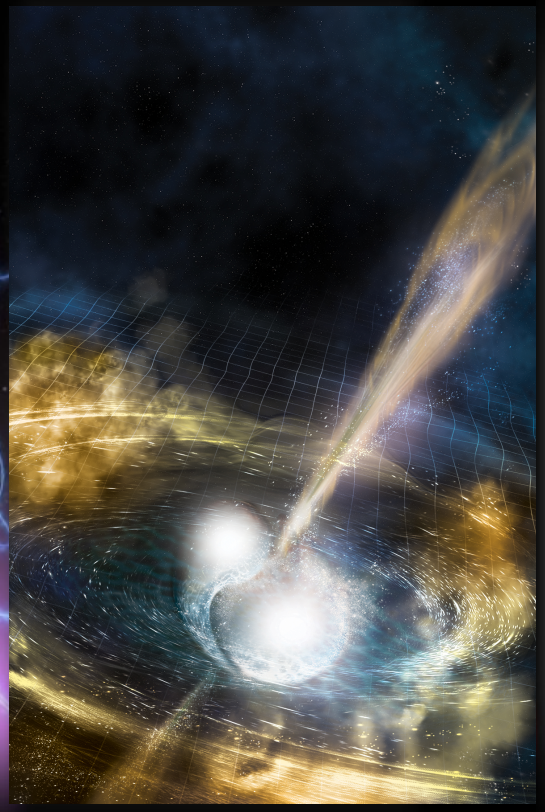
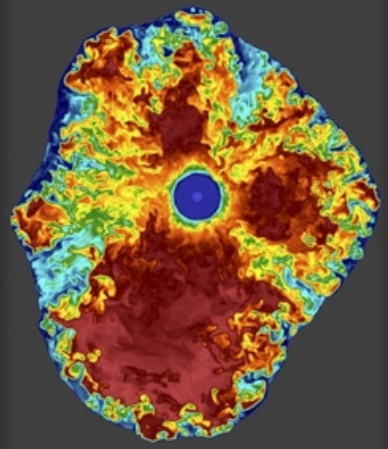
GRAVITATIONAL WAVES AND MULTI-MESSENGER ASTRONOMY





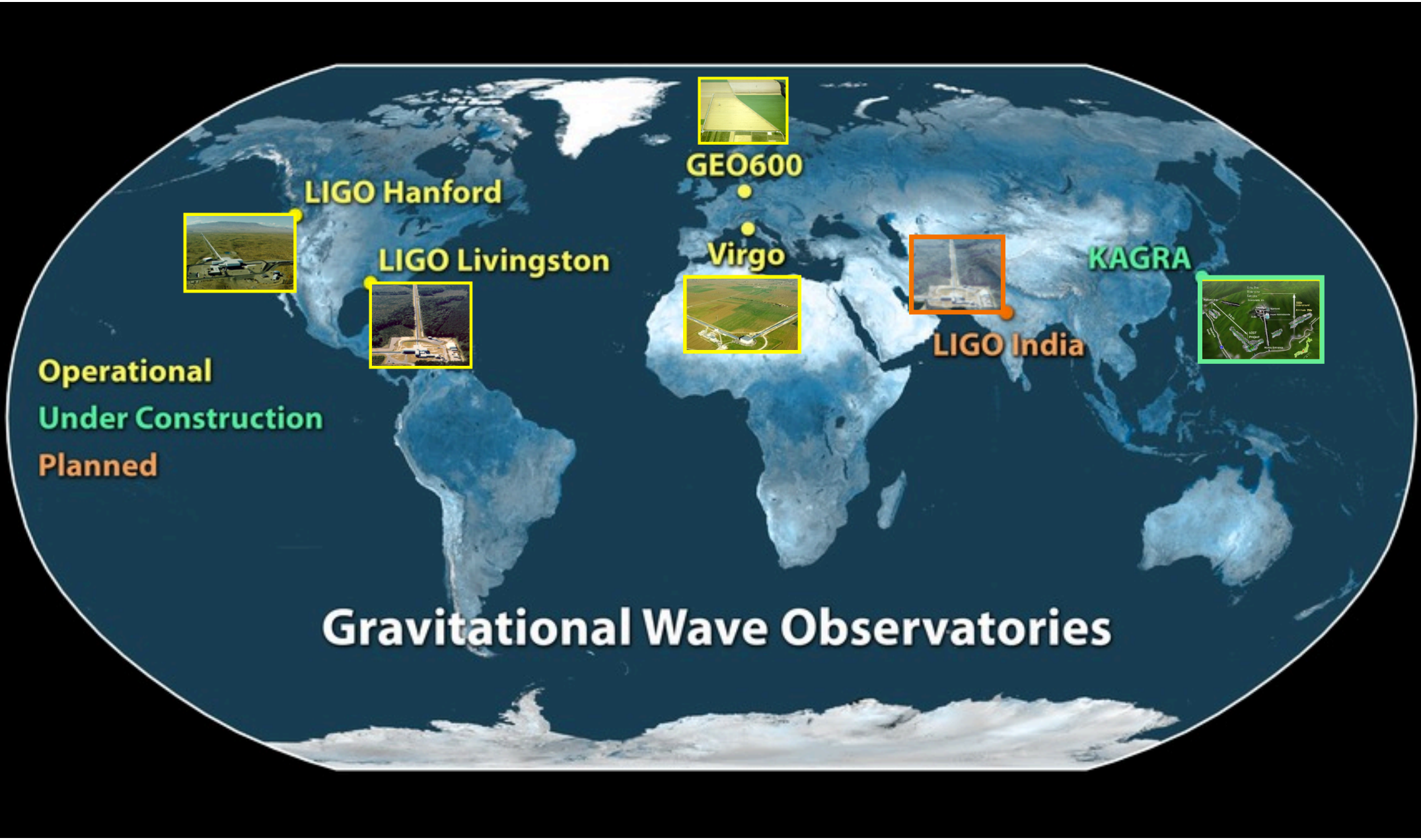
Francesco Pannarale

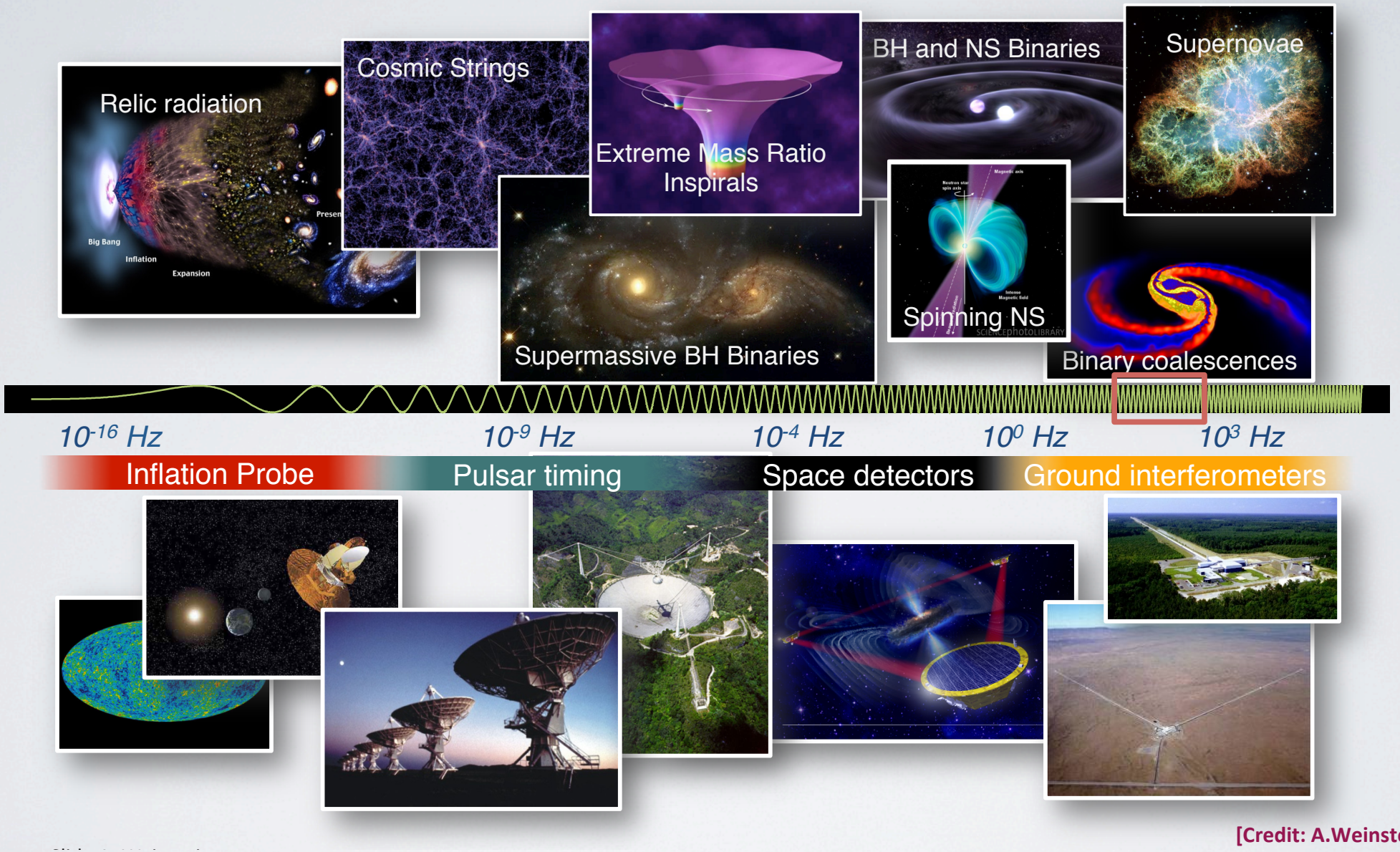
AMALDI RESEARCH CENTER

SAPIENZA UNIVERSITÀ DI ROMA

INFN ROMA Istituto Nazionale di Fisica Nucleare

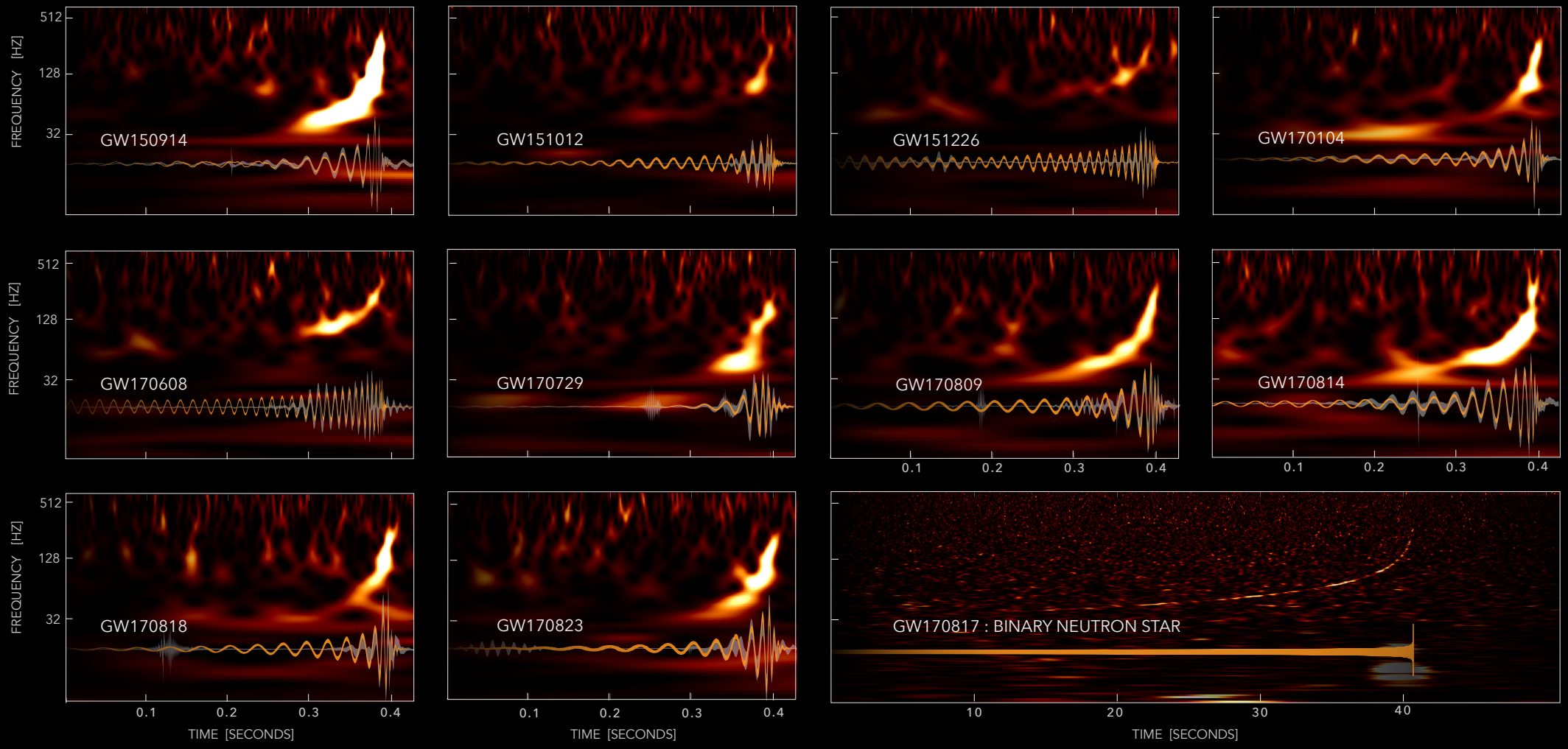
NSF/LIGO/Sonoma State University/Aurore Simonnet


GEO600
LIGO Hanford
LIGO Livingston
Virgo
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories



[Credit: A.Weinstein]

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



[Abbott et al, arXiv:1811.12907]

LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23

WAVELET (UNMODELED) EINSTEIN'S THEORY

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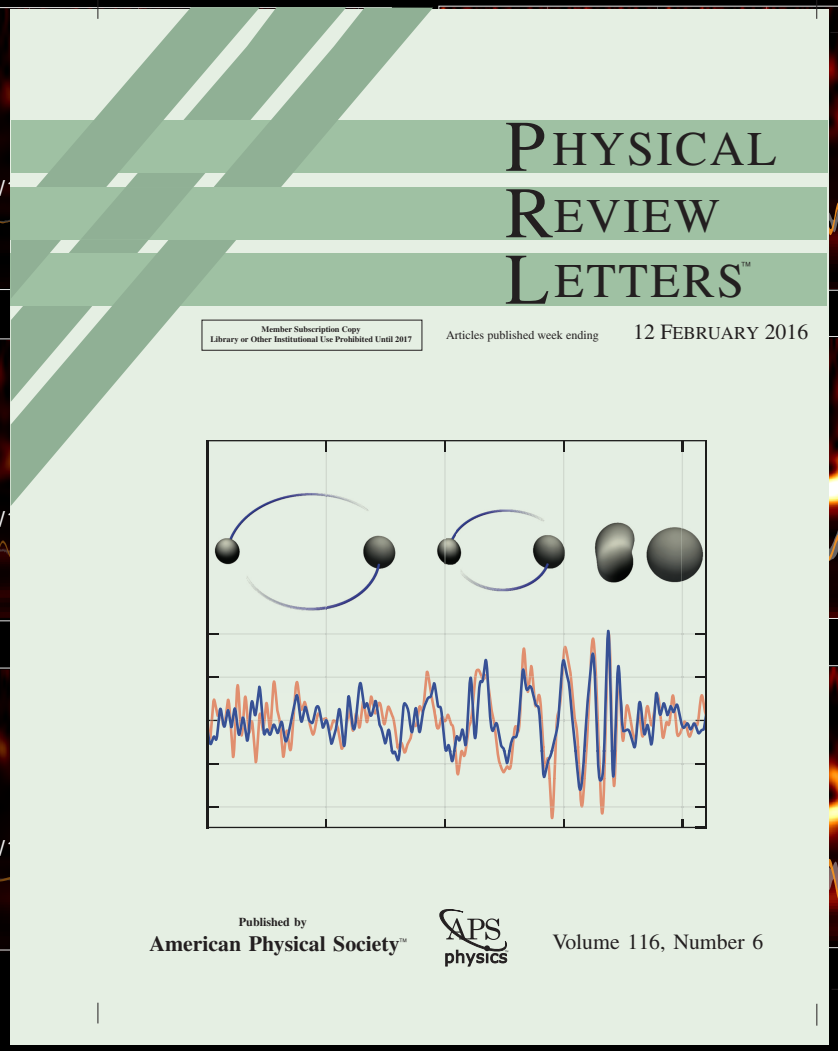
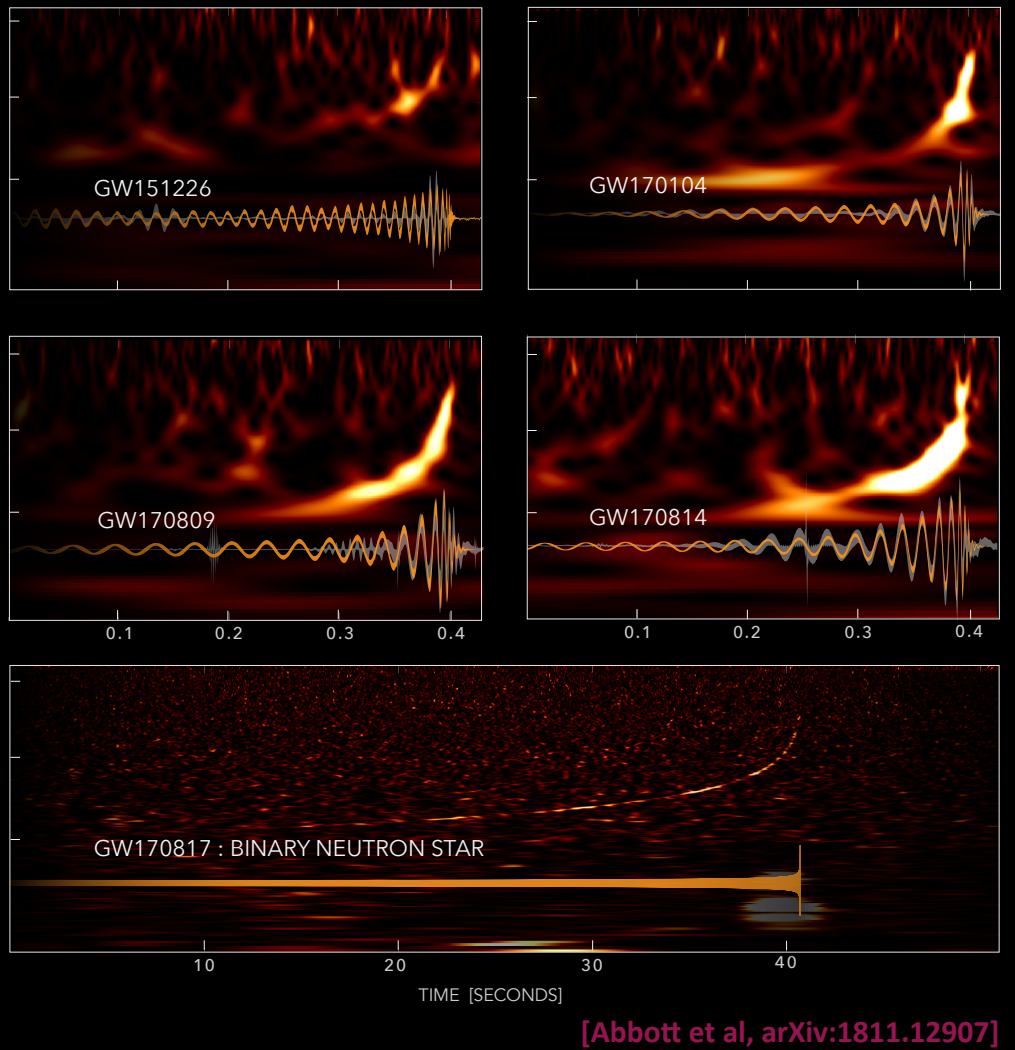
GRAVITATIONAL-WAVE TRANSIENT CATALOG-1

LIGO VIRGO NSF Georgia Tech





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WAVELET (UNMODELED)

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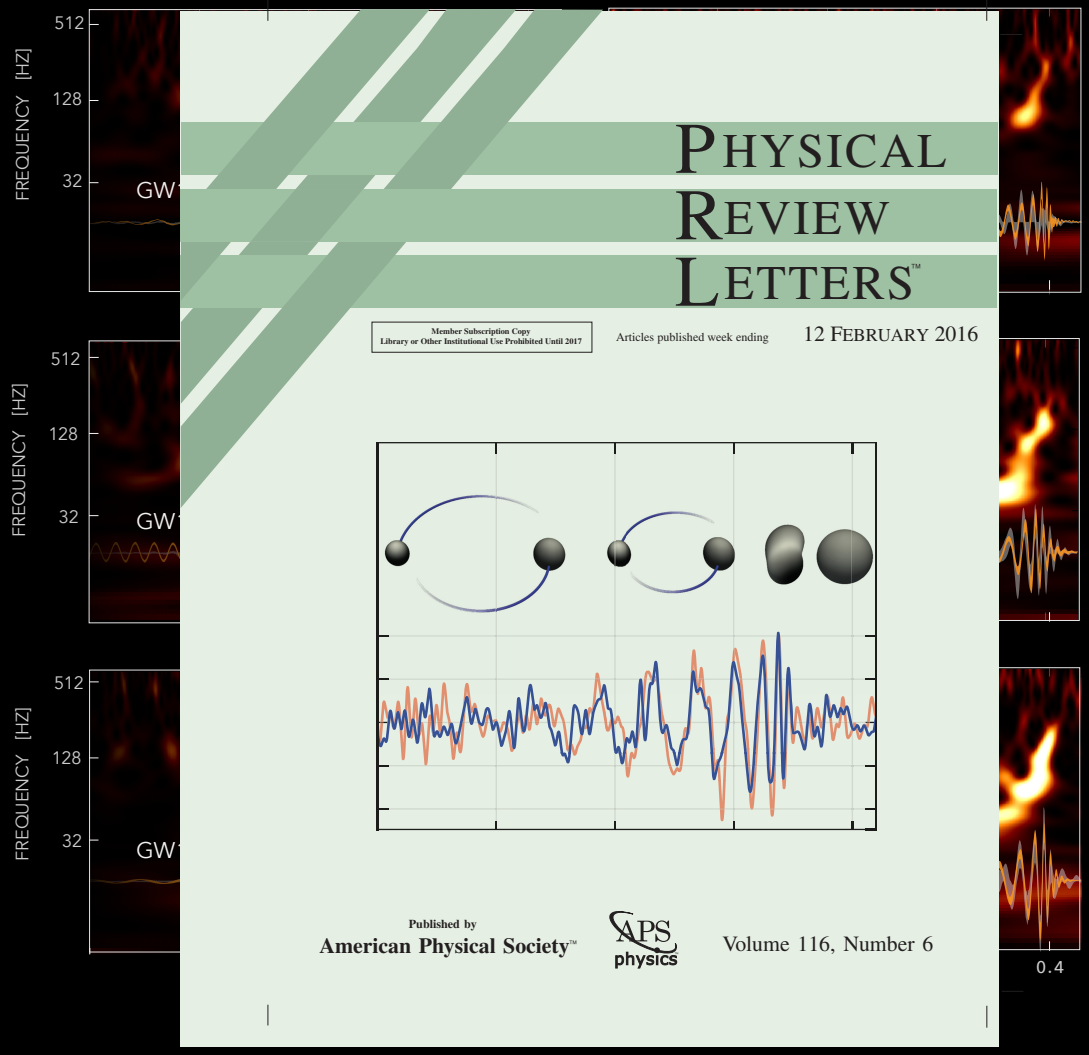

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[Abbott et al, arXiv:1811.12907]

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WAVELET (UNMODELED)

EINSTEIN'S THEORY

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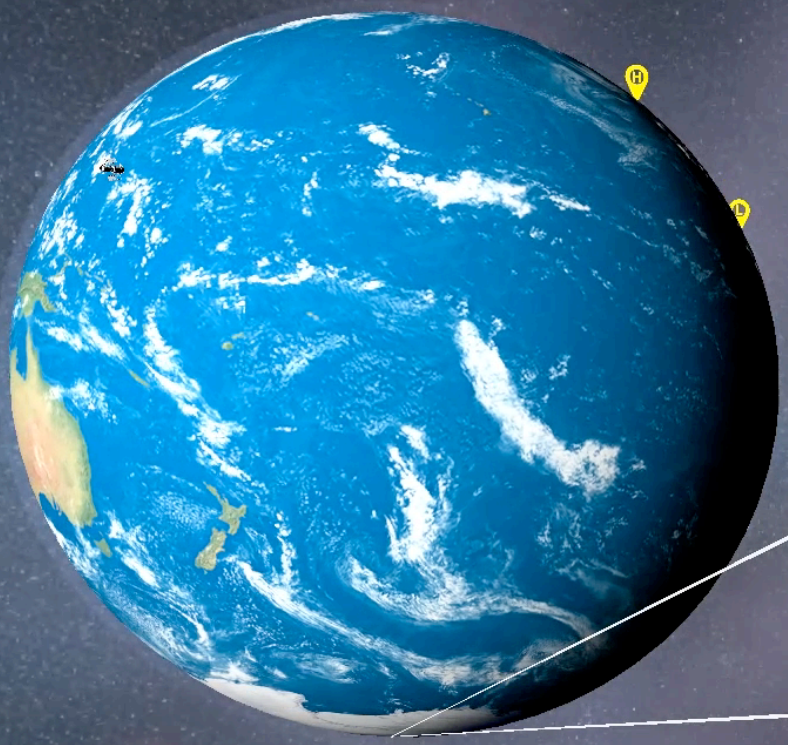
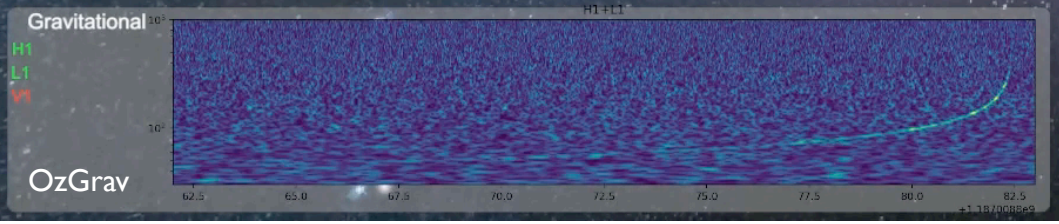
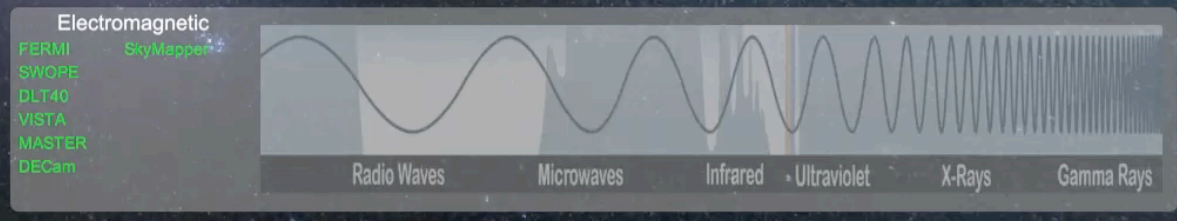
The Most Extensive Observing Campaign Ever

Neutrinos were searched for but not detected.

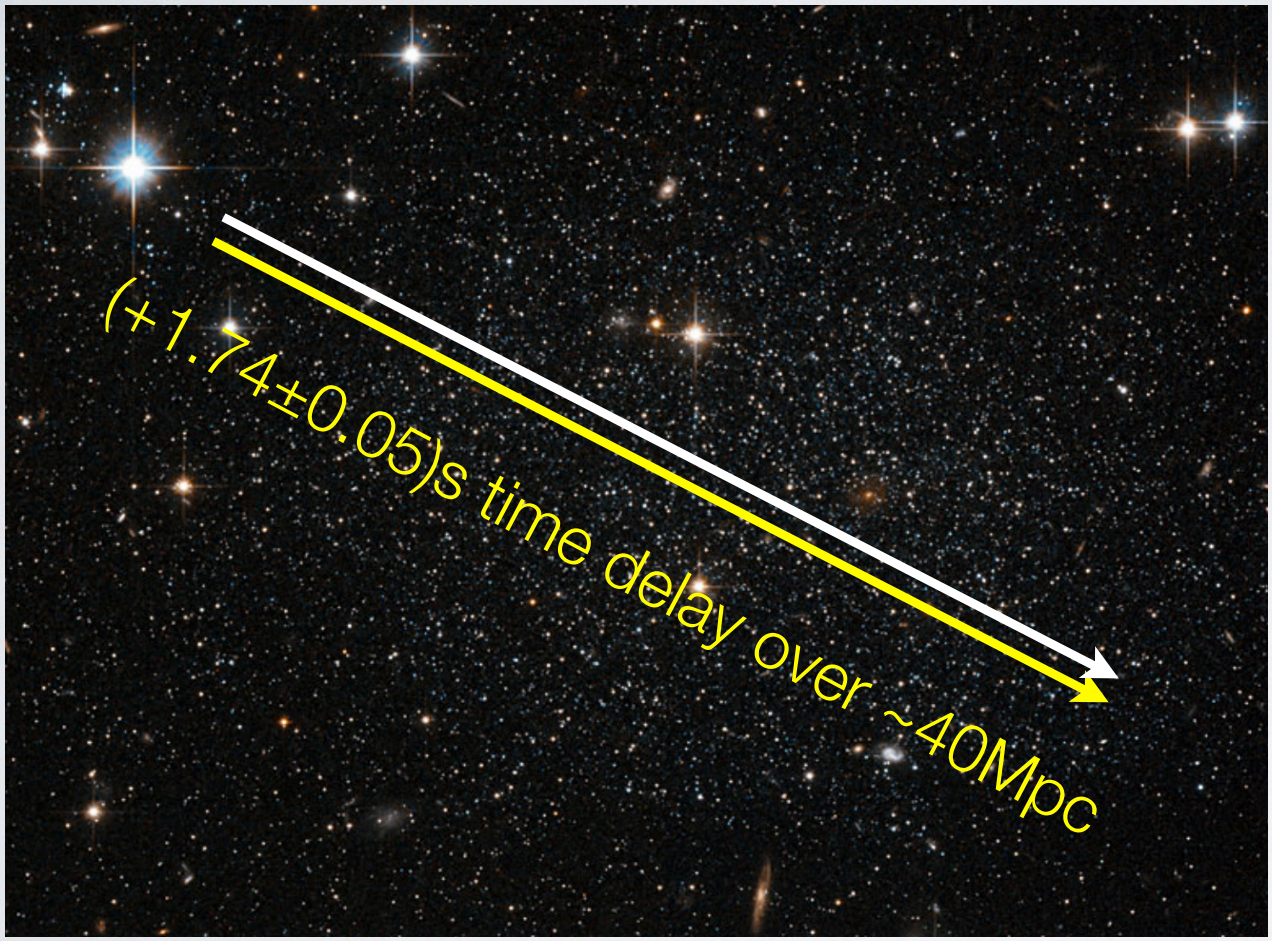


IceCube Neutrino Observatory





GW170817 Highlights: Fundamental Physics



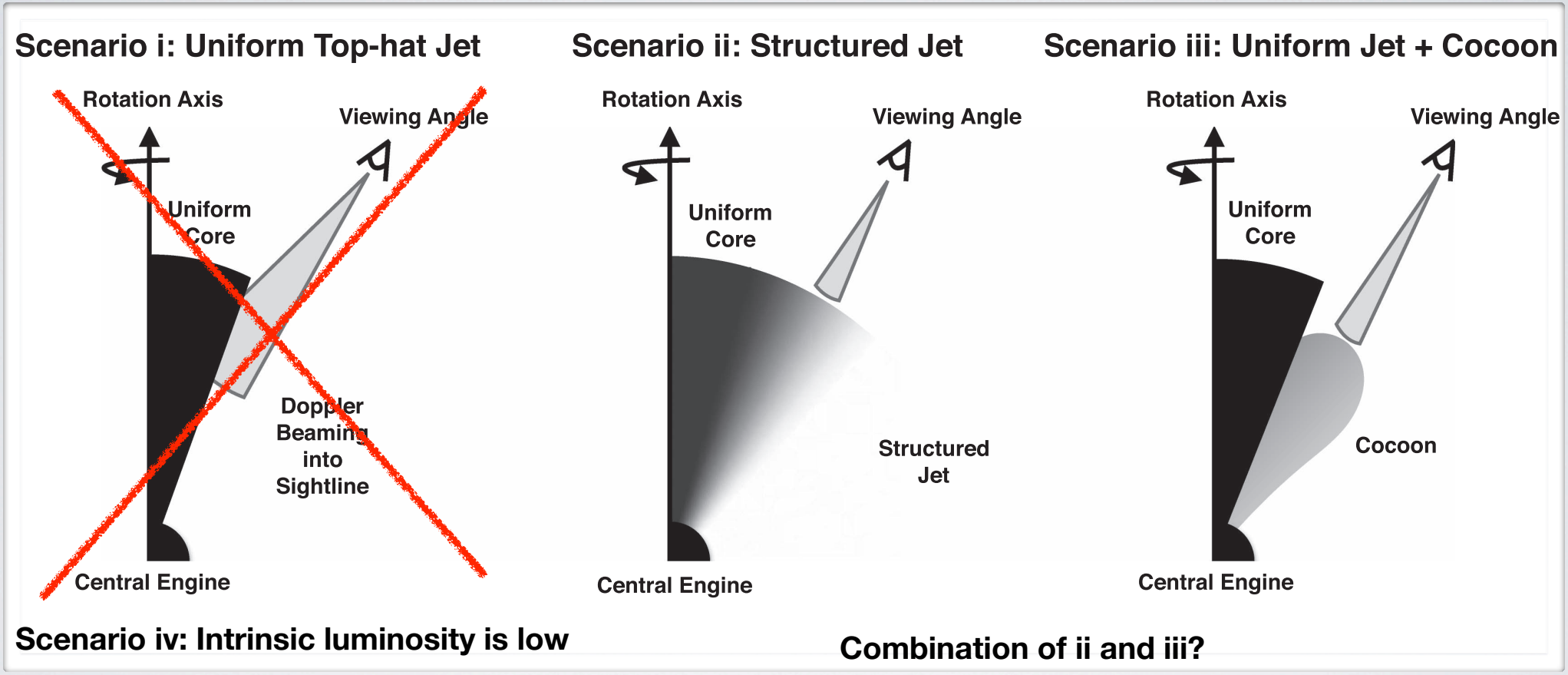
- Speed of gravity:

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

- Used to rule out quartic/quintic Galileons, TeVeS, MOND-like theories [e.g., Baker et al. 2017, Creminelli & Vernizzi 2017]

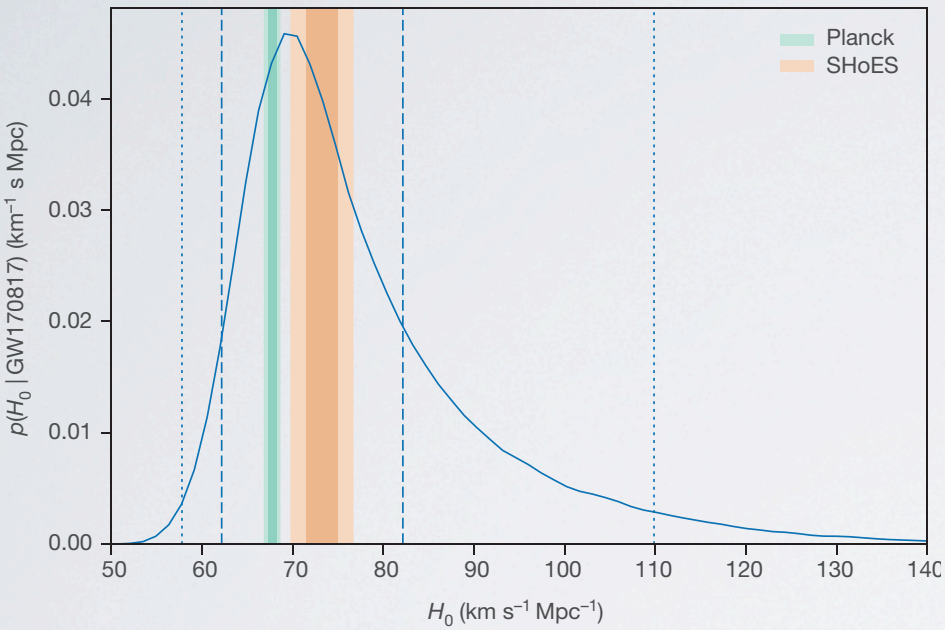
[Abbott et al, ApJL 848, L13 (2017)]

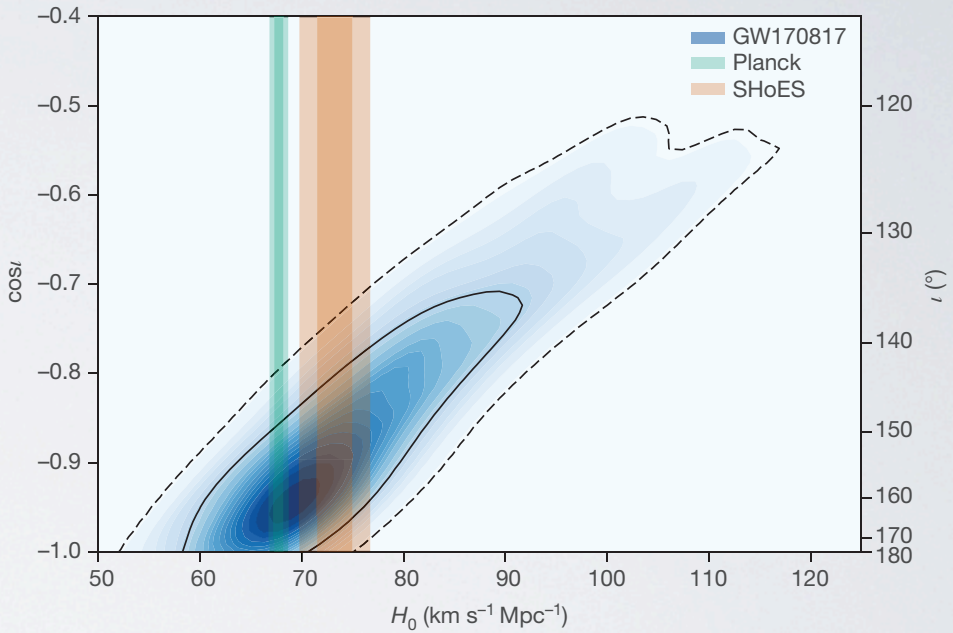
GW170817 Highlights: High-Energy Astrophysics



[Abbott et al., ApJL 848, L13 (2017)]

GW170817 Highlights: Cosmology



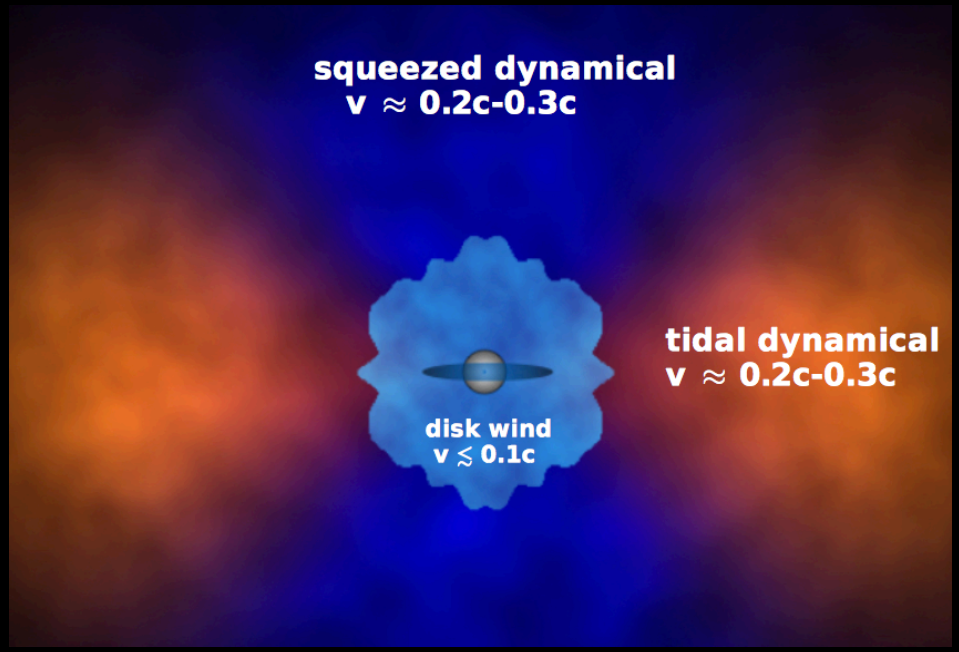


- Combining the GW distance and the recession velocity of the host galaxy:

$$H_0 = v_H/d = 70.0^{12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

[Abbott et al, Nature 551, 85A (2017)]

GW170817 Highlights: Nucleosynthesis



neutron rich ejecta

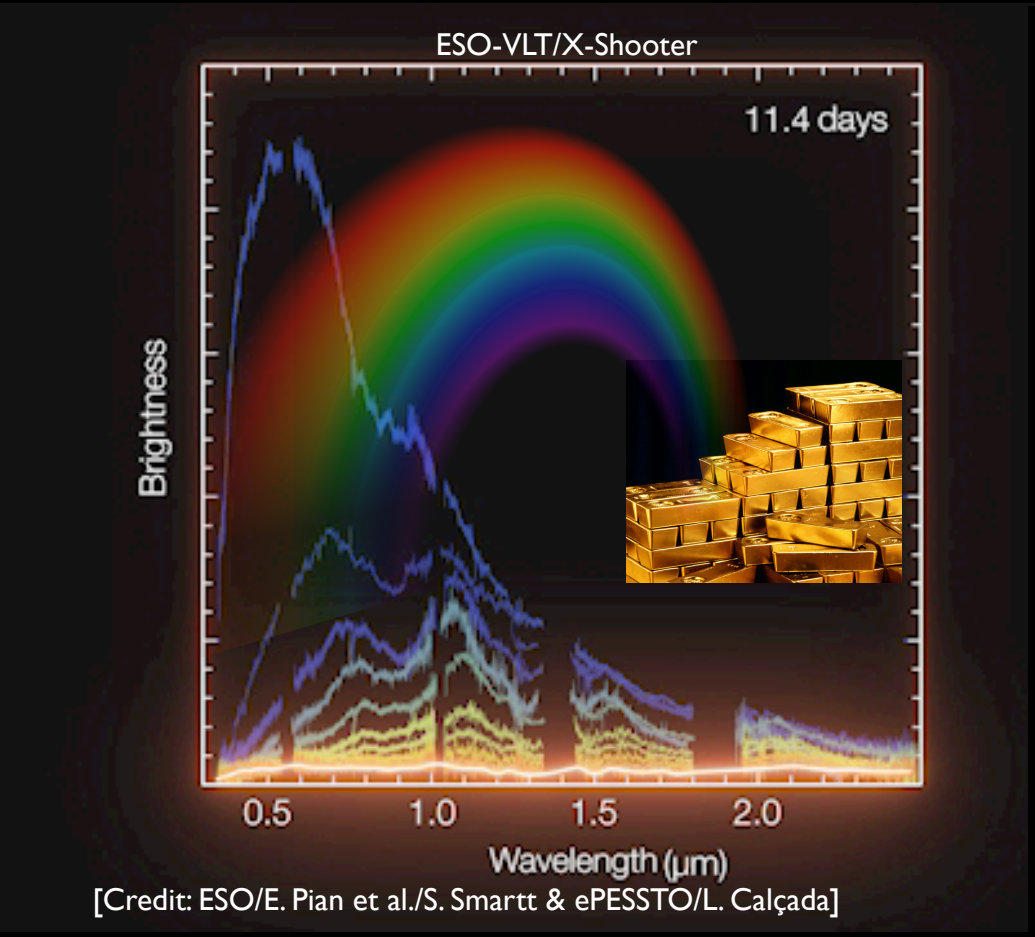
↓ decompression
rapid neutron captrion
(*r*-process)

heavy radioactive elements

~days ↓ alpha, beta decay
nuclear fission
further expansion

quasi-isoptropic
thermal emission
(macronova/kilonova)

GW170817 Highlights: Nucleosynthesis



[Credit: ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada]

- First spectral identification of kilonova emission
  - Signatures of the radioactive decay of *r*-process nucleosynthesis [Pian et al. 2017, Smartt et al. 2017]
  - Site for heavy element production [Cote et al. 2018, Rosswog et al. 2017]

Multi-messenger Astronomy with GWs

1. In the first three highlighted results: multi-messenger = produced using data from gravitational wave and electromagnetic observations of the **same event**
2. In the last highlighted result: multi-messenger = **enabled by localization with gravitational waves**
3. There exists a third class: results obtained combining gravitational wave and electromagnetic data relative to the **same class of sources** (e.g., to constrain the neutron star equation of state, such as Kumar & Landry arXiv:1902.04557)

Prepare to spark **more and new** multi-messenger science with gravitational waves

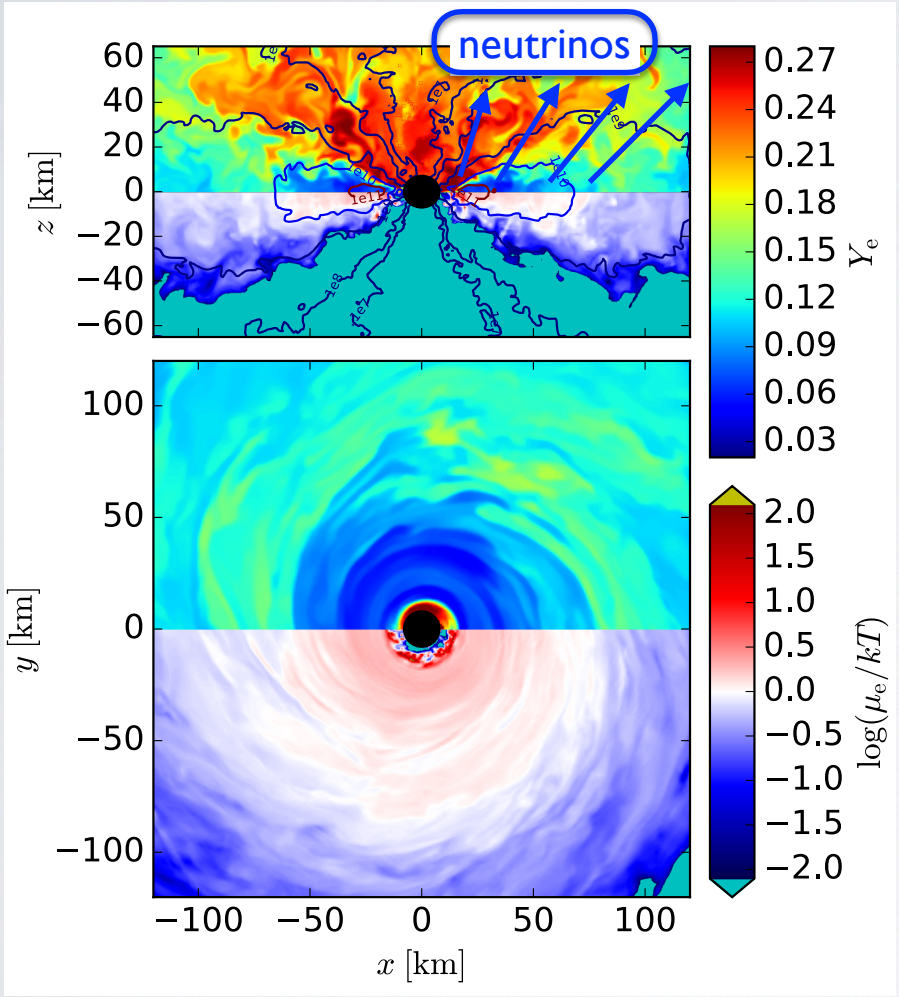
Incomplete Selection of Multi-messenger Scenarios

- GW+neutrino observation could significantly improve the localization of a source, easing electromagnetic follow-up
- GW+neutrino+electromagnetic observations from common sources could help us probe the dynamics of the progenitor

Fast Radio Bursts

- An astrophysical mystery
- 65 published events
- 48 proposed explanations, some involve neutrinos (https://frbtheorycat.org/)

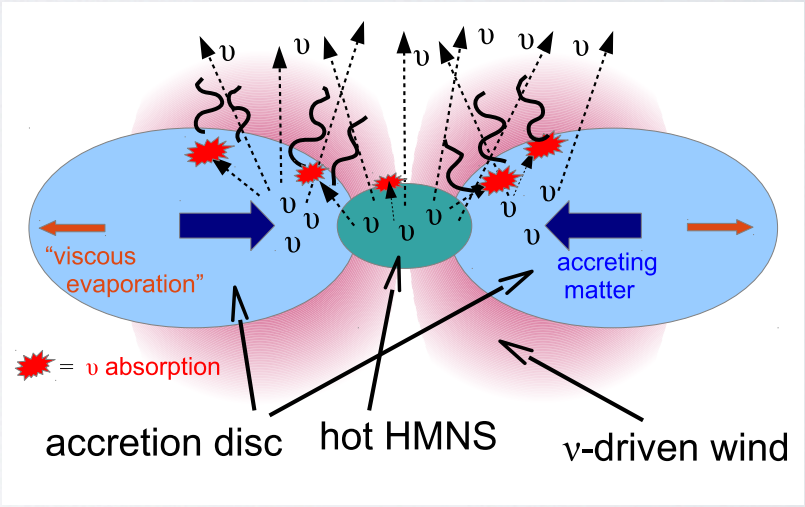
Incomplete Selection of Multi-messenger Scenarios



Viscous heating via magnetic turbulence + ν-cooling: accretion disks self-regulate to mild degeneracy (low Y_e matter)

[Beloborodov 2003, Chen & Beloborodov 2007, Metzger+ 2009]

Corroborated by numerical simulations **[Siegel & Metzger 2017a,b]**



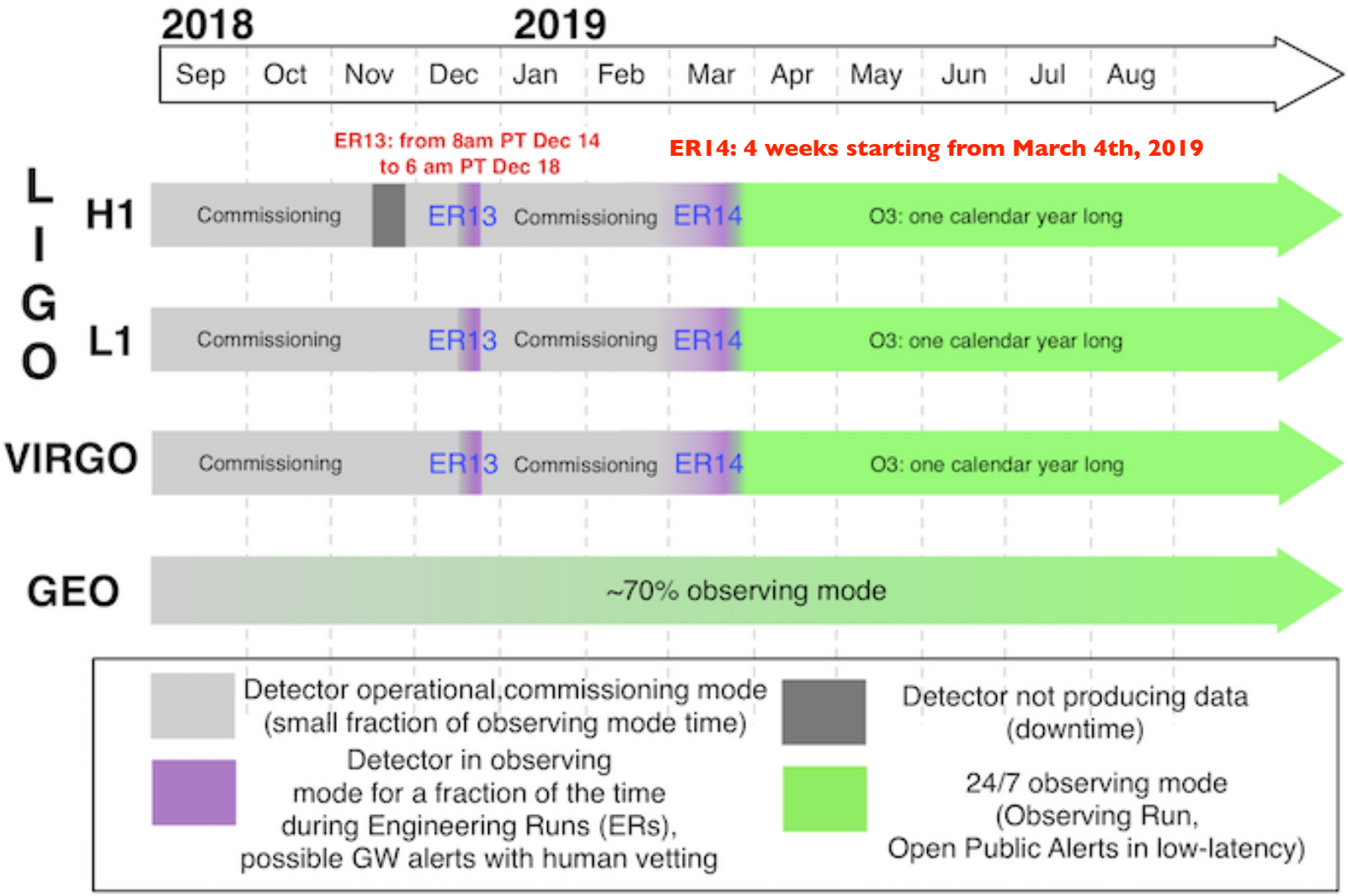
ν-driven wind from hot remnant: energy and momentum deposition by ν_e / $\bar{\nu}_e$'s in the disk drives matter ejection

[Perego+ 2014, Metzger &Fernandez 2014, Just+ 2014, Sekiguchi+ 2015]

LIGO-VIRGO Joint Run Planning Committee

Working schedule for O3

(Public document G1801056-v4, based on G1800889-v7)

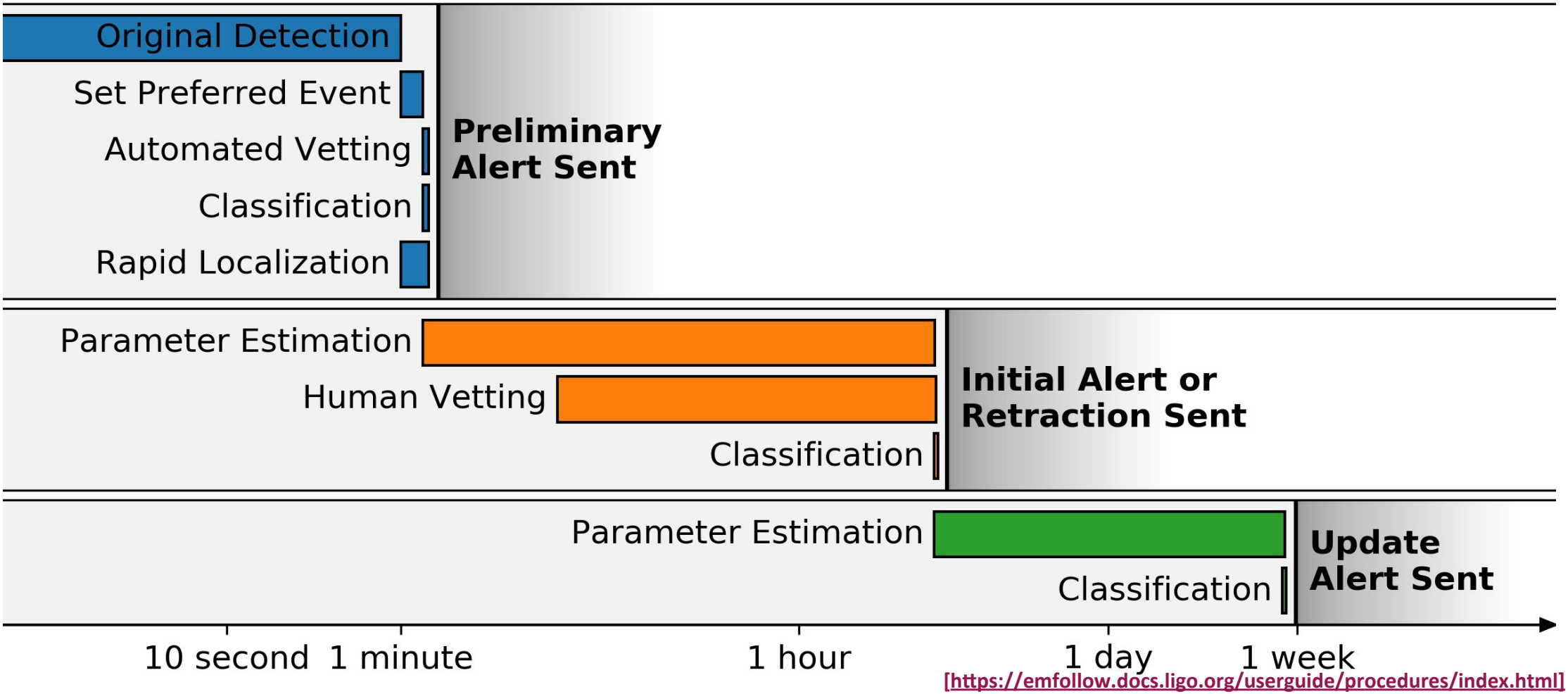


Open Public Alerts in O3

- LIGO/Virgo will immediately release Open, Public Alerts (OPAs) for transient event candidates
  - OPAs available through the Gamma-ray Coordinates Network
  - Event candidates will be publicly available in https://gracedb.ligo.org
  - There will be no human vetting for the **preliminary** alert
- OPAs will enable the physics and astronomy community to pursue multi-messenger observations of gravitational-wave sources and maximize the science reach of the gravitational-wave instruments.
- LIGO-Virgo target contamination of public alerts
  - ~10% of public alerts across all categories together
  - BNS, NSBH & other transients may individually have higher contamination
  - False alarm rate set at ~1/(2 months) for binaries and 1/yr for other transients

[https://emfollow.docs.ligo.org/userguide/quickstart.html]

Open Public Alerts in O3



[https://emfollow.docs.ligo.org/userguide/procedures/index.html]

Detection Rates in O3

- **Binary black hole** rate will dominate, possibly by more than an order of magnitude: ~few/month to ~few/week
- **Binary neutron stars**: 1-10 per year, possibly up to ~1/month; Median 90% credible localization 120-180 deg^2; 12-21% localized < 20 deg^2
- **Neutron star-black hole**: no scenario rules N=0, most give ~50% N>0
- Detection rate calculations depend strongly on mass, but very mildly on assumed spin distribution
- Other transients: unknown

[DCC: LIGO-G1800370, Abbott et al, arXiv:1811.12907, 1811.12940]

Final Remarks

- **Sept 14, 2015** – Advanced LIGO detects gravitational waves from collision of two black holes
- **Aug 17, 2017** – LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars
- **Oct 3, 2017** – LIGO co-founders Rainer Weiss, Barry Barish, and Kip Thorne are awarded the 2017 Nobel Prize in Physics

"Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."
Winston Churchill

Final Remarks

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