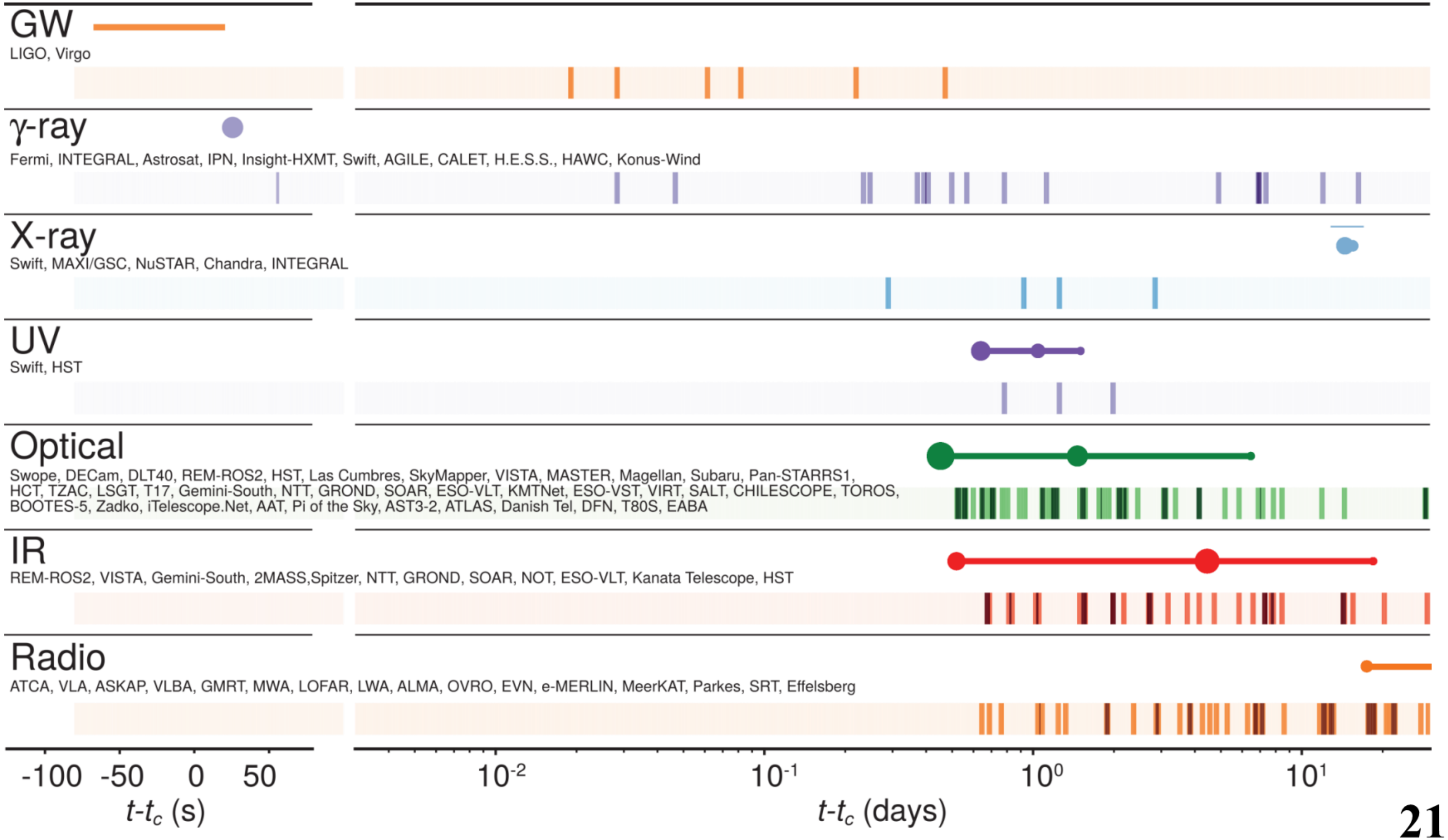
From Thursday:

N. Arnaud

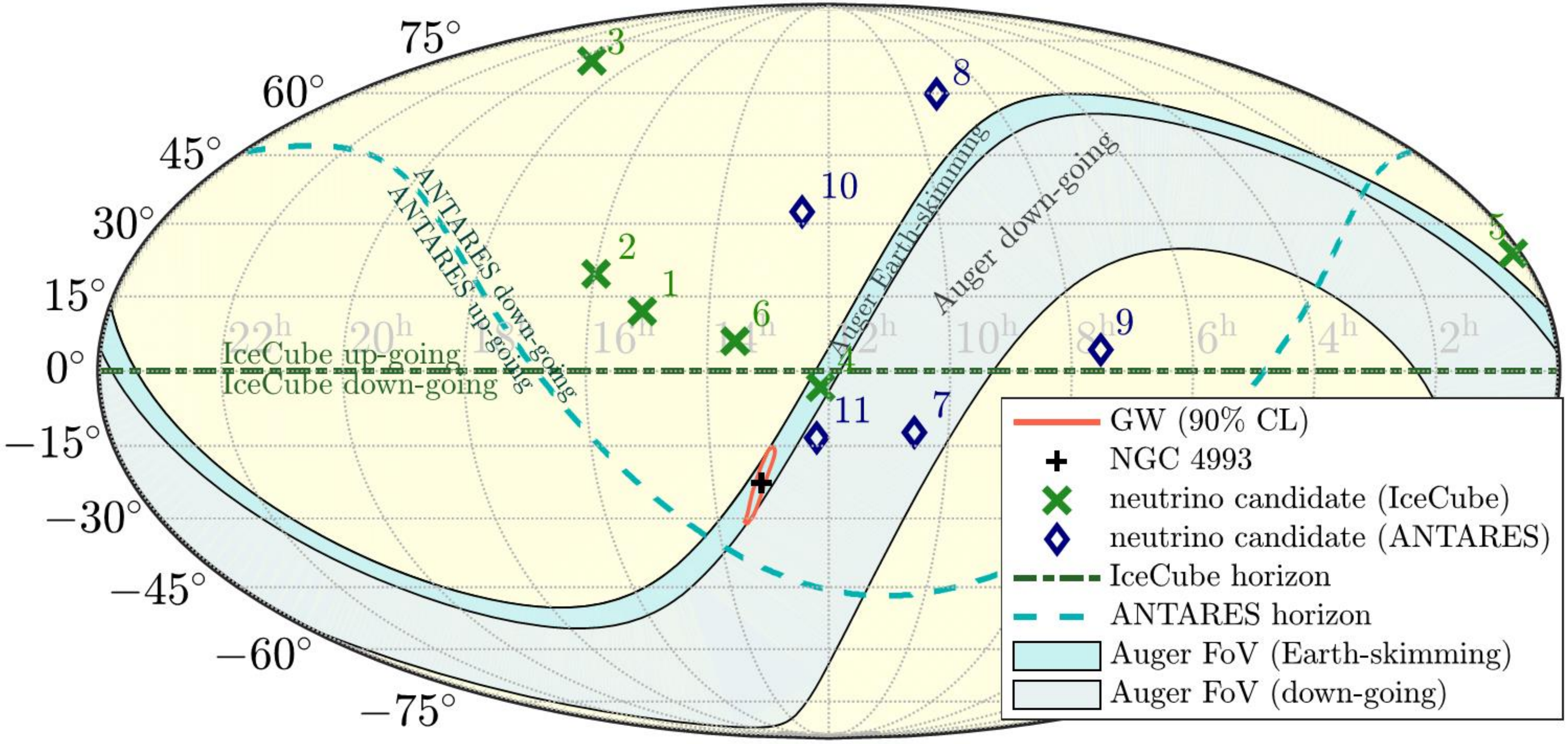
"In between the Observation Runs 2 and 3, a status report on the Advanced LIGO and Advanced Virgo GW detectors"

GW170817 multi-messenger astronomy

- Gravitational waves + gamma ray burst + whole electromagnetic spectrum



No Neutrino Counterpart to GW170817



[Albert et al. (ANTARES, IceCube, Pierre Auger, LIGO and Virgo) 2017, ApJL 850, L35]

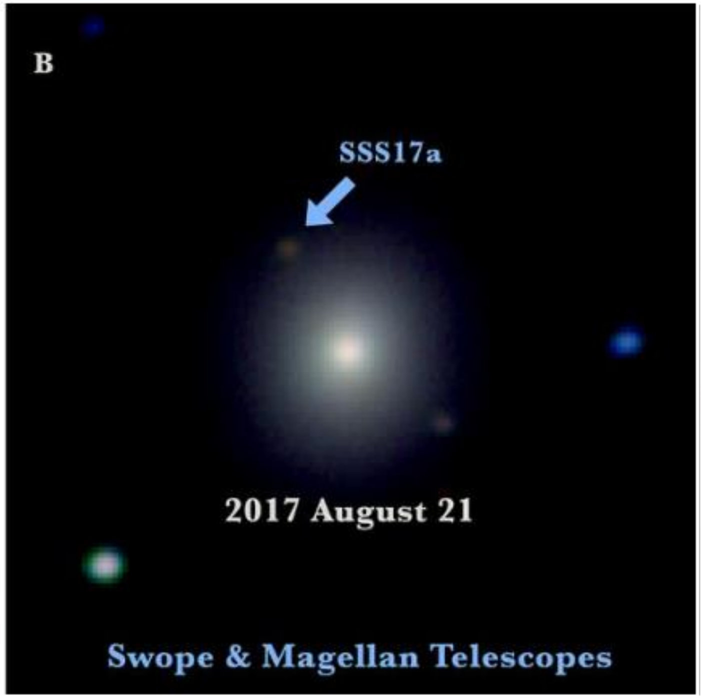
Tidal Disruption of Neutron Stars

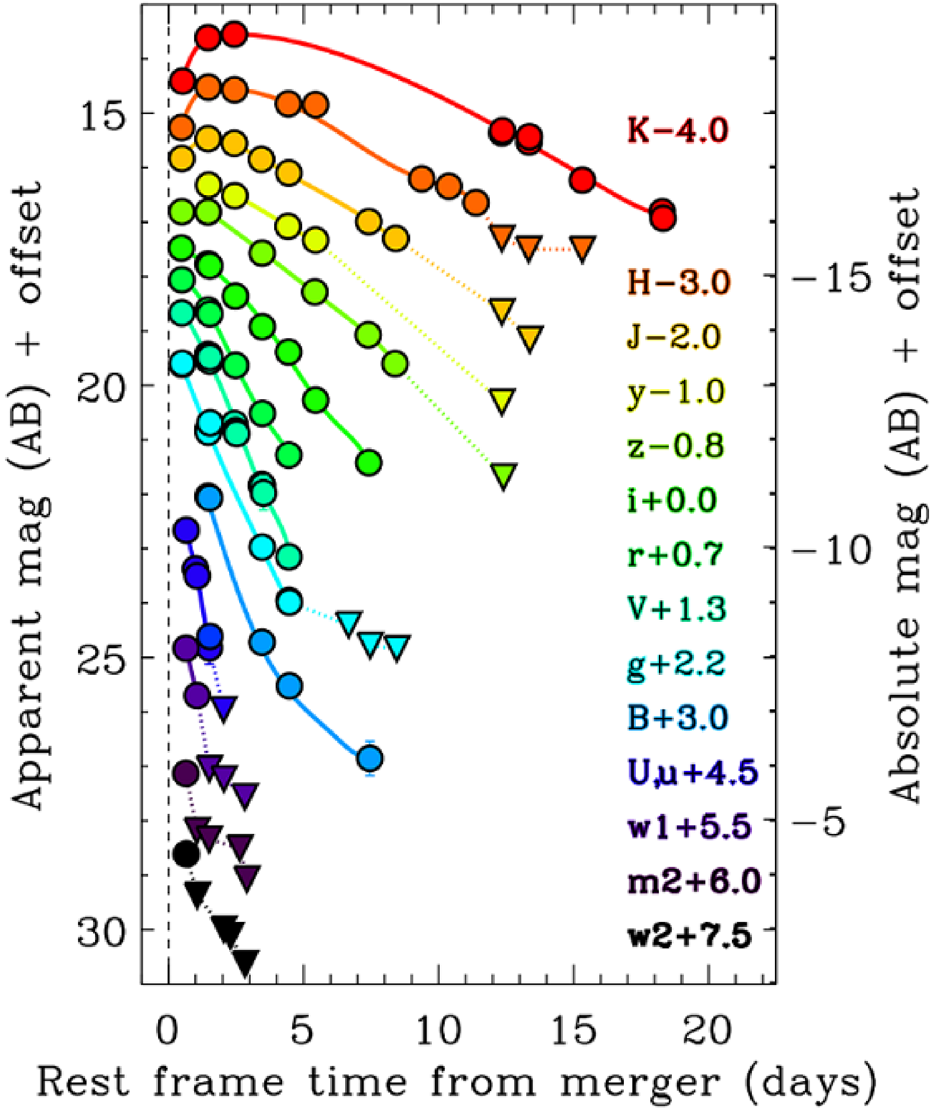
Price/Rosswog/Press

Saw the GW170817 counterpart fade – and change color

Initially visible in ultraviolet and blue – but those faded quickly

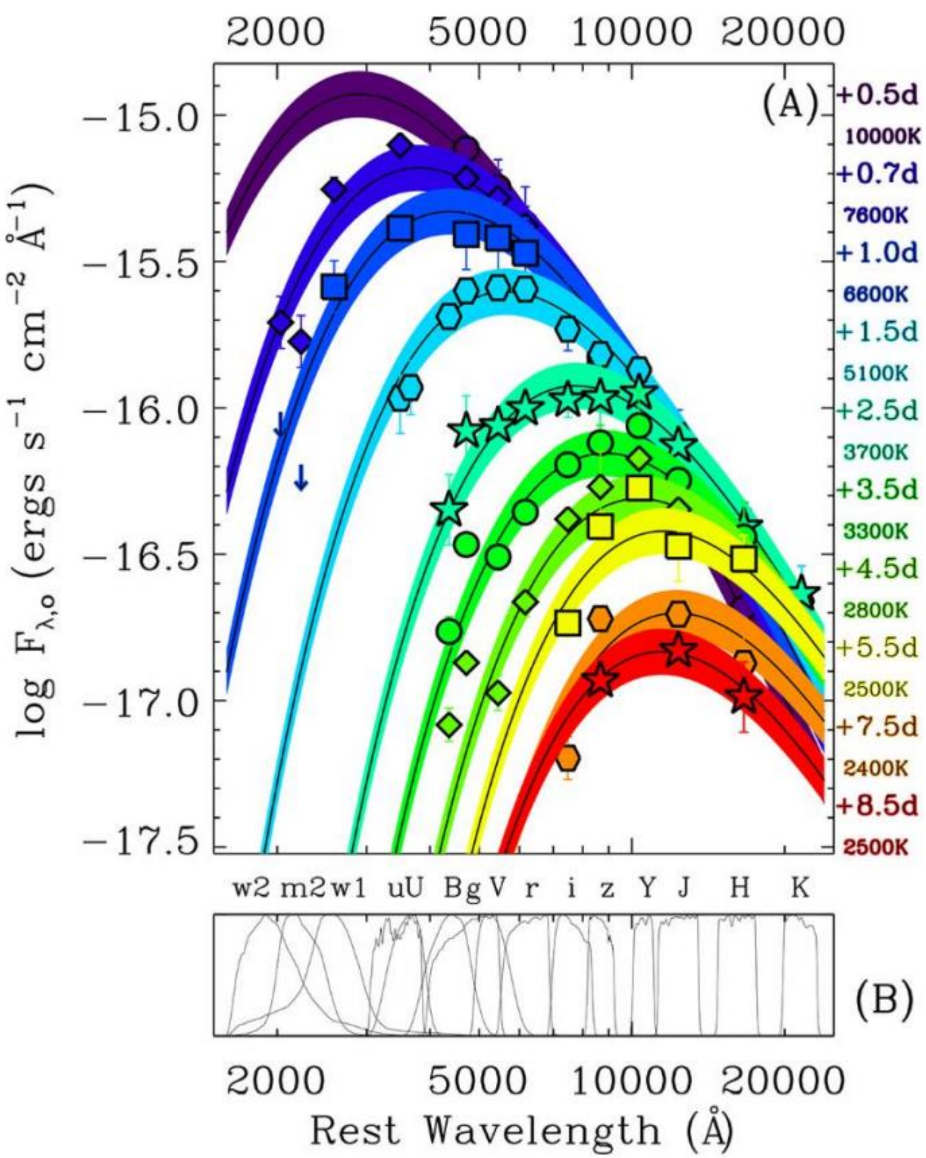
Infrared peaked after 2-3 days, then remained visible for weeks





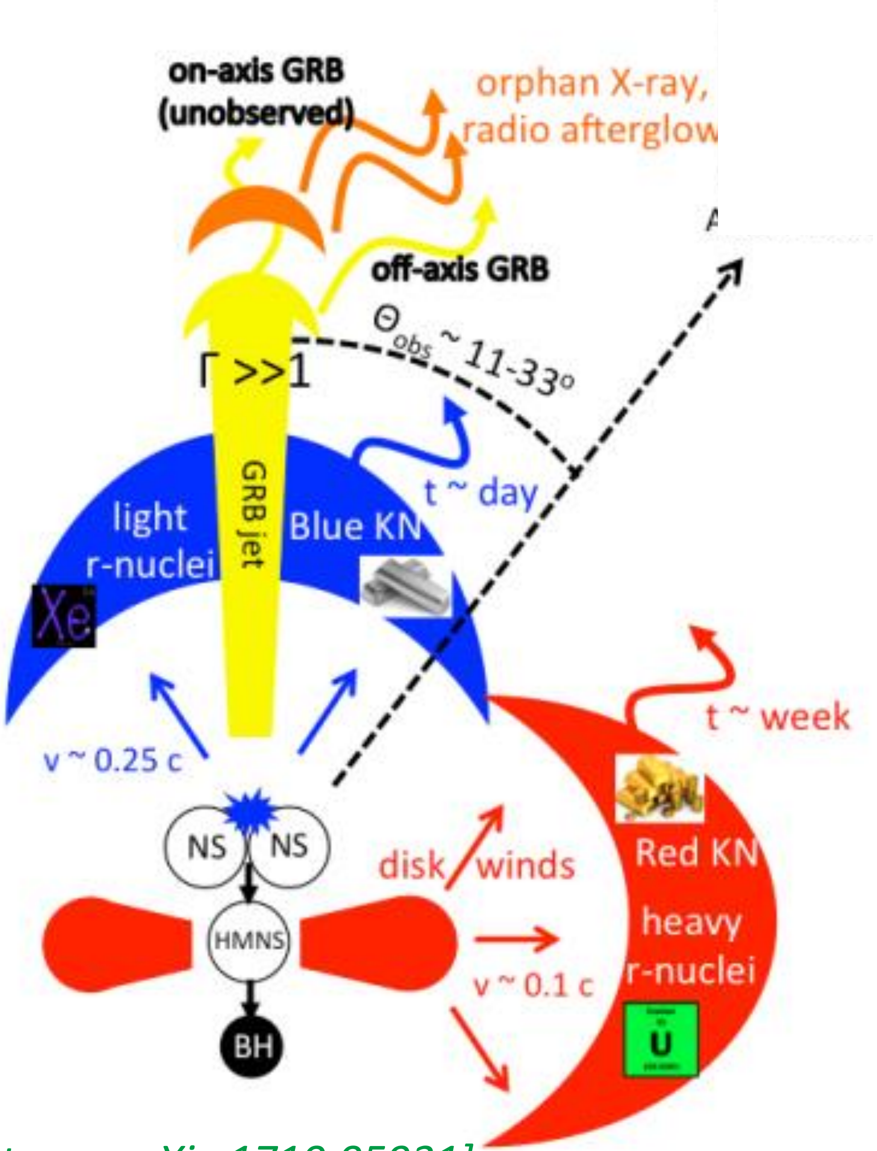
[Drout et al. 2017, Science 10.1126/science.aaq0049]

… as it cooled



[Drout et al. 2017, Science 10.1126/science.aaq0049]

Optical emission matches “kilonova” model



[Metzger, arXiv:1710.05931]

r-process nucleosynthesis takes place in ejected material

Then radioactive decays drive thermal emission

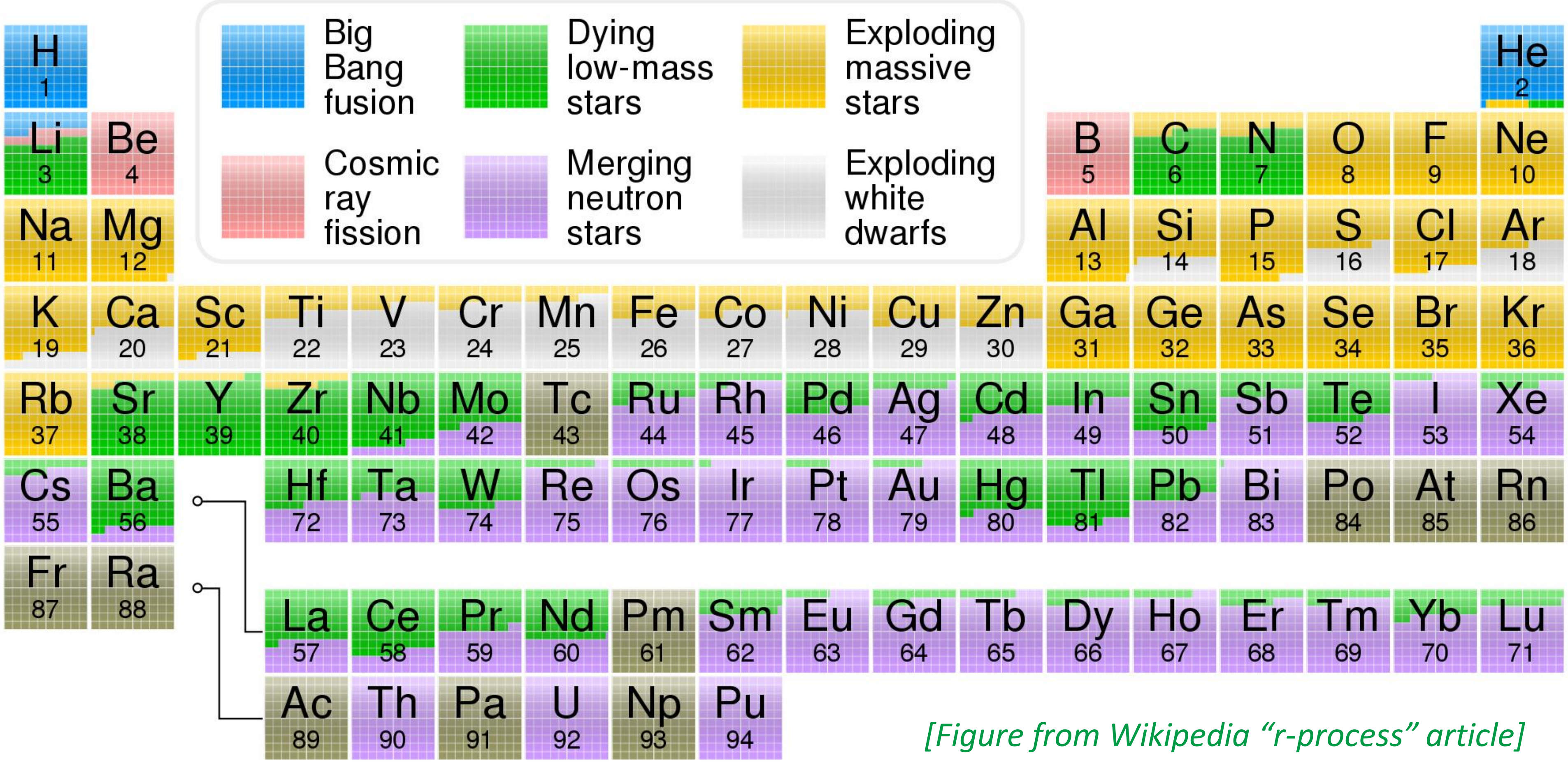
Evidence for two components:
- “blue” (lanthanide-poor) and
- “red” (lanthanide-rich)

Different r-process elements produced ➔ different opacities

- Hypermassive neutron star may irradiate central ejecta with neutrinos, converting some neutrons to protons
- e.g., Cowperthwaite et al. estimate $0.01\ M_\odot$ of “blue” ejecta moving at $\sim 0.3\ c$ plus $0.04\ M_\odot$ of “red” ejecta moving at $\sim 0.1\ c$

Also late-time X-ray and radio afterglows

Strengthens the picture that neutron star mergers produce most of the heaviest elements



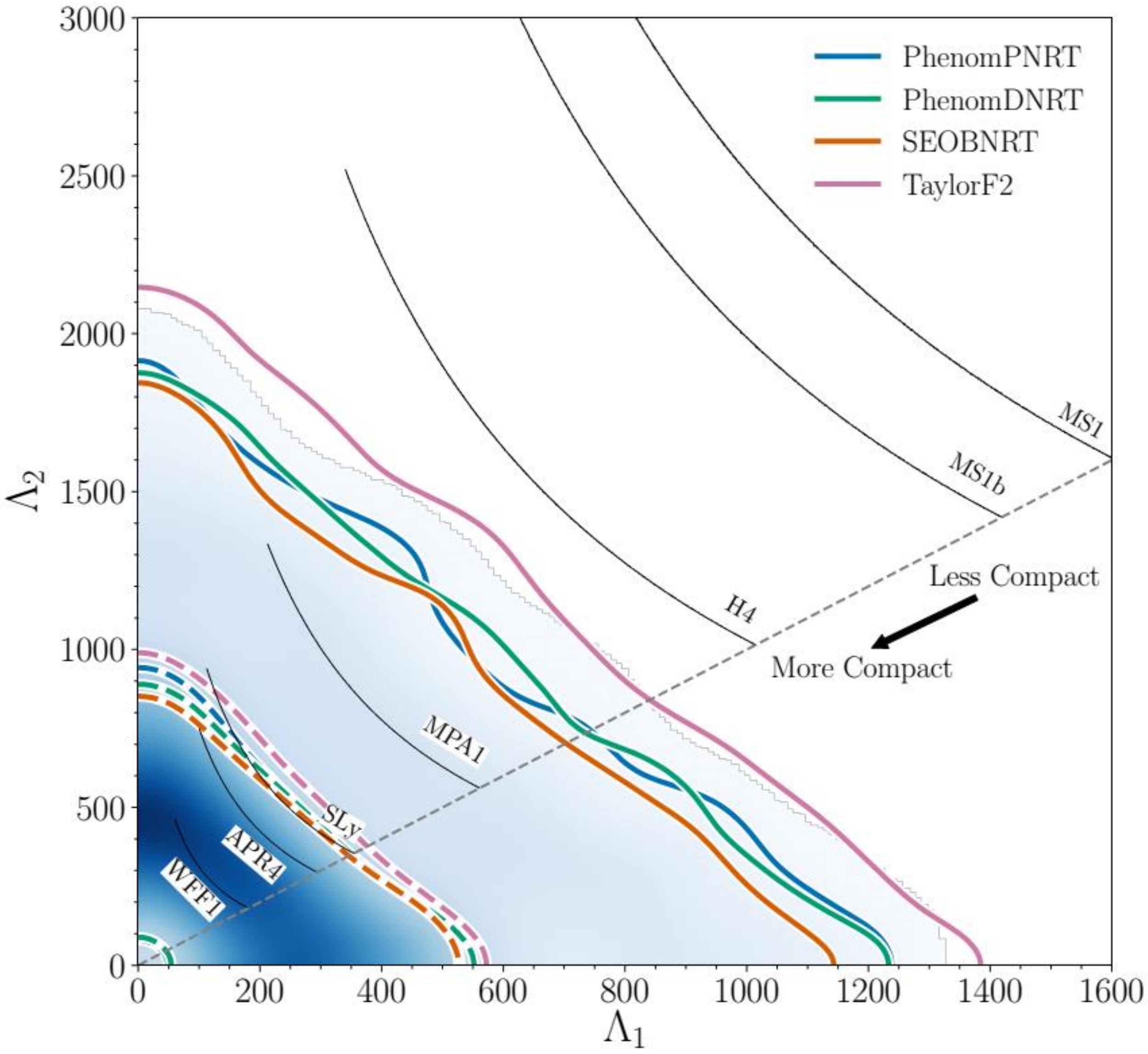
[Figure from Wikipedia "r-process" article]

Constraints on tidal deformability

GW data waveform matching rules out some “stiff” equations of state (EOS) which correspond to particularly un-compact neutron stars

- Improved measurements of neutron star EOS can test nuclear physics at extreme densities, where exotic particles or fields could play a role

[Abbott et al. 2018, PRX submitted, arXiv:1805.11579]



Using binary mergers to probe cosmology

GR relates absolute GW signal amplitude to luminosity distance

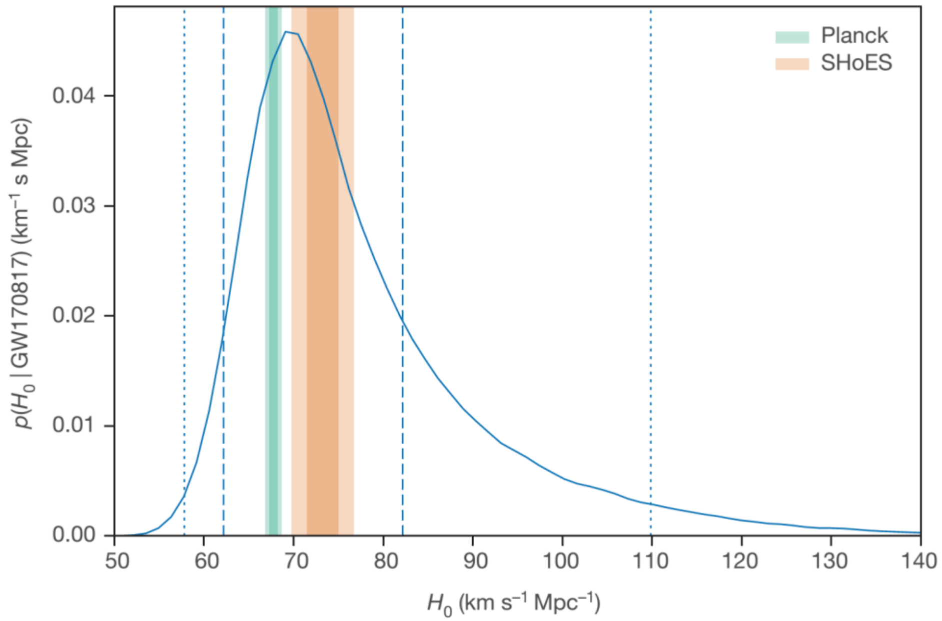
… assuming that other source parameters are known: masses, orbit inclination angle, etc.

➔ A binary merger is a "standard siren", measuring distance
(but with uncertainty if other source parameter aren't known precisely)

For GW170817, combined GW distance estimate with measured redshift of its host (NGC 4993)

➔ $H_0 = 70^{+12}_{-8}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

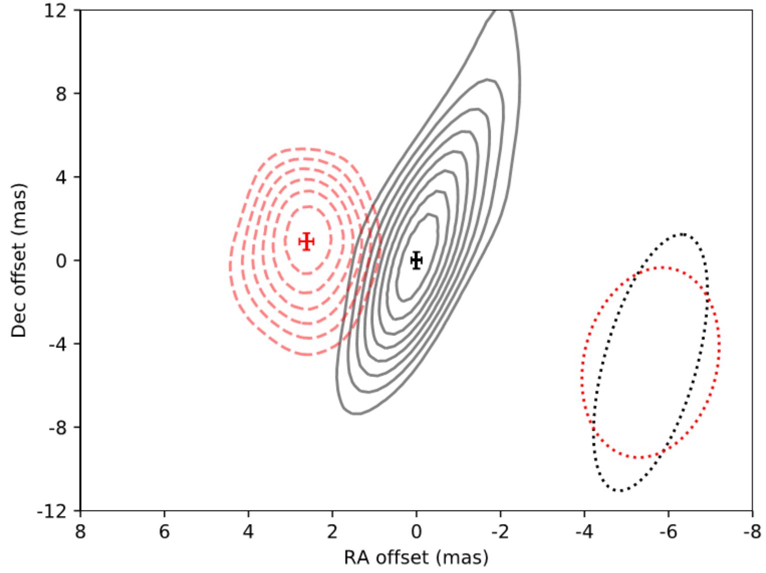
[Abbott et al. 2017, Nature doi:10.1038/nature24471]



There are also a couple of tricks to enable measuring H_0 from GW events without EM counterparts

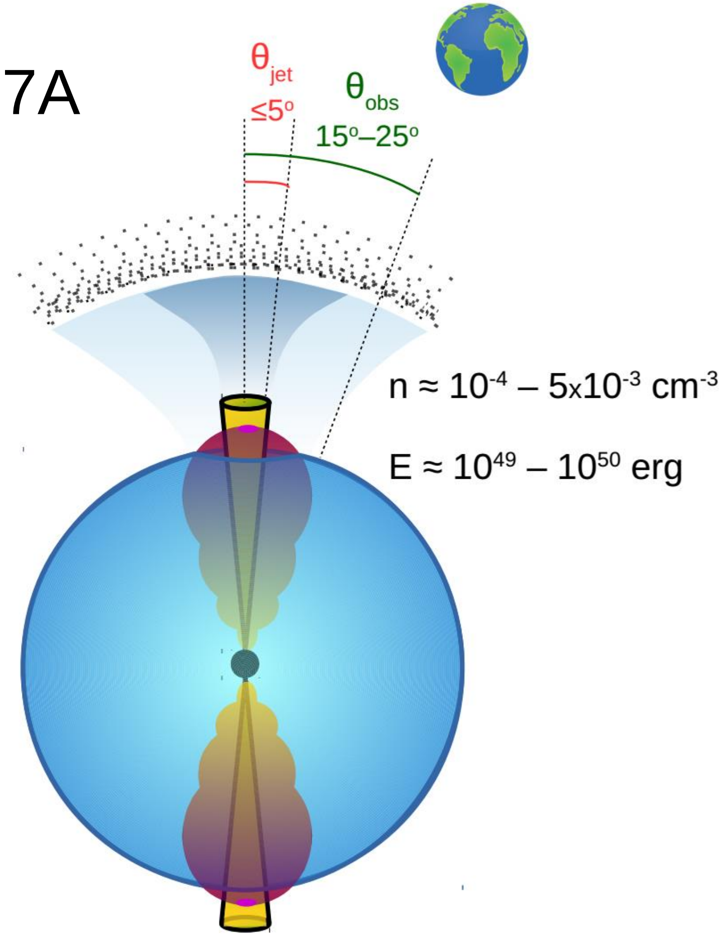
New Information About Orbit Inclination

VLBI imaging of the remnant of GW170817 / GRB 170817A sees the expanding jet! *[Mooley et al., arXiv:1806.09693]*



75 and 230 days after merger

➔ $\theta_{obs} = 20 \pm 5$ deg



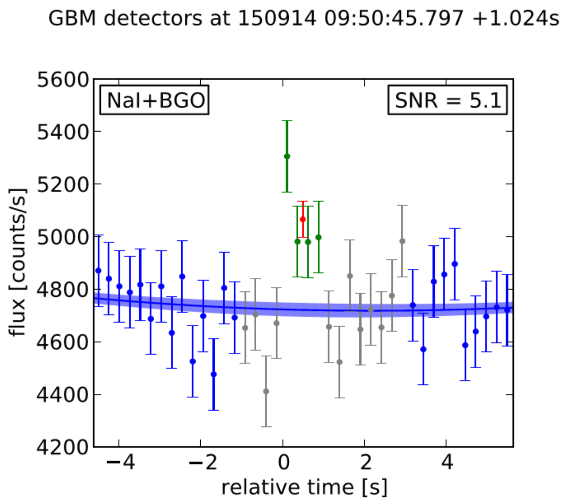
Knowing the inclination angle better improves the distance determination from the GW signal amplitude

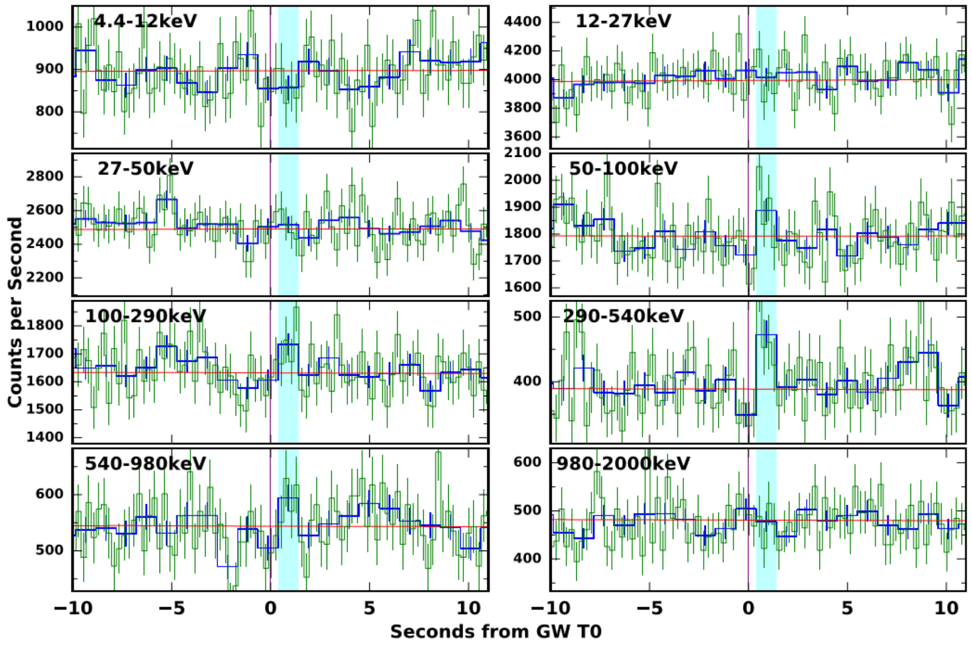
➔ New Hubble constant measurement: $H_0 = 68.9^{+4.7}_{-4.6}$ km/s/Mpc
[Hotokezaka et al., arXiv:1806.10596]

GRBs from Binary Black Hole Mergers??

A weak signal was detected by the Gamma-ray Burst Monitor (GBM) on board the Fermi satellite about 0.4 second after the time of LIGO's first event, GW150914

[Connaughton et al., ApJL 826, L13]





Fermi: NASA E/PO, Sonoma State U., Aurore Simonnet

Post-trials false alarm prob ~ 0.0022

Would be surprising – a possible window for new physics or new astrophysics

No similar signal seen for the 5 other binary black hole events so far

➔ This remains an intriguing hint to be checked with additional events

From Thursday:

N. Arnaud

"In between the Observation Runs 2 and 3, a status report on the Advanced LIGO and Advanced Virgo GW detectors"

KAGRA is aiming to be online before the end of the O3 run (e.g. early 2020)

O3: GW alerts and telescope follow-up

- https://gw-astronomy.org/wiki/OpenLVEM/TownHallMeetings2018, Amsterdam

- LIGO-Virgo alerts during O3 will all be public
  - False alarm rate ↔ Purity
  - Compact binary coalescence candidates / bursts

- Information provided through GCN(*) notices and circulars
  - Lowest possible latency – O(10 minutes), maybe less!?
  - Automated checks (detector status, data quality, environment) followed by human vetting
    → Possible retraction notices after a few hours at most

- Data public after 18 months
  - Work in progress to define the LIGO-Virgo core science program
  - 1 hour of data already public around the event when discovery published

→ Communication expected both ways: LIGO-Virgo ↔ Astronomers

(*) **GCN: gamma-ray burst coordinates network**

Summary and Outlook

We are entering a new era for Multi-Messenger Astronomy and Astrophysics

- Neutrino and gravitational-wave observatories are fulfilling their promises – e.g. GW170817
- Time-domain astronomy community has highly capable instruments and techniques

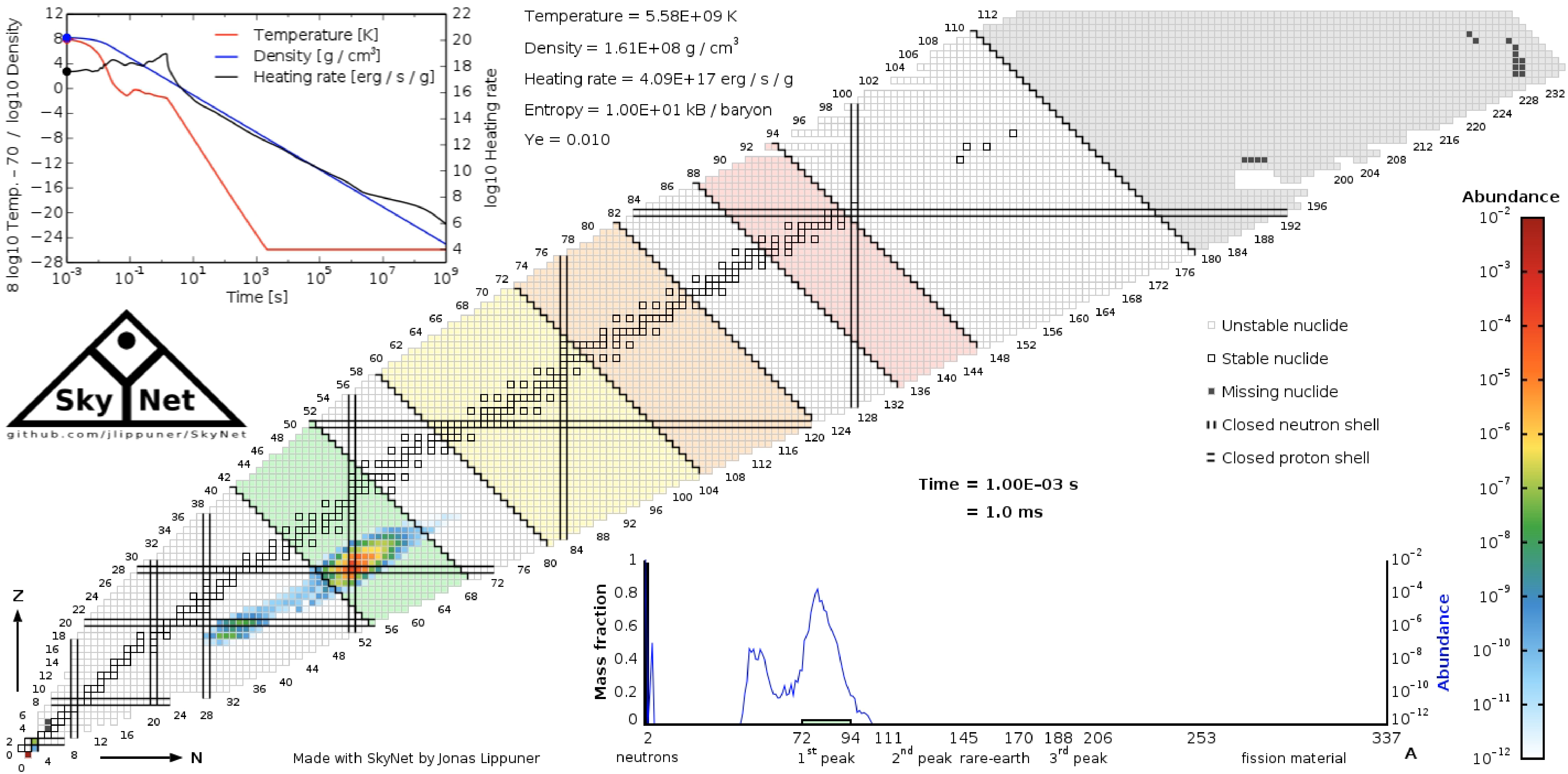
Complementary observations enable tests of astrophysical models and fundamental physics

- Including theories of gravity, nucleosynthesis, and properties of matter at extreme densities (in neutron stars), which could be influenced by exotic particles and fields

Need to maintain and improve our suite of facilities and instruments

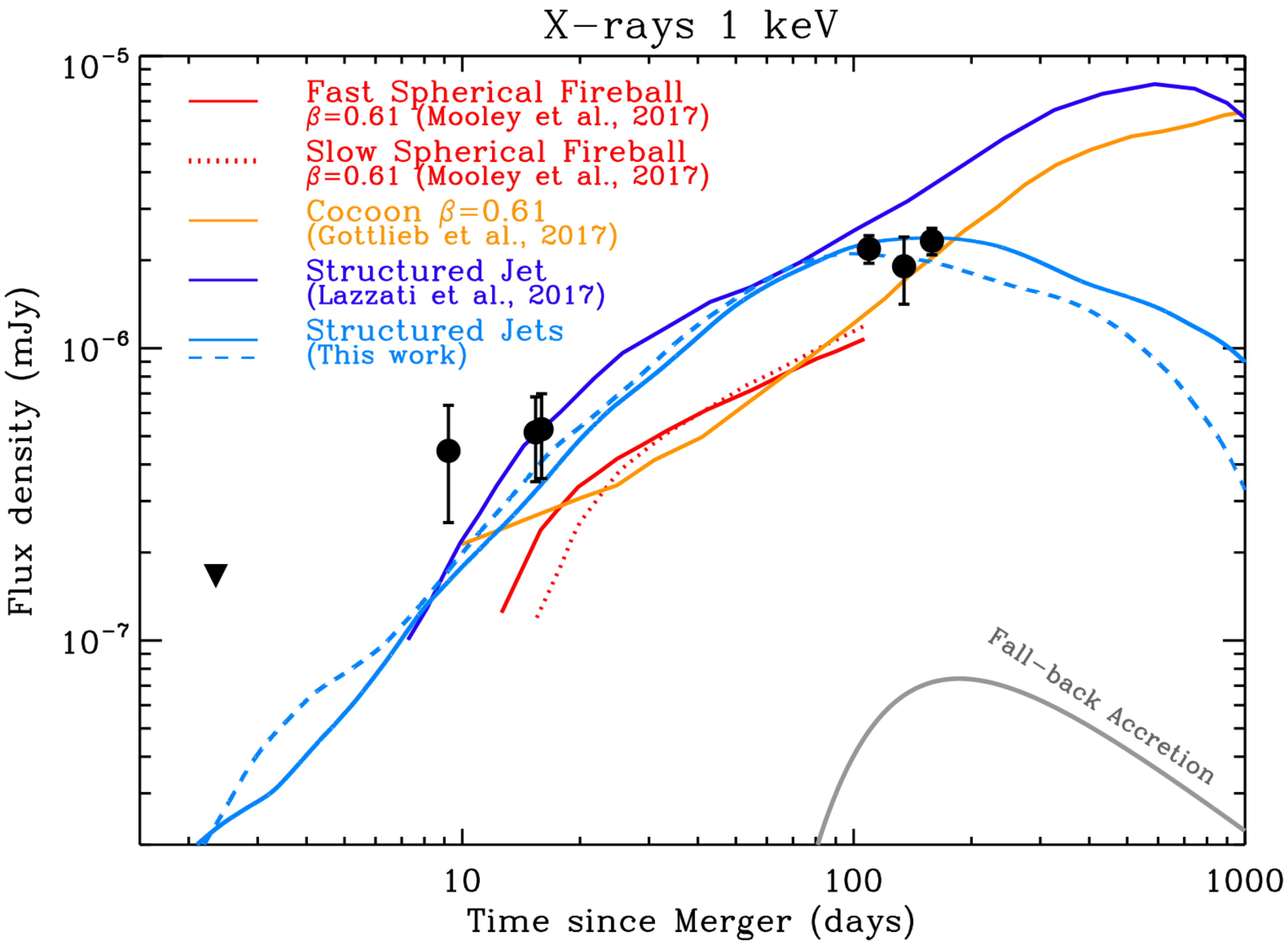
- Some major upgrades on the horizon, including LSST (Large Synoptic Survey Telescope) and bigger neutrino detectors
- Also need to keep excellent gamma-ray and X-ray instruments in orbit
- Low-frequency GW detection with LISA space mission will open new frontiers

r-process nucleosynthesis in action



Credit: J. Lippuner, author of SkyNet simulation software

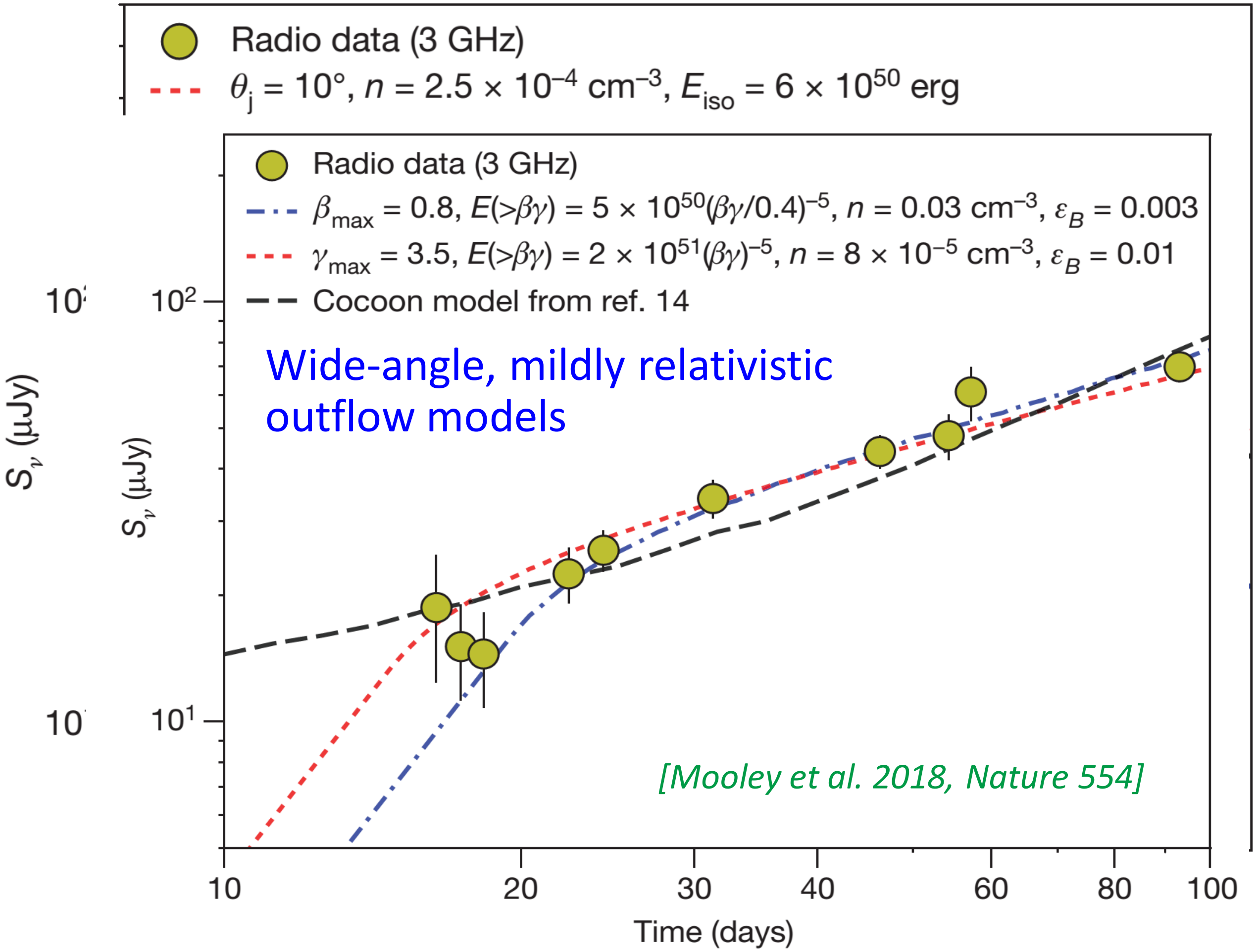
Understanding outflows: X-ray data



[Margutti et al. 2018, ApJL 856, L18]

Understanding outflows: radio data

Consistent with X-ray flux, with constant spectral index



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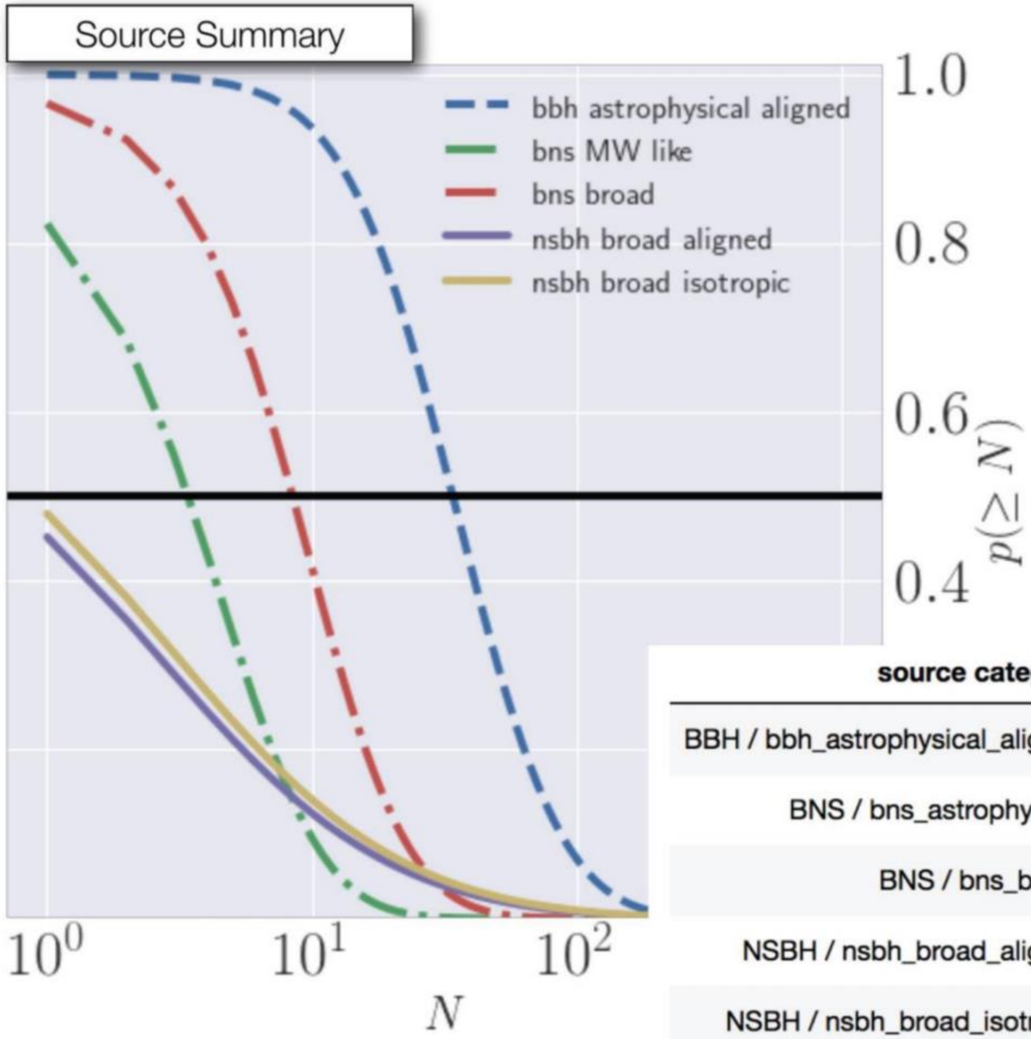
O3: Expected rates

- https://gw-astronomy.org/wiki/OpenLVEM/TownHallMeetings2018, Amsterdam



There are caveats, but the general picture is:

BBH: at least a few per month, maybe more

BNS: 1–10, possibly up to ~1 per month

NSBH: Could detect one or more during O3, but uncertain. We'll see!

source category	full year VT	N_d
BBH / bbh_astrophysical_aligned	6.8×10^8 Mpc^3 yr	34^{+79}_{-25}
BNS / bns_astrophysical	3.2×10^6 Mpc^3 yr	4^{+9}_{-4}
BNS / bns_broad	7.3×10^6 Mpc^3 yr	9^{+19}_{-7}
NSBH / nsbh_broad_aligned	5.0×10^7 Mpc^3 yr	1^{+24}_{-1}
NSBH / nsbh_broad_isotropic	5.7×10^7 Mpc^3 yr	1^{+28}_{-1}