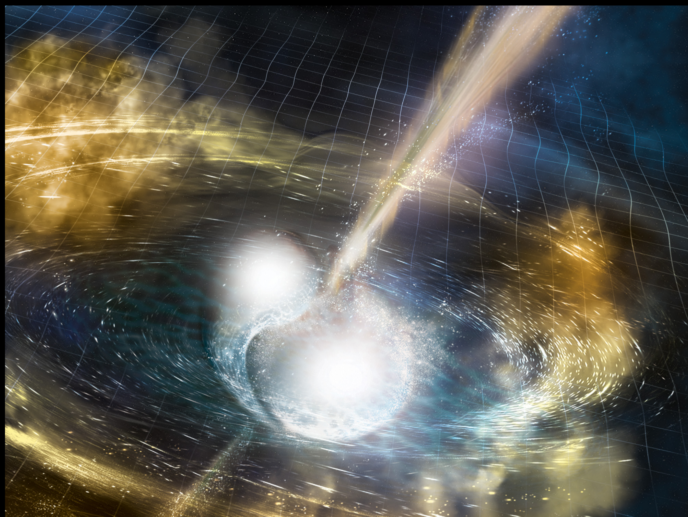
Gravitational-wave Astrophysics

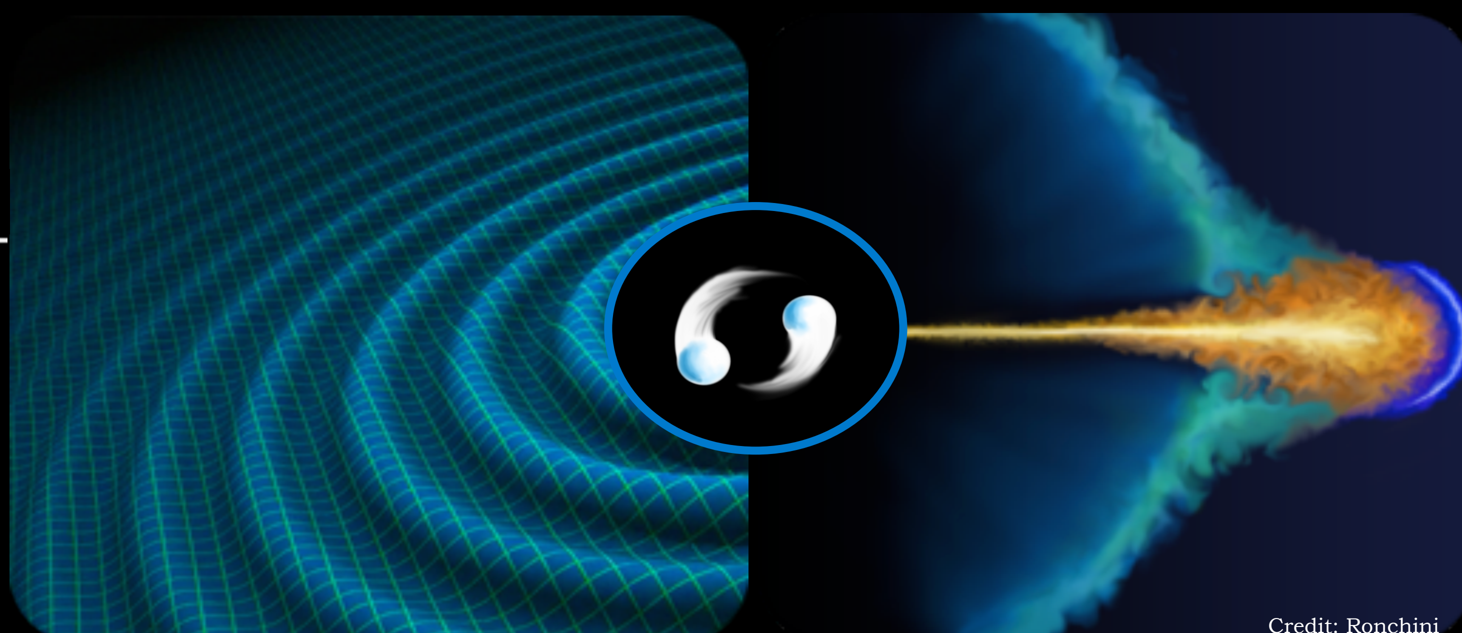


M. Branchesi

Gran Sasso Science Institute

INFN/LNGS and INAF

GSSI GW team



Credit: Ronchini

A new window into the Universe

Credit: LIGO–Virgo

KAGRA, Japan

O1

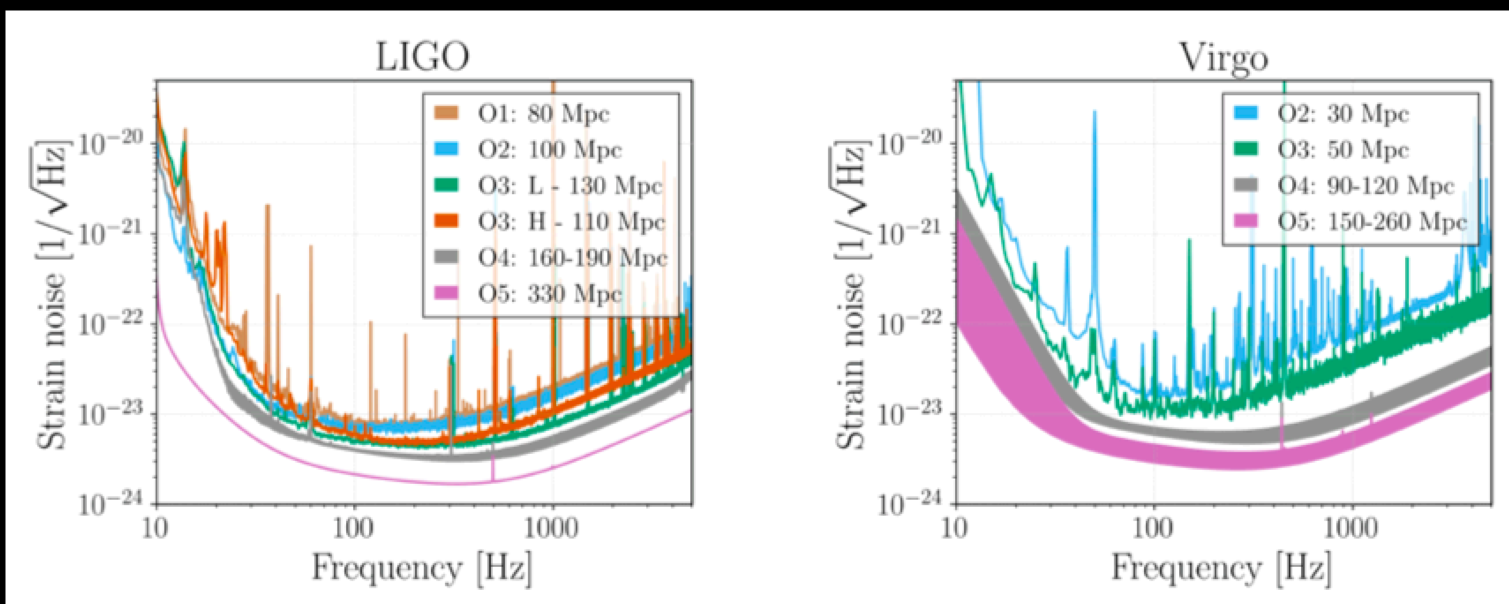
O2

O3

Sep ‘15 - Jan ‘16

Nov ‘16 - Aug ‘17

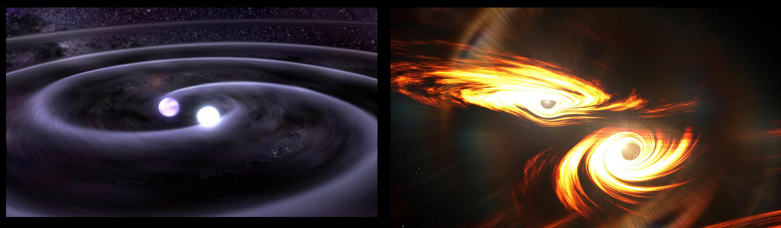
Apr ‘19 - Mar ‘20



Abbott et al. 2020, LRR

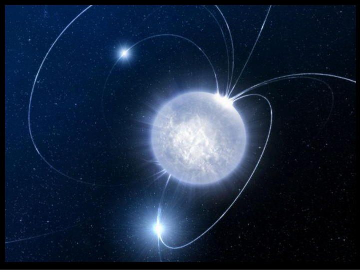
GW SOURCES DETECTABLE BY LIGO, Virgo and KAGRA

Binaries of compact objects



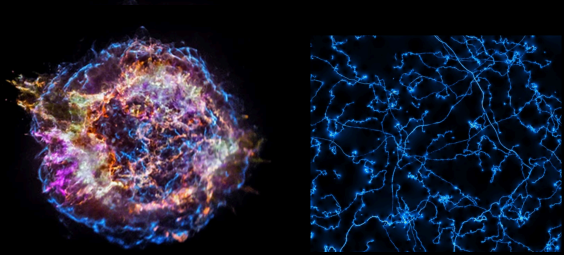
1–170 Myr^{-1}
per Milky Way equivalent galaxy

Continuos signals

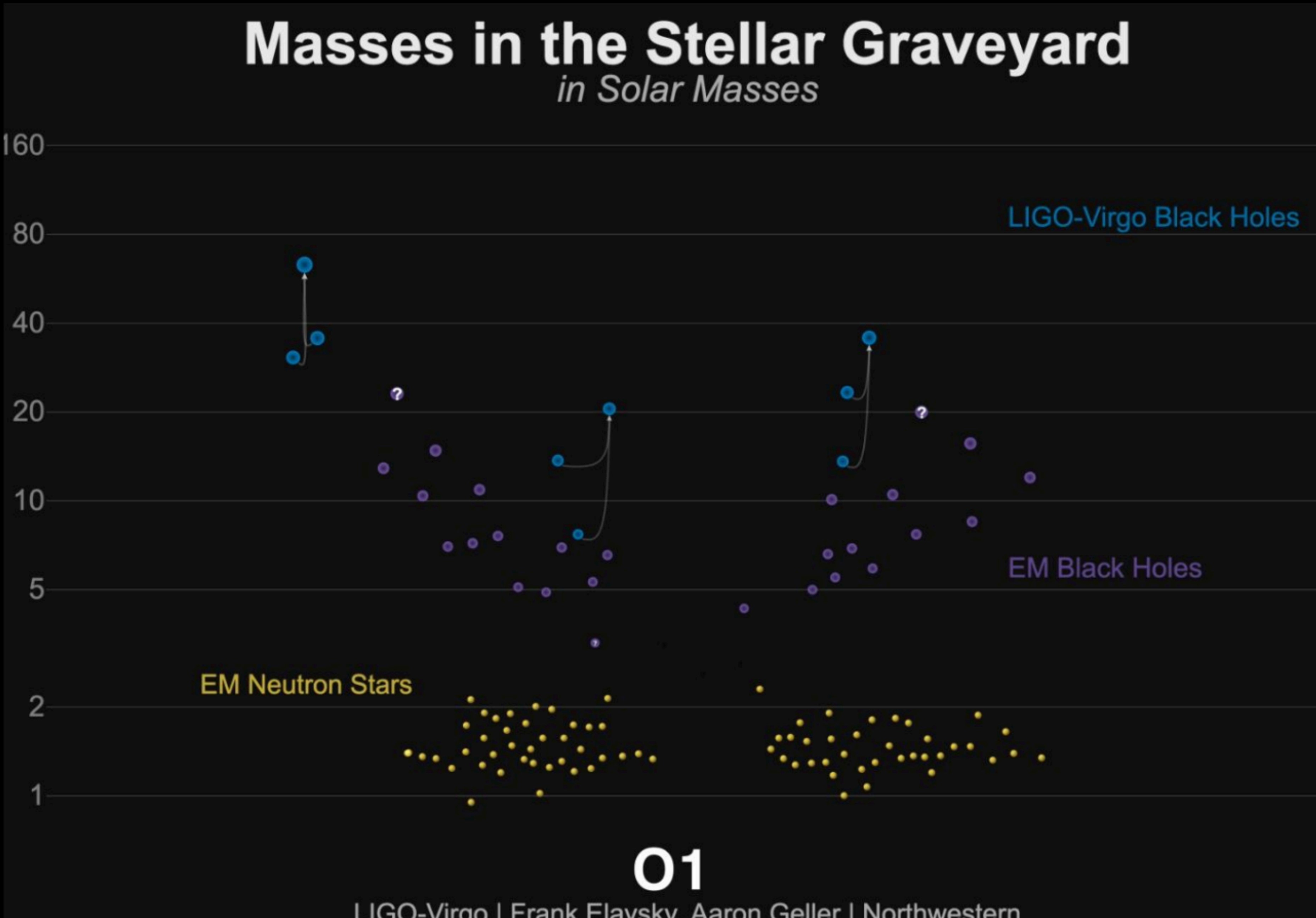


2 per century in
a Milky Way equivalent galaxy

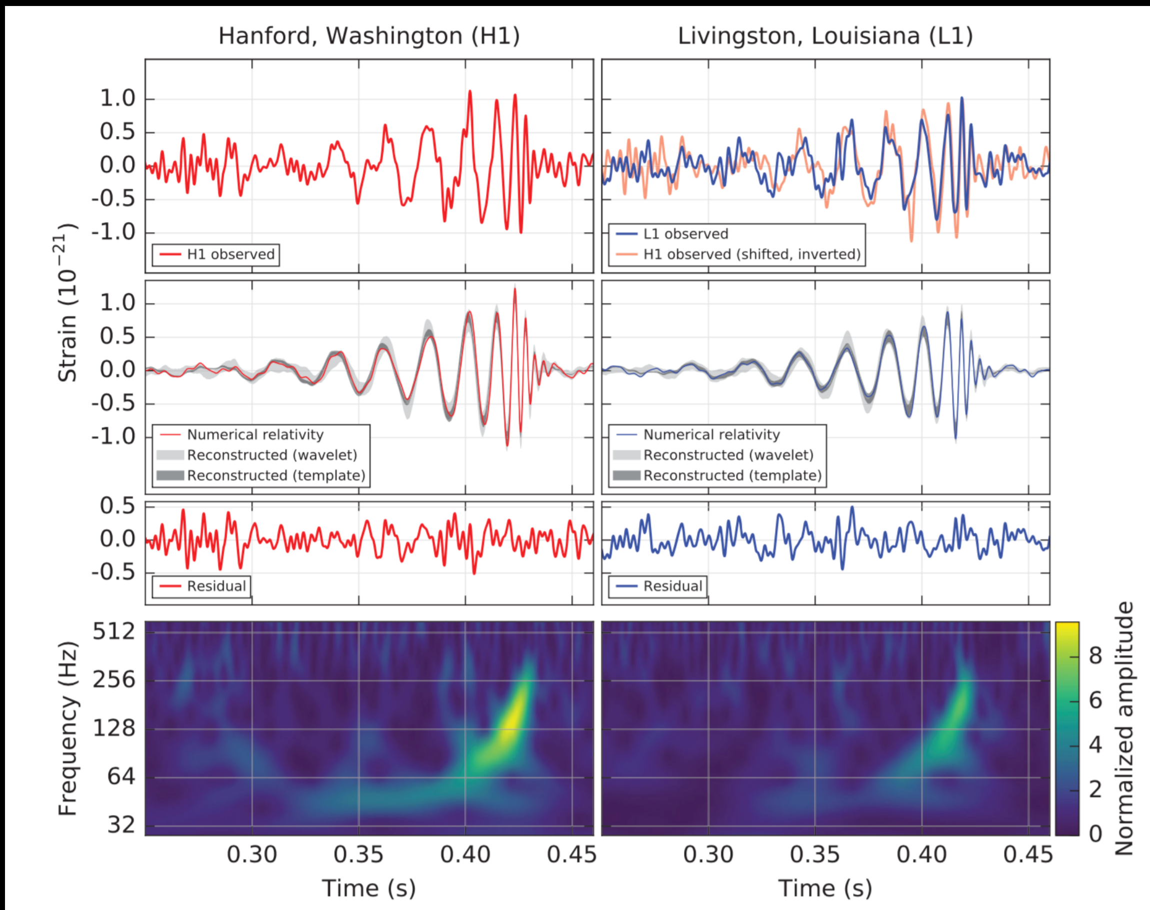
Short-duration busrts



Stochastic background


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
O1
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Observations of gravitational waves from a binary black- hole merger

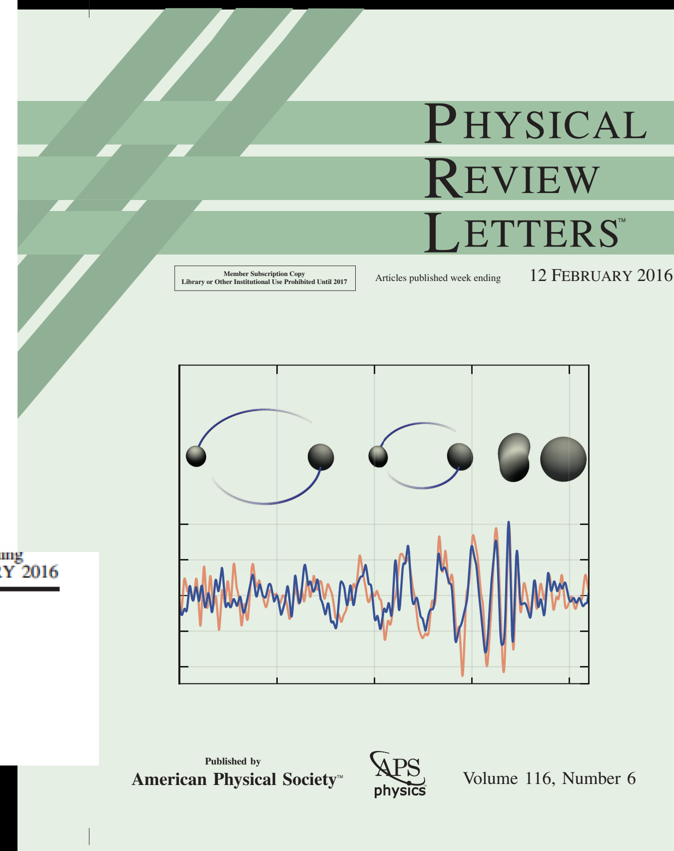


GW150914

PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

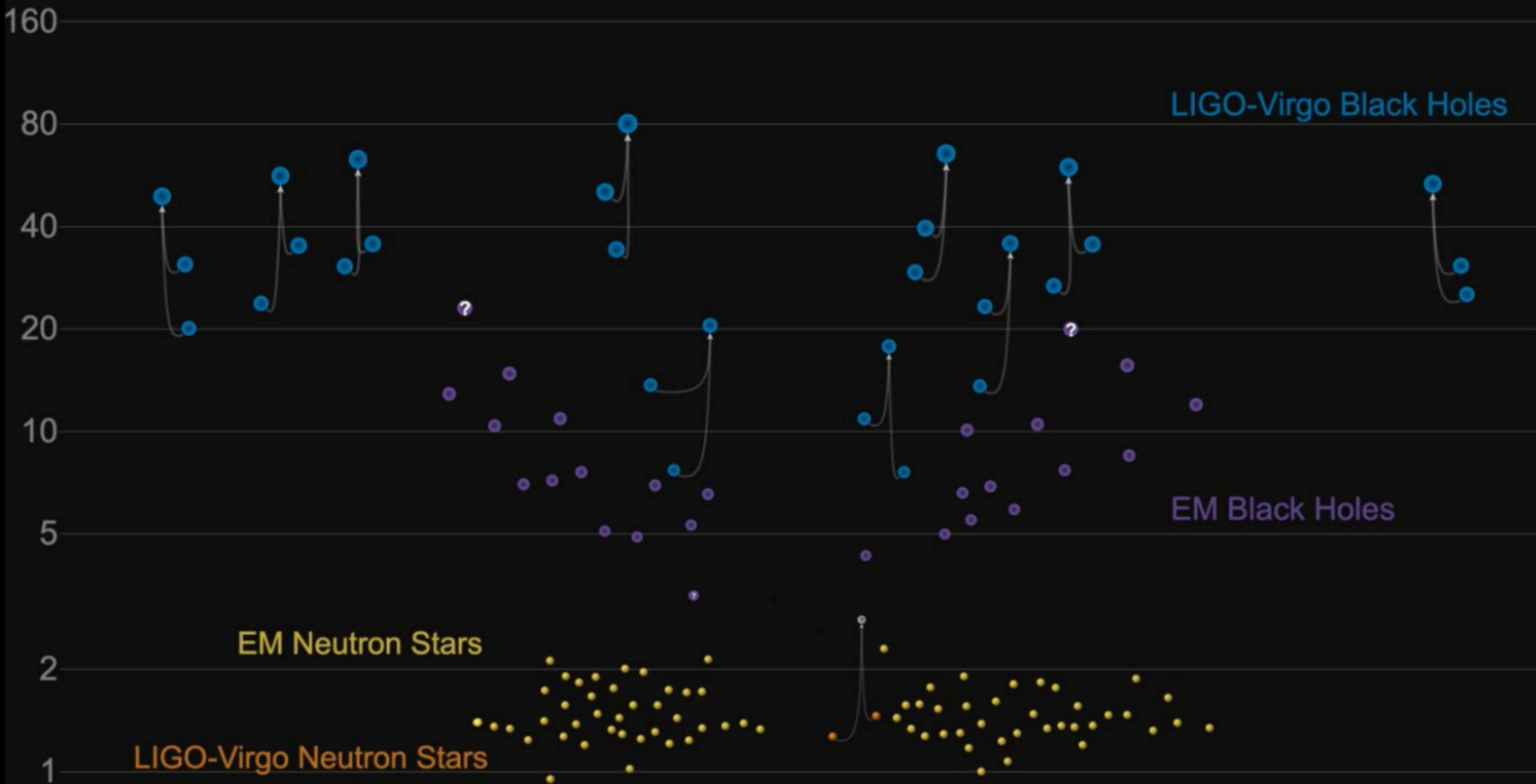
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)



Masses in the Stellar Graveyard

in Solar Masses

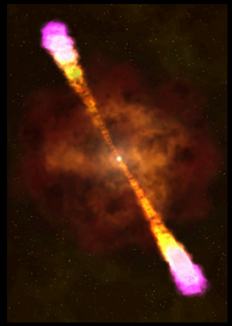


O2

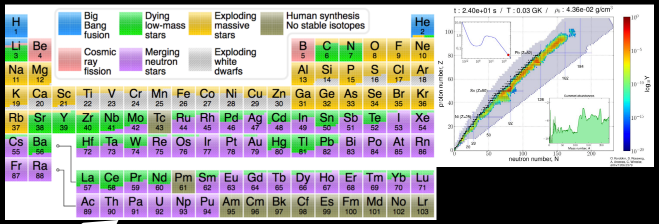
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Radioactively powered transients

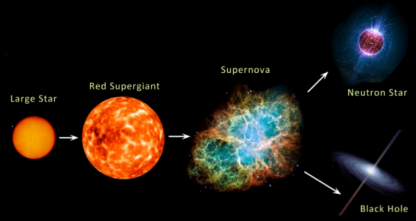
Relativistic astrophysics



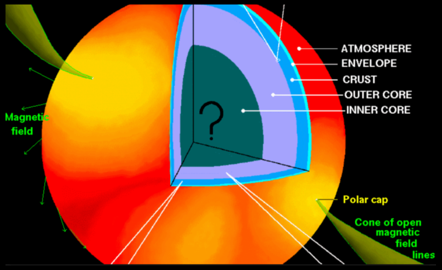
Nucleosynthesis and enrichment of the Universe



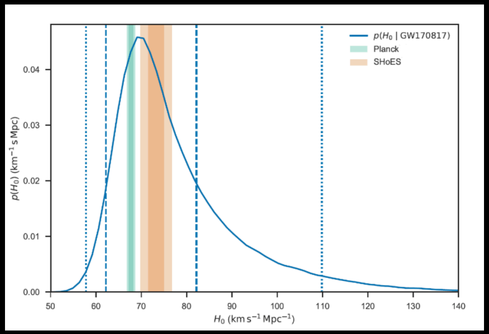
Compact object formation and evolution



Nuclear matter physics



Cosmology

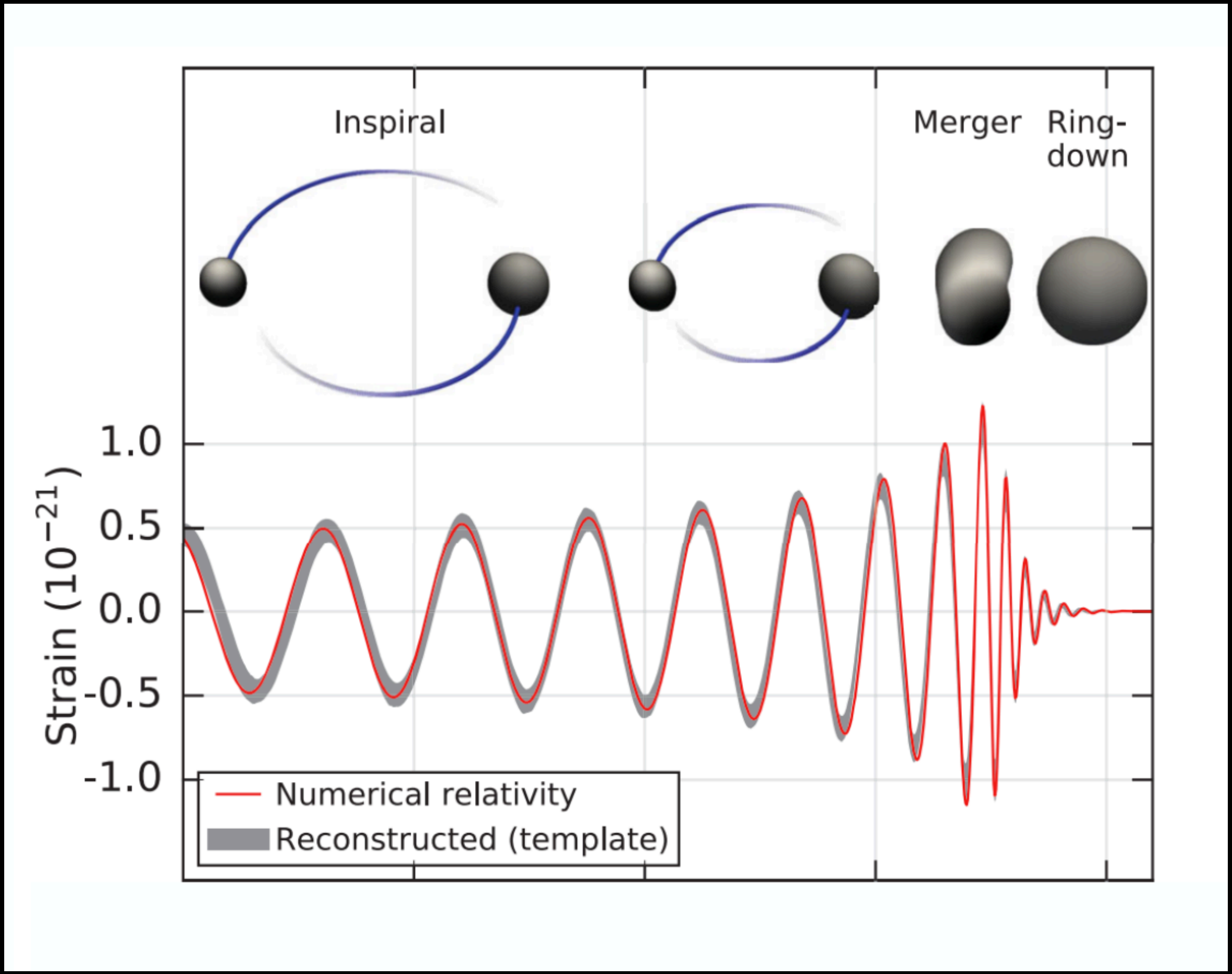


O1+O2+O3

90 GW EVENTS!

LVK arXiv:2111.03606

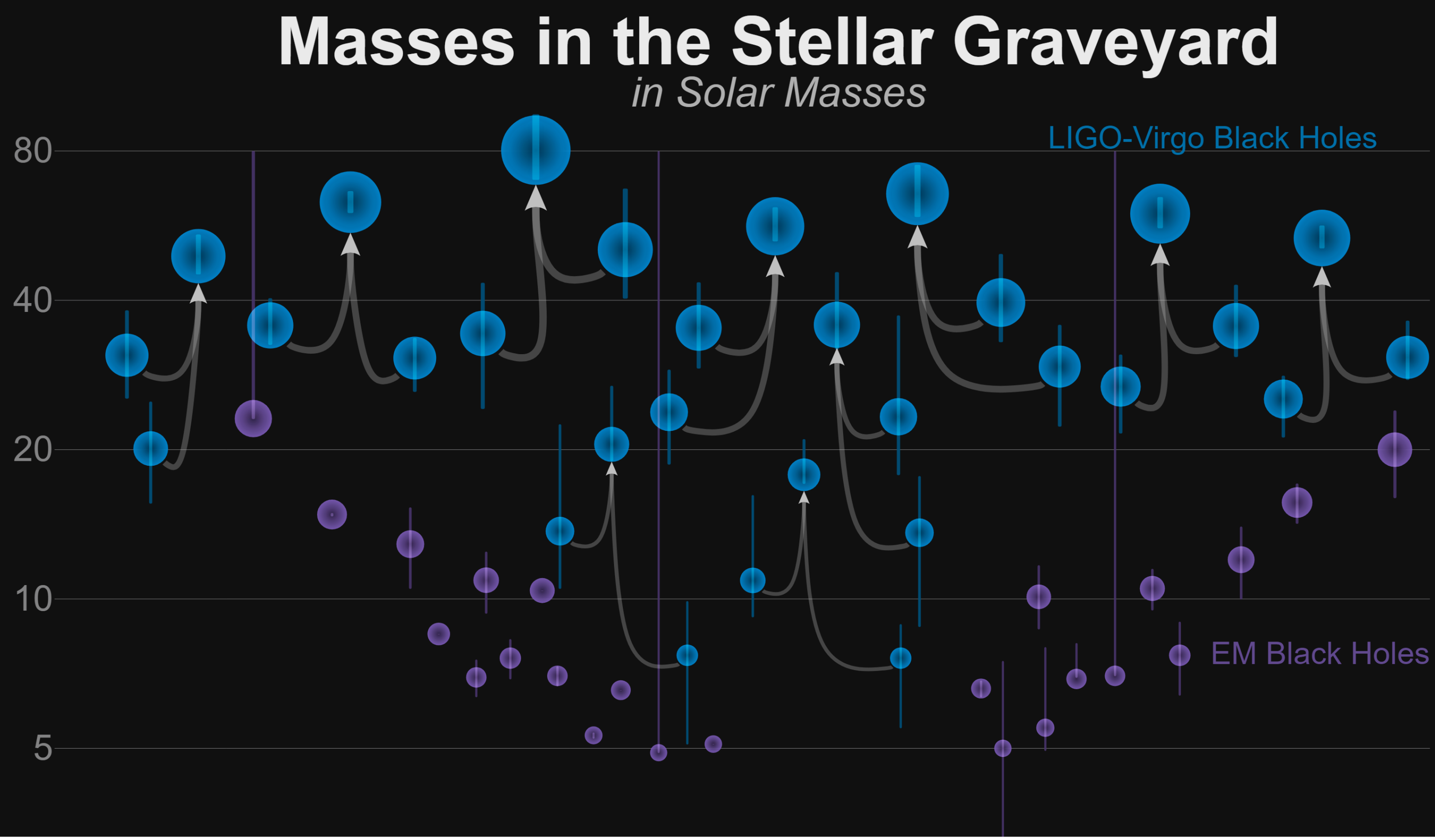
Source modelling



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Chirp mass drive the early inspiral

Late inspiral and merger
→ individual masses

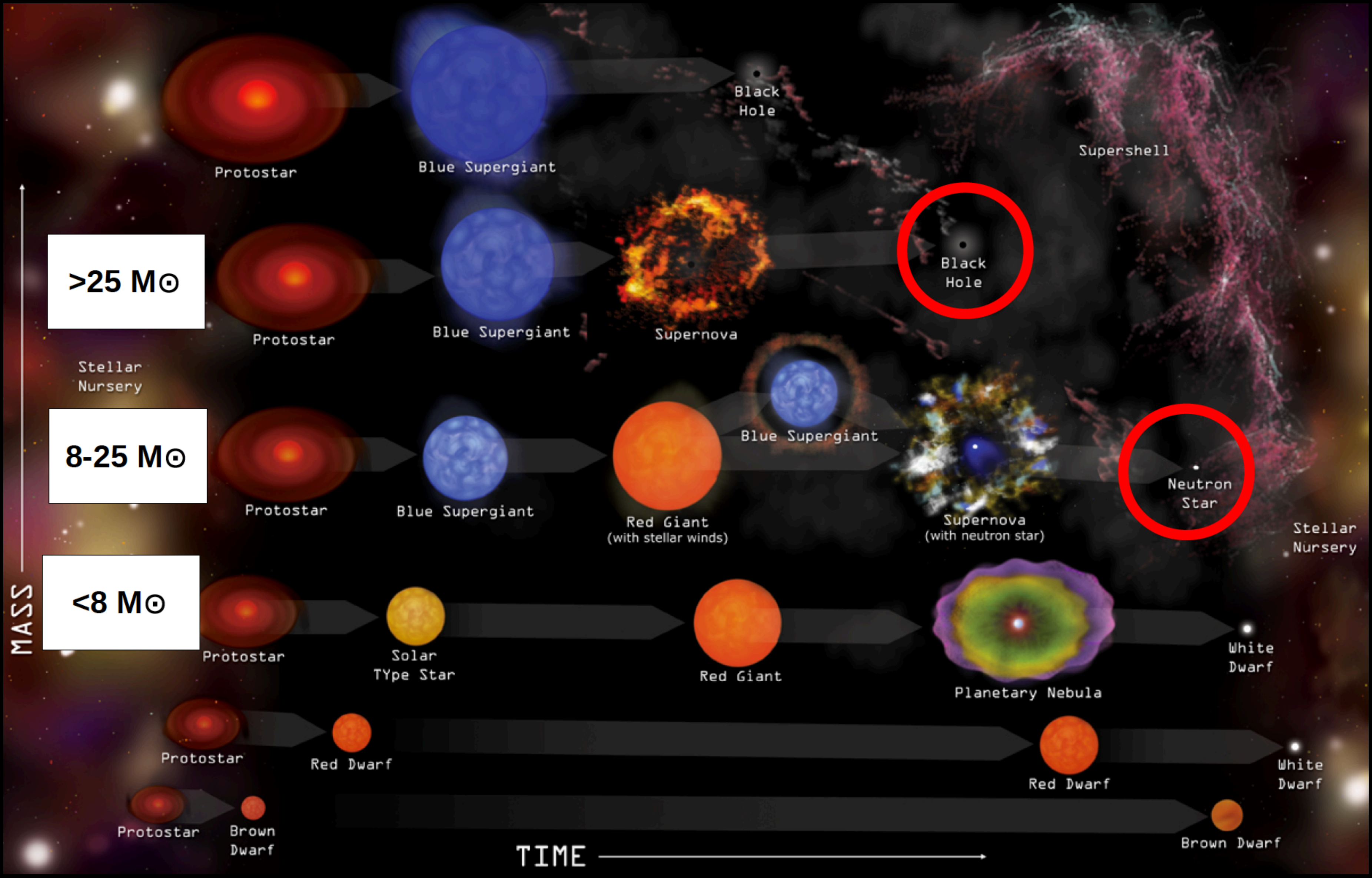


GW OBSERVATIONS

- Binary stellar-mass black holes (BBHs) exist;
- BBHs can inspiral and merge within the age of the Universe;
- Heavy stellar-mass black holes (with mass >20 $M_{\odot}$) exist

(LVC 2018 ApJL, 818)

How do compact object, black hole and neutron star form?



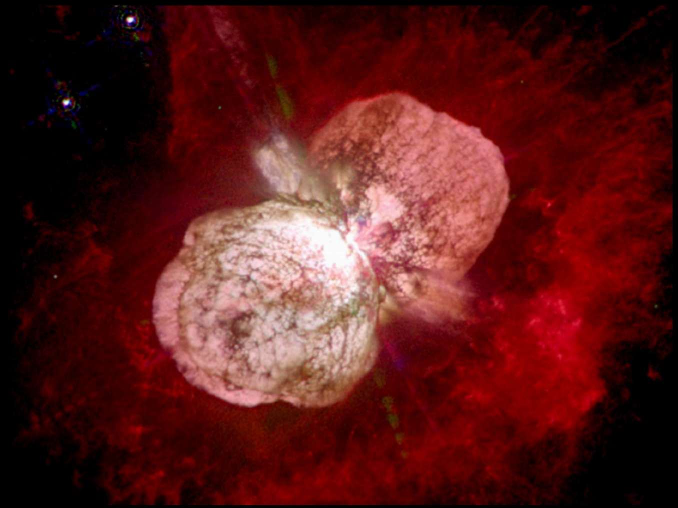
Heger et al. 2003, Fryer 1999, Fryer & Kalogera 2001

THE FORMATION OF COMPACT OBJECTS

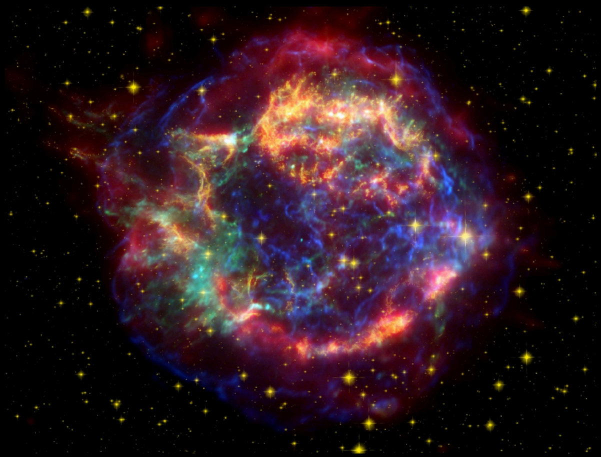
Two critical ingredients:

1) PROGENITOR STAR EVOLUTION (STELLAR WINDS)

2) SUPERNOVA EXPLOSION



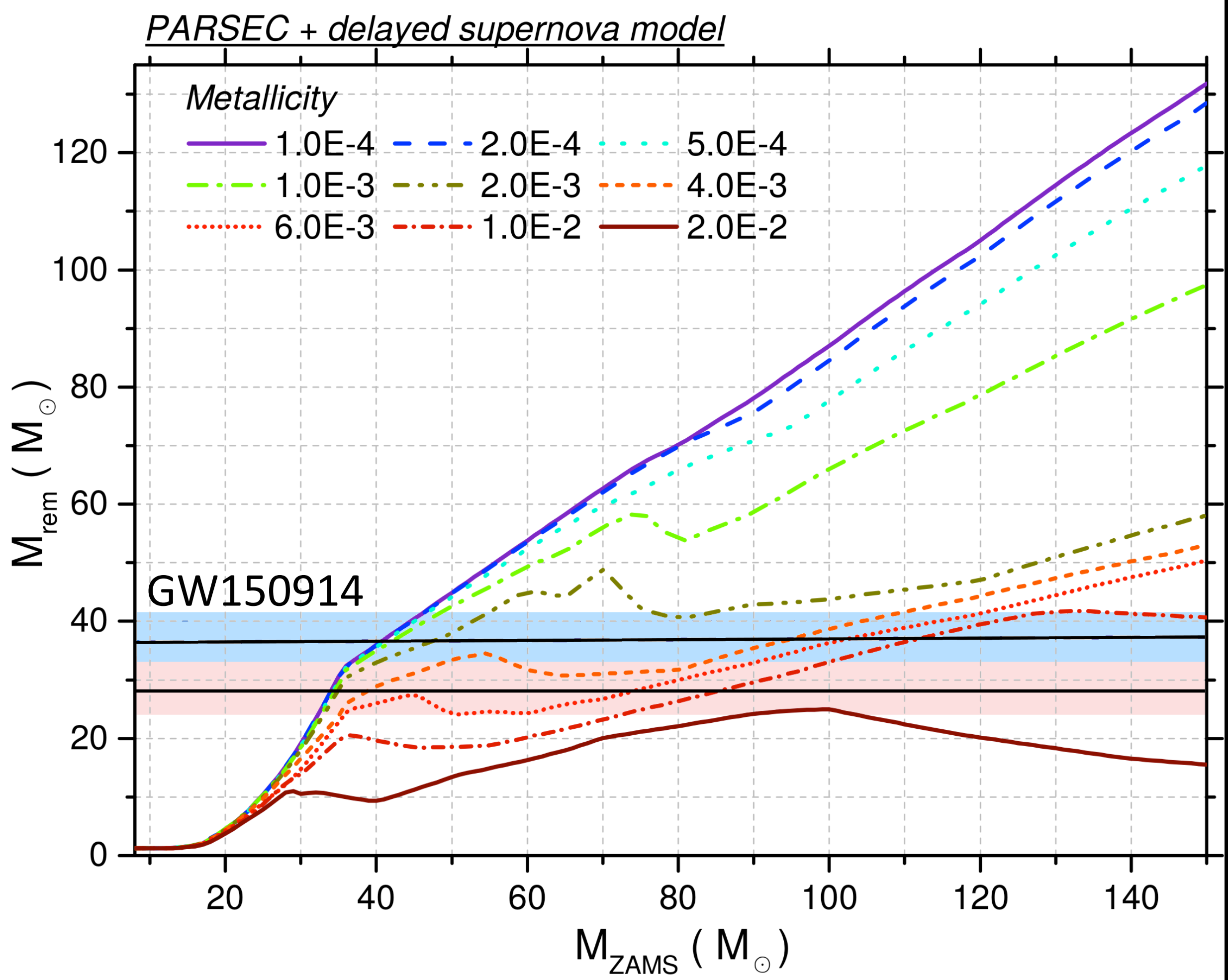
Winds ejected by Eta Carinae (HST, credits: NASA)



Chandra + HST + Spitzer Image of the SN remnant Cassiopeia A

Credits: Mapelli

THE FORMATION OF COMPACT OBJECTS



LVC 2016 ApJL, 818, 22

Mapelli et al. 2013, MNRAS, 429, 2298 Spera et al. 2015, MNRAS, 451, 4086

Belczynski et al. 2010, ApJ, 714, 1217

METALLICITY IN ASTROPHYSICS is NOT same as chemistry

Metals in Astro: **every element heavier than Helium**

Measured with $\boxed{\textbf{Z = FRACTION of mass of a star that is not hydrogen or helium}}$

$$X + Y + Z = 1.0$$

If M = total mass of system

$$X_{\odot} = m_p/M \qquad Y = m_{He}/M \qquad Z = \Sigma i\, m_i/M$$

Sun values:

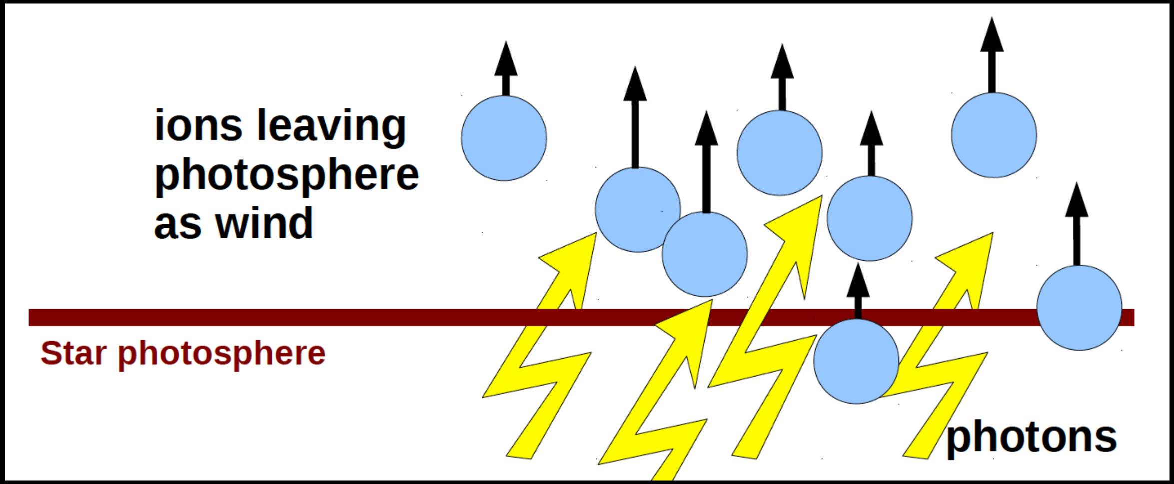
$X_{\odot} \sim 0.73$, $Y_{\odot} \sim 0.25$, $\mathbf{Z_{\odot} \sim 0.02}$

STELLAR WINDS

Photons in atmosphere of a star couple with ions
→ transfer linear momentum to the ions and unbind them

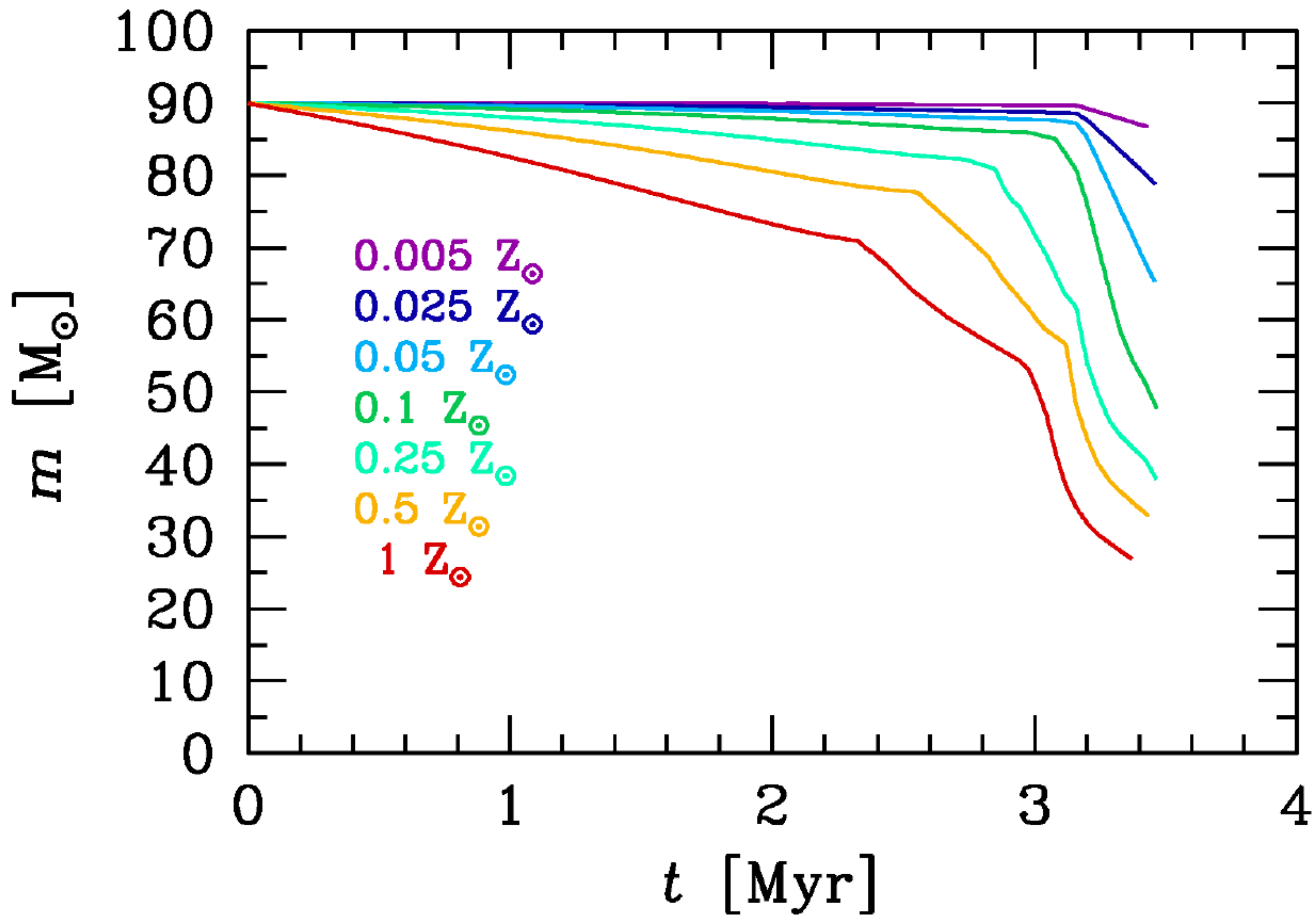
Coupling through resonant METAL LINES (especially Fe lines)
→ MASS LOSS DEPENDS ON METALLCITY

$$\boxed{\dot{M} \propto Z^{\alpha}} \qquad \alpha \sim 0.5 - 0.9$$



Credit: M. Mapelli

Massive stars (>30 Msun) might lose >50% mass by winds
Stellar wind models underwent major upgrade in last ~10 yr
(Vink+ 2001, 2005, 2011; see Vink+ 2016 for a short review)

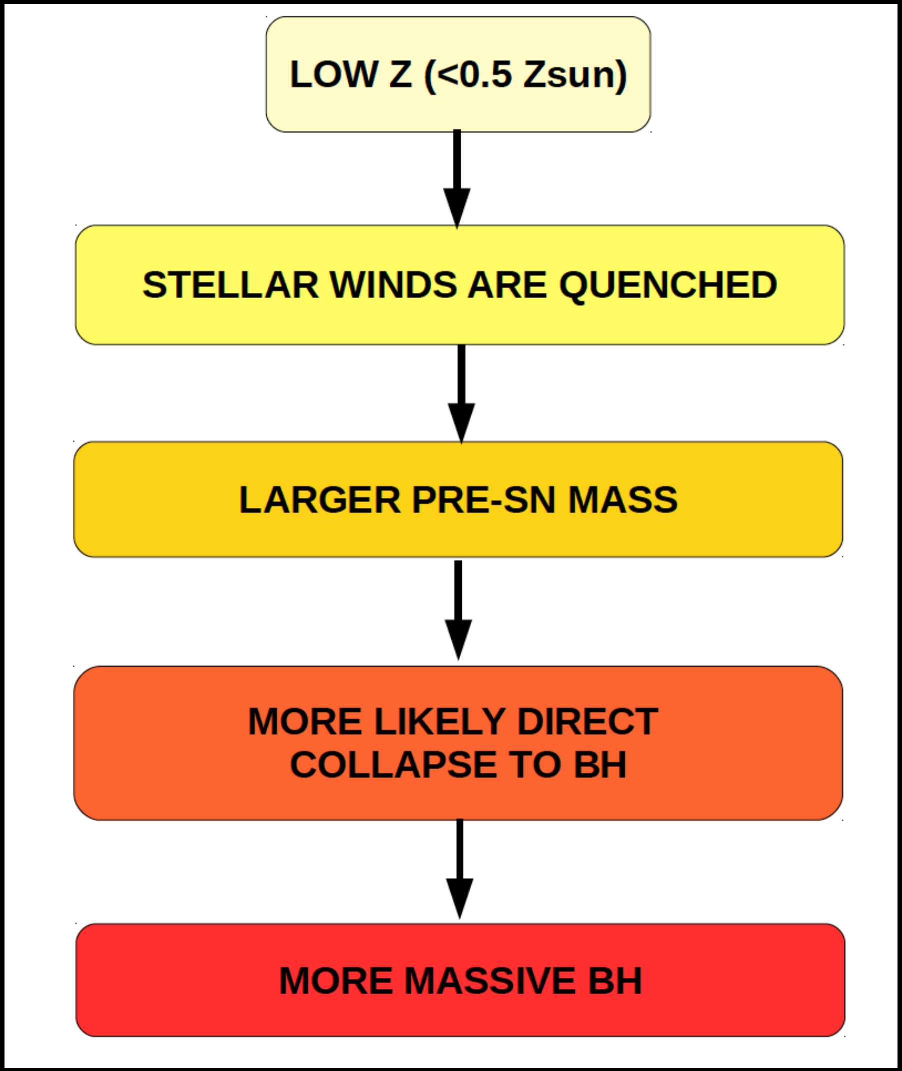


Models from PARSEC stellar evolution code (Bressan+ 2012; Tang+ 2014; Chen, Bressan+ 2015)

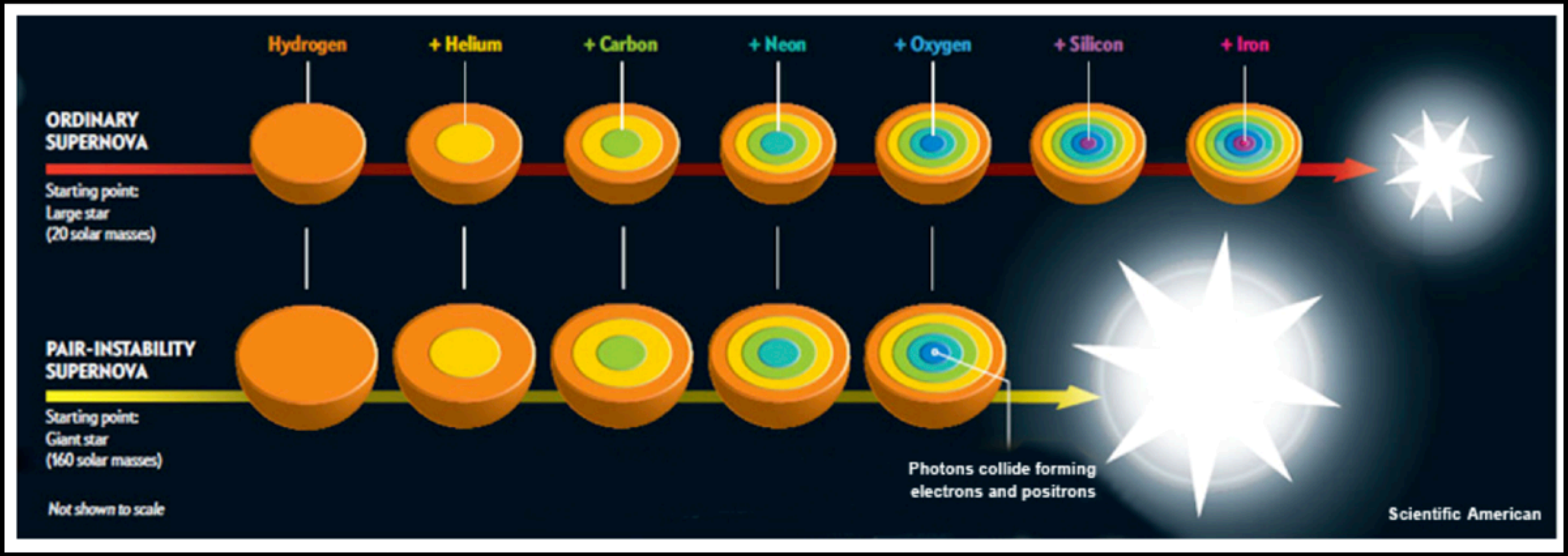
Credit: M. Mapelli

HEAVY BH FORMATION

Very complicated. However, as rule of thumb (Mapelli+ 2009, 2013):

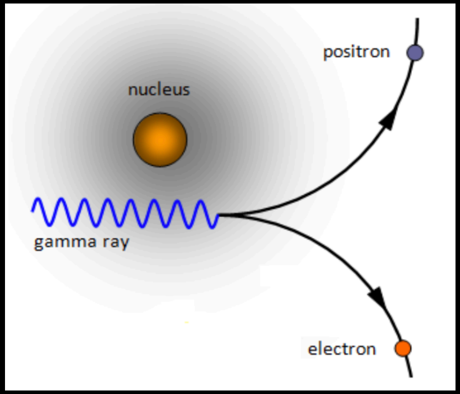


PAIR INSTABILTY SN



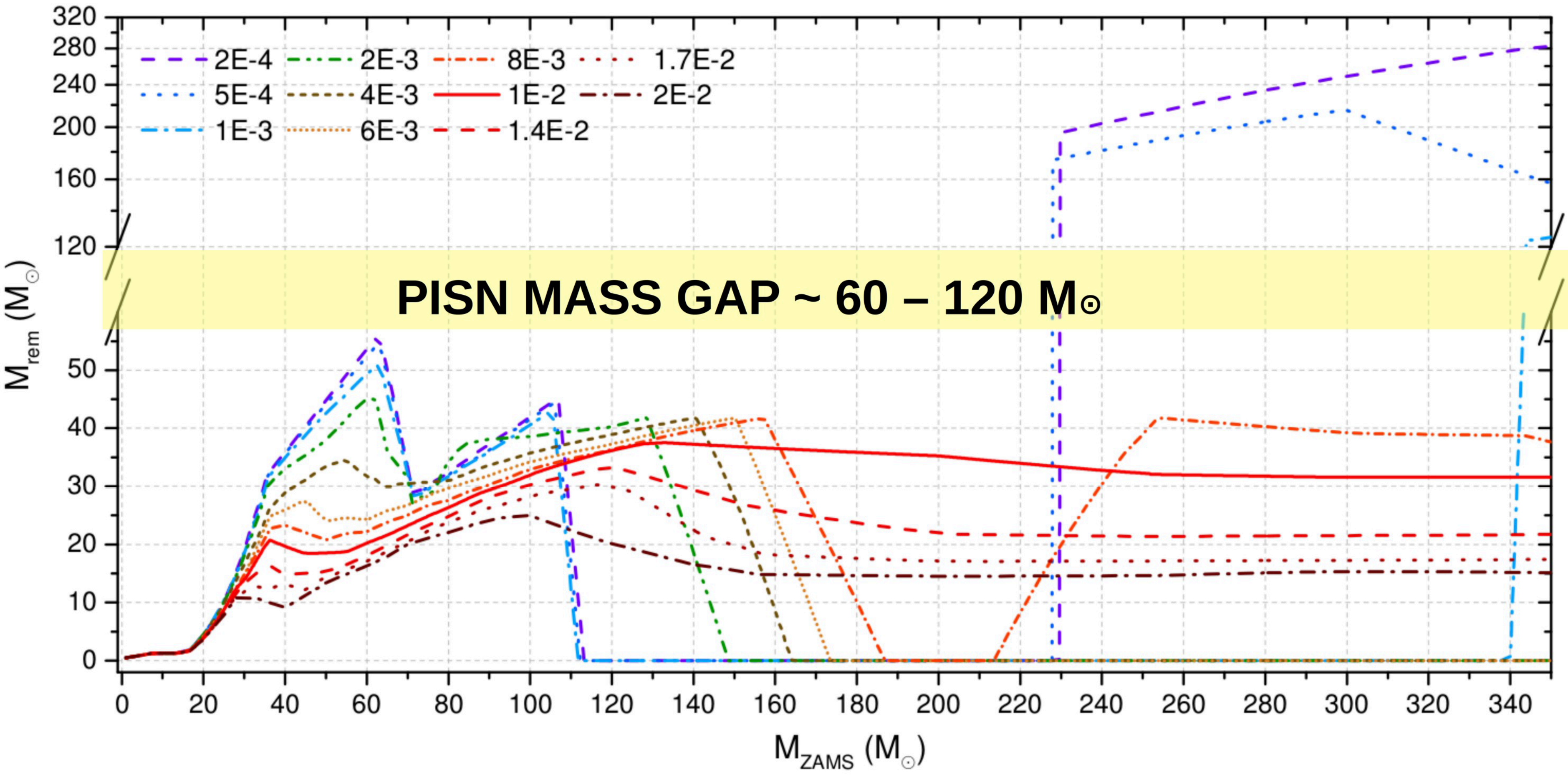
If a star is very massive, Helium core MASS > 64 Mo
→ Central temperature > 7 x 10^8 K
→ Efficient production of gamma-ray radiation in the core

→ Gamma-ray photons scattering by atomic nuclei produce electron-positron pairs (1 Mev)



The high-energy photon near a nucleus lose its energy to produce an e-e+ pair
→ The missing pressure of gamma-ray photons produces dramatic collapse during O burning, without Fe core → NO REMNANT

PAIR INSTABILTY SN



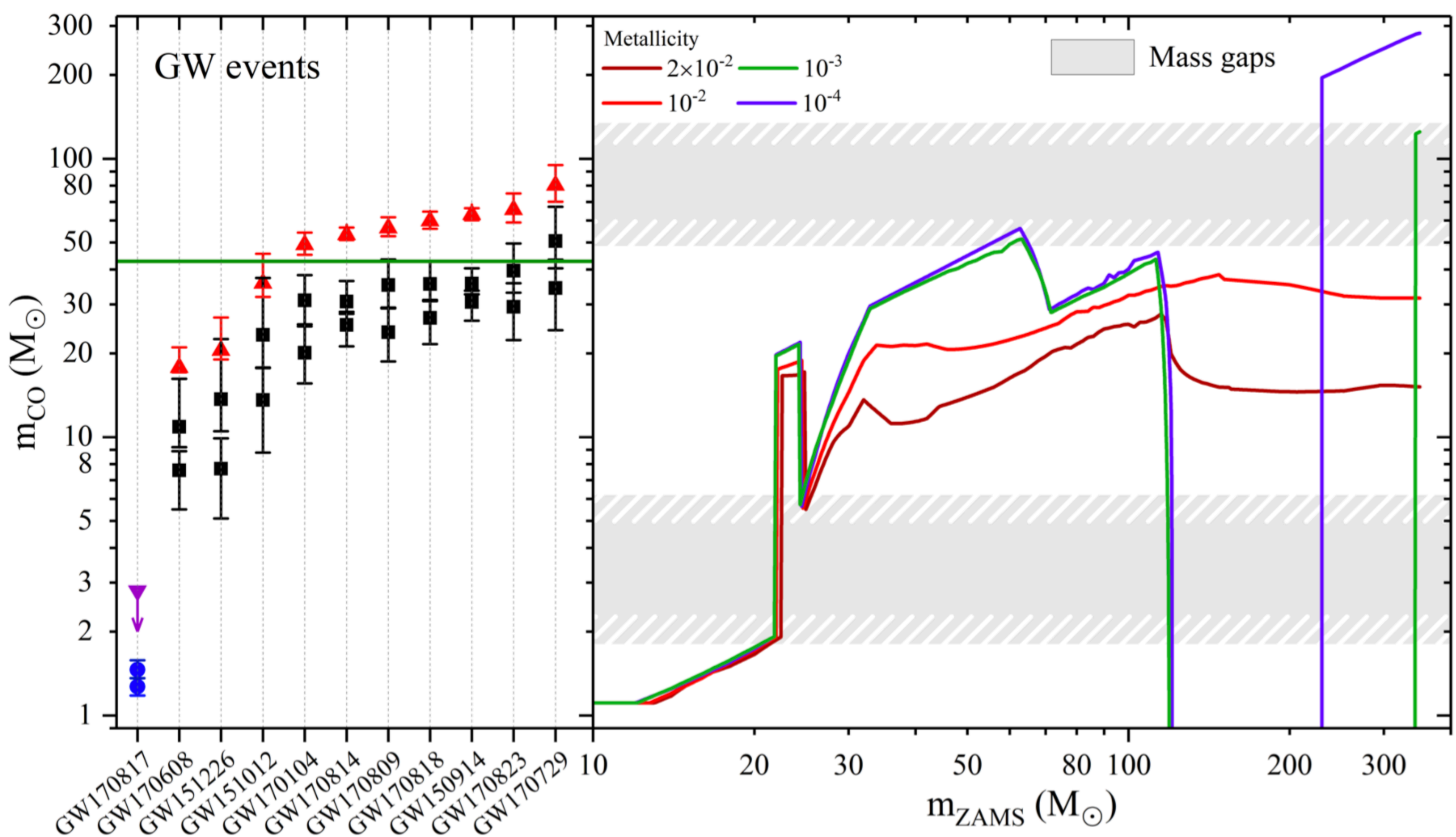
Spera & Mapelli 2017

MASS OF THE COMPACT REMNANT AS A FUNCTION OF THE ZERO-AGE MAIN SEQUENCE MASS OF THE STAR

O1 and O2 RESULTS

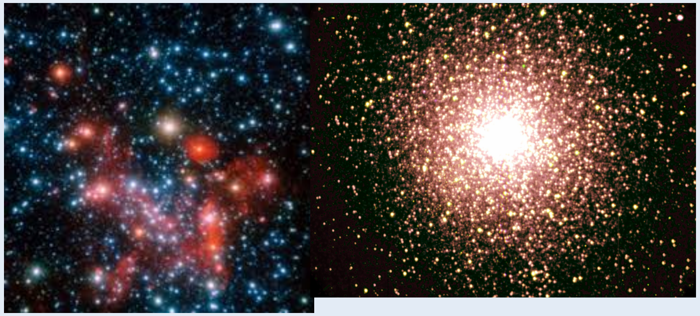
OBSERVED MASSES

PREDICTED COMPACT-OBJECT MASS



Formation pathways to form a massive black hole (>25 Mo)

BHs can form in dense environment or in the galaxy field:



- Globular Cluster/Young Star Cluster

R ~ 1-10 pc, N ~ 10^{3-7} stars

- Galaxy field

R~10 kpc, N ~10^{10} stars

Massive BHs form:

1) from direct collapse of metal-poor progenitor stars
   (BOTH CLUSTER AND FIELD)
2) dynamically triggered mergers of lower mass BHs or BH-star favored by three-body encounters (CLUSTER ONLY)

→ in GC unlikely since BBH ejected from host cluster before merger

→ in YSC low rate

3) GW observations → as second generation of BH from the merger of lower mass BH

Where do binary black holes form?

Galaxy field

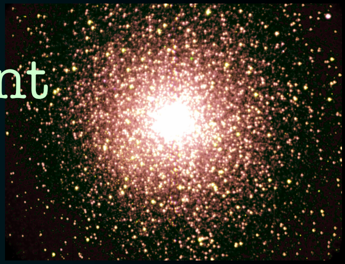
R~10 kpc,

N ~ 10^{10} stars

Dense environment star clusters

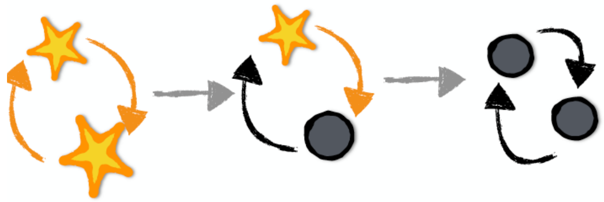
R~1-10 pc,

N ~ 10^{3-7} stars

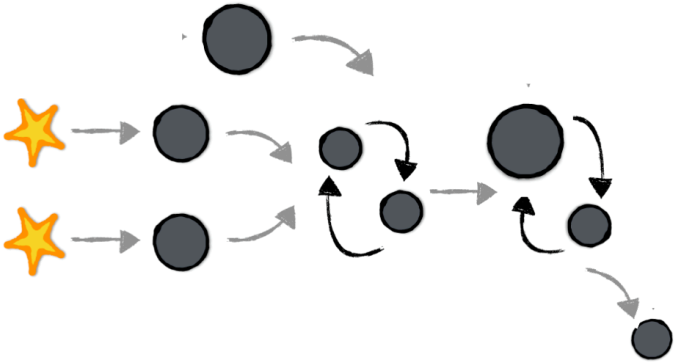


How do they form binary systems?

Isolated binary



Dynamical interactions

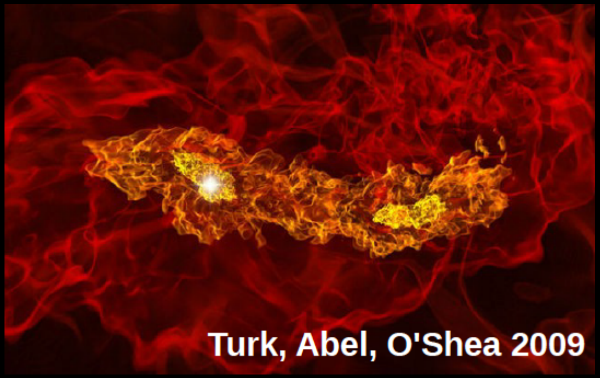


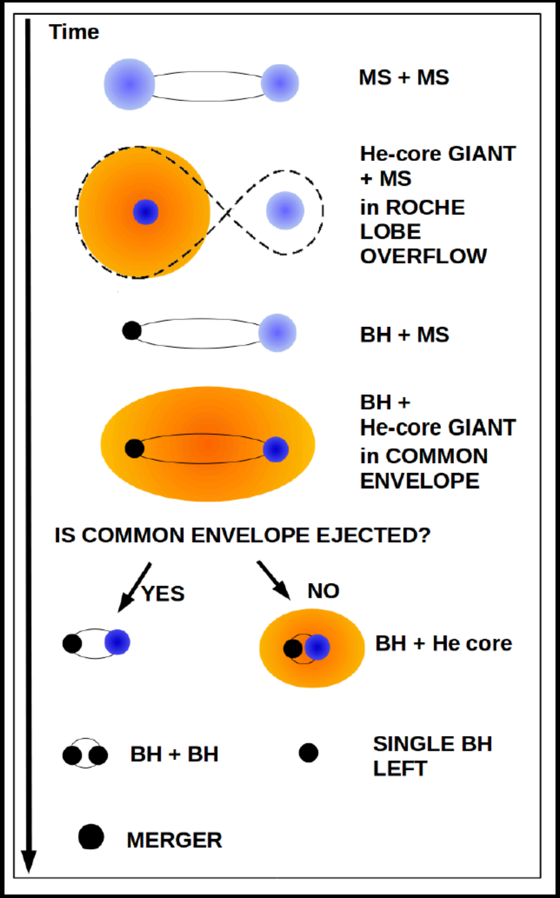
See e.g. Abbott et al. 2016, ApJL, 818, 22

PRIMORDIAL BINARIES or ISOLATED BINARIES:

two stars form from same cloud and evolve into two BHs gravitationally bound

MOST MASSIVE STARS ARE IN BINARY SYSTEMS
70% of massive stars have a companion
(e.g. Sana et al. 2012; Moe & Di Stefano 2017)



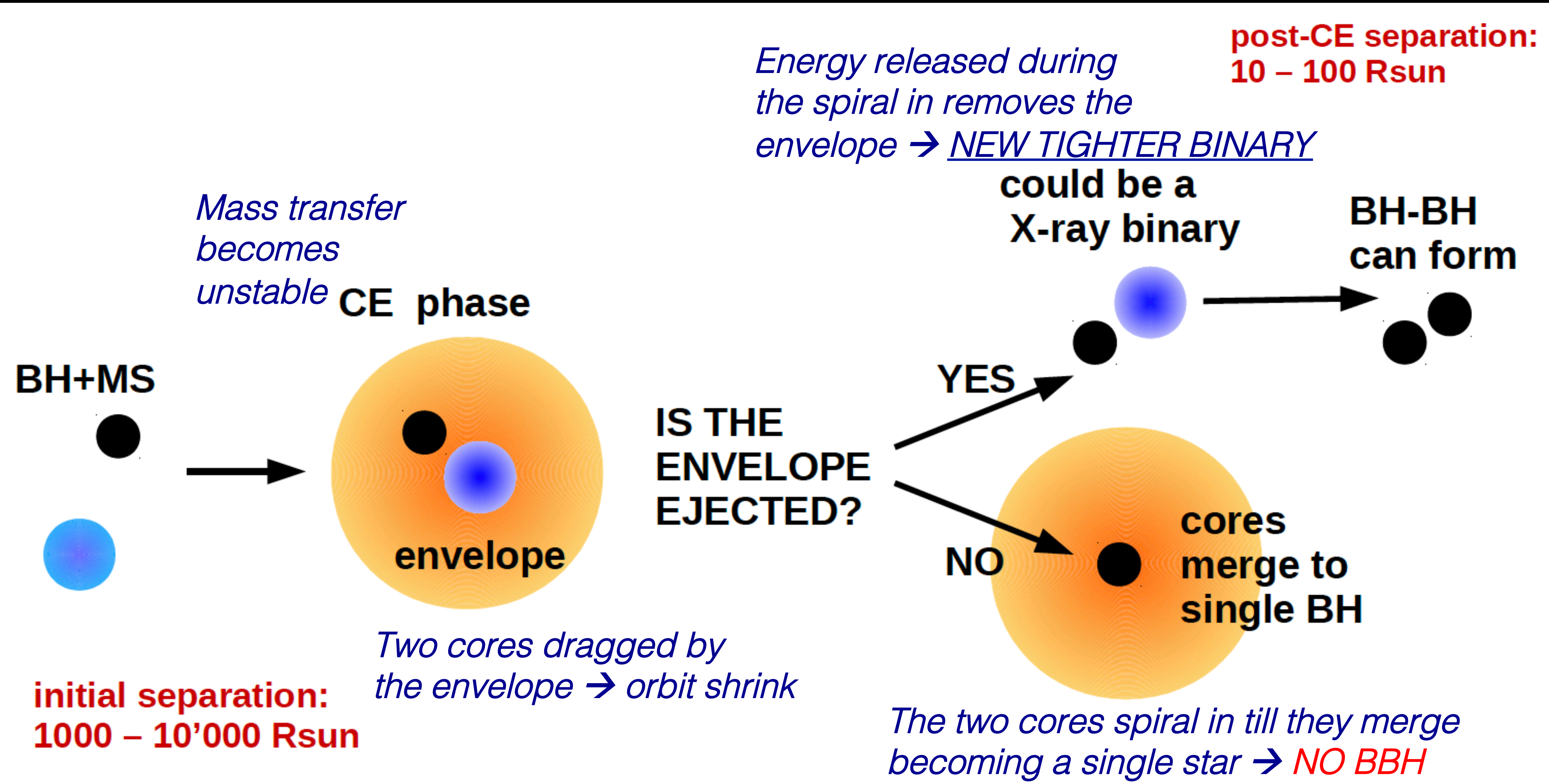


NOT SO EASY:
Many evolutionary processes can affect the binary

- SN kick
- Mass transfer
- Common envelope

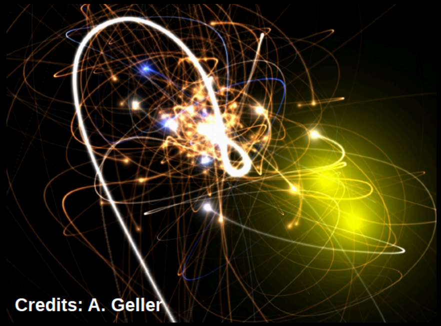
Poor knowledge of the phyisics which governs the binary sytem evolution!

COMMON ENVELOPE



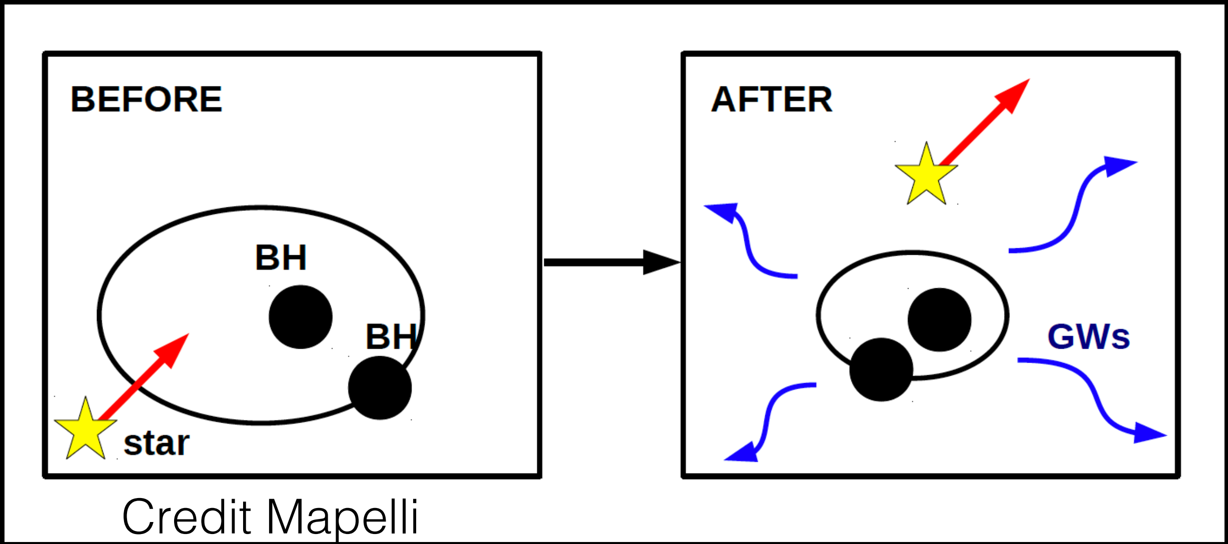
DYNAMICAL BINARIES: BBH forms and/or evolves by dynamical processes

DYNAMICS is IMPORTANT ONLY IF $n > 10^3$ stars pc^{-3} i.e. only in dense star clusters, where encounters are common



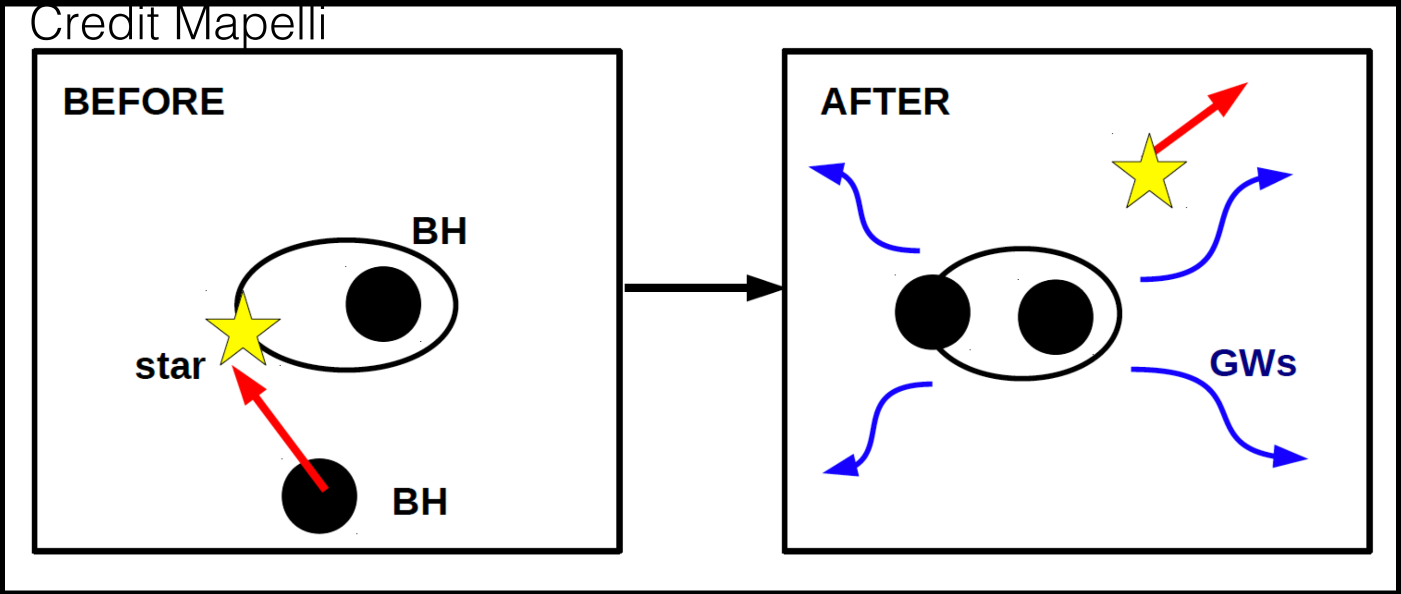
BUT massive stars (compact-object progenitors) form in star clusters
(Lada & Lada 2003; Weidner & Kroupa 2006; Weidner, Kroupa & Bonnell 2010; Gvaramadze et al. 2012; see Portegies Zwart+ 2010 for a review)

The dynamics of stellar BH binaries: FLYBYs



The star acquires kinetic energy from the binary
-the binary shrink
- shorter coalescence time

The dynamics of stellar BH binaries: EXCHANGEs



- *EXCHANGES bring BHs in binaries*
- *BHs are FAVOURED by exchanges because they are MASSIVE!*
- *NS lighter → dynamics is less important for NSs*

>90% BH-BH binaries in young star clusters form by exchange (Ziosi et al. 2014)

EXCHANGES FAVOUR THE FORMATION of BH-BH BINARIES WITH

- *THE MOST MASSIVE BHs*
- *HIGH ECCENTRICITY*
- *MISALIGNED BH SPINS*

Pathways to form "heavy" binary BHs

Isolated binary systems

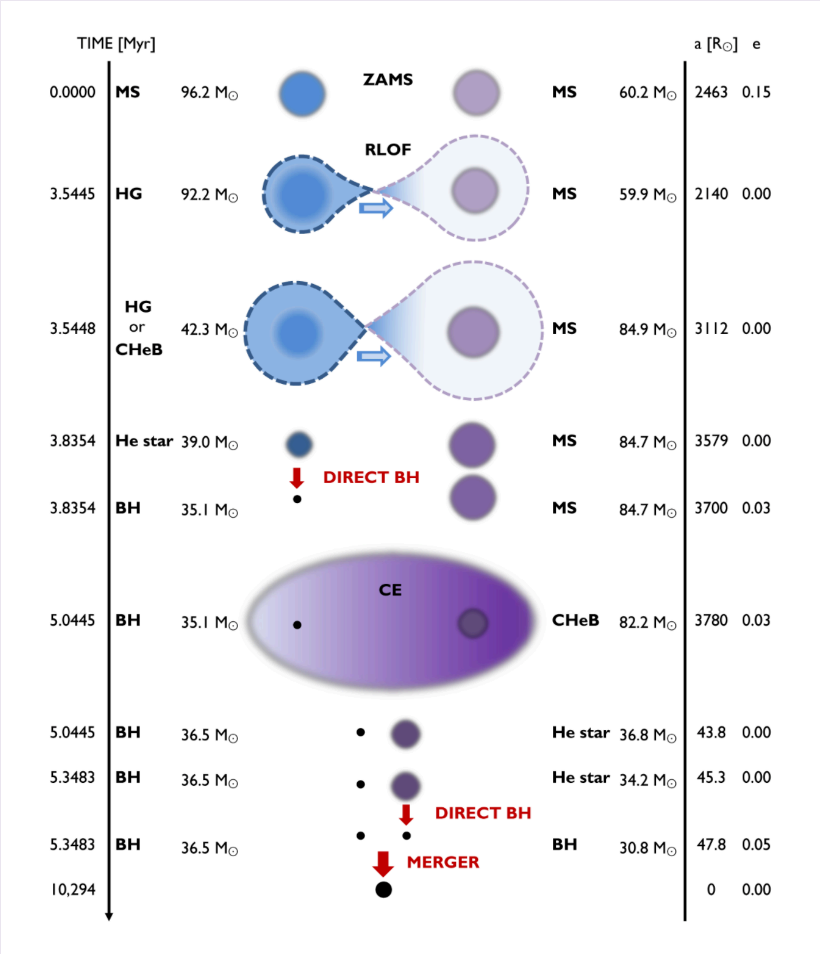


Figure: Belczynsky arXiv:1602.04531

Dense stellar environments – dynamical origin

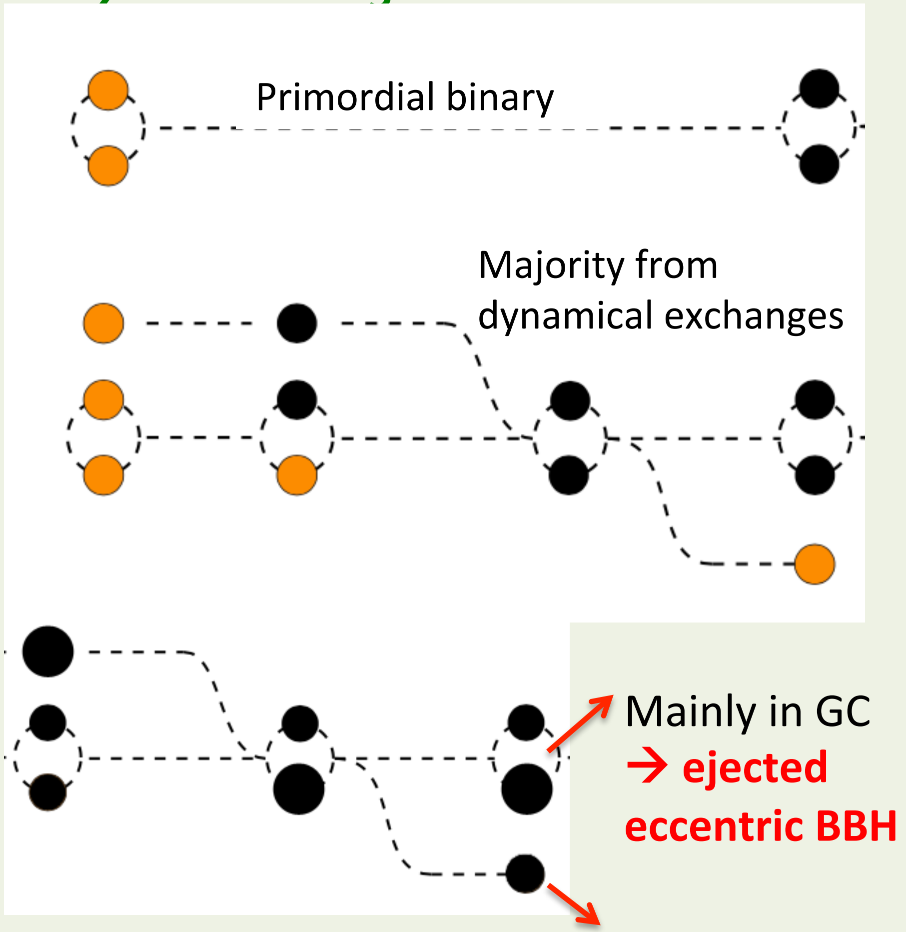
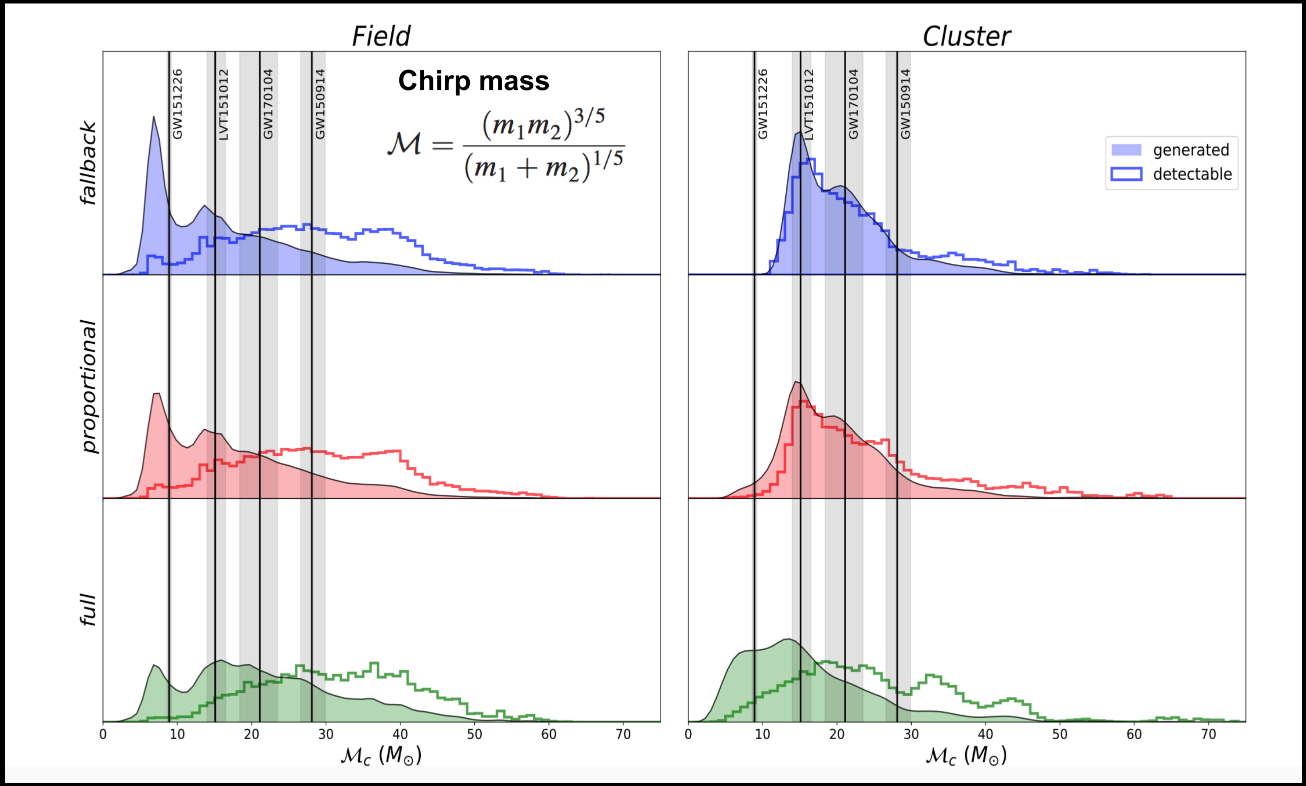


Figure: Ziosi et al. 2014

Both scenarios consistent with heavy BBH observed by LIGO and Virgo in provided metallicities lower than 1/2 Zo

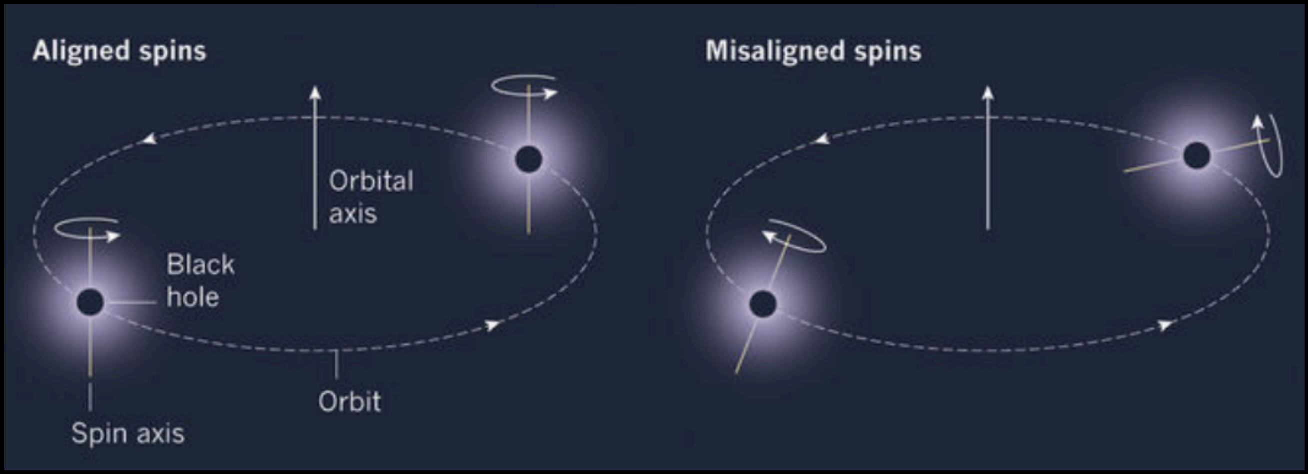
Binary BH Formation: can we distinguish among formation channels (field vs cluster)?



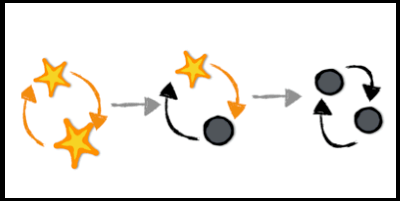
*Could distinguish between formation channels with **O(100) detections** (Zevin et al. 2017, ApJ, 846, 82Z)*

[Isolated binary see Bethe & Brown 1998, ApJ, 506, 780, Belczynski et al. 2016, Nature, 534, 512, Marchant et al. 2016, A&A, 588, 50, Mapelli et al. 2017, MNRAS.472.2422, Stevenson et al. 2017, NatCo, 814906, Dynamical formation see - Portegies Zwart & McMillan 2000, ApJ, 528, L17, Mapelli 2016, MNRAS, 459, 3432, Rodriguez et al. 2016, PhRvD, 93, 4029, Askar et al. 2017, MNRAS, 464, L36, Banerjee 2017, MNRAS, 467, 524]

Spin measurements

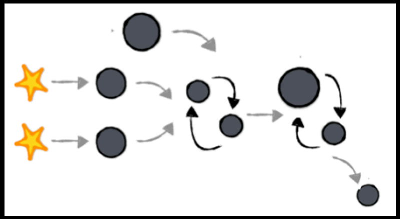


Isolated binary



→ several binary evolution processes tend to align the spins with orbital angular momentum

Cluster binary

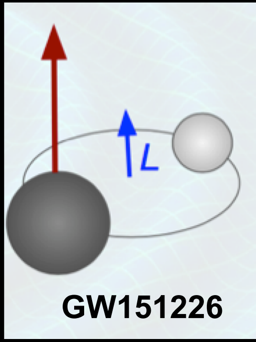


→ isotropic spin orientations

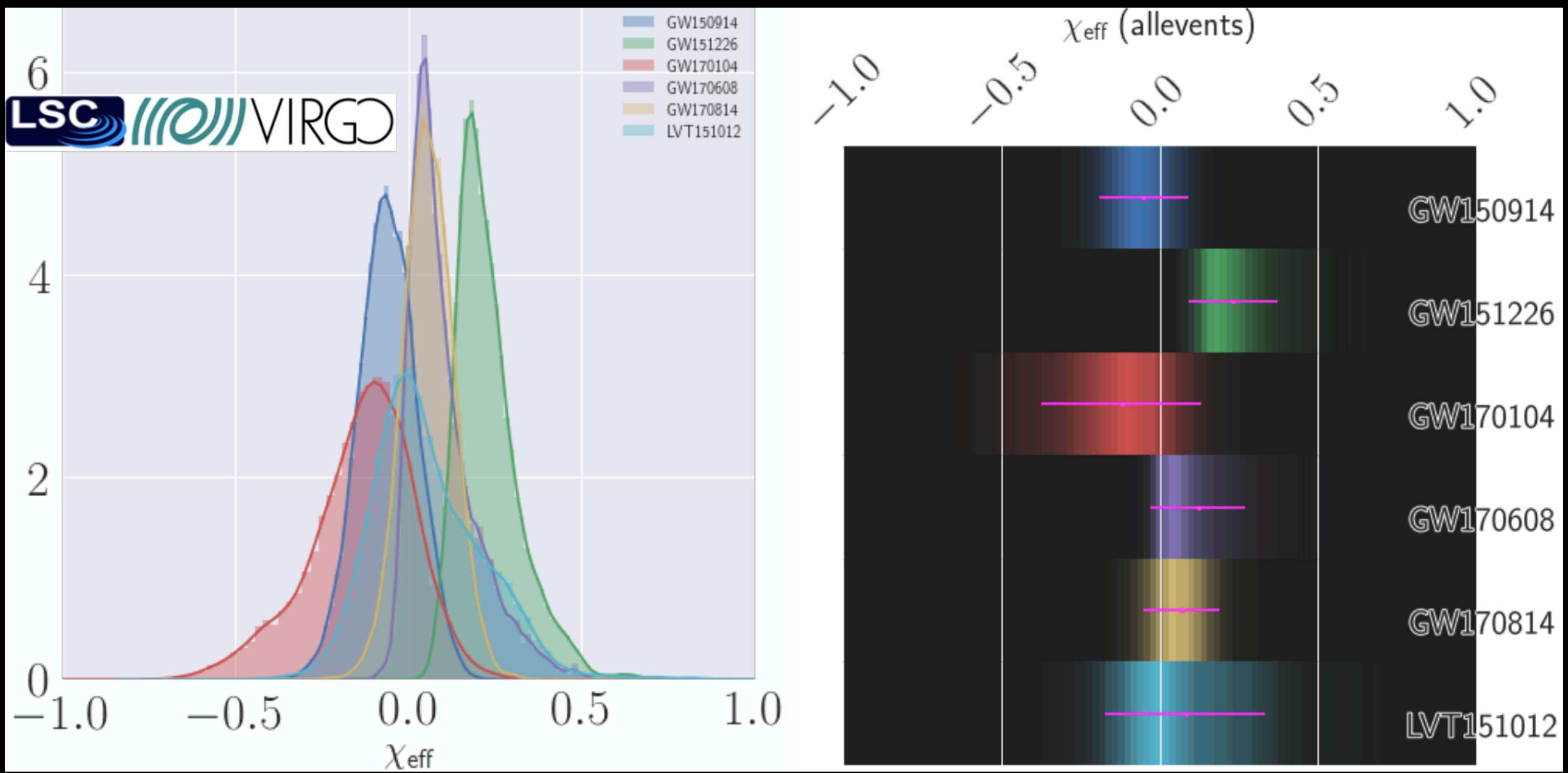
Spin measurements

Effective orbital spin

$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \hat{\boldsymbol{L}}$$



Abbott et al.2017,PhysRevL,118,221101,
Abbott et al. 2016, PhysRevX,6,041015



Farr et al. 2017,Nature, 548, 426,
Farr et al. 2018,ApJL,854,9,
O'Shaughnessy et al. 2017, PhRvL,119,1101
Wysocki et al. 2018, PhRvD, 97, 3014

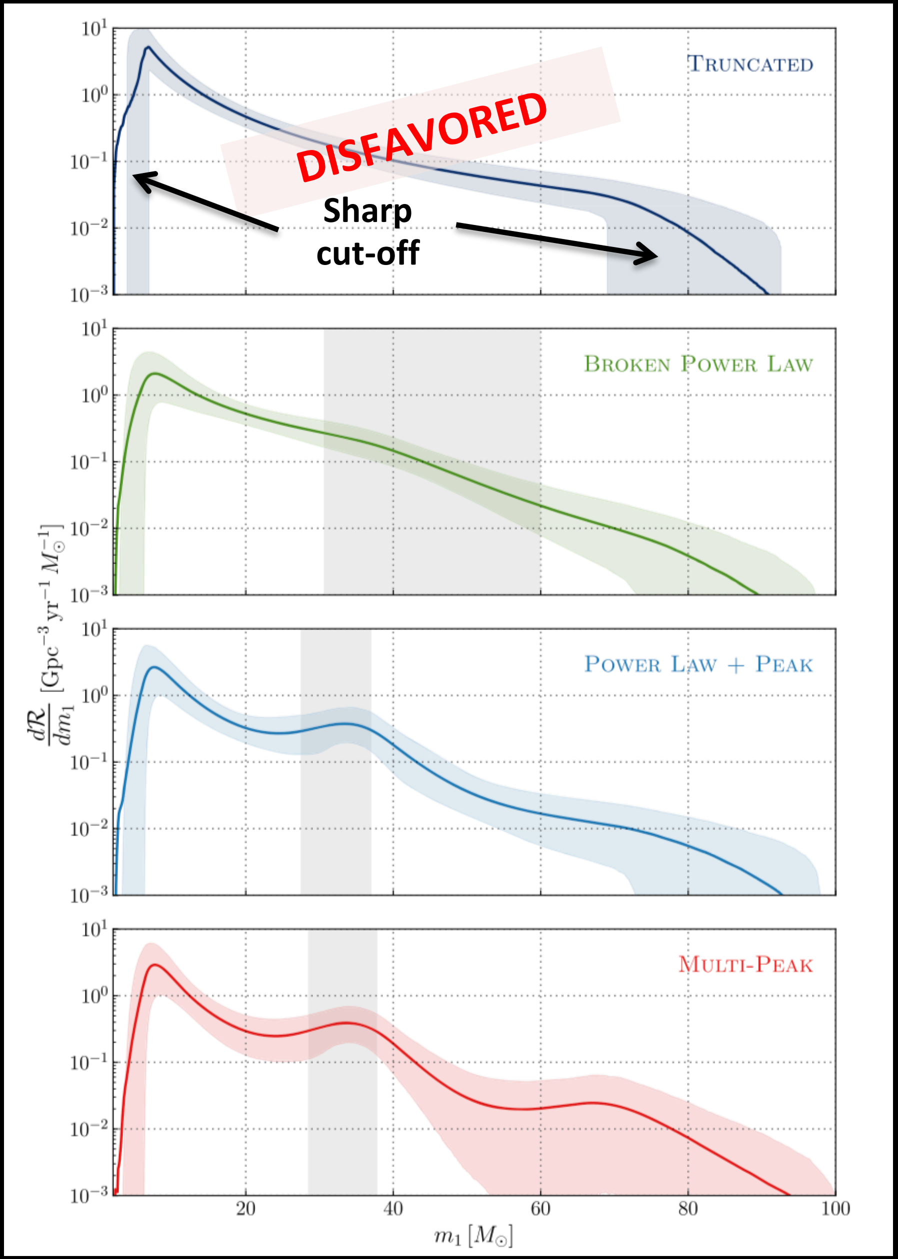
Population Studies

Are we observing binary BHs from multiple formation channel?

PRIMARY BH MASS DISTRIBUTION

BH mass spectrum:

- not well described as a simple power law with an abrupt cutoff

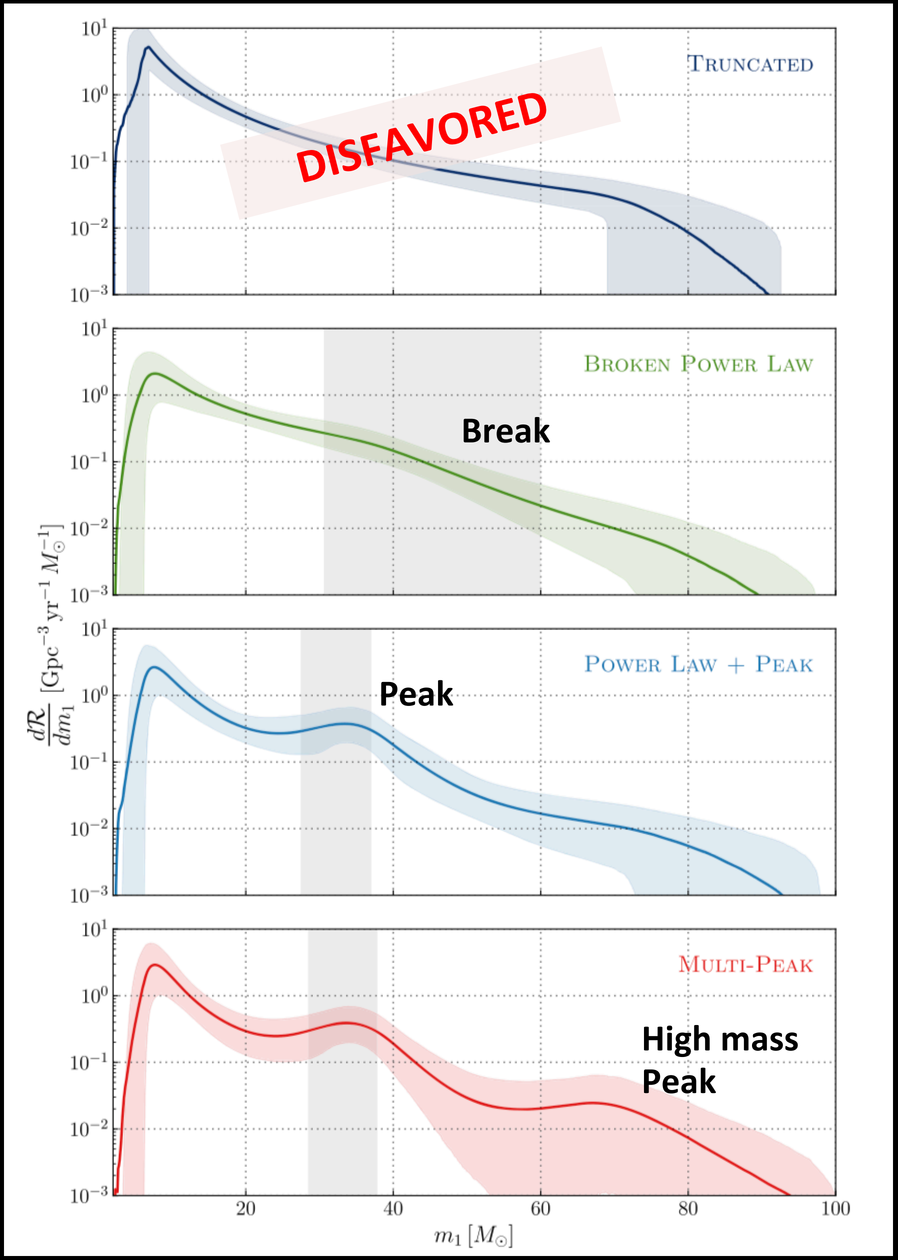


Abbott et al. 2021, ApJL, 913

PRIMARY BH MASS DISTRIBUTION

BH mass spectrum:

- not well described as a simple power law with an abrupt cutoff
- but show a feature at ~40 solar masses, which can be represented by a *break* in the power law or a Gaussian *peak*

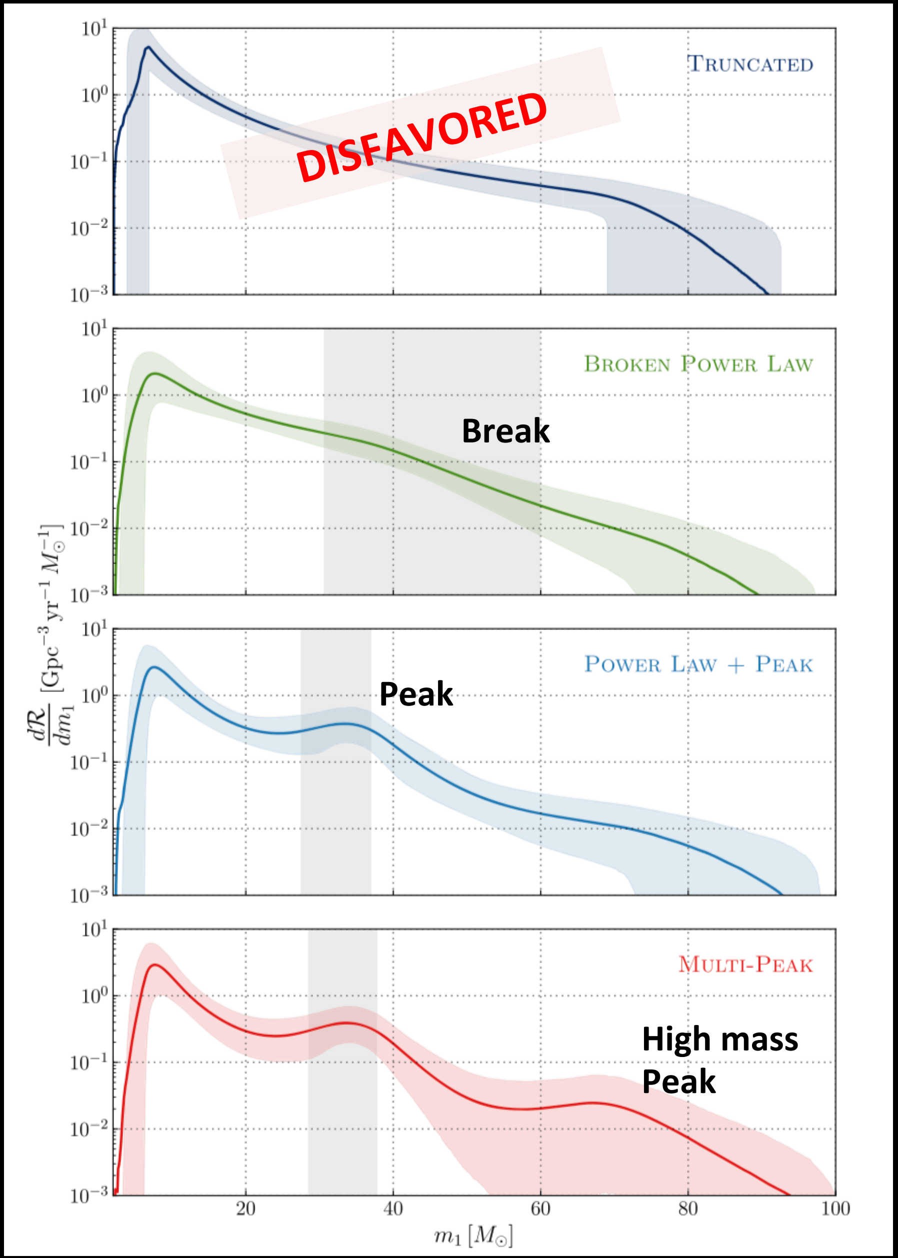


Abbott et al. 2021, ApJL, 913

PRIMARY BH MASS DISTRIBUTION

BH mass spectrum:

- not well described as a simple power law with an abrupt cutoff
- but show a feature at ~40 solar masses, which can be represented by a *break* in the power law or a Gaussian *peak*
- hint of high mass peak

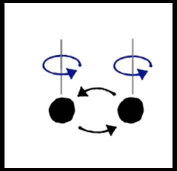


Abbott et al. 2021, ApJL, 913

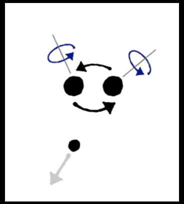
SPINS from statistical studies

- In-plane spin components are present in the BBH population, giving rise to precession of the orbital plane
- 12%- 44% of BBHs have spins tilted by more than 90°, giving rise to a negative effective inspiral spin
- hints, but no clear evidence that the spin distribution varies with mass

Isolated binary



Dynamical formation



Allowing merger rate to evolve with z

$$R(z) = (1+z)^K$$

- It probably evolves with z, but slower than star formation rate
- Merger rate increase of about a factor 2.5 between z=0 and z=1

LOCAL ASTROPHYSICAL RATE

- **BNS 10-1700 $Gpc^{-3}\,yr^{-1}$**
- **NSBH 7.4-320 $Gpc^{-3}\,yr^{-1}$**
- **BBH 17.9-44 $Gpc^{-3}\,yr^{-1}$ (at z=0.2)**

Abbott et al. arXiv:2111.03634

Abbott et al. 2021, ApJL, 913

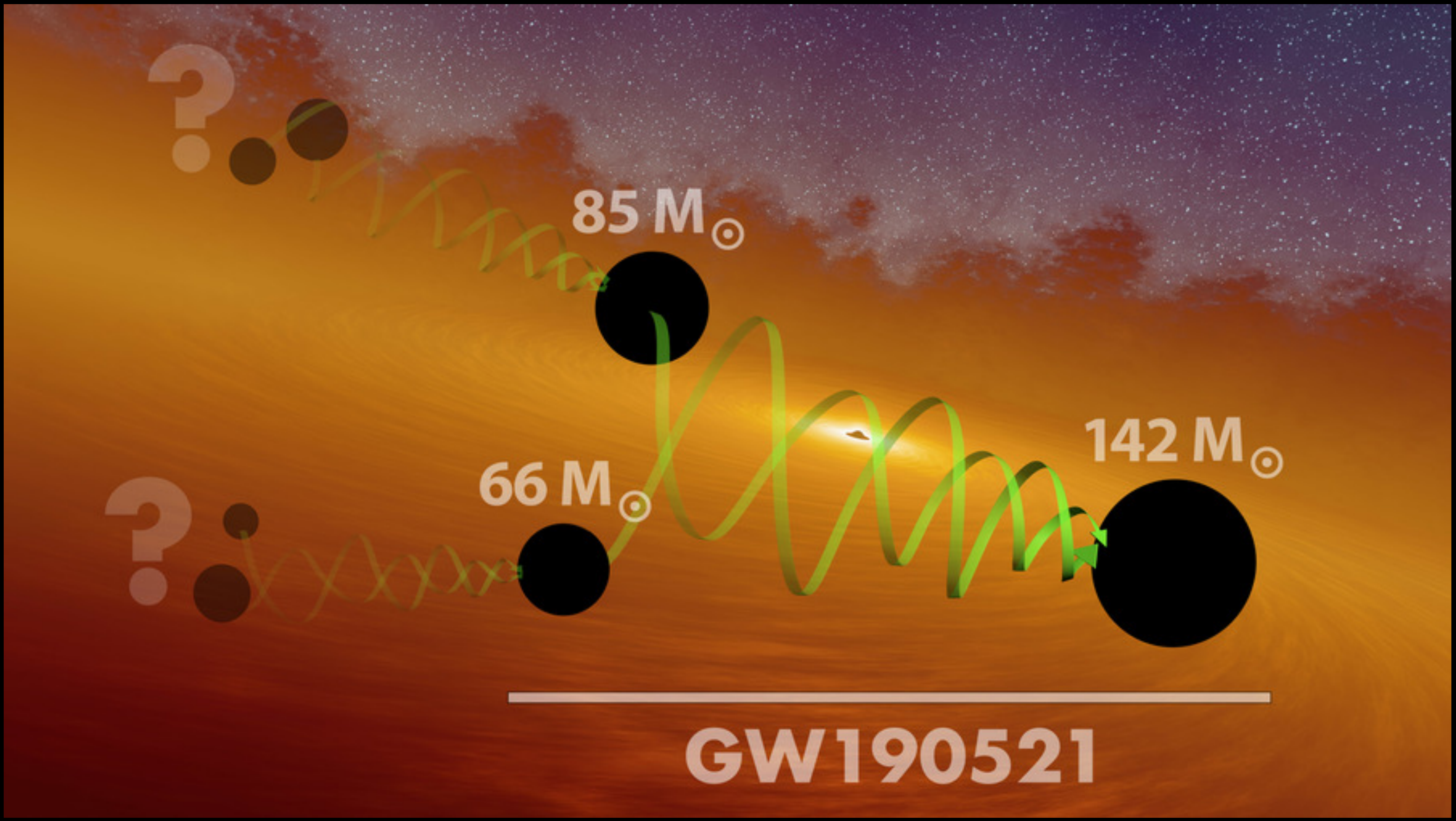
GW190521

The birth of a intermediate massive black-hole!

Credit: Mark Myers, ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav)

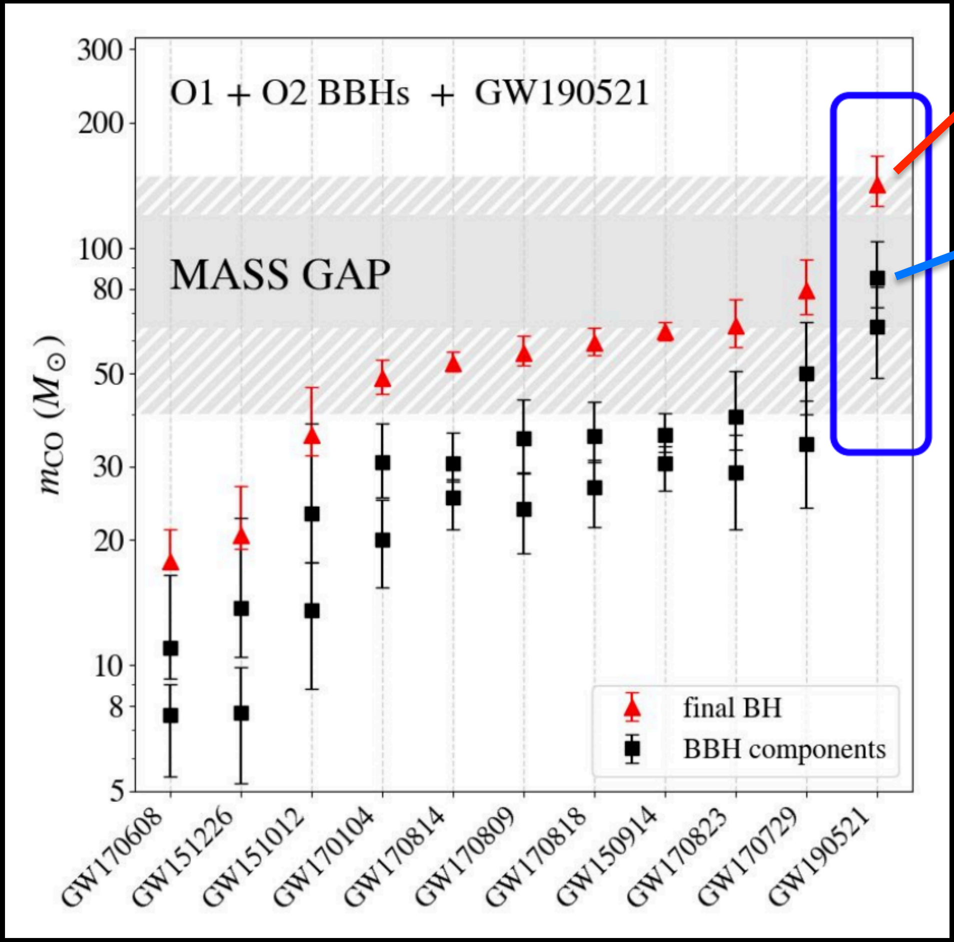
GW190521 – O3

The birth of a intermediate massive black-hole!



credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

Abbott et al 2020, PRL, 125
Abbott et al 2020, APJL, 900

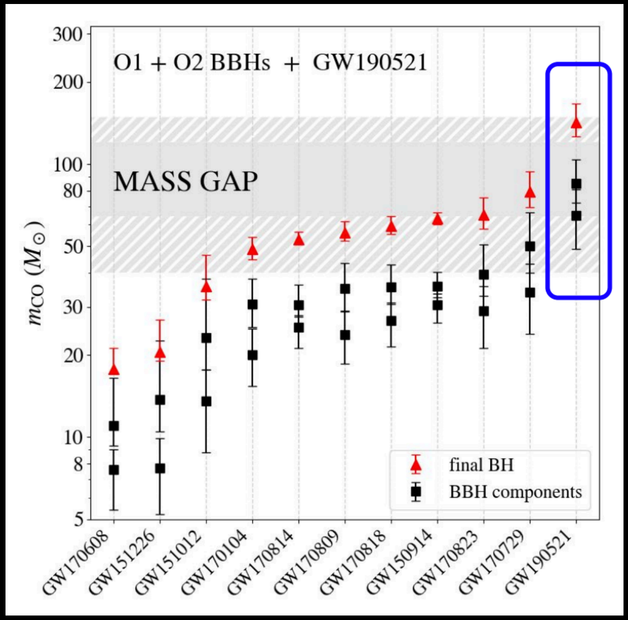


First strong observational evidence for an intermediate-mass black hole

The primary falls in the mass gap by (pulsational) pair-instability SN

CHALLENGE FOR STELLAR EVOLUTION

Abbott et al 2020, APJL, 900

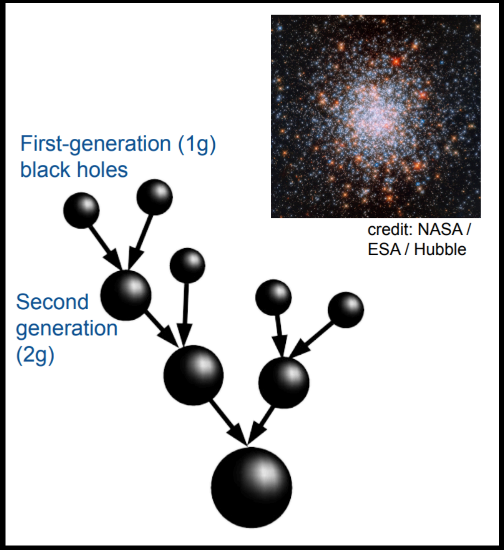


Abbott et al 2020, APJL, 900

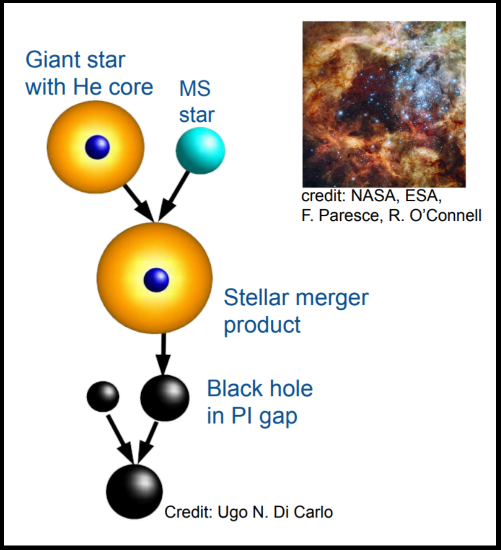
ISOLATED BINARY EVOLUTION DISFAVORED

DYNAMICAL SCENARIOS

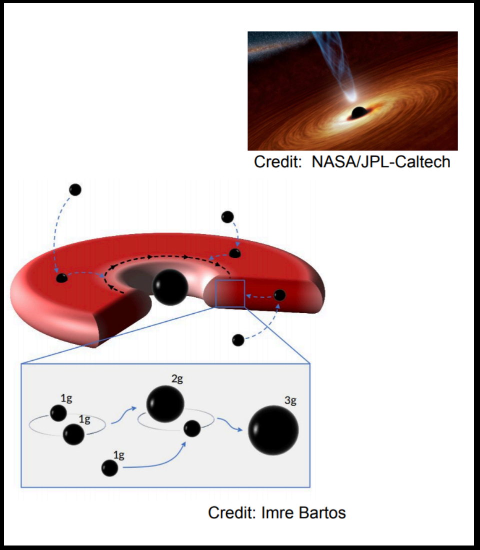
Hierarchical mergers



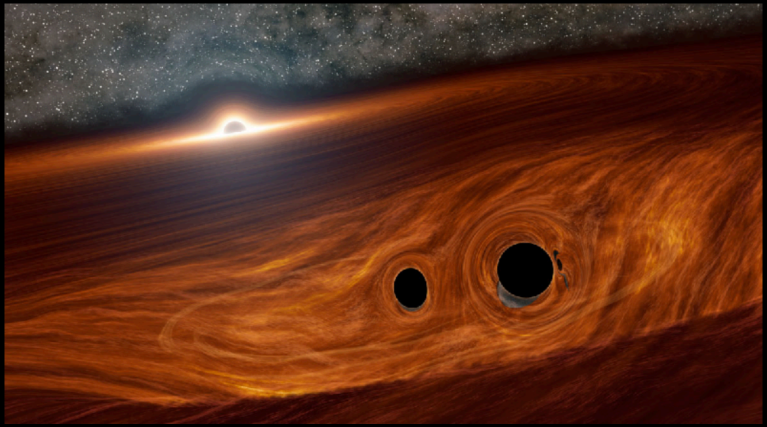
Stellar mergers in young star clusters



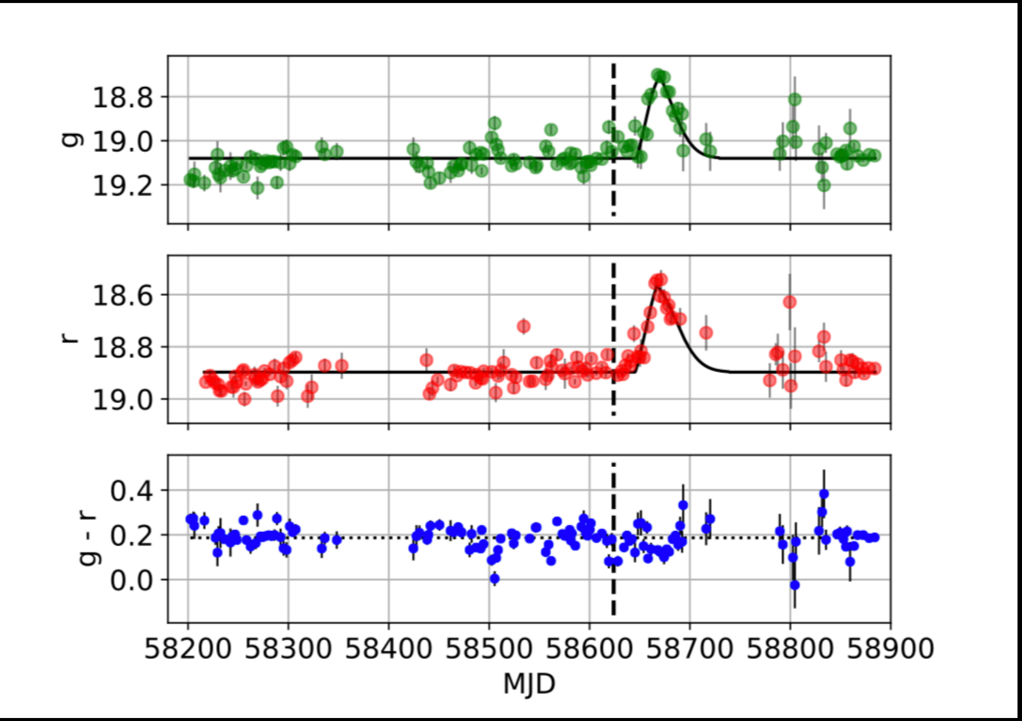
Active galactic nucleus disks



BBH in the accretion disk of a supermassive black hole?



Caltech/R. Hurt (IPAC)



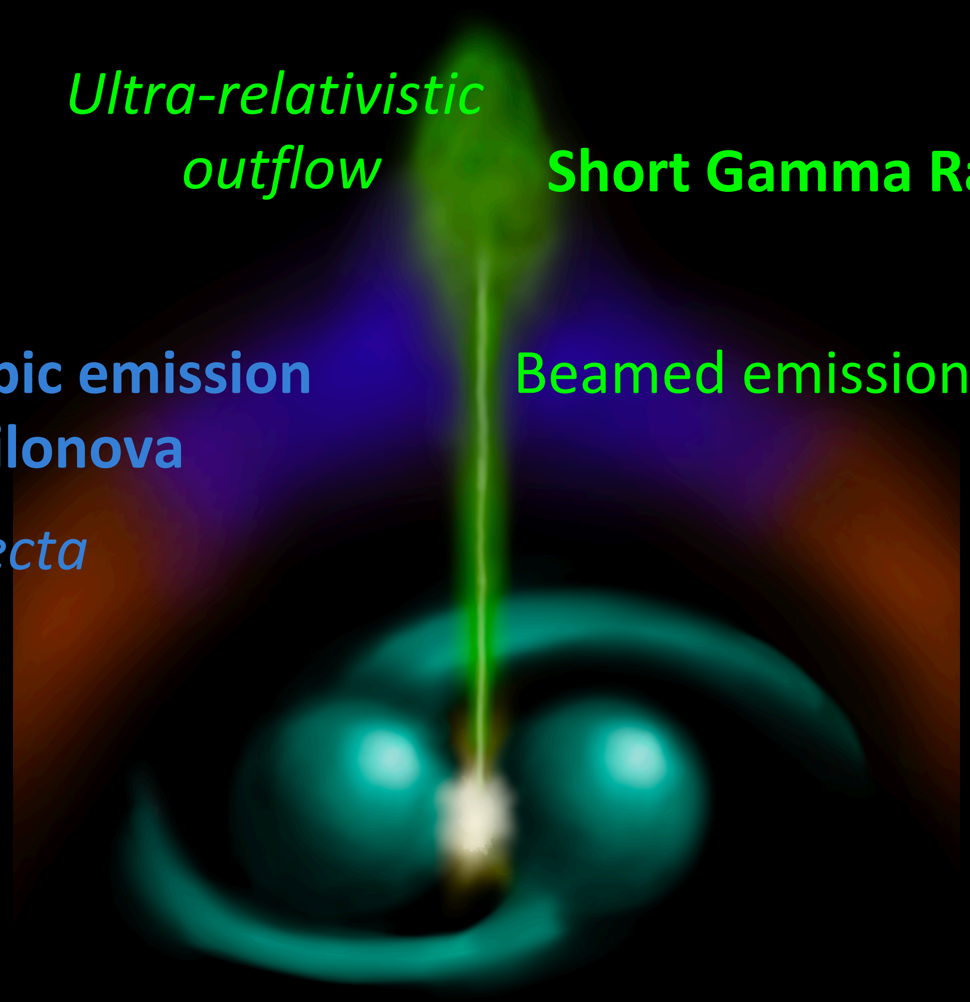
Graham et al 2020, PRL 124

ZTF detected a candidate counterpart(!?)

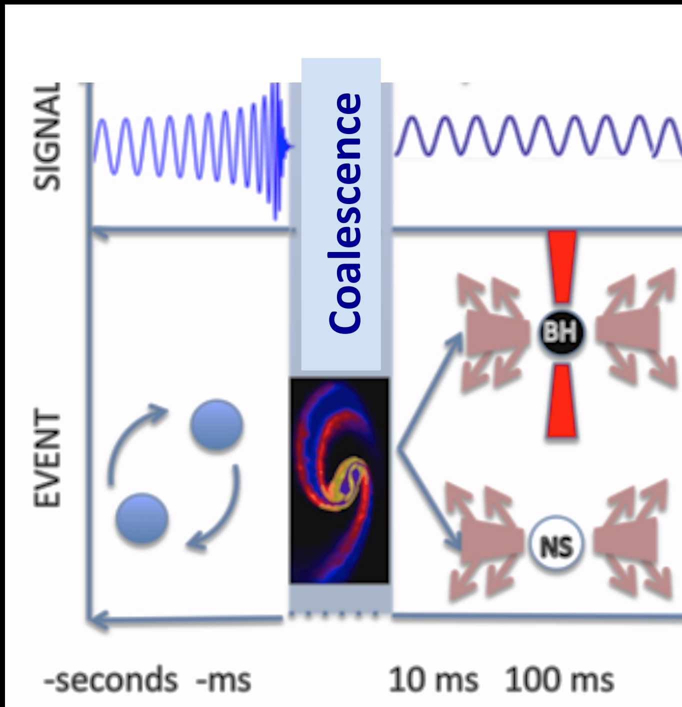
- EM flare close to AGN ~ 34 days after the GW event
- consistent with expectations for a kicked BBH merger in the accretion disk AGN
- 765 deg^2 localization area
- ZTF observed 48% of the 765 deg^2 (90% c.r.)

Binary compact obbject mergers
EM emissions

NS-NS and NS-BH mergers



NS-NS and NS-BH inspiral and merger



Dynamical Phase

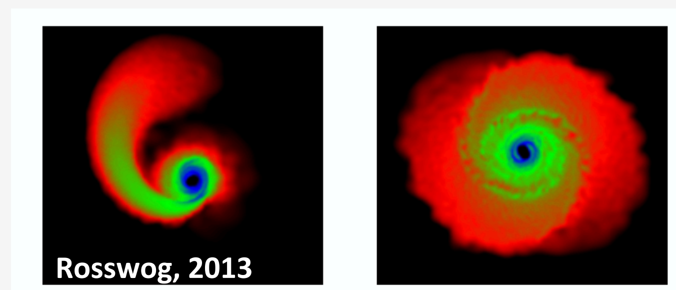
Accretion phase

Fernandez & Metzger 2016, ARNPS, 66

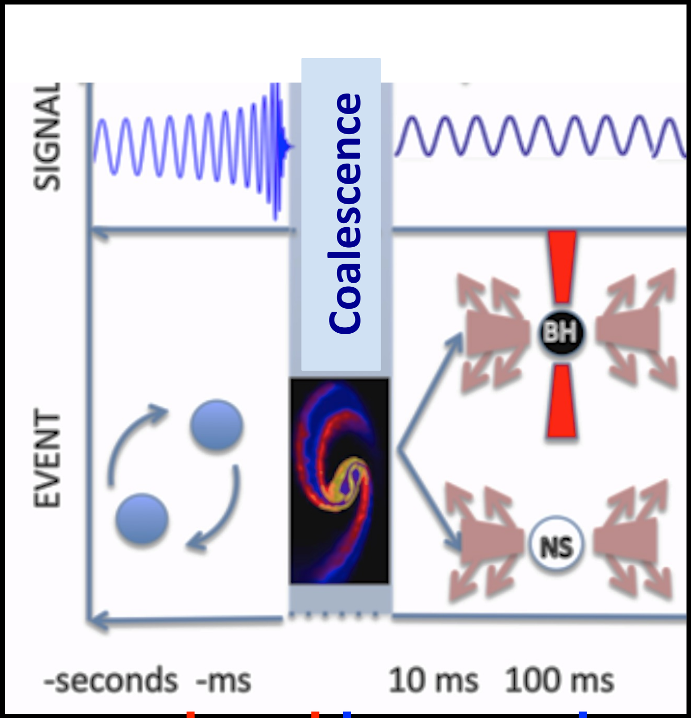
The merger gives rise to:

- dynamically ejected unbound mass
- ejected mass gravitationally bound to the central remnant either falls back or circularizes into an accretion disk

NS-NS binary → **unbound mass of 10^{-4} -10^{-2} Mo ejected at 0.1-0.3c,** which depends on **total mass, mass ratio, EOS NS and binary eccentricity**



NS-NS and NS-BH inspiral and merger



Dynamical Phase

Accretion phase

Fernandez & Metzger 2016, ARNPS, 66

The merger gives rise to:

- dynamically ejected unbound mass
- ejected mass gravitationally bound to the central remnant either falls back or circularizes into an accretion disk

NS-BH binary → <u>unbound mass</u> up to 0.1 Mo depends on **ratio of the tidal disruption radius to the innermost stable circular orbit**

If < 1 → NS swallowed by the BH no mass ejection

If > 1 NS → tidally disrupted, long spiral arms

which depends on **the mass ratio, the BH spin and the NS compactness**

See Kawaguchi et al. 2016,ApJ, 825, 52

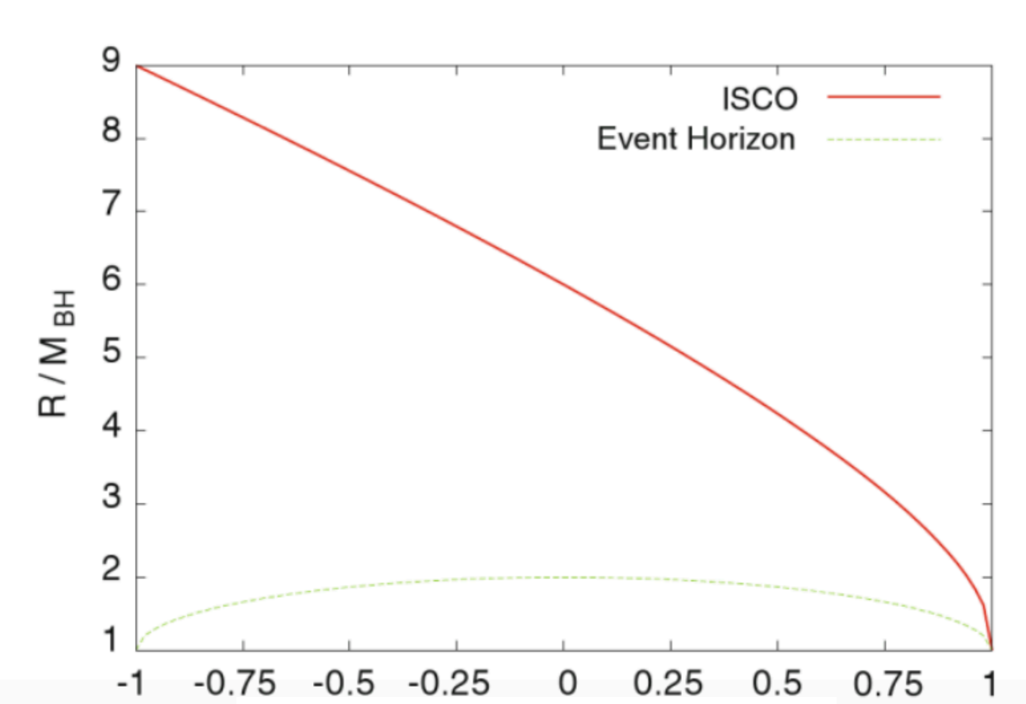
NSBH COALESCENCE

- Before the merger, the BH is described by its mass M_{BH} and spin χ_{BH} which determine the radius of the ISCO, R_{ISCO}
- Once the NS approaches the BH, the tidal forces increase. The objects' internal structure become important as the orbital separation approaches the size of the bodies
- IF $d_{tidal} < R_{ISCO}$ ⇒ NS direct plunge into BH
  → little or no mass left outside of the BH
  → **NO EM COUNTERPART**
- IF $d_{tidal} > R_{ISCO}$ ⇒ NS effectively disrupted
  → BH remnant surrounded by baryon matter
  → **EM COUNTERPARTS**

ISCO = innermost stable circular orbit of the BH, inside which no material have a stable circular orbit around the BH

For a non rotating Schwarzchild BH $$R_{ISCO} = 6GM_{BH} / c^2 = 3R_S$$

For a rotating BH the equatorial ISCO also depends on the spin angular momentum



Kyutoku 2013

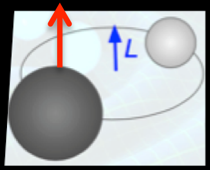
$$\chi_{BH} = cS / (GM^2_{BH}) \longrightarrow$$ Non dimensional spin parameter

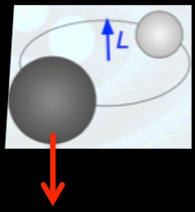
$$\chi = cS / (GM^2_{BH})$$ dimensionless spin parameter

- NS spin negligible → typically assumed $\chi_{NS} \sim 0$

NSs are expected to born rapidly rotating but before NSBH coalescence (which requires long time from their birth) they have time to spin down by dipole-emission (the lack of matter accreting onto the NS prevent spin-up by recycling)

- Assumed non-precessing binaries → BH spin vector aligned or anti- aligned with the orbital angular momentum





- Anti-aligned configurations → larger ISCO, favour direct plunge of the NS into the BH → no baryonic mass left outside the final BH to power an EM counterpart

Tidal disruption radius d_{tidal} radius at which tidal disruption occurs

The tidal disruption occurs when the tidal force of the BH is stronger than the self-gravity of the NS

$$\frac{M_{BH}}{r^3} R_{NS} \geq C^2 \frac{M_{NS}}{R_{NS}^2}$$

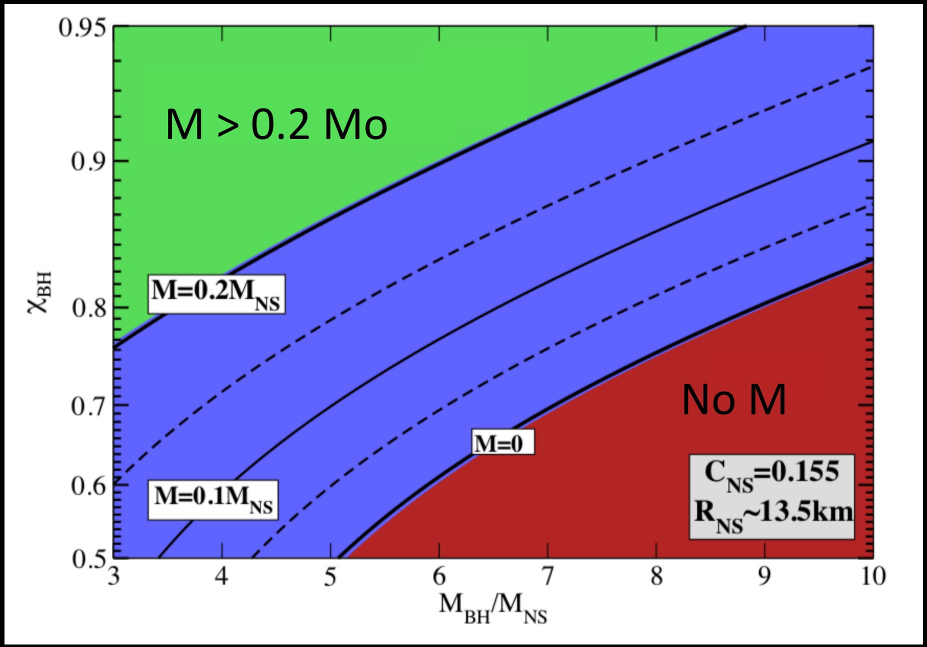
C=non dimensional coefficient
r =orbital separation

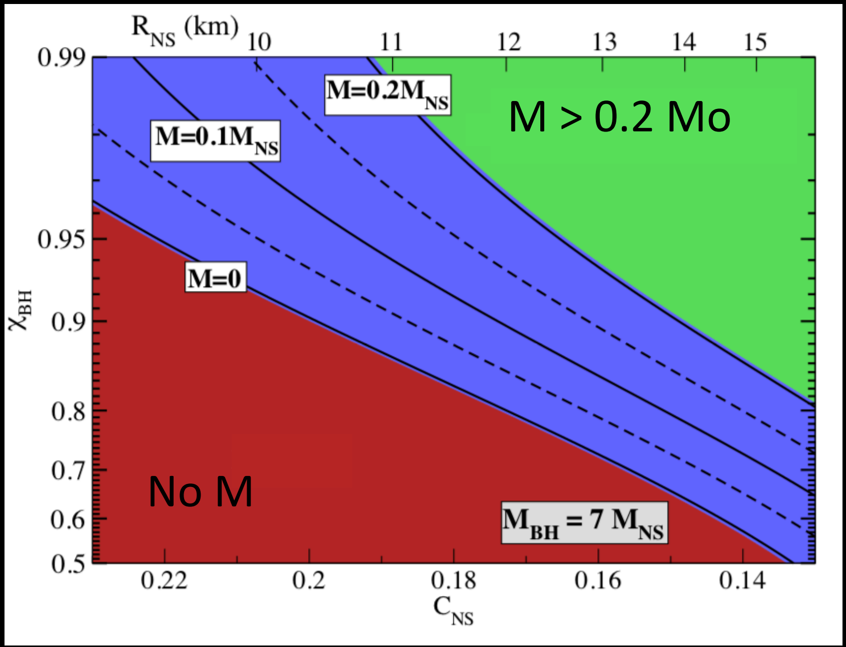
Newtonian theory

$$\frac{3M_{BH}}{d_{tidal}^3} R_{NS} \sim \frac{M_{NS}}{R_{NS}^2} \Rightarrow d_{tidal} \sim R_{NS} \left(\frac{3M_{BH}}{M_{NS}} \right)^{1/3}$$

Foucart et al. 2012

Foucart 2012





Large baryon mass left outside the merger remnant:

- Mass ratio BH/NS small → small BH mass
- Large BH spin angular momentum
- Small NS compactness

NS COMPACTNESS

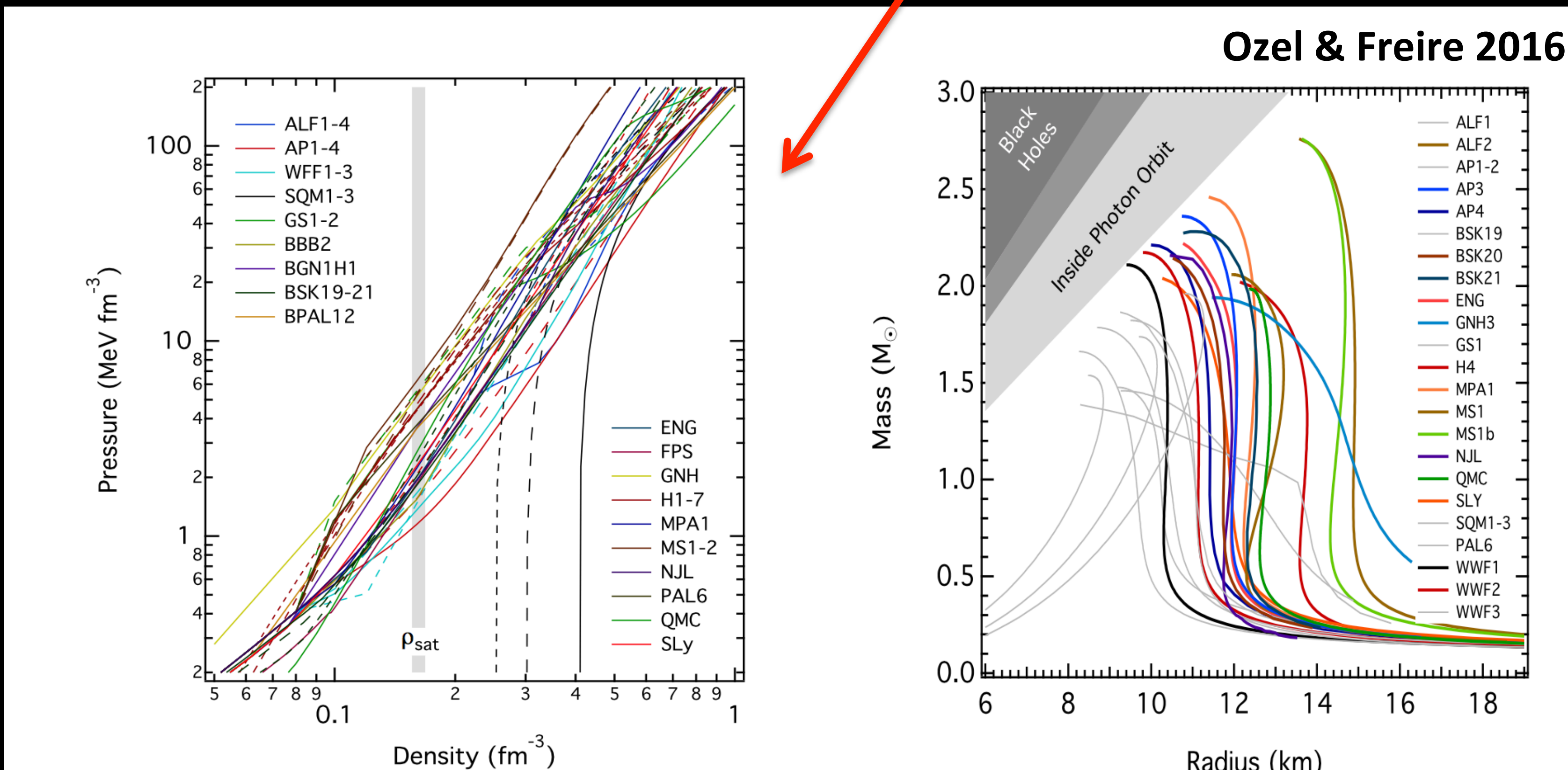
M_{NS}/R_{NS}

See Pannarale & Ohme 2014, Foucart et al. 2018, Barbieri et al. 2019

In the degenerate interiors of neutron stars EOS: $P \propto \rho^{\alpha}$

Small α → soft EOS (easier to compress)

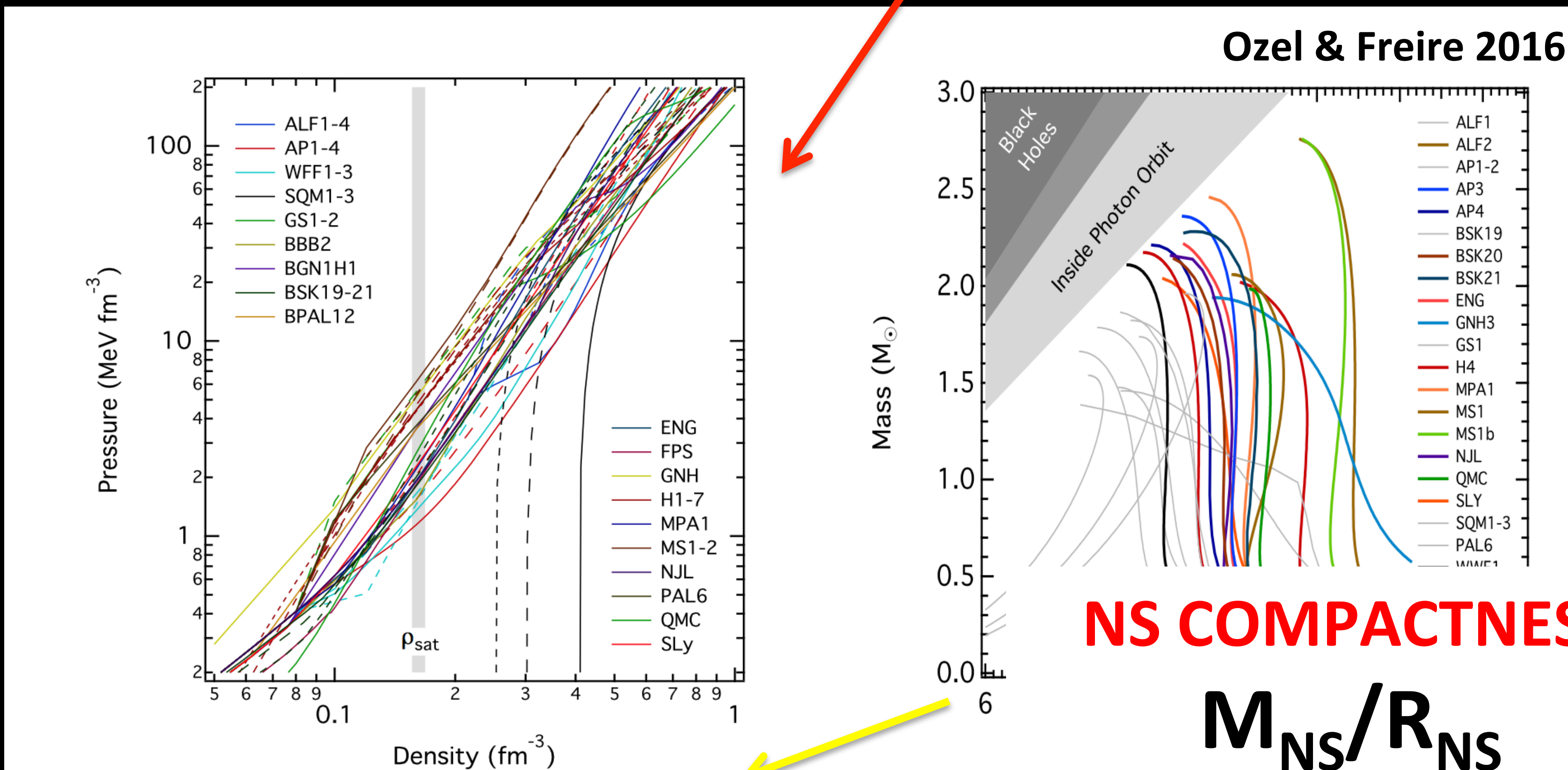
High α → stiff EOS (harder to compress)



In the degenerate interiors of neutron stars EOS: $P \propto \rho^{\alpha}$

Small α → soft EOS (easier to compress)

High α → stiff EOS (harder to compress)



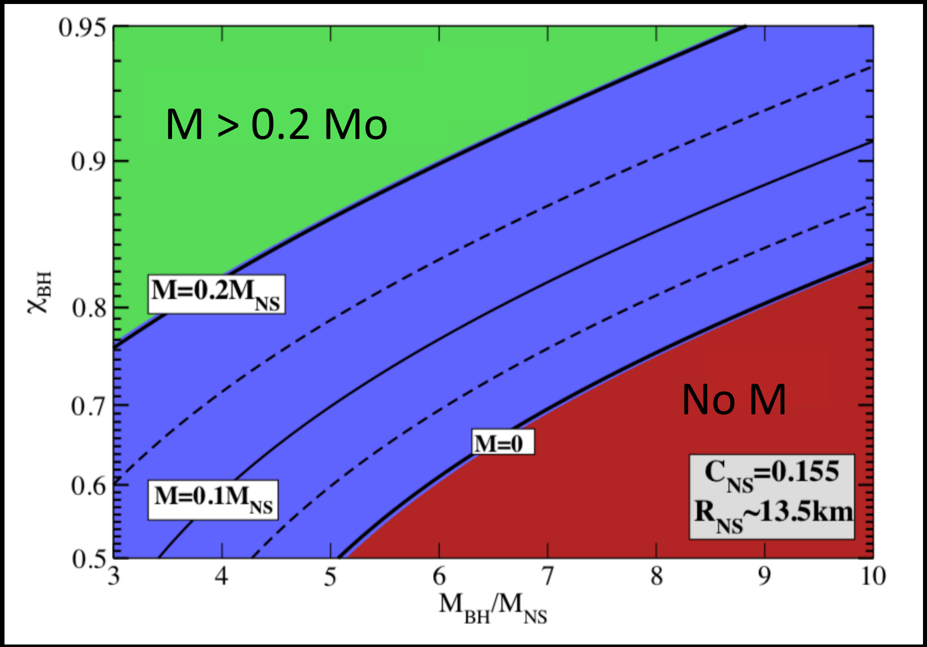
NS COMPACTNESS

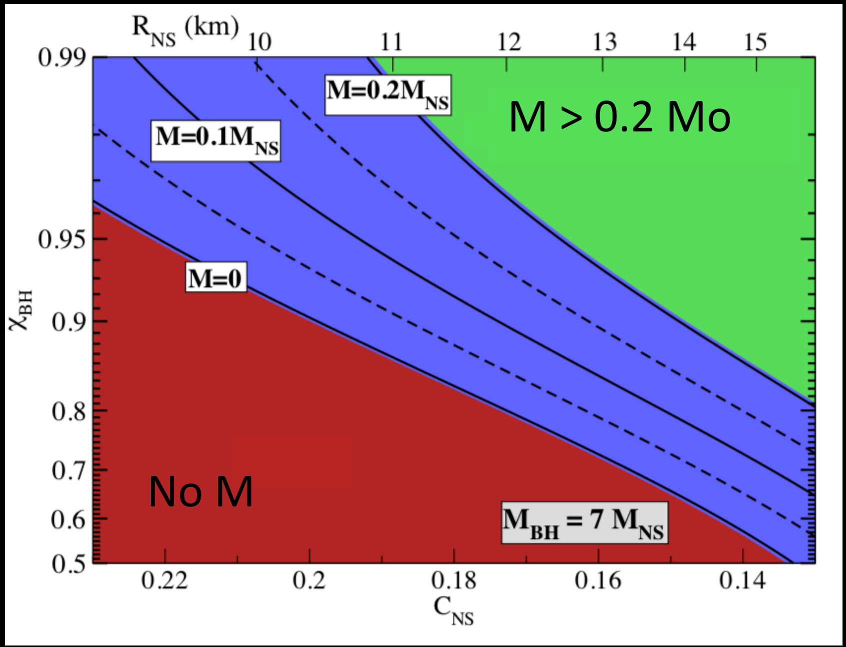
M_{NS}/R_{NS}

Mass-Radius relation is "unique" to the underlying EoS

- Soft EoS: low maximum M and smaller R for the same M (more compact)
- Stiff EoS: high maximum M and larger R for the same M (less compact)

Foucart 2012



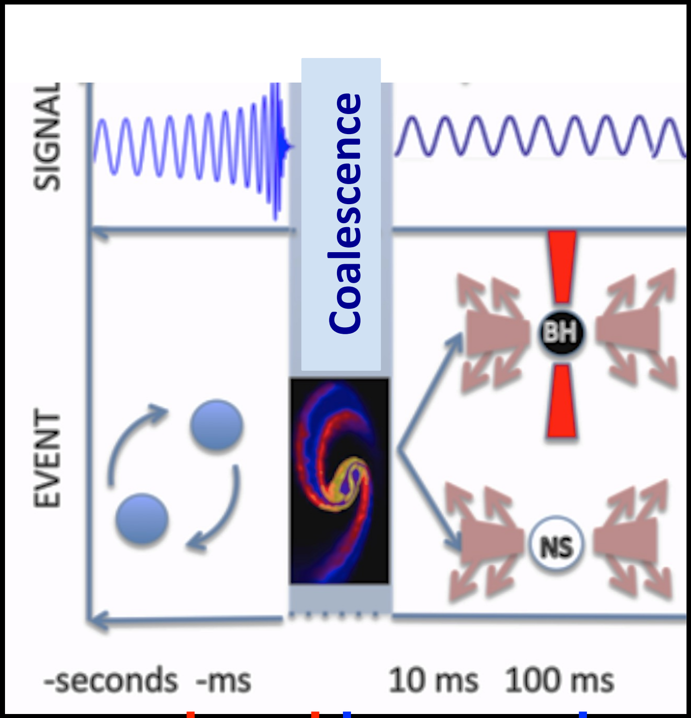


Large baryon mass left outside the merger remnant:

- Mass ratio BH/NS small → small BH mass
- Large BH spin angular momentum
- Small NS compactness → same M large NS radius, stiff EOS
  (harder to compress, easier to be disrupted)

See Pannarale & Ohme 2014, Foucart et al. 2018, Barbieri et al. 2019

NS-NS and NS-BH inspiral and merger



Dynamical Phase

Accretion phase

Fernandez & Metzger 2016, ARNPS, 66

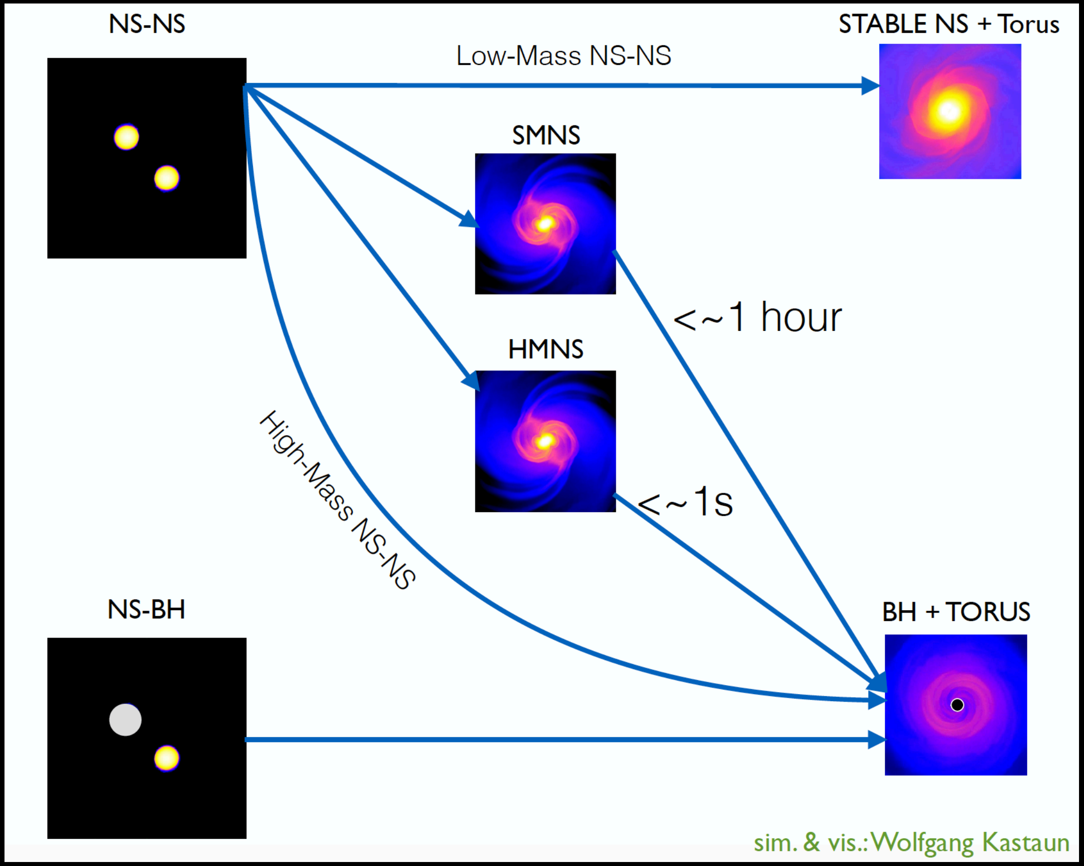
- Ejected material gravitationally bound from the central remnant can fall back or circularizes into an accretion disk

Disk mass up to ~ **0.3Mo**
Disk mass depends on the **mass ratio of the binary, the spins of the binary components, the EOS, and the total mass of the binary**

For NS-BH see e.g. Foucart 2012, PhRvD, 86;
Maselli & Ferrari, PhRvD, 89;
Pannarale & Ohme, ApJL, 791

Outflow mass and geometry influence the EM emission

Central remnant of NS-NS or NS-BH merger



The central remnant influences GW and EM emission

What is central remnant?

- It depends on the total mass of the binary
- The mass threshold above which a BH forms directly depends on EOS

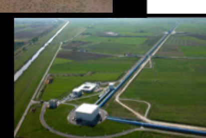
GWs

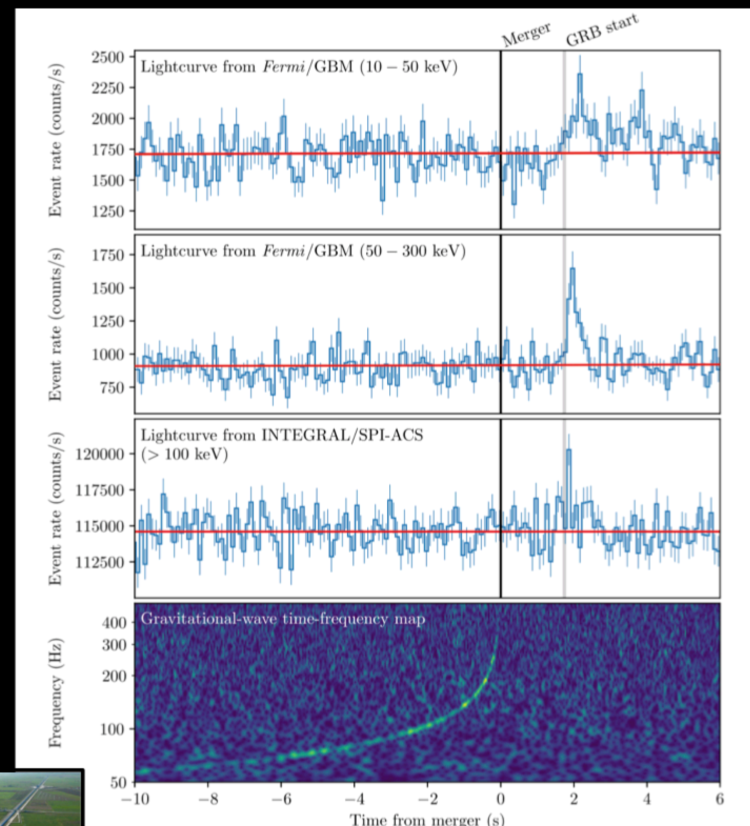
- Mass
- Spins
- Eccentricity
- NS compactness and tidal deformability
- System orientations
- Luminosity distance

EM emission

- Beamed and isotropic EM emissions
- Energetics
- Jet astrophysics
- Nucleosynthesis

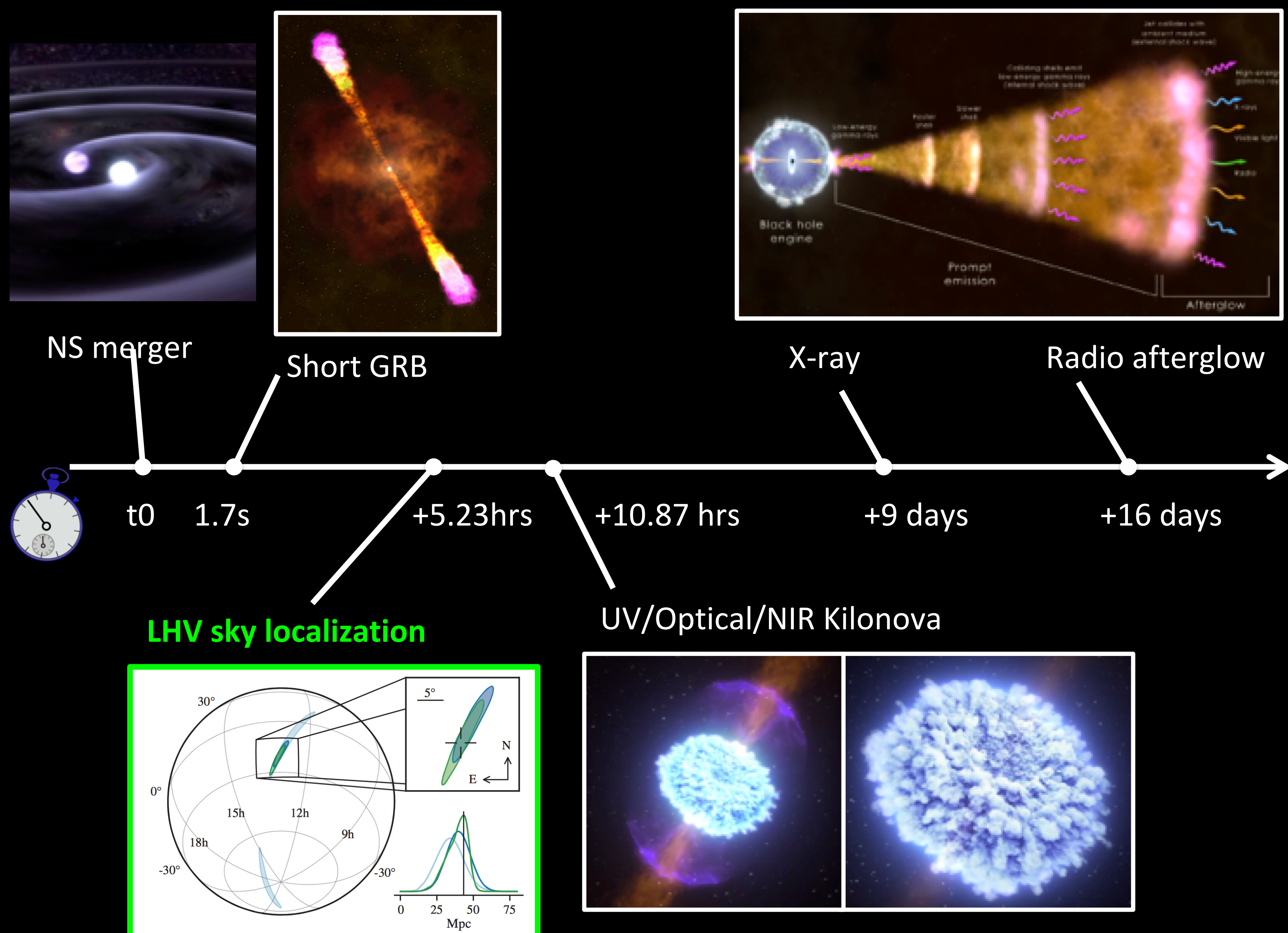
GW170817





GW170817

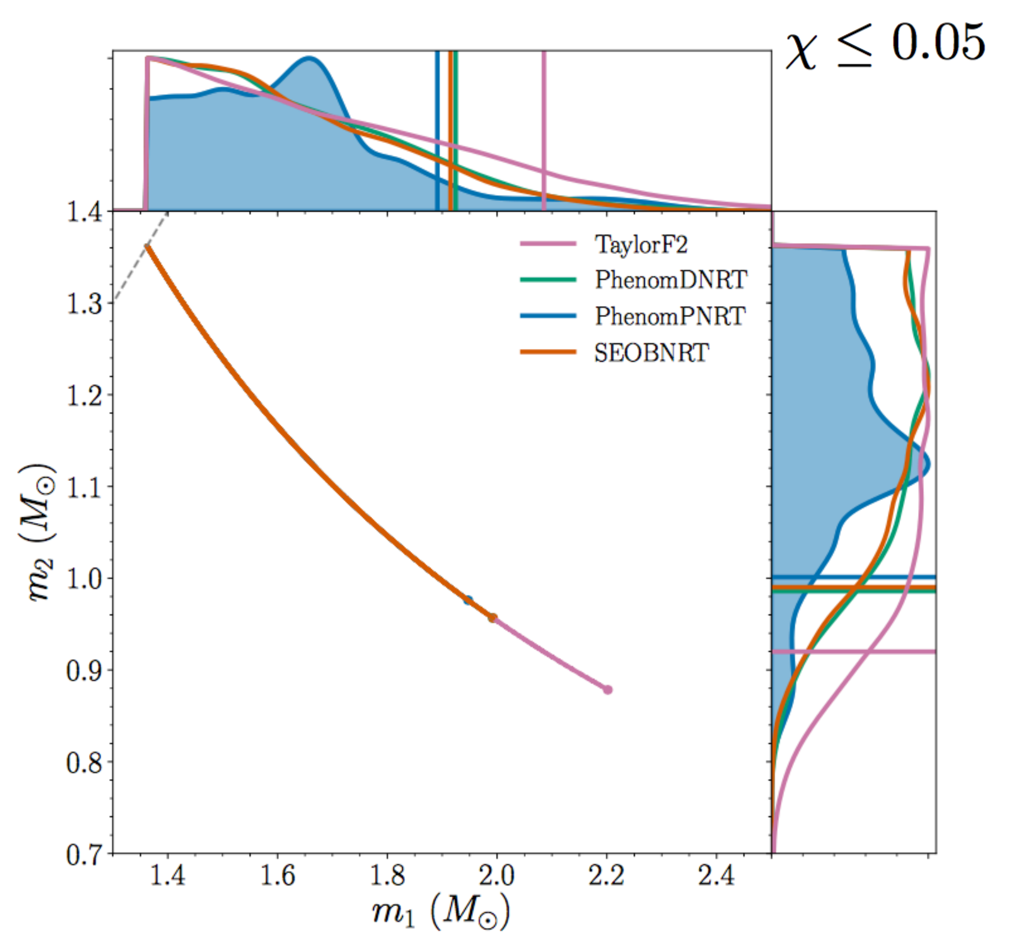
Abbott et al. 2017, PhRvL, 119



LVC + astronomers, ApJL, 848, L12

GW Observables

GW170817: PARAMETERS OF THE SOURCE



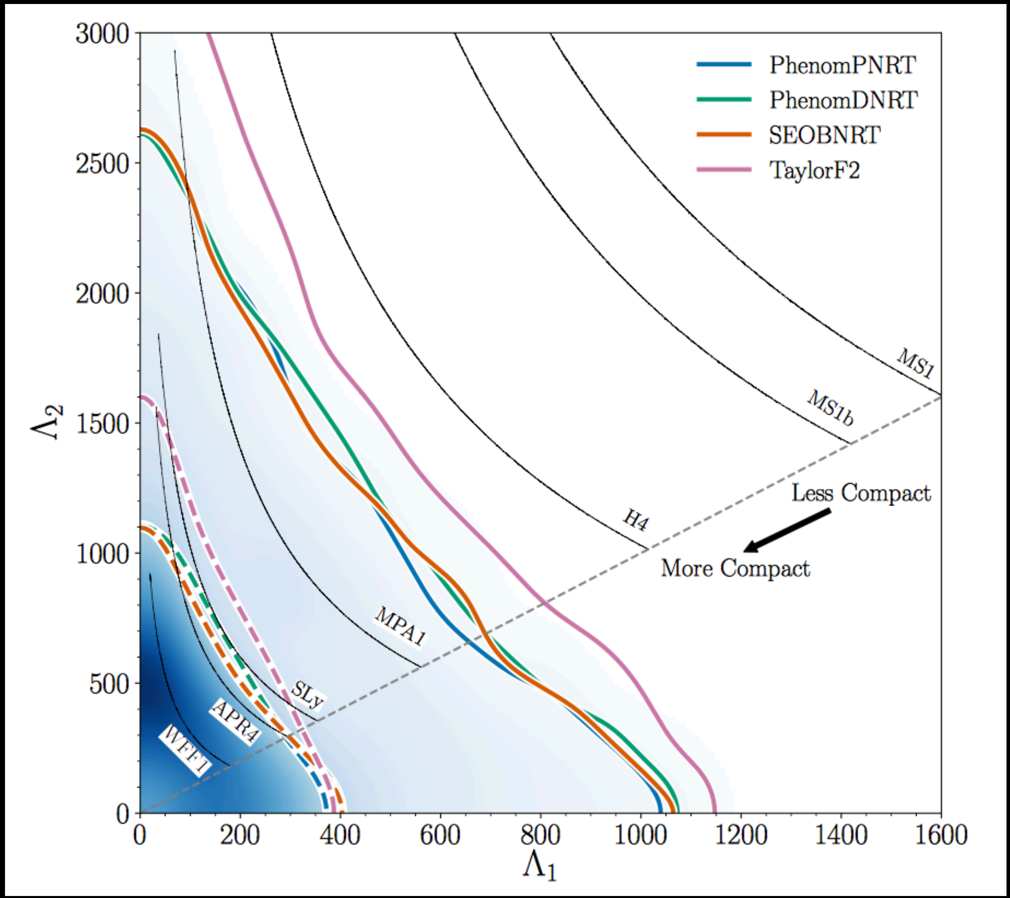
23 < *f* /*Hz* < 2048
Analysis uses source location from EM

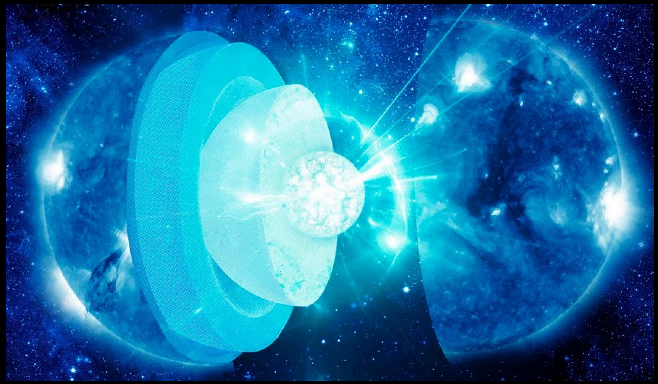
- **Mass range 1.0 – 1.89 Mo**

Masses are consistent with the masses of all known neutron stars!

Abbott et al. 2018, arXiv1805.11579

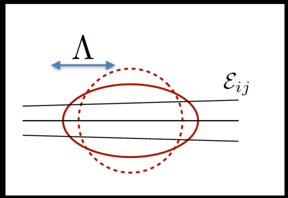
NS LABORATORY FOR STUDYING SUPER-DENSE MATTER





TIDAL DEFORMABILITY

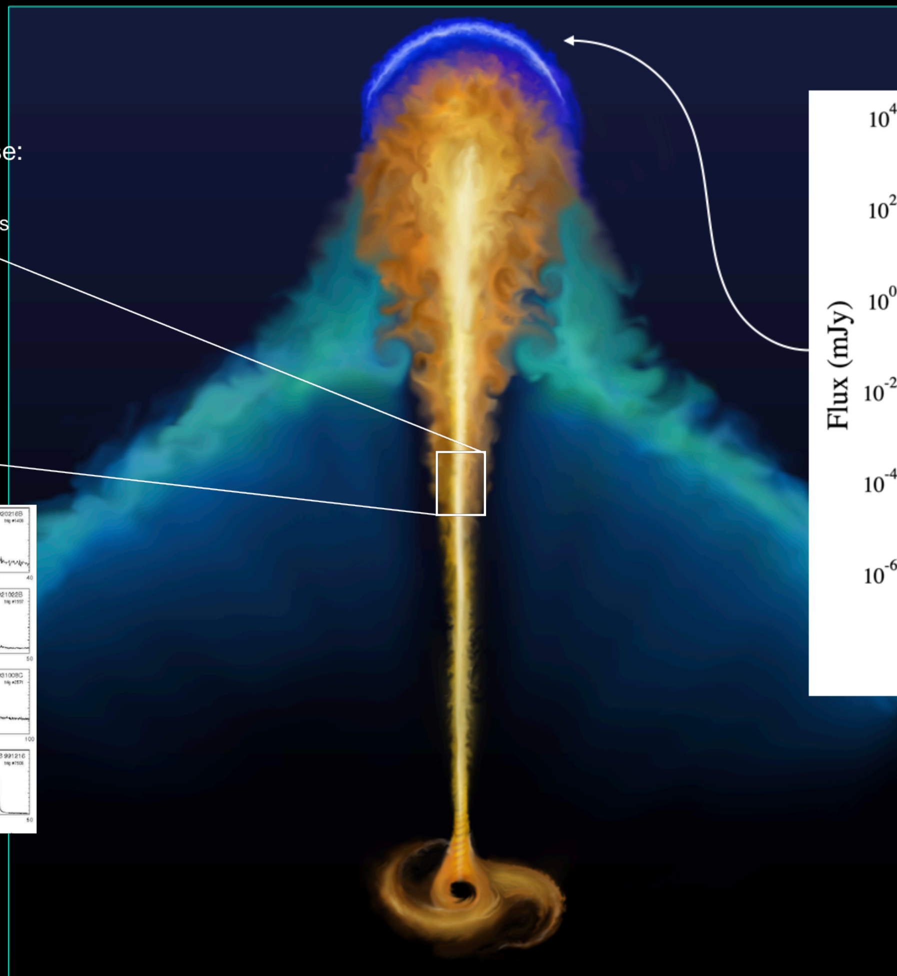
$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$



From only GWs we cannot say both components of the binary were NS

EM non-thermal emission

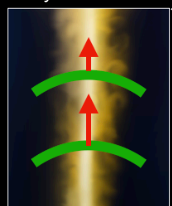
Short Gamma Ray Burst

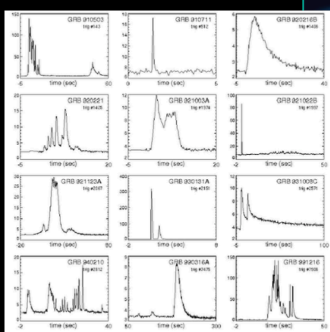


Prompt emission phase:

Energy range: keV-MeV

Variability time-scales: ms-s

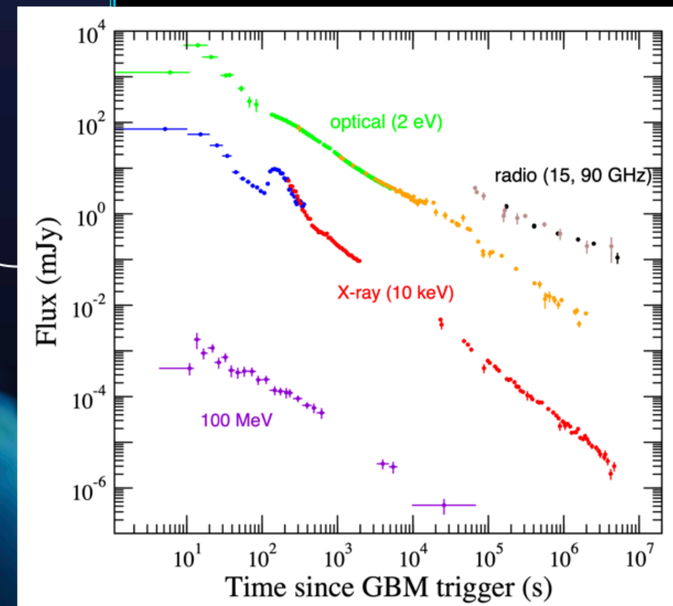




Shemi & Piran (1990)

Rees & Meszaros (1994)

Afterglow phase



From Panaitescu et al (2013)

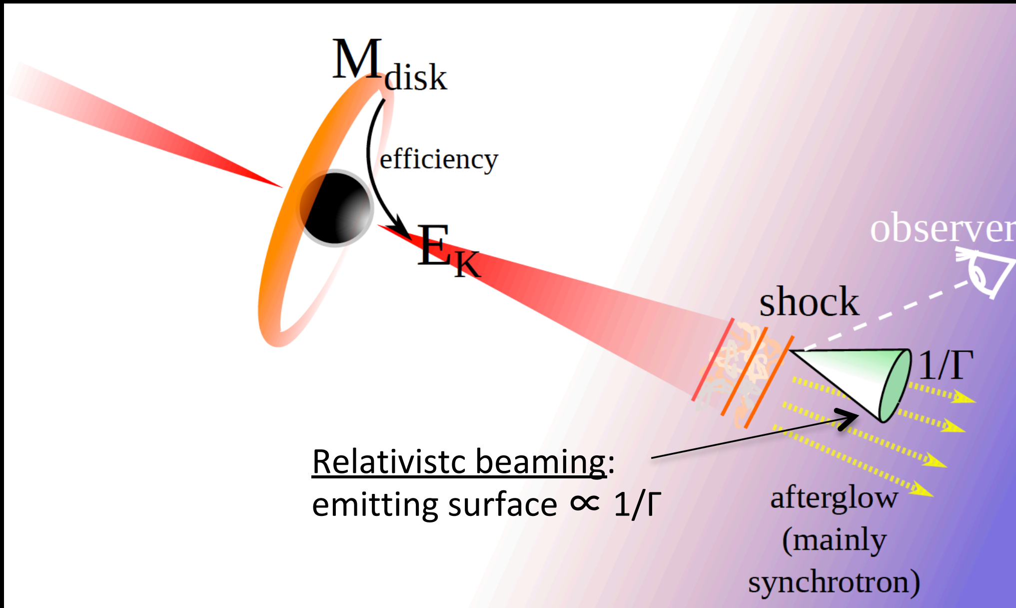
Prompt emission

ϒ-ray within seconds

Afterglow emission

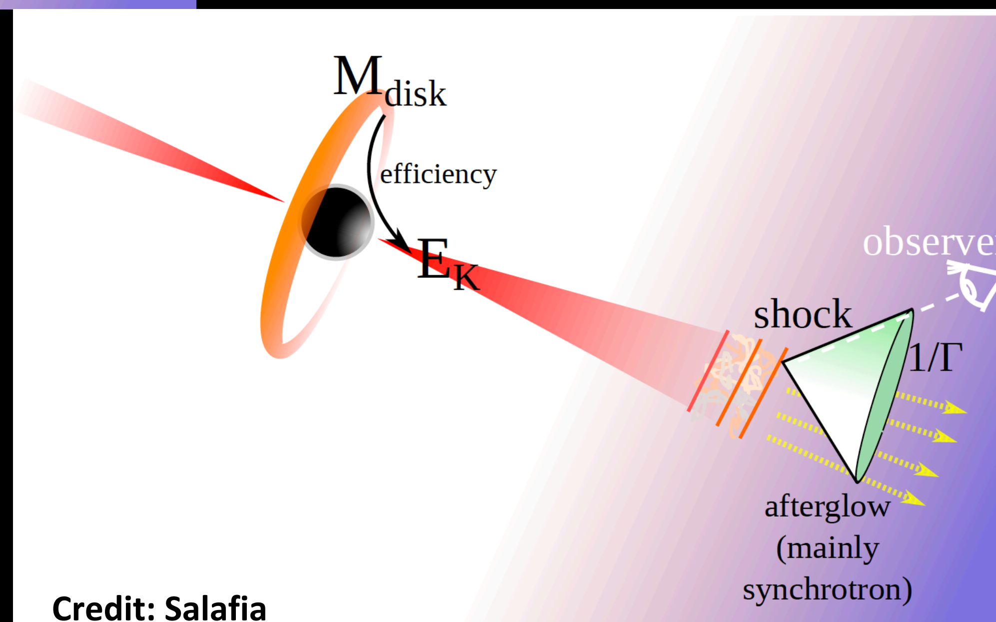
Optical, X-ray, radio

hours, days, months



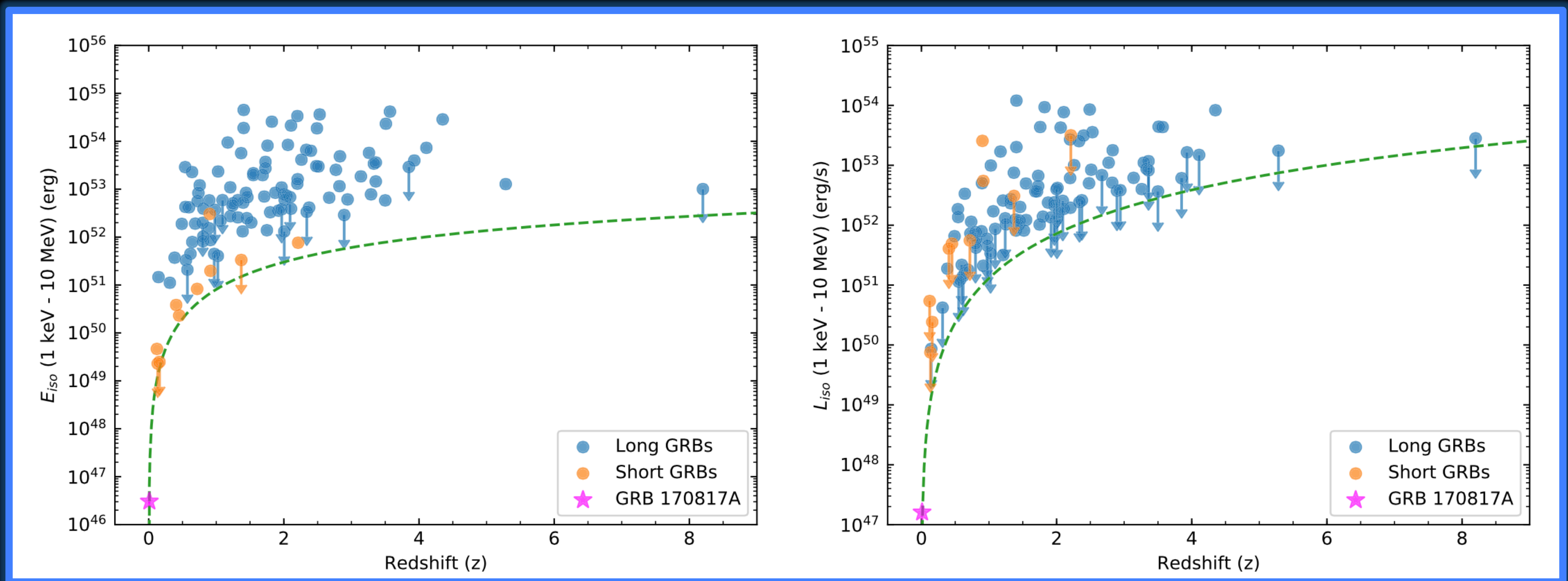
EM emission detectable also by off-axis observers

Early EM emission detectable only by on-axis observers



GRB 170817A

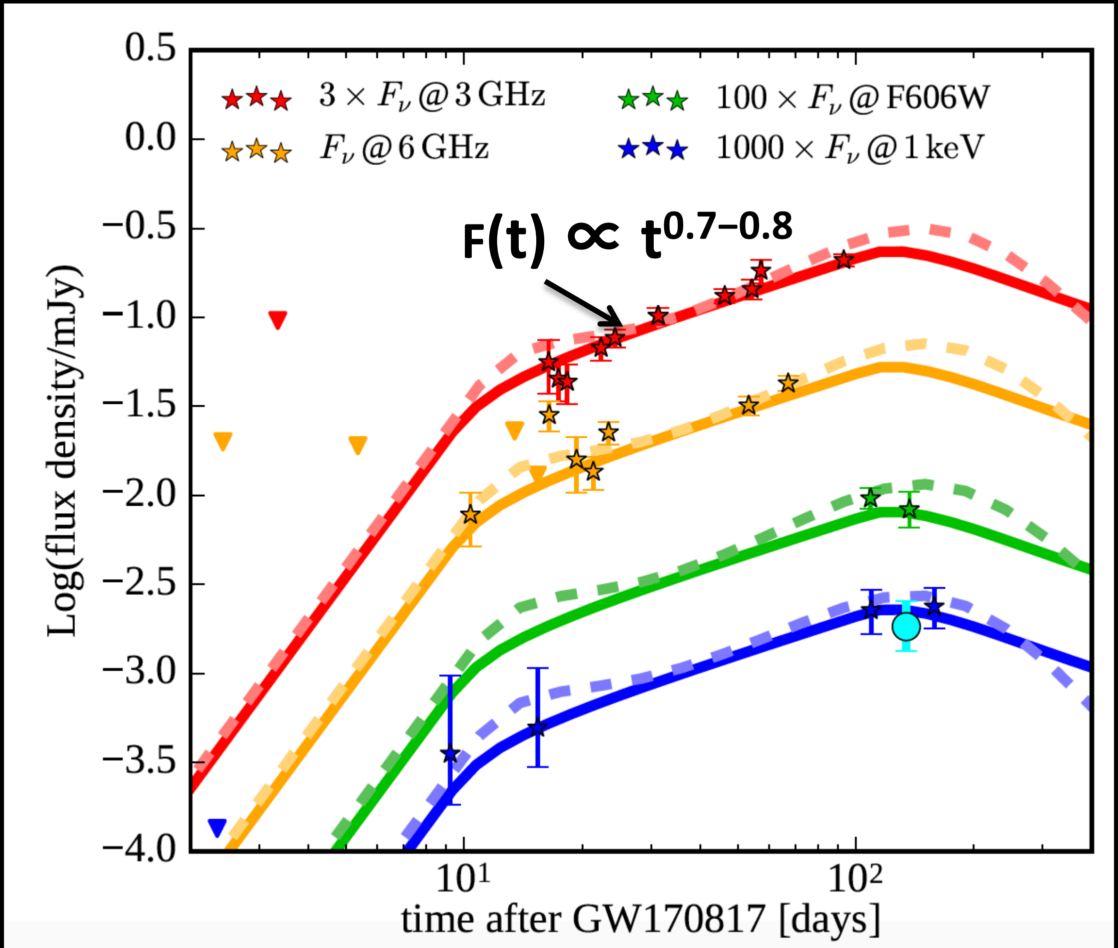
- 100 times closer than typical GRBs observed by Fermi-GBM
- it is also "subluminous" compared to the population of long/short GRBs
- $10^2 - 10^6$ less energetic than other short GRBs



Abbott et al. 2017, APJL, 848, L13

First short GRB viewed off-axis?

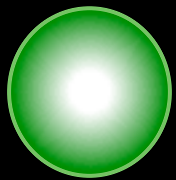
After 150 days from the BNS merger…



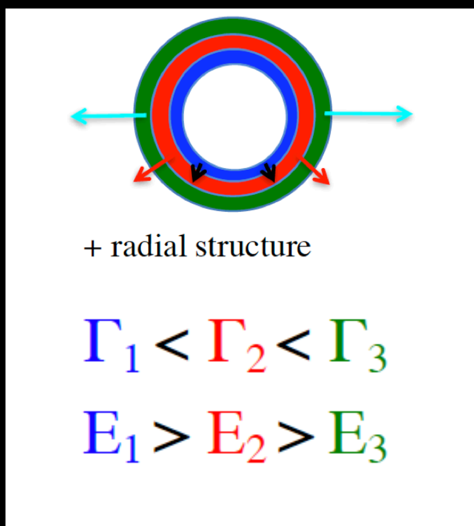
D’Avanzo et al. 2017, A&A

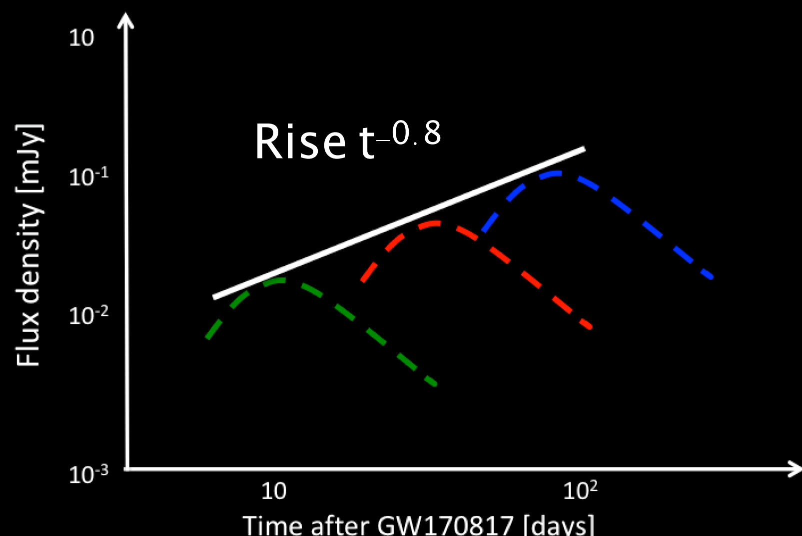
..unexpected slow achromatic flux–rise until ~ 150 days!

RADIAL or ANGULAR STRUCTURE?

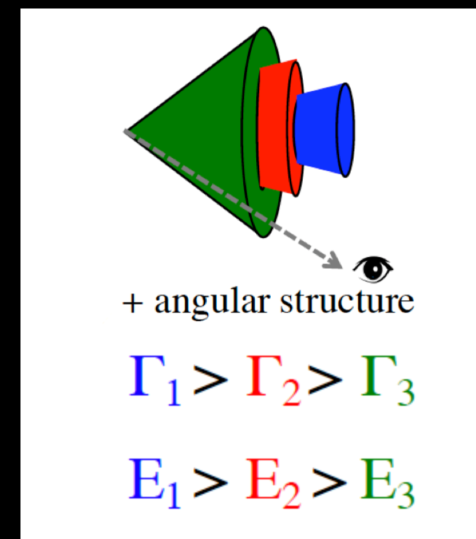


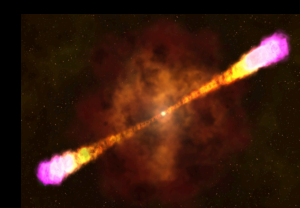
Mildly relativistic isotropic outflow (choked jet)





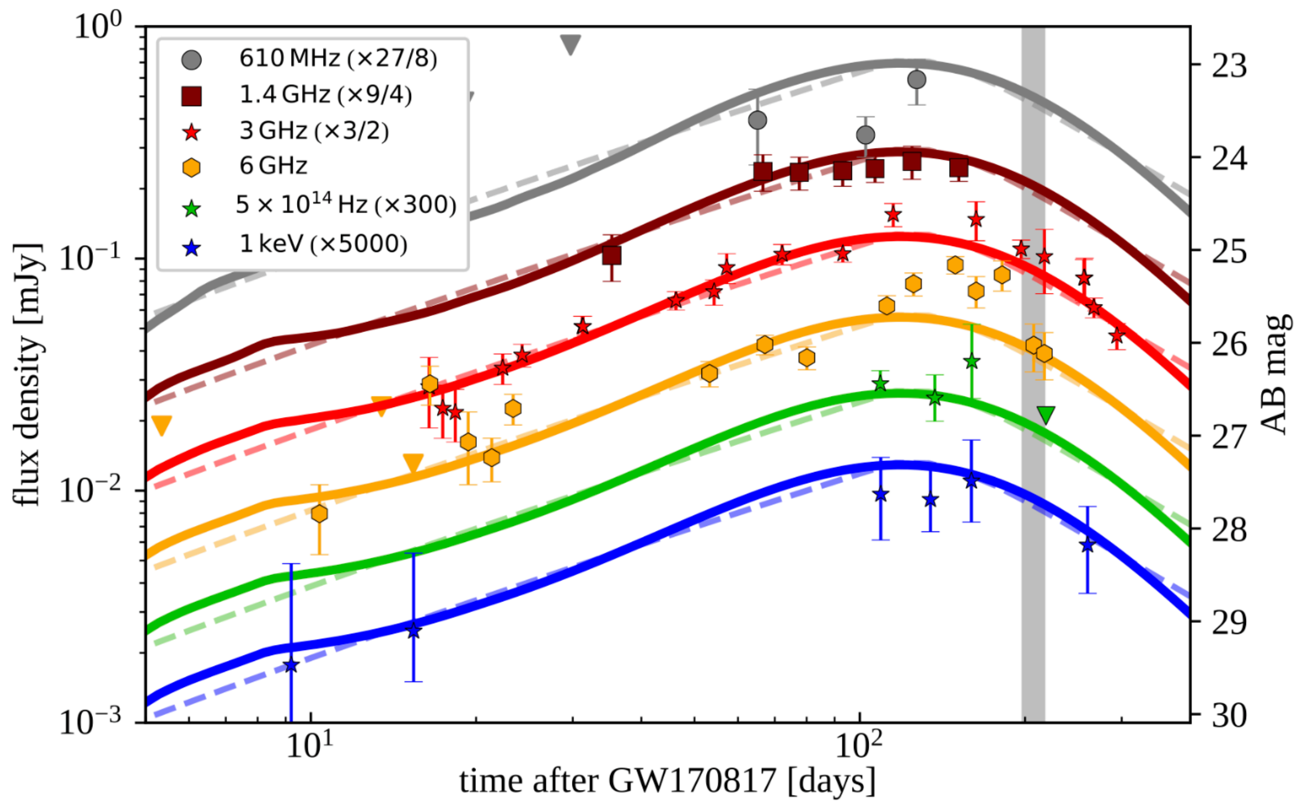
Structured Jet (successful) off-axis jet



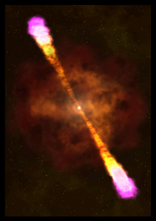


[see e.g. Rossi et al. 2002, Zhang et al. 2002, Ramirez-Ruiz et al. 2002, Nakar & Piran 2018, Lazzati et al. 2018, Gottlieb et al. 2018, Kasliwal 2017, Mooley et al. 2017, Salafia et al. 2017, Ghirlanda et al. 2019]

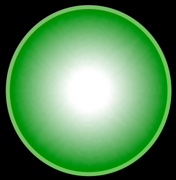
After 150 days from the BNS merger…decaying phase!



Ghirlanda et al. 2018



Solid lines



Dashed lines

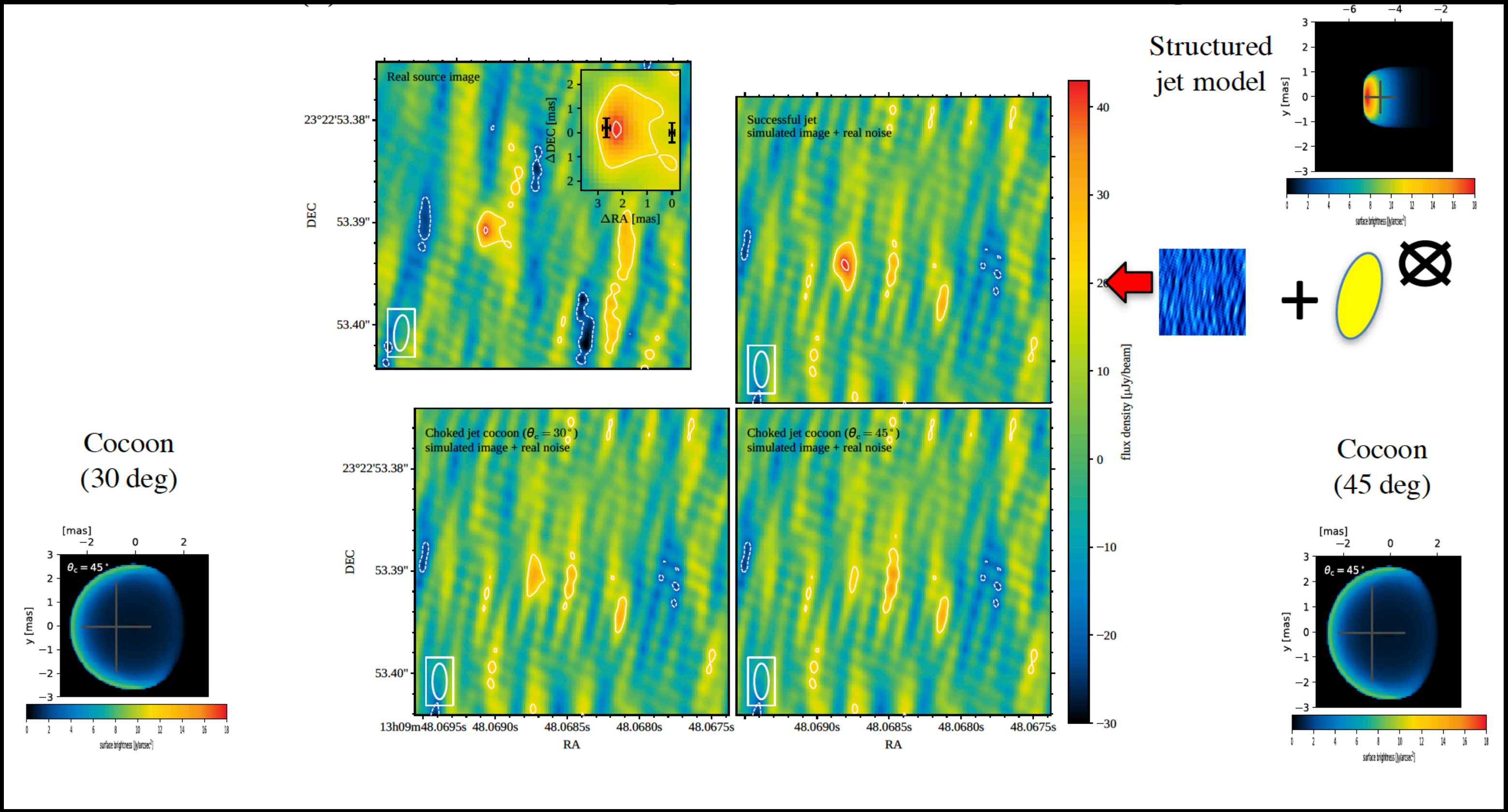
MULTI-WAVELENGTH LIGHT CURVES CANNOT DISENTANGLE THE TWO SCENARIOS!

[Margutti, et al. 2018, Troja, et al. 2018, D'Avanzo et al. 2018, Dobie et al. 2018, Alexander et al. 2018, Mooley et al. 2018, Ghirlanda et al. 2019]

SIZE CONSTRAINTS

Observations 207.4 days after BNS merger by global VLBI network of 33 radio telescopes over five continents constrain SOURCE SIZE < 2 mas

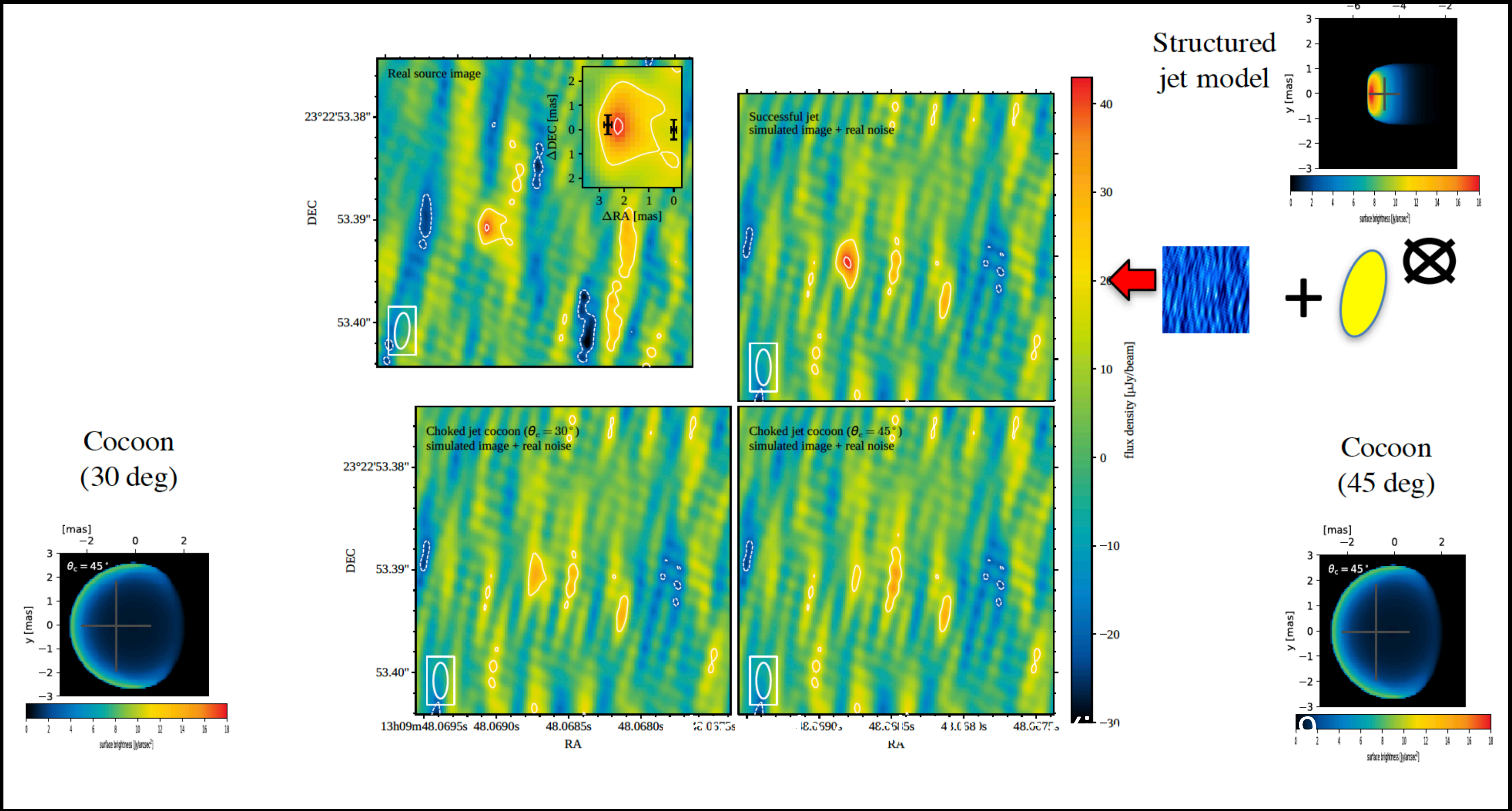
Ghirlanda et al. 2019, Science

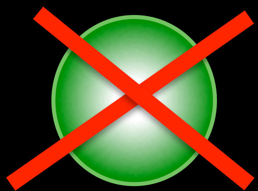


See also Mooley, Deller, Gottlieb et al. 2018

SIZE CONSTRAINTS

Ghirlanda et al. 2019, Science





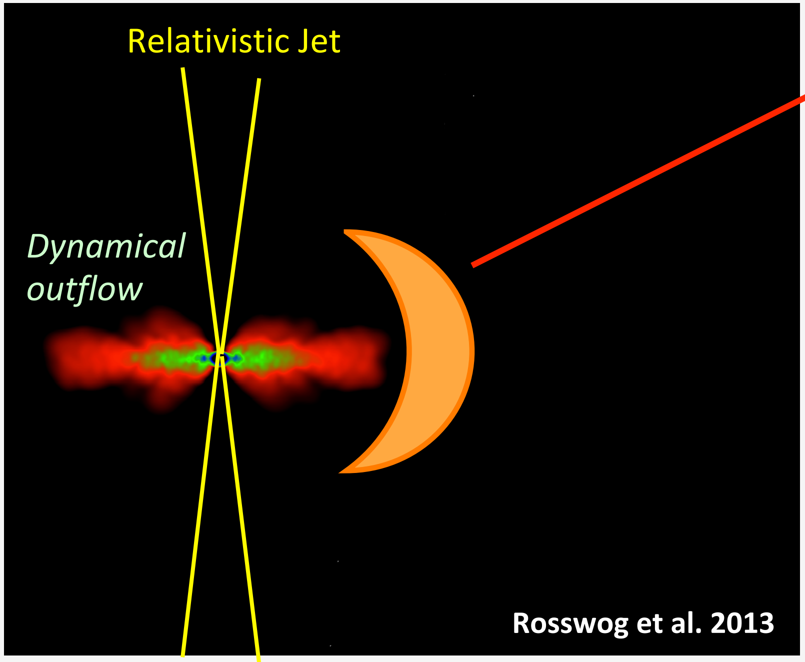
Ruled out nearly isotropic, mildly relativistic outflow , which predicts proper motion close to zero and size > 3 mas after 6 months of expansion

Ghirlanda et al. 2019, Science

A relativistic energetic and narrowly-collimated jet successfully emerged from neutron star merger GW170817!

Thermal-emission

Kilonova



Tidal-tail ejecta → r-process

Neutron capture rate much faster than decay, special conditions: T > 10^9 K, high neutron density 10^{22} cm^{-3}

↓

nucleosynthesis of heavy nuclei

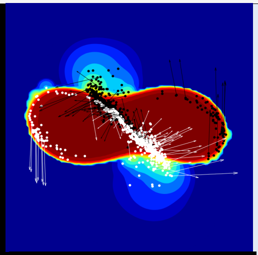
↓

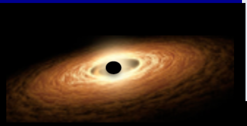
radioactive decay of heavy elements

↓

Power short lived RED-IR signal (days)

Li & Paczynski 1998; Kulkarni 2005 Metzger et al. 2010; Tanaka et al. 2014; Barnes & Kasen 2013



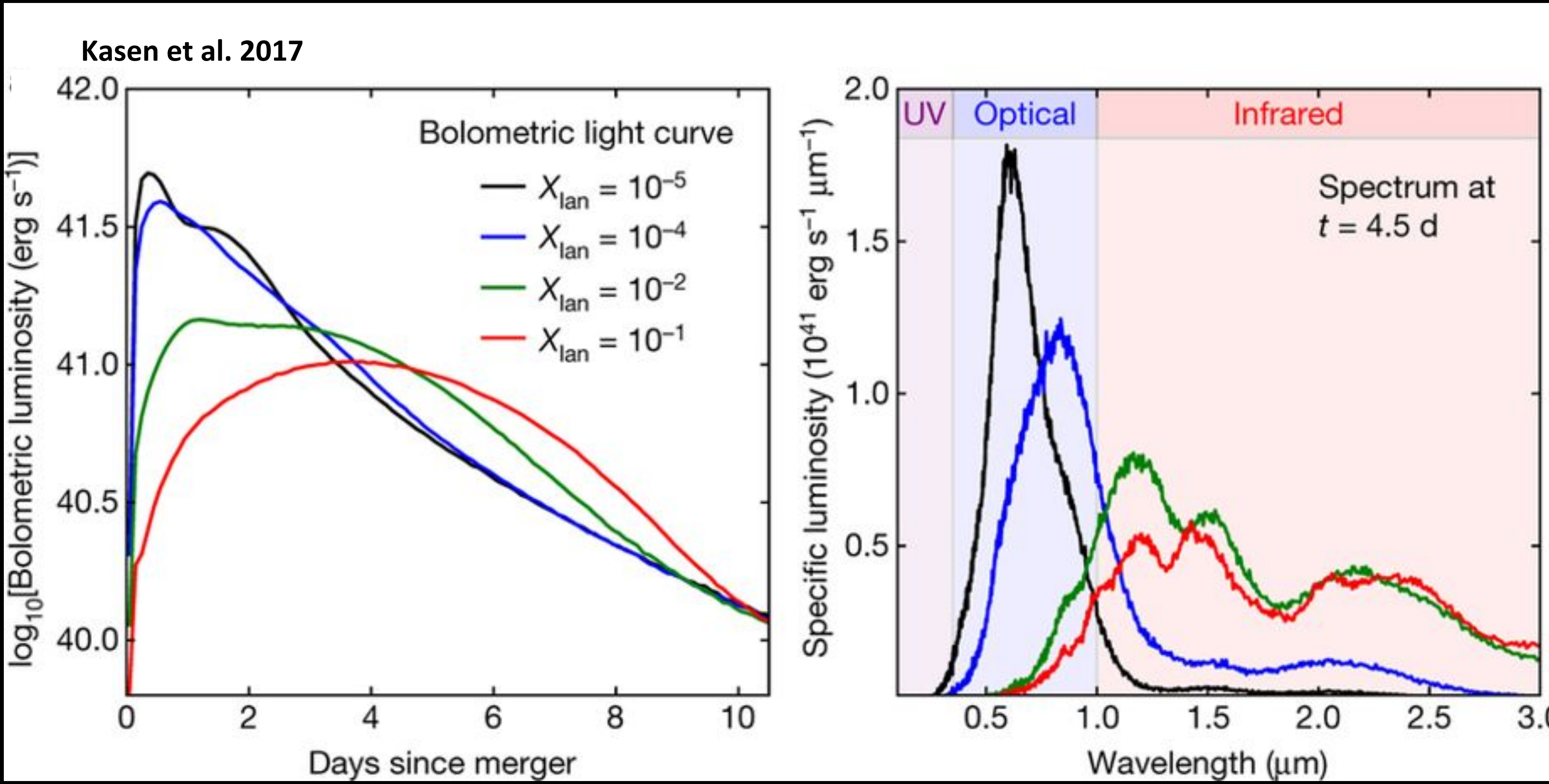


Shock-heated ejecta, accretion disc wind outflow, secular ejecta

- Weak interactions: neutrino absorption, electron/positron capture
- Higher electron fraction, no nucleosynthesis of heavier element
- Lower opacity
- brief (~ 2 day) **blue optical transient**

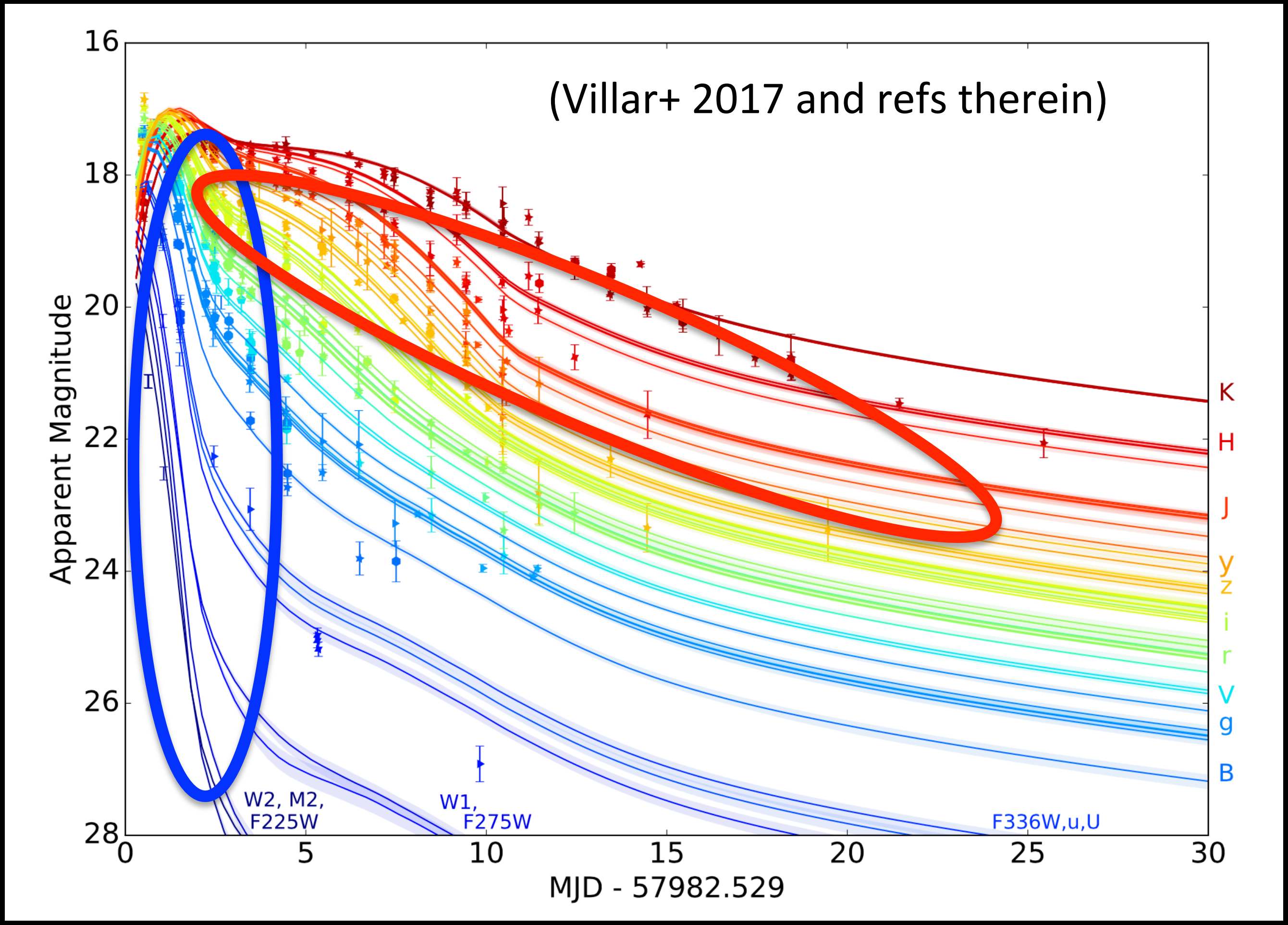
Kasen et al. 2015, Perego et al. 2014, Wanajo et al. 2010

Observables: expectations



Light curve shape (duration and peak luminosity) and spectarl shape are dramatically affected by lanthanides

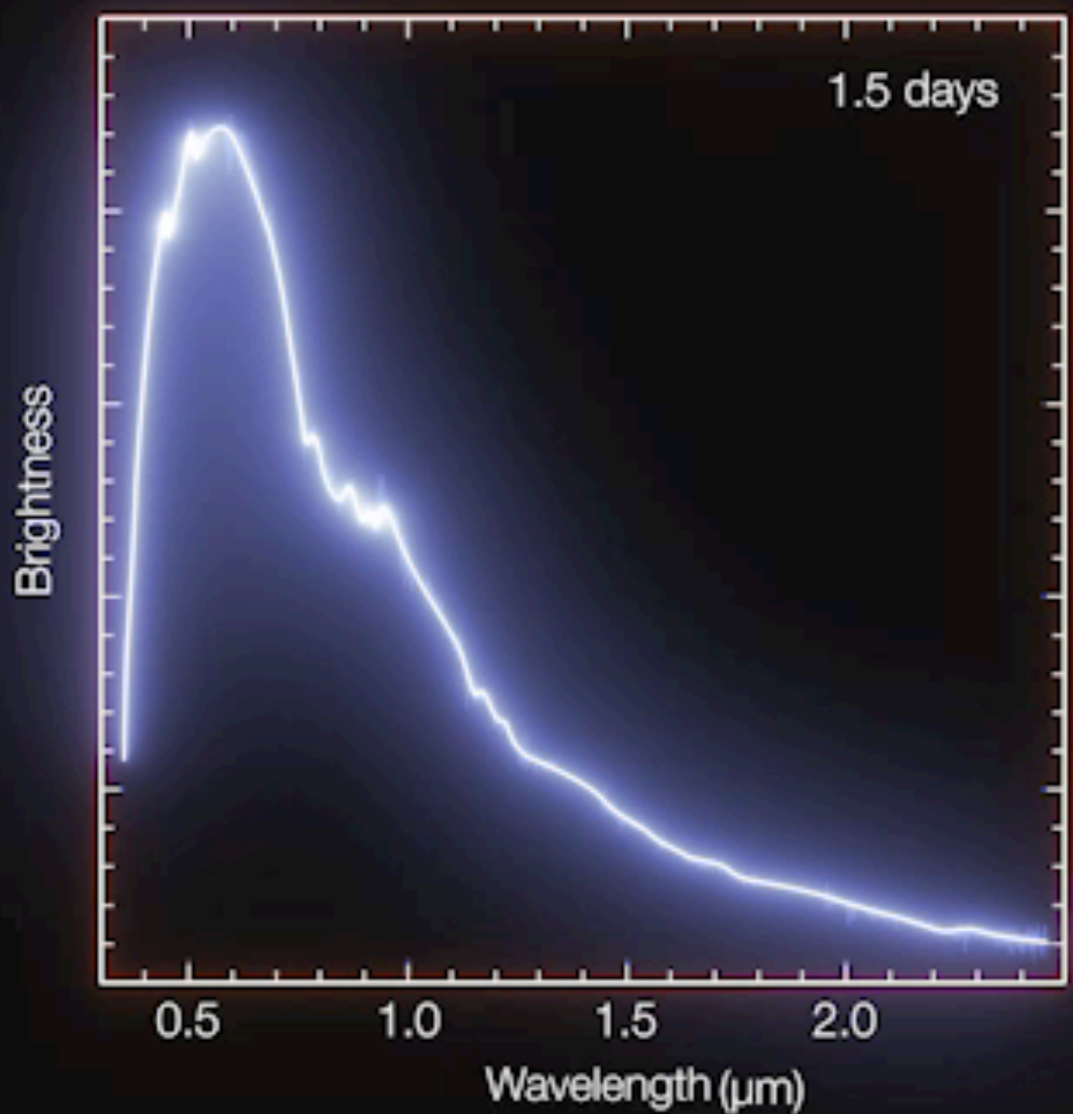
UV/Optical/NIR Light Curves



Extremely well characterized photometry of a Kilonova:

thermal emission by radiocative decay of heavy elements synthesized in multicomponent (2-3) ejecta!

ESO-VLT/X-Shooter



First spectral identification of the kilonova emission

- the data revealed signatures of the radioactive decay of **r-process nucleosynthesis**

(Pian et al. 2017, Smartt et al. 2017)

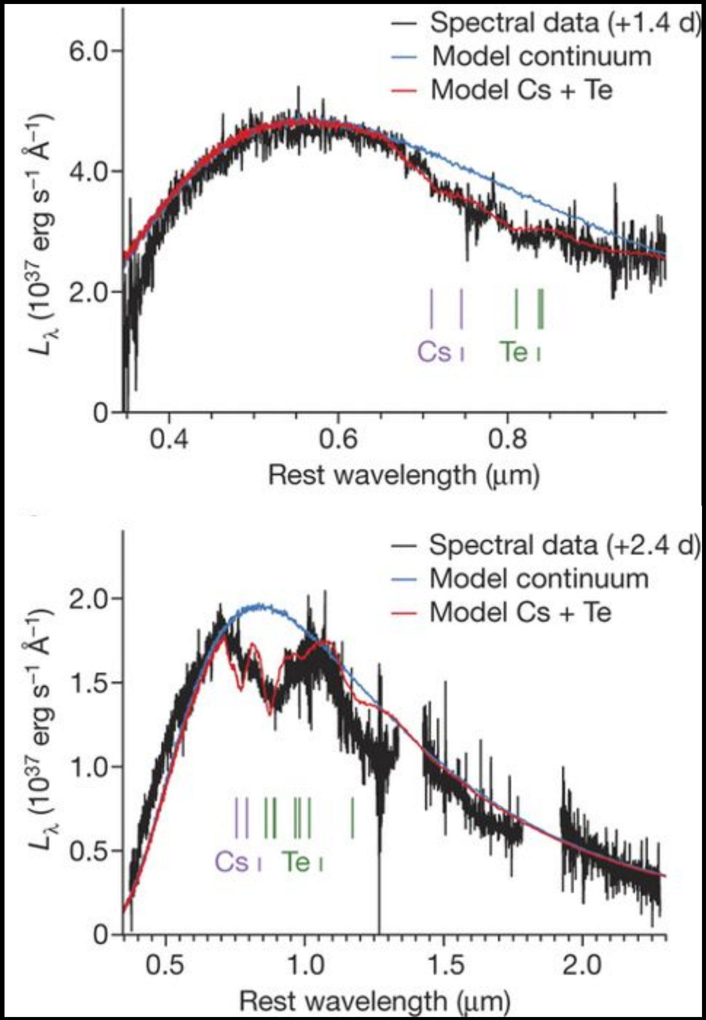
- BNS merger **site for heavy element production in the Universe!**

(Cote et al. 2018, Rosswog et al. 2017)

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

Nucleosynthesis

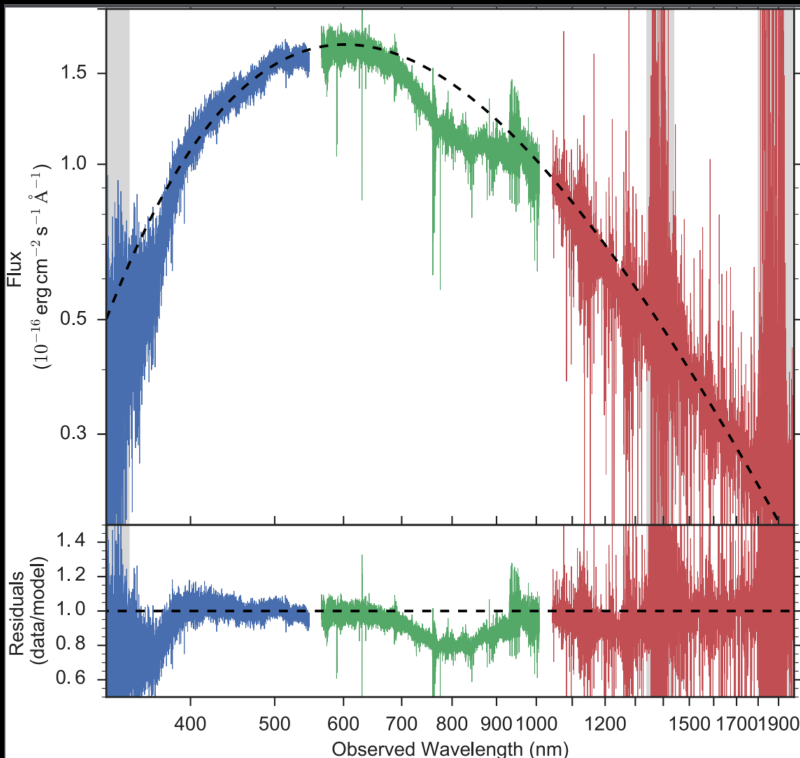
Smartt et al. 2017



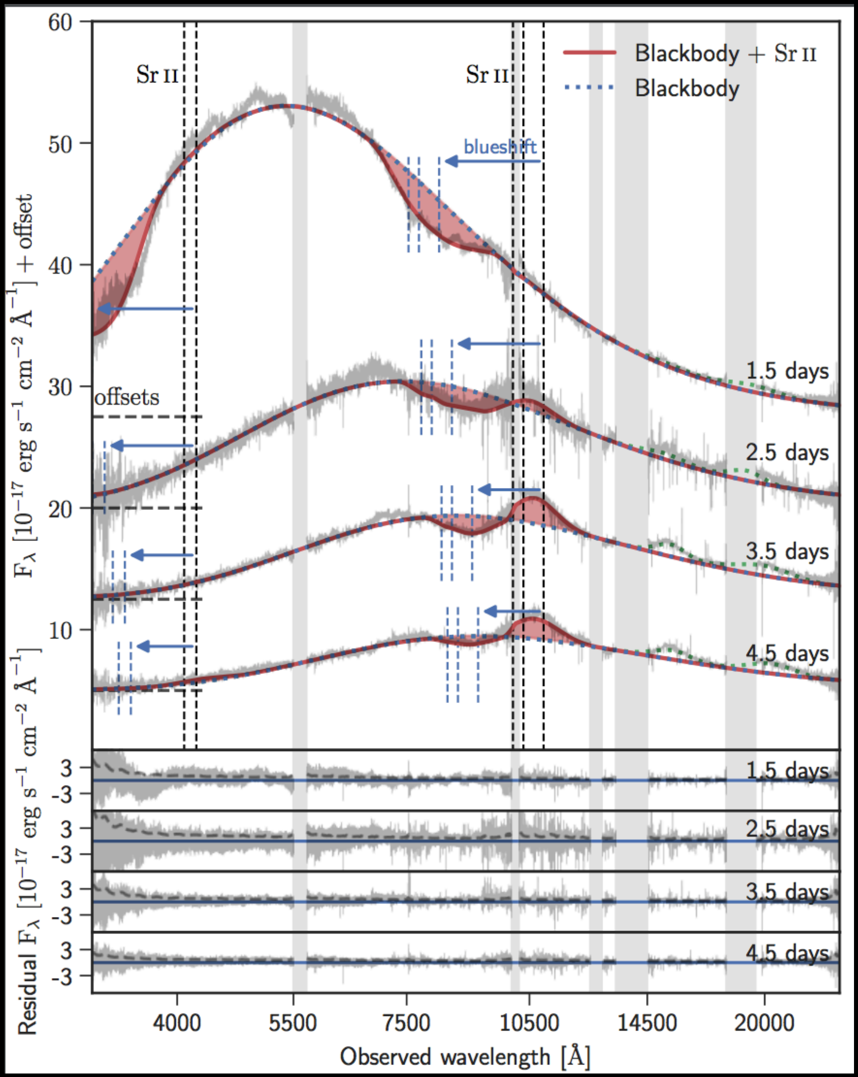
Attempt to identify elements
Neutral caesium
Excited tellurium

Spectral analysis hampered because of:

- heavy elements have forest of lines hence strong blending
- relativistic velocity makes for extremely broad lines (multi-components and different velocities)
- atomic data are incomplete and uncertain



Watson, D. et al. 2019 Nature



identification of the neutron-capture element **strontium**

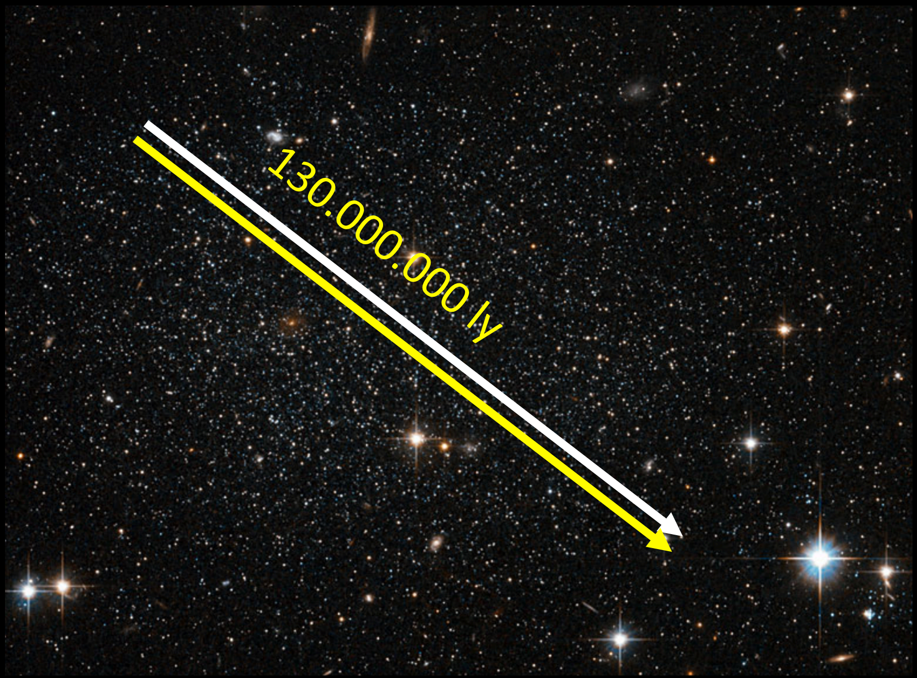
See also Perego et al. 2021

Multi-messenger studies

GRB/GW FUNDAMENTAL PHYSICS/COSMOLOGY







GRB/GW delay

$$\Delta t = (1.74 \pm 0.05)\, s$$

and 40 Mpc distance

→ difference speed of gravity and speed of light between

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

GWs propagate at the speed of light to within $1:10^{15}$!

LVC 2017, APJL, 848, L13

Consequences of multi-messenger detection of GW170817 for cosmology →

Constraint on the speed of GWs ruled out many classes of modified gravity models

(quartic/quintic Galileons, TeVeS, MOND-like theories, see, e.g., Baker et al. ’17, Creminelli & Vernizzi ’17)