Black and Gold

The Astrophysics of the Binary Neutron Star Merger GW170817/GRB170817A

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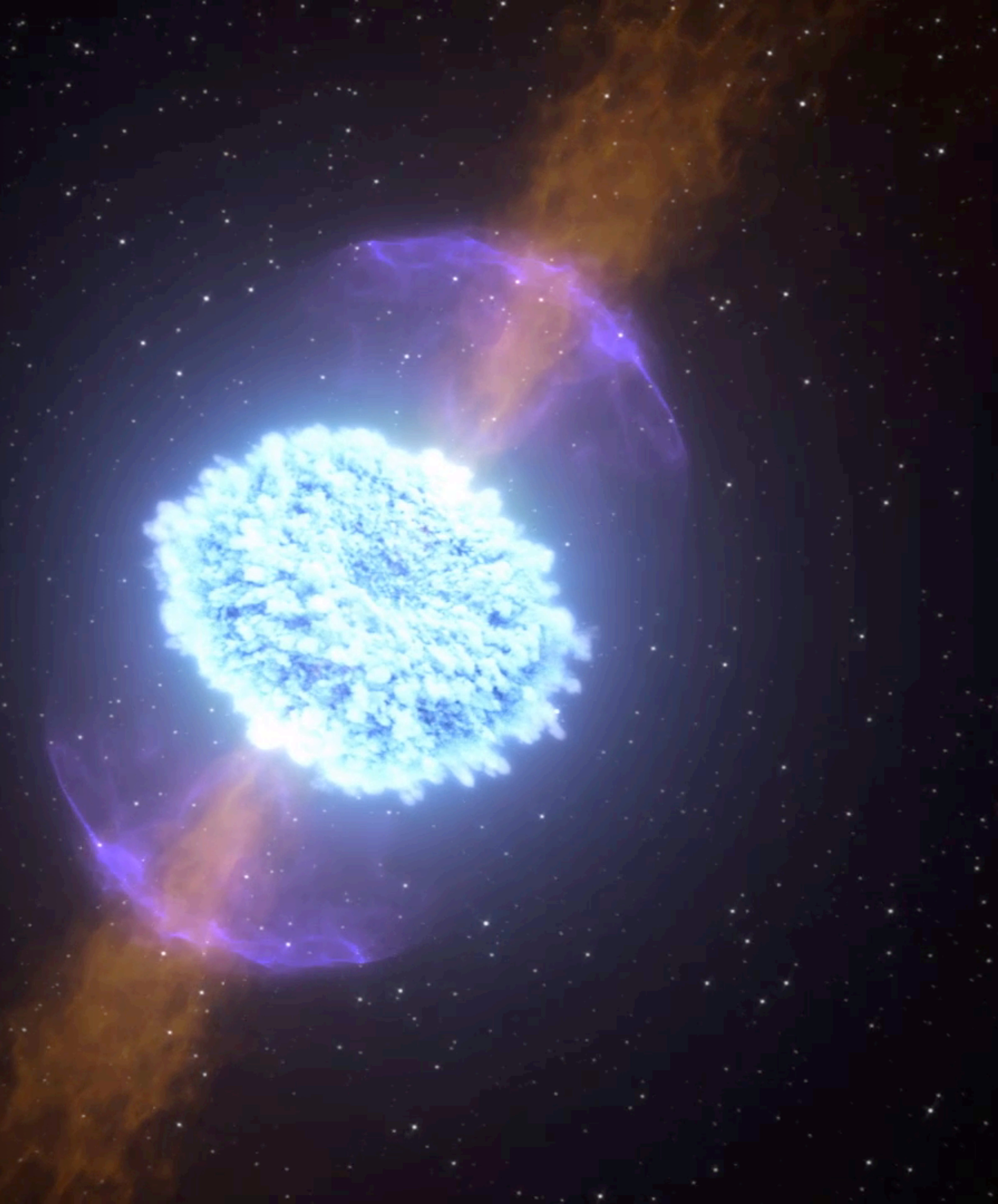
1st GammaSIG Teleconference



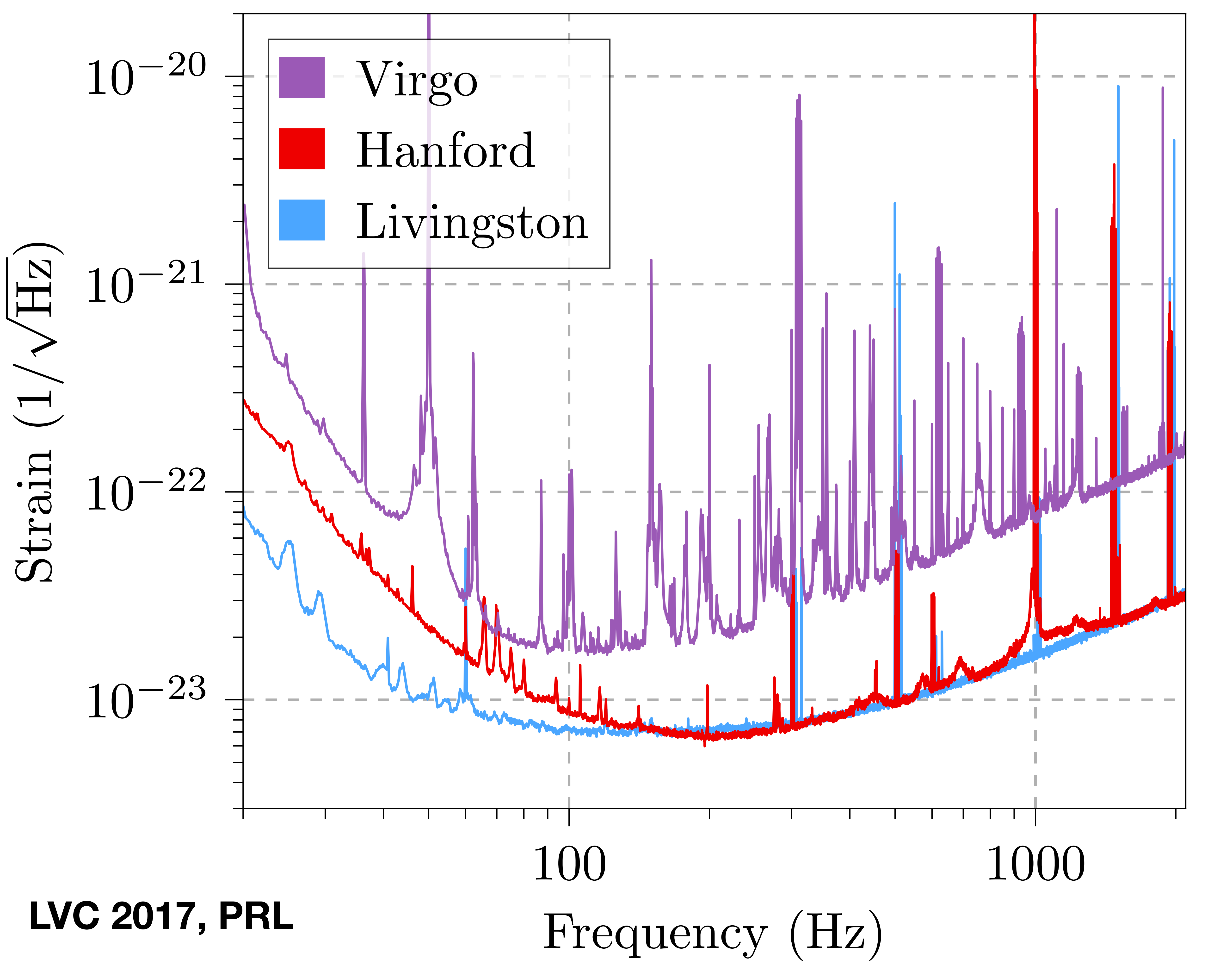
Outline

1. LIGO/Virgo
2. Discovery, Observing Strategies
3. Optical and Near Infrared Observations
4. Interpretation, Radio
5. A Few Open Questions

1. LIGO / Virgo


VIRGO
CASCINA, ITALY

ADVANCED VIRGO
commences observations



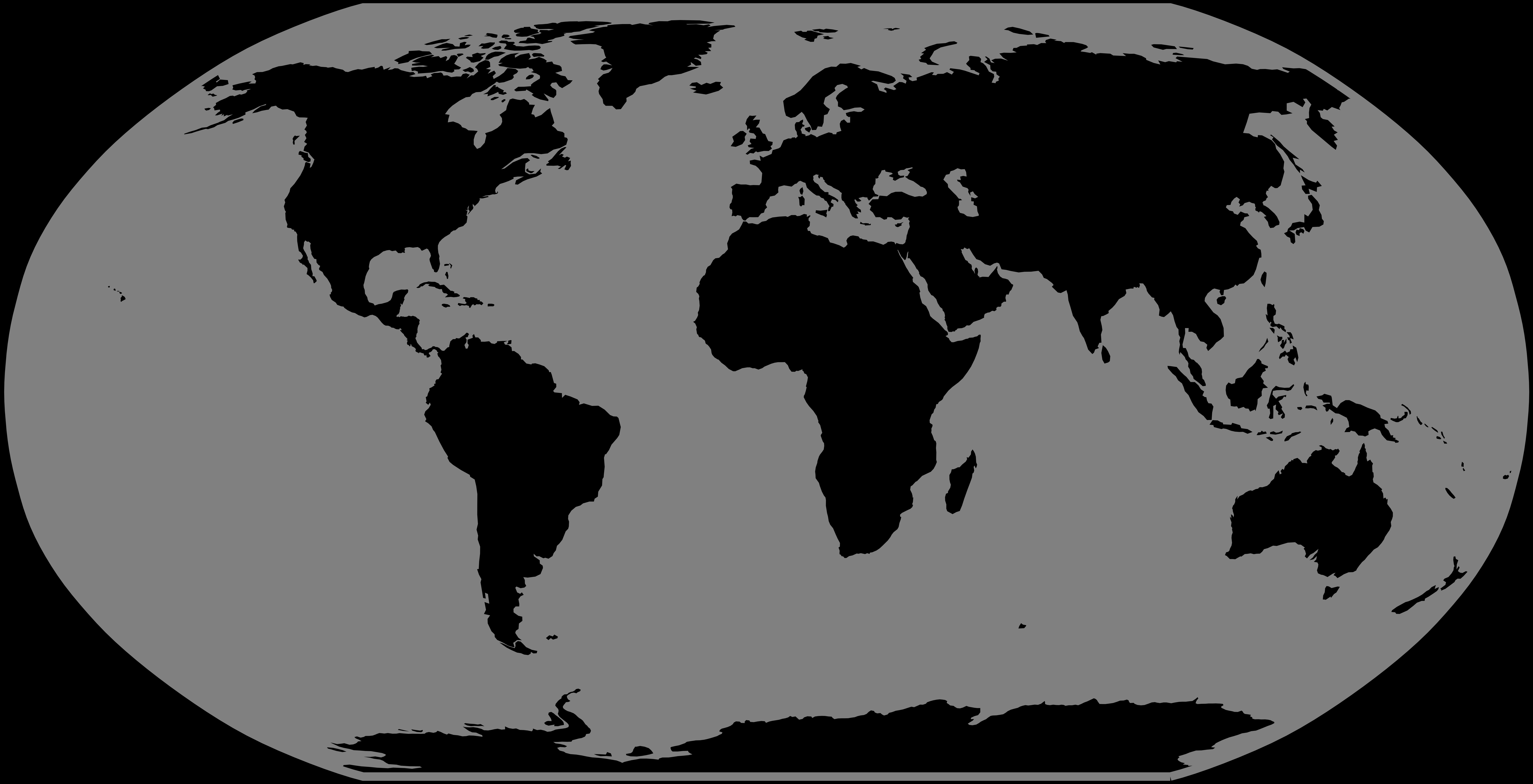
LVC 2017, PRL

Upgrades completed and **Advanced Virgo became operational in August 2017**. Main enhancements over initial Virgo:

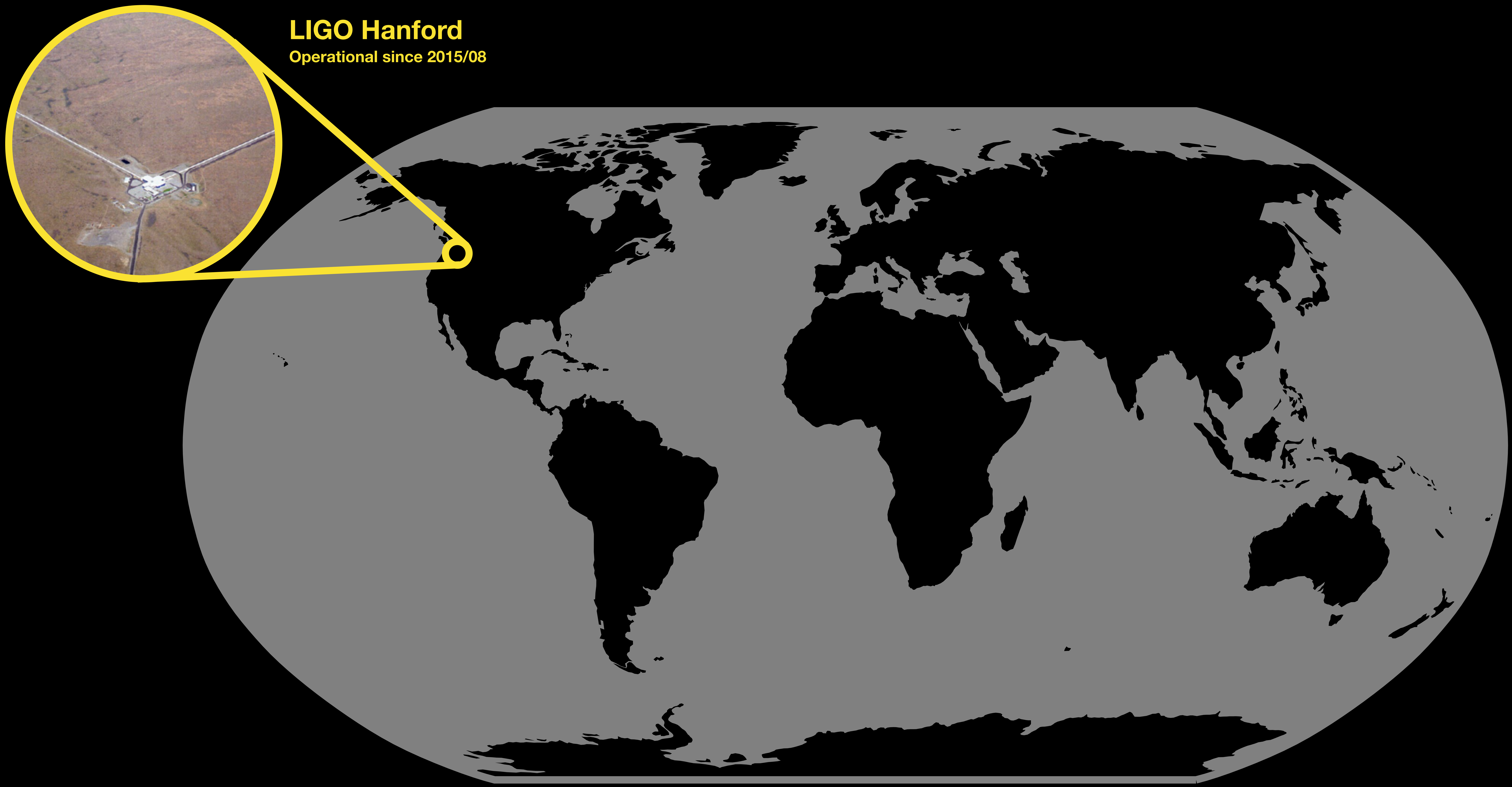
- Increased finesse of arm cavities
- Test masses heavier, lower absorption, higher surface quality
- Size of beam doubled (vacuum system and input/output optics modified accordingly)
- More robust control of final pendulum stage

Not in this talk: LIGO/Virgo **sensitivity improvements in *software*** developed and deployed in O2

- Feed-forward **noise subtraction**
- **Glitch removal** by masking or subtraction
- **Fully coherent rapid localization** for inhomogeneous networks of detectors



Advanced GW Detectors



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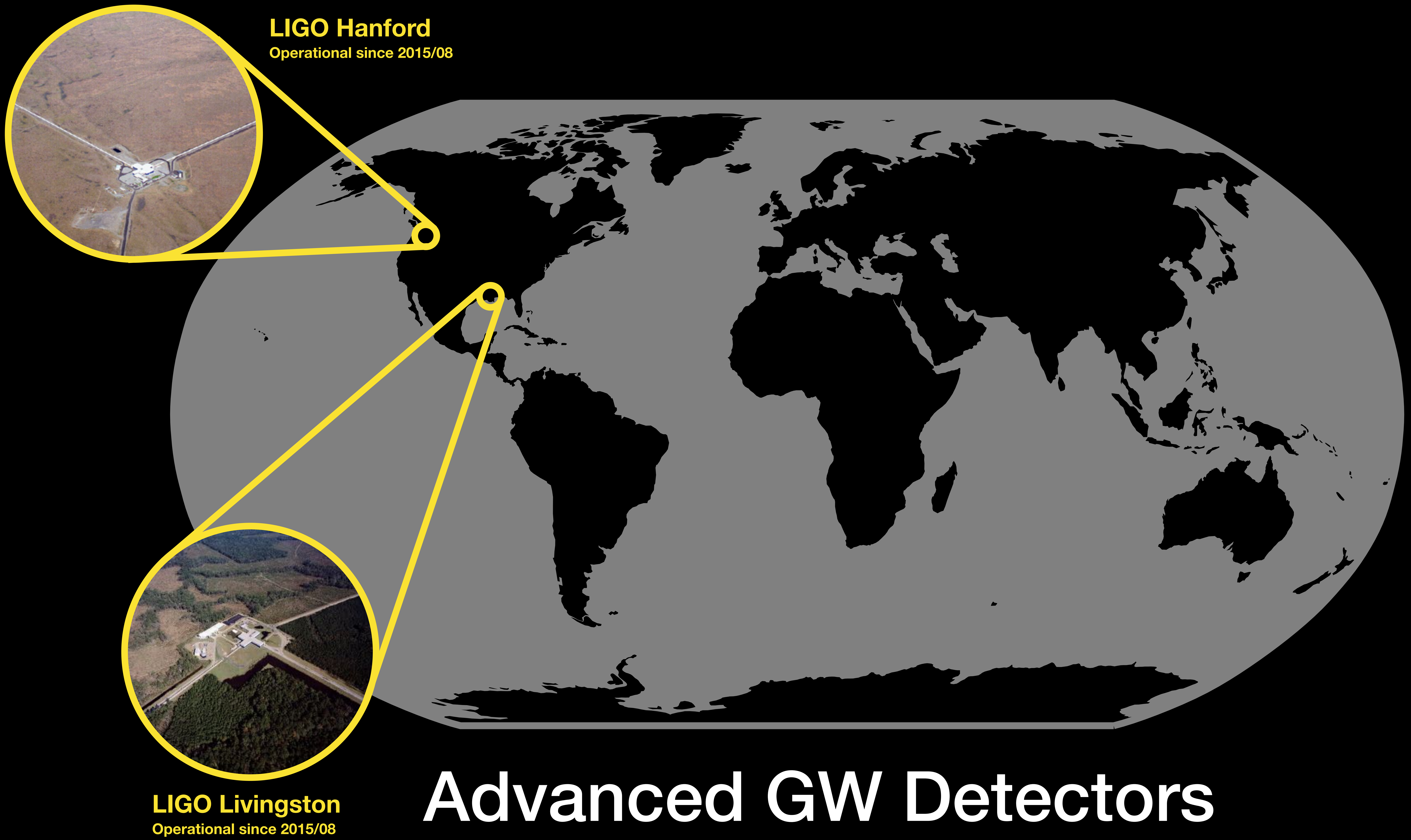

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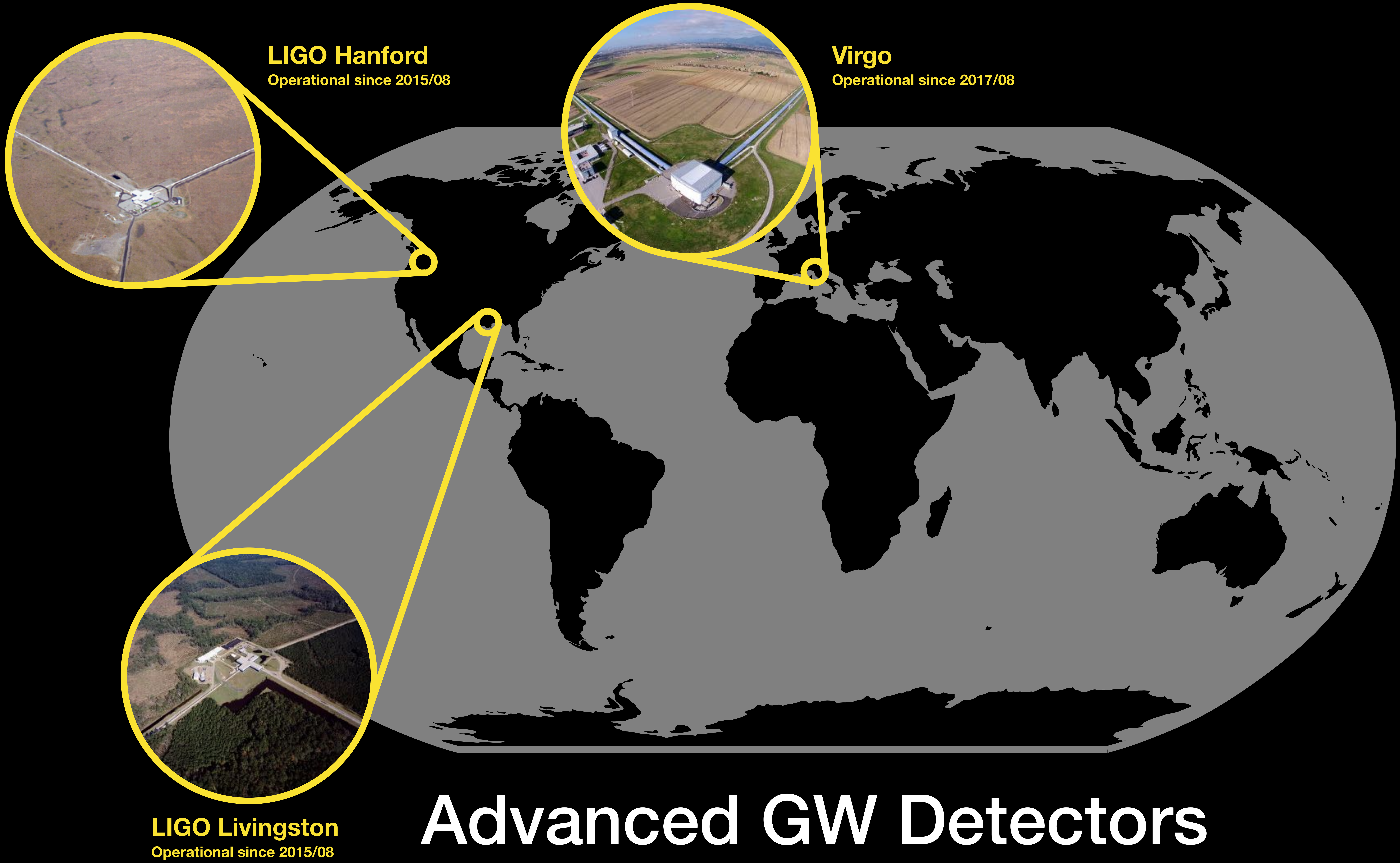
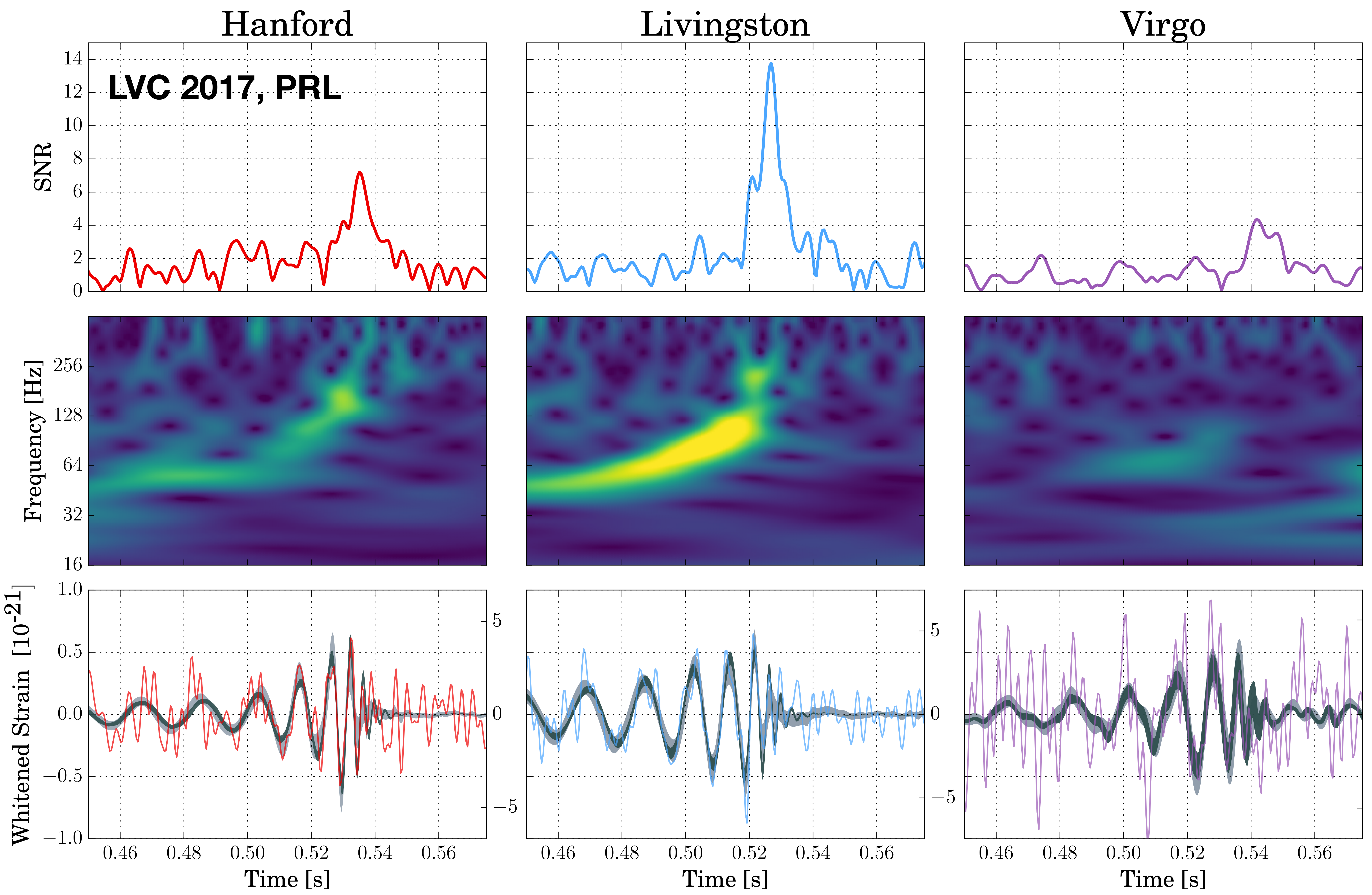


Advanced GW Detectors

AUGUST 14, 2017, 10:30:43 UTC:
the first BBH signal observed with Virgo



- Signal arrived first at **Livingston**, then 8.4 ms later at **Hanford**, then 6.6 ms later at **Virgo**
- Clearly visible chirp trace in Hanford and Livingston spectrograms; faint telltale visible in Virgo
- Independently **detected in low latency** within **30s** of data acquisition by two real-time searches for compact binary inspiral signals: GstLAL (see C. Hanna's colloquium at GSFC on October 31) and PyCBC
- Initial matched-filter signal to noise ratios in H/L/V: **7.3/13.7/4.4**

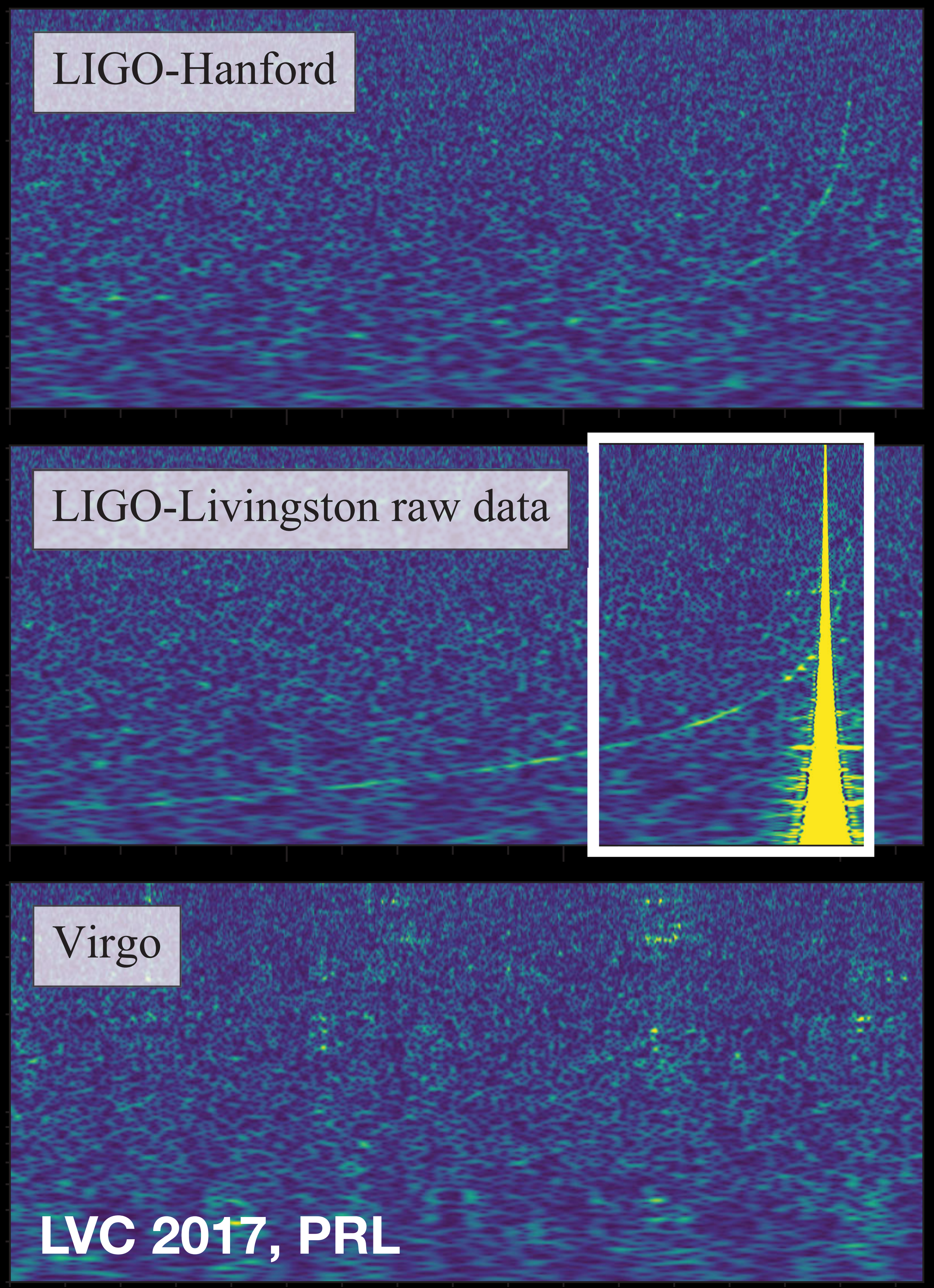
OCTOBER 14, 2017, 10:30:43 UTC:
the first GW signal observed with Virgo

Credit: LIGO/Virgo/NASA/Leo Singer

- A **31 on 25 $M_\odot$ binary black hole merger**
- Thanks to additional detector baseline, **localized to 60 deg²**
- **First measurement of gravitational-wave polarization**: confirmation of tensor nature of gravitational waves as predicted by GR
- **More detailed tests of GR** in progress

AUGUST 17, 2017, 12:41:04 UTC

the first gravitational wave signal from a binary neutron star merger



- Detected in low latency in Hanford data. **Chirp track clearly visible**, long duration immediately implied a **low mass binary merger**!
- **Chirp visible in Livingston** too, but did not trigger due to a **photodiode saturation glitch**.
- **No chirp visible in Virgo.**
- H/L/V signal to noise ratio after **noise subtraction and glitch removal**: 18.8/26.4/2.0
- Component masses: **1.4–1.6 on 1.2—1.4 $M_{\odot}$**
- Localized to only **30 deg²** and 26–48 Mpc despite weak/unresolved signal in **Virgo** due to **proximity to antenna pattern null**

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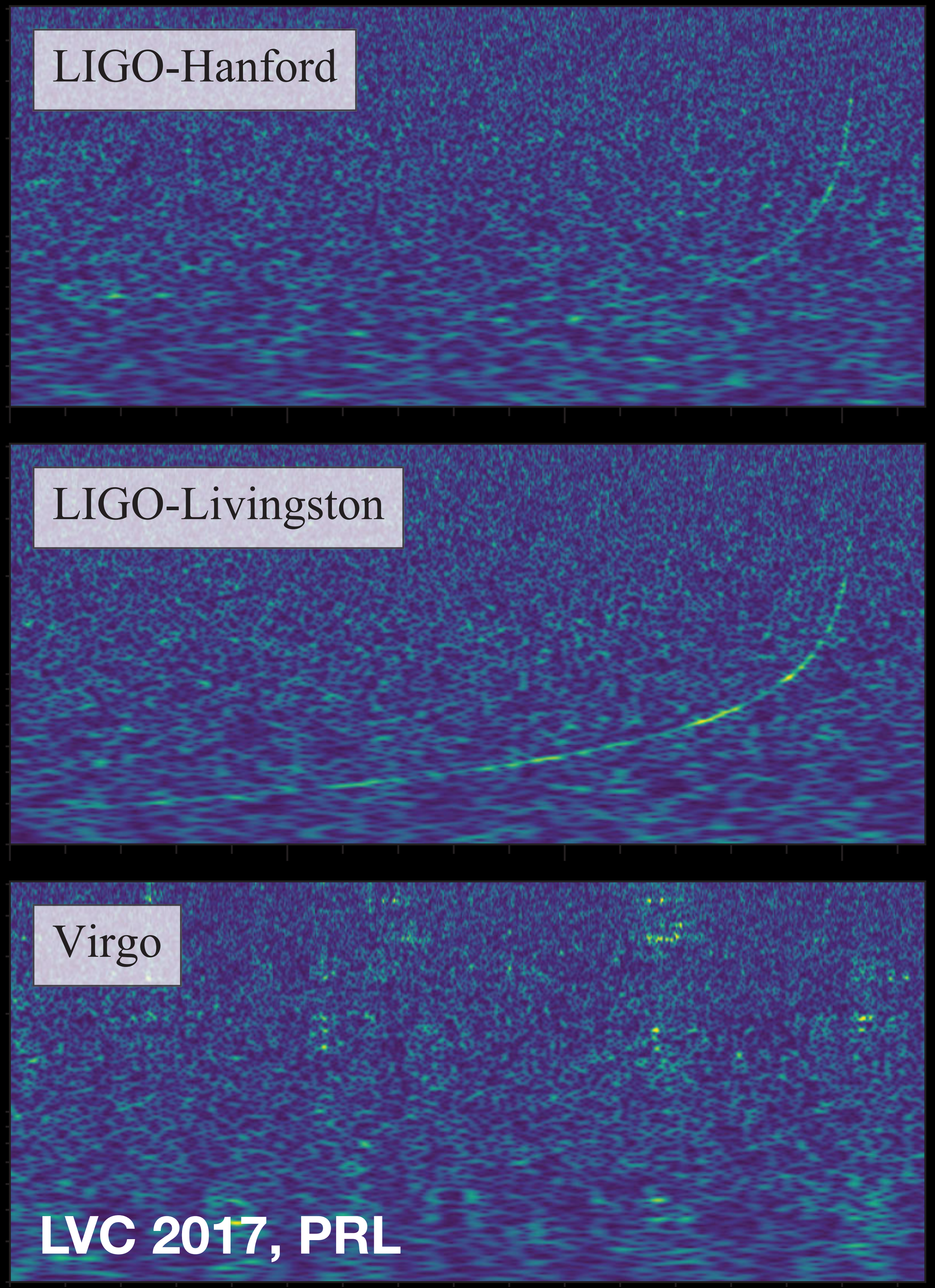

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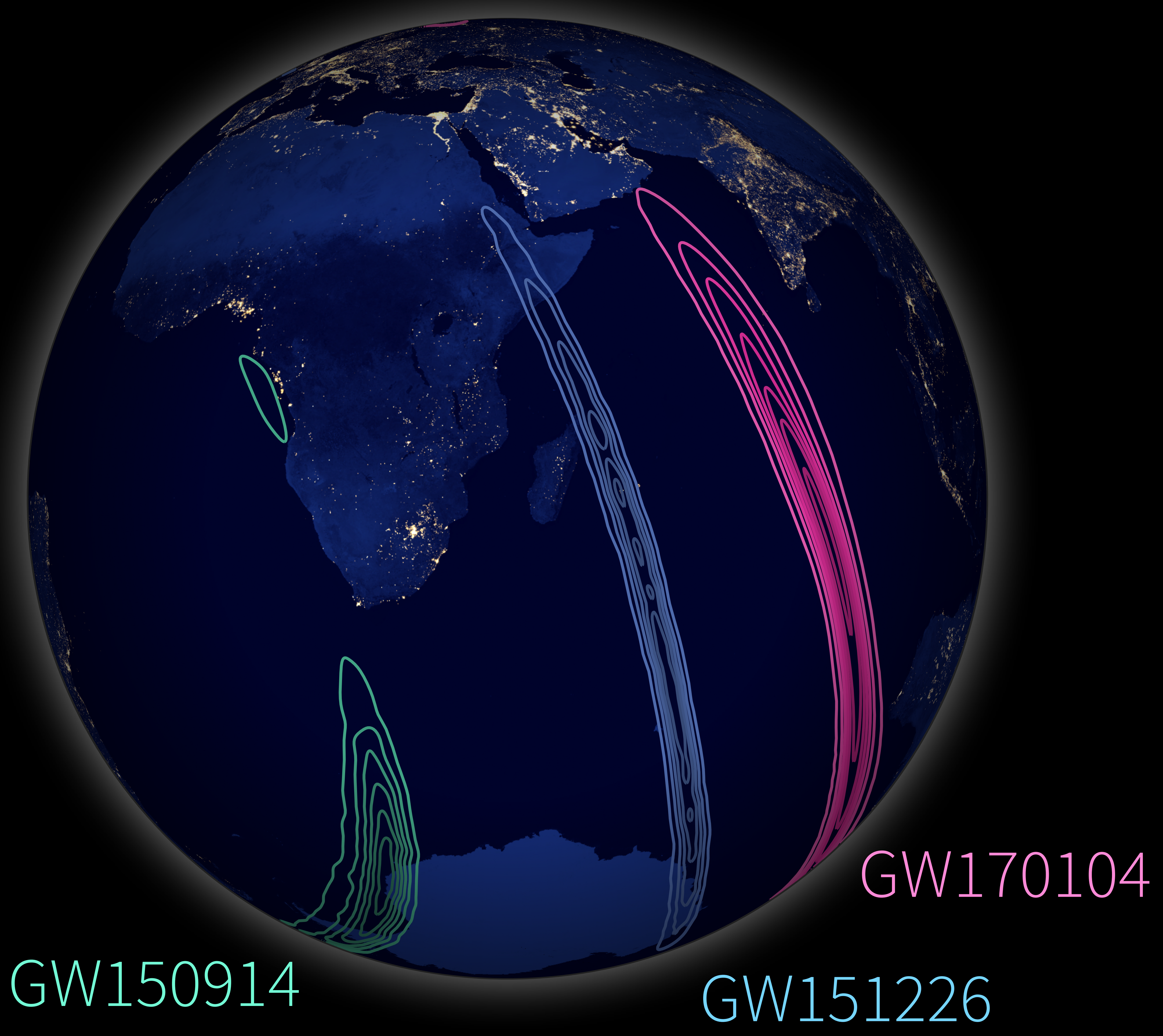
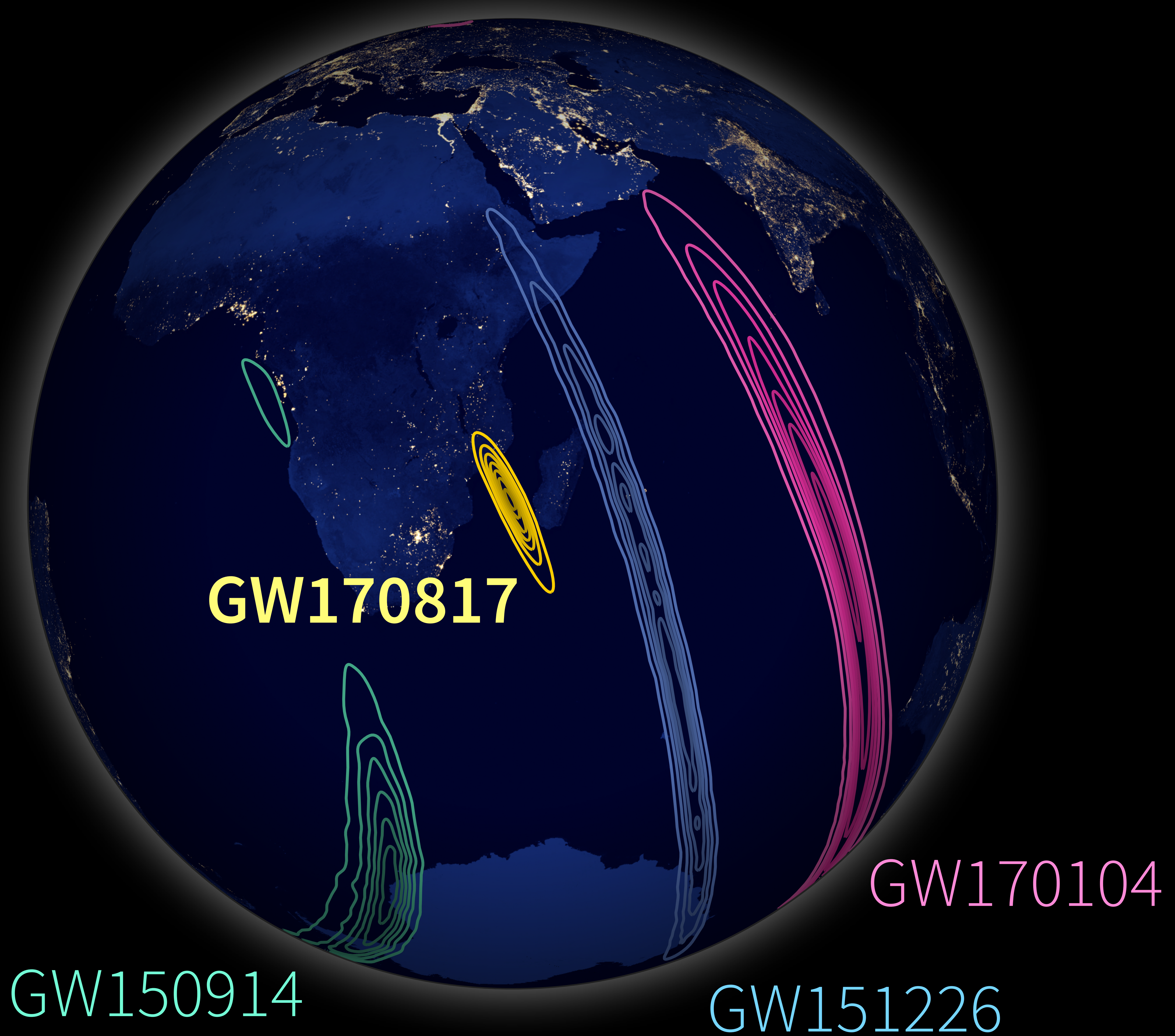
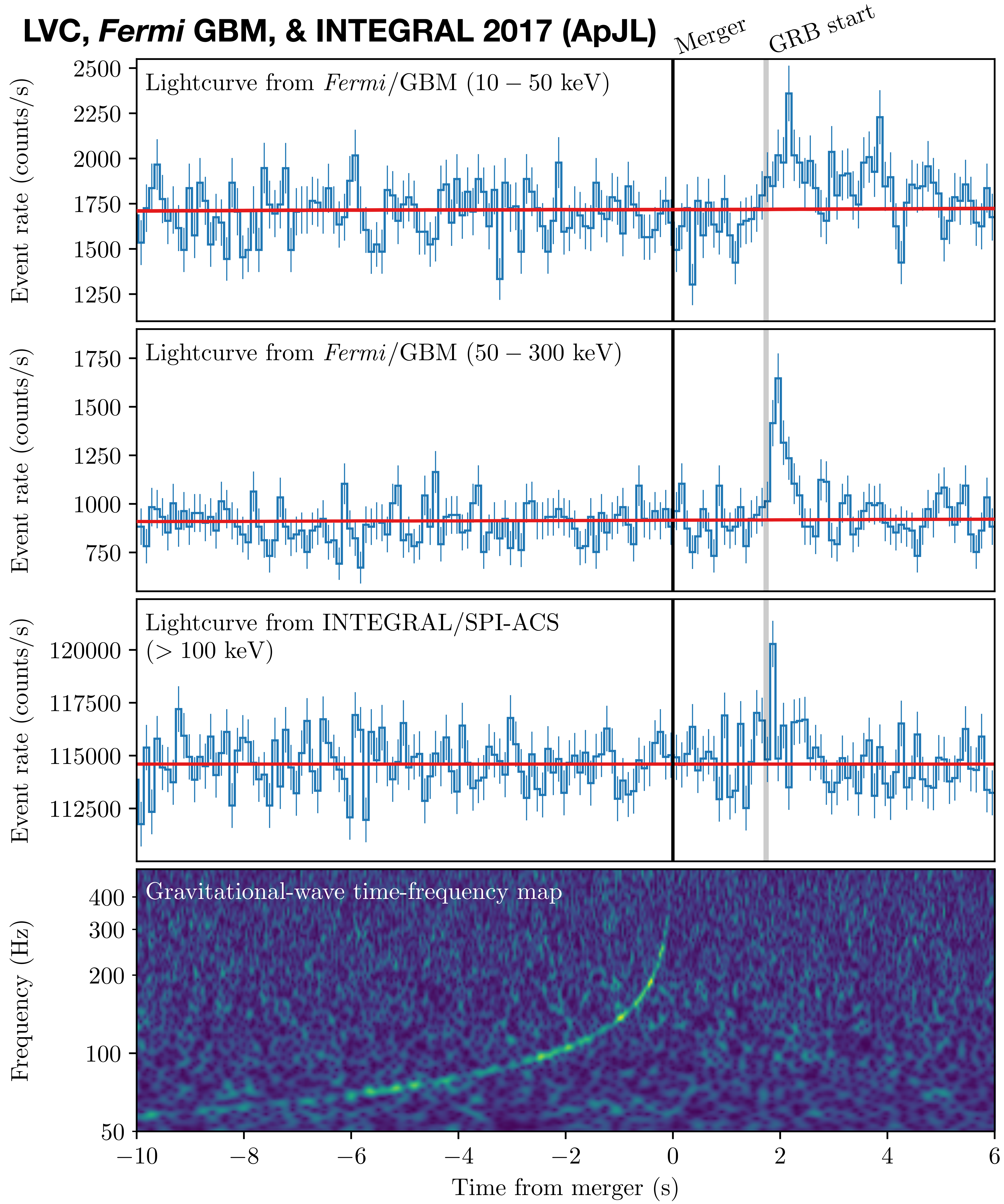


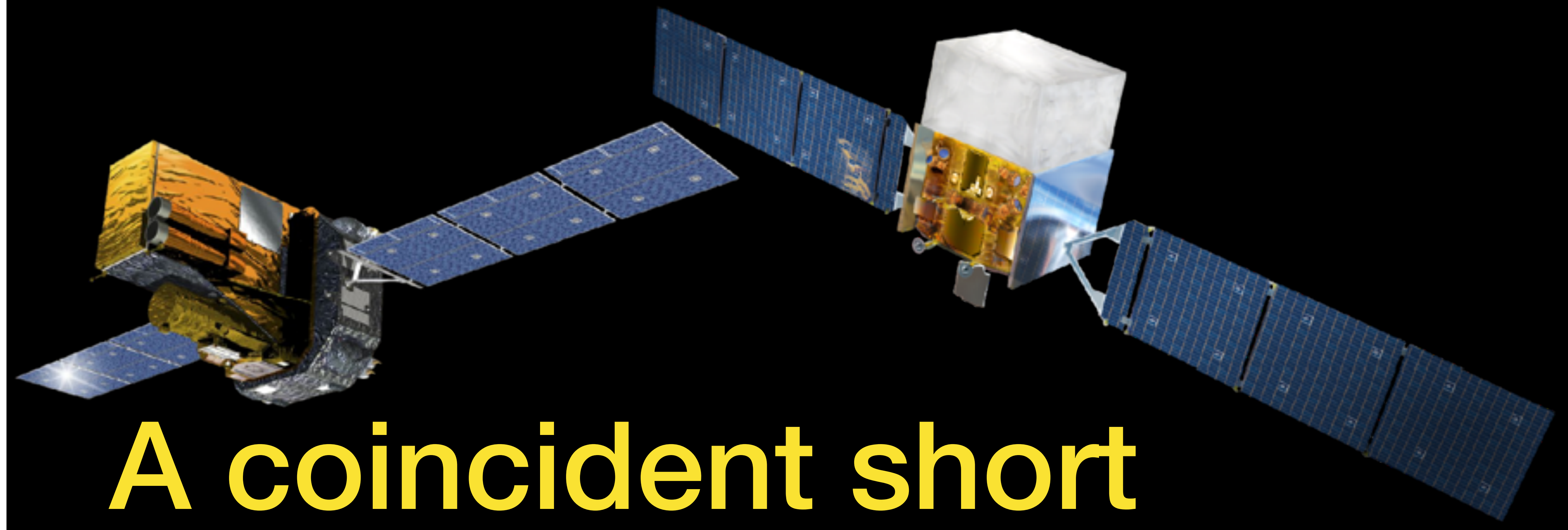
Credit: LIGO/Virgo/NASA/Leo Singer



Credit: LIGO/Virgo/NASA/Leo Singer

LVC, *Fermi* GBM, & INTEGRAL 2017 (ApJL)





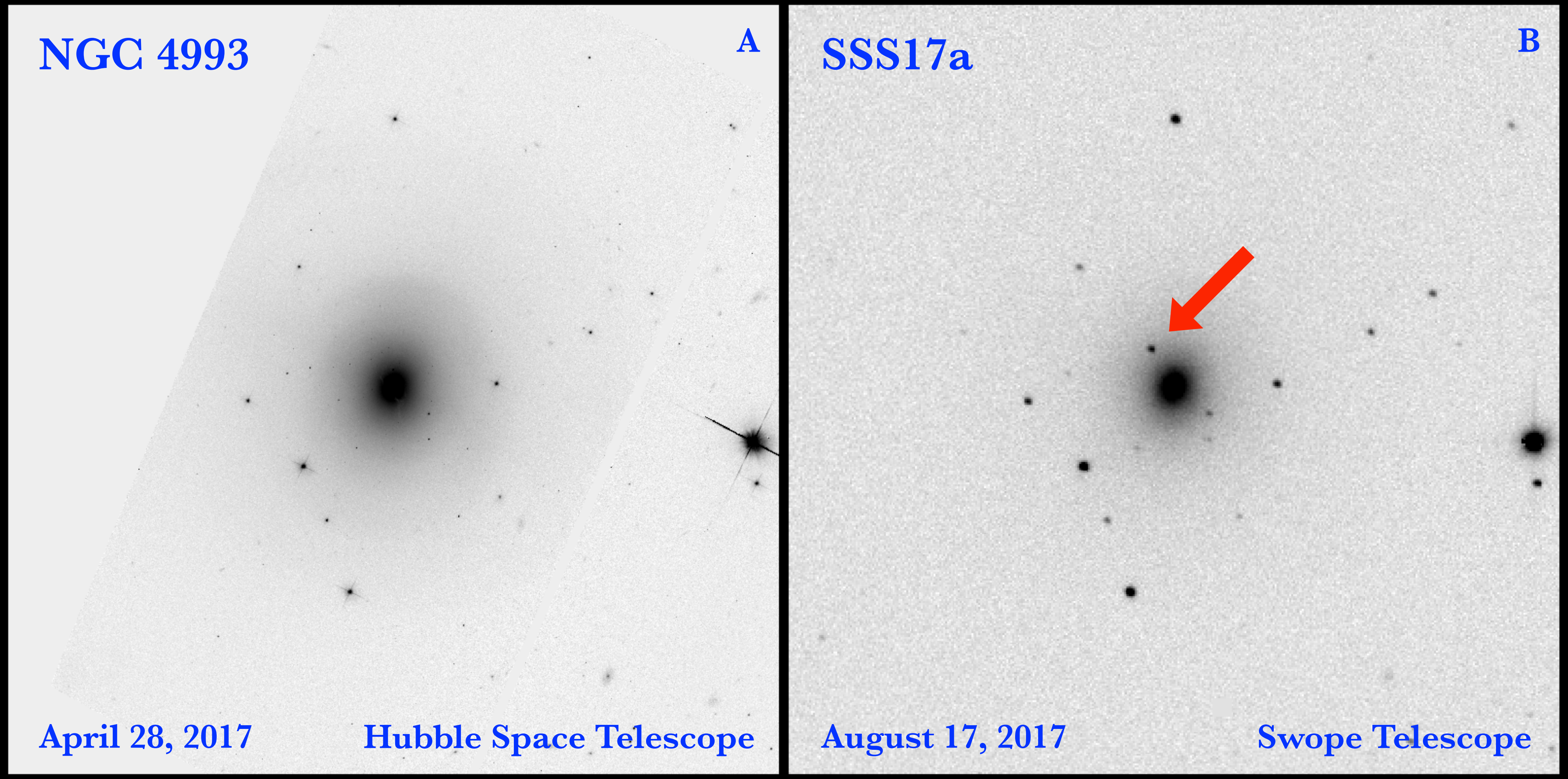
A coincident short gamma-ray burst!!!

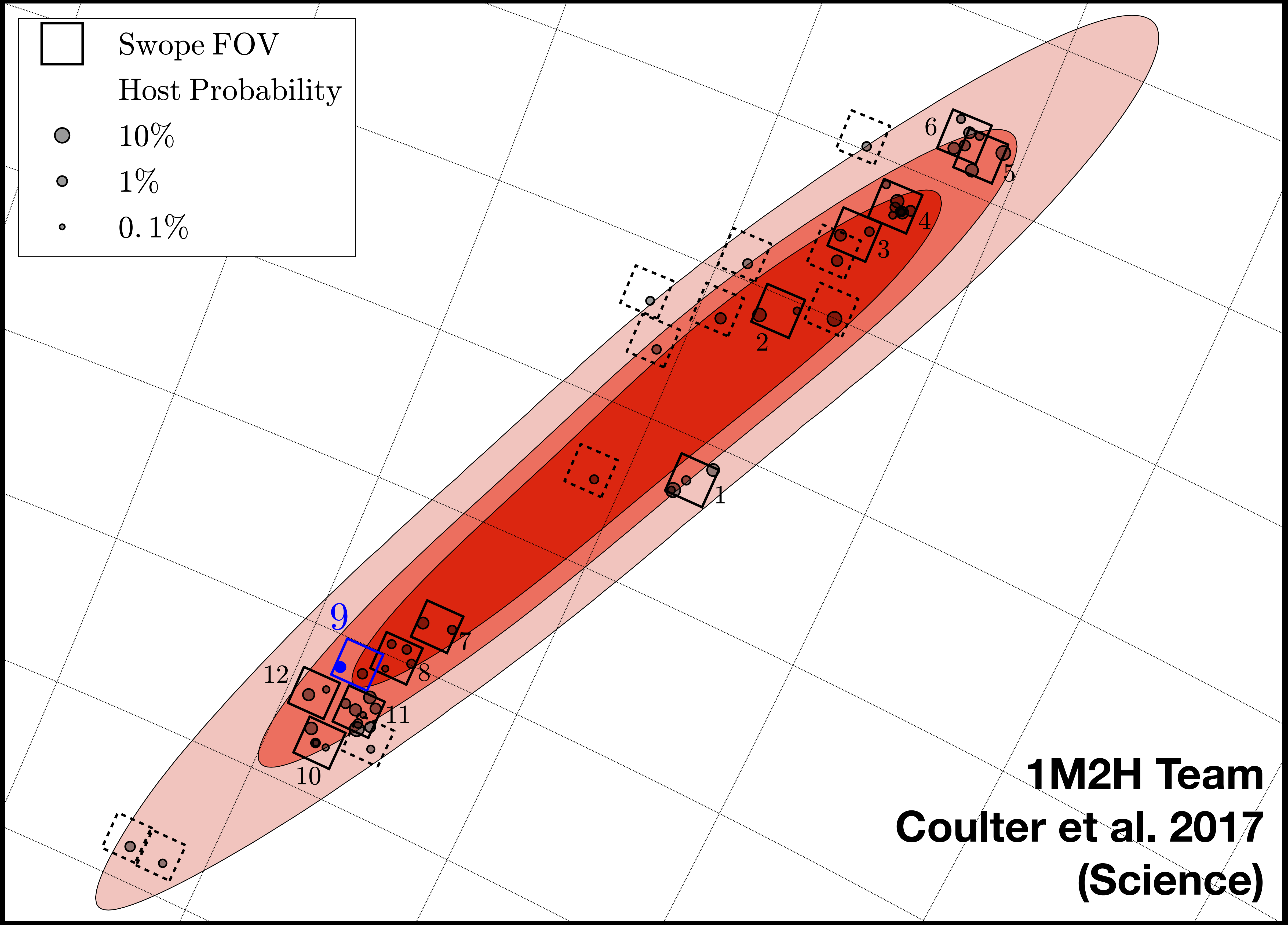
- Short-duration gamma-ray transient detected by *Fermi* GBM and *INTEGRAL* SPI-ACS
- Spatially consistent with GW localization, but arrived 1.74 s *after* GW merger signal
- Two components: short (~0.6 s), hard (Ep~185 KeV) pulse that resembles standard short GRB and delayed, longer (~1.2 s), softer (Ep~10 keV) tail


← TYPICAL
OBSERVER
REACTION

2. Discovery, Observing Strategies

Discovery of a rapidly fading optical counterpart

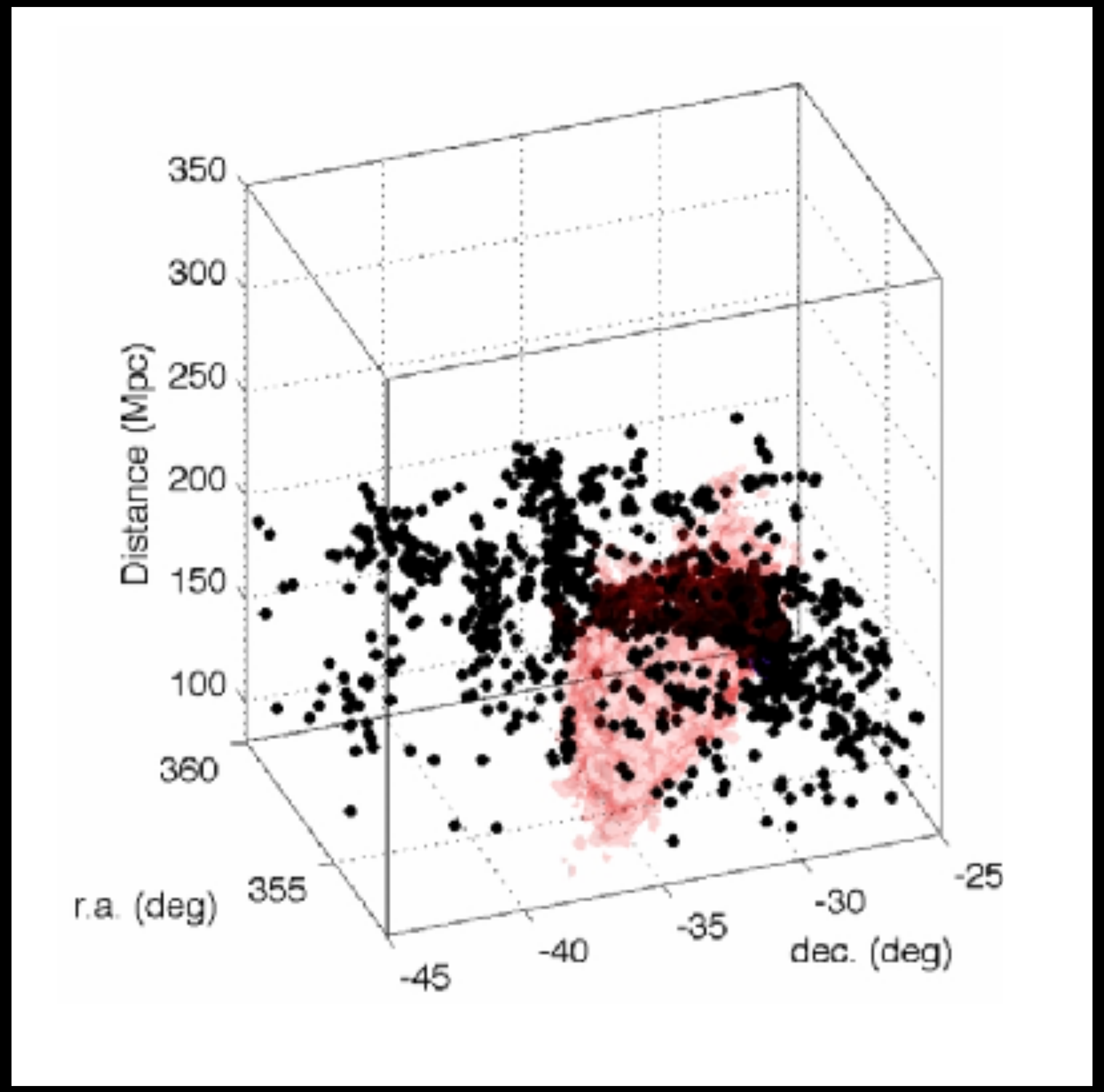




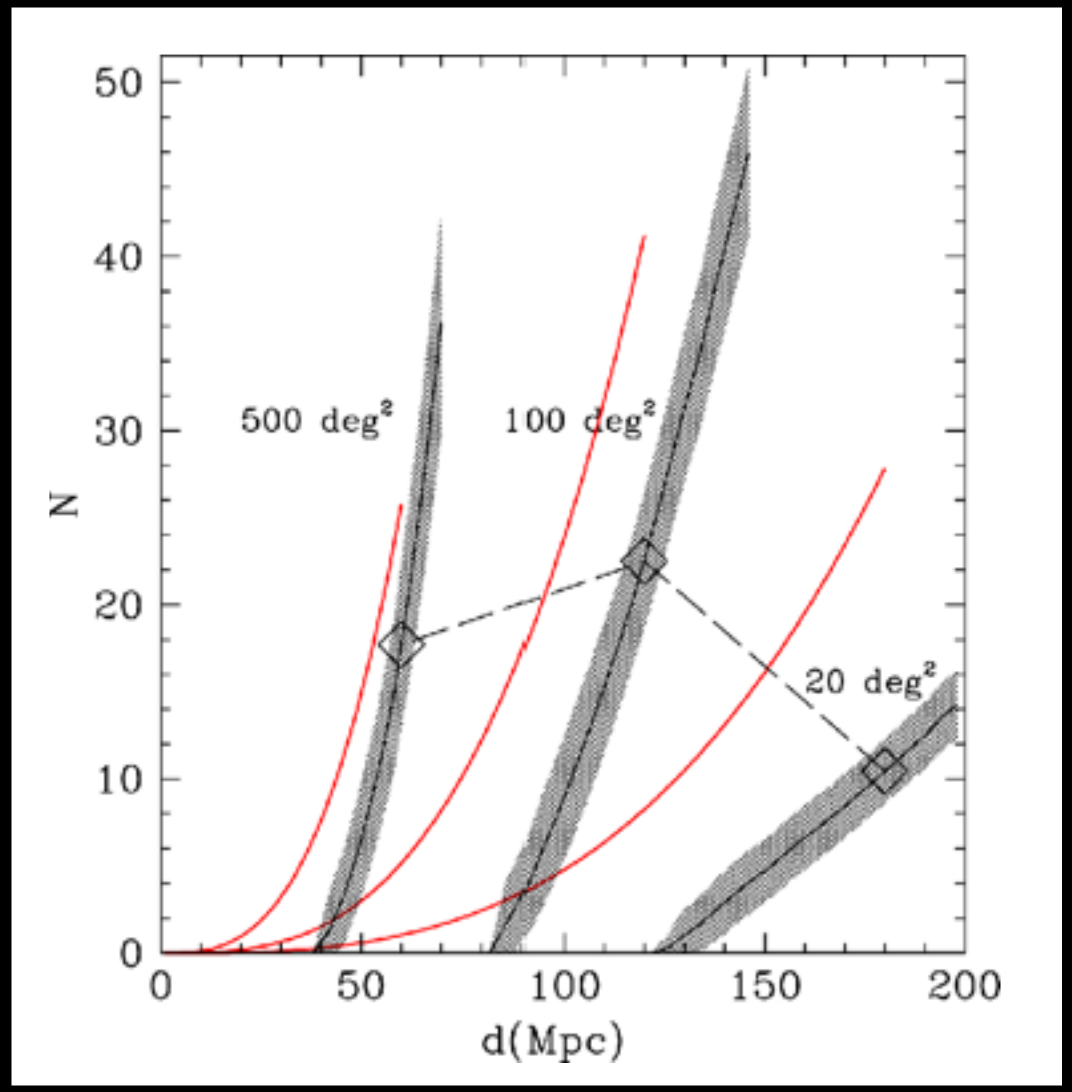
- **Rapidly fading optical transient** detected by One Meter, Two Hemisphere (**1M2H**) team using **Swope** 1m telescope at **Las Campanas**
- Announced as **SSS17a**, also designated **AT2017gfo**
- Position in projected coincidence with the galaxy **NGC 4993** at a distance of **40 Mpc**
- **Confirmed by *many* teams** doing **independent optical counterpart searches** and **targeted follow-up** of source

- Also found using synoptic optical/near infrared telescopes (DECam, VISTA, MASTER)
- But defied common wisdom that it was found by galaxy targeted follow-up on small-FOV (and even small aperture) telescopes

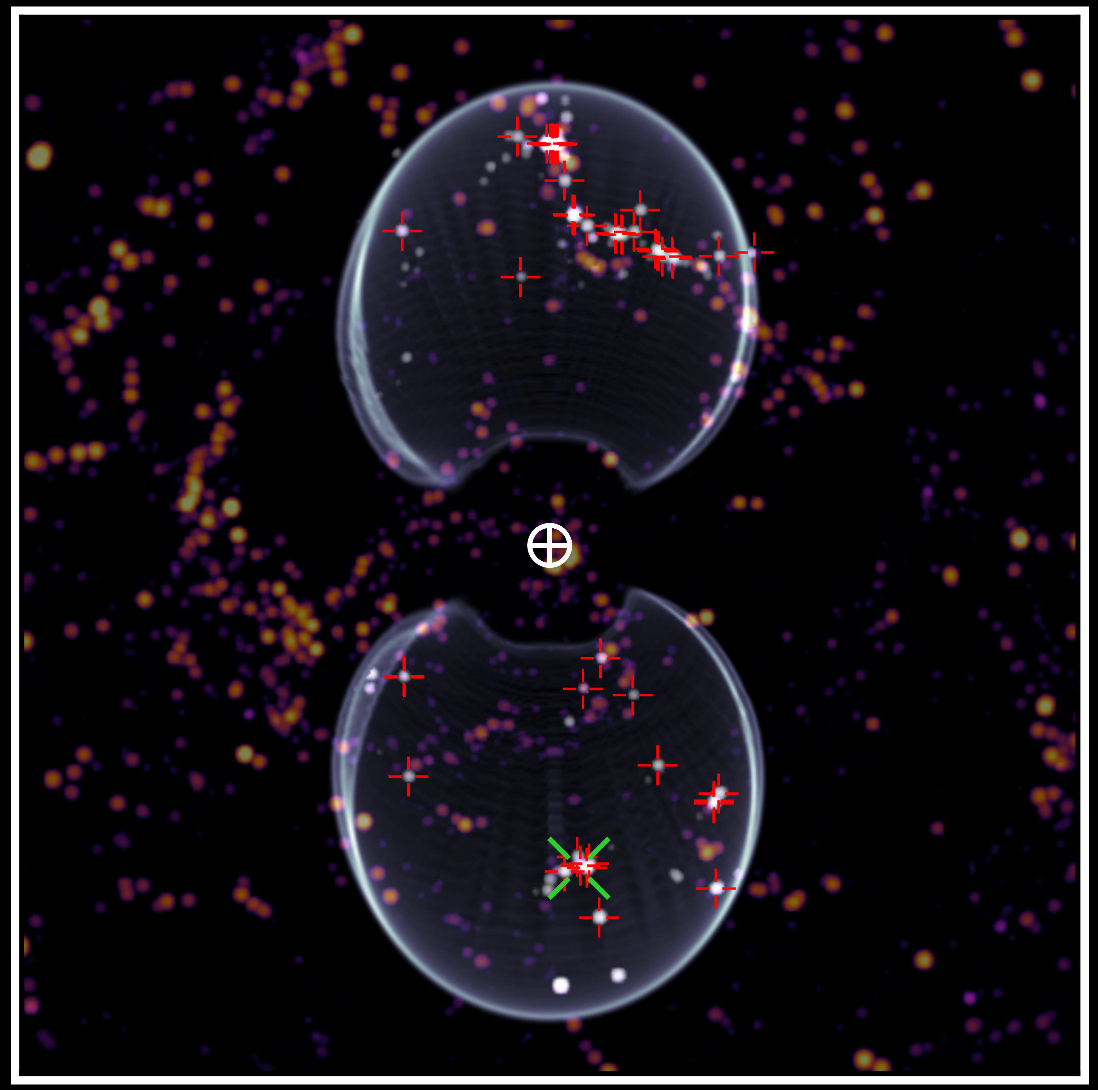
Galaxy strategies for LIGO-Virgo follow-up



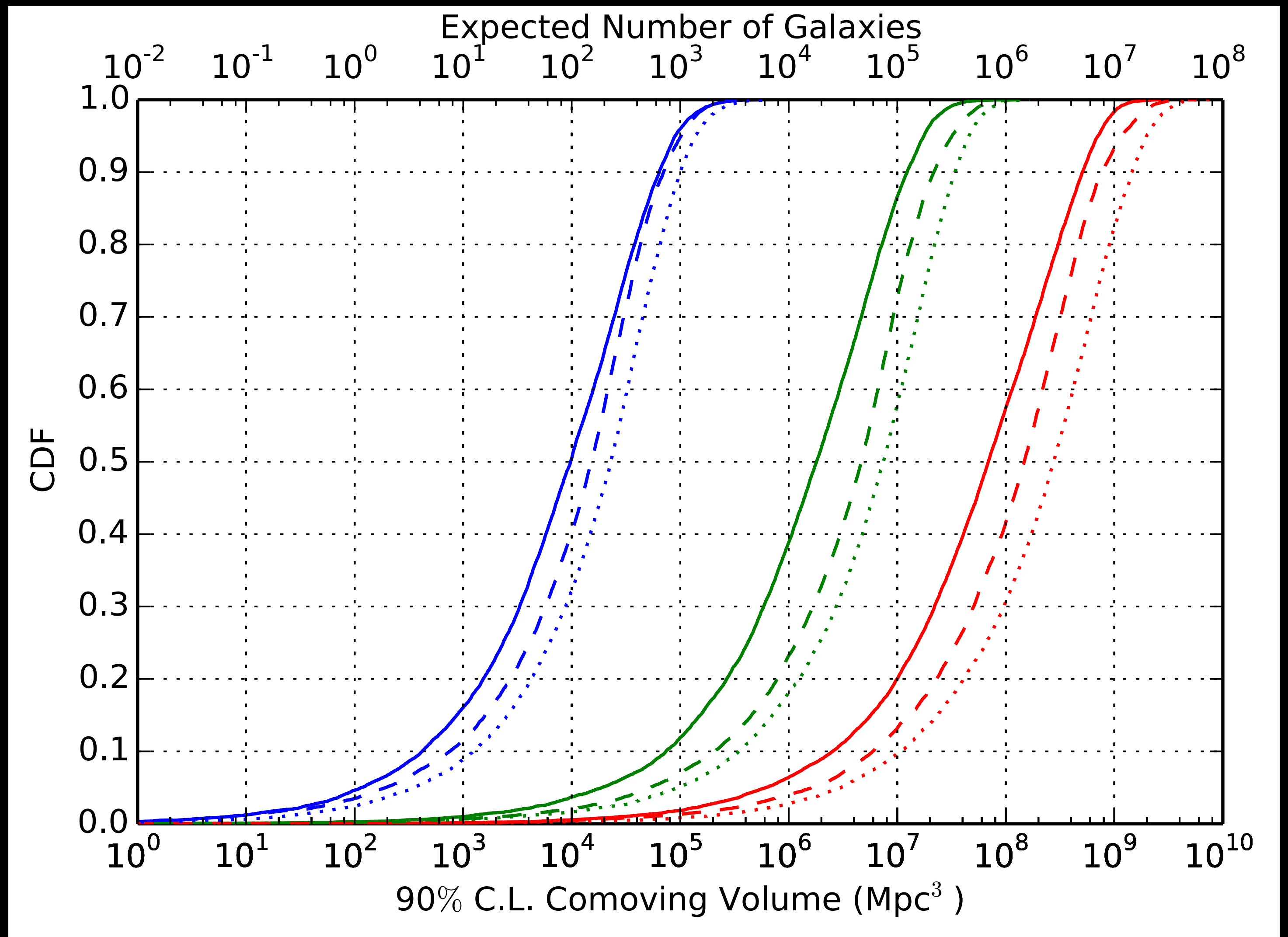
Nissanke, Kasliwal, & Georgieva 2013



Gehrels, Cannizzo, Kanner, Kasliwal, Nissanke, & Singer 2016

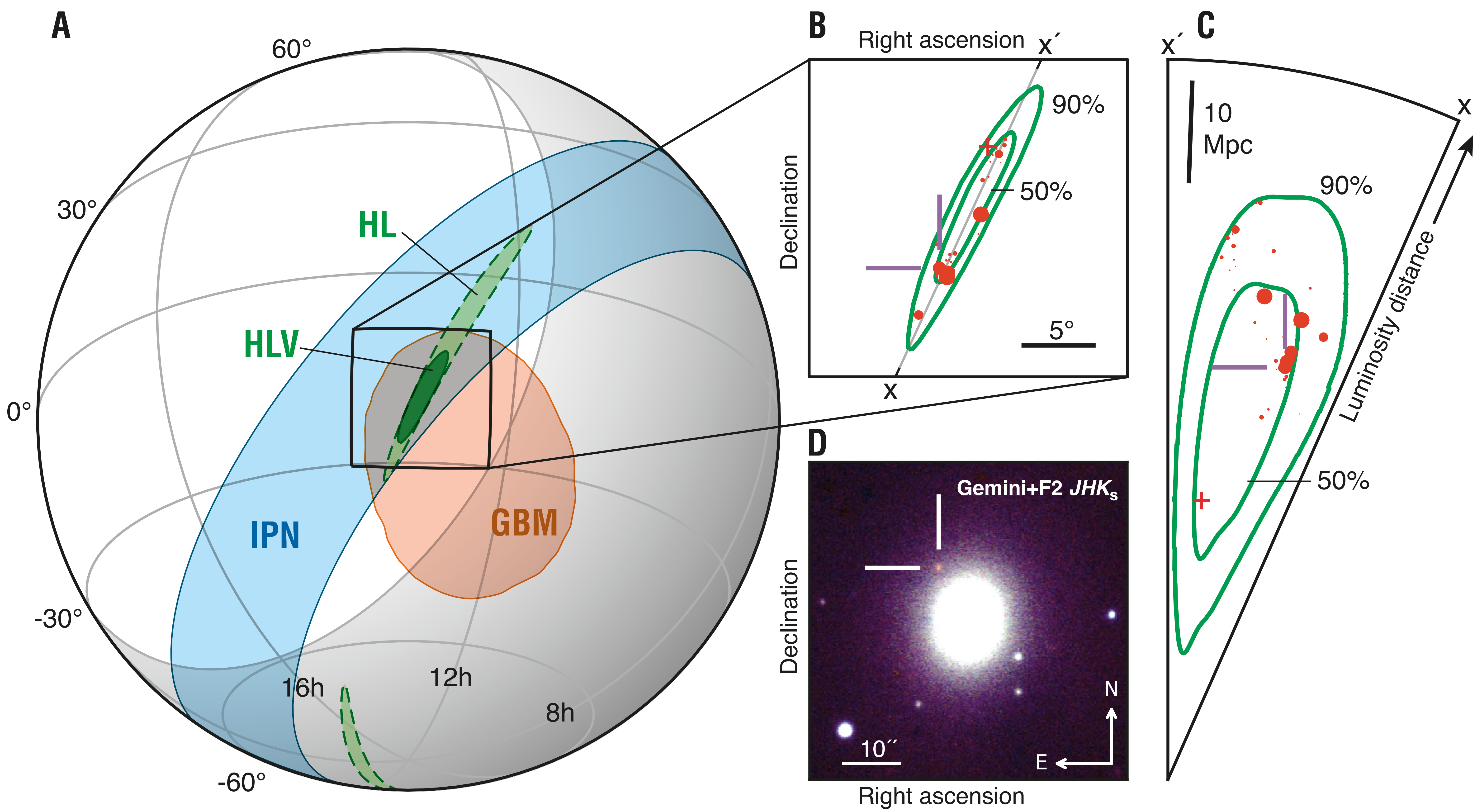


Singer, Chen, Holz, et al. 2016



Chen & Holz 2016

Pinpointing the optical counterpart



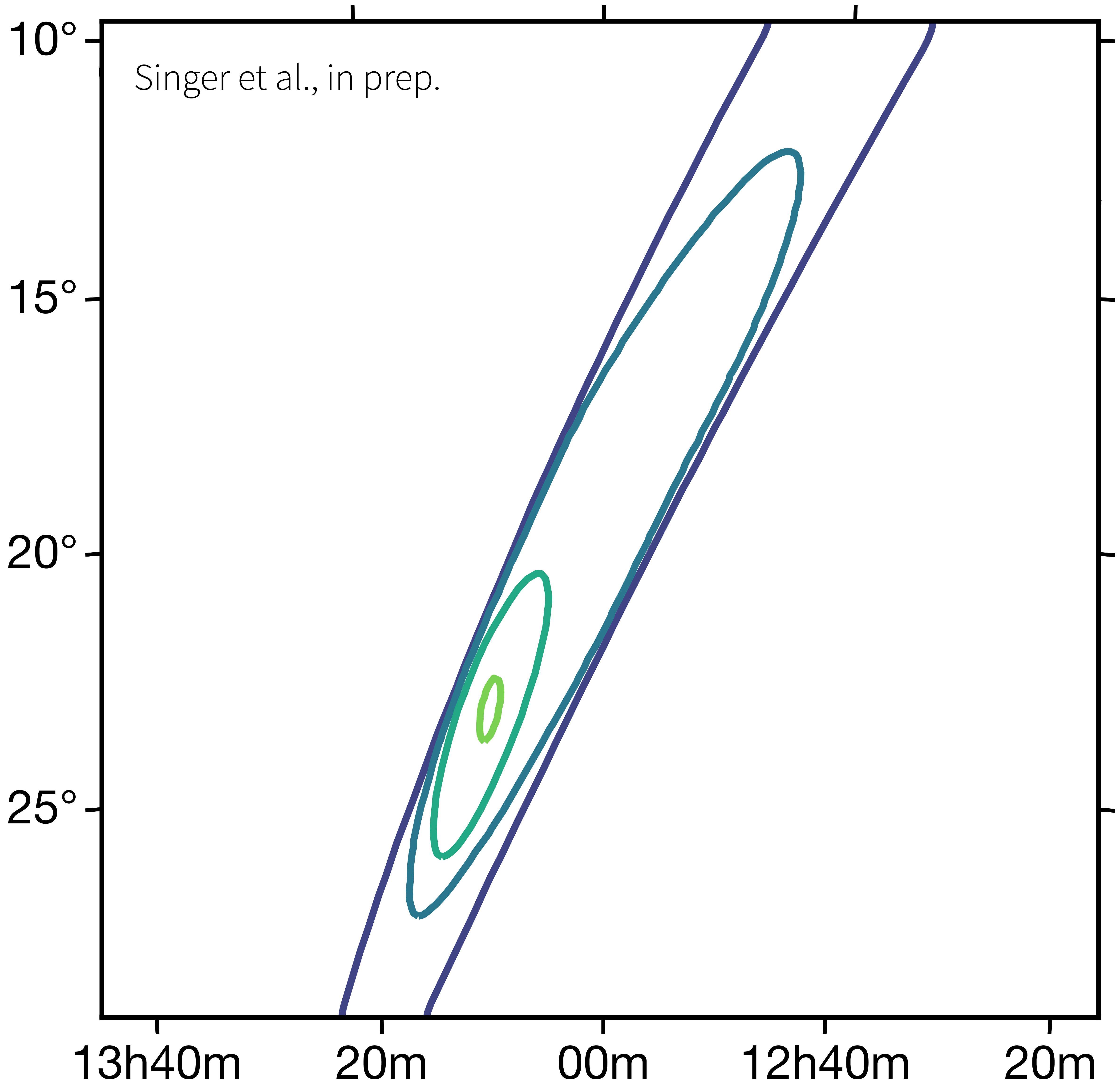
Kasliwal, Nakar, **Singer**+ 2017

- Order of magnitude improvement in localization due to Virgo: **190 → 30 deg²**
- **Of the ~50 galaxies** in the LIGO/Virgo 3D localization volume, **NGC 4993 is the third most massive**
- *A priori*, **the most likely host** assuming stellar mass as a tracer for BNS merger rate

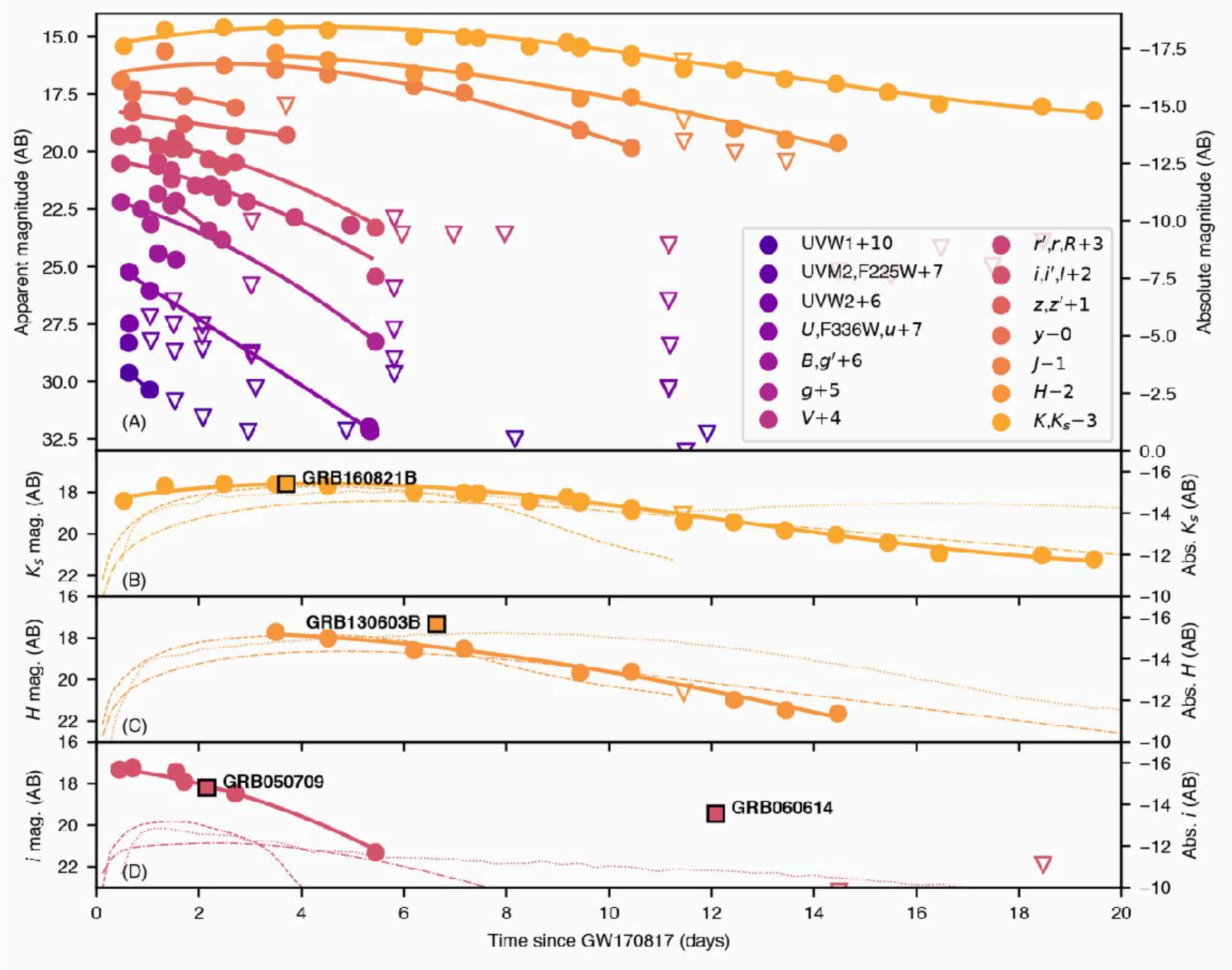
Localization of a GW170817 with **future detectors**

HL as built,
HLV as built,
HLV at O3 sensitivity,
HLVIK at design sensitivity

Caveat: this was an *exceptionally* well localized event because it was so nearby!



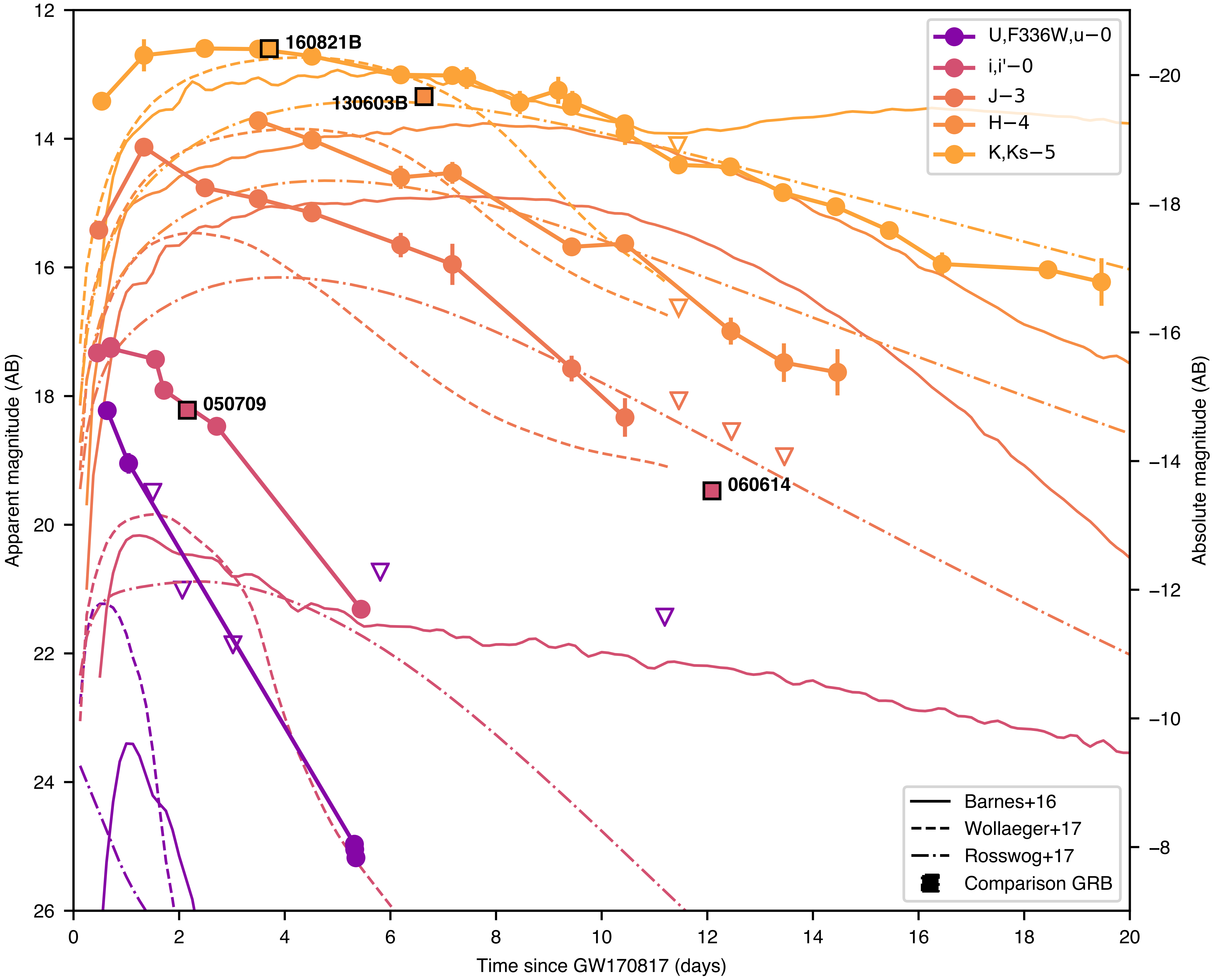
3. Optical and Near Infrared Observations



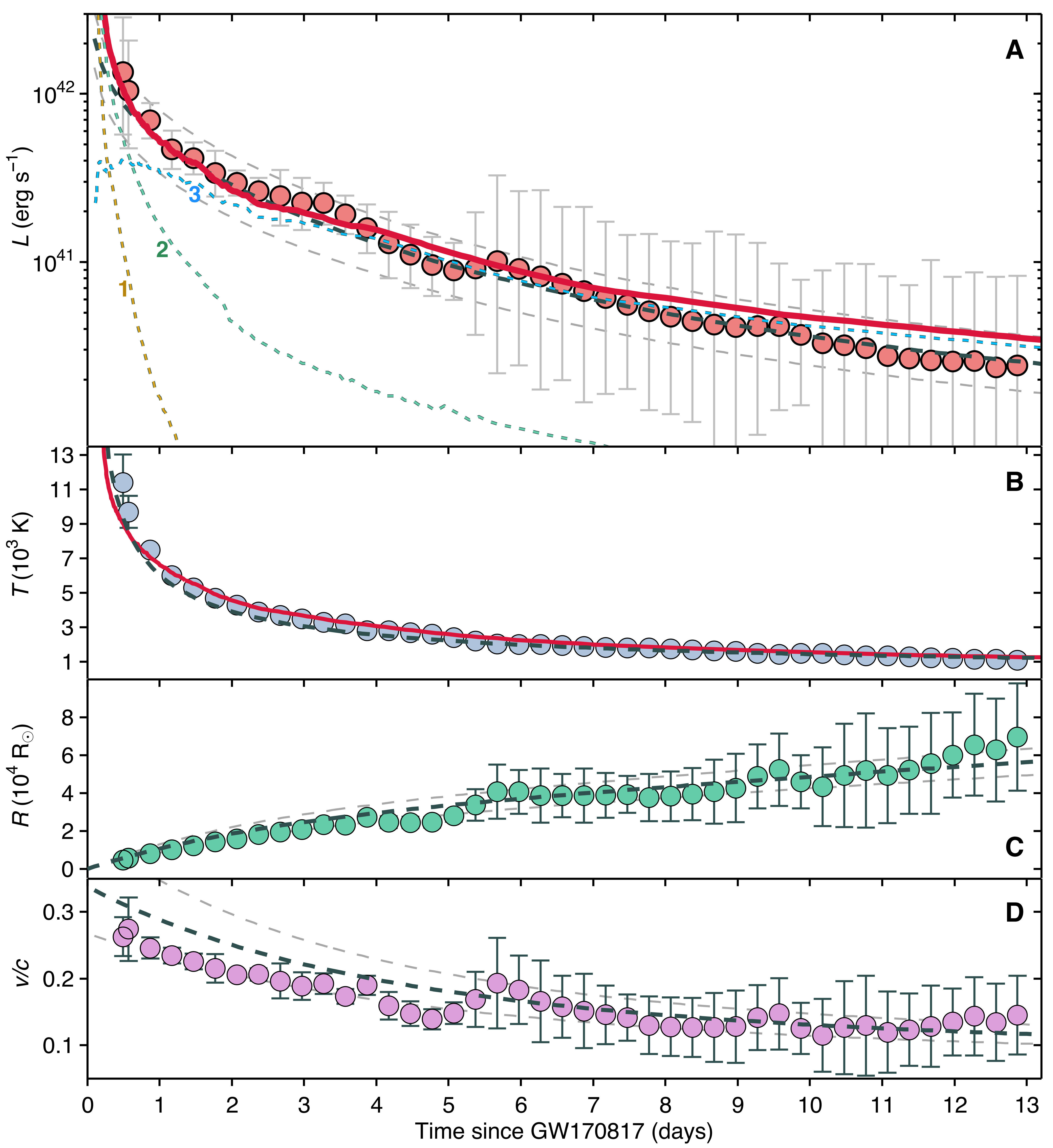
Kasliwal, Nakar, **Singer**+ 2017

Near-infrared imaging

- **8.1m Gemini-South + FLAMINGOS2 *JHK* imaging (PI: Singer)**
- 5m Palomar Hale + WIRC *K* imaging
- 1.4m IRSF *JHK* imaging (PI: Barway)
- 1.3m @ CTIO + ANDICAM (PI Cobb)
- 3.5m @ APO *K* imaging (PI Chanover)



Kasliwal, Nakar, **Singer**+ 2017

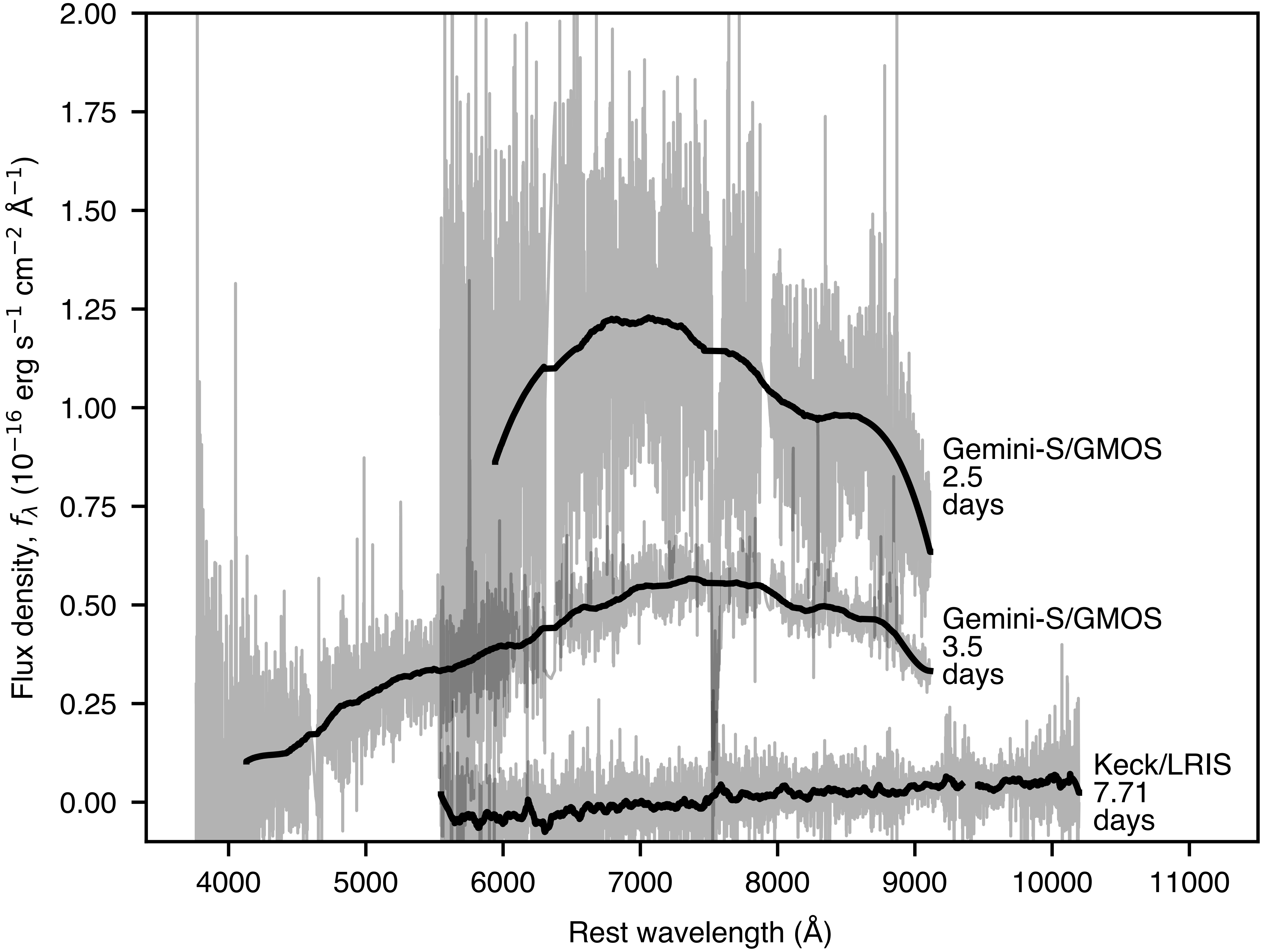


Kasliwal, Nakar, **Singer**+ 2017

Blackbody fits

- Bolometric luminosity, effective temperature, photospheric radius, and expansion velocity
- Red line: hydrodynamic simulation of cocoon + kilonova
- 1: Cocoon cooling component
- 2: Fast-moving (>0.4*c*) radioactive ejecta component
- 3: Slow-moving (<0.4*c*) radioactive ejecta component

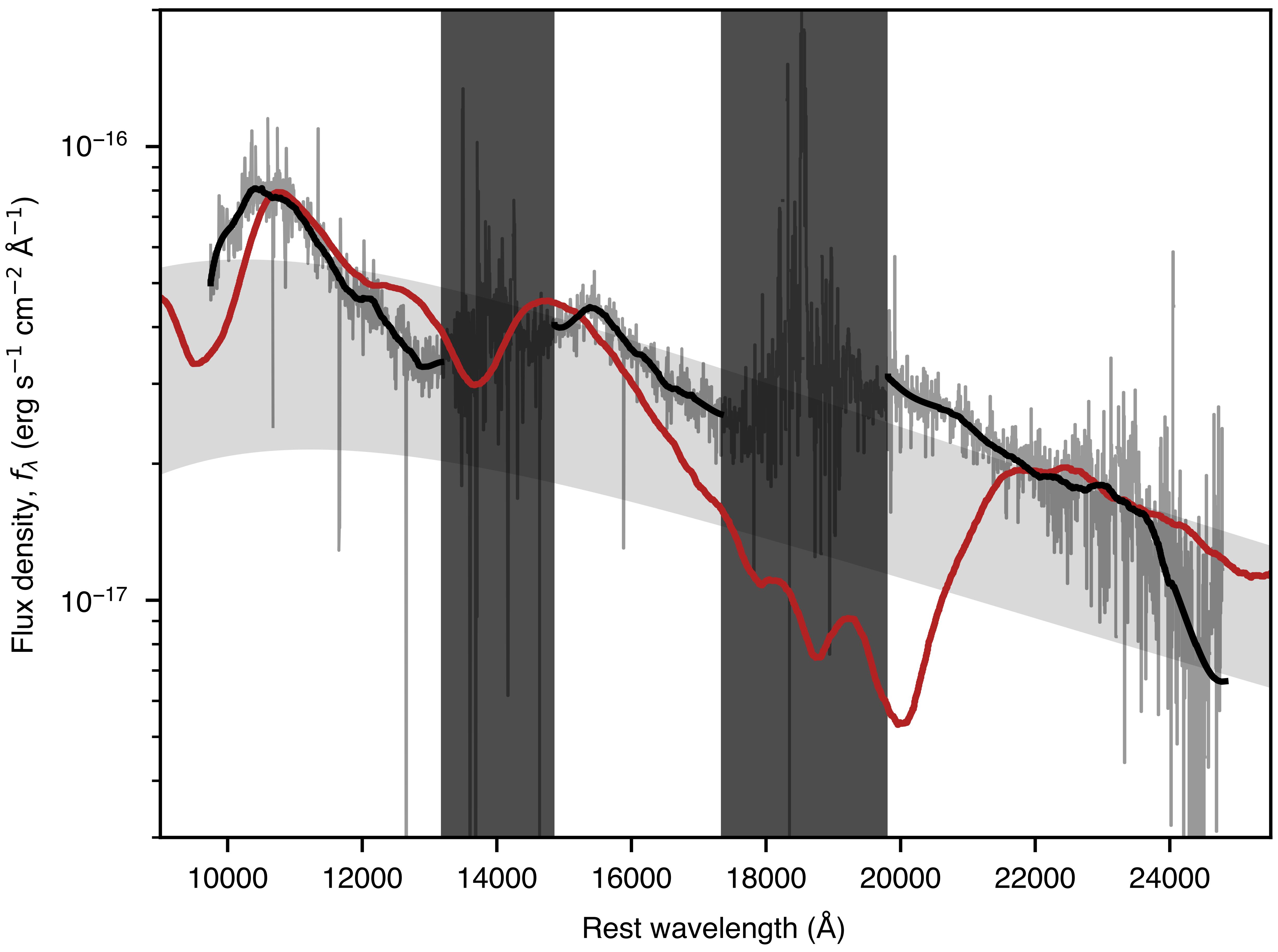
Optical spectroscopy



Kasliwal, Nakar, **Singer**+ 2017

- Gemini-South + GMOS
- Keck + LRIS
- Featureless blackbody continuum

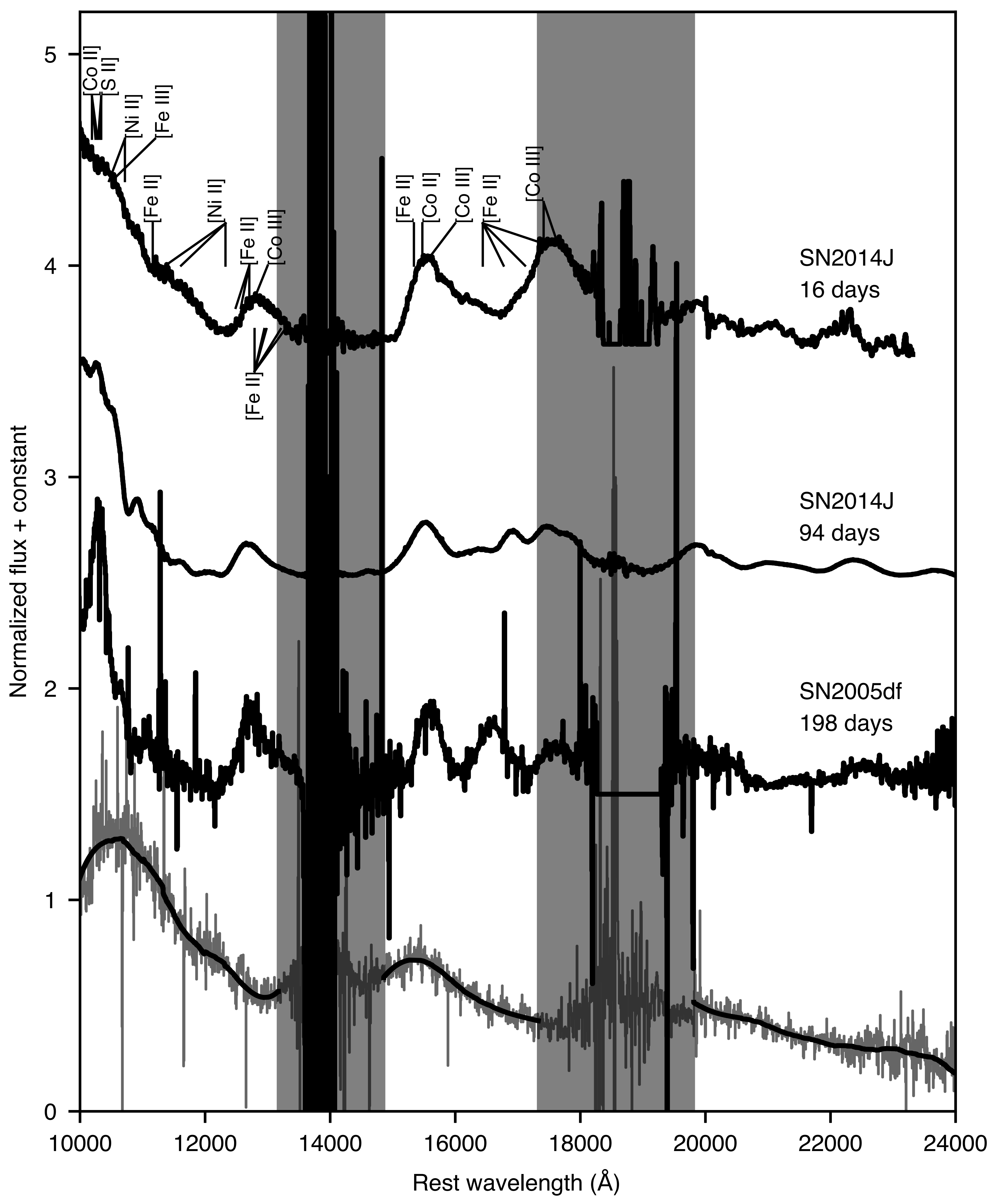
Near-infrared spectroscopy



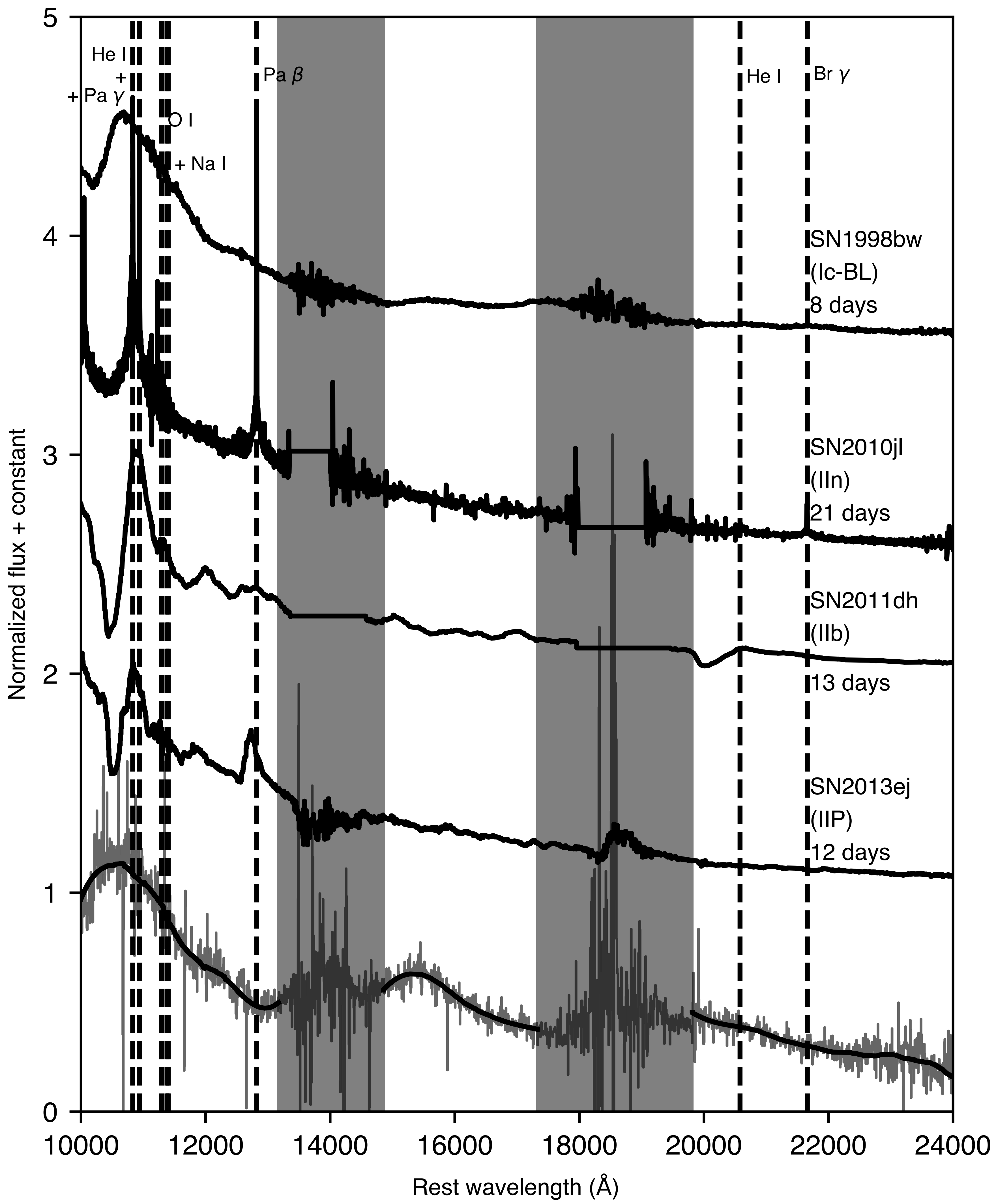
- Gemini-South + FLAMINGOS-2 JH + HK spectrum @ 4.5 days after merger (black)
- Barnes & Kasen (2013) model kilonova spectrum at 4.5 days post merger

Kasliwal, Nakar, **Singer**+ 2017

Looks *nothing* like known explosive transients



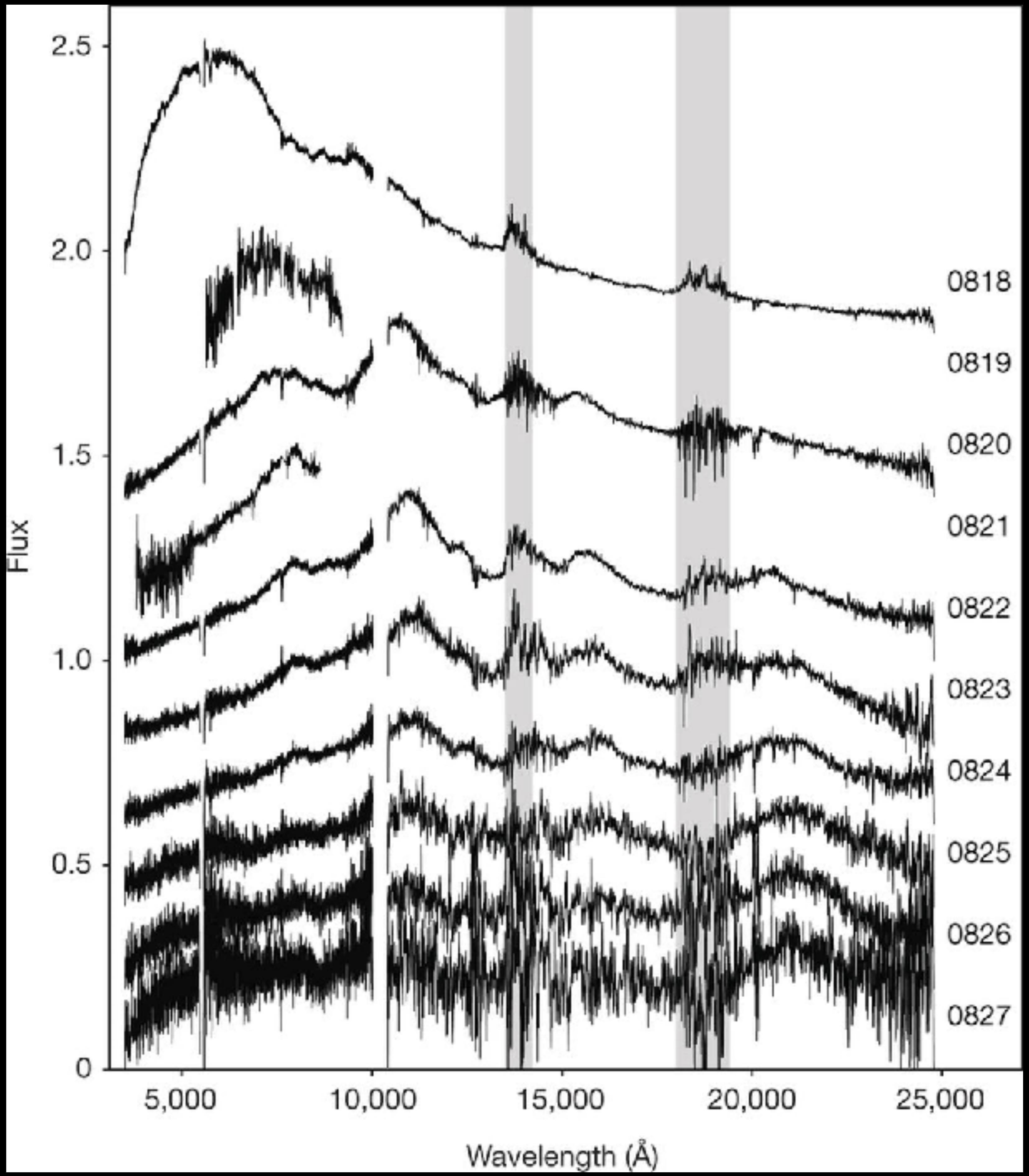
Comparison with SN Ia



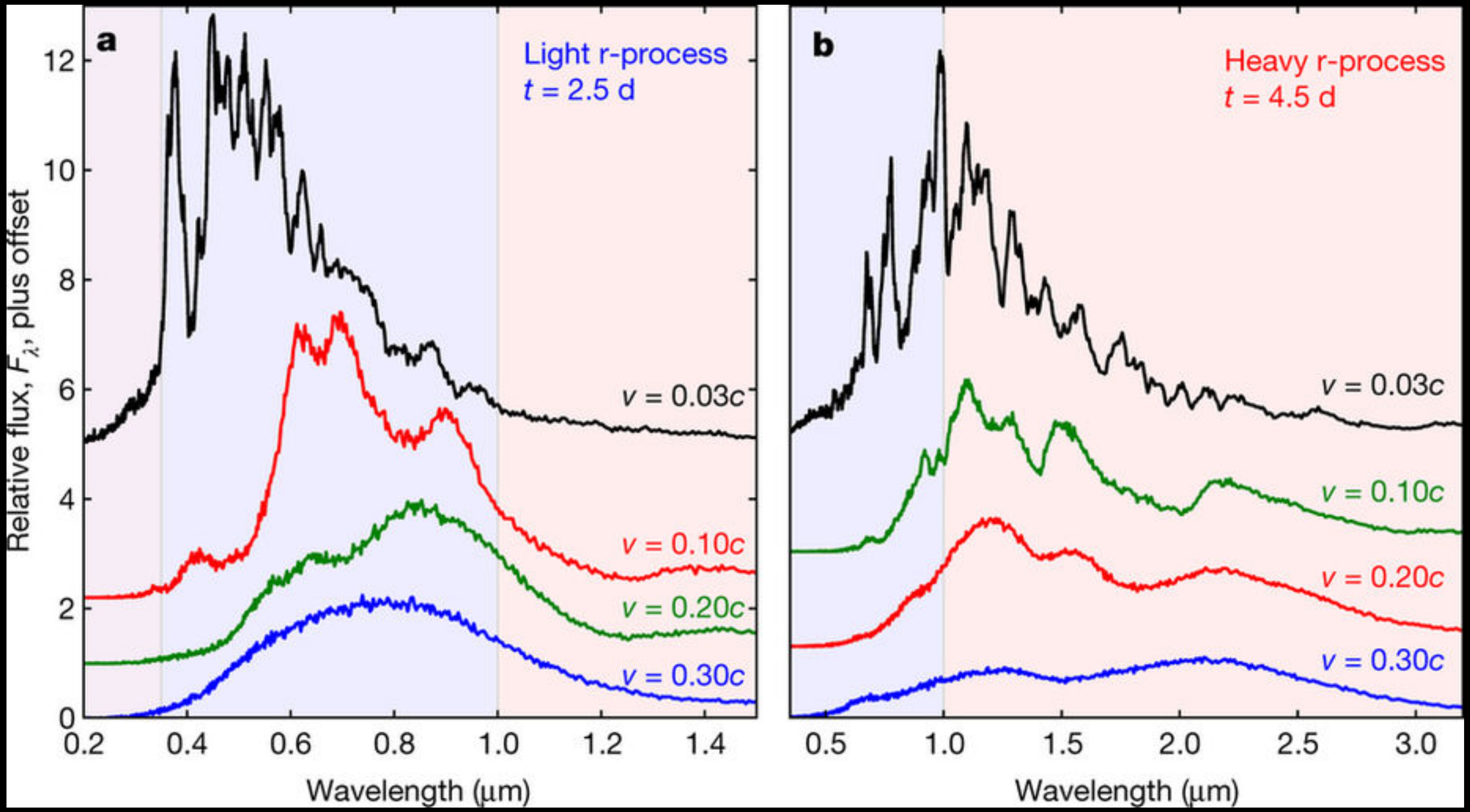
Comparison with CC SN

Kasliwal, Nakar, **Singer**+ 2017

Remarkable agreement between optical/near-IR data and *r*-process kilonova/macronova modeling



Pian+ 2017 (Nature)

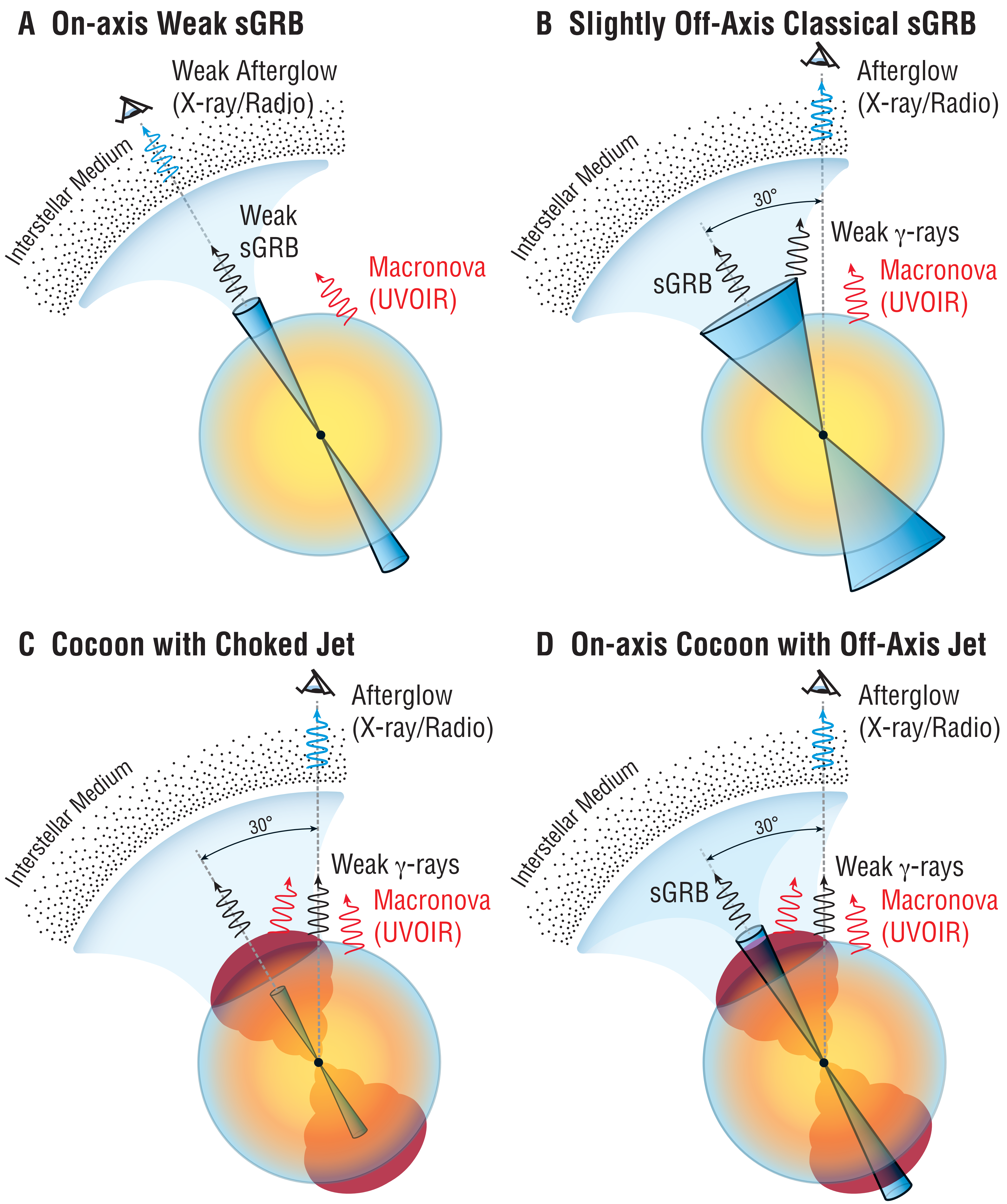


Kasen+ 2017 (Nature)

4. Interpretation, Radio

The puzzle

- Short GRB, but DELAYED and SUB-LUMINOUS
- No evidence for on-axis X-ray/optical/radio afterglow (although no deep observations before ~0.5 days)
- Bright, rapidly fading UV/optical emission → FAST and HOT as inferred from blackbody fits
- DELAYED X-ray and radio emission



Kasliwal, Gottlieb, **Singer**, et al. 2017

A concordant picture

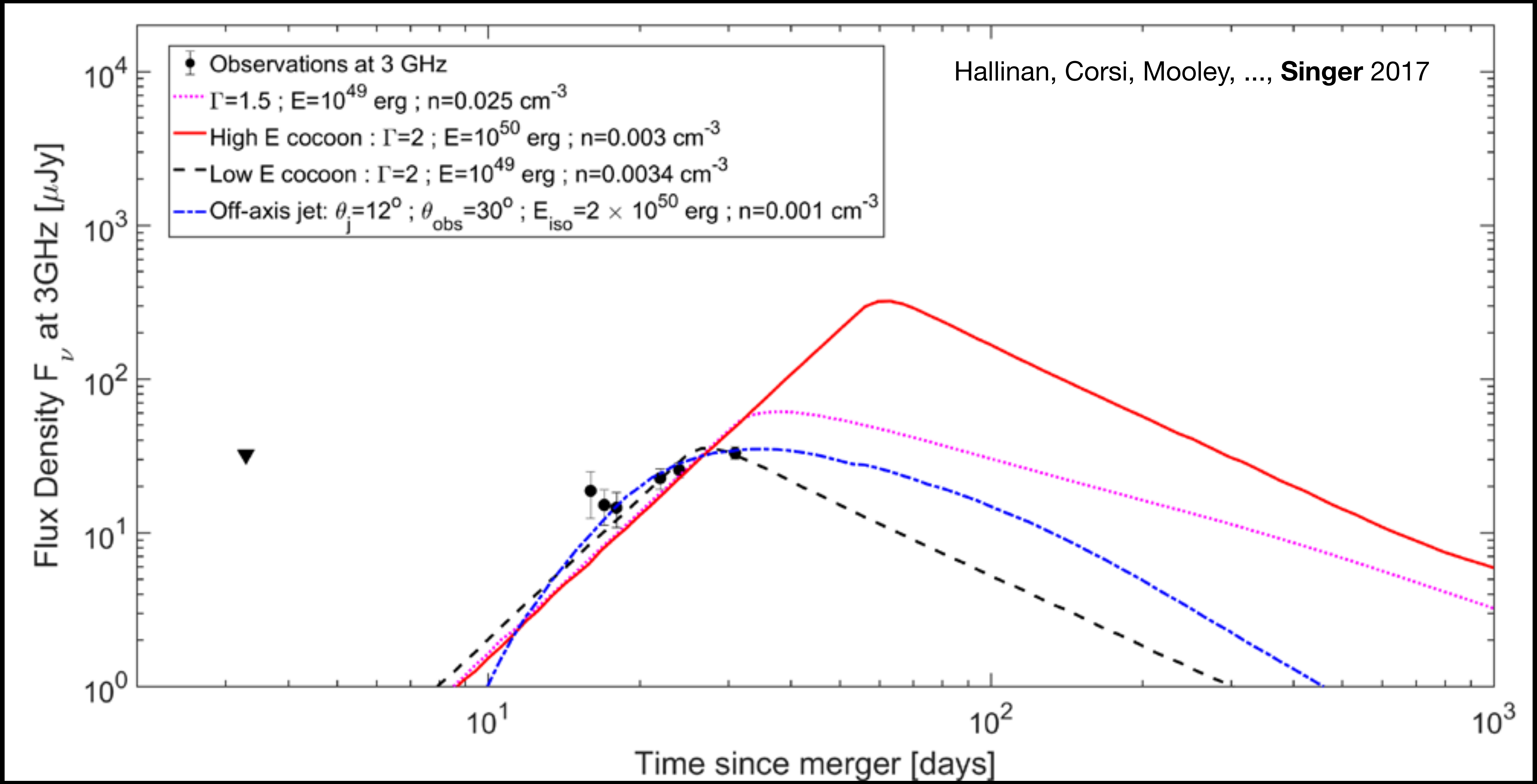
A. Early data sparse, but probably ruled out by lack of early panchromatic afterglow (requires implausibly low circumburst medium density)

B. Requires some fine-tuning of observer geometry (just barely outside of cone of jet) or structured jet

C. Highly energetic cocoon, ultra-relativistic jet is choked and does not break out

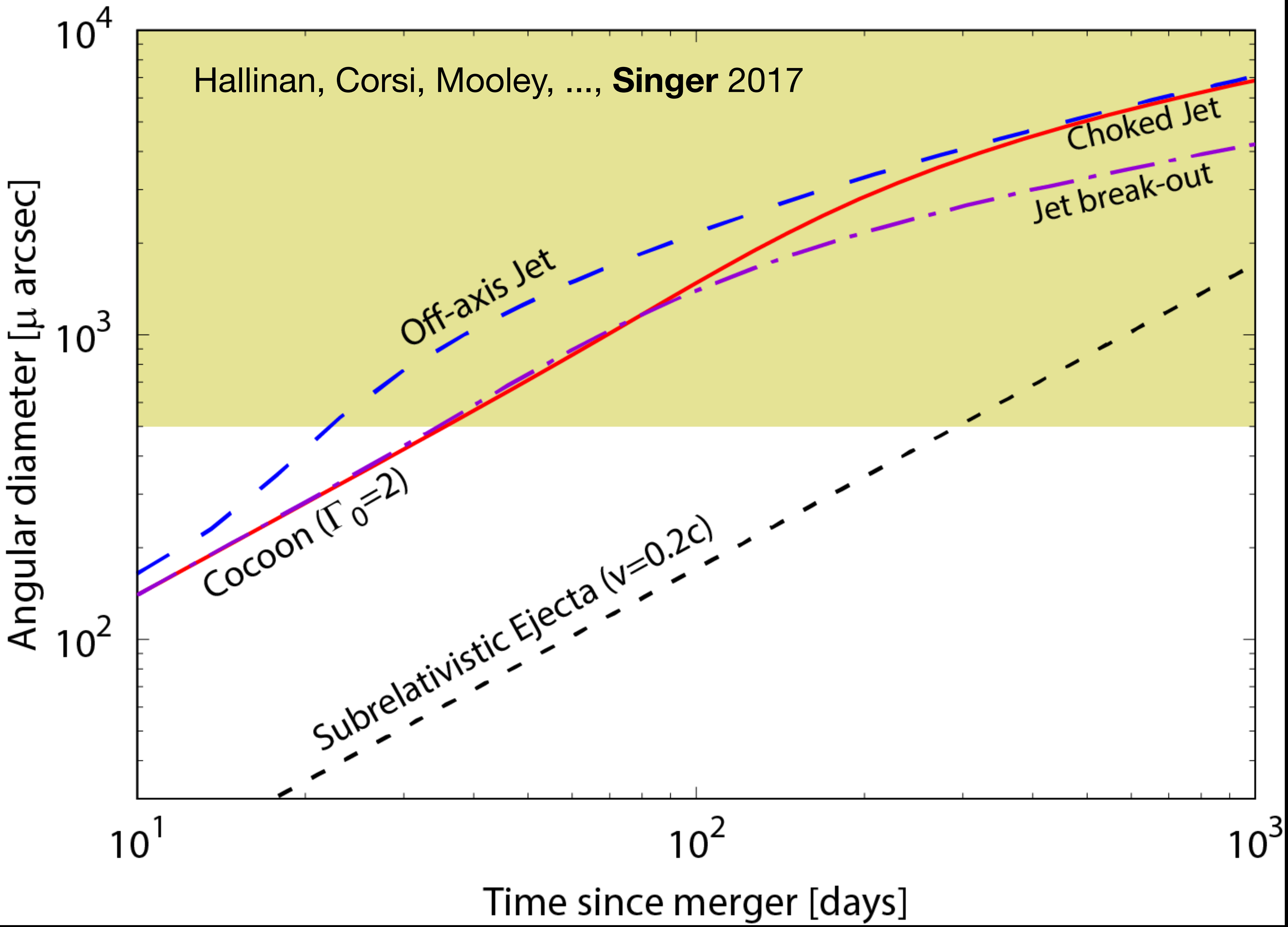
D. Low energy cocoon, ultra-relativistic jet successfully breaks out and is seen off axis

Radio at ~100 days post merger has the power to discriminate between the models



Off-axis jet (cases B or D) predict that the radio already peaked, whereas choked cocoon (case C) predicts peak at ~100 days

VLBI can break tie by resolving angular diameter of blast wave



Angular diameter of blast wave from cocoon/choked jet should be smaller at all times than off-axis relativistic jet because it takes longer and has to travel farther to sweep up sufficient circumburst material

5. A Few Open Questions

1. Why was the prompt emission so faint? Did we merely observe the merger off-axis, or was the burst intrinsically different from typical well-studied sGRBs (e.g. from *Swift* with X-ray afterglows)?

2. What was the cause of the GW-GRB time delay?

3. What was the initial Lorentz factor of the outflow, and what process launched it? Did it interact in any interesting way with the sub-relativistic outflows?

4. What can we learn from early-time observations of future GW-GRB NS binary mergers, particularly in X-ray/optical/ultraviolet?