# Gravitational Waves and Light from Merging Neutron Stars


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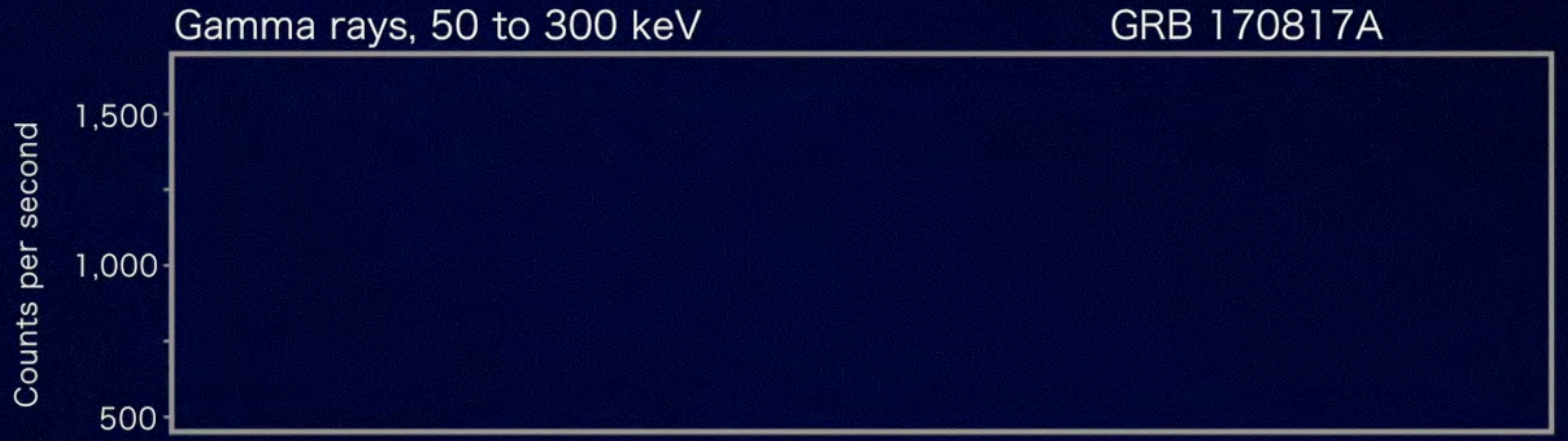
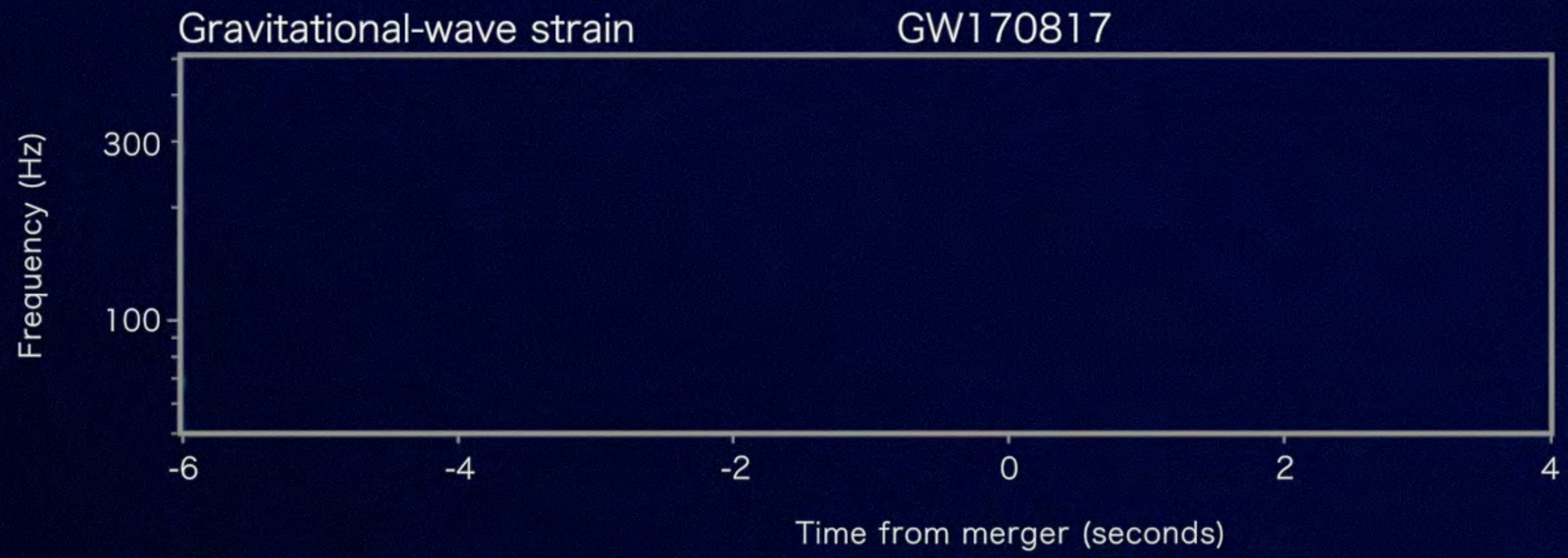
*APS Mid-Atlantic Senior Physics Group, Nov 14, 2018*

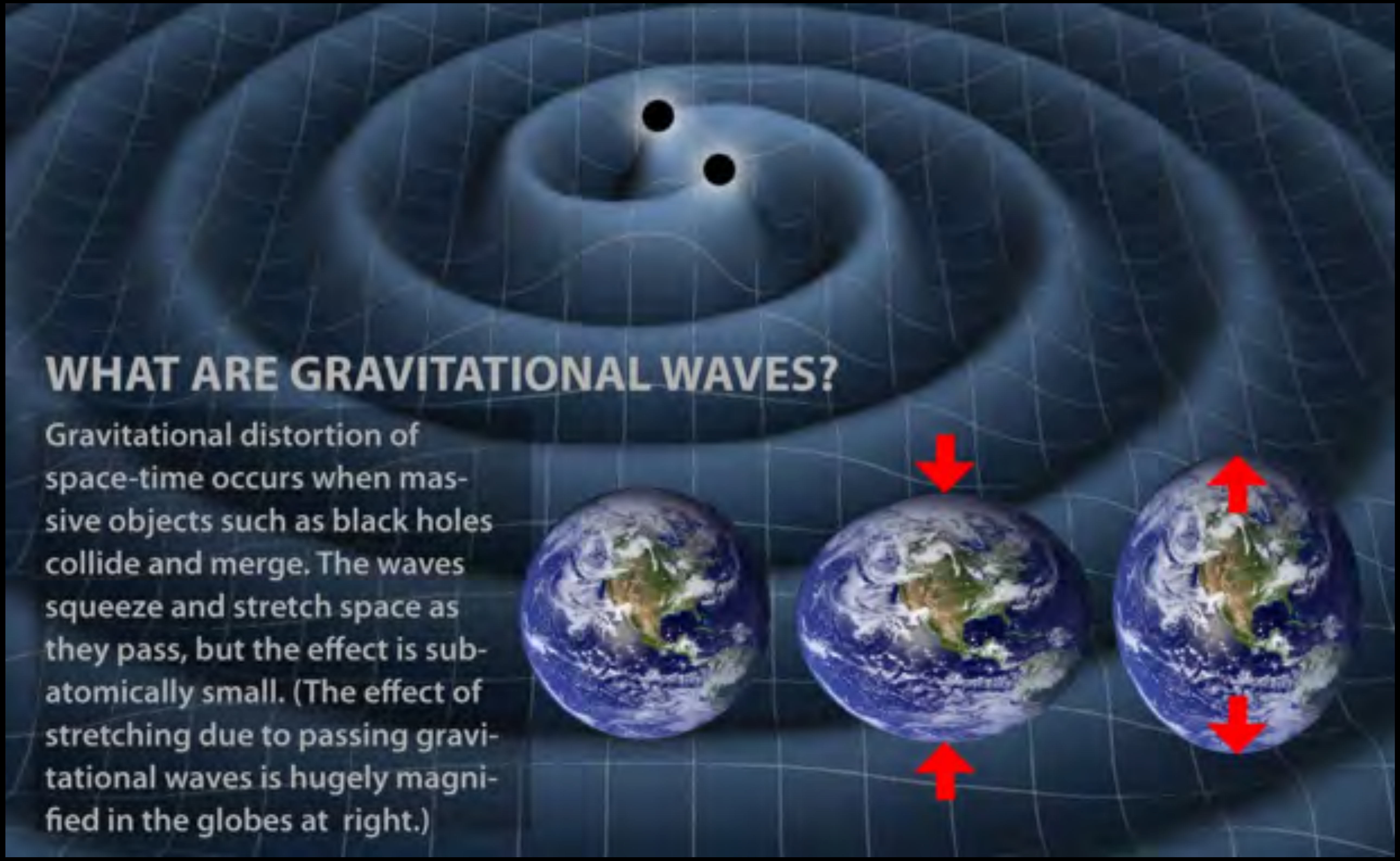
Fermi

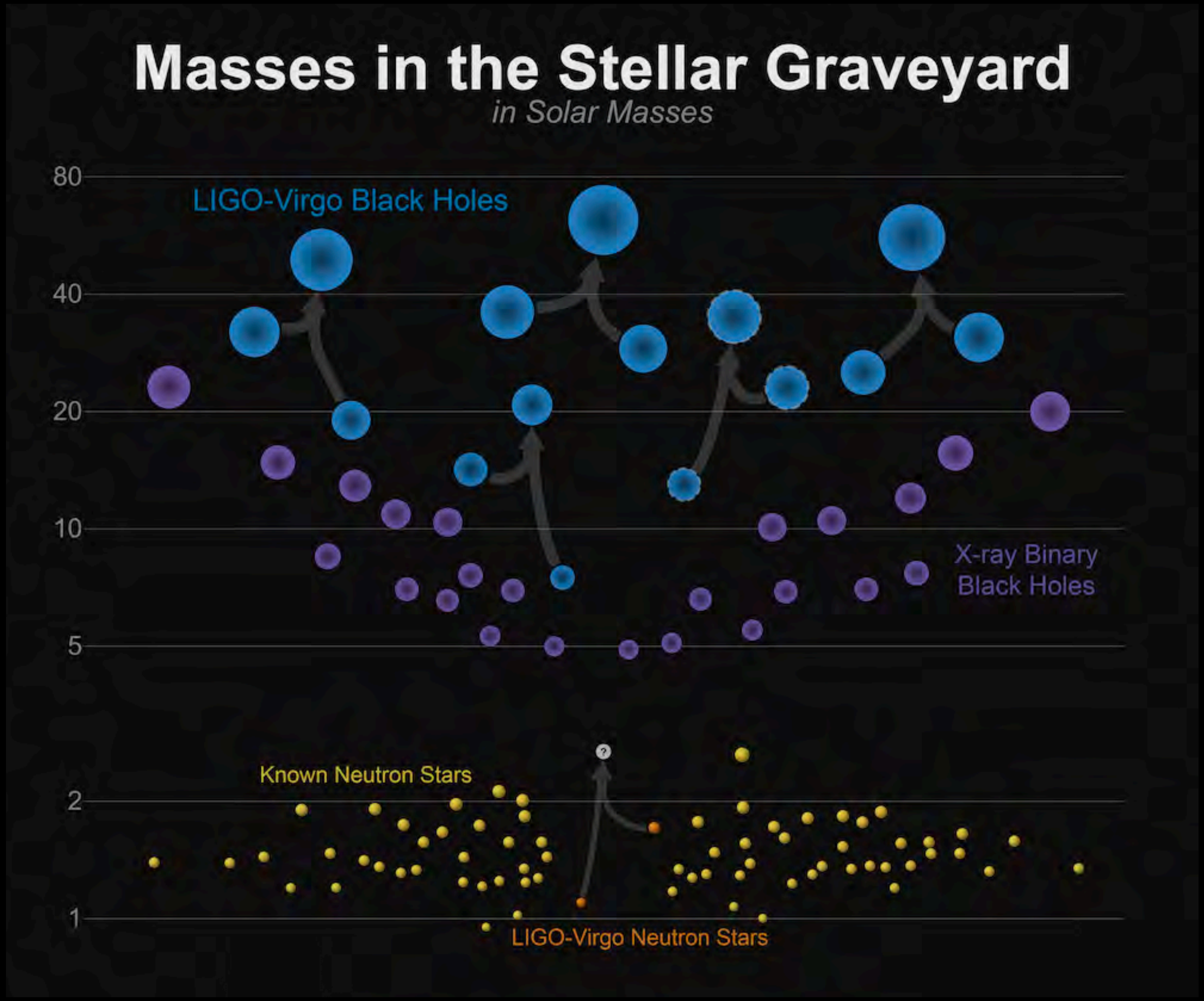

Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500

LIGO

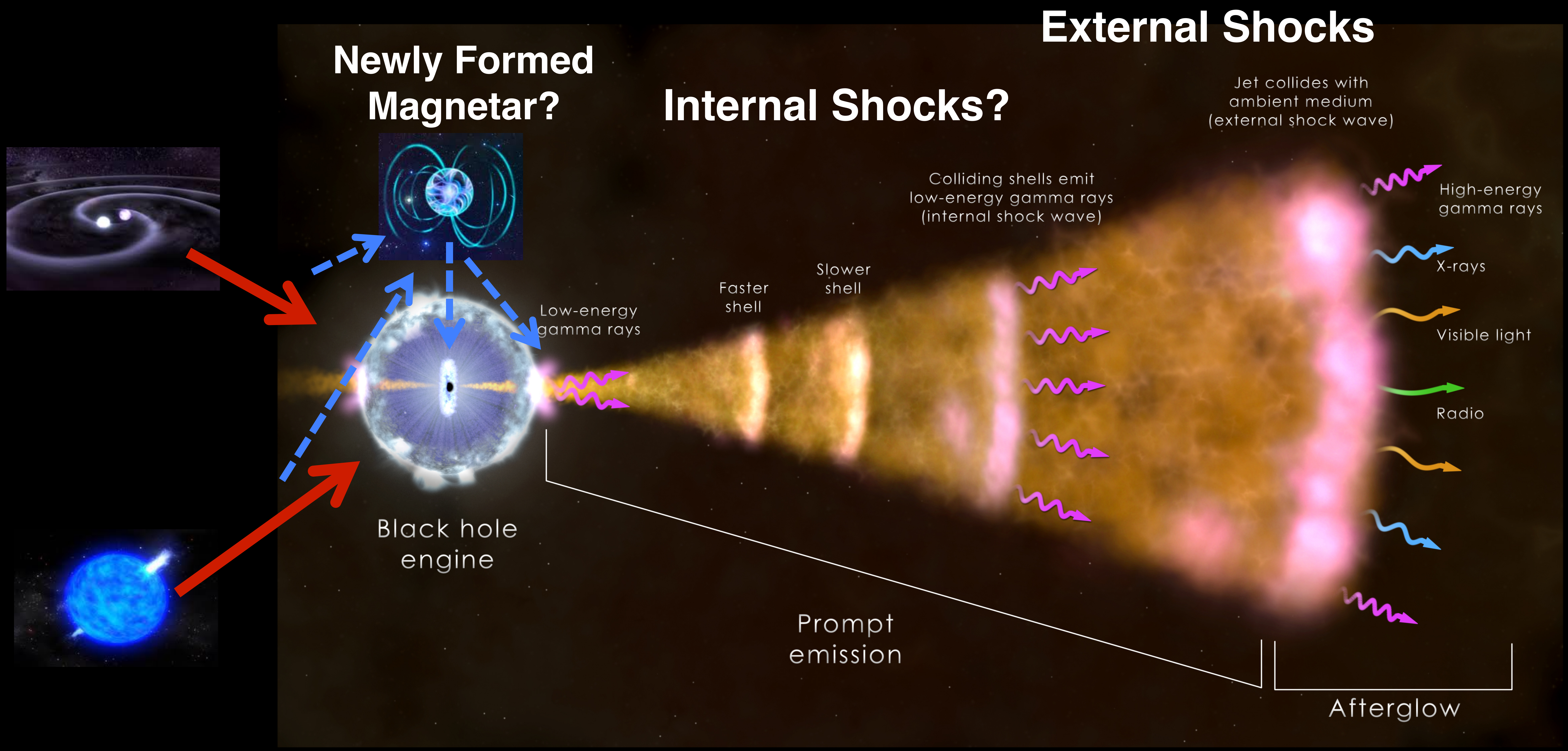

Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

# Gravitational Waves



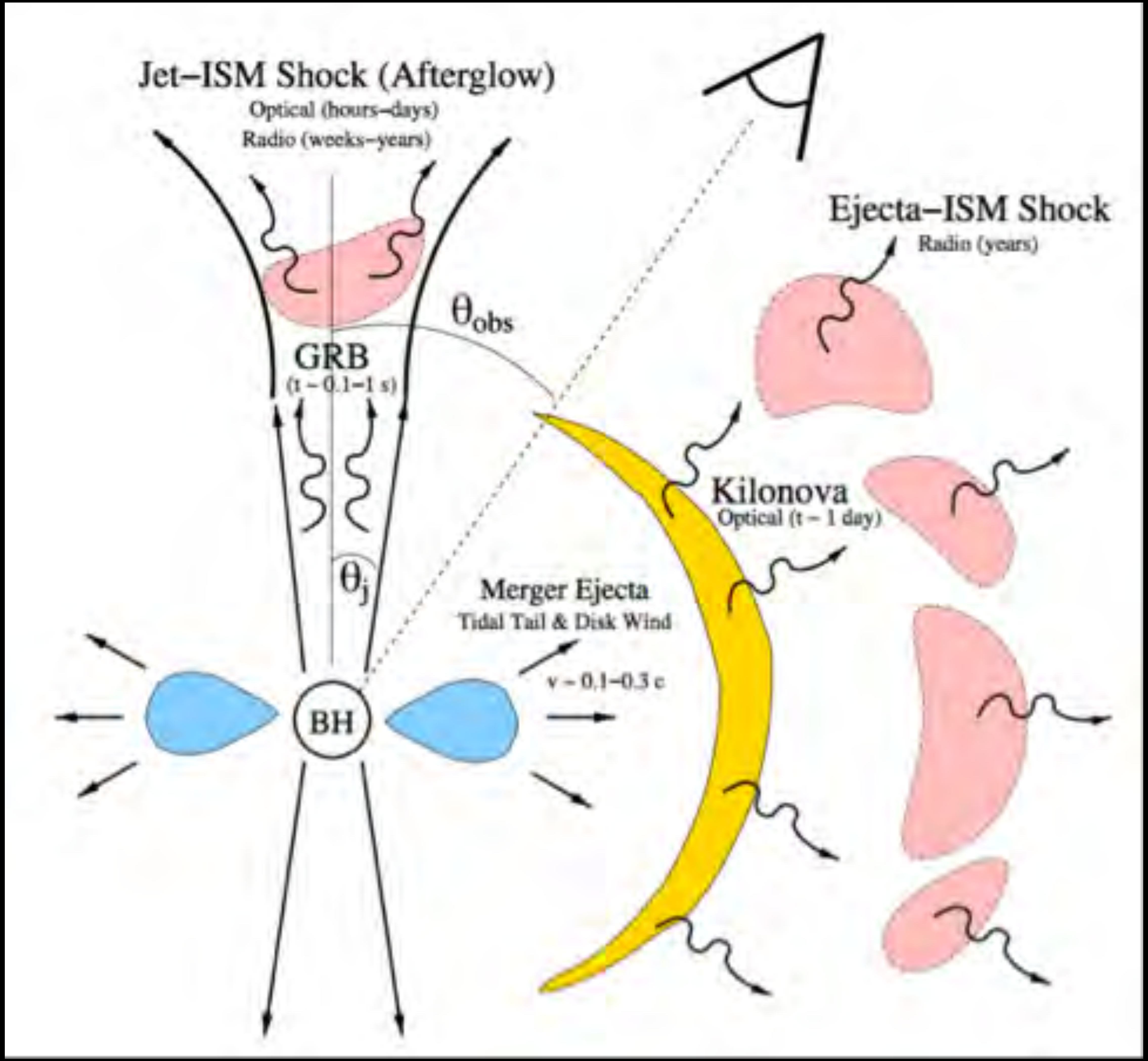



# Gamma-ray Bursts



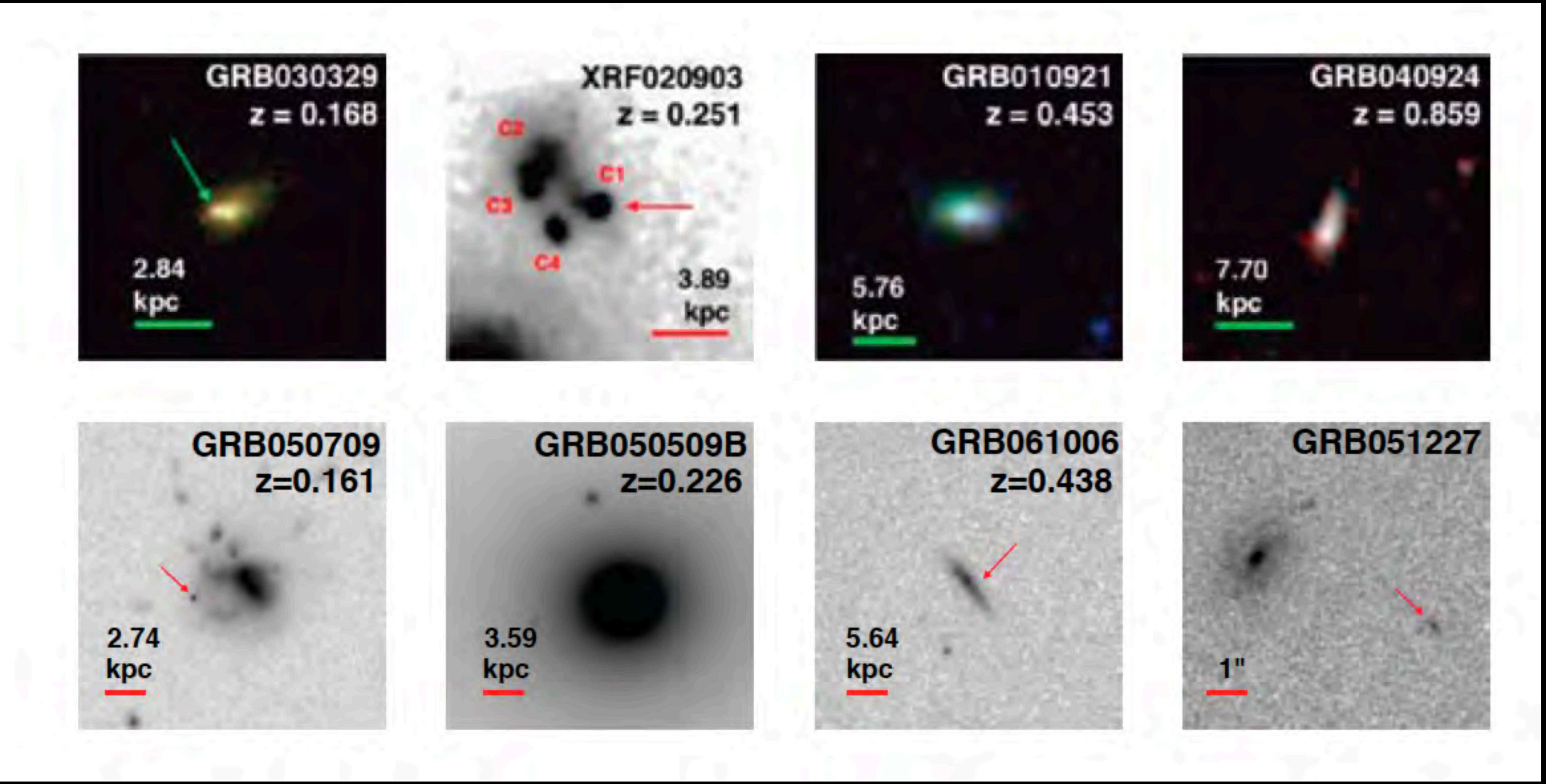
# Kilonovae

- Kilo?
  - 1000x less luminous than supernovae
  - 1000x more luminous than novae
- Production of heavy elements through rapid neutron capture (r-process) and their eventual decay
- Red kilonovae - lanthanide-rich dynamical ejecta via tidal forces
- Blue kilonovae - lanthanide-poor wind driven outflow or cooling of shock-heated ejecta



# Short Gamma-ray Bursts as Neutron Star Mergers

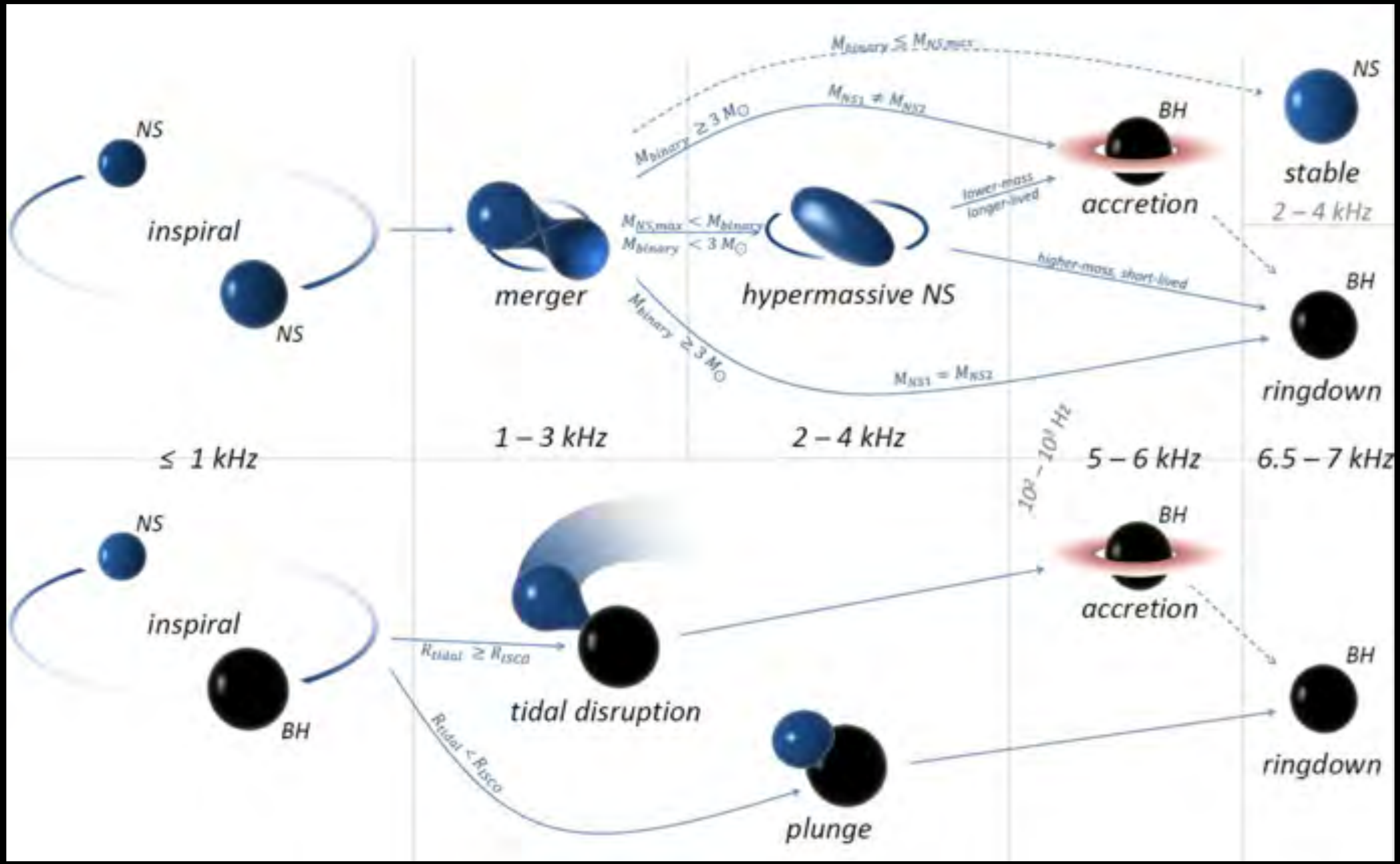
- Live in low density, low star-formation environments
- Occur in all galaxy types
- Often seen slightly outside their hosts
- Associated with old stellar populations
- Less energetic than long GRBs
- Energy spectra peak at slightly higher energies




Gomboc et al. (2012)

# Short Duration Gamma-ray Bursts as Gravitational Wave Counterparts

- Neutron Star + Neutron Star and Neutron Star + Black Hole mergers should produce Gamma-ray Bursts
  - detected if jet is pointed towards Earth (on axis)
- Merging compact objects produce GWs
  - we know this for sure from LIGO/ Virgo
- If short GRBs are within LIGO detection range and pointed towards Earth, we should see gamma rays & GWs concurrently



# The Discovery of GW170817 GRB 170817A SSS17a AT 2017gfo

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/////////////////////////////////////////////////////////////////////////////////////
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
DETECTORS:       0,1,1, 0,0,1, 0,0,0, 0,0,0, 0,0,
LC_URL:          http://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/triggers/2017/
bn170817529/quicklook/glg_lc_medres34_bn170817529.gif
COMMENTS:        Fermi-GBM Trigger Alert.
COMMENTS:        This trigger occurred at longitude,latitude = 321.53,3.90 [deg].
COMMENTS:        The LC_URL file will not be created until ~15 min after the trigger.
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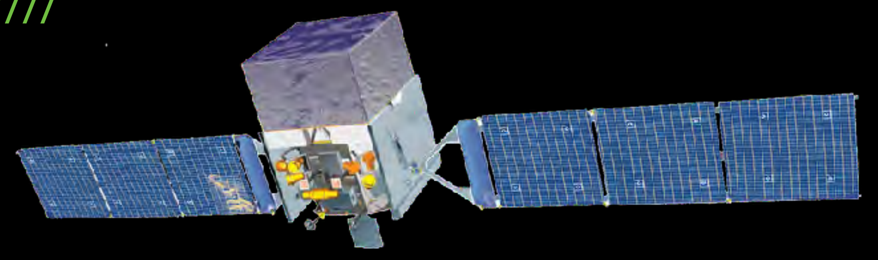
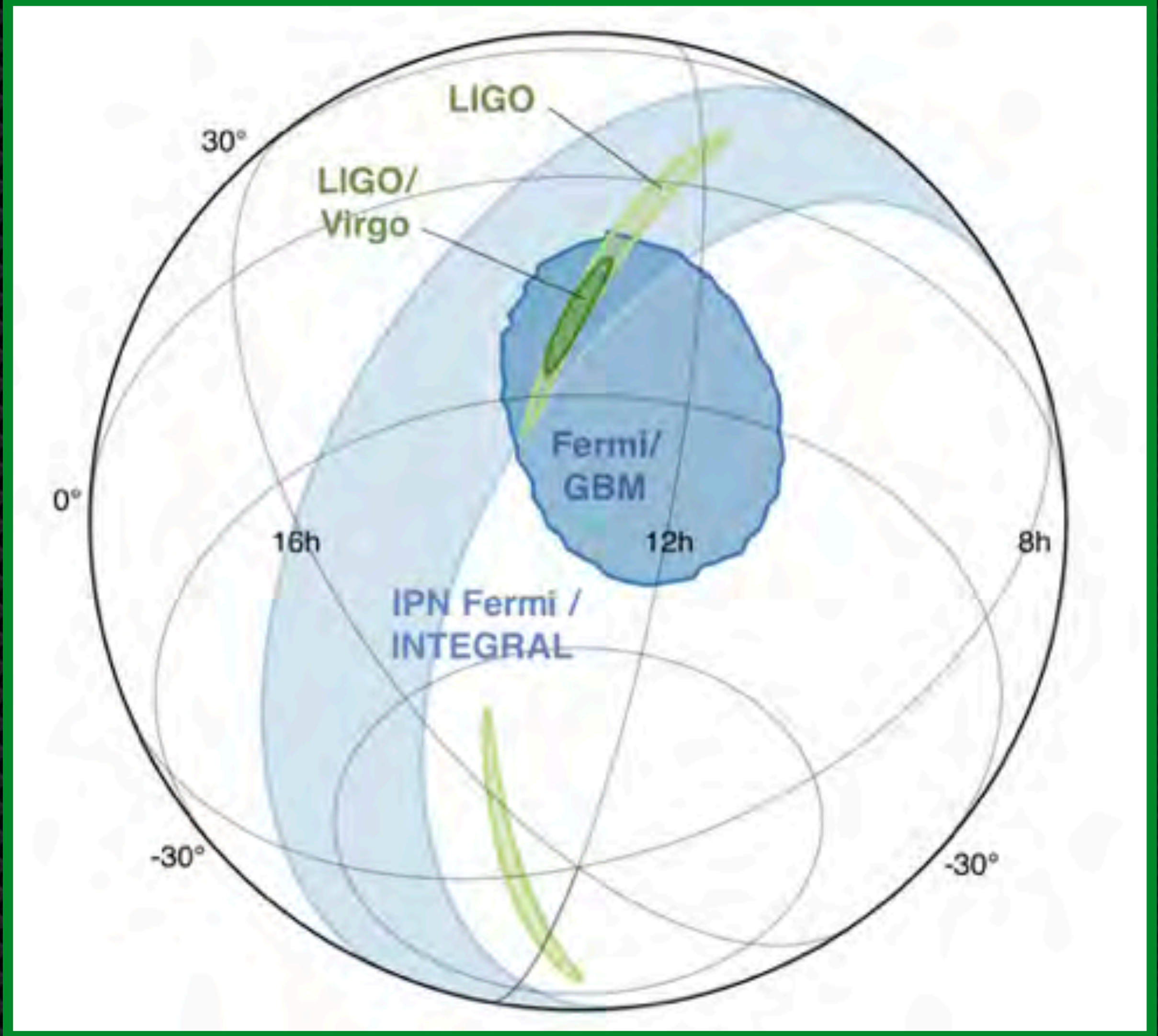





GBM Alert

First On-board GBM Localization

LIGO Report of coincident GW/GRB

Joint LIGO/ Virgo sky map

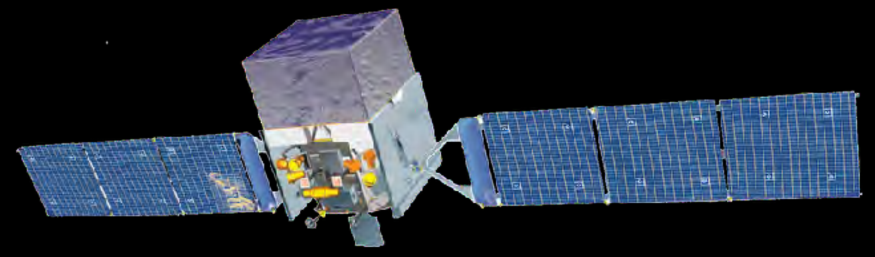
+16 s

+27 s

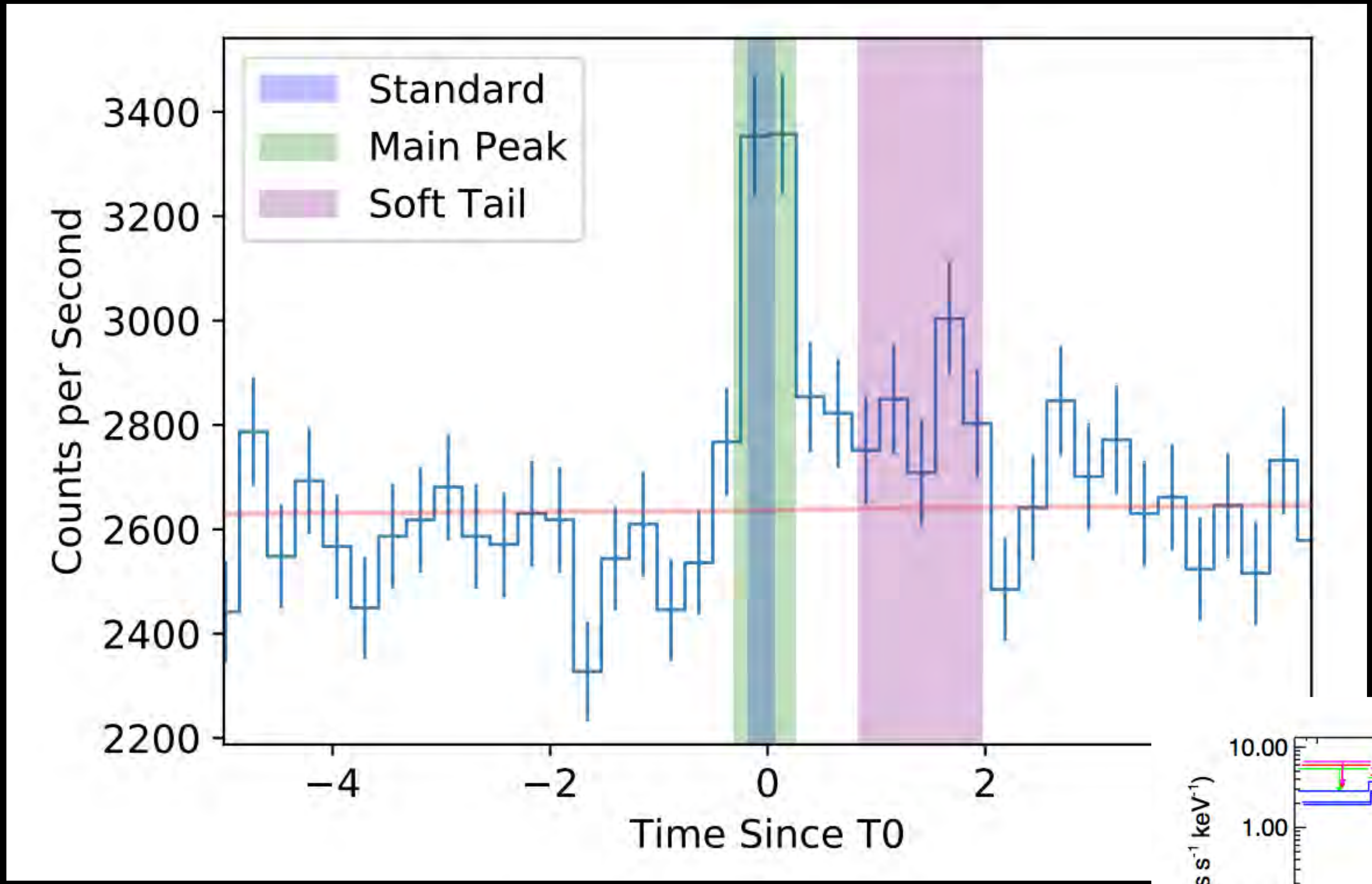
+45 min

+5 hour

Borrowed from Dan Kocevski (NASA/MSFC)

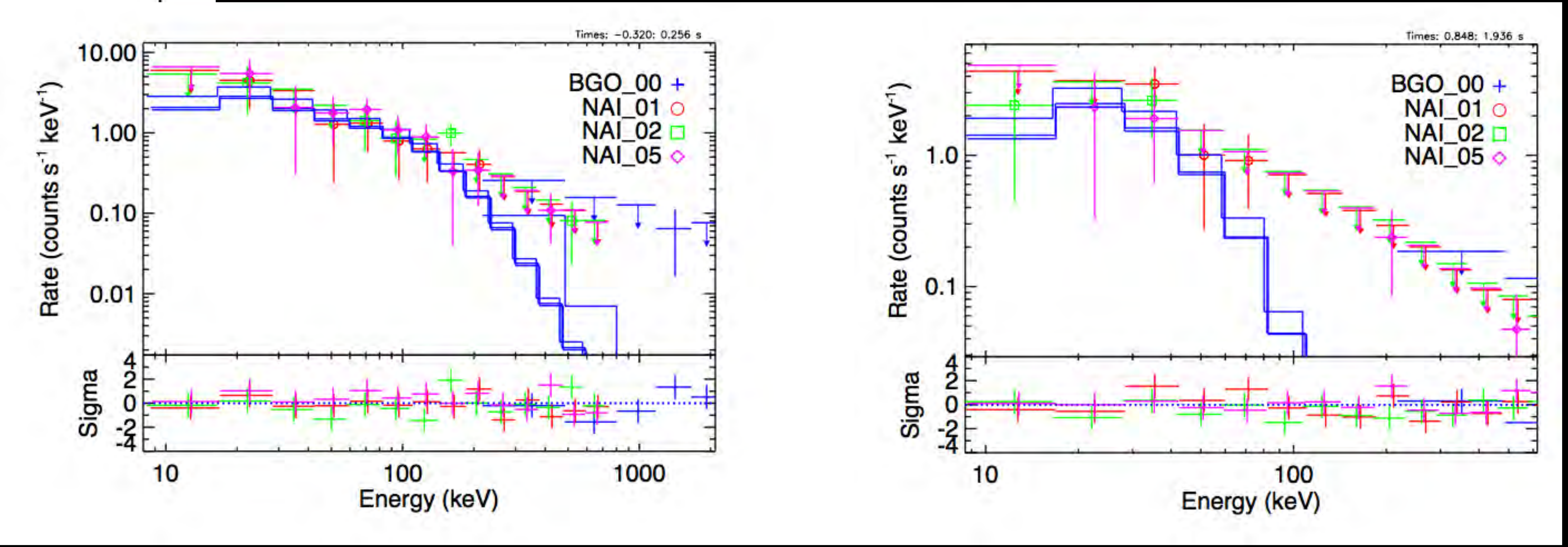


# GRB 170817A Spectral Components

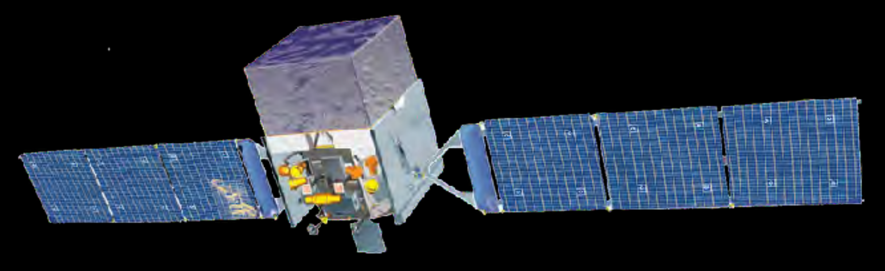


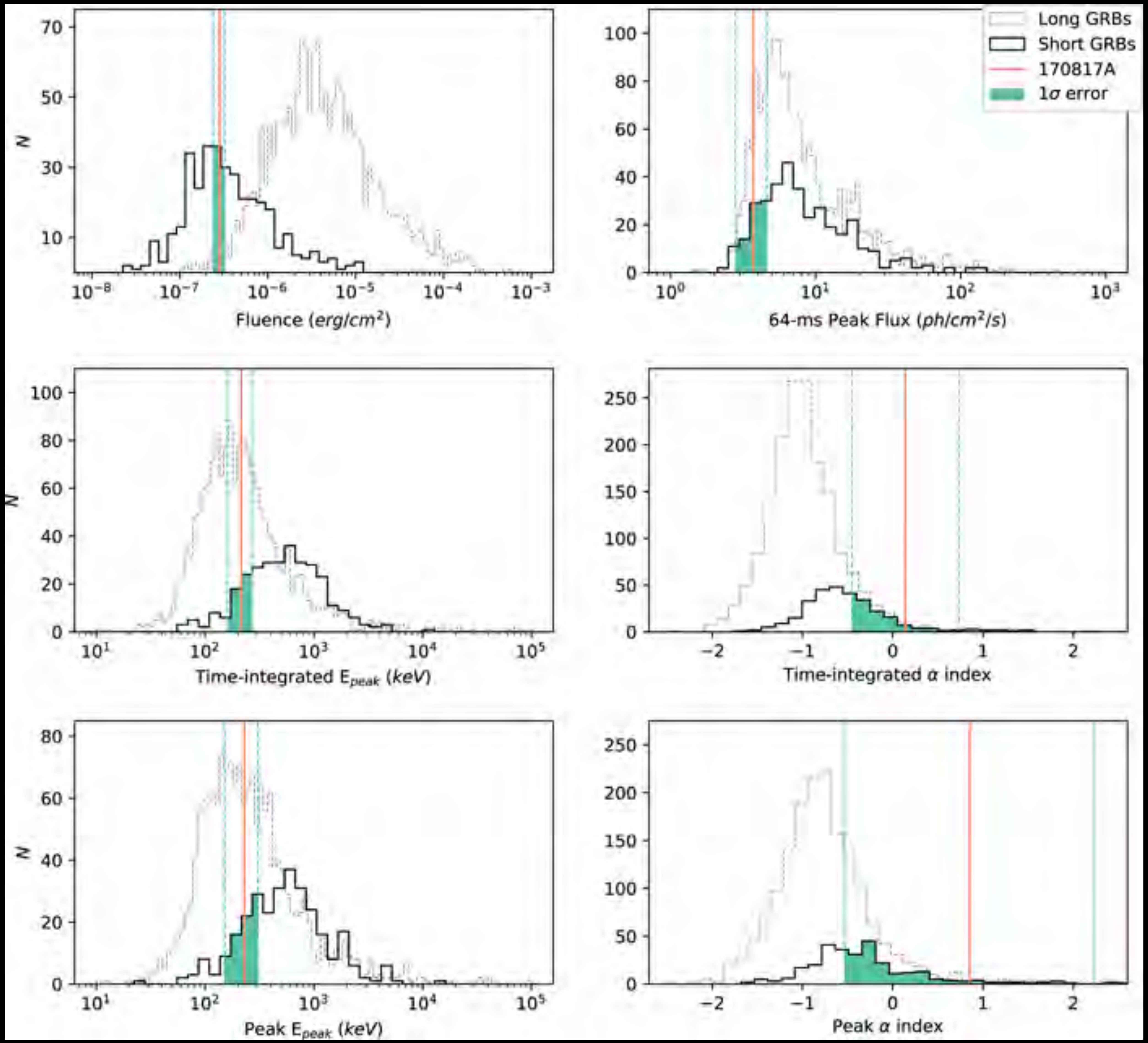

- Typical short (~0.5 s) hard spike
  - α = -0.62 ± 0.40
  - $E_{peak}$ = 185 ± 62 keV
- Longer (~1 s) soft thermal tail
  - kT=10.3 ± 1.5 keV

**Goldstein et al. 2017**

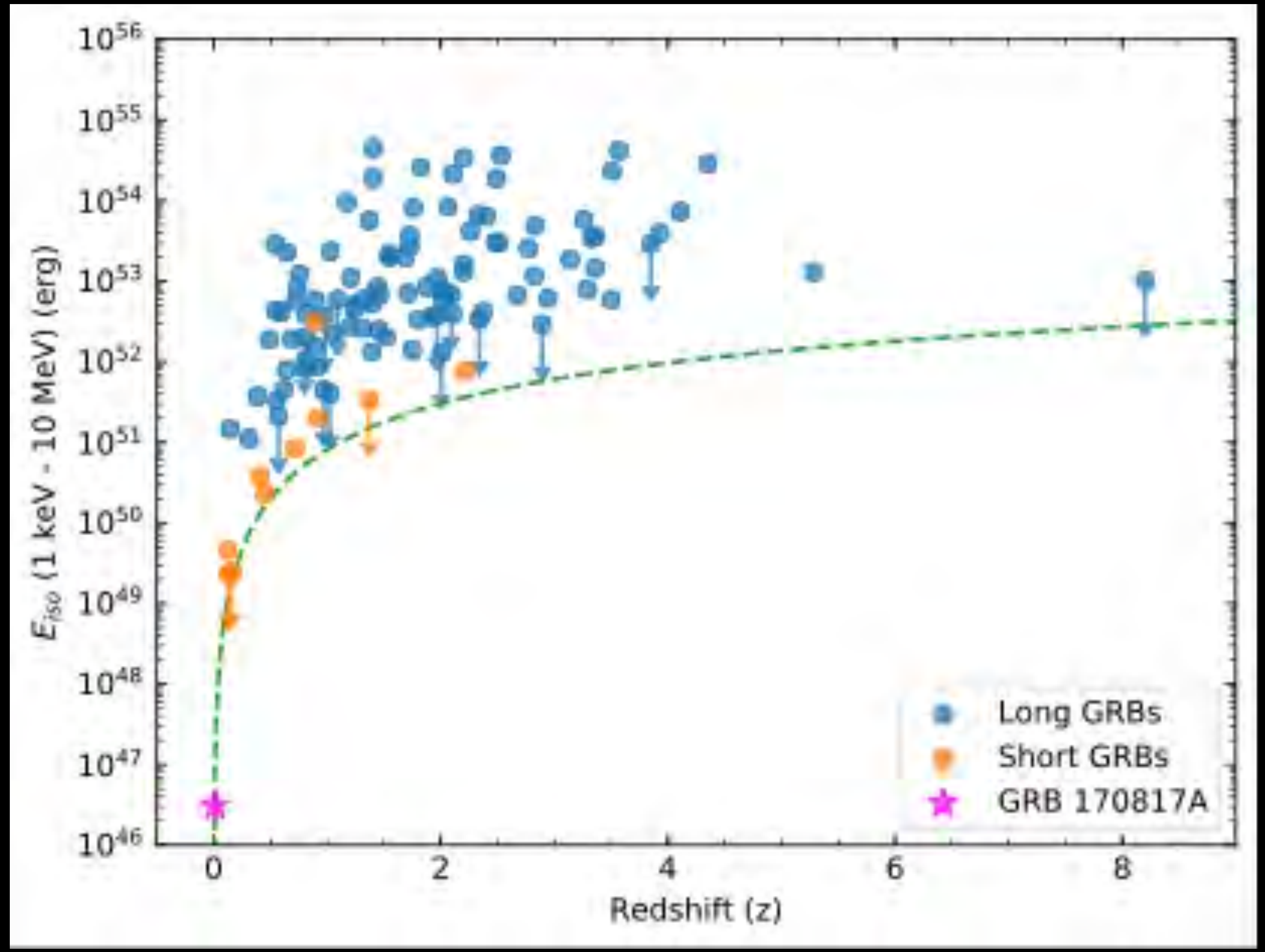


# GRB 170817A Properties

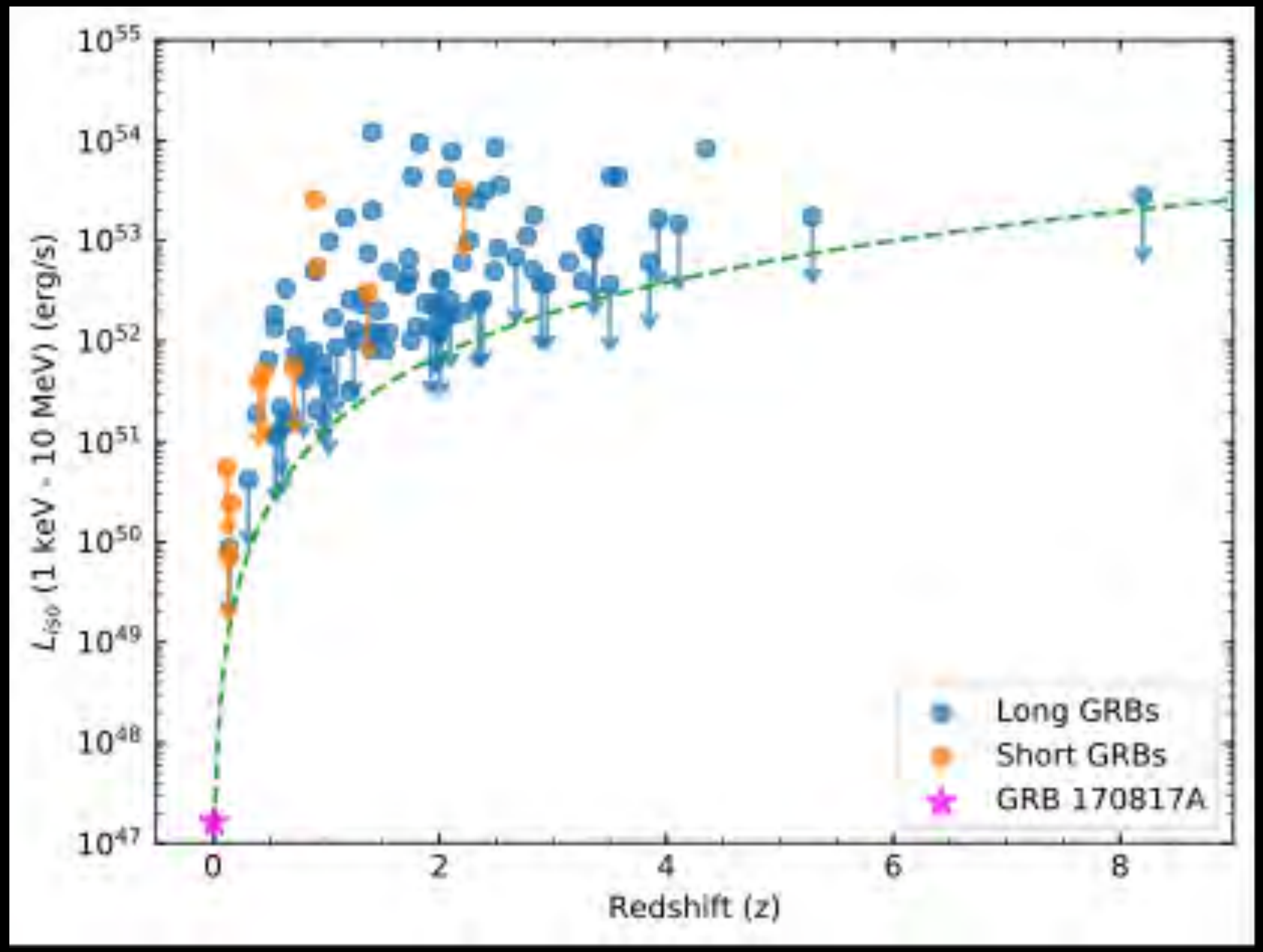


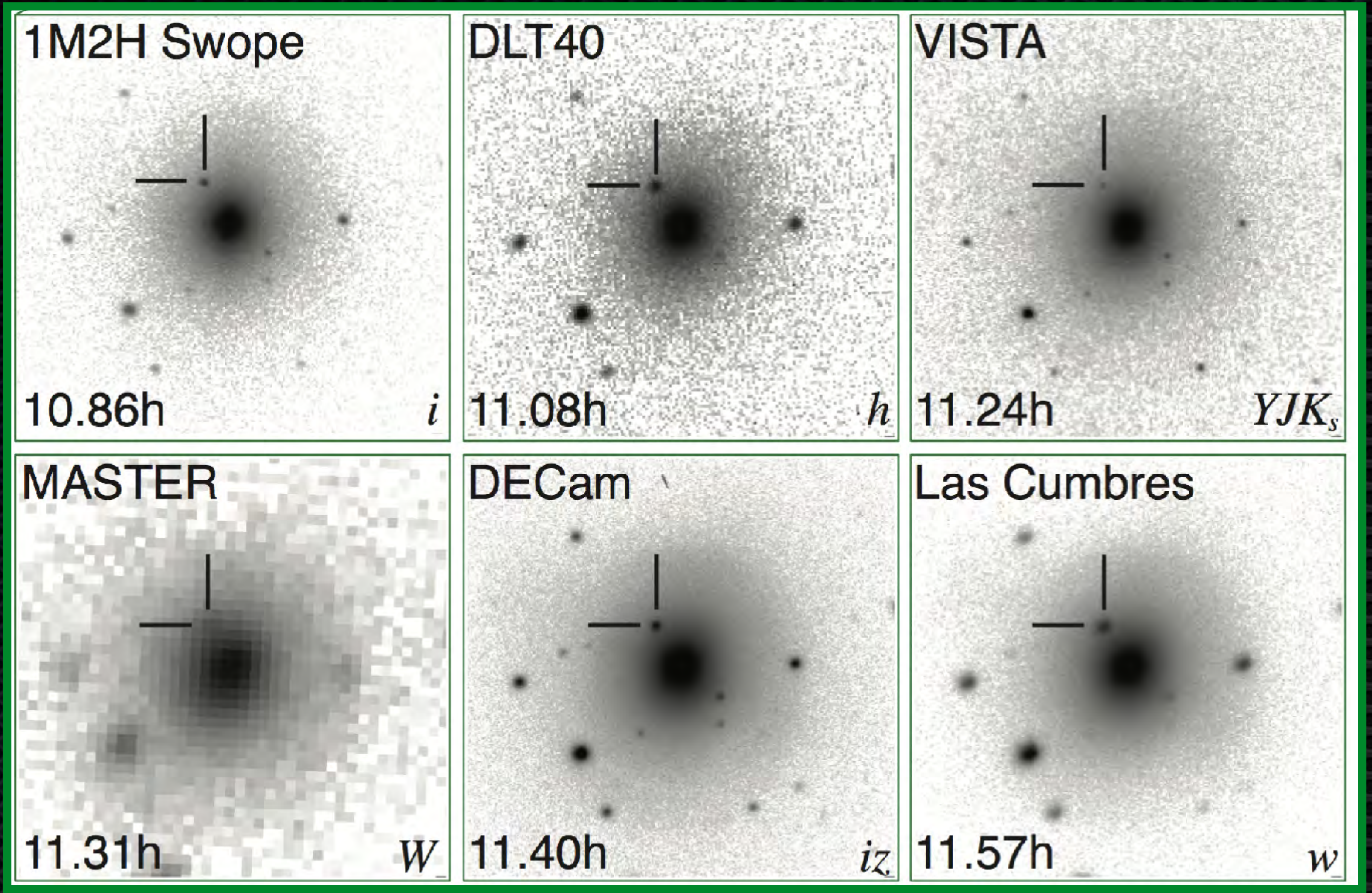



**Goldstein et al. 2017**



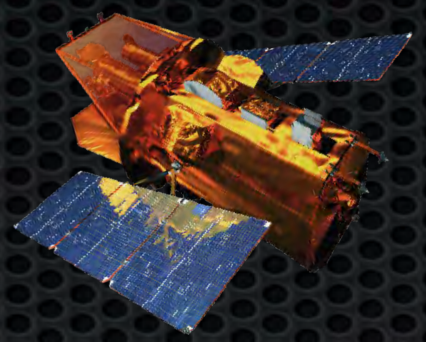

**Abbott et al. 2017**

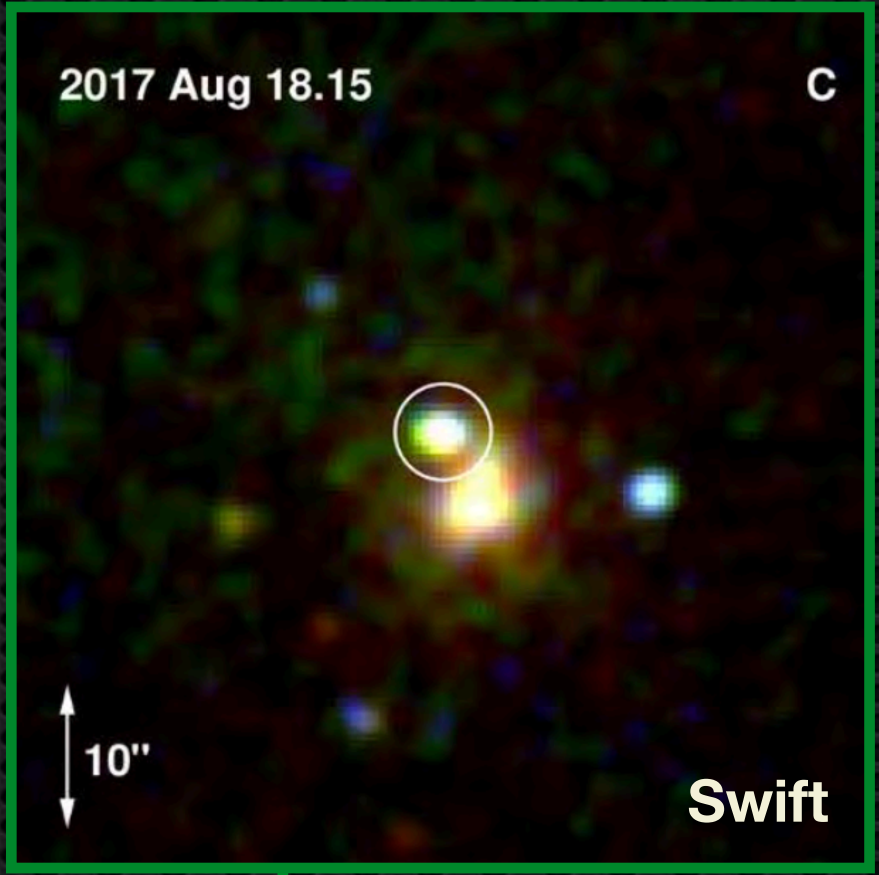





Reports of a blue optical transient near an elliptical S0 type galaxy NGC 4993 at ~40 Mpc (Abbott et al. 2017).

Coulter et al. (2017) first observed the region with the 1m Swope telescope at Las Campaas Observatory






*Swift* observations reveal bright, but quickly fading, UV source with no evidence of X-ray emission (Evans et al. 2017)

*NuStar* observations show no X-ray emission (Evans et al. 2017)

+12 hours

+13 hours

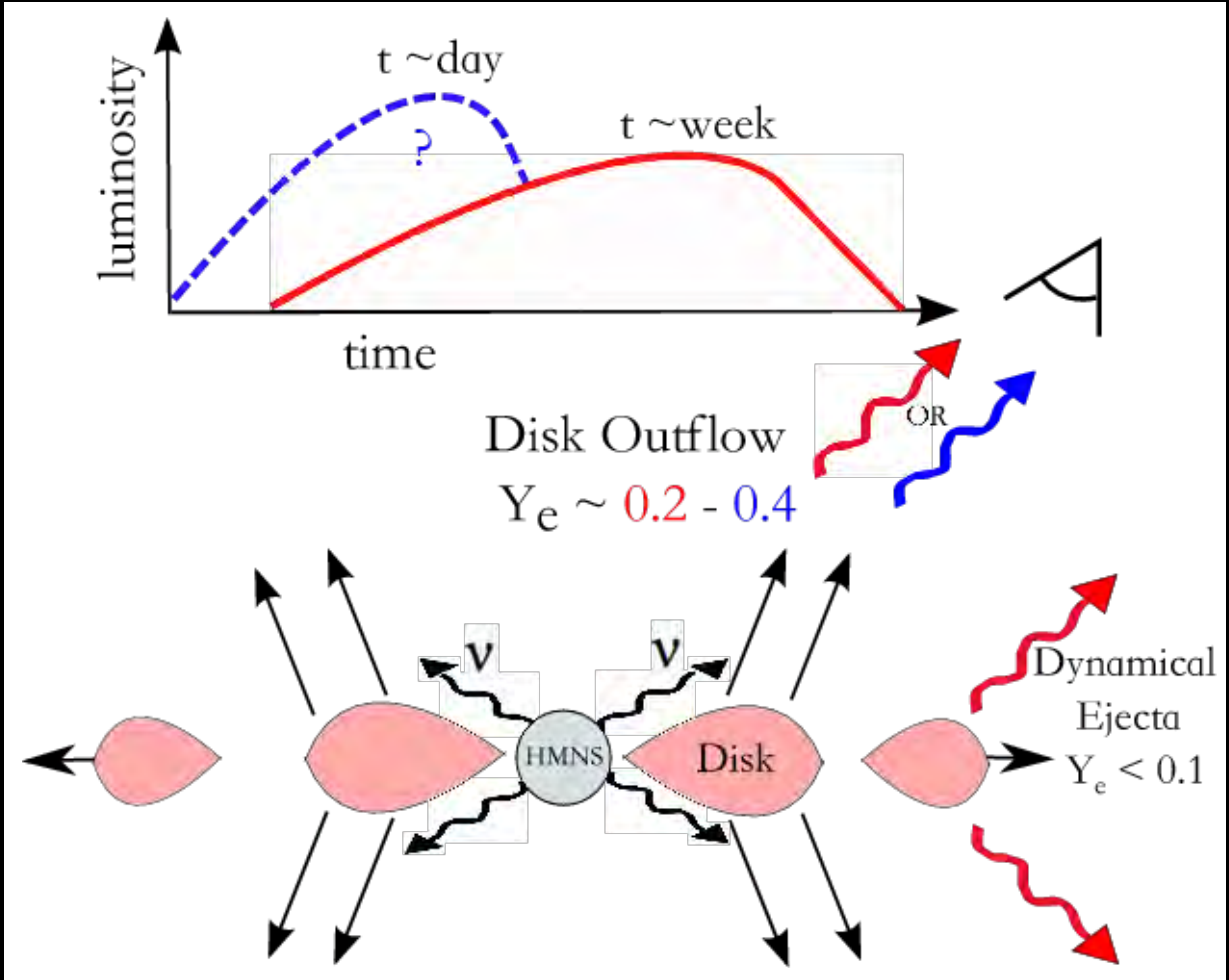
+14 hours

# Kilonova Evolution

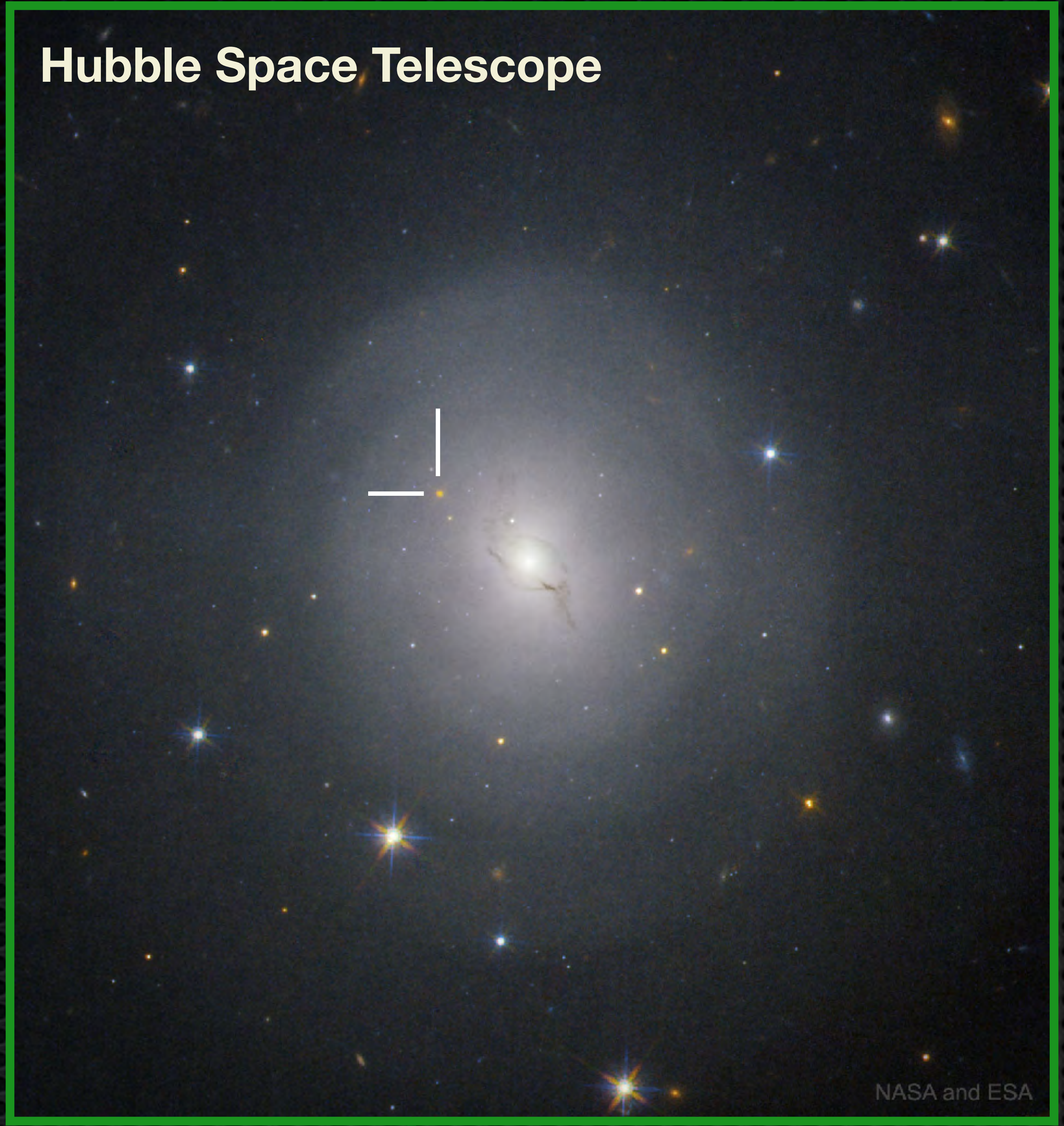
Credit: ESO/E. Pian/S. Smartt & ePESSTO/N. Tanvir/VIN-ROUGE
https://www.eso.org/public/usa/videos/eso1733e/

Two kilonova components?

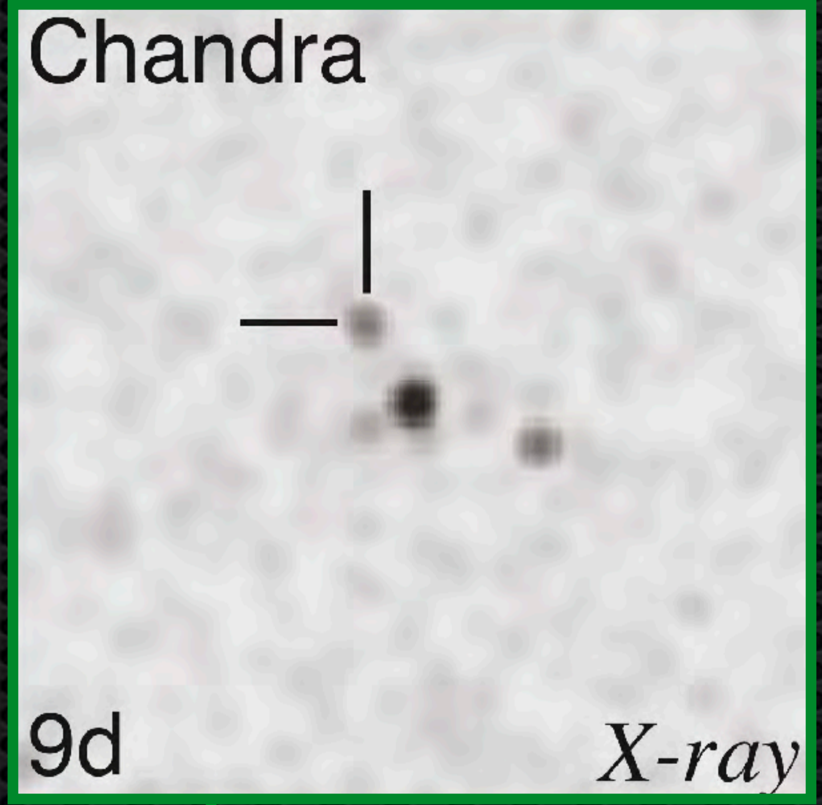
Or, emission from the cocoon?



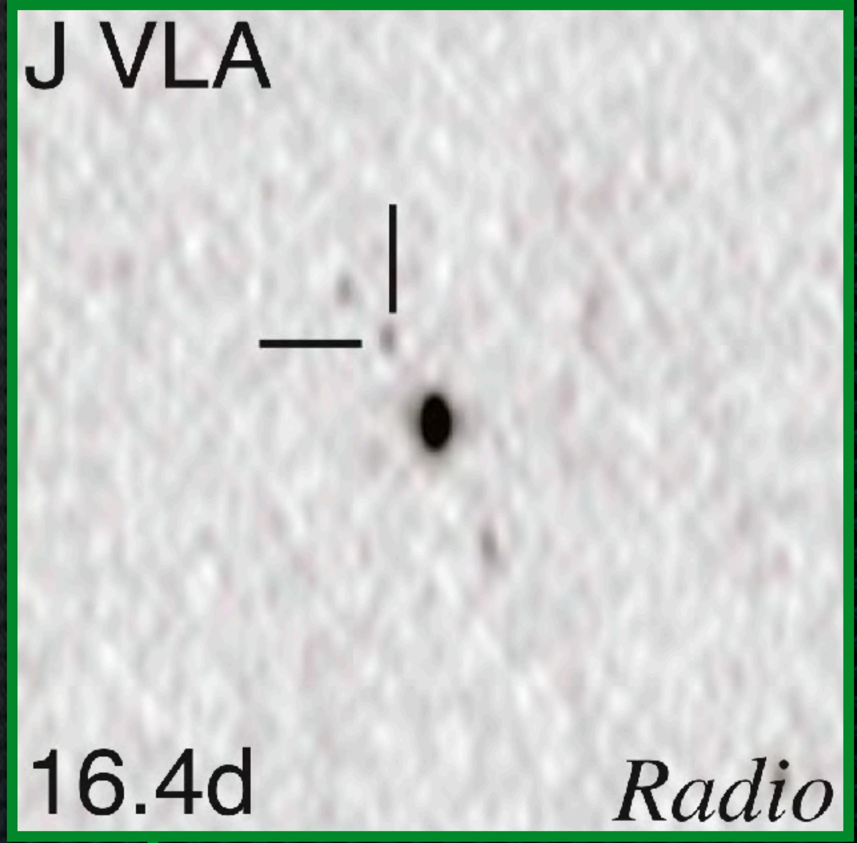
*Chandra* observations show no X-ray emission (Fong et al. 2017)




Hubble observations reveal a reddening source (Adams et al. 2017)




Chandra observations reveal first evidence of delayed X-ray emission (Troja et al. 2017)



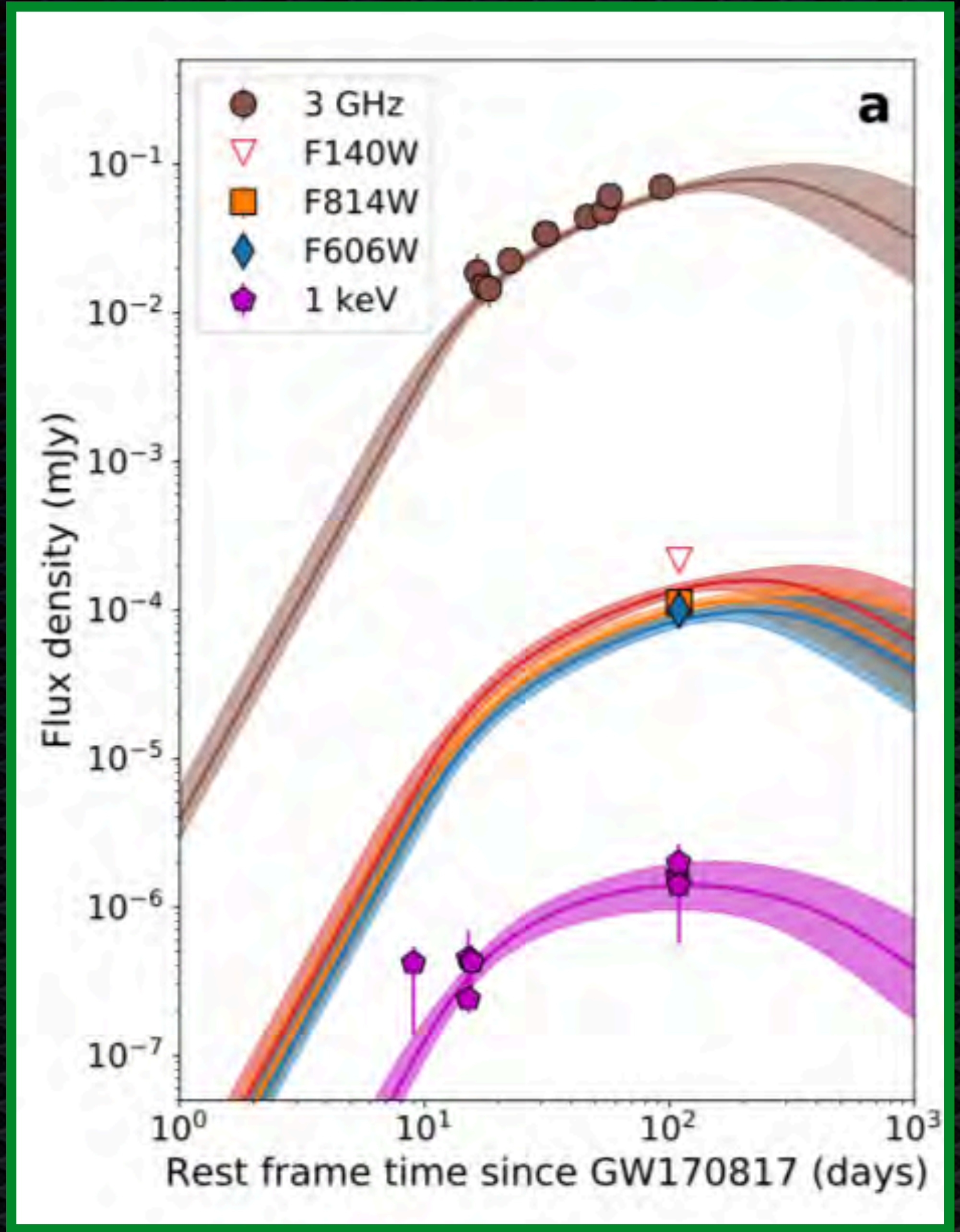

Radio counterpart reported by VLA (Mooley et al. 2017)

+2 days

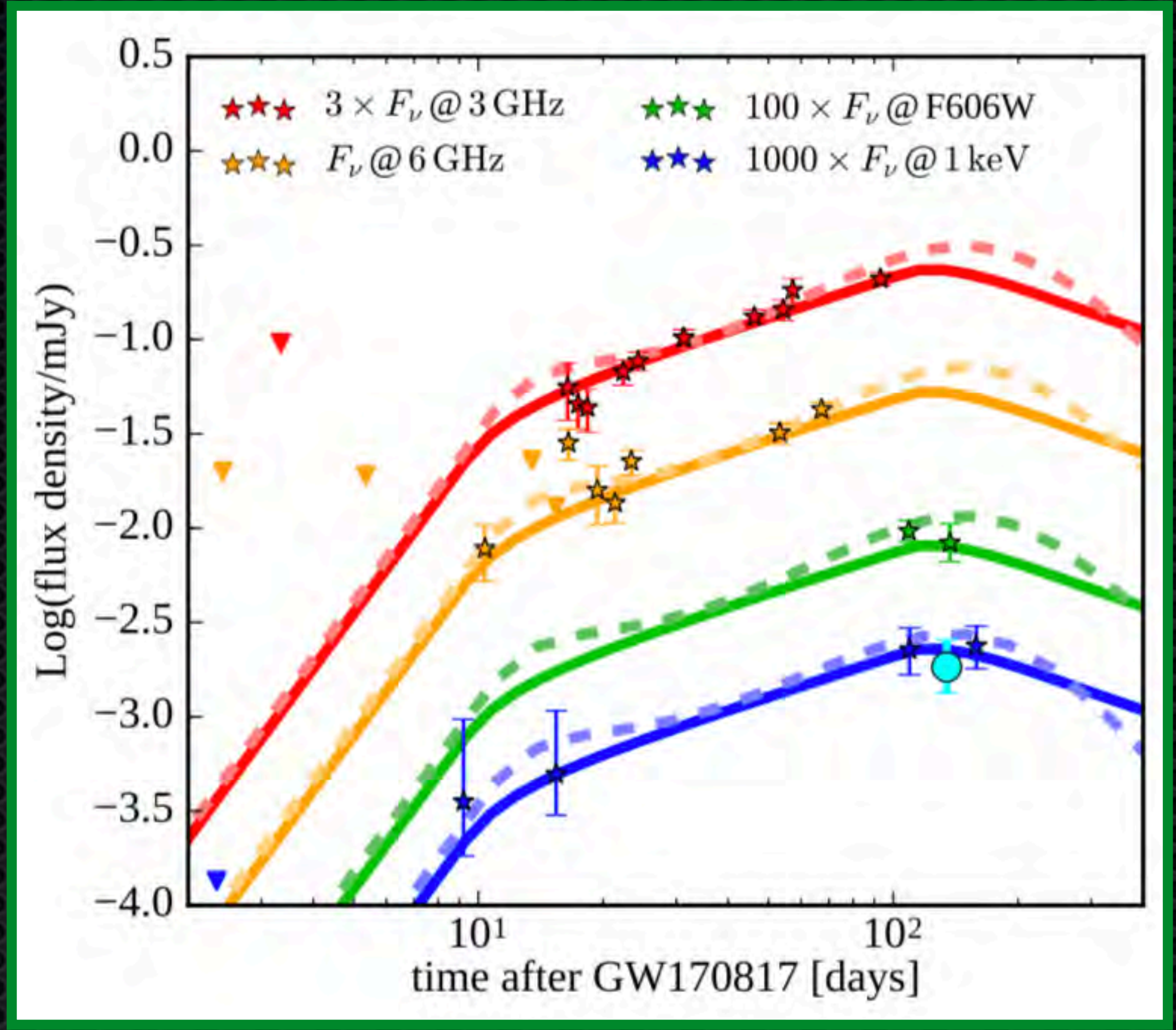
+5 days

+9 days

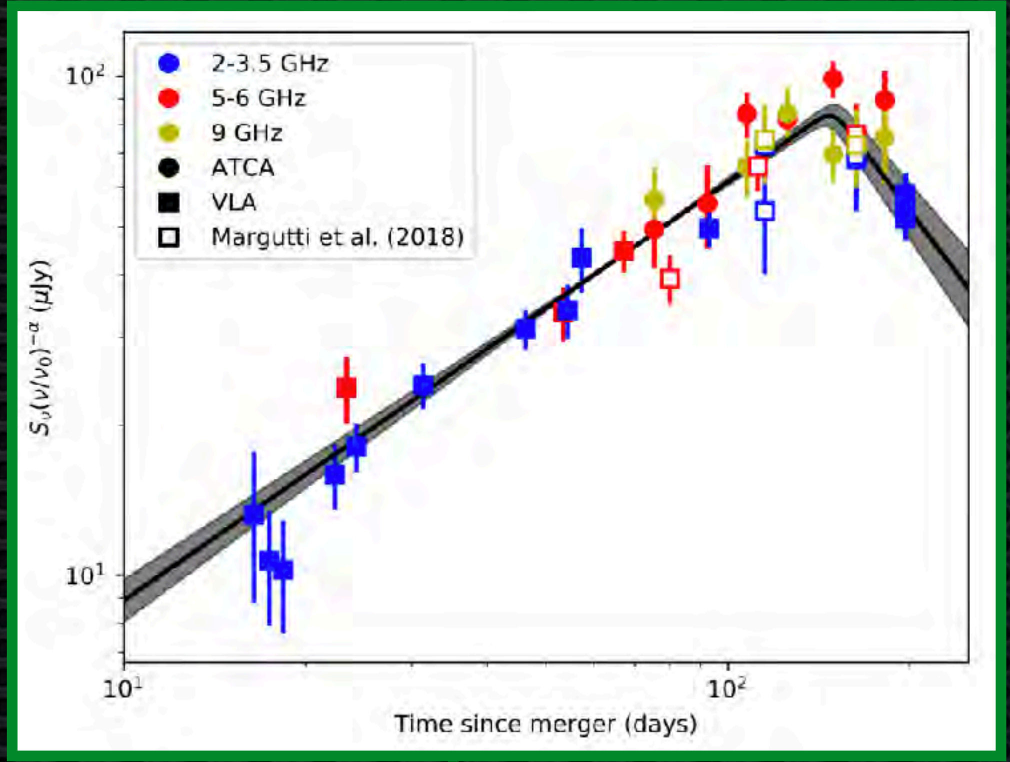
+16.4 days




*HST* and *Chandra* observations continue to show rising afterglow flux (Lyman et al. 2018, Ruan et al. 2018, Troja et al. 2018)




Hints of a plateau in x-rays (D'Avanzo et al. 2018) and radio (Resmi et al. 2018)

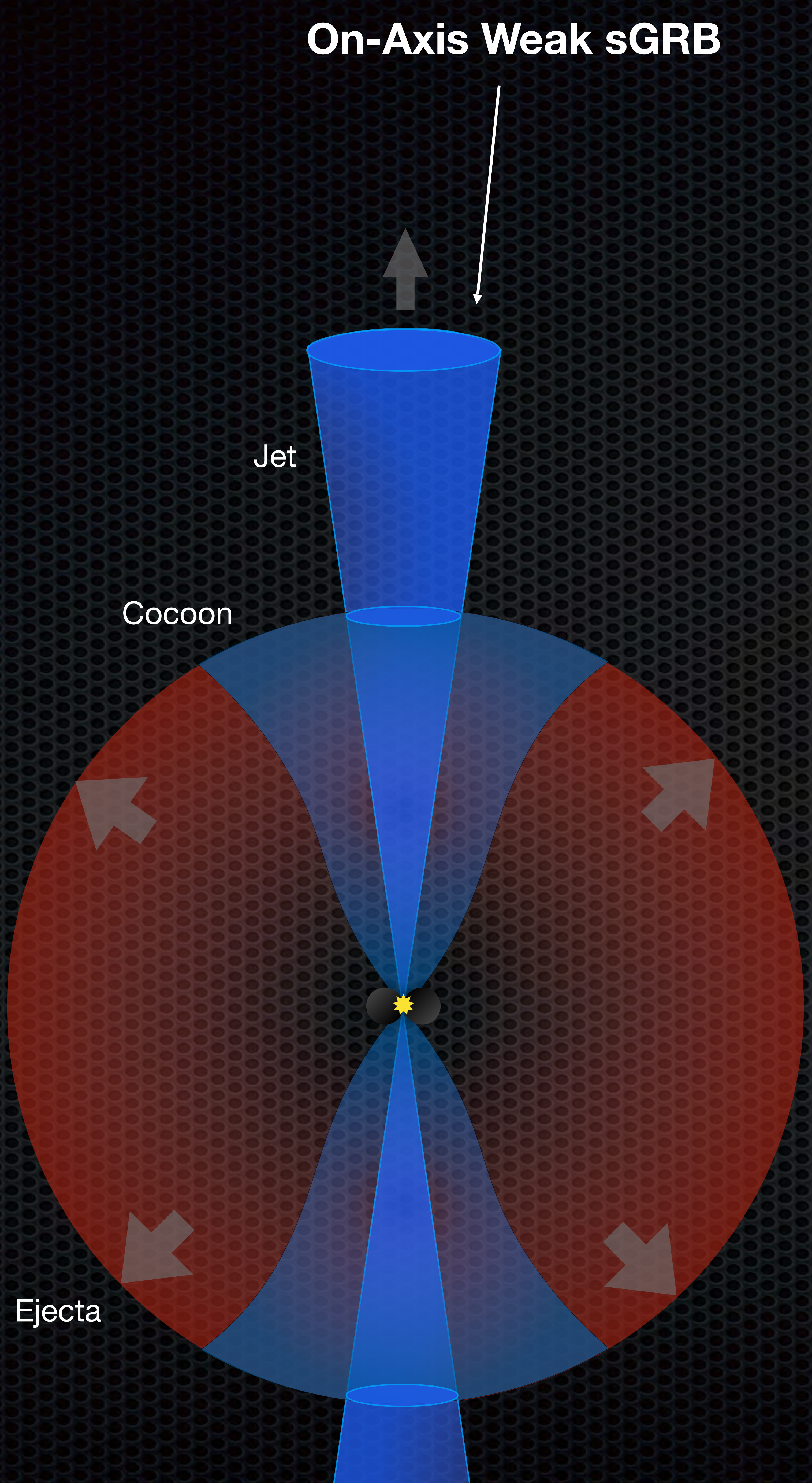



Evidence for a turn over in radio (Dobie et al. 2018)

+100 days

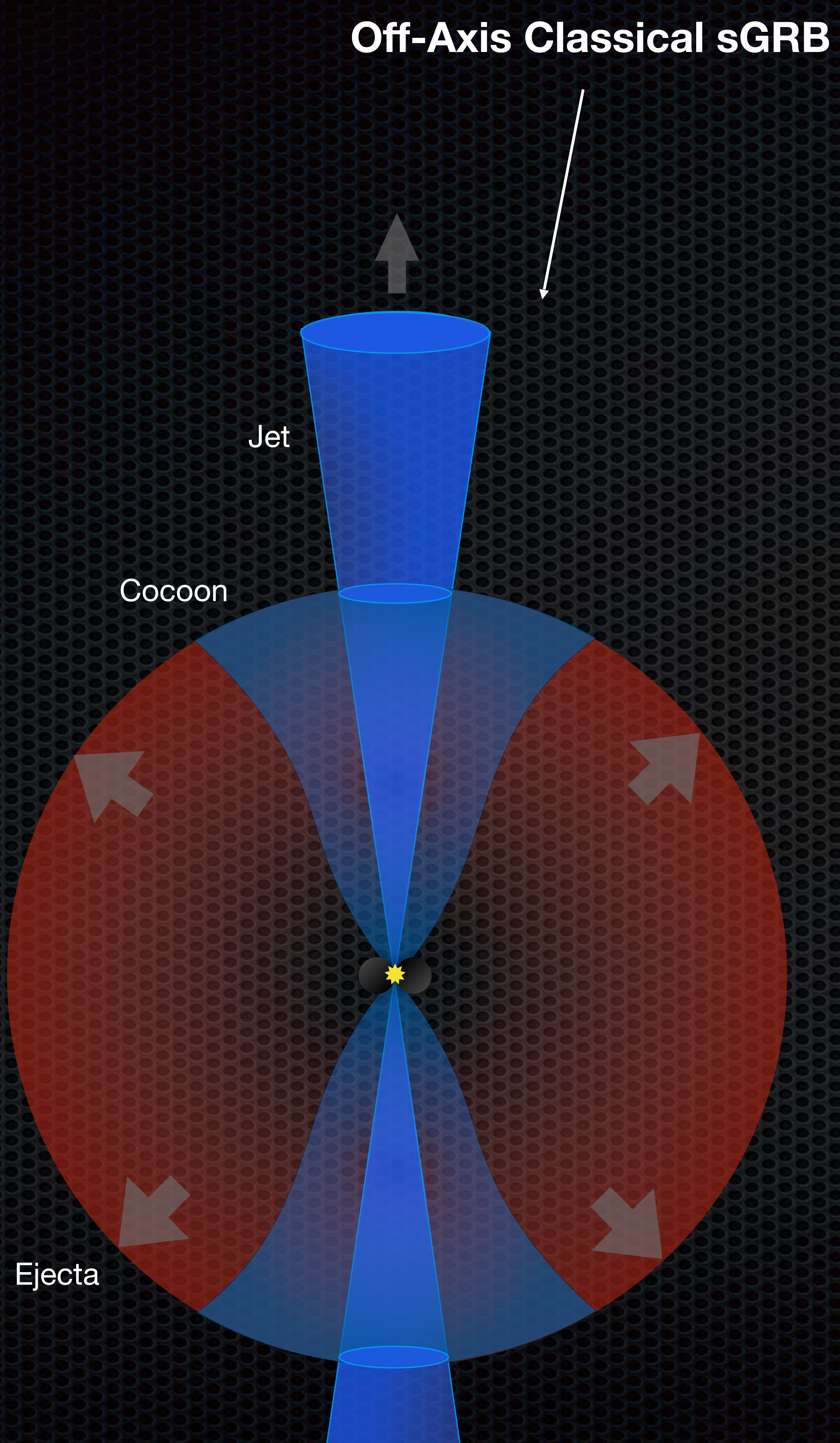
+135 days

+150 days



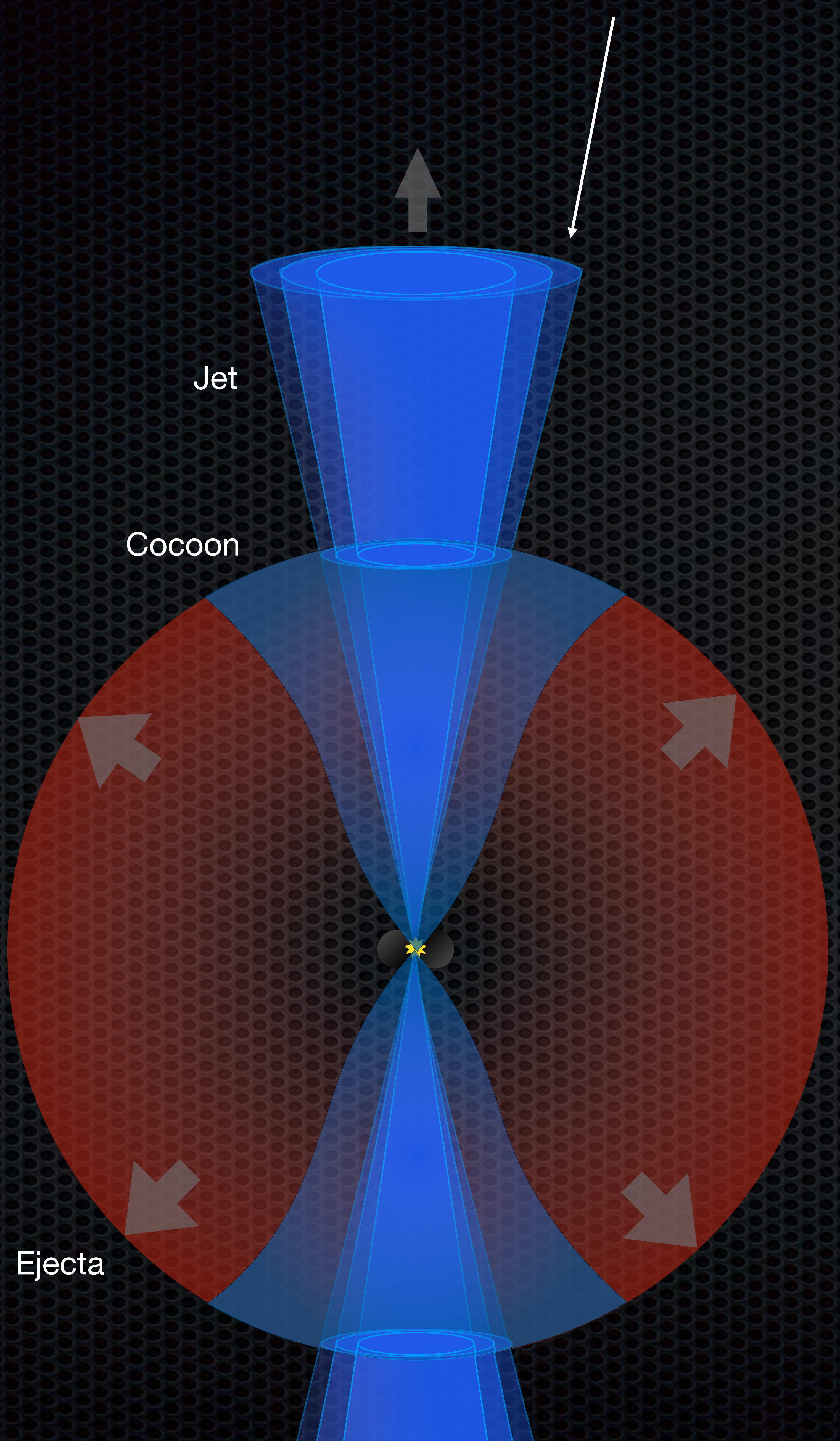

# On-Axis Weak sGRB

- We simply observed a top hat jet on the low end of the GRB luminosity function
- Pros:
    - Logical starting point
    - GW-EM delay is on the order of T90
- Cons:
    - Cannot explain the late-time X-ray and radio observations
    - Not clear how to produce delayed thermal emission
    - Would require very low ejecta mass to allow the low-energy jet to successfully breakout
- GW: $\theta_v \sim 29^\circ +15^\circ/-10^\circ$ (LIGO - arXiv: 1805.11579v1)
    - Average sGRB is $\theta_{jet} \sim 16^\circ$ (Fong et al. 2015)



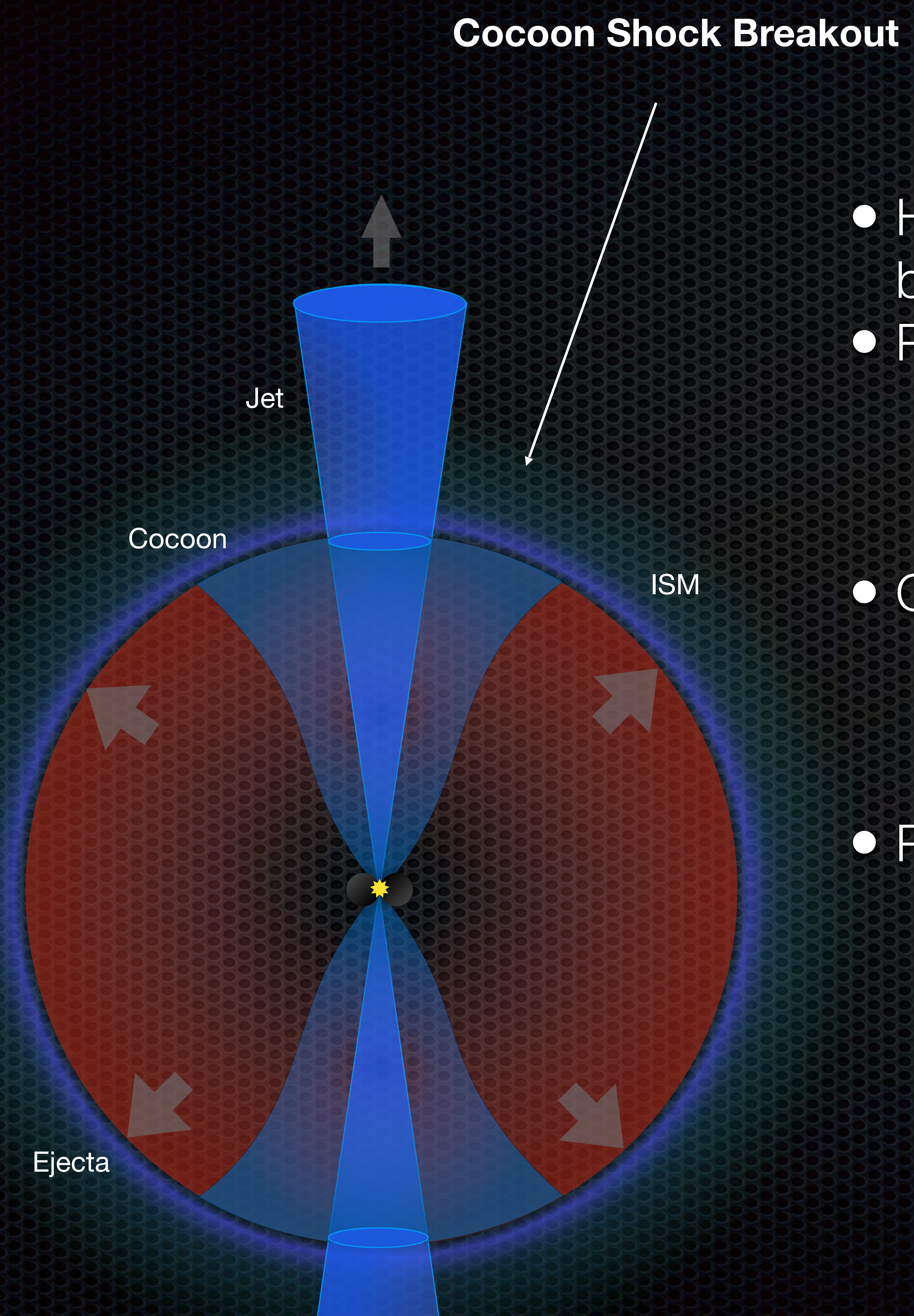

# Off-Axis Classical sGRB

- We observed outside the jet of a classical sGRB
- Pros:
  - Can naturally explain the lower energetics
  - Thermal emission could be from the GRB photosphere or the cocoon
- Cons:
  - Observed Epk & Eiso drop very quickly outside $\theta_{jet}$
    - $\theta_v$ would need to be just outside the jet edge
  - The on-axis Epk would be on the high end of the observed GBM catalog distribution
  - Expect bright afterglow in X-ray after ~1 day



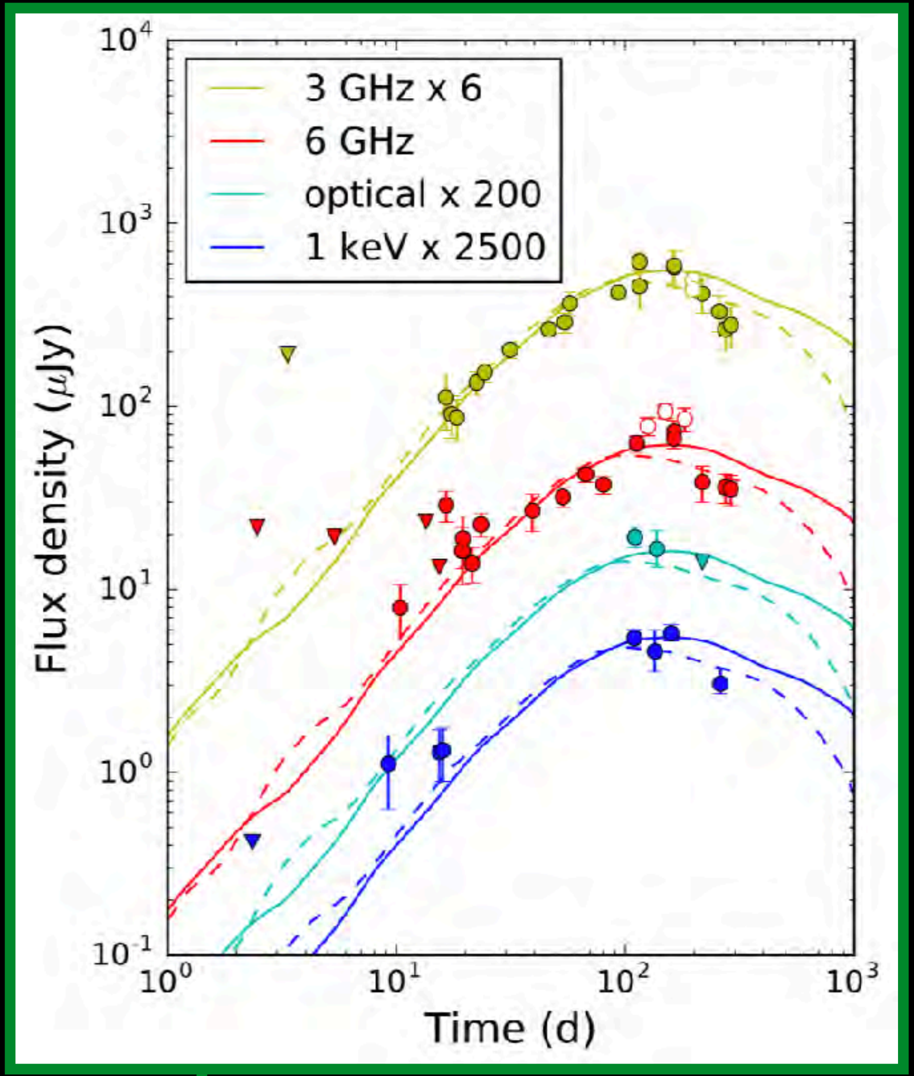

# Off-Axis Structured Jet sGRB

- We observed the less energetic region of a structure jet where the Lorentz factor decreases with θv
- Pros:
  - Could produce arbitrary $E_{peak}$ and $E_{iso}$ values
  - GW-EM delay is on the order of T90
  - Thermal emission could be from the GRB photosphere or the cocoon
- Cons:
  - Not entirely clear how such wings are generated or what their Lorentz profiles look like
  - On-axis Eiso would still need to be relatively low
- Predictions
  - Afterglow should peak and fade as the jet decelerates and we see the more energetic core region of the jet
  - VLBI imaging would reveal proper motion of the jet

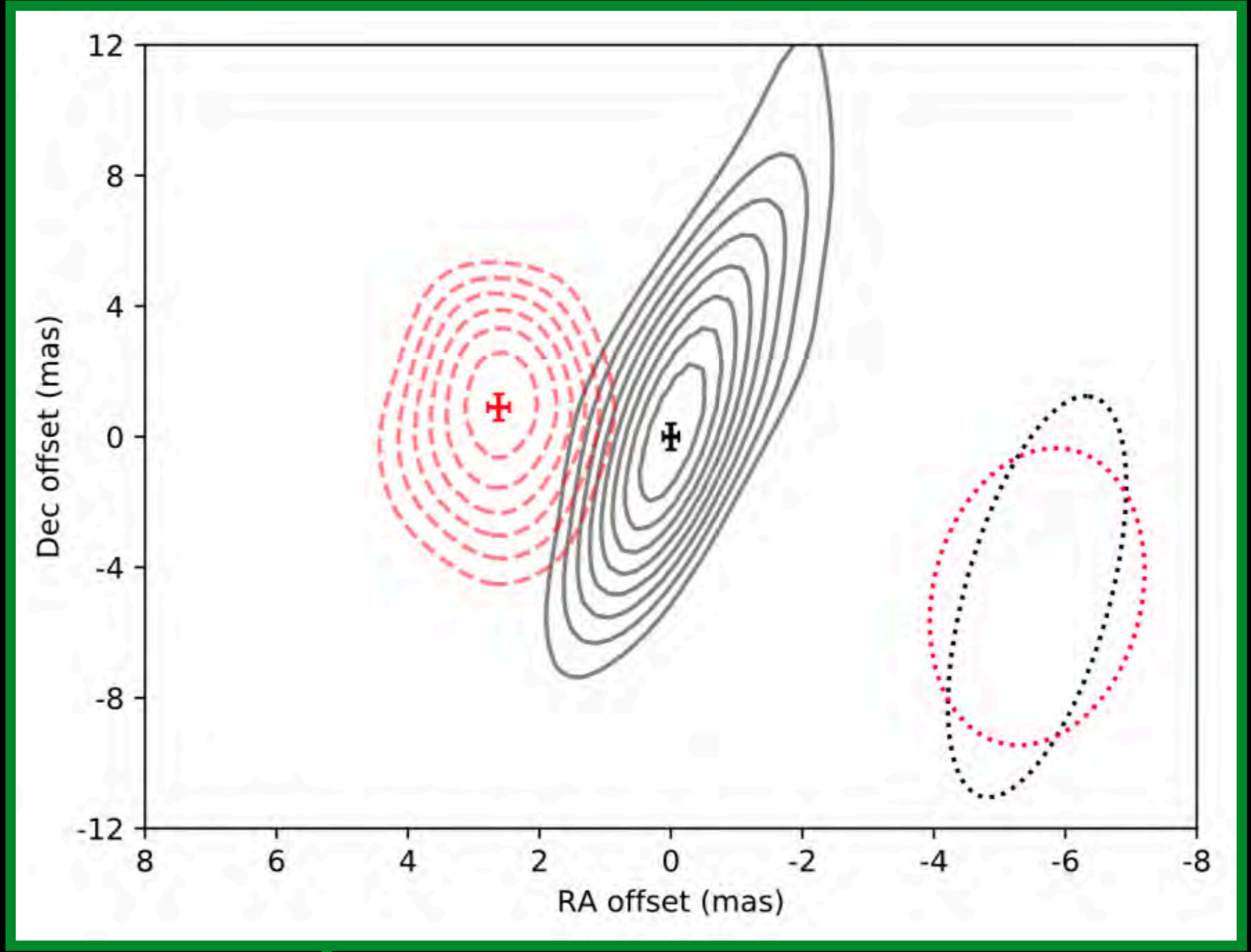



# Cocoon Shock Breakout

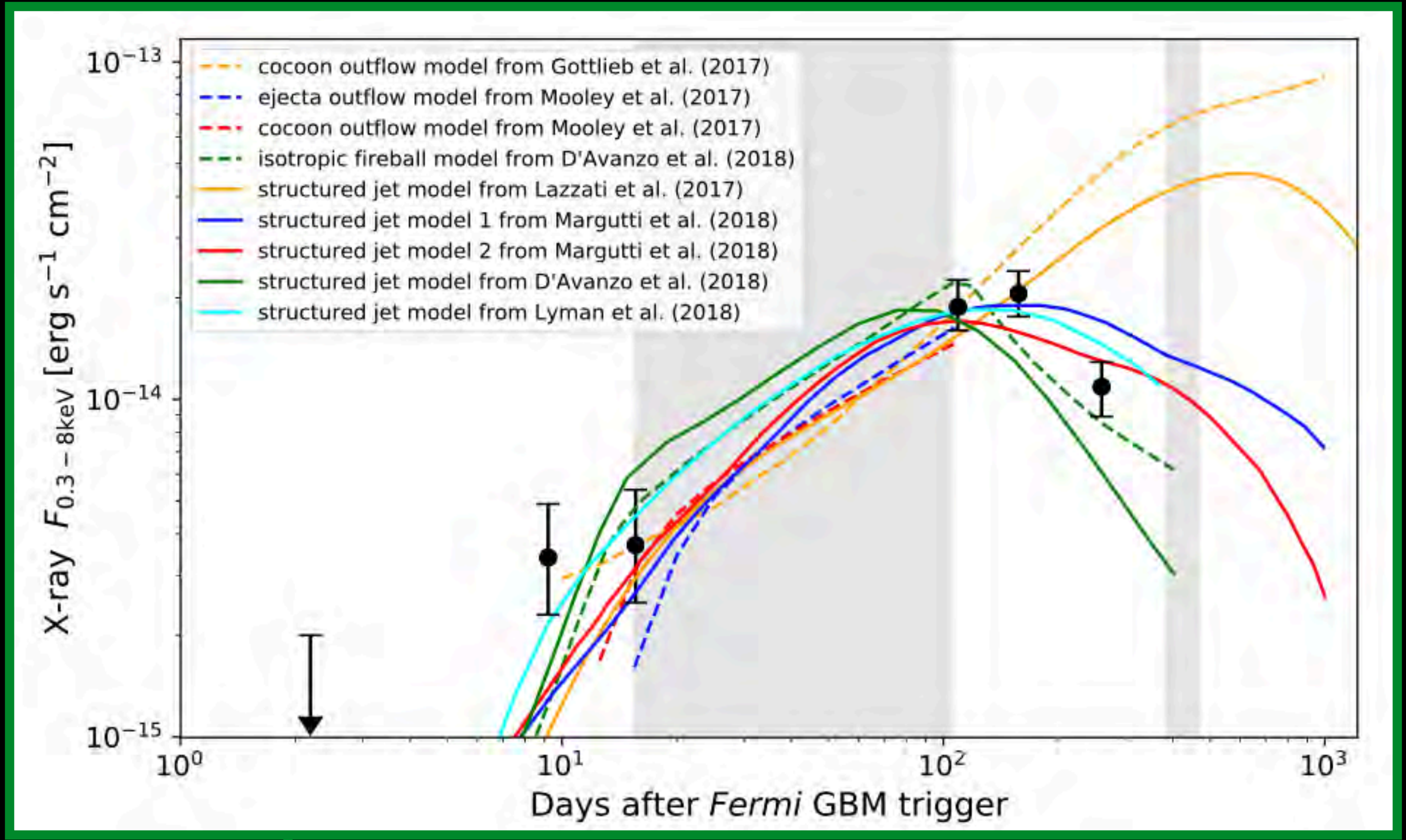
- Hard emission from mildly-relativistic shock breakout and thermal emission from cocoon
- Pros:
  - Can naturally explain the lower energetics
  - Could naturally explain both hard and thermal components
- Cons:
  - Cannot explain very high $E_{peak}$ values
  - Difficult to explain fast variability
  - Should overproduce look alike sGRBs
- Predictions:
  - Late time x-ray and radio should rise for months to years as the cocoon interacts with the ISM
  - Quasi-spherical outflow should not produce any proper motion in VLBI imaging




Further evidence for a turn over (Alexander et al. 2018)




Superluminal motion of the unresolved radio source and undeniable evidence of a off-axis jet (Mooley et al. 2018)




Cocoon is ruled out at late times, but it could still explain prompt and early afterglow (Nynka et al. 2018, Mooley et al. 2018)

+220 Days

+230 days

+260 days

# What can we learn from GW counterparts?

- GRB Physics
  - Jet Structure, Jet Composition, Energetics, Emission Mechanisms, Progenitors
- Origin of heavy elements in the Universe
  - r-process
- Fundamental Physics
  - Speed of Gravity = Speed of Light within $10^{-15}$
- Cosmology
  - Independent Measure of Hubble Constant
- Neutron Star Physics
  - Equation of State

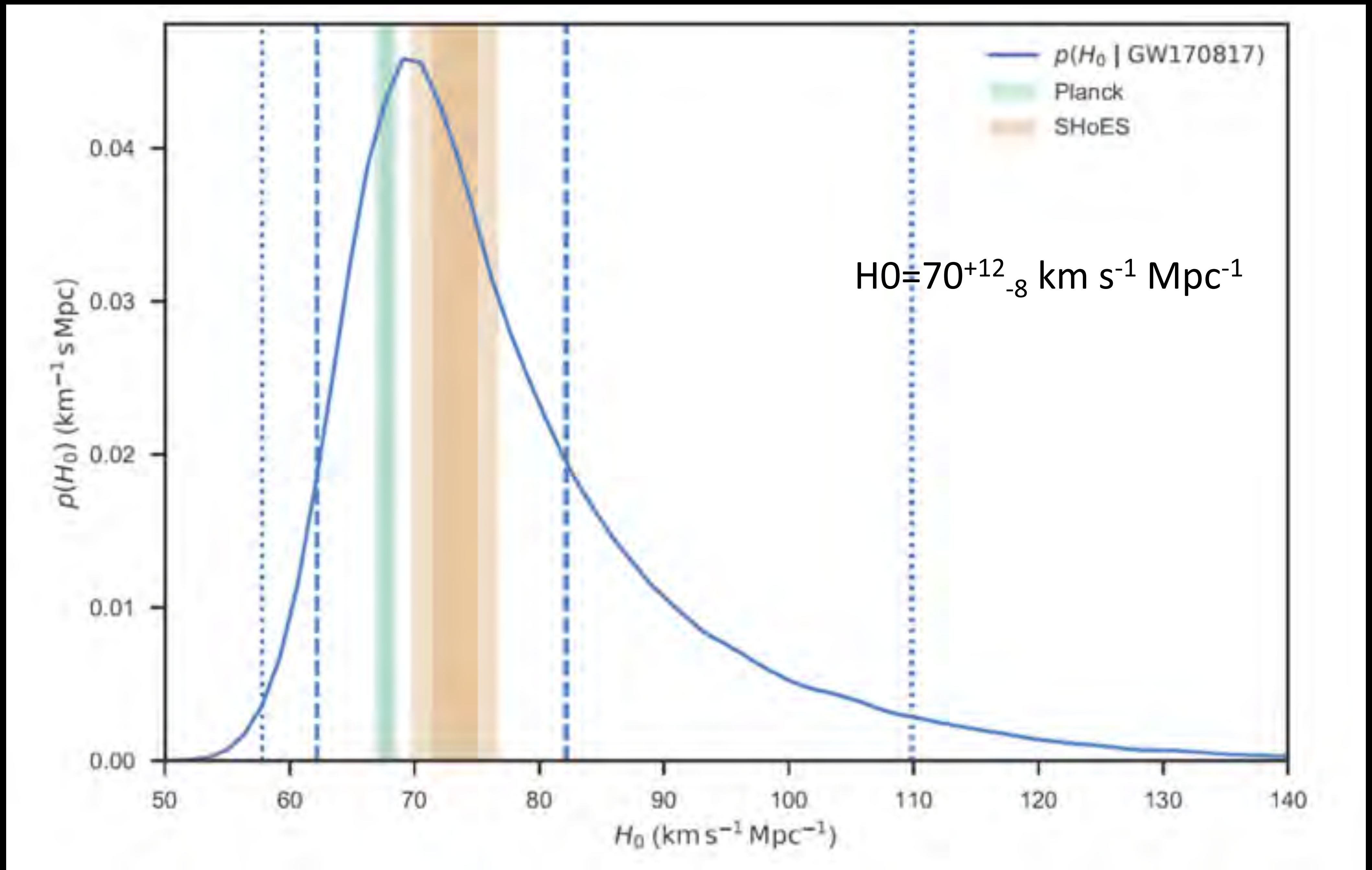
# Gravitational waves

| | Low-spin priors ($|\chi| \leq 0.05$) | High-spin priors ($|\chi| \leq 0.89$) |
|---|---|---|
| Primary mass $m_1$ | 1.36–1.60 $M_\odot$ | 1.36–2.26 $M_\odot$ |
| Secondary mass $m_2$ | 1.17–1.36 $M_\odot$ | 0.86–1.36 $M_\odot$ |
| Chirp mass $\mathcal{M}$ | $1.188^{+0.004}_{-0.002} M_\odot$ | $1.188^{+0.004}_{-0.002} M_\odot$ |
| Mass ratio $m_2/m_1$ | 0.7–1.0 | 0.4–1.0 |
| Total mass $m_{\mathrm{tot}}$ | $2.74^{+0.04}_{-0.01} M_\odot$ | $2.82^{+0.47}_{-0.09} M_\odot$ |
| Radiated energy $E_{\mathrm{rad}}$ | $> 0.025 M_\odot c^2$ | $> 0.025 M_\odot c^2$ |
| Luminosity distance $D_{\mathrm{L}}$ | $40^{+8}_{-14}$ Mpc | $40^{+8}_{-14}$ Mpc |
| Viewing angle $\Theta$ | $\leq 55°$ | $\leq 56°$ |
| Using NGC 4993 location | $\leq 28°$ | $\leq 28°$ |
| Combined dimensionless tidal deformability $\tilde{\Lambda}$ | $\leq 800$ | $\leq 700$ |
| Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$ | $\leq 800$ | $\leq 1400$ |

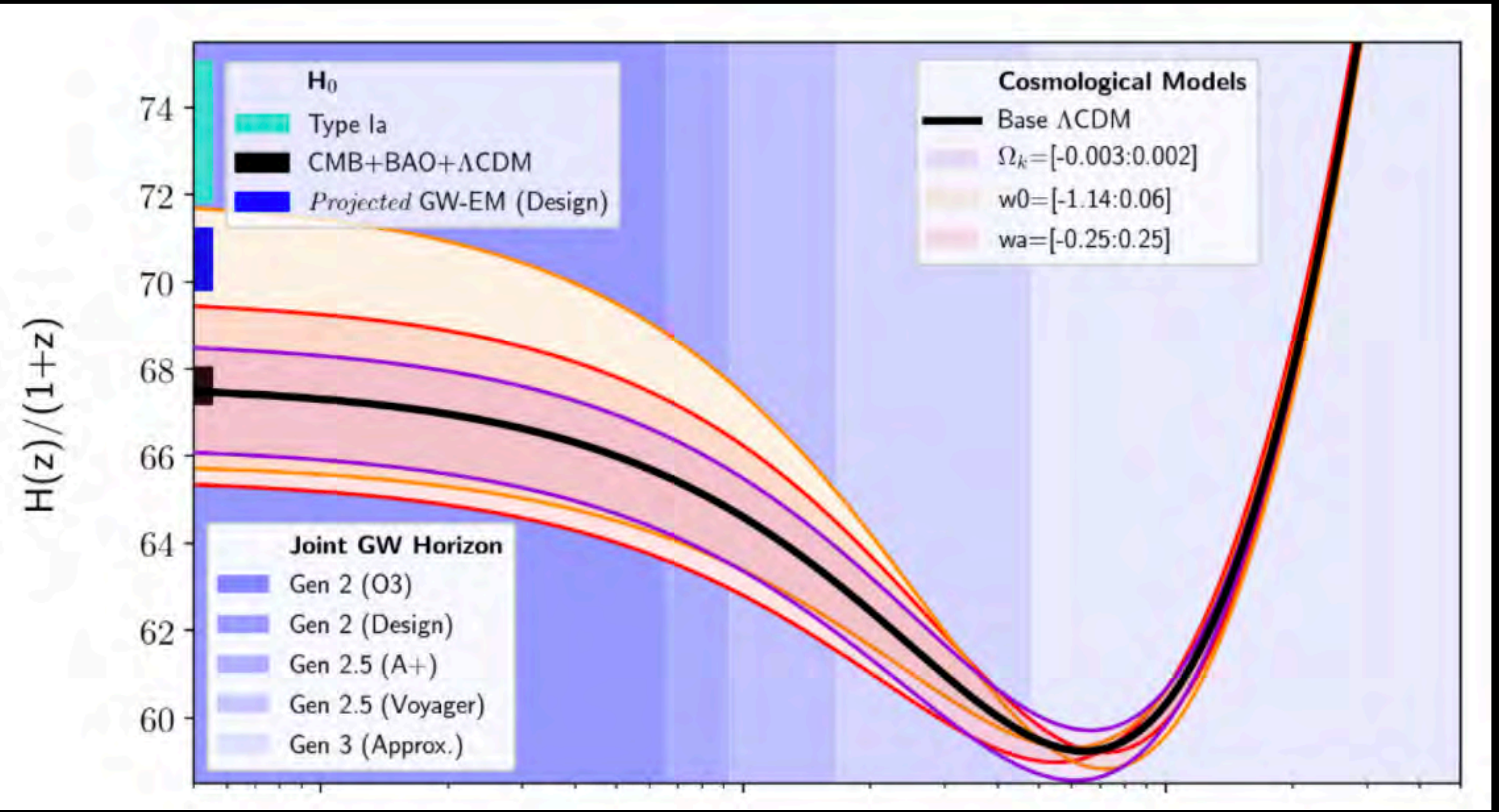
- Masses in the range 1.17 – 1.6 $M_{sun}$ (consistent with neutron stars)
- Distance $40^{+8}_{-14}$ Mpc (close!)
- Viewing angle less than 28 deg (i.e. we are not viewing this side on)
- Rate of neutron star mergers  (based on one detection!)

# Cosmology

- Hubble Constant - Expansion Rate of the Universe
- Measurements currently in conflict between
  - Cosmic Microwave Background
  - Type Ia Supernovae
- GW counterparts (independent distance measurements from GW and redshift) could help reconcile




**Abbott et al., 2017, Nature**




**Burns et al. in-preparation**

# Gravitons and photons arrived ~together

$$\Delta v = v_{\rm GW} - v_{\rm EM}$$

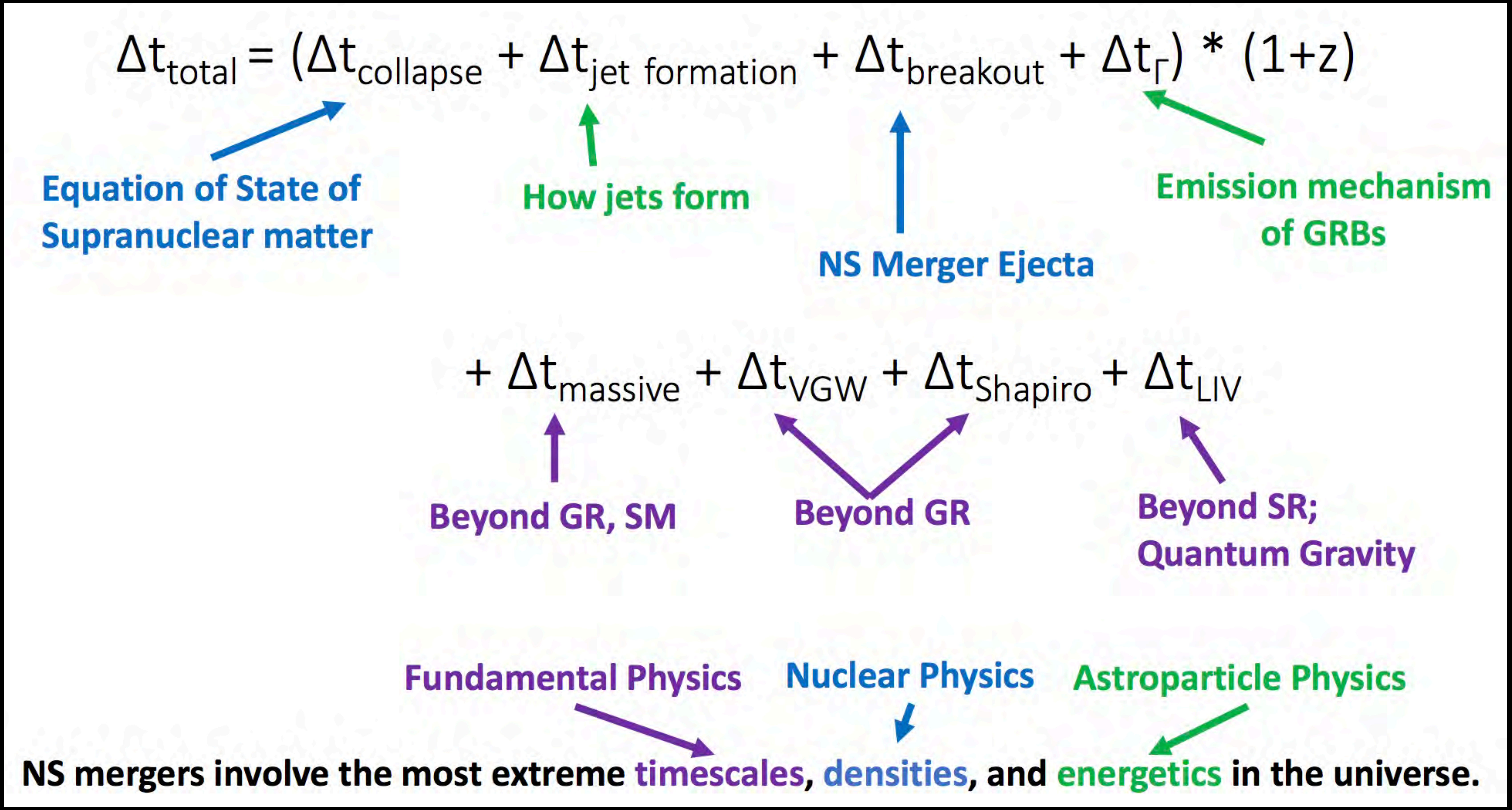
$$\Delta v / v_{\rm EM} \approx v_{\rm EM} \Delta t / D$$

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

Assuming D = 26 Mpc (the lower bound on the 90% confidence interval for distance based on GW data alone, and bounding t between [-10, +1.74] s, where the -10 s is a reasonably conservative assumption.

# Fundamental Physics

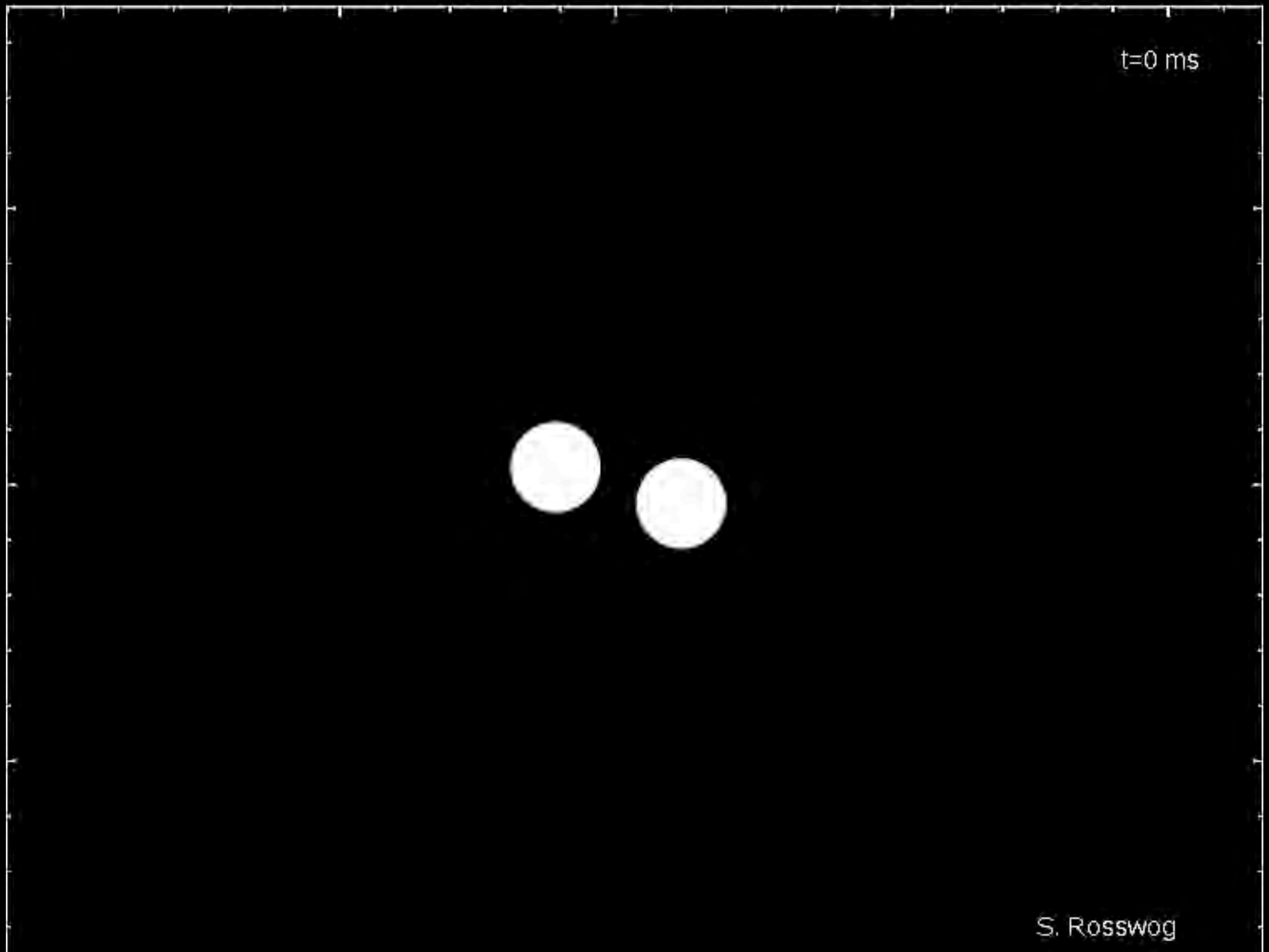
Time delay between merger (GW signal) and GRB = 1.7 s



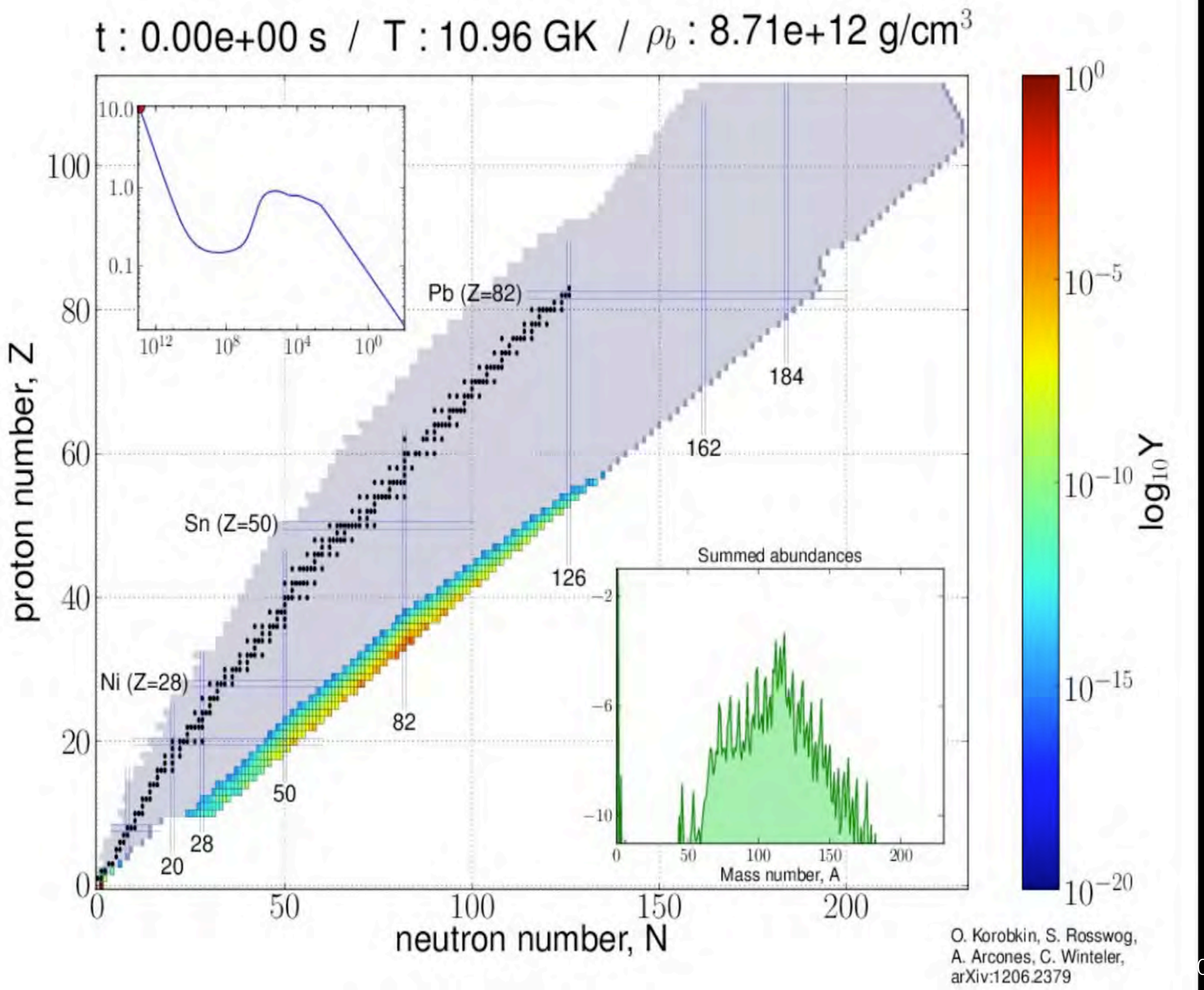

**Burns et al. in-preparation**

***Credit: Eric Burns (NASA/GSFC/USRA)***

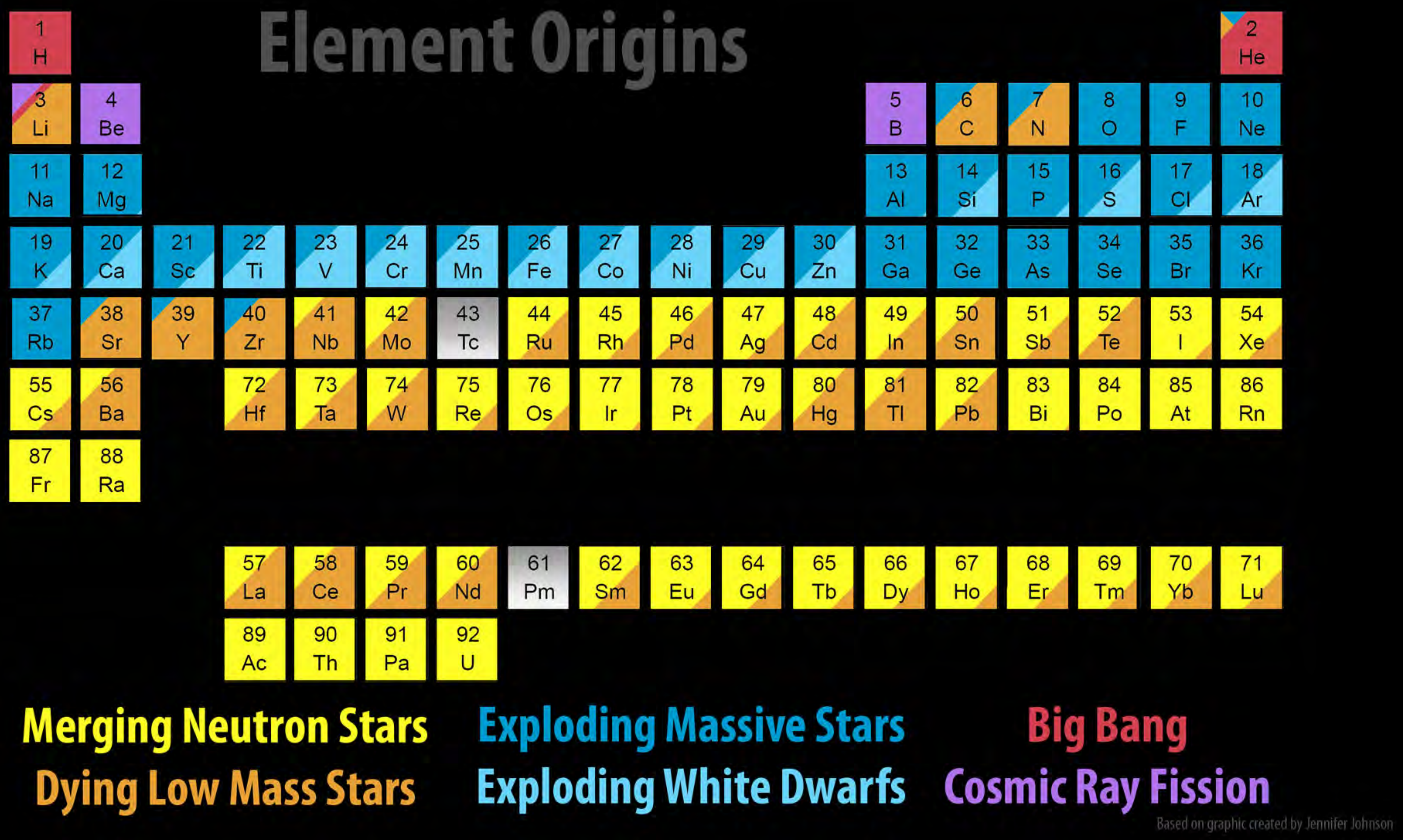
# Neutron star mergers are messy



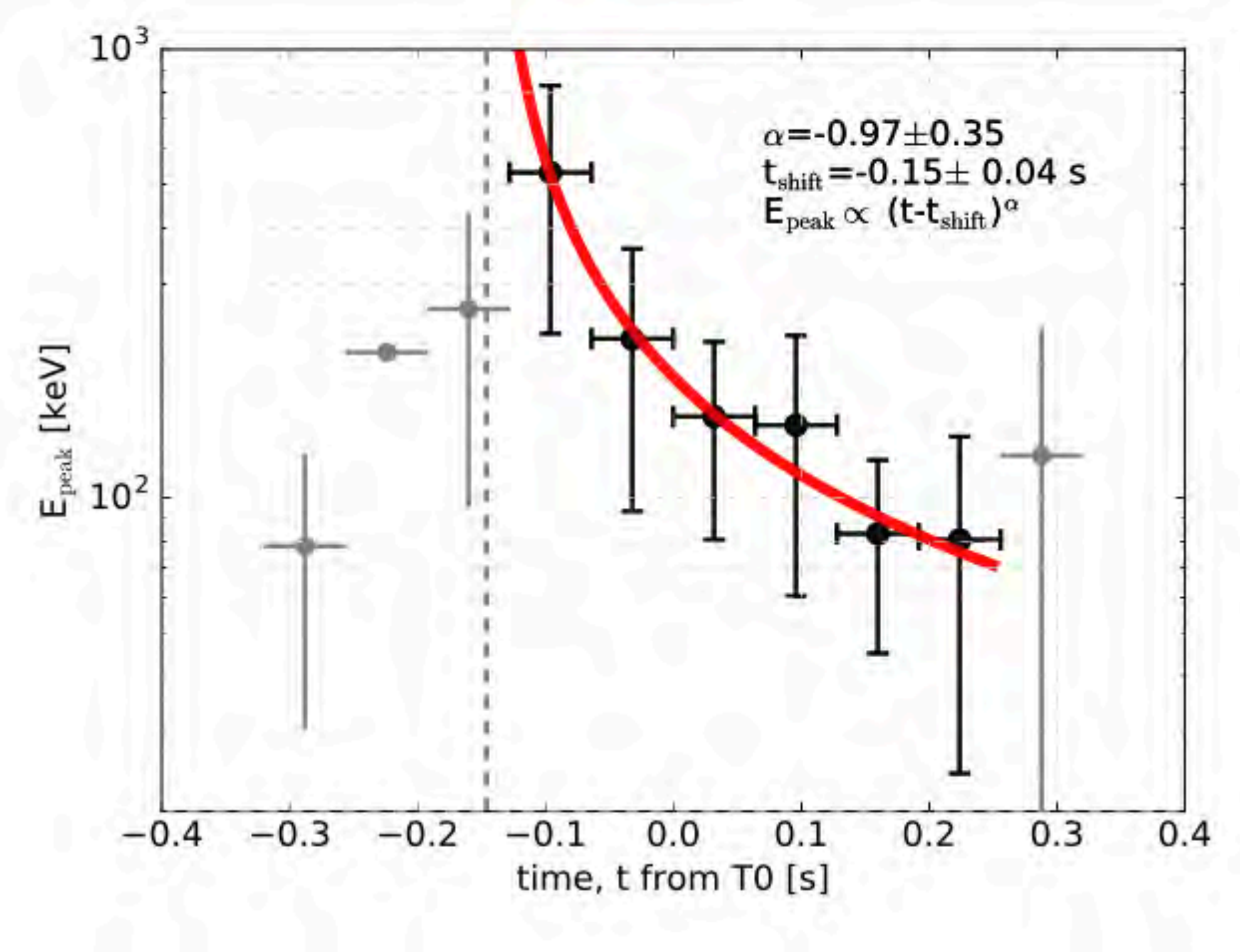
# R-Process Nucleosynthesis



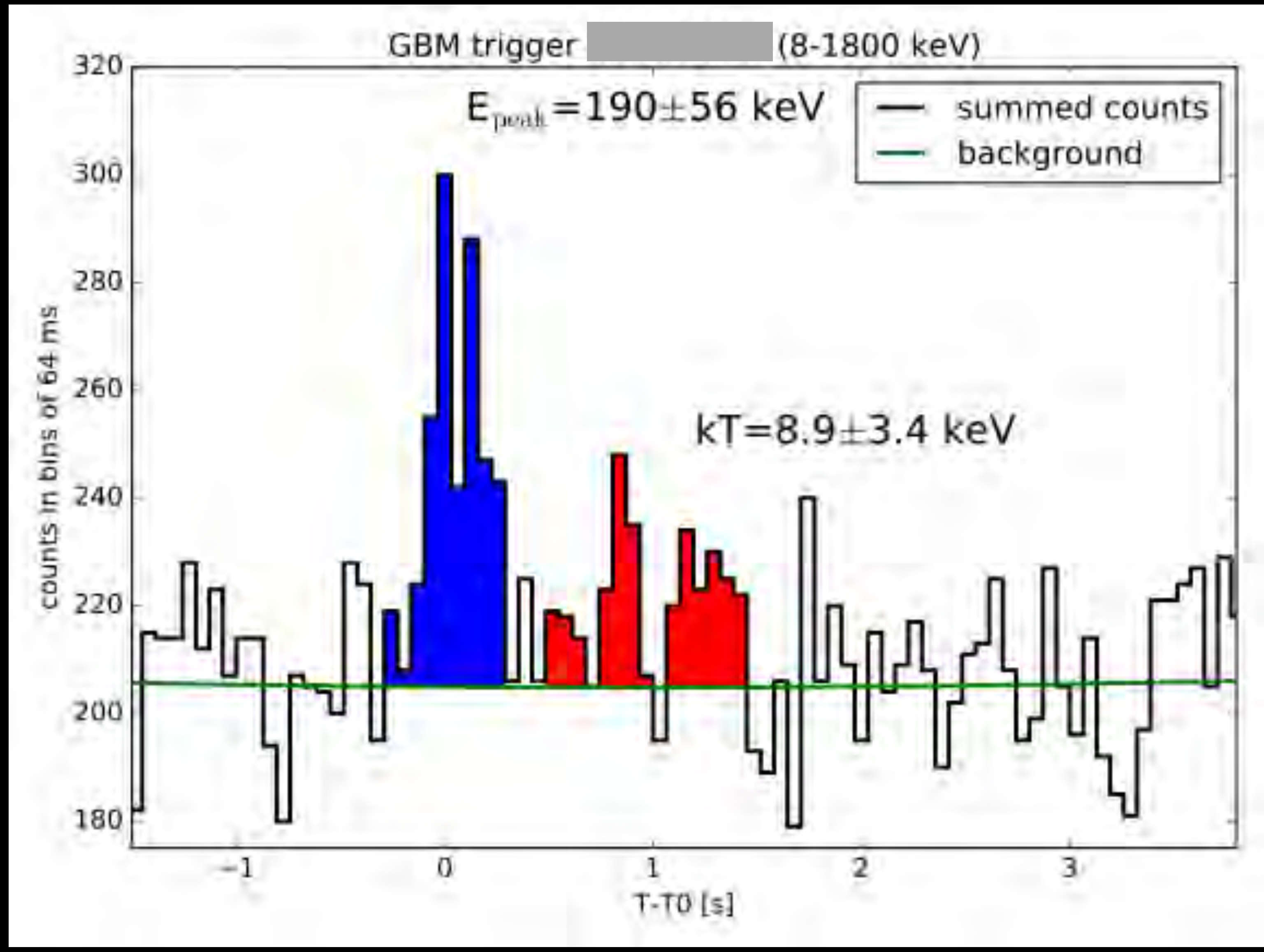
# r-Process Nucleosynthesis



# Challenging Gamma-ray Observations



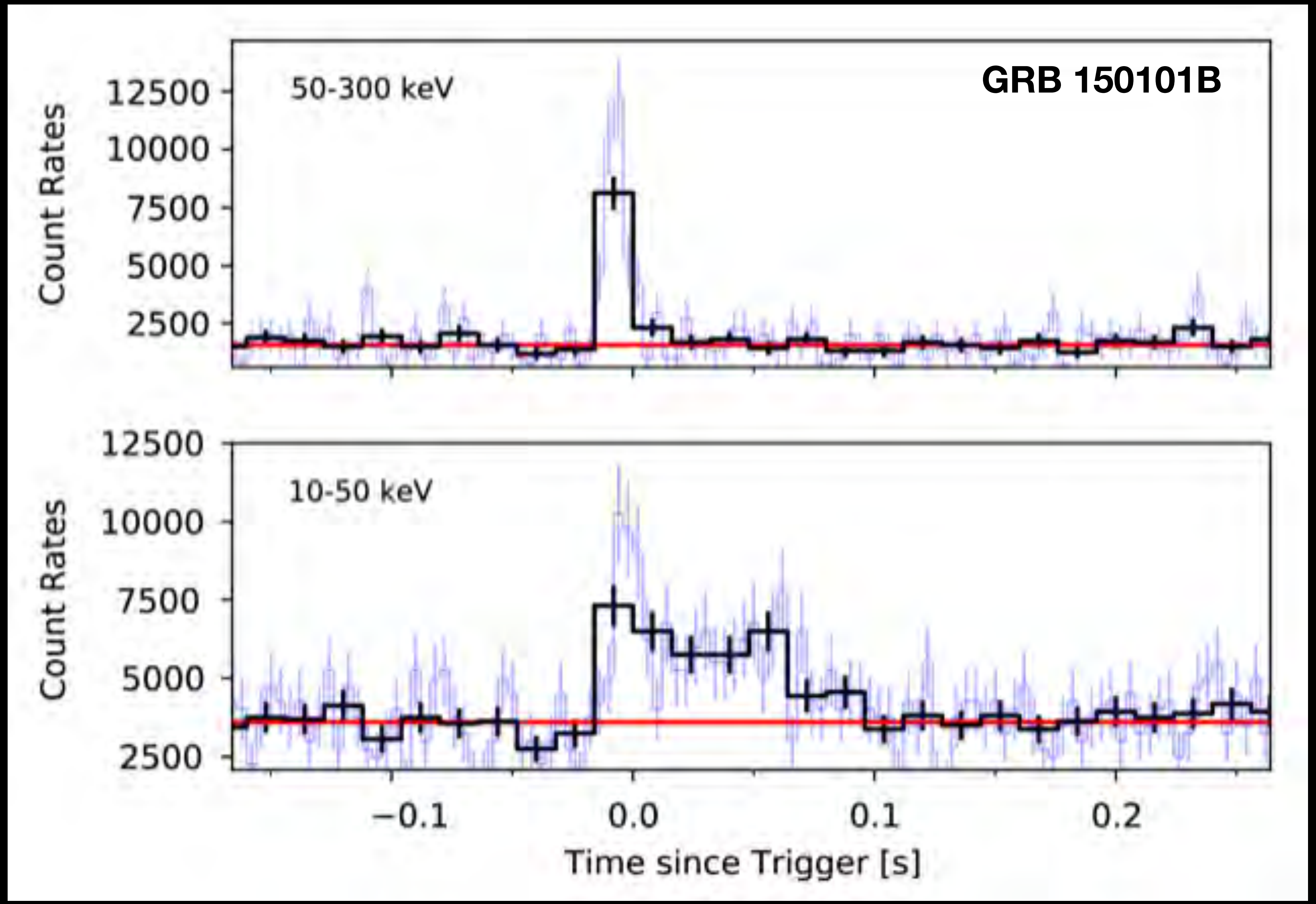

Veres et al. 2018

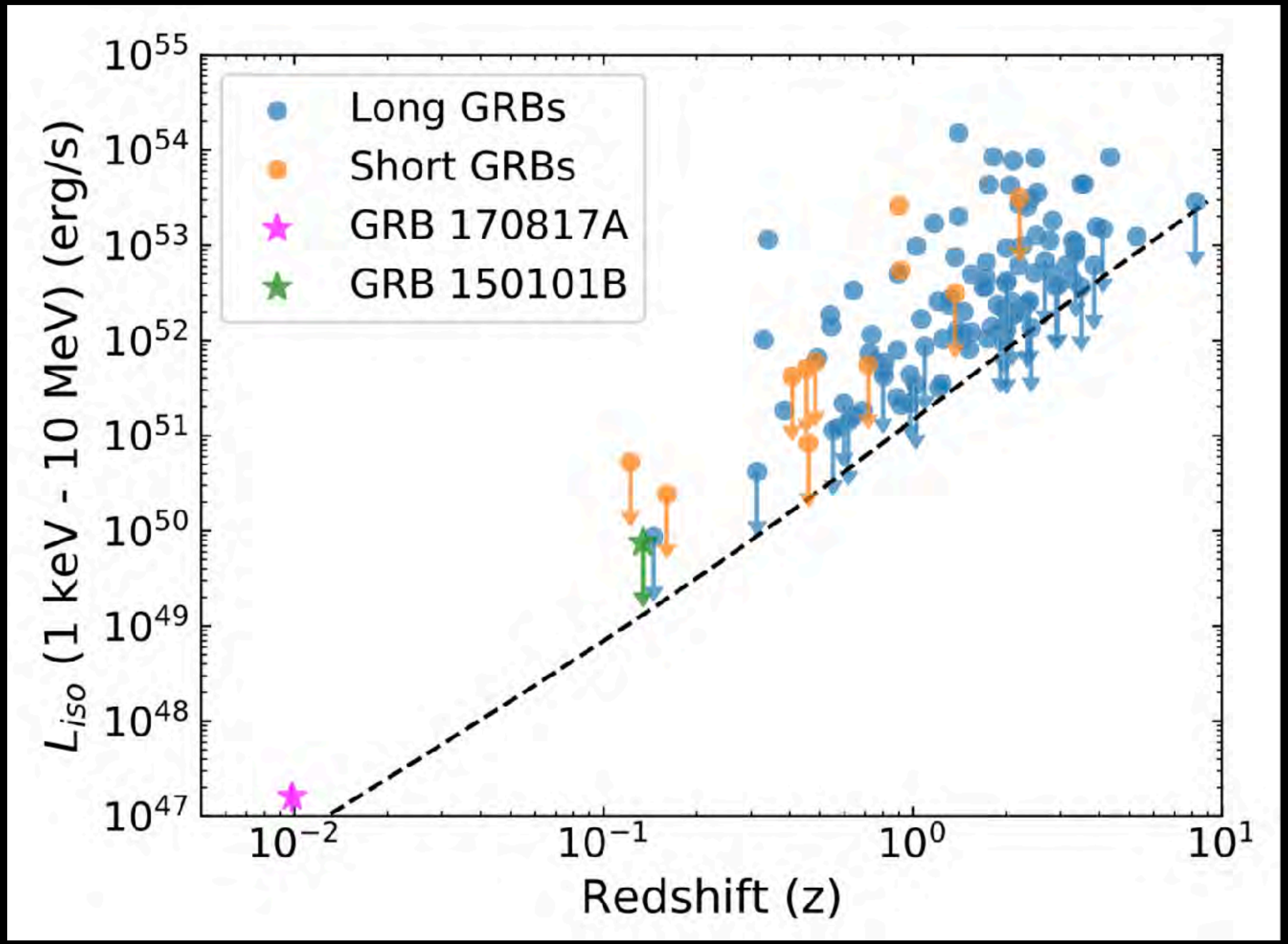



Von Kienlin in prep.

- A time resolved spectral analysis has shown evidence for very high $E_{peak}$ values
- High $E_{peak}$ values become challenging for the cocoon shock breakout model to explain
- We have found bursts that resemble GRB 170817 in BATSE, GBM, and Swift data
- Very preliminary, but evidence for sub-structure in some of these cases

# GRB 150101B




**Burns et al 2018**

- The third closest SGRB with known redshift - GRB 150101B
- Very hard initial pulse with $E_{peak}$ =1280±590 keV followed by a soft thermal tail with kT~10 keV
- Unlike GRB 170817, 150101B was not under luminous and can be modeled as an on-axis burst
- Suggests that the soft tail is common, but generally undetectable in more distant events
- Thermal tail can be explained as GRB photosphere, but degeneracy with the cocoon model still exists

# Open Questions

- Where did the gamma-rays come from? How to reconcile other indicators of off-axis emission?
- Jet structure, implications for rates in future?
- Weak GRB – implications for luminosity function? Lots of nearby weak events?
- Do other short GRBs show short hard and long soft components?
- Do neutron star - black hole mergers also produce short GRBs?
- What's the maximum mass of a neutron star?
- Is there a short lived hyper-massive neutron star?
- What is the minimum mass of a black hole?
- Can GW-GRBs reconcile Hubble Constant debate?

- Looking forward to more observations!

# A Subset of Future GW Counterpart Missions/Concepts

- BurstCube (2021)
- ISS-TAO (2022)
- Nimble (~2024)
- TAP (2028+)
- AMEGO (2028+)