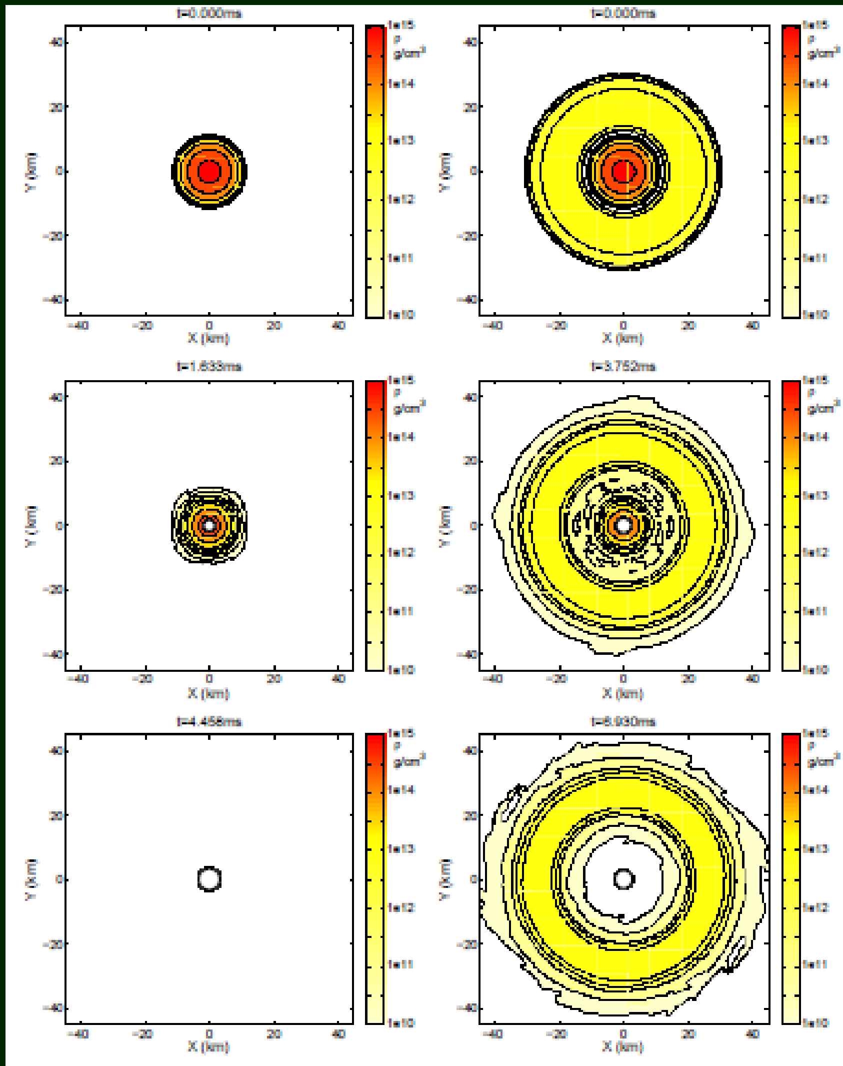
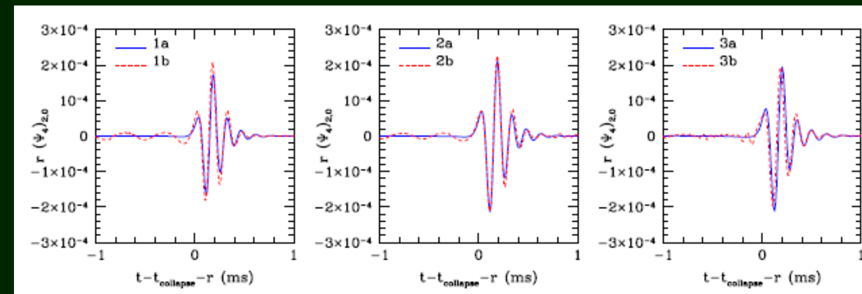
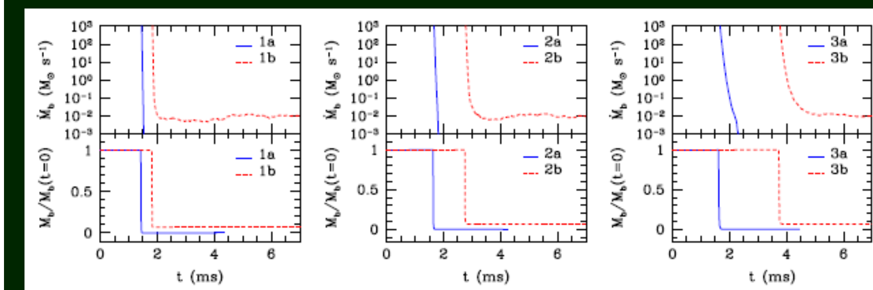
Black holes: Introduction

NS to BH







The authors studied collapse from NS to BH.
Calculations were done for two cases:
with and without massive (7%) disc.
If a disc is present then such objects
can appear as sGRB.
GW signal is weak, and so they are
a subject for the third generation of detectors.

1209.0783, see discussion on dependence on the EoS in 2001.10434

Main general surveys

- **astro-ph/0610657** *Neven Bilic* BH phenomenology
- **hep-ph/0511217** *Scott A. Hughes* Trust but verify: the case for astrophysical BHs
- **arXiv: 0907.3602** *Josep M. Paredes* Black holes in the Galaxy
- **arXiv: 1003.0291** *S.-N. Zhang* Astrophysical Black Holes in the Physical Universe
- **arXiv: 1312.6698** *Narayan, McClintock* Observational Evidence for Black Holes
- **arXiv: 1906.03871** *C. Bambi* Astrophysical black holes: several reviews
- **arXiv: 1808.01507** *Eric Curiel* The Many Definitions of a Black Hole
- **arXiv: 2106.00699** *Michela Mapelli* Formation channels of single and binary stellar-mass black holes
- **arXiv: 1911.04305** *Fabian, Lasenby* Astrophysical black holes

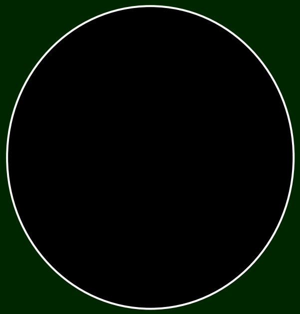
BHs as astronomical sources

- **Primordial BHs**.
  Not discovered, yet. Only upper limits (mostly from gamma-ray observations).
- **Stellar mass BHs**.
  There are more than twenty good candidates in close binary systems.
  Accretion, jets. Observed at all wavelenghts.
  Isolated stellar mass BHs are not discovered up to now.
  But there are interesting candidates among microlensing events.
- **Intermediate mass BHs**.
  Their existence is uncertain, but there are good candidates among ULX.
  Observed in radio, x-rays, and optics.
- **Supermassive BHs**.
  There are many (dozens) good candidates with mass estimates.
  In the center of our Galaxy with extremely high certainty there is supermassive BH.
  Accretion, jets, tidal discruptions of normal stars.
  Observed at all wavelenghts.

What is a black hole ?

For a physicist

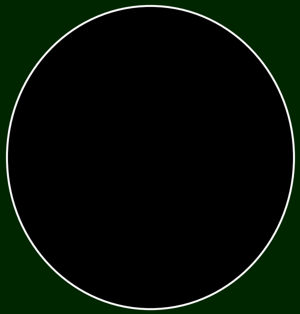
Has specific implicit properties



An object with a horizon
(plus other properties).

For an astronomer

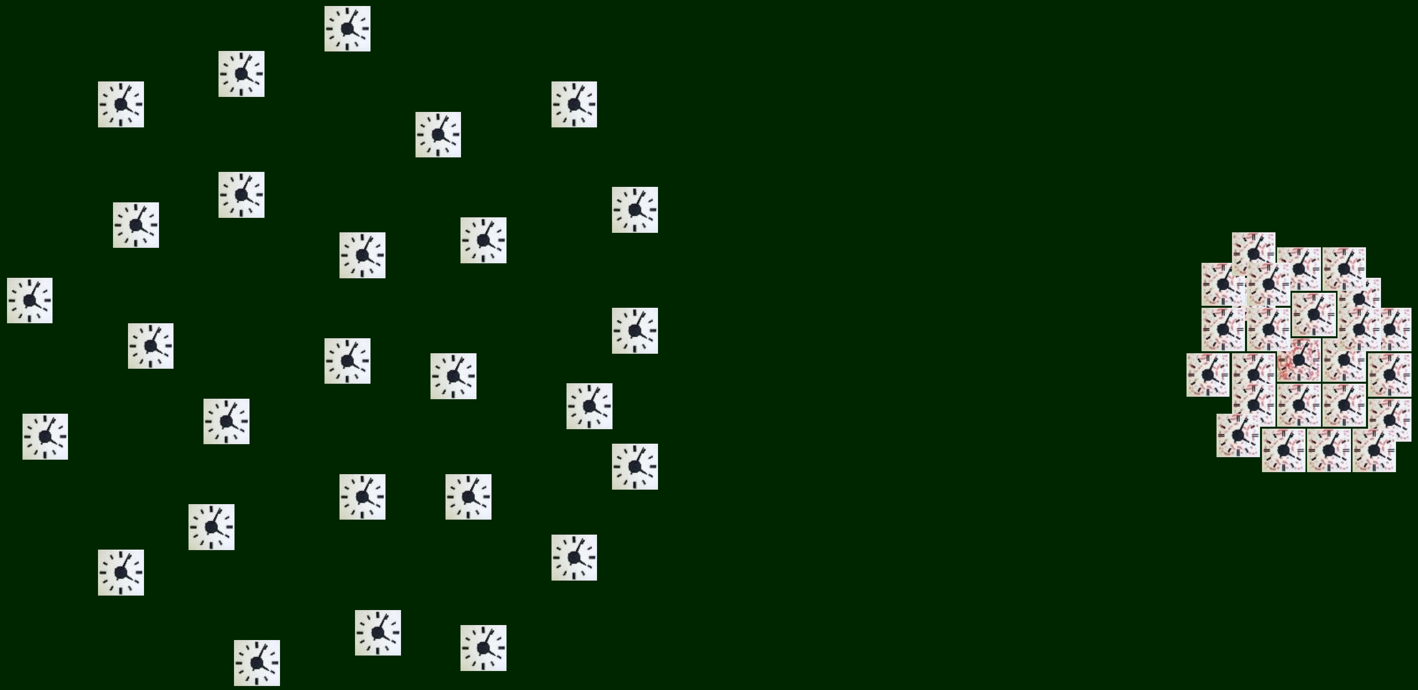
Has specific observational signatures



A compact massive body
(the horizon size scale) which
does not show any evidence of a surface
and which interiors do not produce any
observational phenomenon.

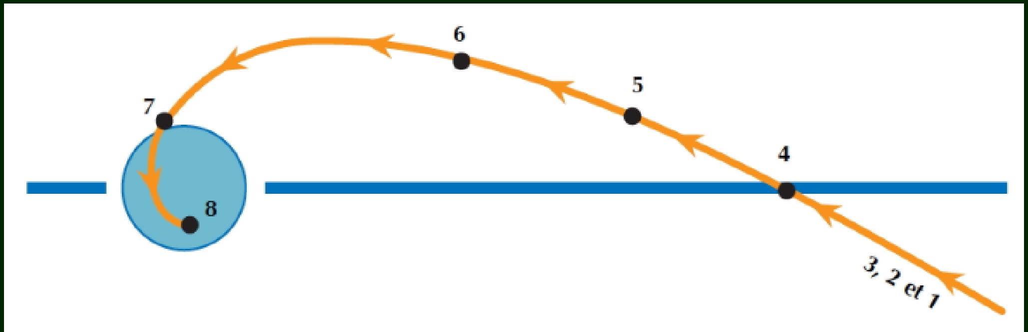
See **1808.01507**
for different definitions of a BH

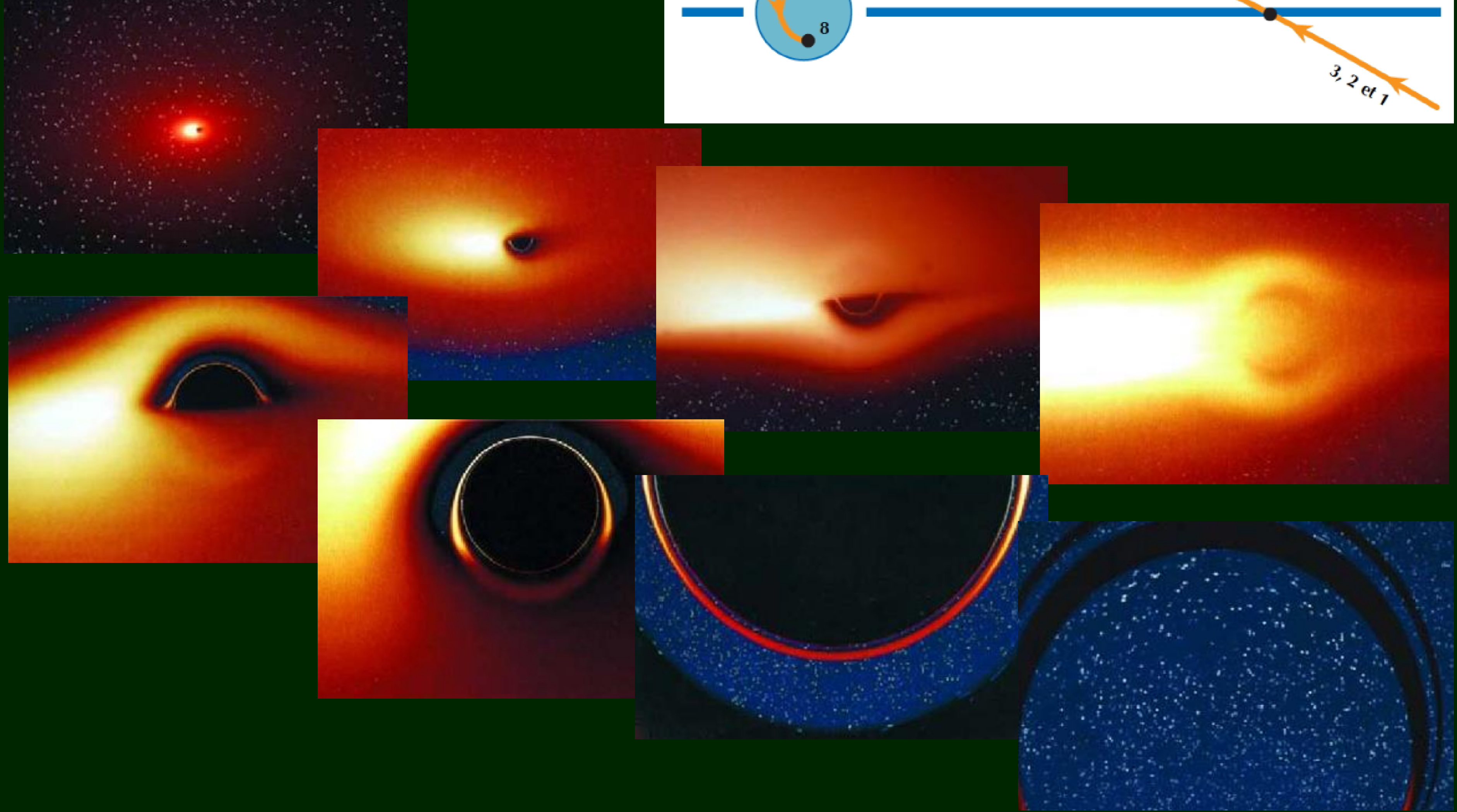
Collapse of a cloud



We always see the clock in the center,
but they become more and more red
and go more and more slowly…

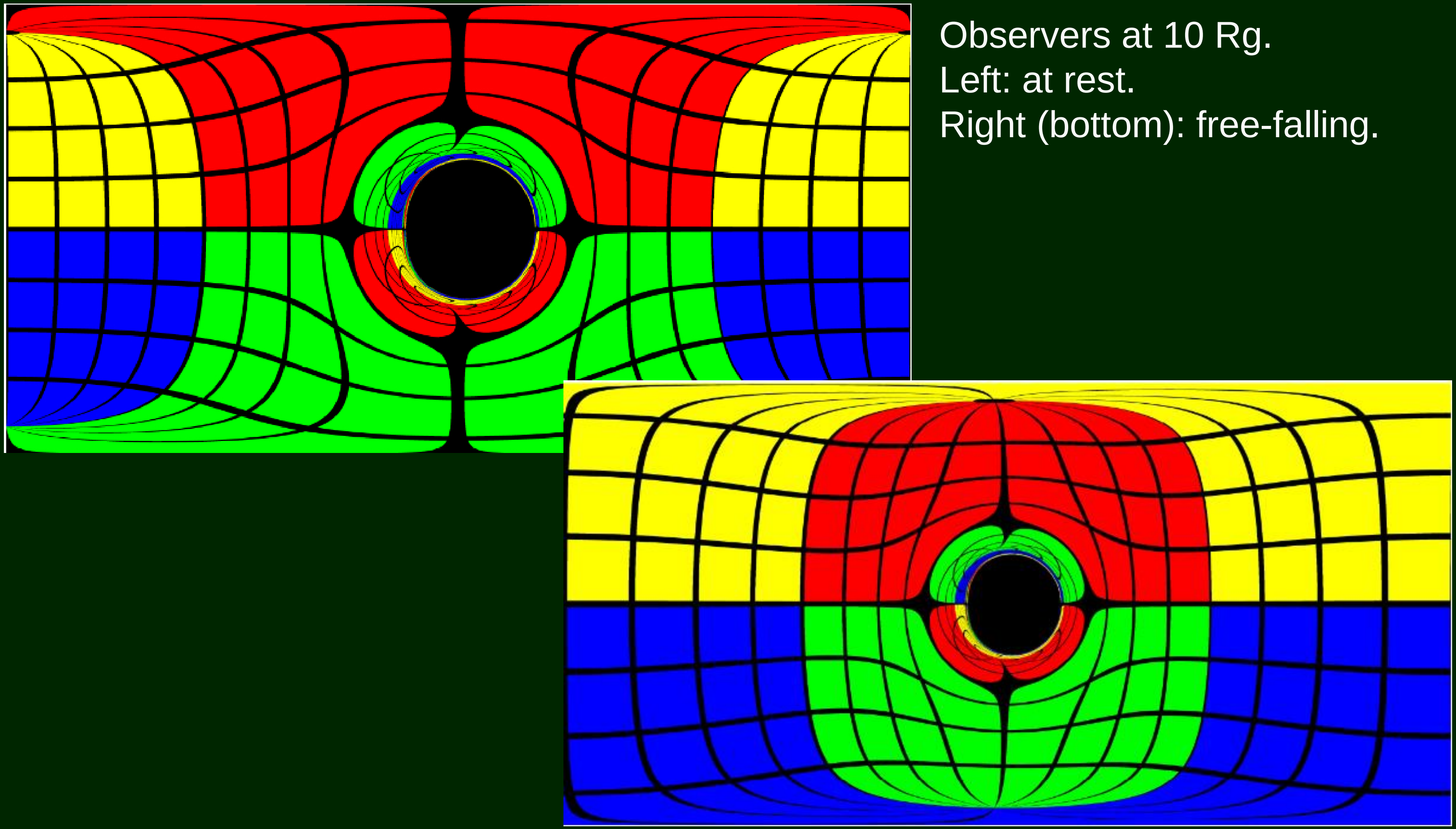
Falling into a BH





1804.03909, see also 1902.11196

BH virtual reality



Observers at 10 Rg.
Left: at rest.
Right (bottom): free-falling.

1811.08369

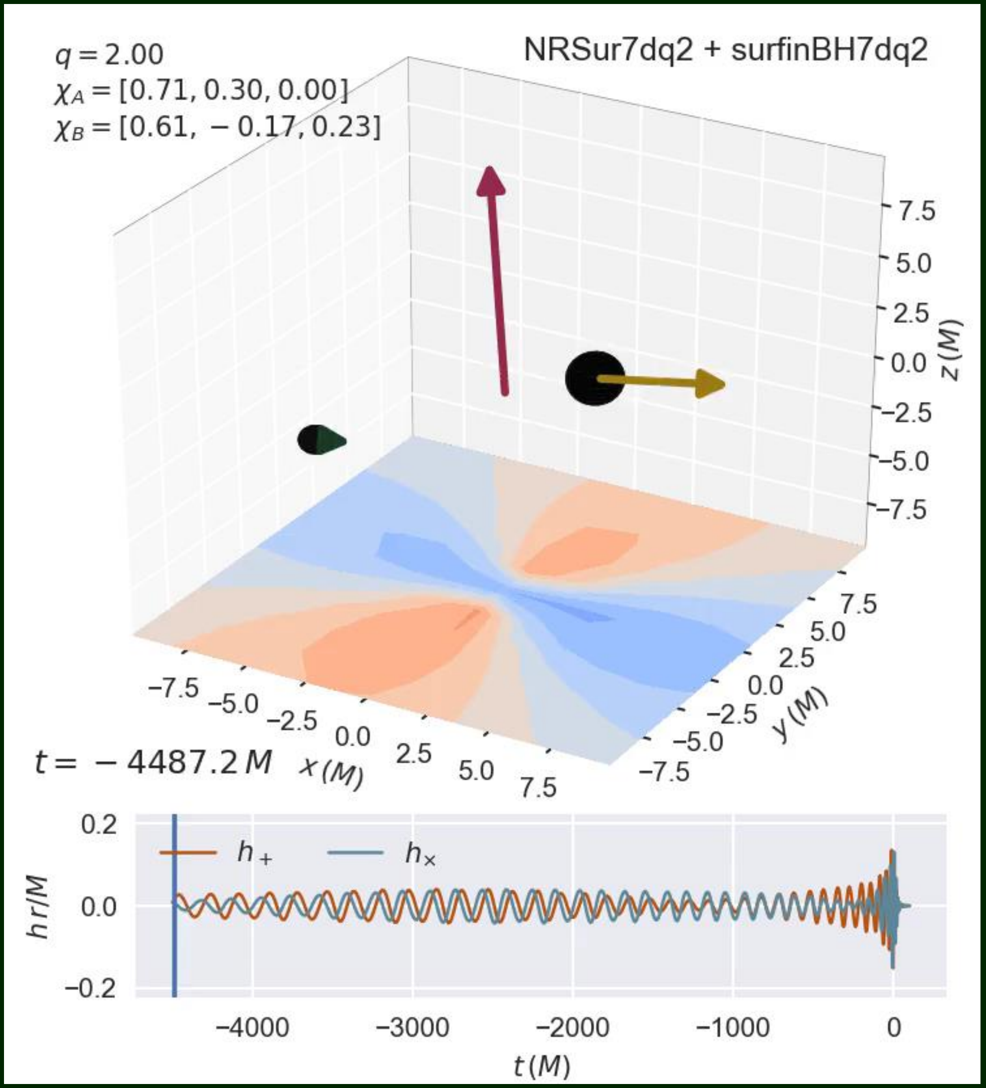
Video for Sgr A*

https://www.youtube.com/watch?v=SXN4hpv977s

https://blackholecam.org/

Binary BH visualization

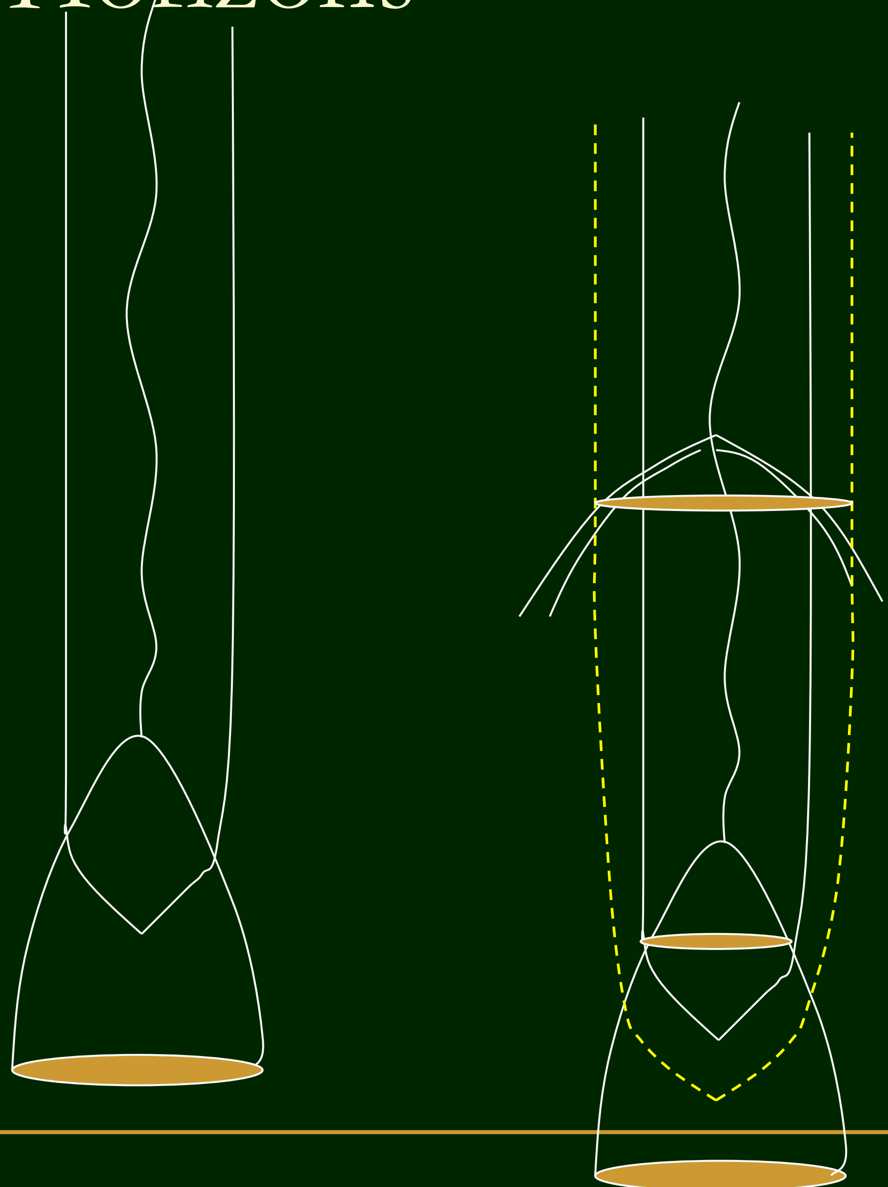
https://vijayvarma392.github.io/binaryBHexp/

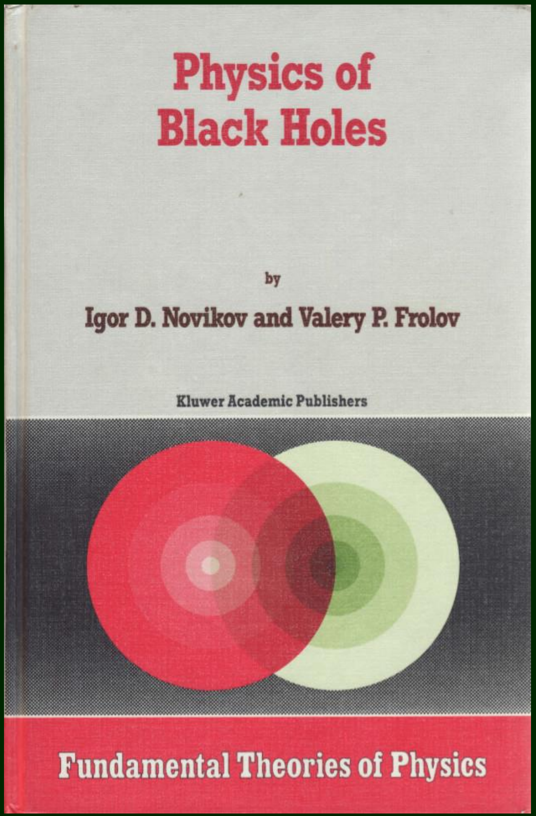


The black holes are shown as oblate spheres, with arrows indicating their spins.
The orbital angular momentum is indicated by the pink arrow at the origin.
The colors in the bottom-plane shows the value of the plus polarization of the GW as seen by an observer at that location;
red means positive and blue means negative, notice the quadrupolar pattern of the radiation.
In the subplot at the bottom, we show the plus and cross polarizations as seen from the camera viewing angle.

1811.06552

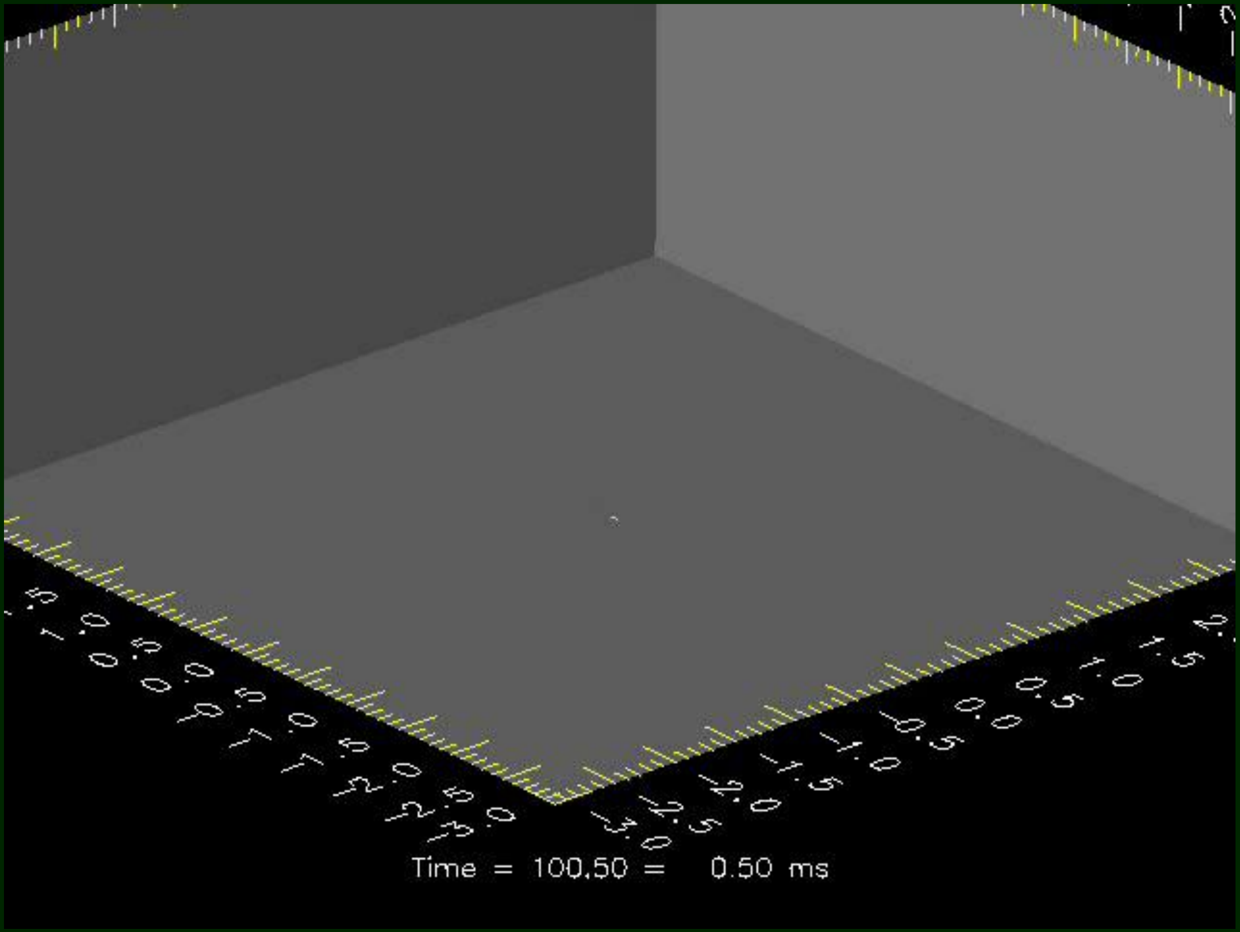
Horizons





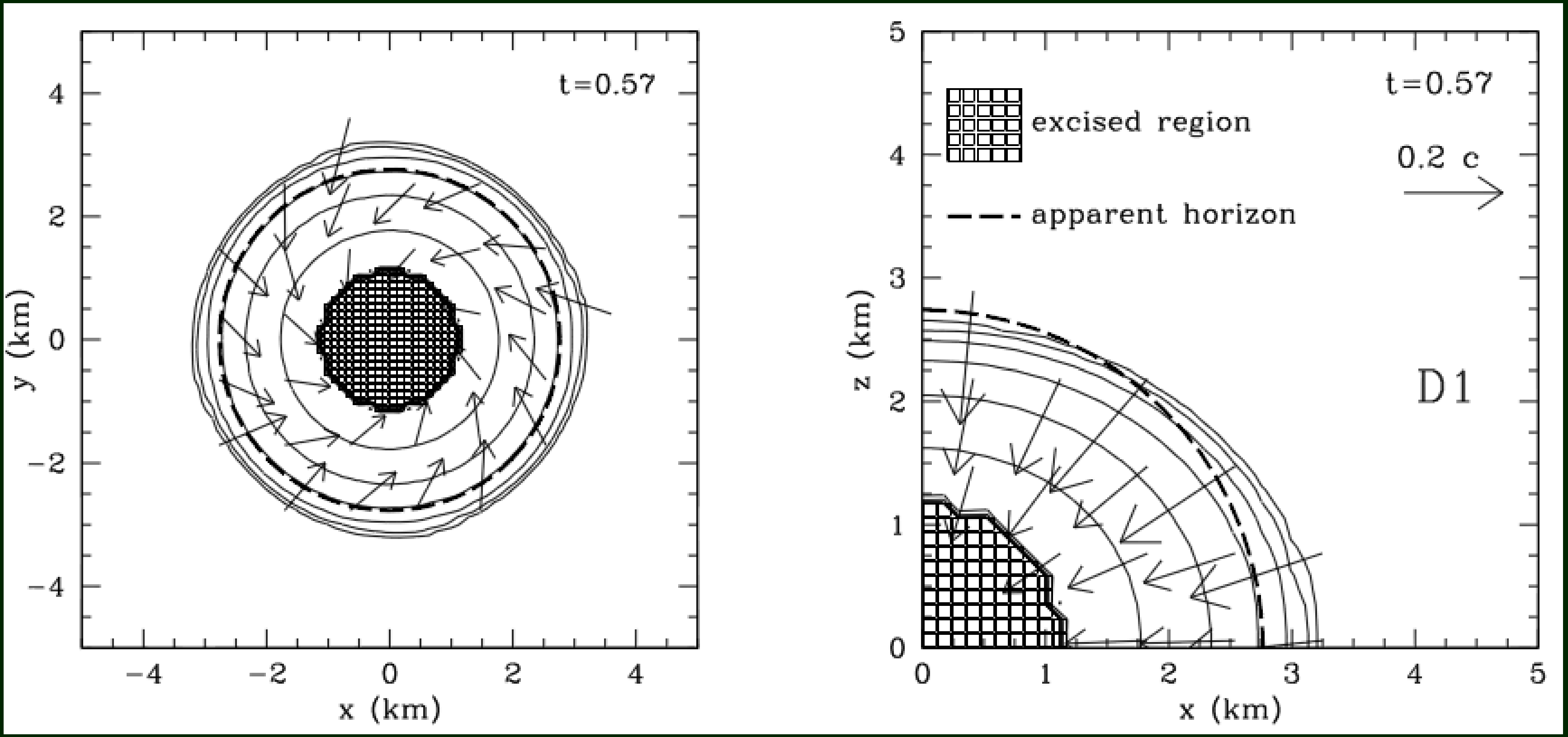
Black holes do not have hairs.

Horizons appearance



L. Baiotti, Rezzolla et al.

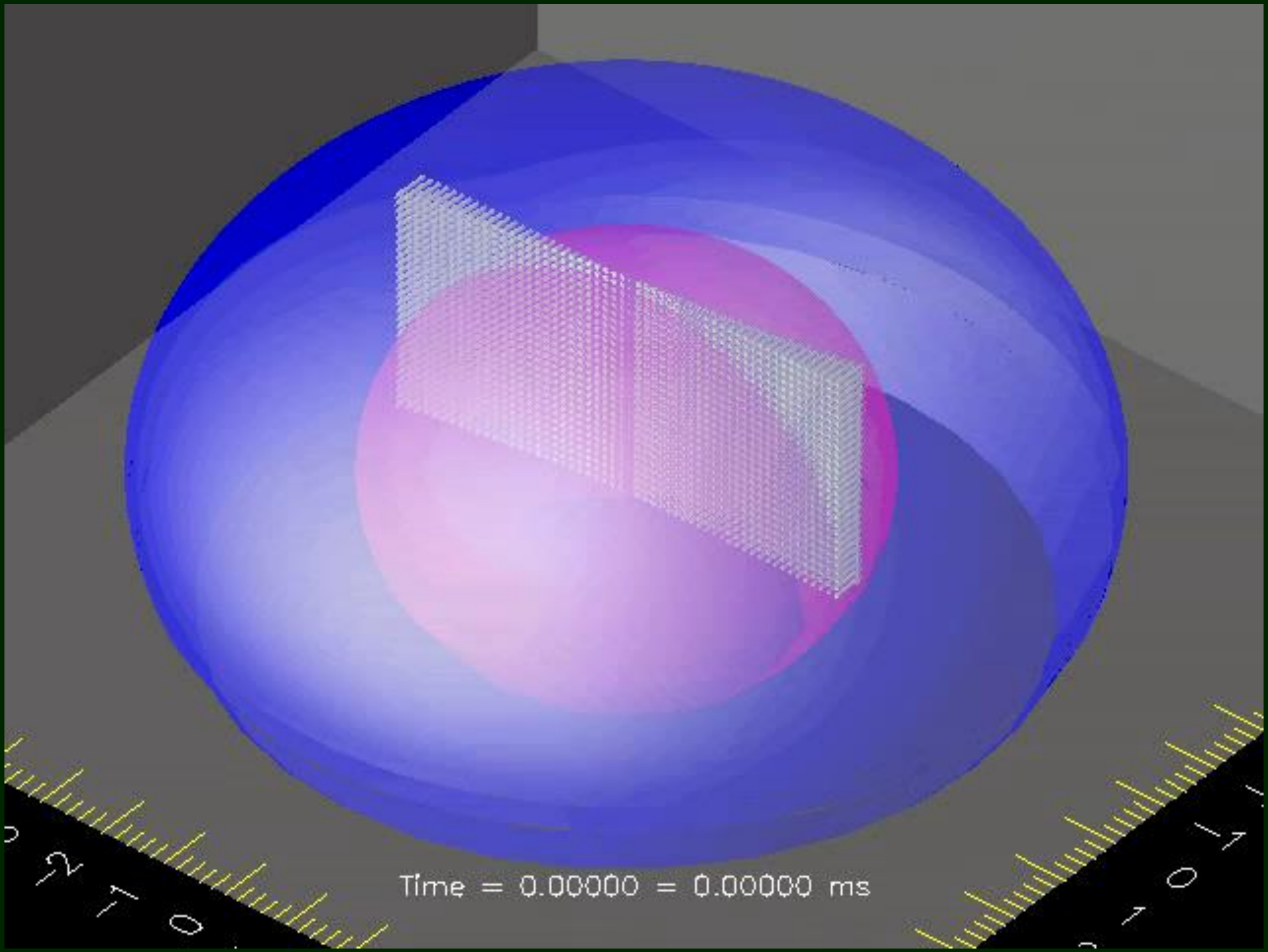
Collapse



Apparent horizon position is calculated at every time step.
The event horizon (which is growing from zero to its final position and is always outside the apparent horizon) is calculated a posteriory, i.e. after calculations are finished.

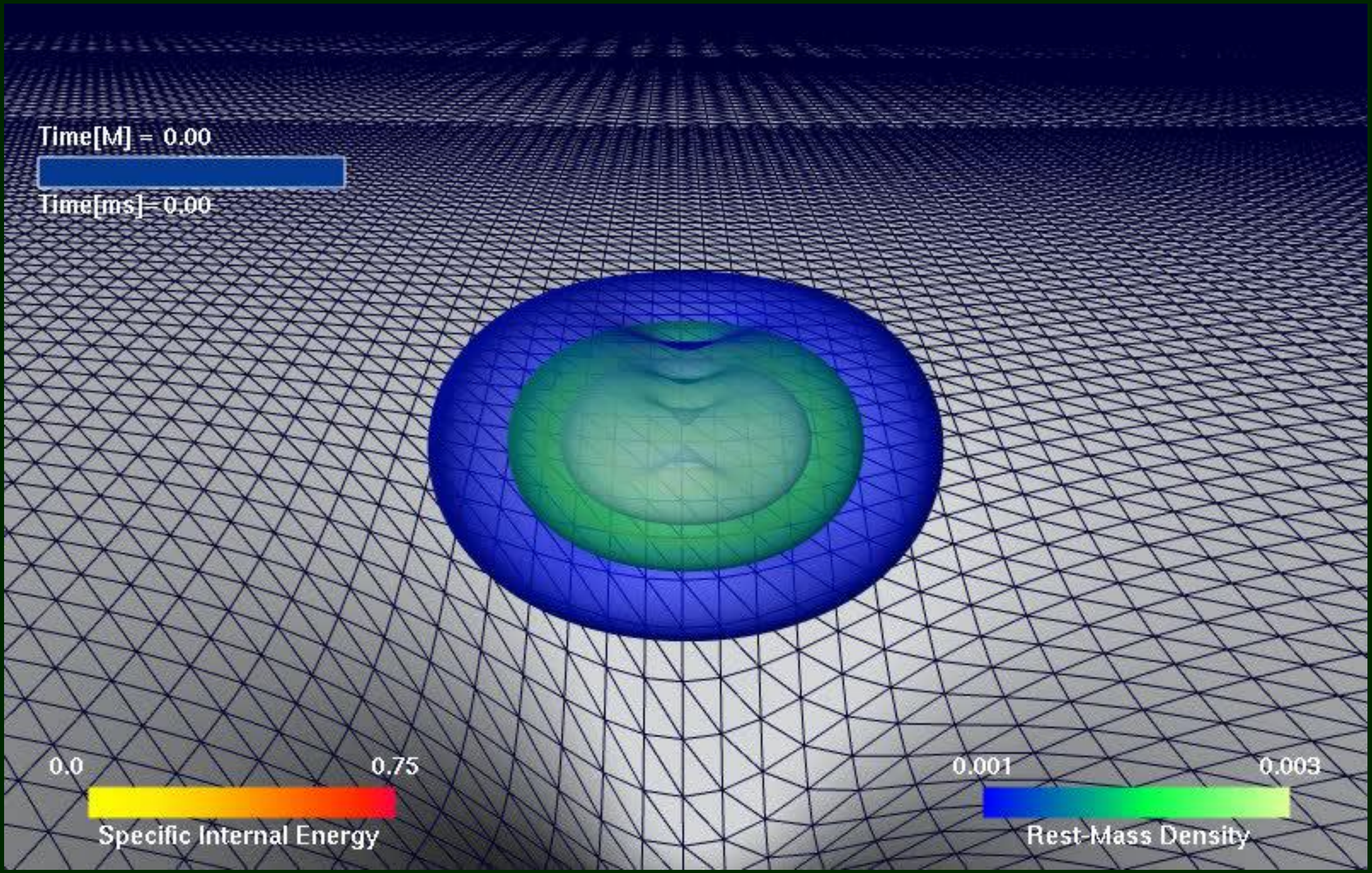
L. Baiotti, Rezzolla et al.

gr-qc/0403029



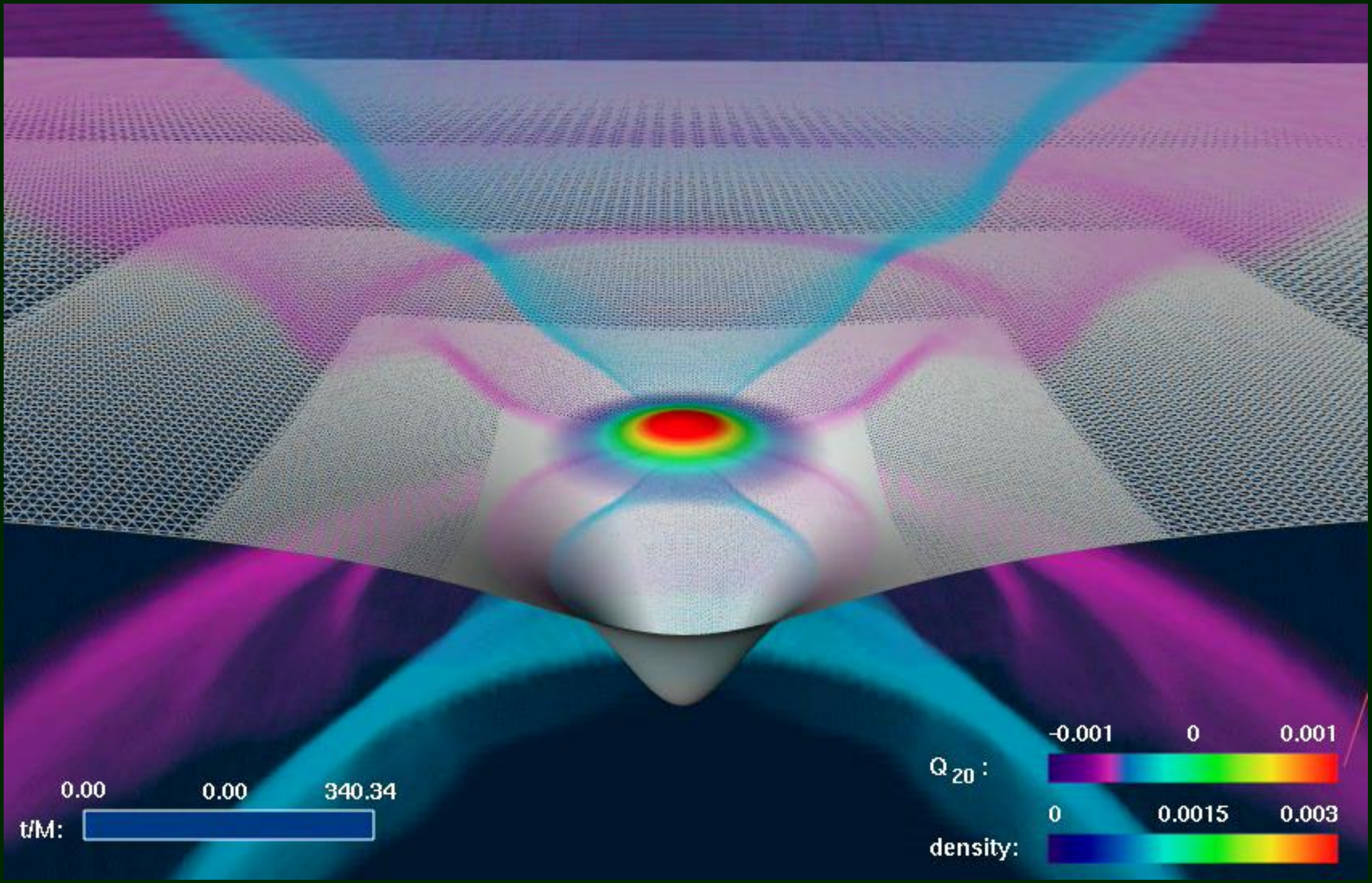
Giacomazzo, Rezzolla et al.

Collapse of a rotating star



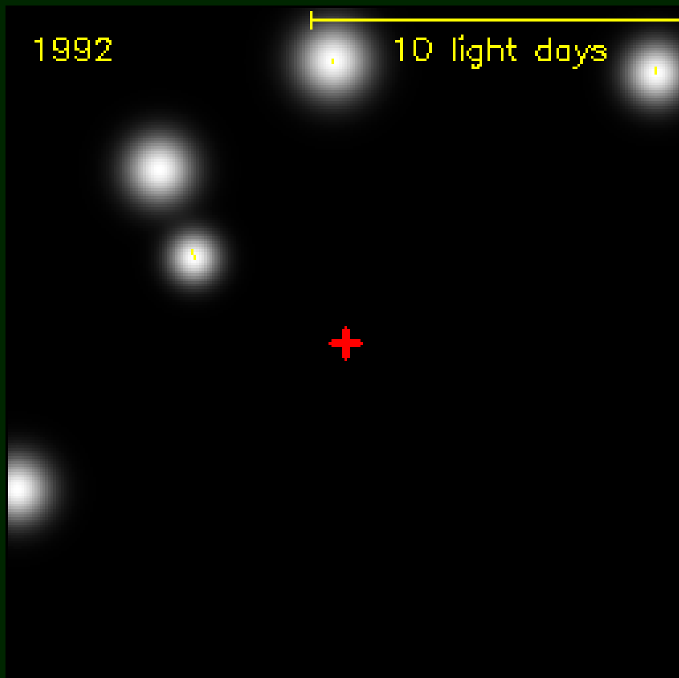
Giacomazzo, Rezzolla et al.

Collapse and GW emission



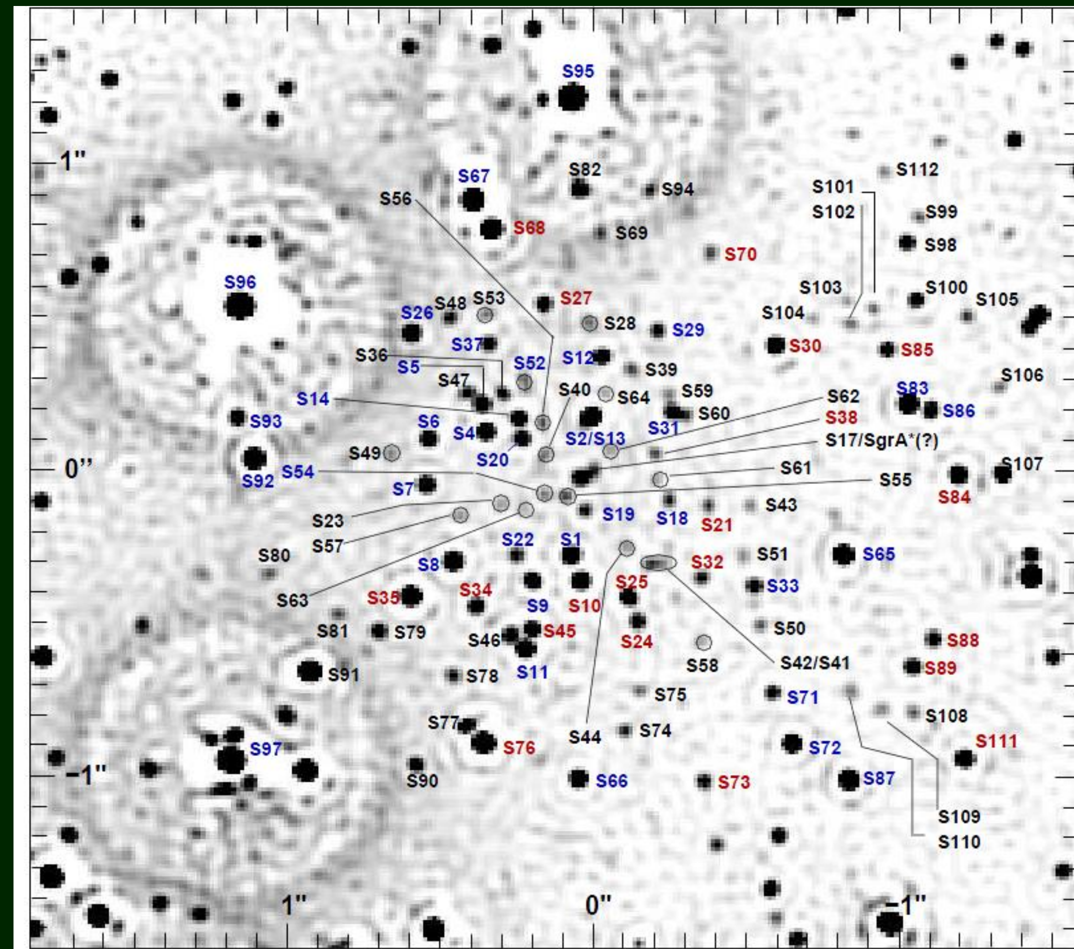
Giacomazzo, Rezzolla et al.

The most certain BH – Sgr A*



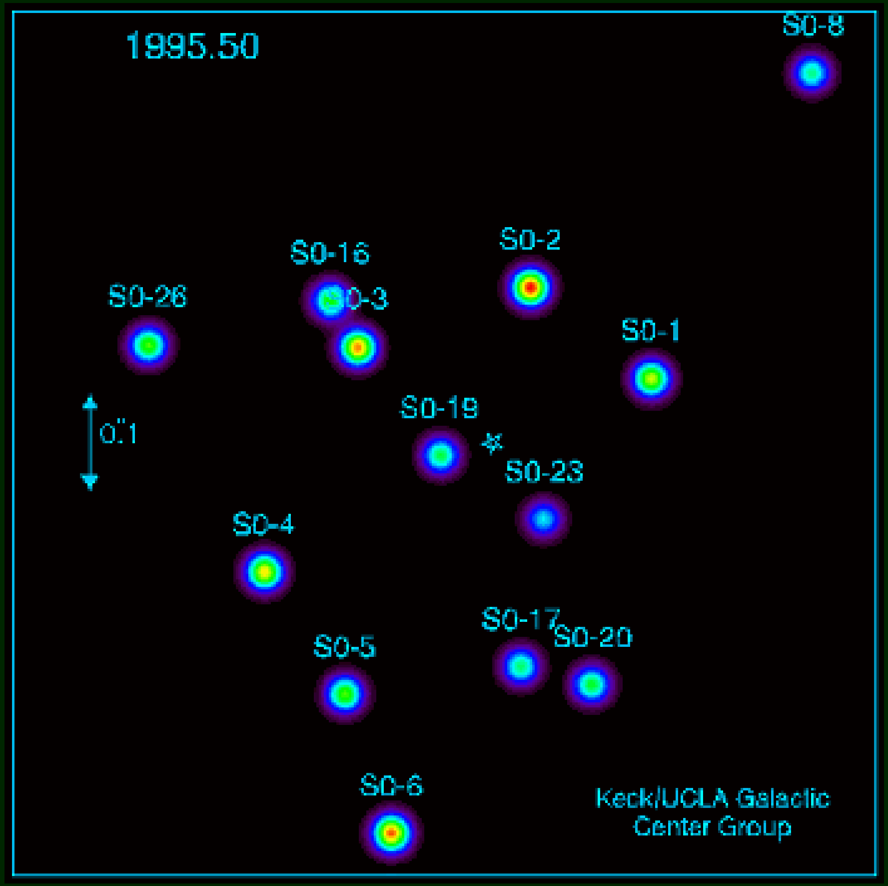
Stellar orbits from 1992 till 2007

(see the reference
in gr-qc/0506078)



arXiv: 0810.4674

... and it becomes more and more certain

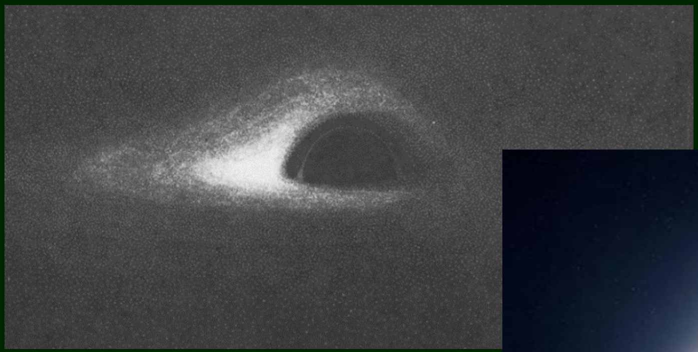


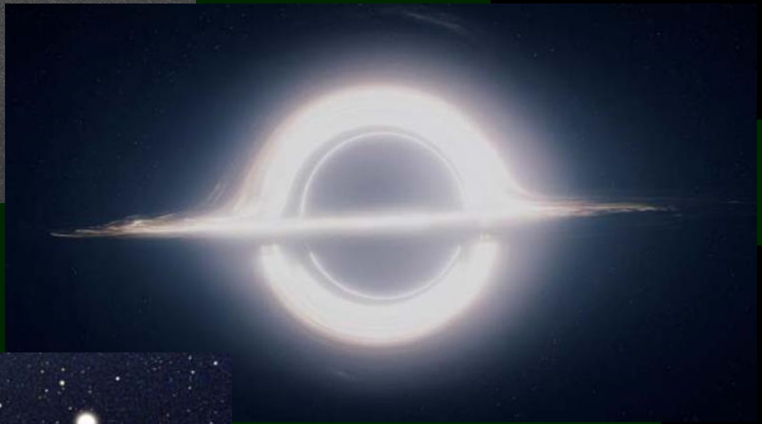
Observations are going on.
So, the number of stars with well measured orbits grows.

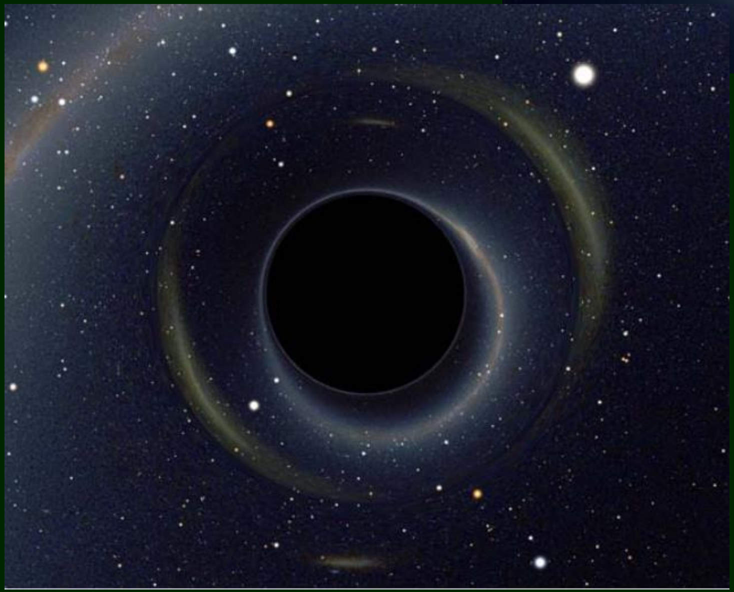
$M_{BH} \sim 4\text{-}5\ 10^6\ M_{solar}$

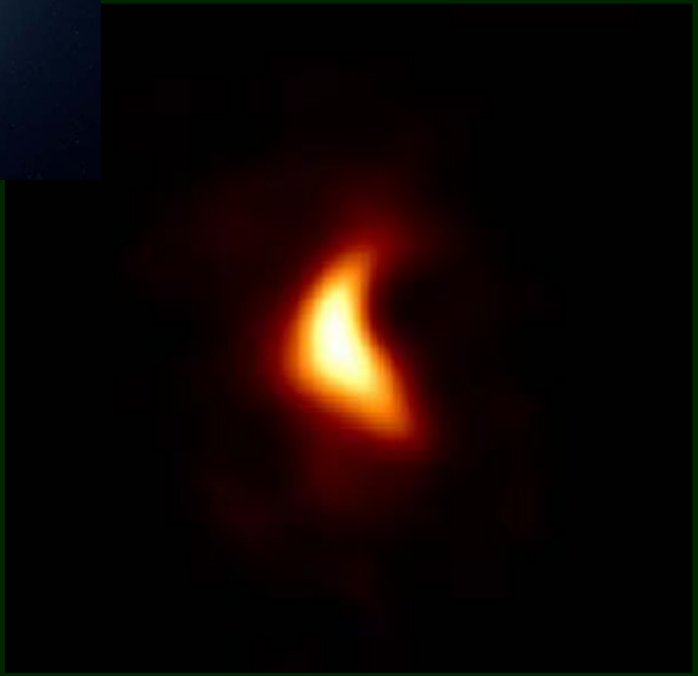
See the reference in gr-qc/0506078
New data in arXiv: 0810.4674
Recent review - 1311.1841

BH visualization





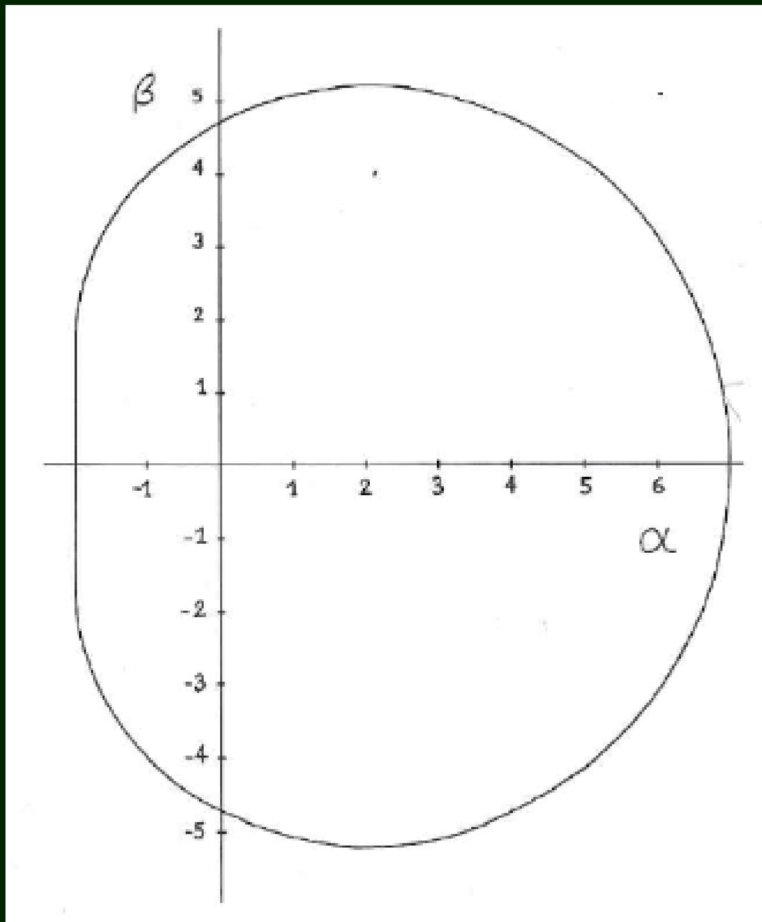


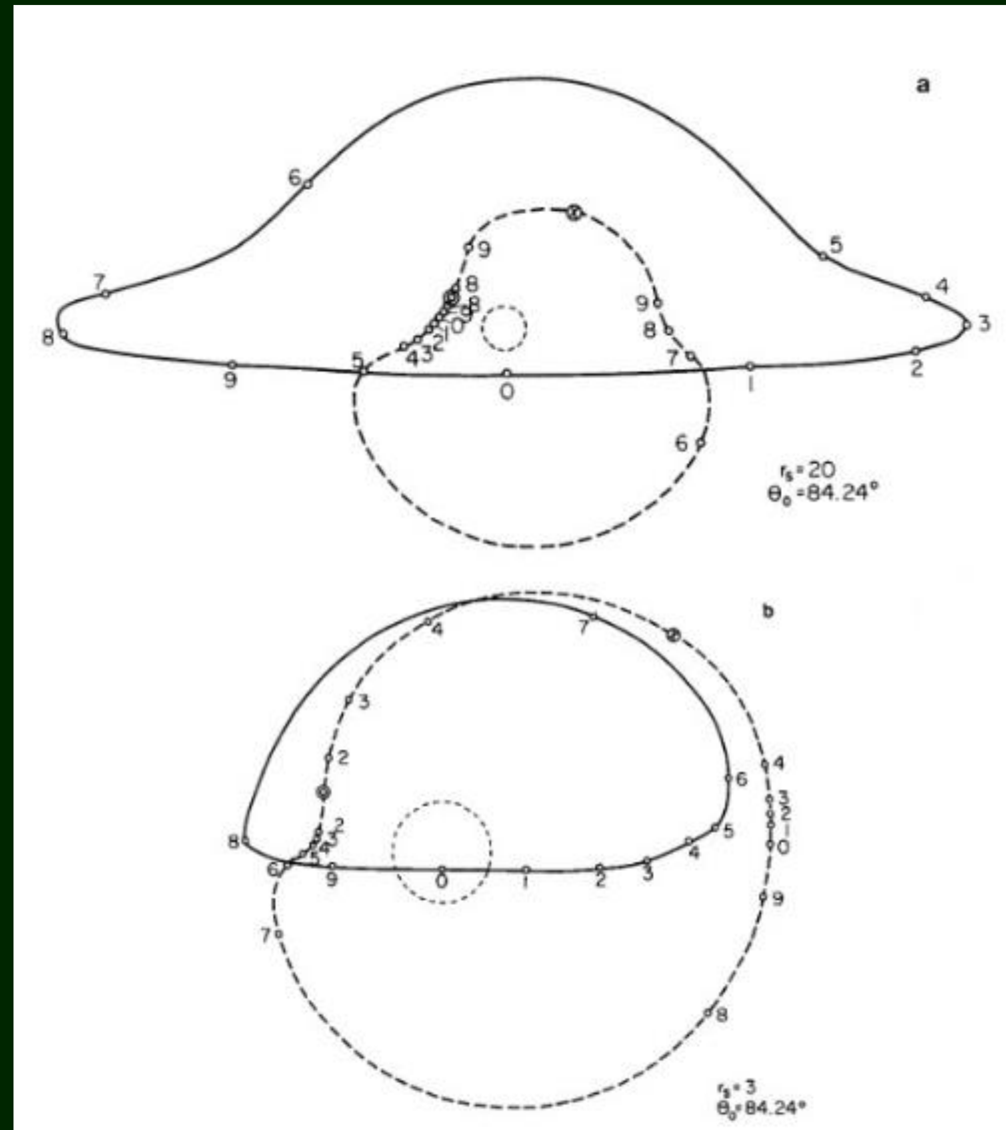


1804.03909, see also 1902.11196

First calculations

Bardeen 1972





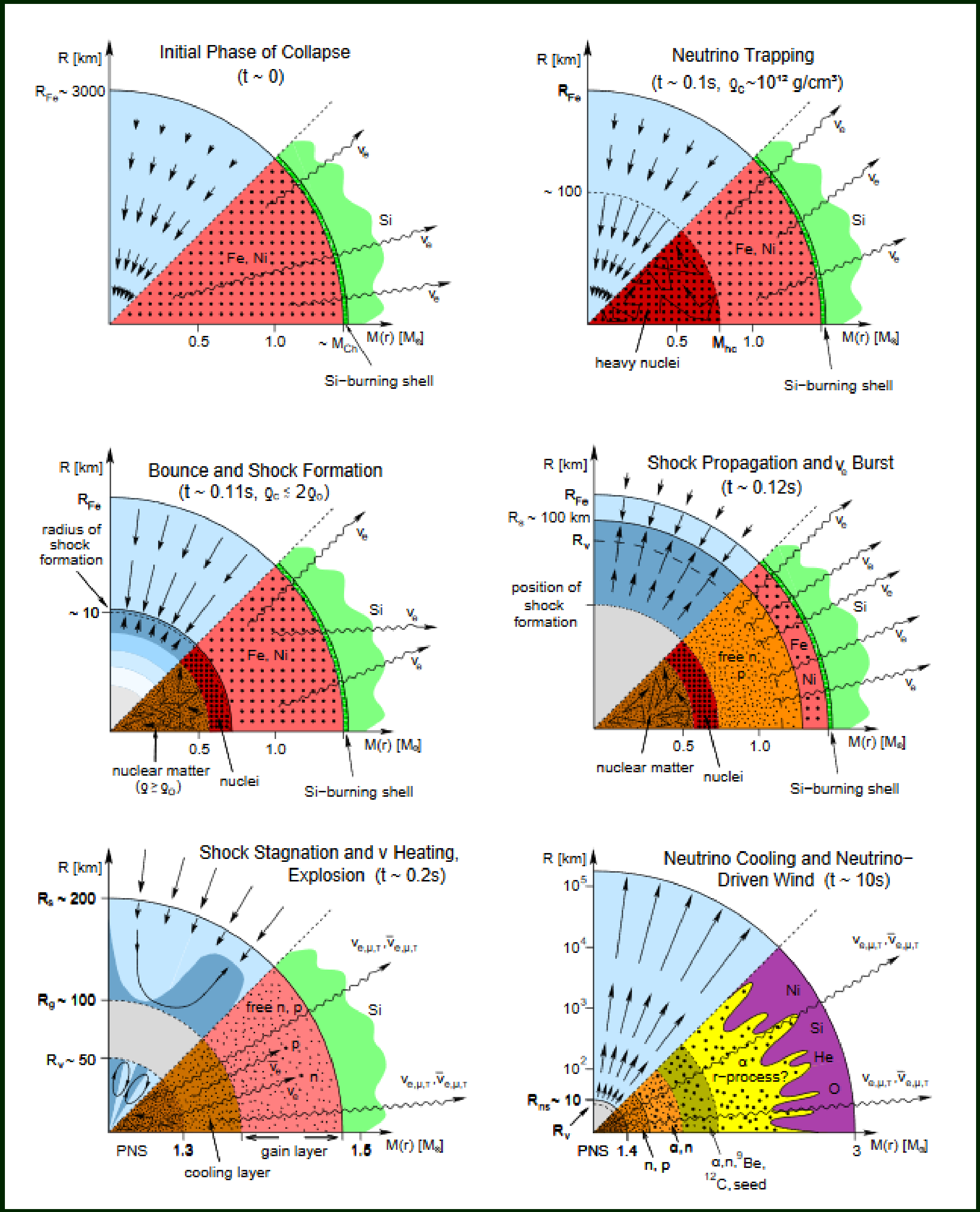
Both for an extremely rotating BH

Cunningham, Bardeen 1973

See a review in 1902.11196

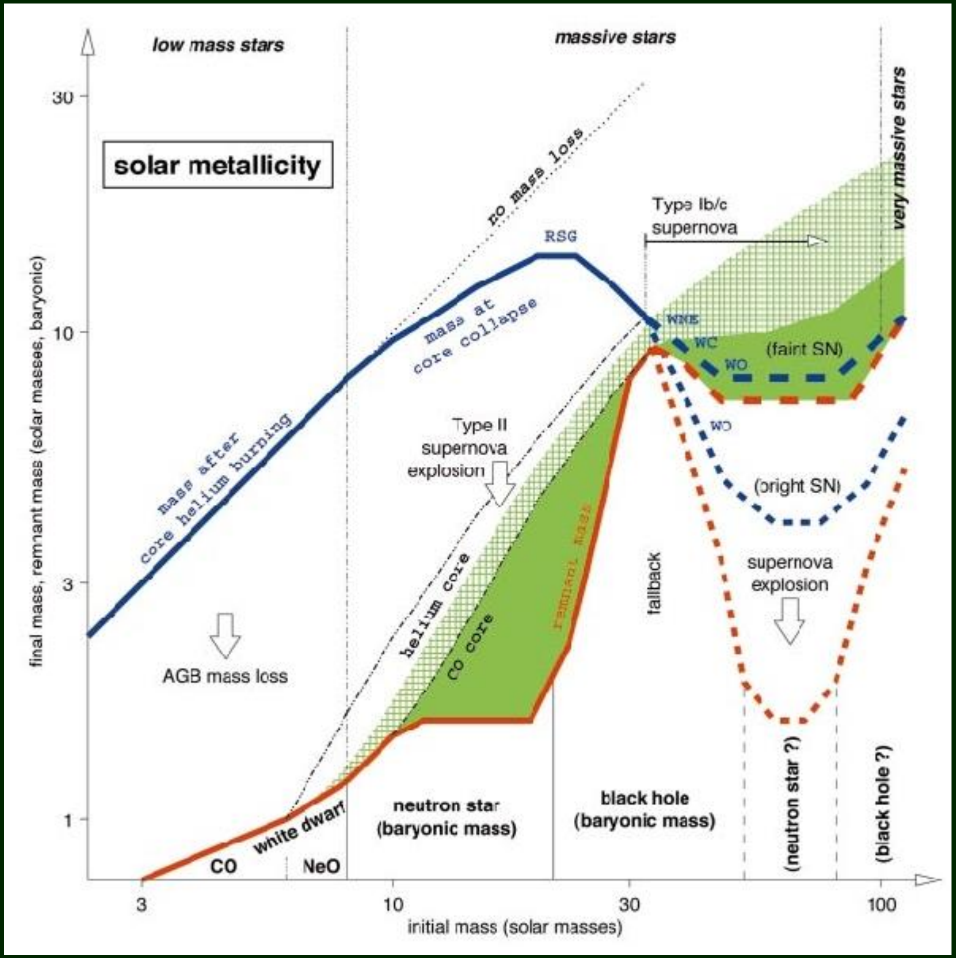
Supernovae

Schematic representation of the evolutionary stages from stellar core collapse through the onset of the supernova explosion to the neutrino-driven wind during the neutrino-cooling phase of the proto-neutron star.
The horizontal axis gives mass information.
M_{hc} is the mass of the subsonically collapsing, homologous inner core.
The vertical axis shows corresponding radii.
R_{Fe} - iron core radius;
R_s - shock radius;
R_g - gain radius;
R_{ns} - neutron star radius;
R_ν – neutrinosphere.



astro-ph/0612072

Stellar mass BHs.
The case of solar metallicity.

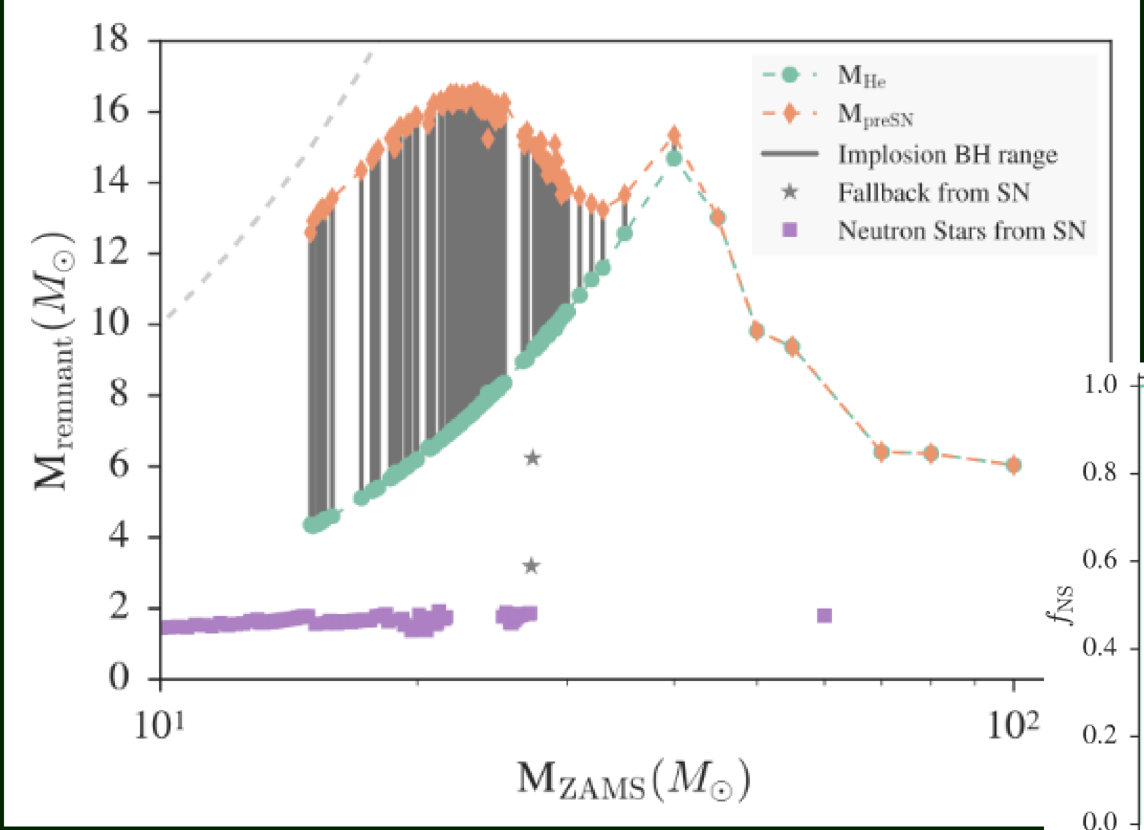


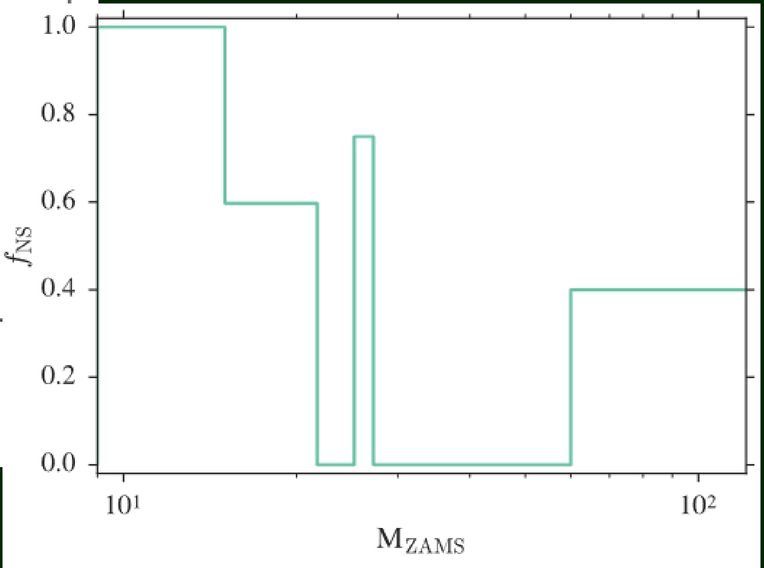
BHs are formed by massive stars.
The limiting mass separating BH and NS progenitors is not well known.
In addition, there can be a range of masses above this limit in which, again NSs are formed (also, there can be a range in which both types of compact objects form).

See 1011.0203 about progenitors

Woosley et al. 2002

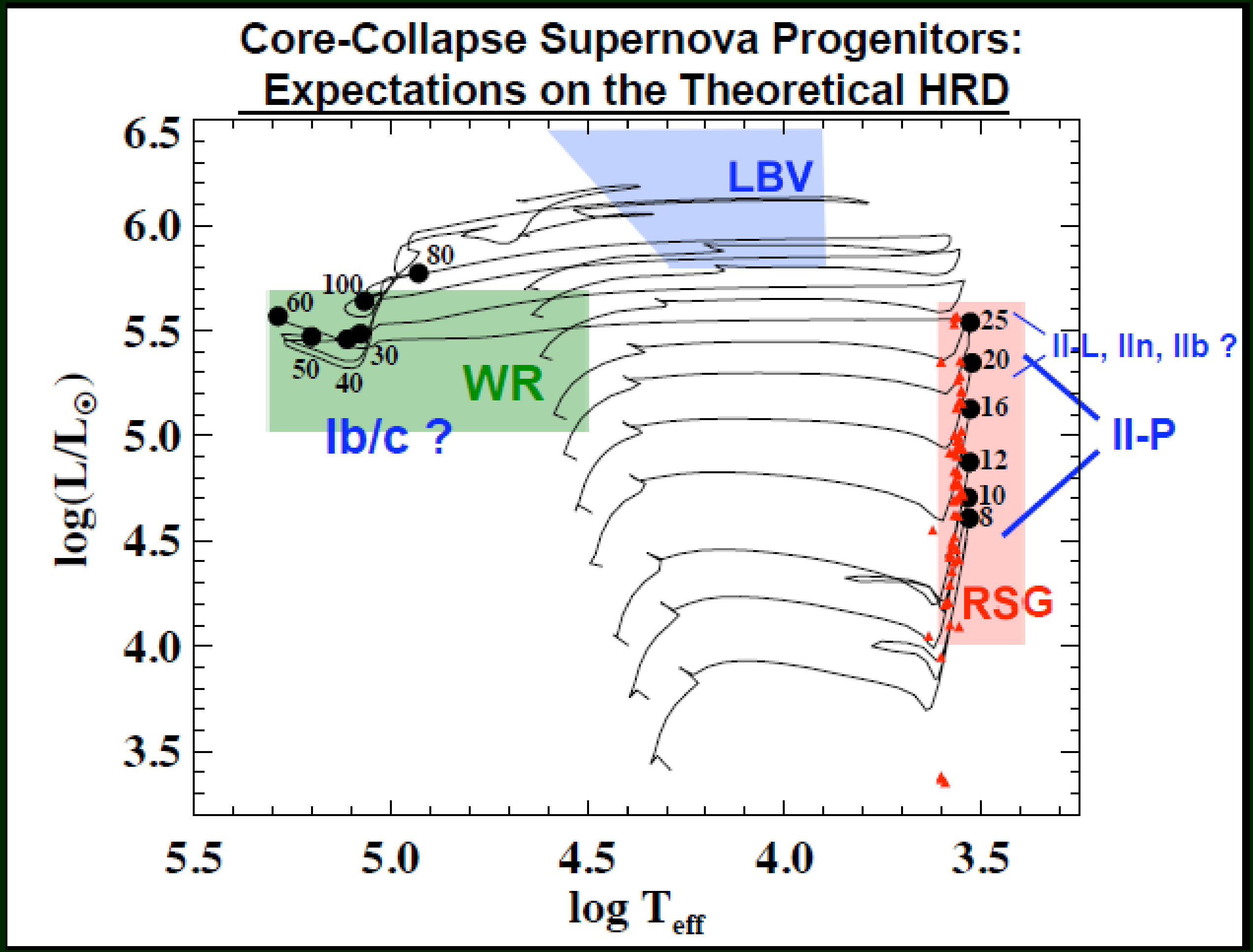
Initial mass vs. final: ZAMS vs. compact object





1712.00021, 1904.01773

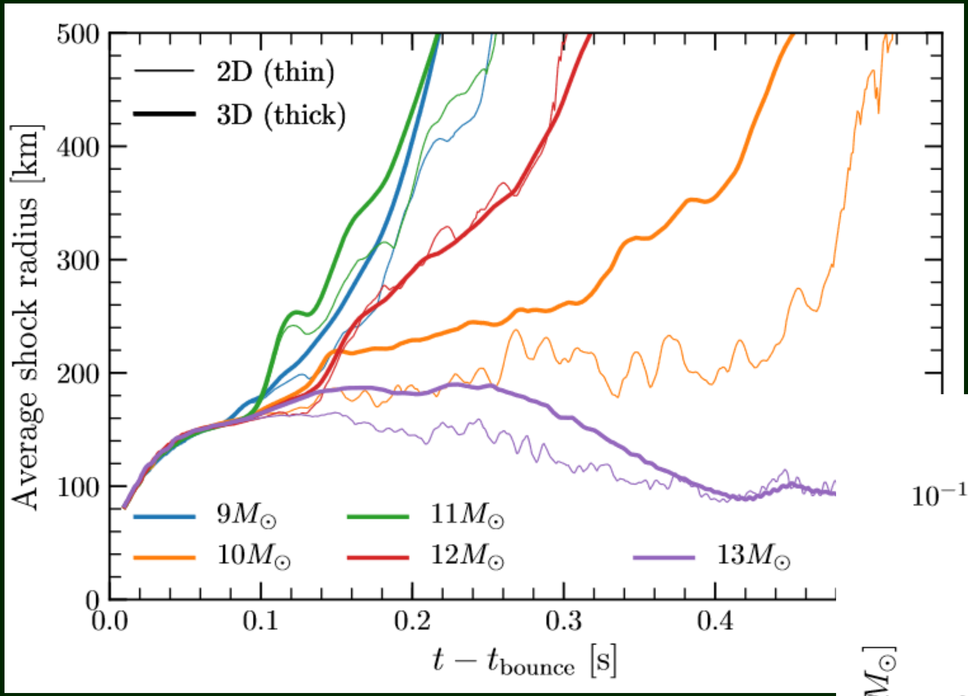
Supernova progenitors



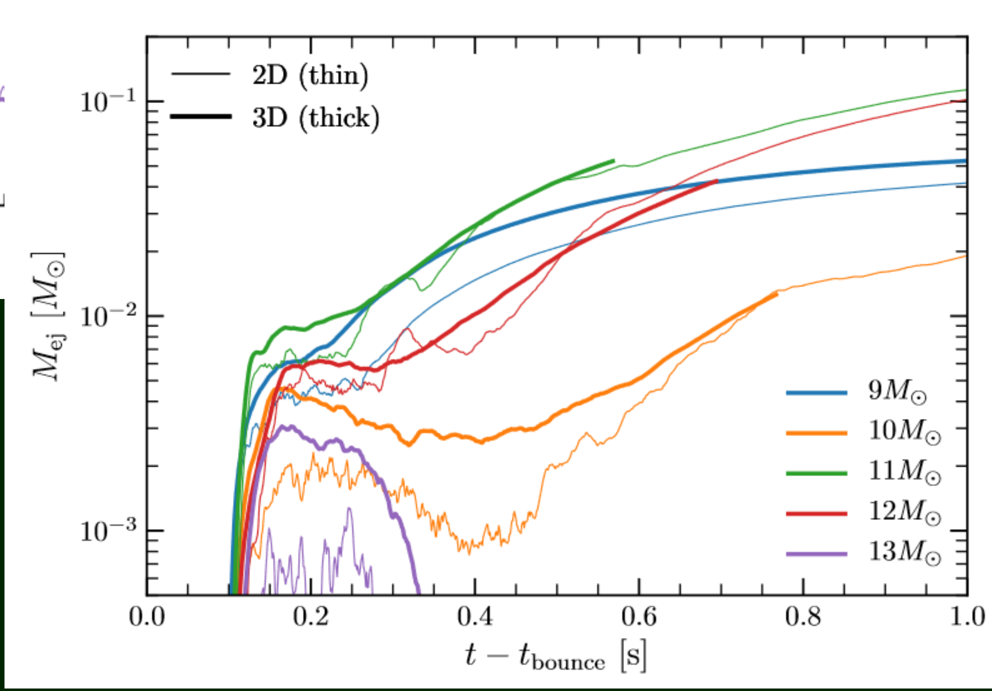
However, there are claims that most of stars $>18M_0$ produce BHs
(see a review in Smartt arXiv: 1504.02635)

1011.0203

No explosions for 13 solar mass?



Probably non-rotating progenitors with 12<M<14 solar mass do not explode.

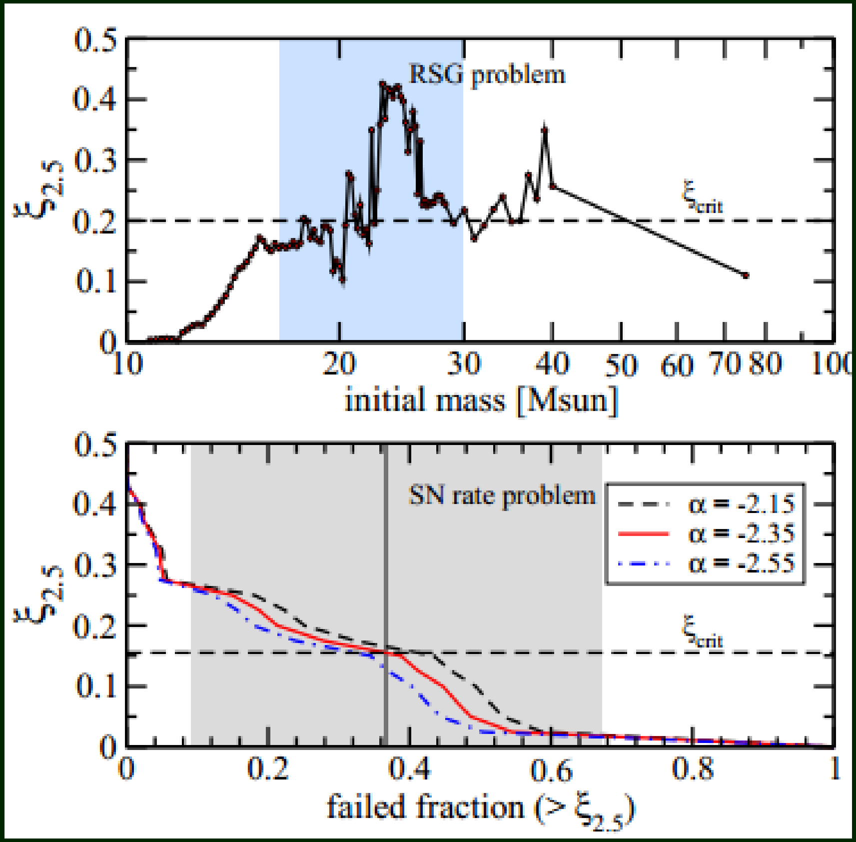


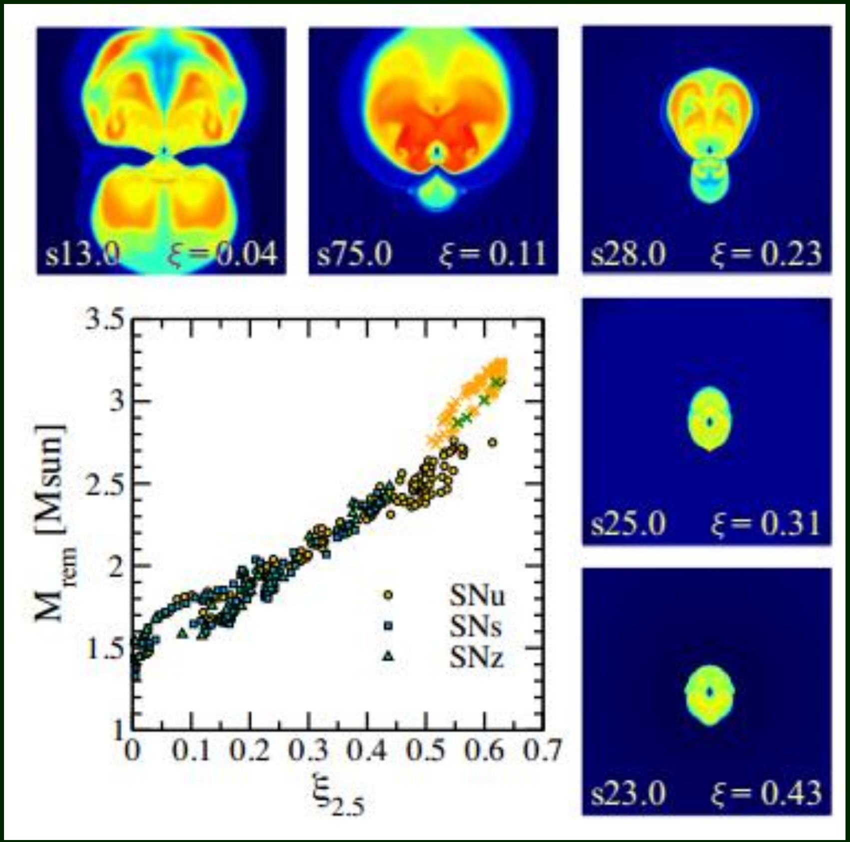
1902.00547

Which stars form BHs?

It is proposed that stars with compact internal structure (M~20-30 Msolar) form BHs not NSs. This expains data on RGs and the SN rate.

$$\xi_M = \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}}$$

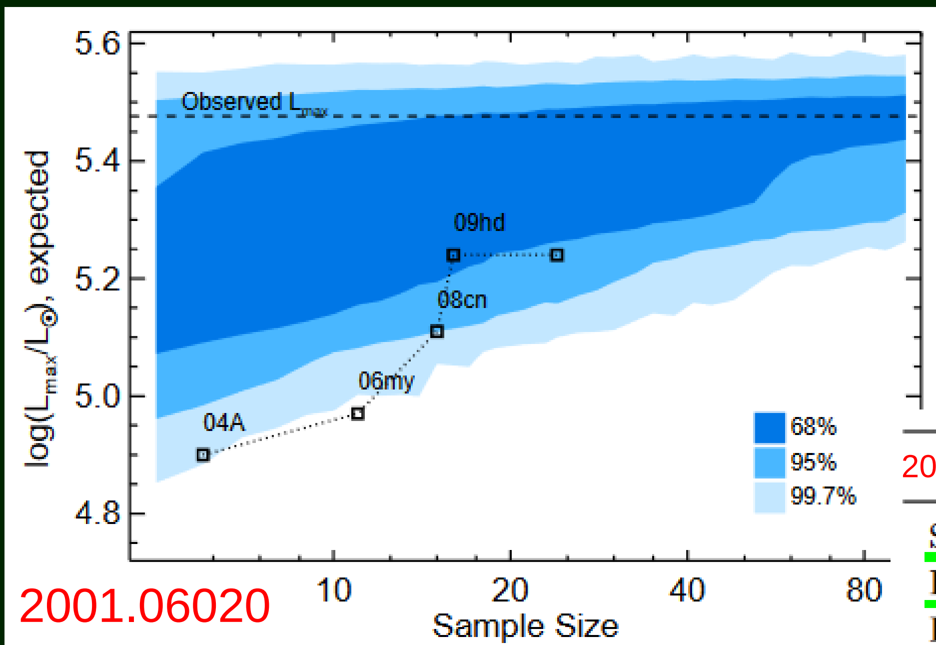




1409.0006

Red supergiants problem: discussion

2001.06020 – just a 2-sigma case;
2001.07216 – the problem remains;
2005.13855 – no, still <3-sigma….



Solutions:

- Modification in stellar evolution (massive stars explode not as RSG)
- Wrong luminosity determination
- Statistics (see the figure)
- No SN for $M>M_h$

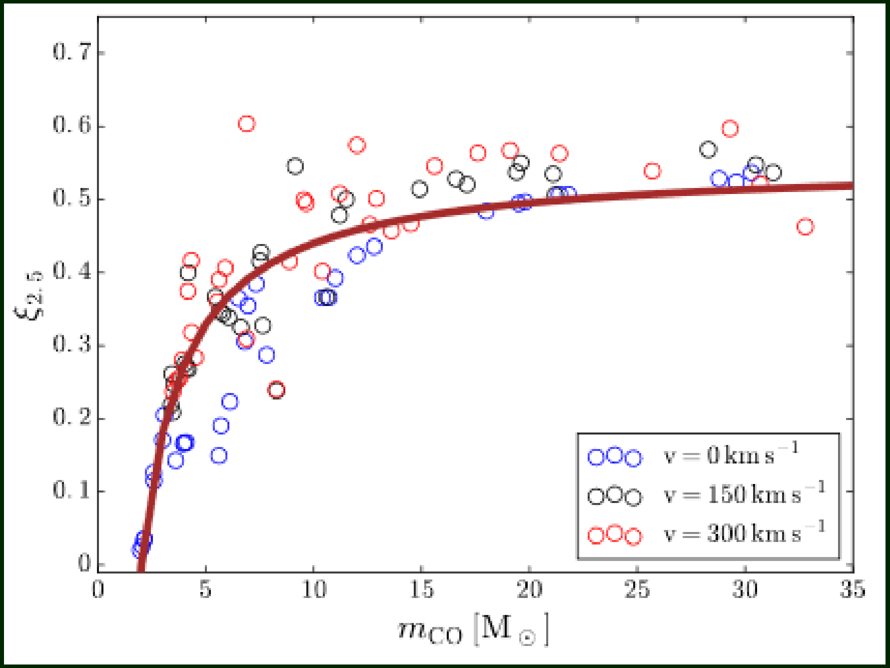
2001.07216

Model	$M(L)$	$M_l/M_\odot$	$M_h/M_\odot$
Smartt (2015)	ET04	$9.5^{+0.5}_{-2.0}$	$16.5^{+2.5}_{-2.5}$
Davies & Beasor (2018)	ET04	$7.5^{+0.3}_{-0.2}$	$19.0^{+2.5}_{-1.3}$
Davies	ET04	$7.49^{+0.25}_{-0.27}$	$19.05^{+2.22}_{-1.30}$
Bayes	ET04	$6.30^{+0.48}_{-0.54}$	$19.01^{+4.04}_{-2.04}$
Smartt (2015)	S18	$10.0^{+0.5}_{-1.5}$	$18.5^{+3.0}_{-4.0}$
Davies	S18	$8.38^{+0.28}_{-0.30}$	$21.33^{+2.48}_{-1.46}$
Bayes	S18	$7.06^{+0.54}_{-0.61}$	$21.28^{+4.52}_{-2.28}$

Rotation and compactness

$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M)/1000\,\mathrm{km}}$$

$$\xi_{2.5} = a + b\left(\frac{m_{\mathrm{CO}}}{1\,\mathrm{M}_\odot}\right)^c$$



V – initial equatorial rotational velocity

Different critical values are discussed: from 0.45 down to 0.2.
Here the authors assume 0.3

$$m_{\mathrm{BH}} = m_{\mathrm{He}} + f_{\mathrm{H}}\left(m_{\mathrm{fin}} - m_{\mathrm{He}}\right)$$

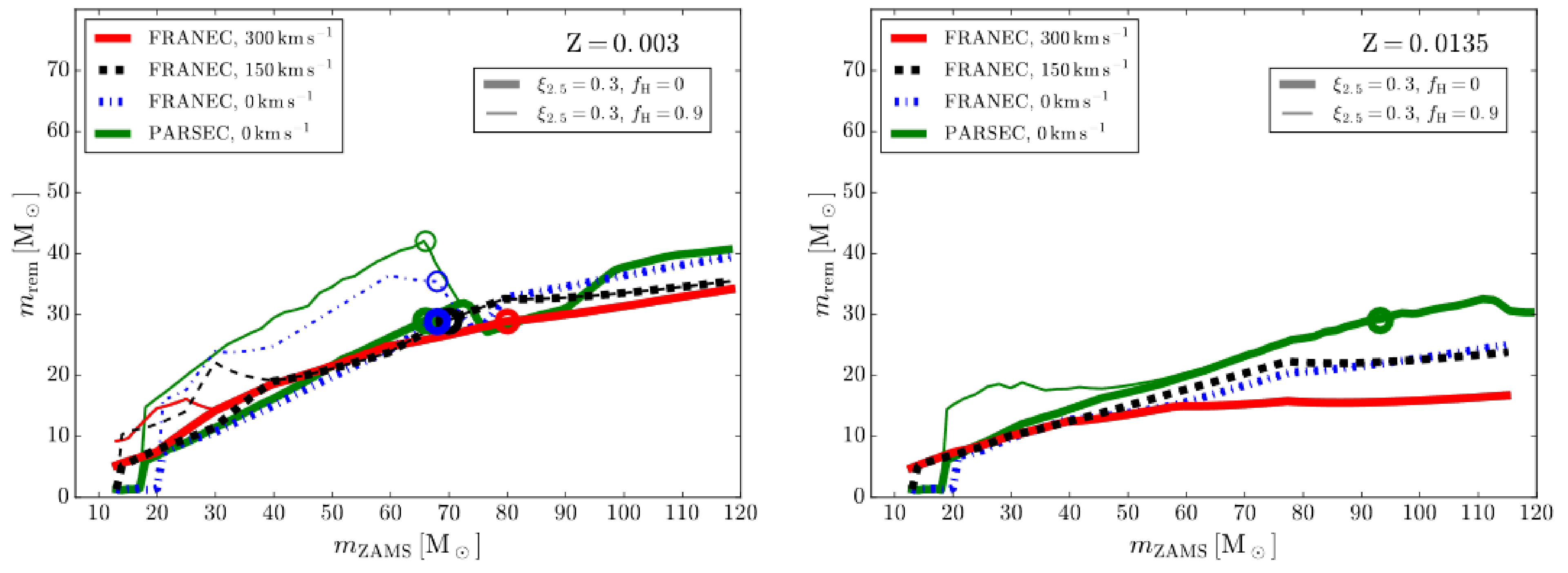
f_H is a parameter: from 0 to 0.9

For most massive stars – PISN, and so, no compact object:

$$135 \geq m_{\mathrm{He}}/\mathrm{M}_\odot \geq 64,$$

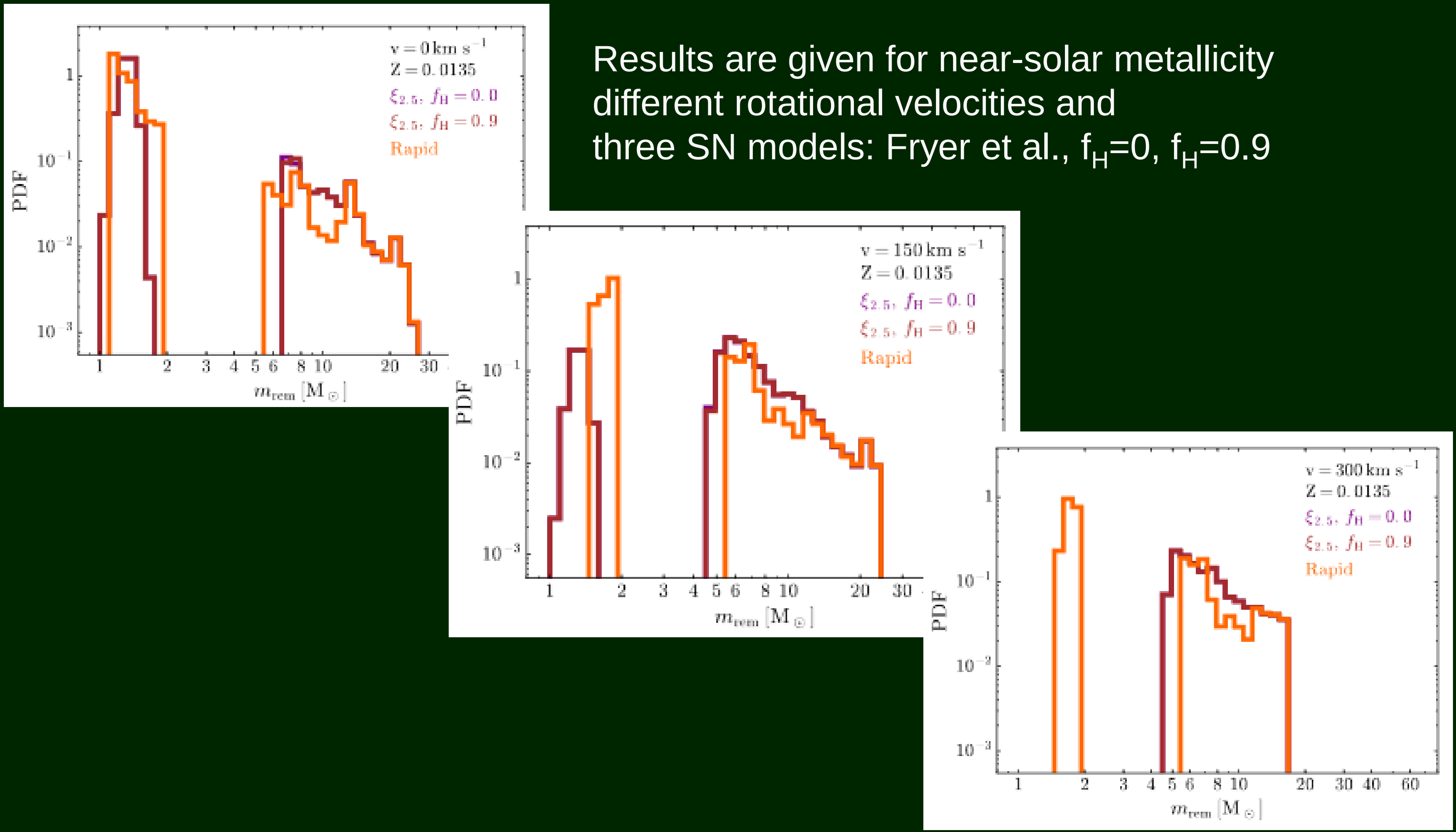
1909.01371

Compact objects masses: effects of rotation and metallicity



1909.01371

Mass distribution



Results are given for near-solar metallicity different rotational velocities and three SN models: Fryer et al., f_H=0, f_H=0.9

1909.01371

Transients from BH formation

Supergiant progenitors of BHs can have huge convective envelopes.
Convective motions in the outer parts of supergiants generate mean horizontal flows at a given radius with velocities of ~1 km/s.
Failed explosions of supergiants - in which the accretion shock onto the neutron star does not revive, leading to black hole formation - may often produce accretion discs that can power day-week (blue supergiants) or week-year (yellow and red supergiants) non-thermal and thermal transients through winds and jets.
These transients will be especially time variable because the angular momentum of the accreting material will vary substantially in time. Observed sources such as Swift J1644+57, iPTF14hls, and SN 2018cow, as well as energetic Type II supernovae (OGLE-2014-SN-073) may be produced by this mechanism.

$$v_h \sim \frac{v_c}{\sqrt{4\pi}} \frac{H}{r}$$

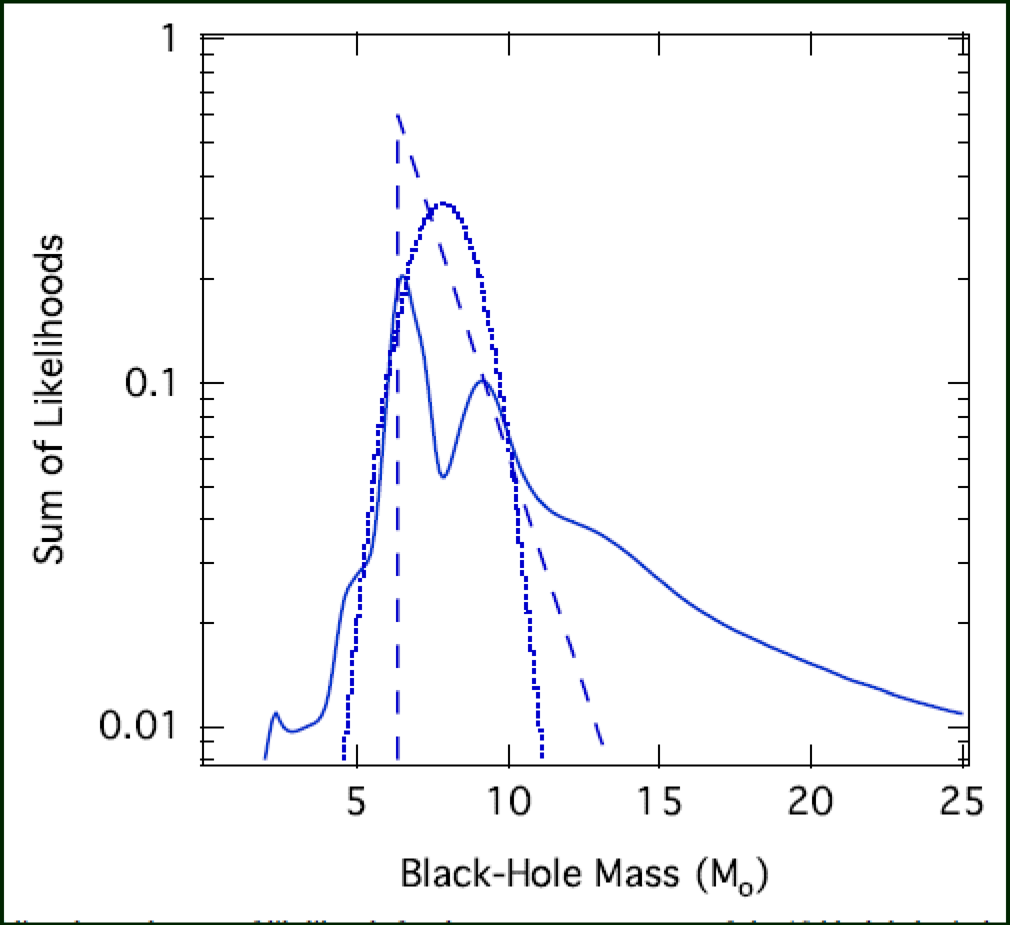
$$j_{\rm rand} \sim \frac{H v_c}{\sqrt{4\pi}} \sim 6\times 10^{17} \frac{r\, v_c}{10^3 R_\odot \text{ km s}^{-1}} \left(\frac{H/r}{0.3}\right) \text{cm}^2\,\text{s}^{-1}$$

v_c (~10 km/s) – convective velocity
v_h – horizontal velocity

$$j_{\rm ISCO} = 1.15 - 3.5\,\frac{GM}{c} \sim 0.5 - 1.5\times 10^{17} \left(\frac{M}{10\,M_\odot}\right) \text{cm}^2\,\text{s}^{-1}$$

1811.12427

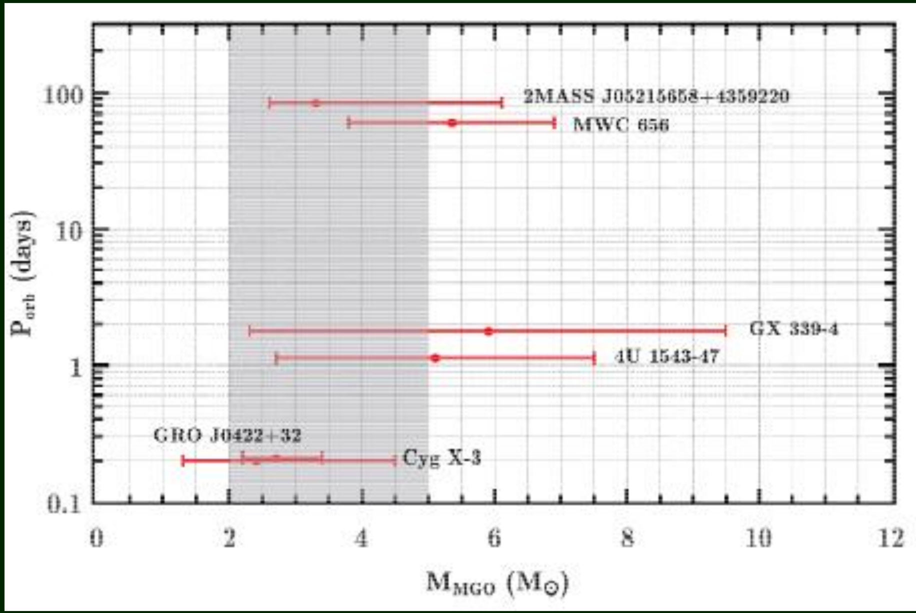
BH mass function



Likelihood based on 16 systems

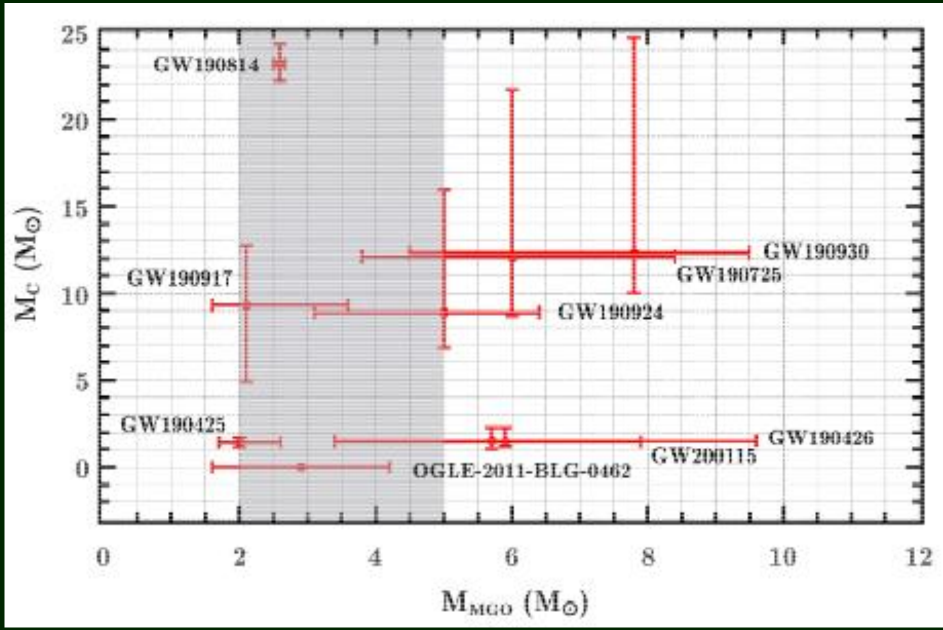
1006.2834

Mass gap objects



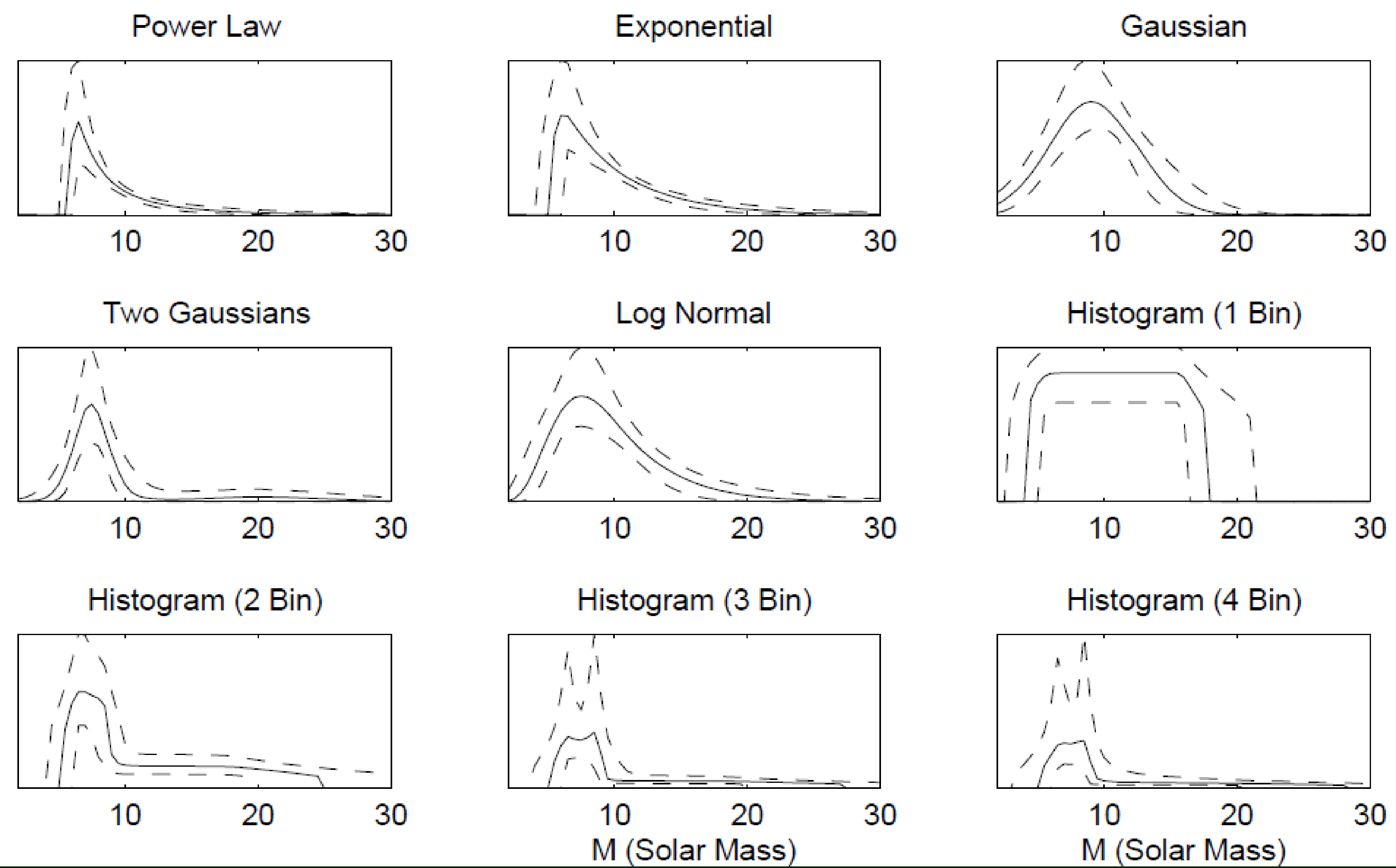
Sources of different natures:

- LMXBs
- HMXBs
- detached binaries
- GW
- lensing



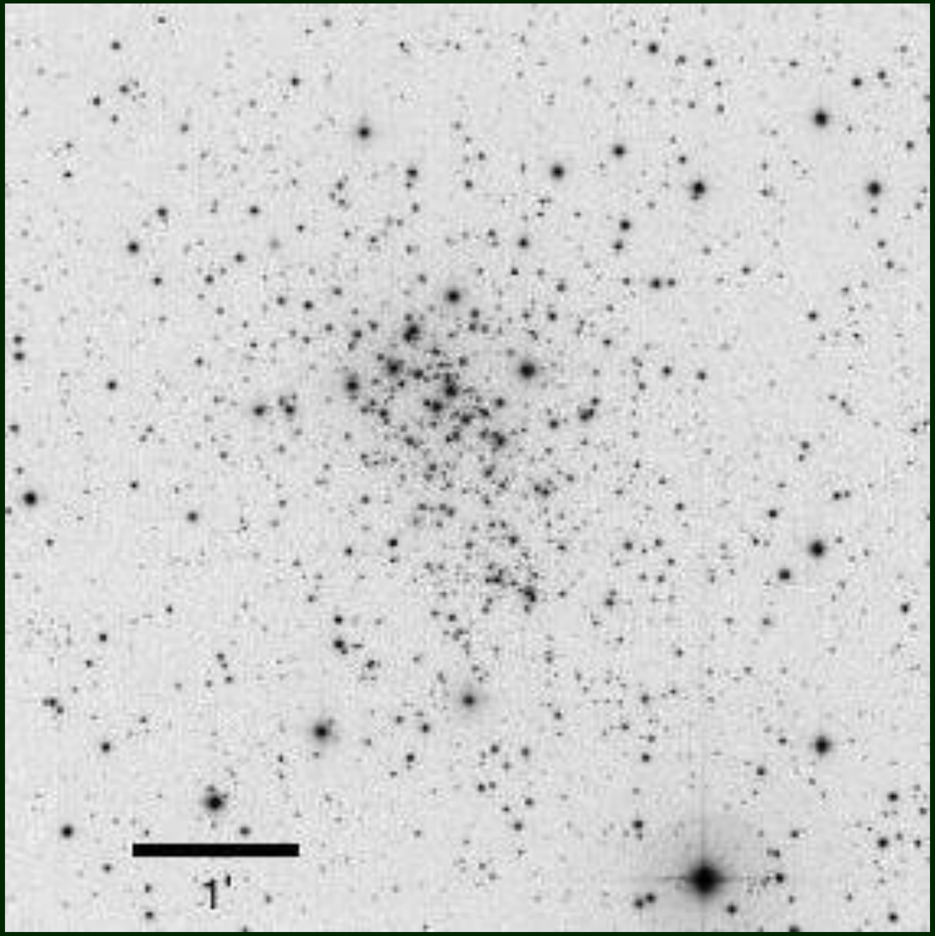
2210.00425

BH mass distribution



1011.1459

A NS from a massive progenitor

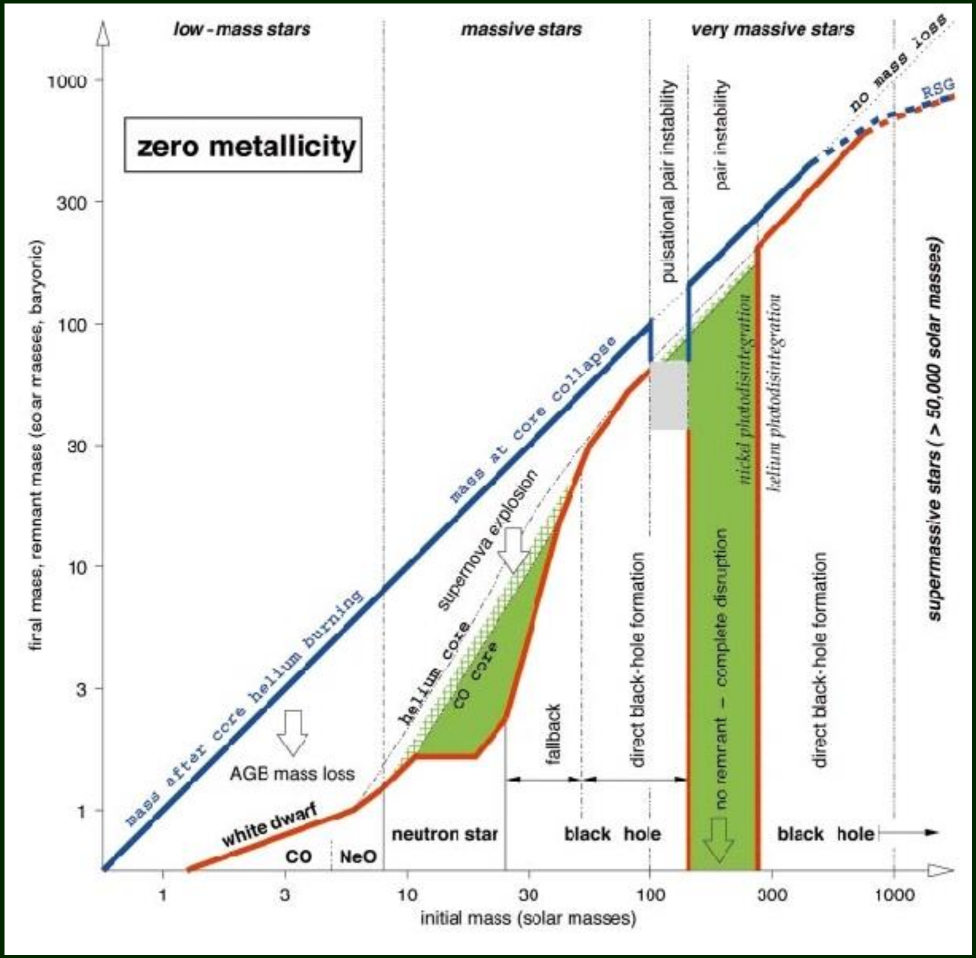


Anomalous X-ray pulsar in the cluster Westerlund1most probably has a very massive progenitor, >40 M_{O}.

In 2021 the age of the cluster was slightly re-estimated (2103.02609): ~5-8 Myrs. Older than estimated before.

astro-ph/0611589

Stellar mass BHs.
The case of zero metallicity

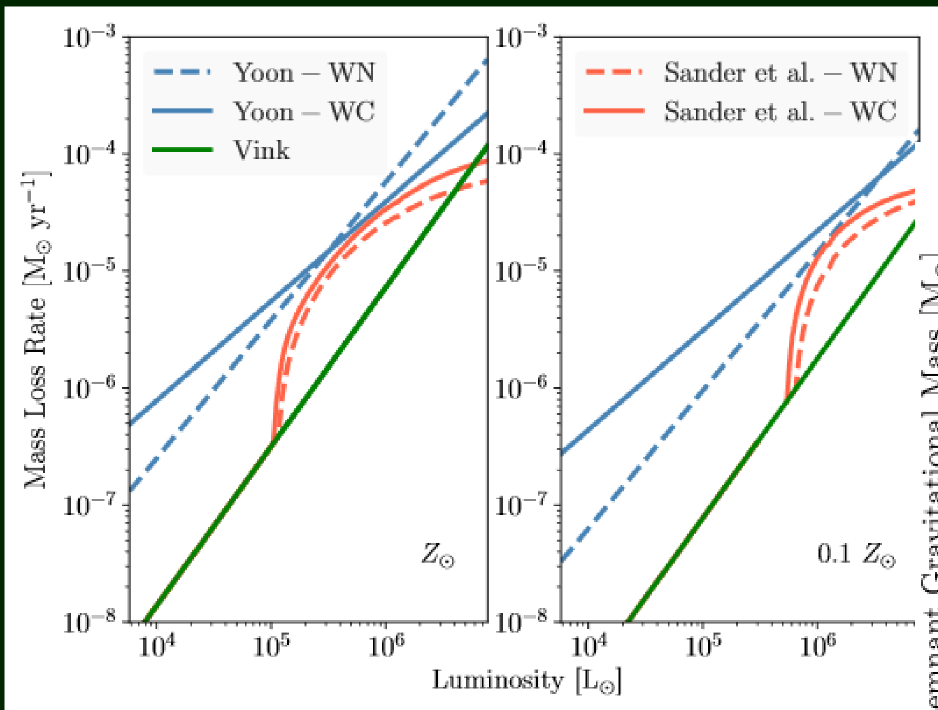


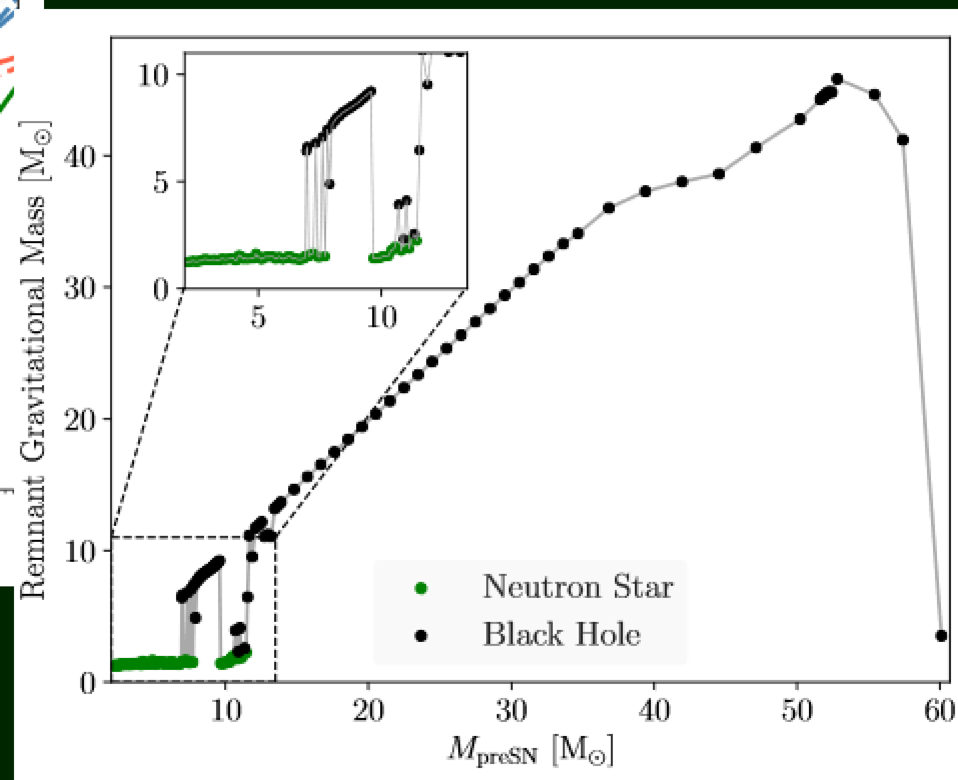
Pop III massive stars could produce very massive BHs which became seeds for formation of supermassive BHs.

Woosley et al. 2002

Mass function of NS and BH in binaries

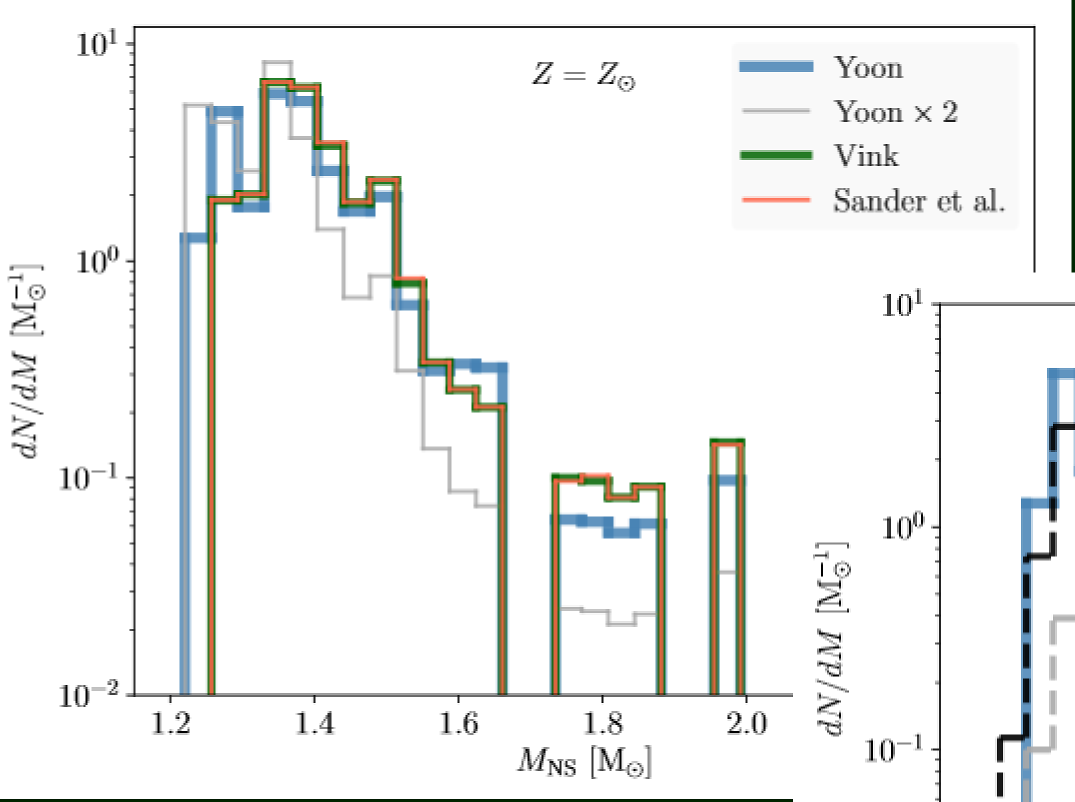
The authors study the following effect: in a binary system hydrogen envelope can be lost, and the star evolves further starting from a stripped helium core.



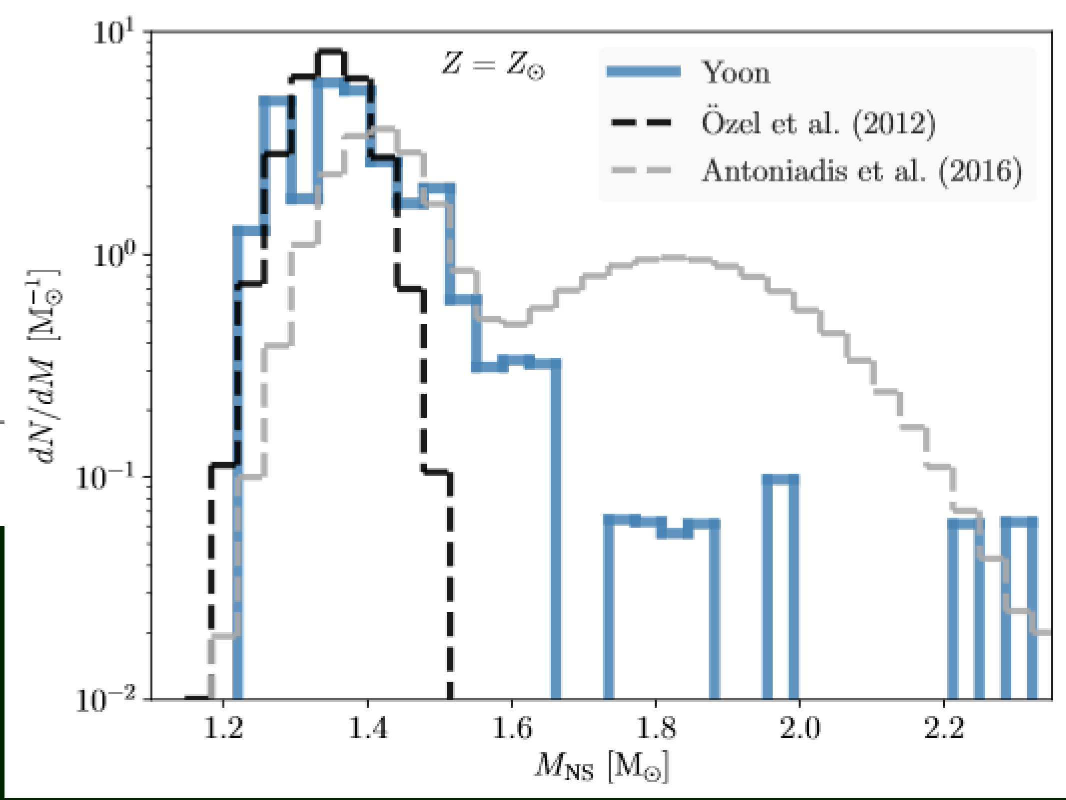


2001.10492

Neutron stars

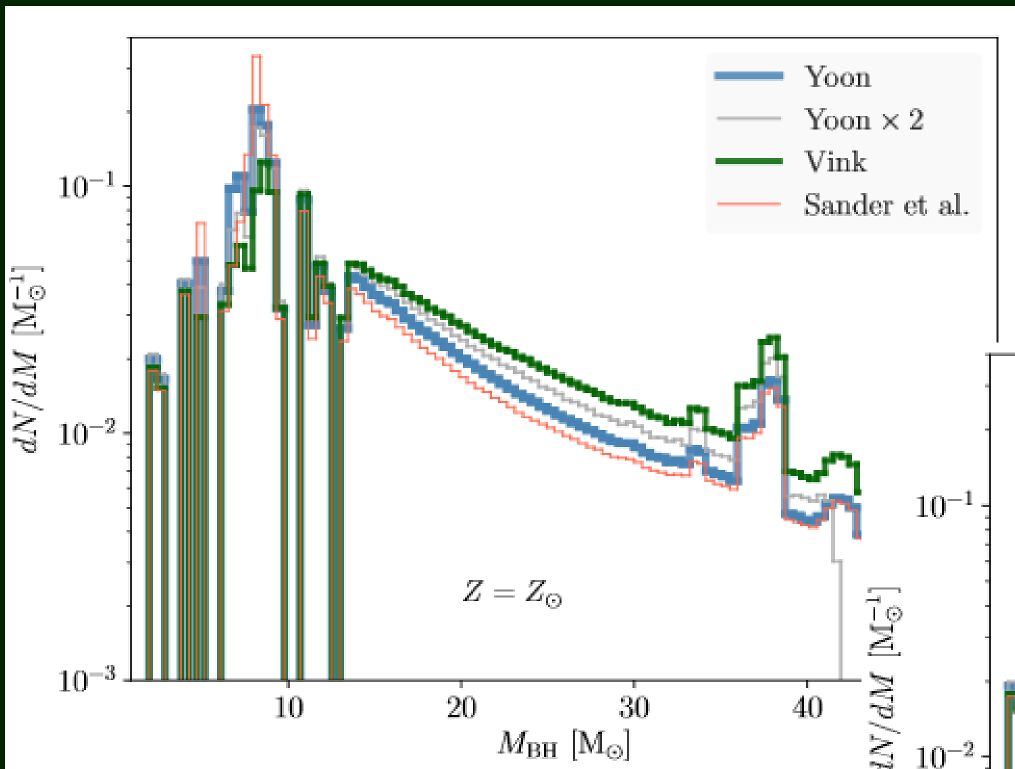


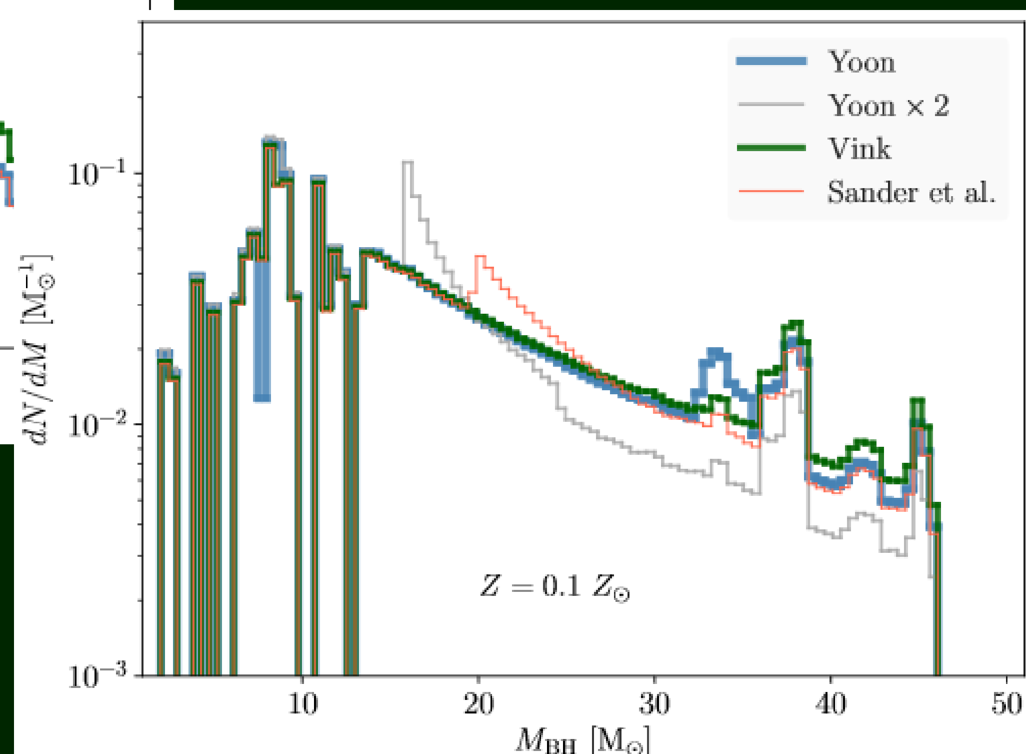
Salpeter stellar mass function.



2001.10492

Black holes





2001.10492

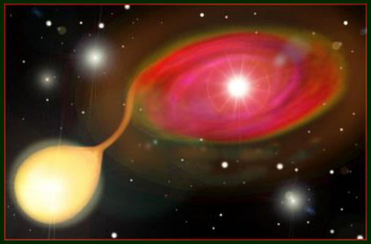
BHs and NSs in close binary systems

Studying close binaries with compact objects we can obtain
mass estimates for progenitors of NSs and BHs
(see, for example, Ergma, van den Heuvel 1998 A&A 331, L29).

An interesting result was obtained for the NS system GX 301-2.
The progenitor mass was found to be equal to 50 solar masses or more.
On the other hand, for many systems with BHs
estimates of progenitor masses are lower: 20-50 solar masses.

Finally, for the BH system LMC X-3 the mass of the progenitor
is estimated as >60 solar masses.

So, the situation is rather complicated.
Most probably, in some range of masses, at least in binary systems,
both variants are possible.



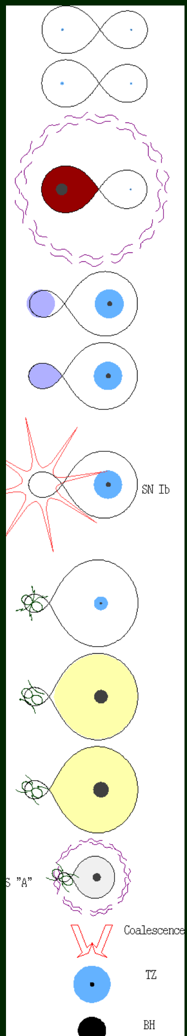
Number of systems

Detectable, not detected!

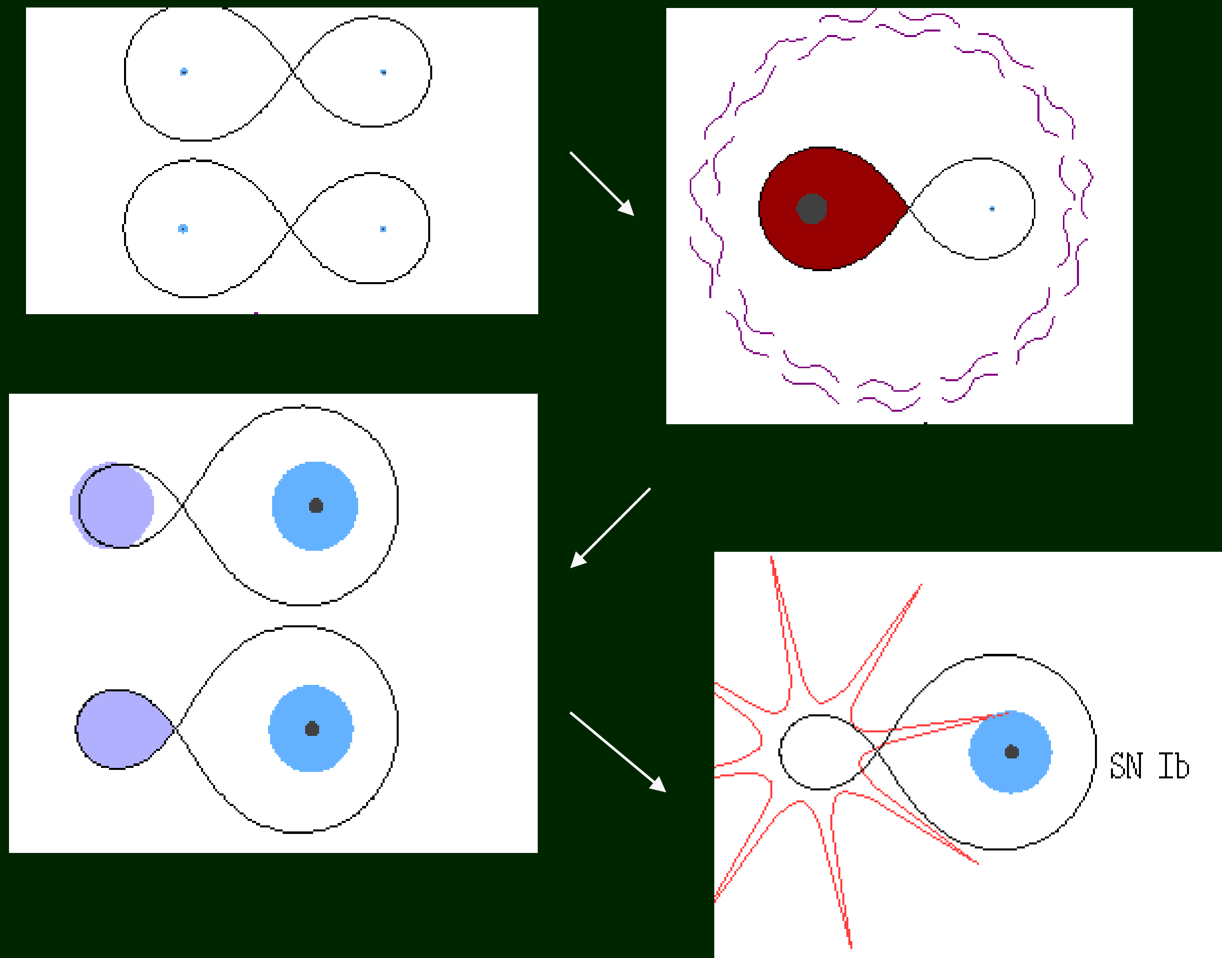
Binary types	$R_{\rm birth}$ ($\rm Myr^{-1}$)	$N_{\rm total}$	$N_{\rm detect}$
BH+MS	$45 - 130$	$470 - 12000$	$260 - 930^a$
BH+G	–	$2 - 600$	$2 - 50^a$
RLO XRB	–	$50 - 820$	–
BH+OB	–	$110 - 440$	$10 - 30^b$
BH+Be	–	$330 - 1000$	–
BH+He	–	$200 - 540$	$30 - 110^b$
BH+PSR	$1 - 10$	$3 - 80$	$< 8^c$
BH+BH	$20 - 150$	$10^5 - 10^6$	$12 - 26^d$
BH+NS	$4 - 30$	$10^4 - 10^5$	$2 - 14^d$
BH+WD	$10 - 100$	$10^5 - 10^6$	$< 38^d$

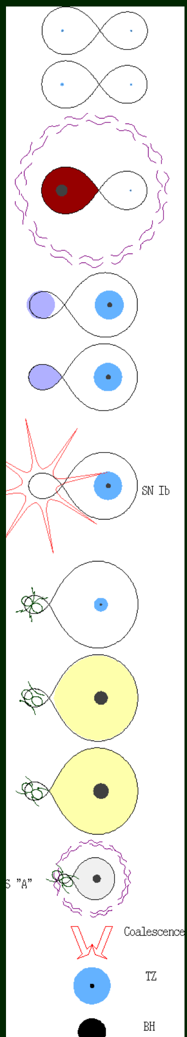
2210.00425

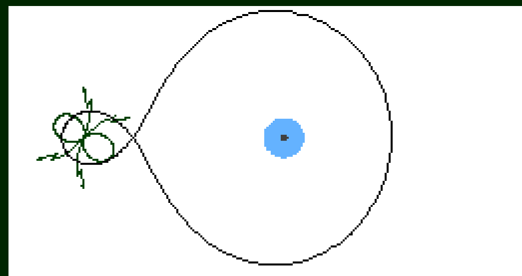
Binary evolution

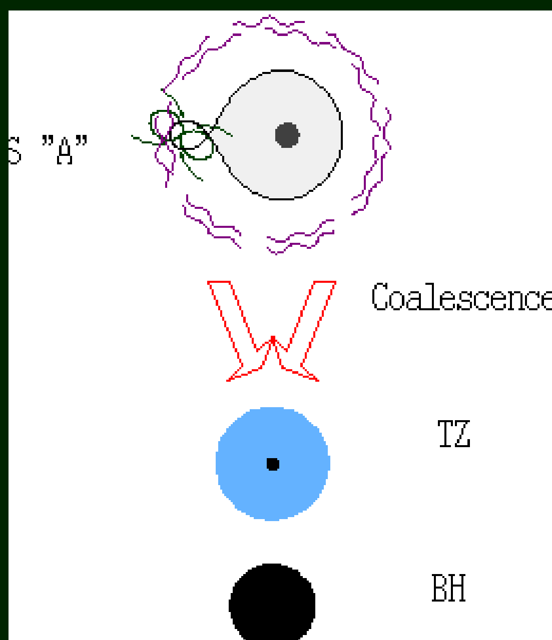


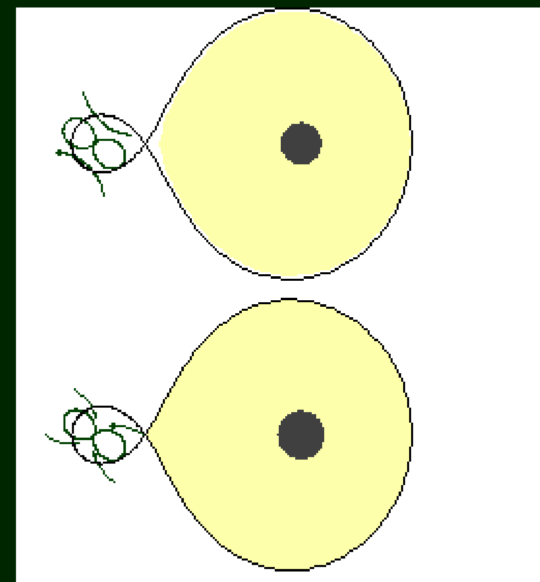
A BH can be formed even from stars each below the limit.











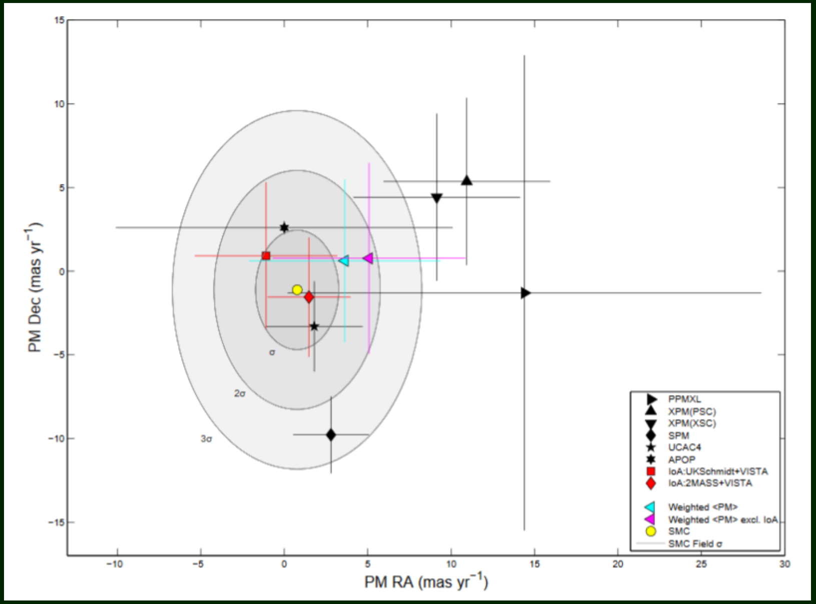
“Scenario machine” calculations

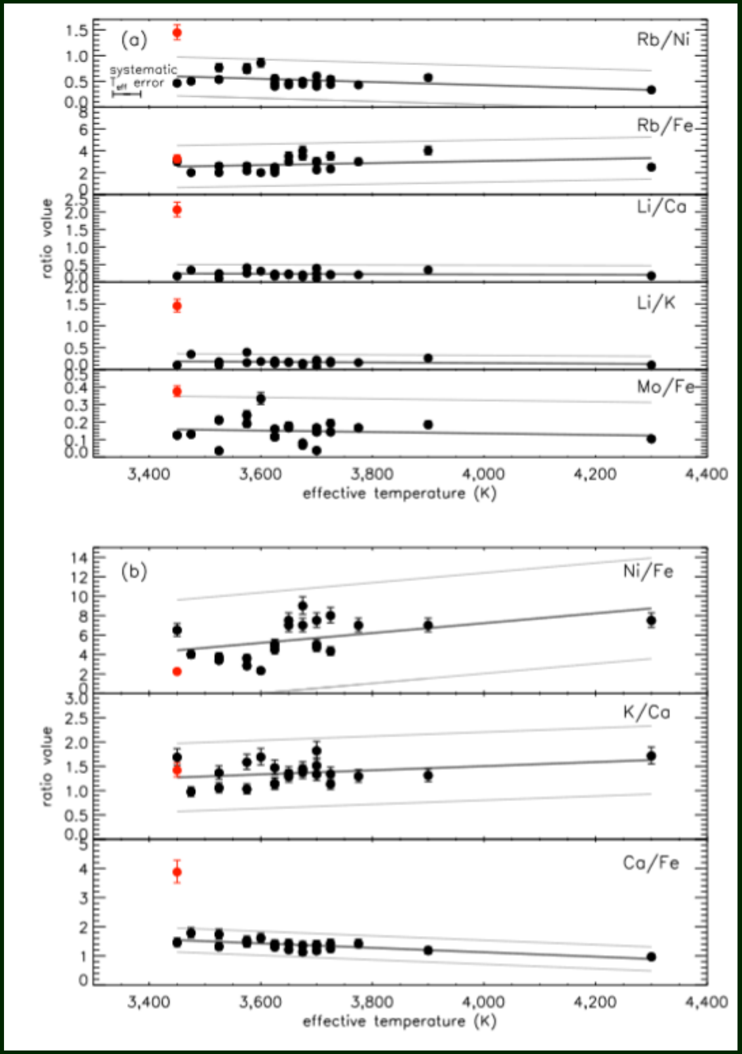
Thorne-Zytkow candidates

Chemical composition anomalies.

Discussion:

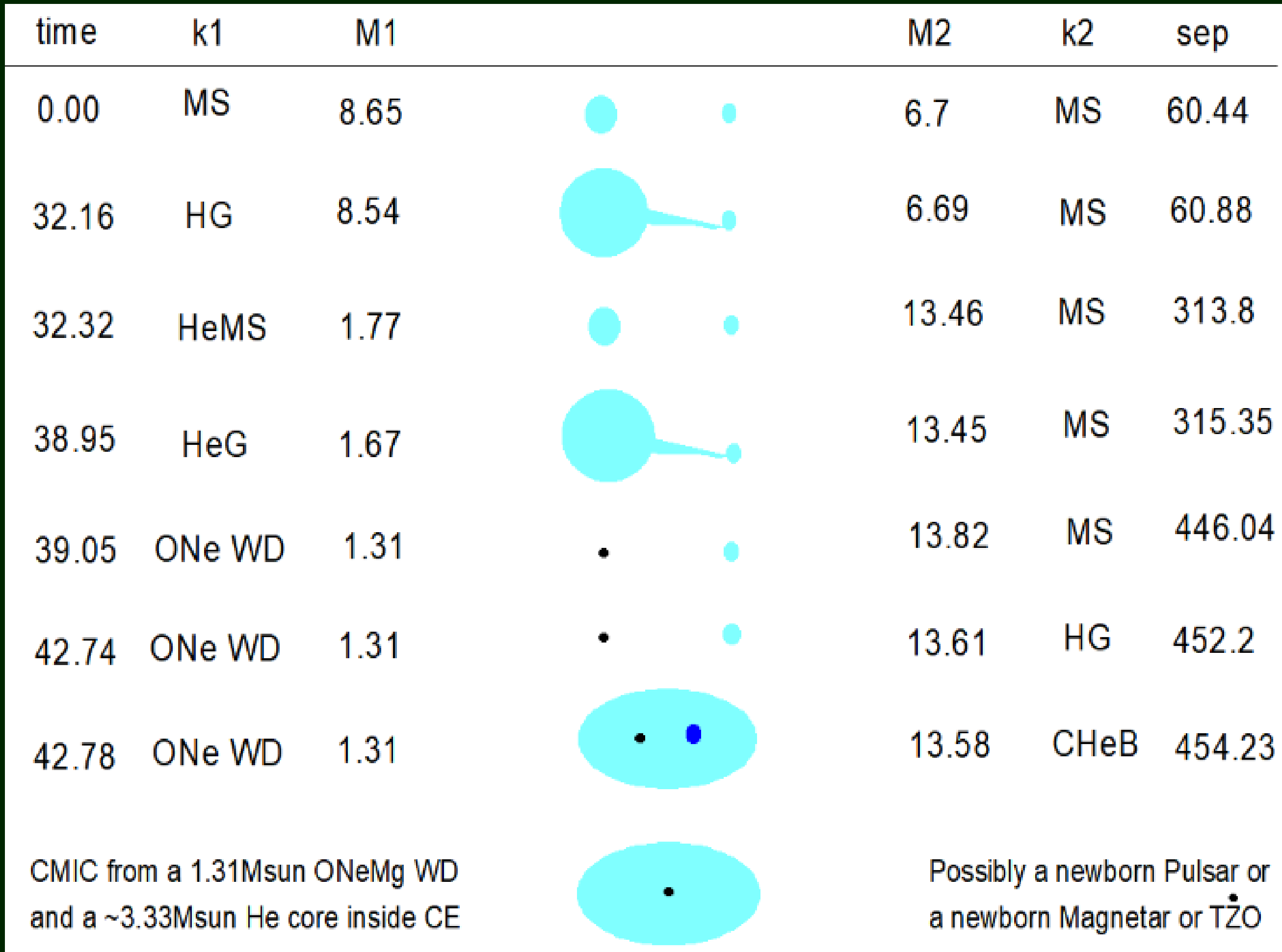
1. Large proper motion – not in SMC
   1601.05455
2. In SMC 1602.08479
   Gaia DR2 confirms 1804.10192





1406.0001

TZO formation due to stellar mergers

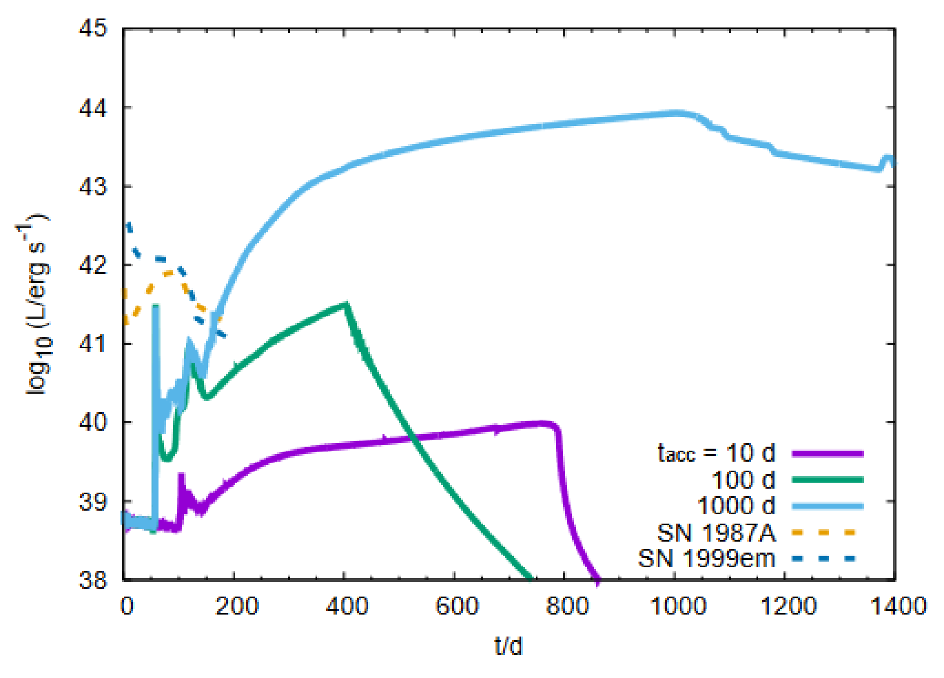


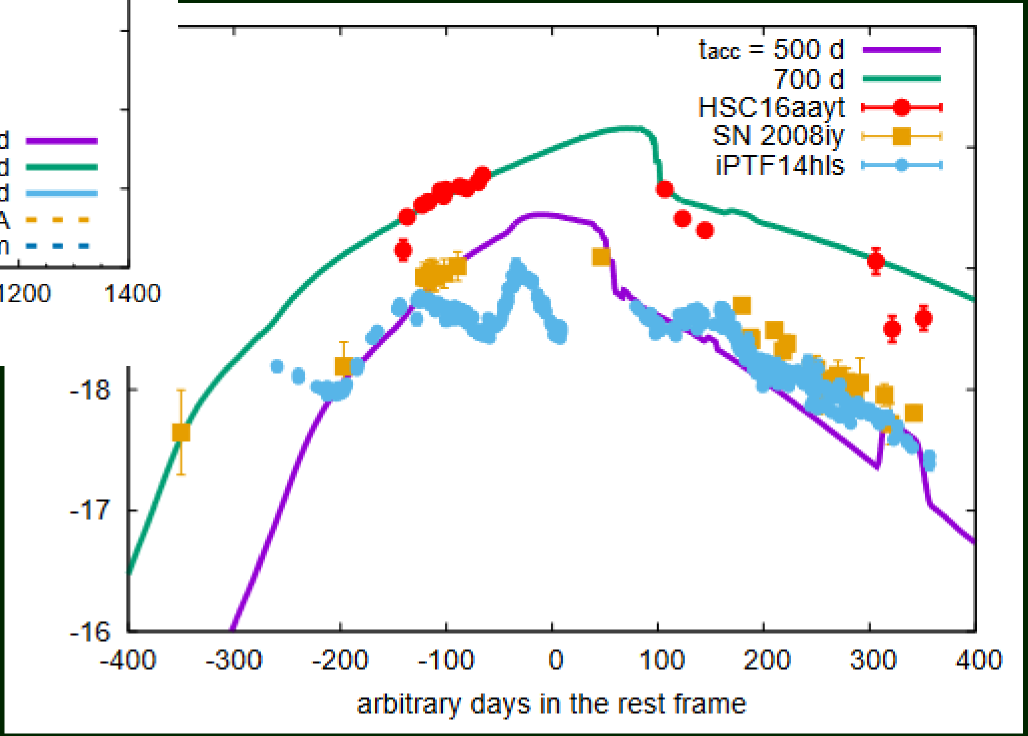
time	k1	M1	M2	k2	sep
0.00	MS	8.65	6.7	MS	60.44
32.16	HG	8.54	6.69	MS	60.88
32.32	HeMS	1.77	13.46	MS	313.8
38.95	HeG	1.67	13.45	MS	315.35
39.05	ONe WD	1.31	13.82	MS	446.04
42.74	ONe WD	1.31	13.61	HG	452.2
42.78	ONe WD	1.31	13.58	CHeB	454.23

Magnetars, including those producing FRBs, can be also formed that way.

2108.08430

TZO can produce peculiar explosions





t_{acc} – duration of accretion

2109.01250

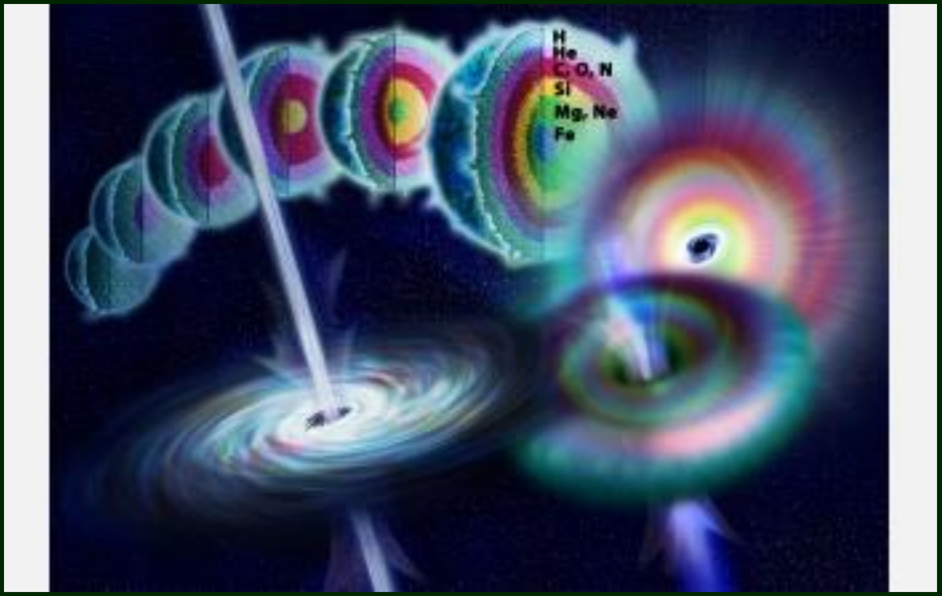
GRBs and BHs

According to the standard modern model of long GRBs,
a BH is the main element of the “central engine”.

So, studying GRBs we can hope to get important information
about the first moments of BH’s life.

See a very brief review in
arXiv:1302.6461

About spins of newborn BHs
producing GRBs see 2302.07271.

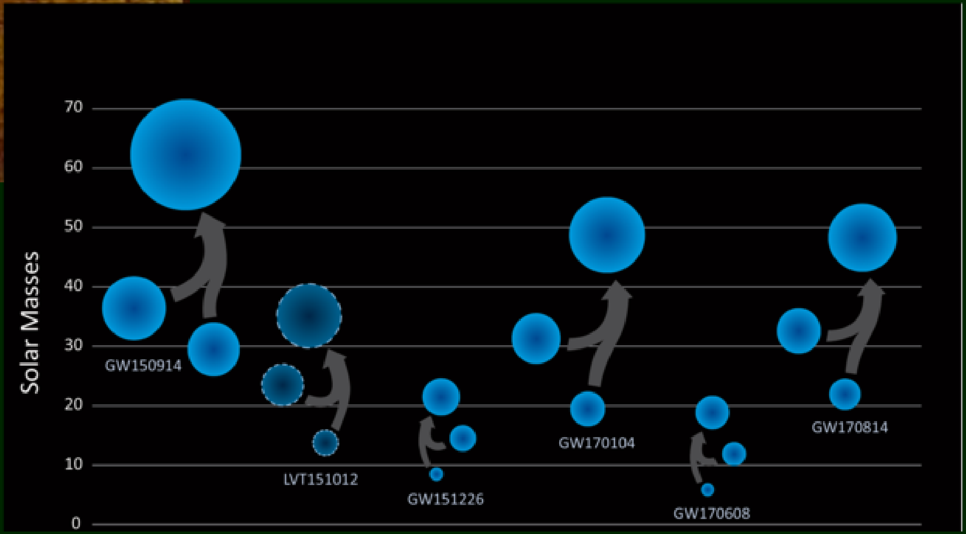


BHs from GW signals

LIGO measure signals
from compact object mergers.

These signals are more powerful for larger masses. So, even being rarer per unit volume,
BH+BH mergers are more frequent in the data.

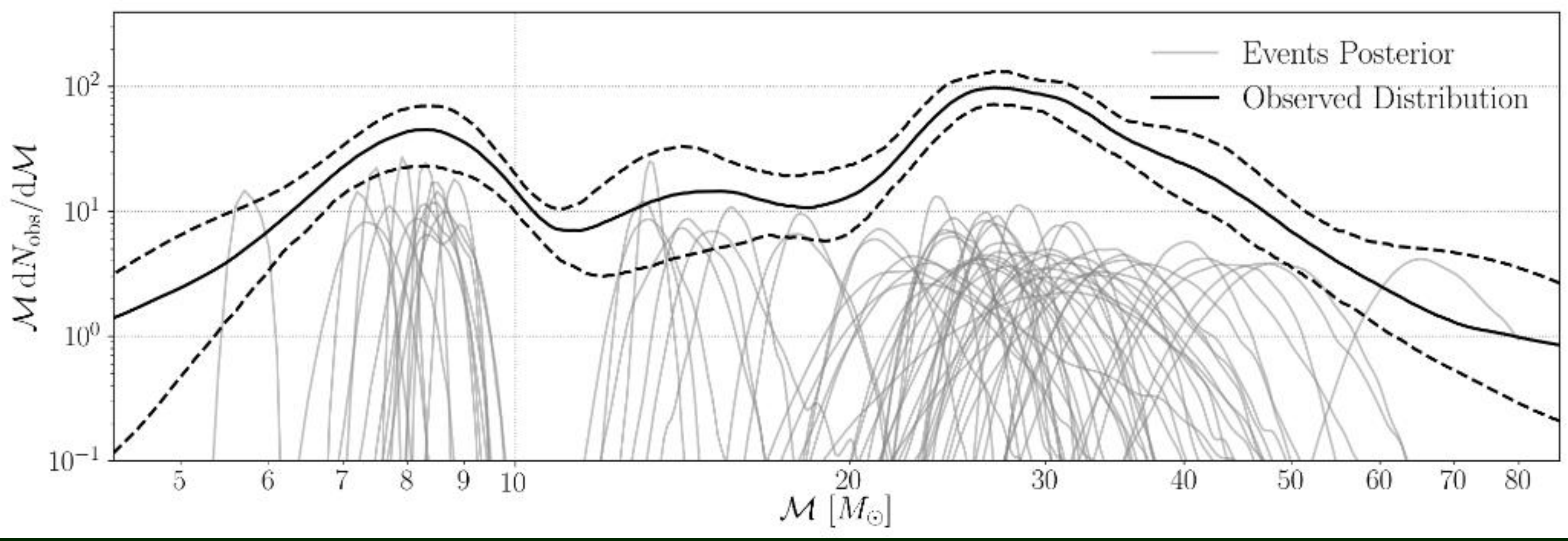
GW190814: 23+2.6 solar masses.
Two BHs or BH+NS?
See 2006.12611.



GWTC-3 catalogue

Chirp mass distribution

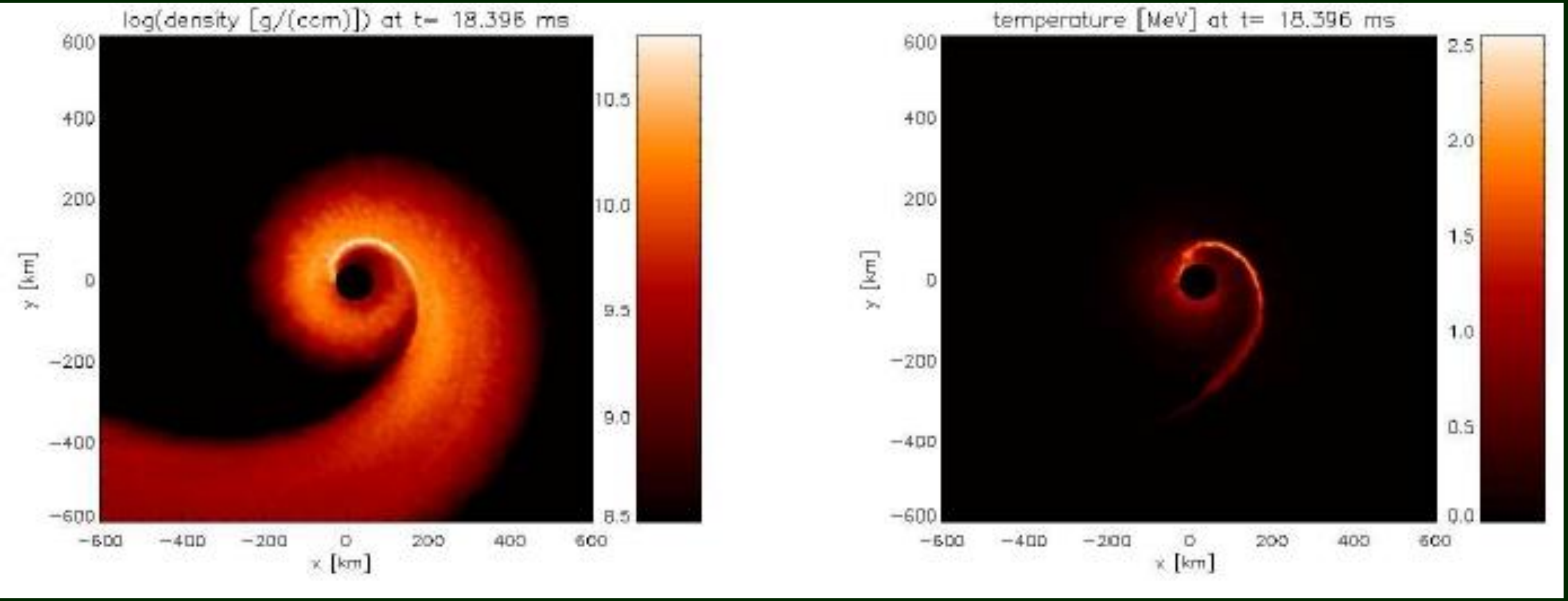
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}.$$



2111.03634, 2111.03606

NS and BH coalescence

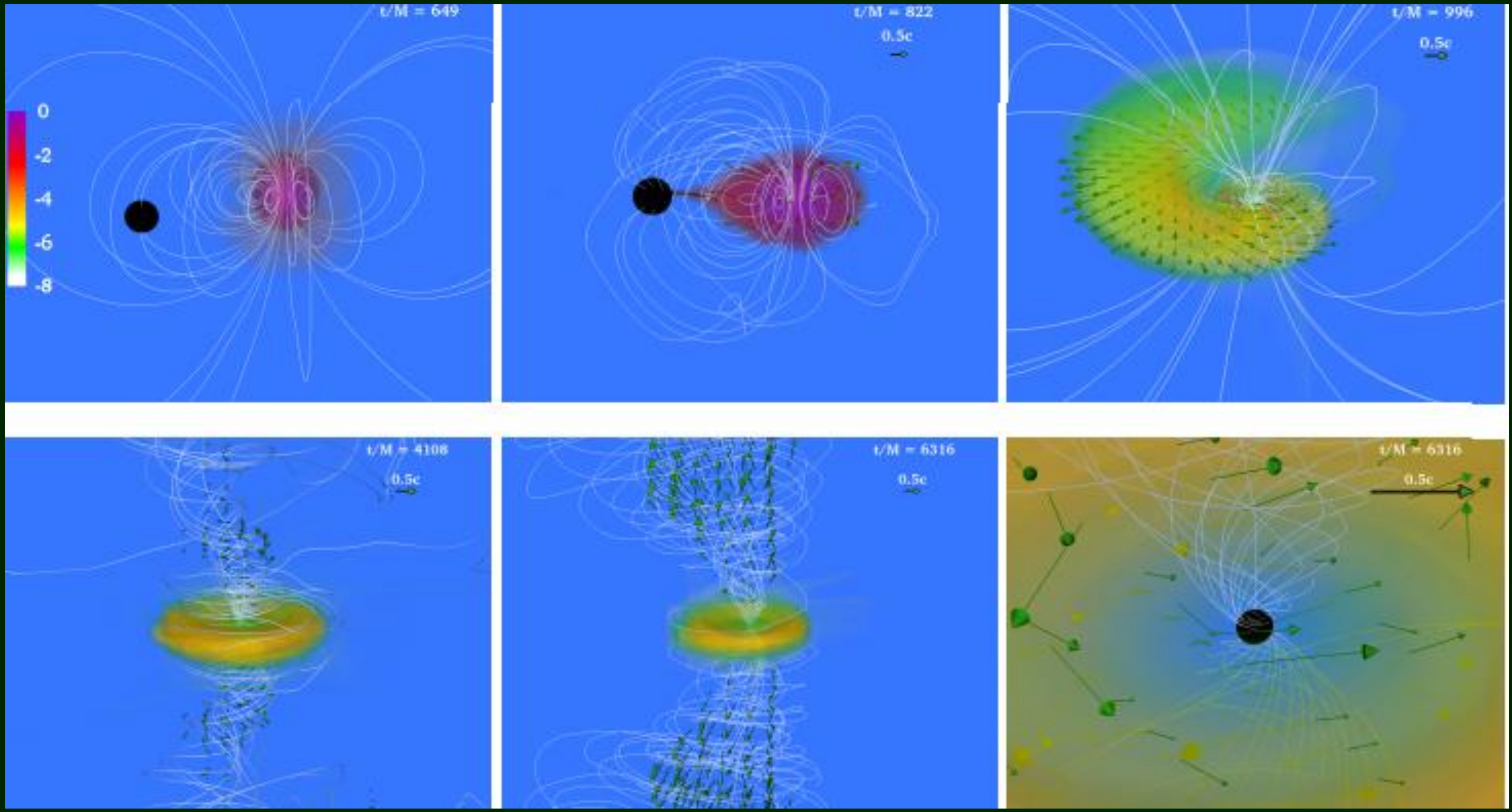
Some numerical models show (astro-ph/0505007, 0505094) that such events do not produce GRBs. Some show that they do.



BH-NS mergers are still a popular subject of studies:
1105.3175, 1103.3526, 1210.8153, 1302.6297, 1301.5616, 1304.3384.
see a brief review in 2006.10570 and a detailed one in 2110.06218.

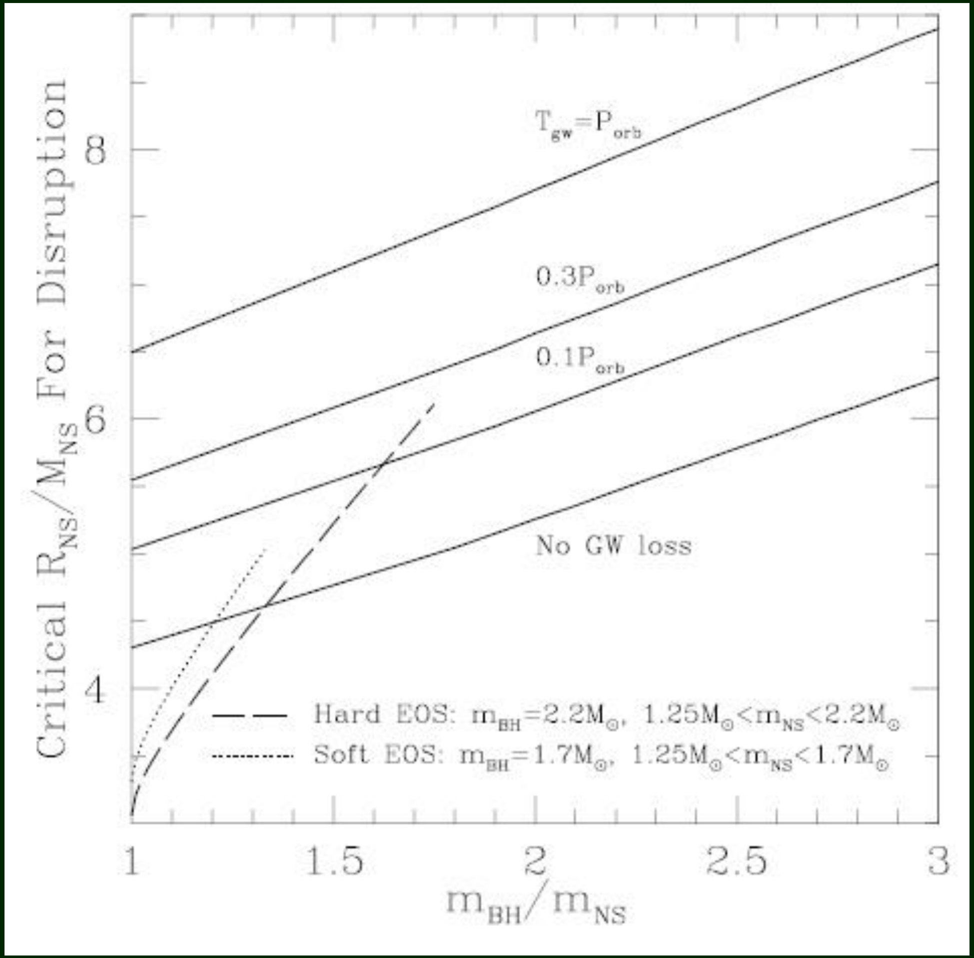
Magnetic field jet launch

Neutron star magnetic field helps to launch the jet. But disc is still necessary!



1410.7392, see new results by the same group in 2011.08863

Prompt mergers of NSs with BHs

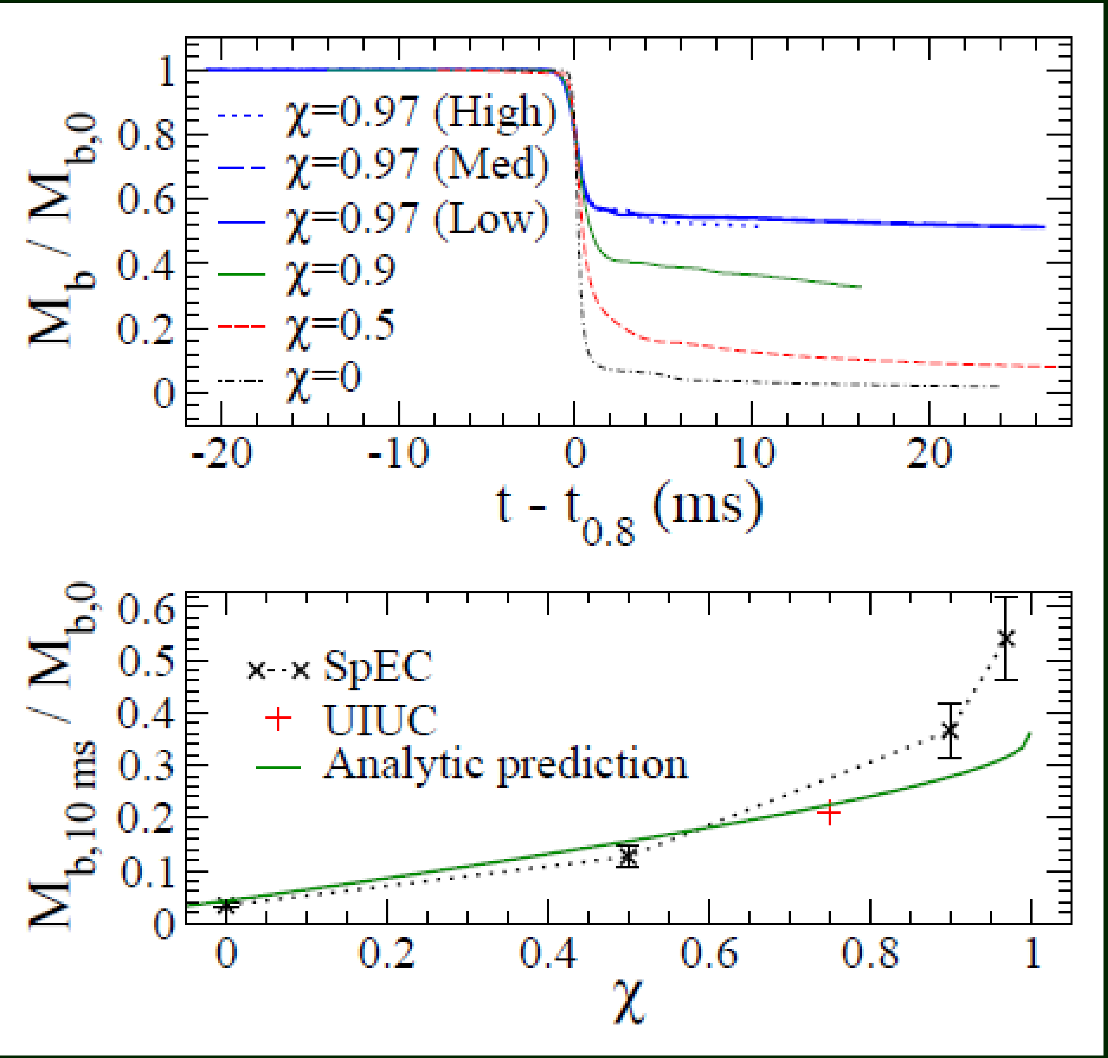


Coleman Miller demonstrated that in NS-BH coalescence most probably there is no stable mass transfer and an accretion disc is not formed. This means – **no GRB**!

The top solid line is constructed by assuming that the neutron star will plunge when, in one full orbit, it can reduce its angular momentum below the ISCO value via emission of gravitational radiation.
The next two solid lines reduce the allowed time to 30 and 10% of an orbit
The bottom line ignores gravitational radiation losses entirely.

astro-ph/0505094

Extremal BH-NS mergers



It is possible to form
a massive disc
around a BH
during BH-NS merger.
However,
not for non-rotating BHs.

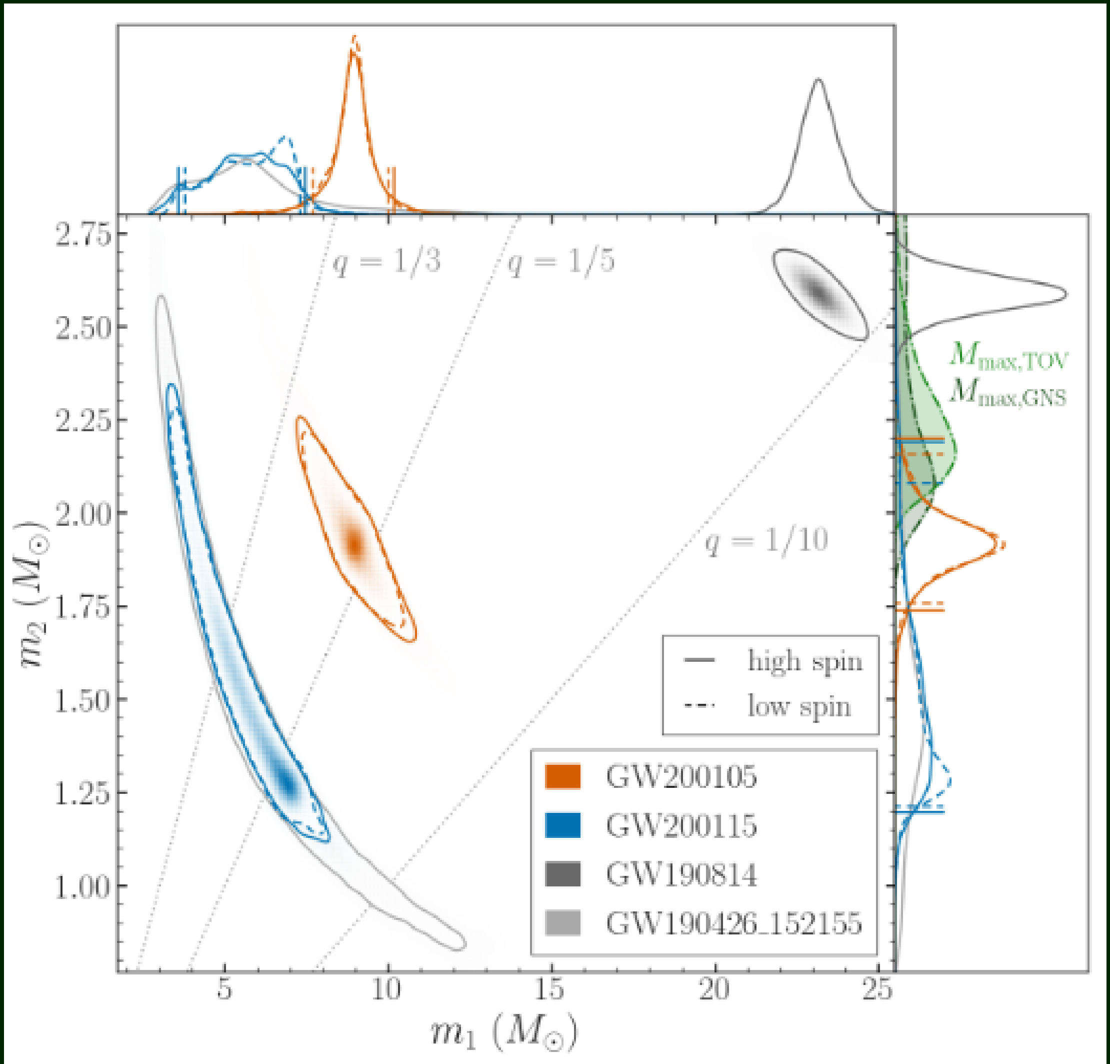
1302.6297

Two BH-NS coalescence observations

GW200105

GW200115

plus two candidates

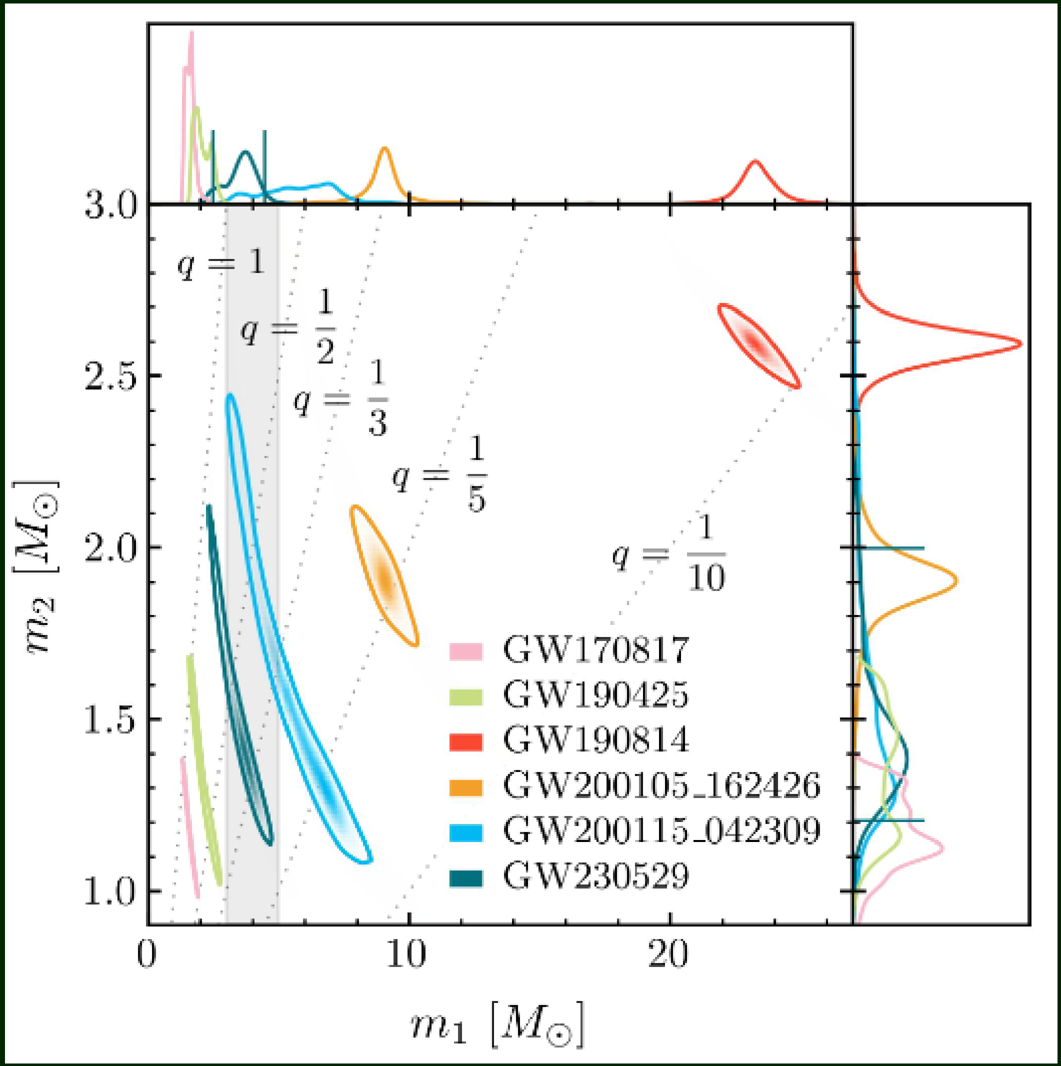


2106.15163

A mass gap BH coalescence with an NS?

GW230529_18150

Primary mass $m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$
Mass ratio $q = m_2/m_1$	$0.39^{+0.41}_{-0.12}$
Total mass $M/M_\odot$	$5.1^{+0.6}_{-0.6}$
Chirp mass $\mathcal{M}/M_\odot$	$1.94^{+0.04}_{-0.04}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$2.026^{+0.002}_{-0.002}$
Primary spin magnitude χ_1	$0.44^{+0.40}_{-0.37}$
Effective inspiral-spin parameter $\chi_{\rm eff}$	$-0.10^{+0.12}_{-0.17}$
Effective precessing-spin parameter $\chi_{\rm p}$	$0.40^{+0.39}_{-0.30}$
Luminosity distance $D_{\rm L}/\rm Mpc$	201^{+102}_{-96}
Source redshift z	$0.04^{+0.02}_{-0.02}$

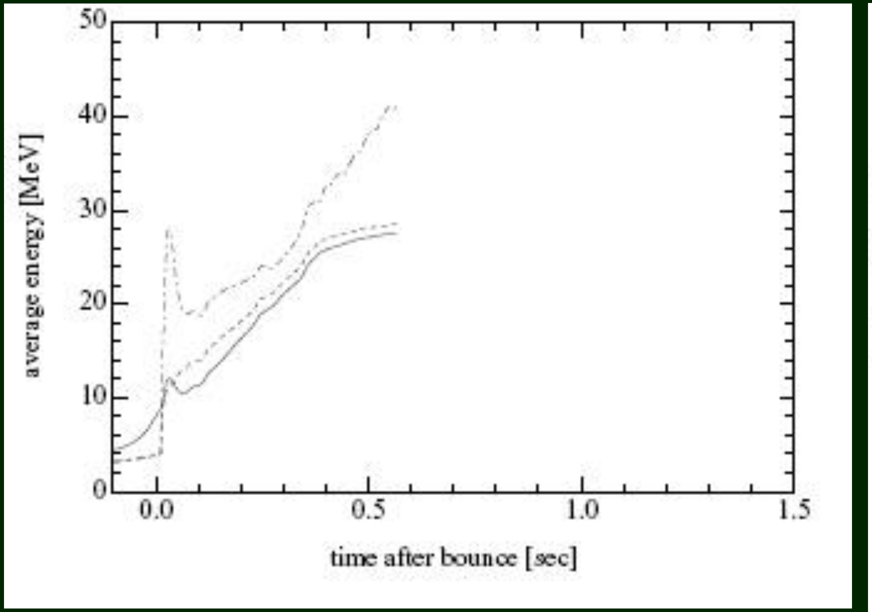


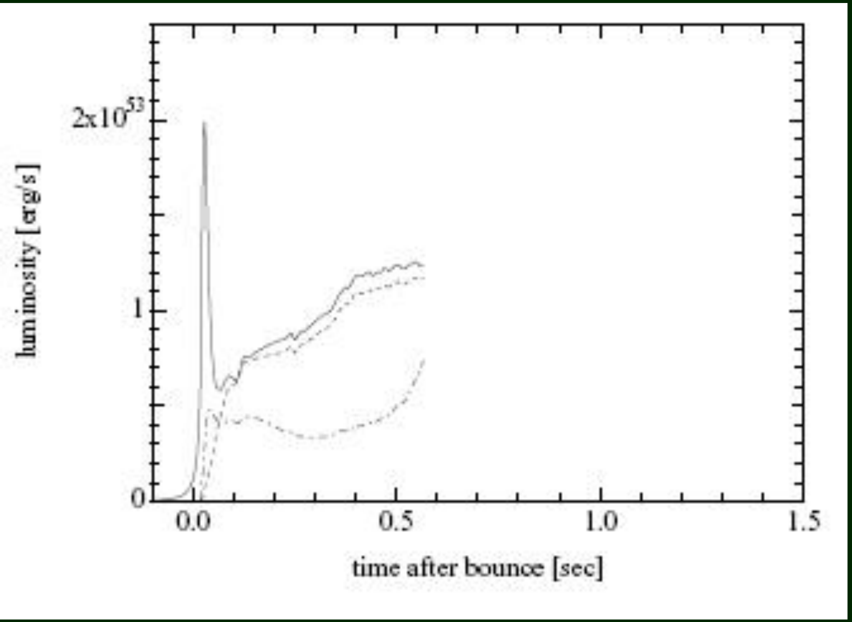
Detected just by the LIGO Livingston observatory.
Hanford and Virgo were offline.
KAGRA does not have sufficient sensitivity.

2404.04248

Supernovae

The neutrino signal during a (direct) BH formation must be significantly different from the signal emitted during a NS formation. (arXiv: 0706.3762)



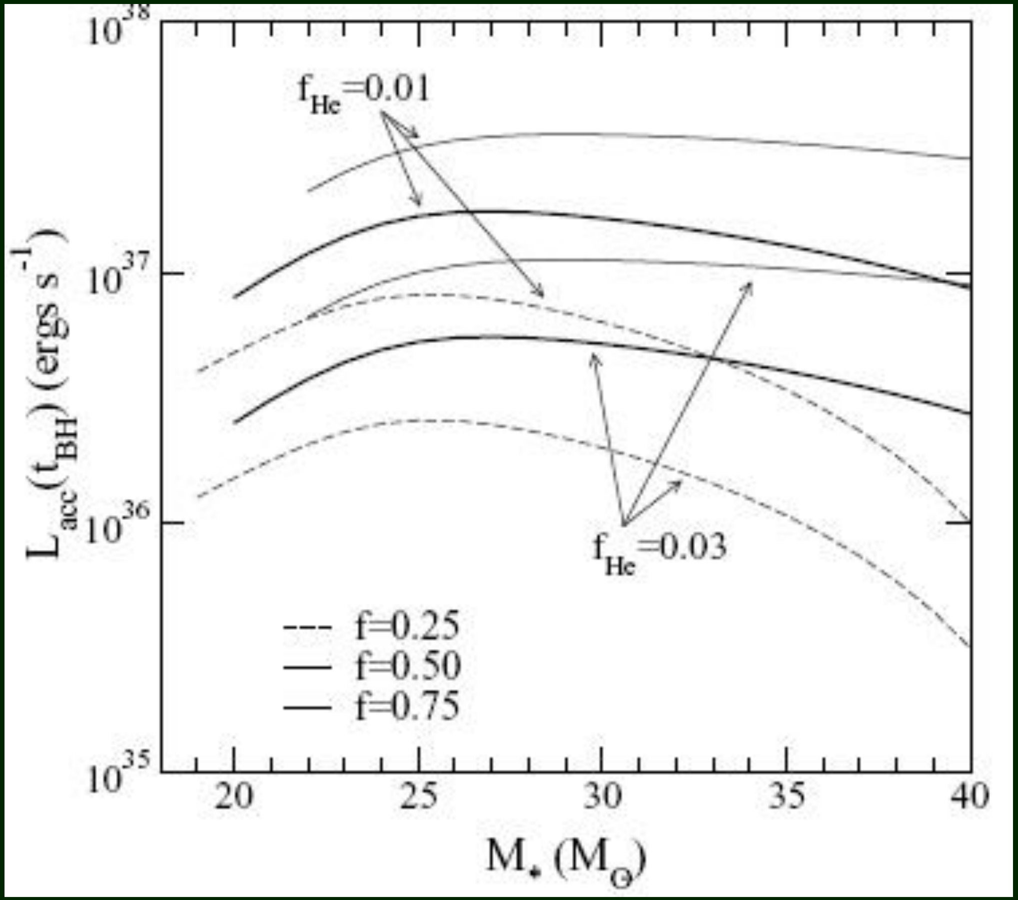


Different curves are plotted for different types of neutrino: electron – solid, electron anti-neutrino – dashed, mu and tau-neutrinos – dot dashed.

Constant growth of neutrino energy and a sharp cut-off indicate a BH formation. Result depends on the EoS.

See some new results in: arXiv:0809.5129
BH formation in a PNS collapse and neutrino spectra

BH signatures in SN light curves



$$\dot{M} \propto t^{-5/3}$$

$$L_{acc}(t) = L_{Edd}\left(\frac{t}{t_{dust}}\right)^{-25/18}$$

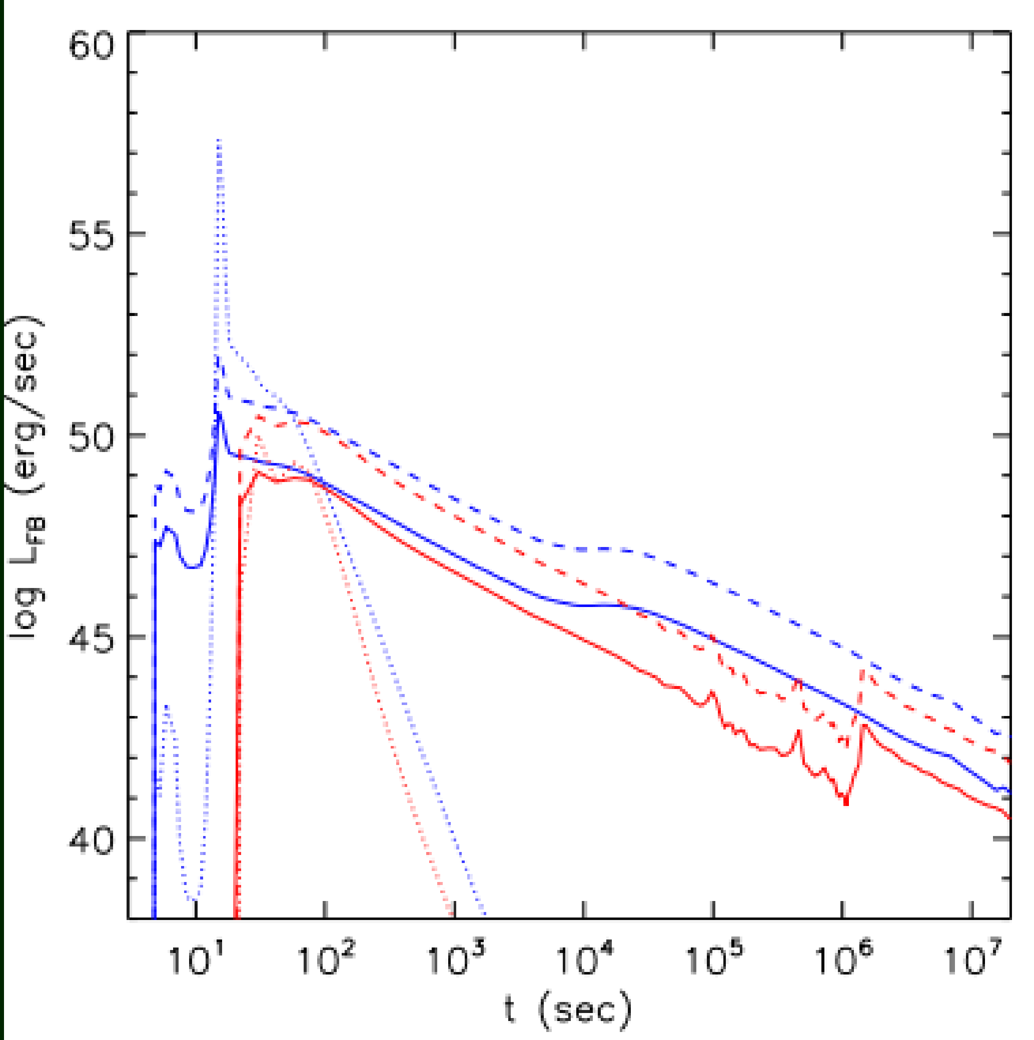
For this plot no radioactive heating is taken into account.

An accreting BH can “emerge” after ~few months-years.

Balberg, Shapiro astro-ph/0104215

(see also Zampieri et al., 1998, ApJ 505, 876)

Early stages of fall-back



Several mechanisms of energy release in a fall-back are calculated:

- "accretion heating" (solid line)
- neutrino annihilation (dotted line)
- Blandford-Znajek emission (dashed line).

Estimates show that fallback can potentially lead to large amount of energy deposition to the ejecta, powering super-luminous supernovae.

1401.3032

A BH birth???

EVIDENCE FOR A BLACK HOLE REMNANT IN THE TYPE IIL SUPERNOVA 1979C

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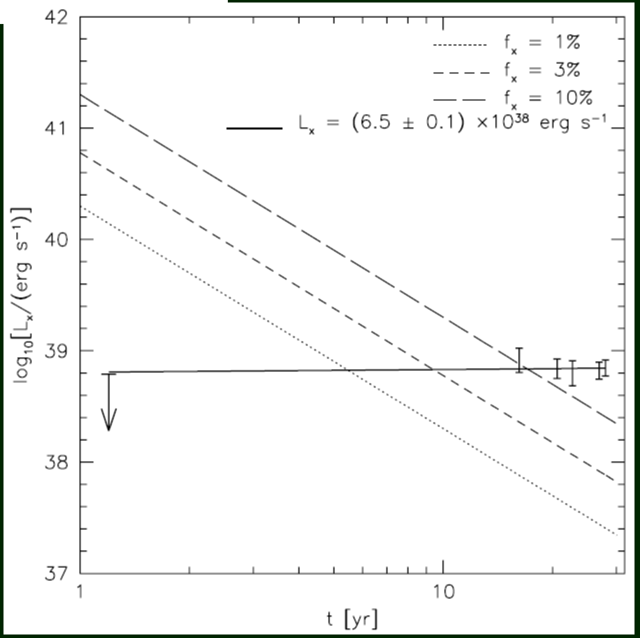
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
Draft version December 8, 2009

ABSTRACT

We present an analysis of archival X-ray observations of the Type IIL supernova SN 1979C. We find that its X-ray luminosity is remarkably constant at $(6.5 \pm 0.1) \times 10^{38}$ erg s^{-1}. The high and steady luminosity is evidence for a stellar-mass ($\sim$ 5–10$M_\odot$) black hole accreting material from either a supernova fallback disk or possibly from a binary companion. We find that the bright and steady X-ray light curve is not consistent with either a model for a supernova powered by magnetic braking of a rapidly rotating magnetar, or a model where the blast wave is expanding into a dense circumstellar wind.

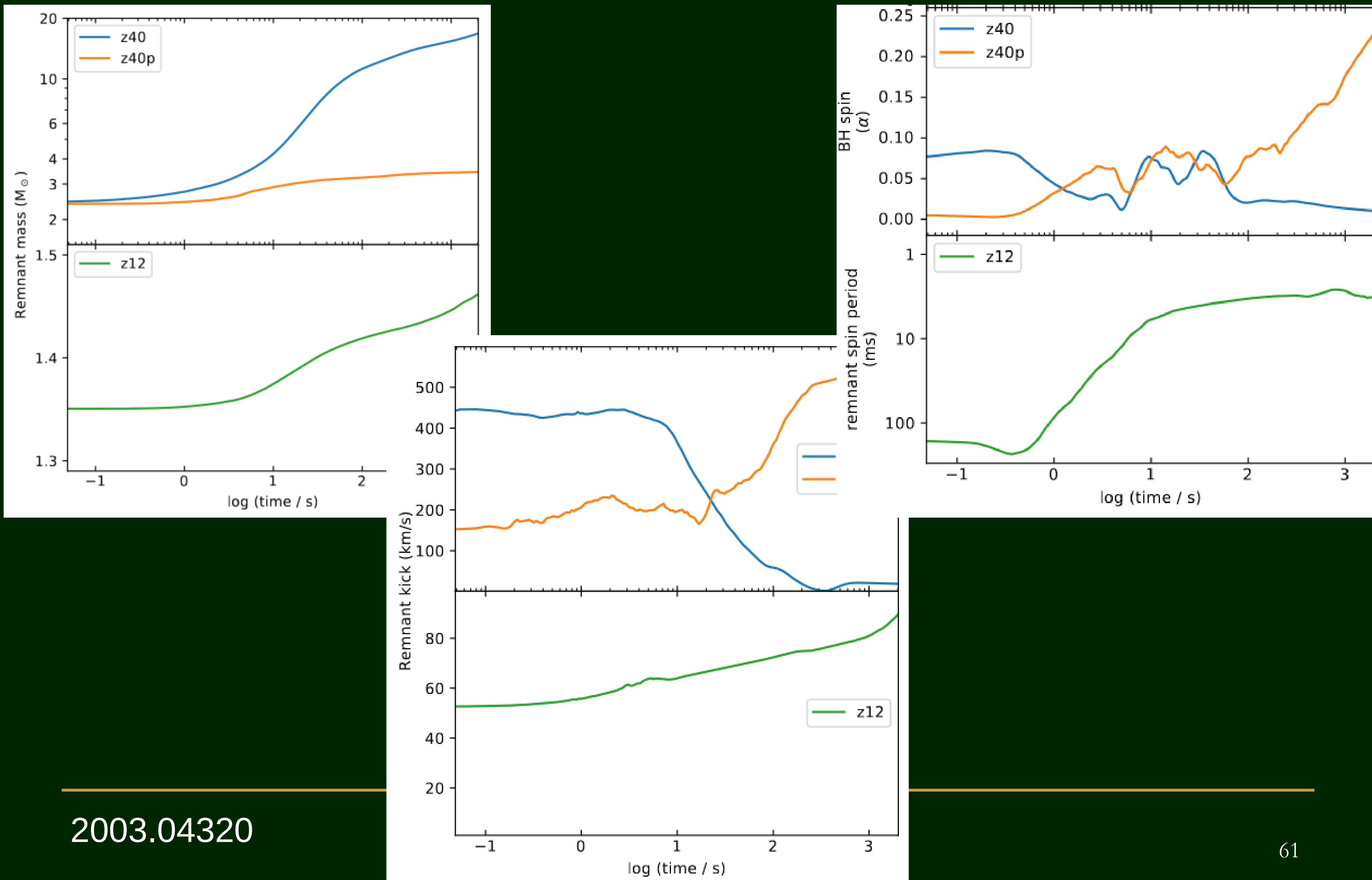
TABLE 1
X-ray observations of SN 1979C

Δt yr	Count Rate 10^{-4} cps	F_X [a] 10^{-14} erg cm^{-2} s^{-1}	L_X [b] 10^{38} erg s^{-1}	Mission
0.7	< 3.0	< 2.3	< 6.3	*Einstein* (HRI)
16.2	6.7±0.7	3.0±0.3	8.2±0.9	*ROSAT* (HRI)
20.6	42.±2.0	2.5±0.2	6.9±0.6	*Chandra* (ACIS-S)
22.7[c]	...	2.3±0.3	6.3±0.7	*XMM–Newton* (MOS)
26.9	40.±0.8	2.4±0.2	6.6±0.5	*Chandra* (ACIS-S)
28.0	43.±0.3	2.6±0.2	7.0±0.5	*Chandra* (ACIS-S)



0912.1571

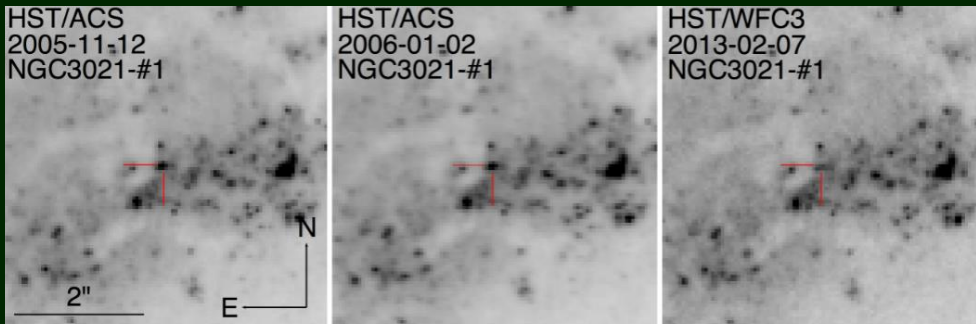
Role of fall-back for kicks and spin

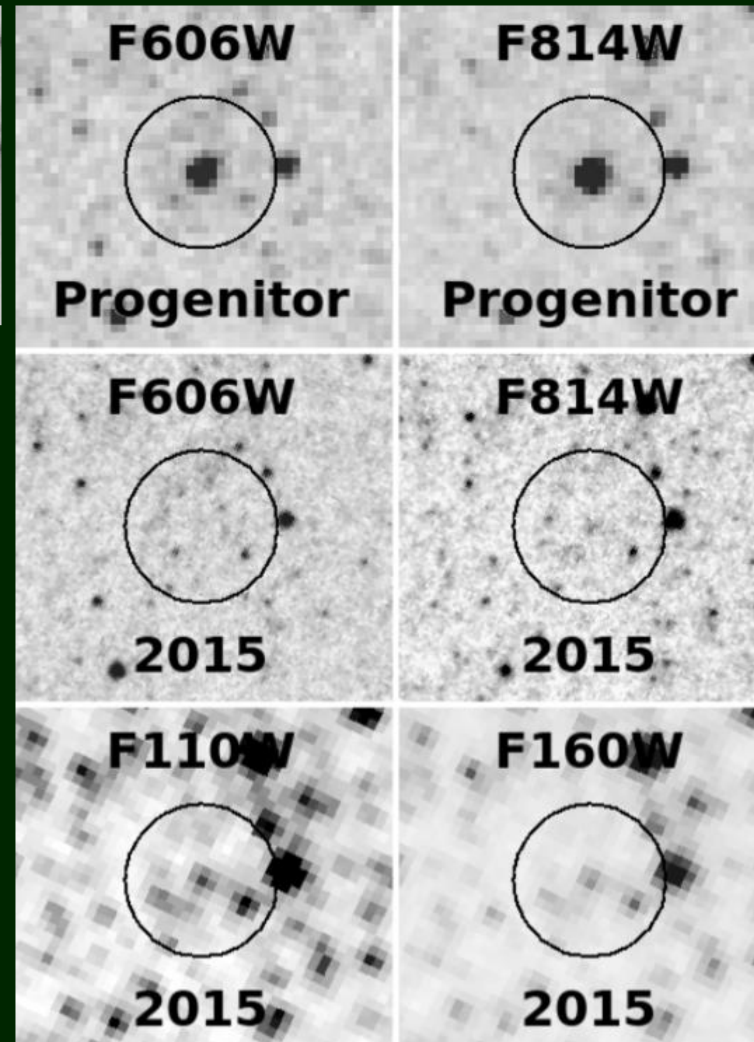


2003.04320

Disappearance of stars

1507.05823





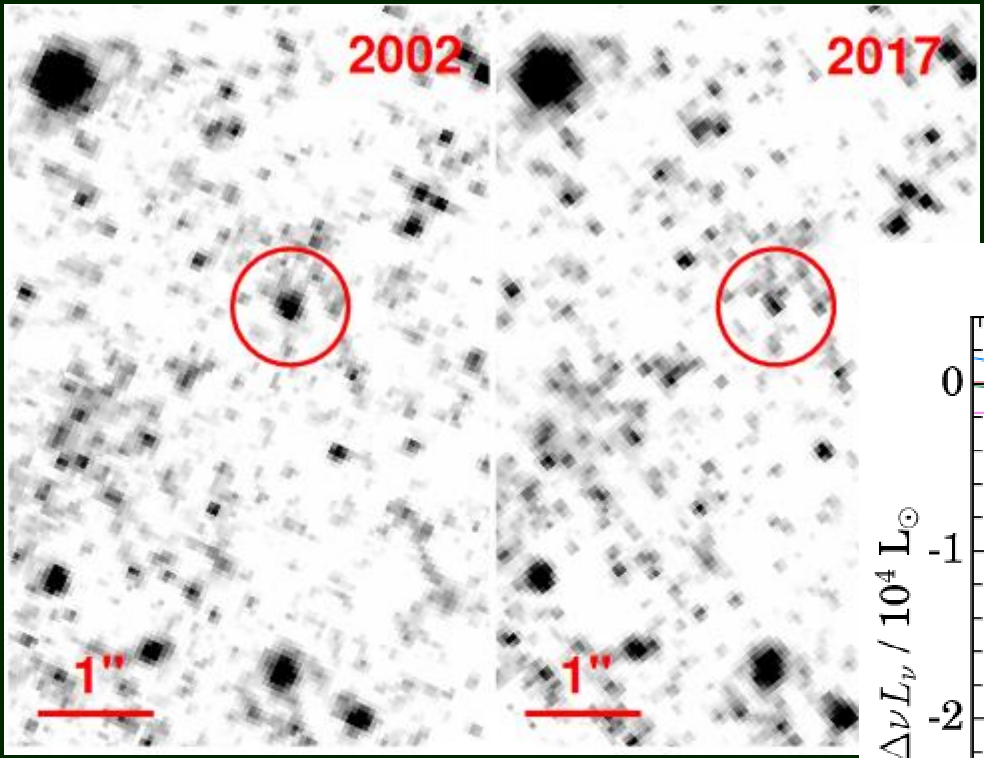
1609.01283

The event is consistent with the ejection of the envelope of a red supergiant in a failed supernova and the late-time emission could be powered by fallback accretion onto a newly-formed black hole.

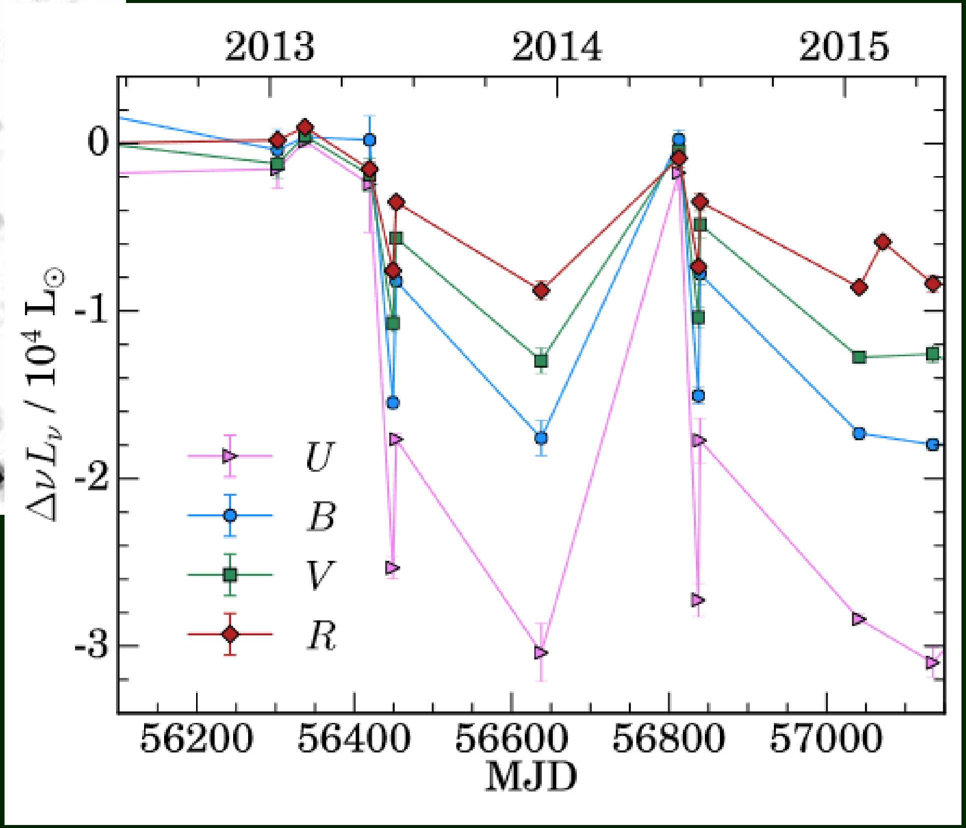
Progenitor mass ~23-28 solar.
Consistent with the missing RSG problem.

In 2018 ~30 examples of identified SN progenitors are known, and there ~40 upper limits (1802.07870).

New example of a disappeared star



Blue supergiant in M101

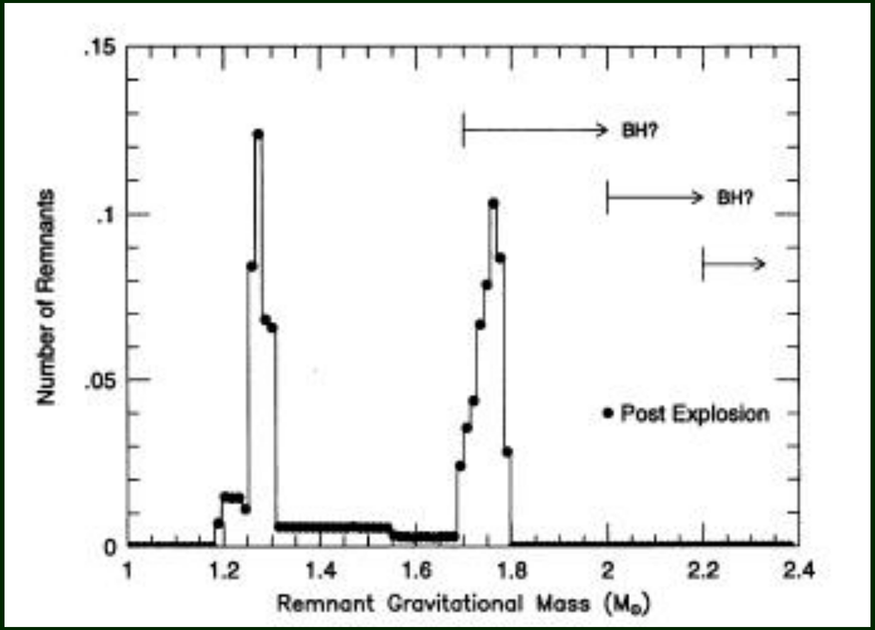


2104.03318

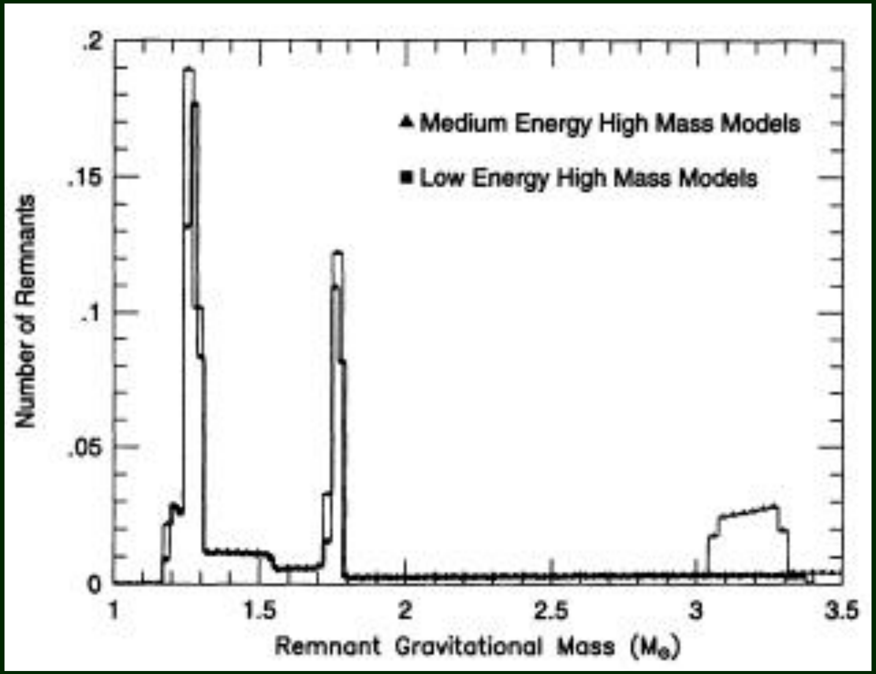
Conclusions

- There can be different kinds of BHs: PBH, stellar, IMBH, SMBH
- Stellar mass BHs can be observed due to
  - accretion in binaries
  - GRBs
  - GW
  - in SN
- Mass interval for stellar mass BH formation is not certain

Mass spectrum of compact objects



Results of numerical models



Timmes et al. 1996, astro-ph/9510136