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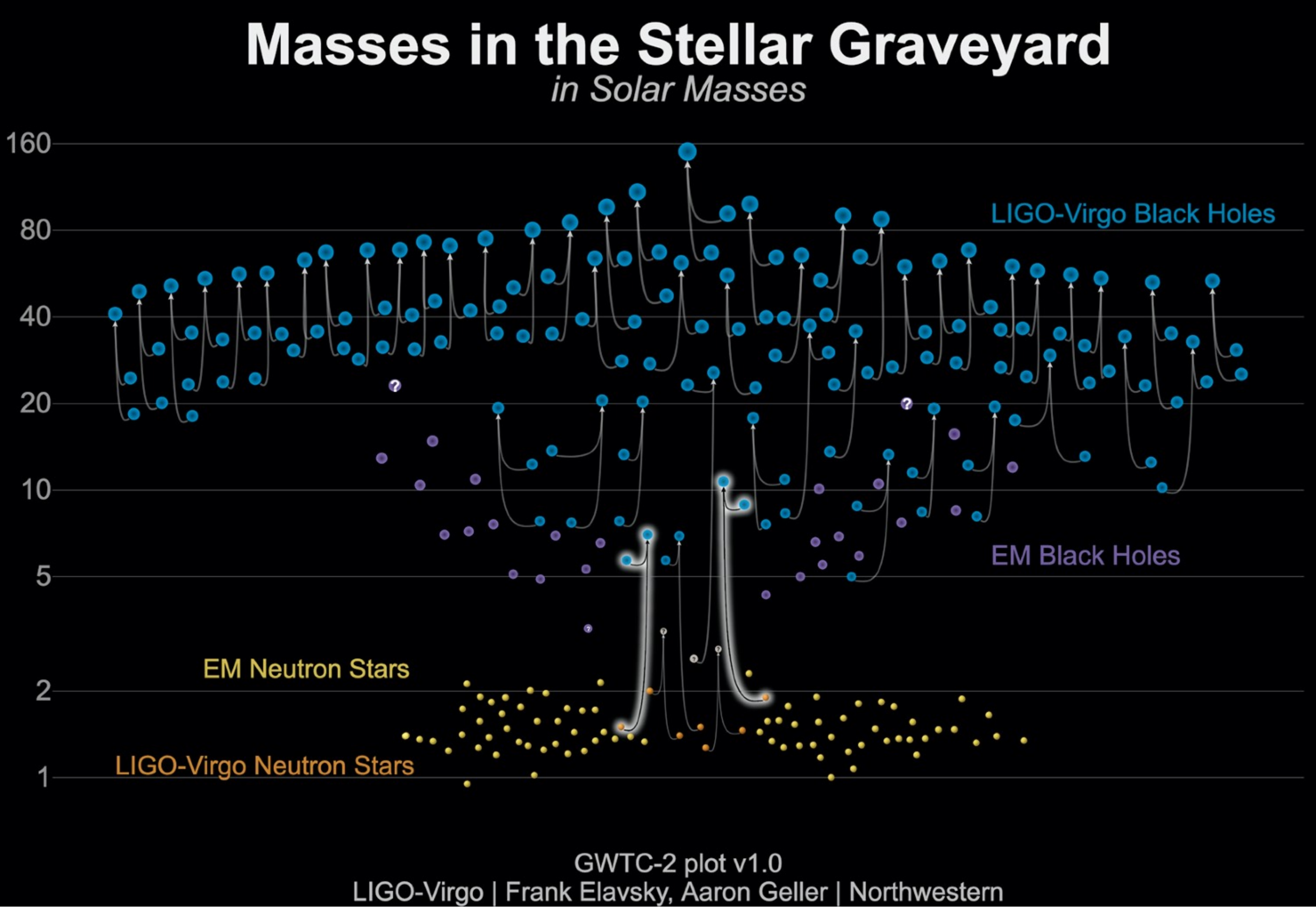
Probing neutron star mergers with gravity and light

Soumi De
Los Alamos National Laboratory, USA

Free Meson Seminar, TIFR Bombay, India

July 22, 2021

LA-UR-21-27041



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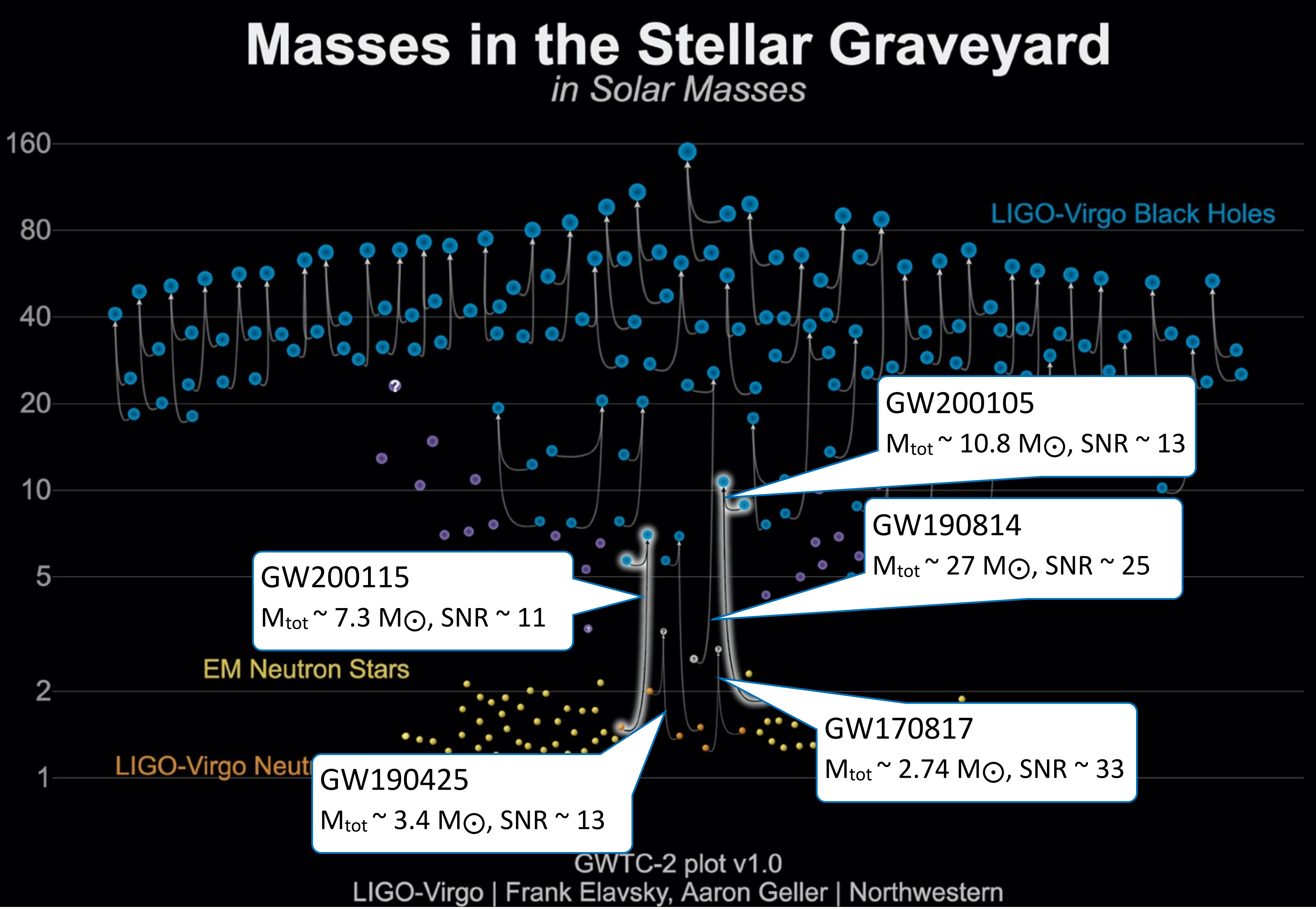
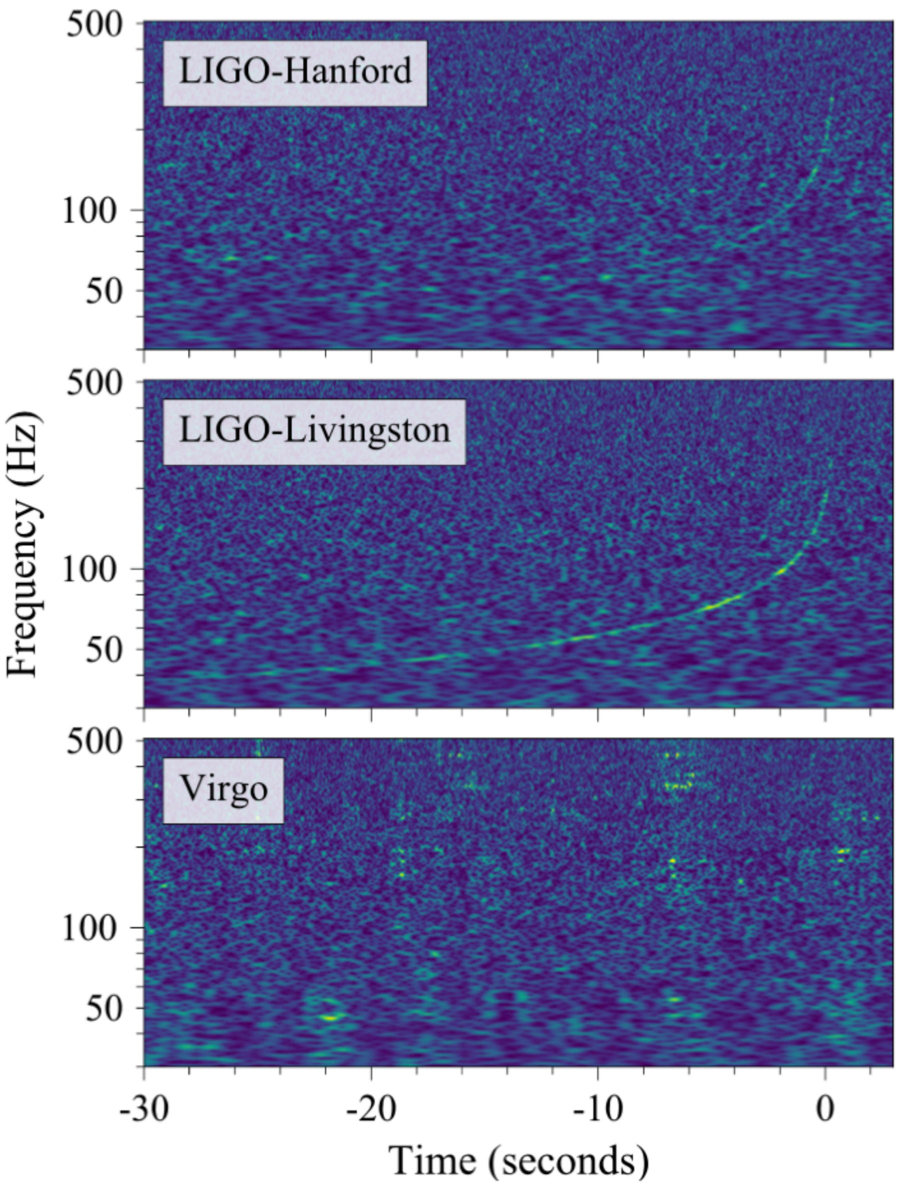
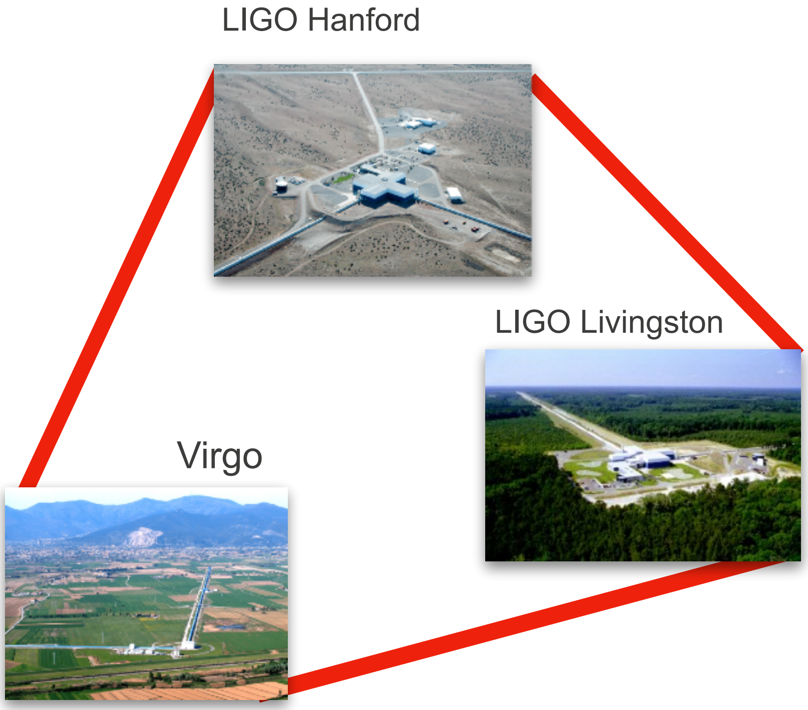

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Neutron Stars
LIGO-Virgo Neut
GW200105
Mtot ~ 10.8 M⊙, SNR ~ 13
GW190814
Mtot ~ 27 M⊙, SNR ~ 25
GW200115
Mtot ~ 7.3 M⊙, SNR ~ 11
GW190425
Mtot ~ 3.4 M⊙, SNR ~ 13
GW170817
Mtot ~ 2.74 M⊙, SNR ~ 33
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

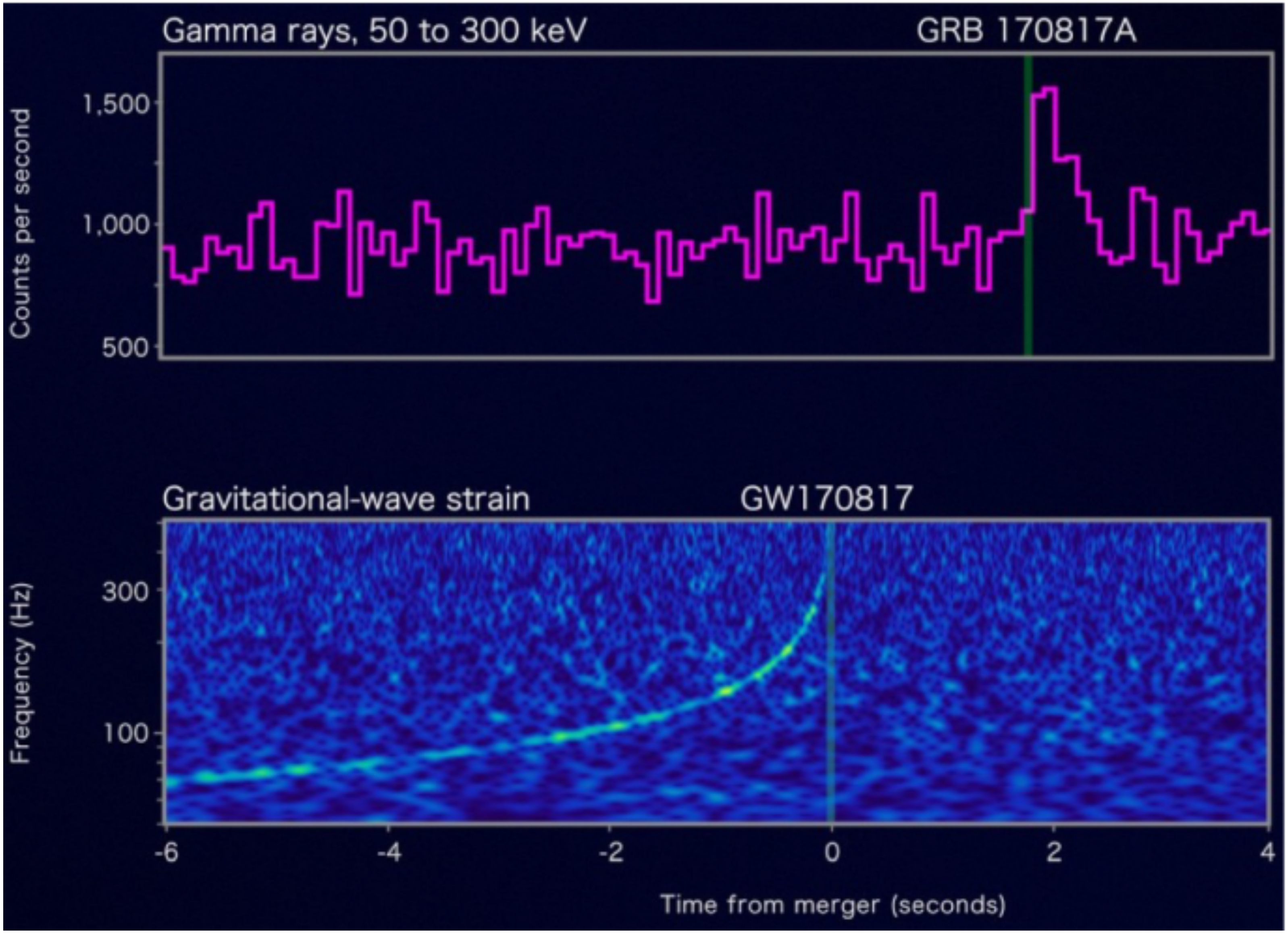
GW170817





Abbott,…, **SD** et al. ApJL **848**, 2 (2017)

Multimessenger observation of GW170817



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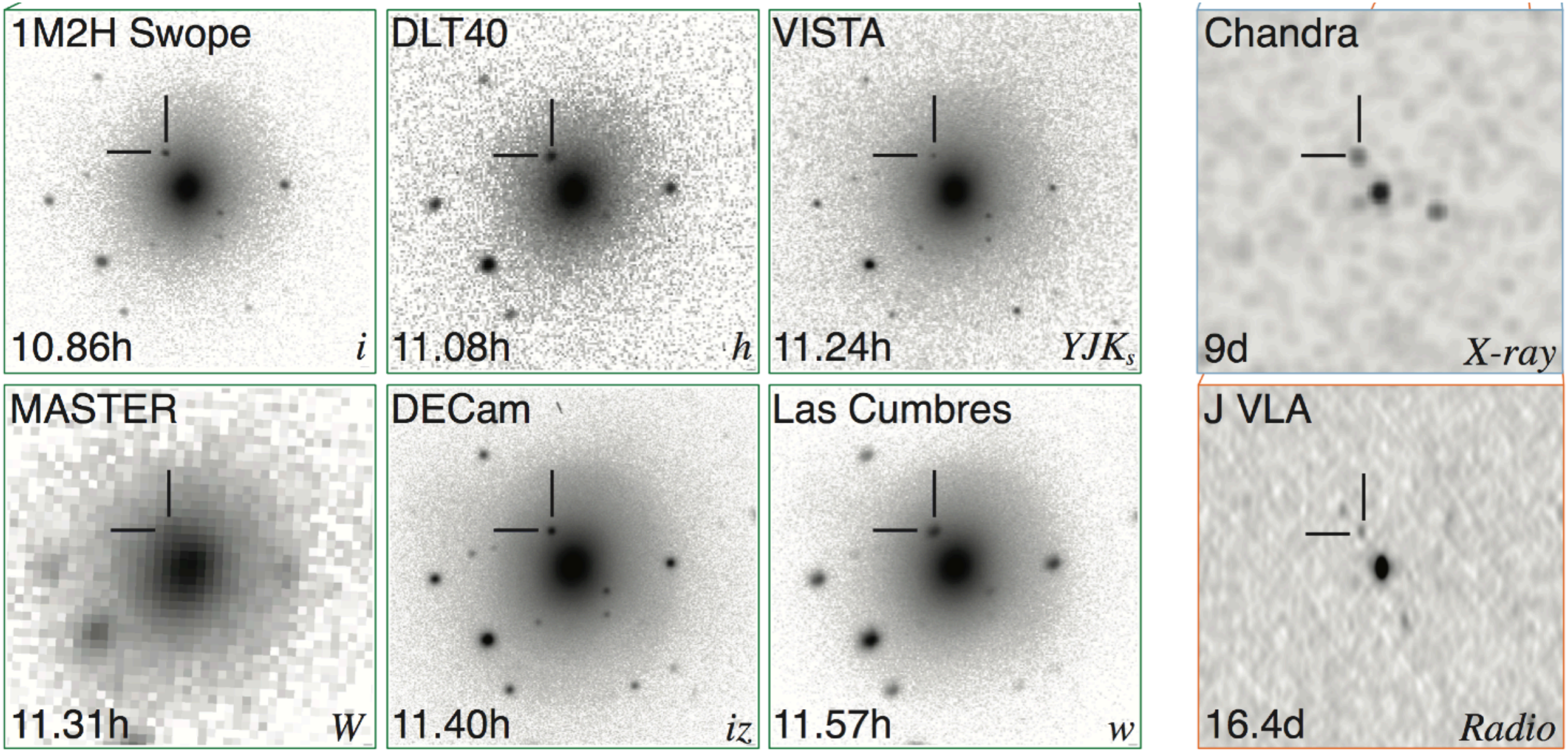

Abbott,…, **SD** et al. ApJL **848**, 2 (2017)

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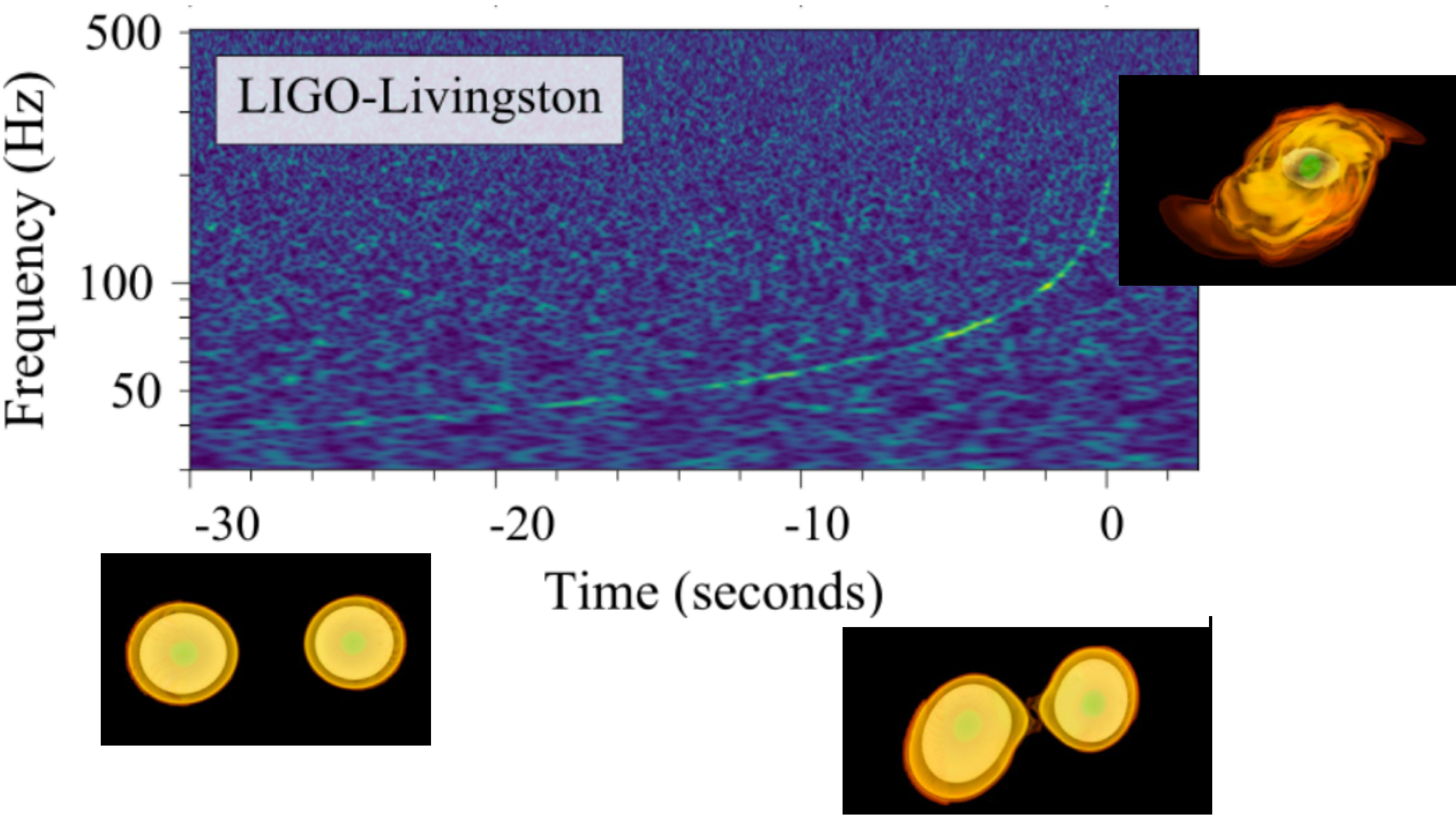
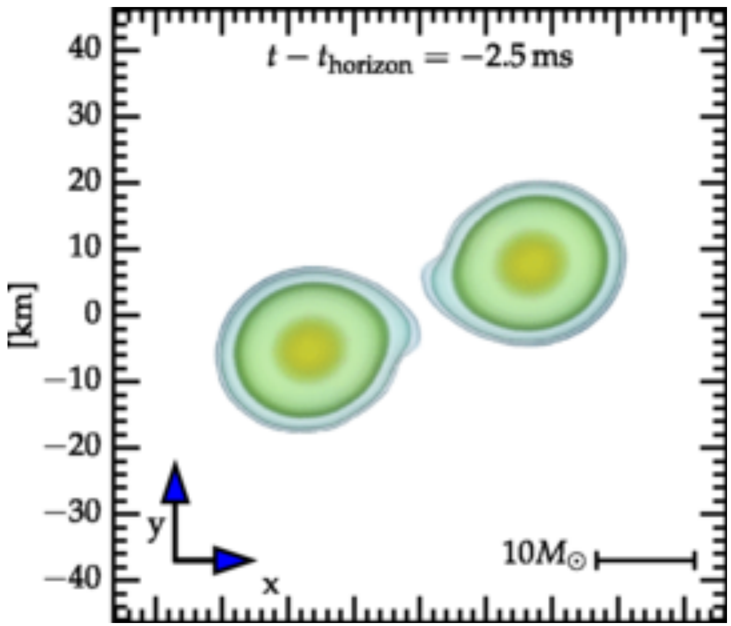
Nuclear matter information from gravitational waves



The tidal deformation of each star can be parameterized as $\Lambda = f(m, R, EOS)$

Tidal deformability

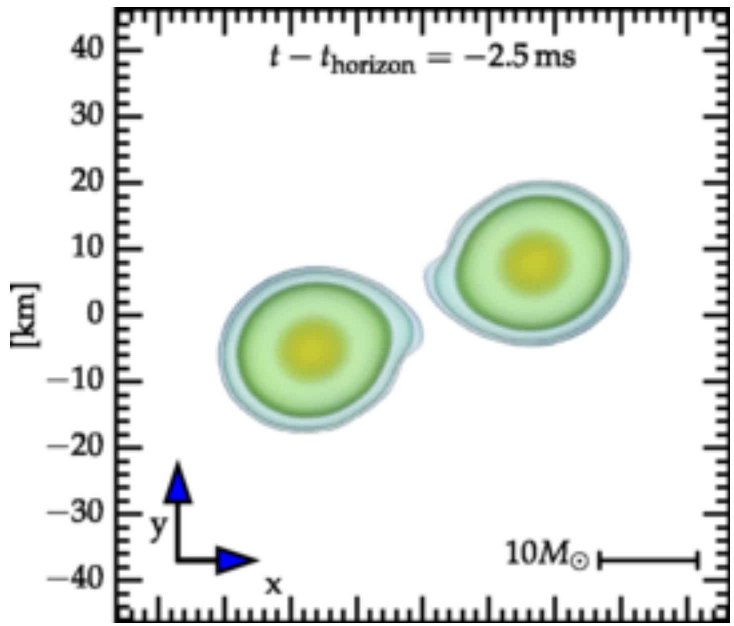


Haas et al (2016)

$\epsilon_{i,j}$

gravitational field of each component star

Tidal deformability



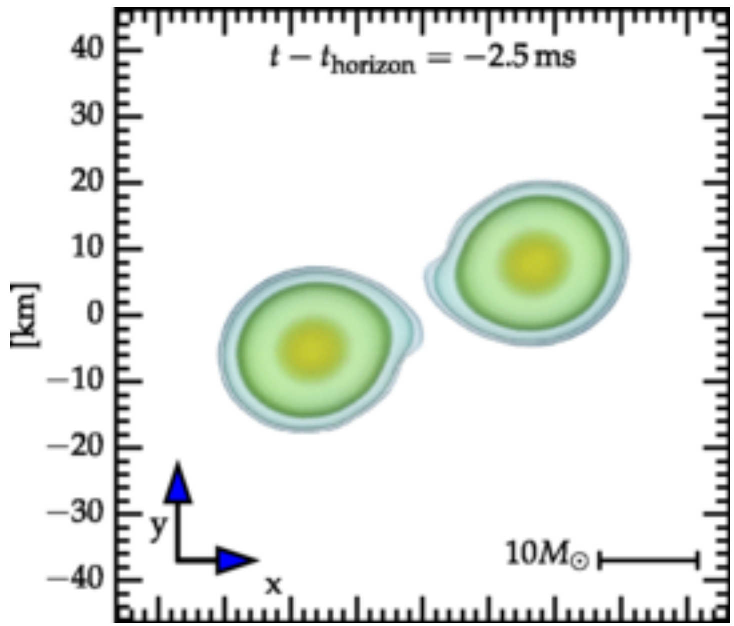
Haas et al (2016)

$$Q_{i,j} \qquad \epsilon_{i,j}$$

gravitational field of each component star

induced quadrupole moment on companion

Tidal deformability



Haas et al (2016)

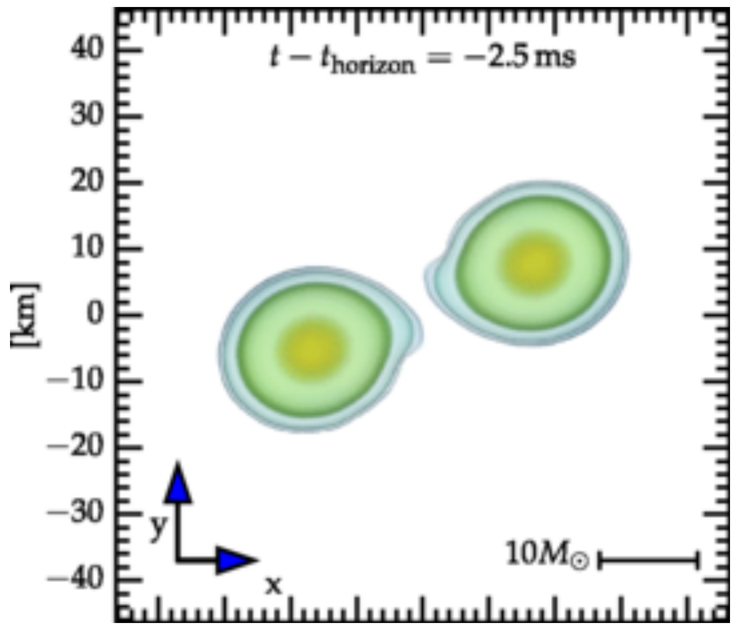
$$Q_{i,j} = -\lambda\epsilon_{i,j}$$

gravitational field of each component star

tidal deformability

induced quadrupole moment on companion

Tidal deformability



Haas et al (2016)

$$Q_{i,j} = -\lambda \epsilon_{i,j}$$

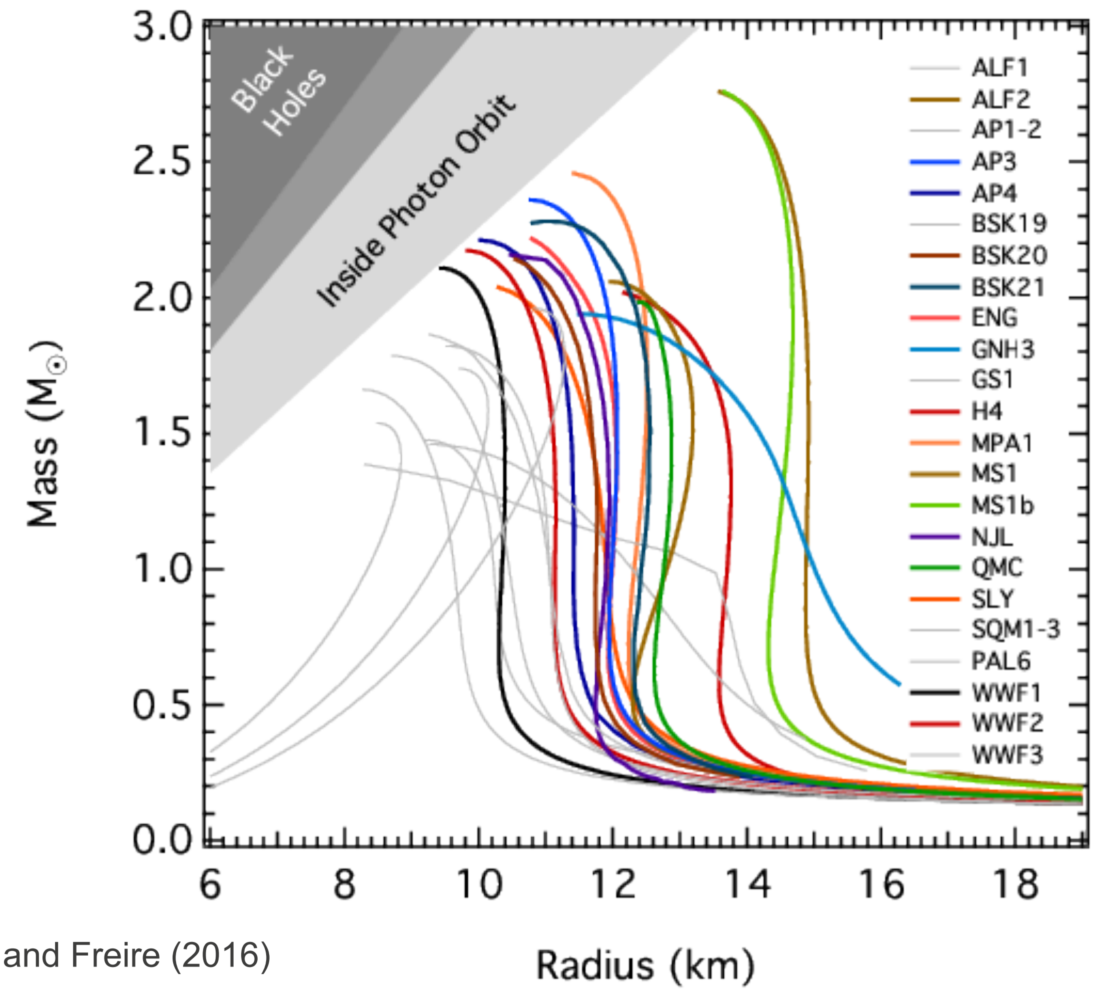
- $\epsilon_{i,j}$: gravitational field of each component star
- λ: tidal deformability
- $Q_{i,j}$: induced quadrupole moment on companion

dimensionless tidal deformability:

$$\Lambda = \lambda / m^5 \qquad \Lambda_{1,2} = \frac{2}{3} k_2 \left(\frac{R_{1,2} c^2}{G m_{1,2}} \right)^5$$

Λ is a measurement of how deformable the neutron star is

How does the tidal deformation connect to the nuclear equation of state?



Ozel and Freire (2016)

$$\Lambda = f(m, R, EOS)$$

Each proposed equation of state generates a specific mass radius curve

We are trying to find what the nuclear equation of state is using GW170817

Effect of tidal deformability on gravitational waves

Information about the tidal deformability is encoded in the phase of the gravitational-wave signal

$$\Phi(t) \sim \phi_0(\mathcal{M};t)\left[1 + \phi_1(\eta;t)\left(\frac{v}{c}\right)^2 + \qquad ... + \phi_5(\tilde{\Lambda};t)\left(\frac{v}{c}\right)^{10}\right]$$

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chirp mass

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

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symmetric mass ratio

$$\eta = \frac{(m_1 m_2)}{(m_1 + m_2)^2}$$

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chirp mass

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

symmetric mass ratio

$$\eta = \frac{(m_1 m_2)}{(m_1 + m_2)^2}$$

binary deformability

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

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Effect of tidal deformability on gravitational waves

Information about the tidal deformability is encoded in the phase of the gravitational-wave signal

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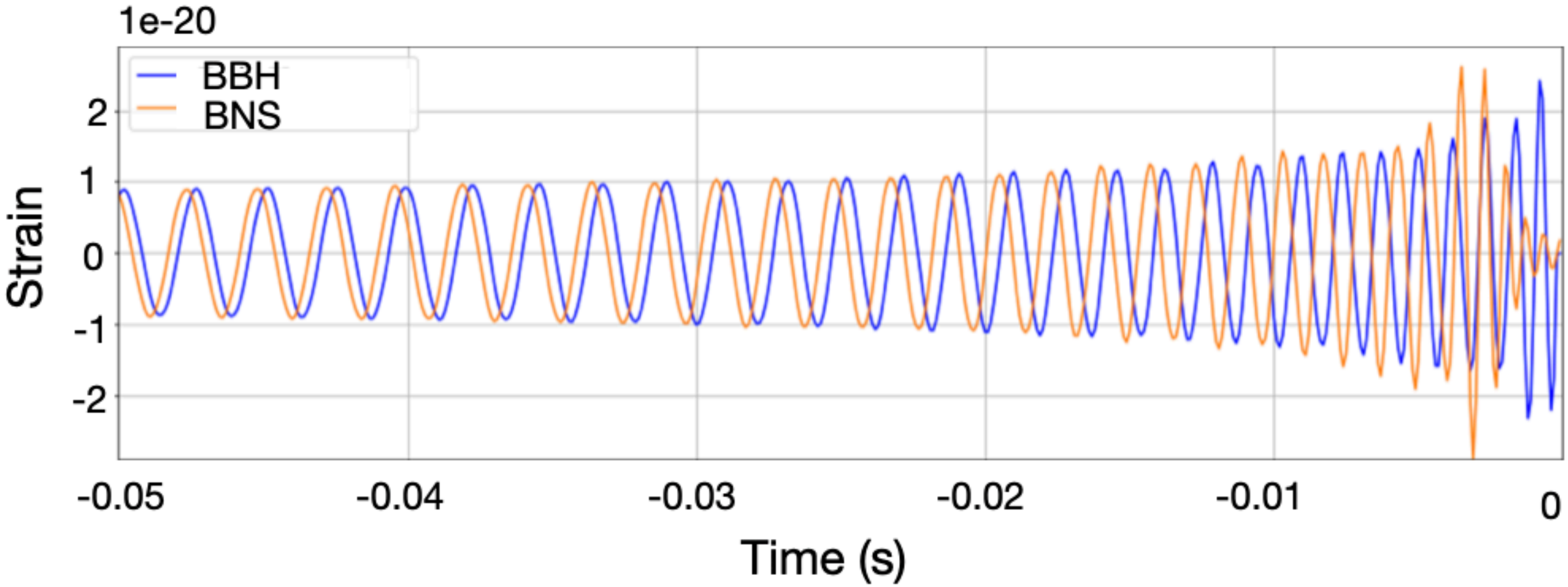
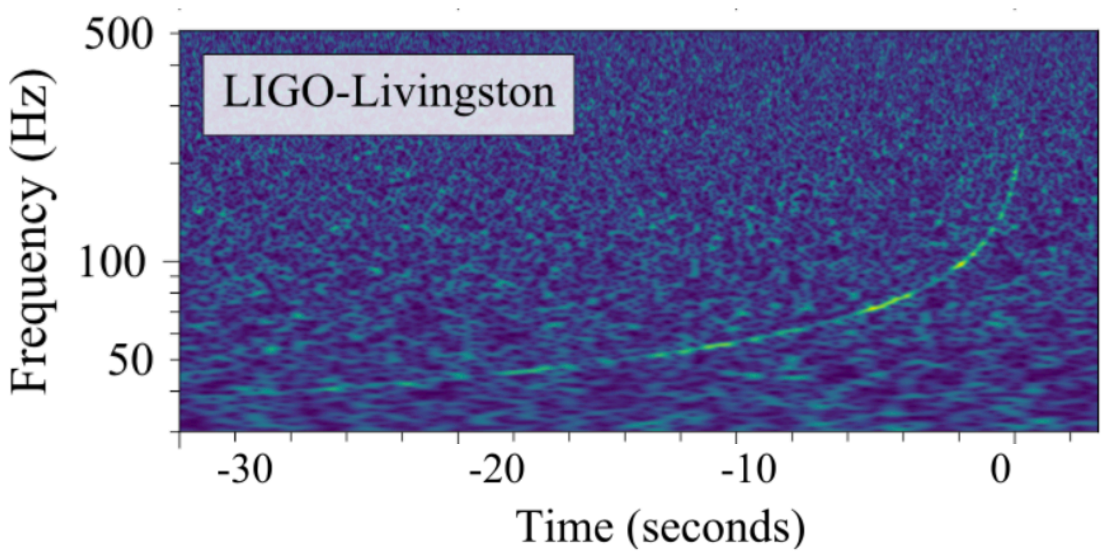
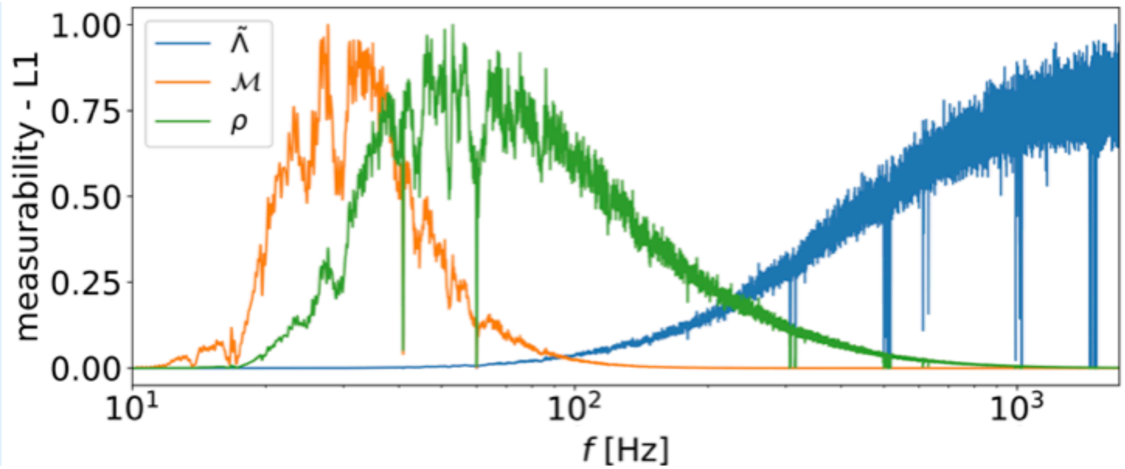


How strong is the effect of tidal deformation?





SD et al., Phys. Rev. Lett. 121, 091102 (2018)

What else is encoded in the gravitational wave data

Parameter space $\vec{\theta}$

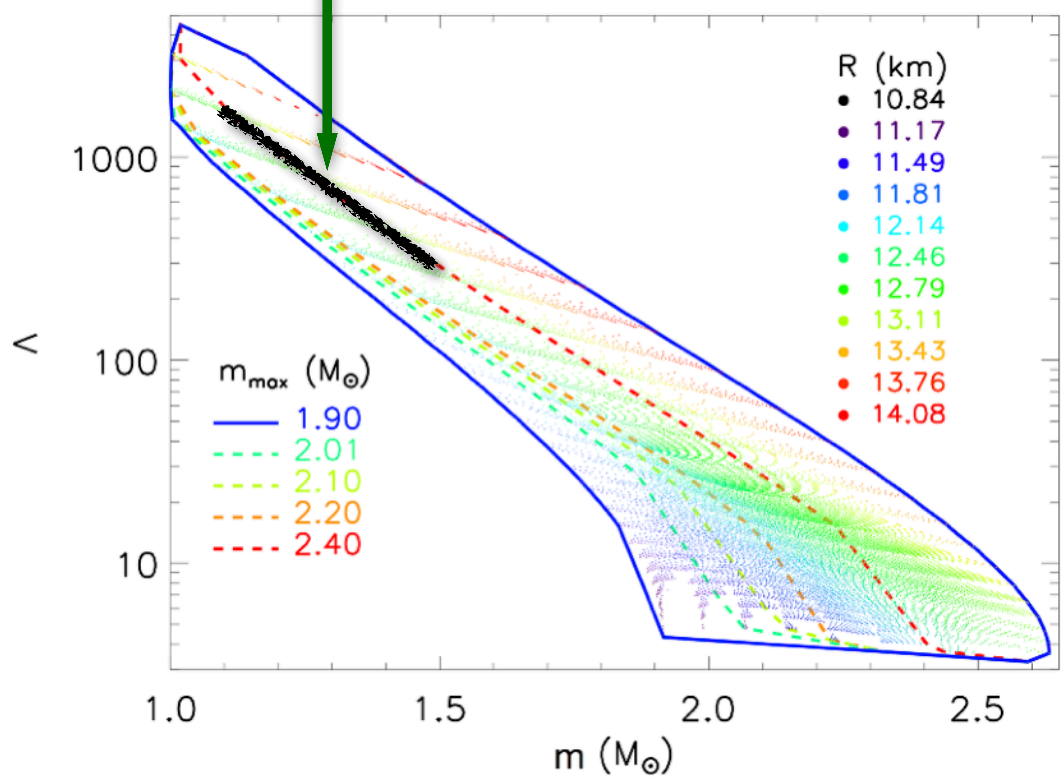
- Component masses : m_1, m_2
- Component spins : $\vec{s_1}, \vec{s_2}$
- Distance to the source : d_L
- Source location and orientation : $\alpha, \delta, \psi, \iota$
- Coalescence time and phase : t_c, ϕ_c
- Component tidal deformabilities : Λ_1, Λ_2

Bayesian inference analysis of GW data to extract these parameters

Common equation of state for GW170817

$\Lambda \propto m^{-6}$

TOV integrations for thousands of physically realistic EOSs



$$\Lambda = a\left(\frac{Gm}{Rc^2}\right)^{-6}$$

Every equation of state allows a very small variation of radius.

$R_1 \simeq R_2$ $\Lambda_1 \simeq q^6 \Lambda_2$

Common EOS constraint

SD et al., Phys. Rev. Lett. 121, 091102 (2018)

Common radius for GW170817

$$\tilde{\Lambda} = \frac{16}{13}\frac{(12q+1)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5}$$

$$\Lambda = a\left(\frac{Gm}{Rc^2}\right)^{-6}$$

$$R_1 \simeq R_2$$

$$\hat{R} = (11.2 \pm 0.2)\frac{\mathcal{M}}{M_\odot}\left(\frac{\tilde{\Lambda}}{800}\right)^{1/6}$$

Common radius

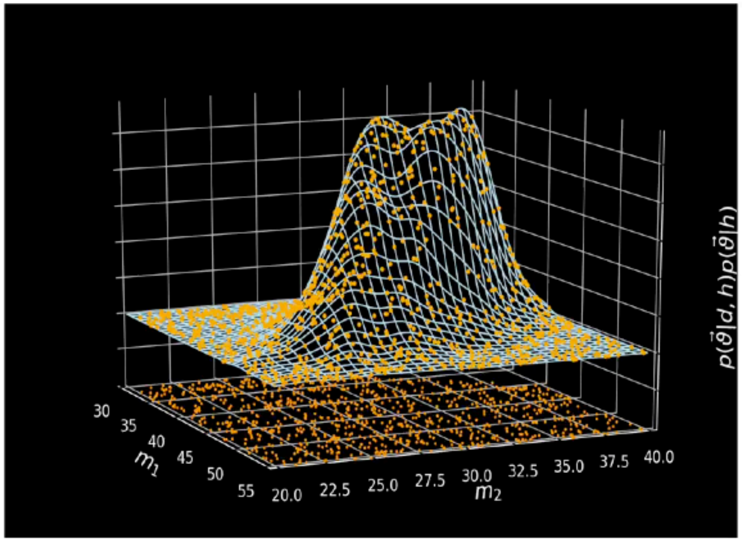
SD et al., Phys. Rev. Lett. 121, 091102 (2018)

How do we extract the parameters?

- We choose a waveform model and we have a noise model for the detectors
- We start with a **Prior** distribution on the parameters of the waveform based on our beliefs about the universe
- We remove our guesses for the gravitational-wave signal from the data, calculate residuals, and ask - how gaussian are the residuals?
  - This our **Likelihood** $\sim \exp\left[-\frac{1}{2}\sum_{i=1}^{N} < d_i - h_i(\theta)|d_i - h_i(\theta) > \right]$
- We then update our beliefs based on the data
  - **Posterior** = **Likelihood** X **Prior**

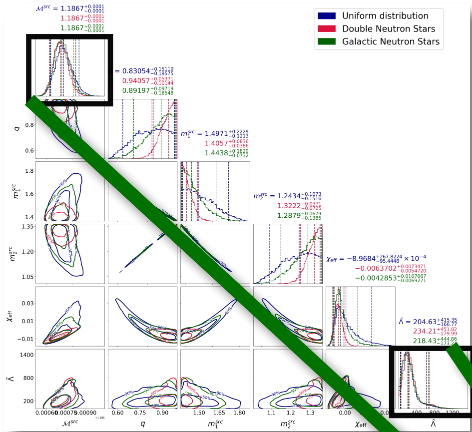
p(physics | data)

Computed using **Markov Chain Monte Carlo**



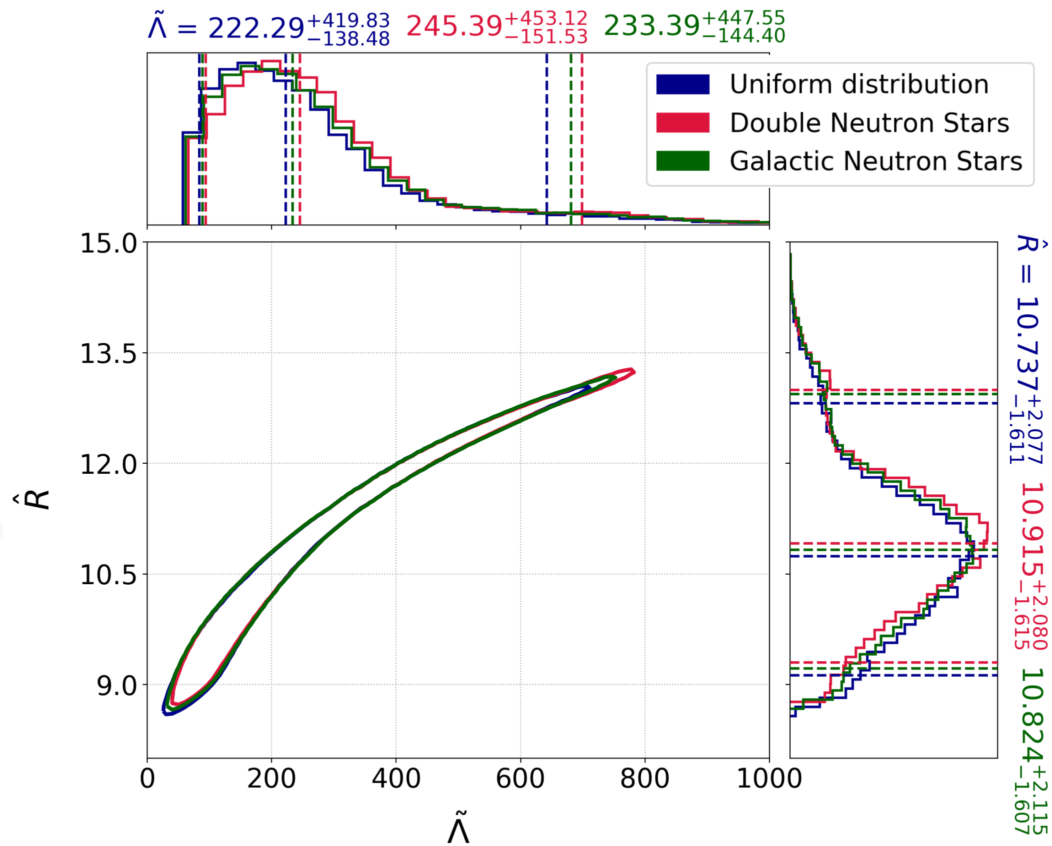
Biwer, Capano, **SD** et al. (2019), PASP 131, 996

Measurement of neutron star tidal deformabilities and radii from GW170817



$$\tilde{\Lambda} < 500$$

$$8.9 < \hat{R} < 13.2 \text{ km}$$



SD et al., Phys. Rev. Lett. 121, 091102 (2018)

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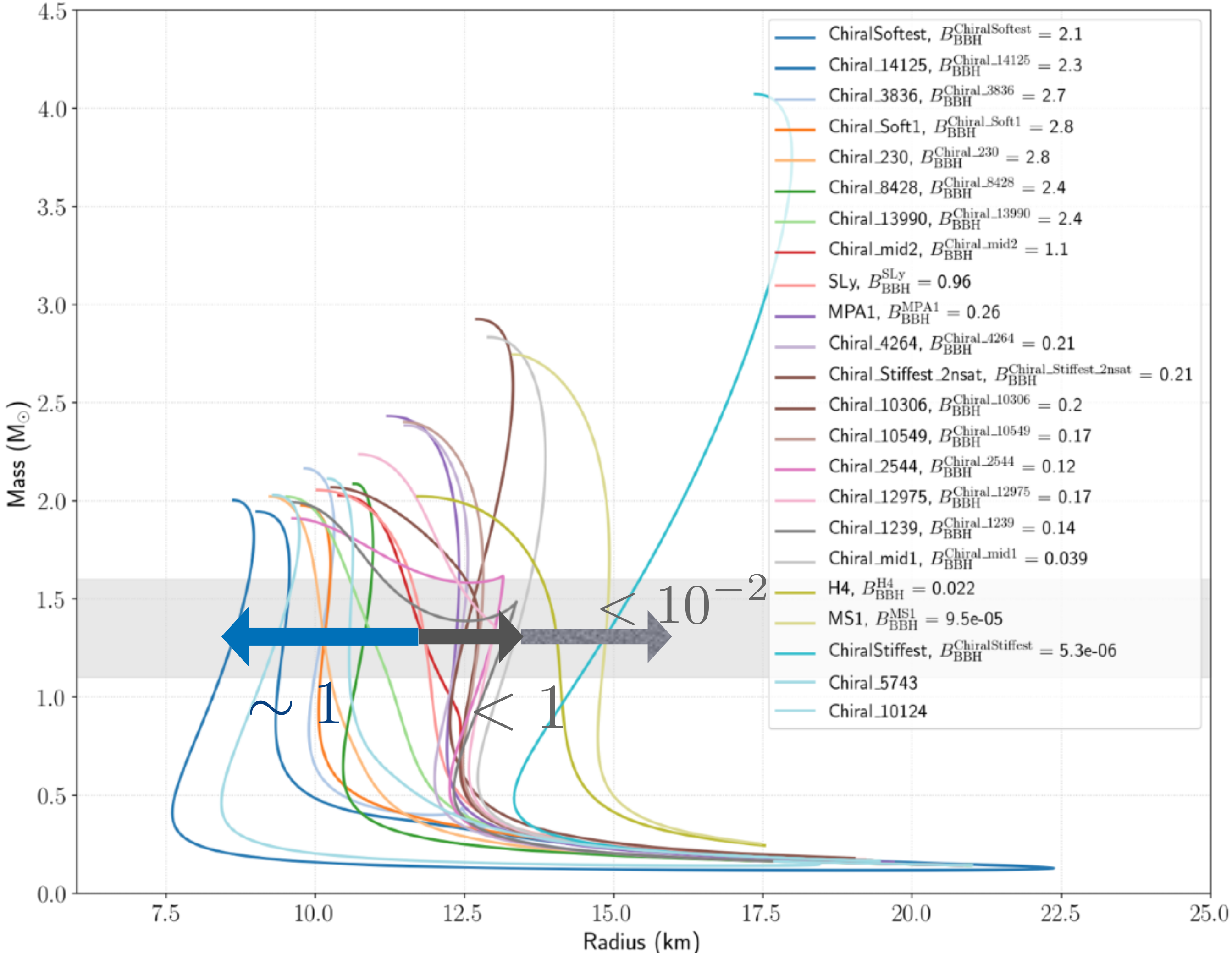
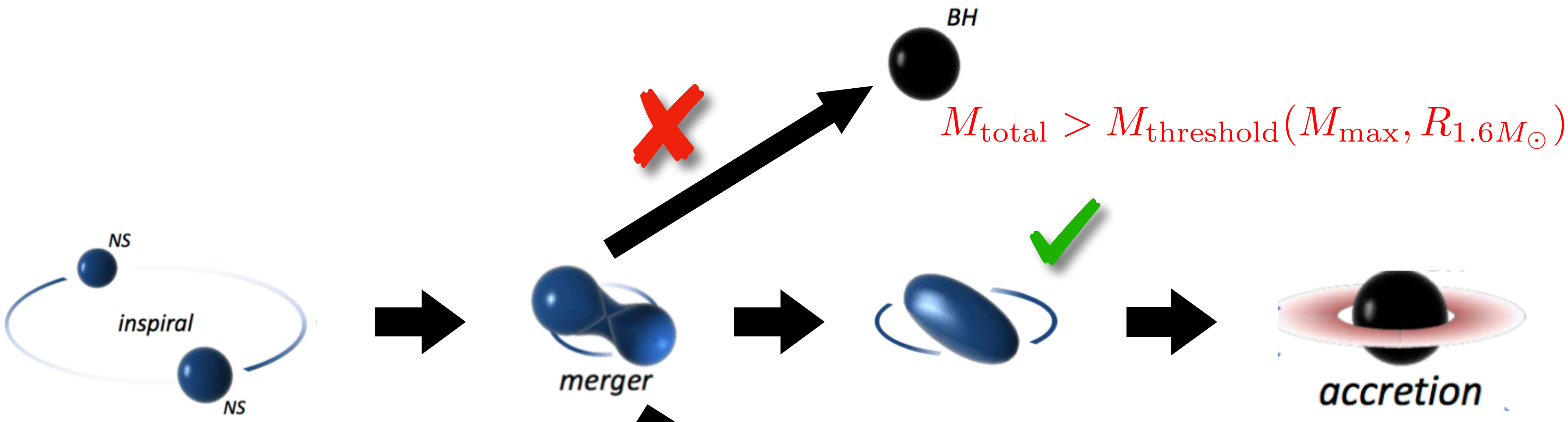
GW170817 constraints on equations of state



For GW170817, gravitational waves alone cannot distinguish between a binary black hole and a binary neutron star merger

See also: Abbott et al 2020, CQG 37 045006

Information from electromagnetic counterparts of GW170817



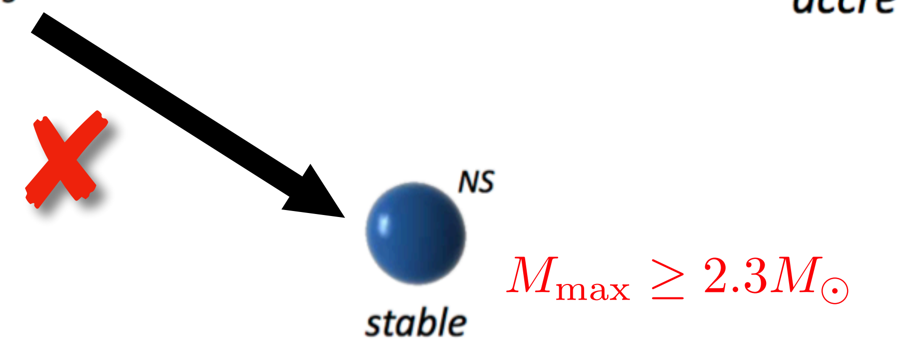
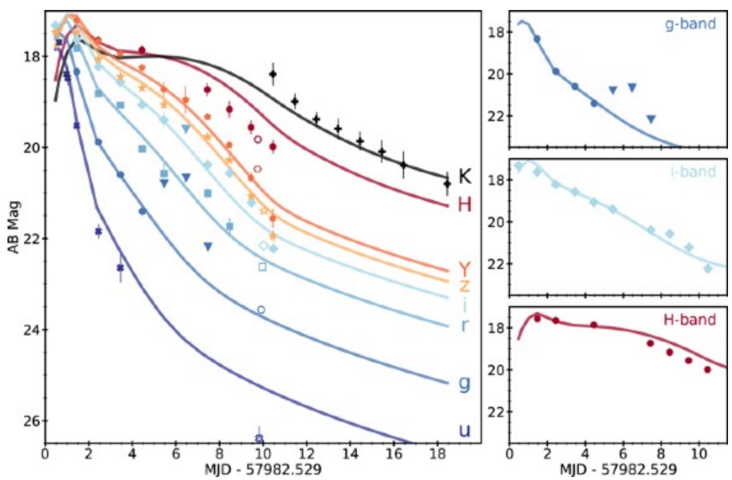
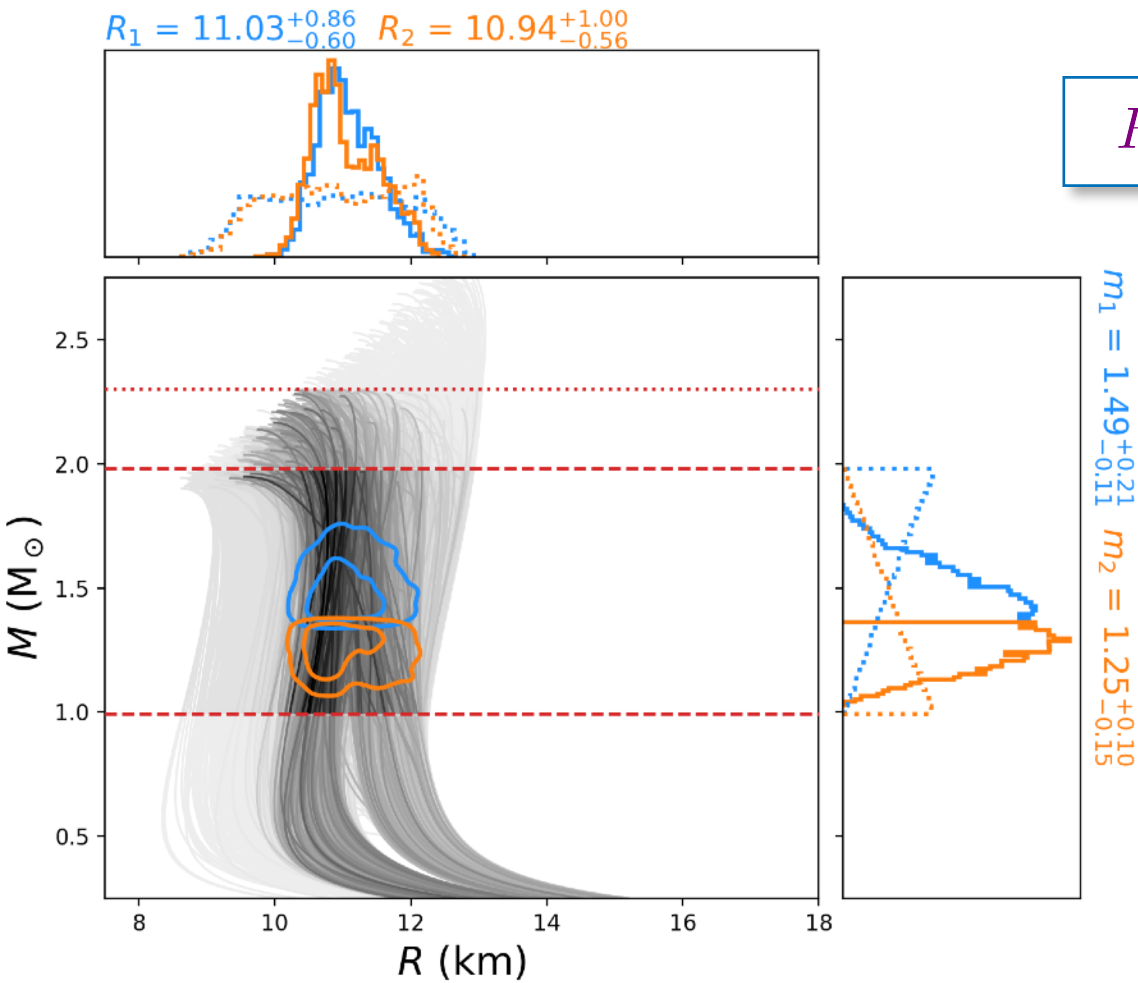


Diagram adapted from: Bartos et al. (2013) CQG 30, 123001



Cowperthwaite et al (2017), ApJL 848 L17

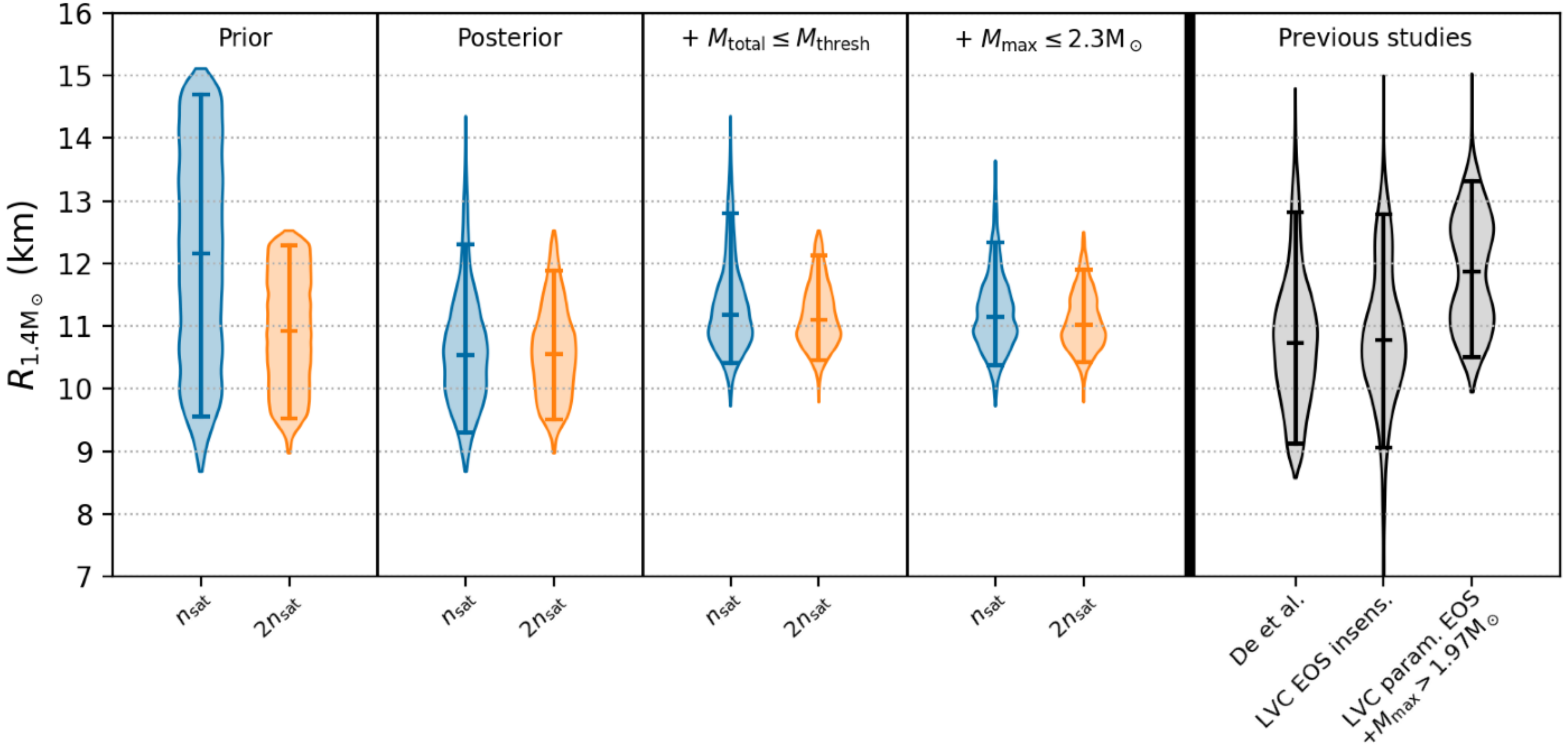
Multimessenger constraints on allowed equations of state



$$R_{1.4} = 11.2^{+1.2}_{-0.8}\ \mathrm{km}$$

Capano, Tews, Brown, Margalit, **SD** et al, Nature Astronomy 4 (2019)

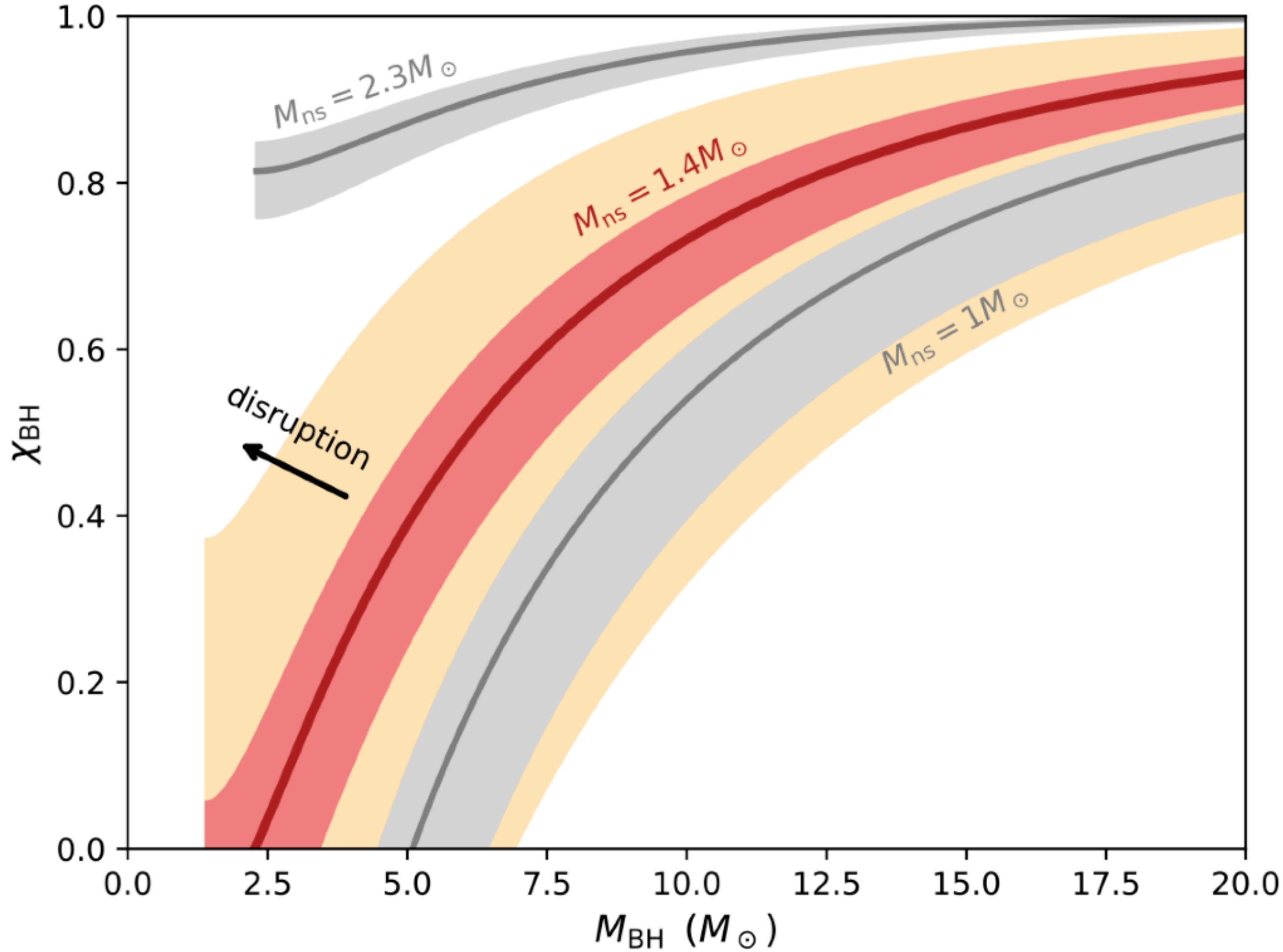
Radius measurements from GW170817 analyses



Capano, Tews, Brown, Margalit, **SD** et al, Nature Astronomy 4 (2019)

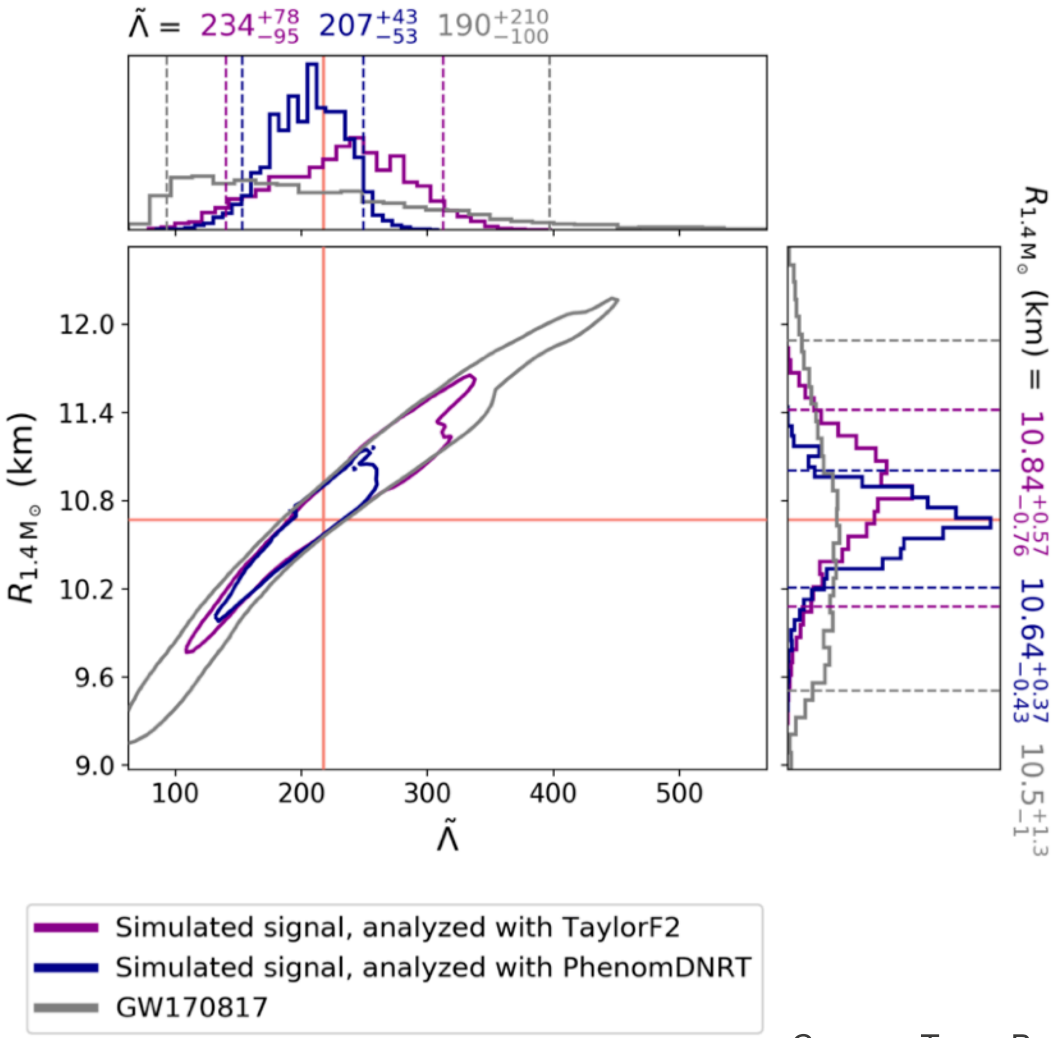
Implications of the radius measurement:

Prospects of observing EM counterparts from a neutron star - black hole merger



Capano, Tews, Brown, Margalit, **SD** et al, Nature Astronomy 4 (2019)

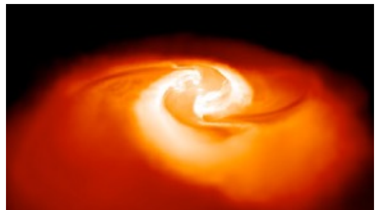
Prospects of improving constraints with future observations



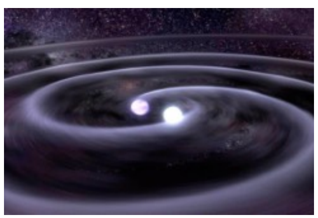
- Using simulated signals at SNR ~100 we find ~2.9x improvement in measurement uncertainty
- Gravitational waves alone will be able to constrain upper and lower bounds of tidal deformability and radii for high SNR signals
- Low SNR signals would need combination of information from GW + EM + nuclear theory

Capano, Tews, Brown, Margalit, **SD** et al, Nature Astronomy 4 (2019)

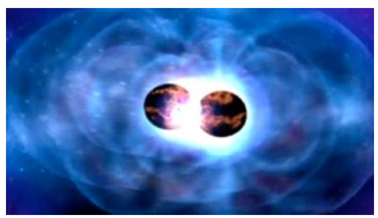
Aftermath of neutron star mergers



Production of kilonovae:
Radioactive transients powered by *r*-process decay



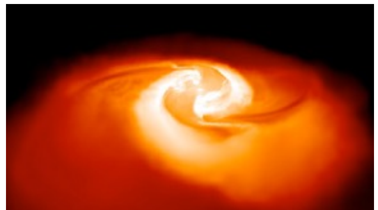
tidal tail ejecta



shock heated polar ejecta

disk wind ejecta

Aftermath of neutron star mergers



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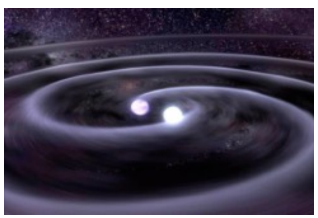

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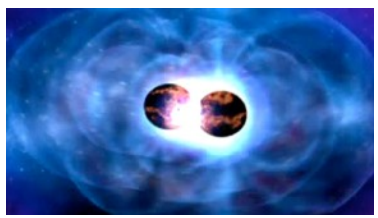

shock heated polar ejecta

disk wind ejecta

GRMHD simulations of remnant accretion disks for different merger scenarios

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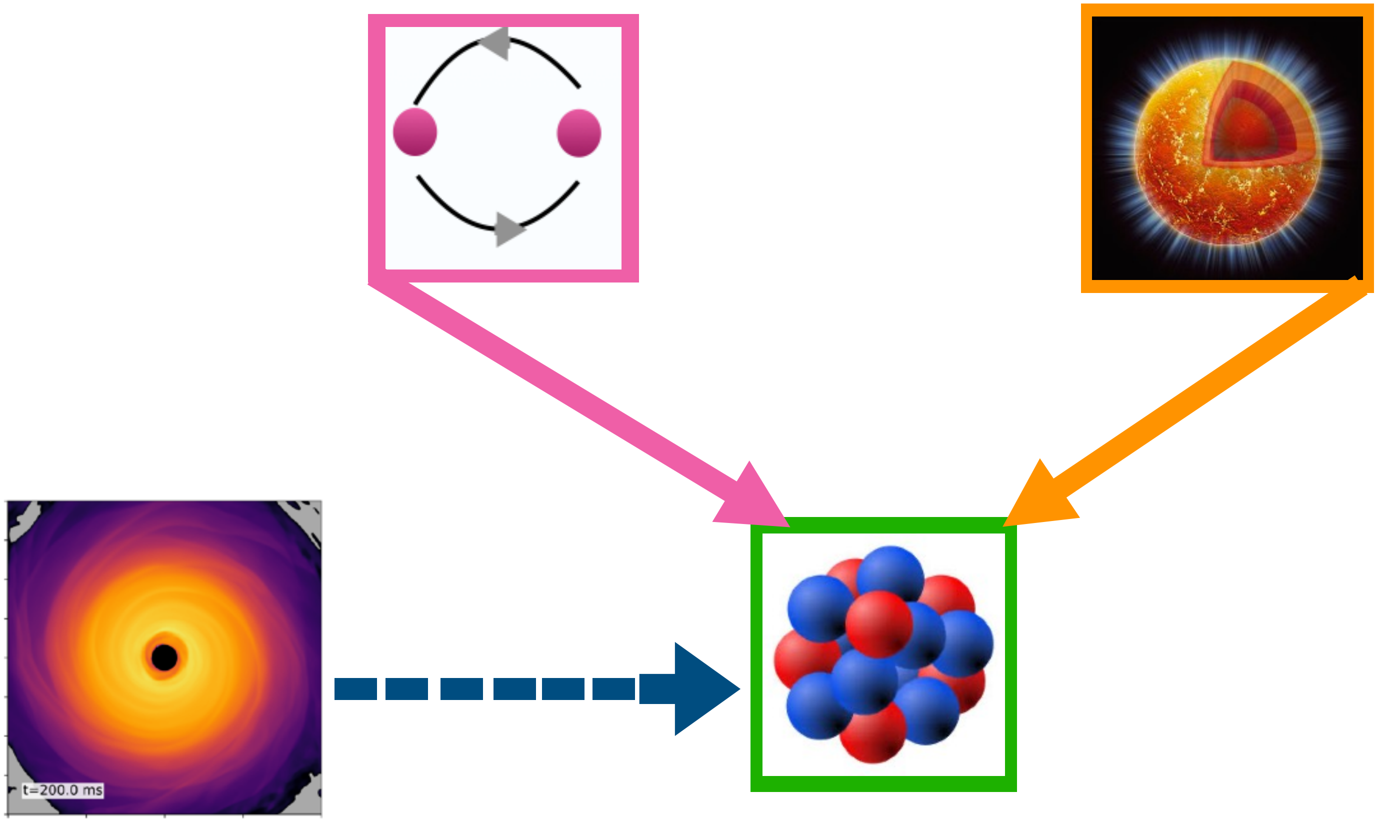
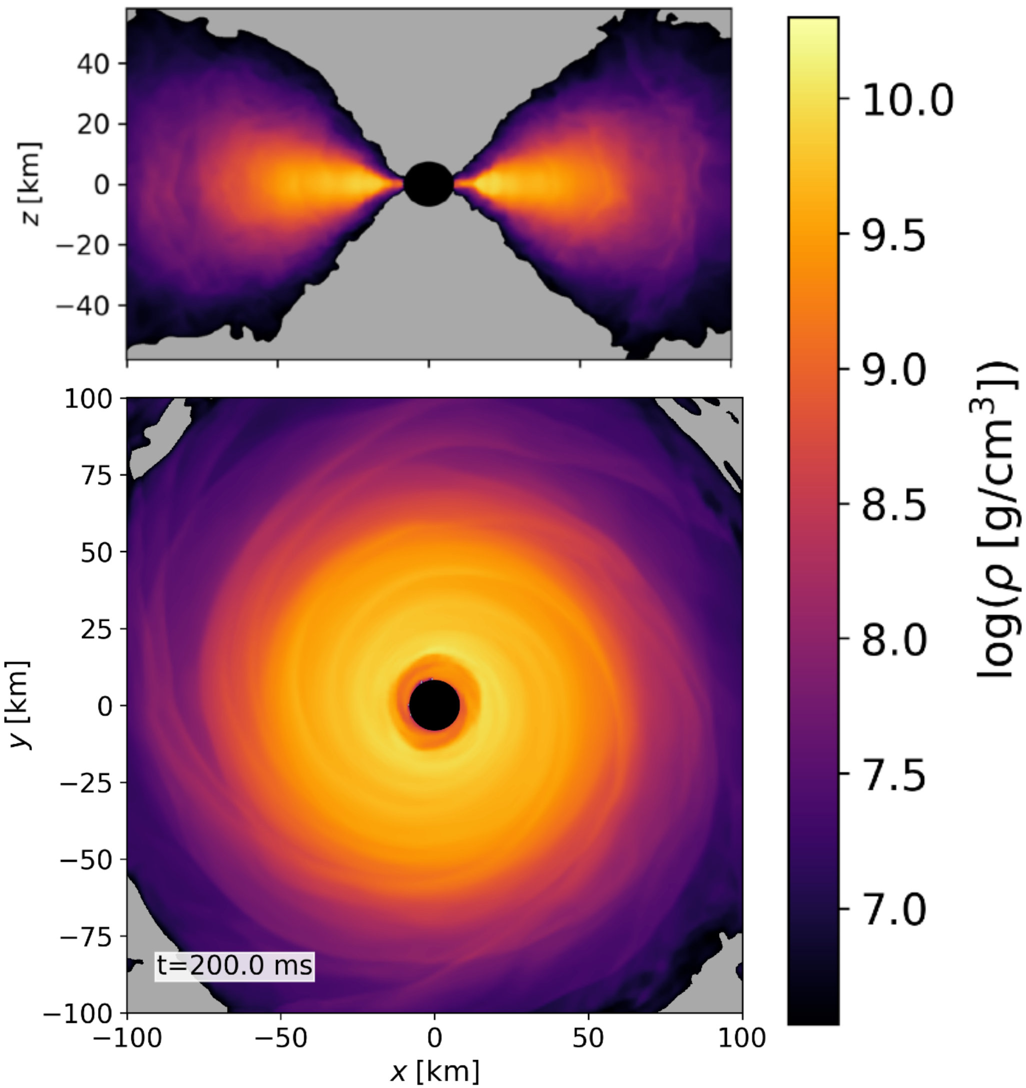
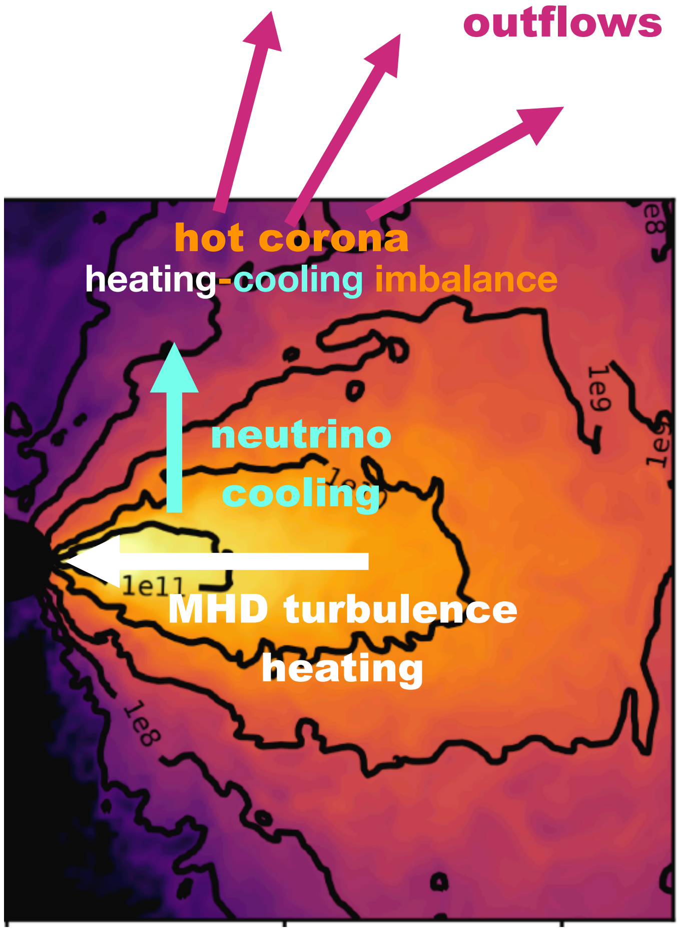
Initial conditions for nucleosynthesis



Postmerger accretion disk dynamics





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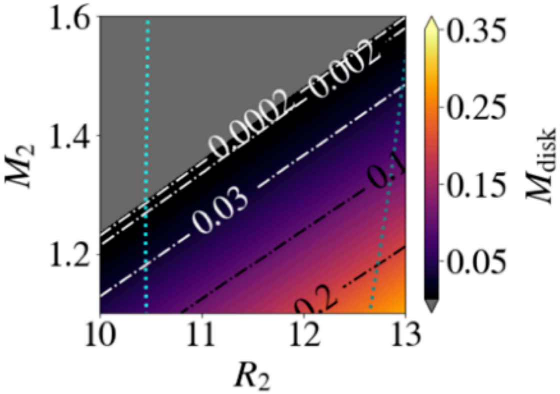
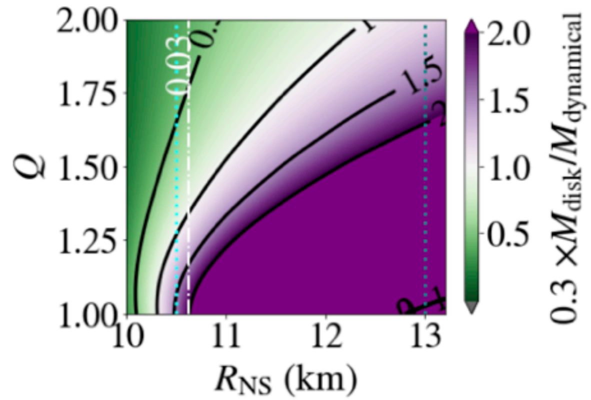
Parameter space for binary neutron star mergers

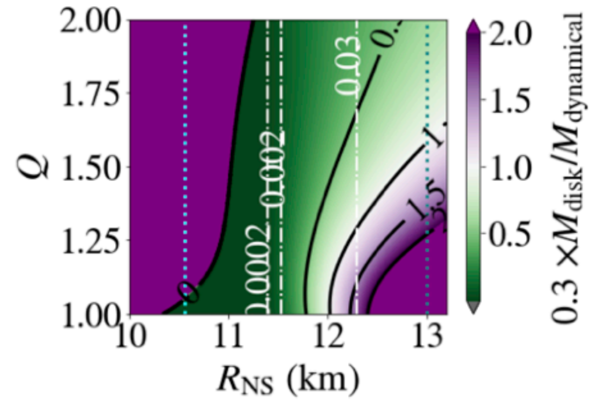
disk mass increases



disk mass increases



$M_2 = 1.2\ M_\odot$

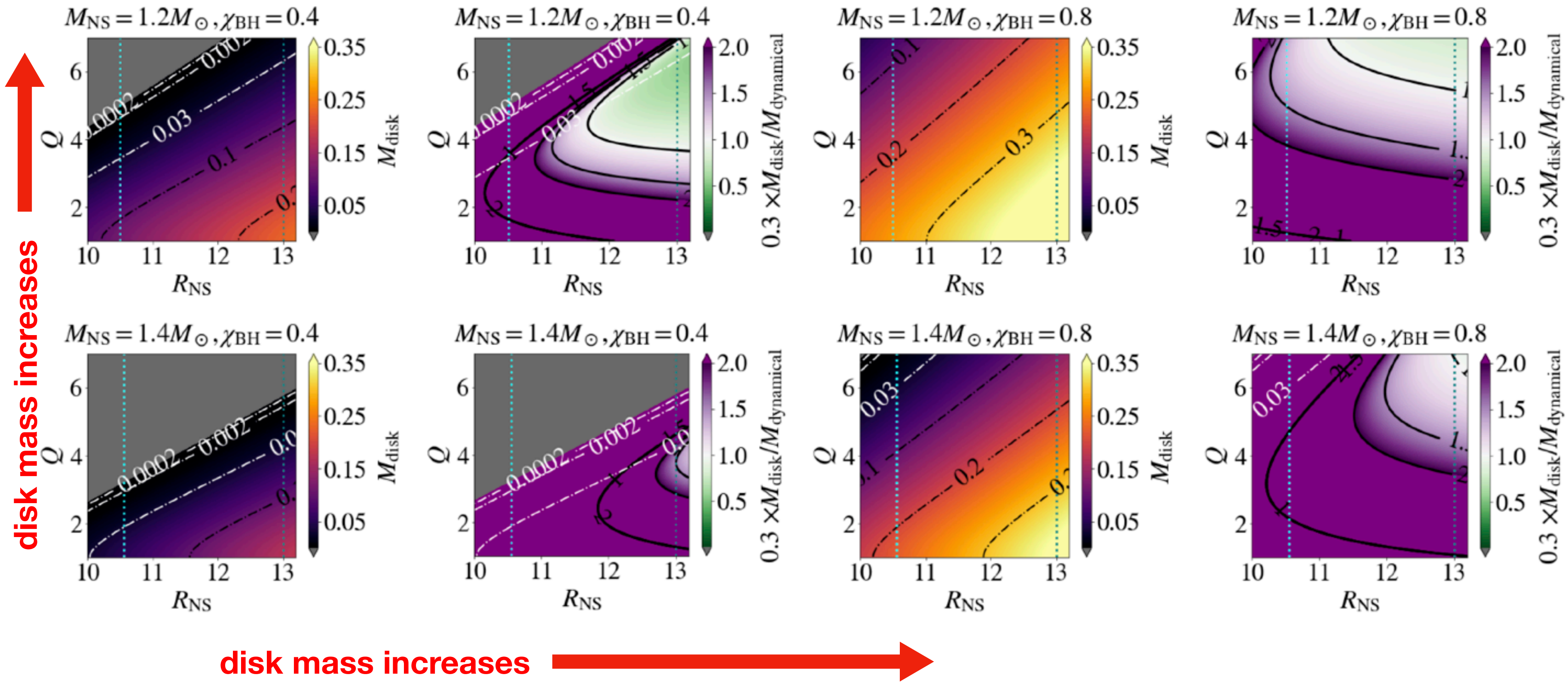


$M_2 = 1.4\ M_\odot$

SD & Siegel, arxiv:2011.07176 (2020)

Based on fitting relations from Kruger & Foucart (2020) & Foucart et al (2018)

Parameter space for neutron star black hole mergers



SD & Siegel, arxiv:2011.07176 (2020)

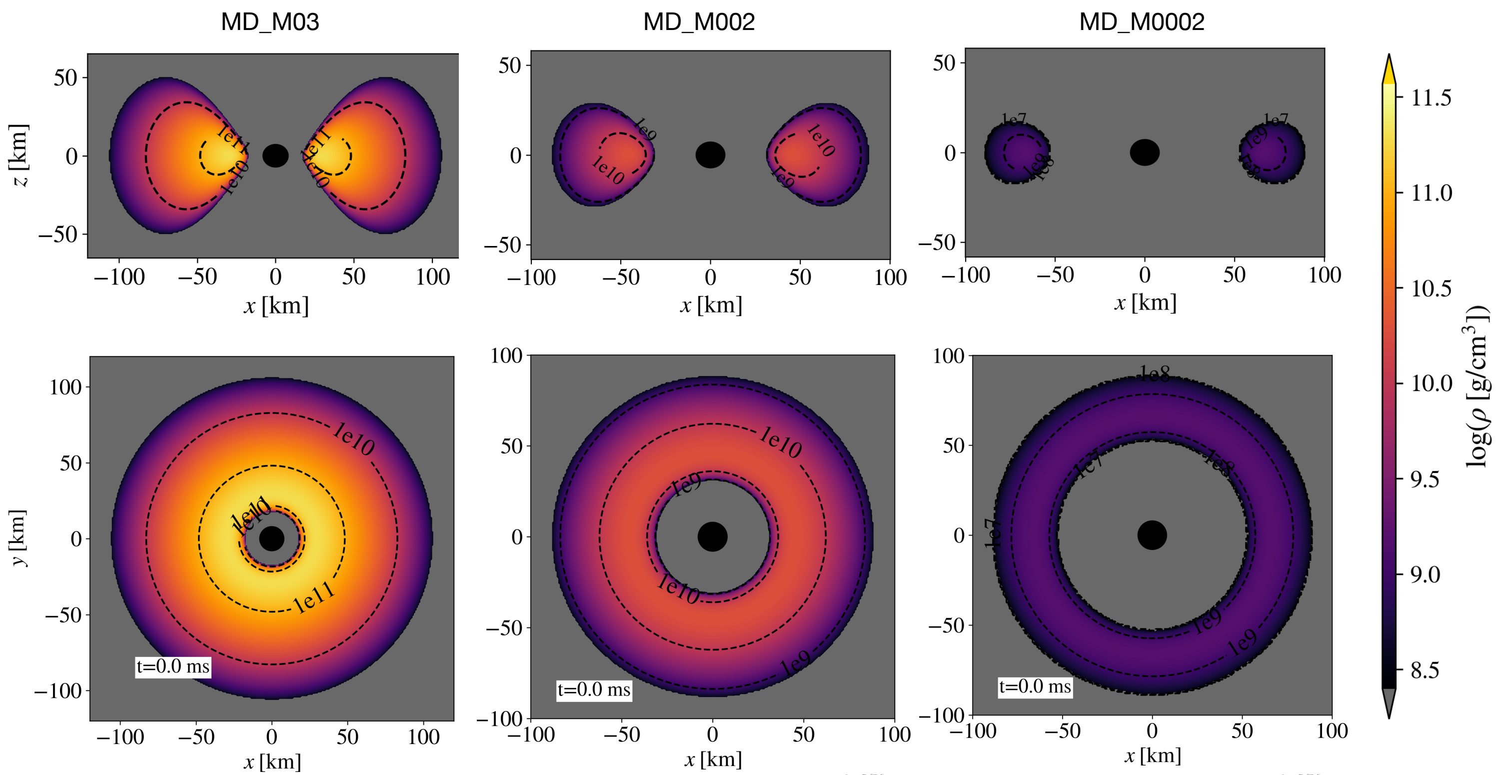
Based on fitting relations from Kruger & Foucart (2020)

Simulation setup

Remnant black hole:
$M_{\mathrm{BH}} = 3M_{\odot}, \chi_{\mathrm{BH}} = 0.8$

+

Accretion disk:
constant specific angular momentum
constant specific entropy: $8k_B/b$
electron fraction: 0.1



$M_{\mathrm{disk}} = 0.03M_{\odot}$ | $M_{\mathrm{disk}} = 0.002M_{\odot}$ | $M_{\mathrm{disk}} = 0.0002M_{\odot}$

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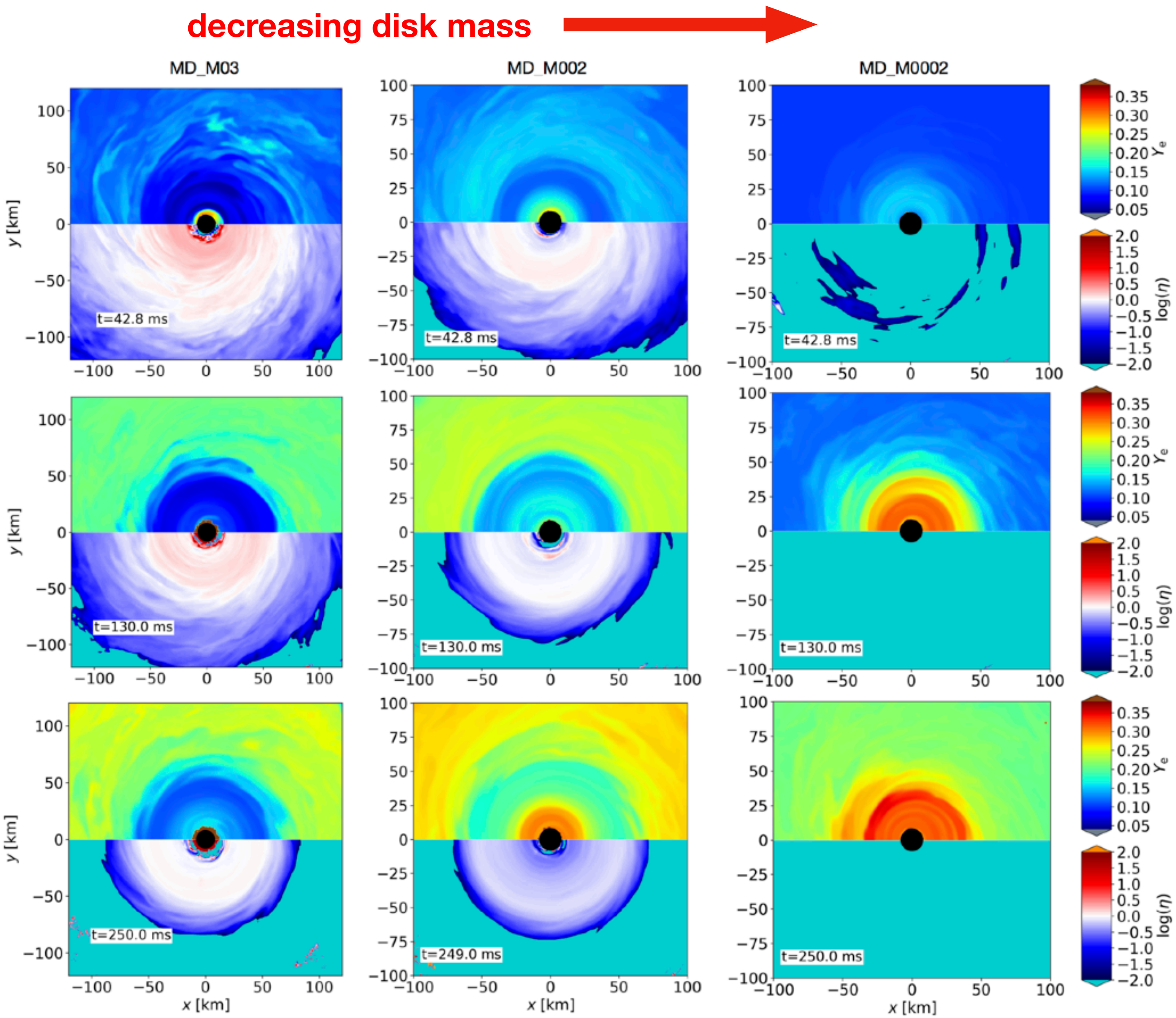
Simulation results: Disk physics across the parameter space

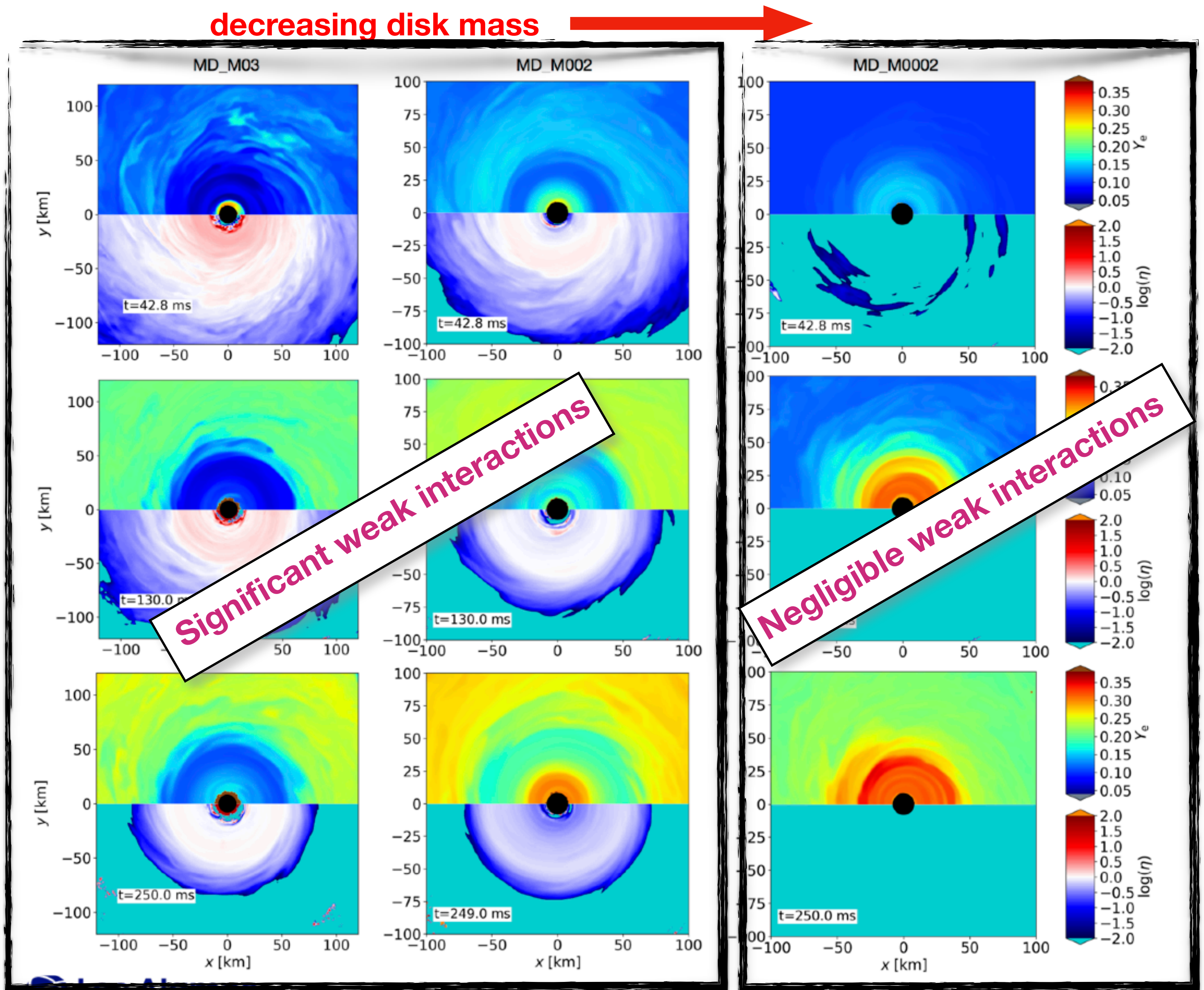


MD_M03 and MD_M002: lower electron fraction in inner disk, higher electron fraction in outer disk

MD_M0002: higher electron fraction in inner disk, lower electron fraction in outer disk

SD & Siegel, arxiv:2011.07176 (2020)

Simulation results: Disk physics across the parameter space

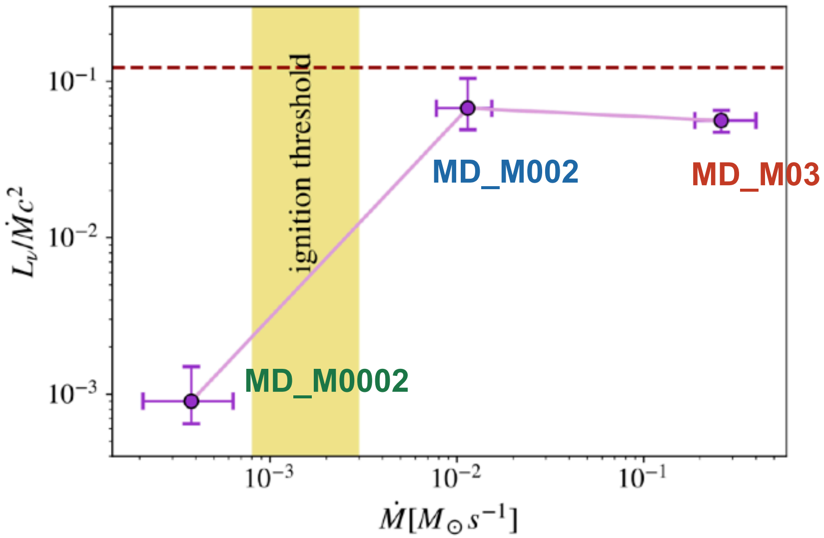


MD_M03 and MD_M002: lower electron fraction in inner disk, higher electron fraction in outer disk

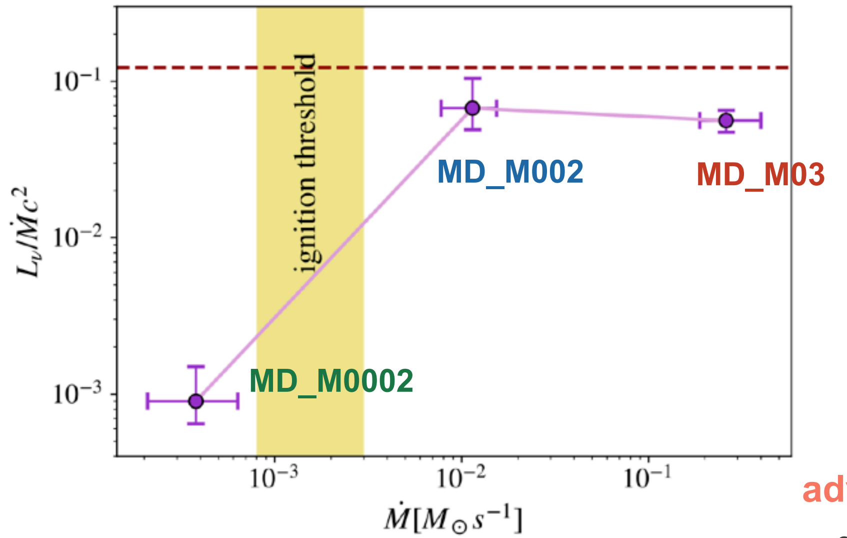
MD_M0002: higher electron fraction in inner disk, lower electron fraction in outer disk

SD & Siegel, arxiv:2011.07176 (2020)

Ignition of weak interactions



Outflow properties: velocity distributions

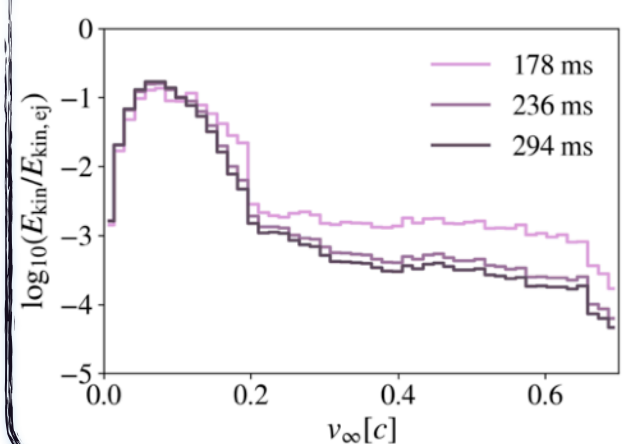


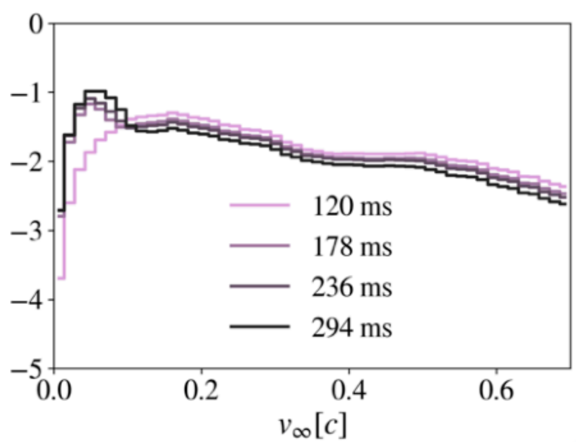
neutrino cooled

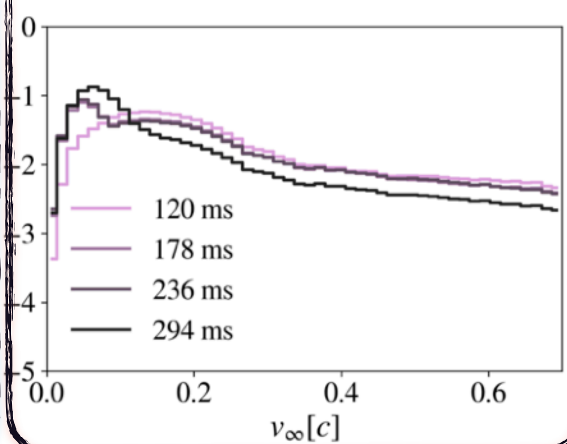
~30-50% material ejected

advection heating dominated

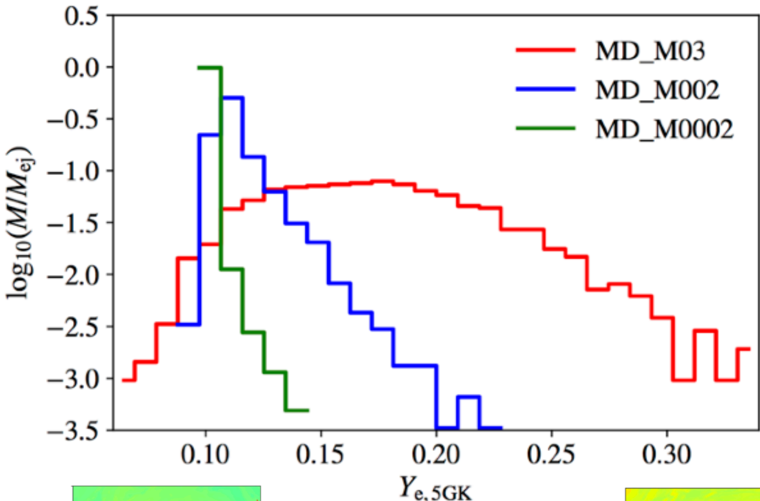
~60% material ejected

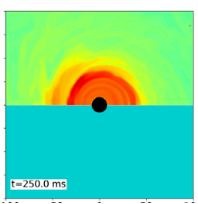


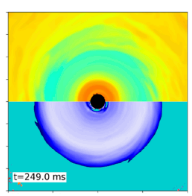


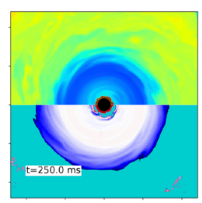


Outflow properties: nucleosynthetic yields







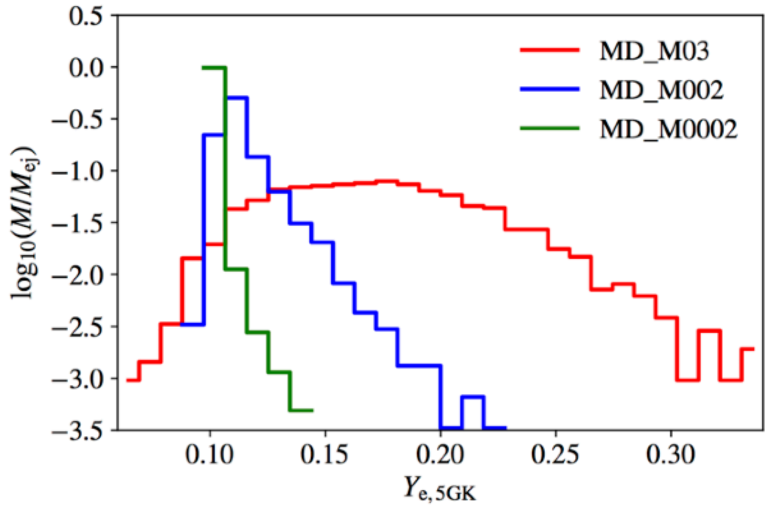


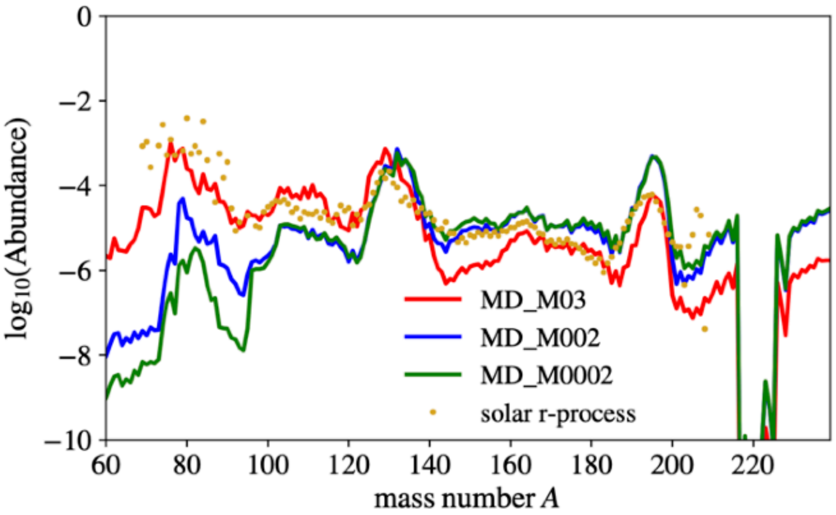
Negligible weak interactions

Significant weak interactions

SD & Siegel, arxiv:2011.07176 (2020)

Outflow properties: nucleosynthetic yields

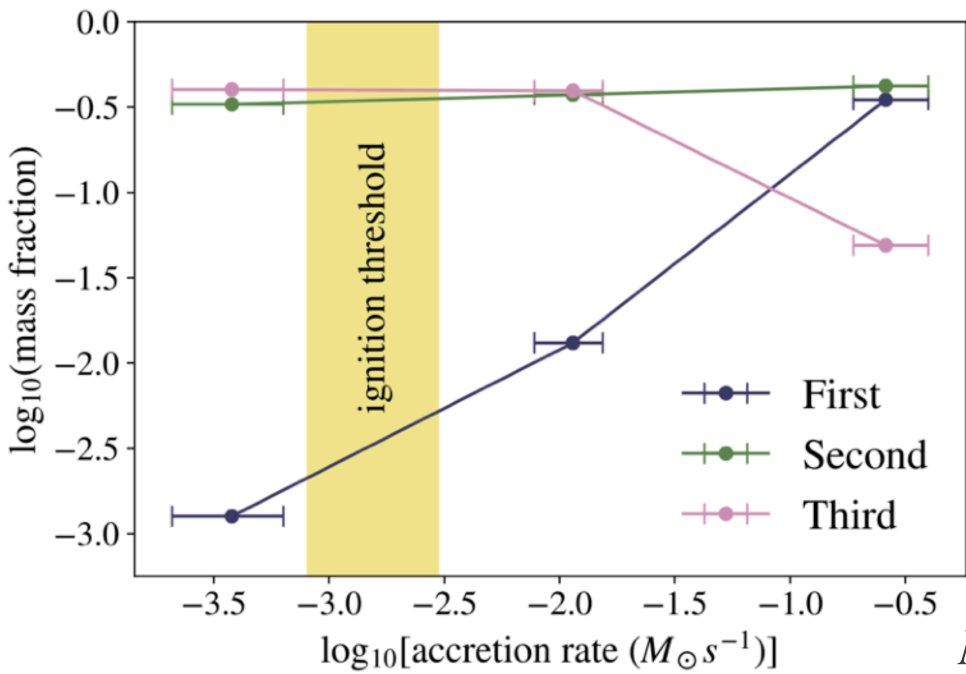


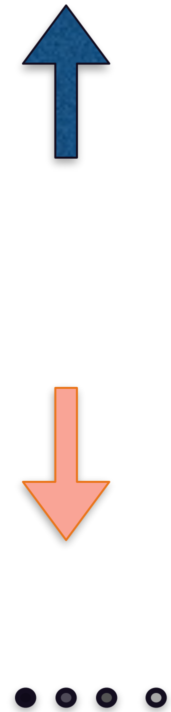


- All disk models produce neutron rich material
- Highest disk mass model also produce proton rich material due to
  - Fast protonization of outer disk
  - Strong neutrino emission changing ejecta composition

SD & Siegel, arxiv:2011.07176 (2020)

Outflow properties: nucleosynthetic yields





$M_\odot$ **increased**

Trends may continue for larger disk masses.

See Miller et al (2019)

SD & Siegel, arxiv:2011.07176 (2020)

Conclusions

- GW170817 told us that neutron star mergers can indeed be used to study the nature of nuclear matter and these mergers are sites for r-process nucleosynthesis
- Multimessenger observations of GW170817 constrain the neutron star radii to an uncertainty of at least 2.4km eliminating many equations of state in nuclear physics
- In the next decade, with increasing detector sensitivity, gravitational waves will be able to place confident constraints on both lower and upper bounds of neutron star radius and tidal deformability
- There exists an ignition threshold in the parameter space of neutron star postmerger accretion disks, $\sim 10^{-3} M_{\odot} s^{-1}$, that separates two distinct regimes (neutrino cooled and advection heating dominated)
- Accretion disks around the ignition threshold produce heavy r-process elements. Lighter r-process elements are underproduced as disk mass is tuned down. Massive disks required for strong blue kilonova components from accretion disks

Thank you for your attention!

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Image credit: NASA & ESA