

Discovery of the First Optical Counterpart to a Gravitational Wave Source and Neutron Star Equation of State



Ryan Foley < UC Santa Cruz > 1M2H Team

SSS17a

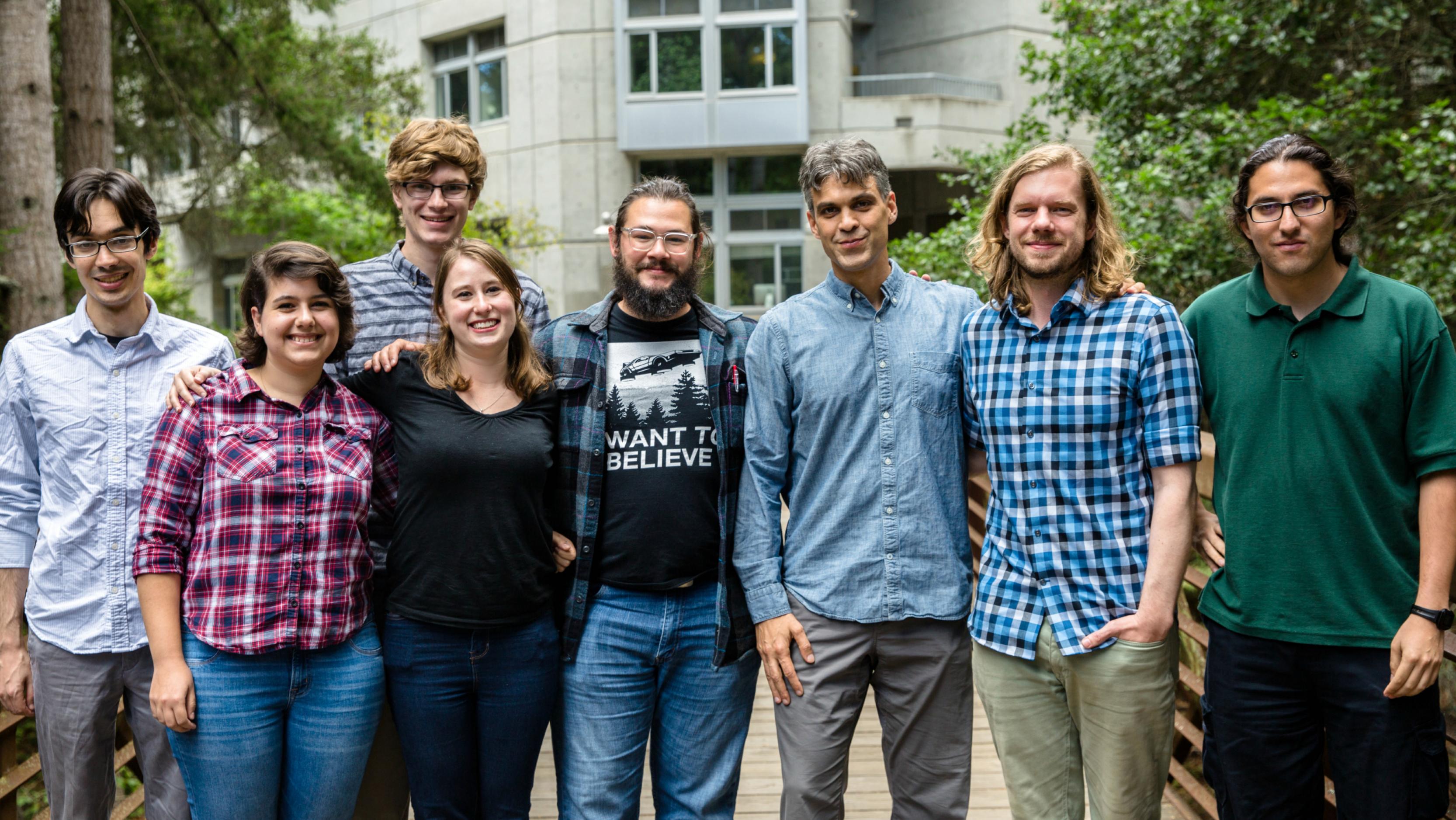


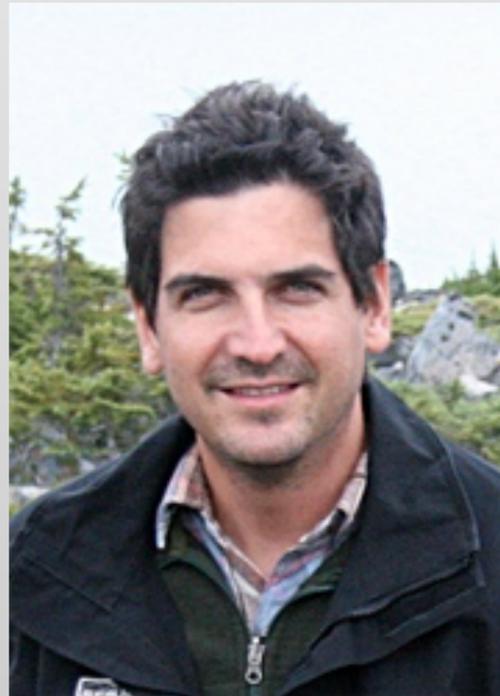
2017 August 17



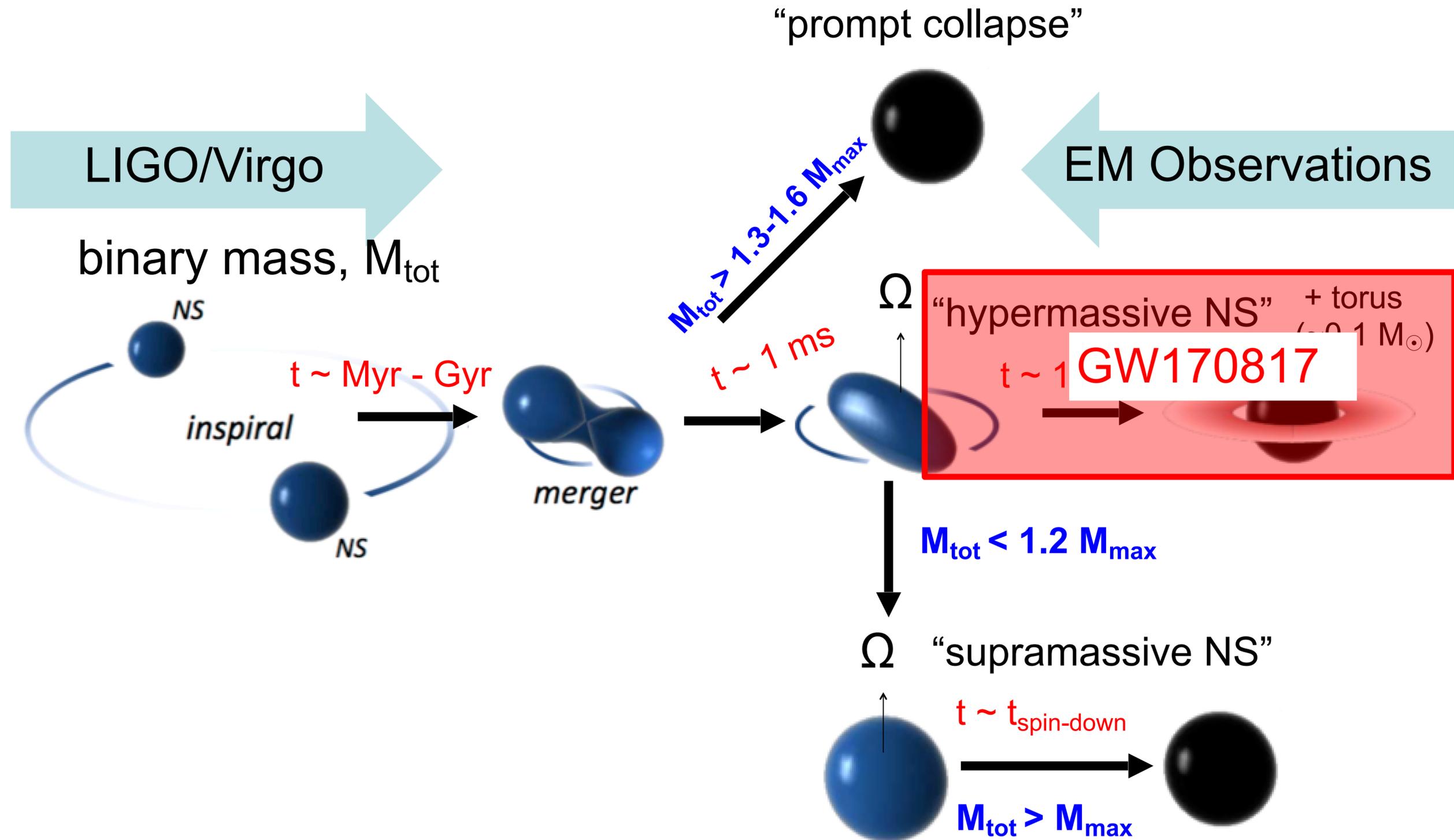
2017 August 21

Swope & Magellan Telescopes

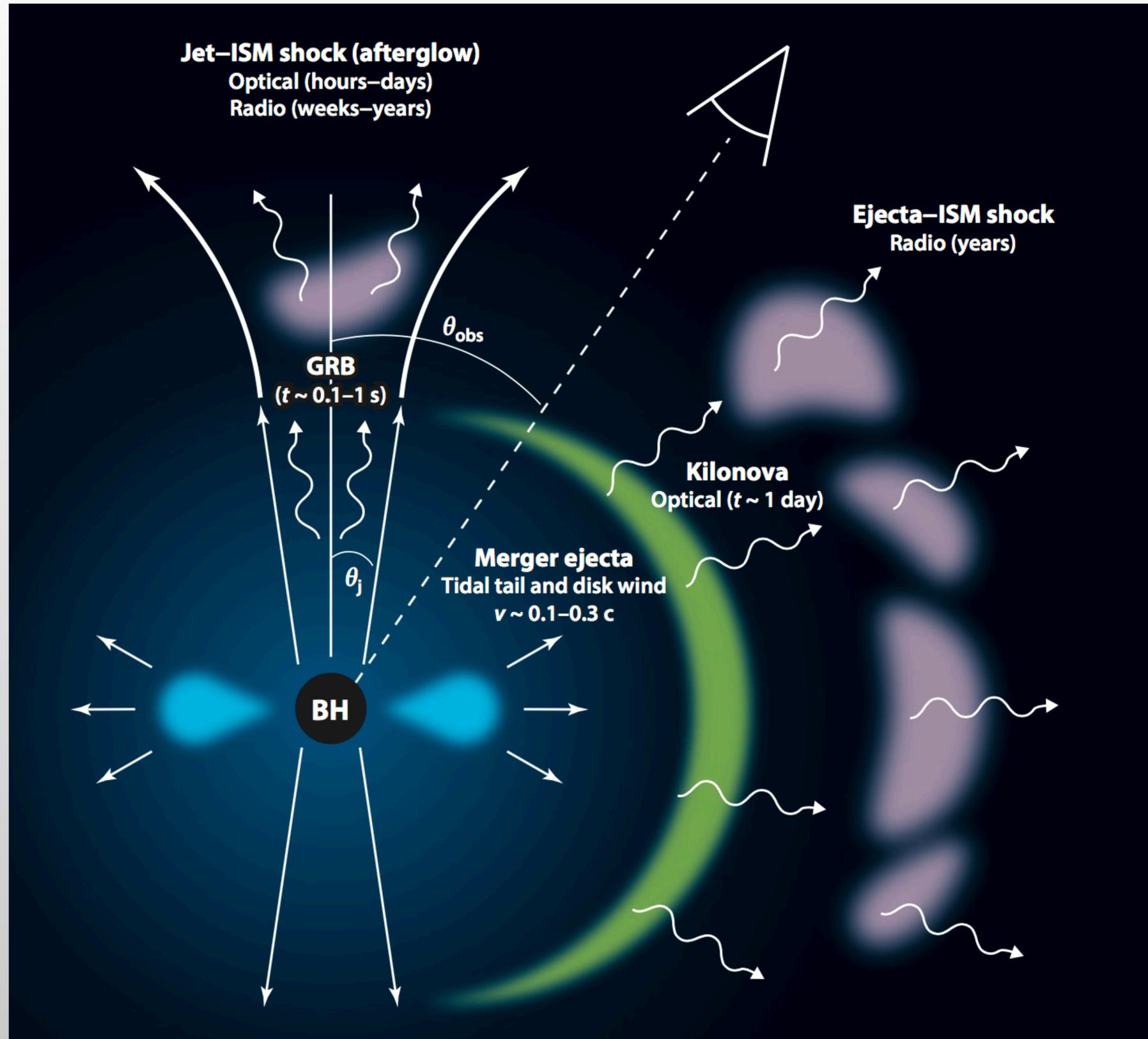




Outcomes of Neutron Star Mergers



What are the EM Counterparts?



Metzger &
Berger 2012

Neutron-Rich Ejecta

“Dynamical”

$$M_{\text{ej}} \sim 10^{-3} - 10^{-2} M_{\odot}$$

$$t_{\text{exp}} \sim \text{milliseconds}$$

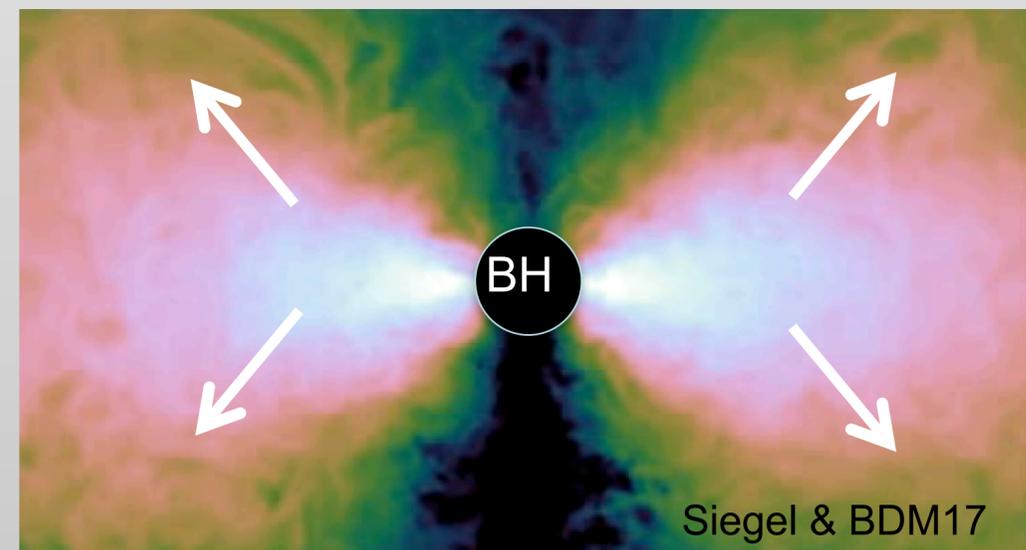
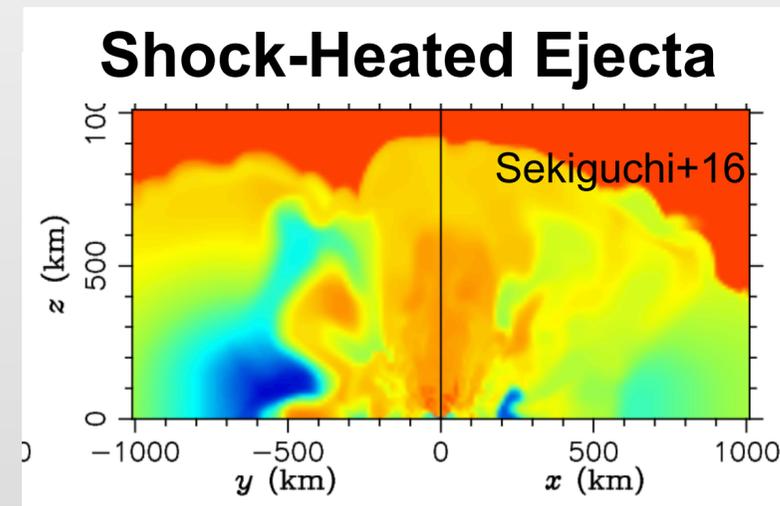
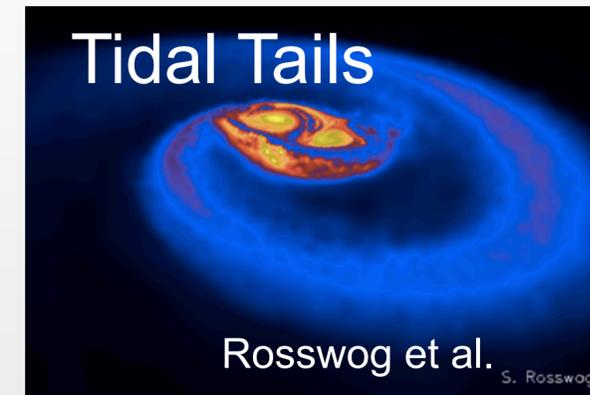
$$v_{\text{ej}} \sim 0.3 c$$

Disk Winds

$$M_{\text{ej}} \sim 10^{-2} - 10^{-1} M_{\odot}$$

$$t_{\text{exp}} \sim \text{seconds}$$

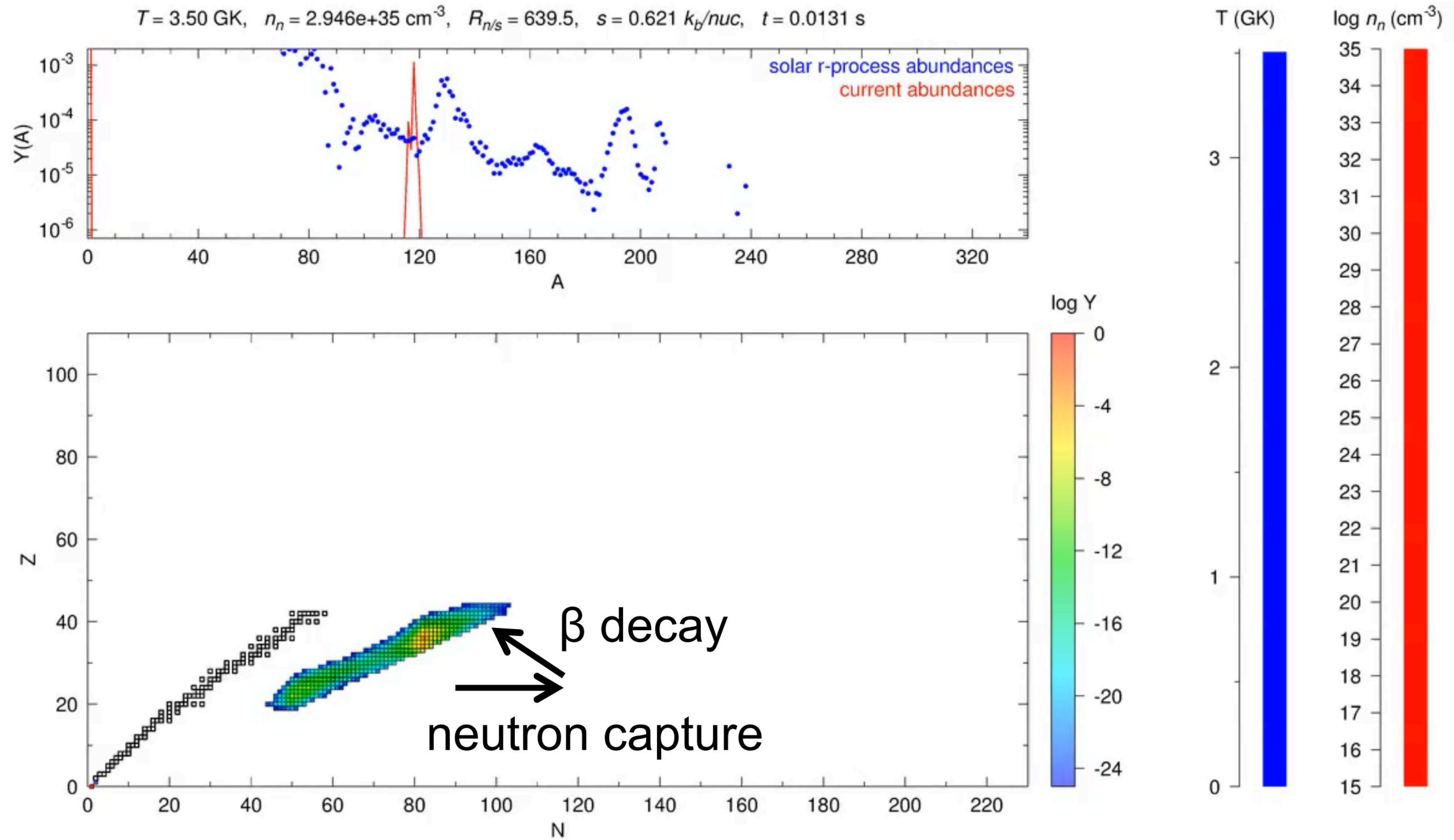
$$v_{\text{ej}} \sim 0.1 c$$



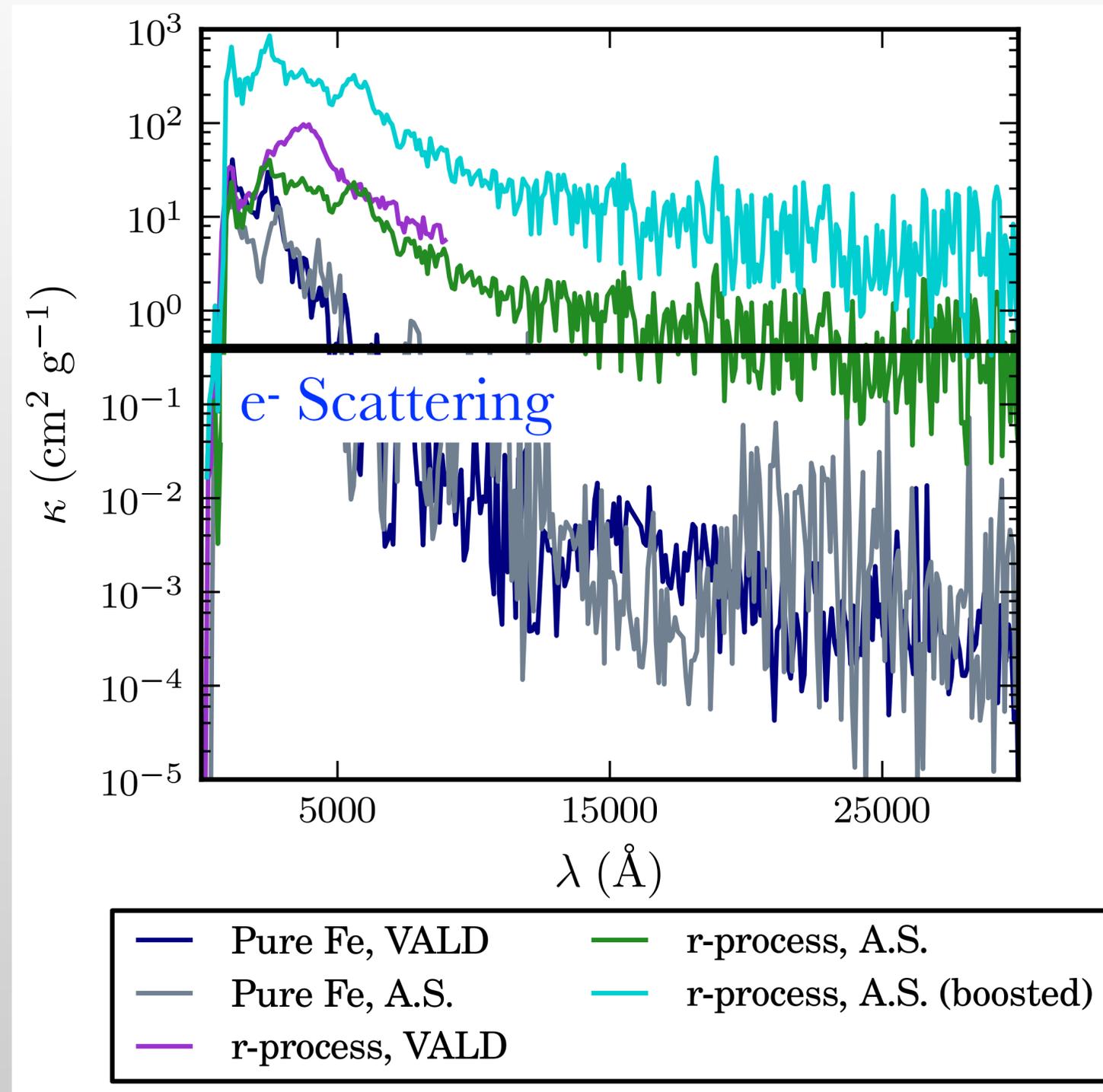
time



R-Process Network (neutron captures, photo-dissociations, α - and β -decays, fission)

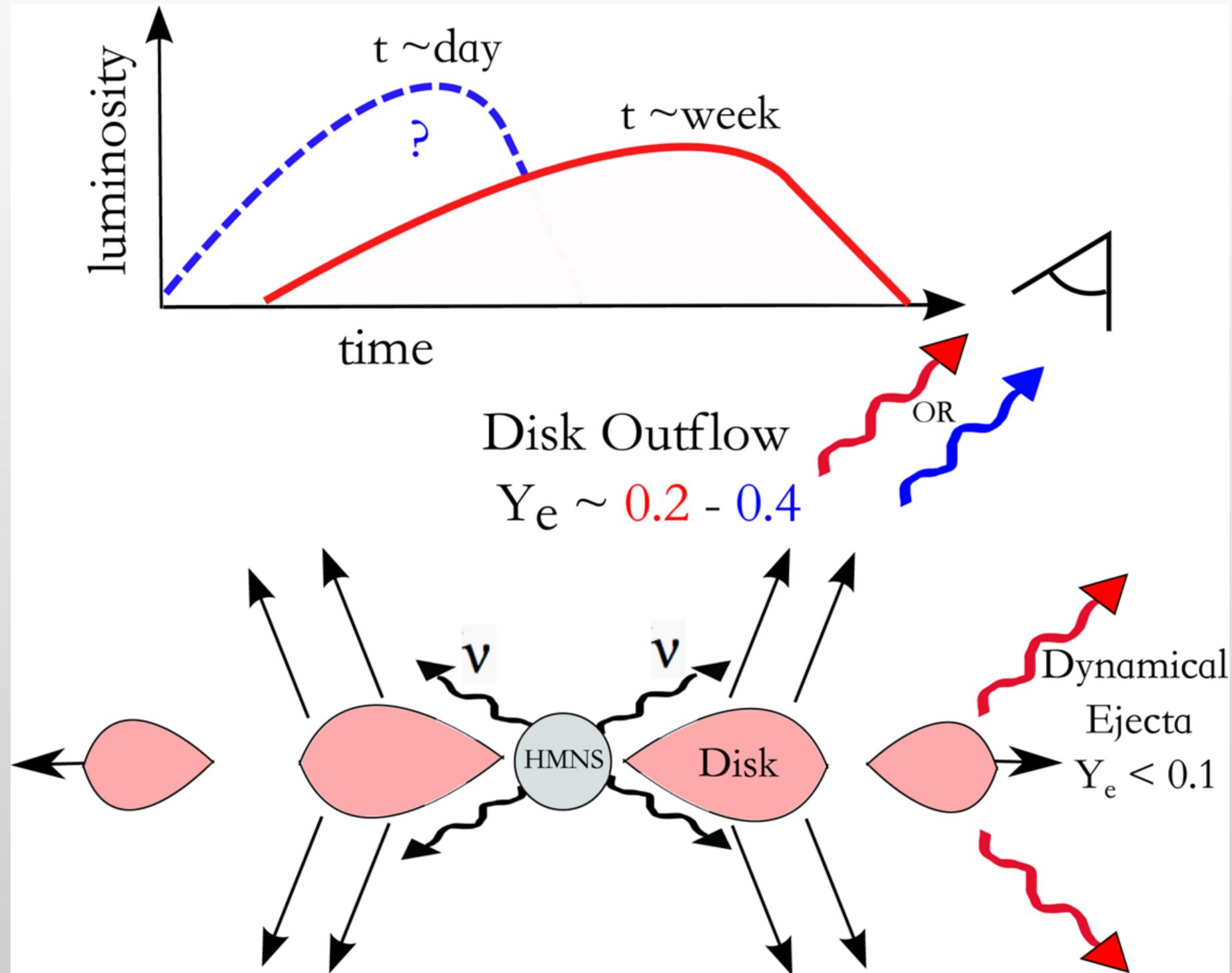


Lanthanides Have Very High Opacities



Kasen, Badnell, & Barnes 2013

Fast Blue and Slower Red Components

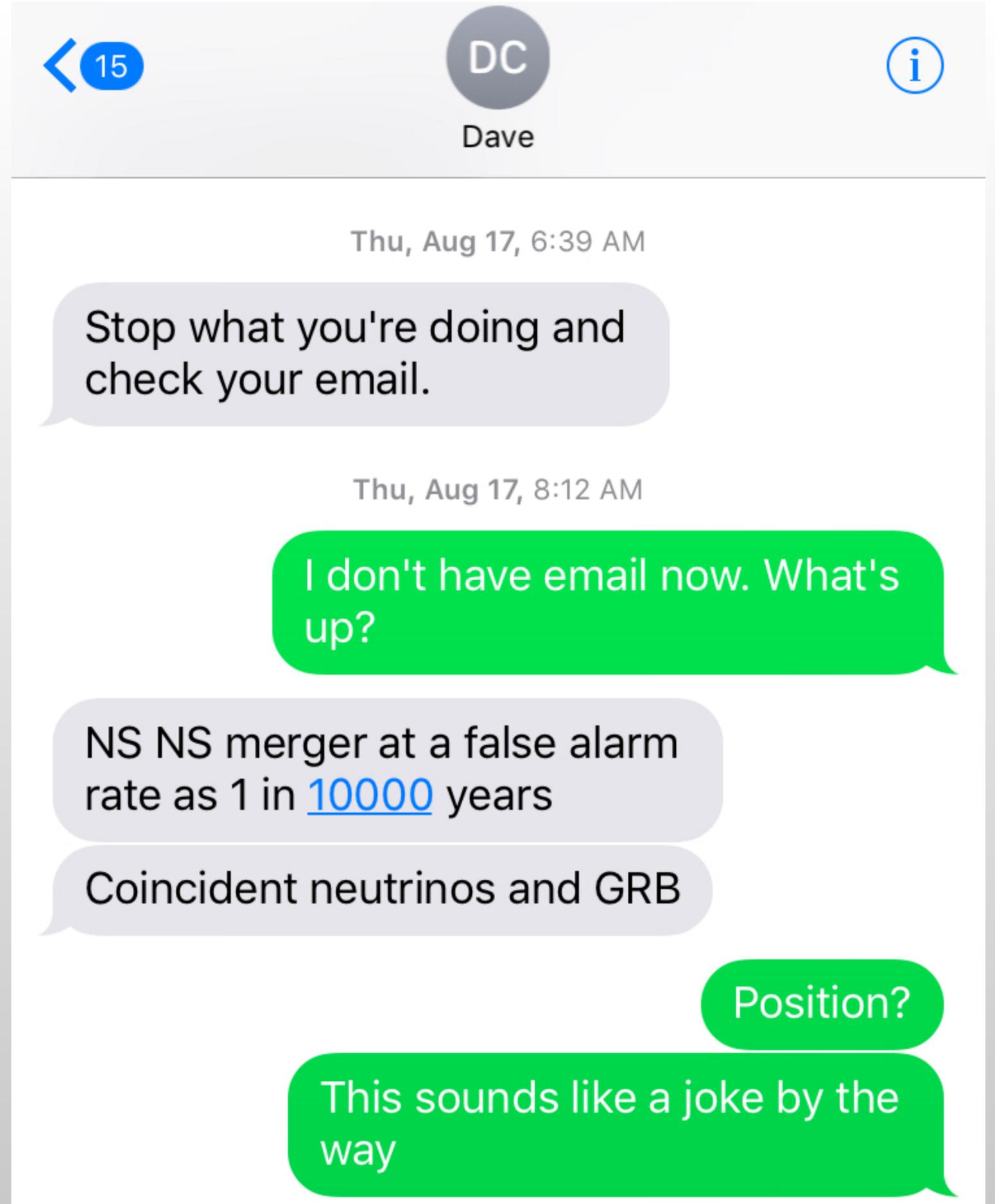


One Meter, Two Hemispheres (1M2H)



On August 17, 2017..







See who else is on Magellan,
and ask

I might leave, but if you're
joking and don't tell me now I
will not be amused

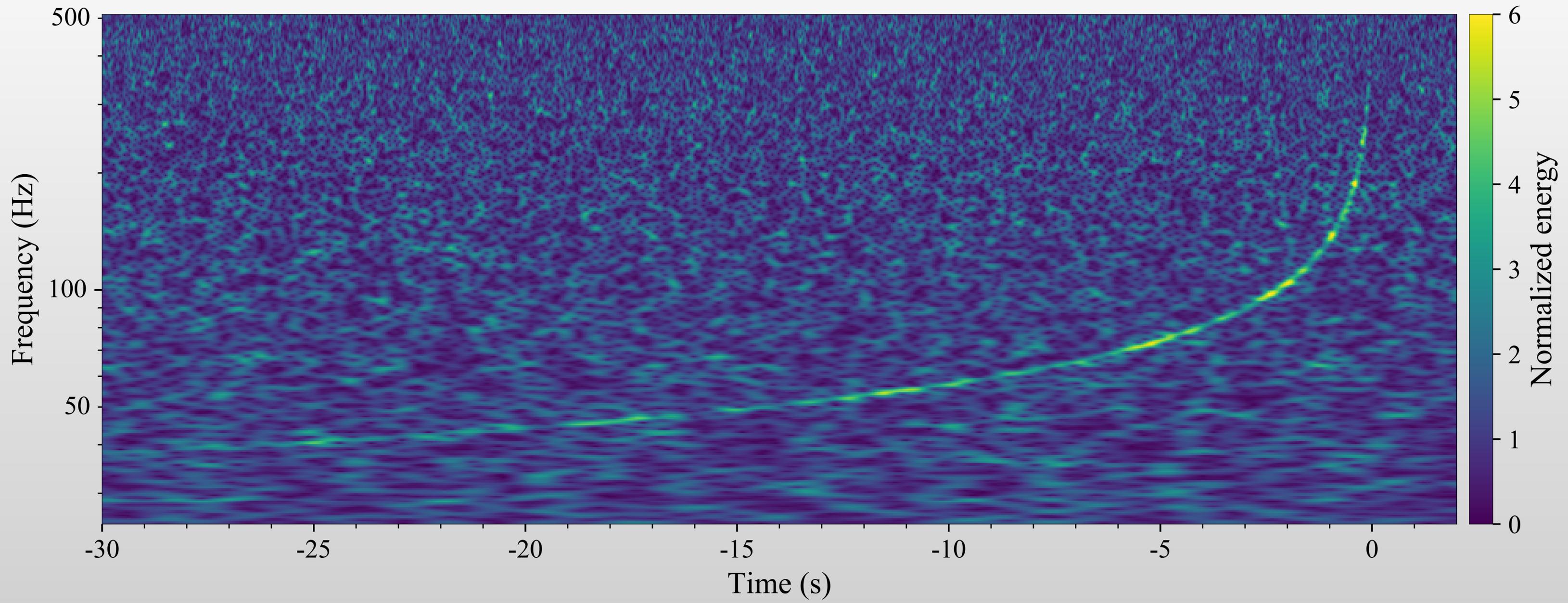
Although, I keep fucking up my
coordinates. One sec.

Well, it's a 11 degree radius for
1 sigma. So we have a big area.

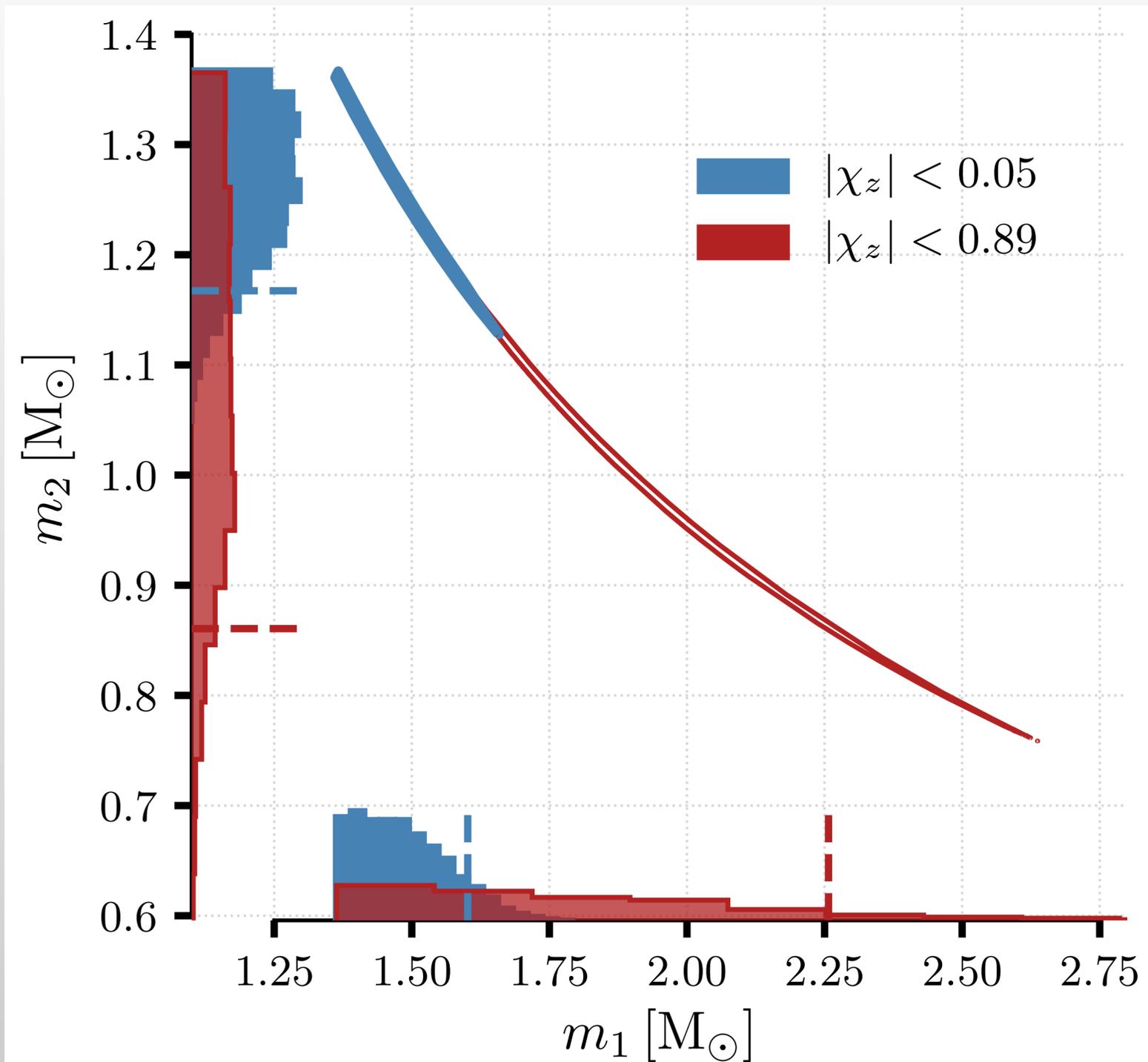
If there is a grb, it would have a
better coordinate

There should be booming x
rays

I'M NOT JOKING. JESUS MAN,
I WOULDN'T JOKE ABOUT
THIS.

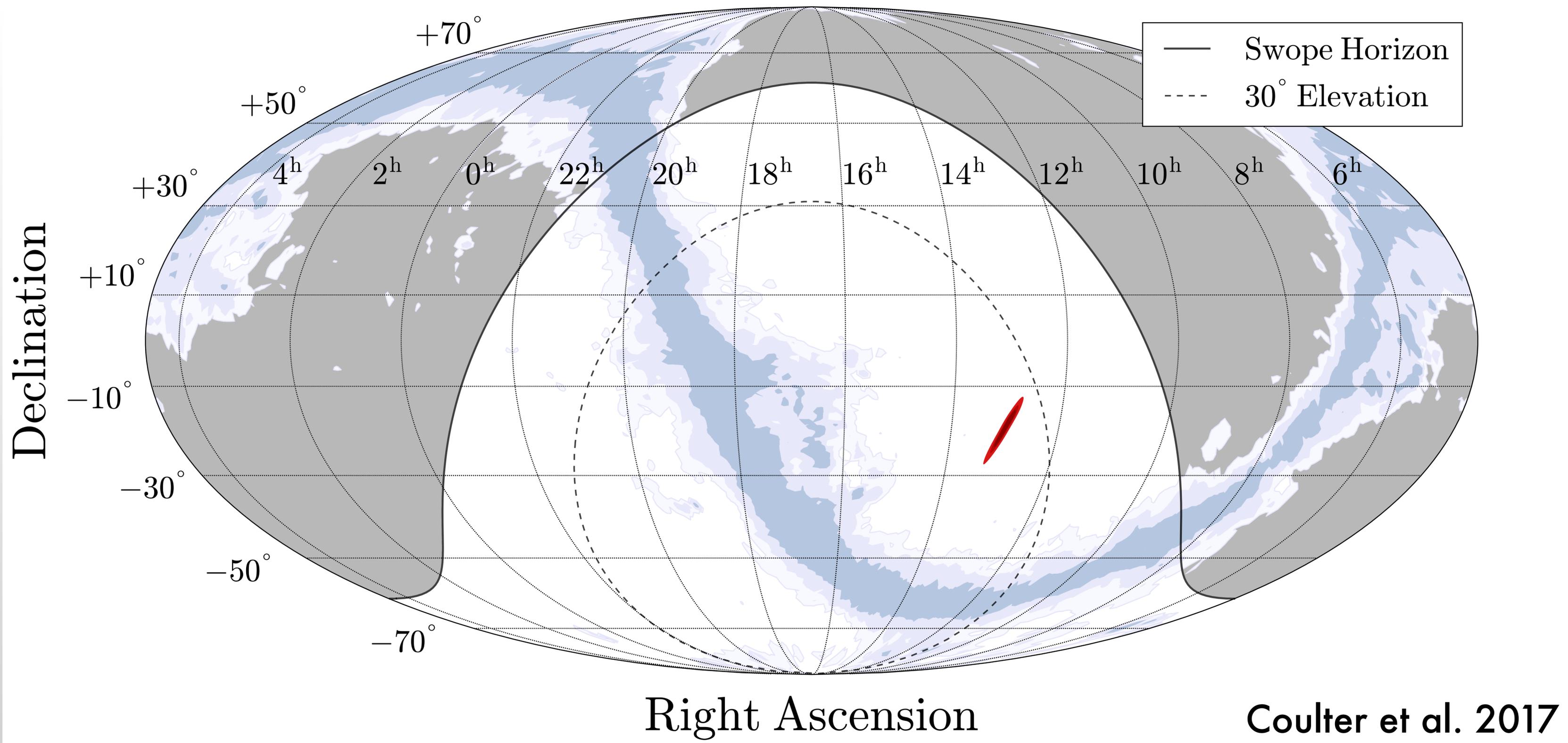


Masses Squaredly in NS Territory



$m_1 = 1.36 - 1.60 \text{ Msun}$
 $m_2 = 1.17 - 1.36 \text{ Msun}$
 $M_{\text{tot}} = 2.74 \text{ Msun}$
Mass ratio = $0.7 - 1.0$
Viewing angle $\leq 31 \text{ deg}$

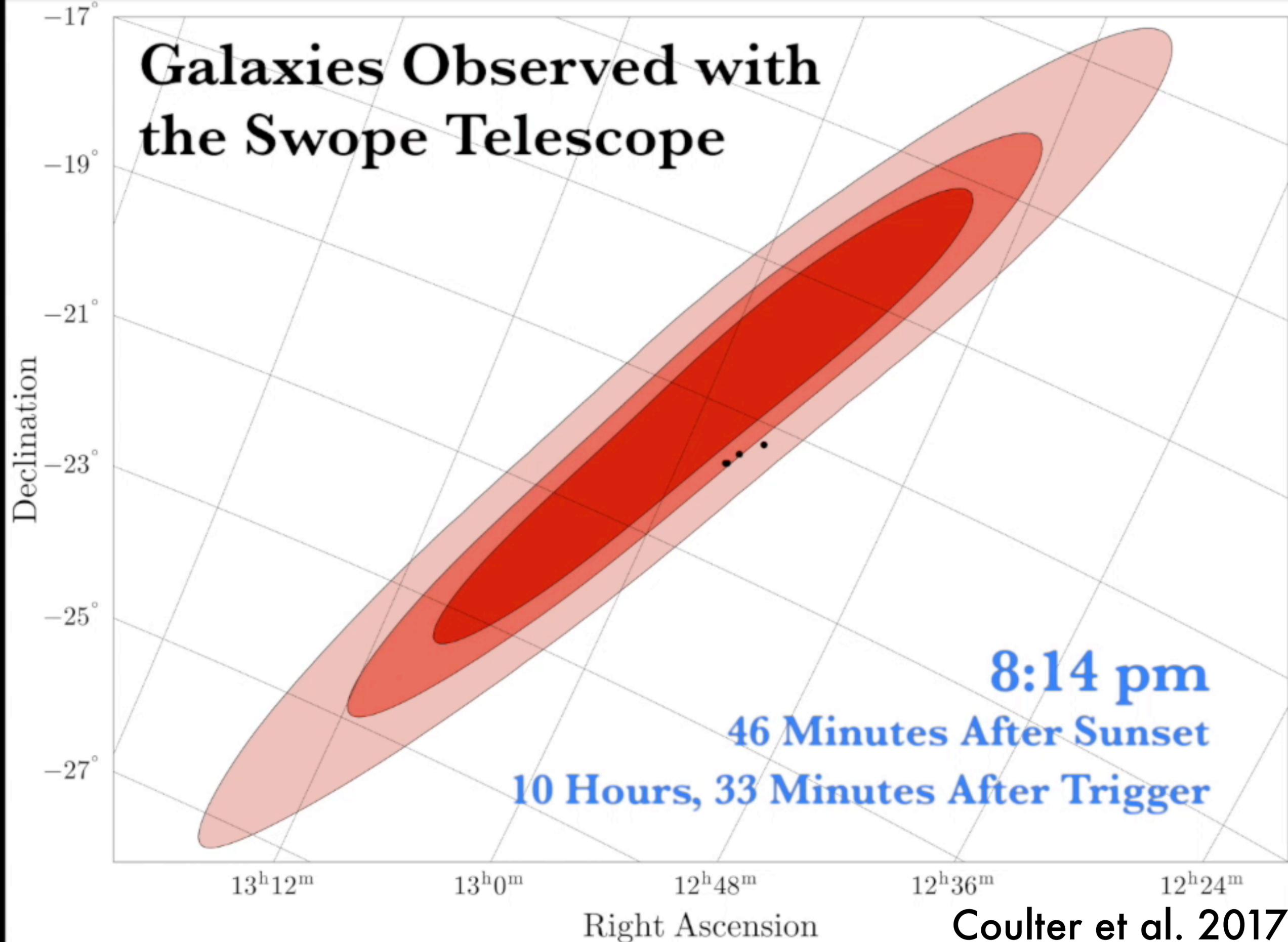
LVC 2017

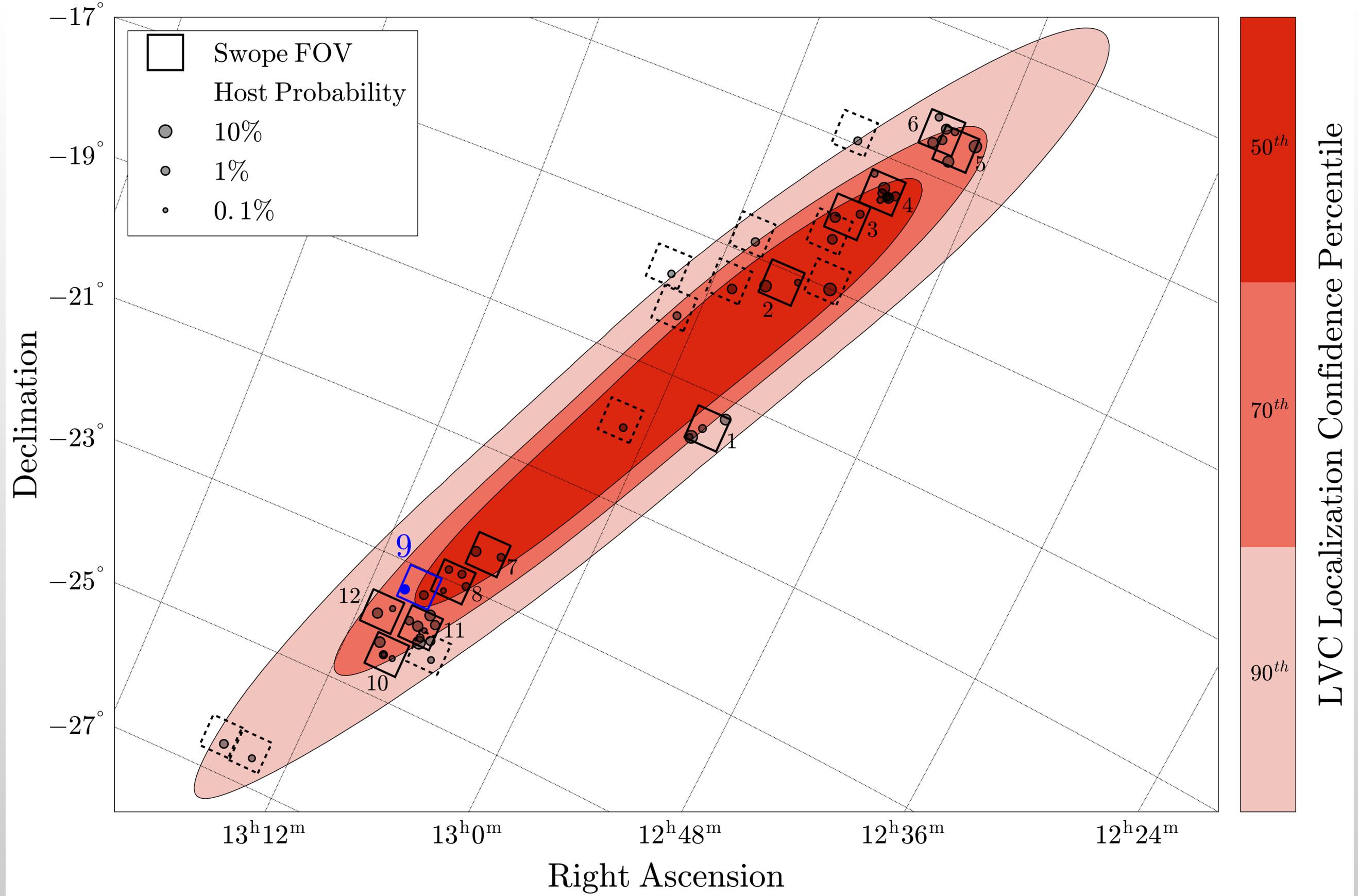






Galaxies Observed with the Swope Telescope







davecoulter 8:29 AM

Yeah

I got Ryan on text

He's on his way. He recommended a Galaxy comparison too



davecoulter 8:35 AM

Charlie

Do you think using the White 2011 catalog would be a good place to start?

I can make a distance cut, everything less than 50 Mpc, and then do a separation cut, where I got 12 degrees from the central point

and then match



ckilpatrick 8:38 AM

yes, use the white catalog



davecoulter 8:38 AM

OK

I am working on that now



ckilpatrick 8:38 AM

thanks



foley 8:51 AM

im at my apartment



davecoulter 8:51 AM

OK



foley 4:27 PM

[@ckilpatrick](#) when you get a chance, please verify that i didnt completely mess up those pointings and that we have multiple galaxies in those first pointings



ckilpatrick 4:28 PM

there are 4
galaxies



foley 4:28 PM

great!



ckilpatrick 4:28 PM

nothing im fields12



foley 4:29 PM

no transients, right?



ckilpatrick 4:29 PM

no transients

sorry, image is fine



foley 4:29 PM

fantastic



ckilpatrick 4:29 PM

but nothing I can see by eye



davecoulter 4:34 PM

uploaded this file ▾



ckilpatrick 4:27 PM
but nothing I can see by eye



davecoultter 4:34 PM
uploaded this file ▾



LCO_Swope_20170817_Plot.png

3MB PNG



ckilpatrick 4:38 PM
ok, nothing in fields10

there was a bug in fields11 that we just fixed, but we're going back to that one
nothing in fields11



ckilpatrick 4:59 PM
[@foley](#) found something
sending you a screenshot



foley 4:59 PM
wow!



davecoultter 4:59 PM
!



ckilpatrick 4:59 PM
template



ckilpatrick 4:59 PM
uploaded this image: [Screen Shot 2017-08-17 at 4.59.27 PM.png](#) ▾



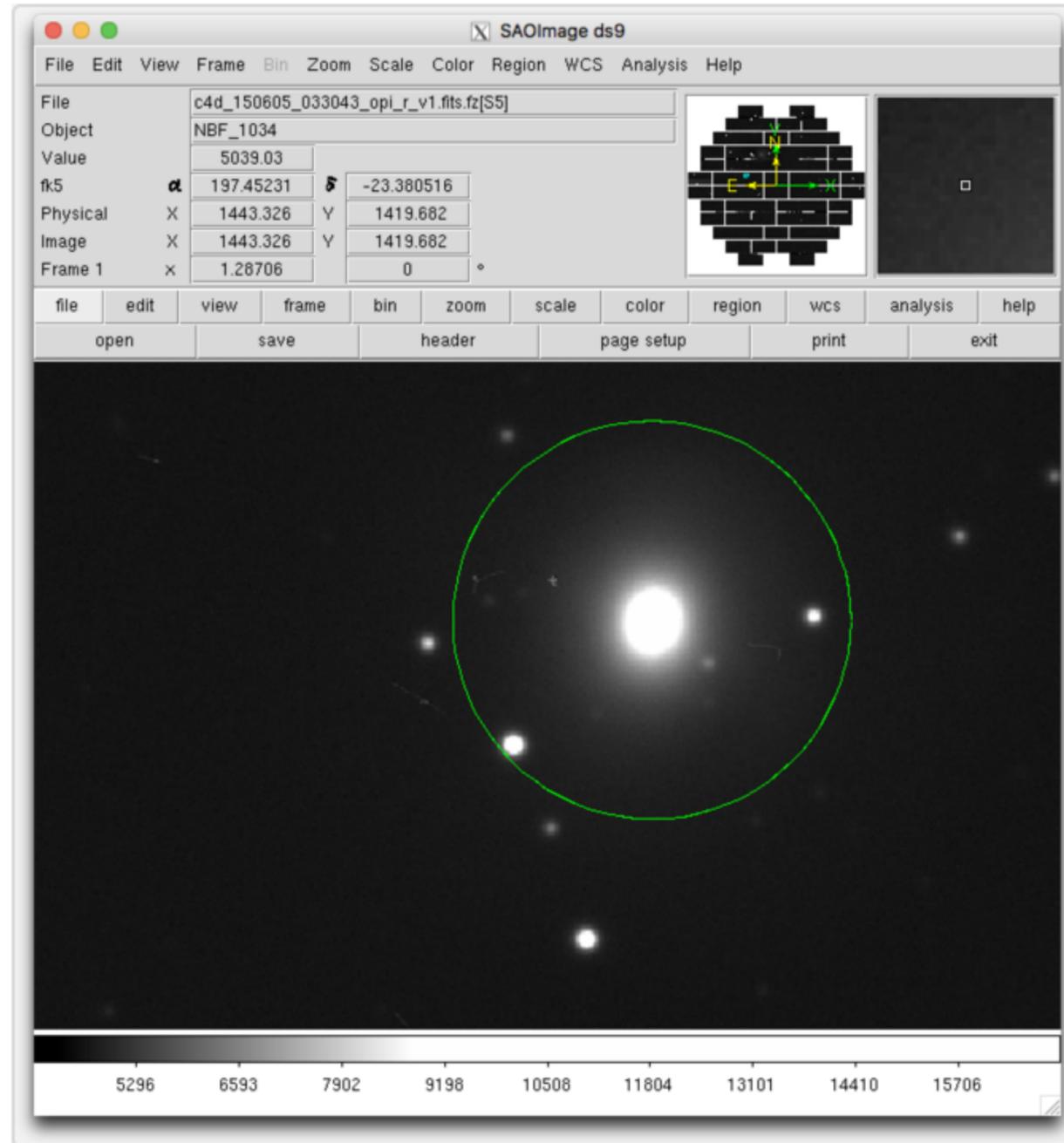
ckilpatrick 4:59 PM

template



ckilpatrick 4:59 PM

uploaded this image: [Screen Shot 2017-08-17 at 4.59.27 PM.png](#)



ckilpatrick 5:00 PM

US



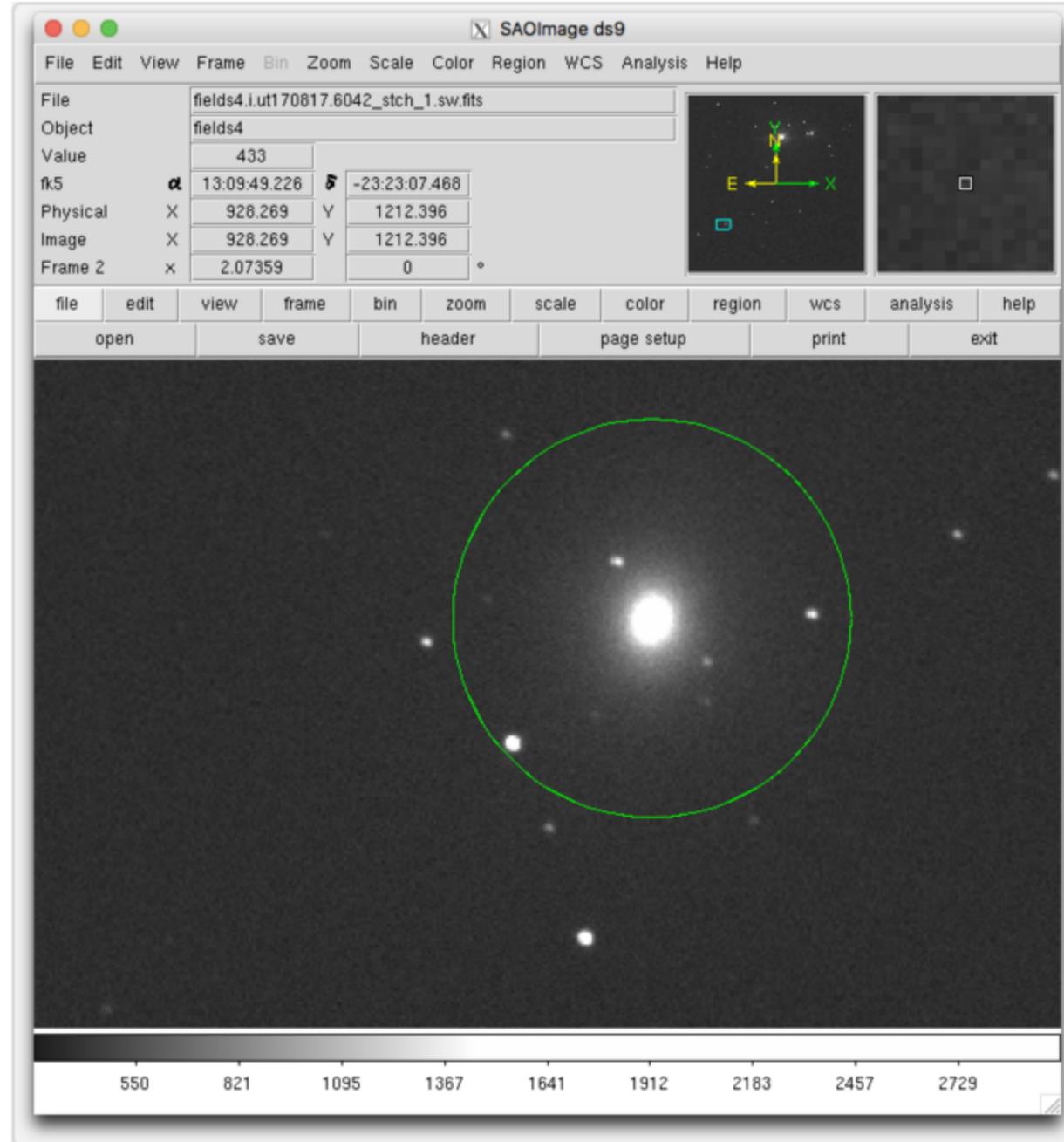
ckilpatrick 5:00 PM

US



ckilpatrick 5:00 PM

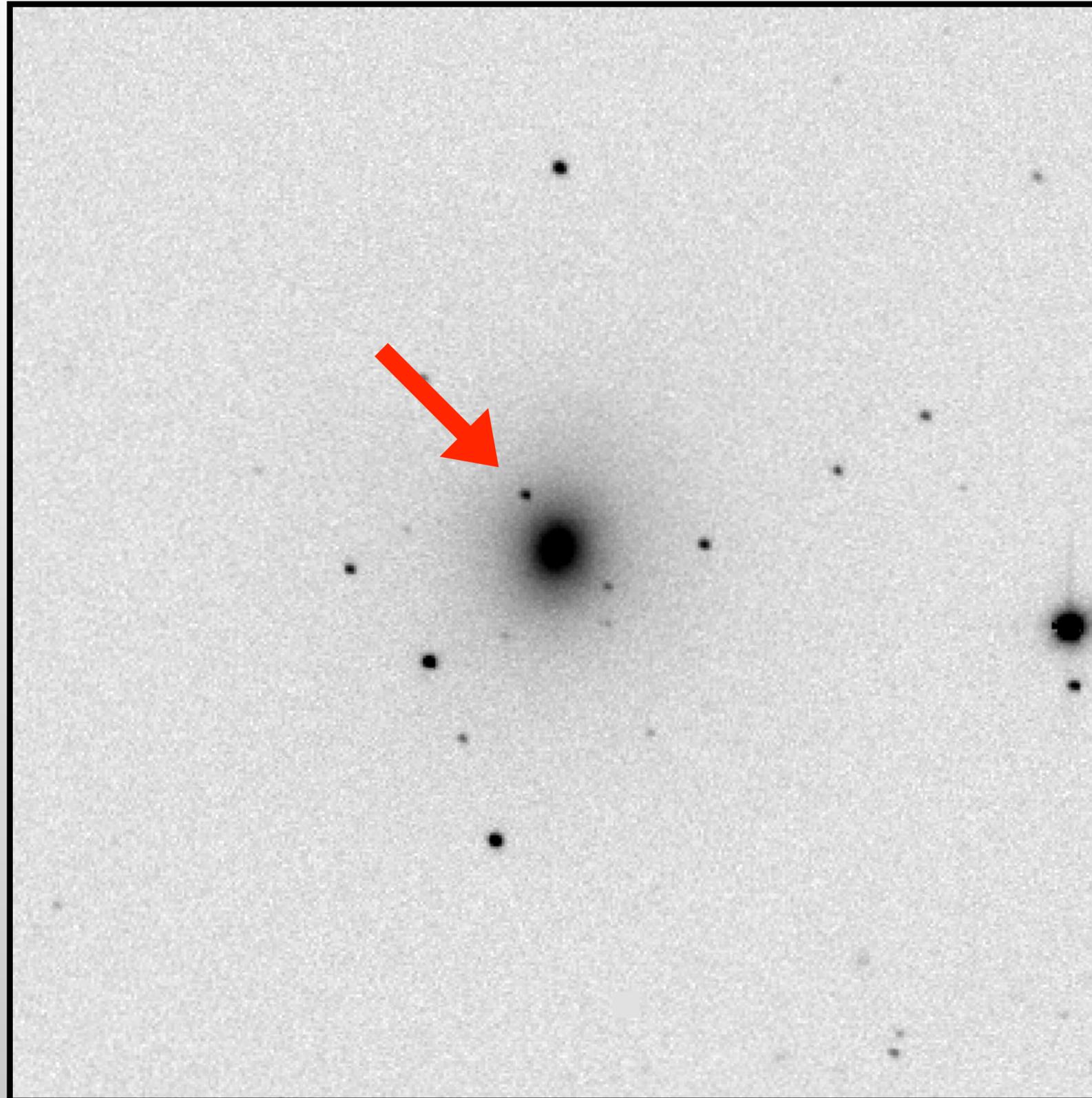
uploaded this image: [Screen Shot 2017-08-17 at 4.59.53 PM.png](#)



foley 5:00 PM

yep!

NGC 4993 and SSS17a



First Image of a Gravitational Wave

NGC 4993



April 28, 2017

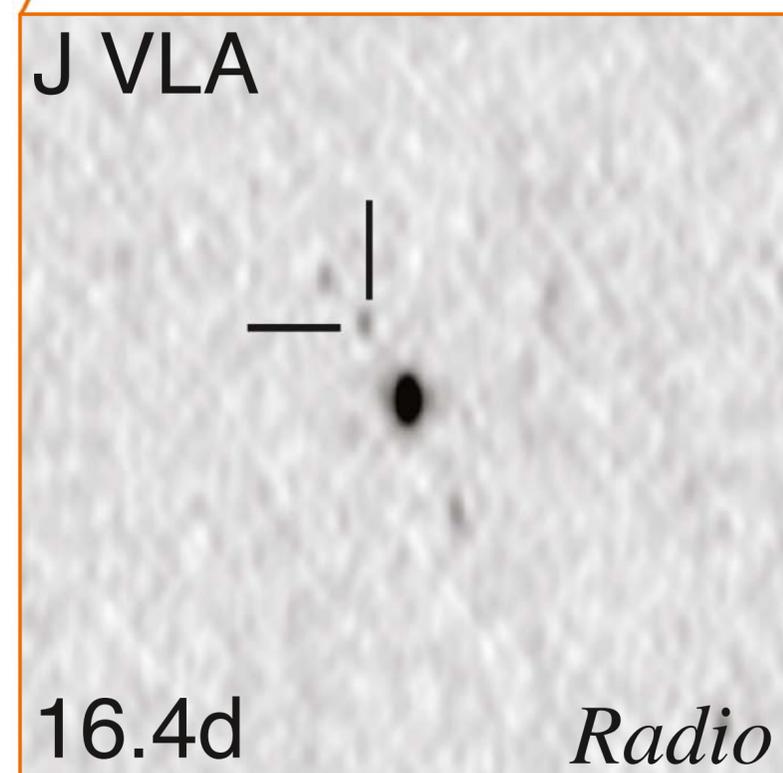
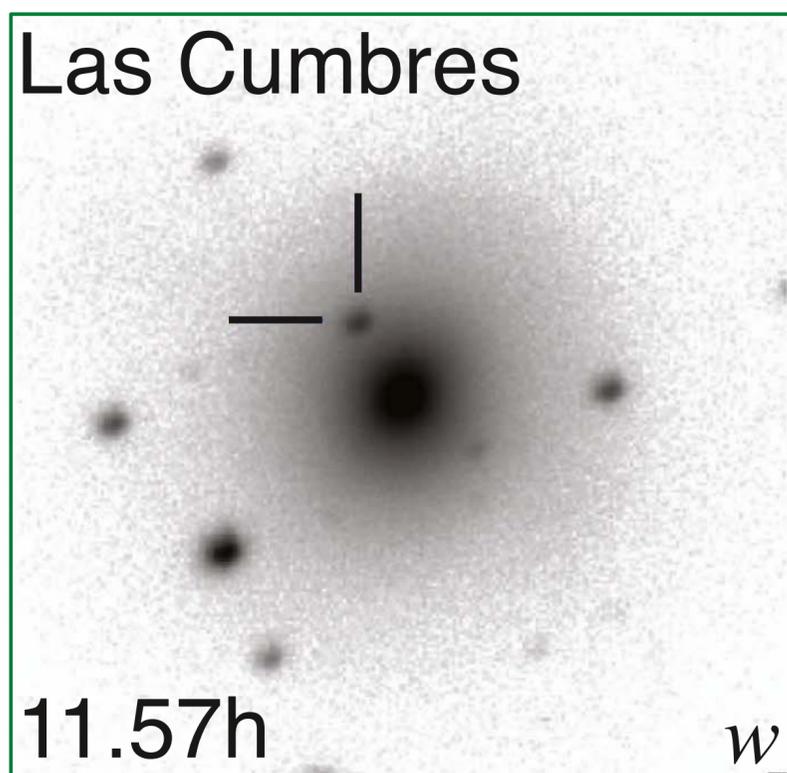
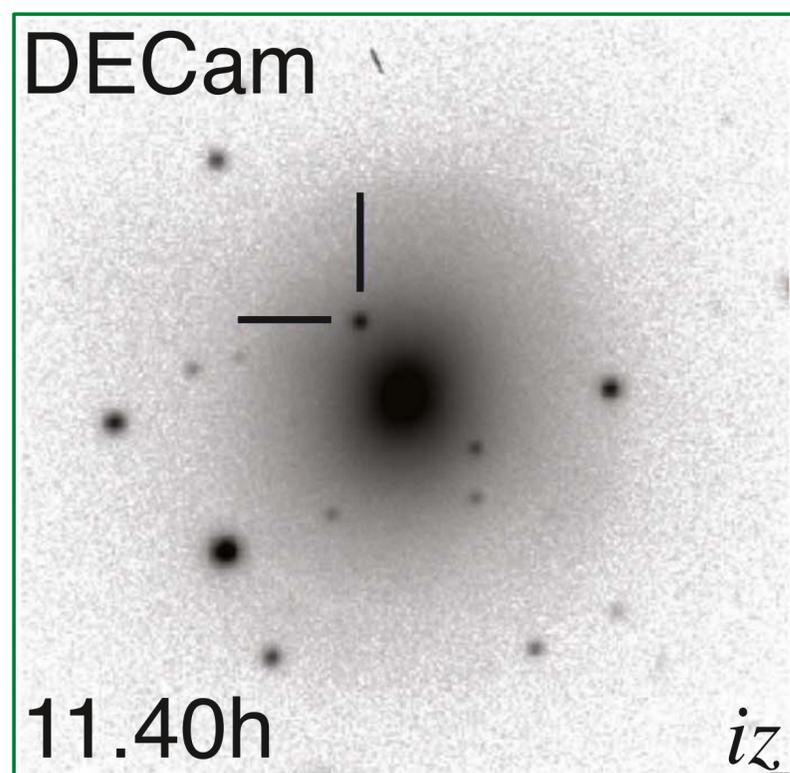
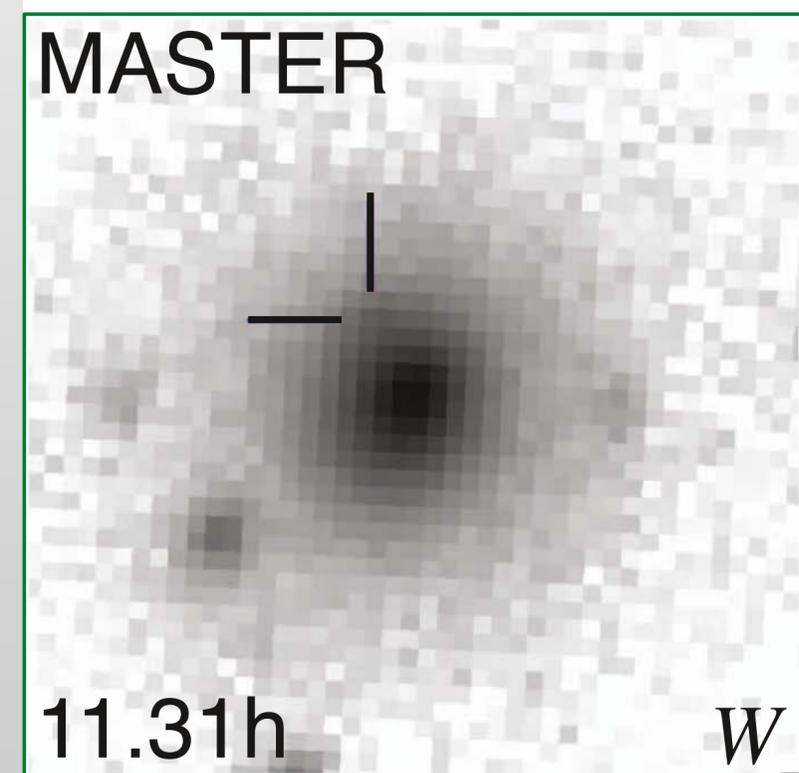
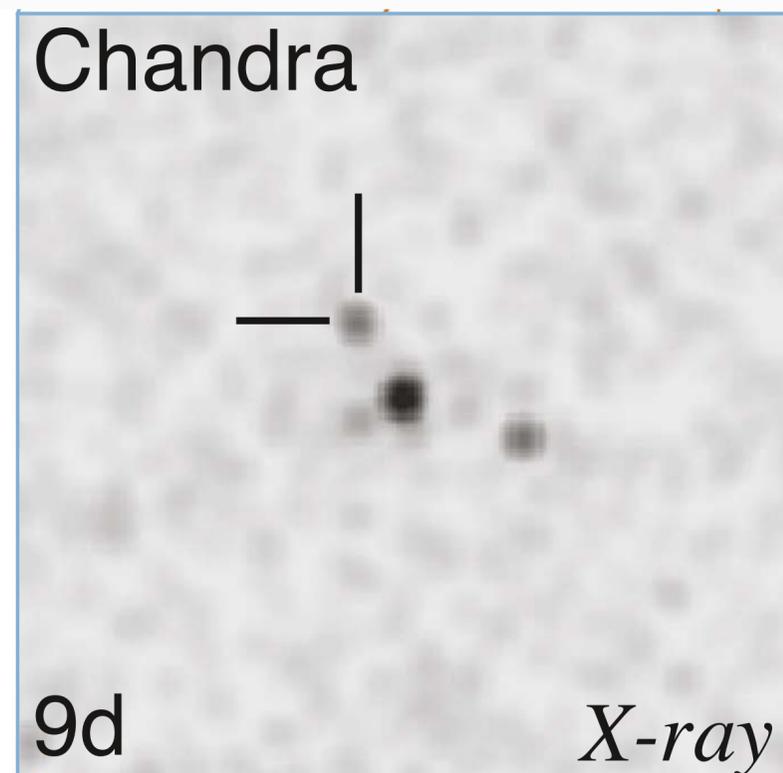
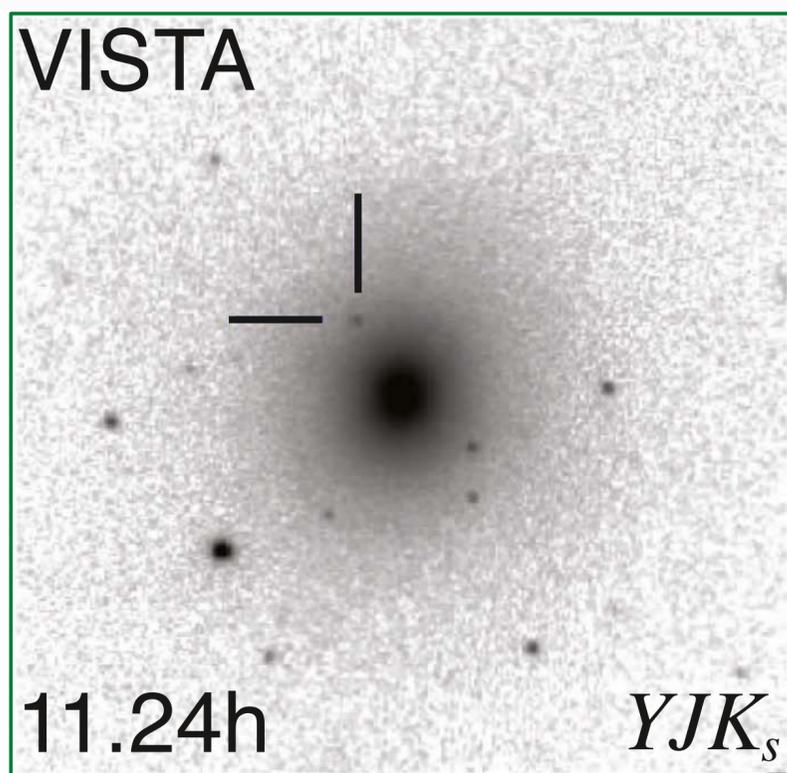
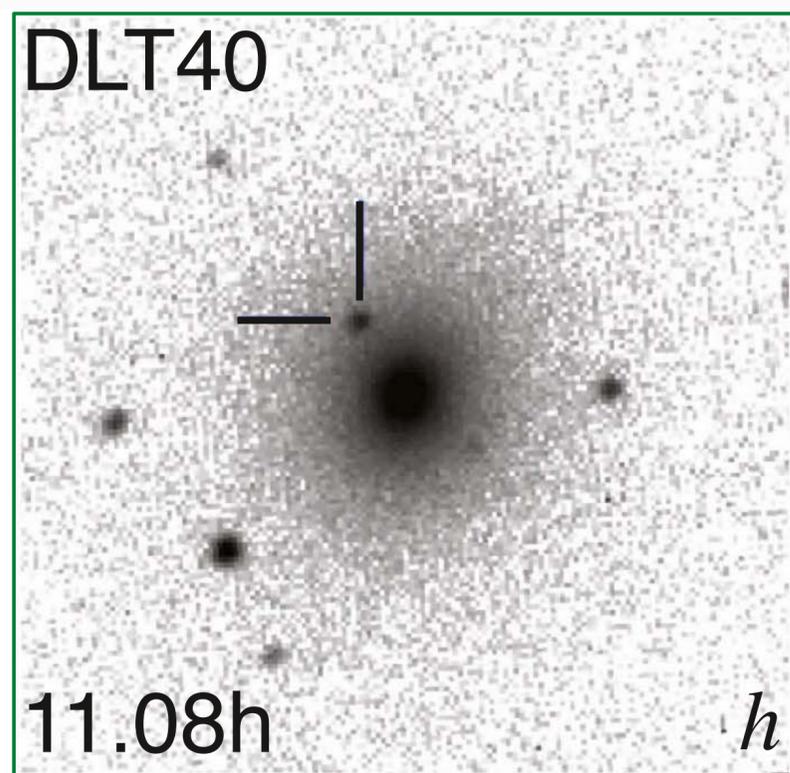
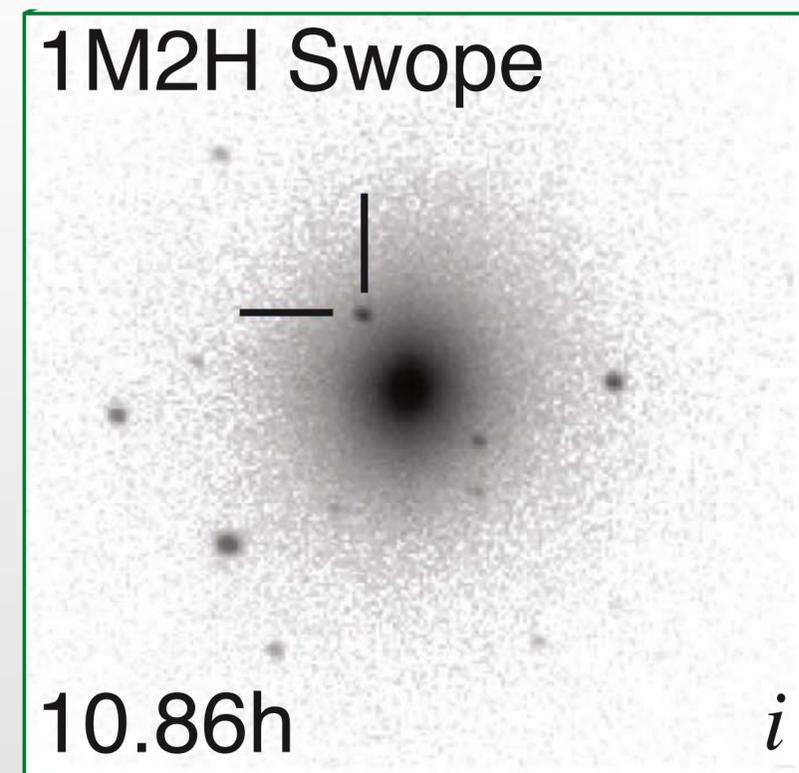
Hubble Space Telescope

SSS17a



August 17, 2017

Swope & Magellan Telescopes





SSS17a

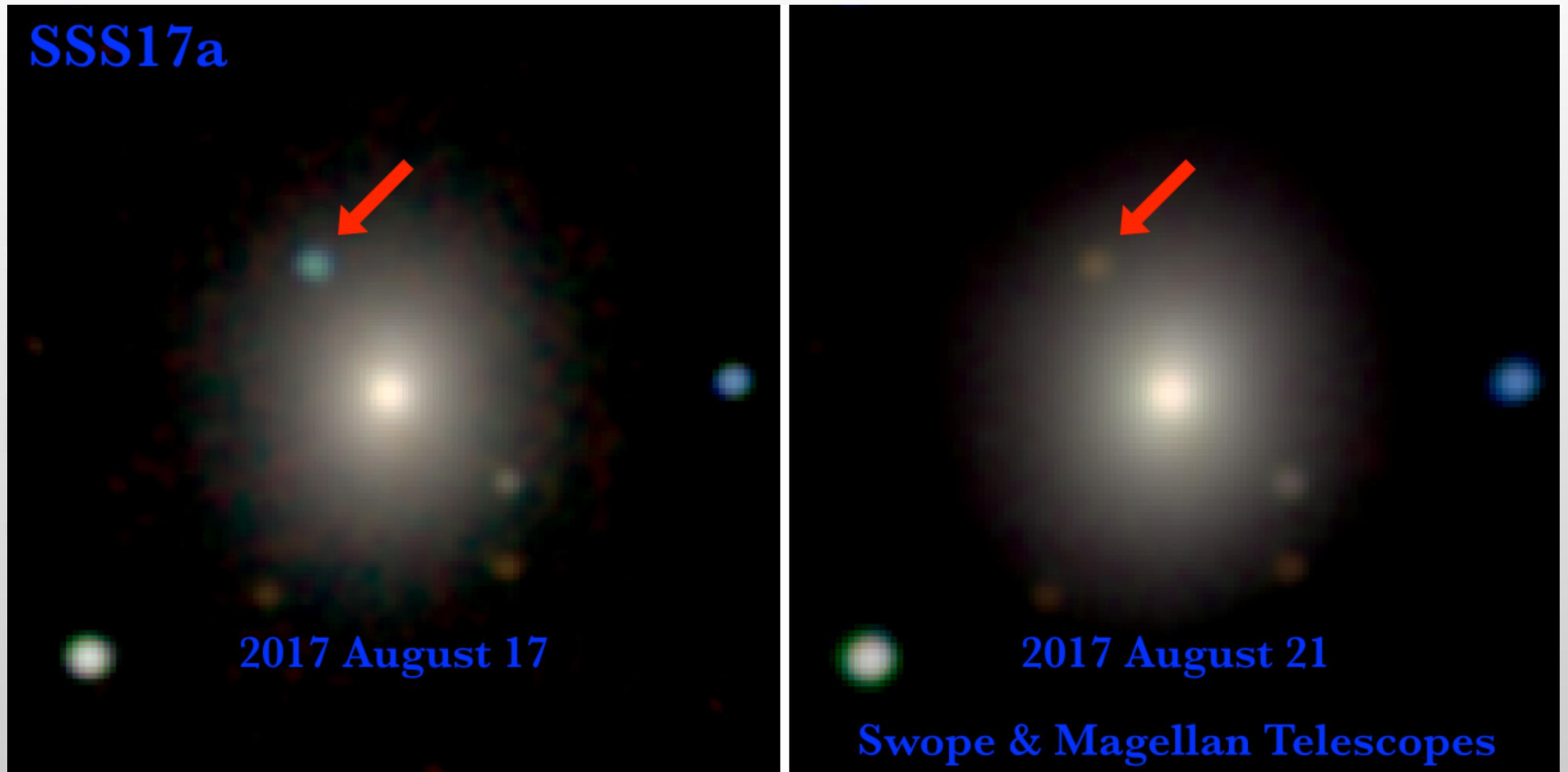
12 Hours After Trigger



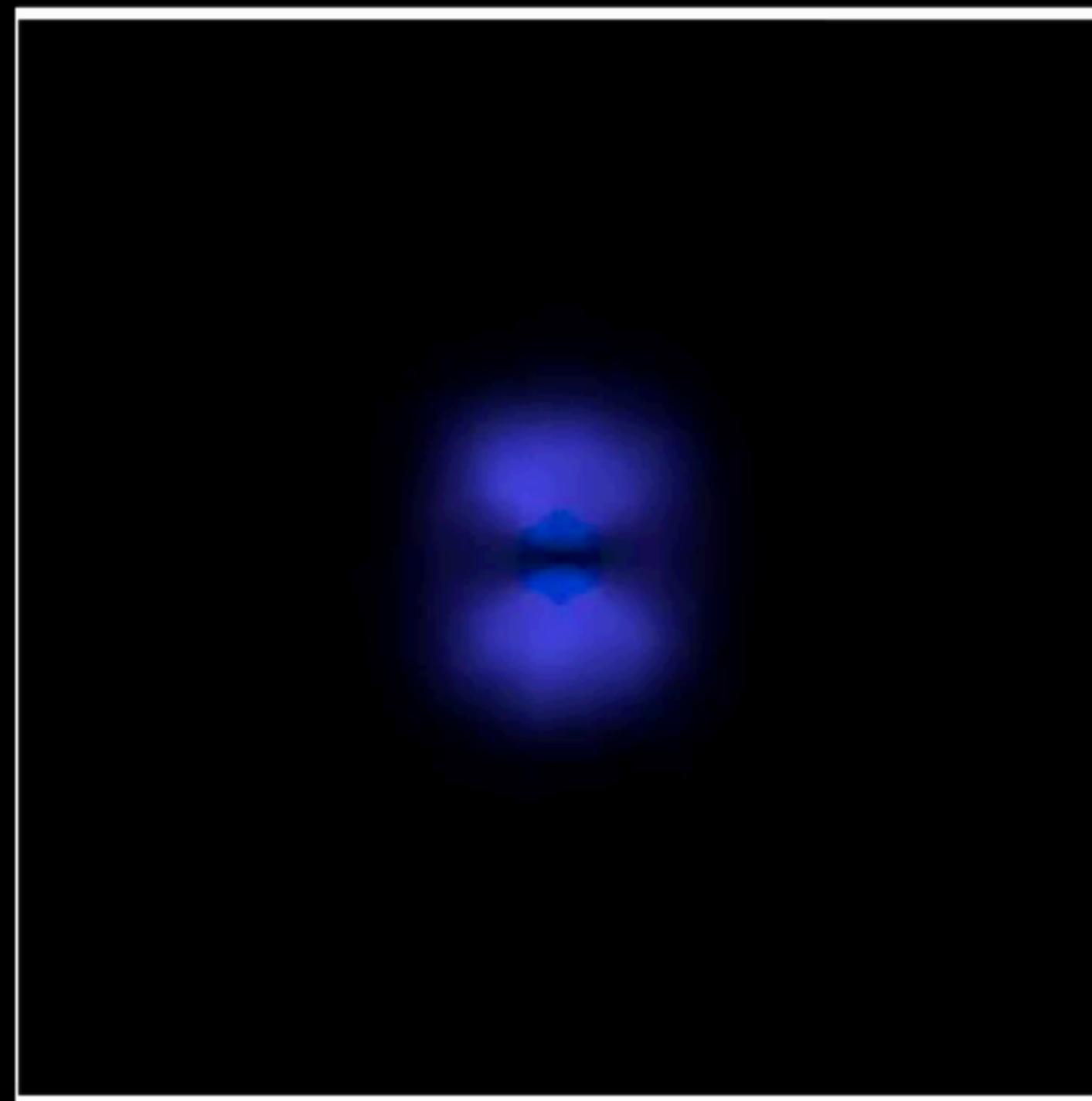
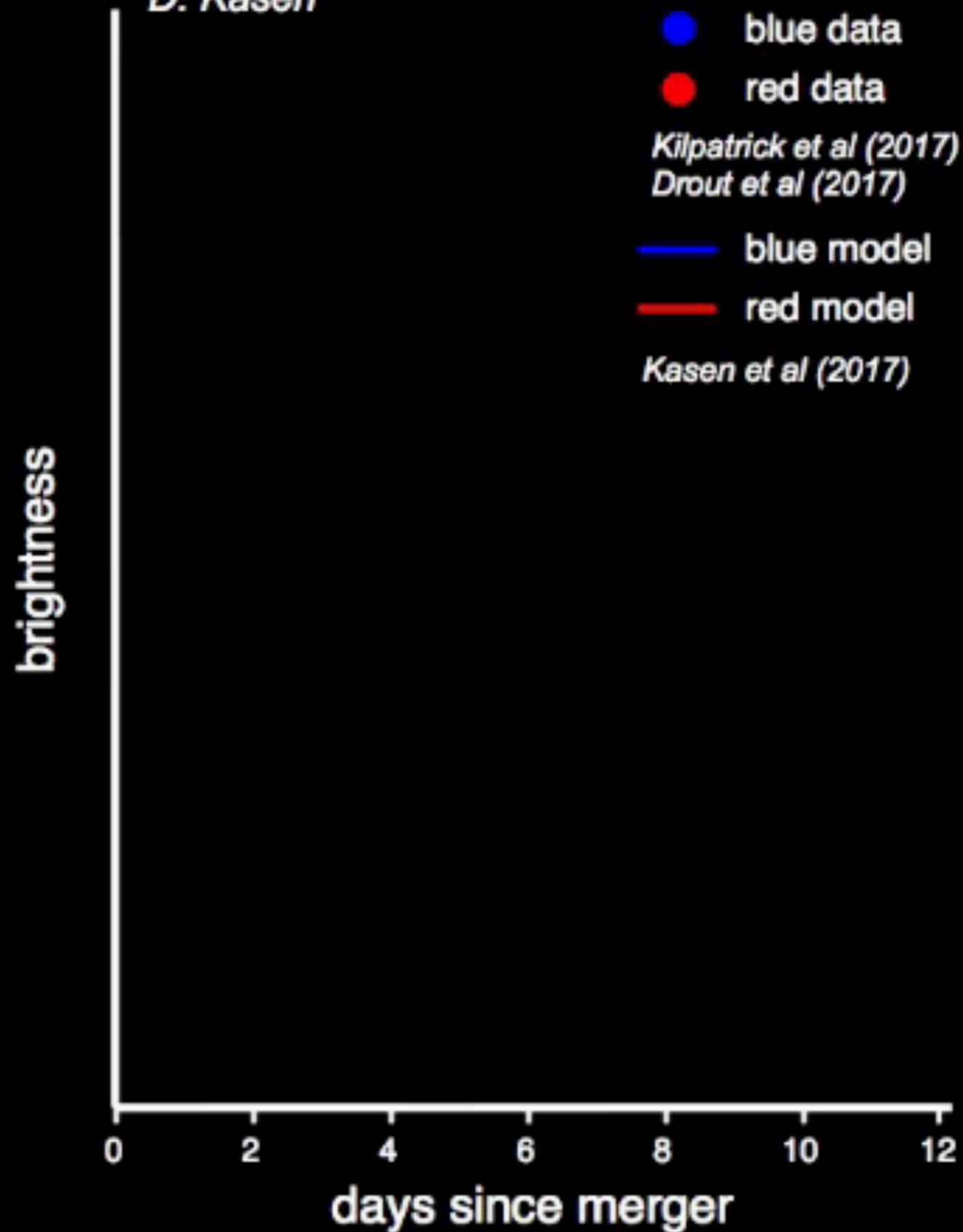
SSS17a

4.5 Days After Trigger

SSS17a Quickly Turned Blue to Red



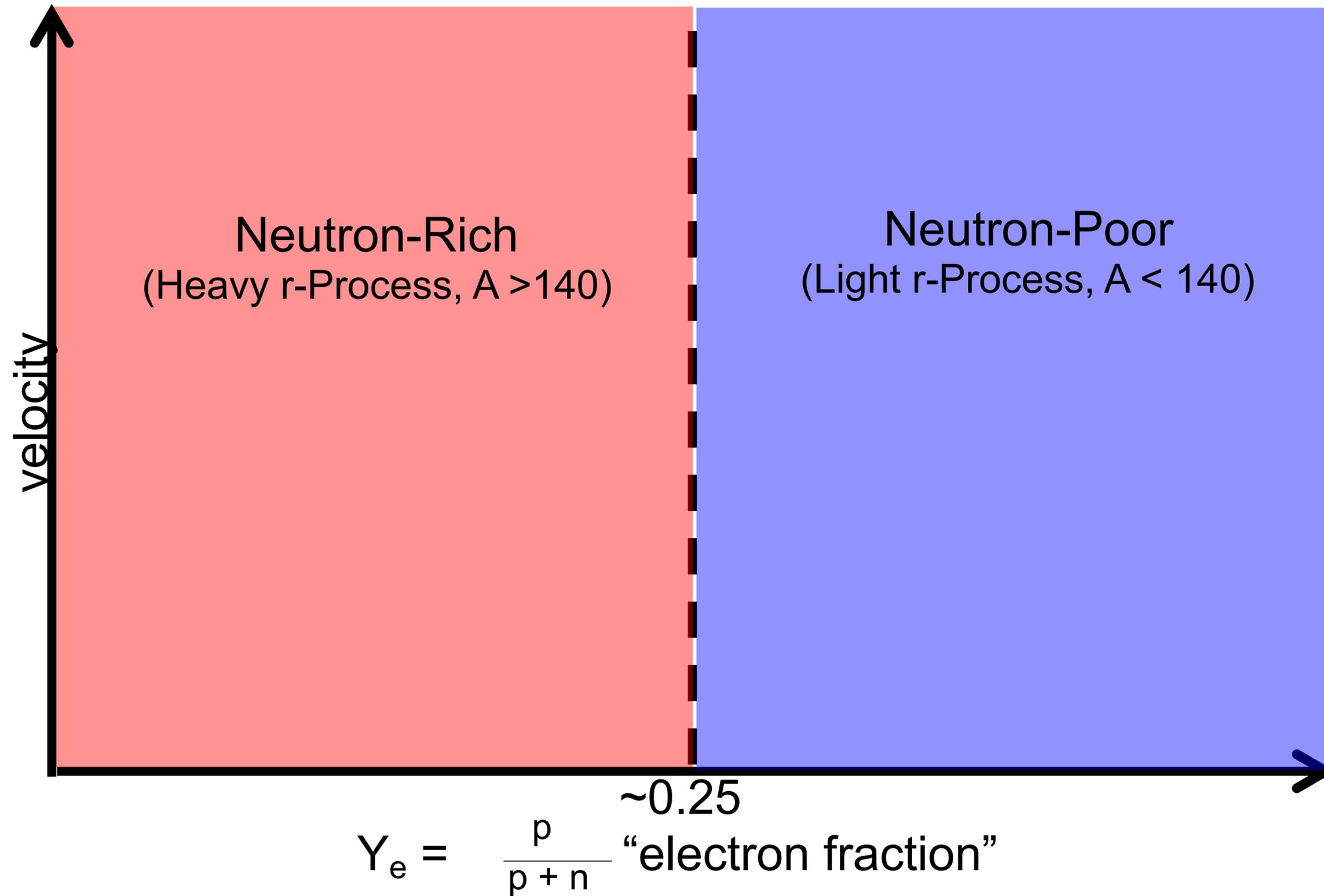
D. Kasen



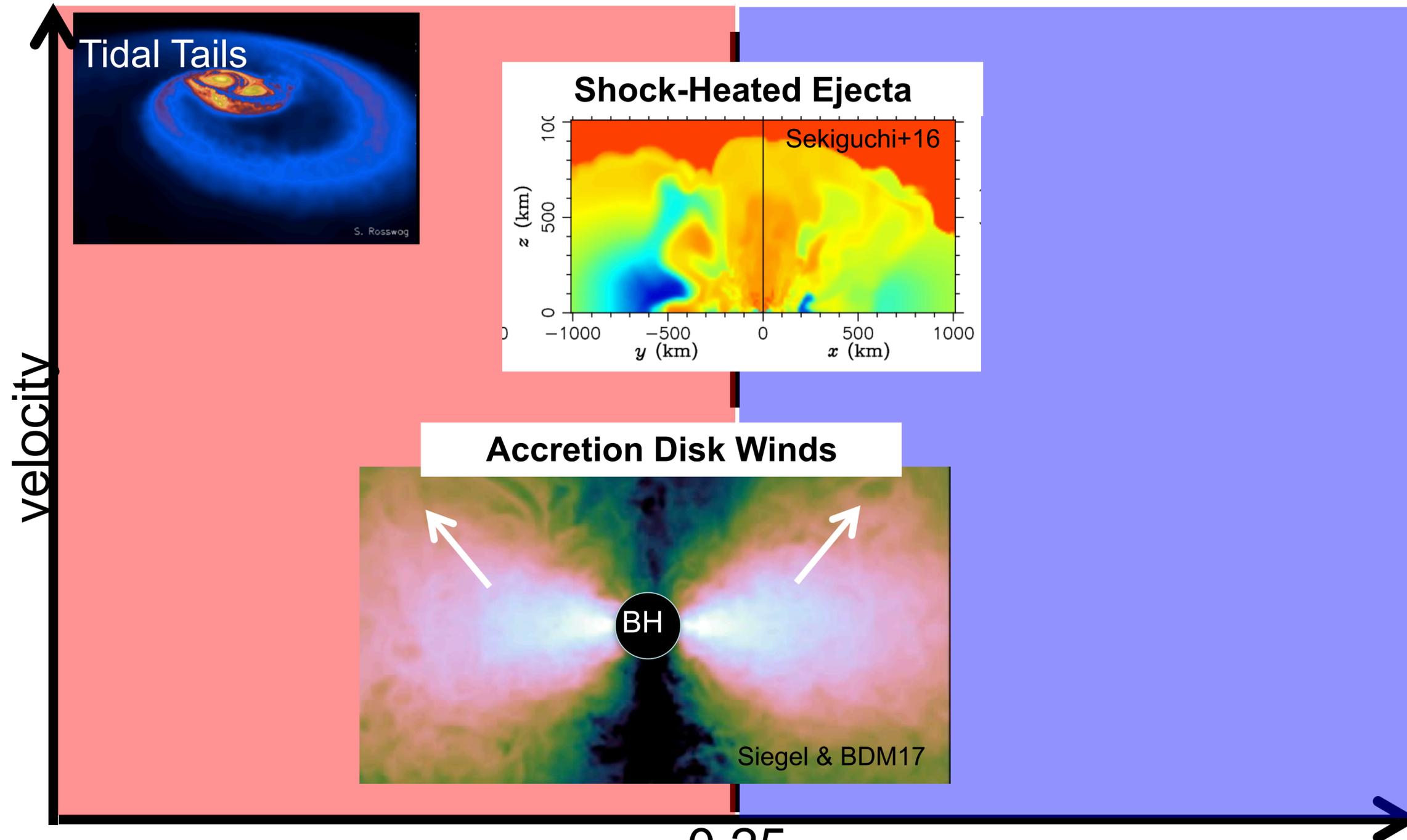
radioactive debris cloud



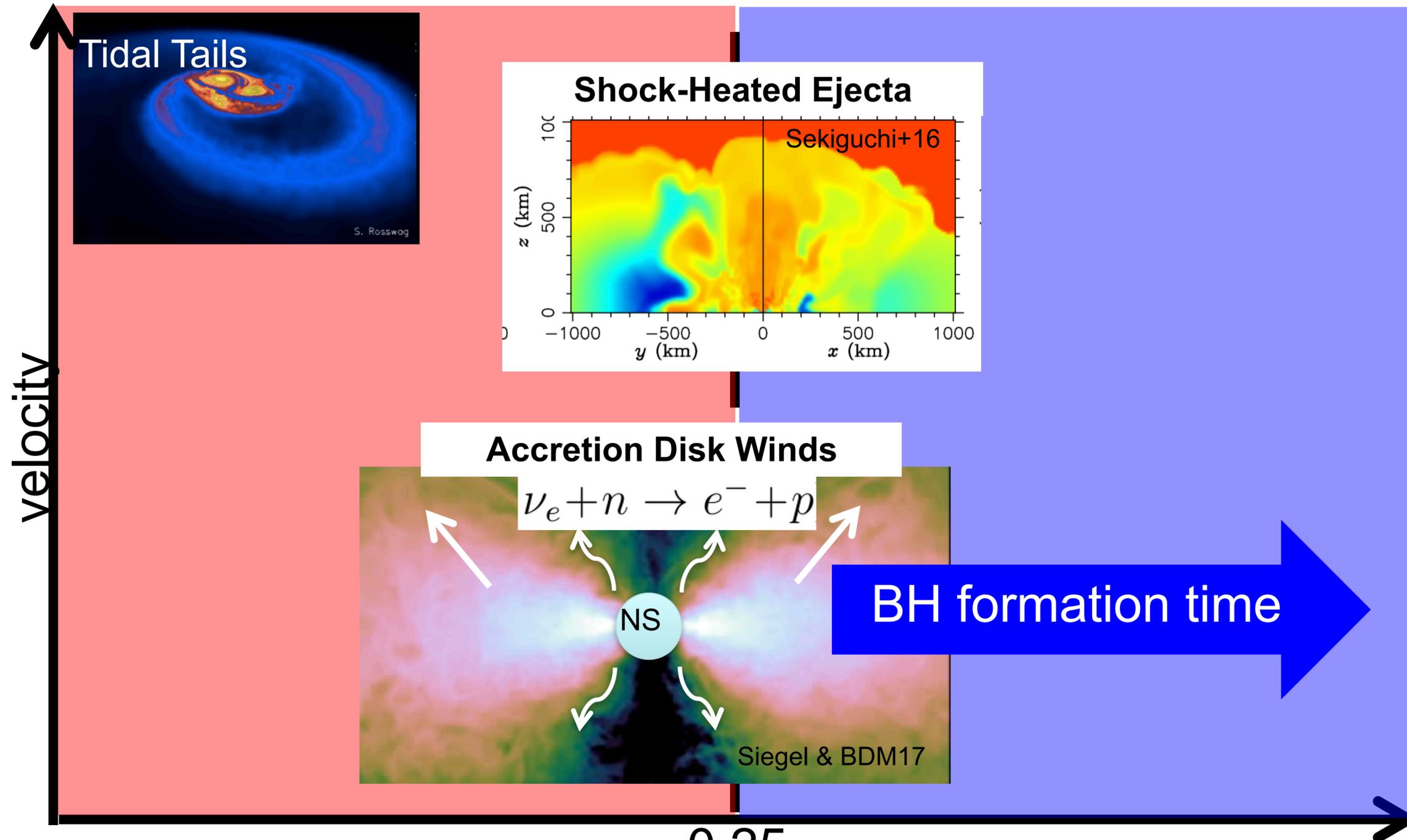
Red vs. Blue Kilonovae



Red vs. Blue Kilonovae

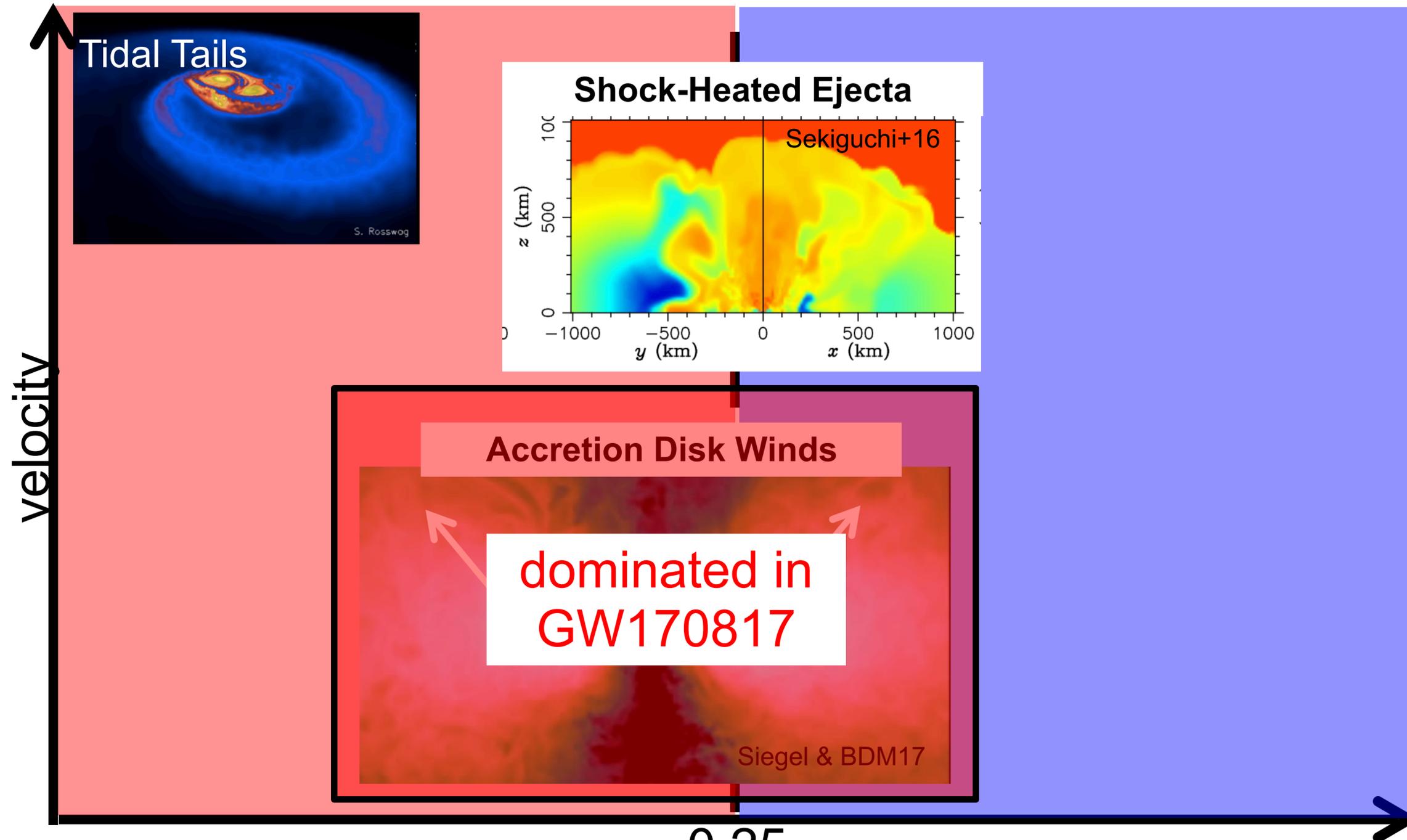


Red vs. Blue Kilonovae



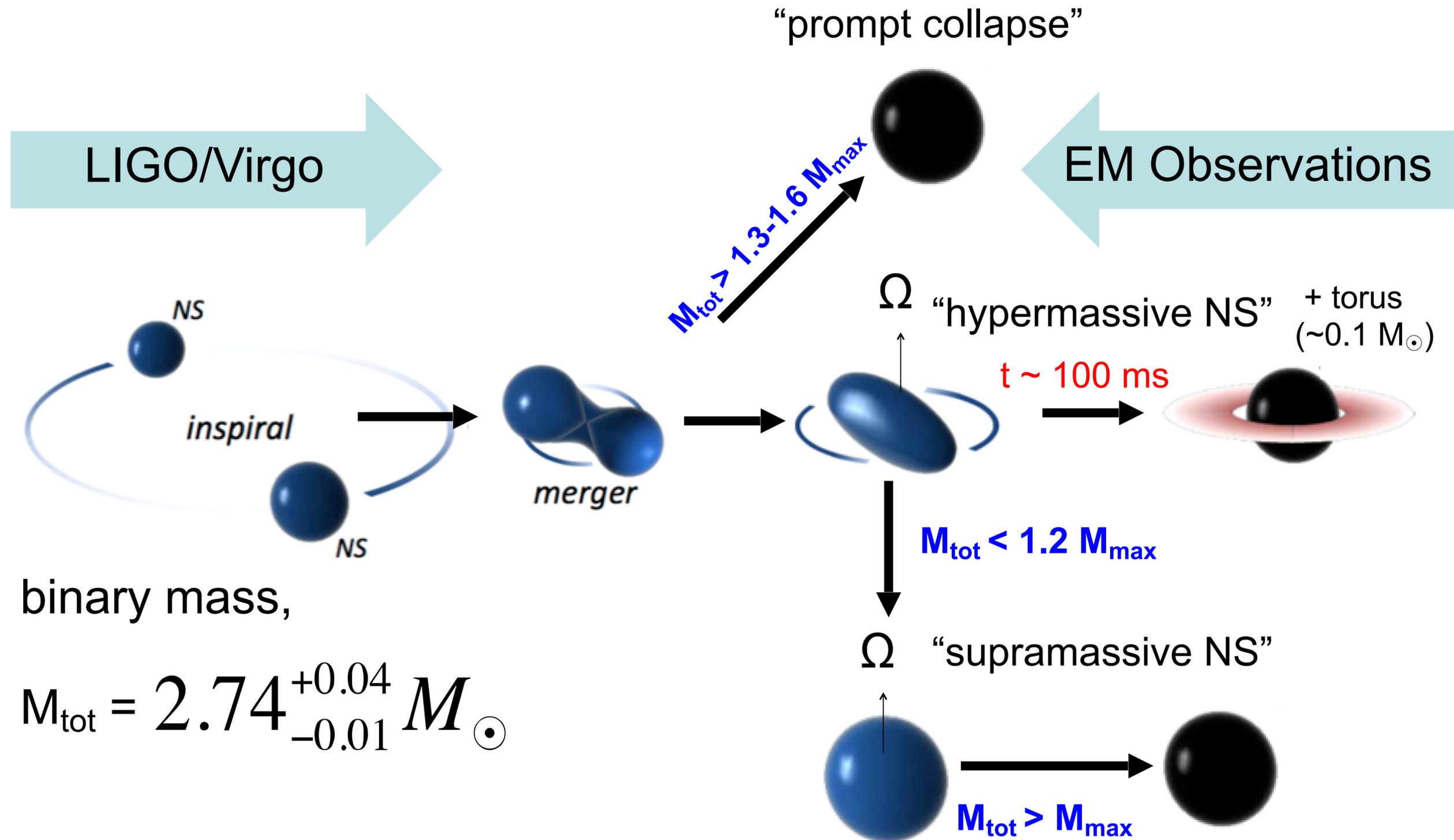
$$Y_e = \frac{p}{p + n} \sim 0.25 \text{ "electron fraction"}$$

Red vs. Blue Kilonovae

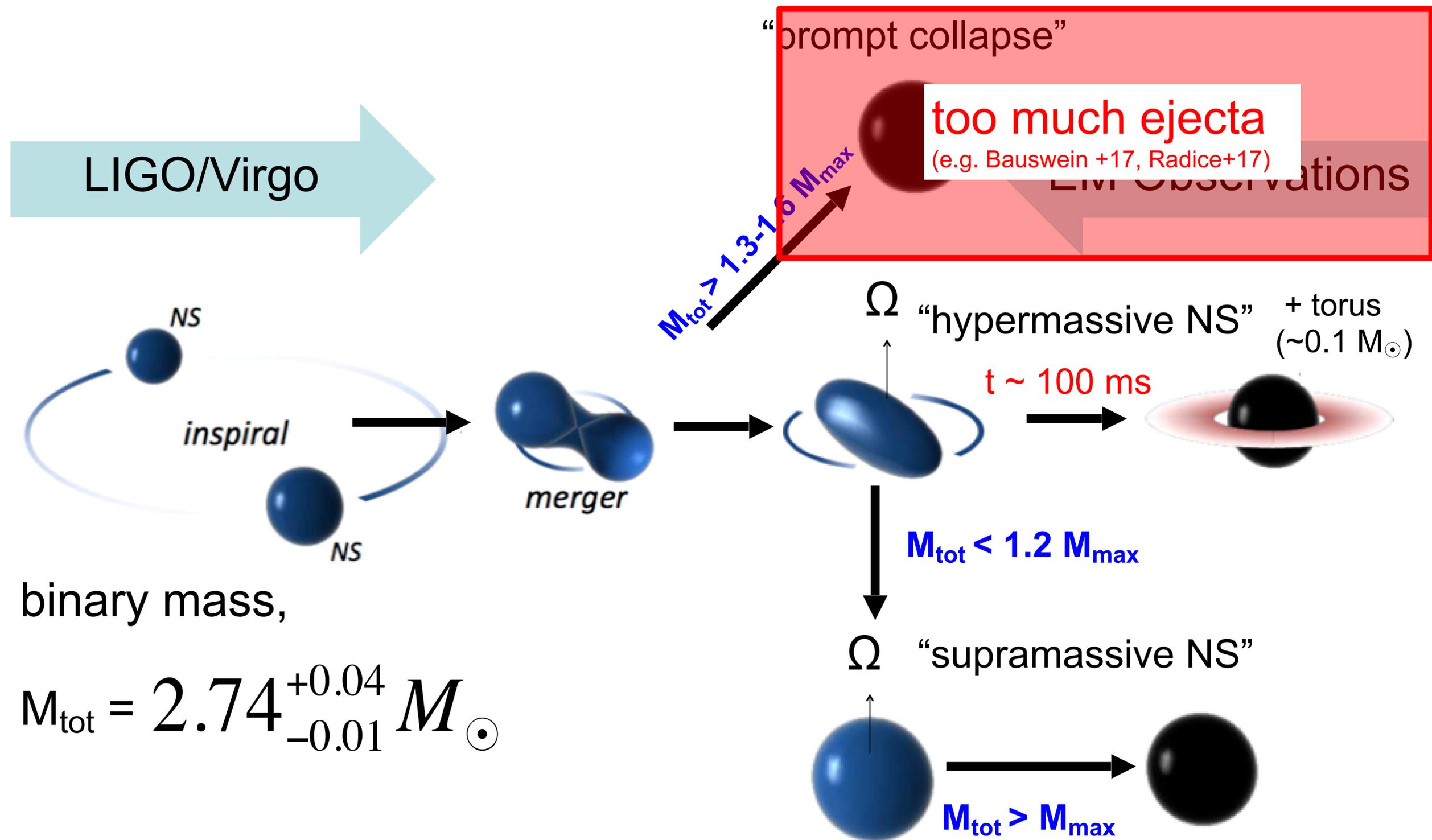


$$Y_e = \frac{p}{p+n} \text{ "electron fraction"}$$

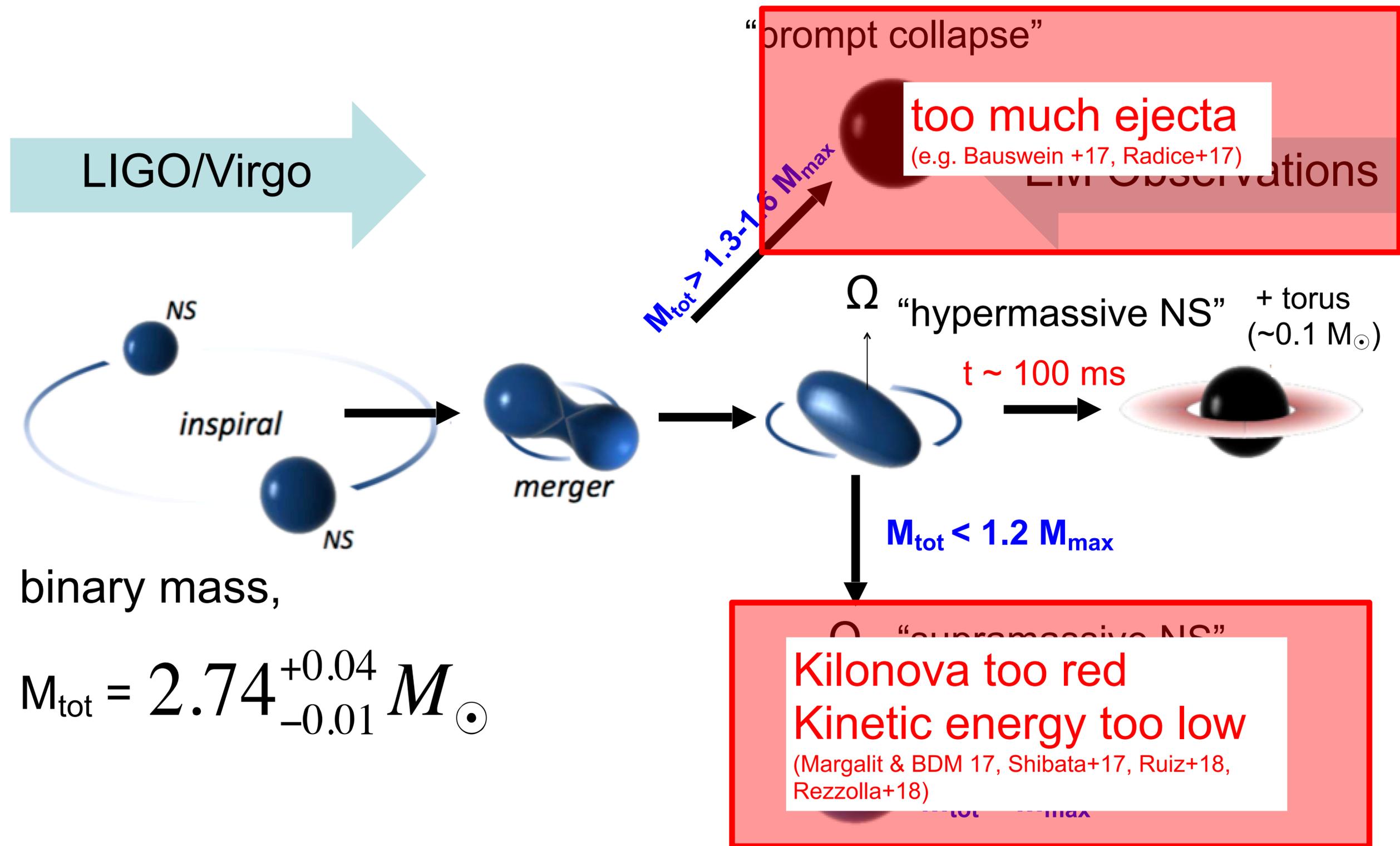
Outcomes of Neutron Star Mergers



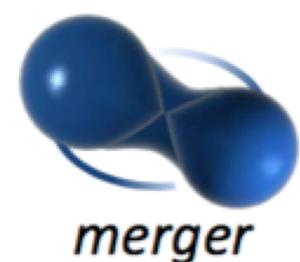
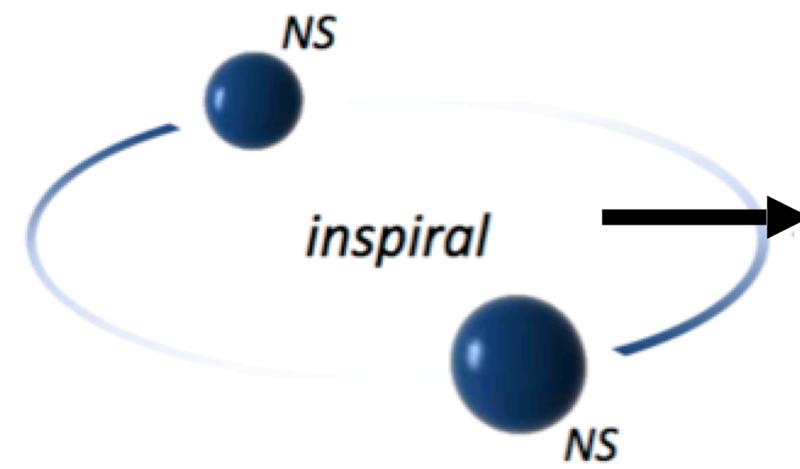
Outcomes of Neutron Star Mergers



Outcomes of Neutron Star Mergers



LIGO/Virgo

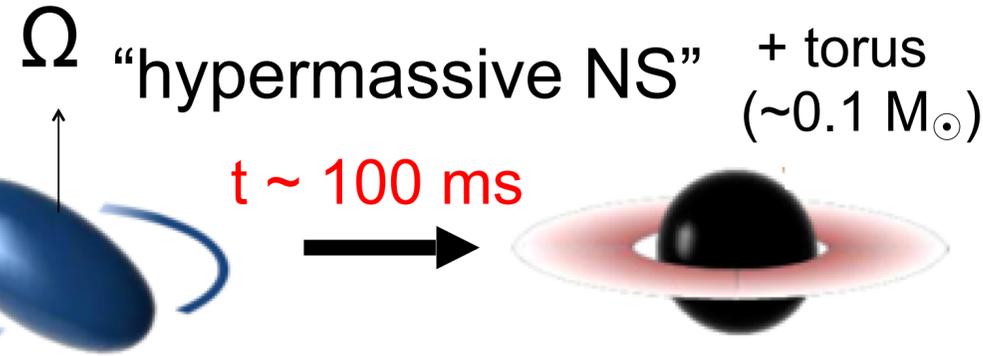


"prompt collapse"

too much ejecta
(e.g. Bauswein +17, Radice+17)

EM observations

$M_{\text{tot}} > 1.3 - 1.6 M_{\text{max}}$



$M_{\text{tot}} < 1.2 M_{\text{max}}$

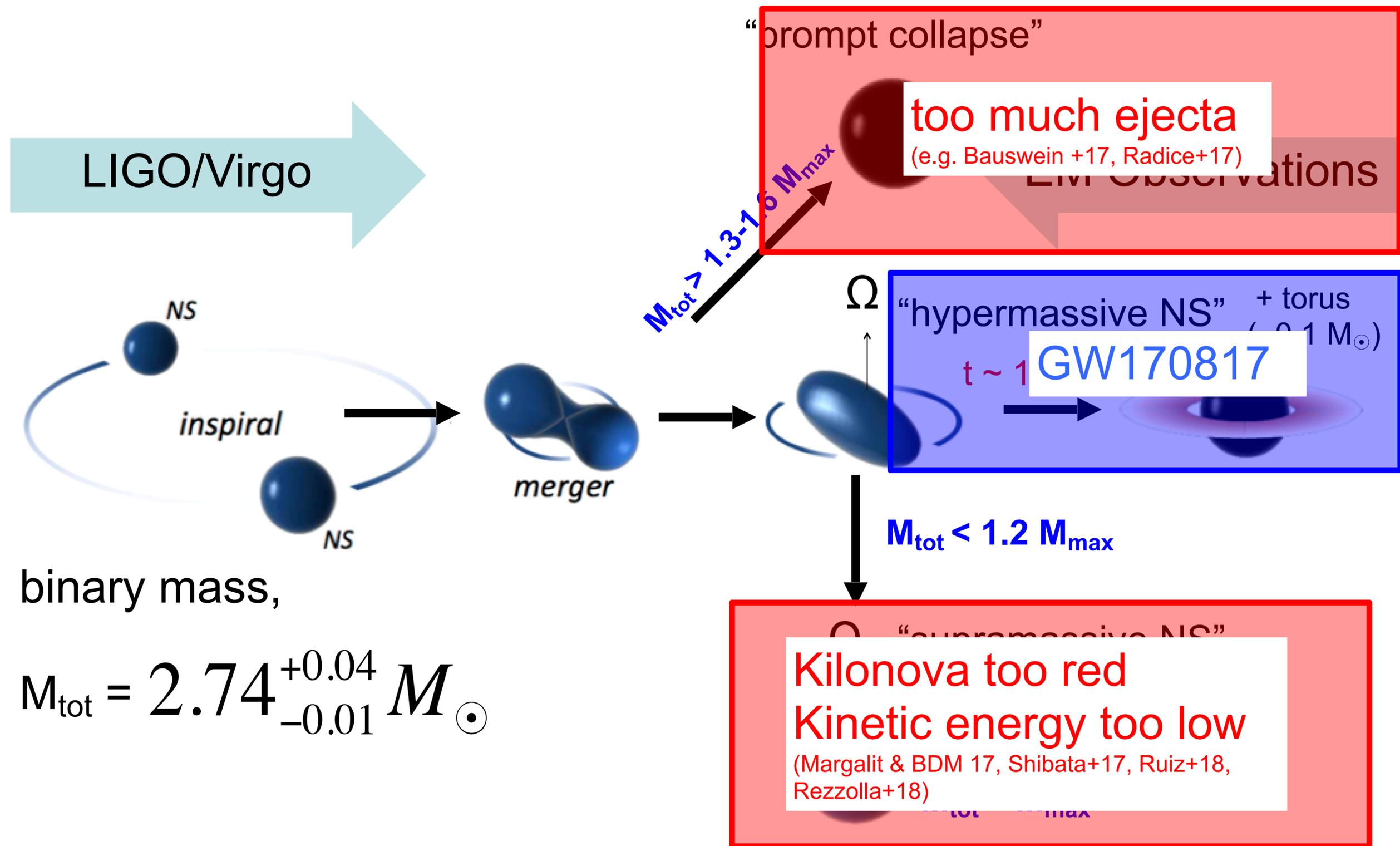
"supramassive NS"

Kilonova too red
Kinetic energy too low
(Margalit & BDM 17, Shibata+17, Ruiz+18, Rezzolla+18)

binary mass,

$$M_{\text{tot}} = 2.74^{+0.04}_{-0.01} M_{\odot}$$

Outcomes of Neutron Star Mergers

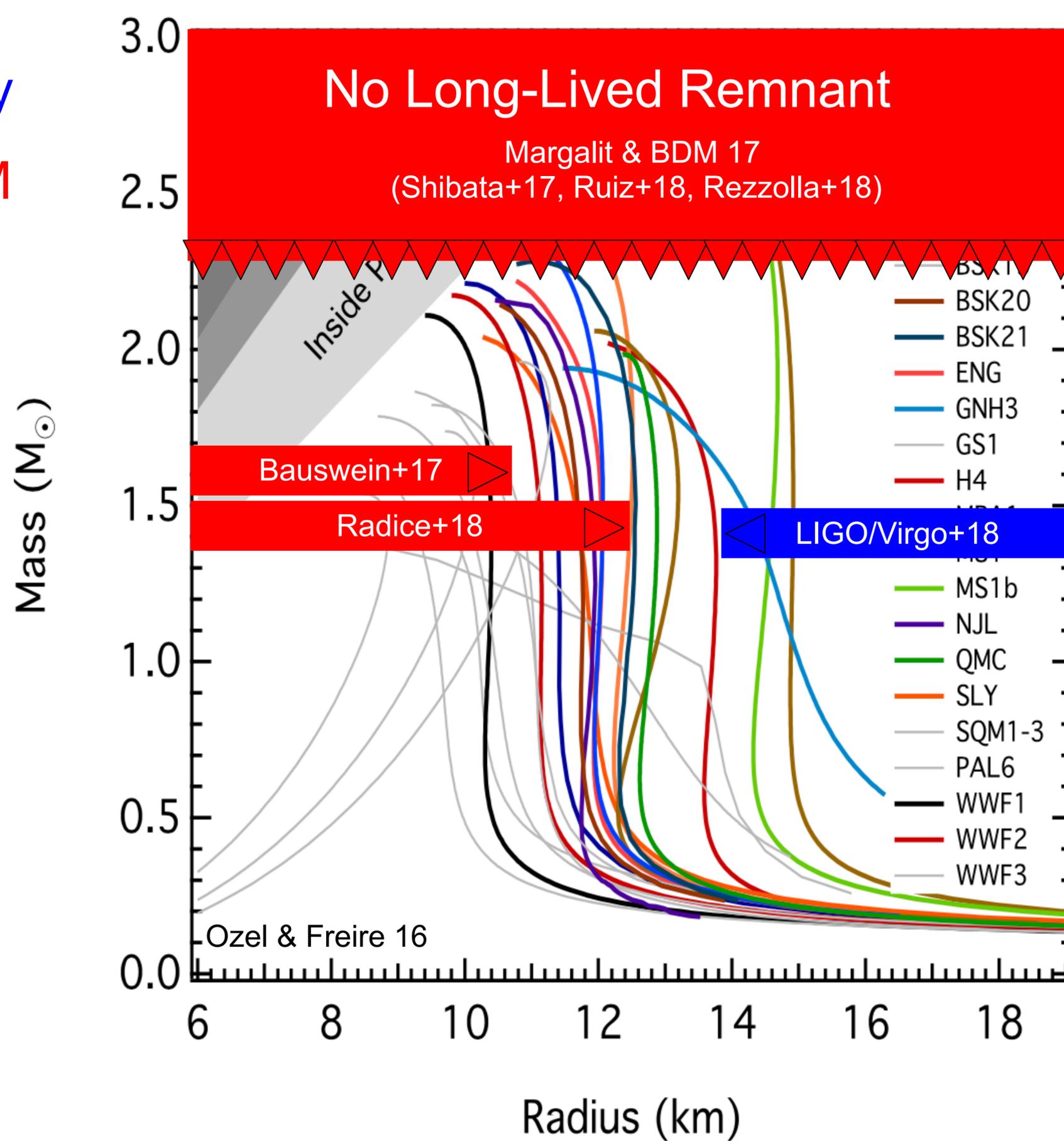


binary mass,

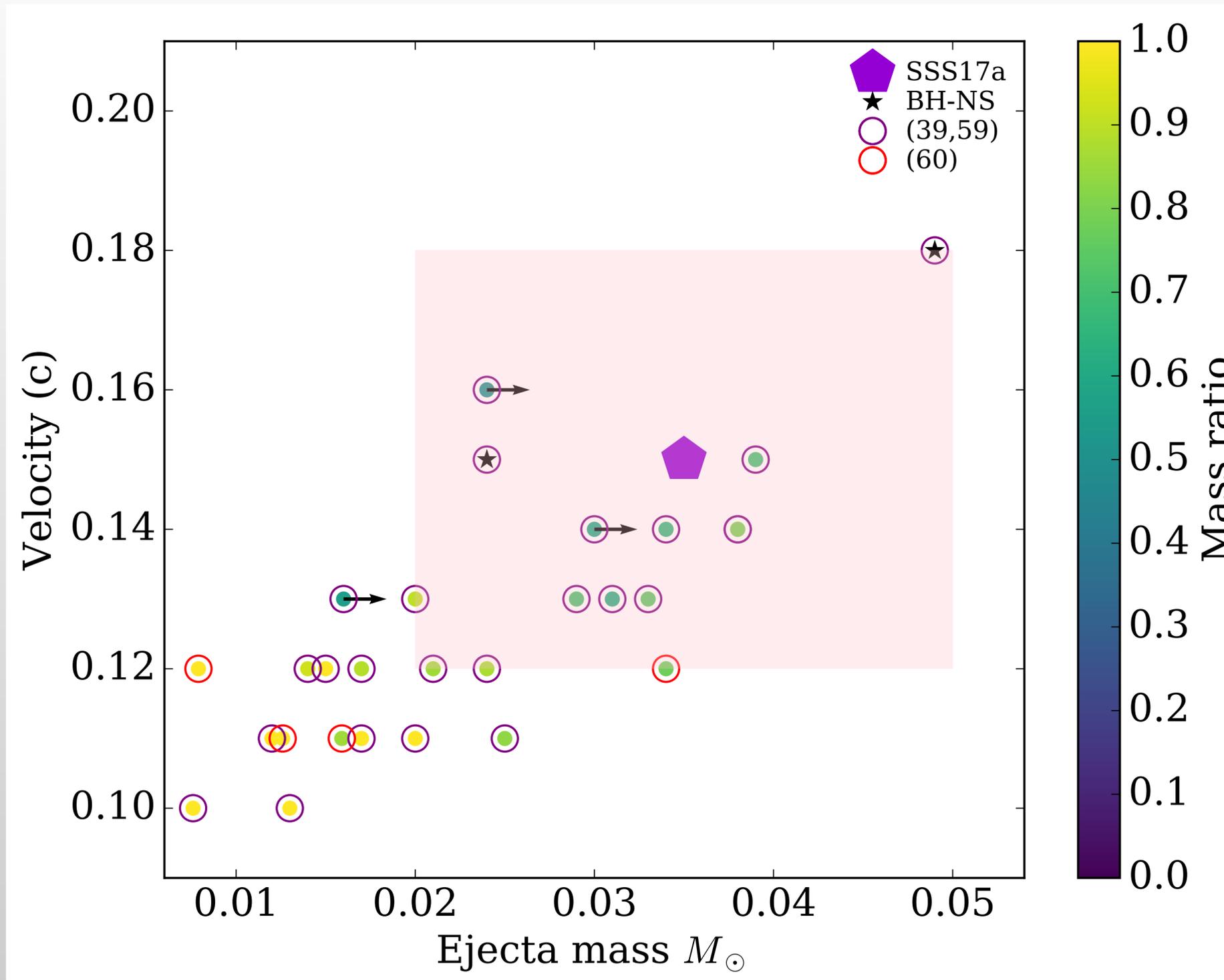
$$M_{\text{tot}} = 2.74^{+0.04}_{-0.01} M_{\odot}$$

GW only

GW+EM



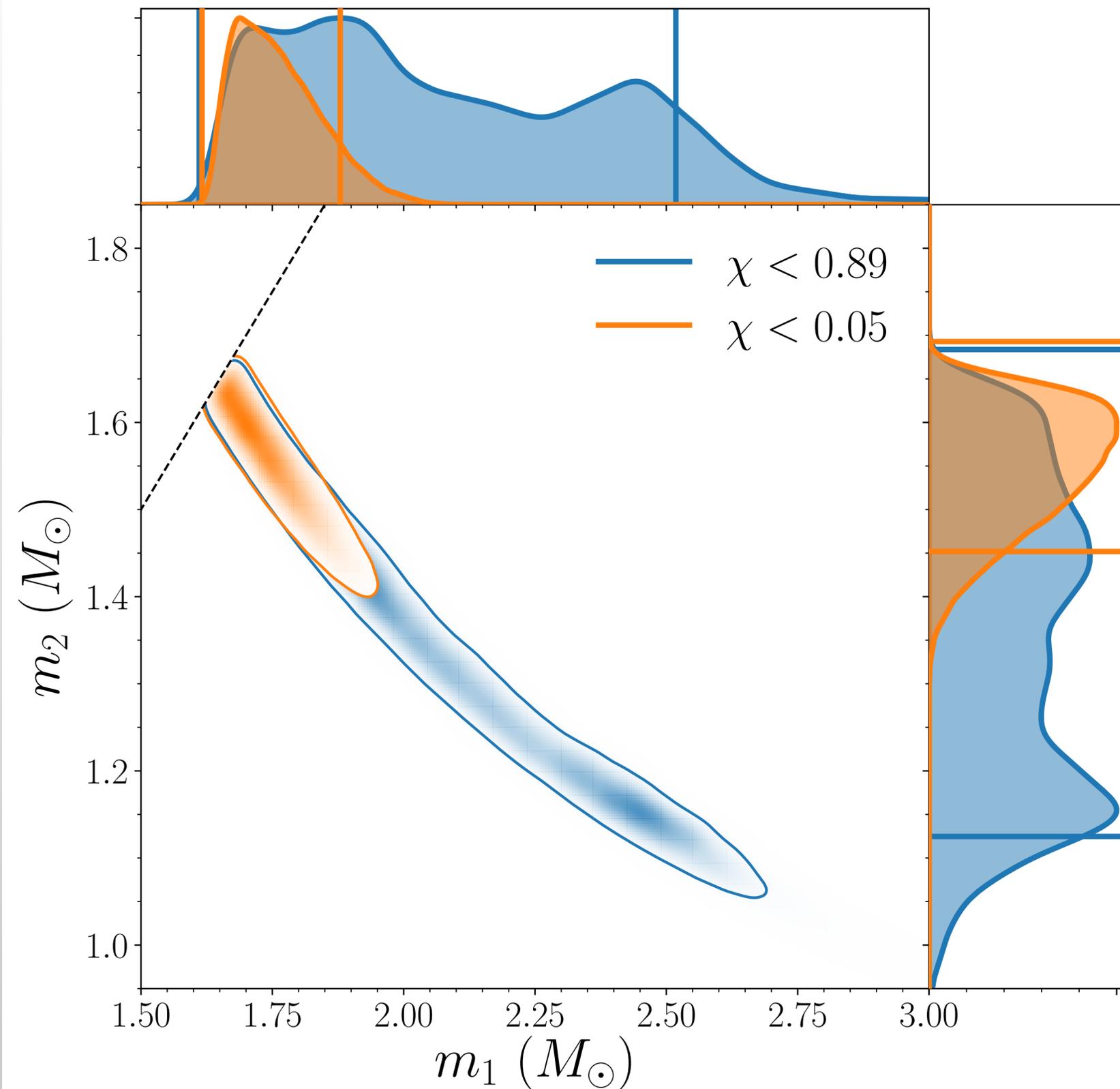
Mass Ratio of ~ 0.75 from EM Data



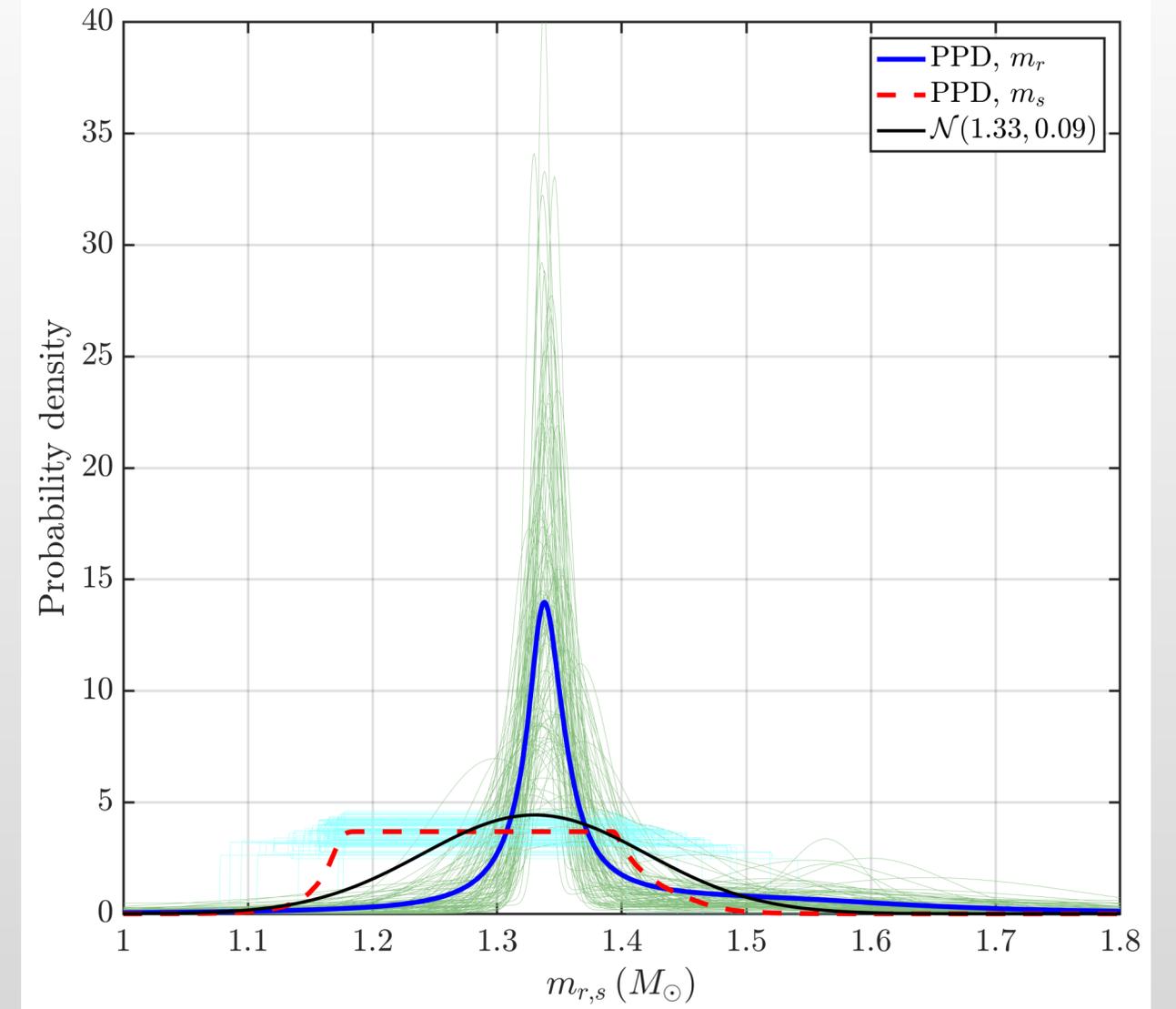
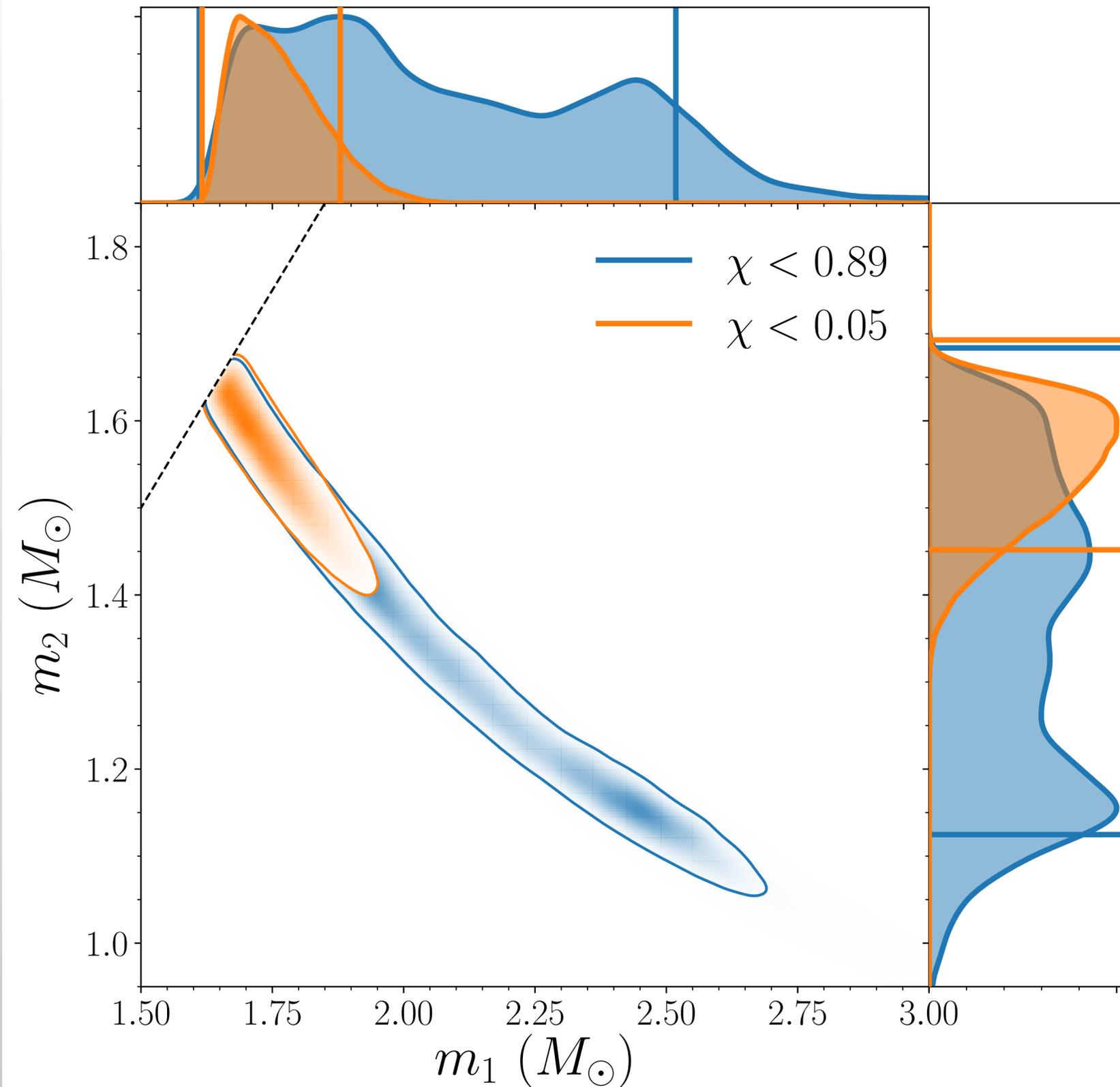
Kilpatrick et al. 2017

GW190425

$$M_{\text{tot}} = 3.4^{+0.3}_{-0.1} M_{\text{sun}}$$
$$m_1 = 1.61 - 2.52 M_{\text{sun}}$$
$$m_2 = 1.12 - 1.68 M_{\text{sun}}$$



GW190425: 1.4+2.0 BNS



Farrow, Zhu, & Thrane, 2019

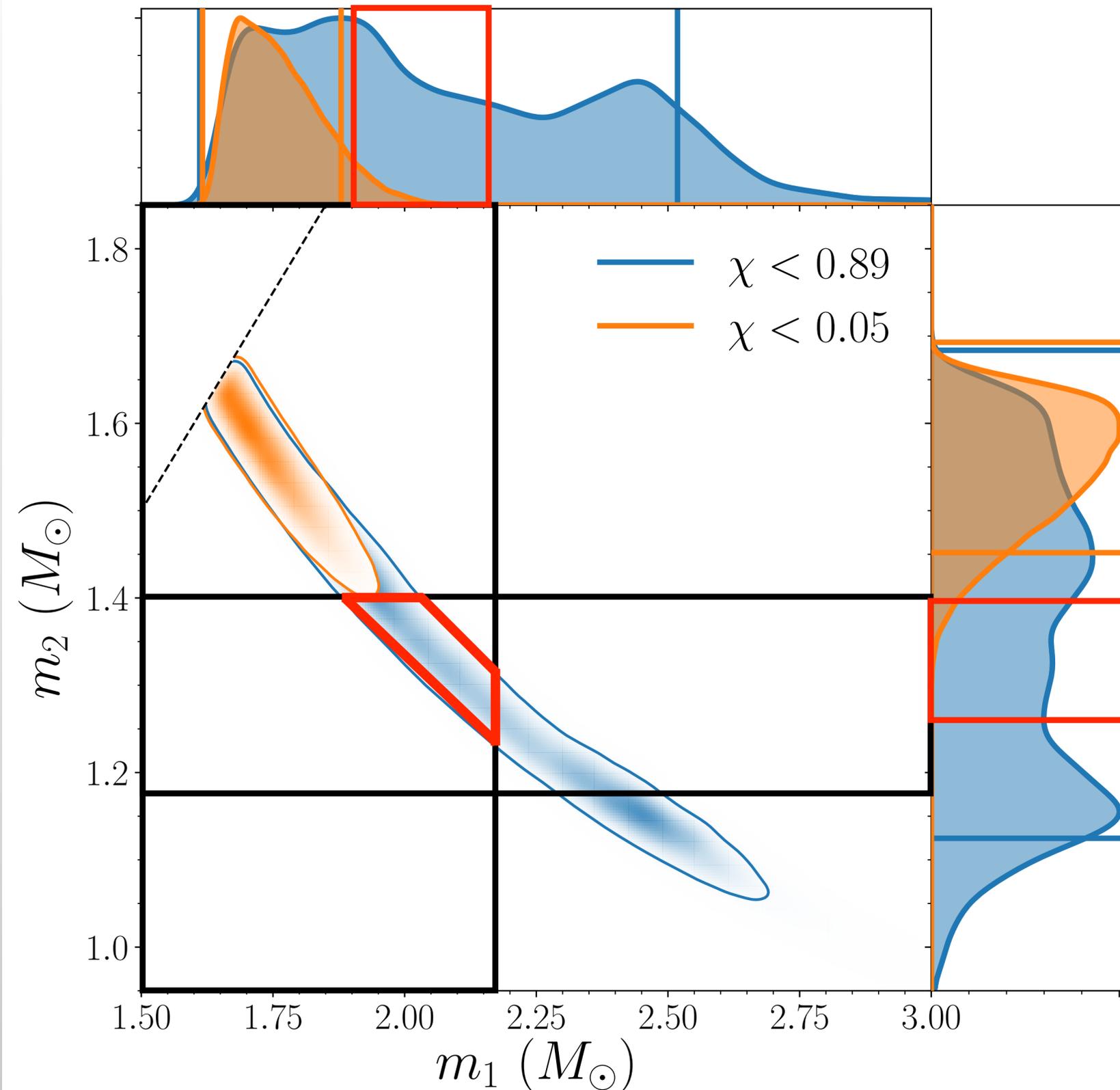
LVC 2020

GW190425: 1.4+2.0 BNS

$$M_{\text{tot}} \approx 3.35 \pm 0.07 M_{\text{sun}}$$

$$m_1 \approx 1.90 - 2.16 M_{\text{sun}}$$

$$m_2 \approx 1.26 - 1.38 M_{\text{sun}}$$



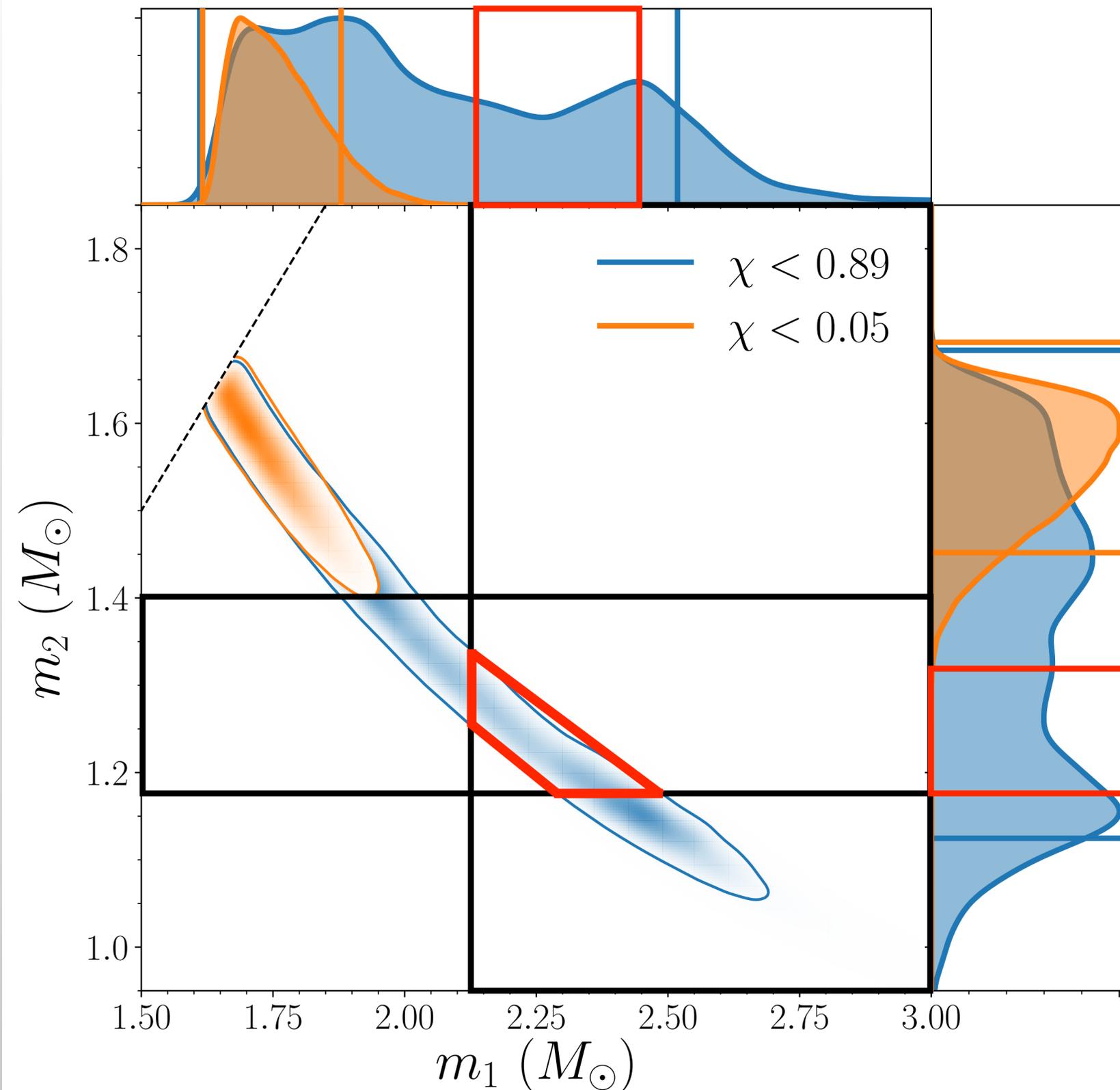
LVC 2020

GW190425: 1.2+2.2 NSBH

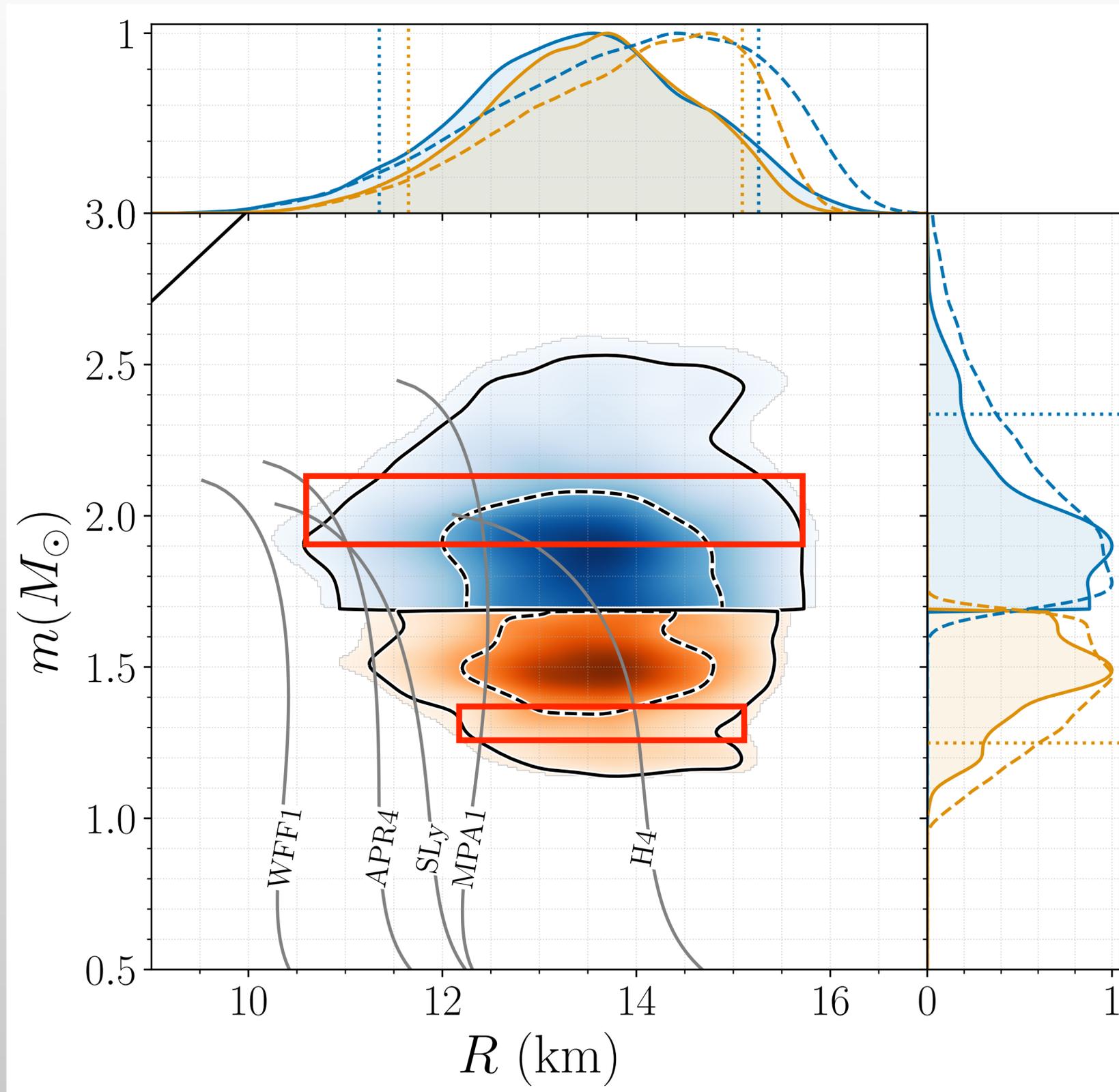
$$M_{\text{tot}} \approx 3.54 \pm 0.07 M_{\text{sun}}$$

$$m_1 \approx 2.15 - 2.44 M_{\text{sun}}$$

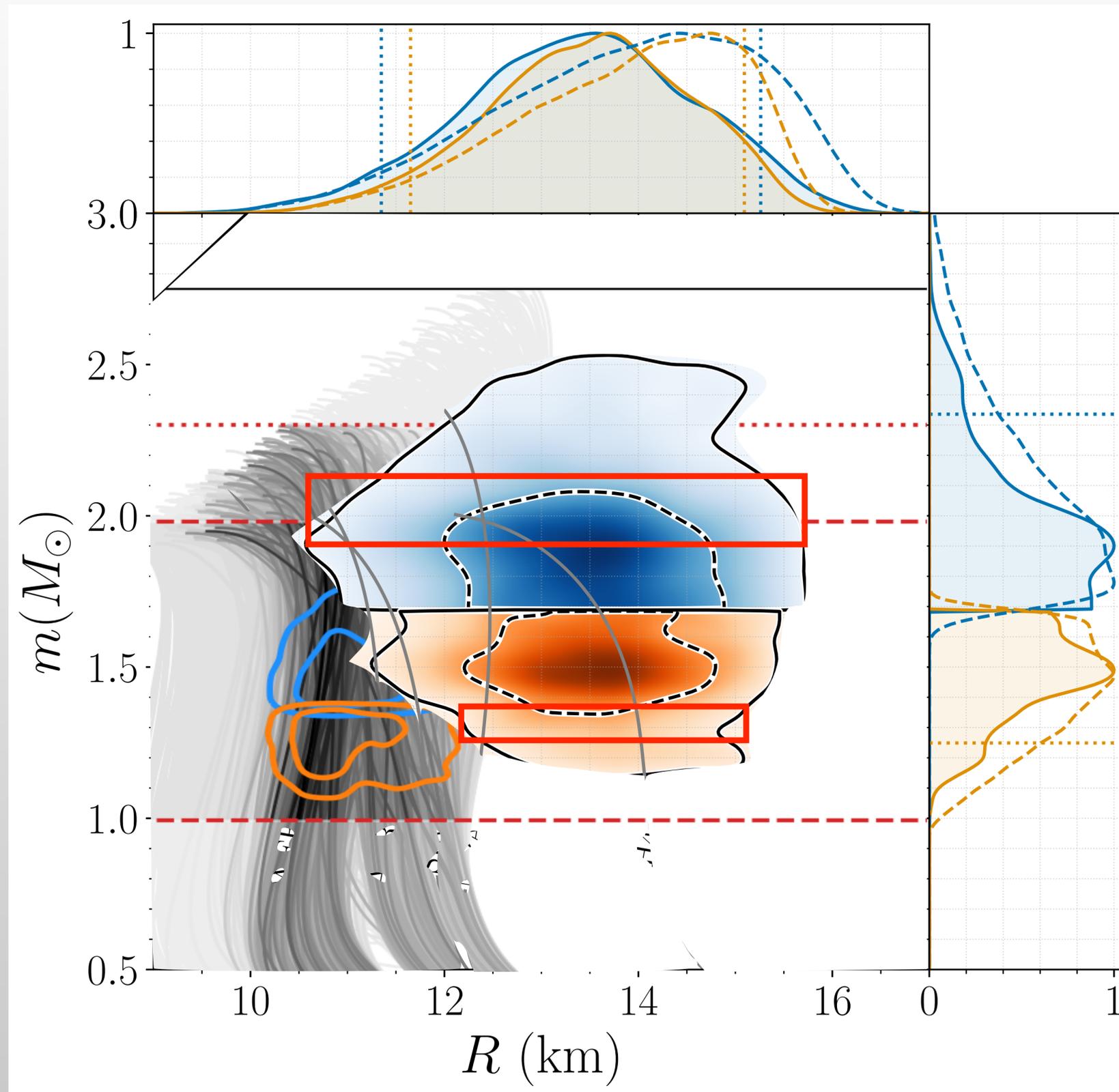
$$m_2 \approx 1.17 - 1.32 M_{\text{sun}}$$



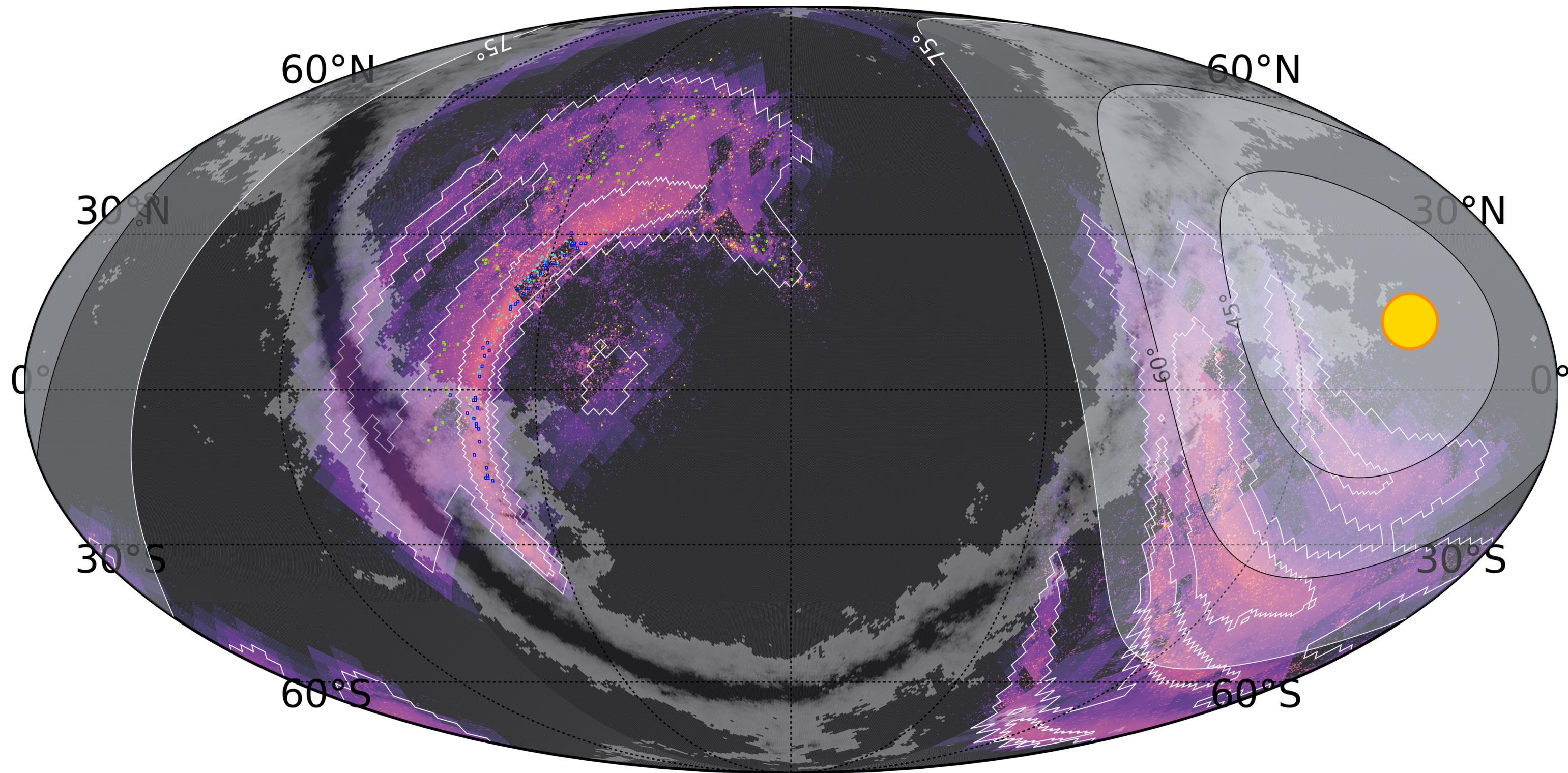
GW190425: Updated EOS

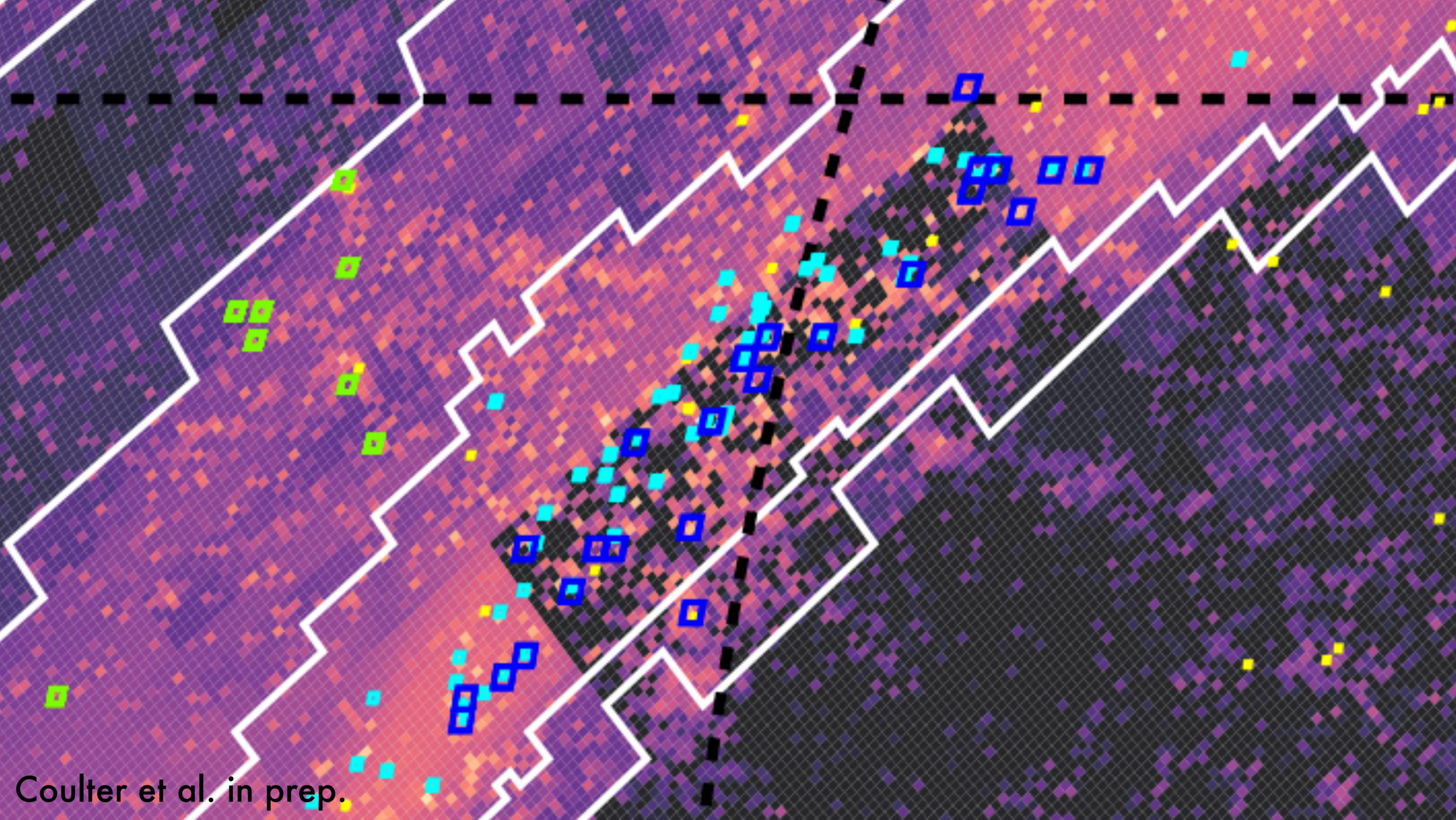


GW190425: Updated EOS



Declination

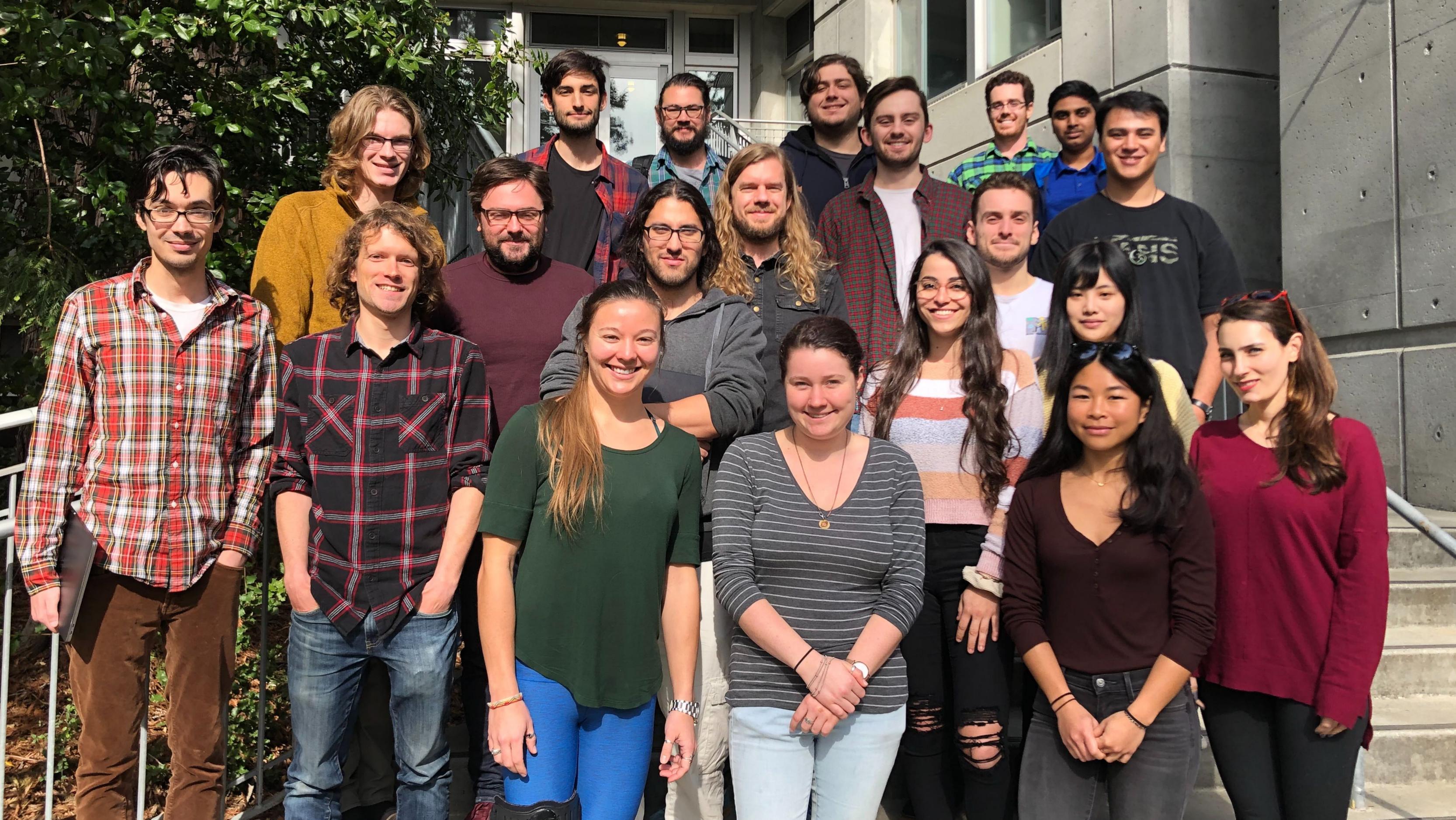




Some Thoughts

- We found the counterpart to a Gravitational Wave source!
- Huge improvements in EOS studies, especially when combining EM and GW
- There is a population of high-mass BNS systems
- GW190425 likely was a $1.3+2.0$ BNS system, improving constraints
- GW and Multi-messenger Astronomy is Taking Off – Join the Revolution!
- Images, Movies, and Papers at <http://ziggy.ucolick.org/sss17a/>





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