A Chorus of ‘Cosmic Messengers’ Heralds a New Era of Astrophysics

John Ruan
Bishop’s University

Outline

1. Major multi-messenger science questions
2. Multi-messenger gravitational wave astrophysics: The landmark discovery of GW170817
3. Questions and challenges for the next decade

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1. **Major multi-messenger science questions**

2. Multi-messenger gravitational wave astrophysics: The landmark discovery of GW170817

3. Questions and challenges for the next decade

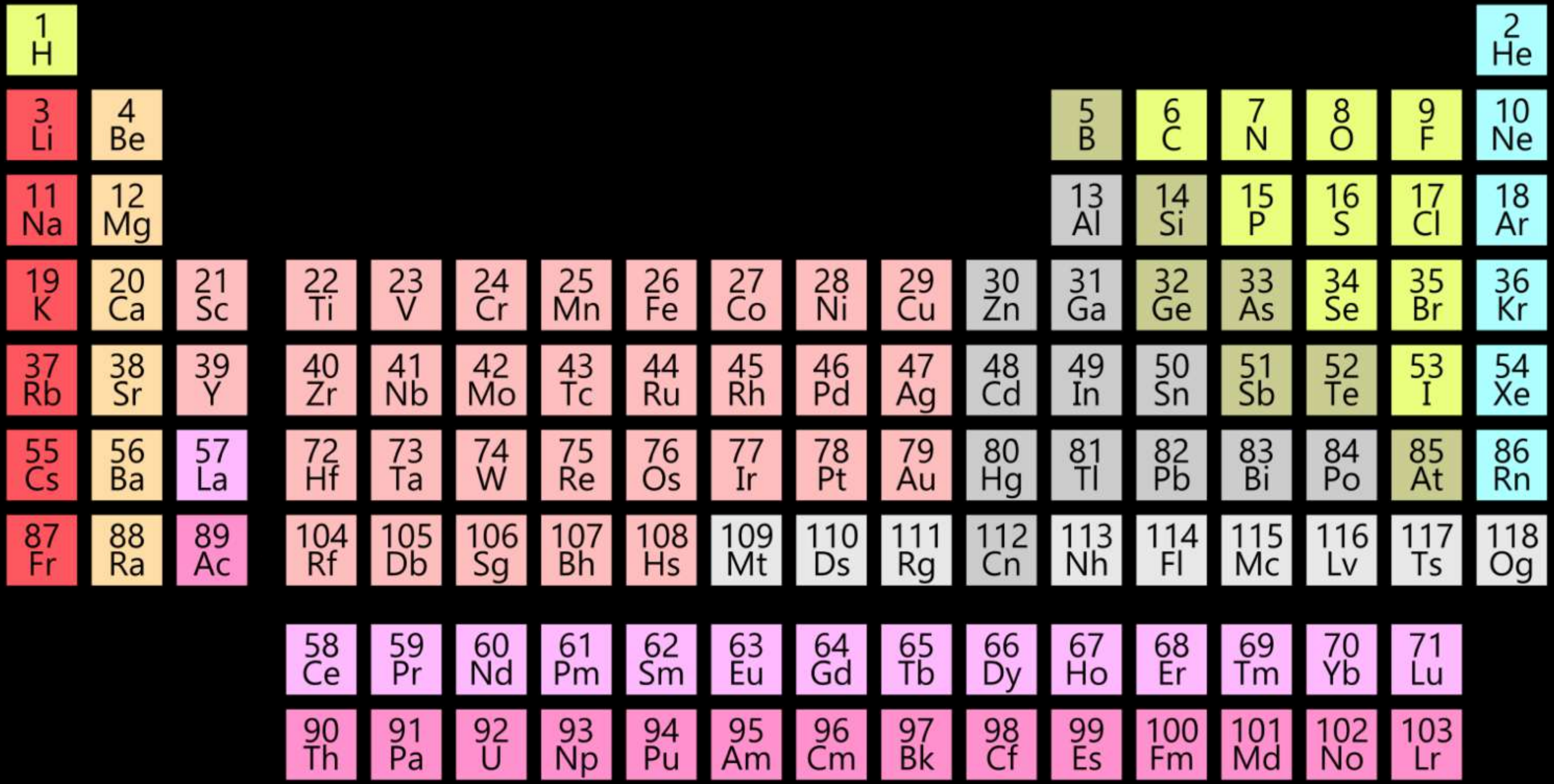
Open questions

1. What is the origin of the heaviest elements in the Universe?

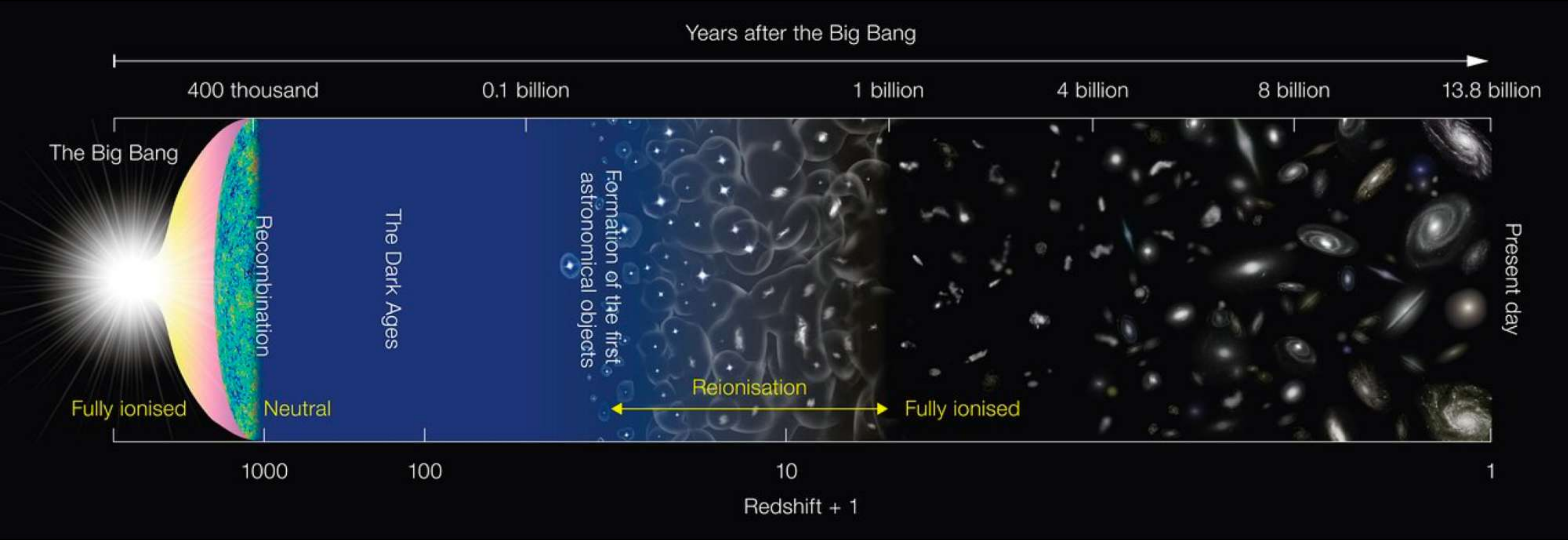
2. What is the origin of short Gamma-ray bursts?

3. What is the expansion rate of the Universe?

We see different types of elements all around us, but where do they come from?



Hydrogen, Helium, and Lithium were produced in the hot and dense early Universe



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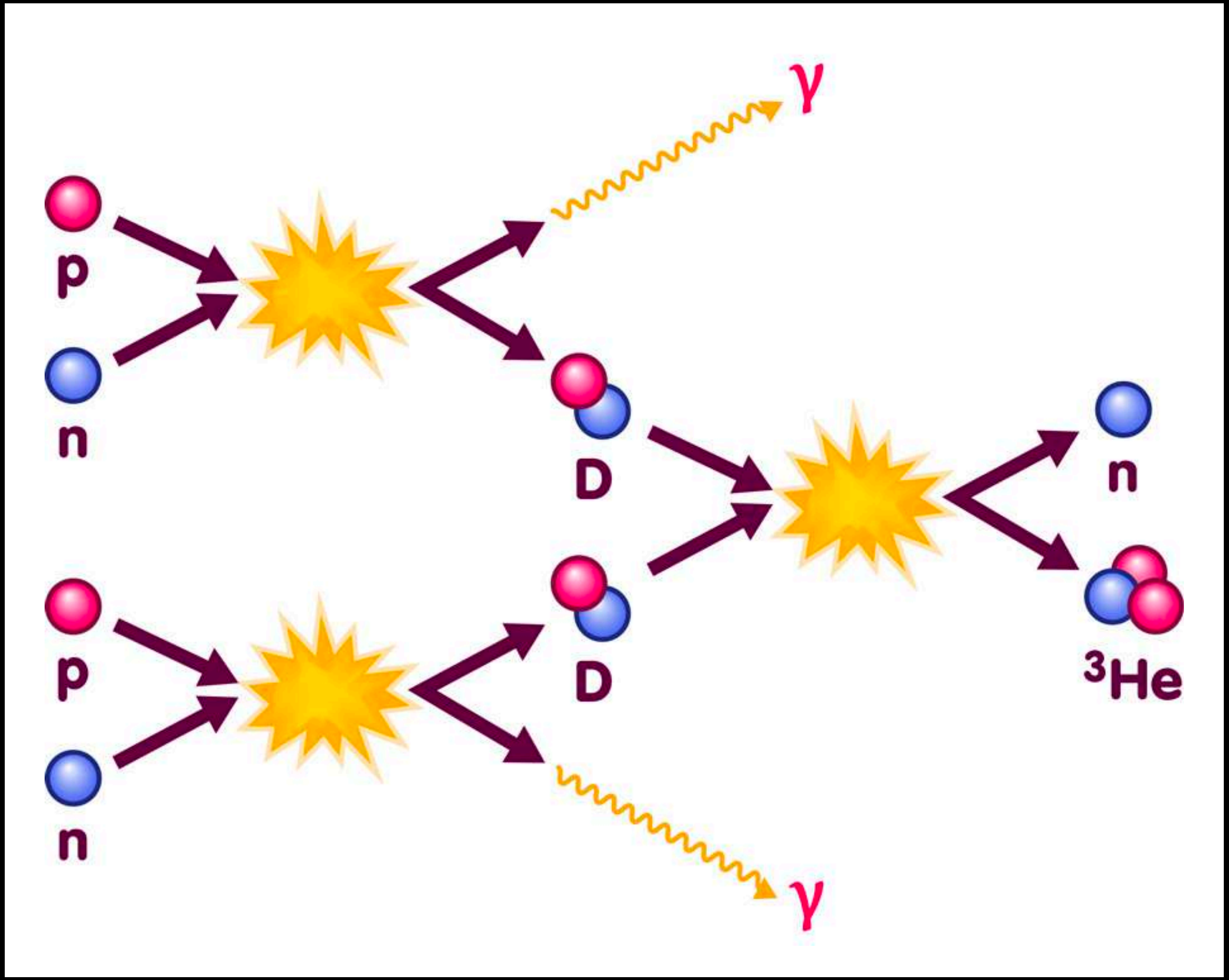

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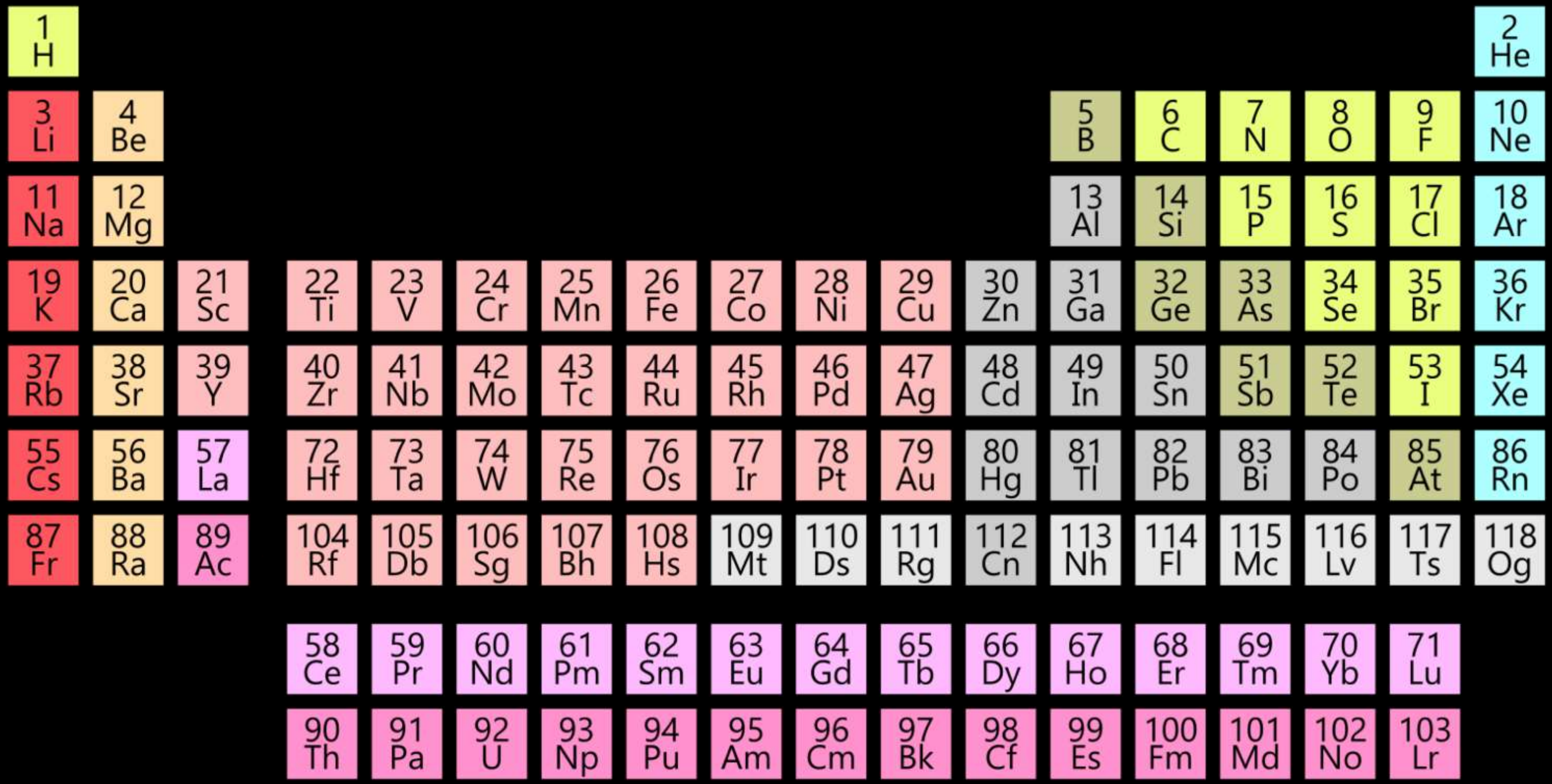
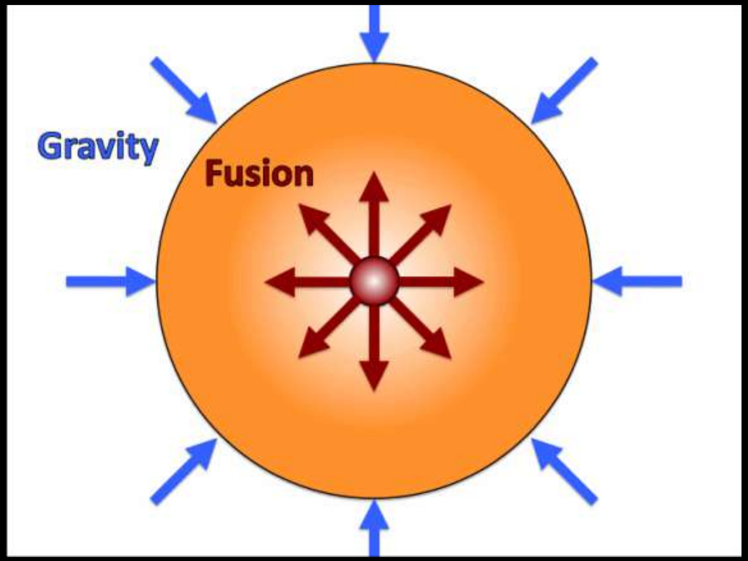
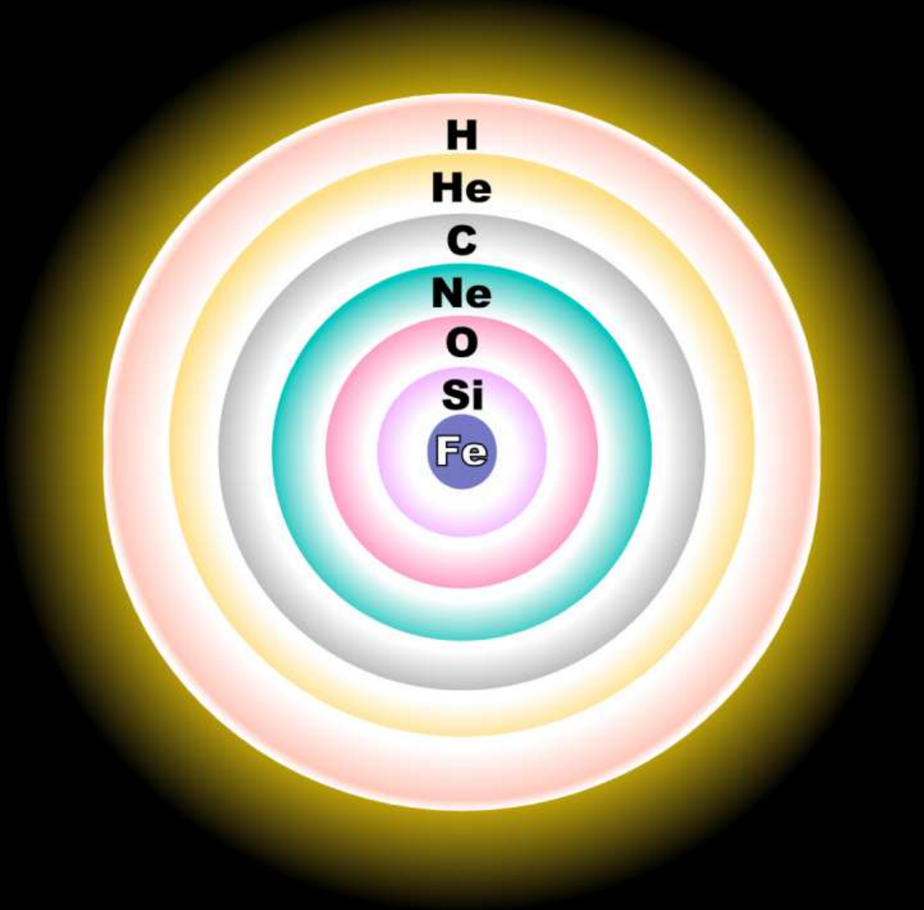
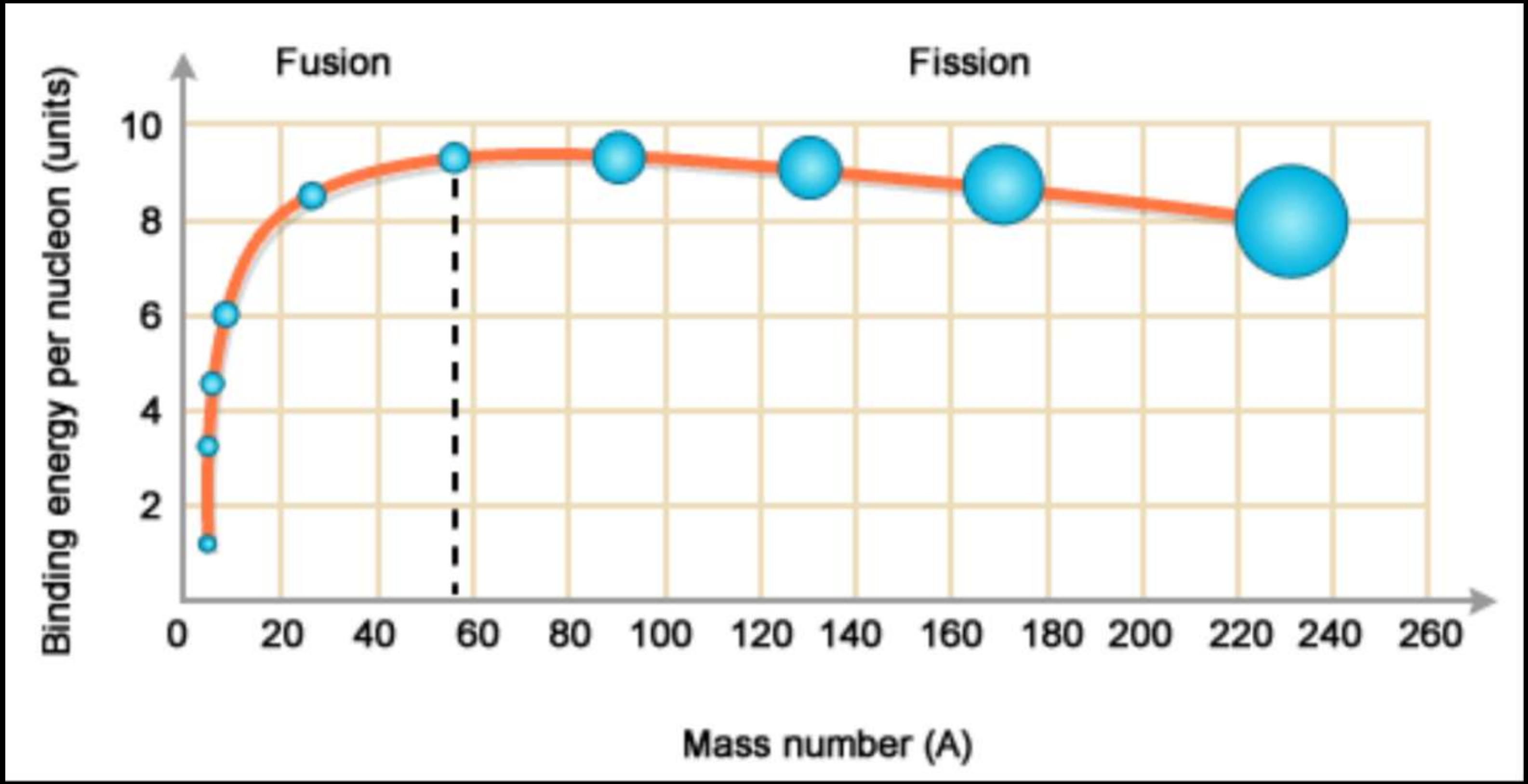


Heavier elements were forged in stars





Fusion in stars stops at iron. Fusion of elements heavier than iron results in a net loss of energy.



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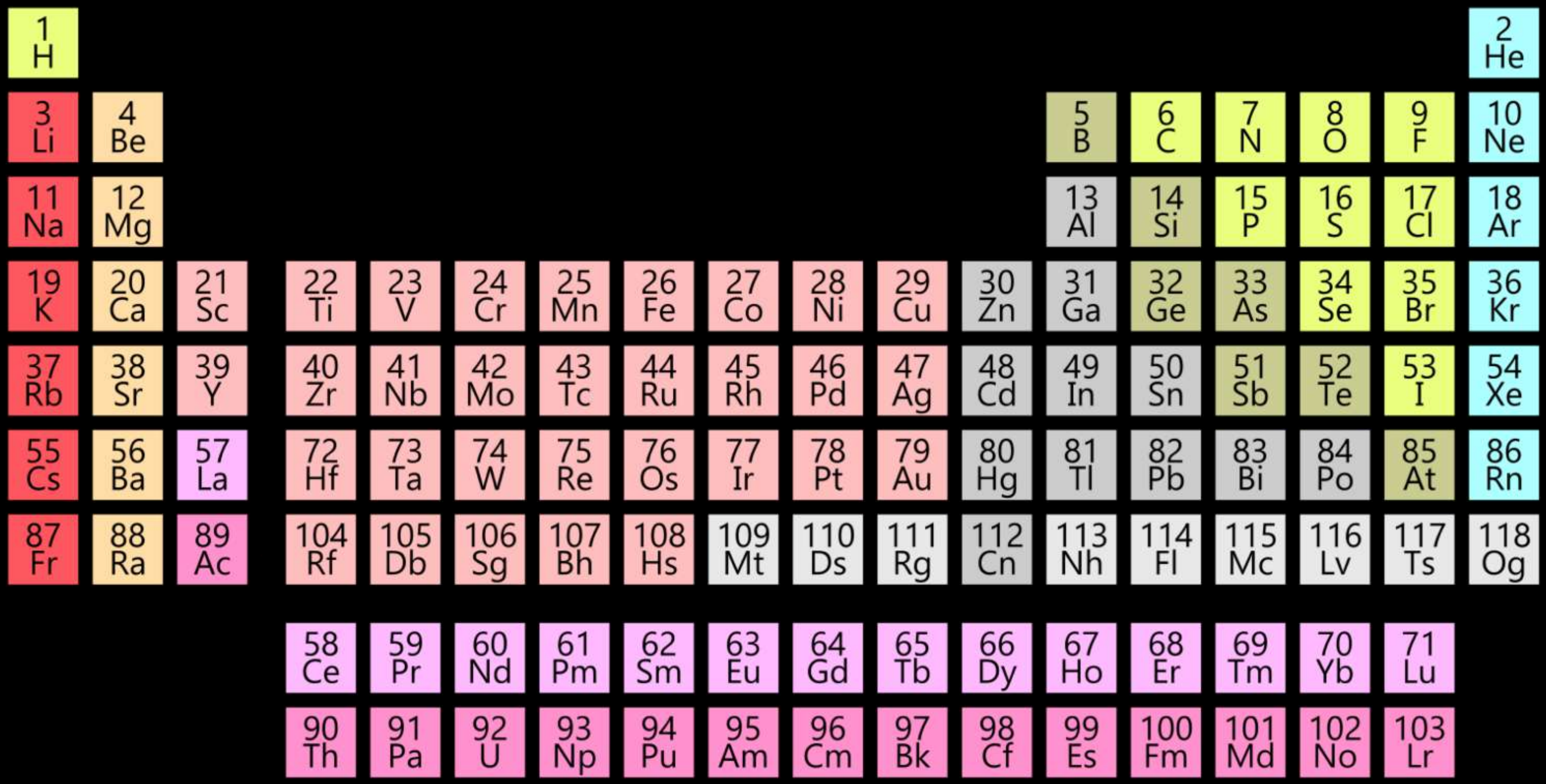
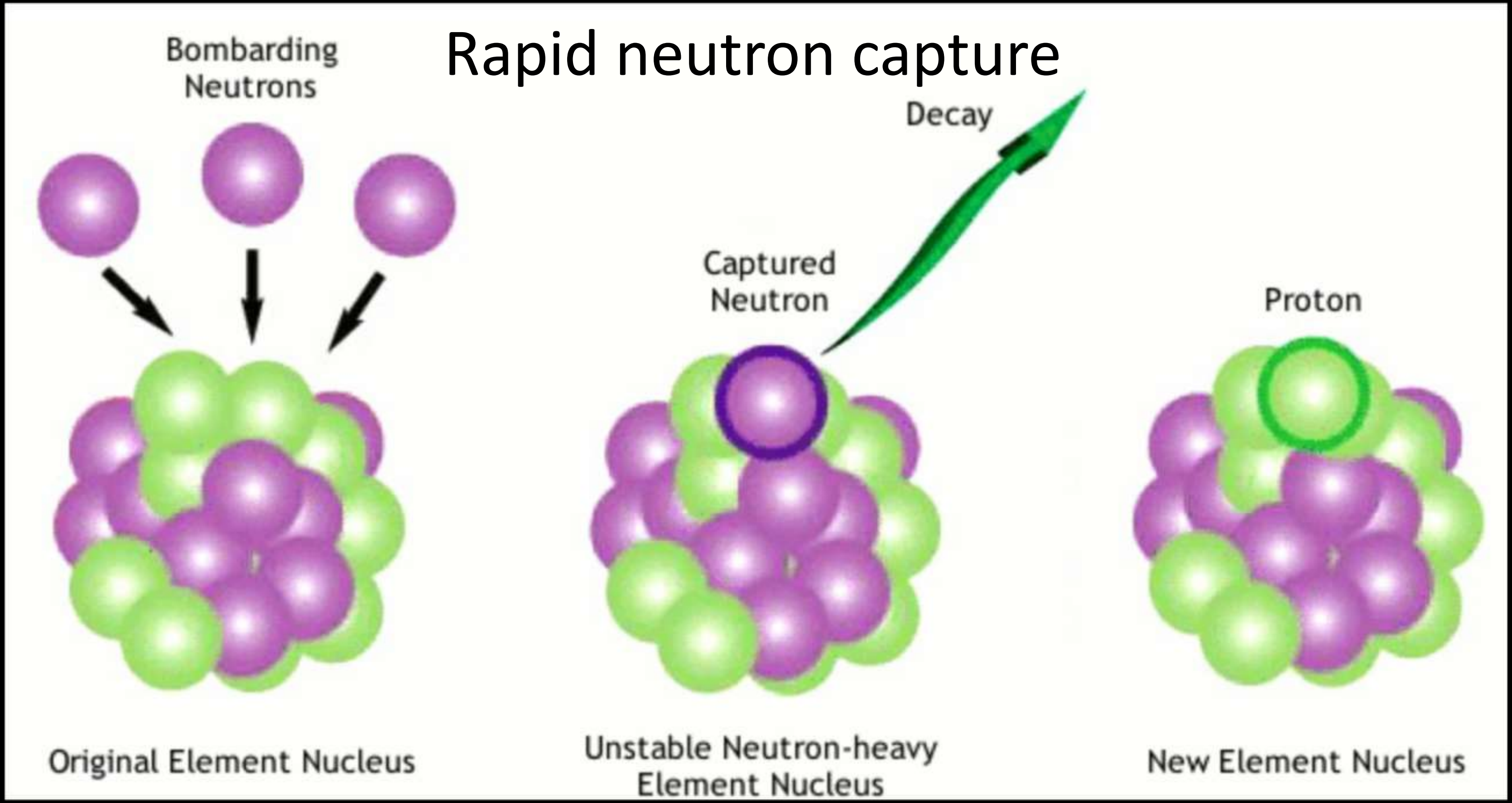
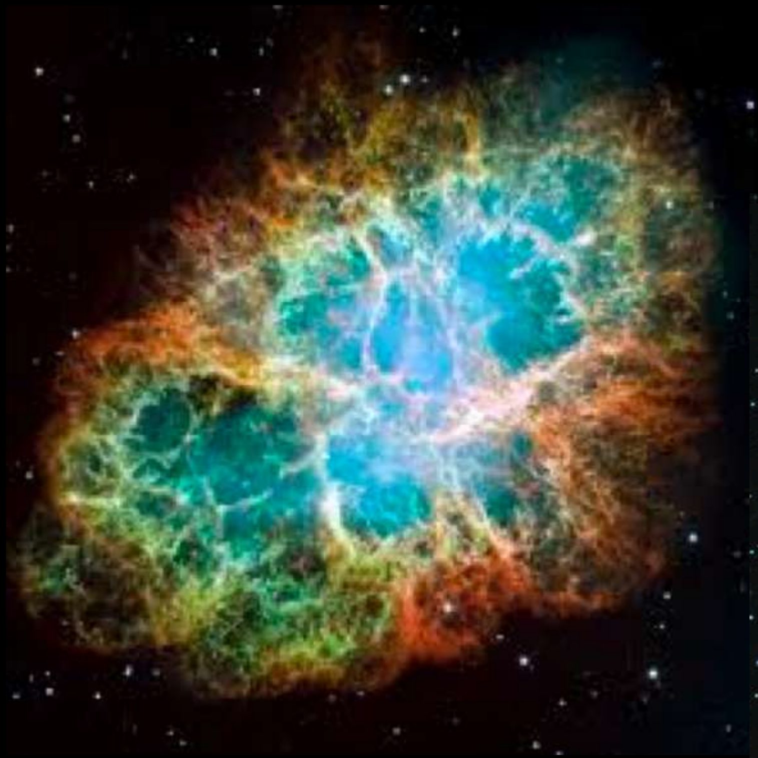


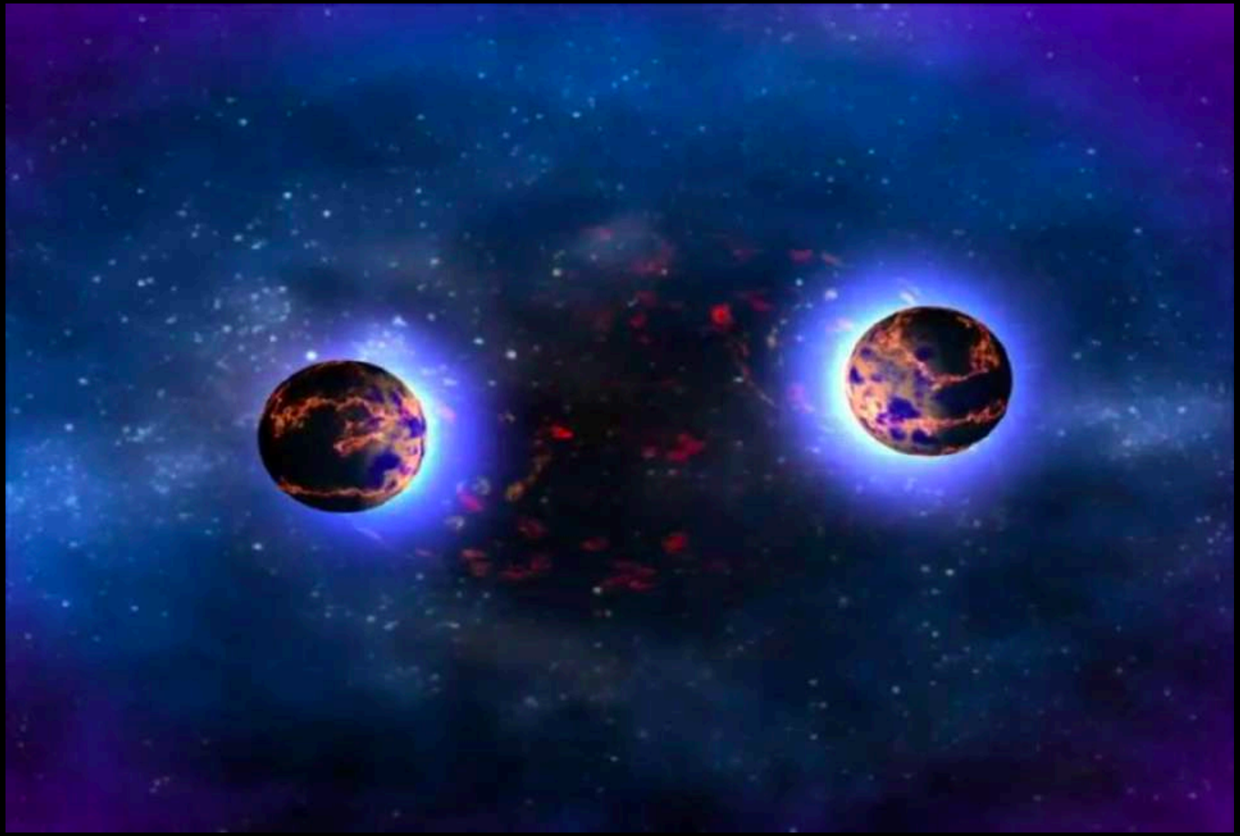
Rapid neutron capture (r-process) nucleosynthesis is needed to produce the heaviest elements



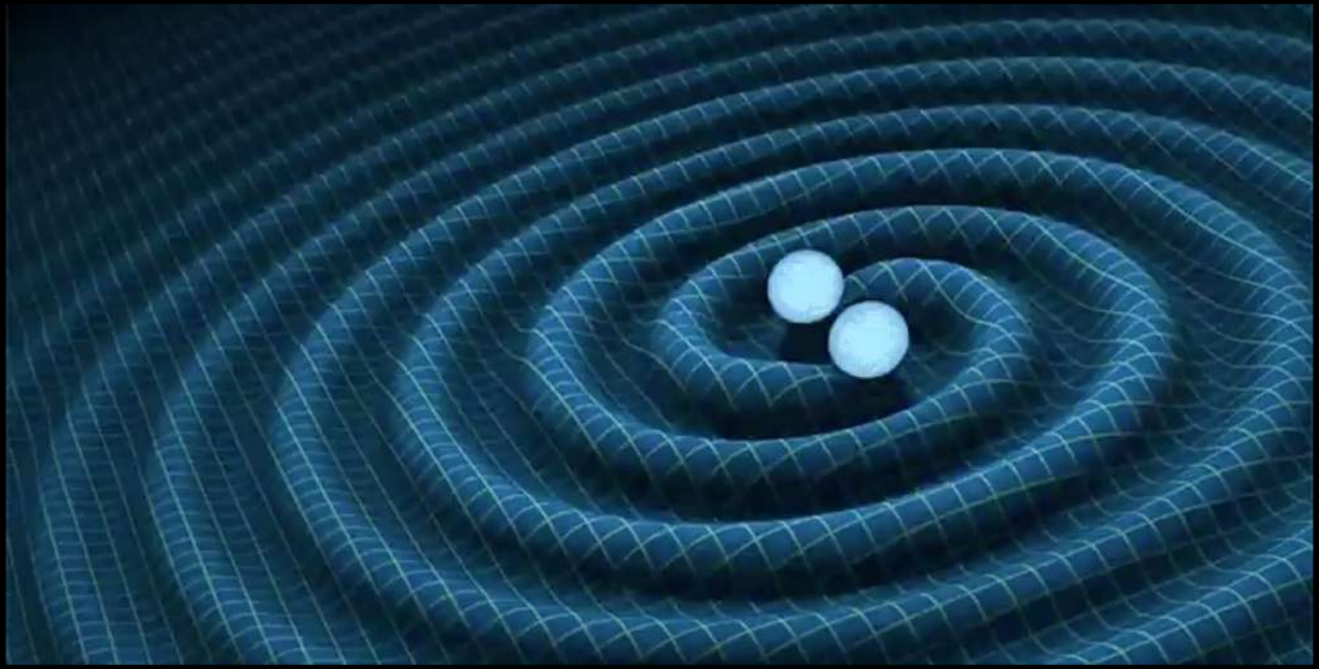
Supernovae do not produce a significant amount of r-process elements



A merger of two neutron stars would liberate a lot of neutron-rich material, enabling rapid neutron capture to produce elements higher than iron



How can we detect neutron star mergers? Gravitational waves



Open questions

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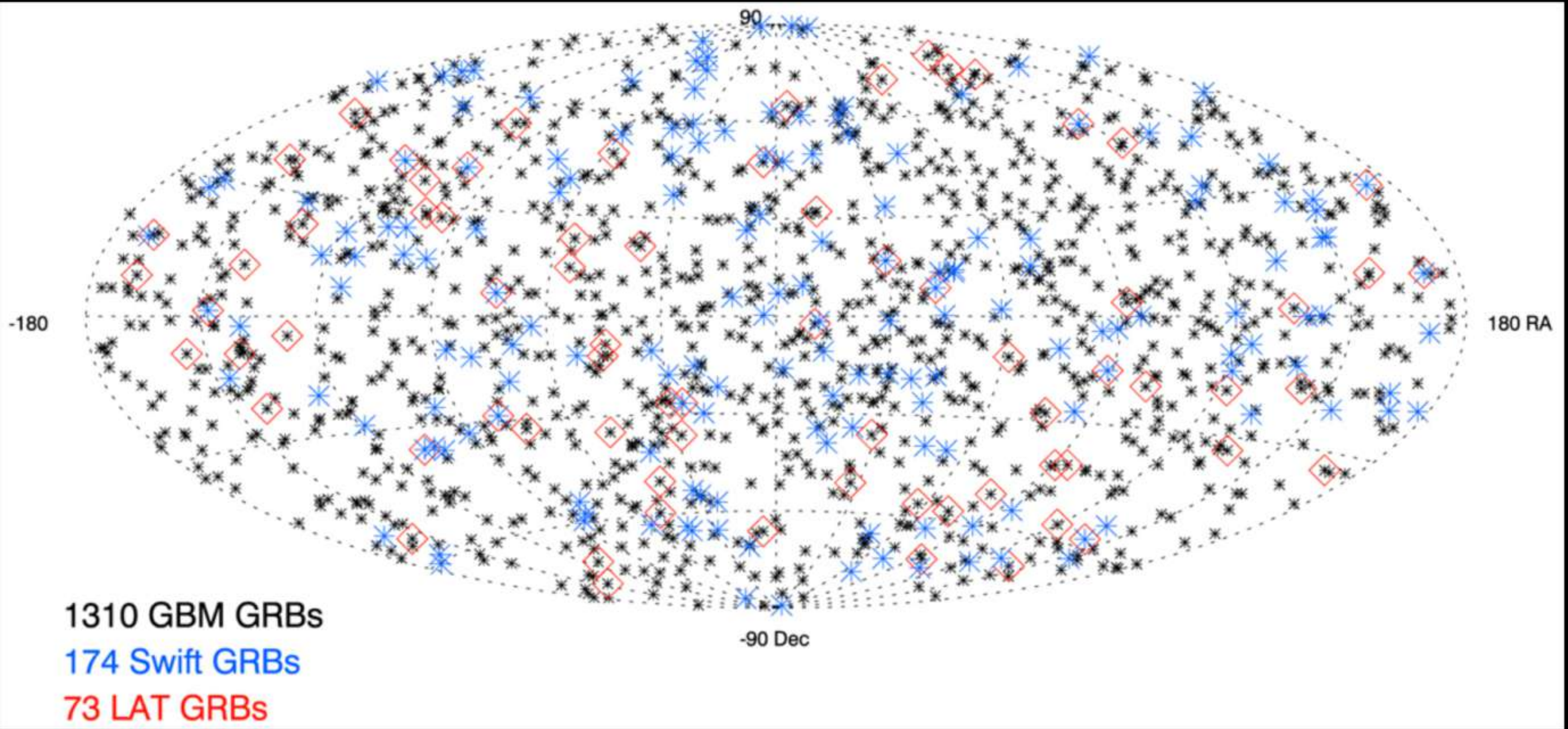
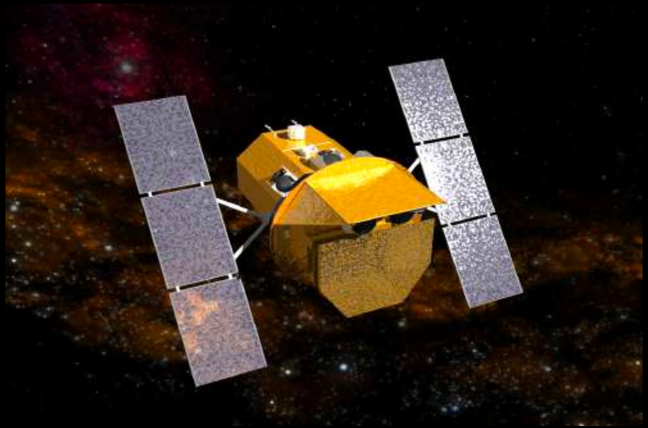
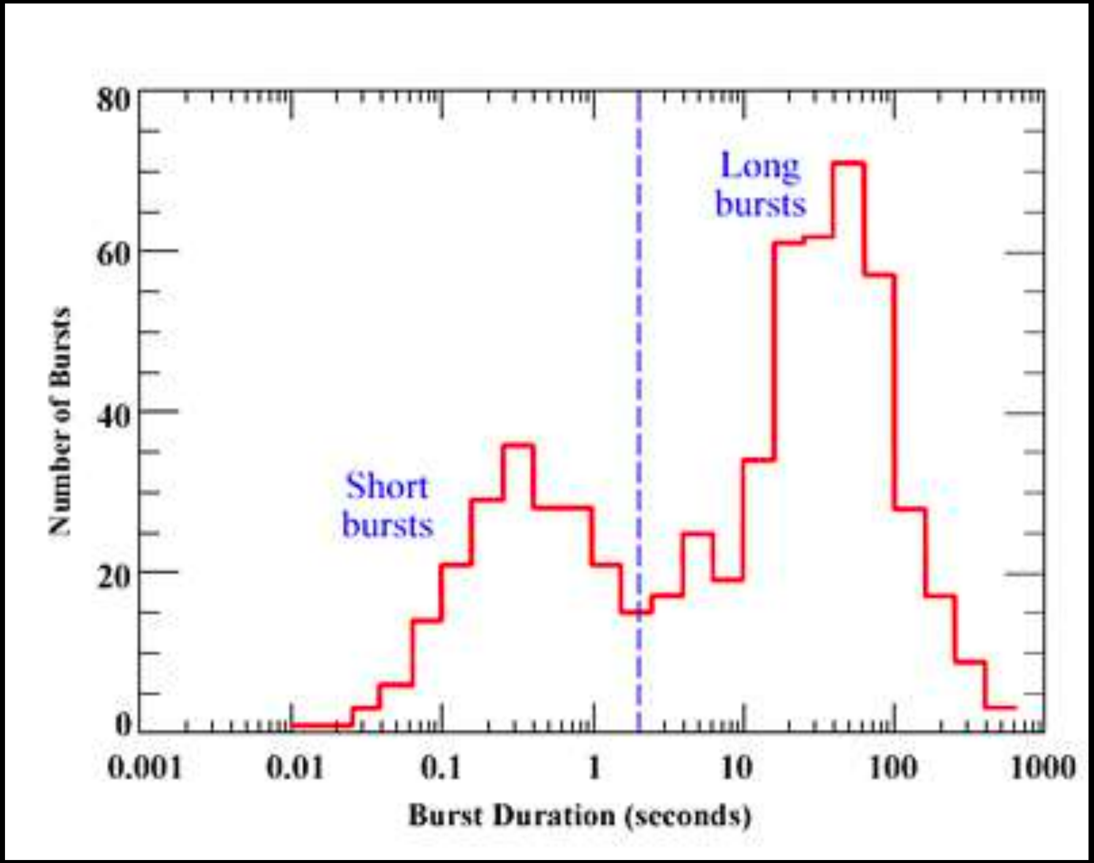
Gamma-ray bursts are flashes of gamma-rays from extragalactic sources

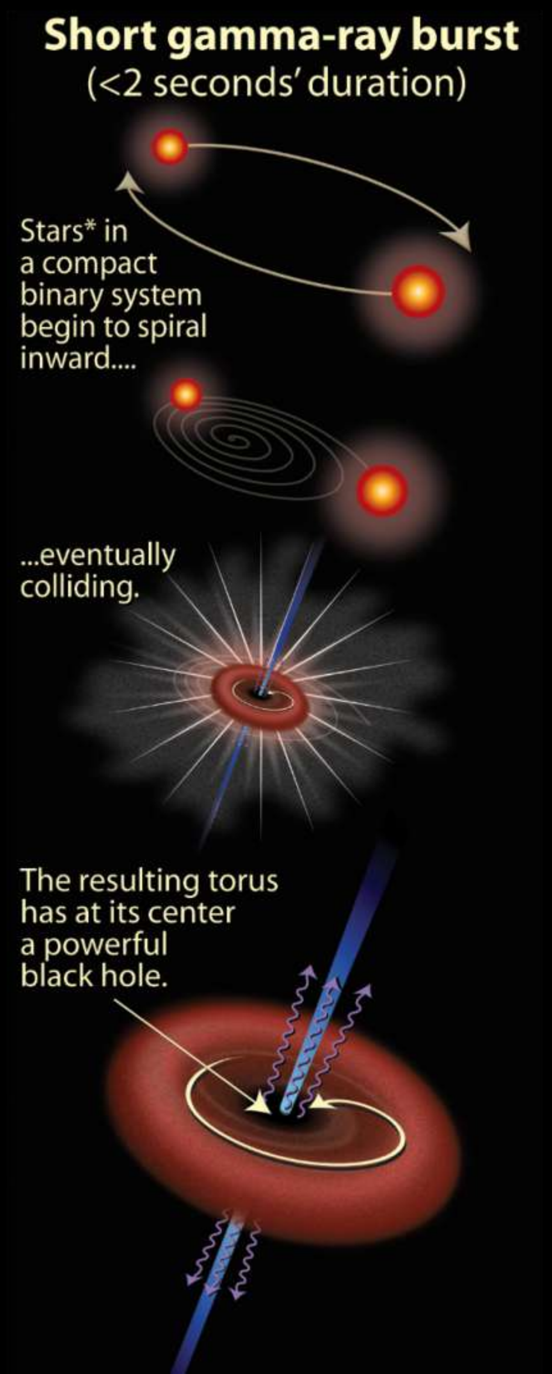




The distribution of burst durations is bimodal, and the origin of short bursts is unclear



It has long been speculated that short gamma-ray bursts result from neutron star mergers



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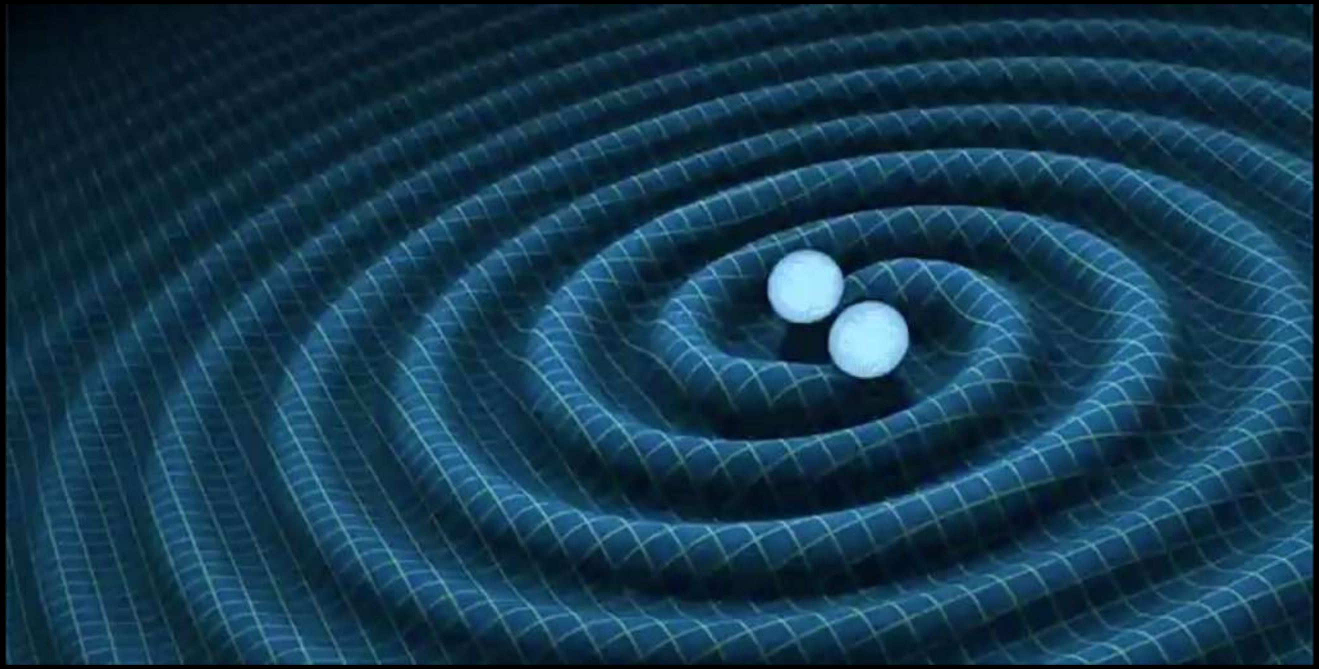

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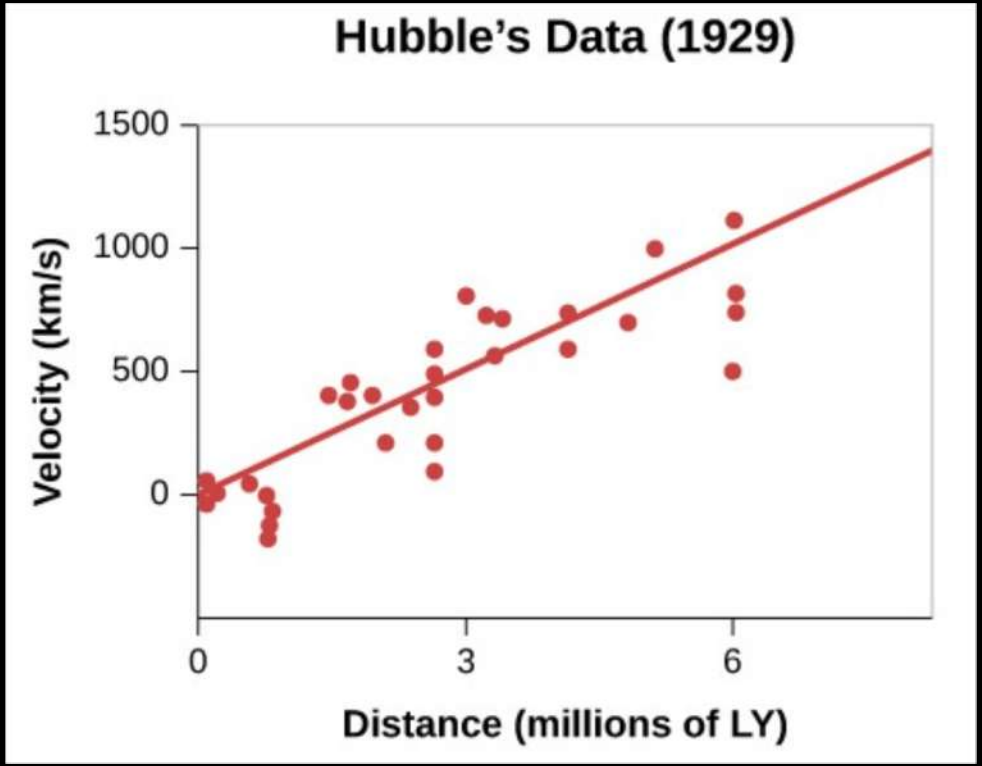
The expansion rate of the Universe (parameterized through the Hubble constant) is can be measured precisely through both the cosmic microwave background and the cosmic distance ladder



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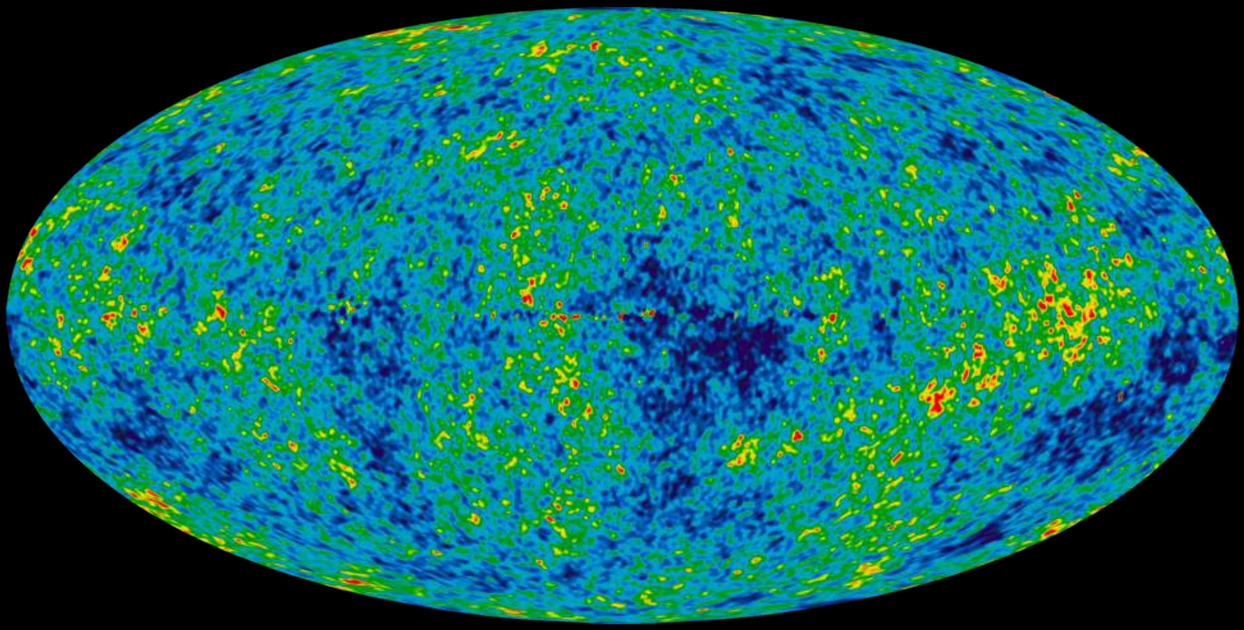
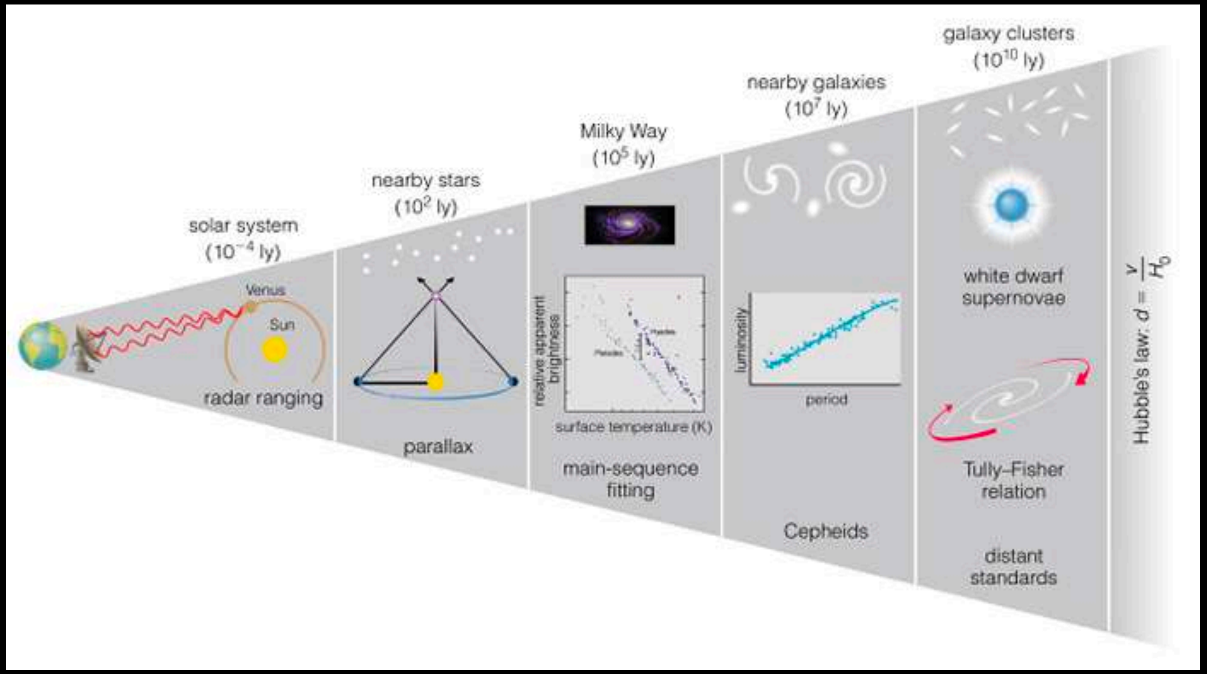
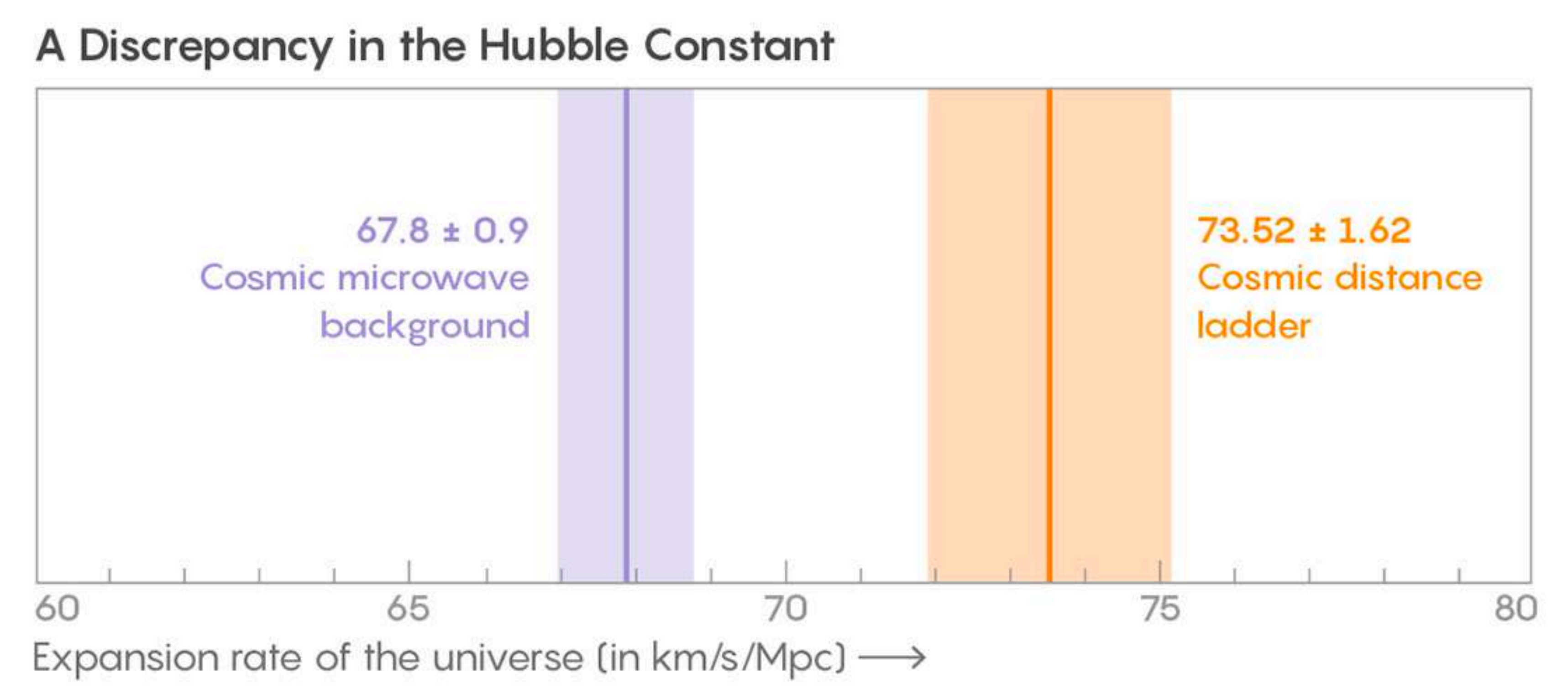
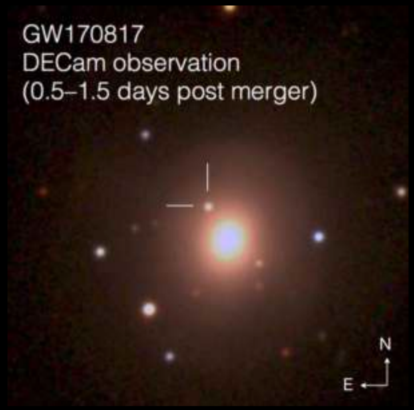


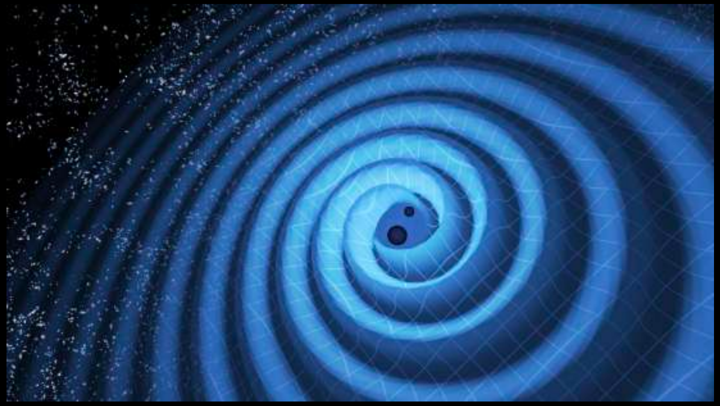


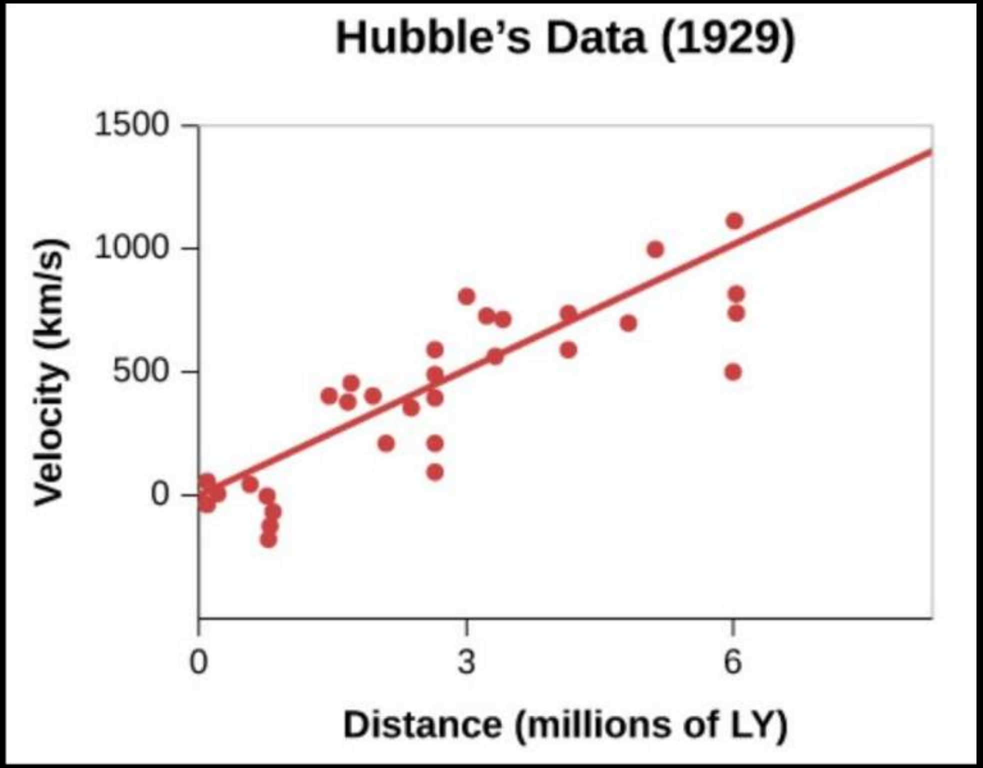
There is currently a >3 sigma tension between these measurements, possibly indicative of new physics



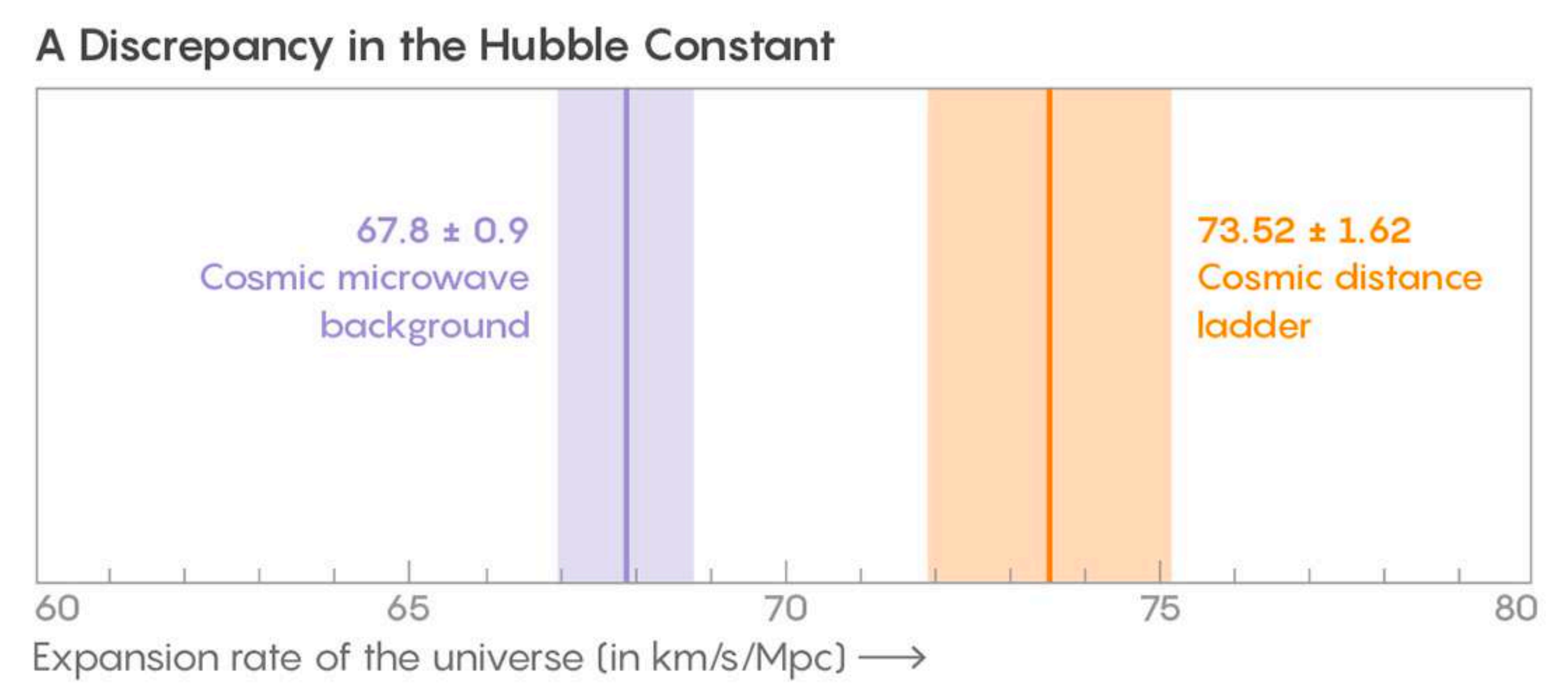
Gravitational waves are ‘standard sirens’ and provide a luminosity distance, while localizing its origin would provide a recessional velocity



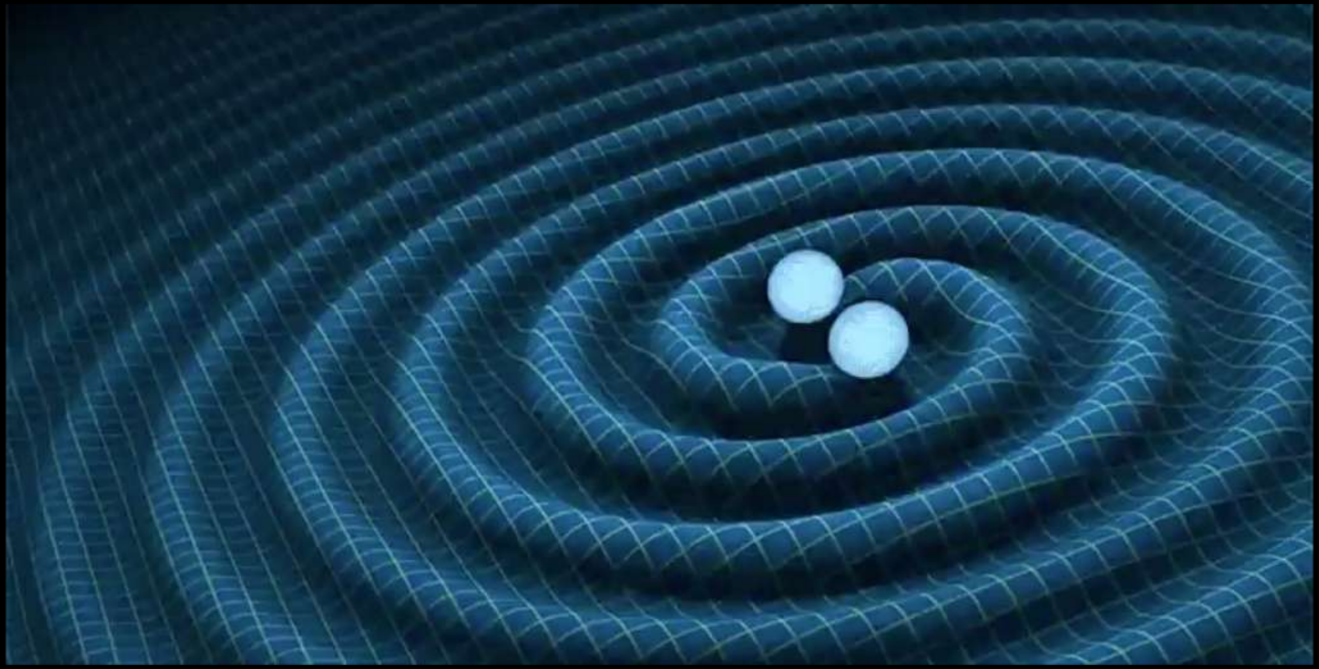




Multi-messenger detections of gravitational wave source would thus provide a new, independent probe of the Hubble constant



How can we detect neutron star mergers? Gravitational waves



Outline

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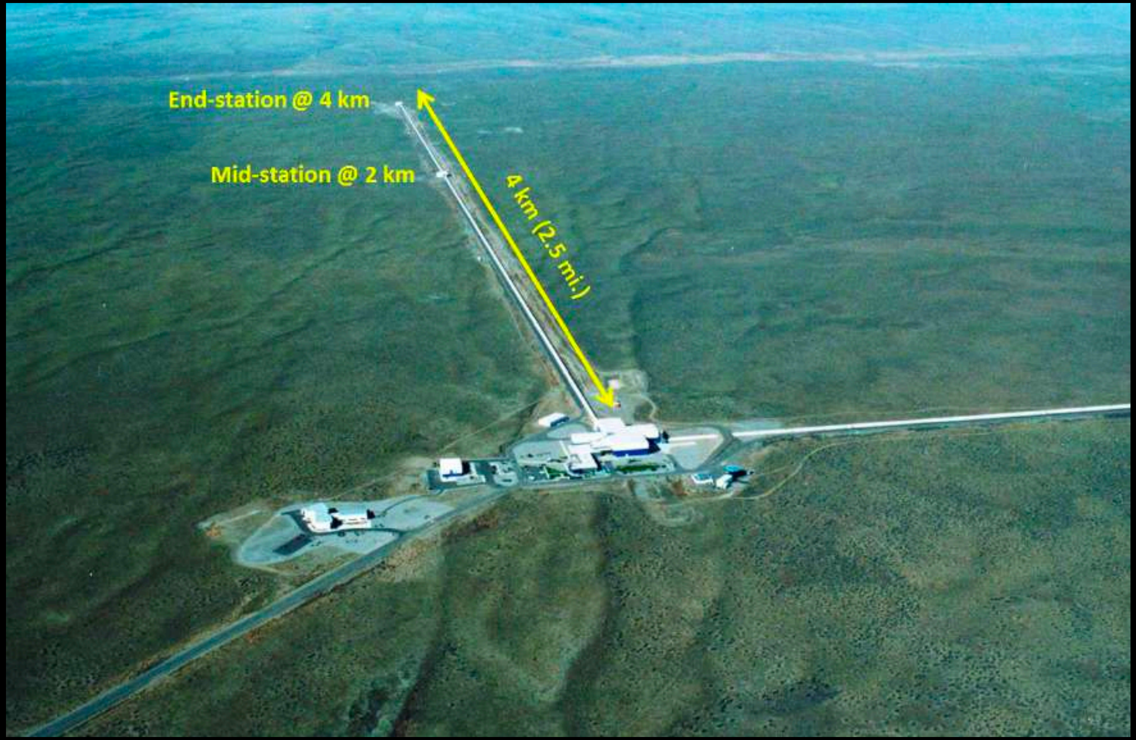
2. **Multi-messenger gravitational wave astrophysics: The landmark discovery of GW170817**

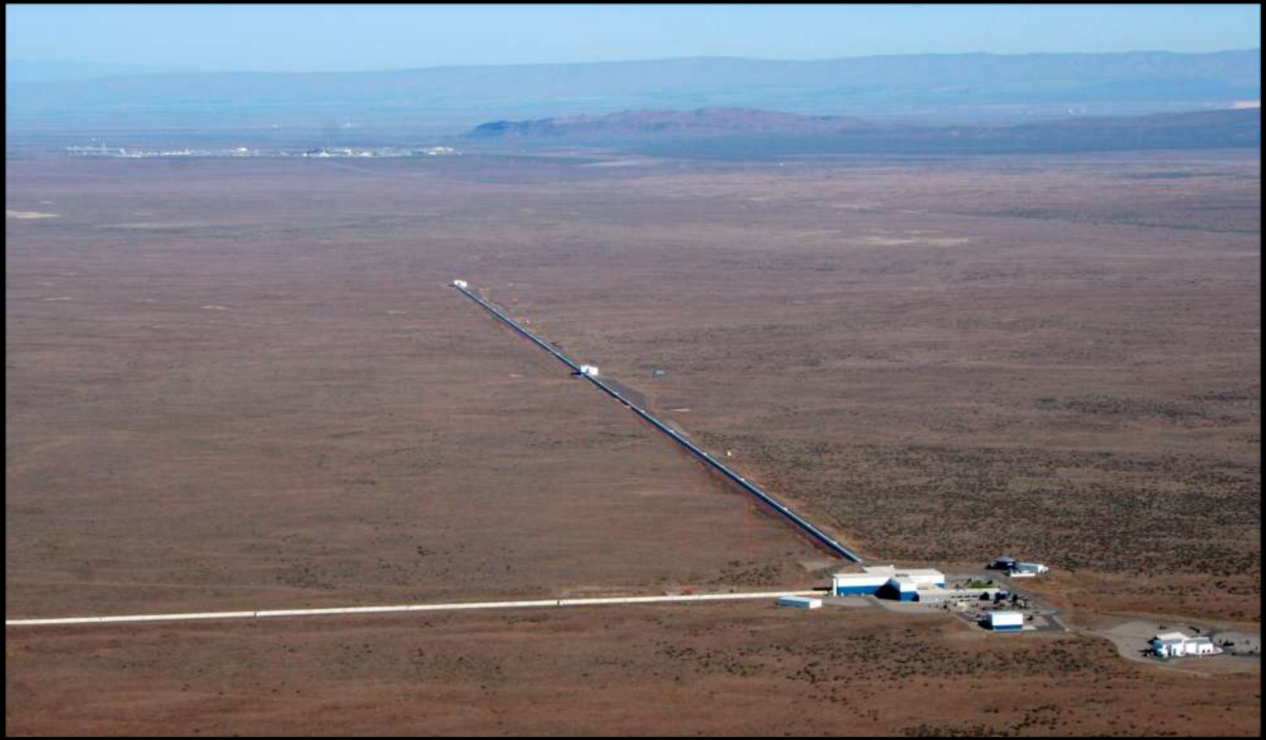
3. Challenges for the next decade

The Laser Interferometer Gravitational-wave Observatory (LIGO)

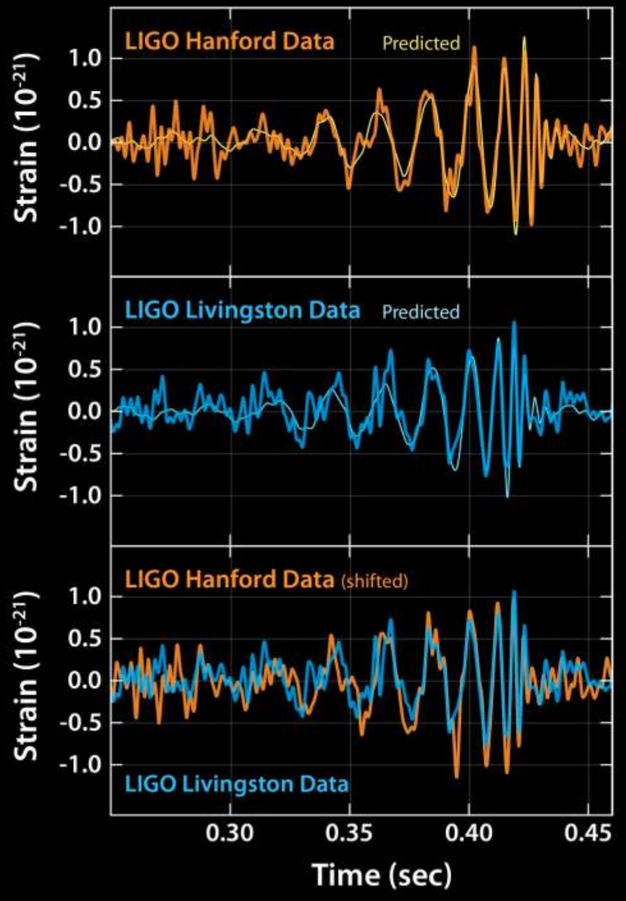
Livingston, Louisiana



Richland, Washington



14 Sept 2015: LIGO detects the first BH-BH merger and confirms prediction from General Relativity



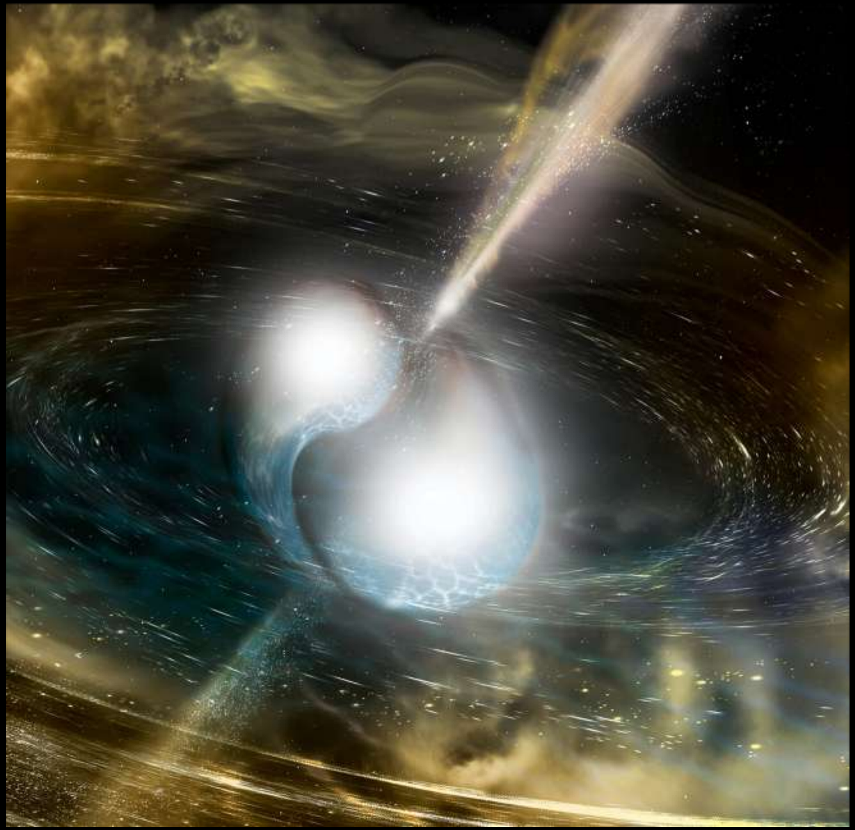
Abbott+17

This first detection of gravitational waves by LIGO lead to the 2017 Nobel Prize in Physics

In addition to gravitational waves, light can be emitted from a merger if at least one neutron star is involved

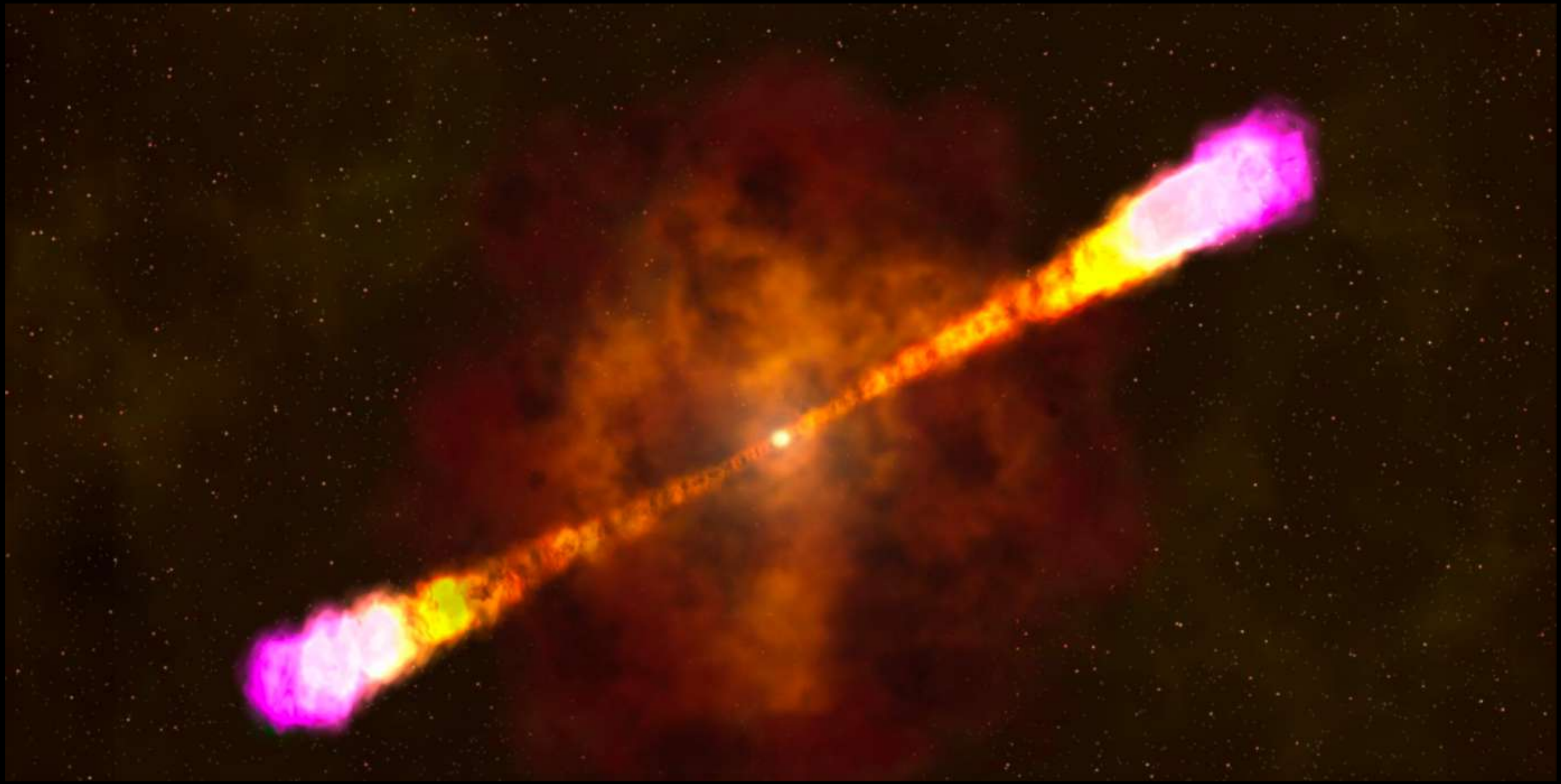
BH-BH merger

NS-NS merger



Simulations suggest neutron star mergers will eject neutron-rich material to produce a ‘kilonova’

Neutron star mergers have been long predicted to be the progenitors of short Gamma-ray bursts



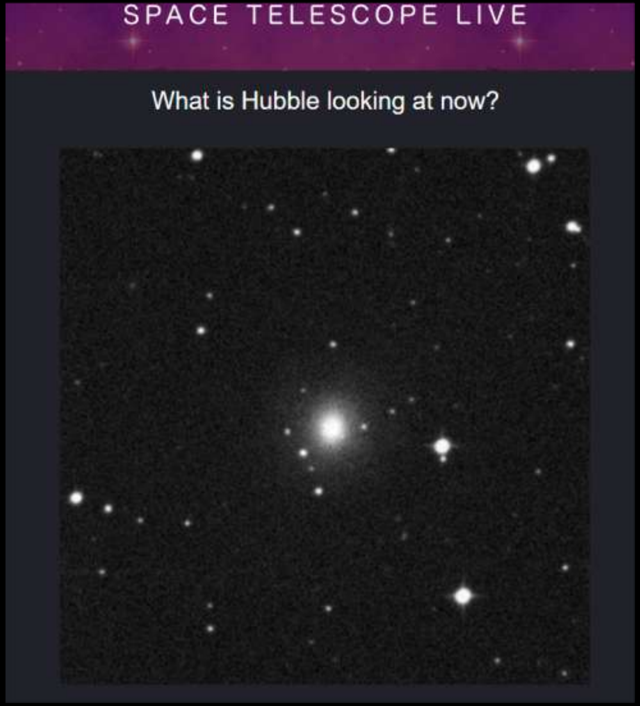
GW170817: a landmark multi-messenger breakthrough discovery

GW170817: a landmark multi-messenger breakthrough discovery

The most intensively-studied astronomical event in history!

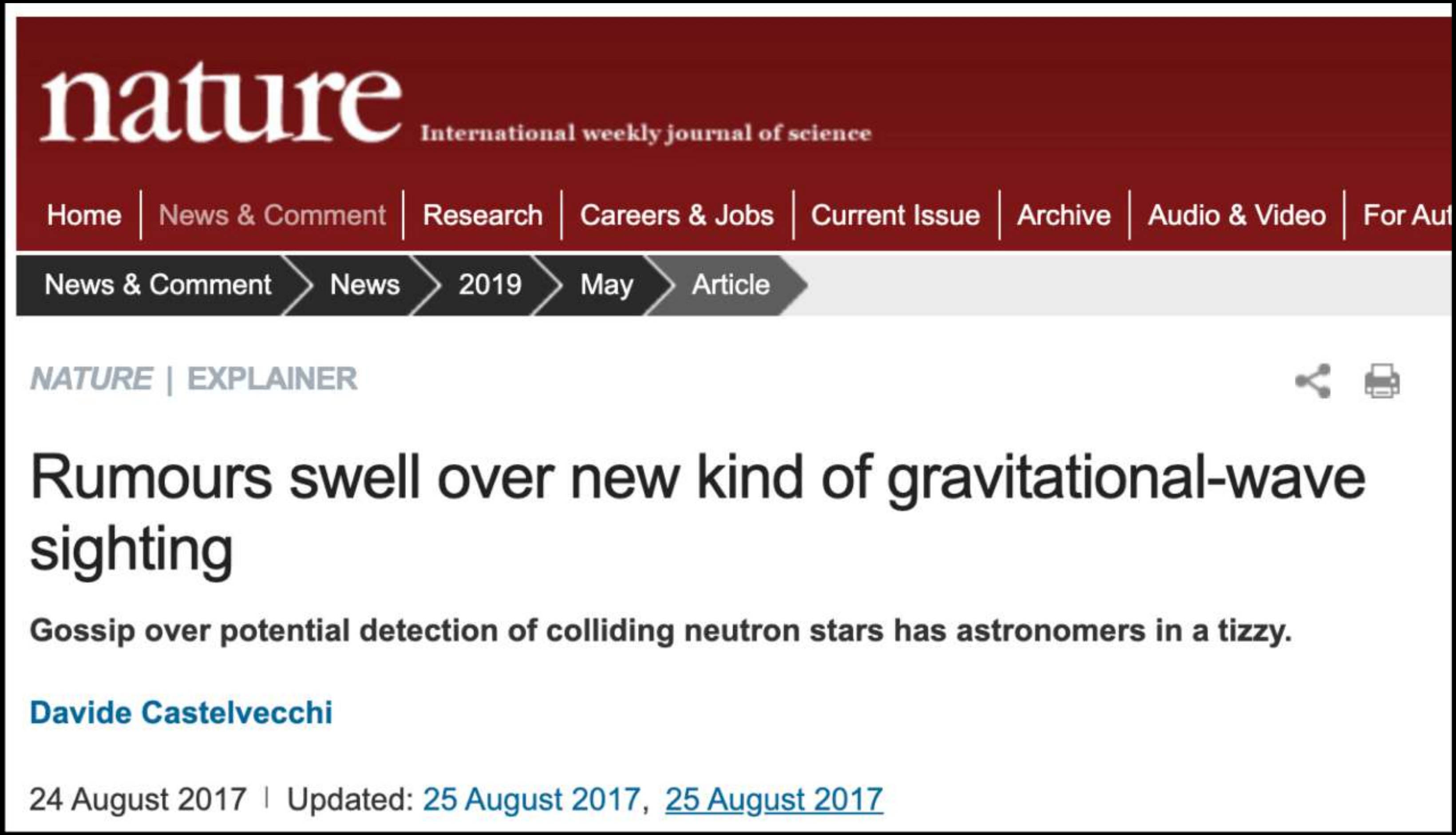
The first public hint of a multi-messenger discovery came through Twitter

An automated Hubble Space Telescope announcement accidentally revealed the host galaxy



I am looking at the Star BNS-MERGER with Space Telescope Imaging Spectrograph for on Tue, 22 Aug 2017 22:38:01 -04:00

Rumors swirled around the astrophysics community about a multi-messenger discovery



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NATURE | EXPLAINER

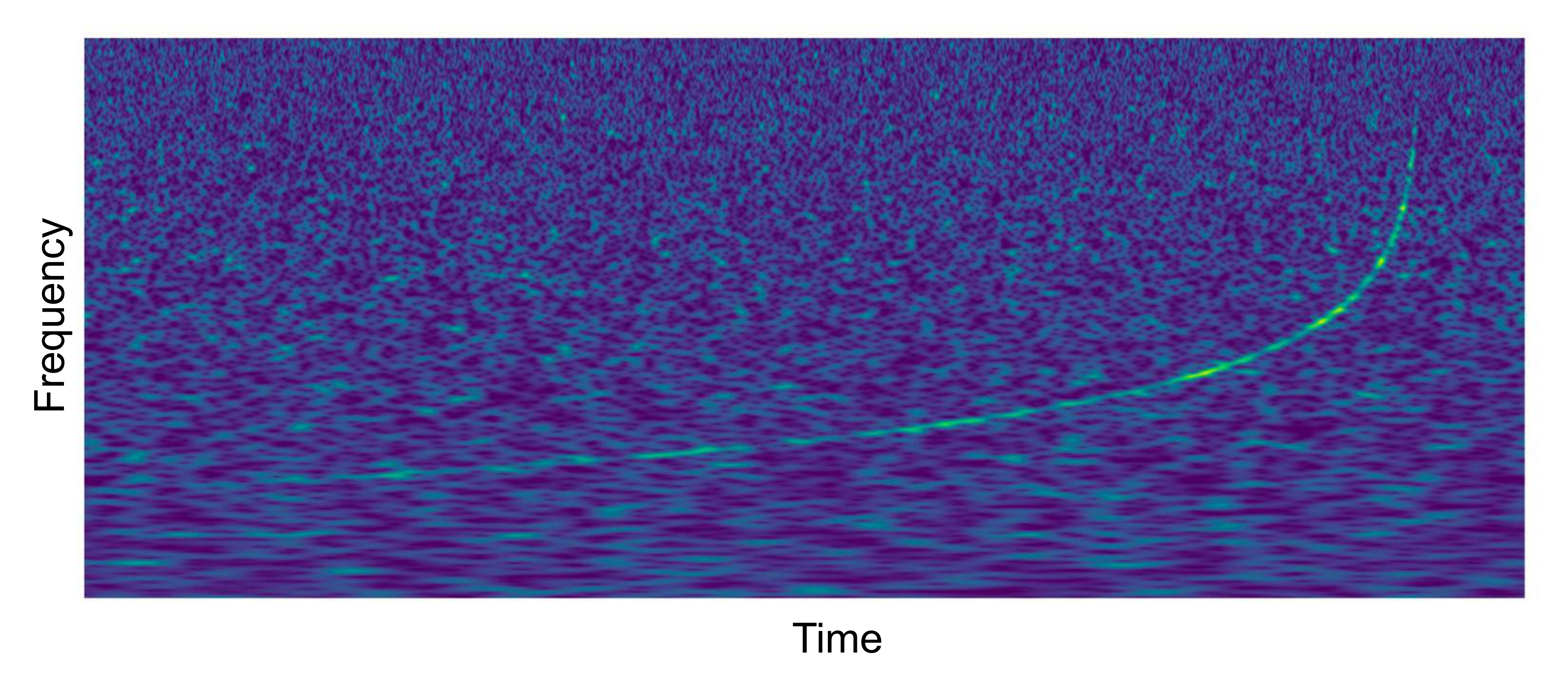
Rumours swell over new kind of gravitational-wave sighting

Gossip over potential detection of colliding neutron stars has astronomers in a tizzy.

Davide Castelvecchi

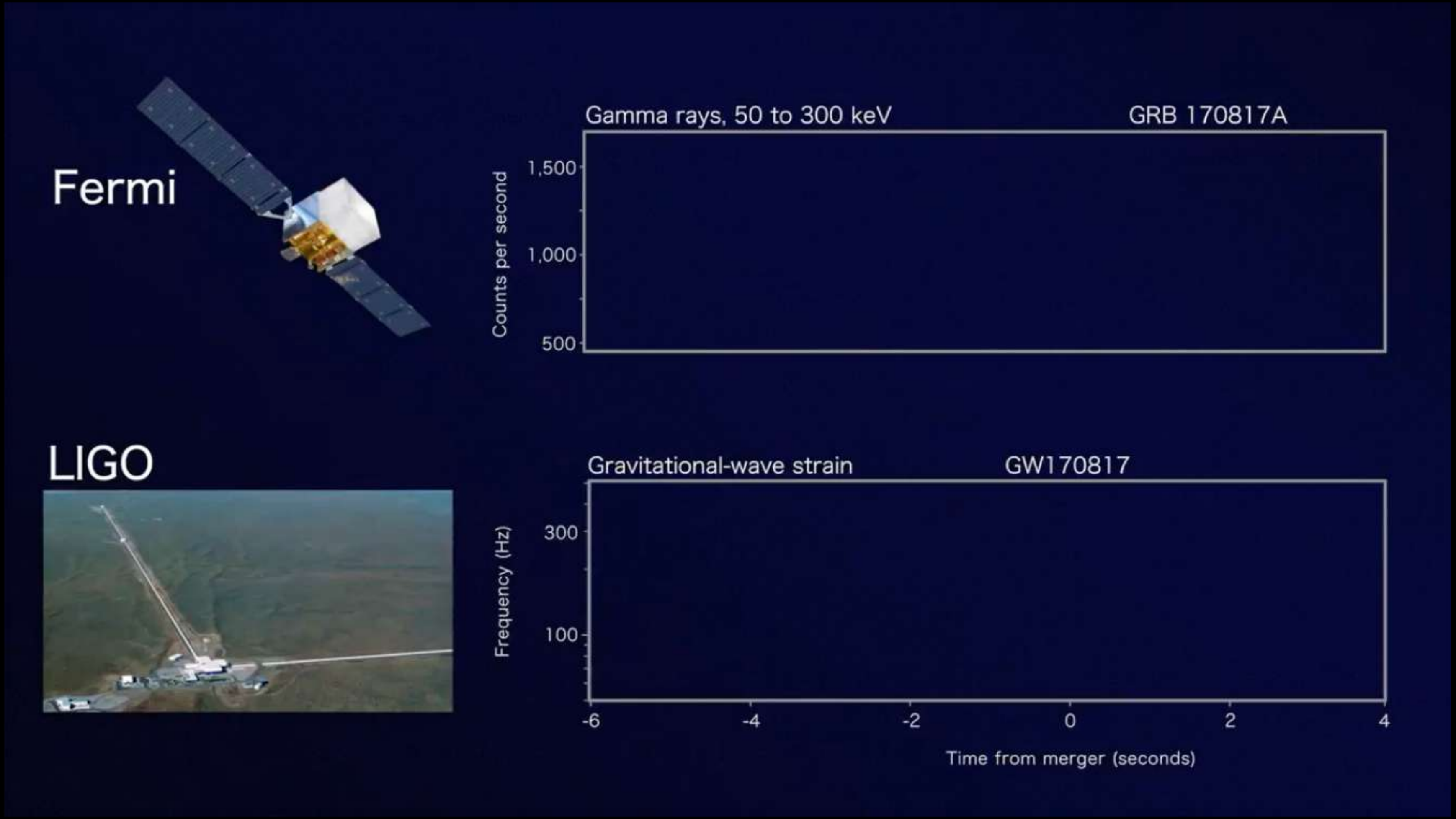
24 August 2017 | Updated: 25 August 2017, 25 August 2017

17 August 2017: LIGO detects the first neutron star – neutron star merger

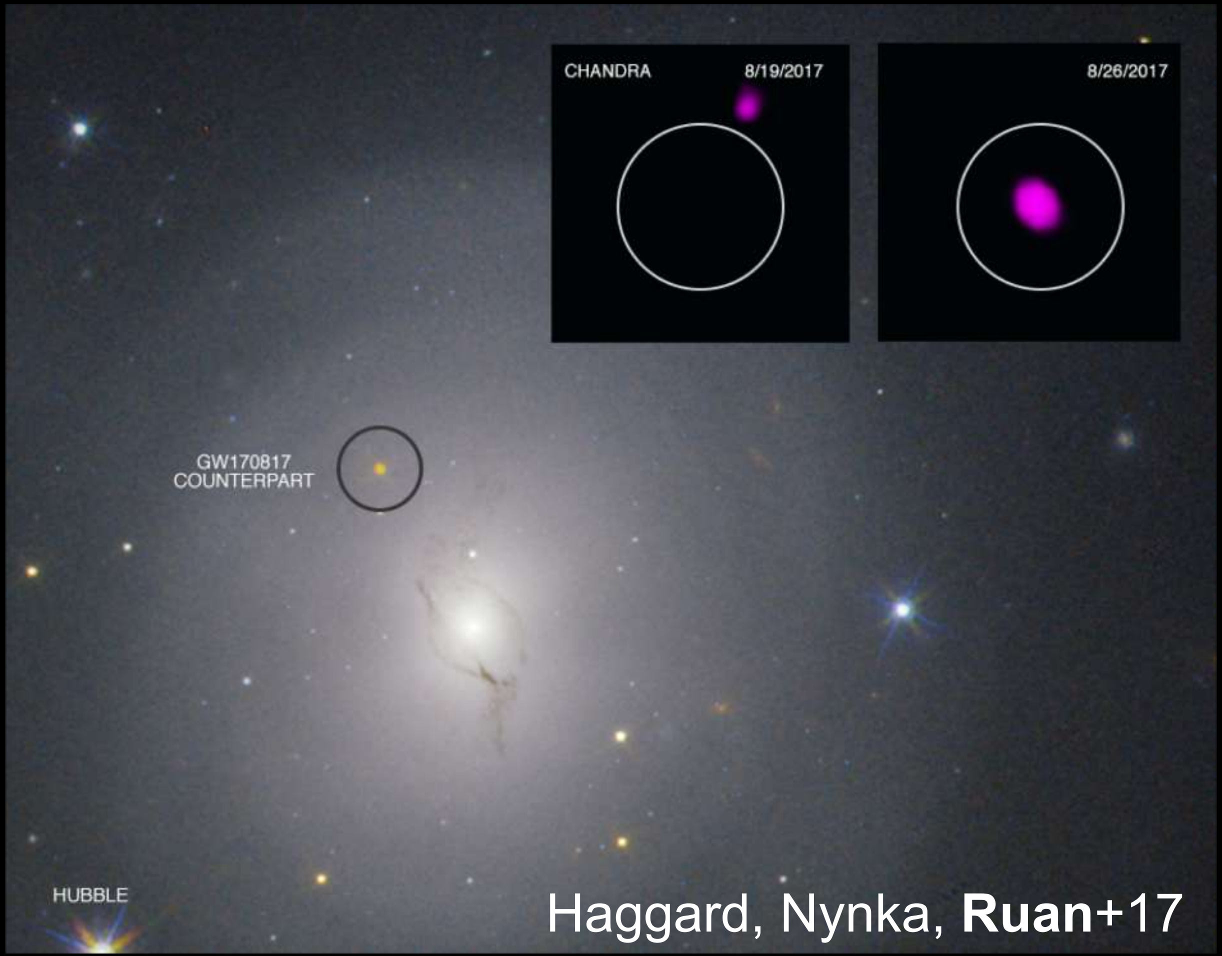


Abbott+17

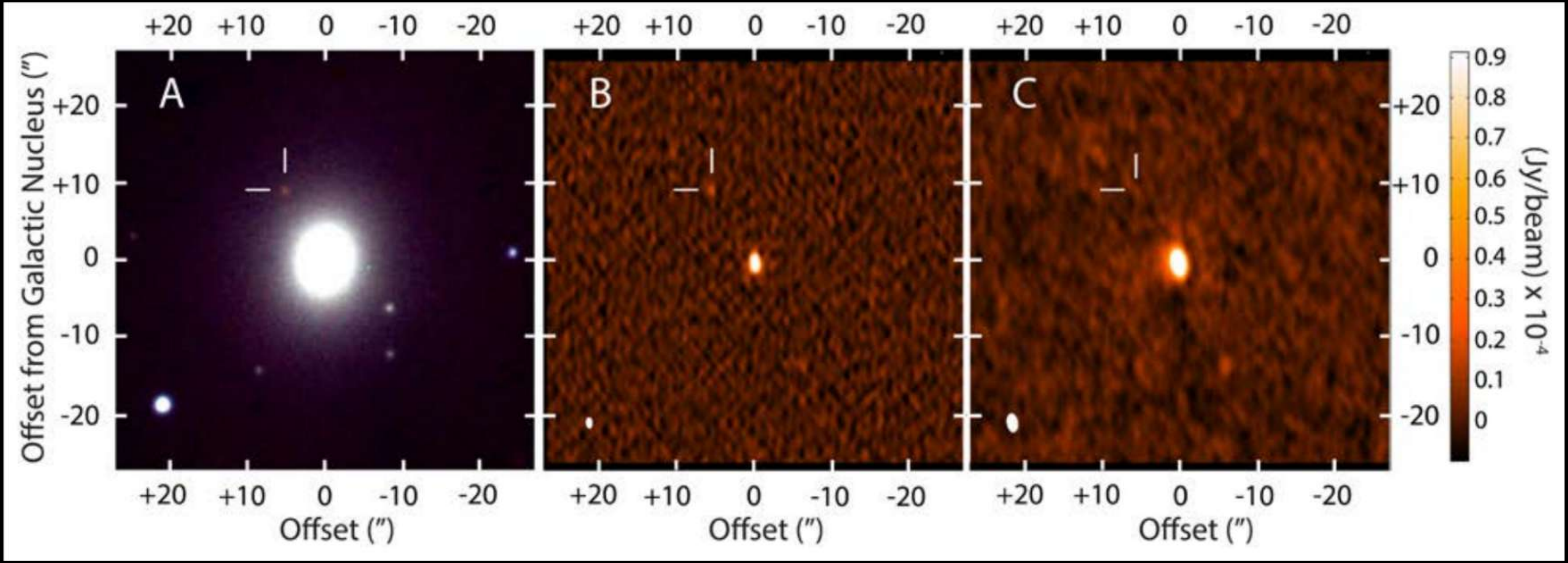
A short Gamma-ray burst was detected at the same time and sky region as the gravitational waves



X-ray emission emerged 9 days post-merger

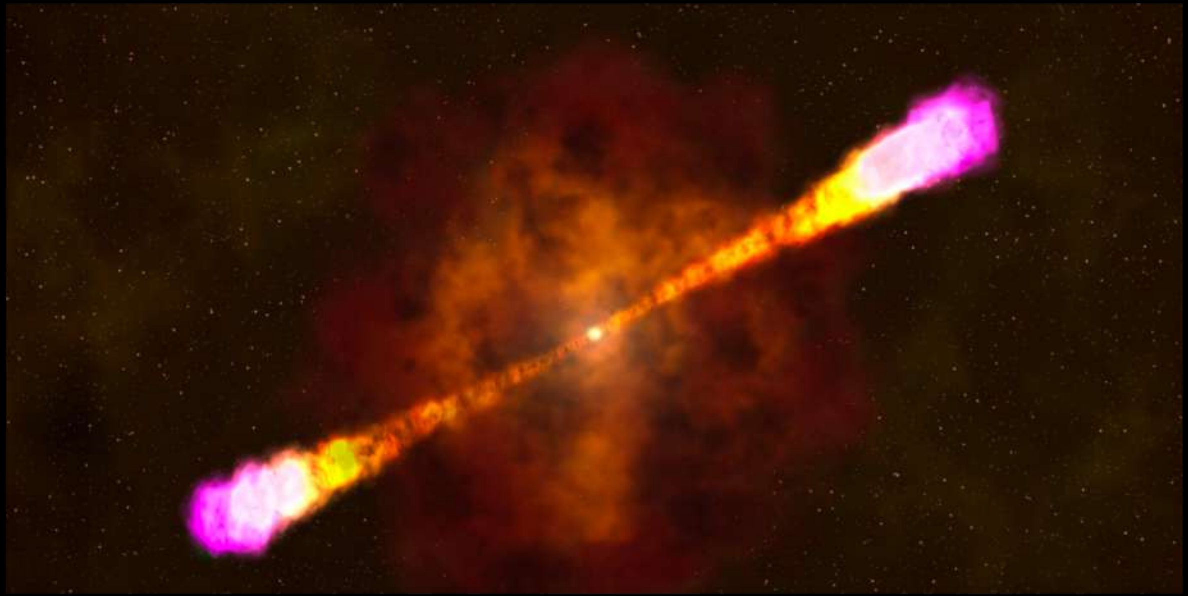


Radio emission emerged 16 days post-merger

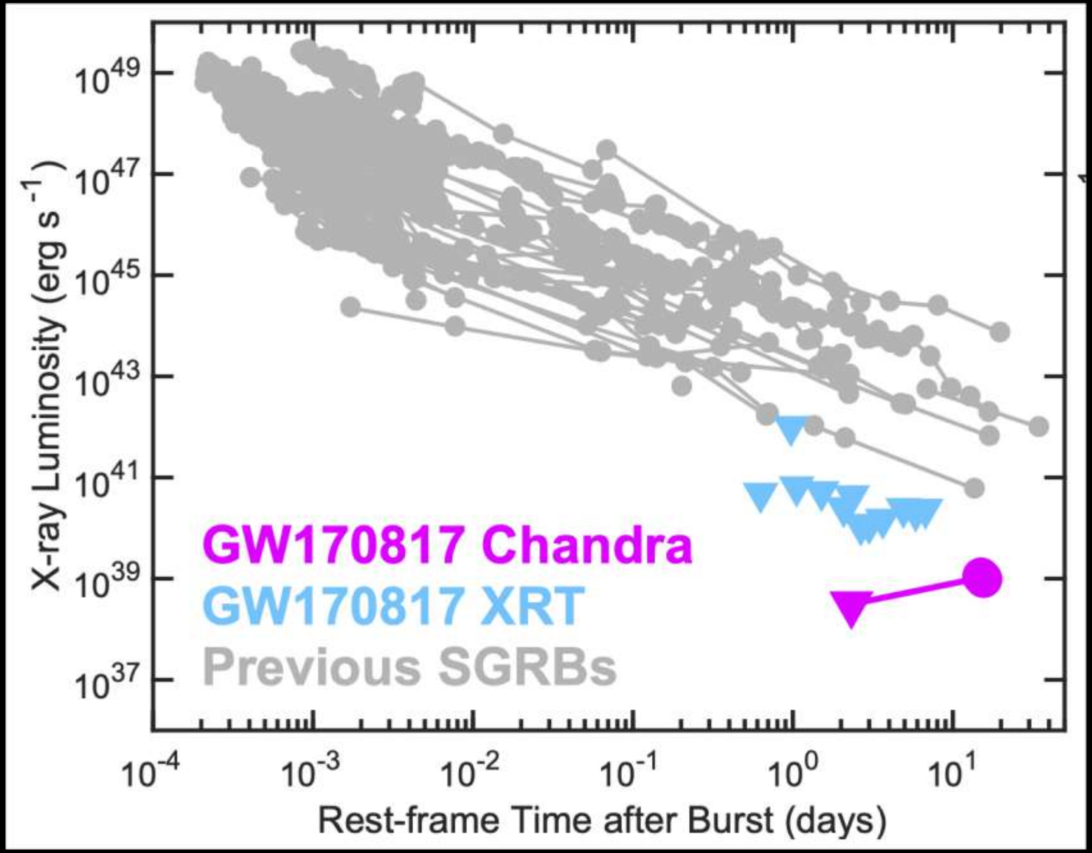


Hallinan+17

Synchrotron X-ray and radio ‘afterglow’ emission is produced by the jet as it shocks the surrounding gas

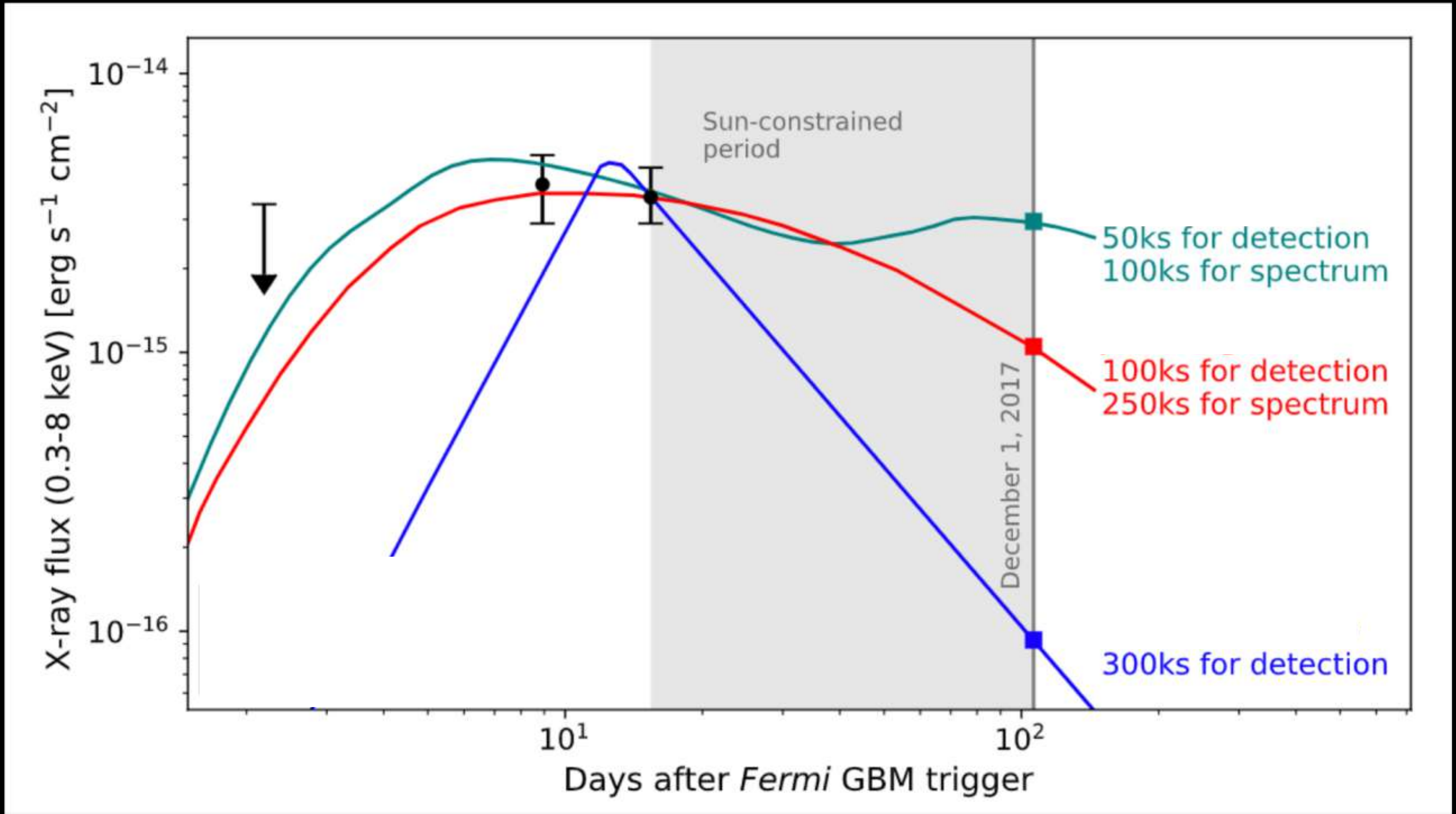


This long-term brightening of the synchrotron afterglow has *never* been observed in short GRBs

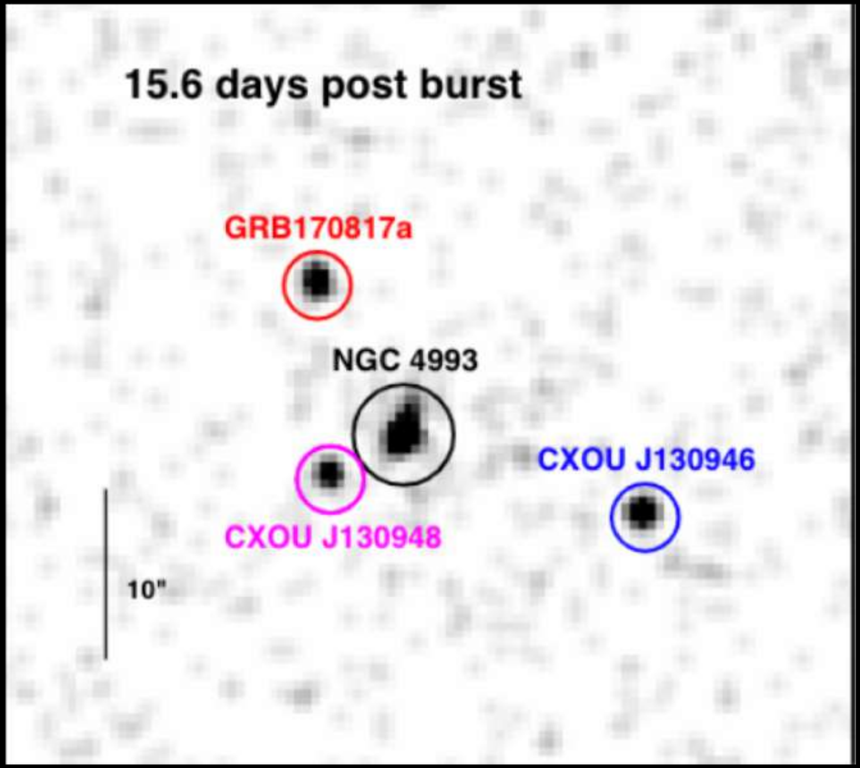


Fong+17

Continued Chandra X-ray observations were Sun-constrained for the next 3 months

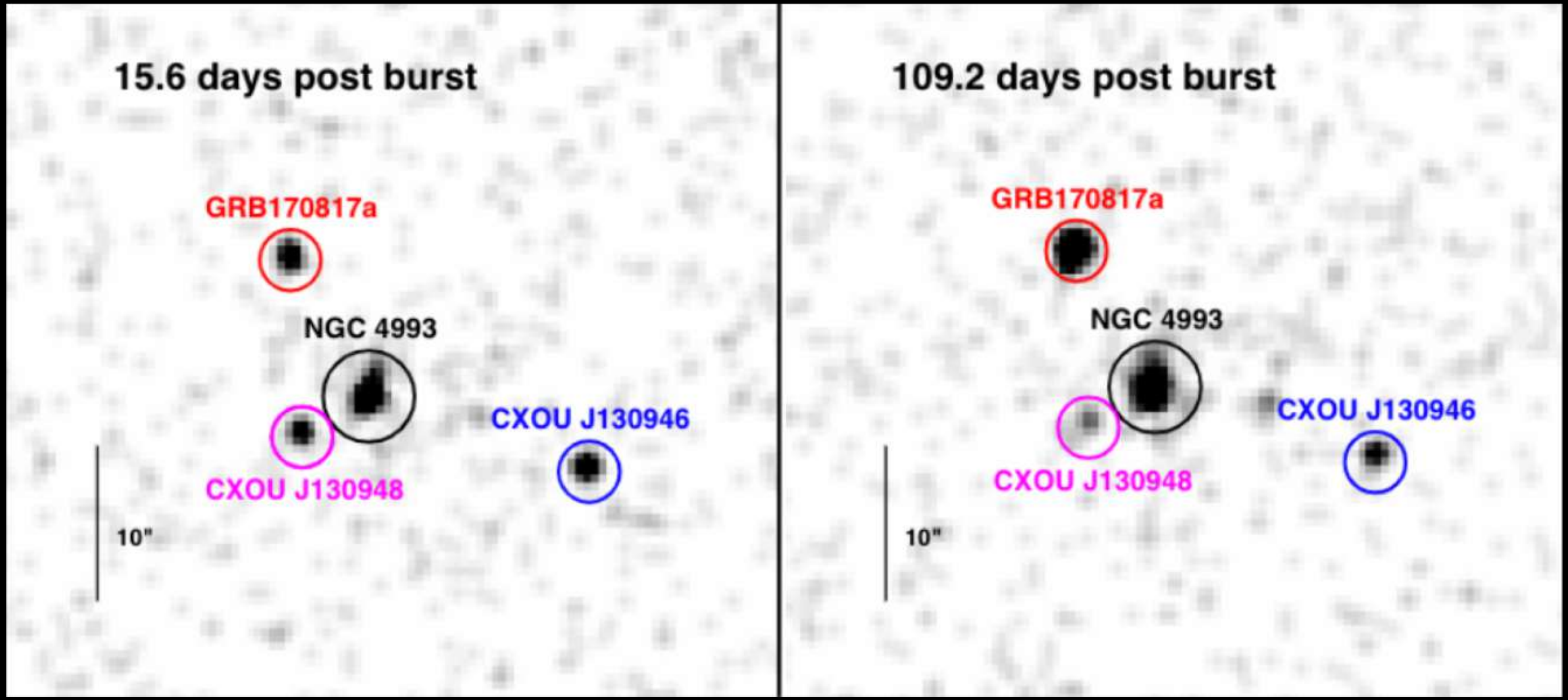


The first X-ray observations after Sun-constraints were lifted….



Ruan+18

Surprisingly, the X-ray emission dramatically *brightened* over 110 days post-merger



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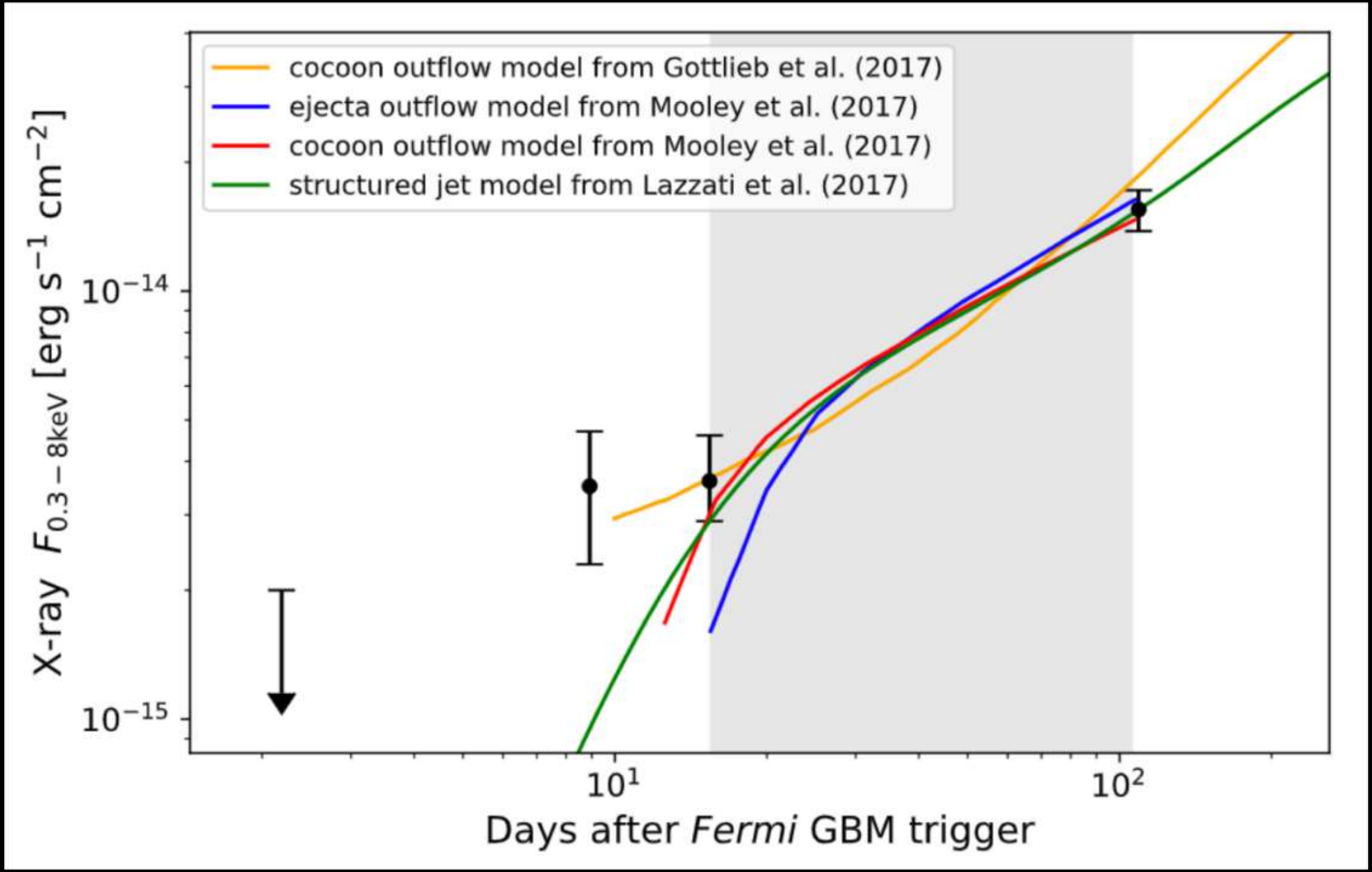
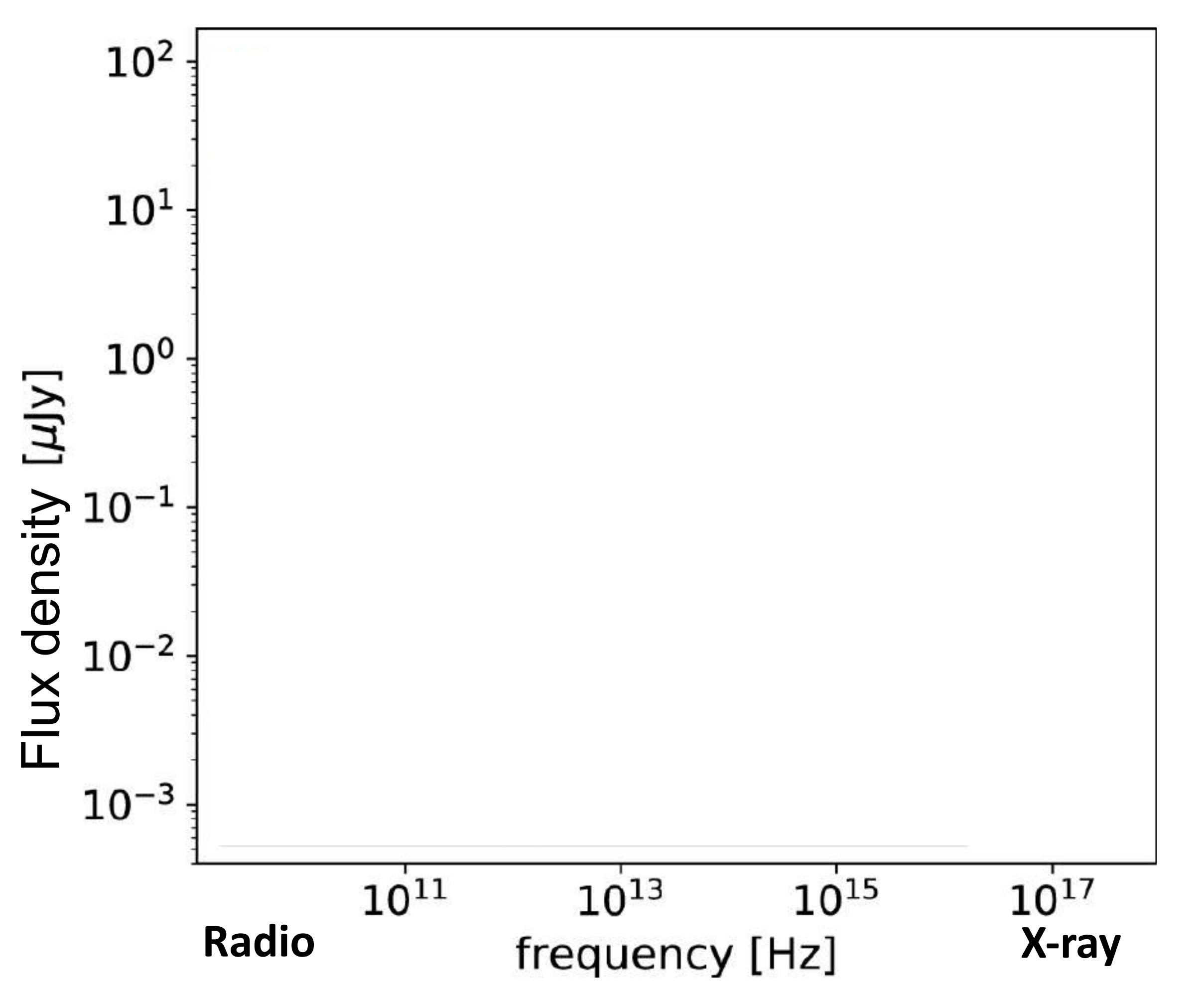


Ruan+18

The similar radio and X-ray brightening pointed to a common origin in **optically-thin synchrotron**



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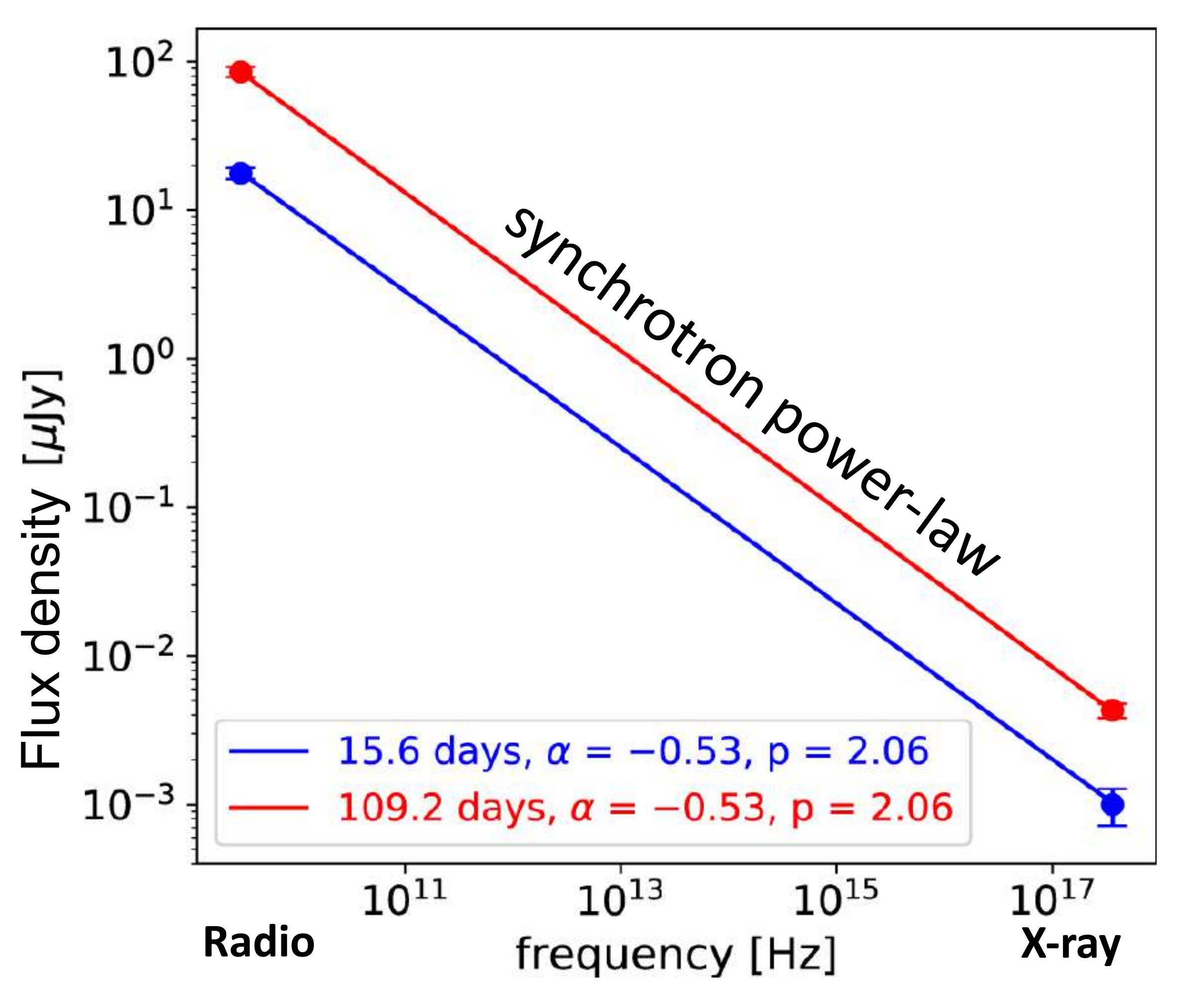
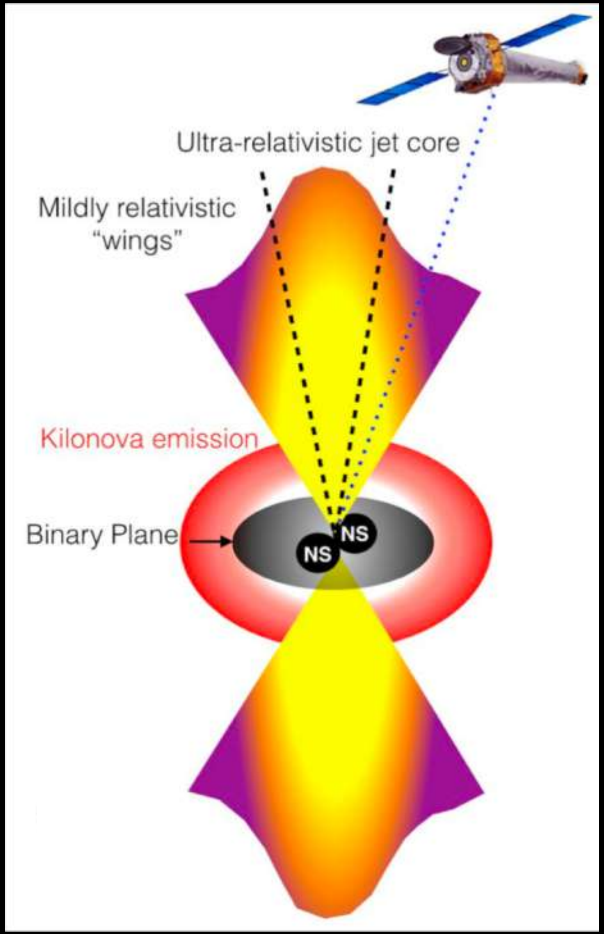
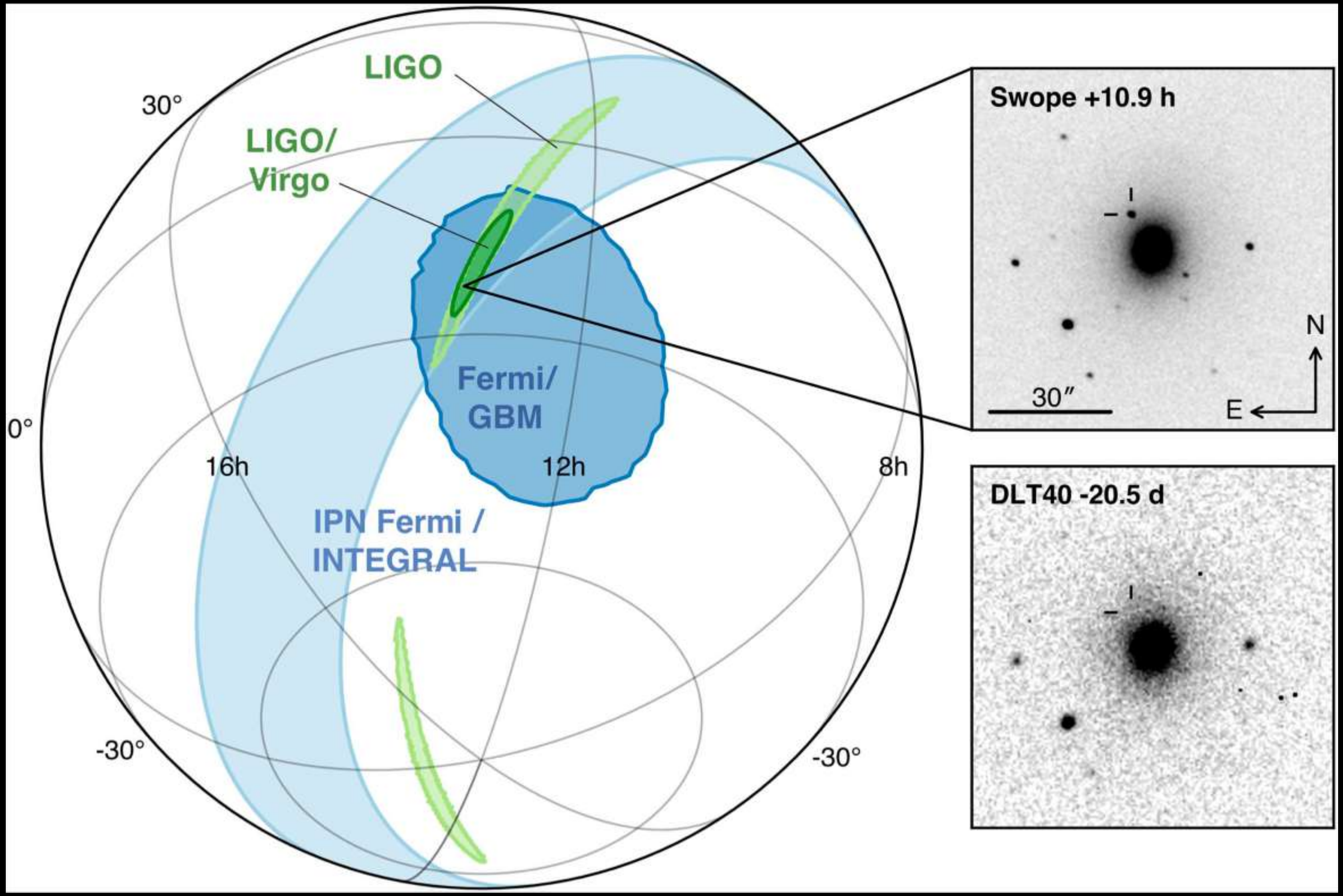


Ruan+18

Interpretation of the X-ray synchrotron afterglow: an off-axis 'structured' jet

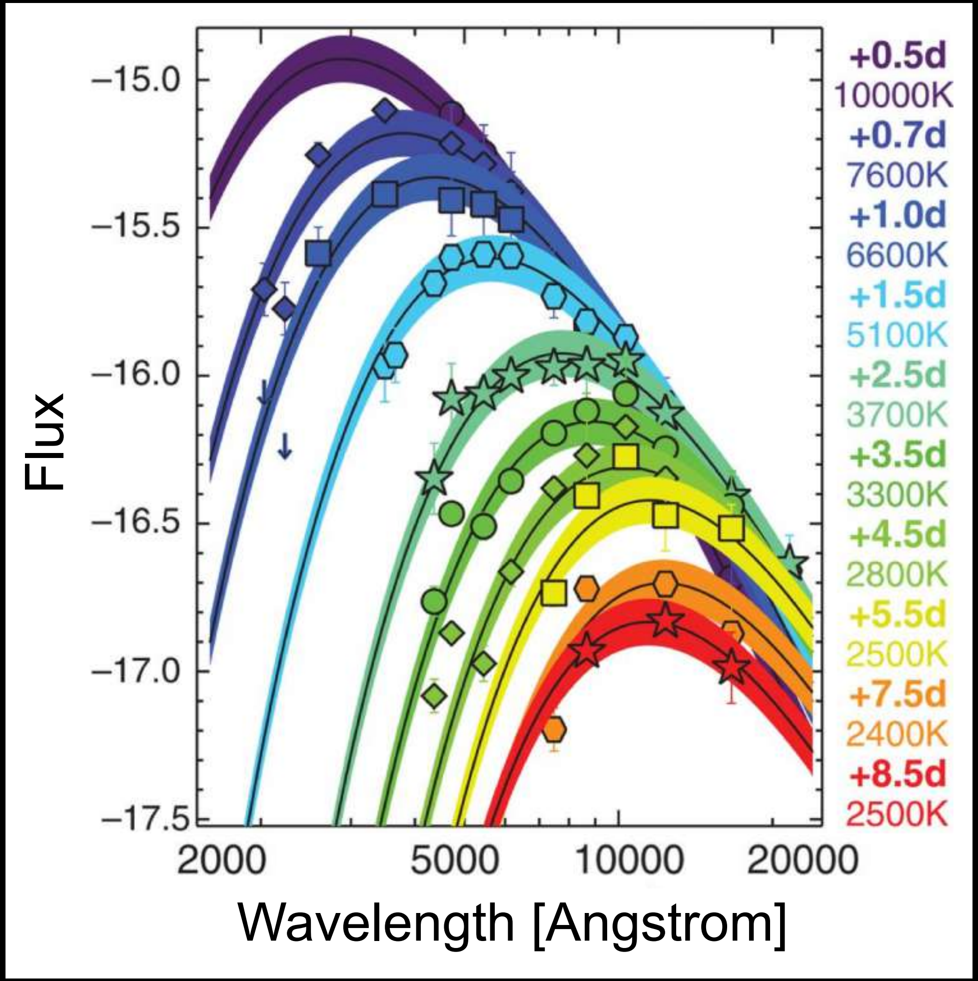


An optical counterpart to the gravitational waves was also discovered in the localization region



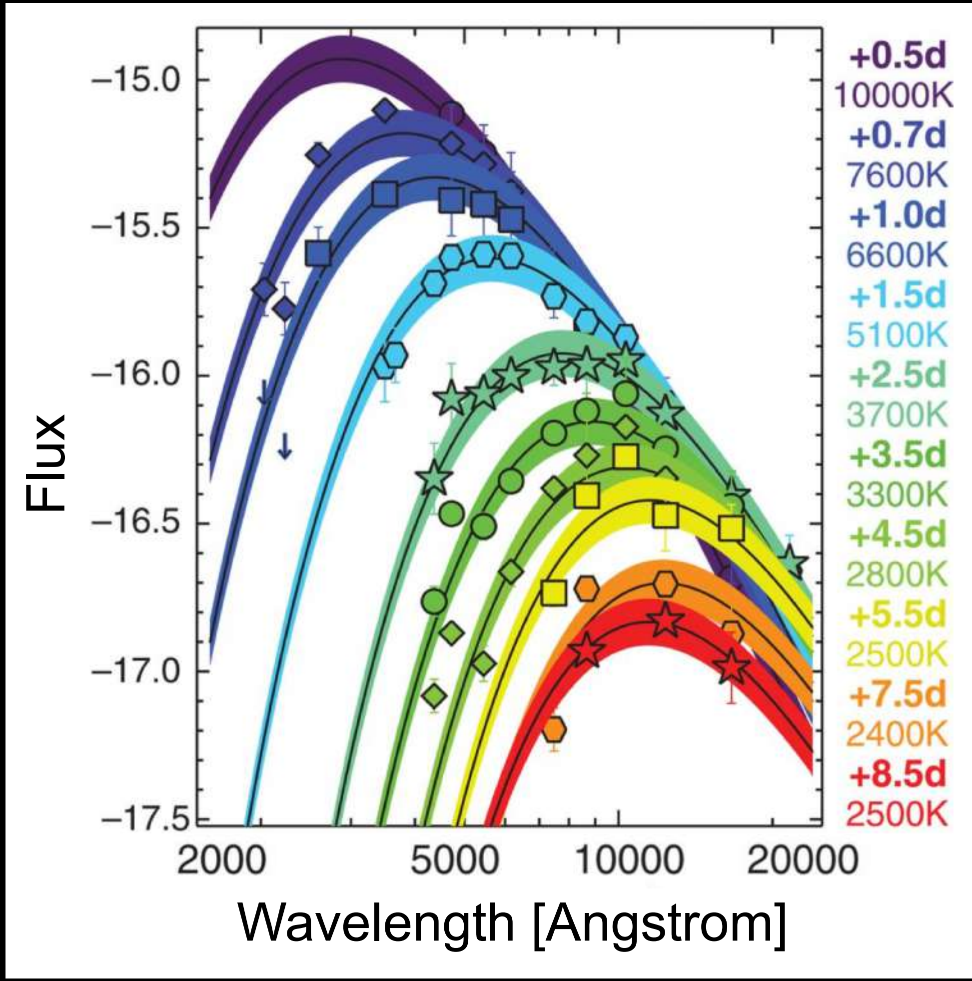
Abbott+17

Multi-band photometric monitoring revealed a transient that faded and got redder over weeks

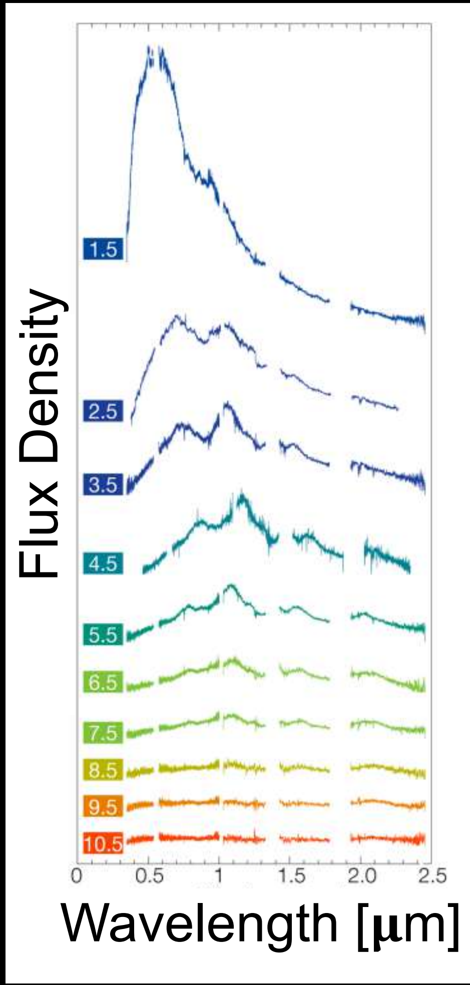


Drout+17

This behavior was also observed in optical/infrared spectroscopic monitoring

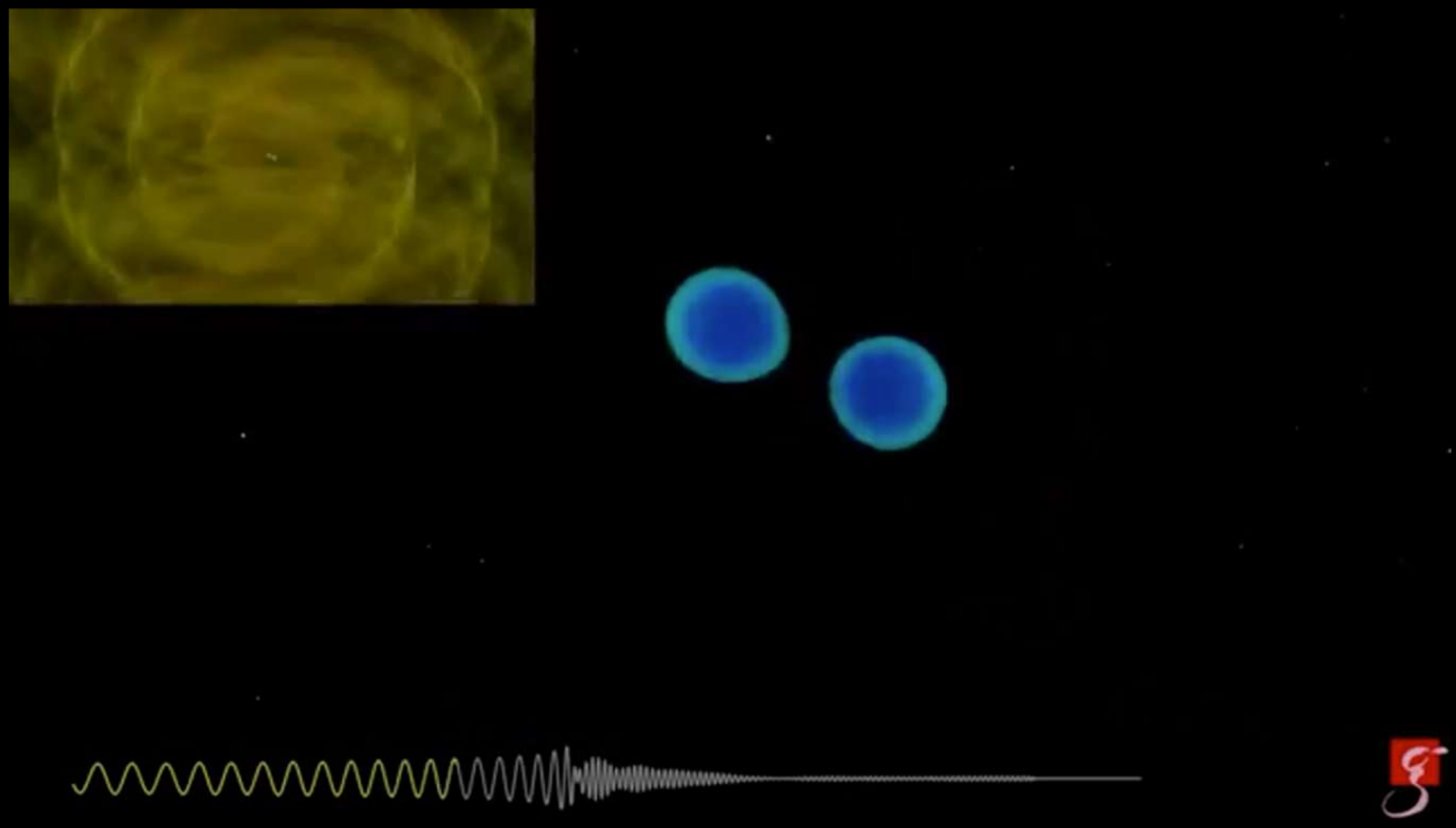


Drout+17

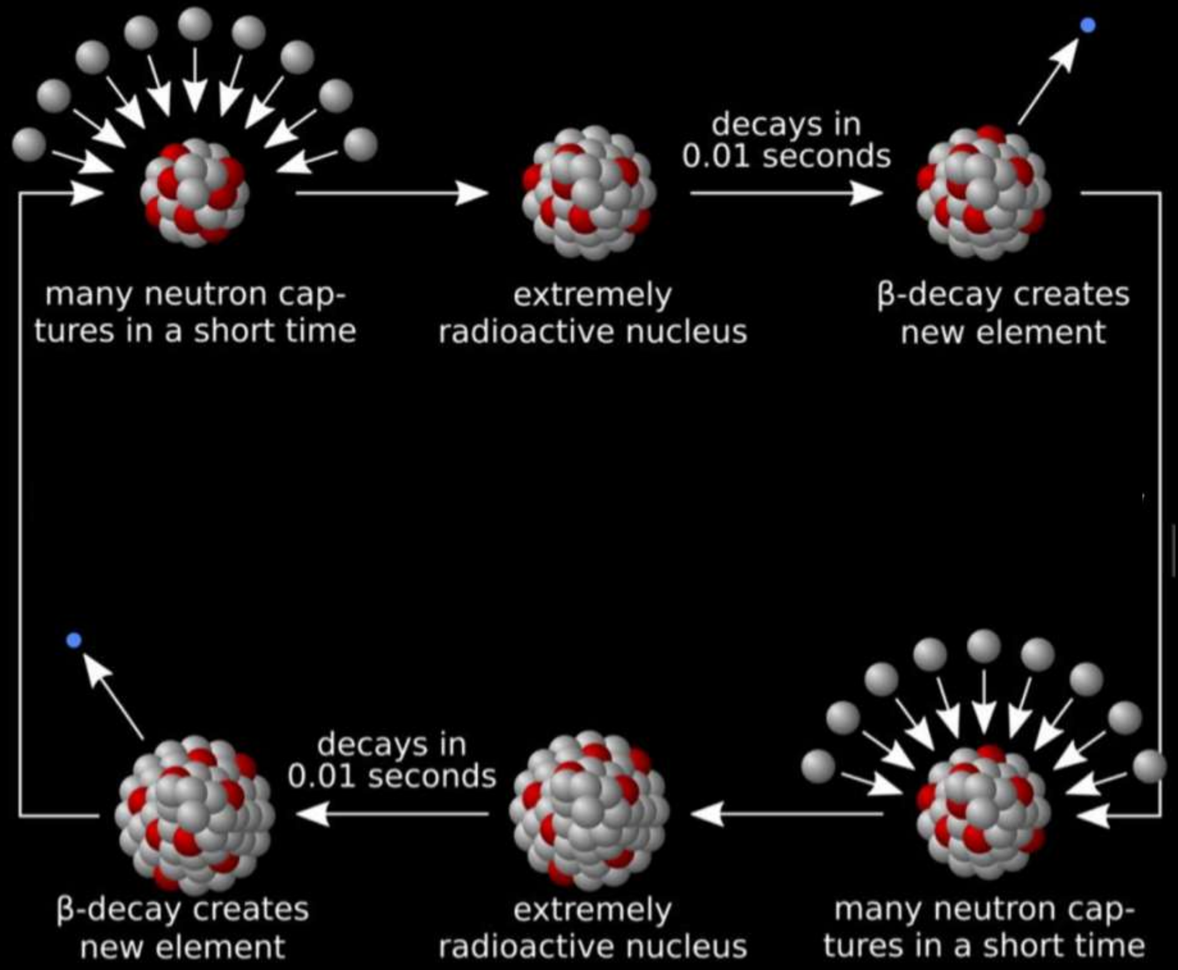


Pian+17

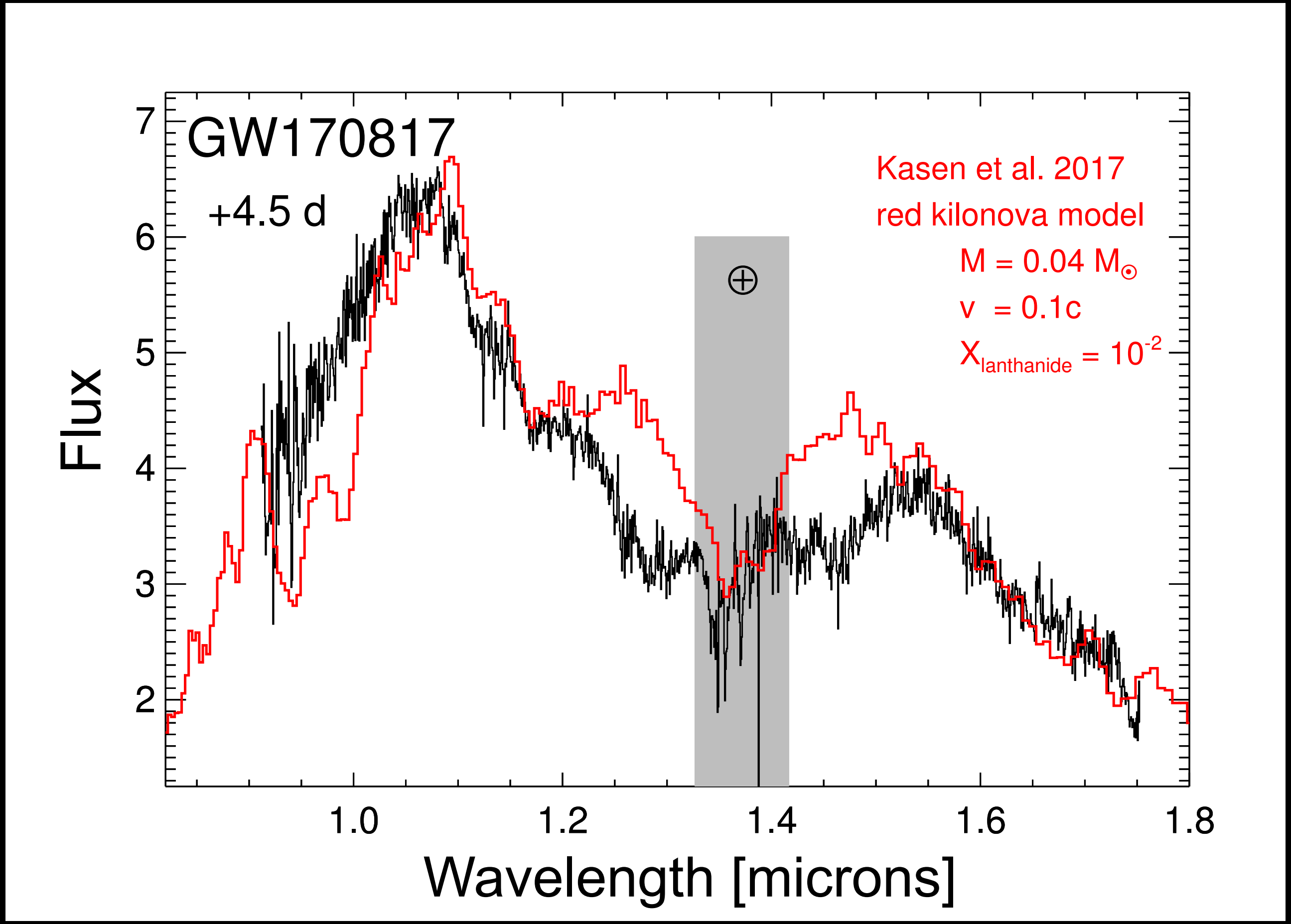
Interpretation of the UV/optical/infrared transient emission: the NS-NS merger produced a ‘kilonova’



This kilonova was powered by *r*-process nucleosynthesis of the heaviest elements

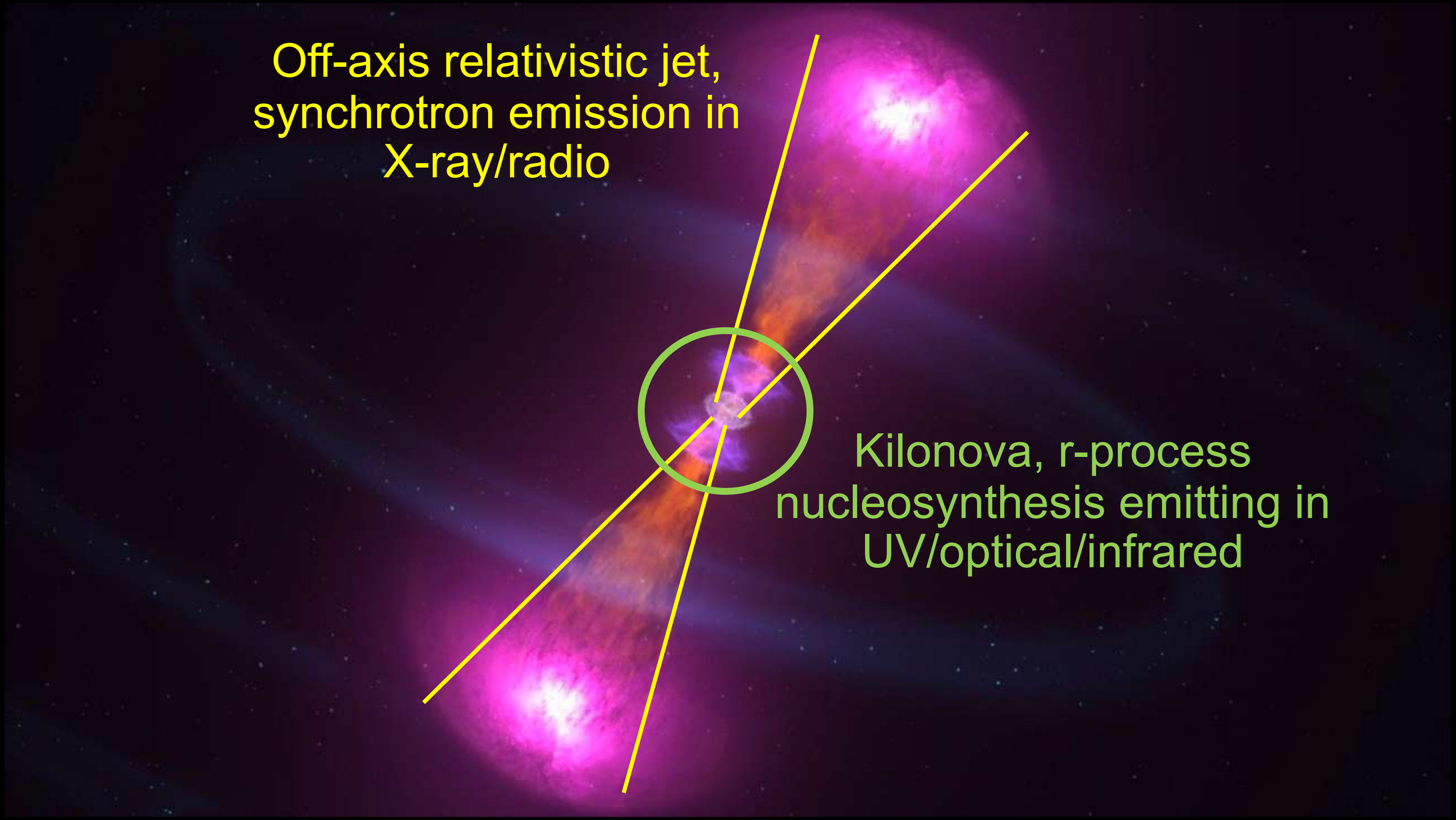


Optical/infrared spectroscopy revealed spectral features consistent with *r*-process nucleosynthesis



Chornock+17

A concordant multi-messenger picture of GW170817 has now emerged



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3. **Questions and challenges for the next decade**

Multi-messenger observations of GW170817 raised a plethora of *new* questions

- What is the origin of the kilonova ejecta?
- Do neutron star mergers produce all of the *r*-process elements?
- What is expansion rate of the Universe?
- Surprise discoveries?

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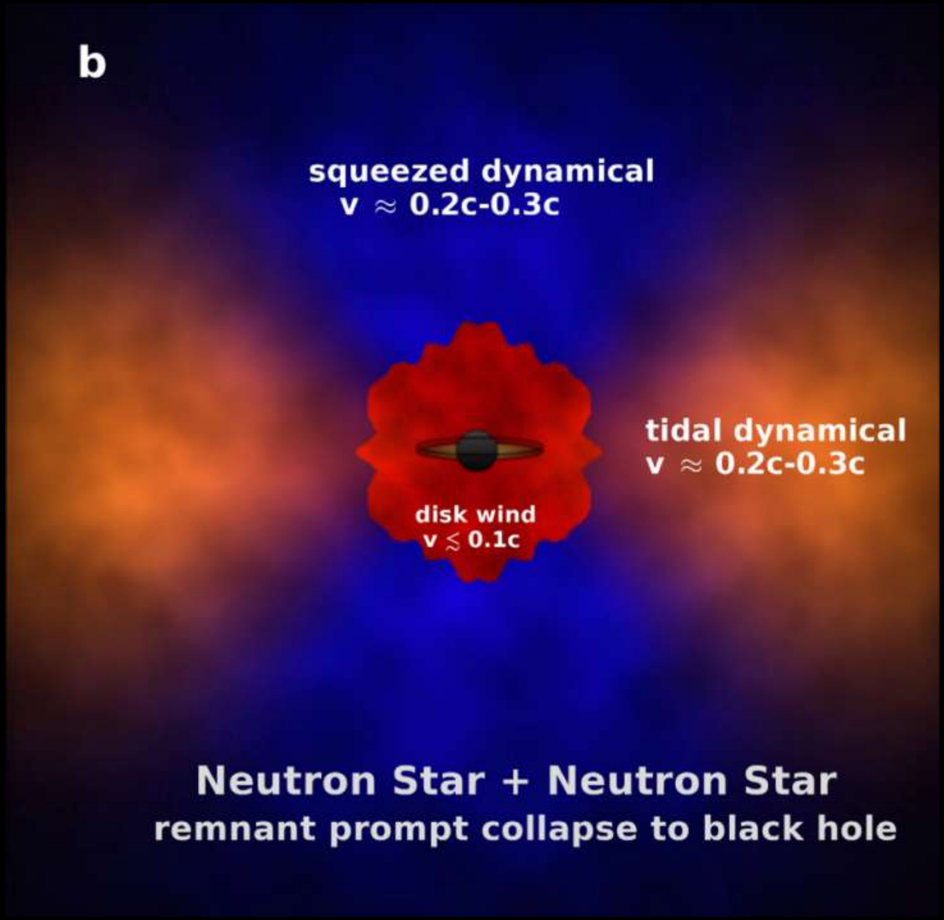
The exact origin of the ejecta that powers the emission from GW170817 is still mysterious



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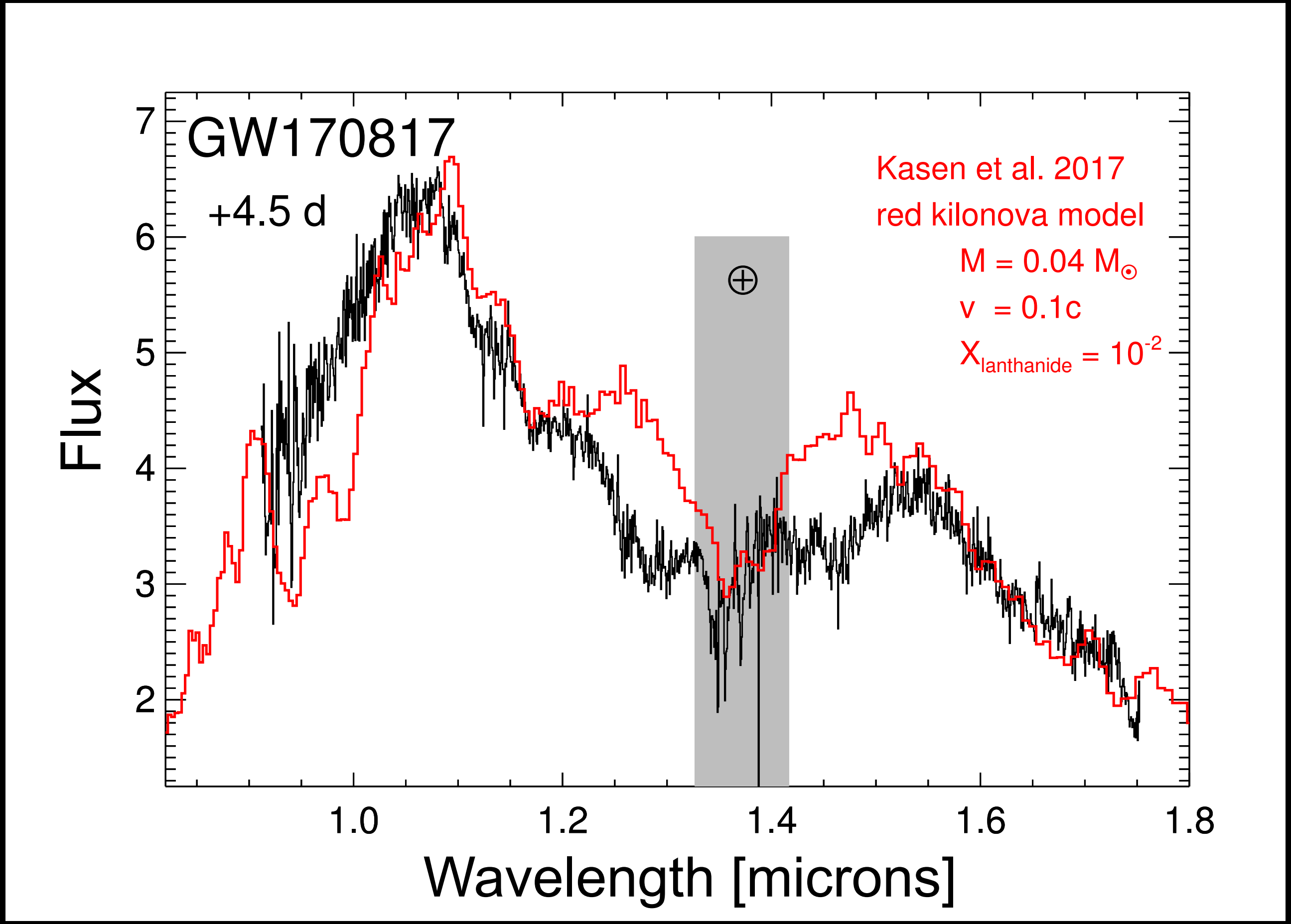
Current estimates of *r*-process yields and abundance patterns are based only on GW170817



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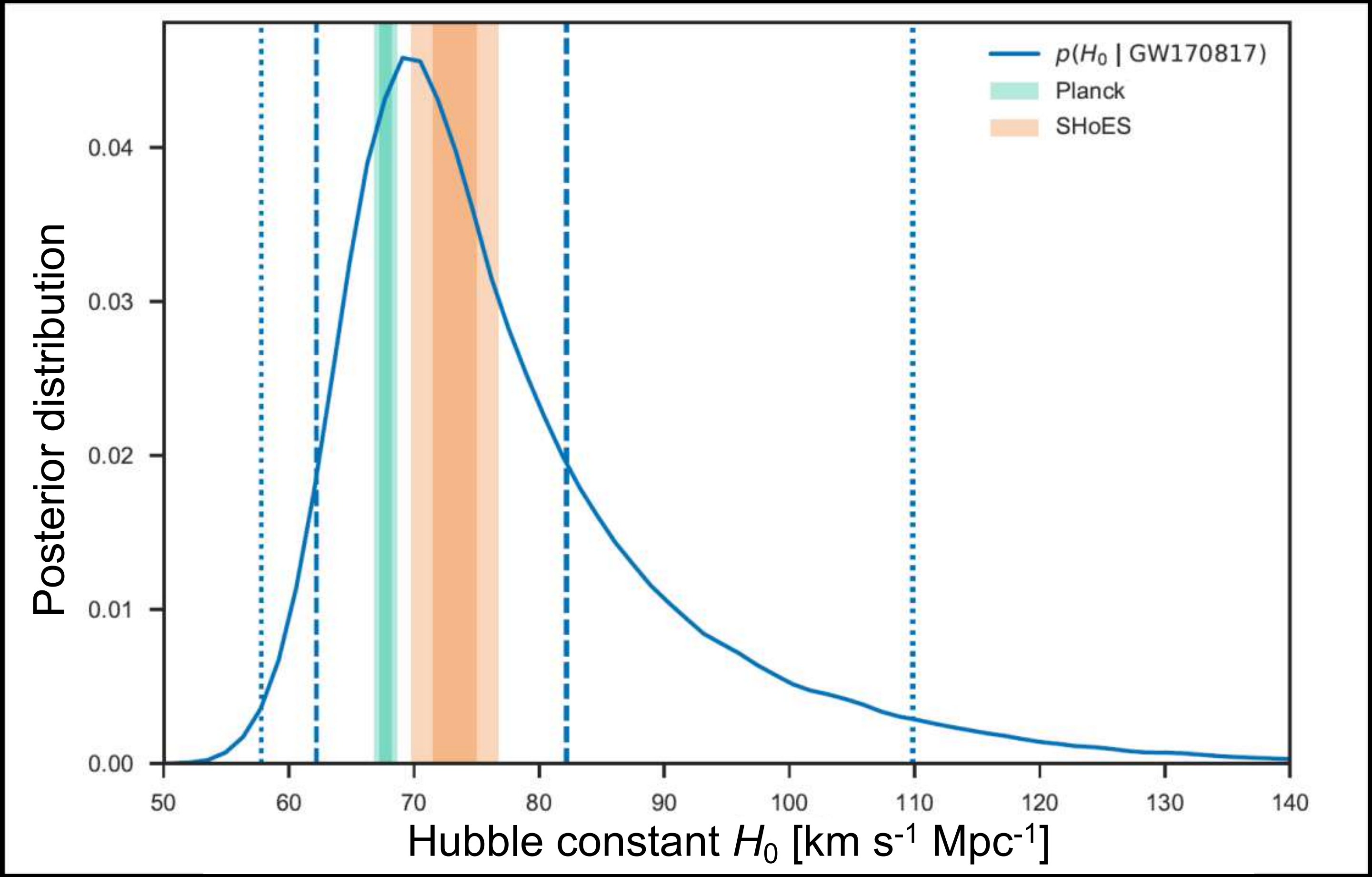
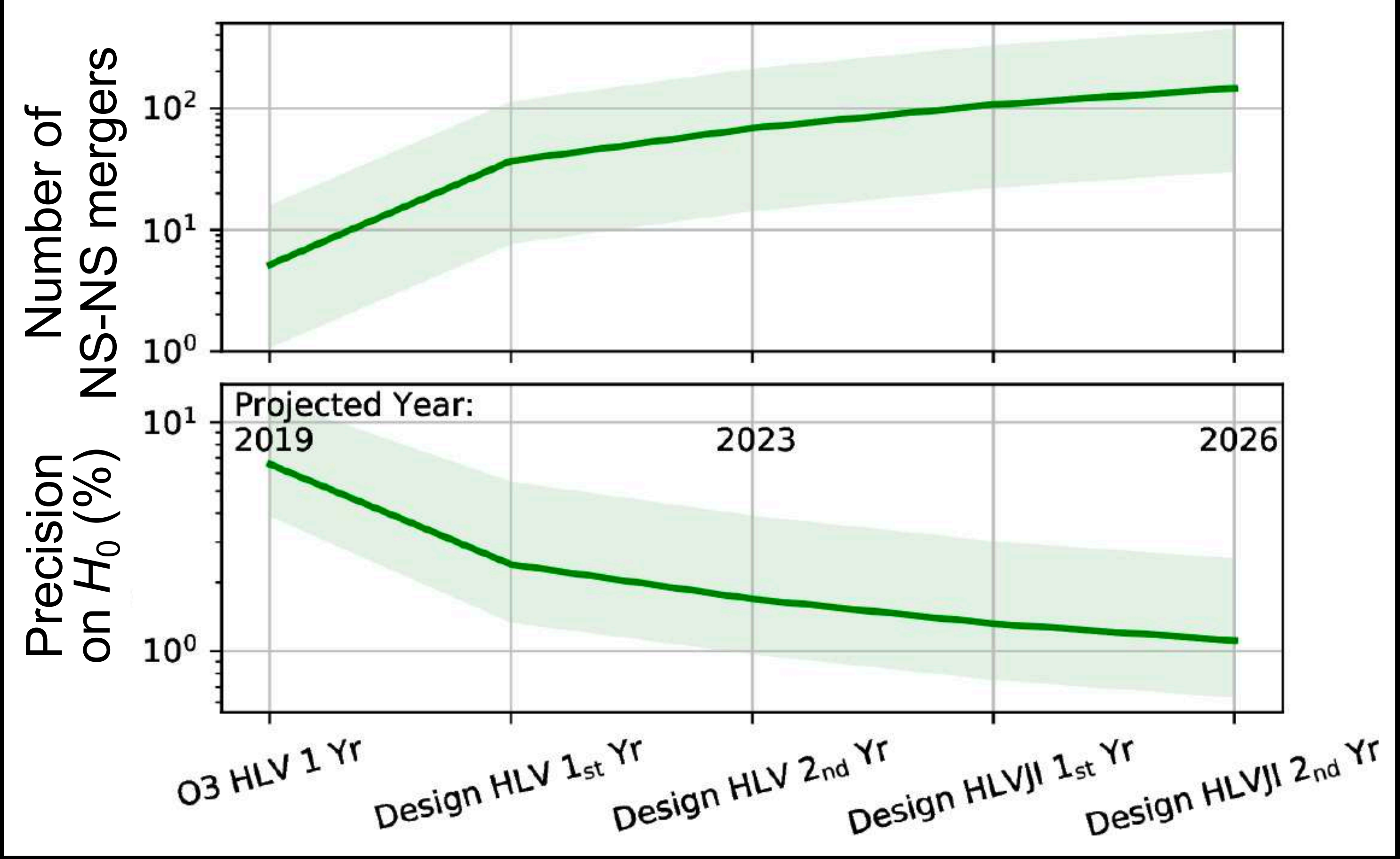
GW170817 marked the dawn of gravitational wave cosmology, using neutron star mergers as ‘standard sirens’



Abbott+17

Observations of more neutron mergers will provide a 1% precision measurement of the Hubble constant in the next decade



Chen+18

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- What is the origin of the kilonova ejecta?
- Do NS-NS mergers produce all of the *r*-process elements?
- What is expansion rate of the Universe?
- **Surprise discoveries?**

Multi-messenger discoveries of new types of gravitational wave sources are expected

Known Unknowns

- Core-collapse supernovae?
- Magnetar outbursts?
- Pulsars?

Unknown Unknowns

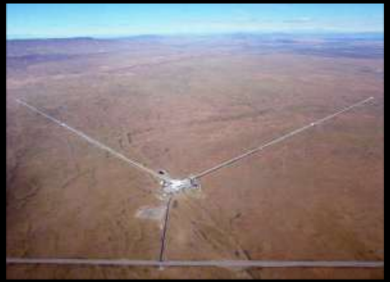
- ???

Canadian astronomers have formed a Canadian-wide coalition for multi-messenger astrophysics

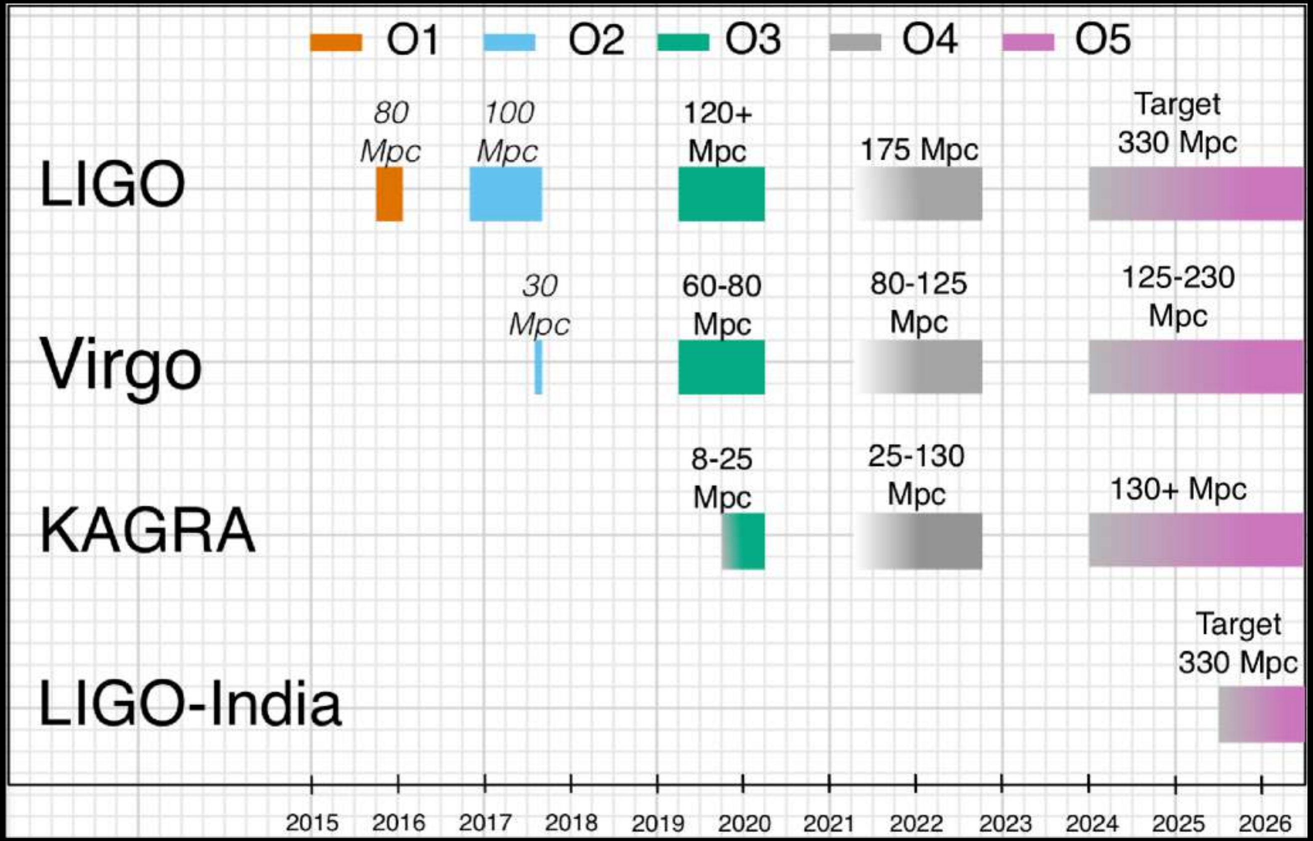
- Optical imaging search for counterparts using CFHT (PI: **Ruan**)
- Optical/NIR photometric monitoring of counterparts using CFHT (PI: **Ruan**)
- Optical/NIR spectroscopic monitoring of counterparts using Gemini (PI: Drout)
- X-ray/radio monitoring of counterparts using Chandra and Jansky VLA (PI: Haggard)

The progressively larger detection horizon of GW facilities will detect *hundreds* of new NS-NS mergers over the next decade

LIGO-Hanford

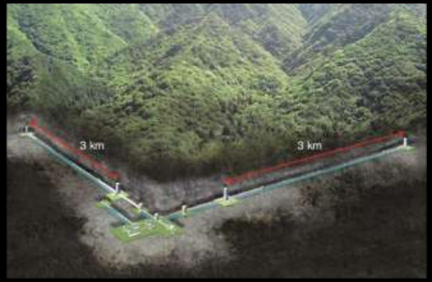


LIGO-Livingston



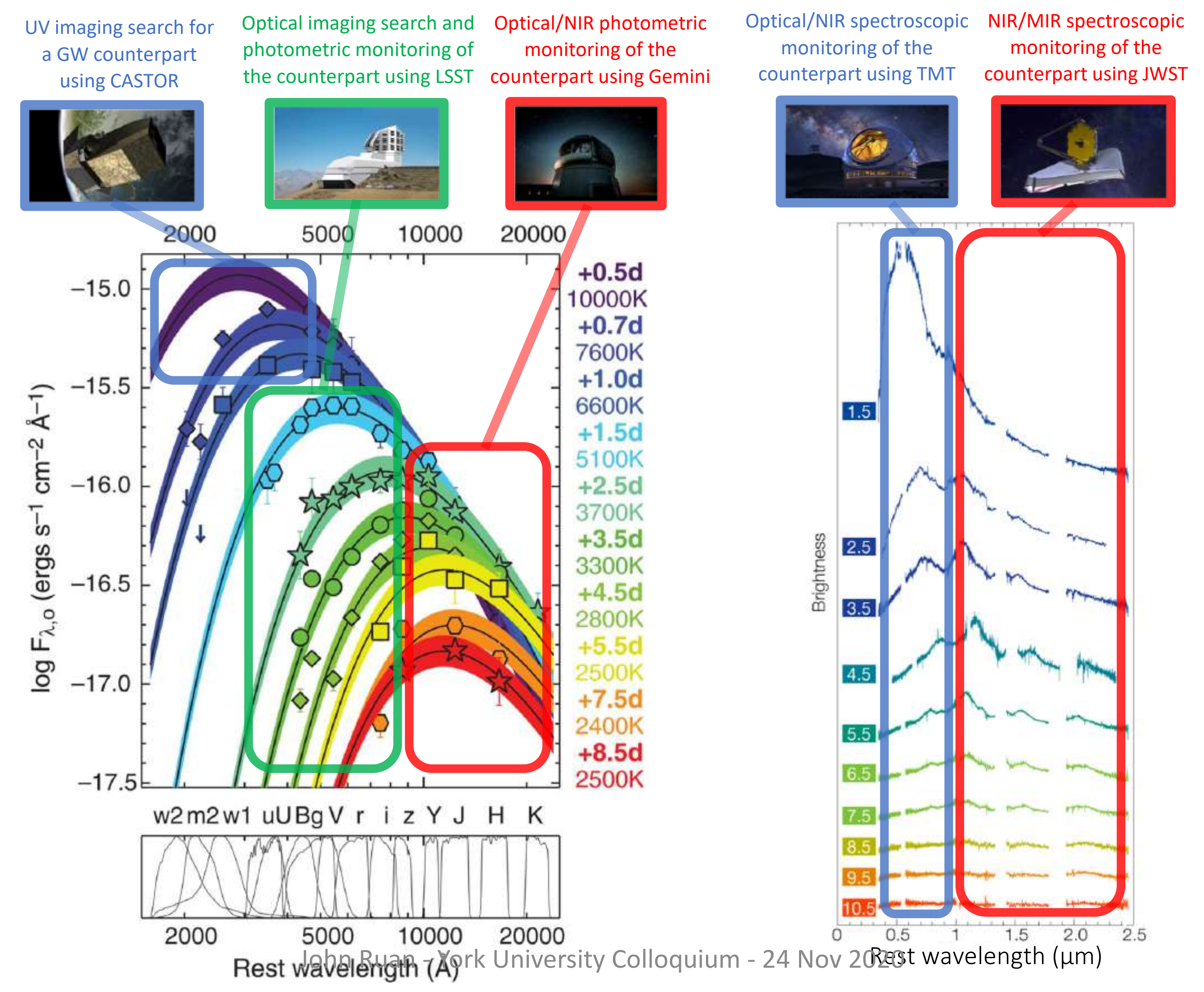
Abbott+19

KAGRA



LIGO-India

Key Issue: future EM counterparts to GW events will be *faint*, large-aperture telescopes are needed

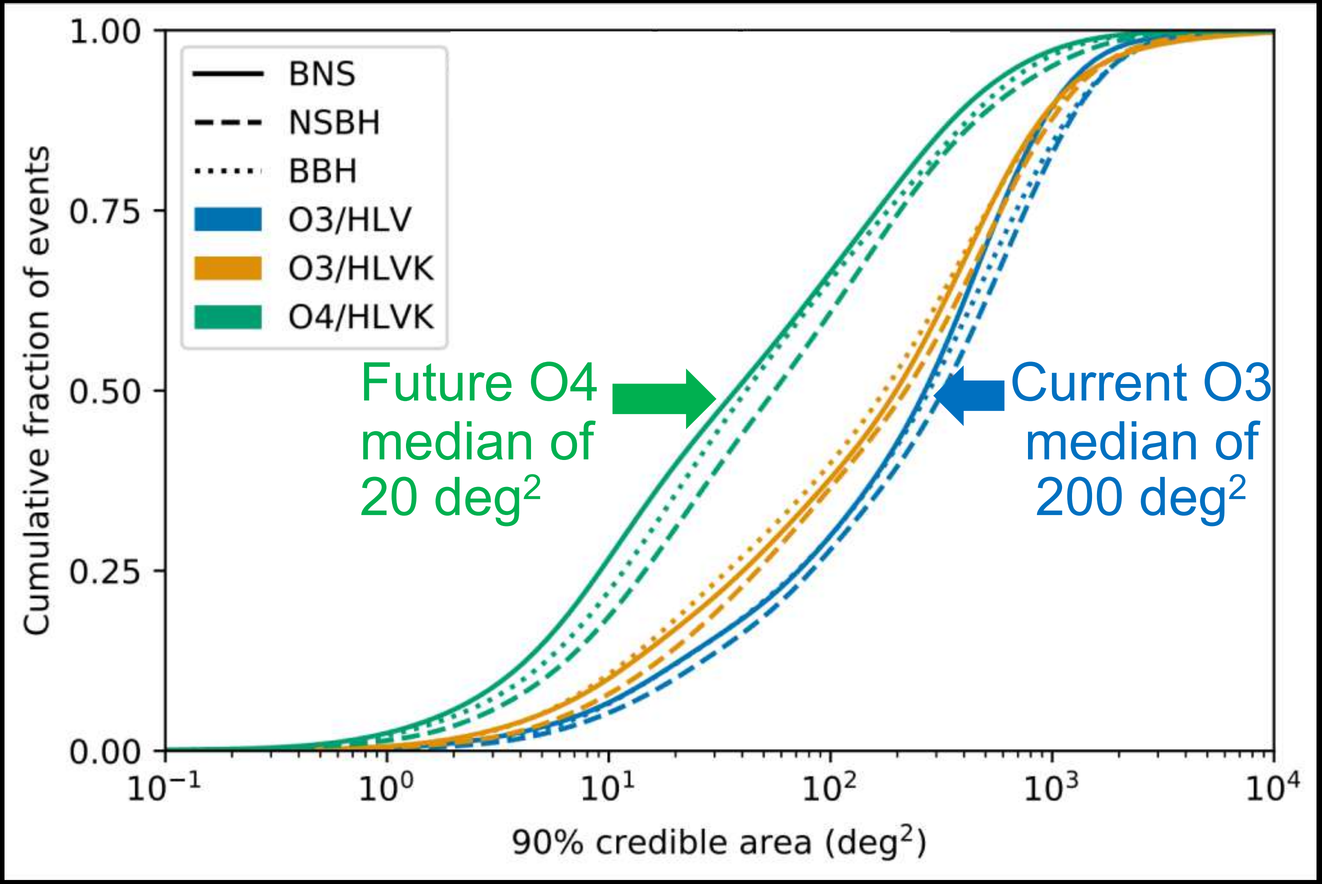


Conclusions

- Multi-messenger observations of GW170817 provided transformational insights into a diverse array of fundamental question
- However, many new questions have emerged that demand multi-messenger observations of more gravitational wave events
- The next decade will be the golden age for multi-messenger astrophysics

Extra slides

New GW detectors and sensitivity upgrades will improve NS-NS merger localizations to <20 deg^2 in the next 2 years



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Hundreds of new NS-NS mergers will be detected through gravitational waves over the next decade