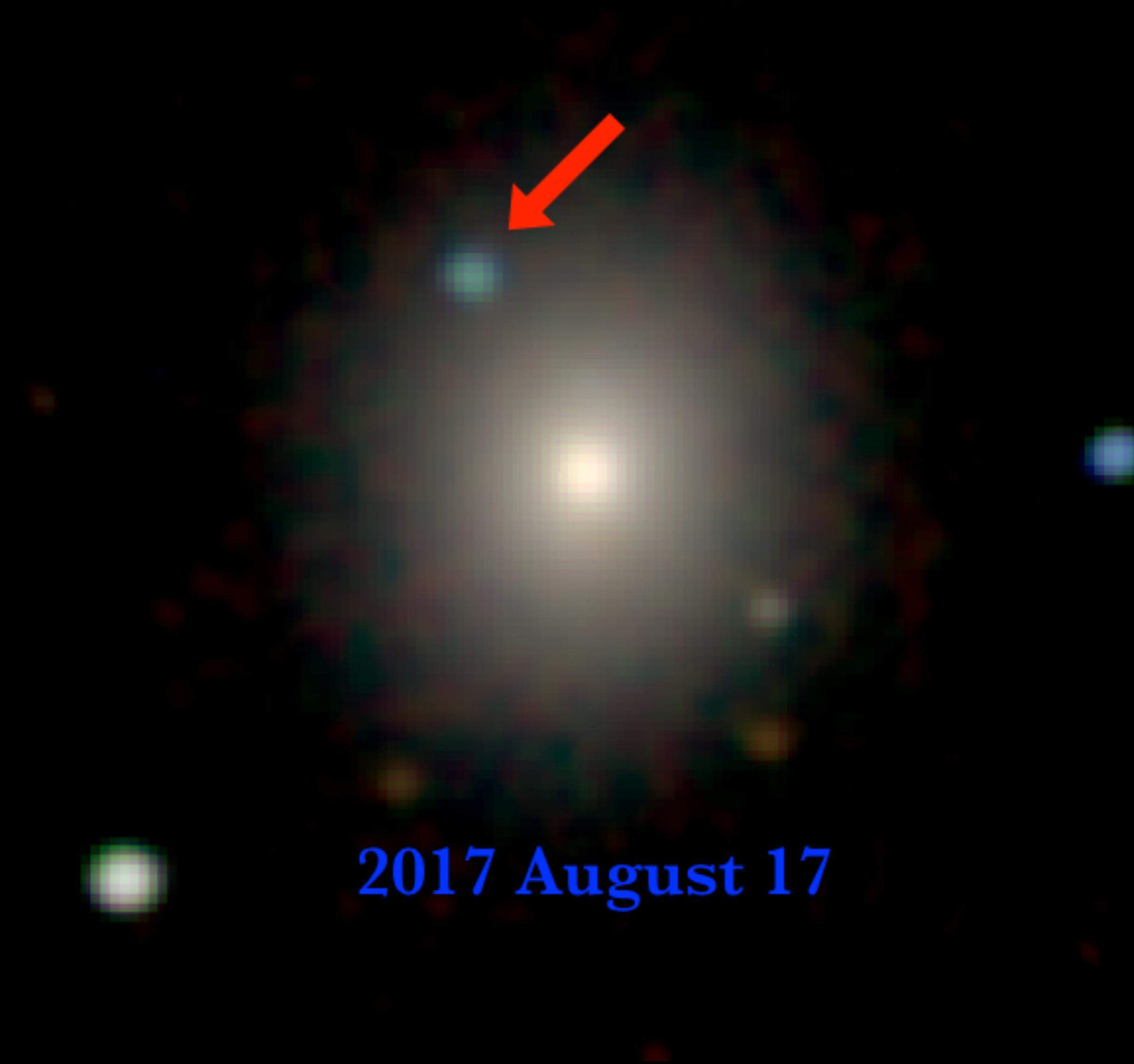


Discovery of the First Optical Counterpart to a Gravitational Wave Source and Neutron Star Equation of State

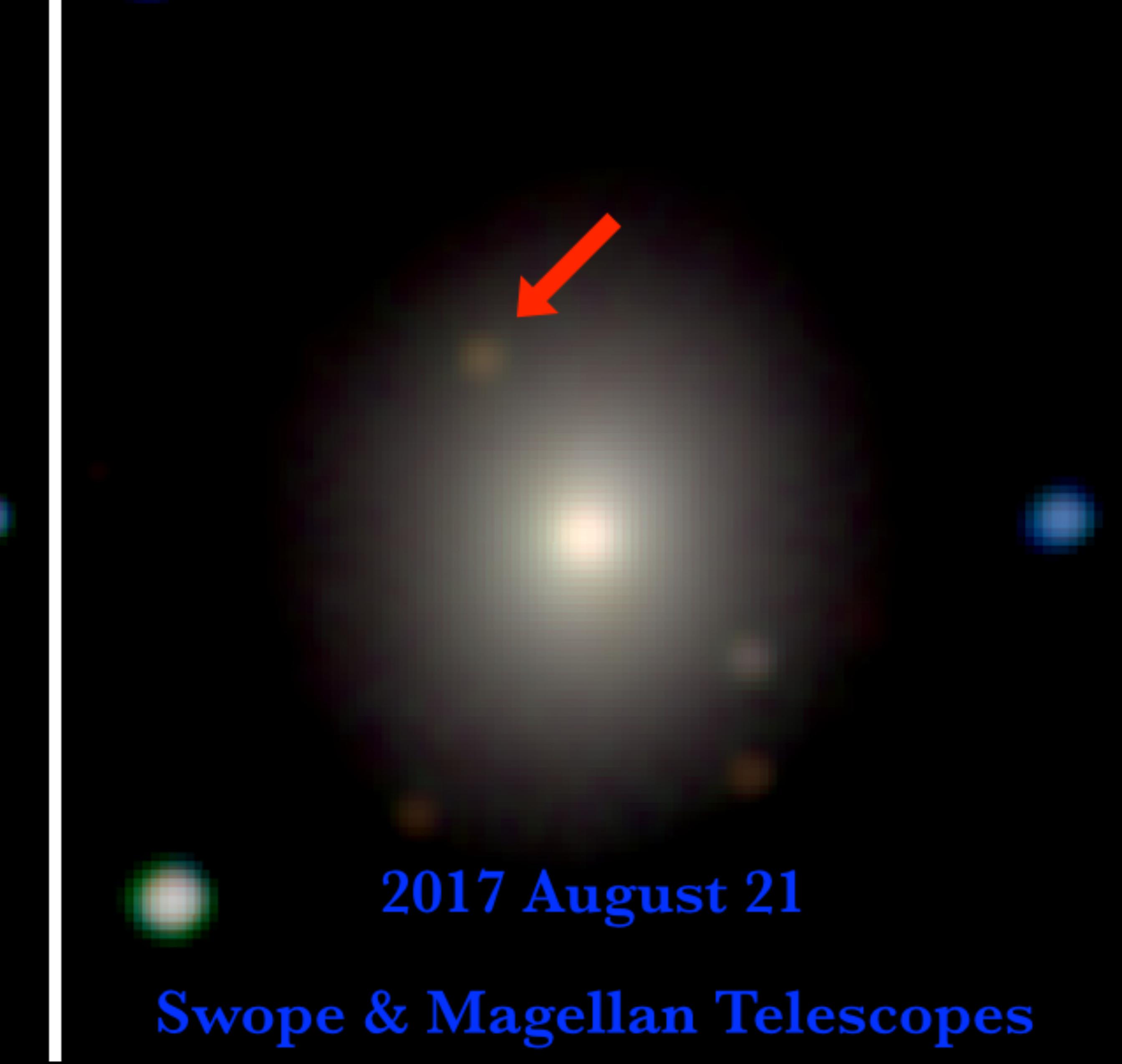


Ryan Foley < UC Santa Cruz > 1M2H Team

SSS17a

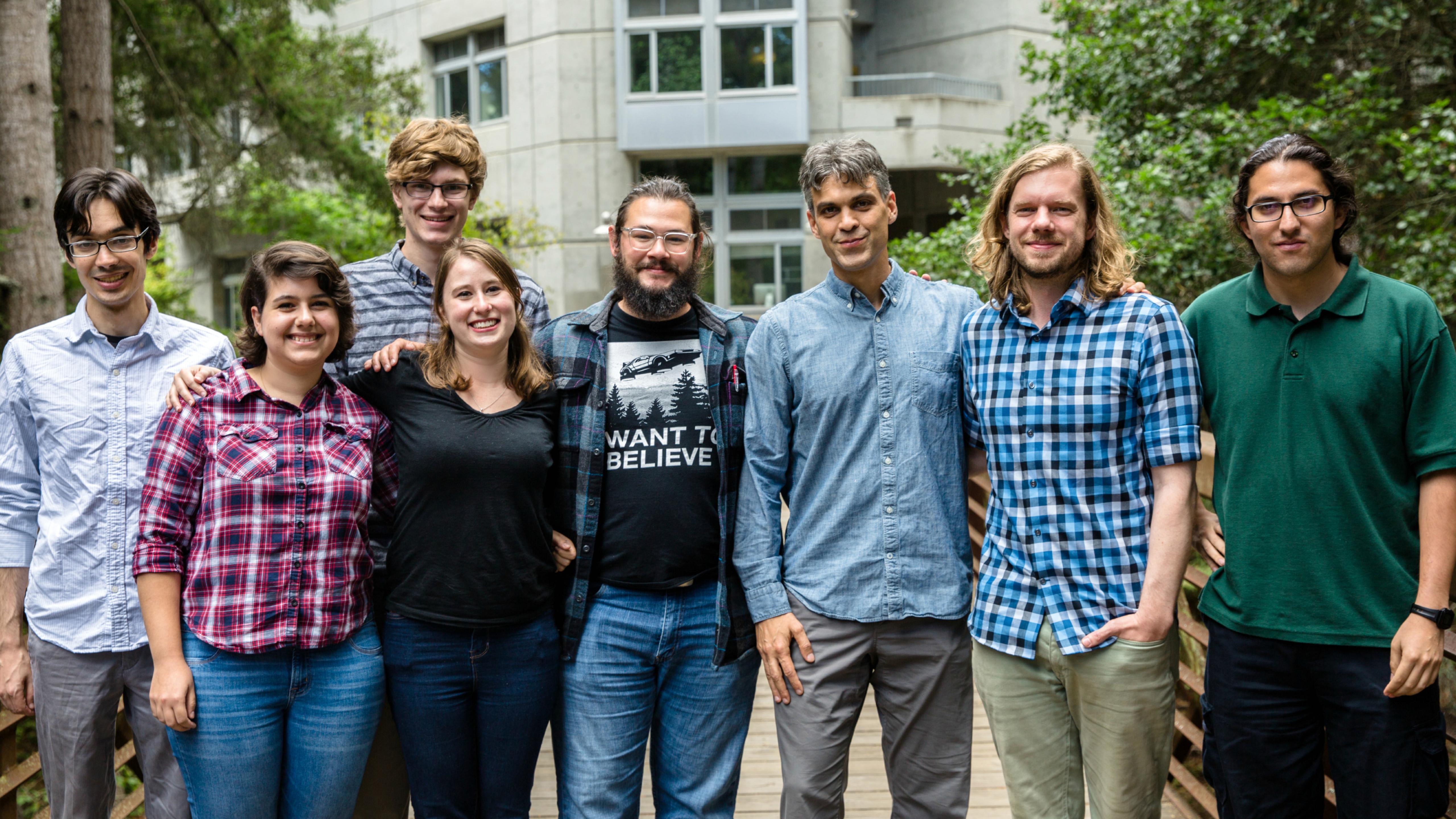


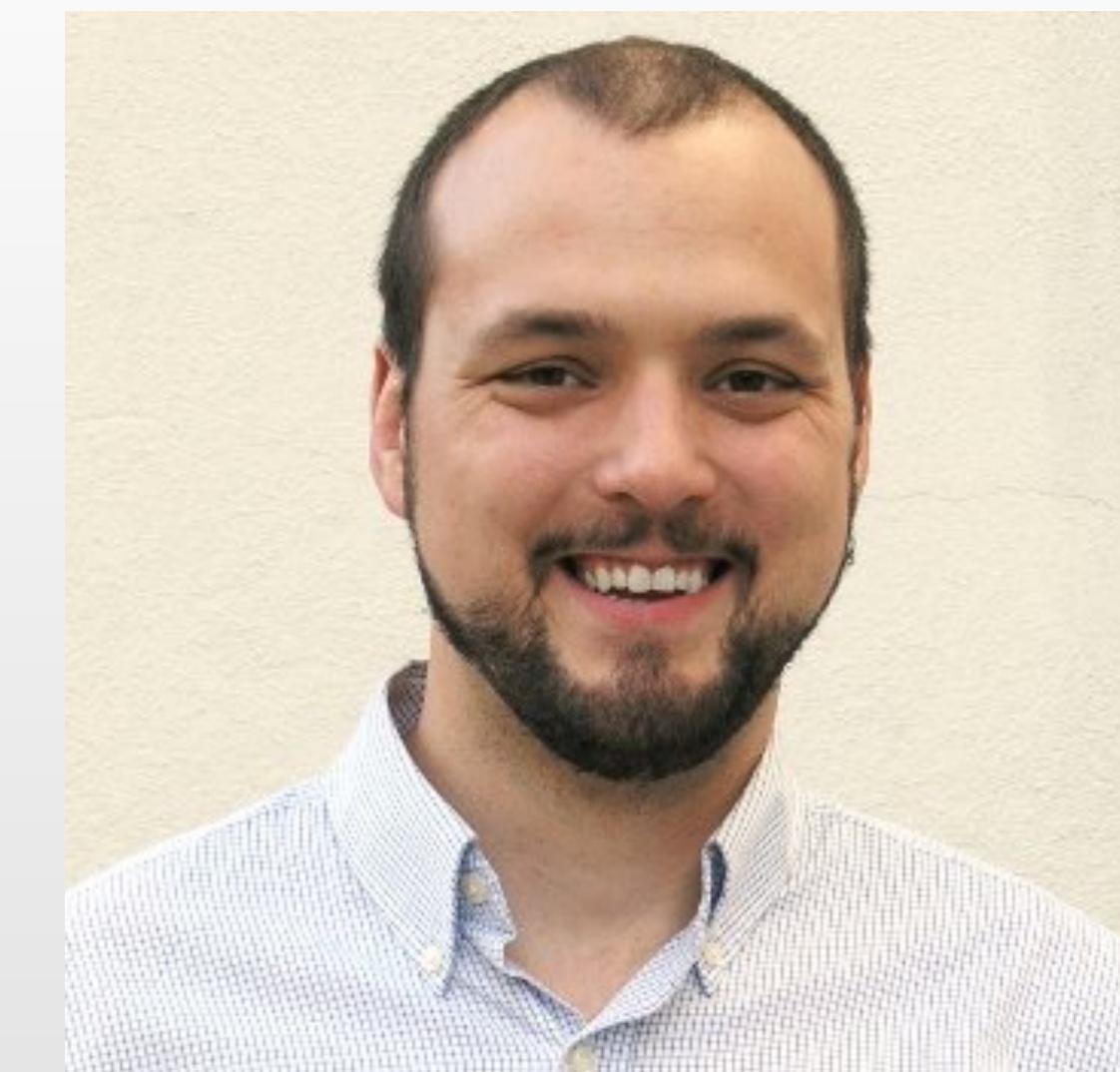
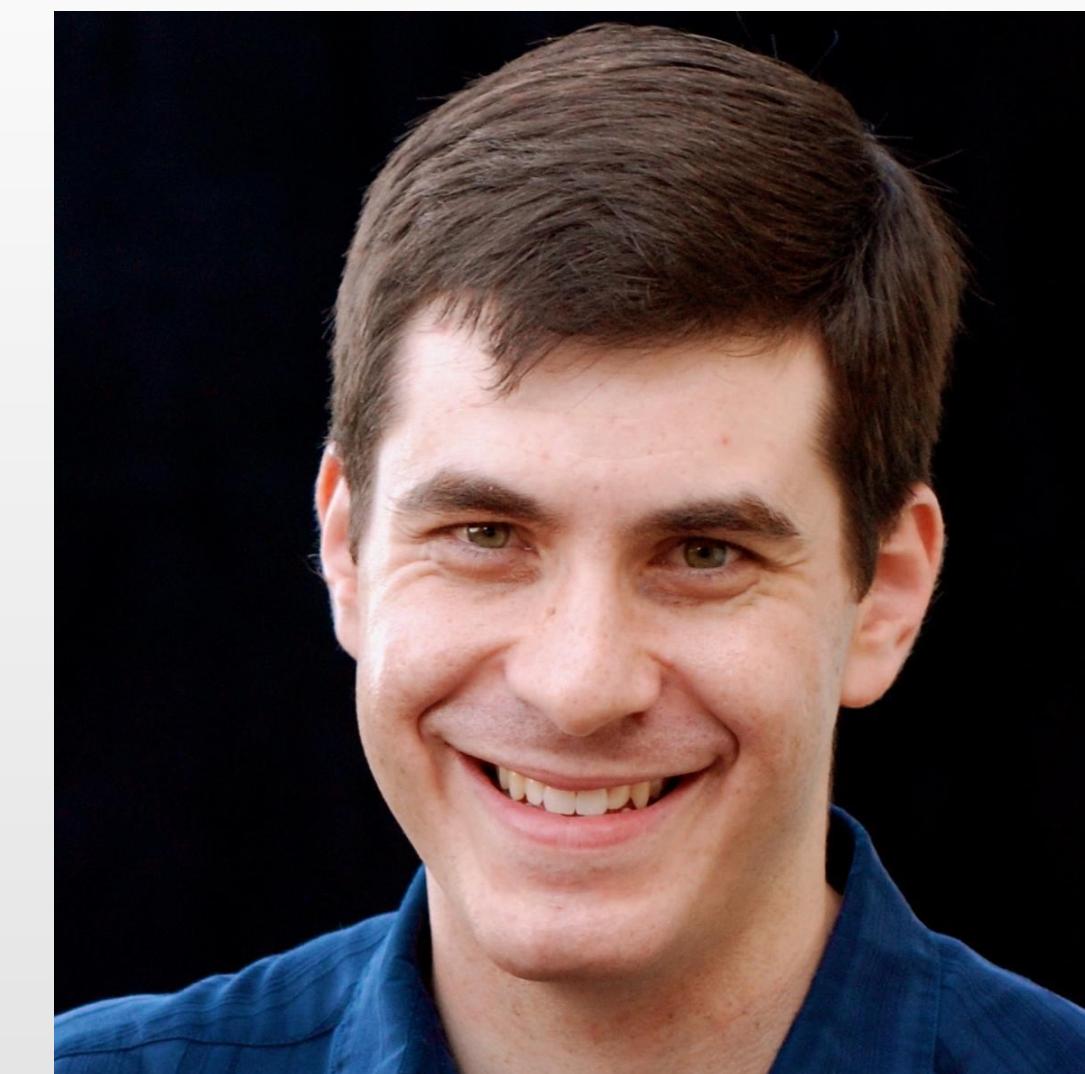
2017 August 17



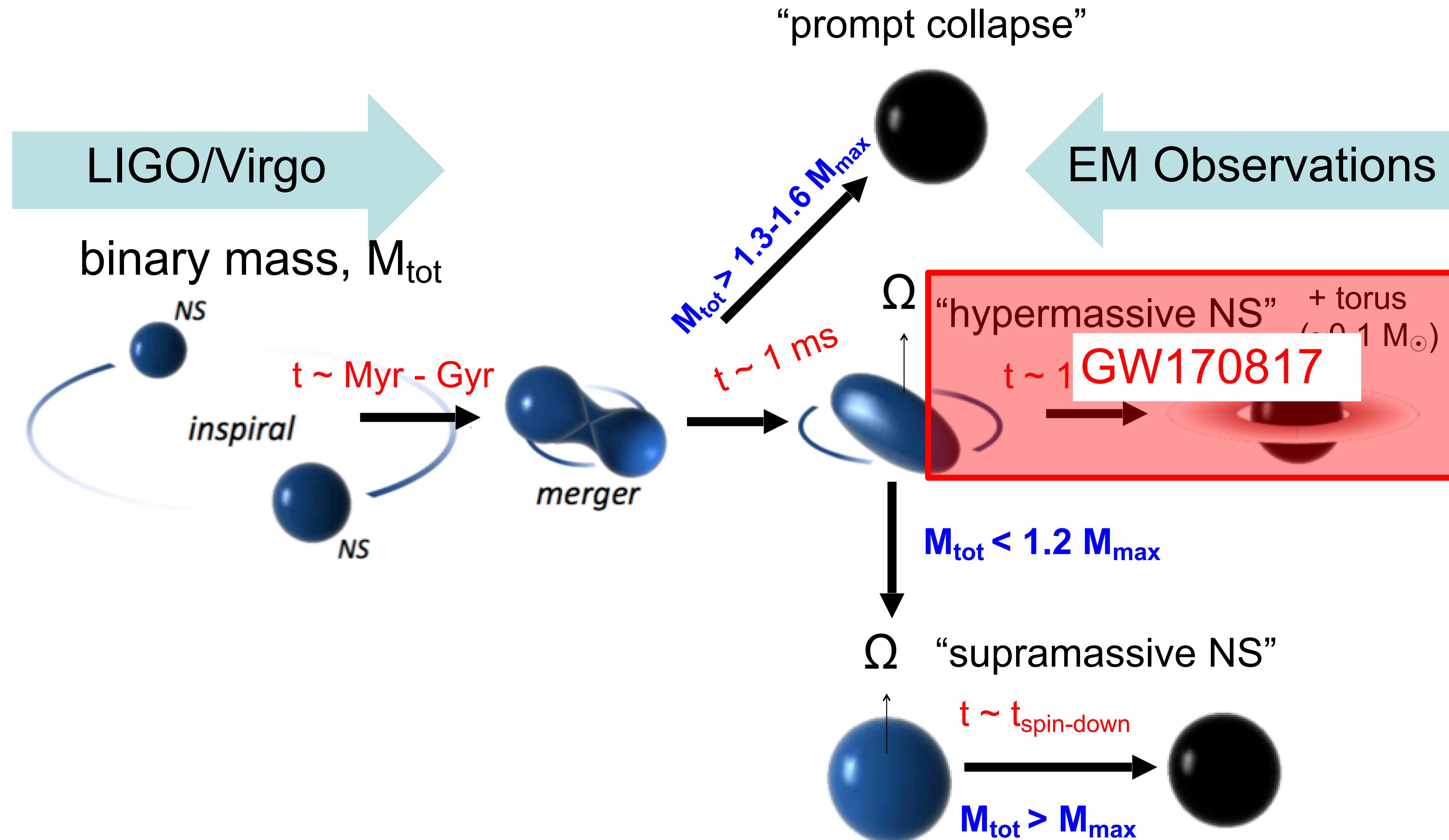
2017 August 21

Swope & Magellan Telescopes

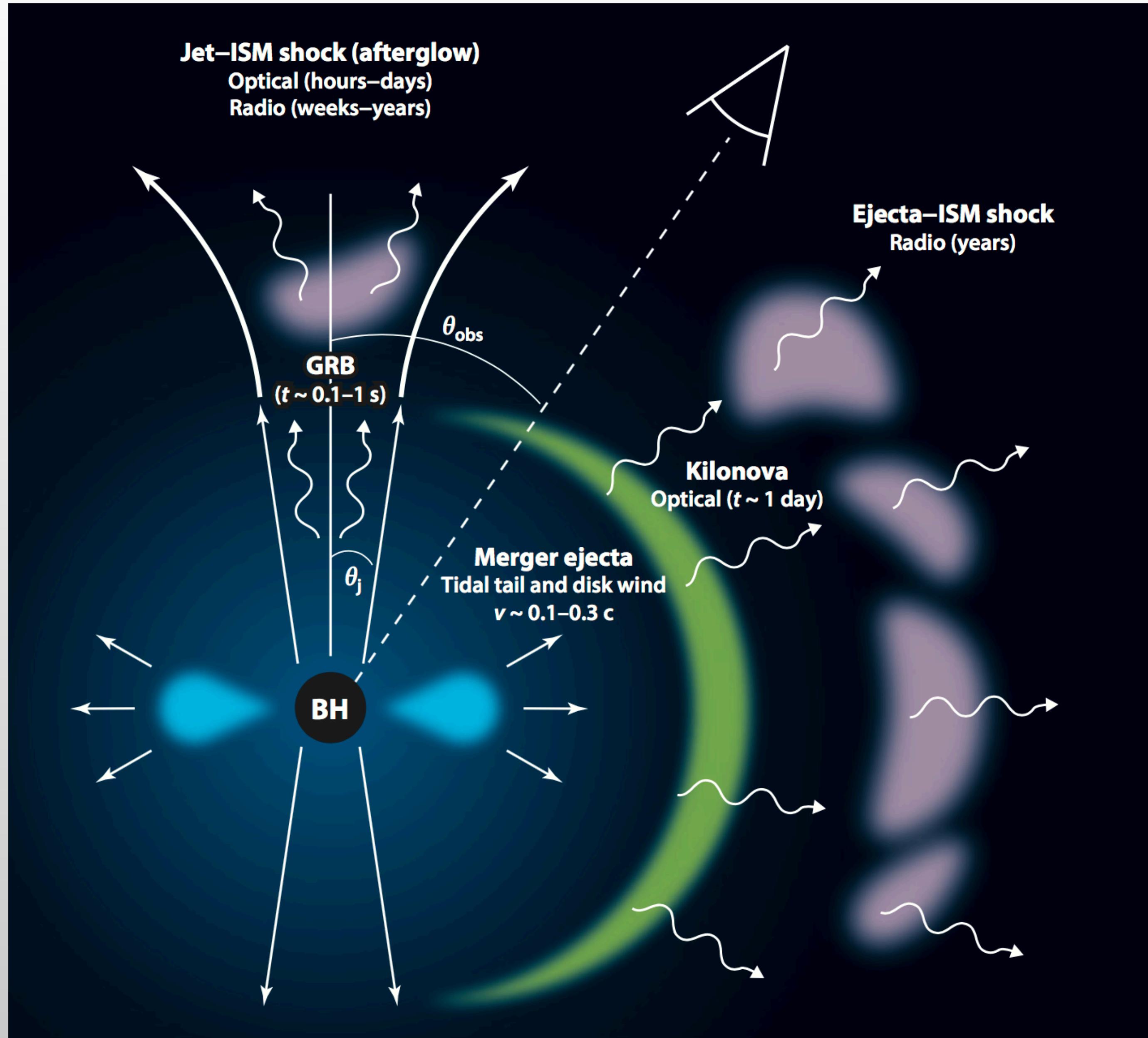




Outcomes of Neutron Star Mergers



What are the EM Counterparts?



Metzger &
Berger 2012

Neutron-Rich Ejecta

“Dynamical”

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

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

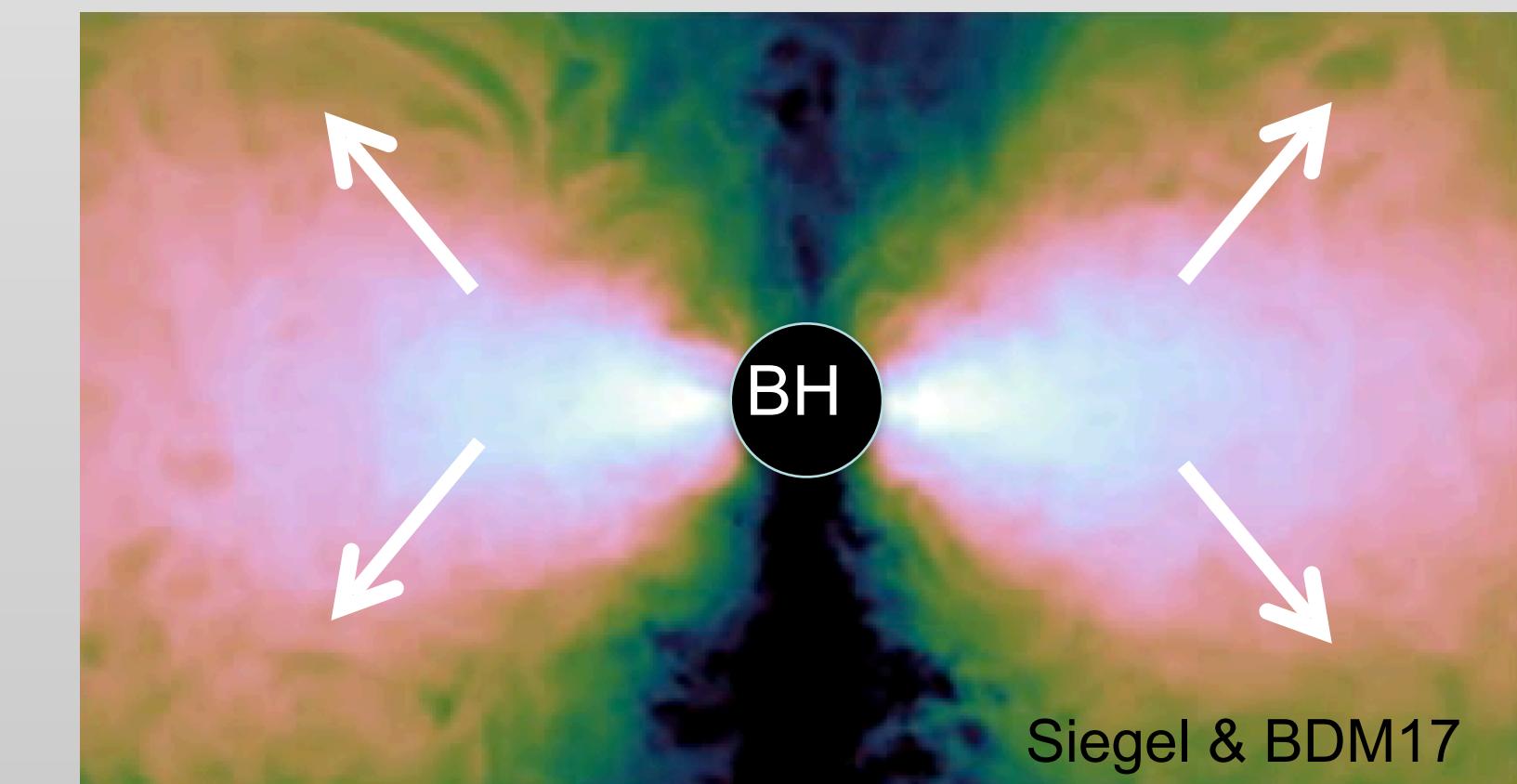
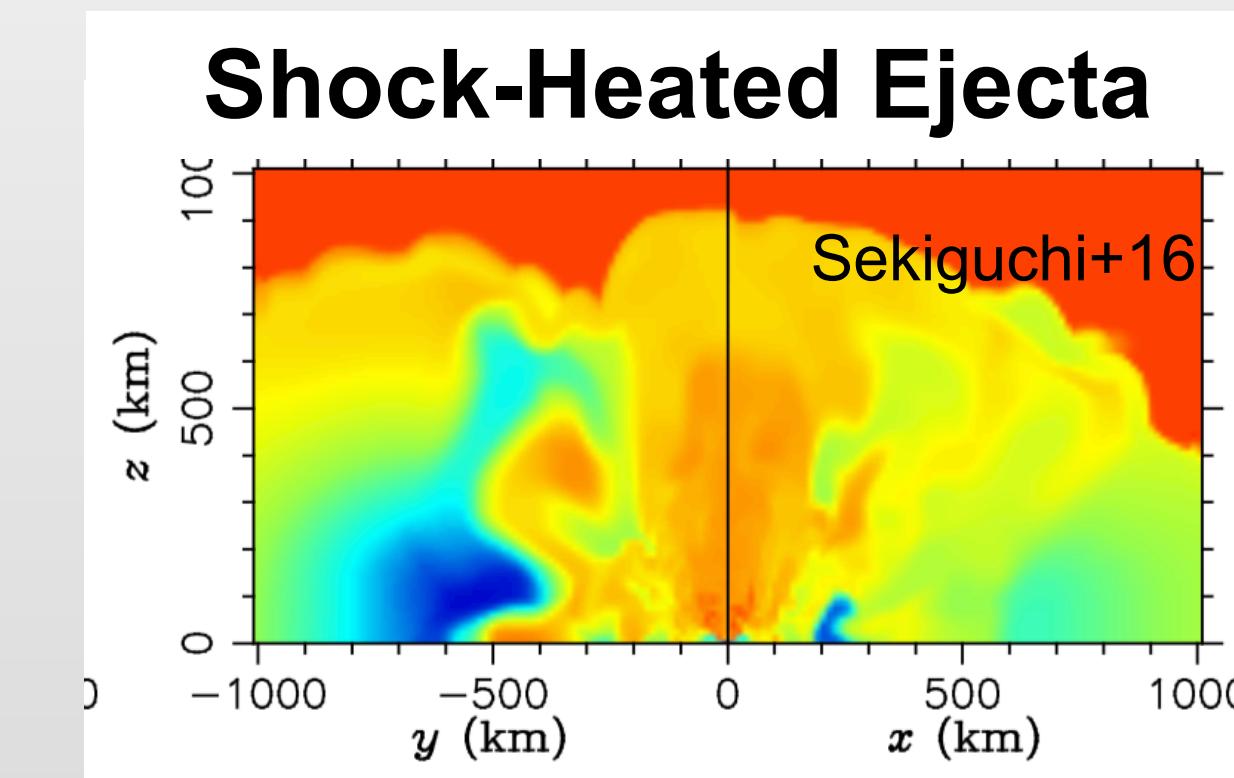
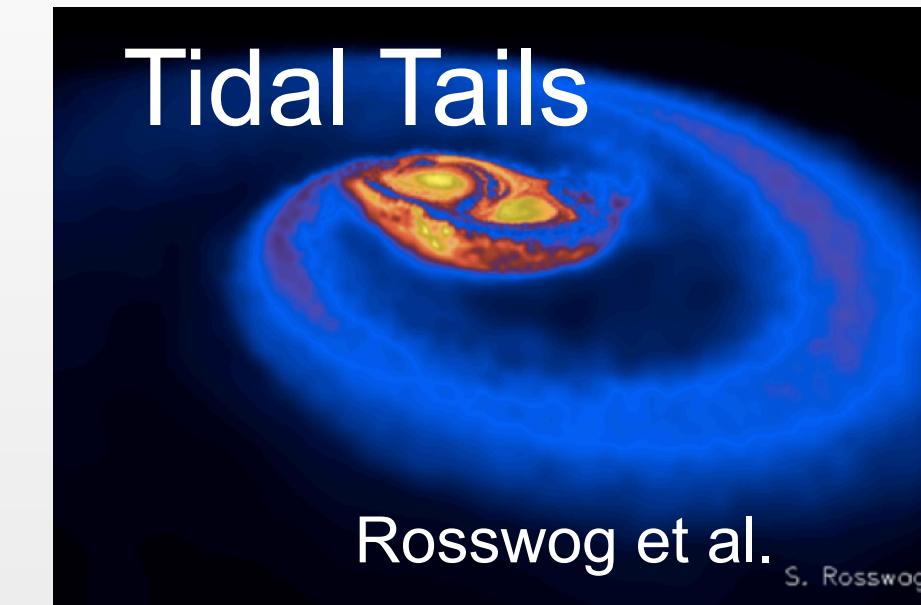
$$v_{ej} \sim 0.3 c$$

Disk Winds

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

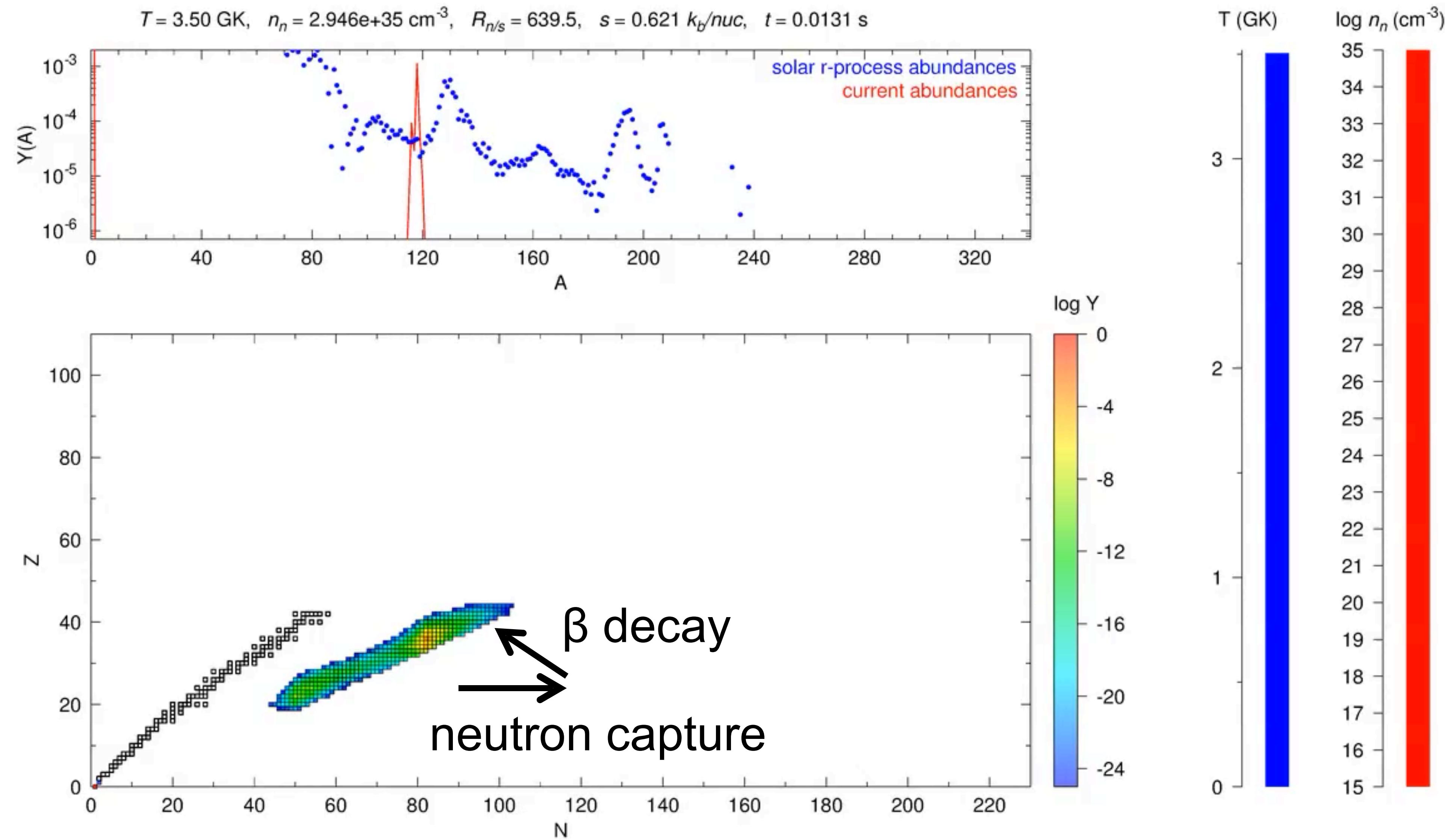
$$t_{exp} \sim \text{seconds}$$

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



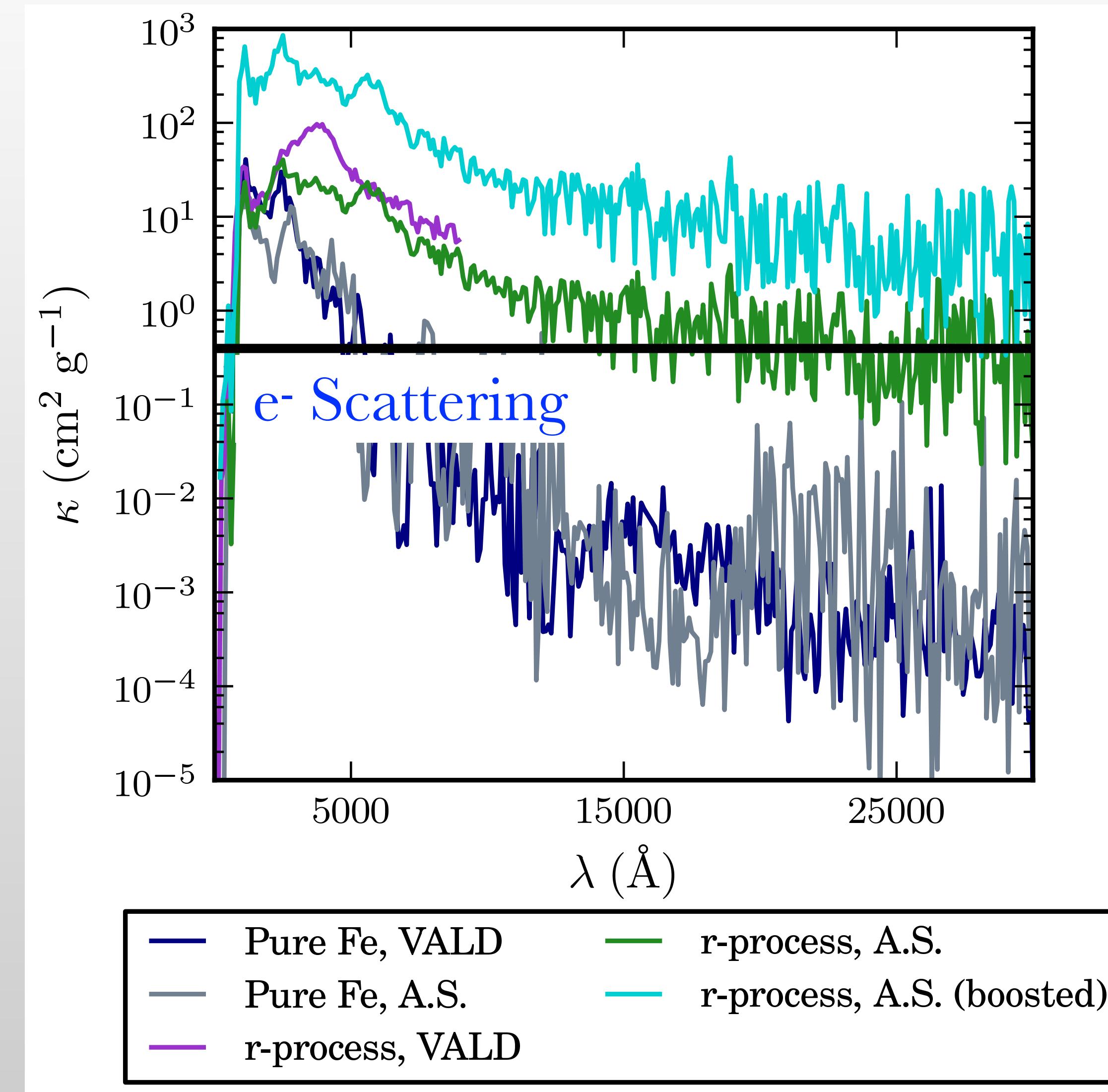
time

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



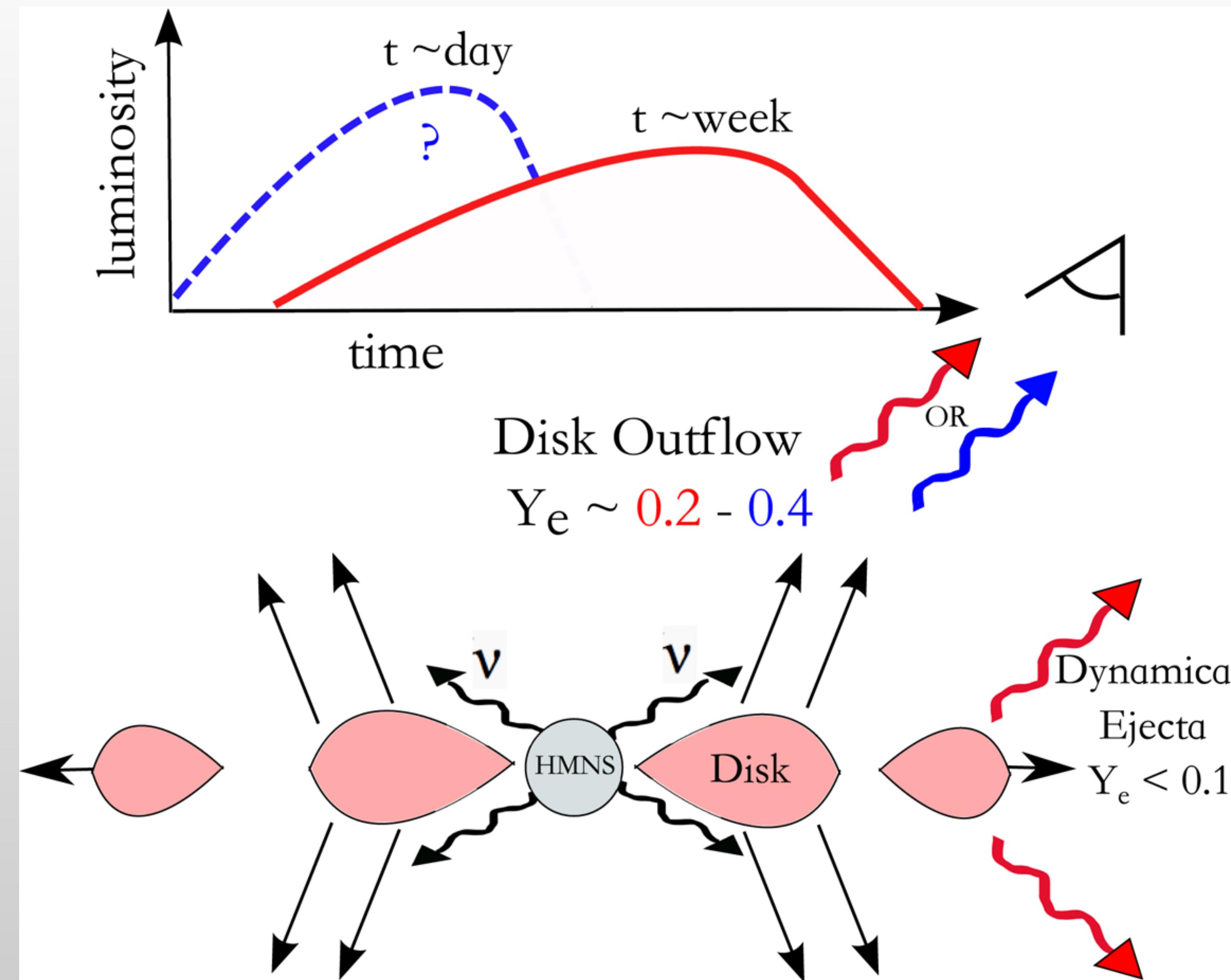
Courtesy Gabriel Martinez-Pinedo

Lanthanides Have Very High Opacities



Kasen, Badnell, & Barnes 2013

Fast Blue and Slower Red Components



Metzger & Fernández 2014

One Meter, Two Hemispheres (1M2H)



On August 17, 2017...



< 15



DC

Dave



Thu, Aug 17, 6:39 AM

Stop what you're doing and check your email.

Thu, Aug 17, 8:12 AM

I don't have email now. What's up?

NS NS merger at a false alarm rate as 1 in [10000](#) years

Coincident neutrinos and GRB

Position?

This sounds like a joke by the way



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

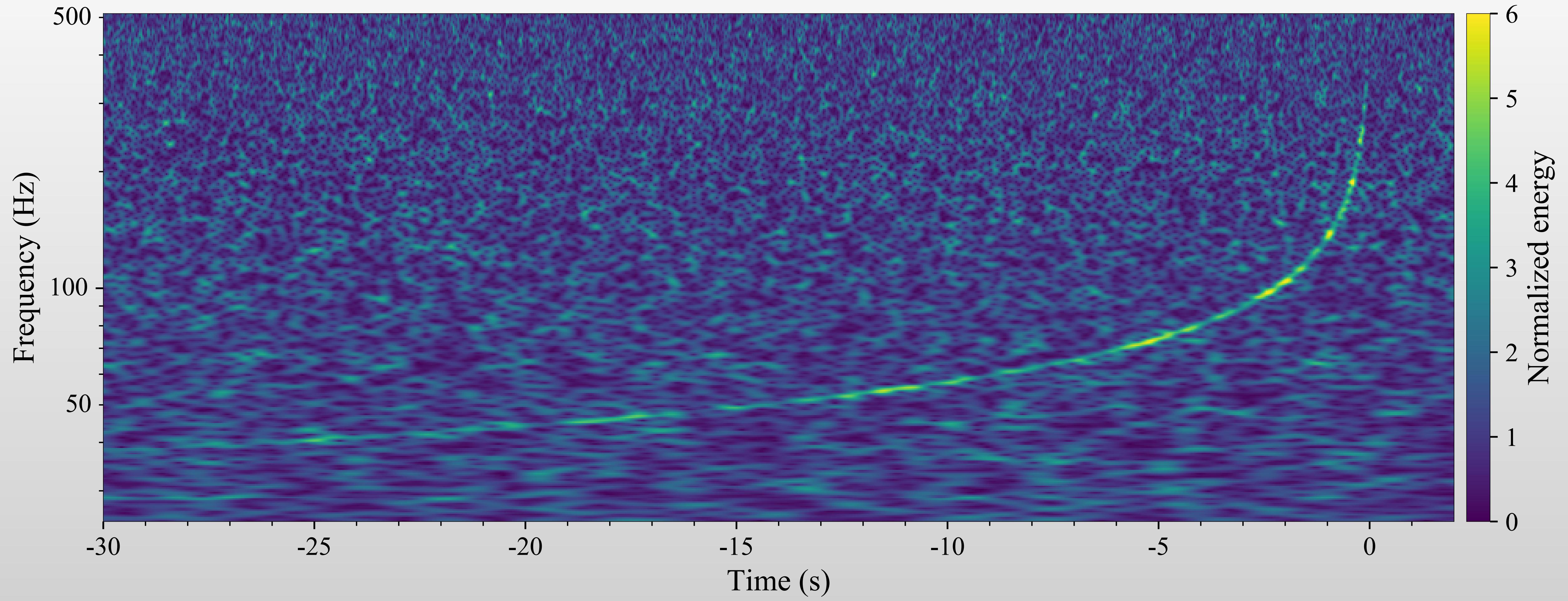
Although, I keep fucking up my
coordinates. One sec.

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

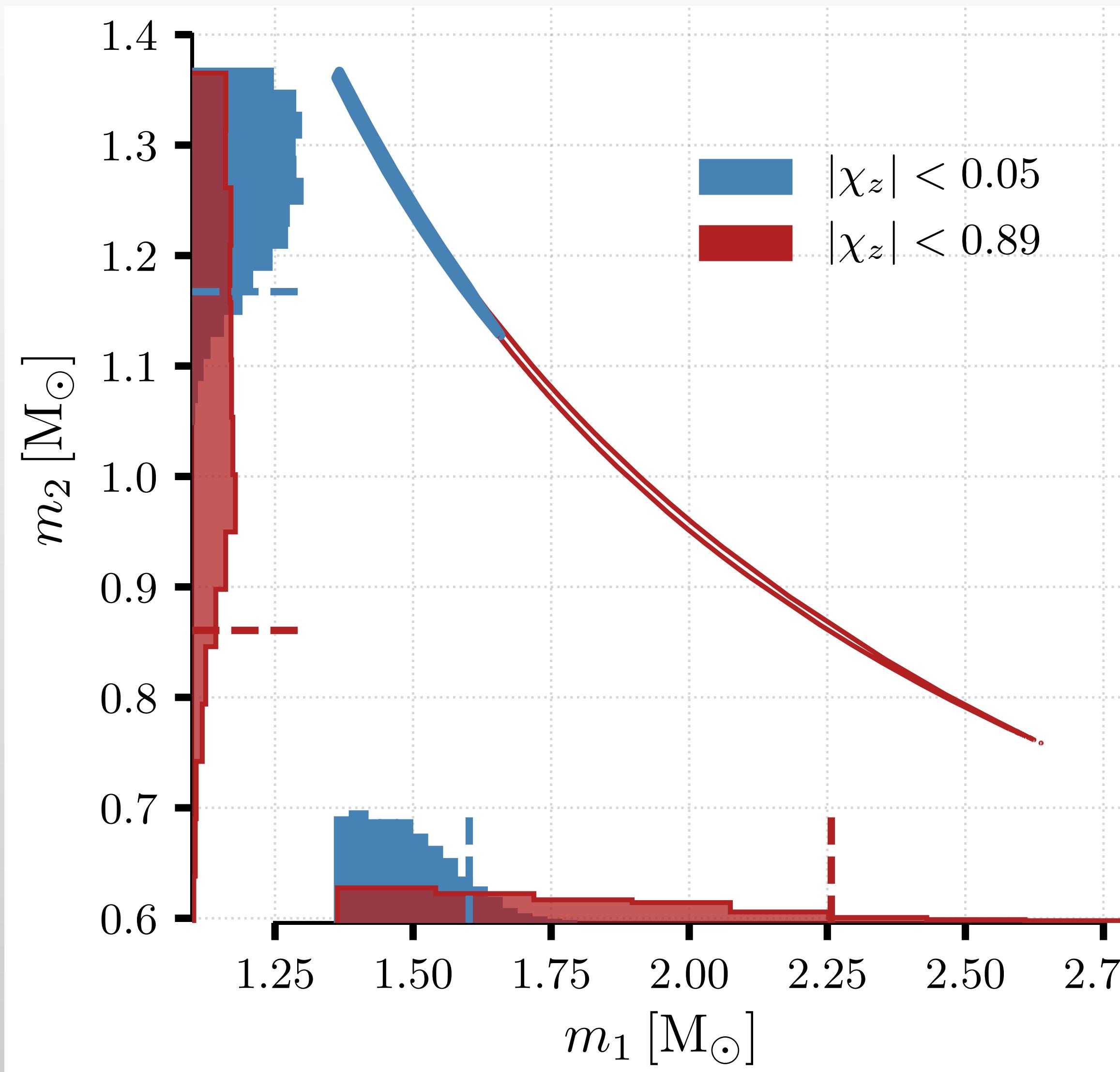
If there is a grb, it would have a
better coordinate

There should be booming x
rays

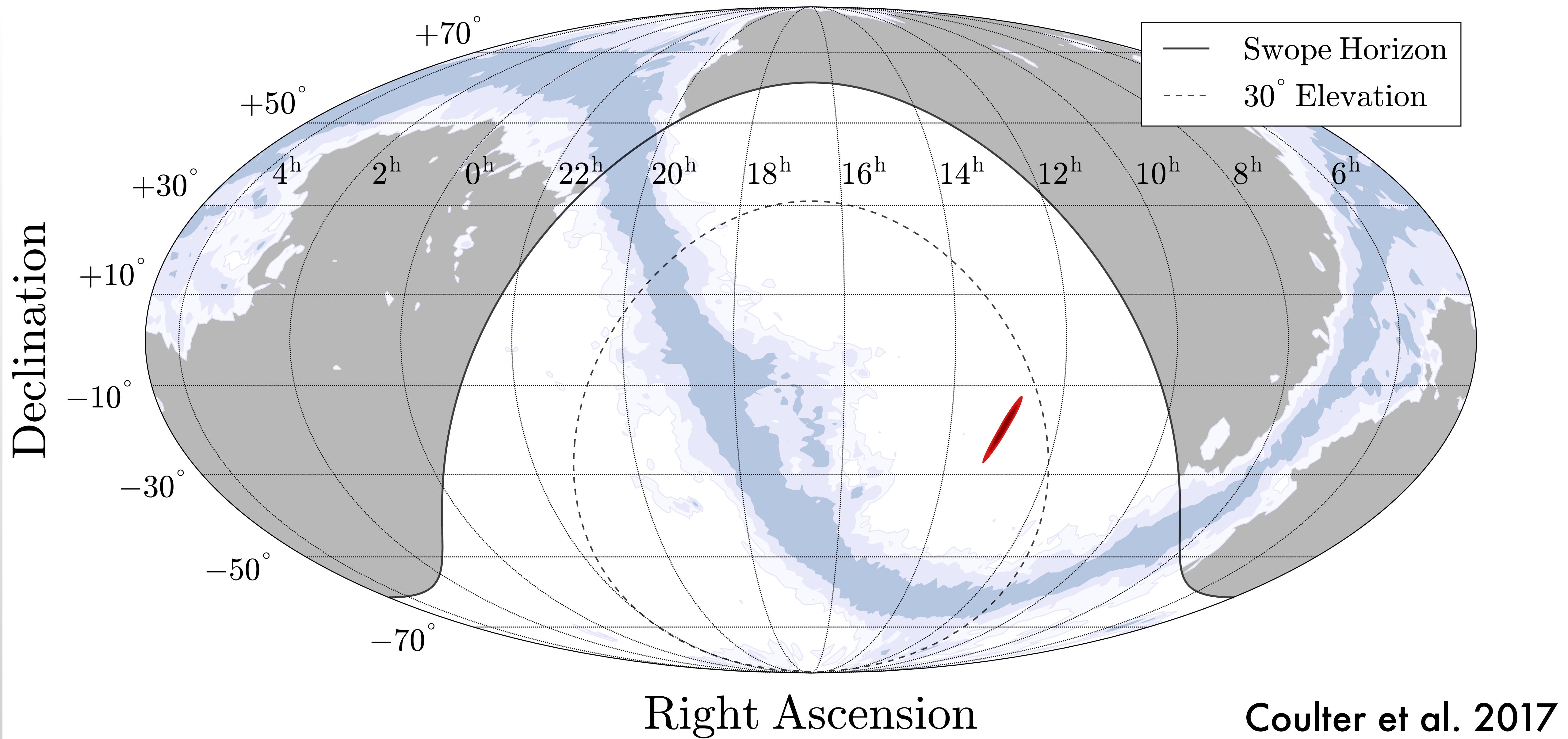
I'M NOT JOKING. JESUS MAN,
I WOULDN'T JOKE ABOUT
THIS.



Masses Squarely in NS Territory



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

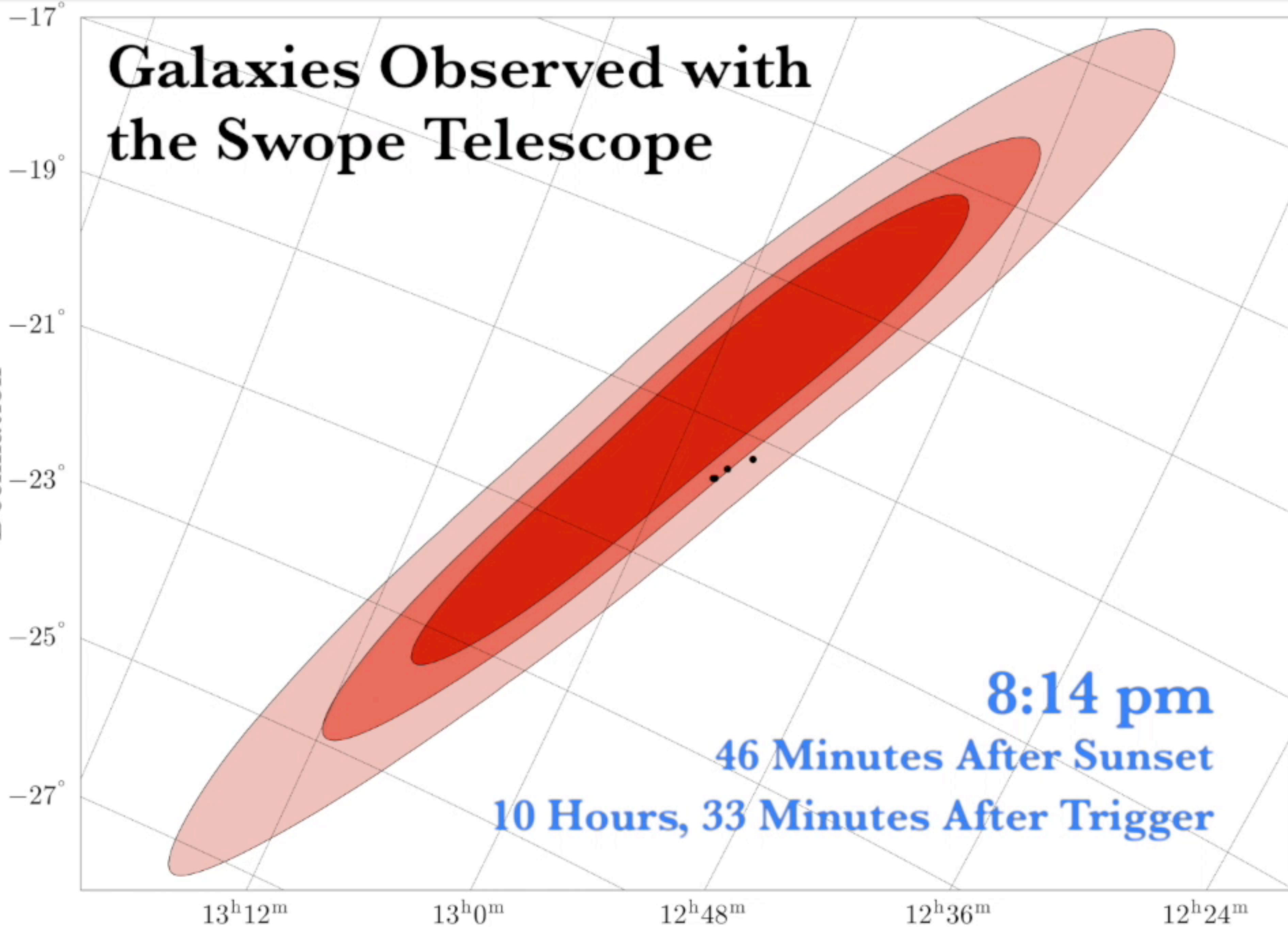


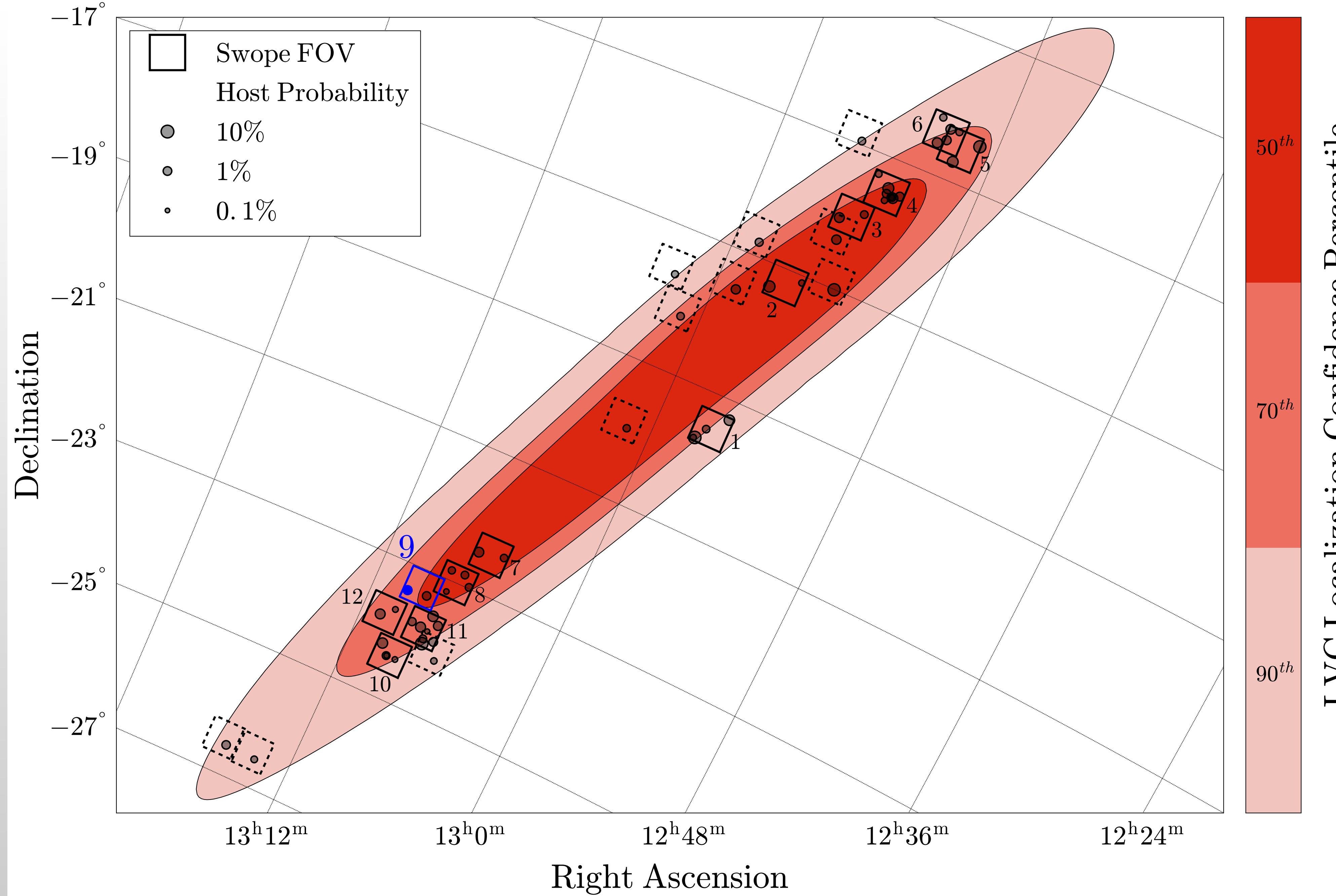




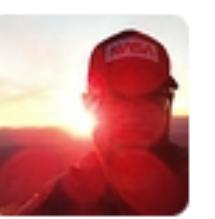
Galaxies Observed with the Swope Telescope

Declination





Coulter et al. 2017



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

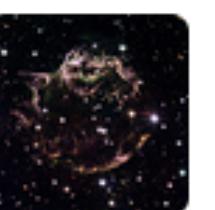
yes, use the white catalog



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!



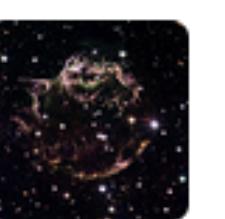
ckilpatrick 4:28 PM

nothing im fields12



foley 4:29 PM

no transients, right?



ckilpatrick 4:29 PM

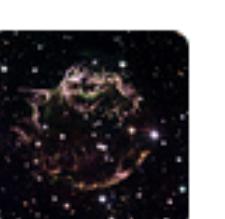
no transients

sorry, image is fine



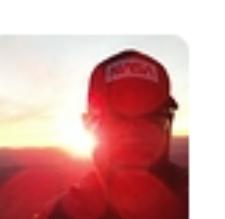
foley 4:29 PM

fantastic



ckilpatrick 4:29 PM

but nothing I can see by eye



davecoulter 4:34 PM

uploaded this file ▾



ckilpatrick 4:29 PM
but nothing I can see by eye



davecouler 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!



davecouler 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](#) ▾



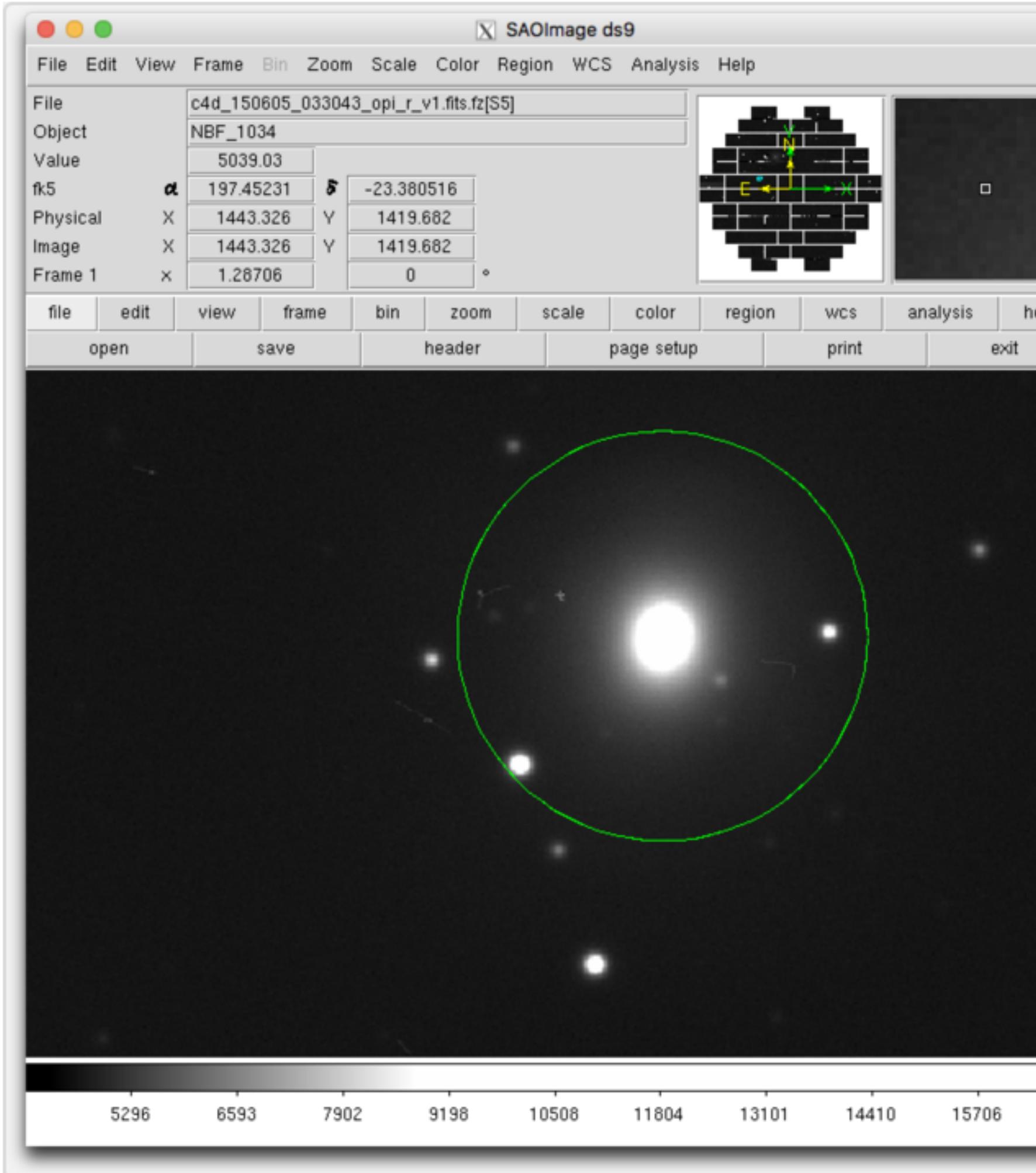
ckilpatrick 4:59 PM

template



ckilpatrick 4:59 PM

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



ckilpatrick 5:00 PM

us



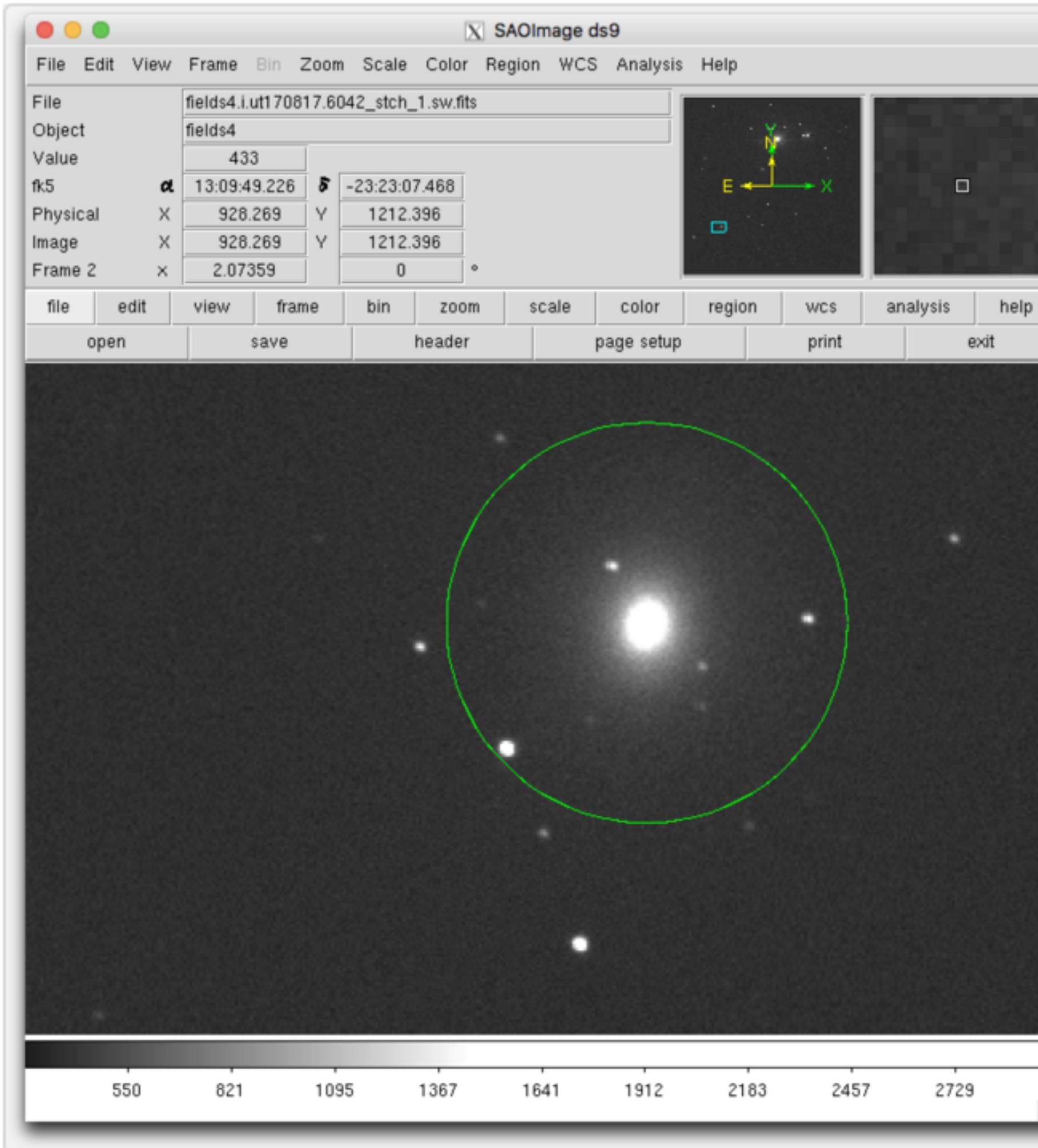
ckilpatrick 5:00 PM

US



ckilpatrick 5:00 PM

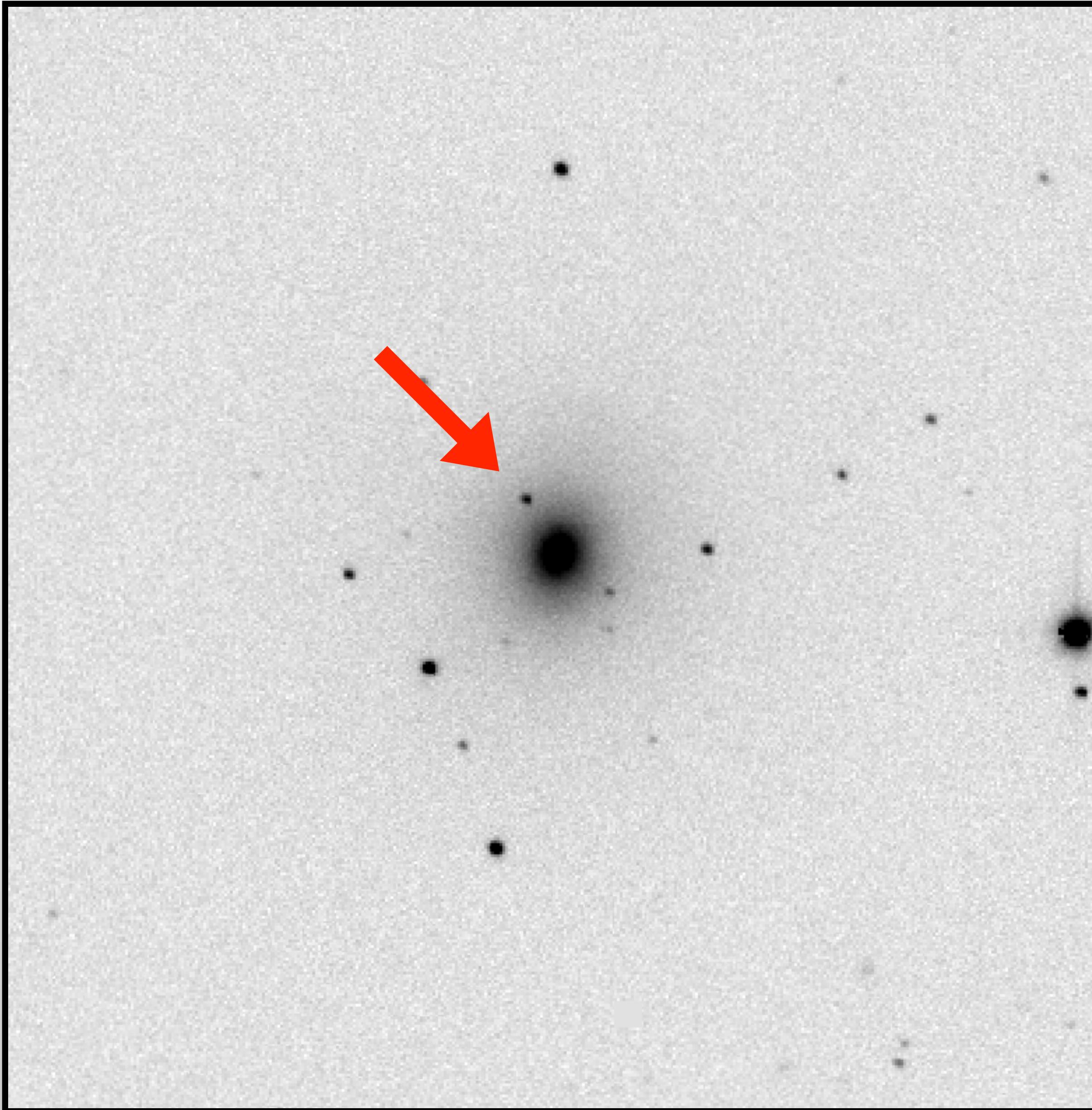
uploaded this image: [Screen Shot 2017-08-17 at 4.59.53 PM.png](#) ▾



foley 5:00 PM

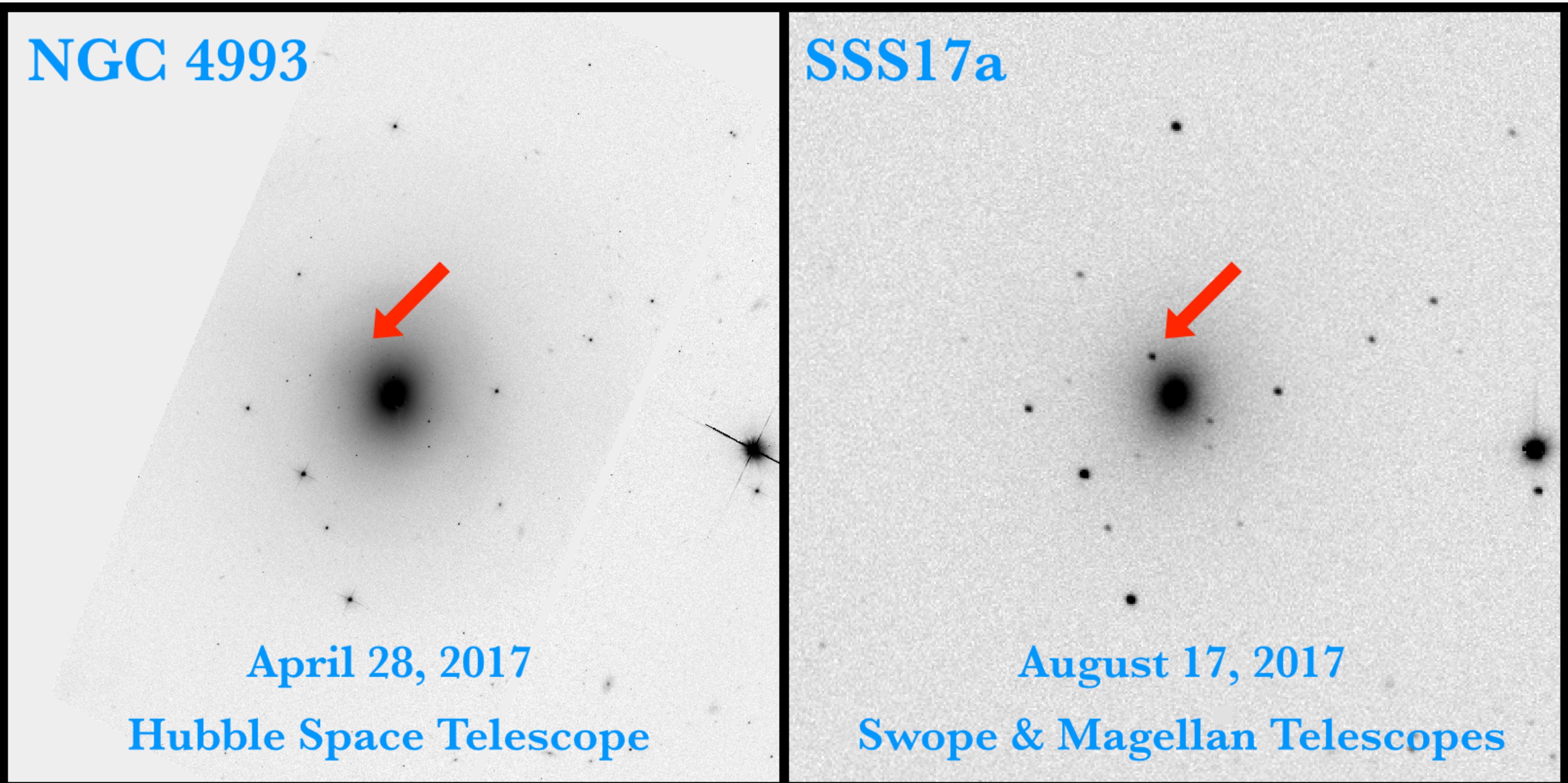
yep!

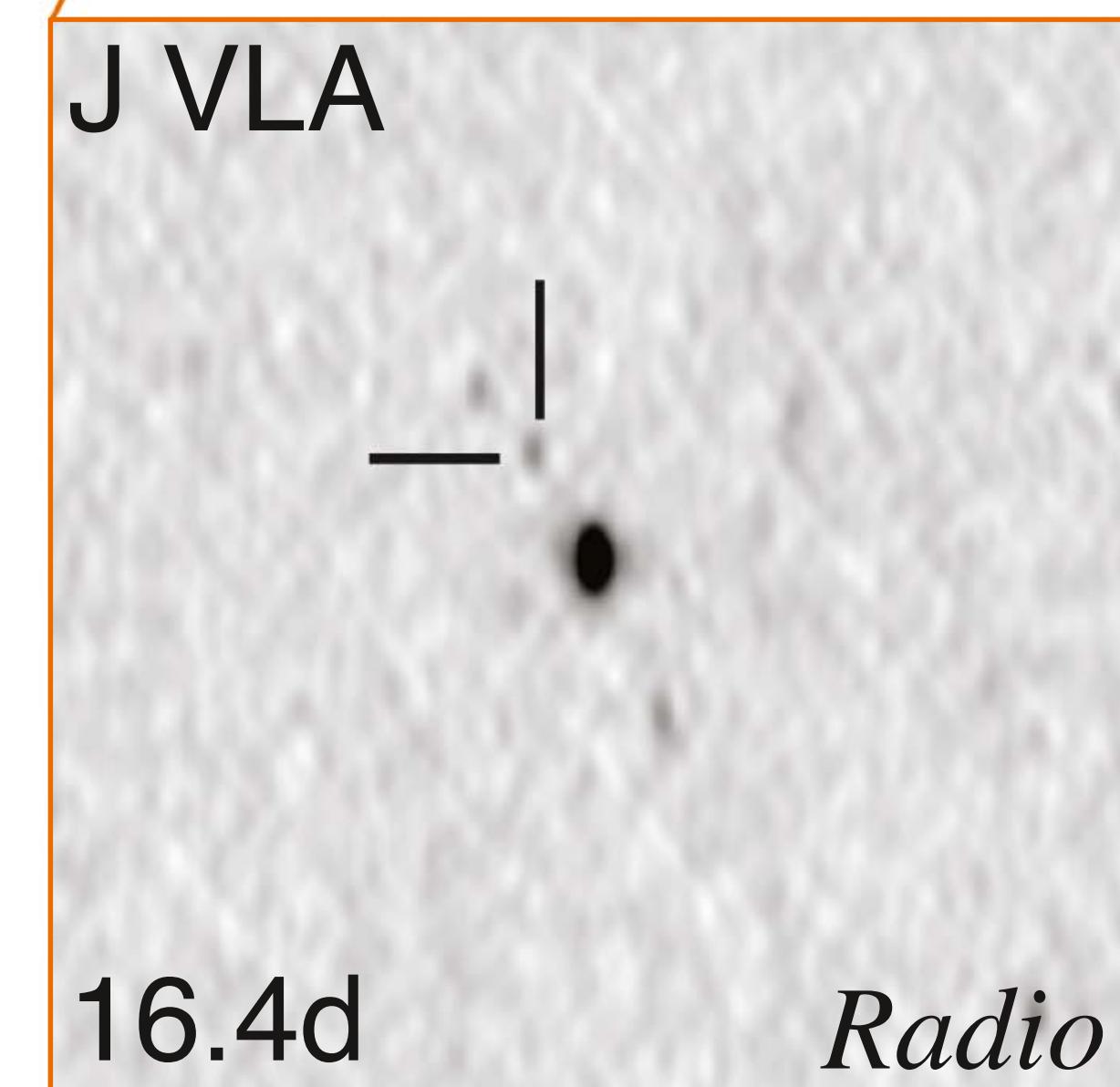
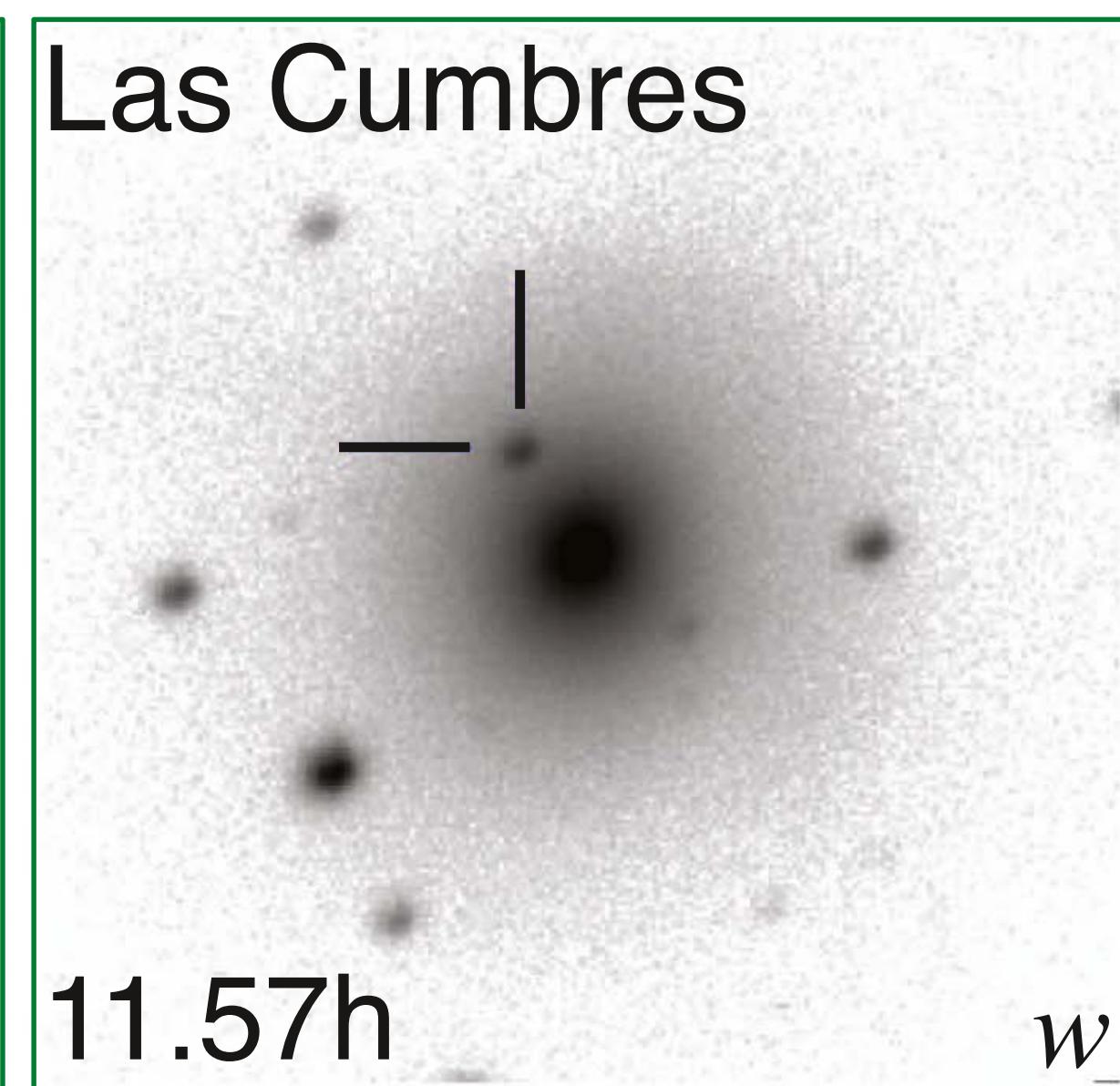
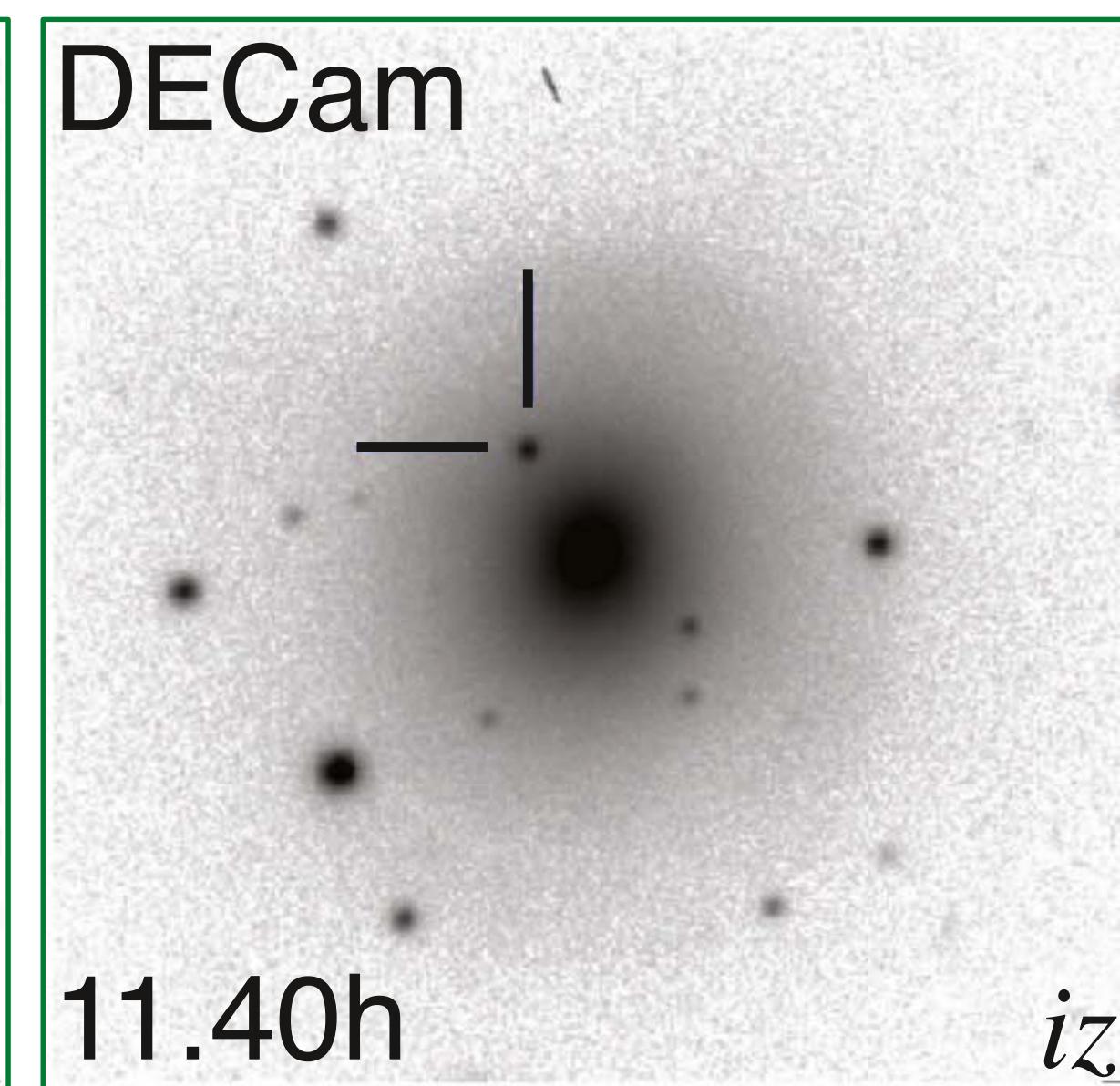
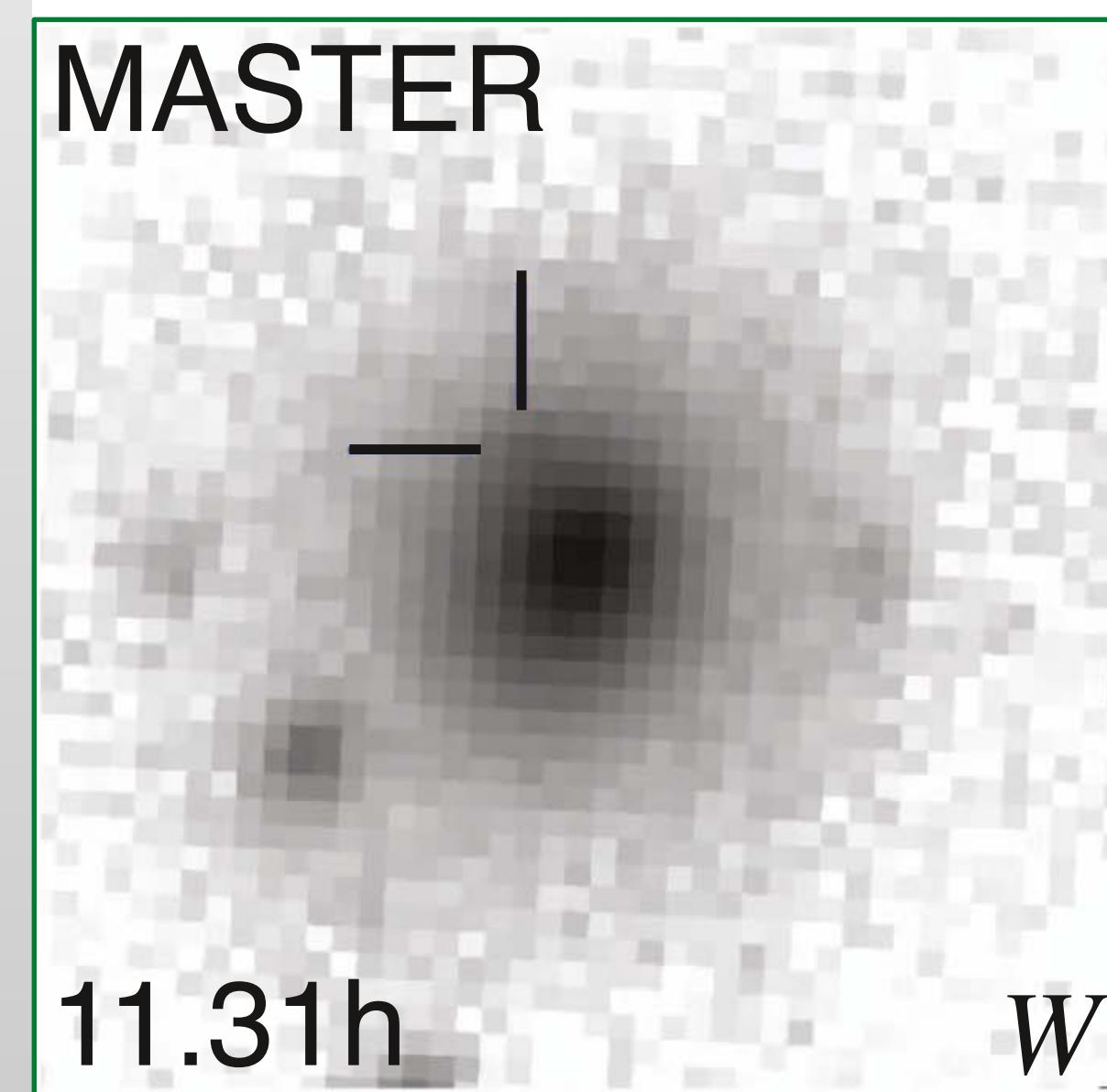
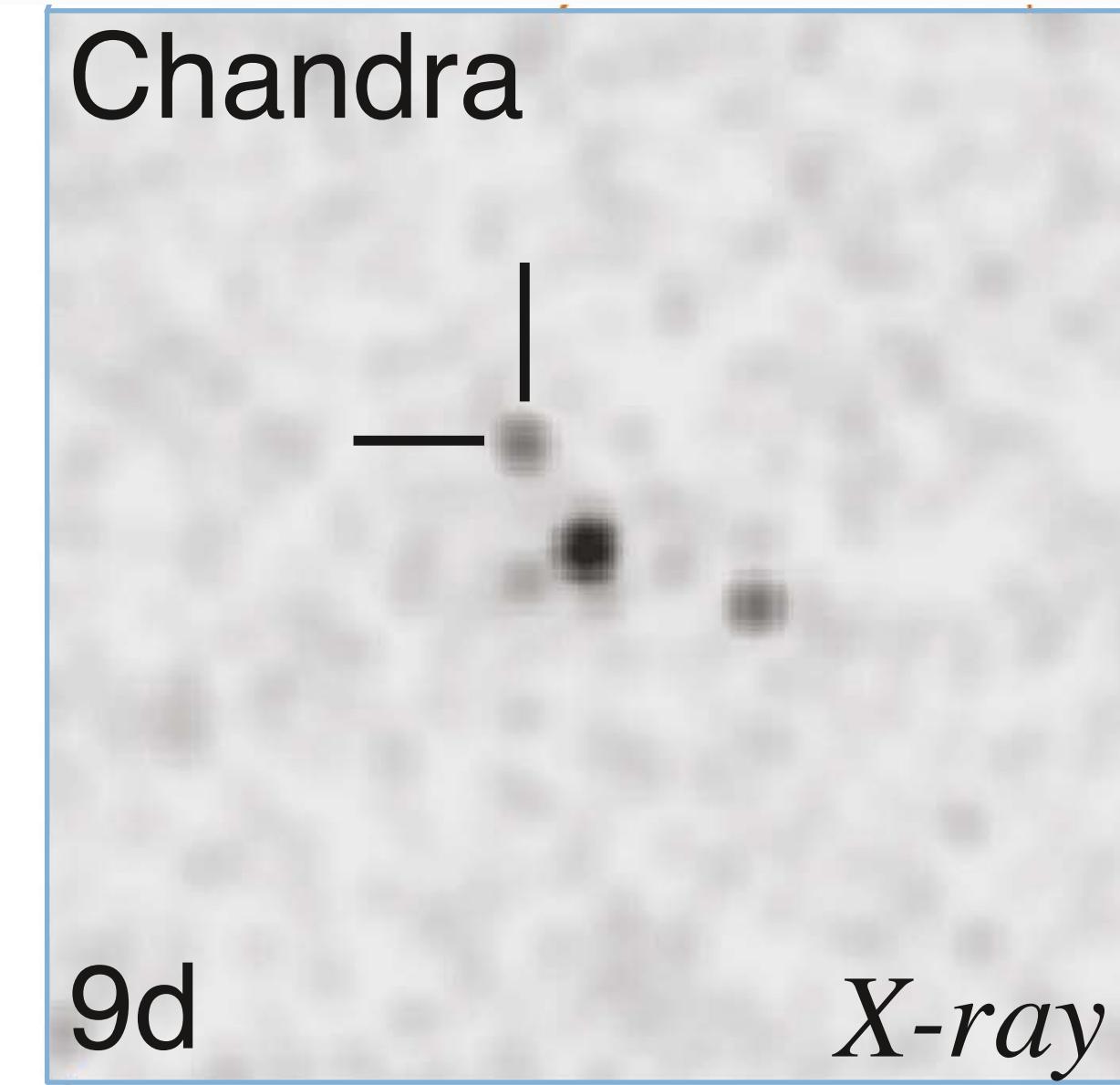
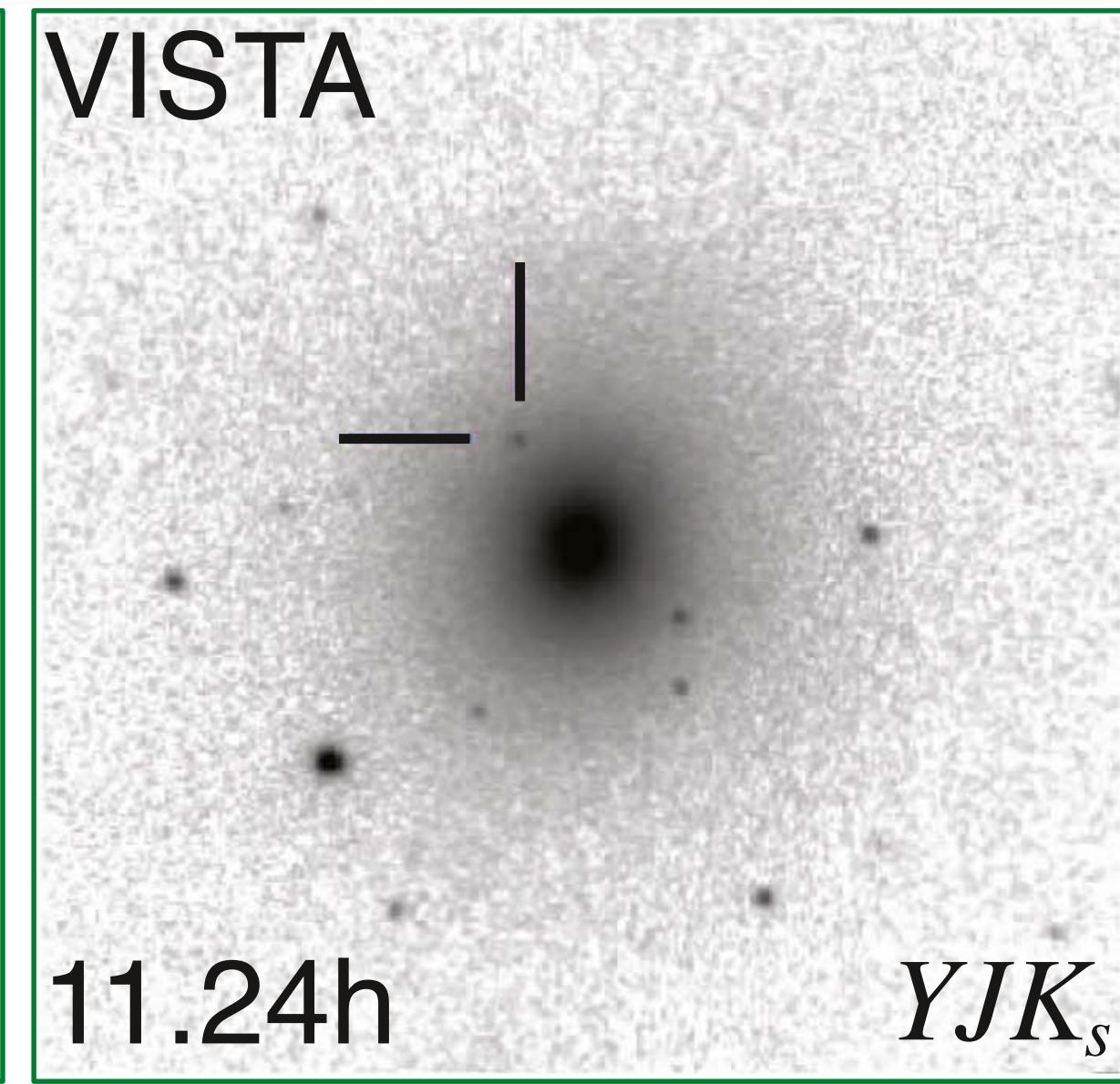
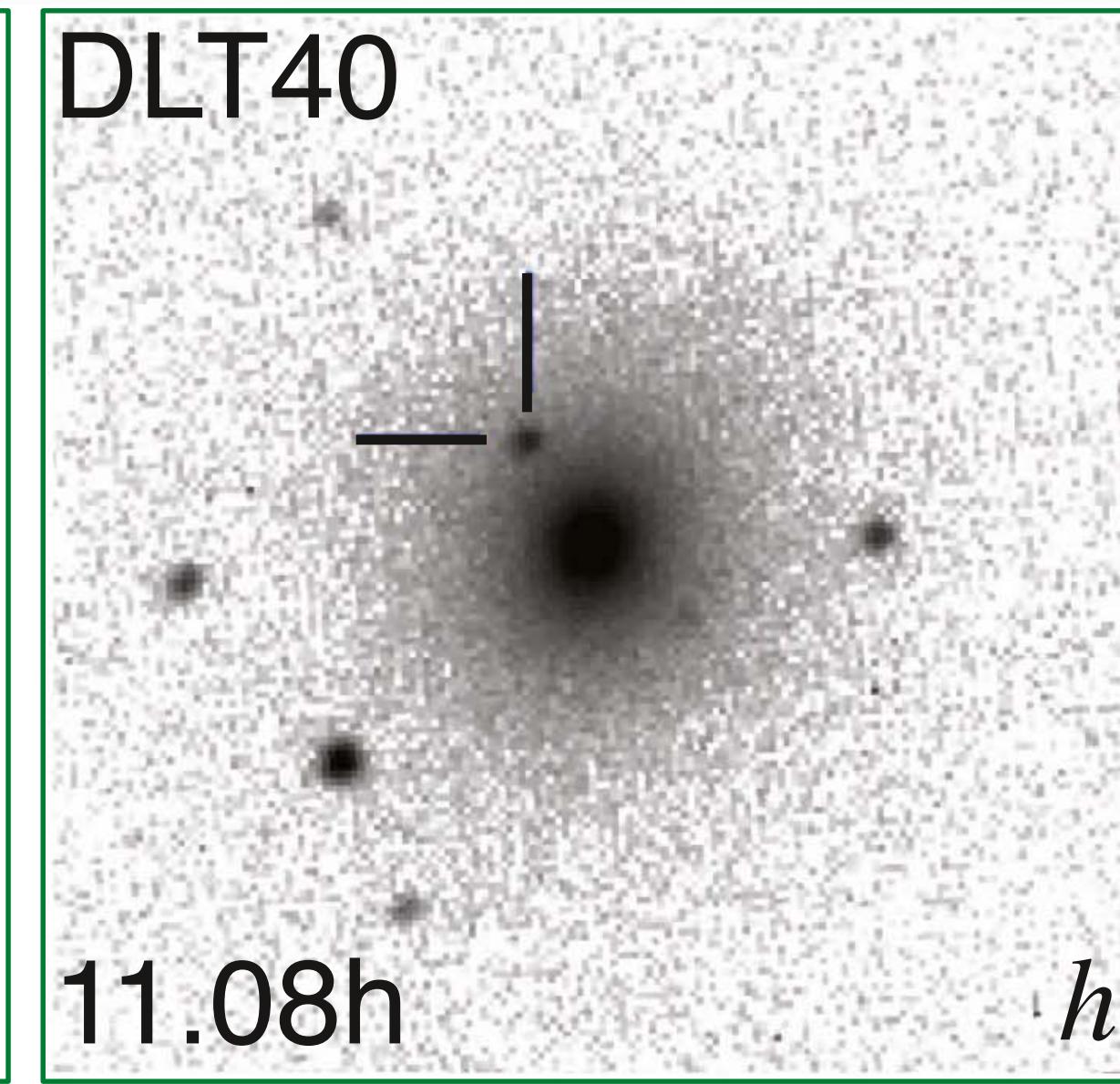
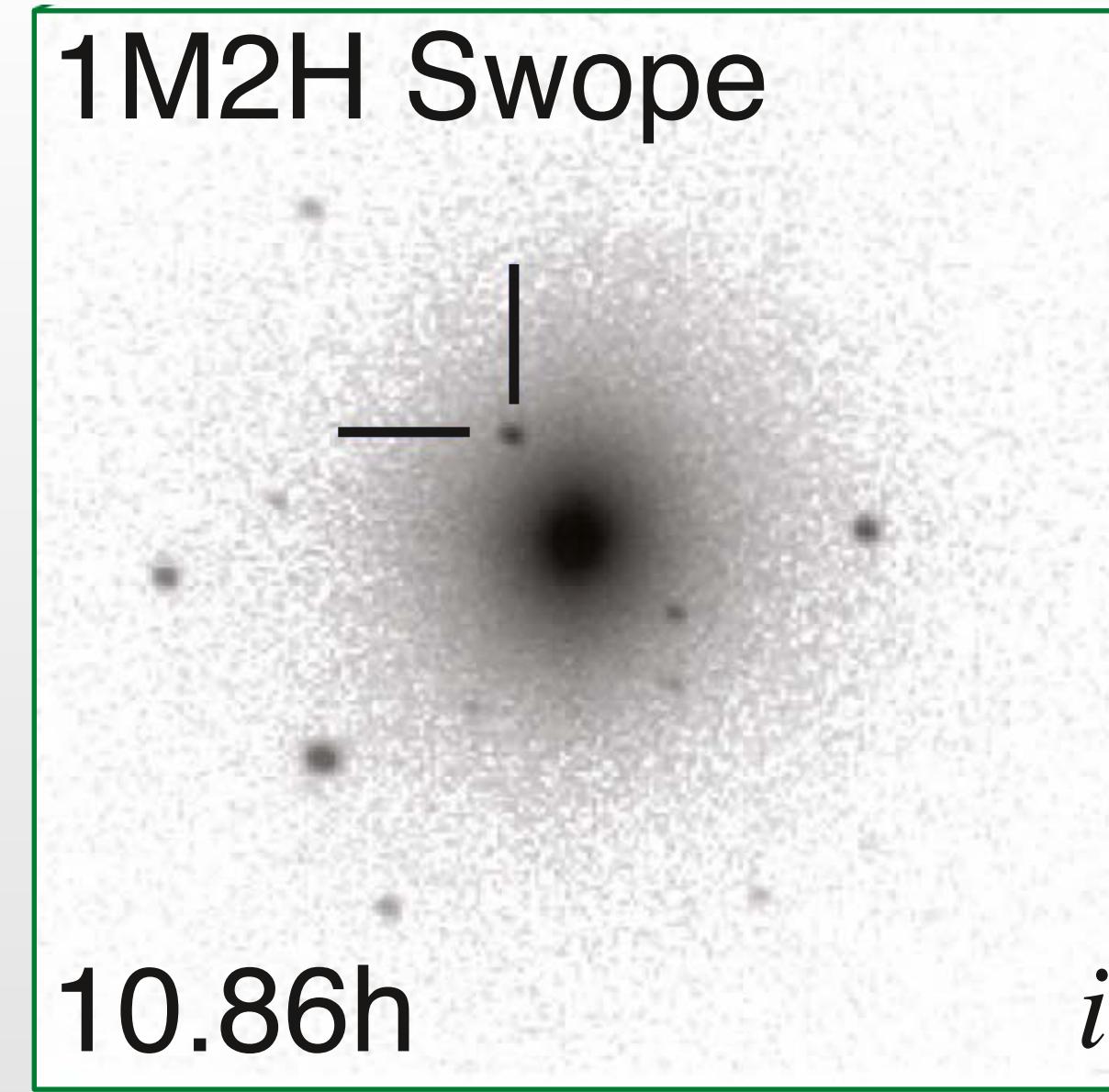
NGC 4993 and SSS17a



Coulter et al. 2017

First Image of a Gravitational Wave





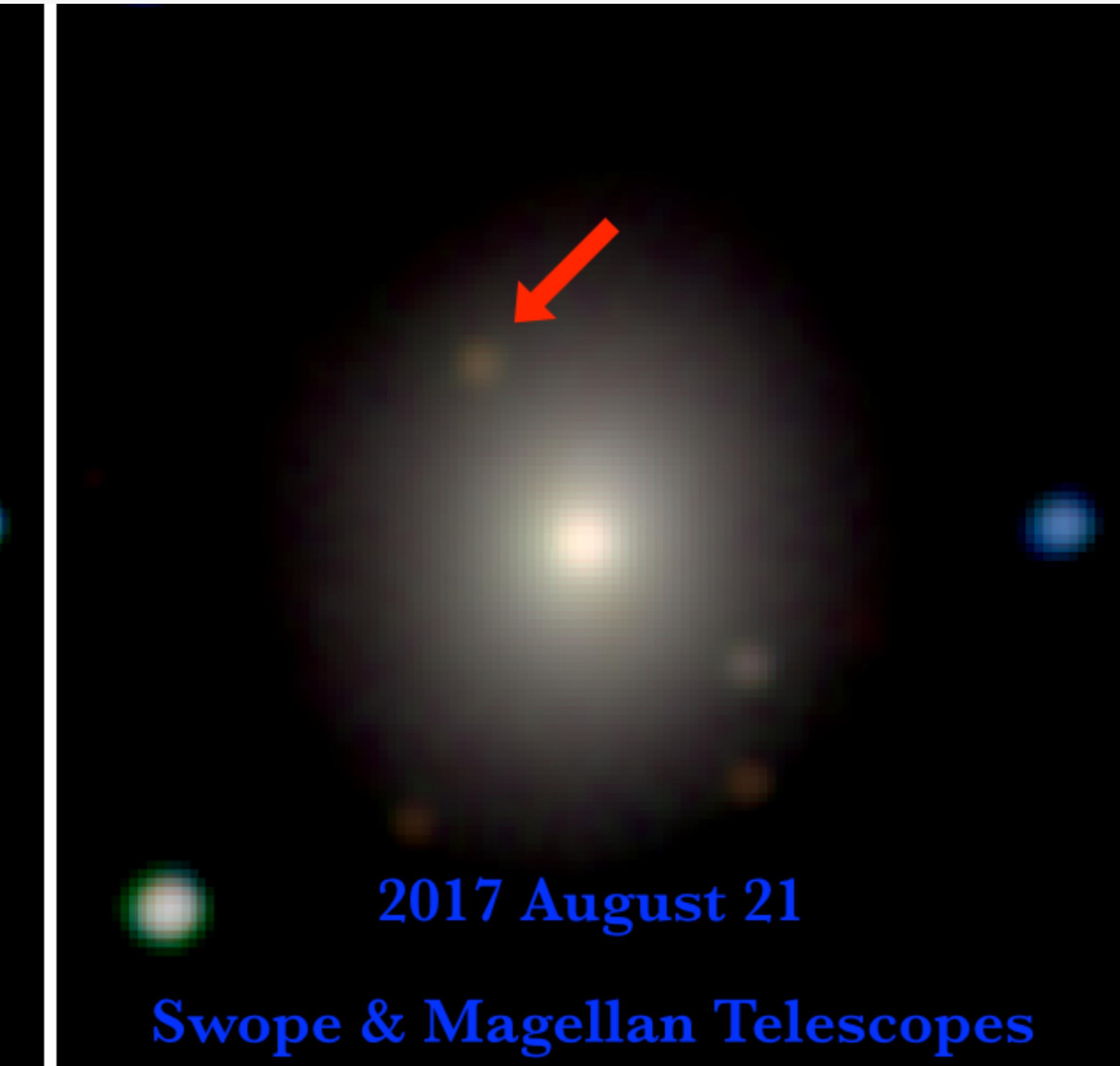


SSS17a
12 Hours After Trigger

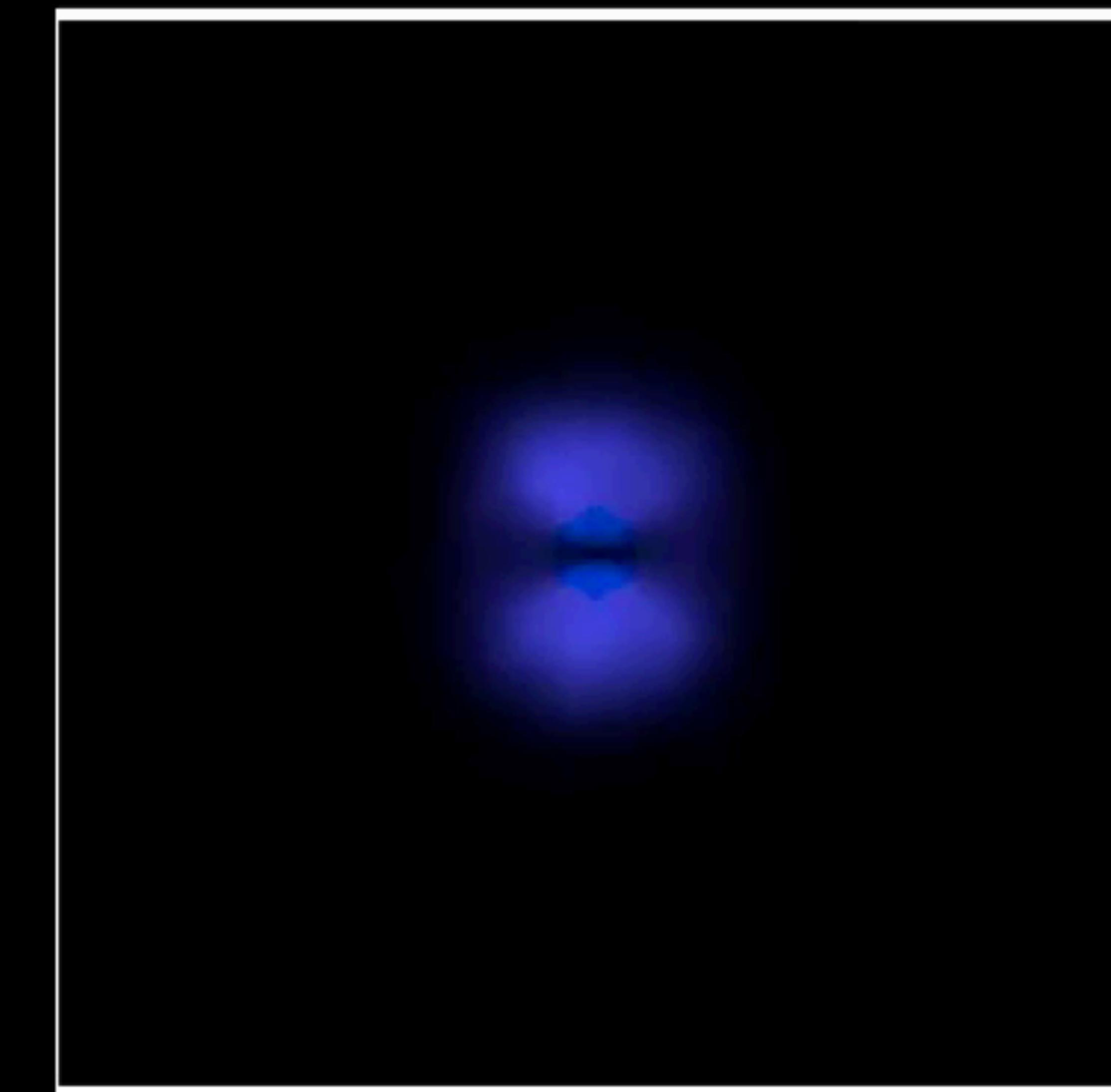
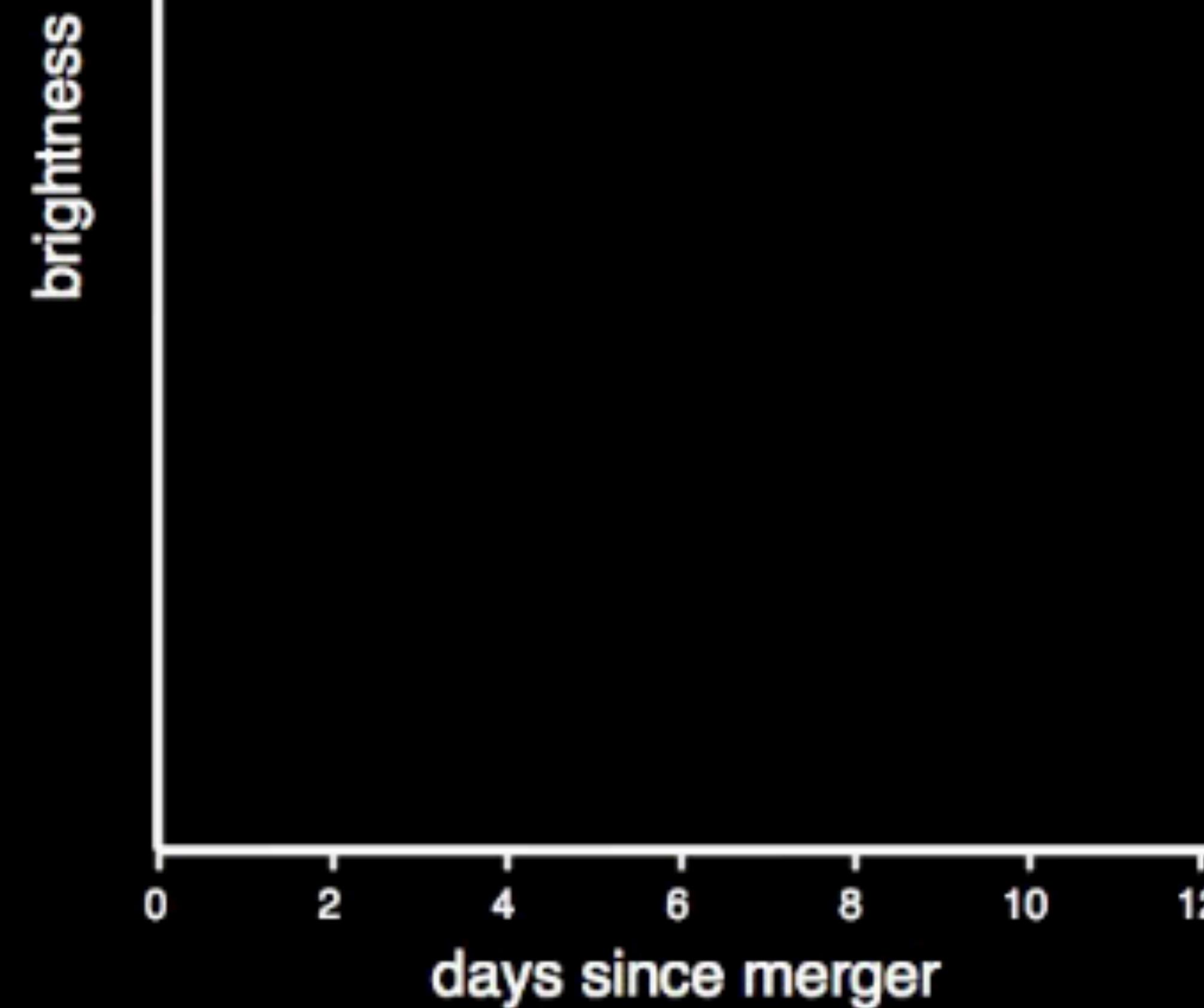
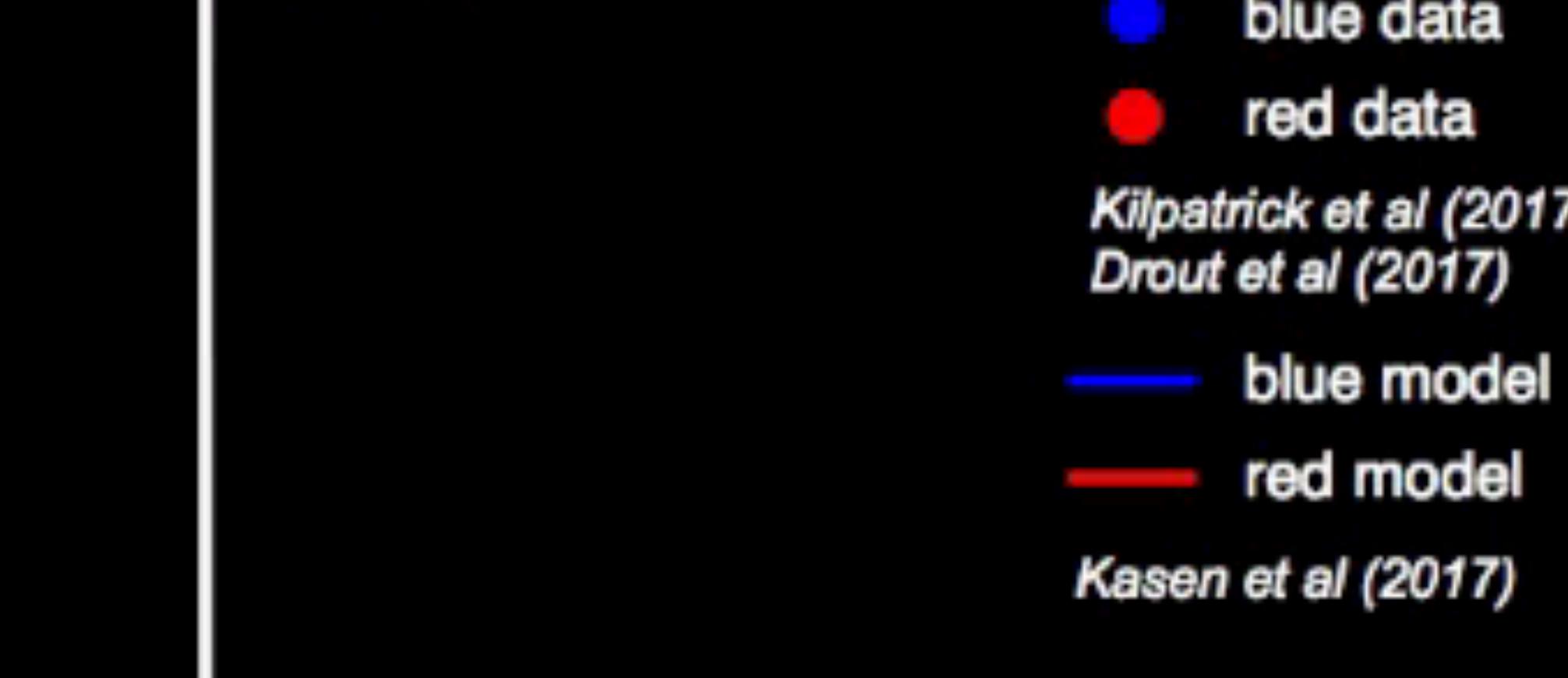


SSS17a
4.5 Days After Trigger

SSS17a Quickly Turned Blue to Red



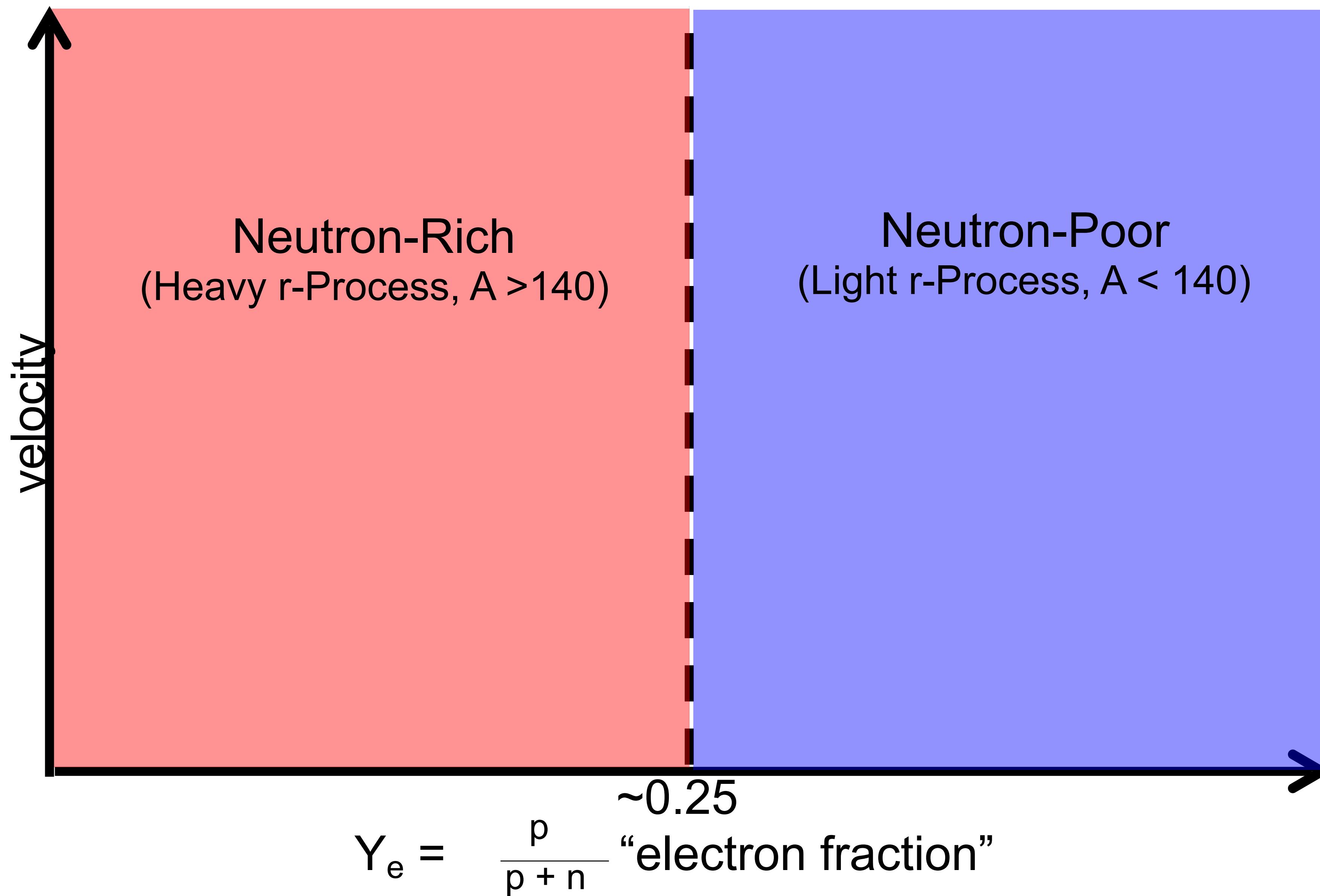
D. Kasen



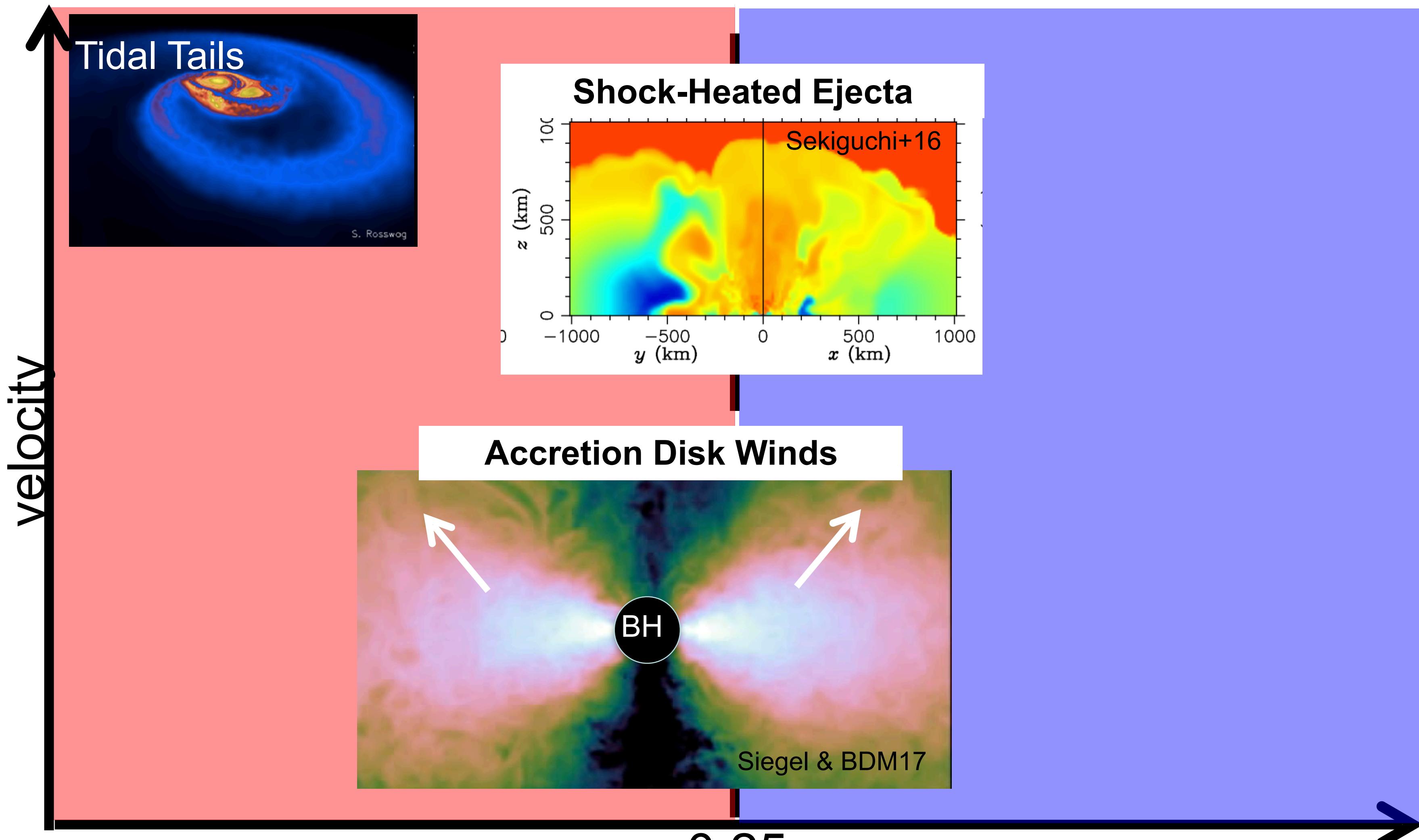
radioactive debris cloud



Red vs. Blue Kilonovae

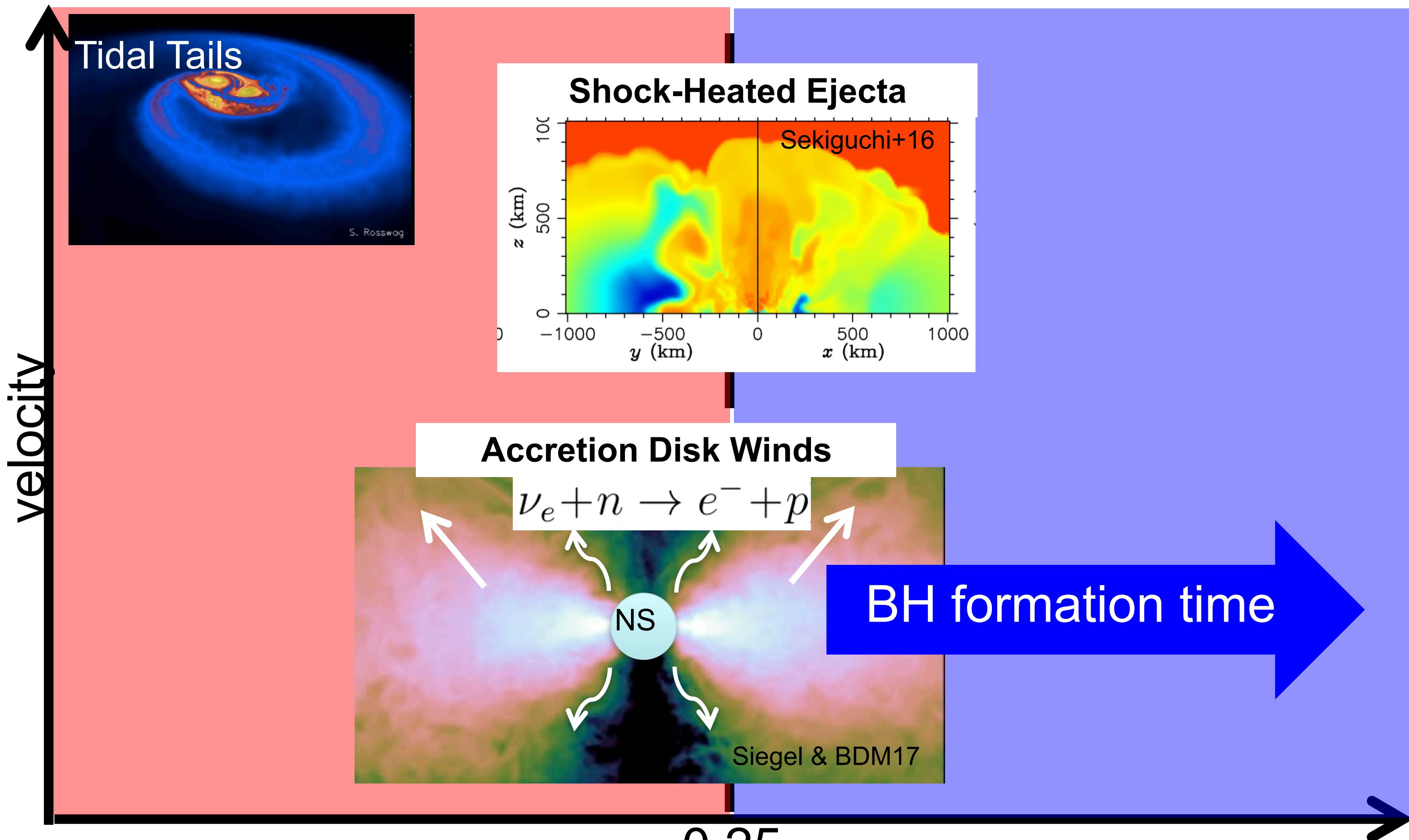


Red vs. Blue Kilonovae



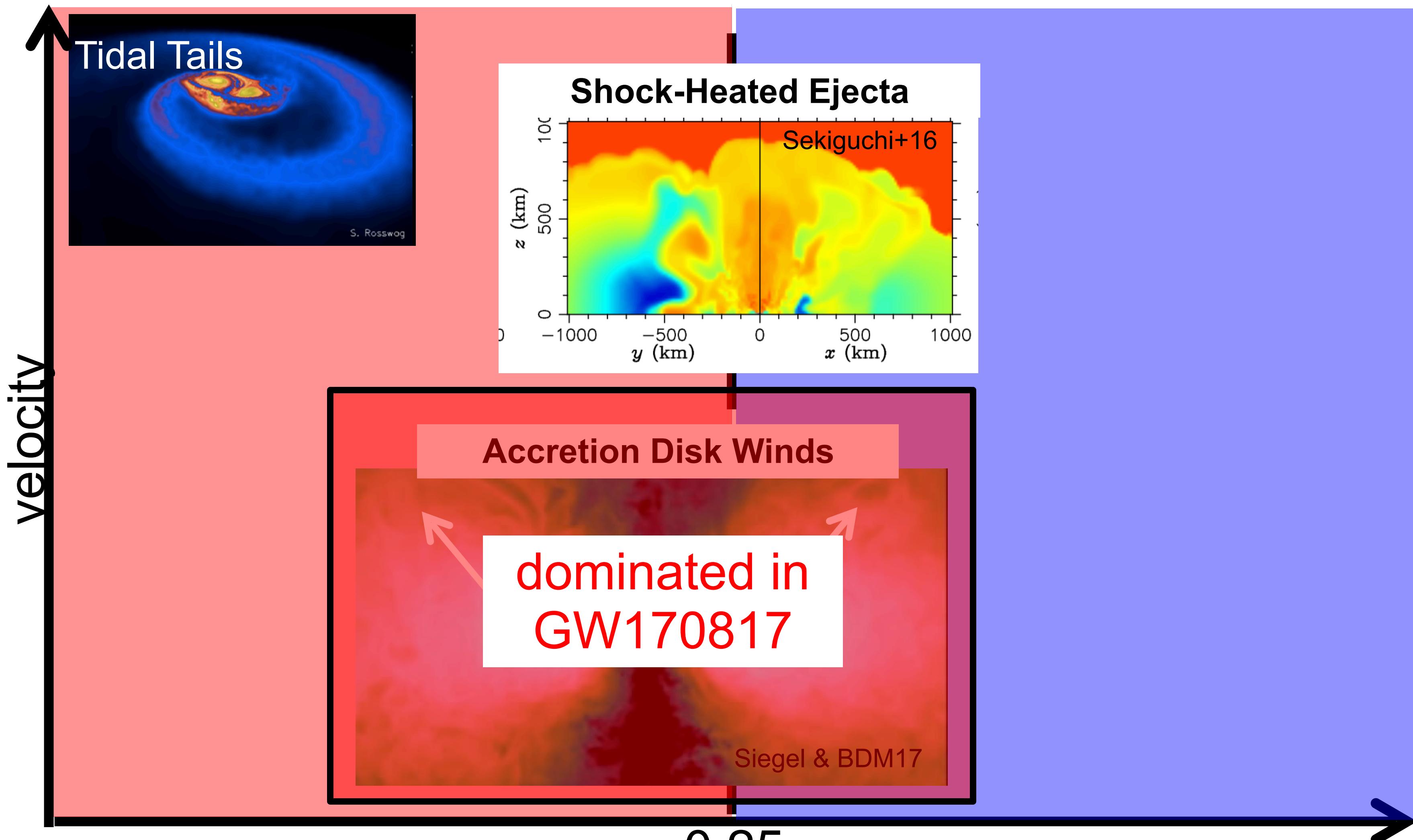
$$Y_e = \frac{p}{p+n} \text{ "electron fraction"}$$

Red vs. Blue Kilonovae



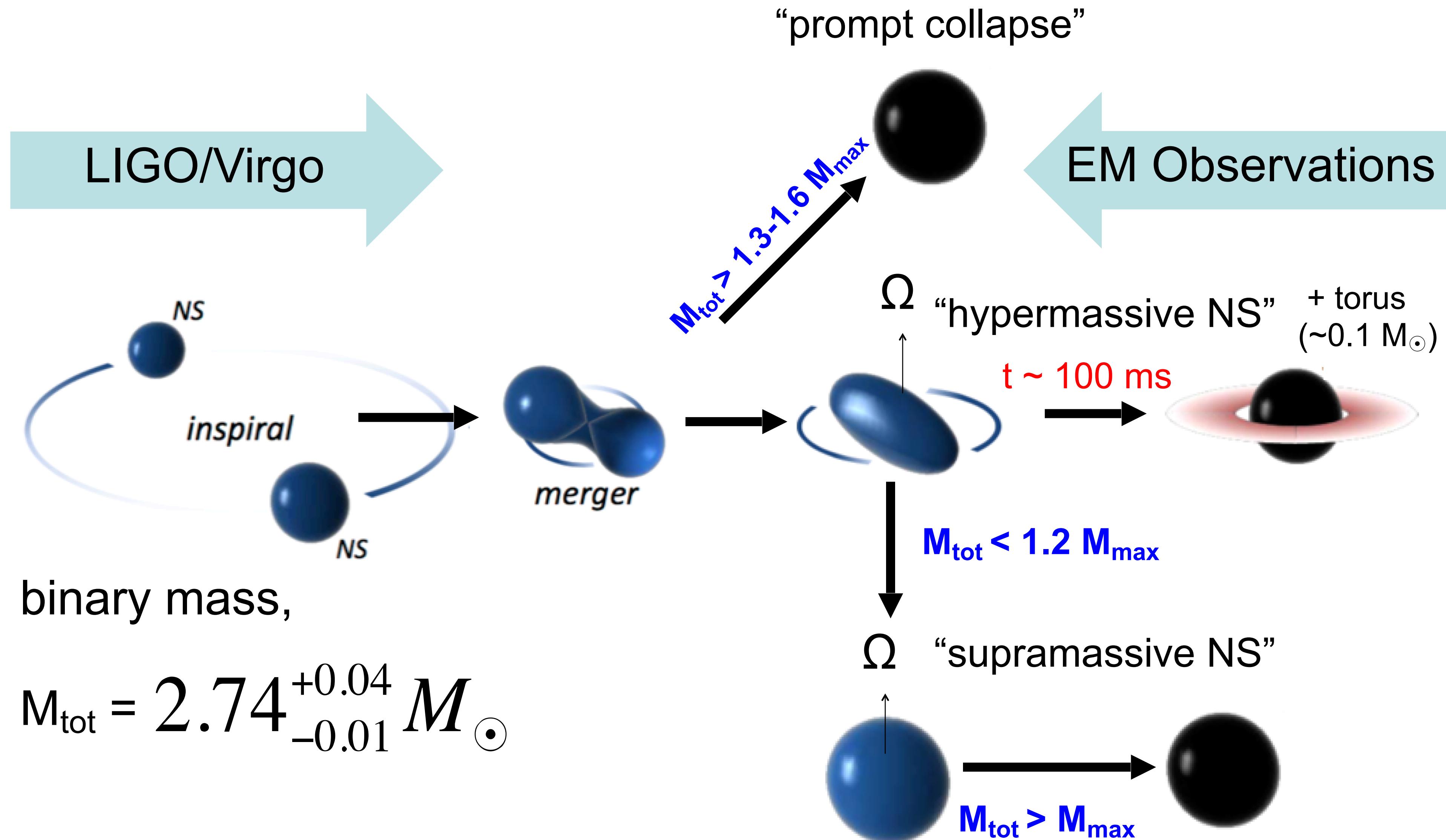
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Red vs. Blue Kilonovae

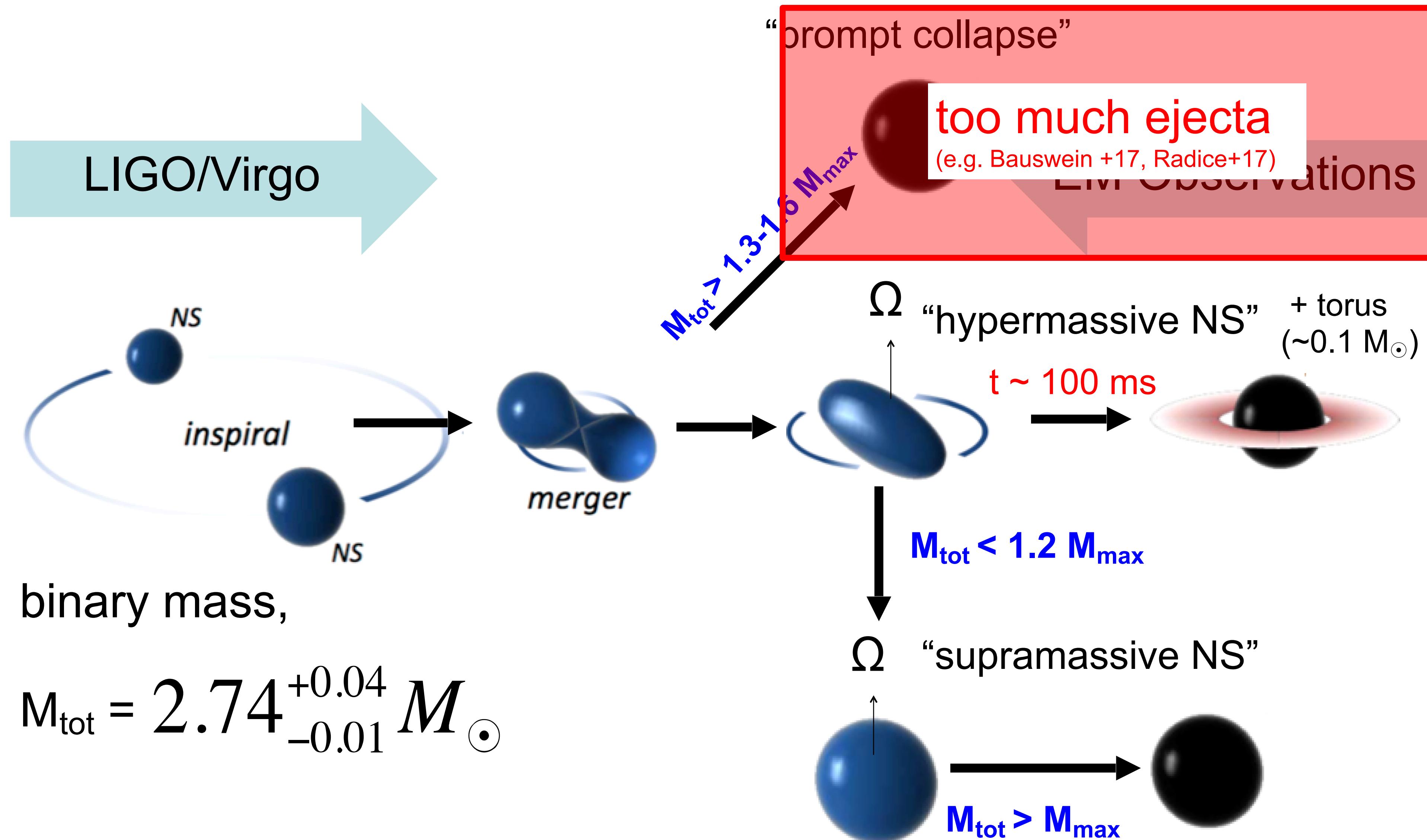


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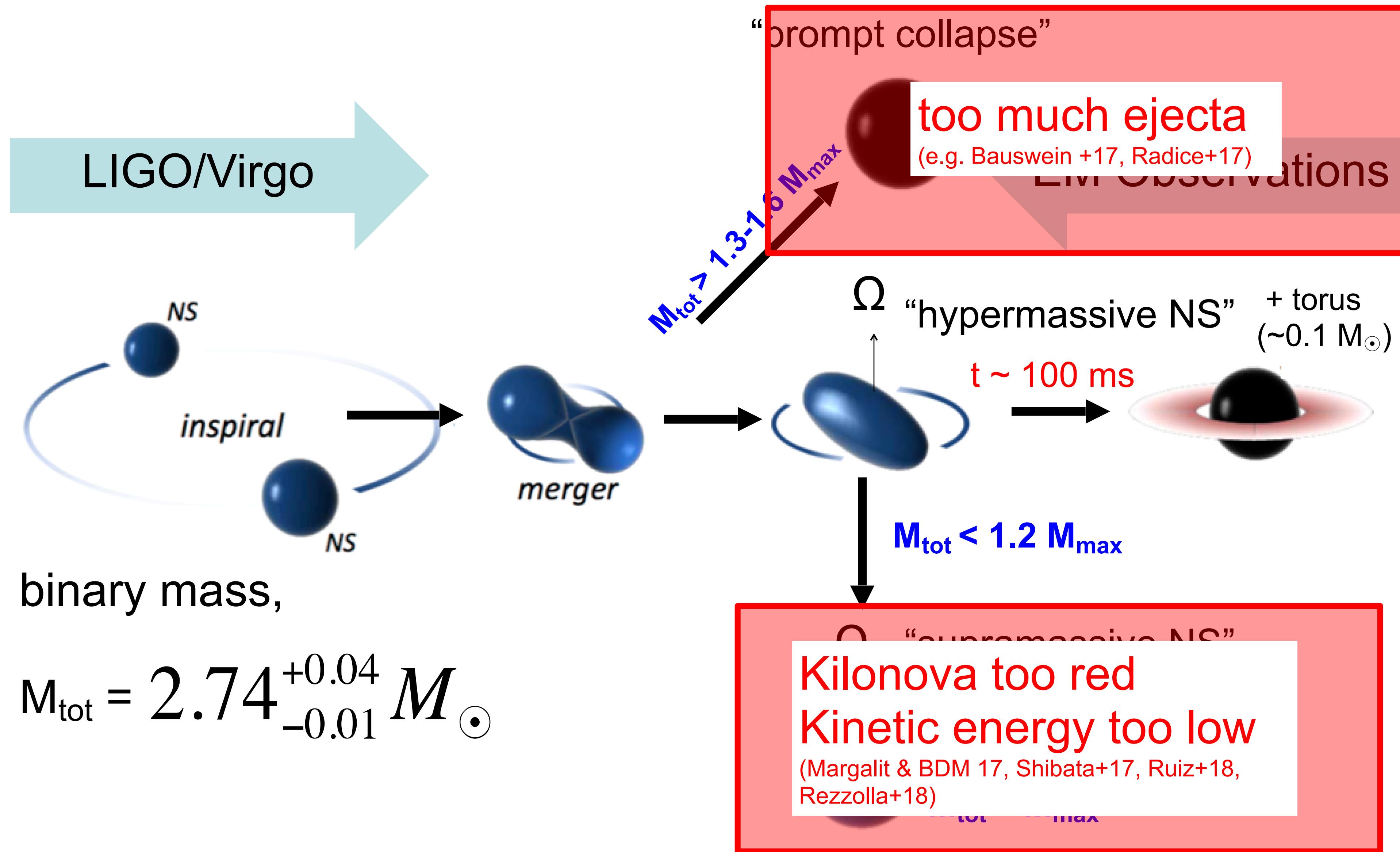
Outcomes of Neutron Star Mergers



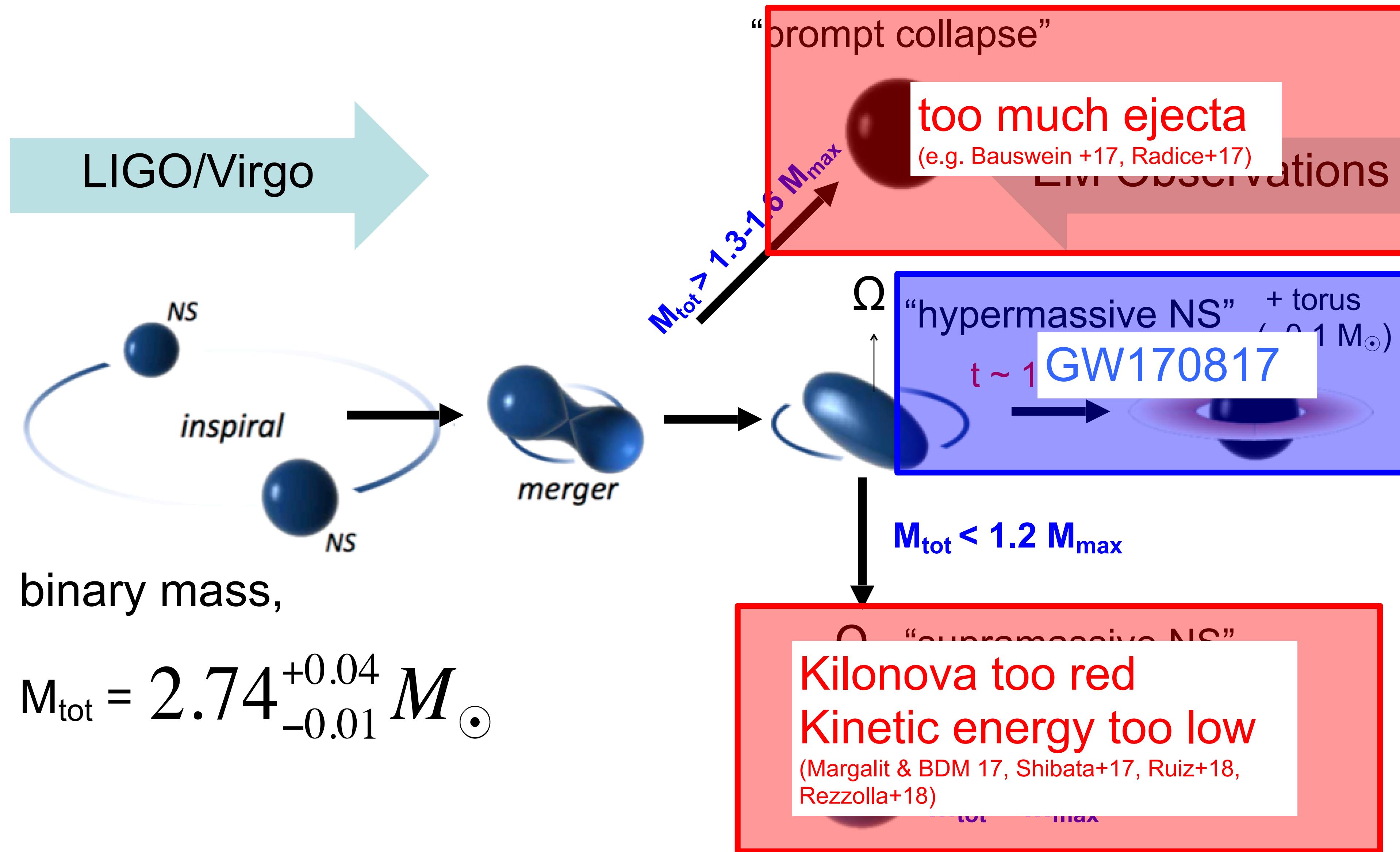
Outcomes of Neutron Star Mergers



Outcomes of Neutron Star Mergers

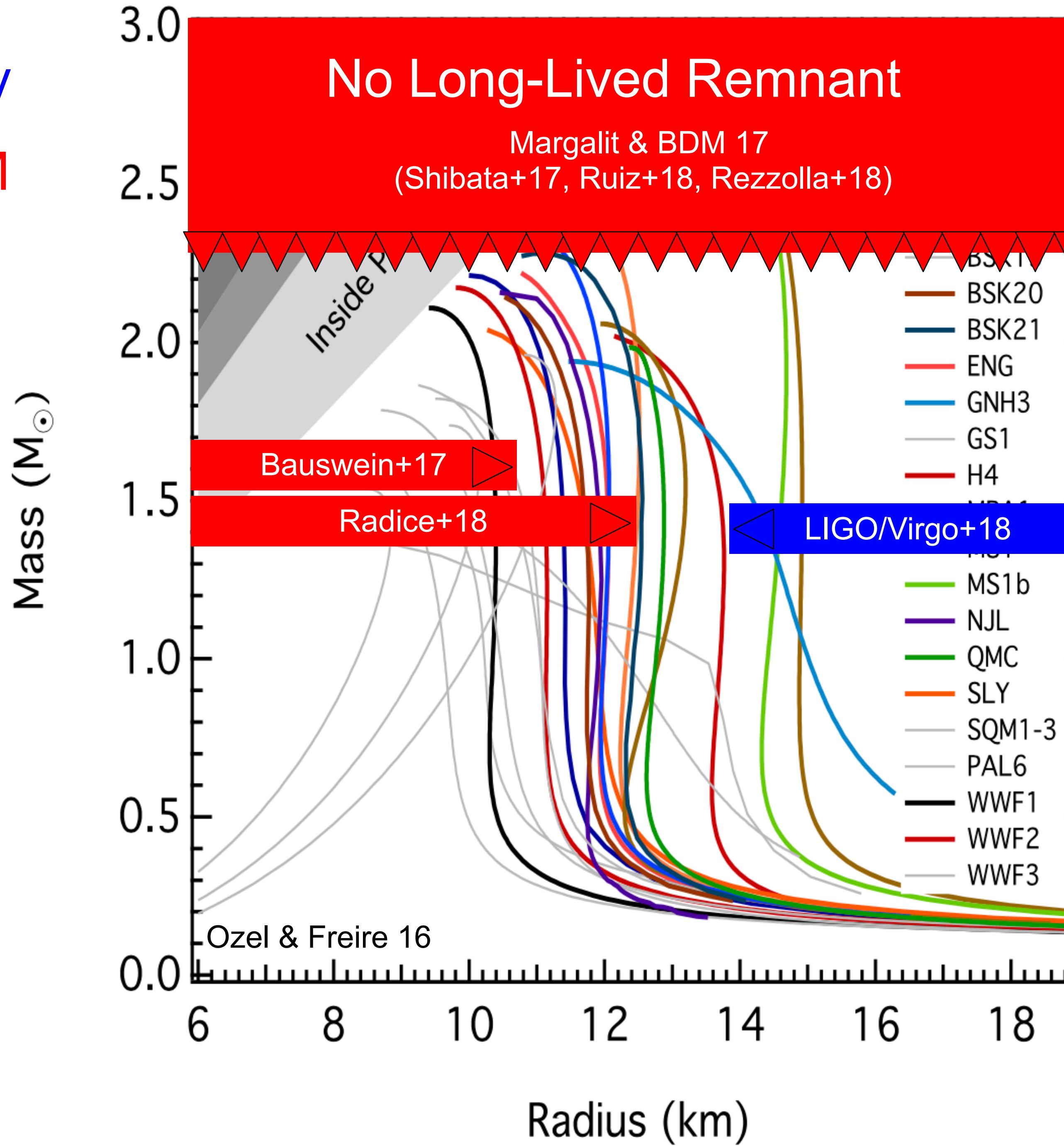


Outcomes of Neutron Star Mergers

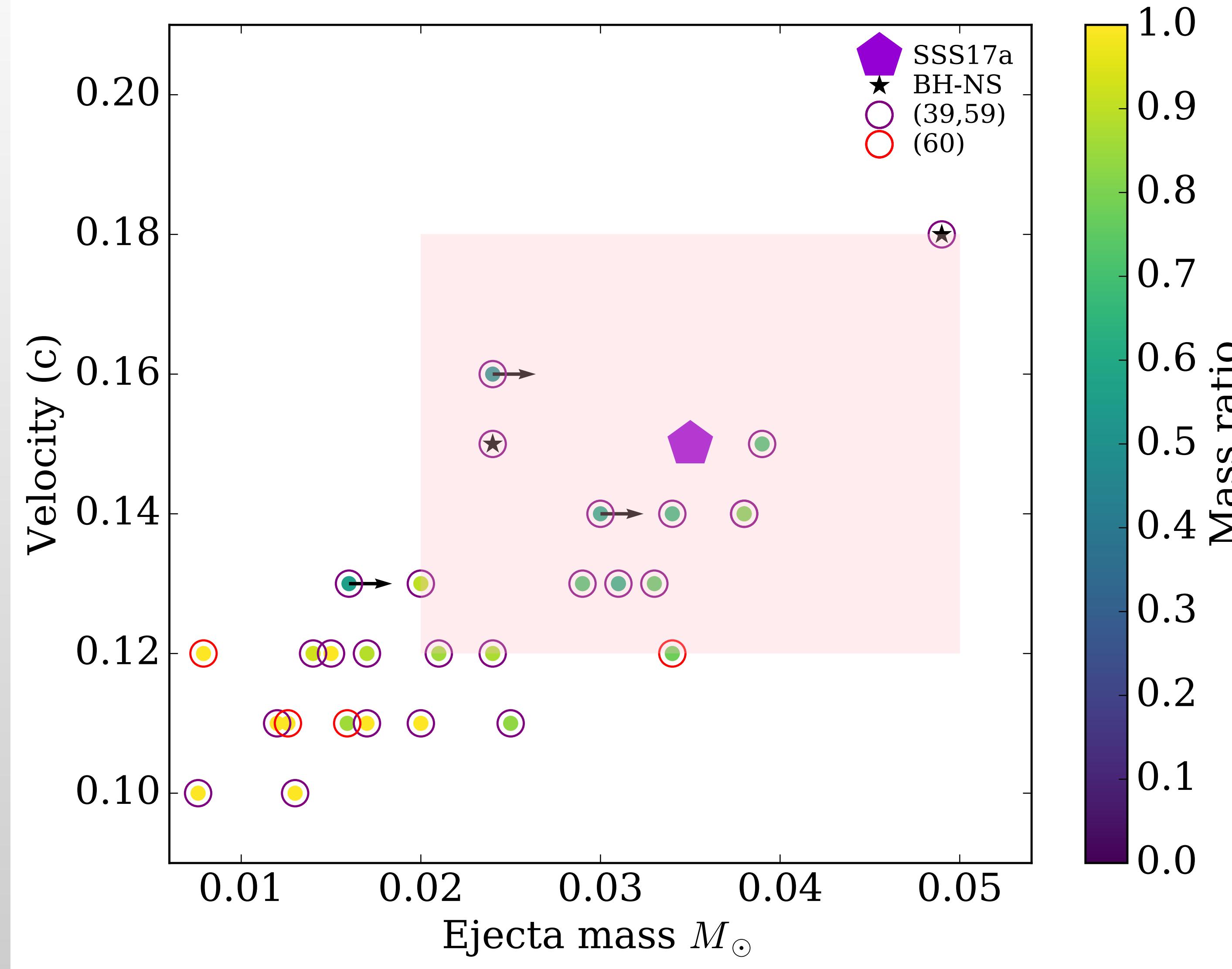


GW only

GW+EM

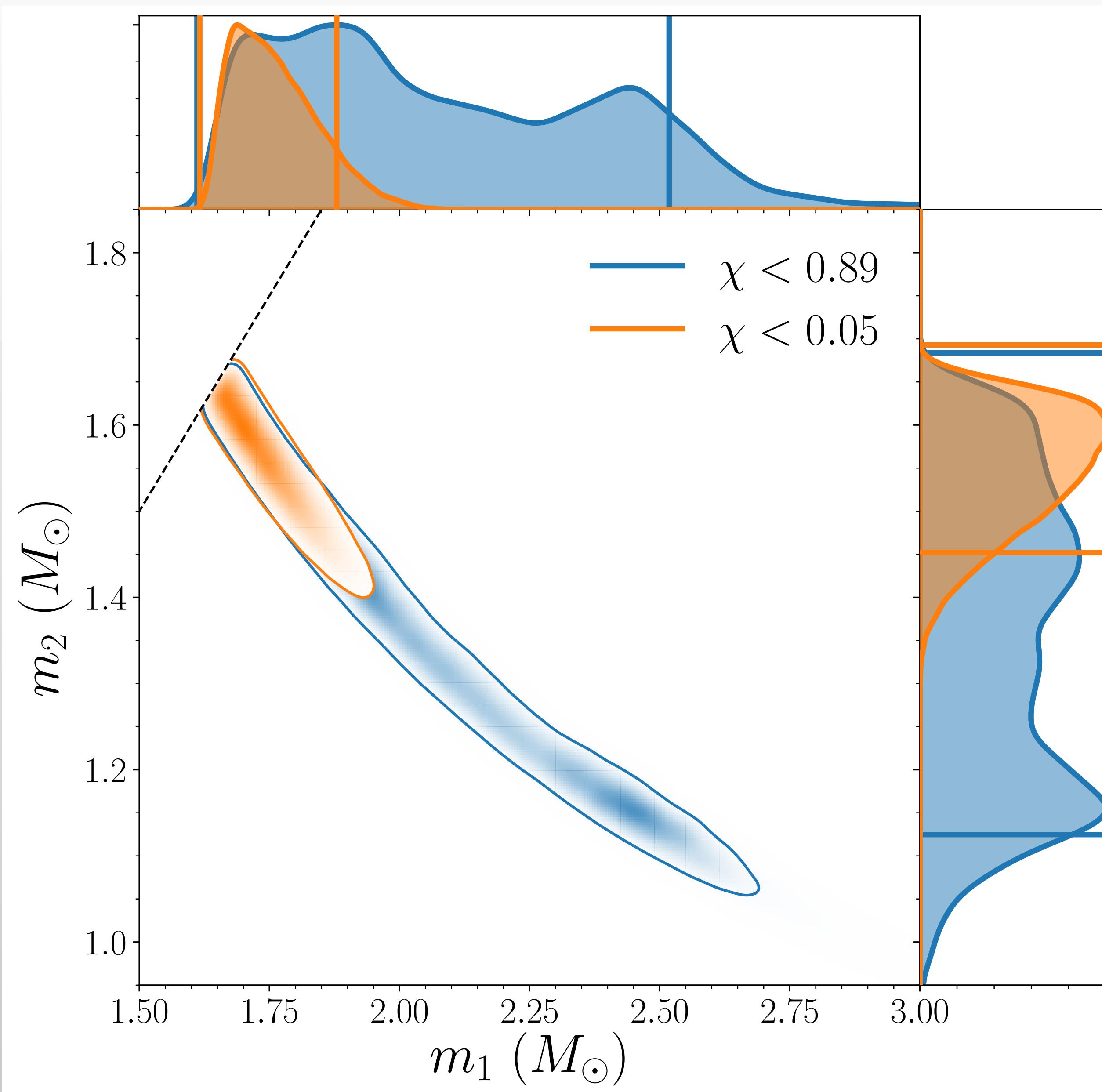


Mass Ratio of ~ 0.75 from EM Data



Kilpatrick et al. 2017

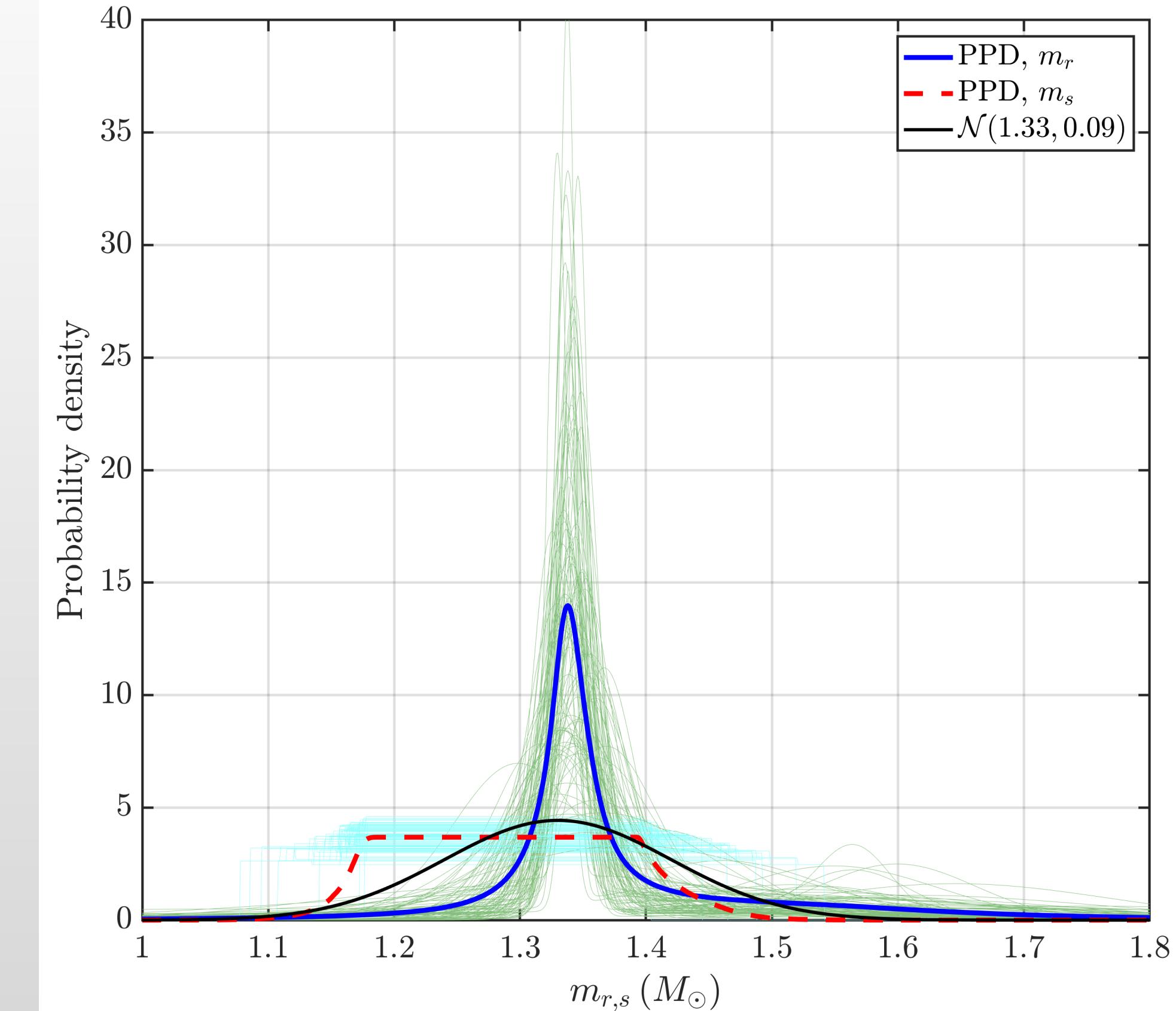
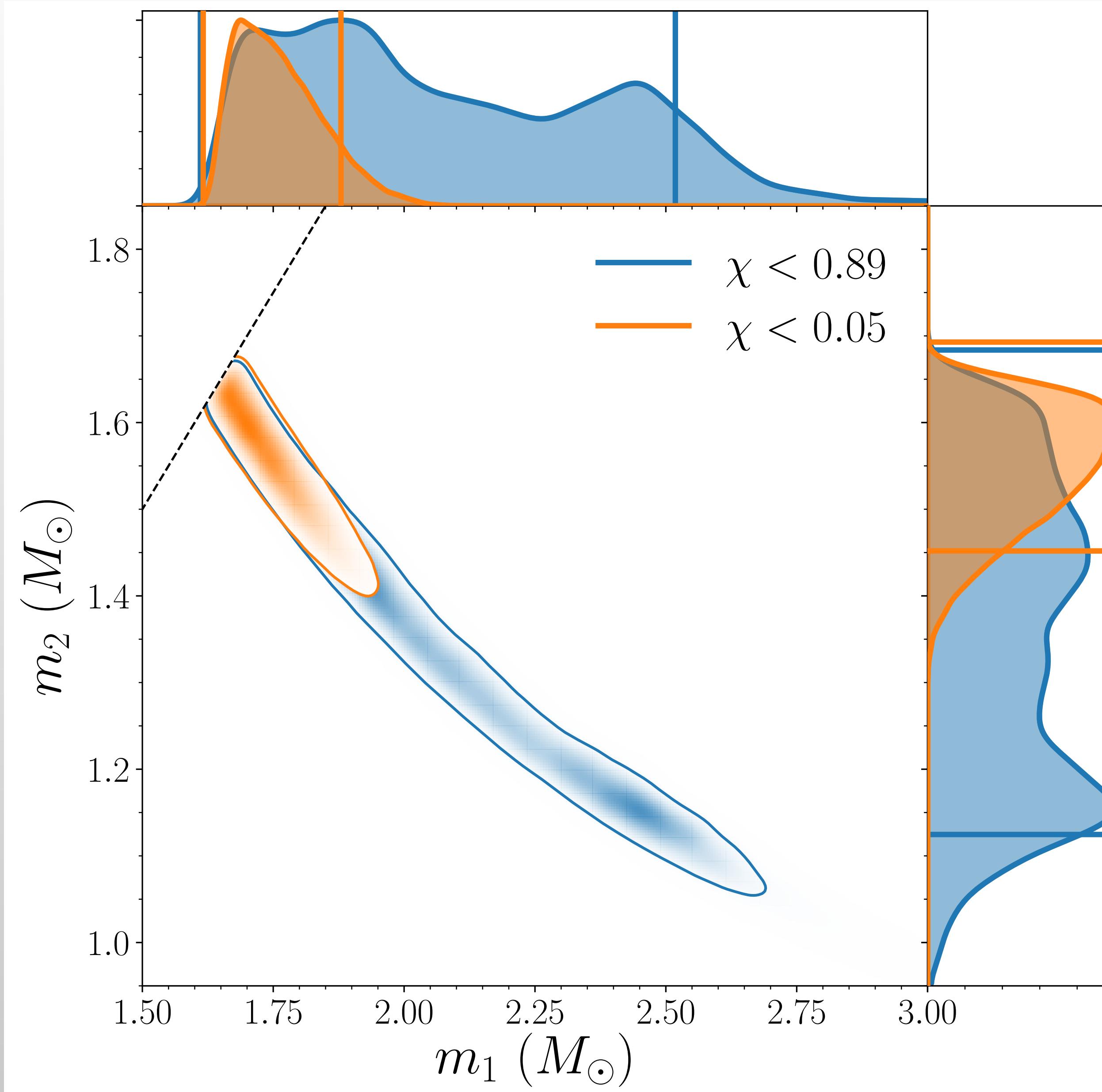
GW190425



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

LVC 2020

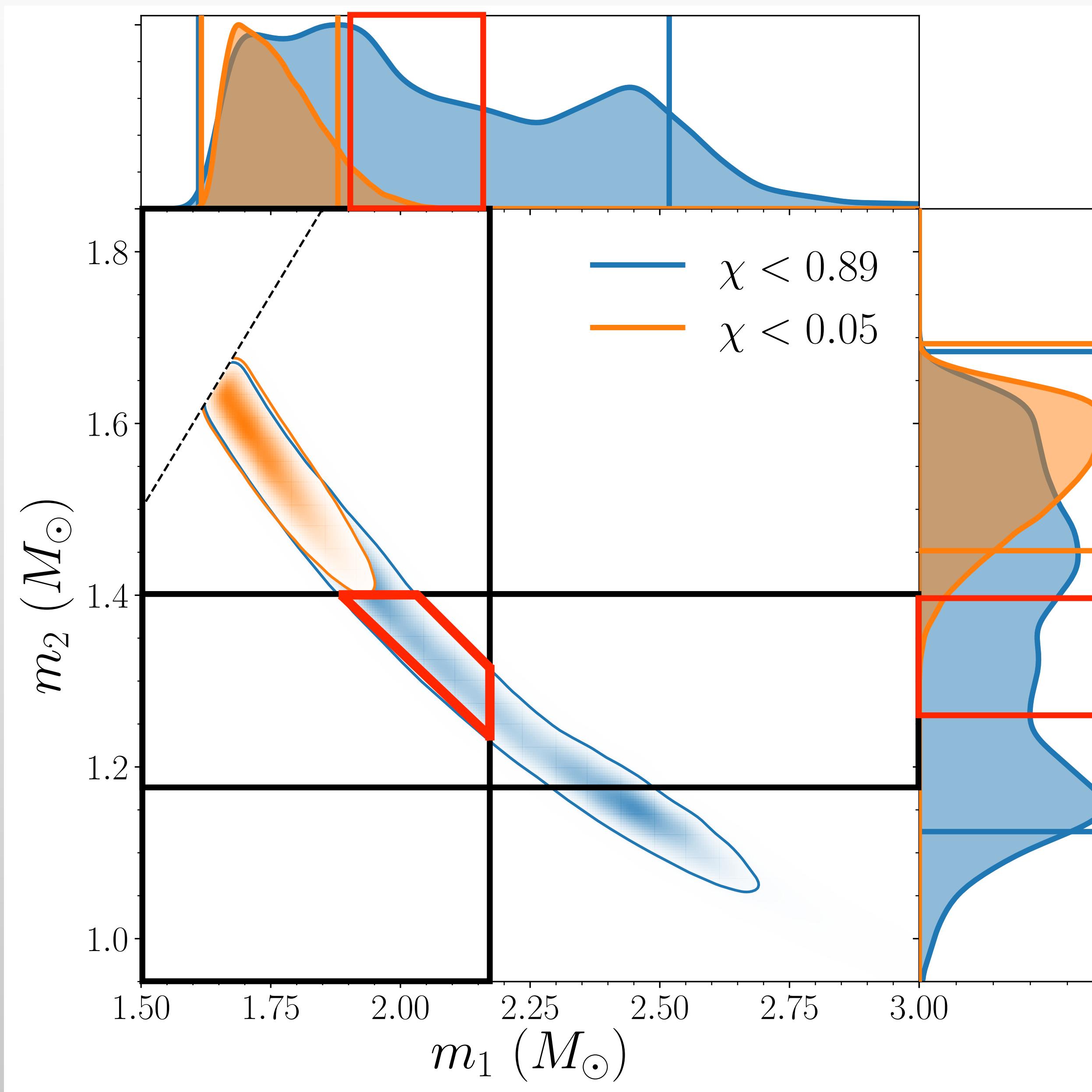
GW190425: 1.4+2.0 BNS



Farrow, Zhu, & Thrane, 2019

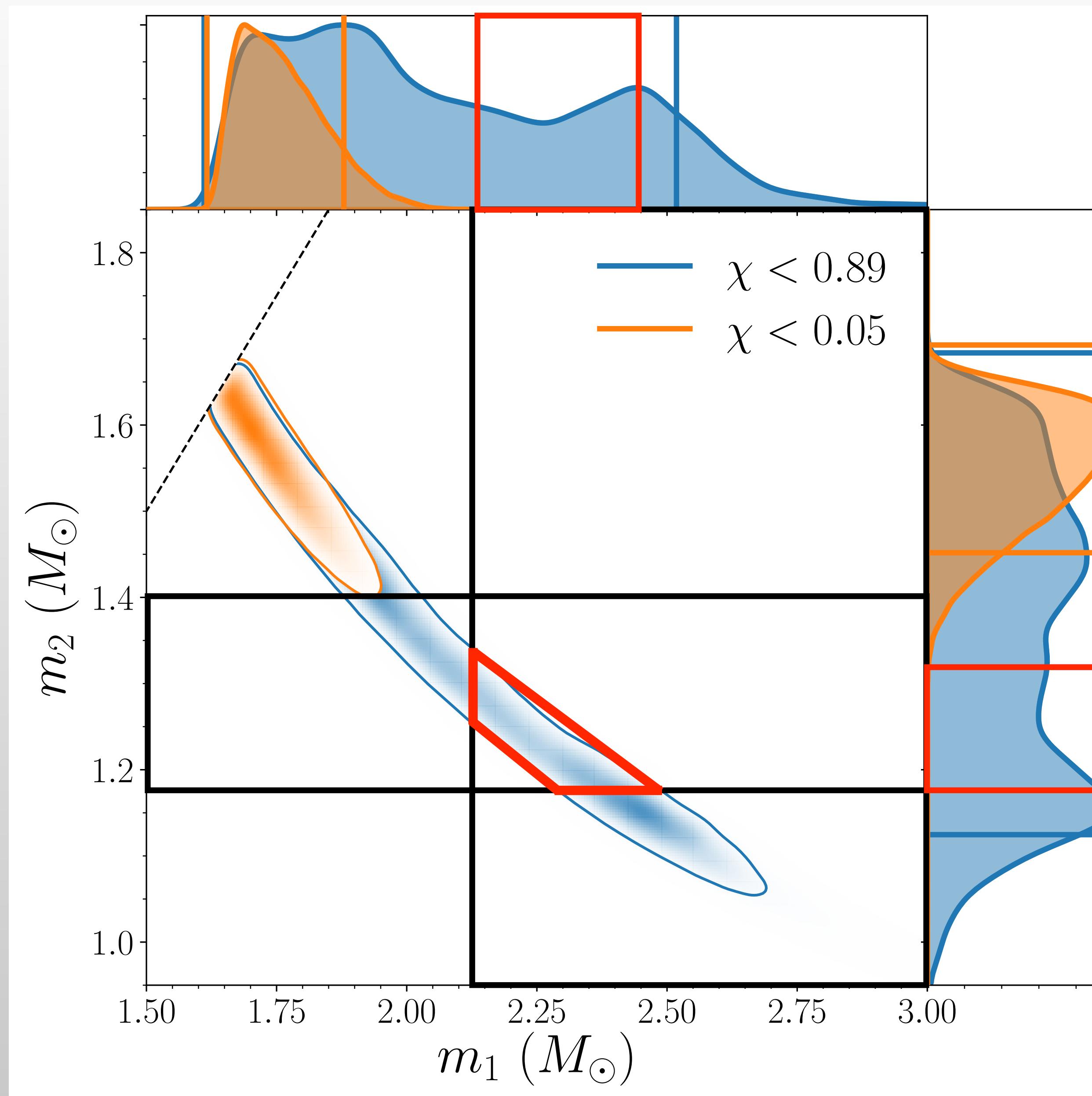
LVC 2020

GW190425: 1.4+2.0 BNS



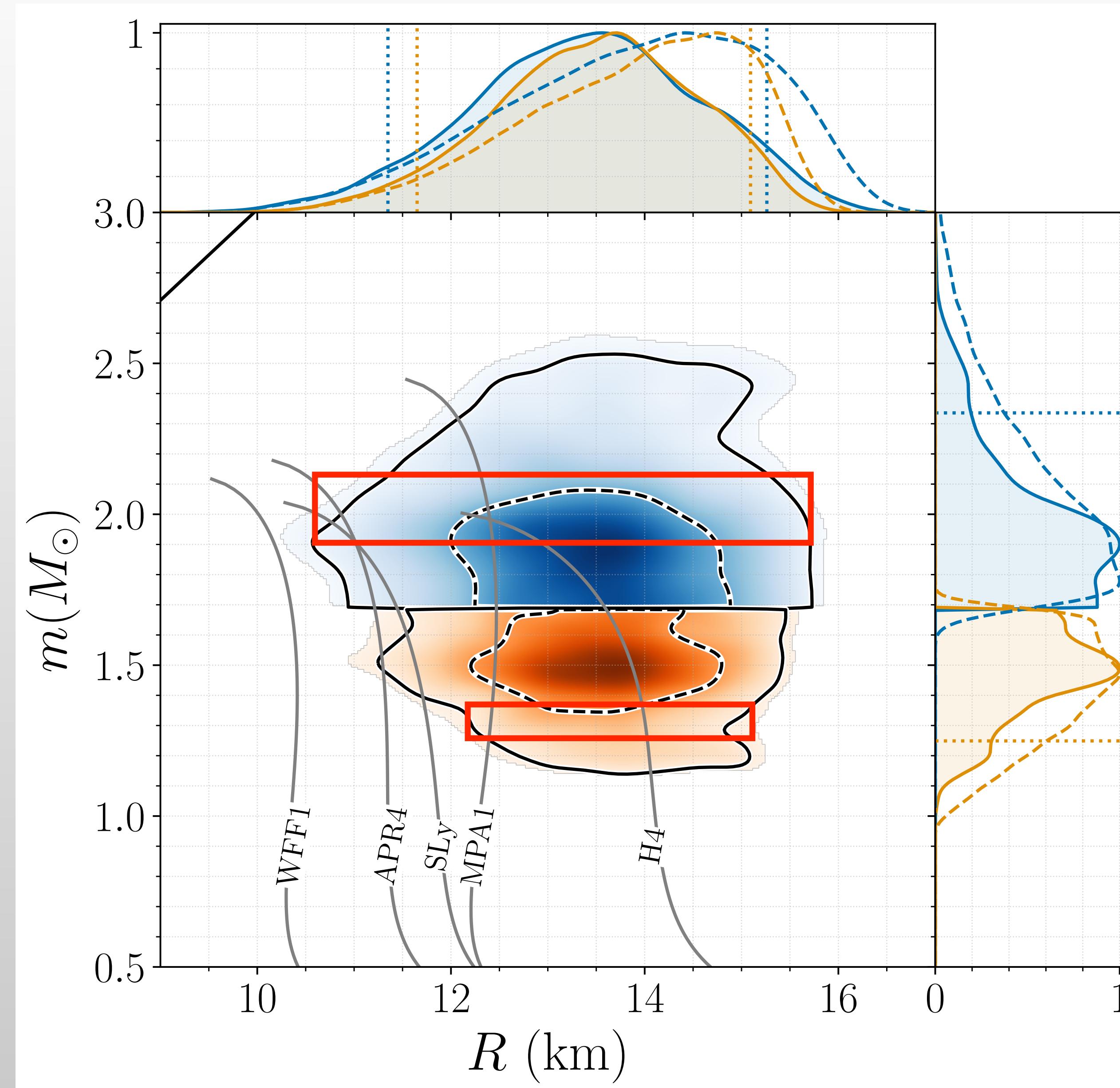
$M_{\text{tot}} \approx 3.35 \pm 0.07 M_\odot$
 $m_1 \approx 1.90 - 2.16 M_\odot$
 $m_2 \approx 1.26 - 1.38 M_\odot$

GW190425: 1.2+2.2 NSBH



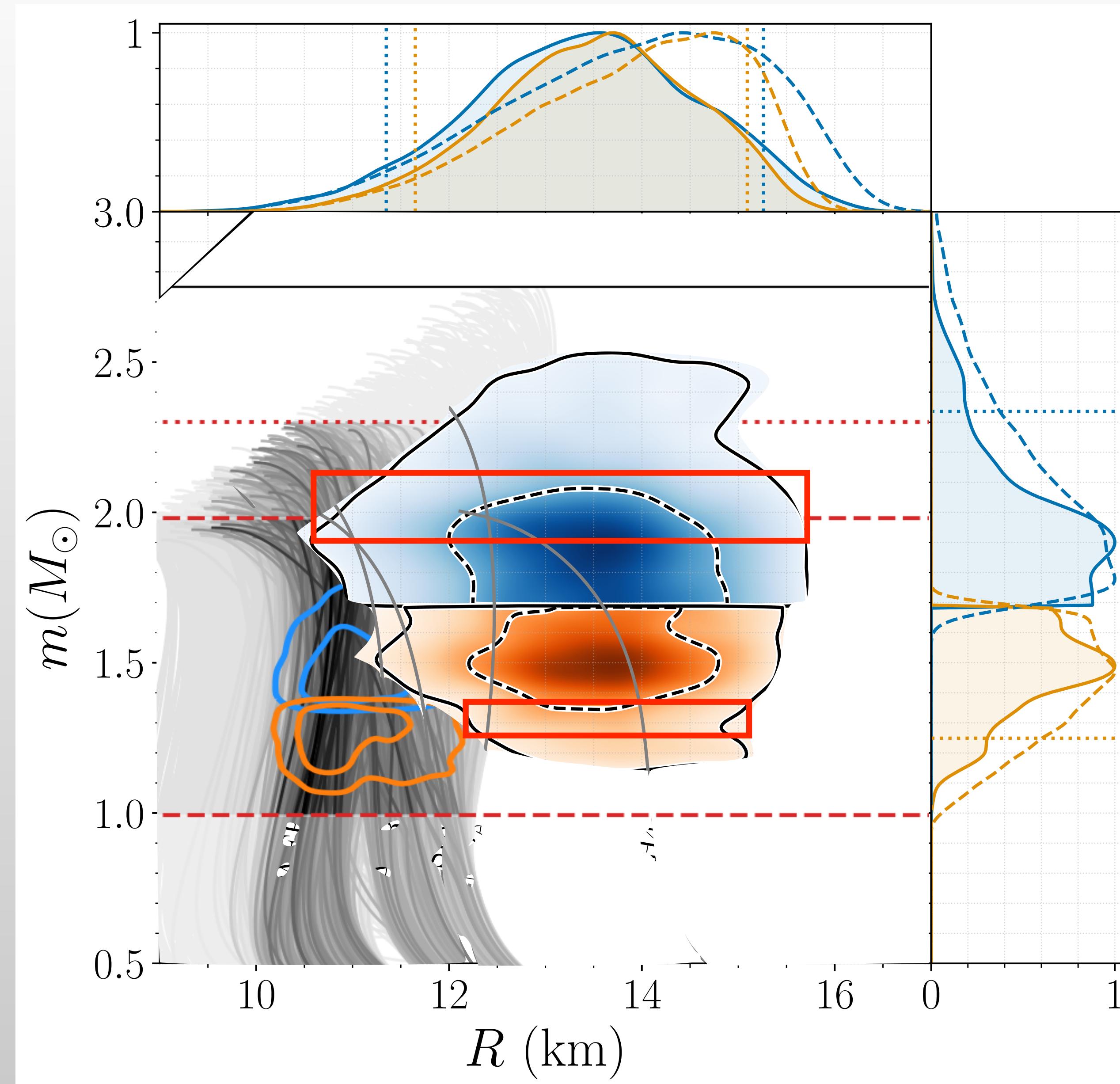
$M_{\text{tot}} \approx 3.54 \pm 0.07 M_\odot$
 $m_1 \approx 2.15 - 2.44 M_\odot$
 $m_2 \approx 1.17 - 1.32 M_\odot$

GW190425: Updated EOS



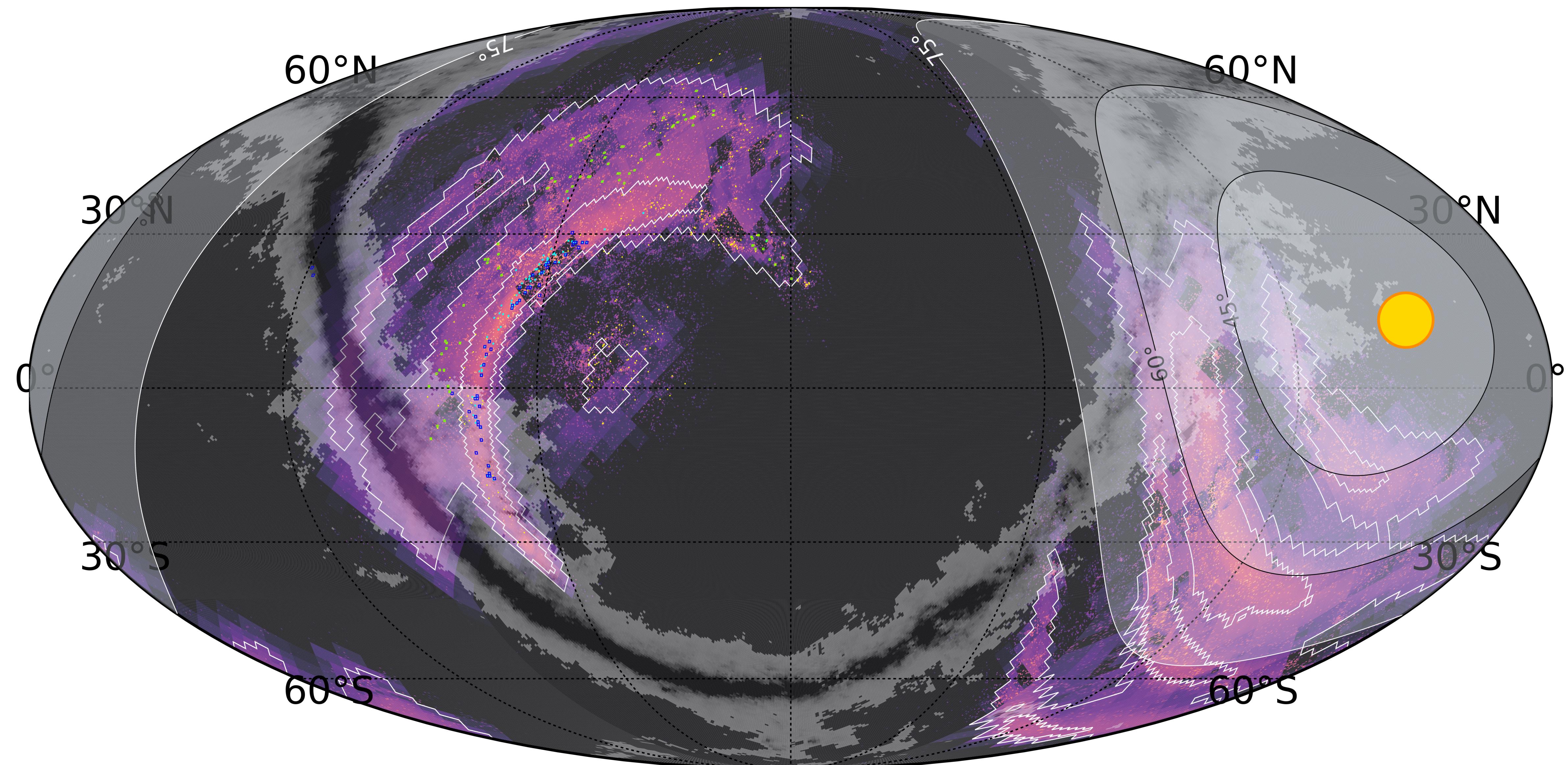
LVC 2020

GW190425: Updated EOS



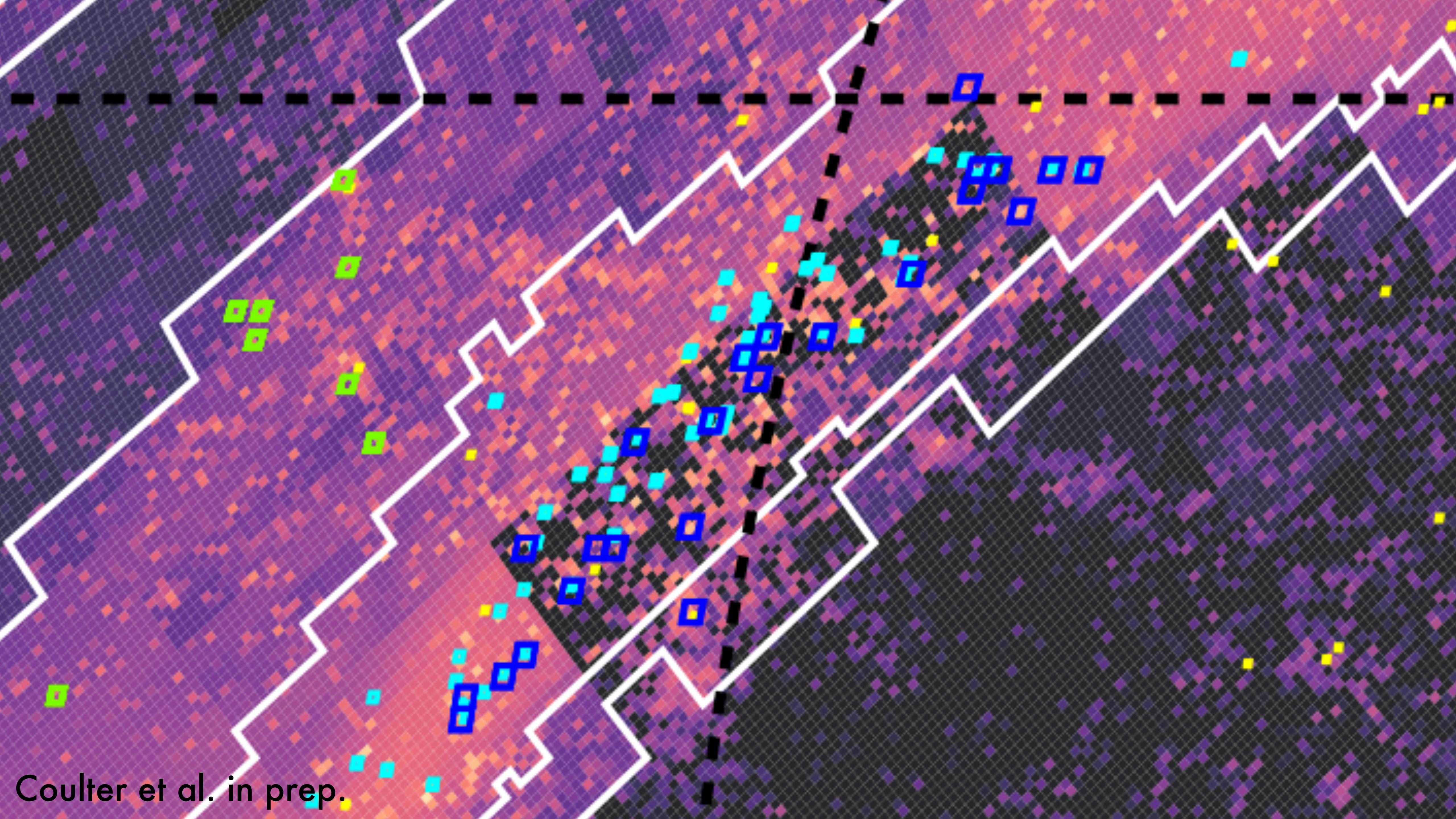
LVC 2020

Declination



Right Ascension

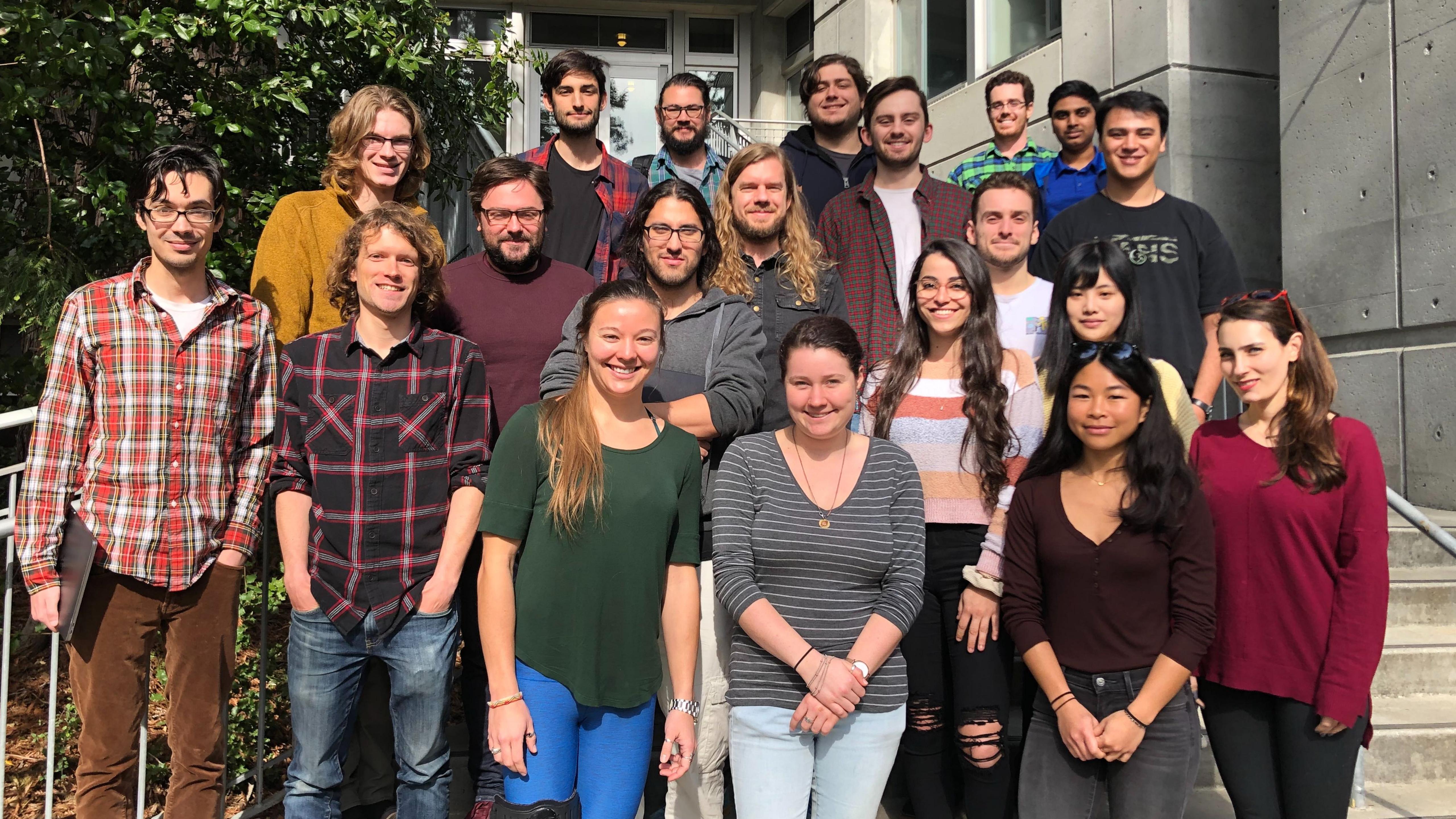
Coulter et al. in prep.



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/ss17a/>





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