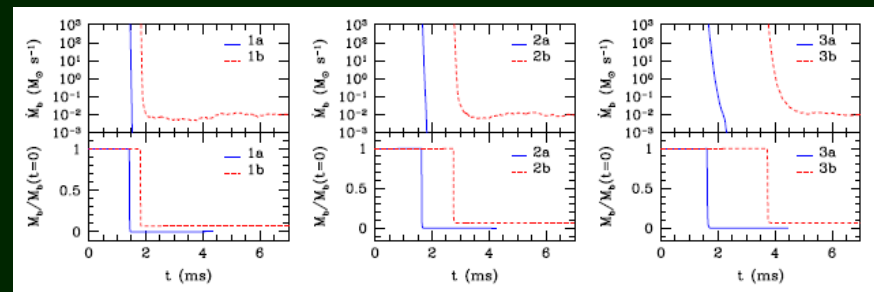
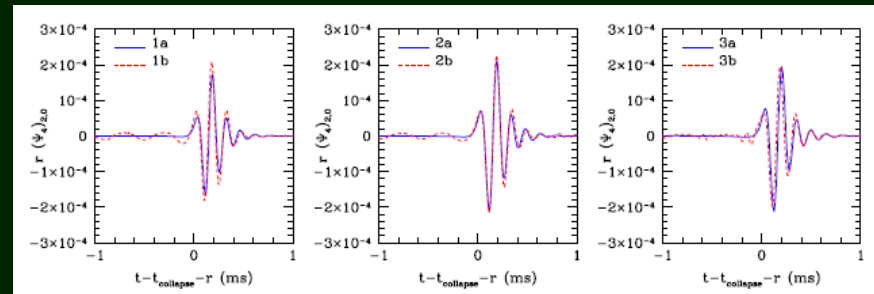
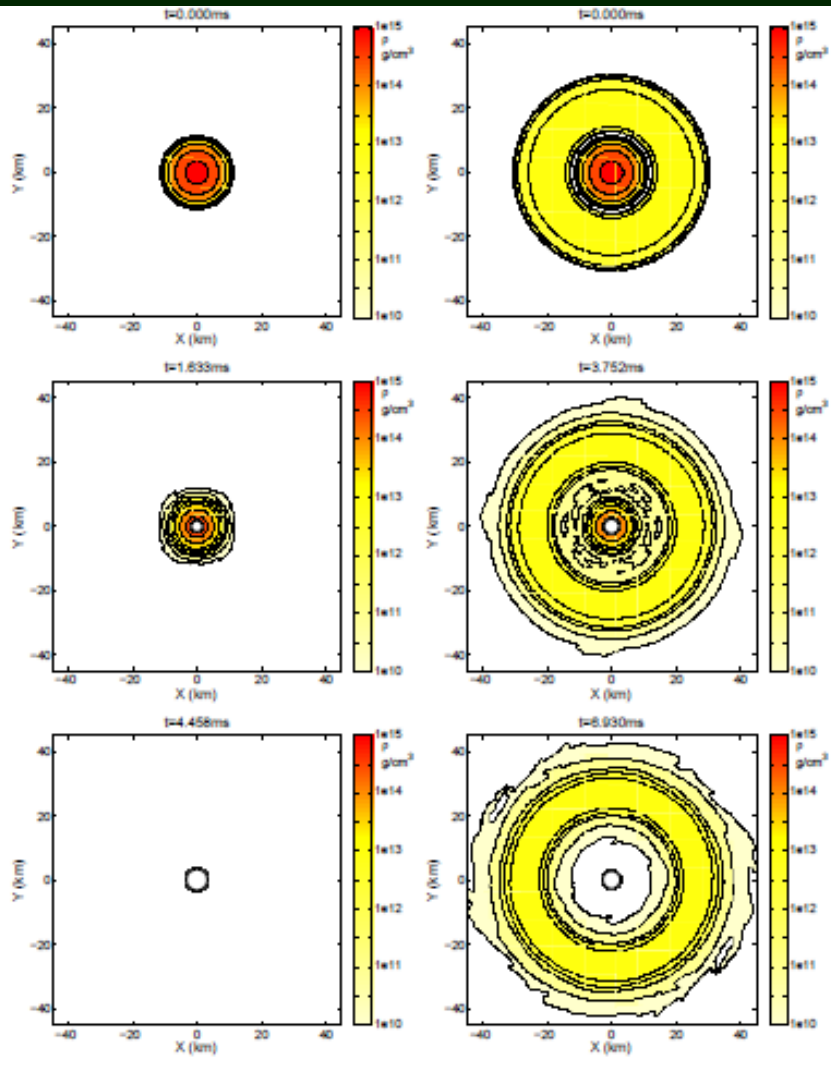

Black holes: Introduction

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.

Main general surveys

- [astro-ph/0610657](#) *Neven Bilic* BH phenomenology
- [astro-ph/0604304](#) *Thomas W. Baumgarte* BHs: from speculations to observations
- [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

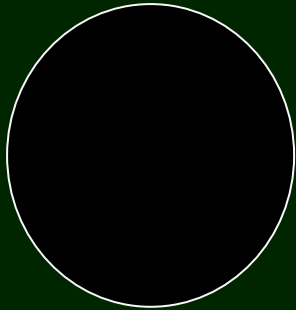
- **Primordial BHs.**
Not discovered, yet. Only upper limits (mostly from gamma-ray observations).
- **Stellar mass BHs.**
There are more than twenty good candidates in close binary systems.
Accretion, jets. Observed at all wavelengths.
Isolated stellar mass BHs are not discovered up to now.
But there 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 disruptions of normal stars.
Observed at all wavelengths.



Что такое черная дыра?

Для физика

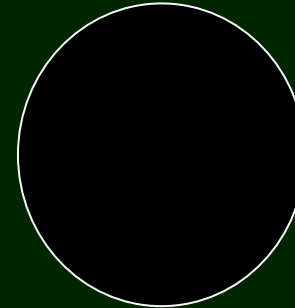
Обладает определенными внутренними свойствами



Объект, обладающий горизонтом.

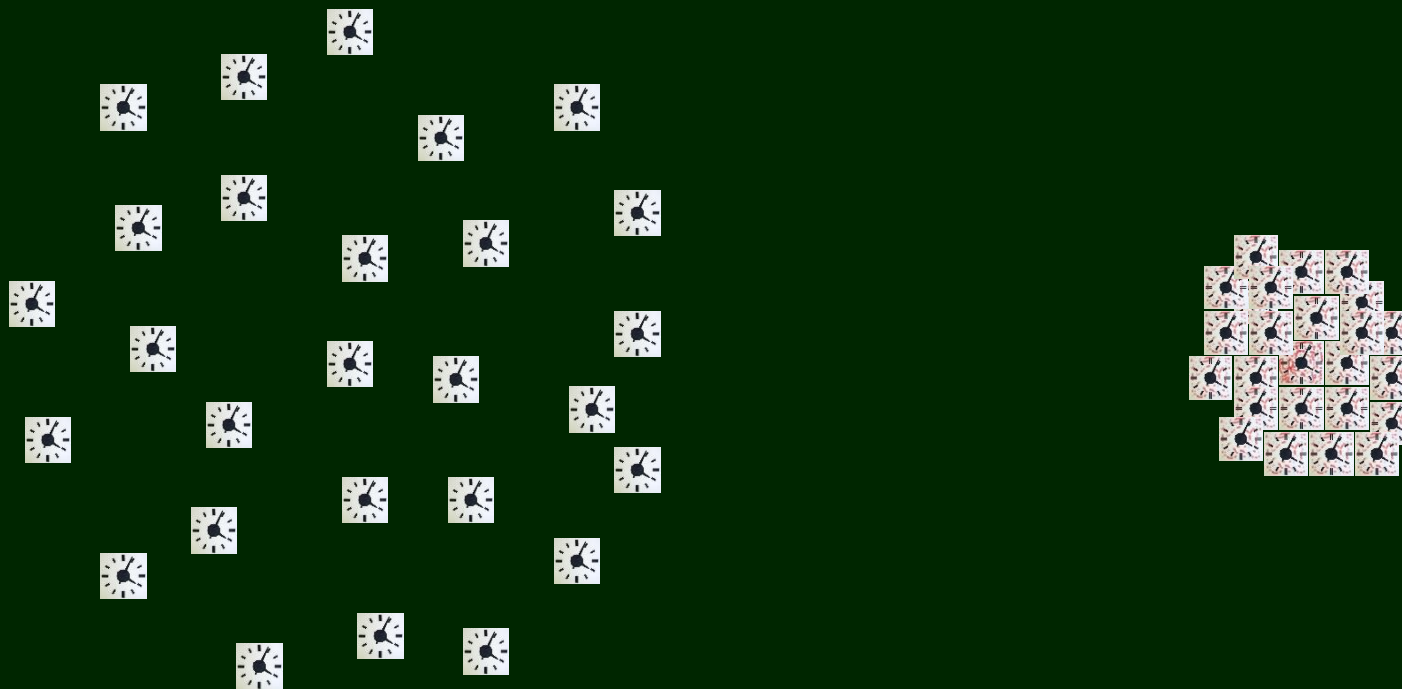
Для астронома

Обладает определенными внешними проявлениями



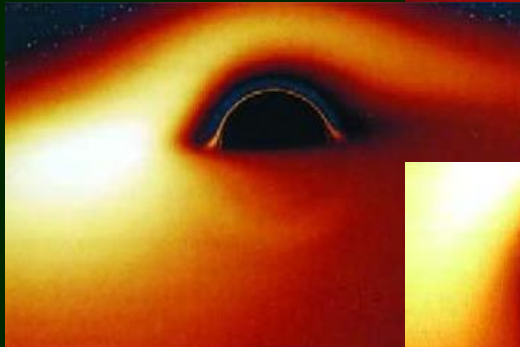
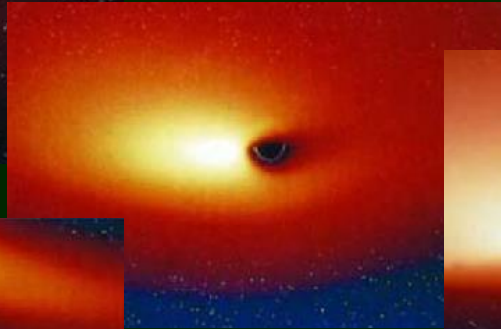
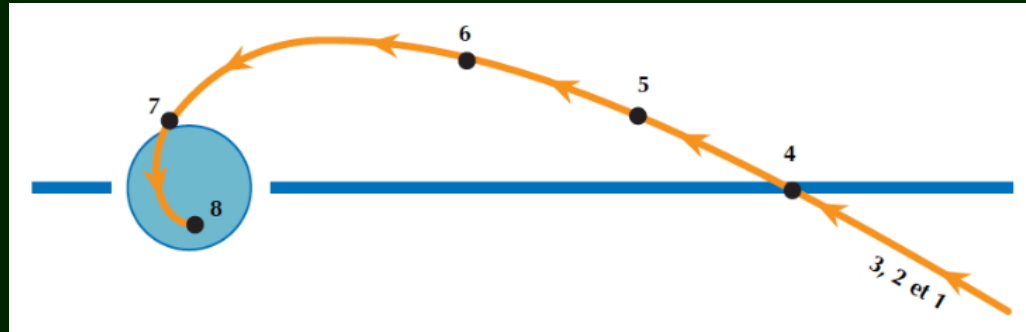
Компактное (размер горизонта) массивное тело, не проявляющее признаков наличия поверхности, и чьи недра недоступны для наблюдений.

Коллапс облака



Мы всегда видим часы в центре,
но они все краснее и краснее...

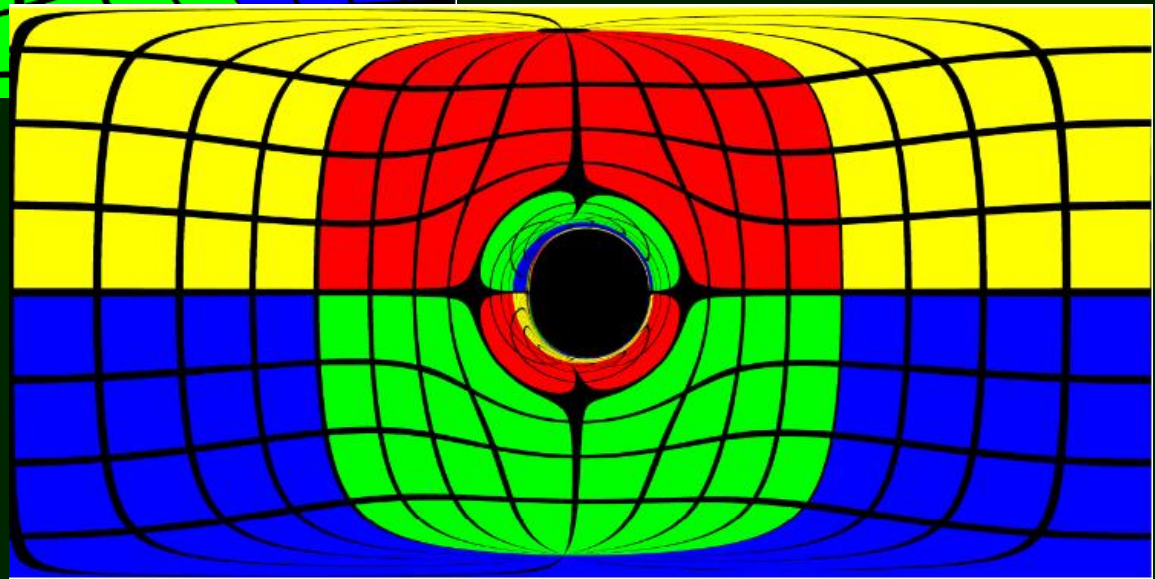
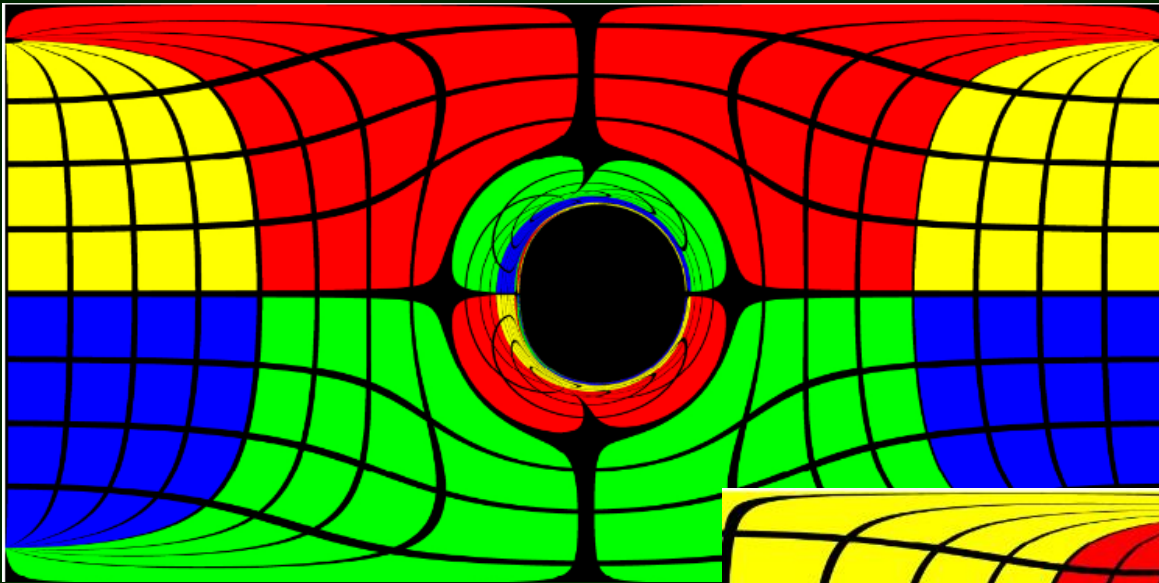
Falling into a BH



1804.03909, see also 1902.11196

BH virtual reality

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



Video for Sgr A*

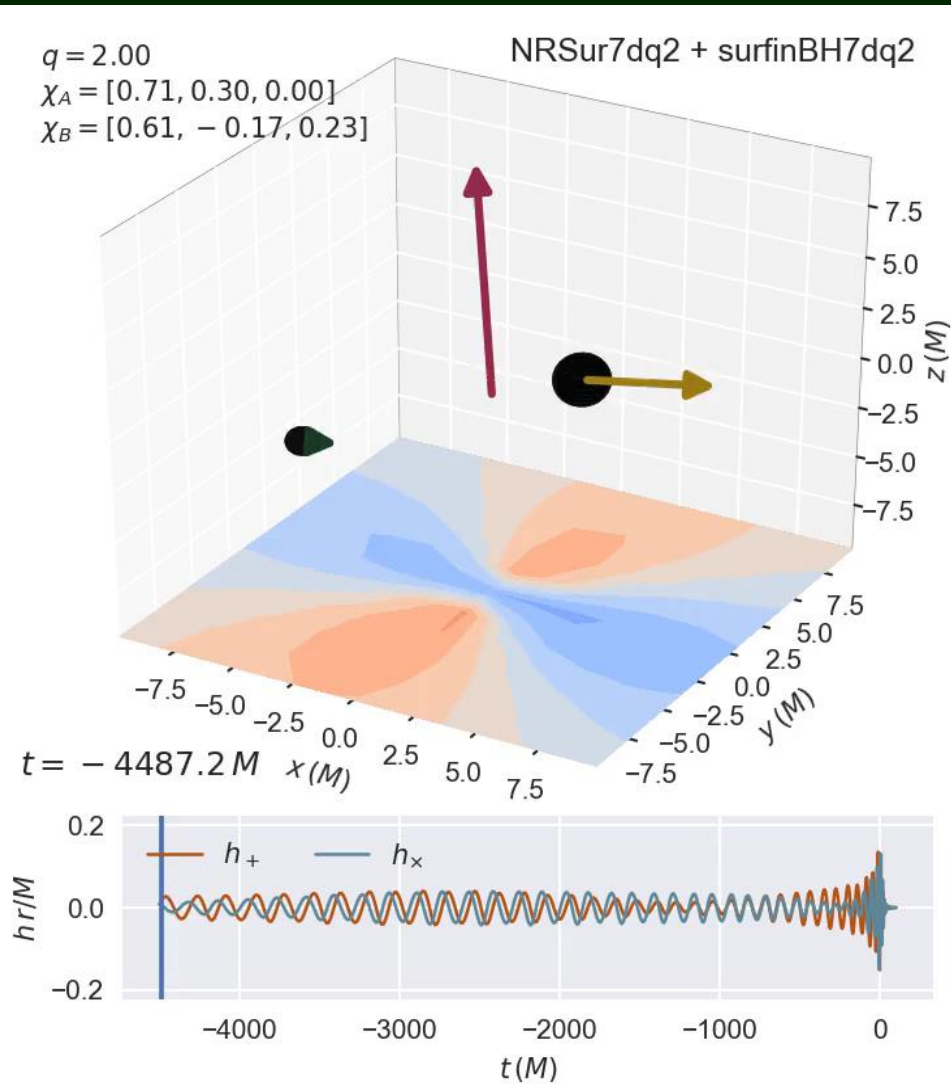


<https://www.youtube.com/watch?v=SXN4hvp977s>

<https://blackholecam.org/>

Binary BH visualization

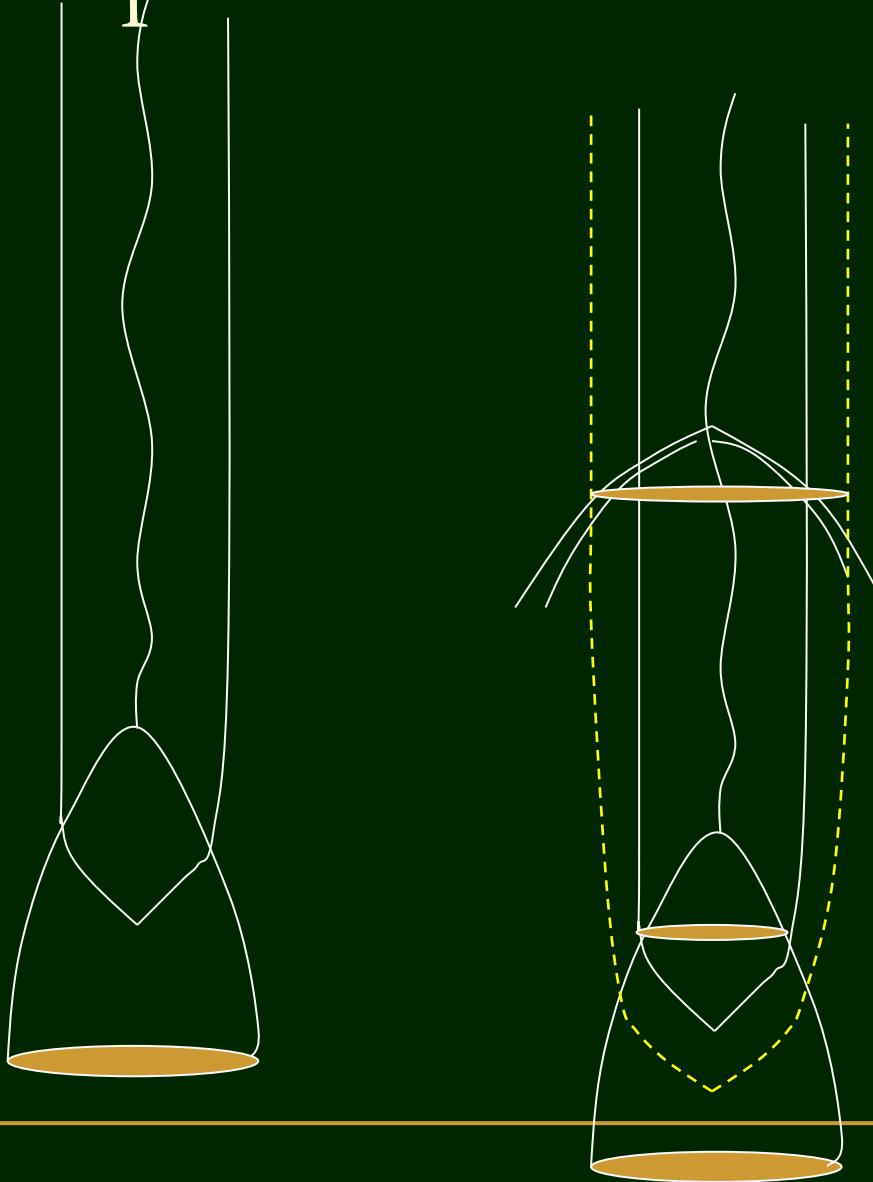
<https://vijayvarma392.github.io/binaryBHexp/>



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.

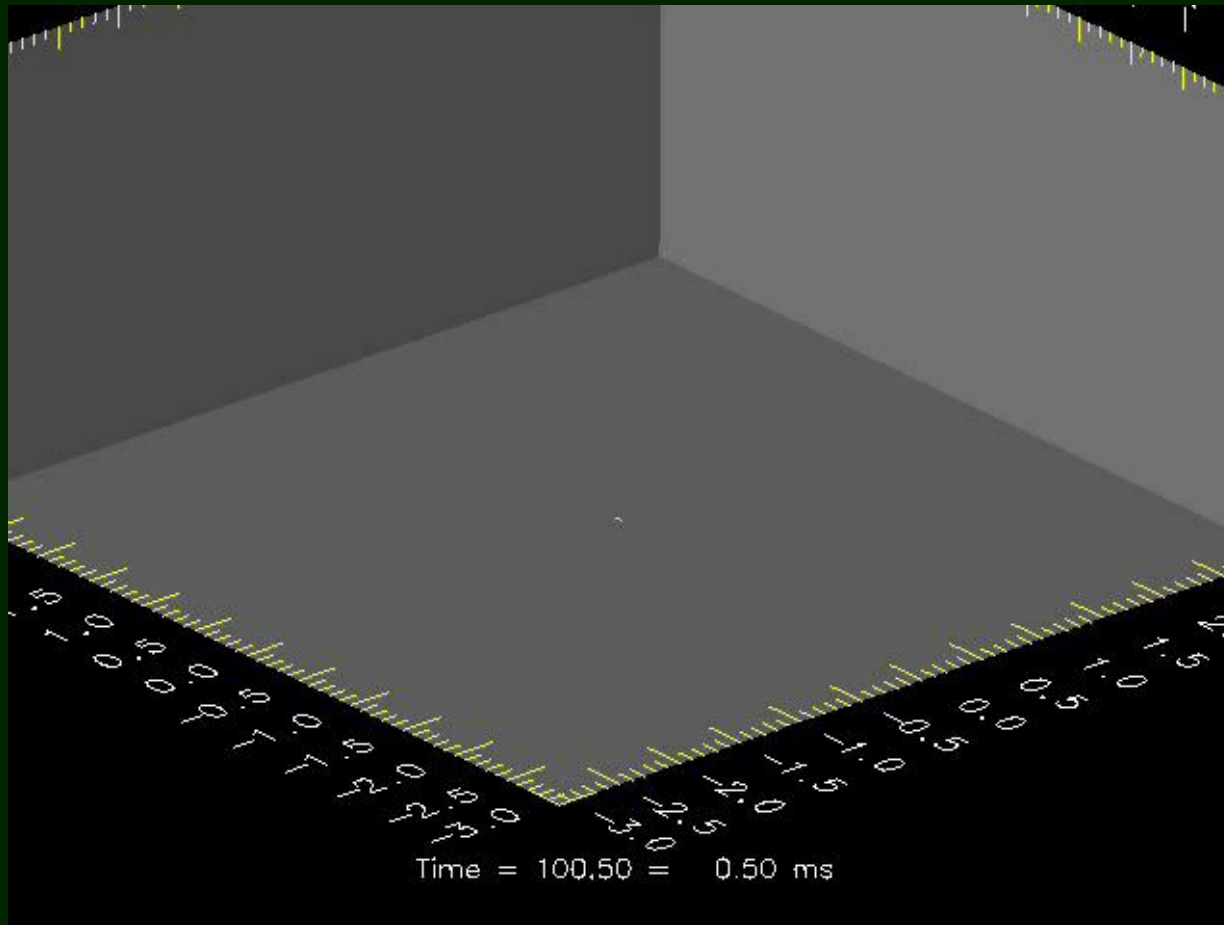
1811.06552

Горизонты

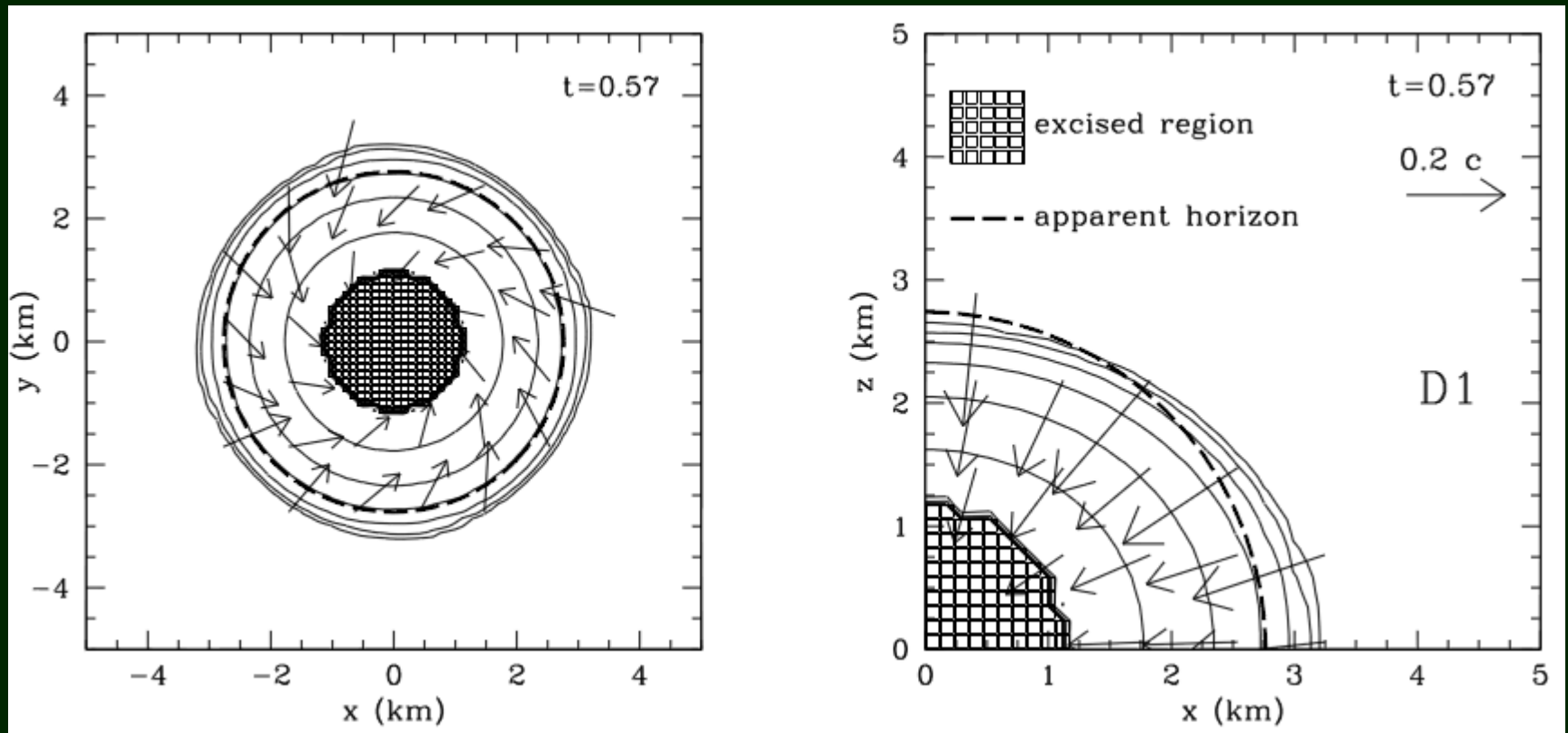


Теорема об отсутствии волос:
«Черные дыры не имеют волос».
Черная дыра полностью описывается
массой и вращением.

Horizons appearance



ΚΟΛΛΑΠΣ

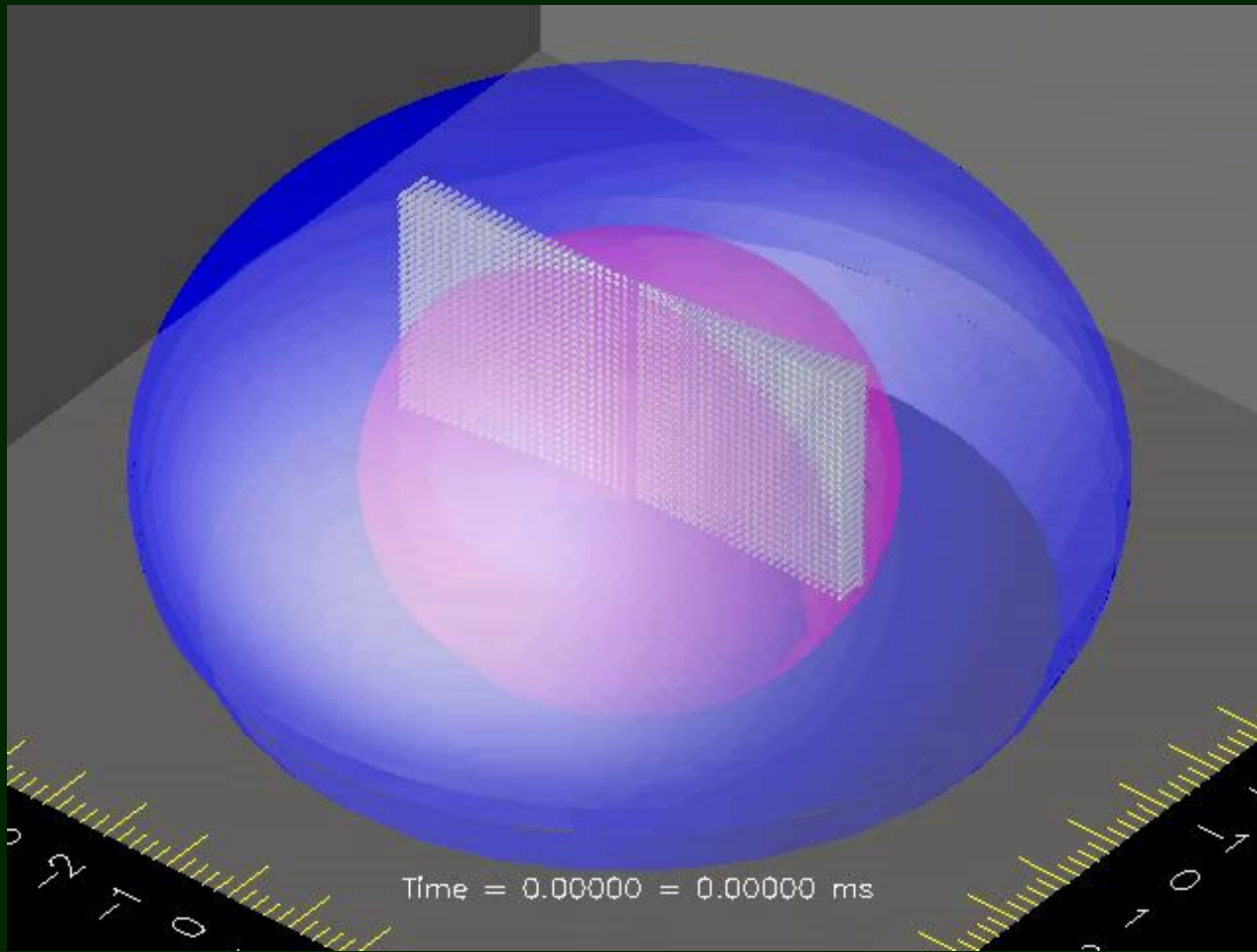


Apparent horizon position is calculated at every time step.

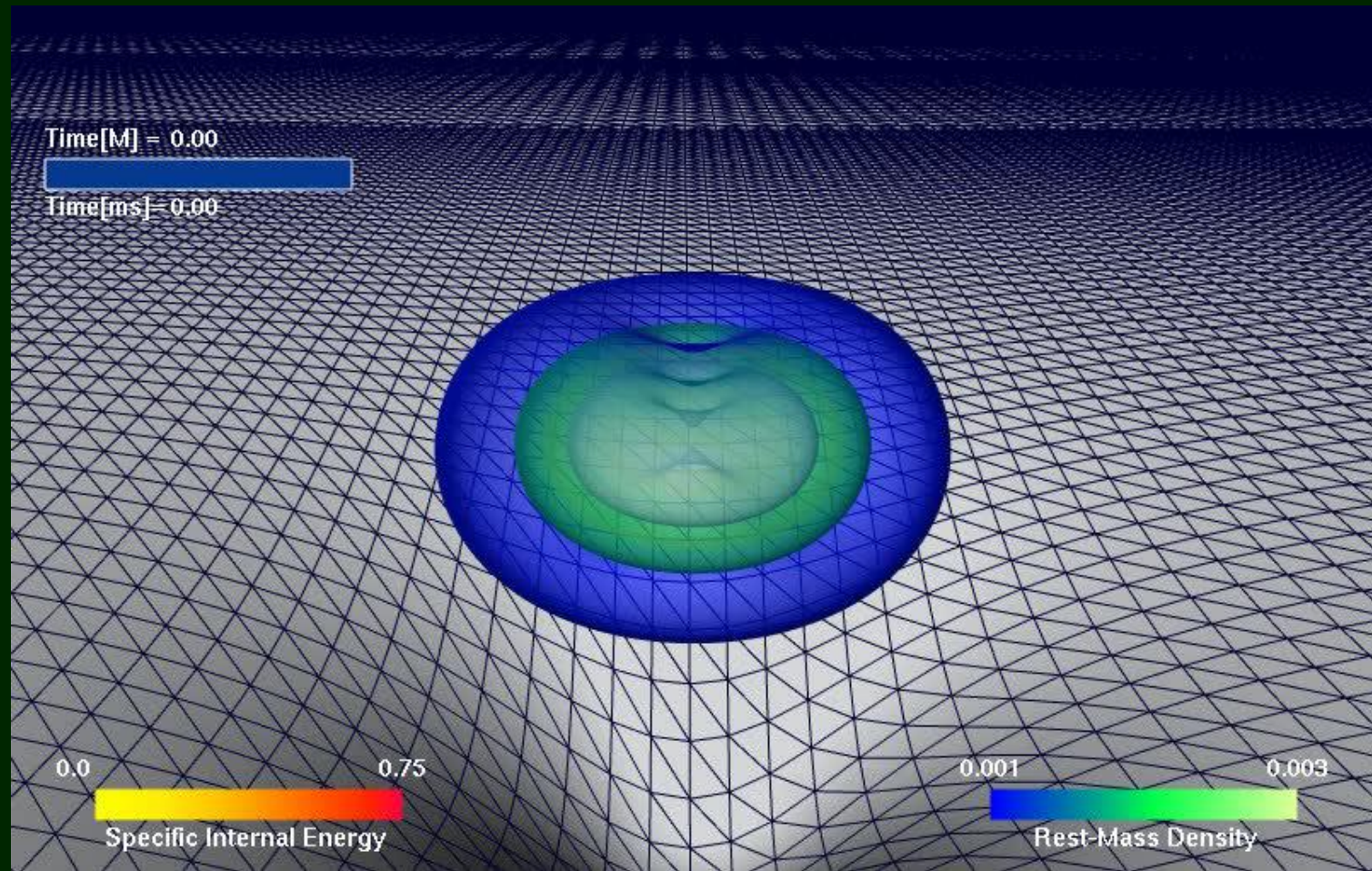
The event horizon (which is growing from zero to its final position and is always outside the apparent horizon) is calculated a posteriori, i.e. after calculations are finished.

L. Baiotti, Rezzolla et al.

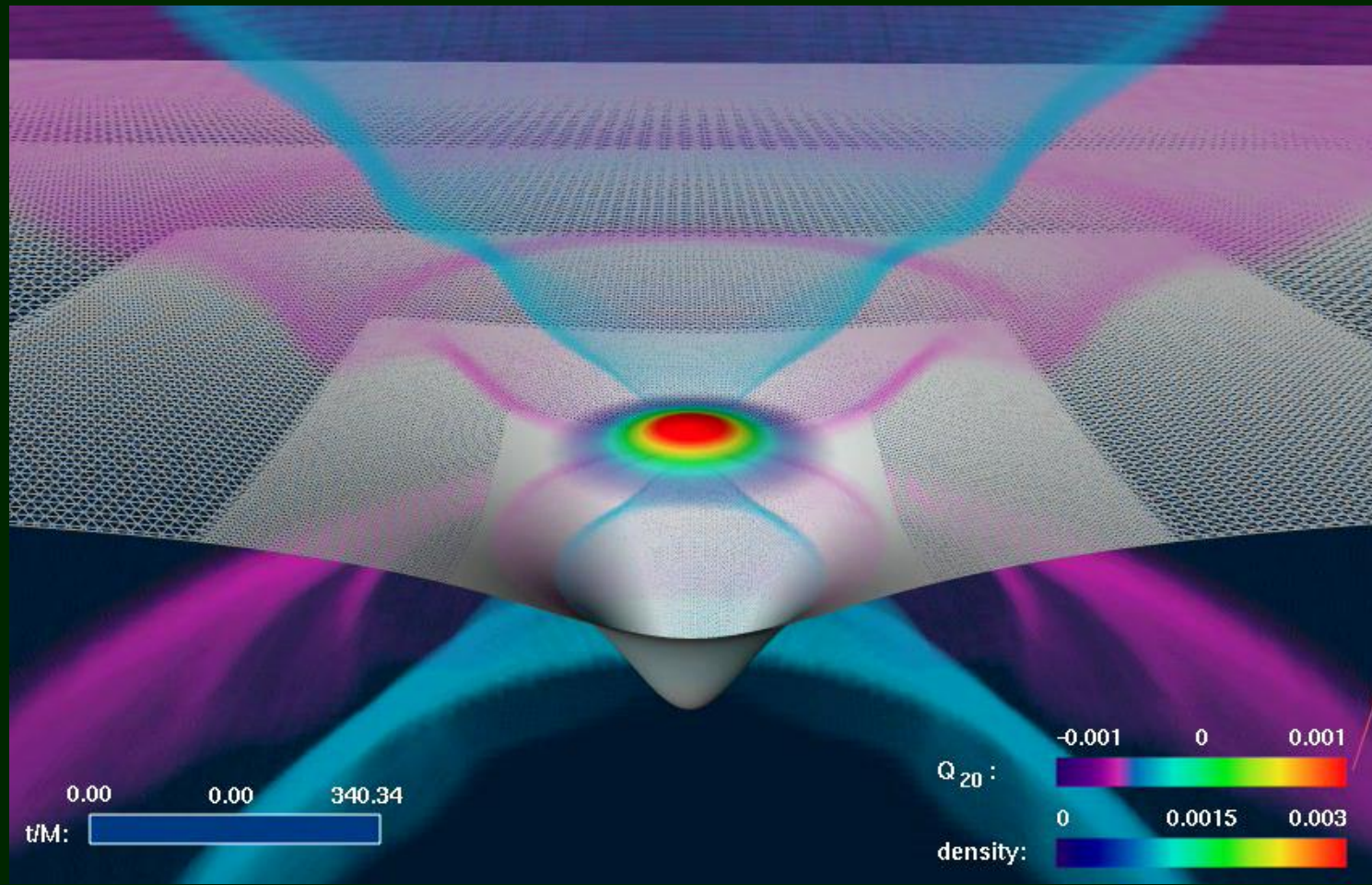
gr-qc/0403029



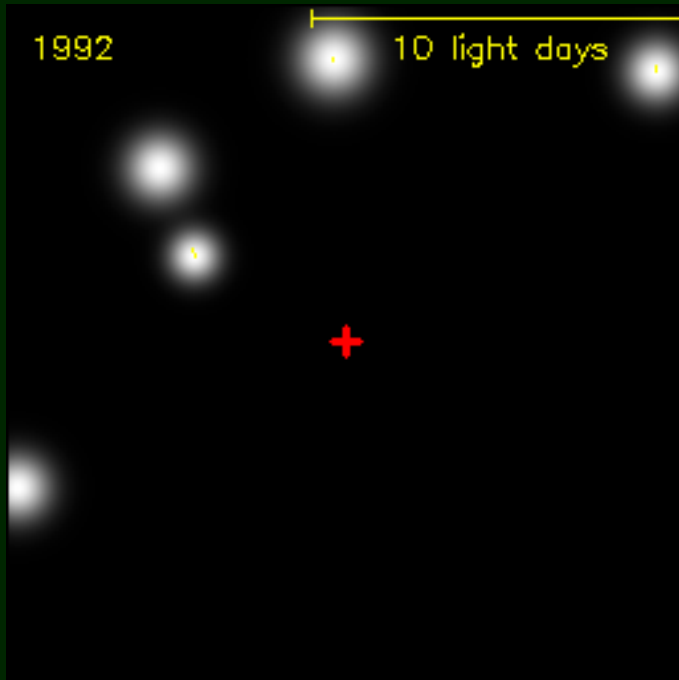
Collapse of a rotating star



Collapse and GW emission

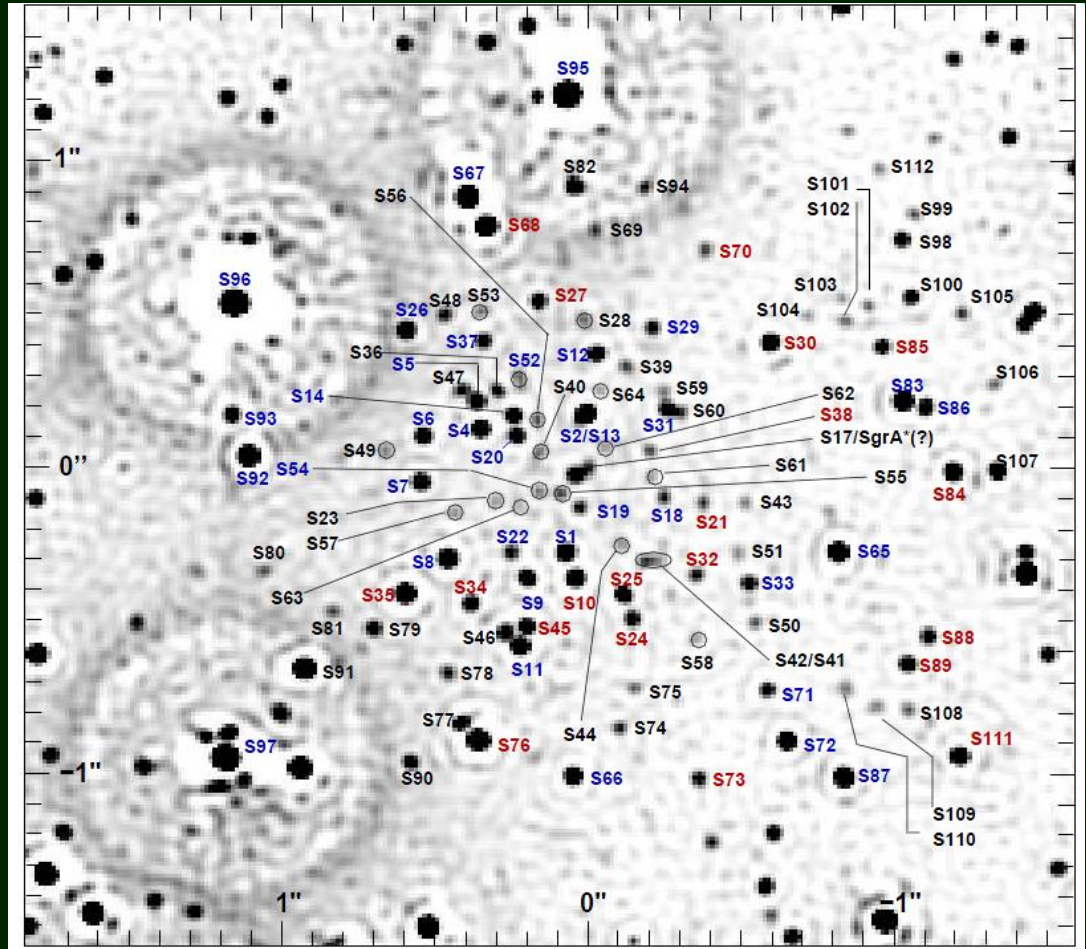


The most certain BH – Sgr A*



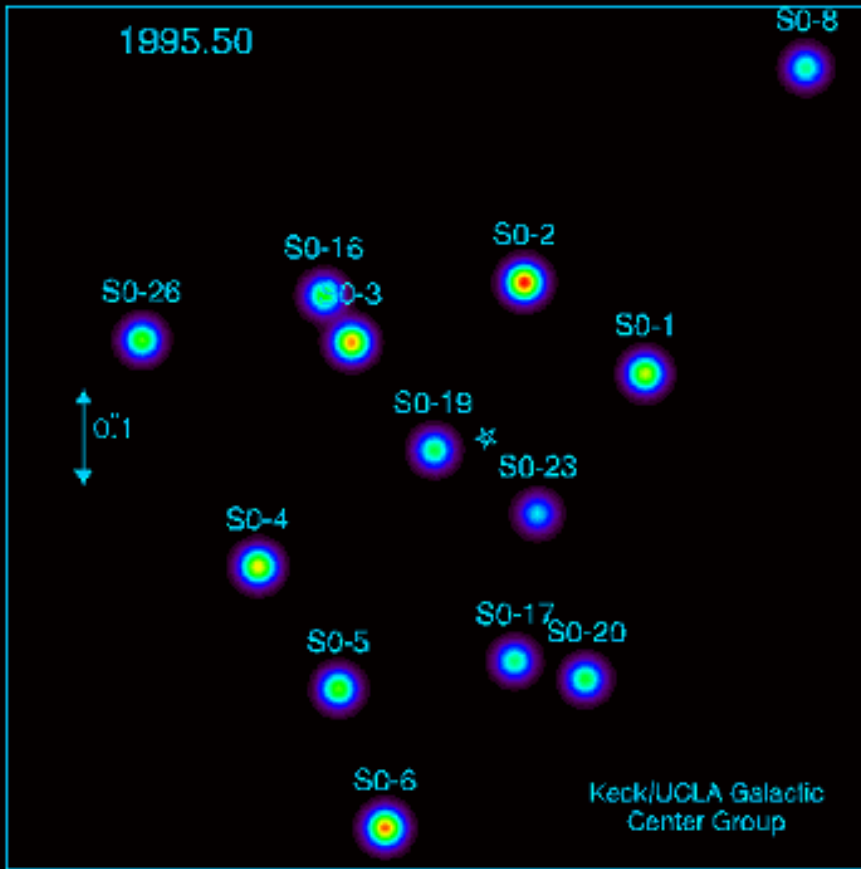
Stellar orbits from 1992 till 2007

(see the reference
in gr-qc/0506078)



arXiv: 0810.4674

... and it becomes more and more certain

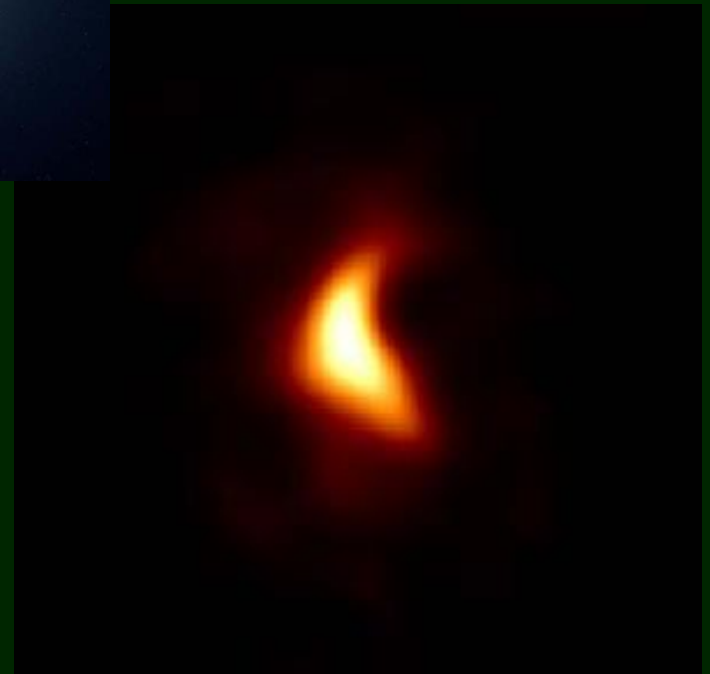
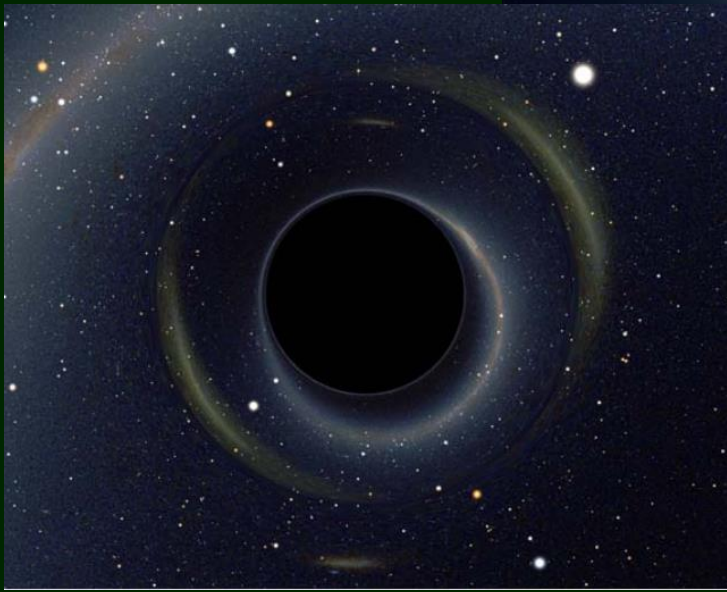
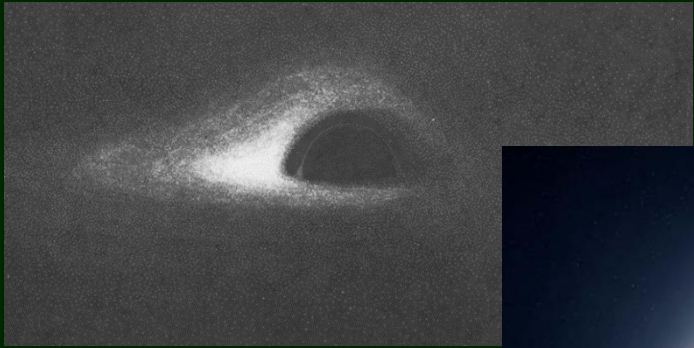


Observations are going on.
So, the number of stars with
well measured orbits grows.

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

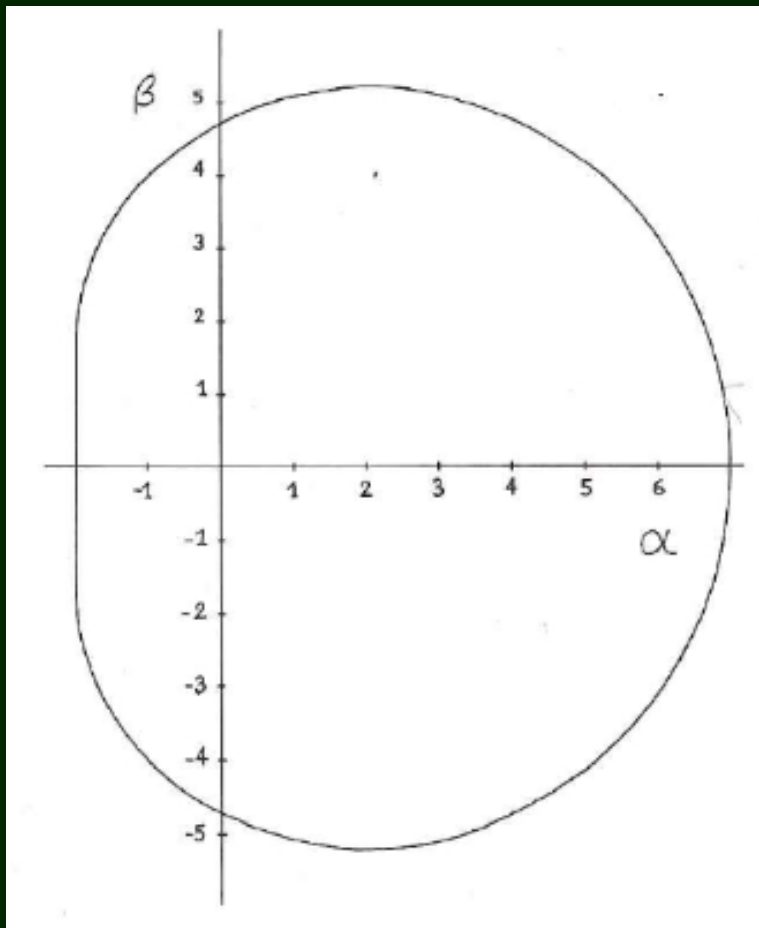
See the reference in [gr-qc/0506078](https://arxiv.org/abs/gr-qc/0506078)
New data in [arXiv: 0810.4674](https://arxiv.org/abs/0810.4674)
Recent review - [1311.1841](https://arxiv.org/abs/1311.1841)

BH visualization



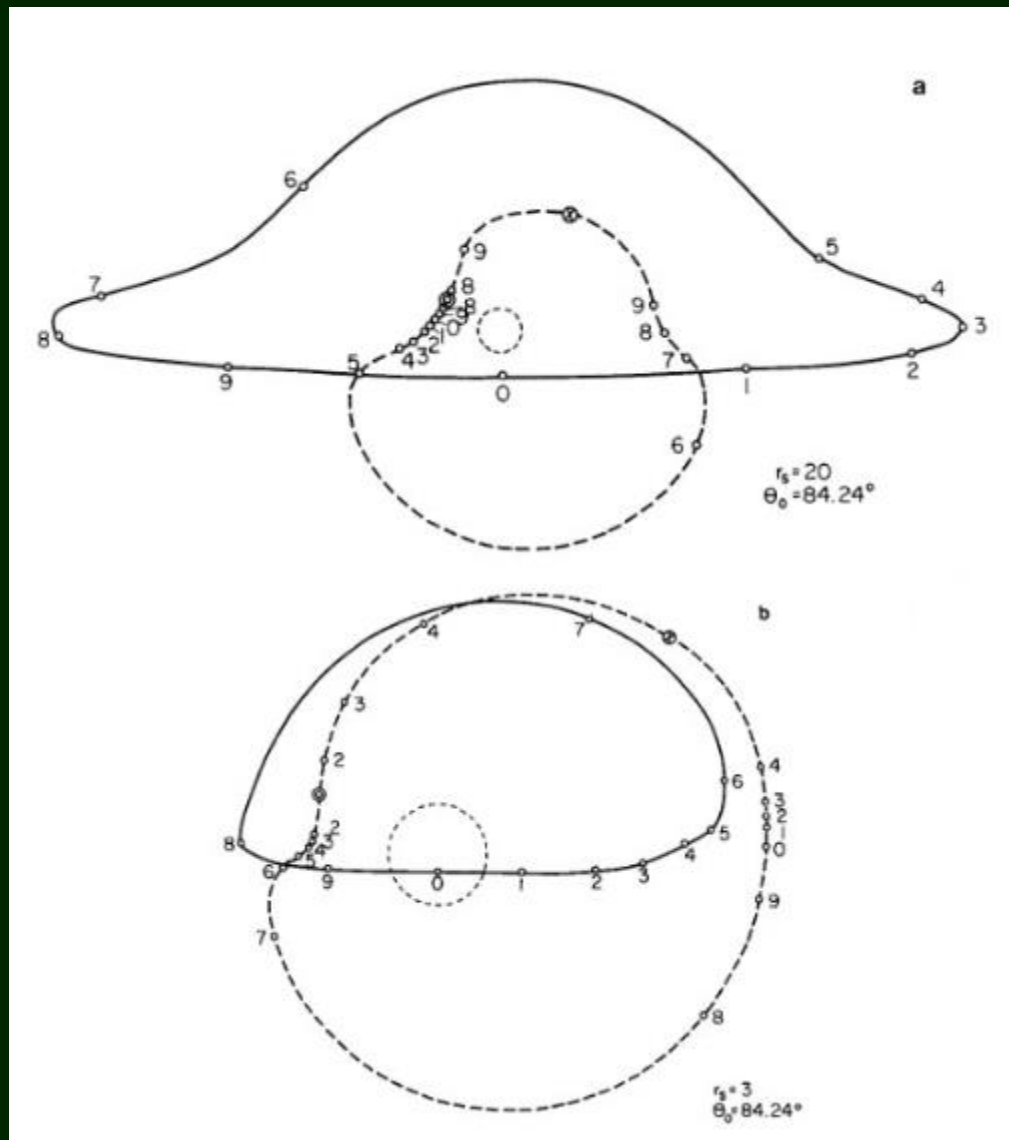
1804.03909, see also 1902.11196

First calculations



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.

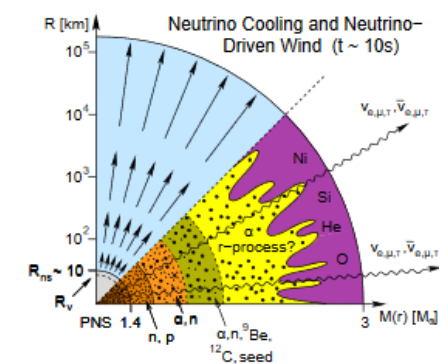
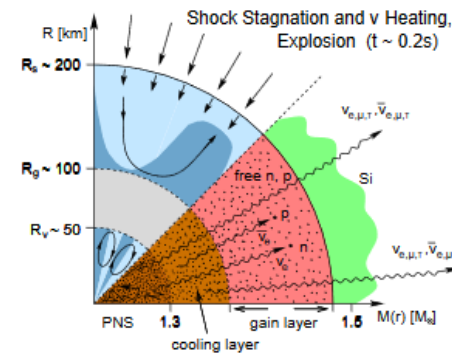
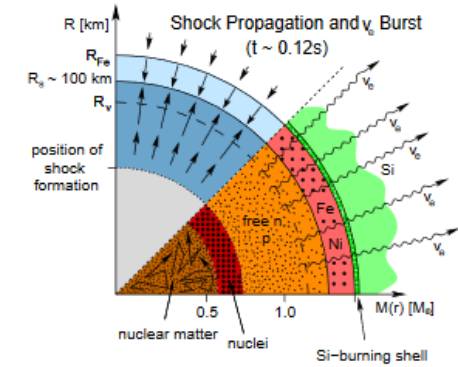
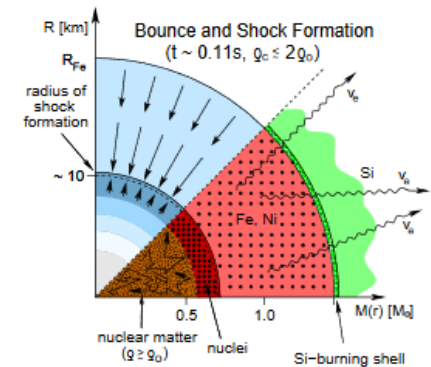
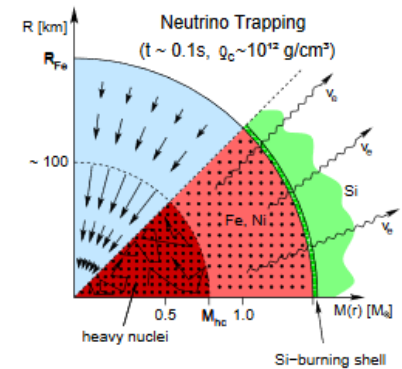
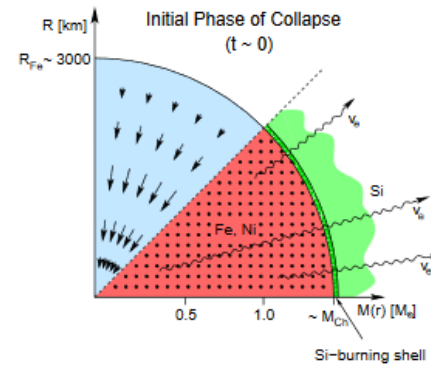
R_{Fe} - iron core radius;

R_s - shock radius;

R_g - gain radius;

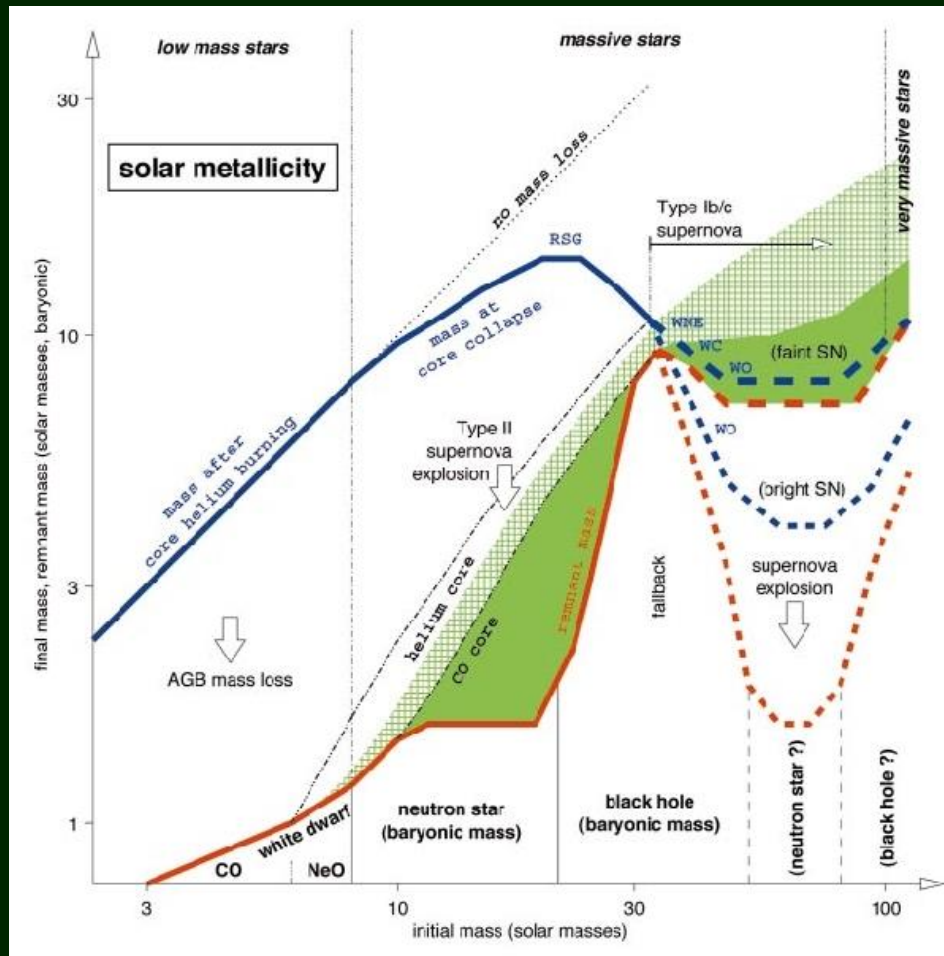
R_{ns} - neutron star radius;

R_v - neutrinosphere.



Stellar mass BHs.

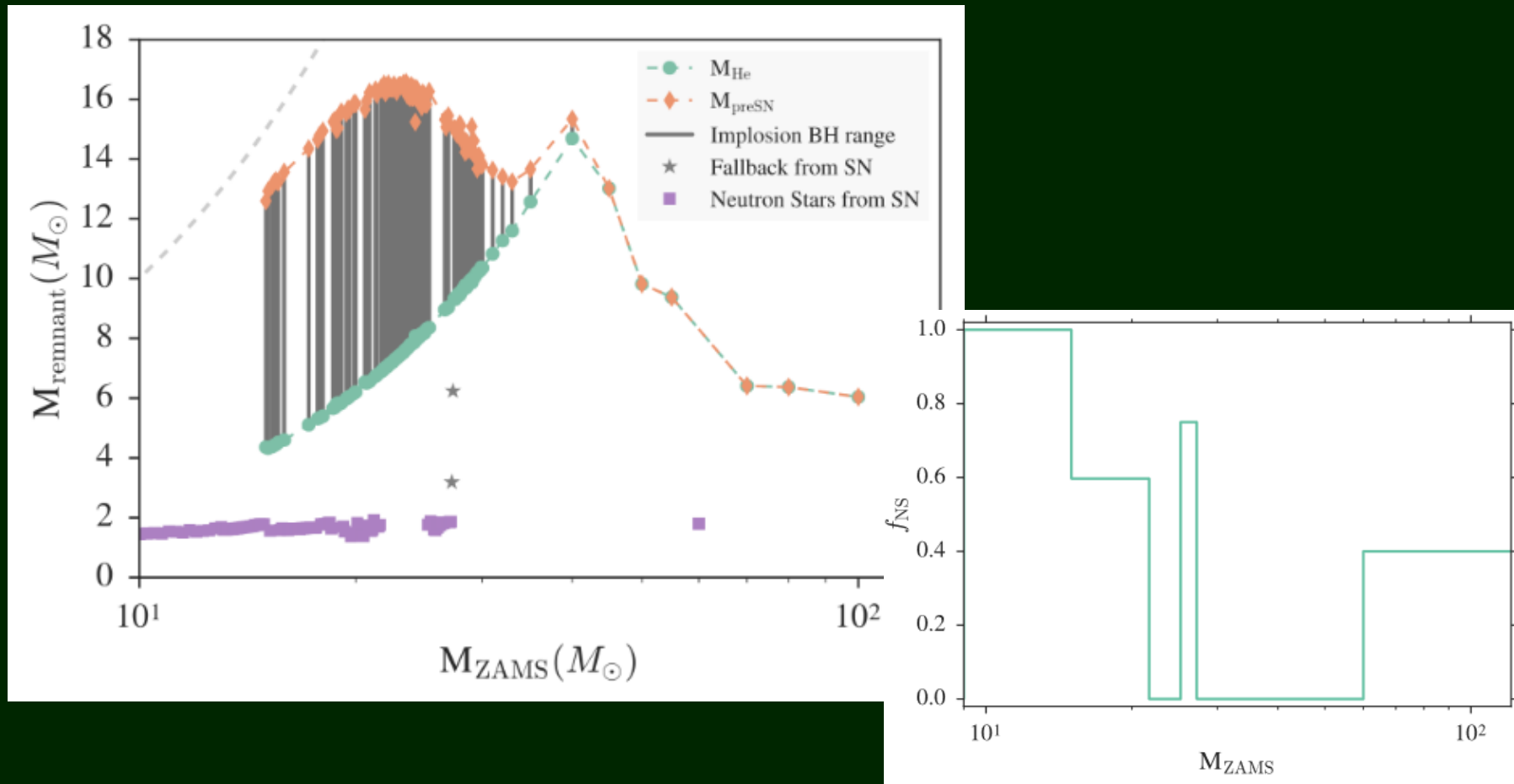
The case of solar metallicity.



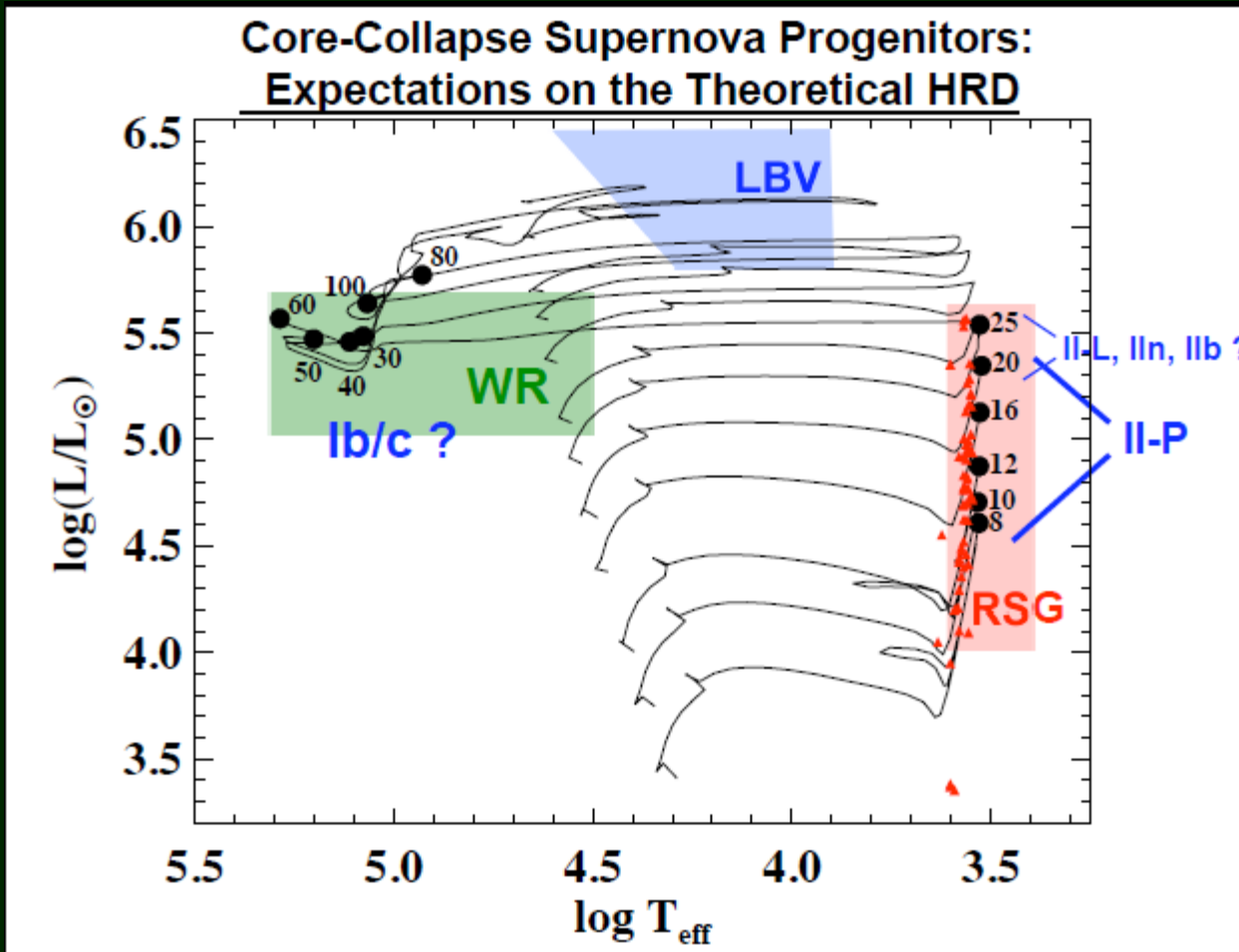
BHs are formed by massive stars. The limiting mass separating BH and NS progenitors is not well known. In addition, there can be a range of masses above this limit in which, again NSs are formed (also, there can be a range in which both types of compact objects form).

See 1011.0203 about progenitors

Initial mass vs. final: ZAMS vs. compact object

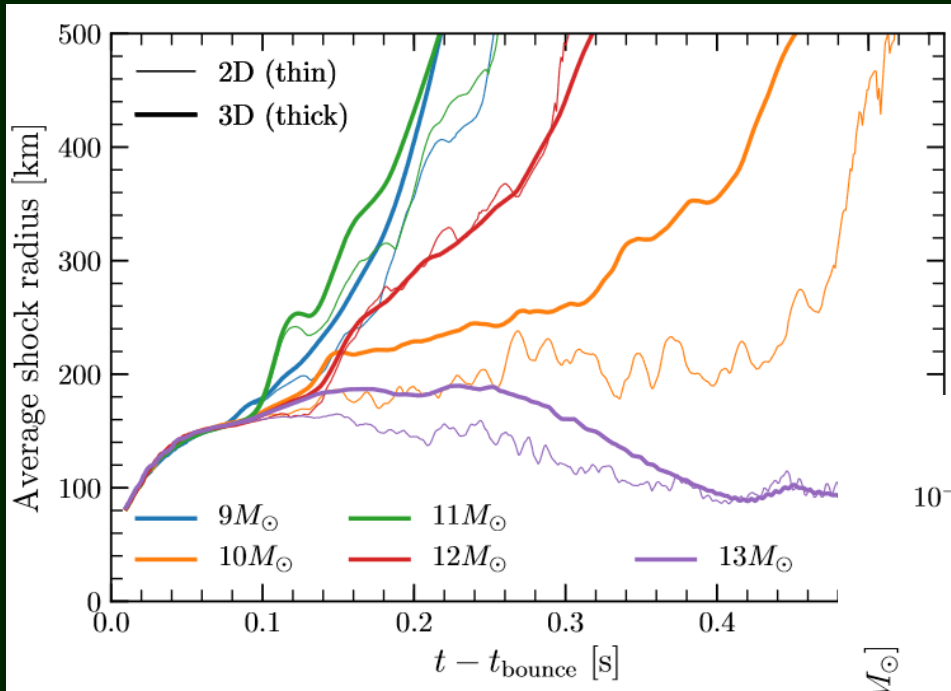


Supernova progenitors

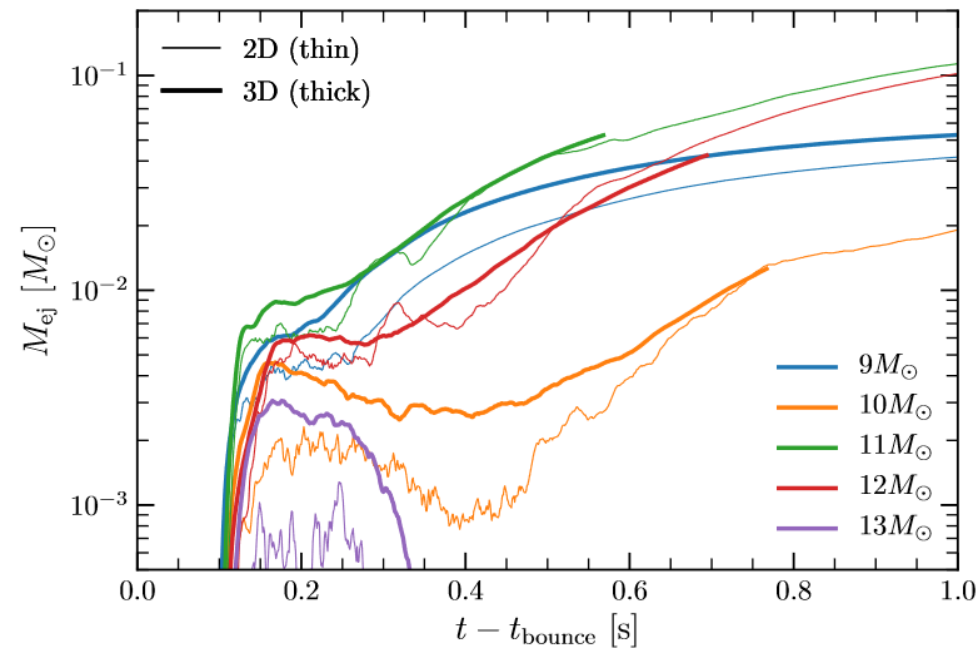


However, there are claims that most of stars $>18M_{\odot}$ produce BHs (see a review in Smartt arXiv: 1504.02635)

No explosions for 13 solar mass?



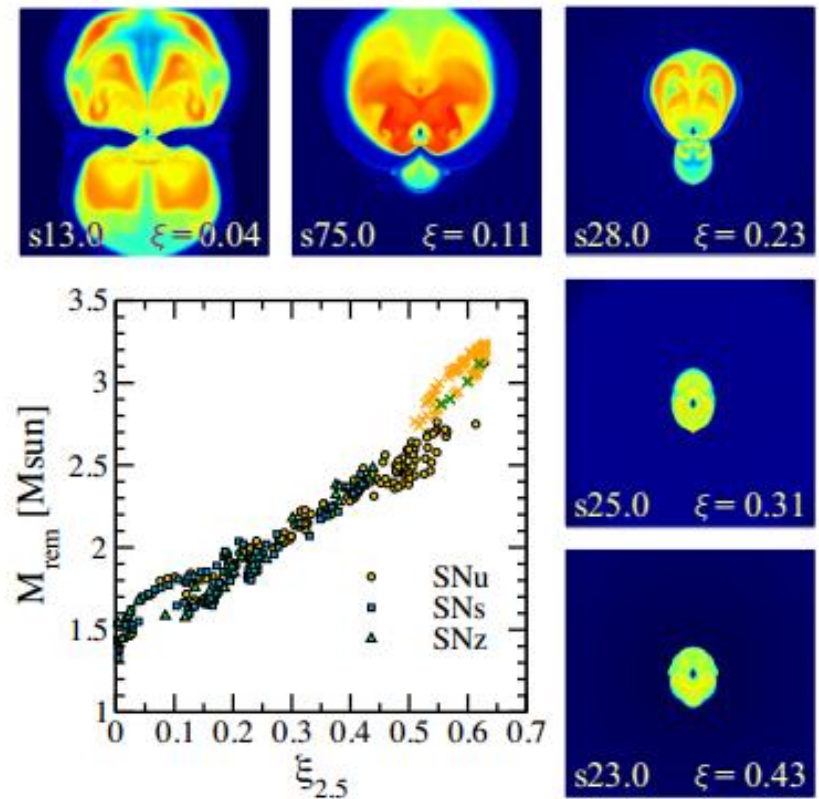
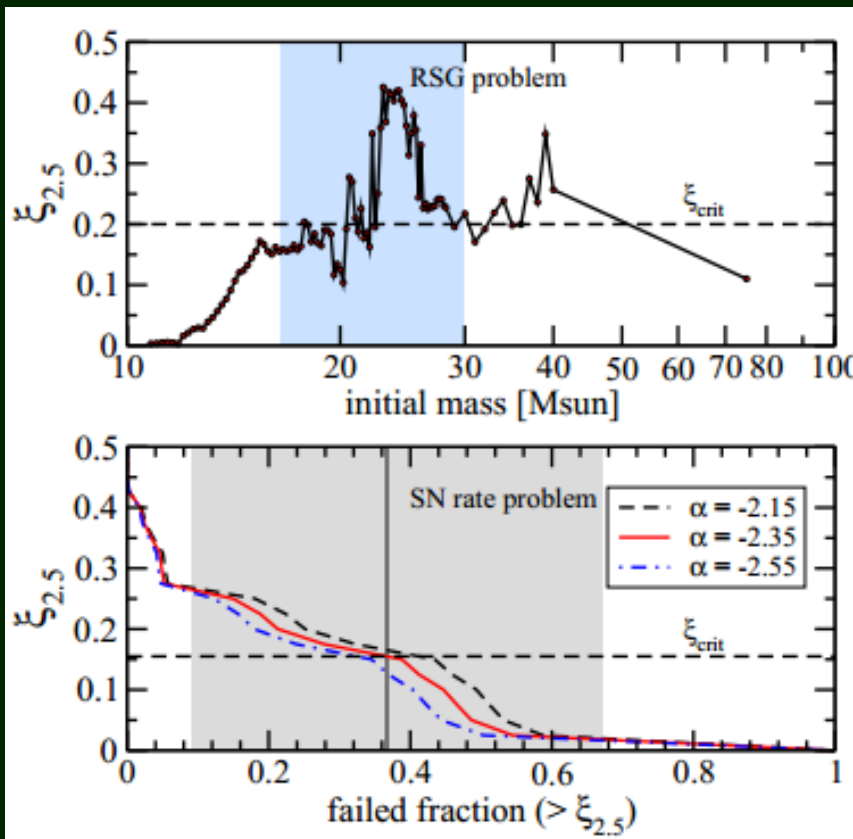
Probably non-rotating progenitors with $12 < M < 14$ solar mass do not explode.



Which stars form BHs?

It is proposed that stars with compact internal structure ($M \sim 20\text{-}30 M_{\text{solar}}$) form BHs not NSs. This explains data on RGs and the SN rate.

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

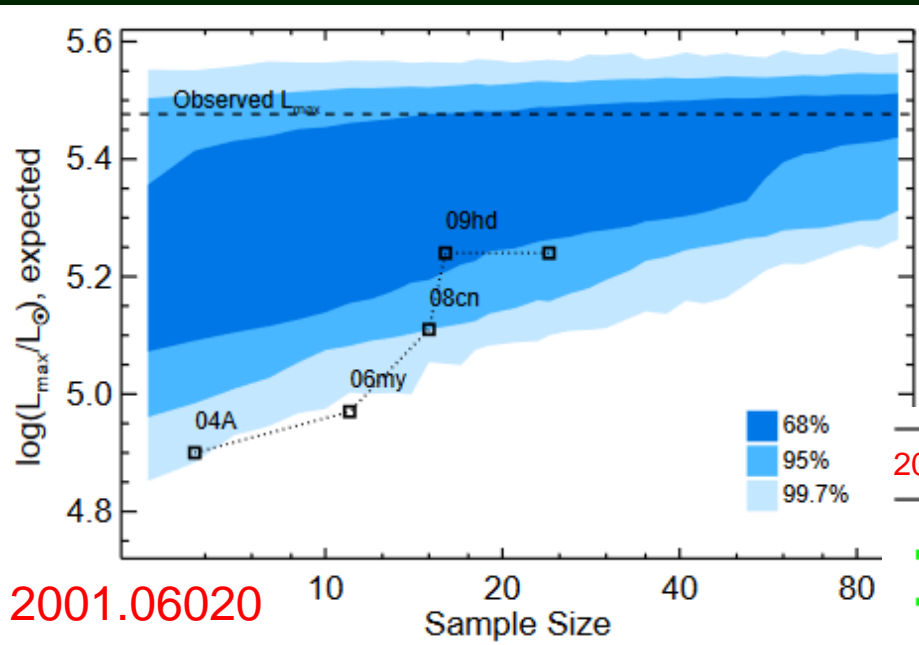


Red supergiants problem: discussion

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 $M > M_h$

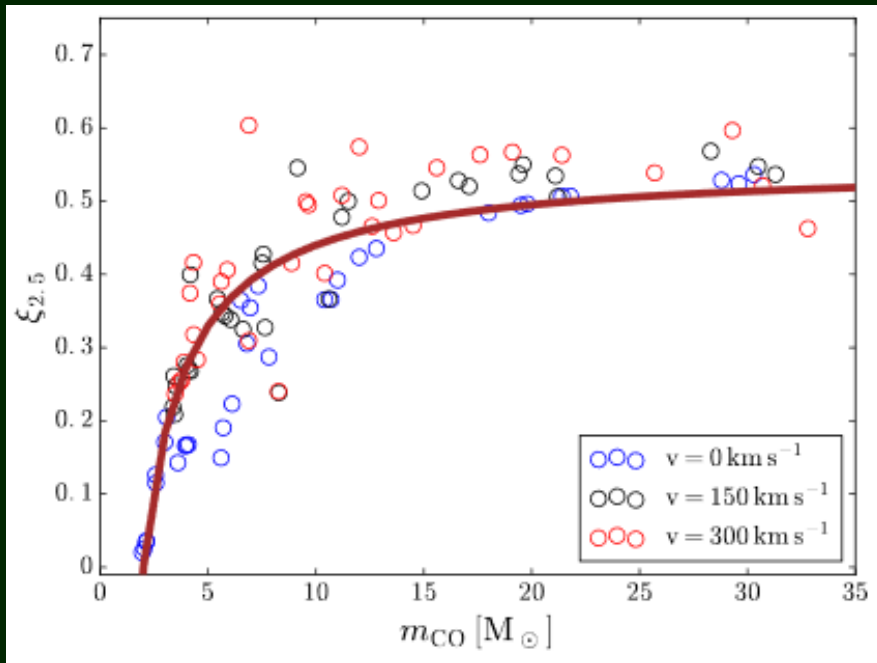


| 2001.07216 Model | $M(L)$ | M_l/M_\odot | M_h/M_\odot |
|-----------------------------------|--------|------------------------|-------------------------|
| <u>Smartt (2015)</u> | ET04 | $9.5^{+0.5}_{-2.0}$ | $16.5^{+2.5}_{-2.5}$ |
| <u>Davies & Beasor (2018)</u> | ET04 | $7.5^{+0.3}_{-0.2}$ | $19.0^{+2.5}_{-1.3}$ |
| Davies | ET04 | $7.49^{+0.25}_{-0.27}$ | $19.05^{+2.22}_{-1.30}$ |
| Bayes | ET04 | $6.30^{+0.48}_{-0.54}$ | $19.01^{+4.04}_{-2.04}$ |
| <u>Smartt (2015)</u> | 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

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

$$\xi_{2.5} = a + b \left(\frac{m_{\text{CO}}}{1 M_\odot} \right)^c$$



v – initial equatorial rotational velocity

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

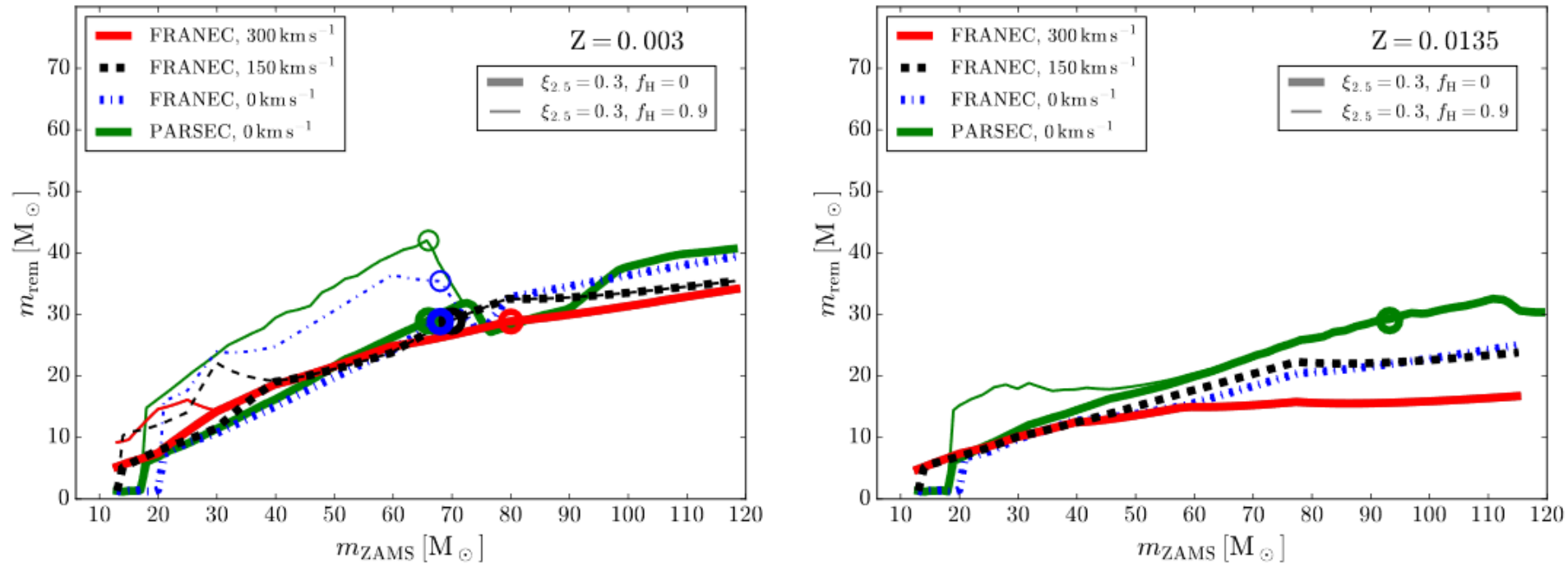
$$m_{\text{BH}} = m_{\text{He}} + f_{\text{H}} (m_{\text{fin}} - m_{\text{He}})$$

f_{H} is a parameter: from 0 to 0.9

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

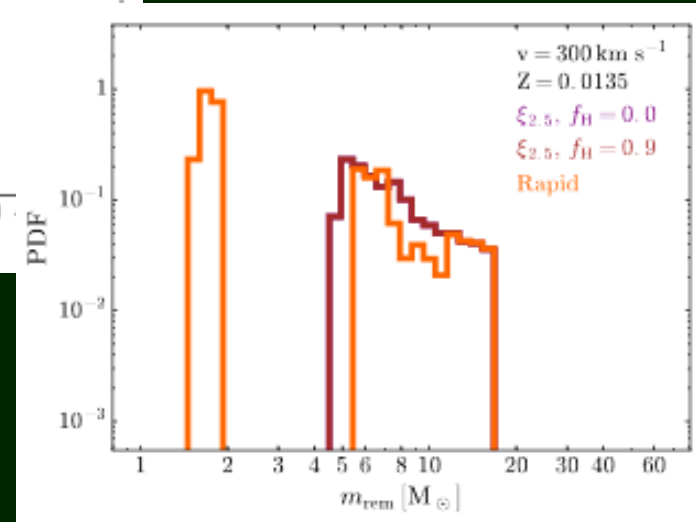
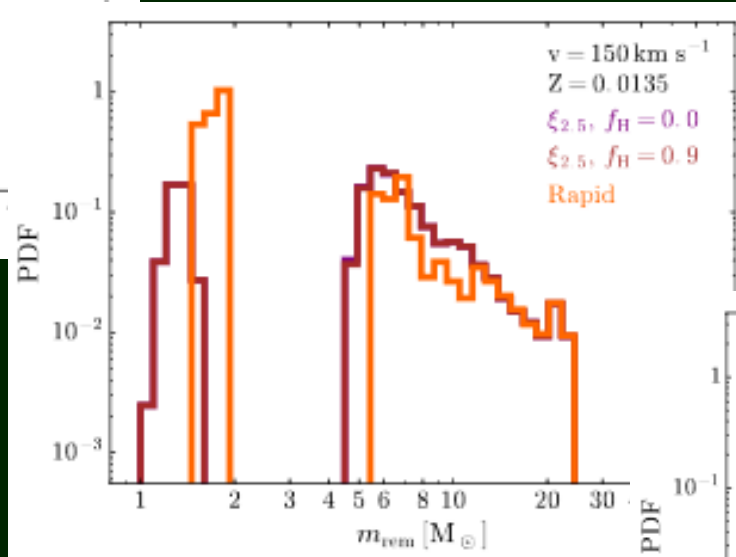
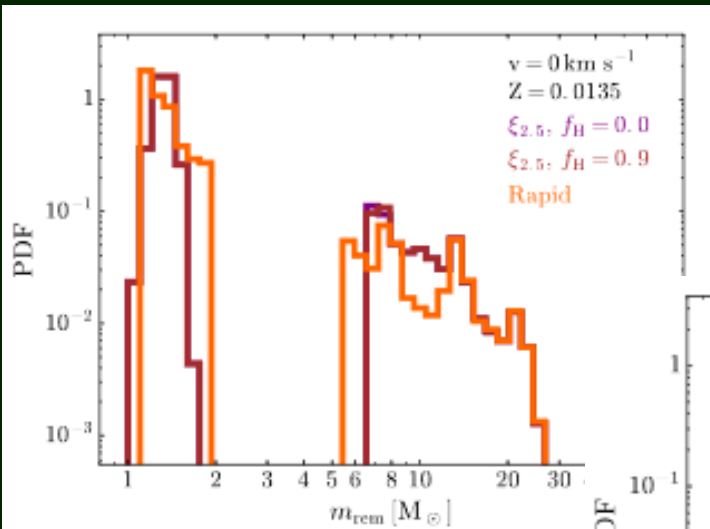
$$135 \geq m_{\text{He}}/M_\odot \geq 64,$$

Compact objects masses: effects of rotation and metallicity



Mass distribution

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



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.

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

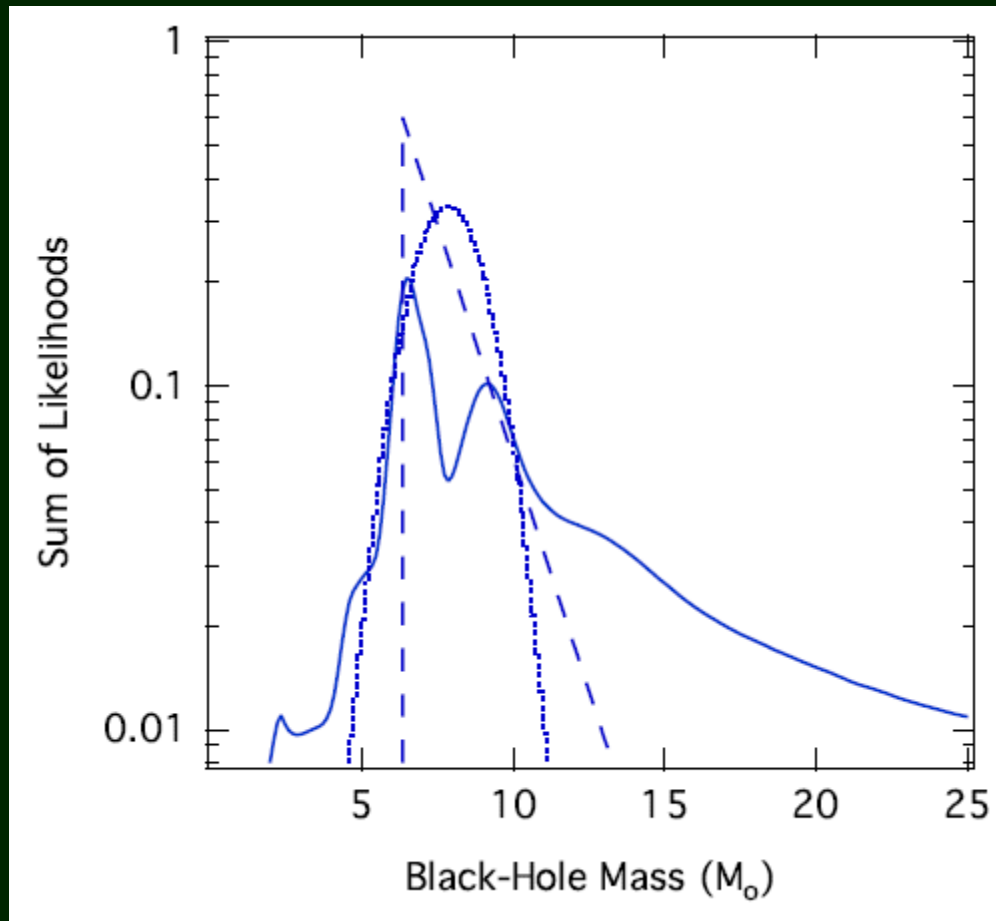
$$j_{\text{rand}} \sim \frac{H v_c}{\sqrt{4\pi}} \sim 6 \times 10^{17} \frac{r v_c}{10^3 R_\odot \text{ km s}^{-1}} \left(\frac{H/r}{0.3} \right) \text{ cm}^2 \text{ s}^{-1}$$

v_c (~ 10 km/s) –
convective velocity

v_h – horizontal velocity

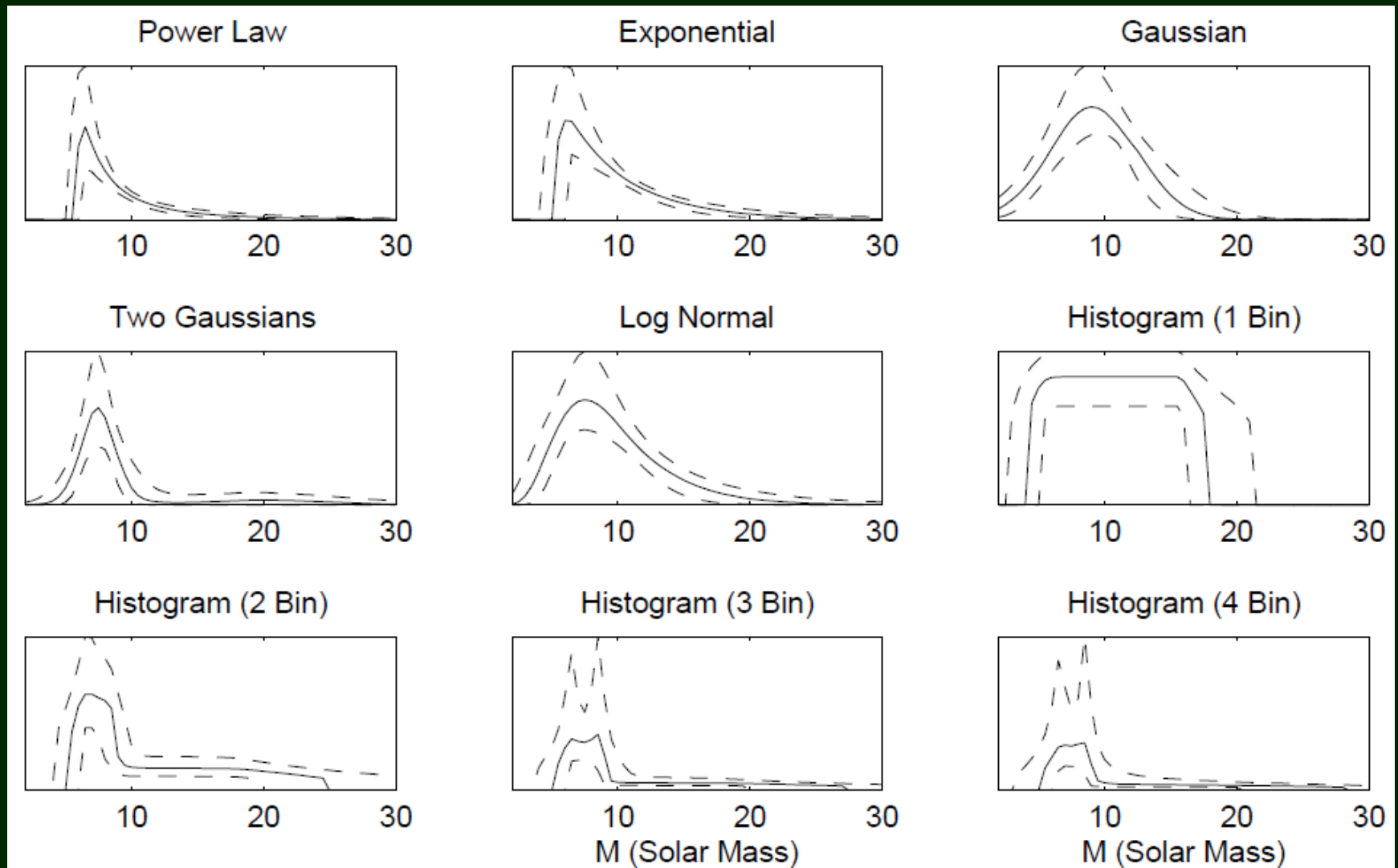
$$j_{\text{ISCO}} = 1.15 - 3.5 \frac{GM}{c} \sim 0.5 - 1.5 \times 10^{17} \left(\frac{M}{10 M_\odot} \right) \text{ cm}^2 \text{ s}^{-1}$$

BH mass function

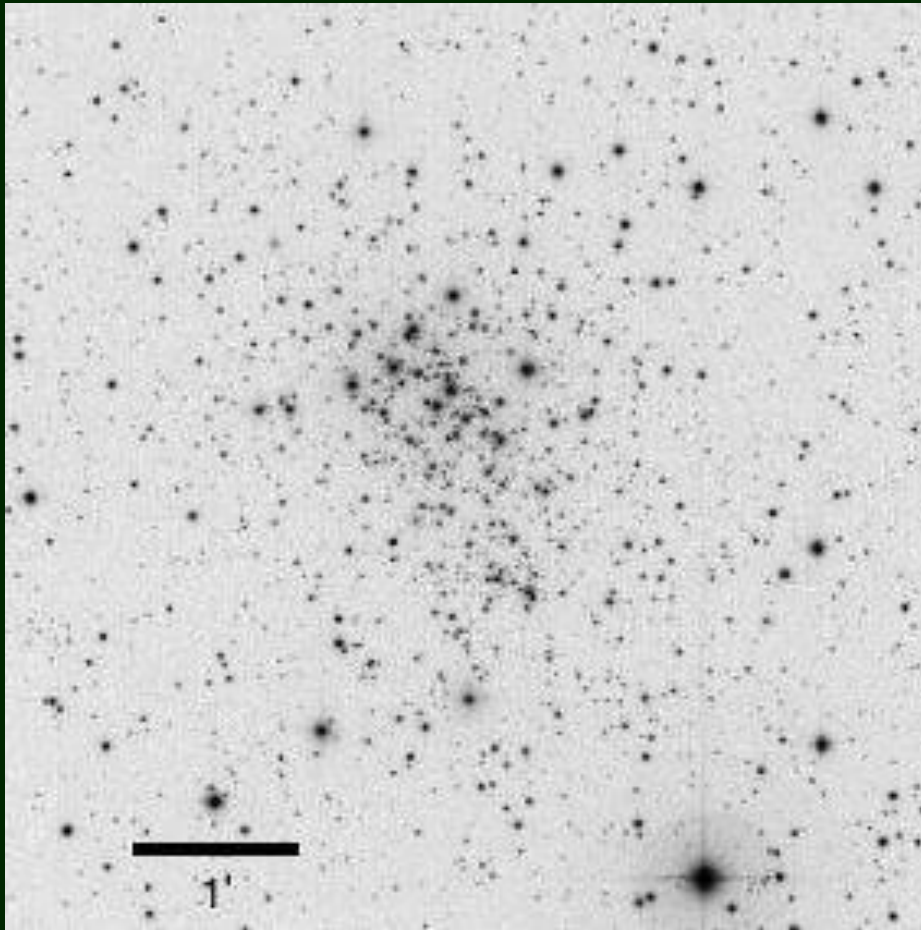


Likelihood based on 16 systems

BH mass distribution



A NS from a massive progenitor

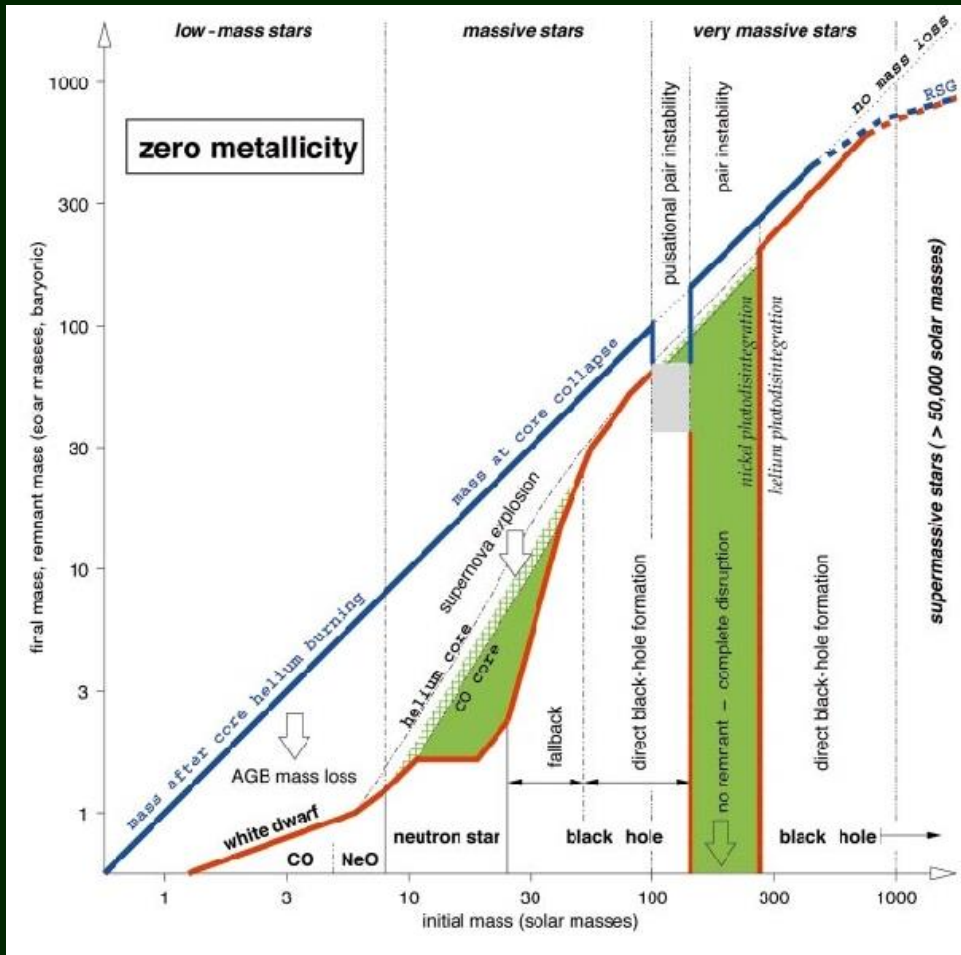


Anomalous X-ray pulsar in the cluster Westerlund1 most probably has a very massive progenitor, $>40 M_{\odot}$.

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

Stellar mass BHs.

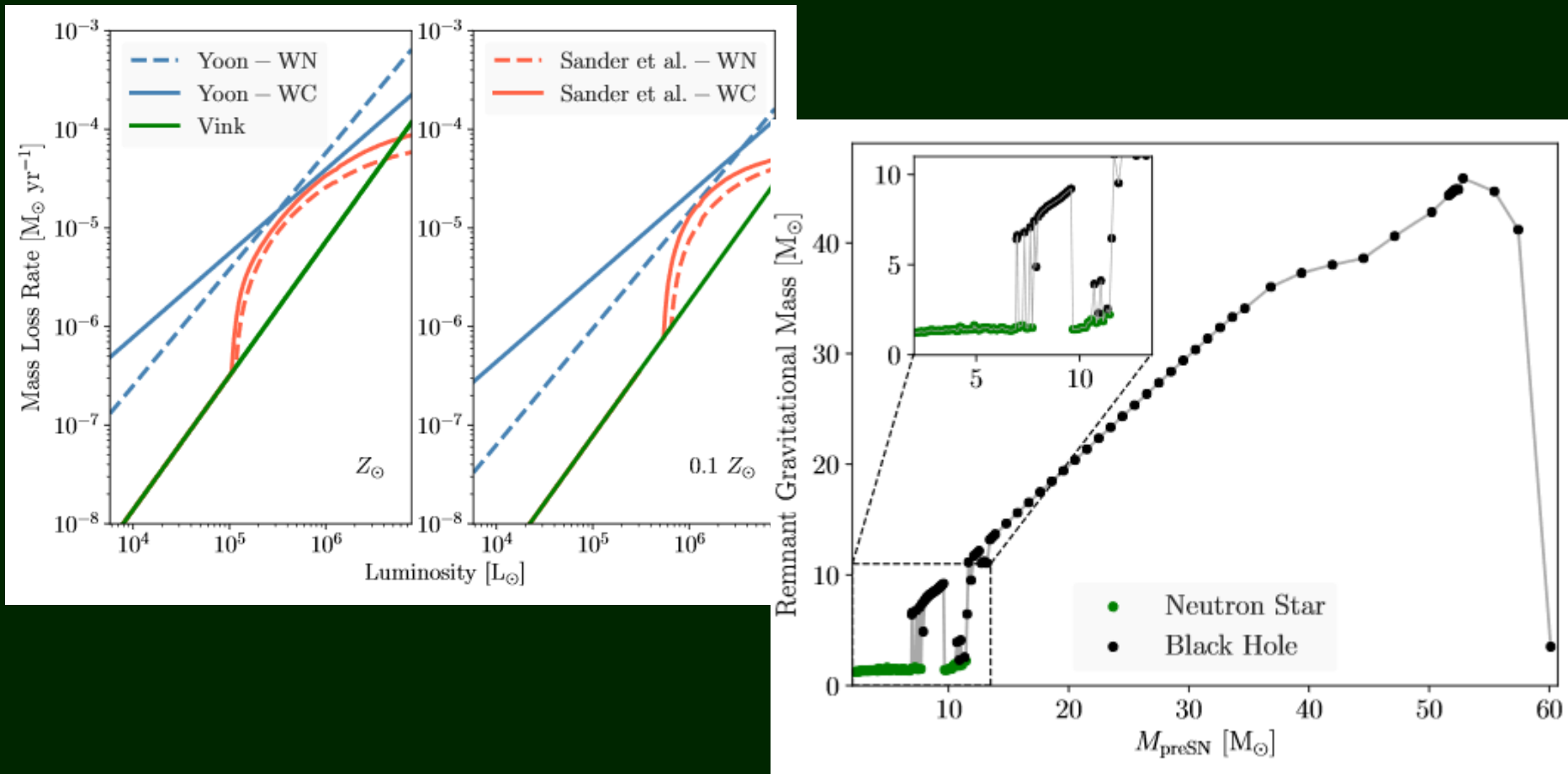
The case of zero metallicity



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

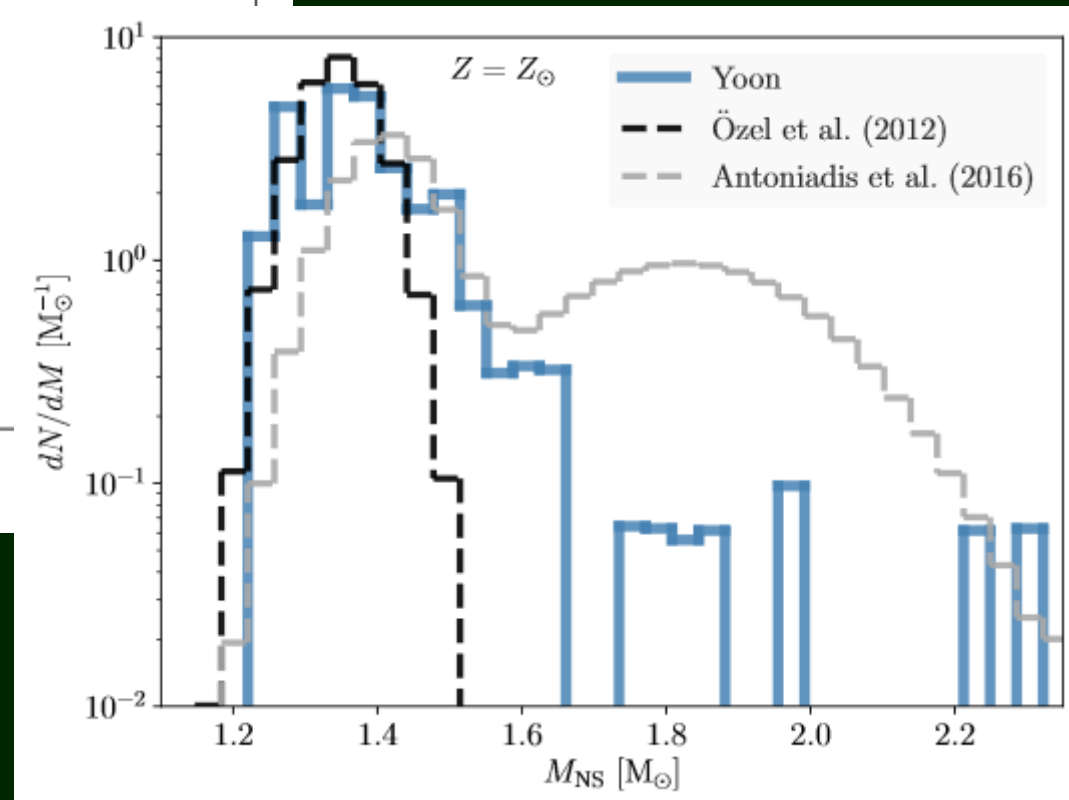
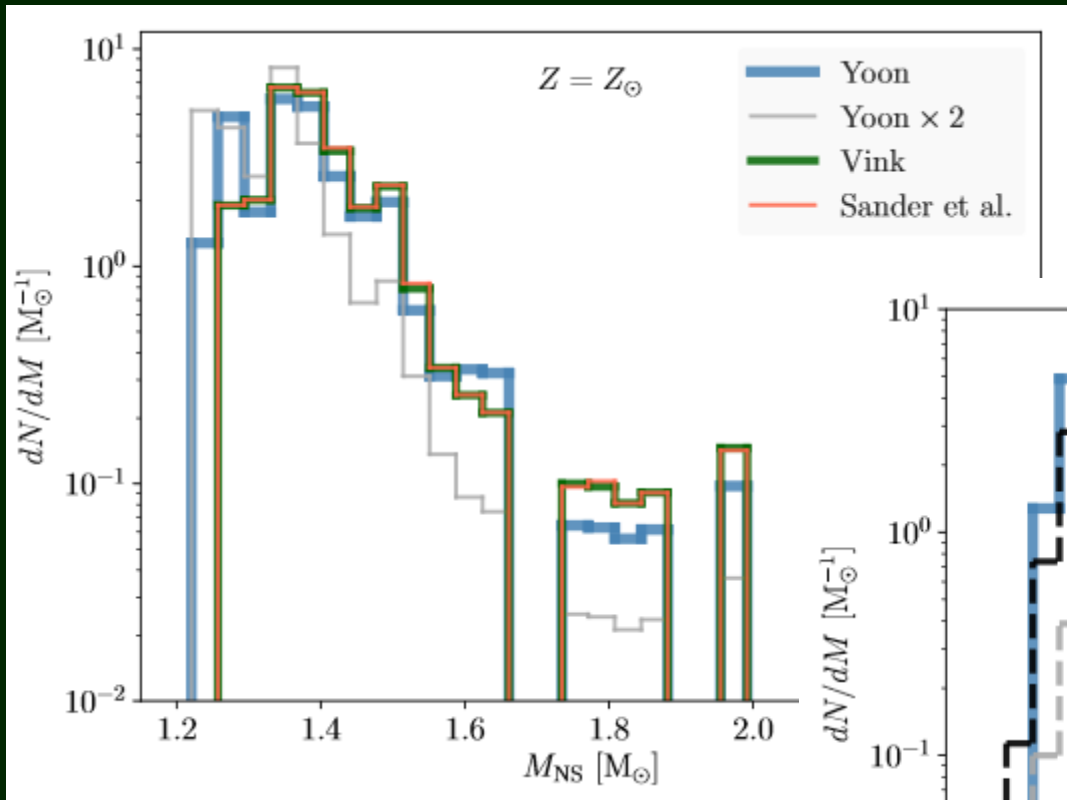
Mass function of NS and BH in binaries

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.

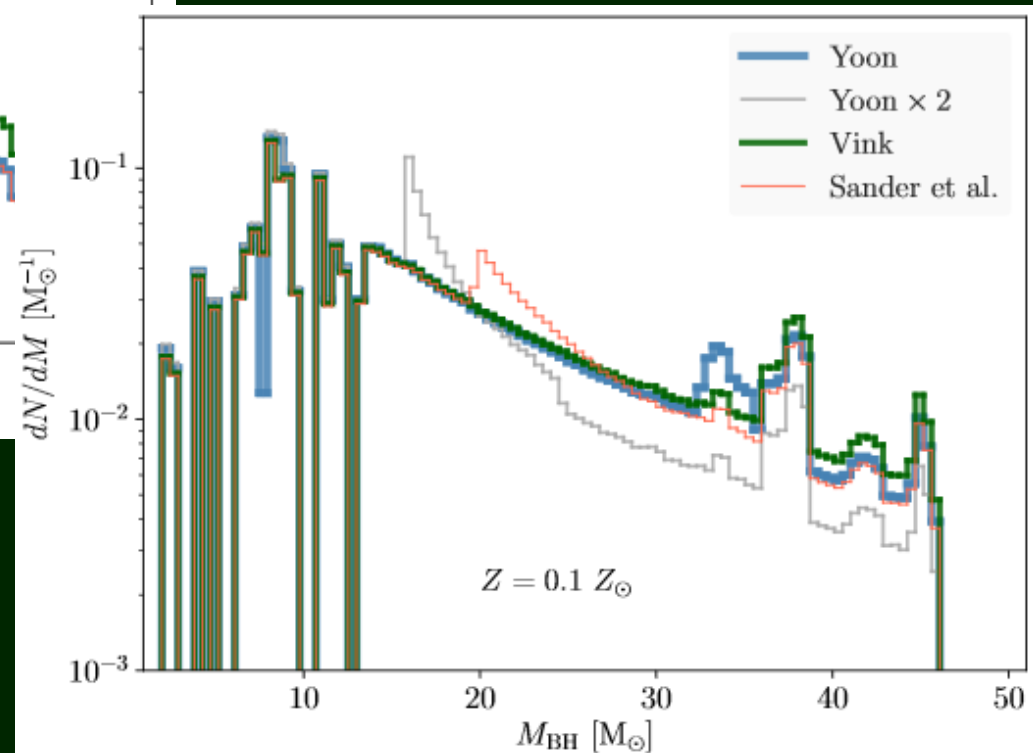
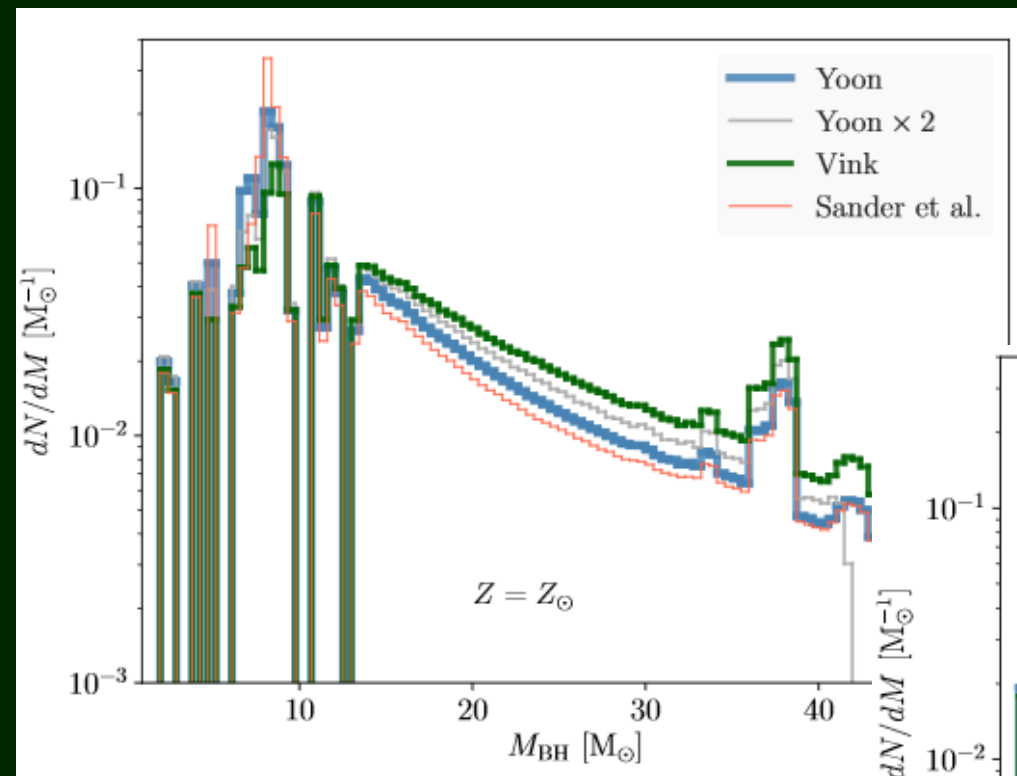


Neutron stars

Salpeter stellar mass function.



Black holes



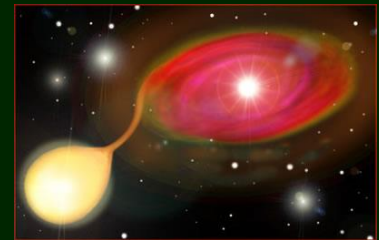
BHs and NSs in close binary systems

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.

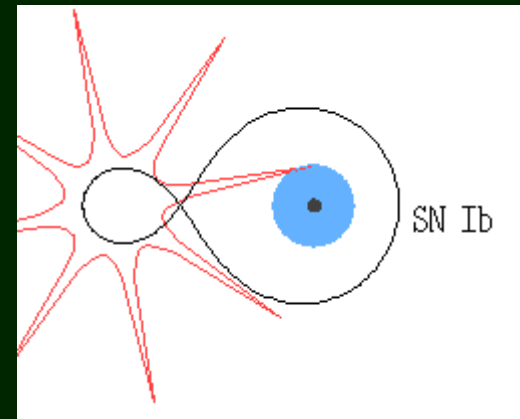
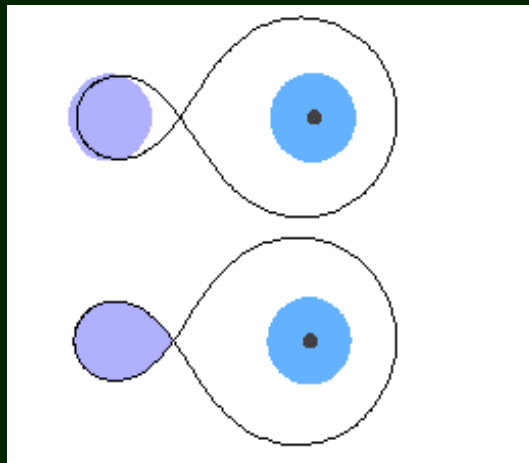
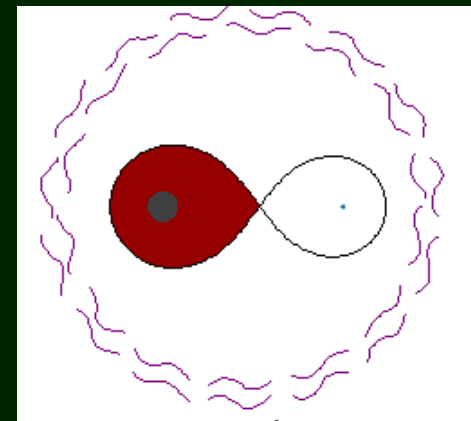
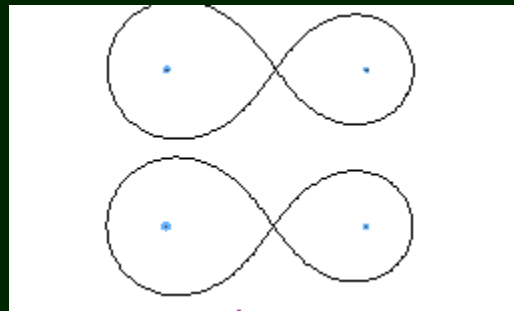
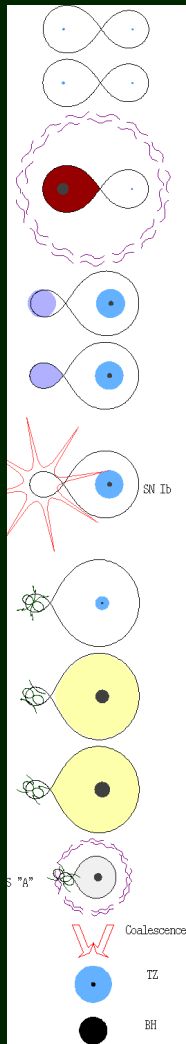
Finally, for the BH system LMC X-3 the mass of the progenitor is estimated as >60 solar masses.

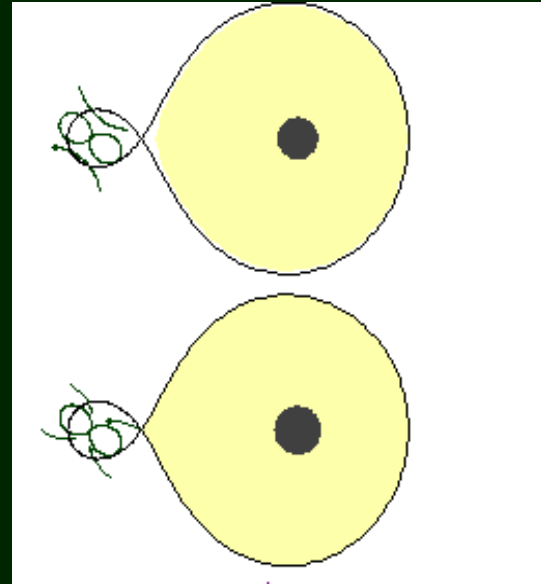
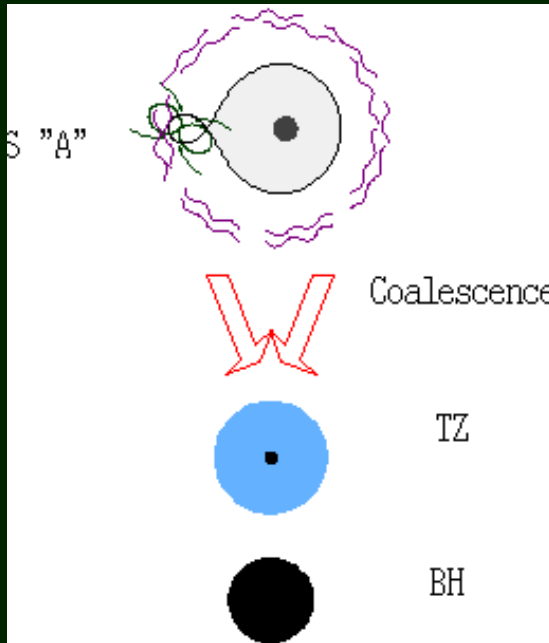
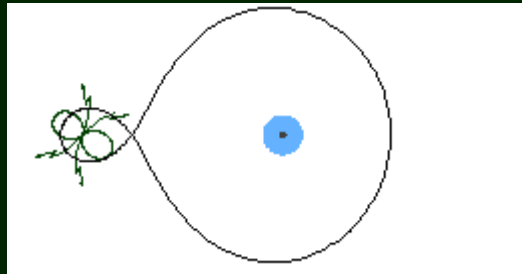
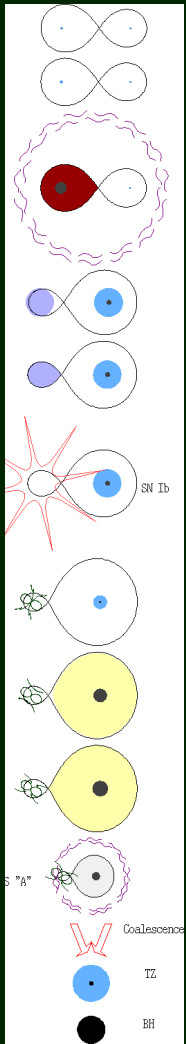
So, the situation is rather complicated. Most probably, in some range of masses, at least in binary systems, both variants are possible.



Binary evolution

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





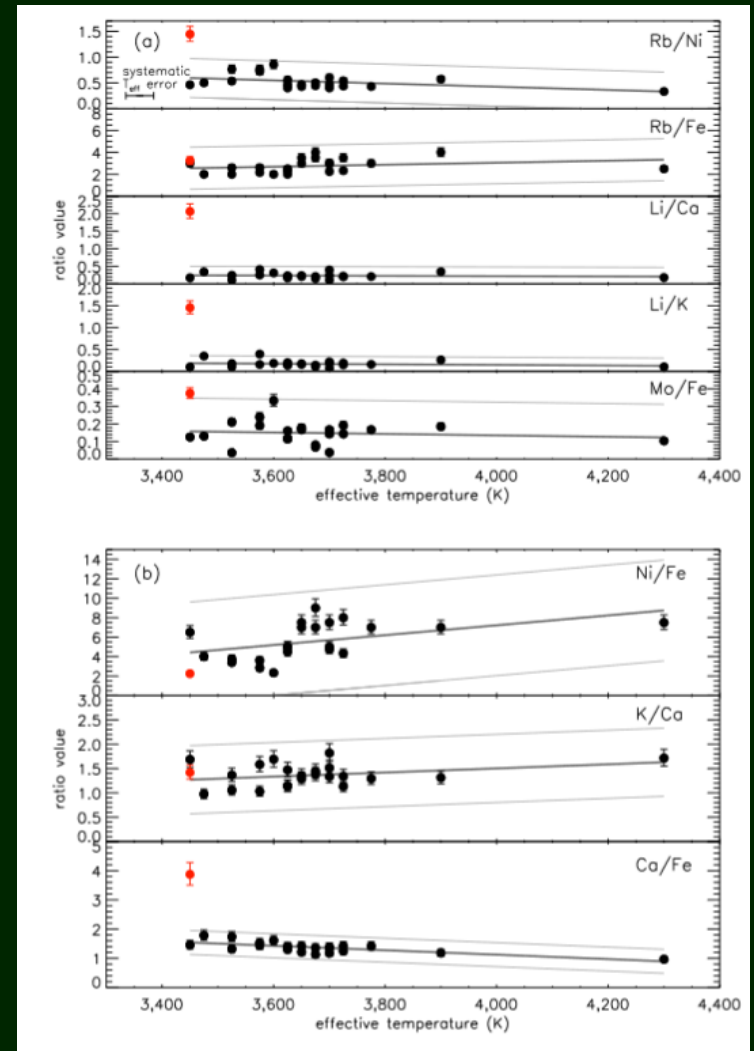
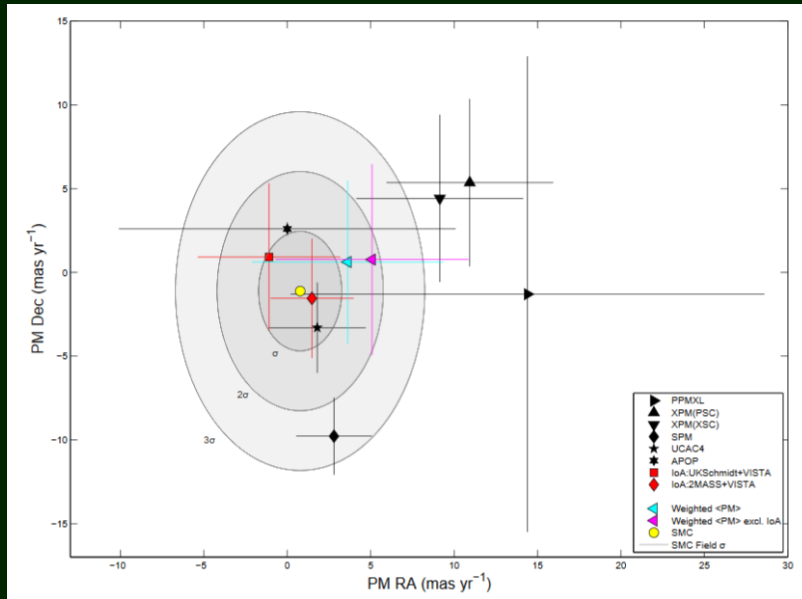
“Scenario machine” calculations

Thorne-Zytzkow candidates

Chemical composition anomalies.









Discussion:

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



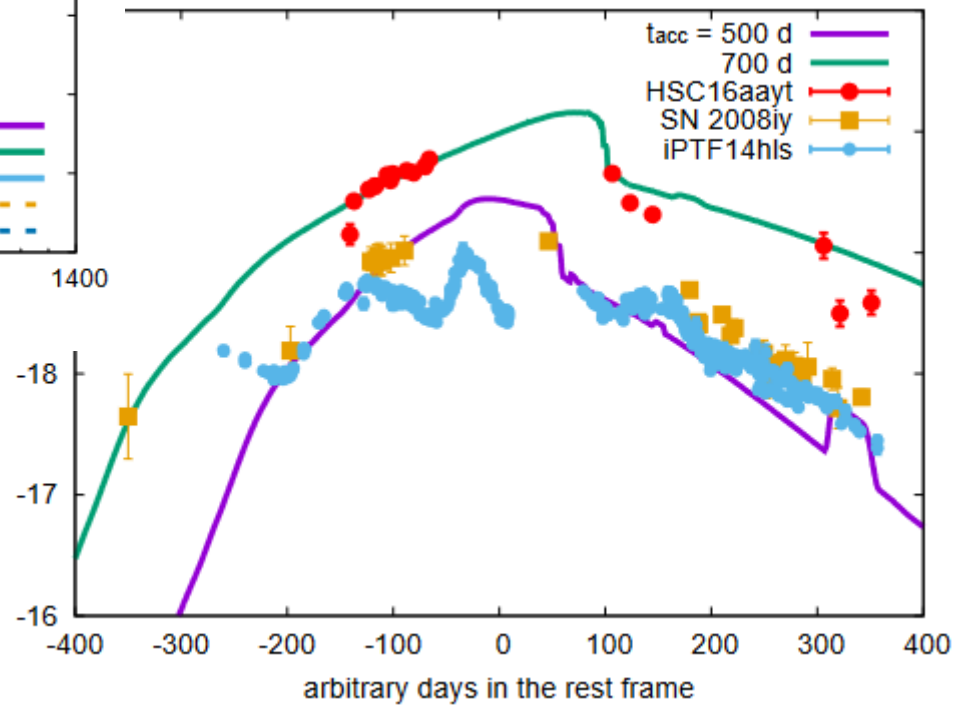
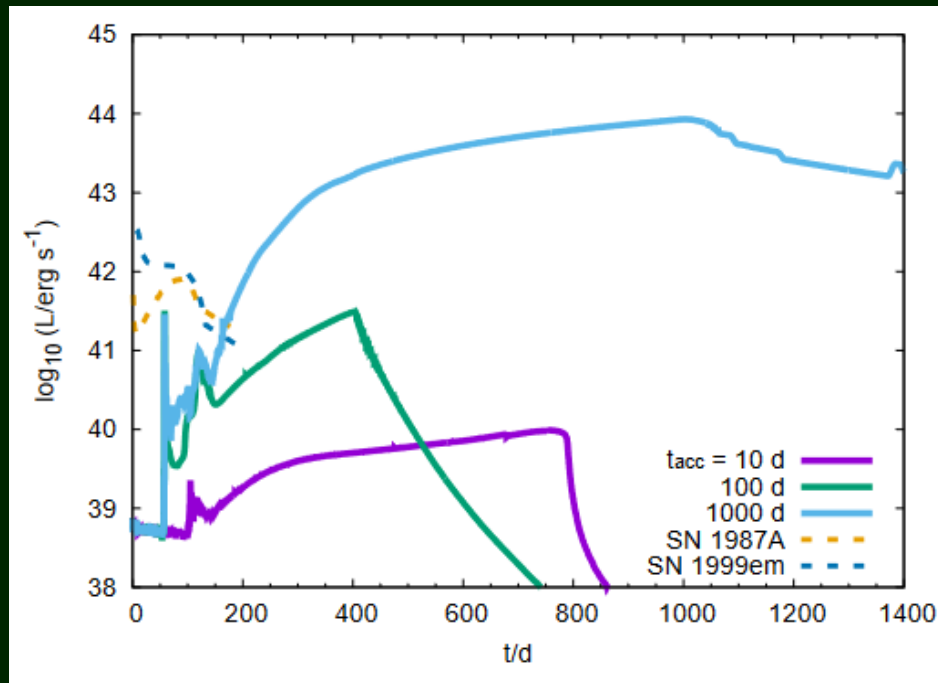
1406.0001

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 |
| CMIC from a 1.31Msun ONeMg WD and a ~3.33Msun He core inside CE | | |  | Possibly a newborn Pulsar or a newborn Magnetar or TZO | | |

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

TZO can produce peculiar explosions

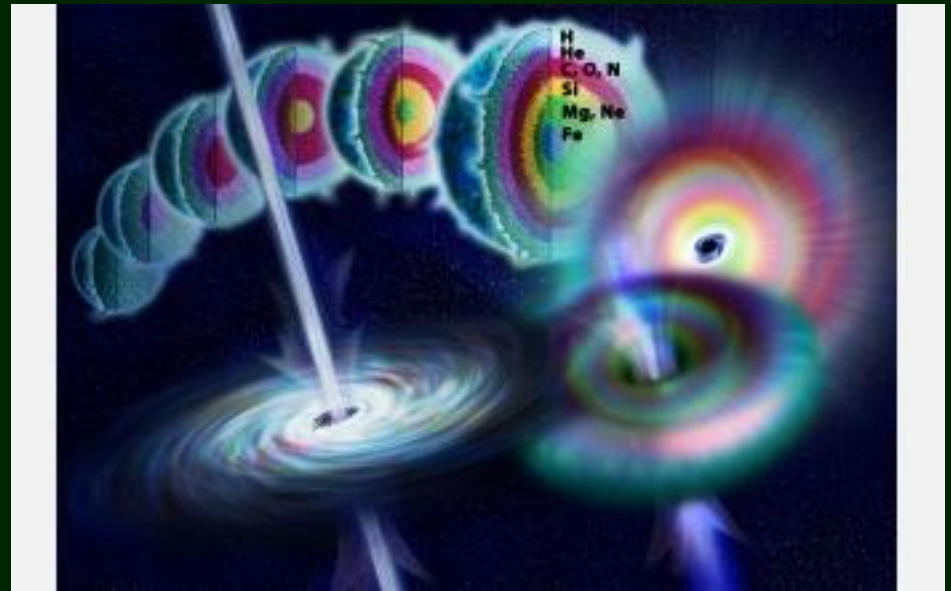


GRBs and BHs

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](https://arxiv.org/abs/1302.6461)



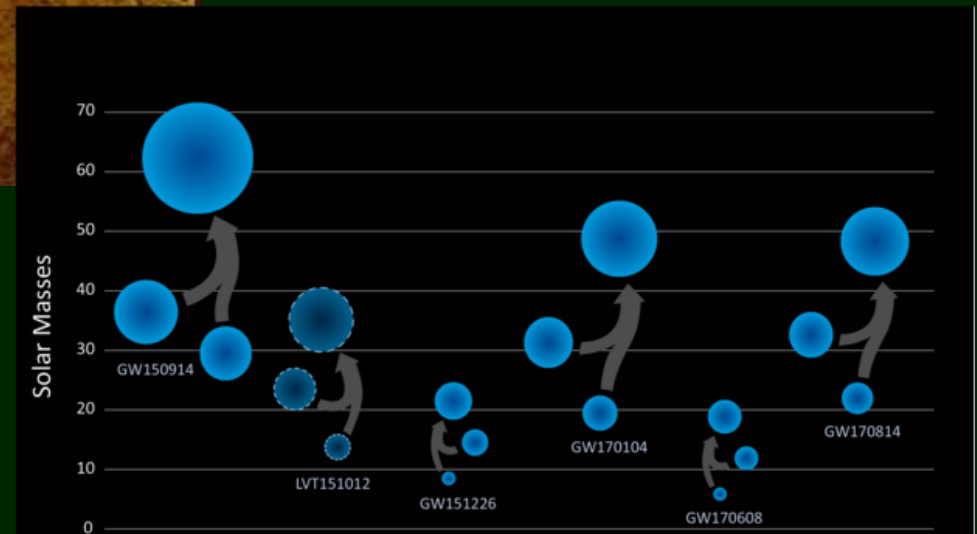
BHs from GW signals



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.

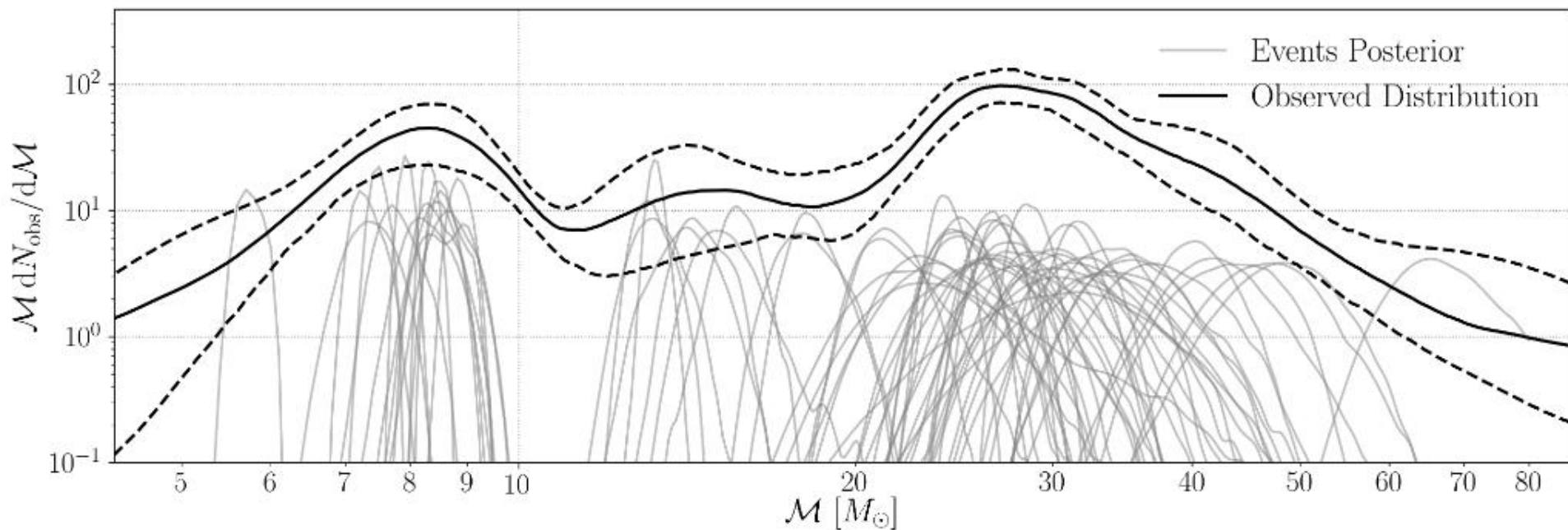
GW190814: 23+2.6 solar masses.
Two BHs or BH+NS?
See 2006.12611.



GWTC-3 catalogue

Chirp mass distribution

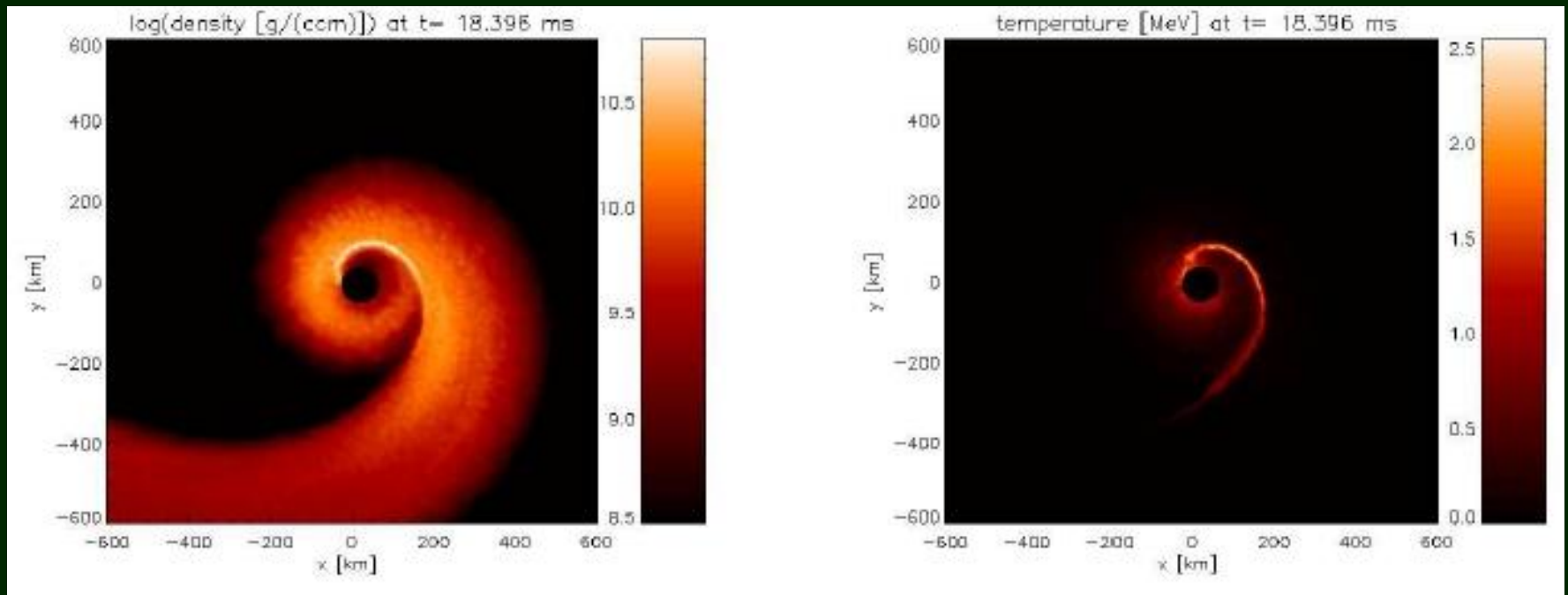
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$



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.



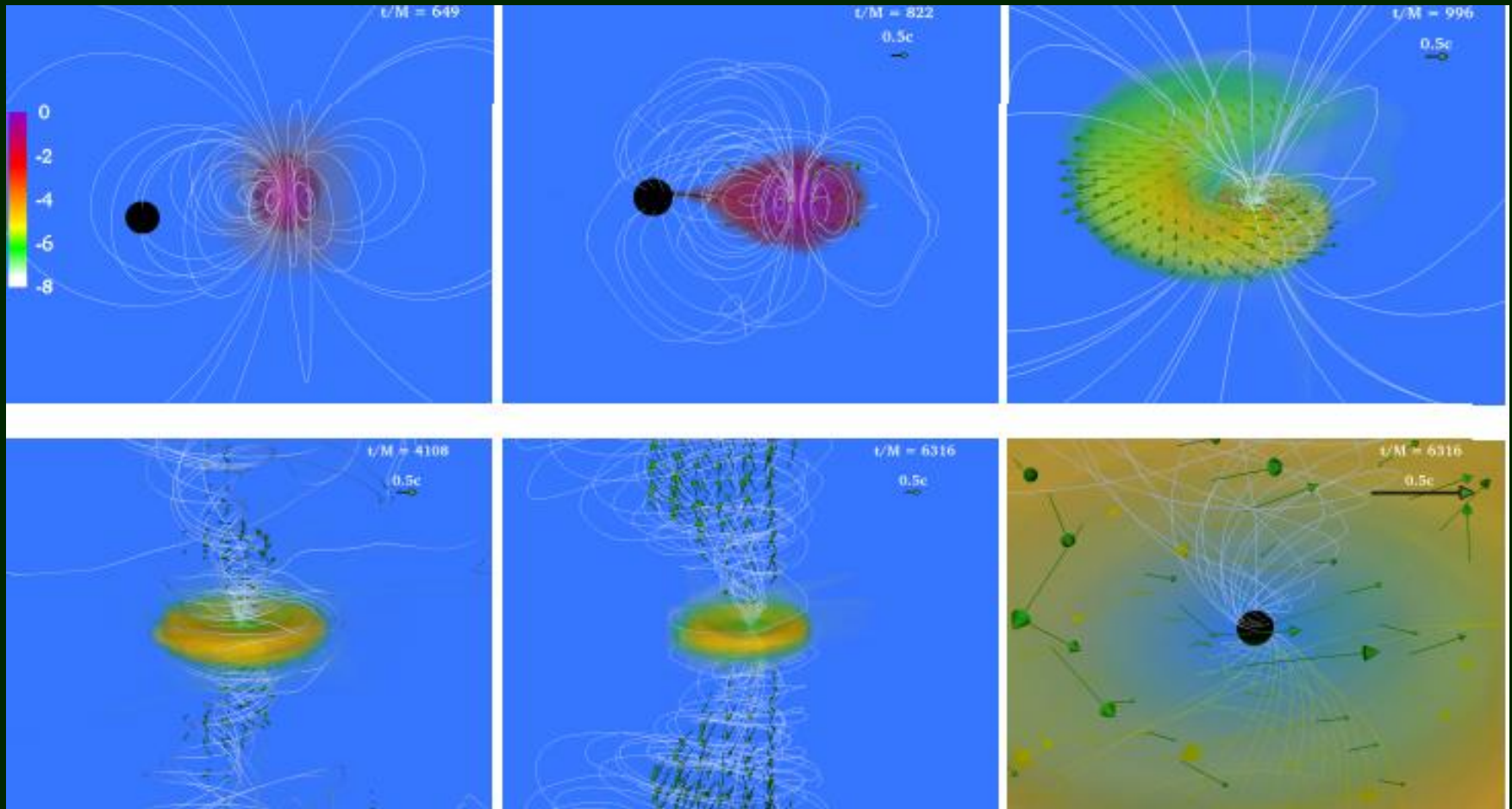
BH-NS mergers are still a popular subject of studies:

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.

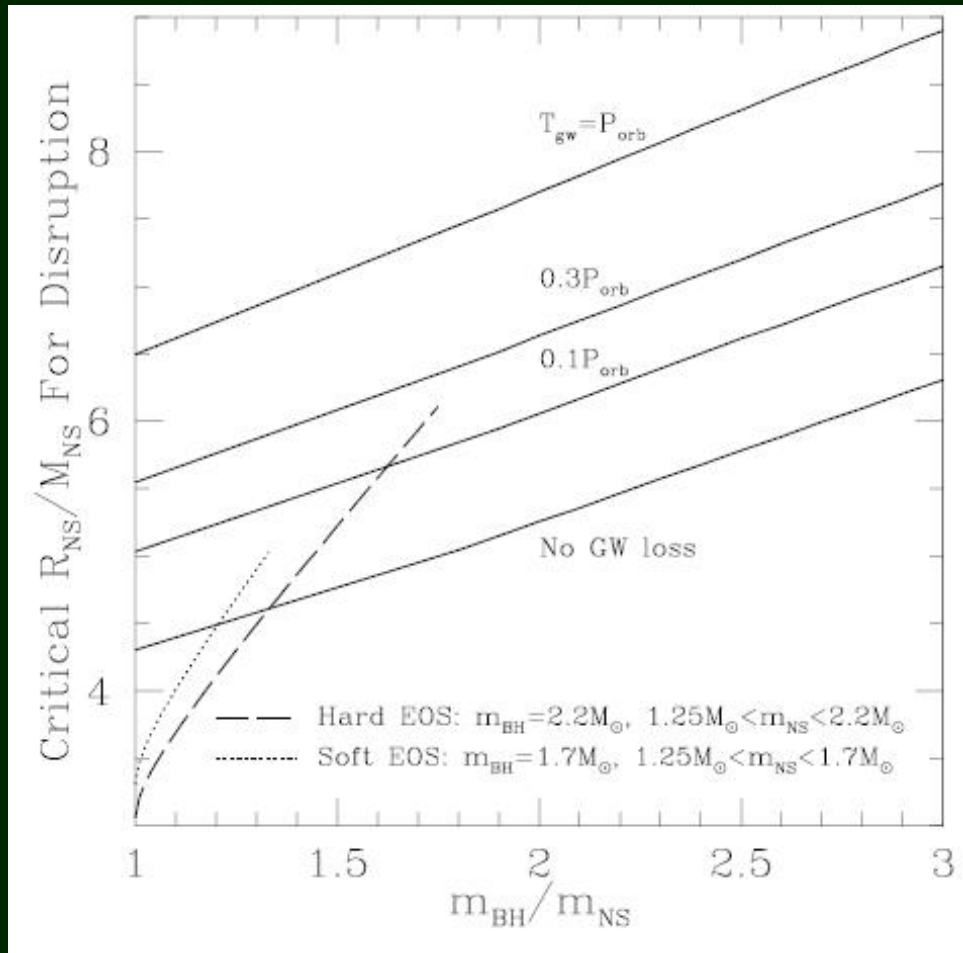
Magnetic field jet launch

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

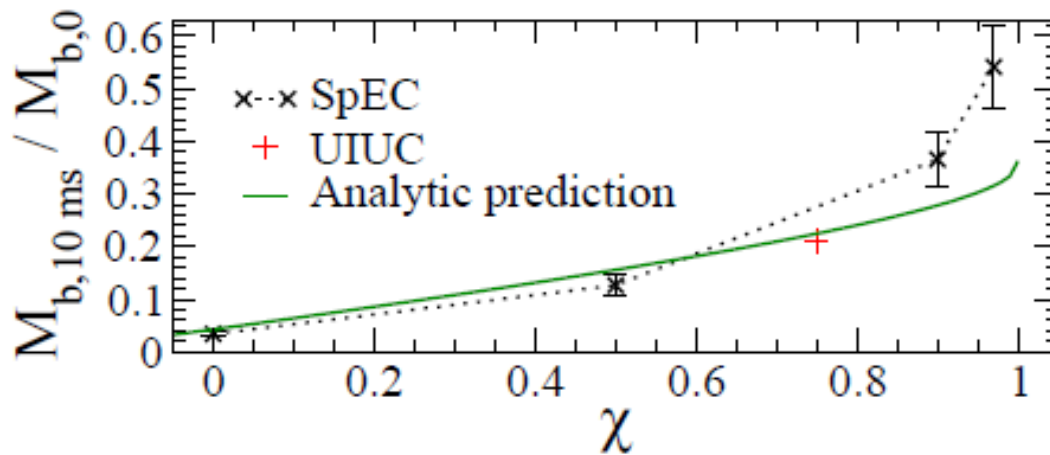
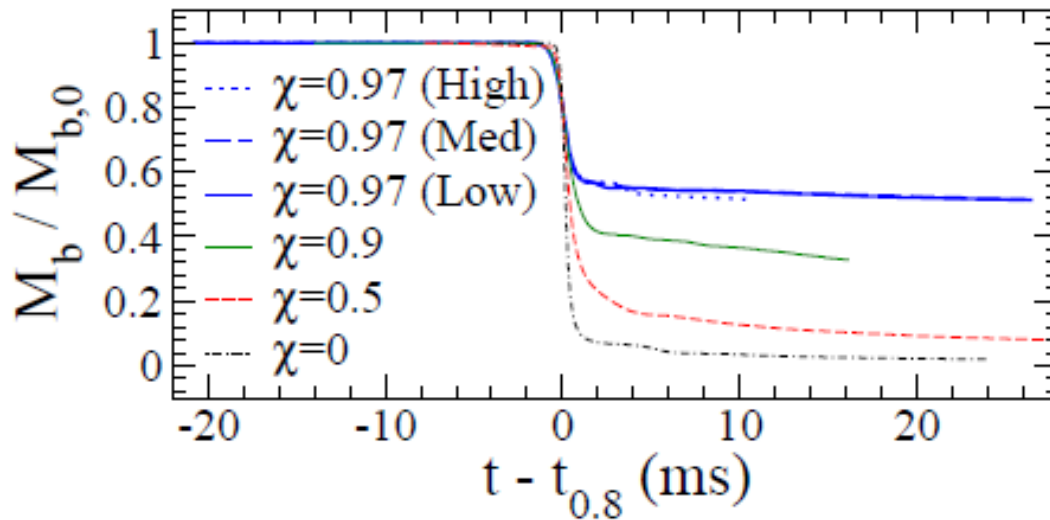
Prompt mergers of NSs with BHs



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.

Extremal BH-NS mergers

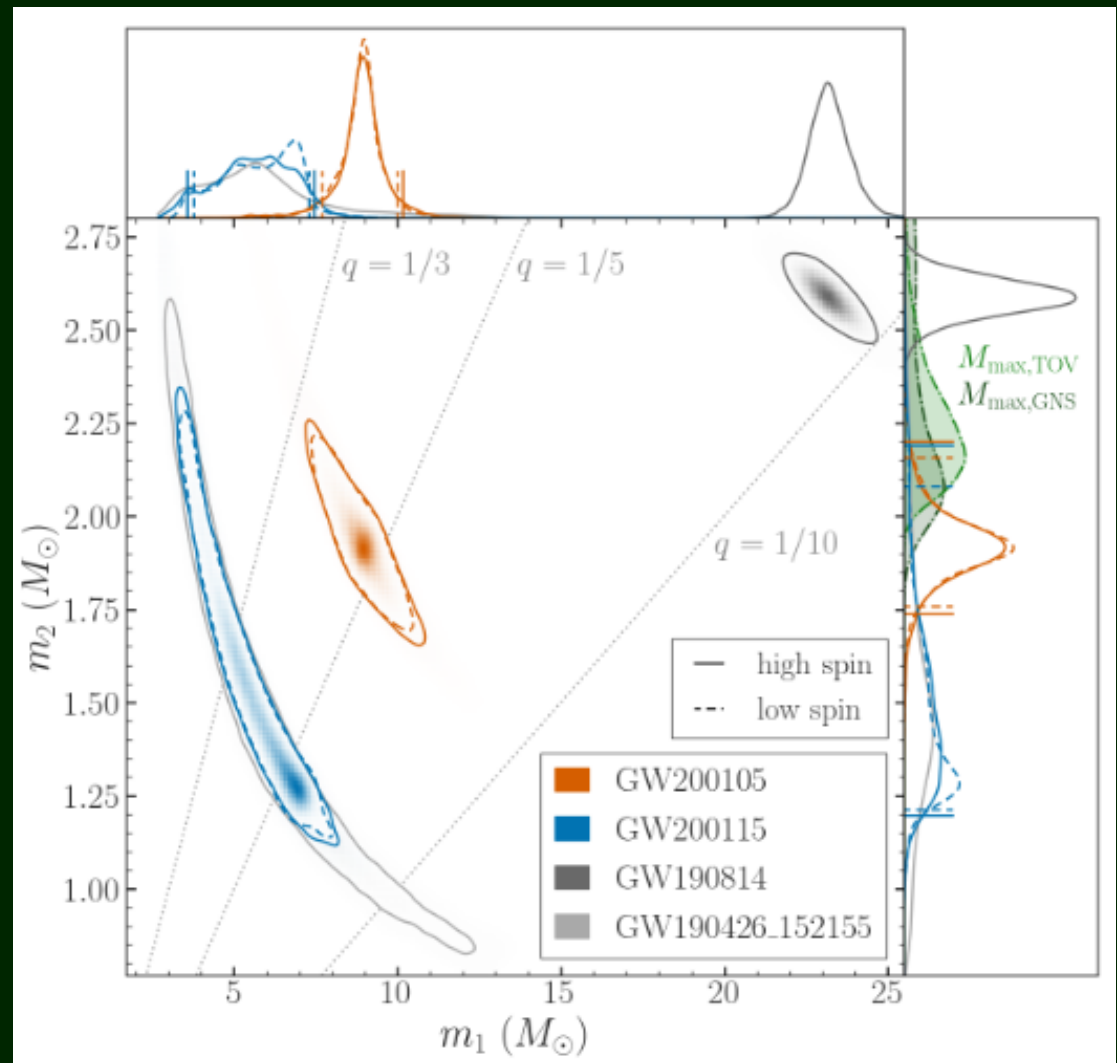


It is possible to form a massive disc around a BH during BH-NS merger. However, not for non-rotating BHs.

Two BH-NS coalescence observations

GW200105

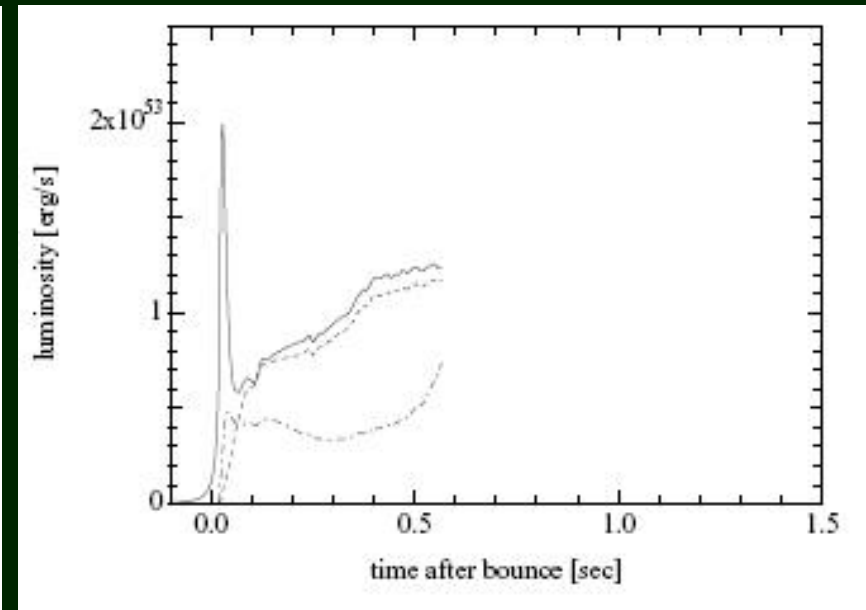
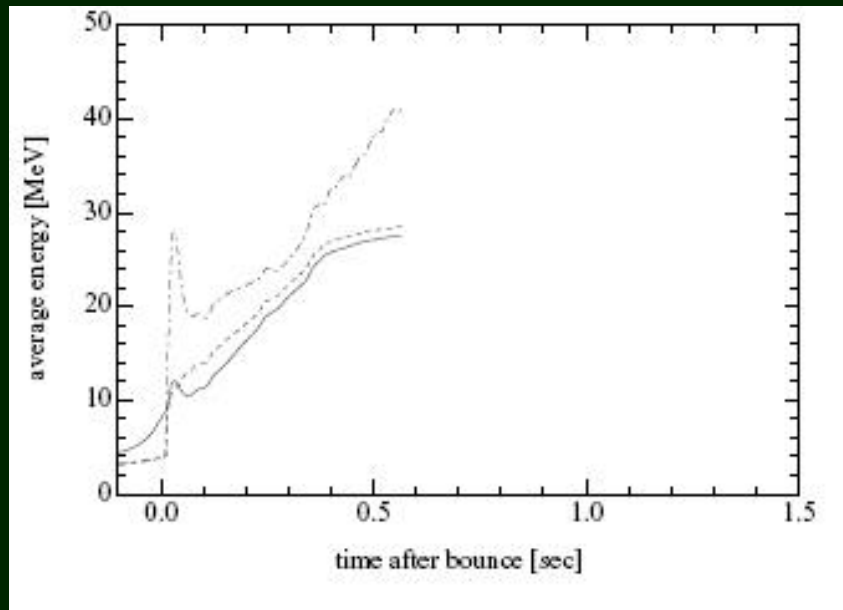
GW200115



2106.15163

Supernovae

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



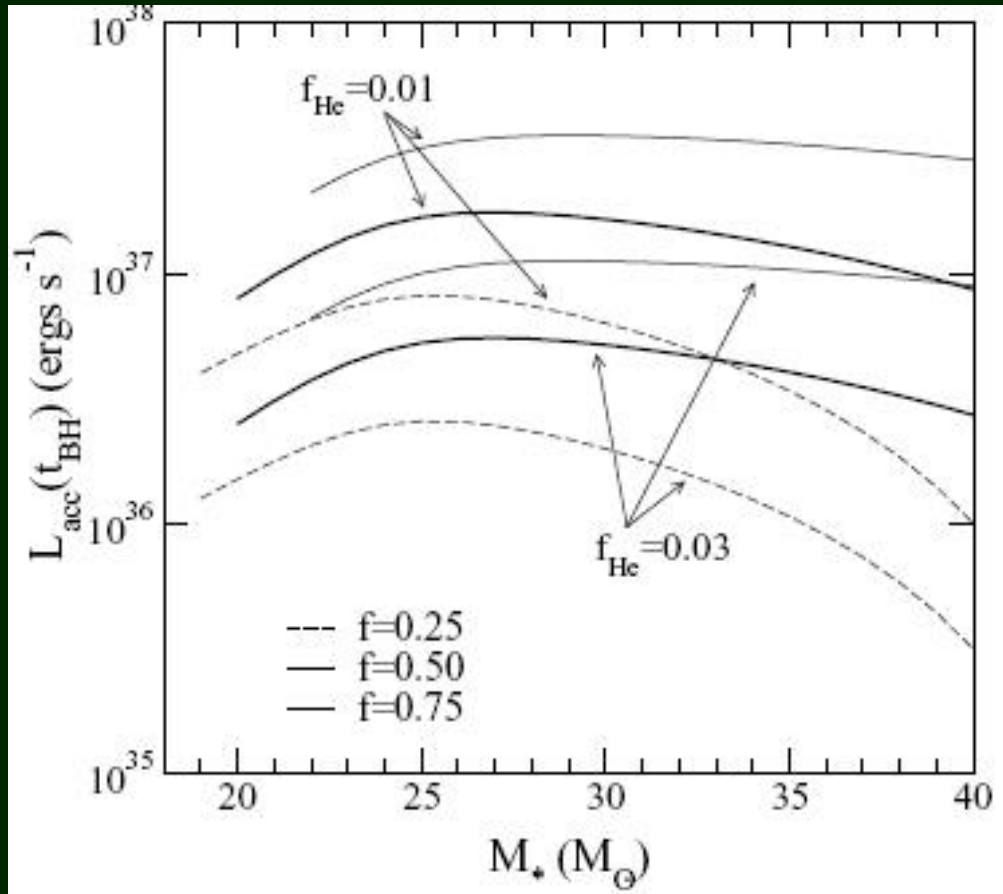
Different curves are plotted for different types of neutrino: electron – solid, electron anti-neutrino – dashed, mu and tau-neutrinos – dot dashed.

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



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

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

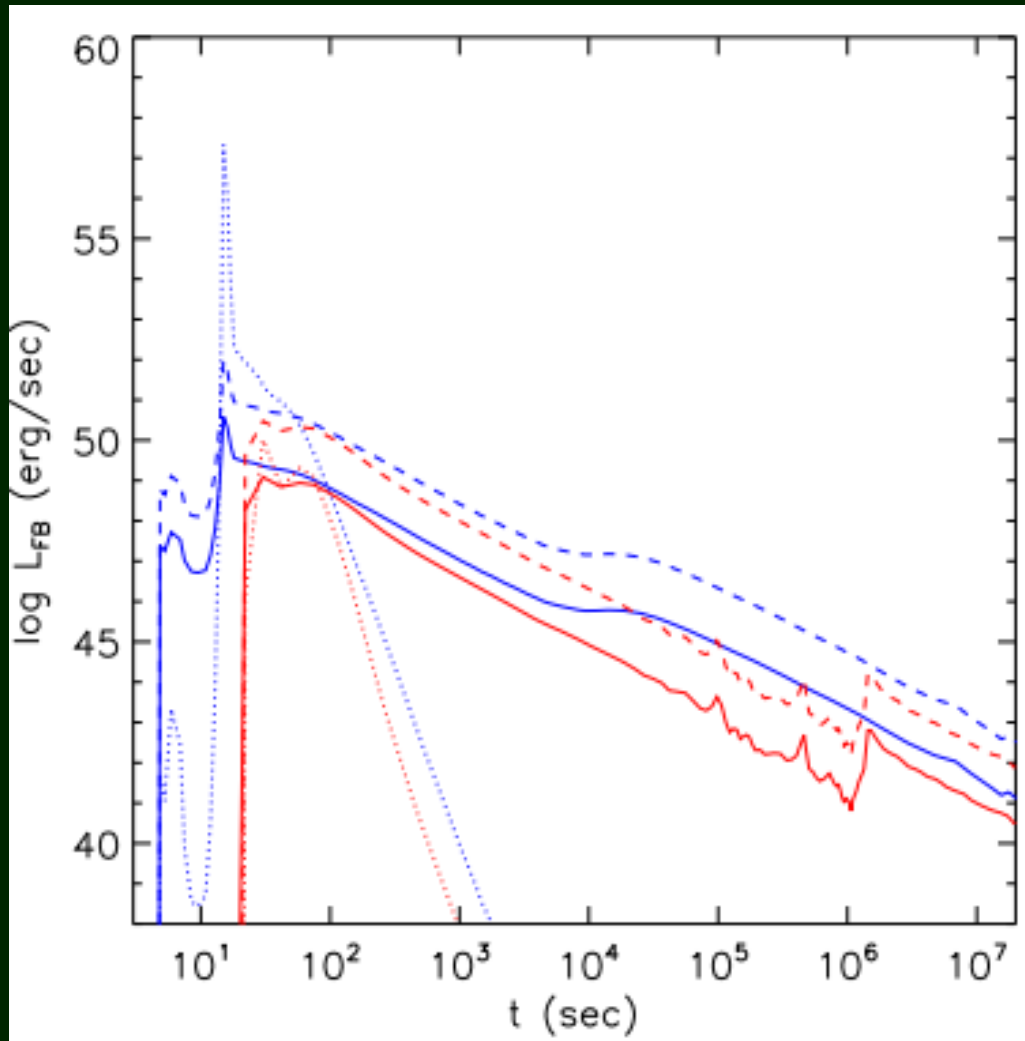
For this plot no radioactive heating is taken into account.

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.

A BH birth???

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

D. J. PATNAUDE, A. LOEB, & C. JONES

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Draft version December 8, 2009

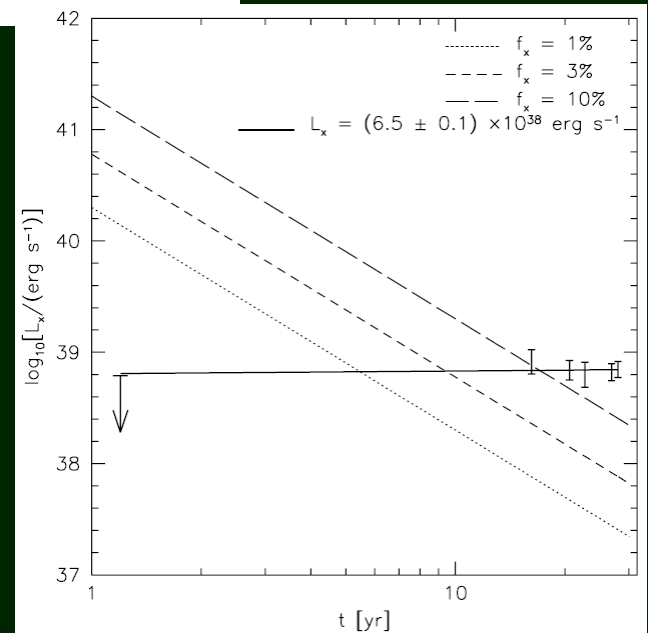
ABSTRACT

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 $(6.5 \pm 0.1) \times 10^{38} \text{ erg s}^{-1}$. The high and steady luminosity is evidence for a stellar-mass ($\sim 5\text{--}10M_{\odot}$) 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.

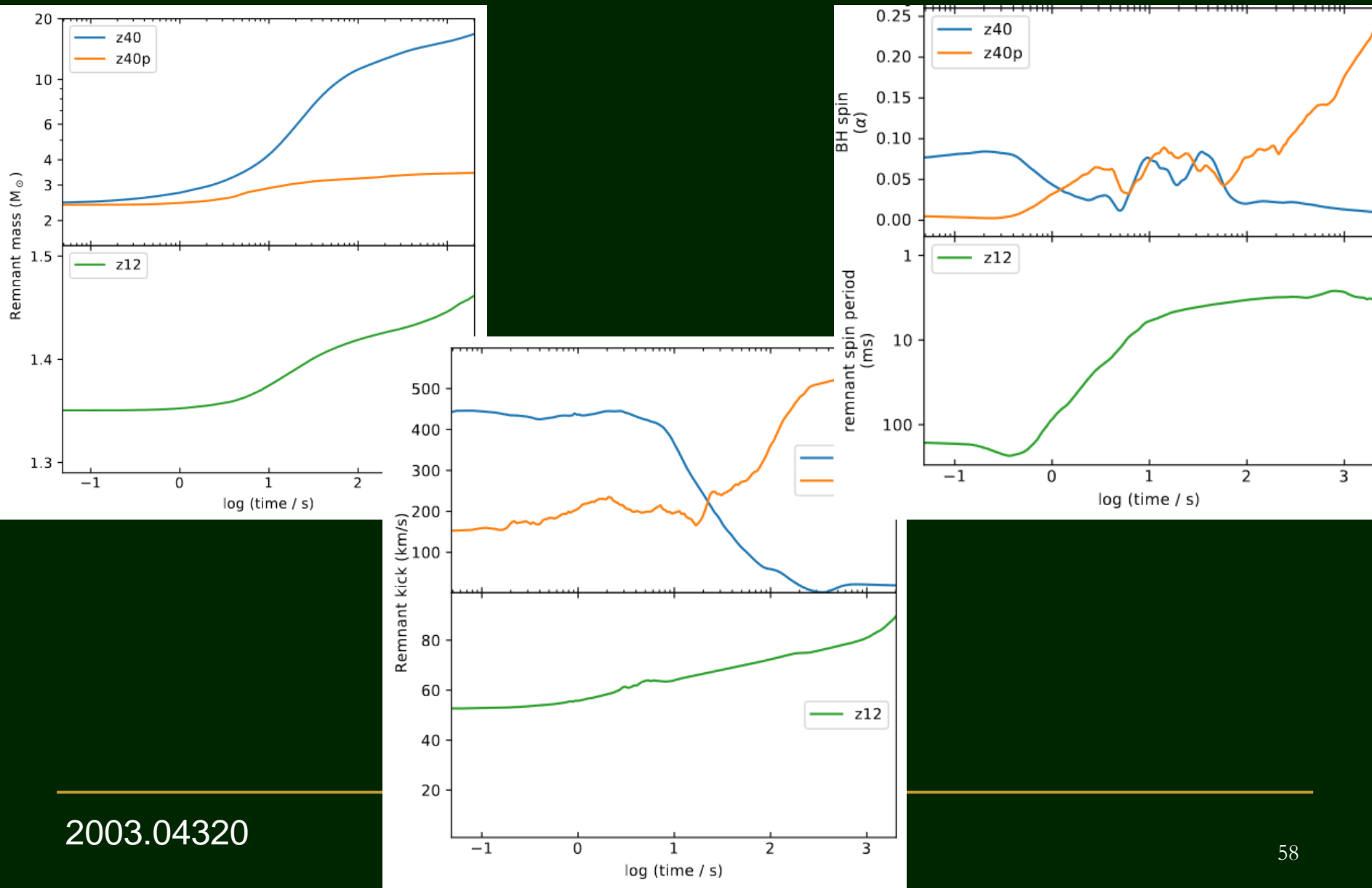
Submitted to *ApJ* (DOI: 10.1088/0004-637X/201001001) 2009 Dec 8

TABLE 1
X-RAY OBSERVATIONS OF SN 1979C

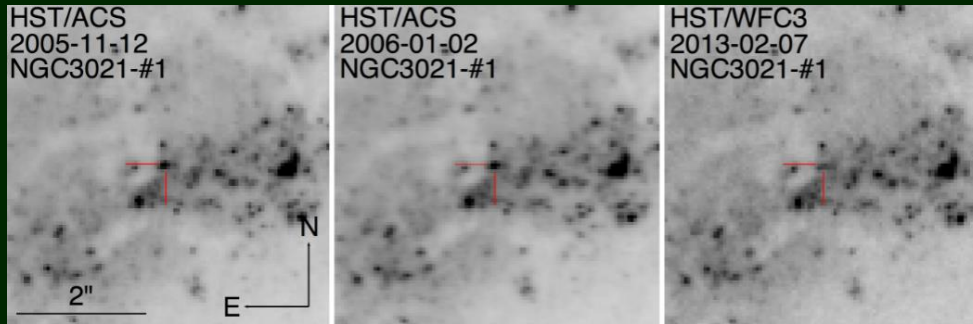
| Δt yr | Count Rate 10^{-4} cps | F_X^a $10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ | L_X^b $10^{38} \text{ erg s}^{-1}$ | Mission |
|-------------------|-----------------------------|--|---|-------------------------|
| 0.7 | < 3.0 | < 2.3 | < 6.3 | <i>Einstein</i> (HRI) |
| 16.2 | 6.7 ± 0.7 | 3.0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



Role of fall-back for kicks and spin



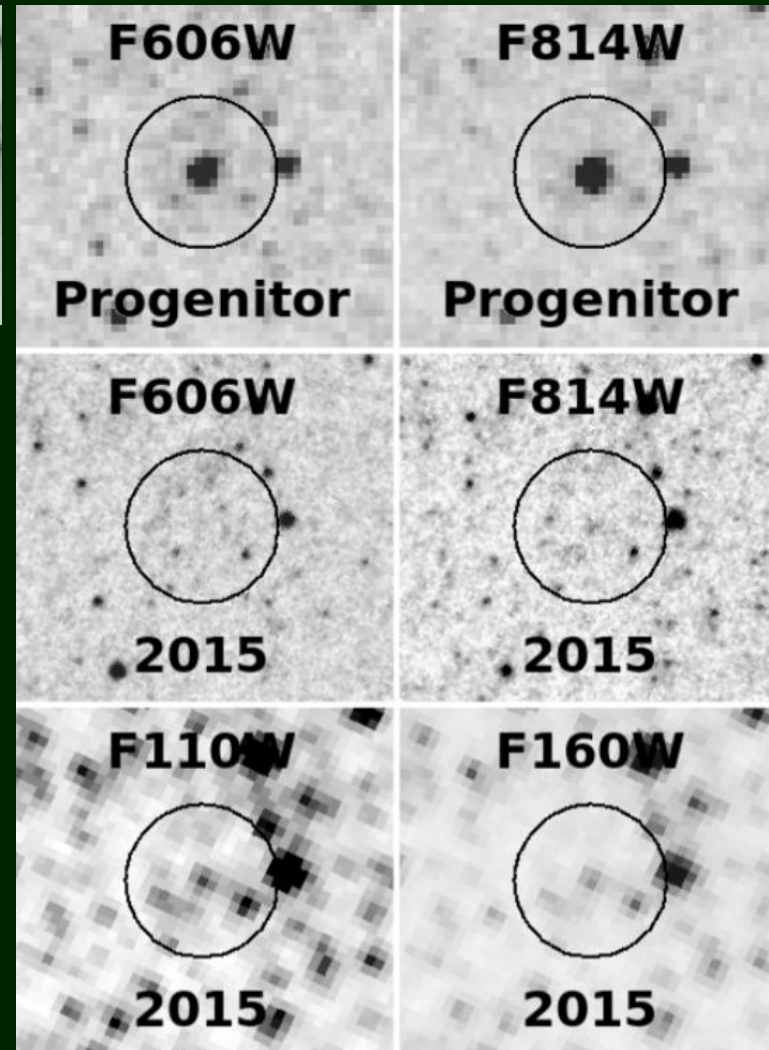
Disappearance of stars



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.

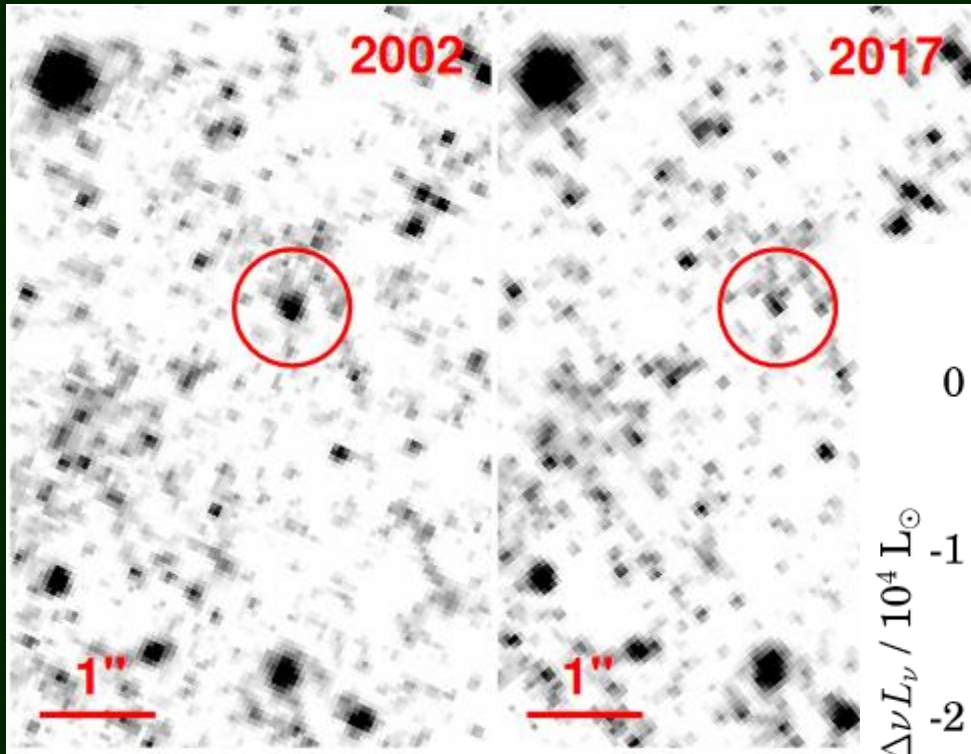
Progenitor mass ~ 23 -28 solar.
Consistent with the missing RSG problem.

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

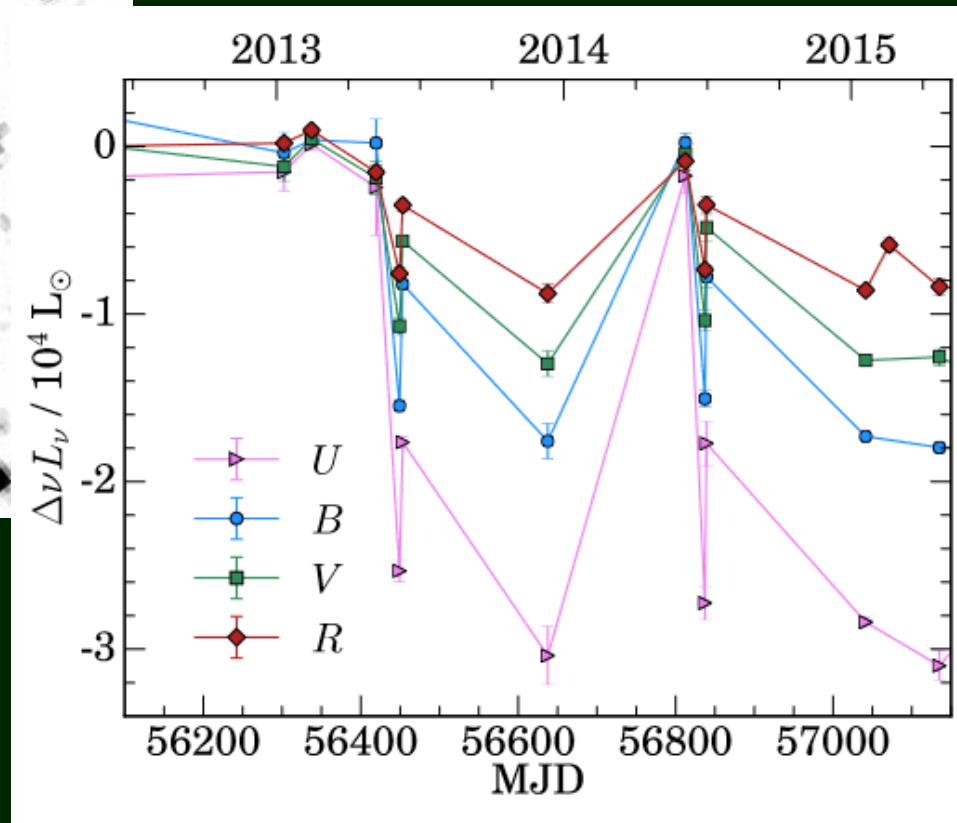


1609.01283

New example of a disappeared star



Blue supergiant in M101



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

