Formation and evaporation of strangelets during the merger of two compact stars

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purpose:

understand the **Equation of state (EOS) = $\boldsymbol{p(e)}$** of neutron stars (NS)

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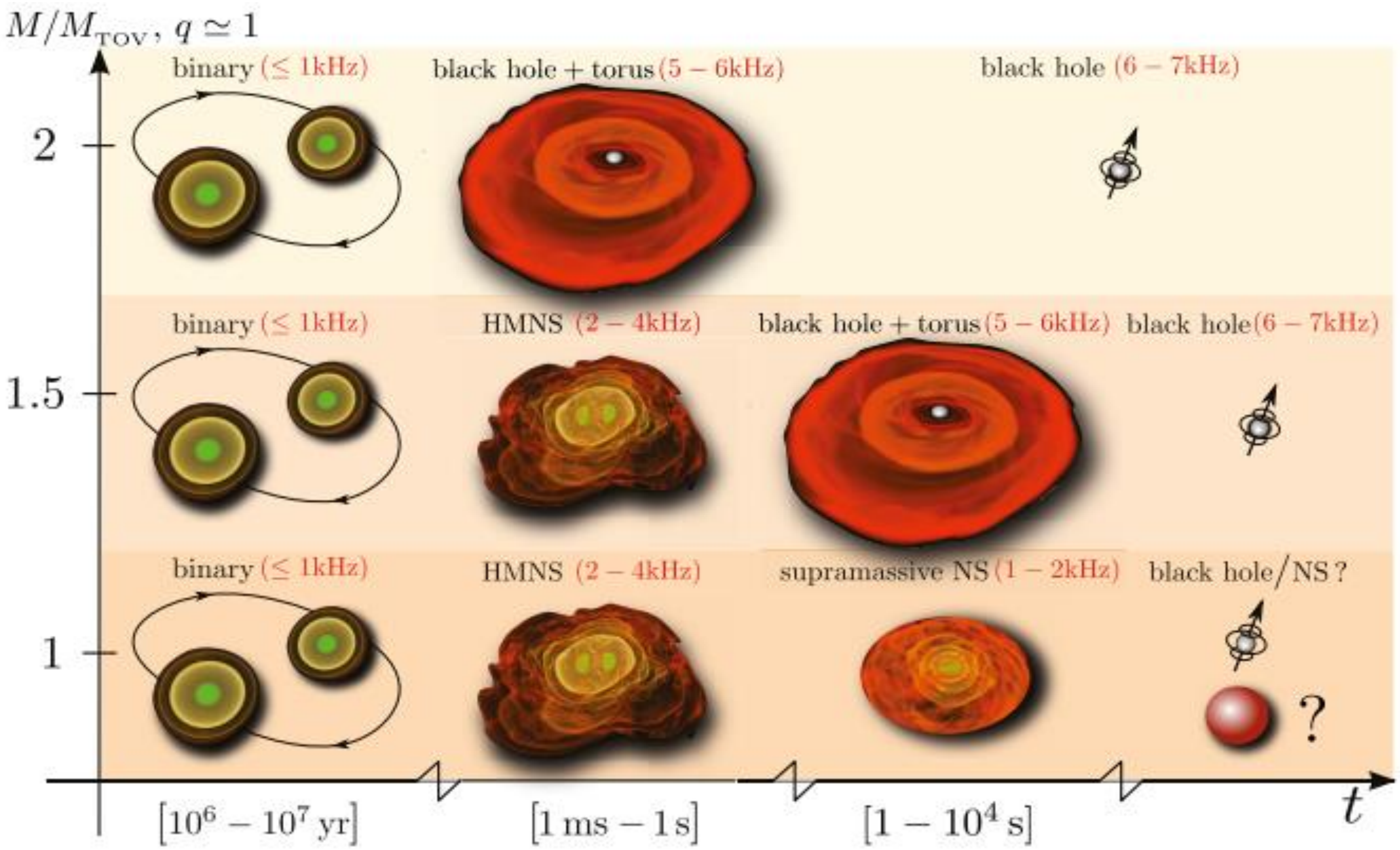
? ? ? ? EOS —probe→ **Binary NSs merger**

Stages of the merger



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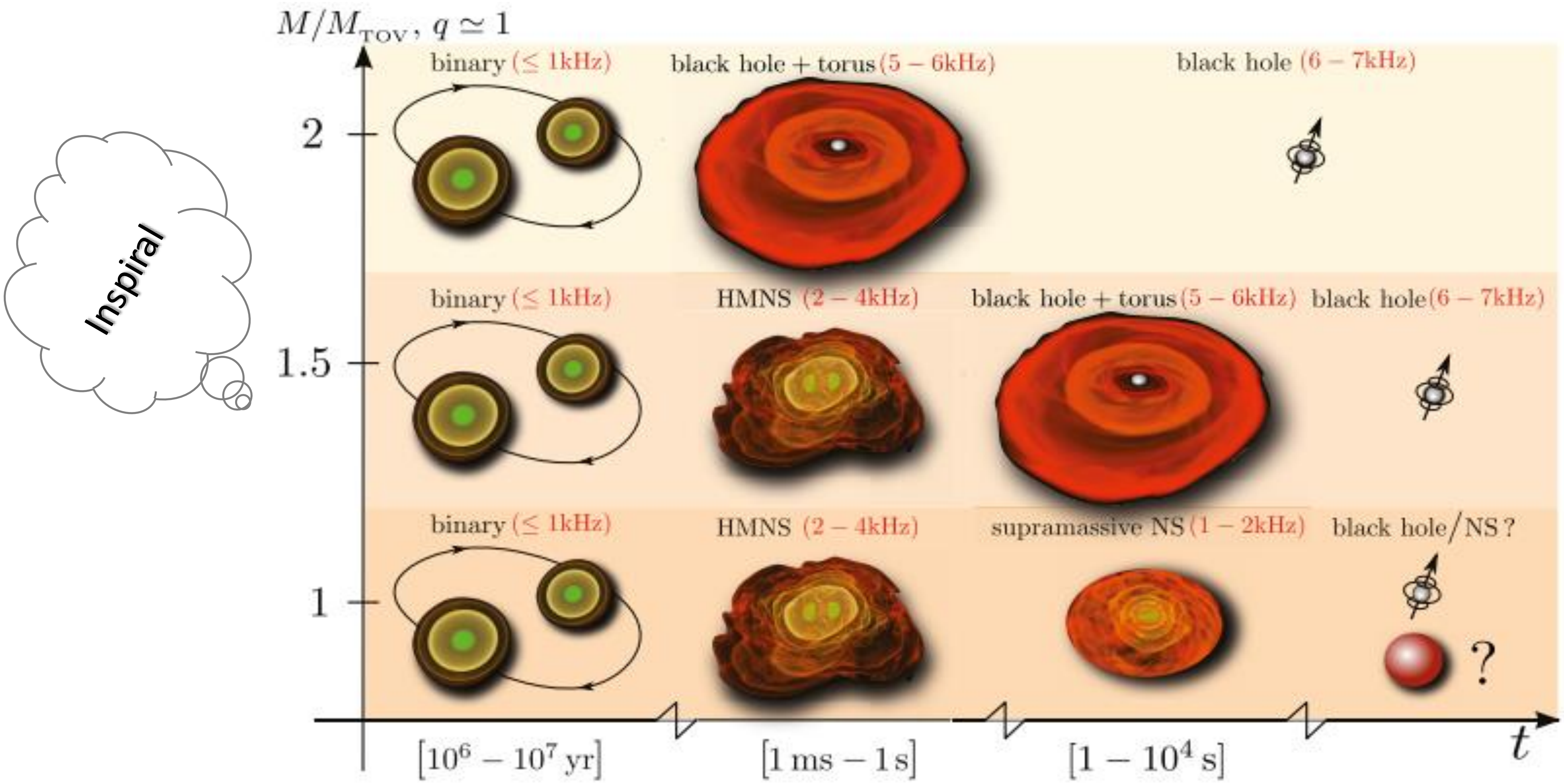

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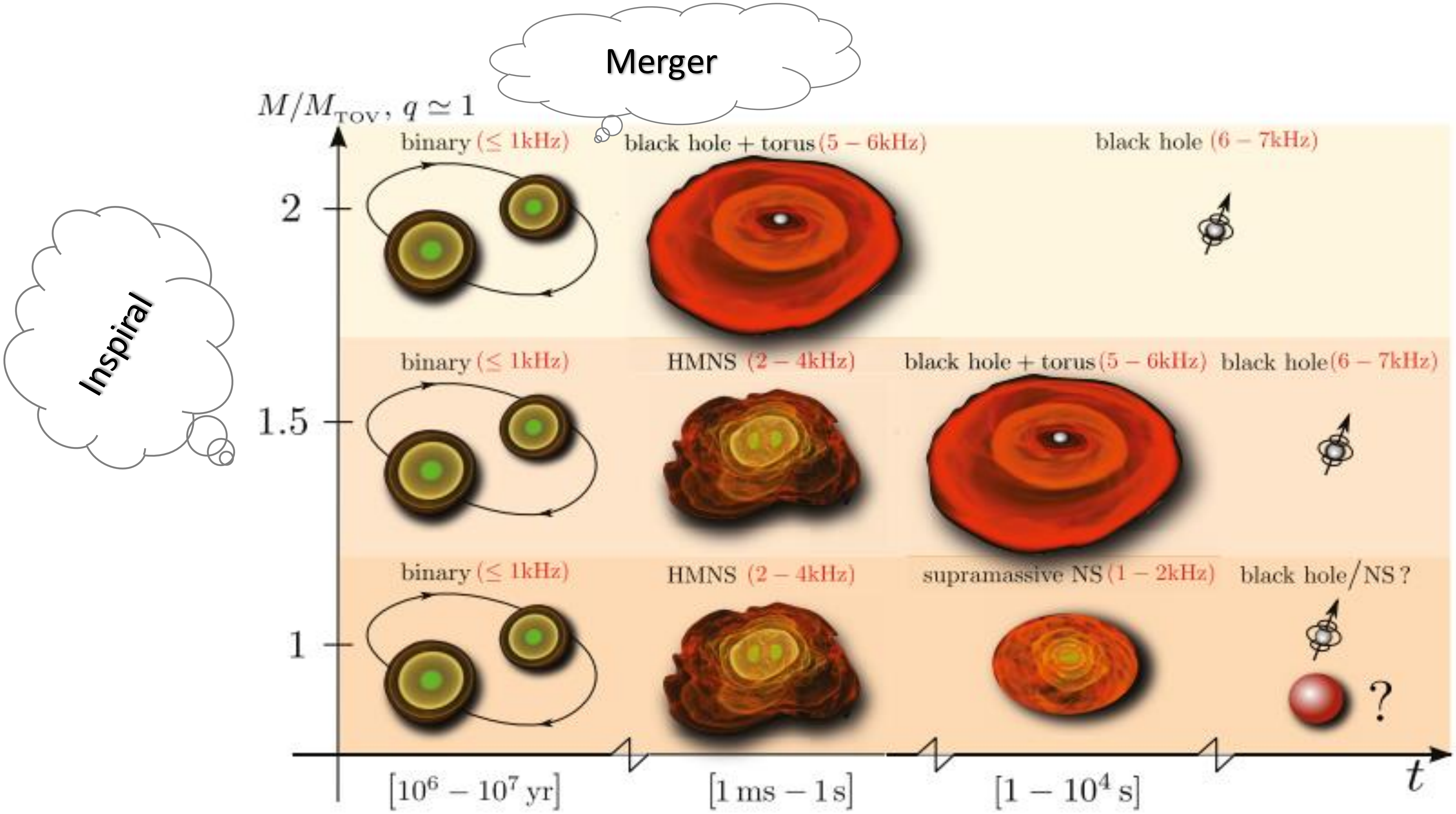

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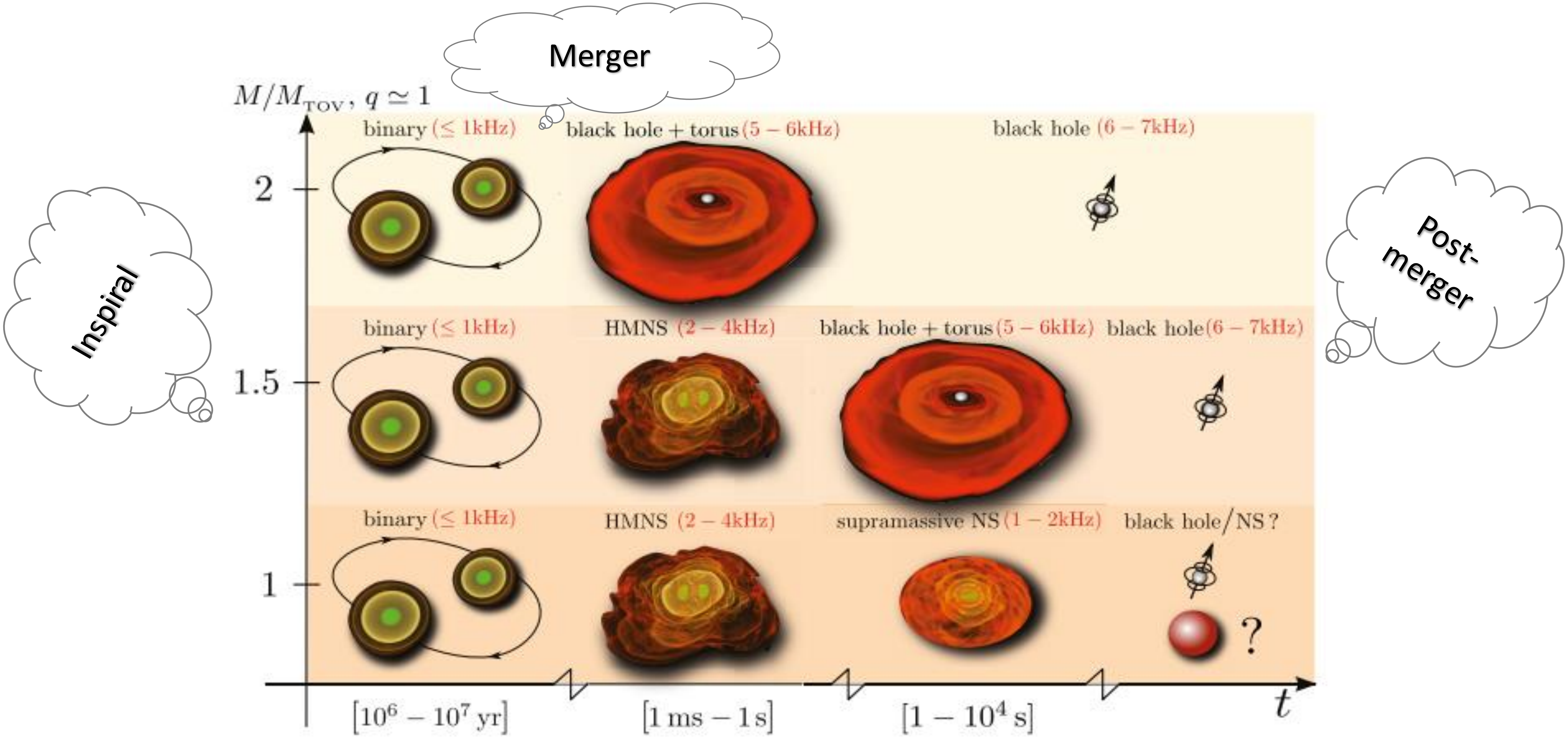
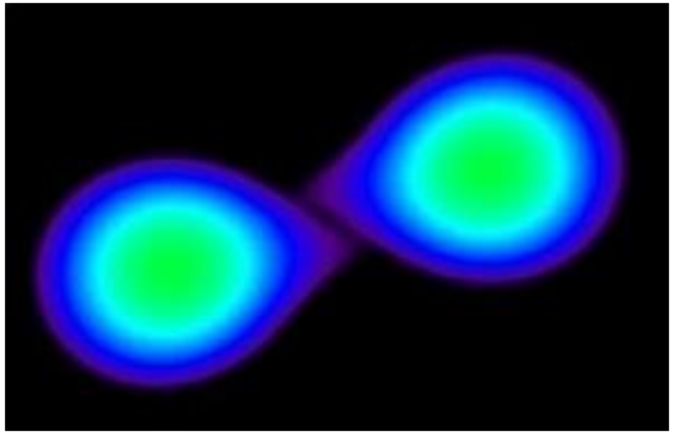


Ejection mechanisms

Ejection mechanisms

- Dynamical ejection:

  - Tidal deformation: equatorial plane



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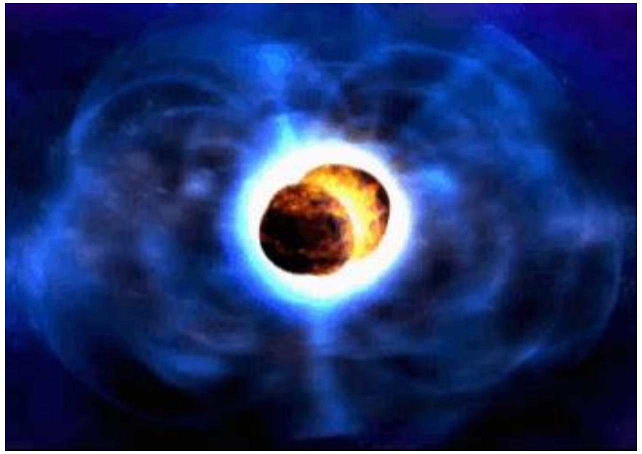

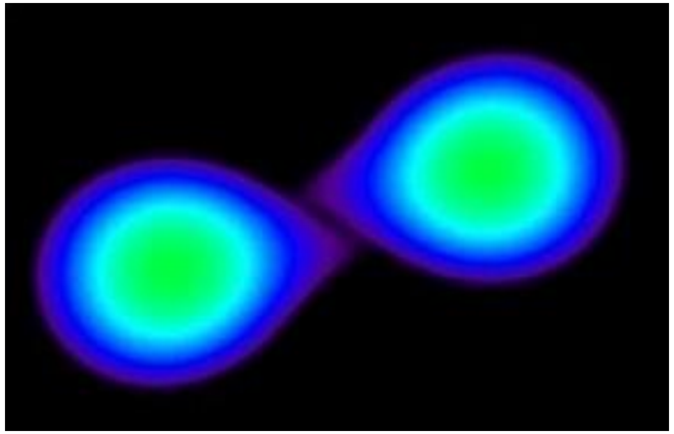

❖ Shock at NSs interface and radial oscillations

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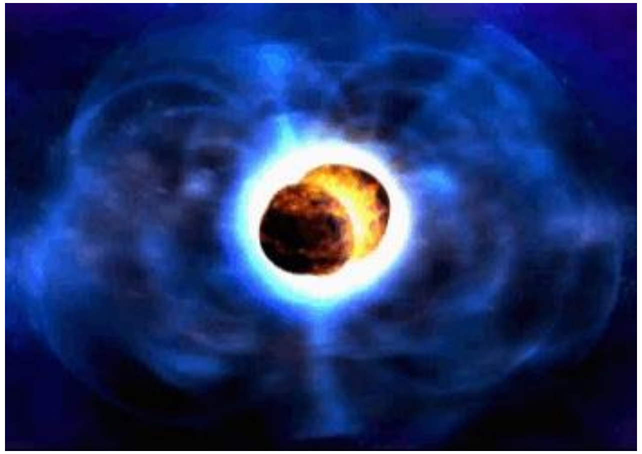
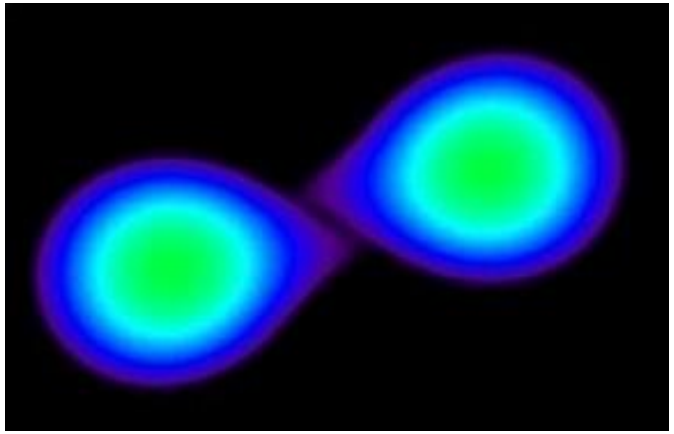
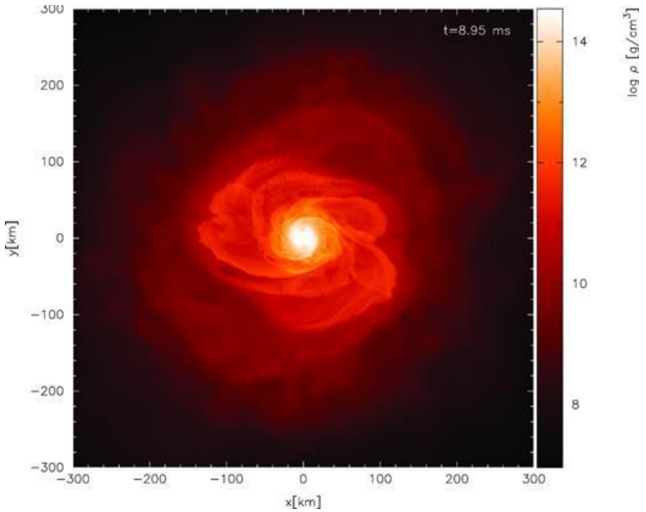
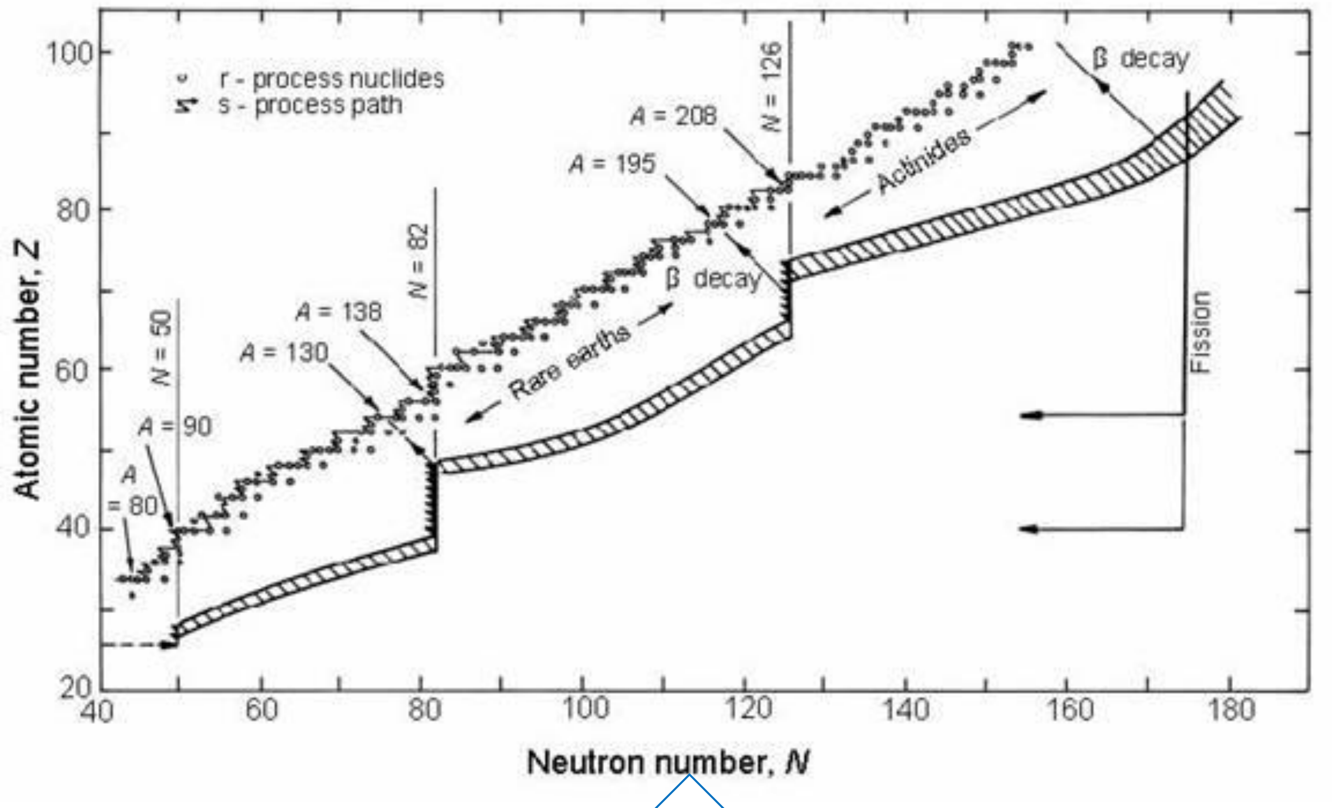




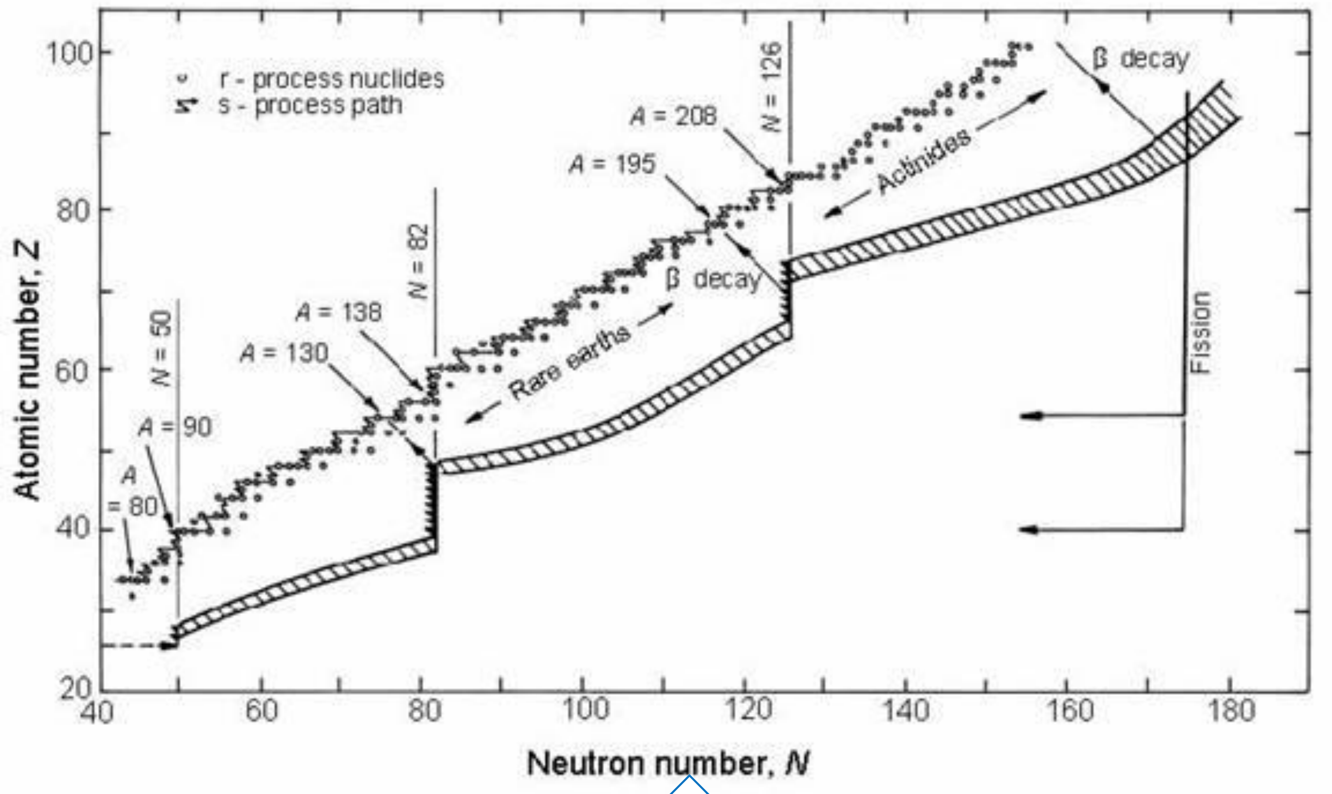
  - Shock at NSs interface and radial oscillations

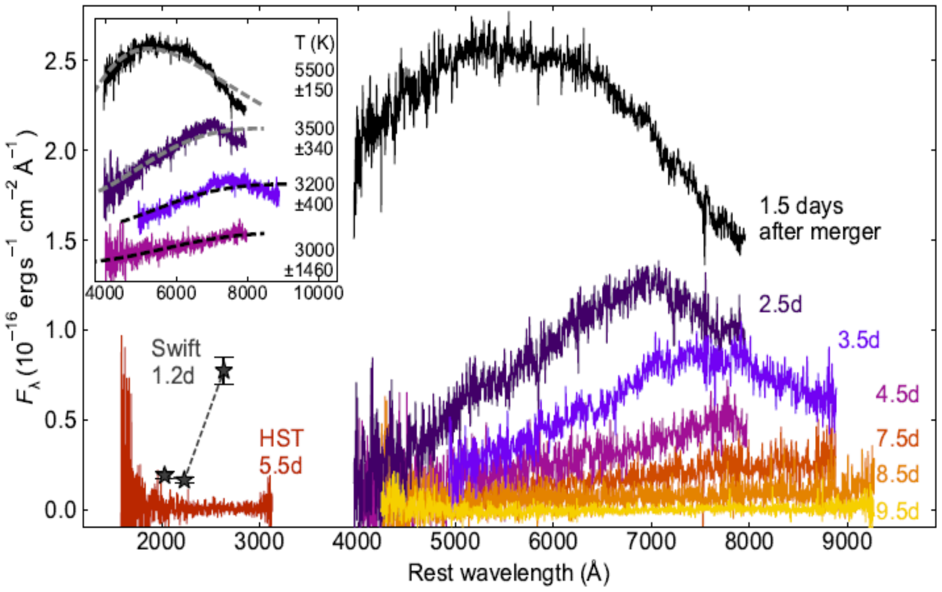
- **Disk:** $10^{-3}\, M_{\odot} < M_{disk} < 0.03 M_{\odot}$
  - Viscous or neutrino heating





R-process path





Nicholl et al. [arXiv:astro-ph.HE/1710.05456]

R-process path

kilonova signal

$$t_{peak} \propto \left(\frac{kM_{ej}}{v}\right)^{1/2} \qquad L_{peak} \propto \left(\frac{vM_{ej}}{k}\right)^{1/2}$$

$$T_{peak} \propto \left(vM_{ej}\right)^{-1/8} k^{-3/8}$$

Why quark matter?

Merger of compact objects August 2017 → Limit on $\breve{\Lambda}$ from the inspiral phase

$$2 < M_{max} < 2.2 M_{\odot}\ ,\ R_{1.5} < 13.5\ km$$ ← Limit on ejecta from the Kilonova signal

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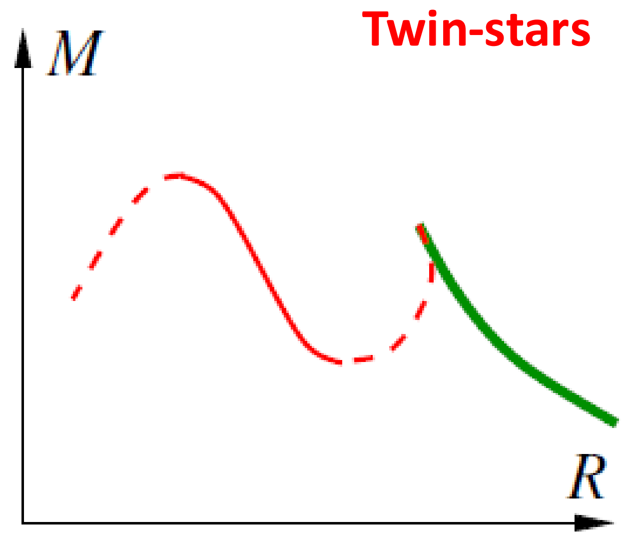
Radii measurements from x-ray binaries ≈ 11 km

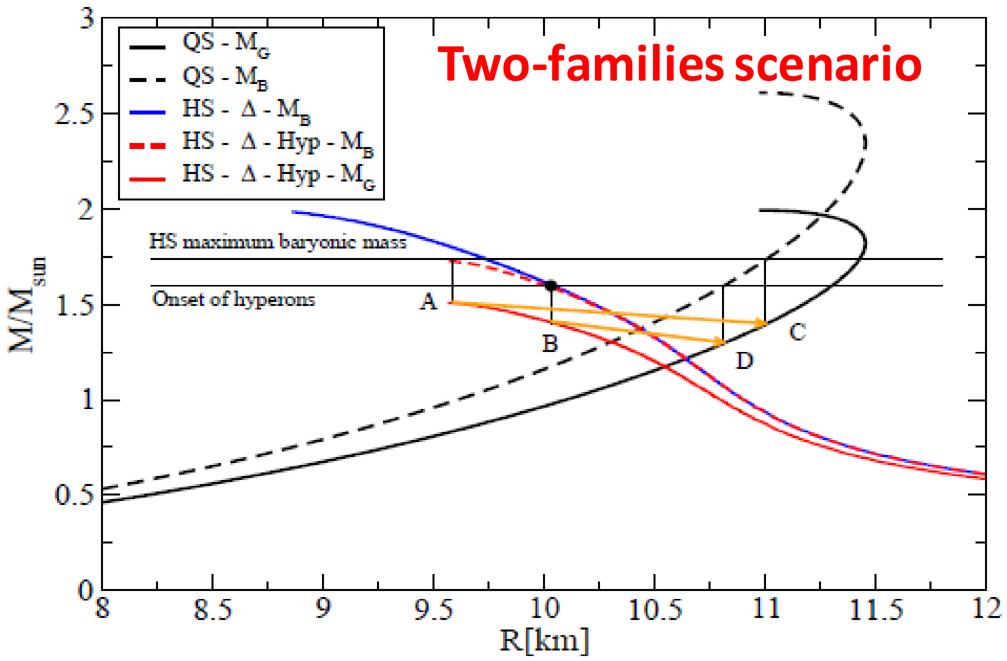
- $\mathbf{R_{1.5} < 11.5\ km}$ **: only disconnected solutions of the TOV** → **Two different configurations**

1. **Hadronic Matter**

2. **Partially or totally deconfined quark matter**



- 1 order phase transition
- The quark stars have the **smallest** radii



A. Drago, A. Lavagno, and G. Pagliara, Phys. Rev. D89,043014 (2014), 1309.7263

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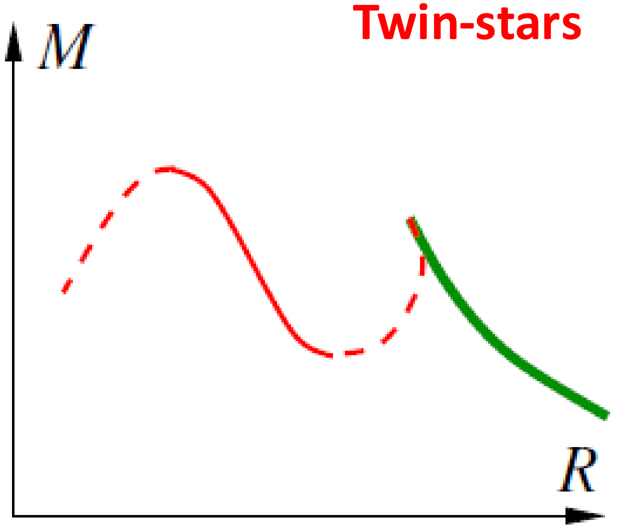

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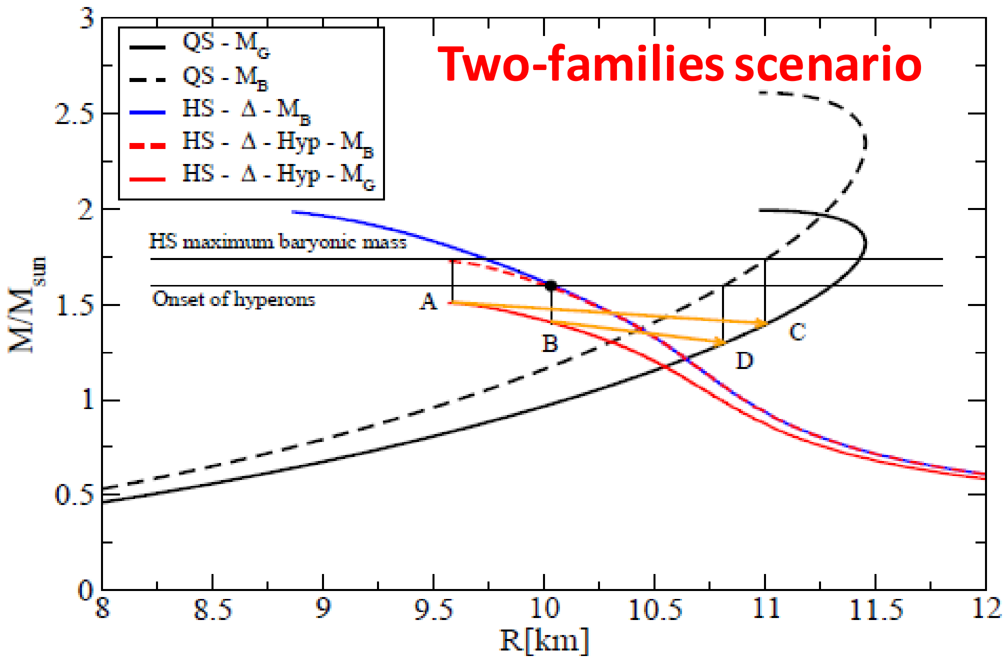

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Strange quark matter

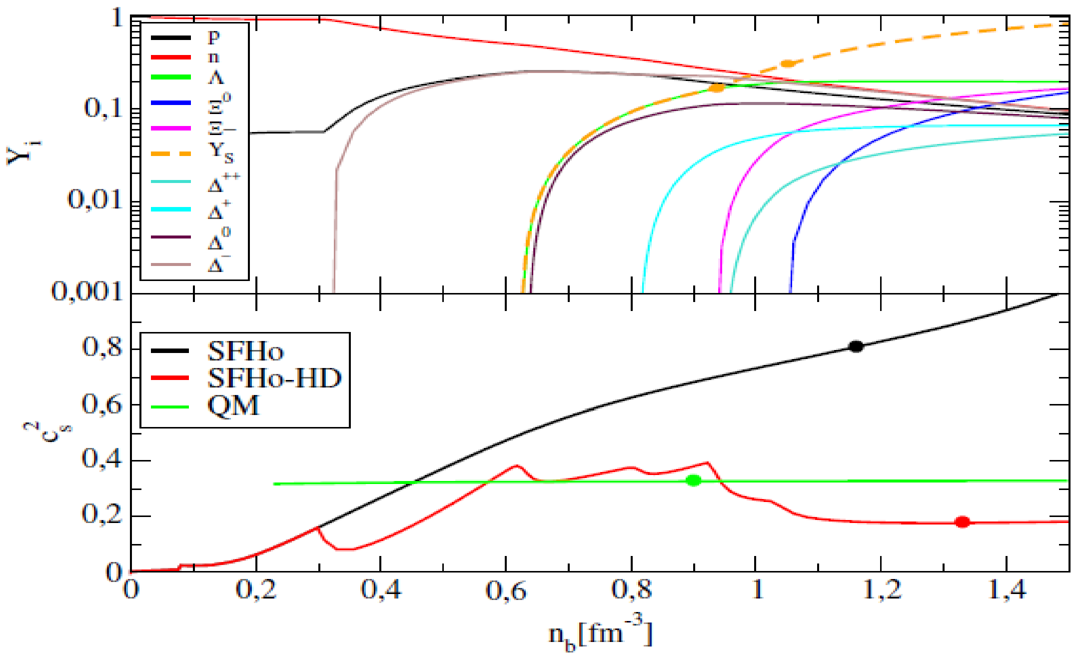
- u, d, s quarks, gluons and electrons
- Witten: absolutely stable → energy per baryon < 930 MeV
- it can exist in lumps from **few fm** to **10 km** (quark star)

Two-families scenario…

Appearance of hyperons and Δ-resonances
Softening of the EOS

1. **Hadronic stars: $M_{max} \sim 1.5 M_\odot$, $R \sim 10 km$**

2. **Quark stars: $M_{max} \sim 2 M_\odot$, $R > 11 km$**



R. De Pietri, A. Drago, A. Feo, G. Pagliara, M. Pasquali, S. Traversi, and G. Wiktorowicz, "Merger of compact stars in the two-families scenario,"2019

Strangeness fraction

$$Y_S = \frac{n_\Lambda + 2(n_{\Xi^0} + n_{\Xi^-})}{n_b}$$

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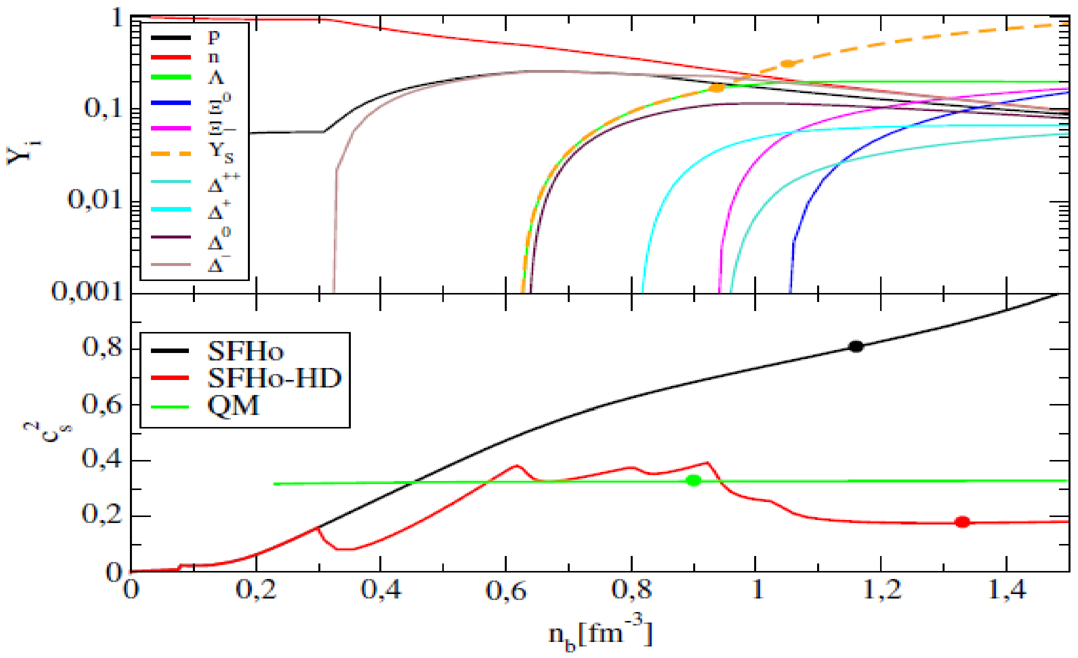

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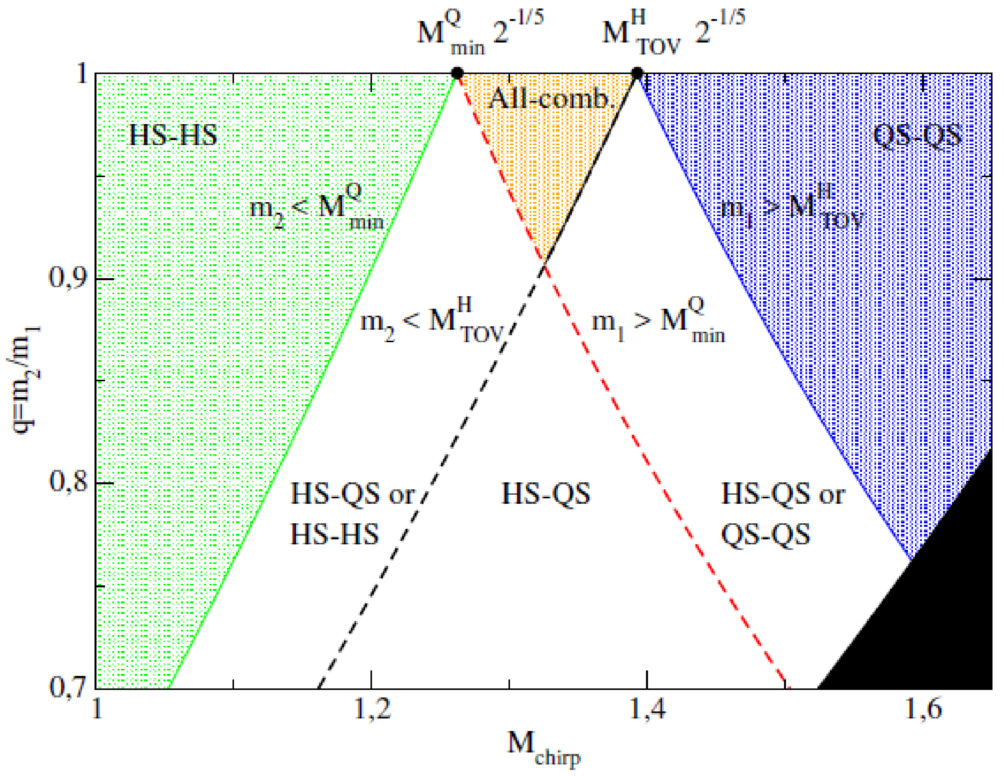
$$d_s \leq n_0^{-1/3}$$

$$Y_s \approx 0.2 - 0.3$$

Classification of the mergers

1. Hadronic-Hadronic (HS-HS)
2. Hadronic-Quark (HS-QS)
3. Quark-Quark (QS-QS)



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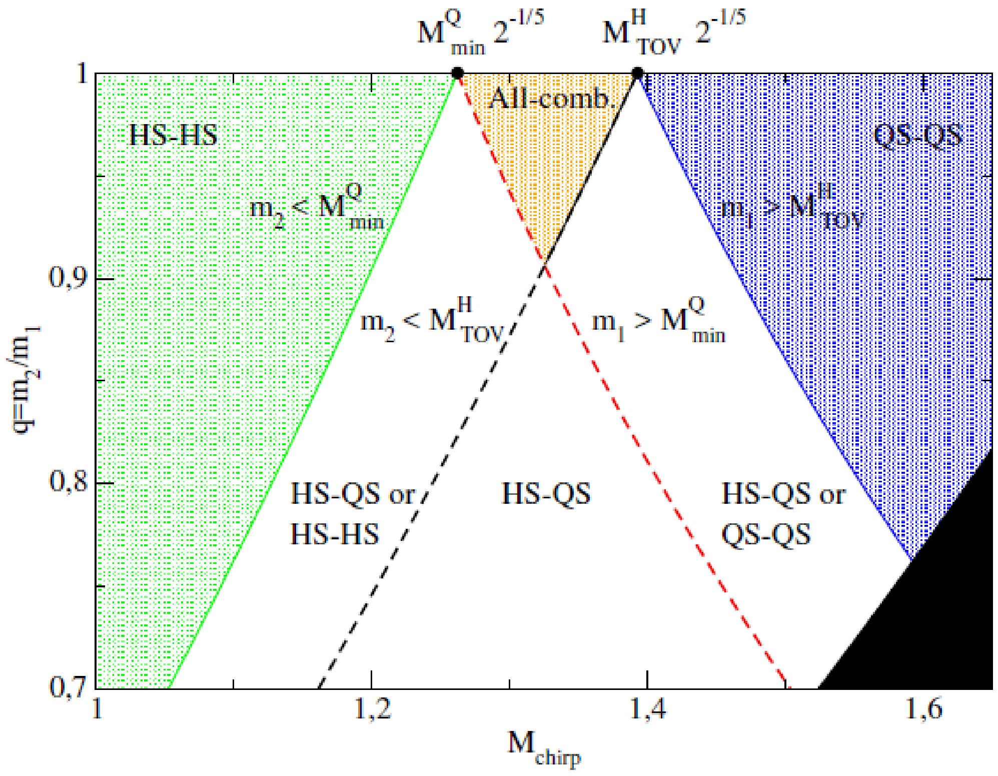
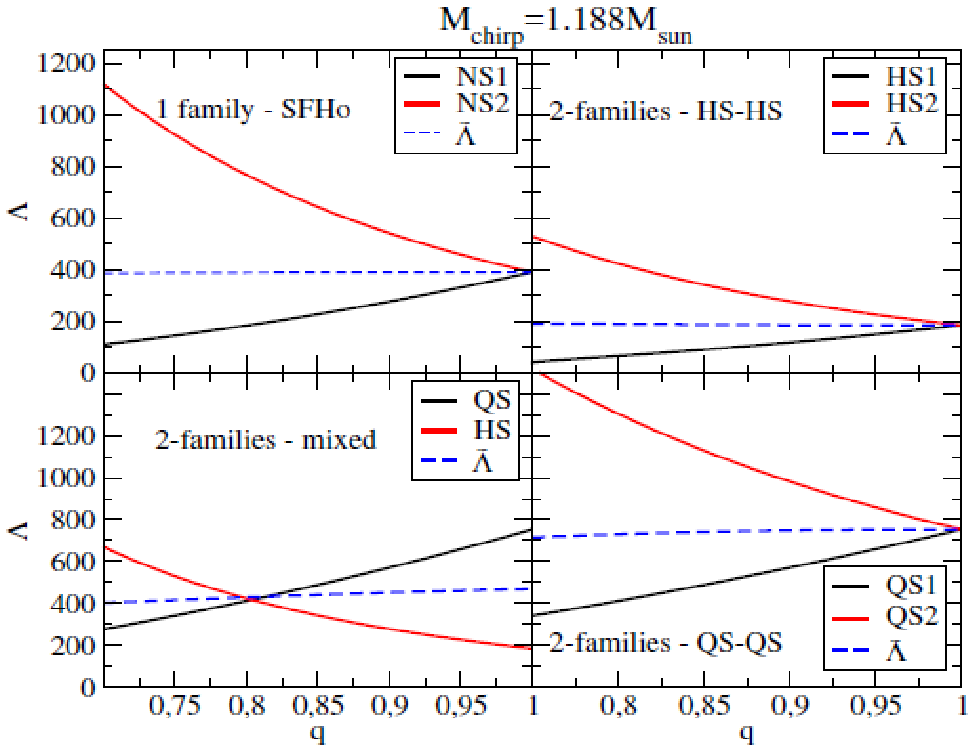




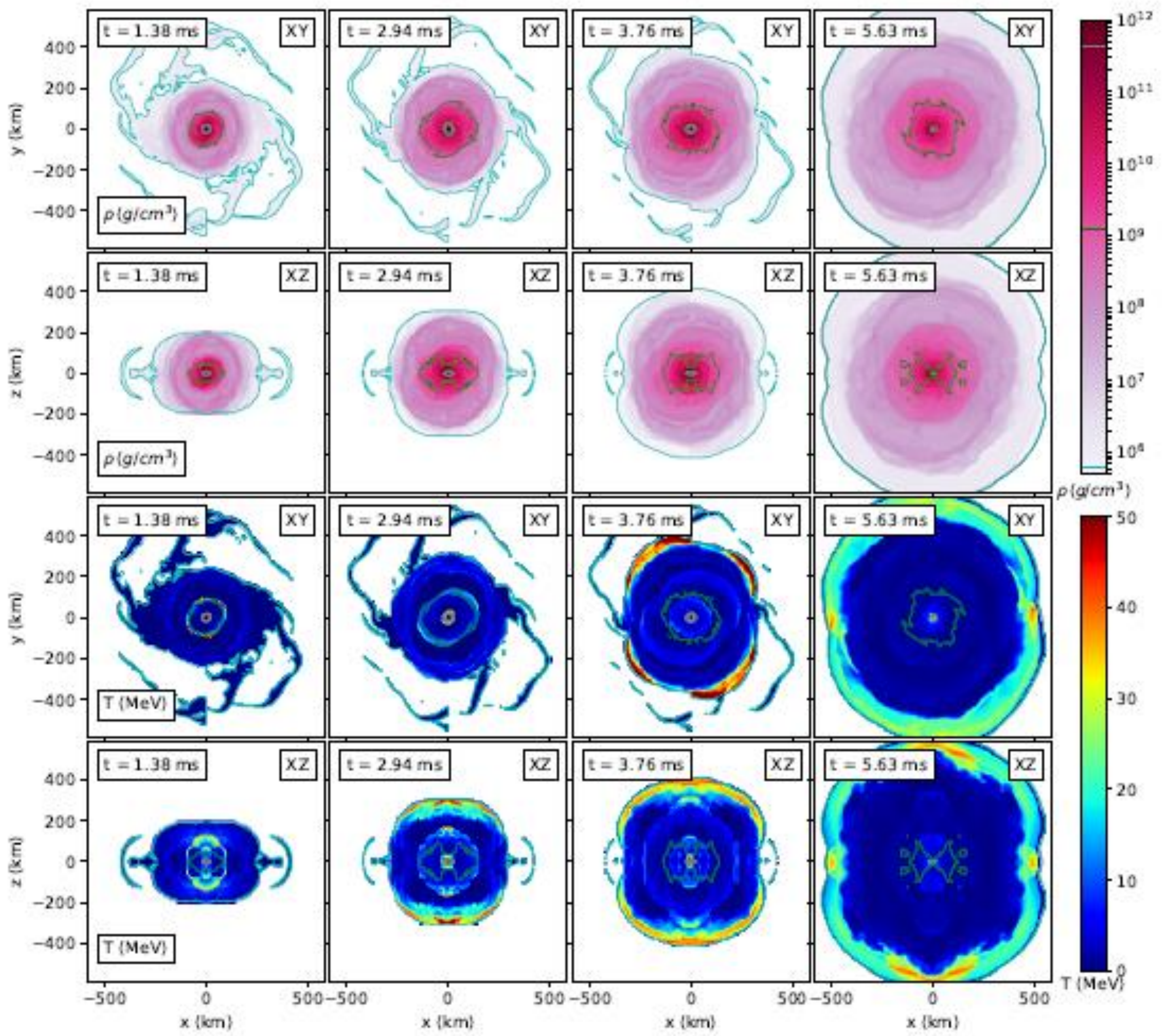
GW170817

HS-QS compatible with the limits on $\breve{\Lambda}$

Kilonova?

❖ the radii of the two compact objects are both rather small, the system is asymmetric and the threshold mass is large

❖ Issue: fate of quark matter
Strangelets evaporation?



Astrophys. J. 881, 122 (2019)

Formation and evaporation of strangelets during the merger of two compact stars

arXiv:1908.02501

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Lumps of strange matter with baryon number A:

- 3A quarks in quark-matter phase
- radius ≈ $A^{1/3}$
- mass = eA where e ≈ 860 – 880 MeV → **ionization energy ≈ 50 – 70 MeV**

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The universe cools down from 100 to 1 MeV in 1s: **is that time enough to evaporate the lumps?**

Formation and evaporation of strangelets during the merger of two compact stars arXiv:1908.02501

$$\frac{dA}{dt} = \left[\frac{m_n T_s^2}{2\pi^2} e^{-I/T_s} - N_n \left(\frac{T_s}{2\pi m_n}\right)^{1/2}\right](f_n + f_p)\sigma_0 A^{2/3}$$

- m_n : mass of the neutron
- I : ionization energy
- T_s : temperature of the strangelets
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- $\sigma_0 A^{2/3}$: geometric cross section
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Fragmentation of strangelets to infer the typical size

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❖ **Shock waves** ⇨ larger energies and smaller length scales

⇨ **small strangelets**

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re-absorption of neutrons from the environment

cooling of the strangelet due to evaporation

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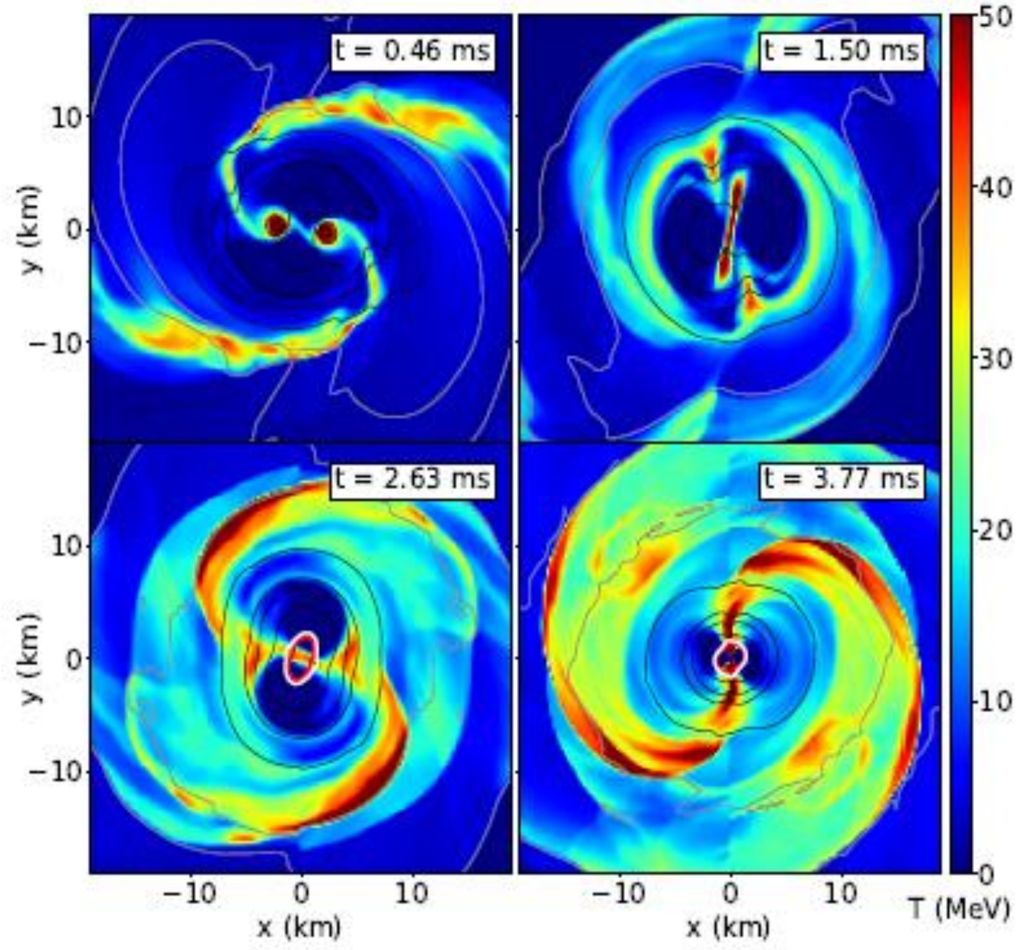
$$4\pi r_s^2 \left[\frac{7\pi^2}{160}\right]\left[T_u^4 p(r_s, T_u) - T_s^4 p(r_s, T_s)\right] = \frac{dA}{dt}(I + 2T_s)$$

ν absorption — ν emission — evaporation

Energy gained — Energy loss

Evaporation: shocked strangelets



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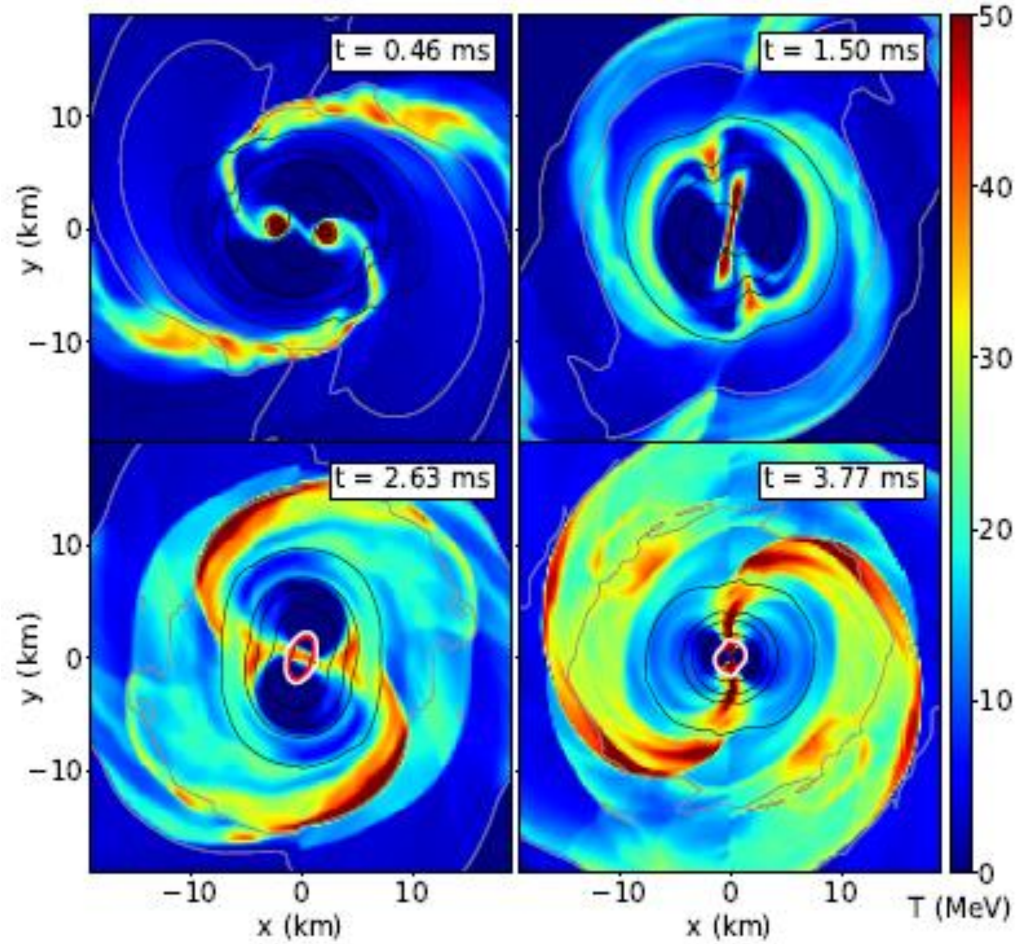
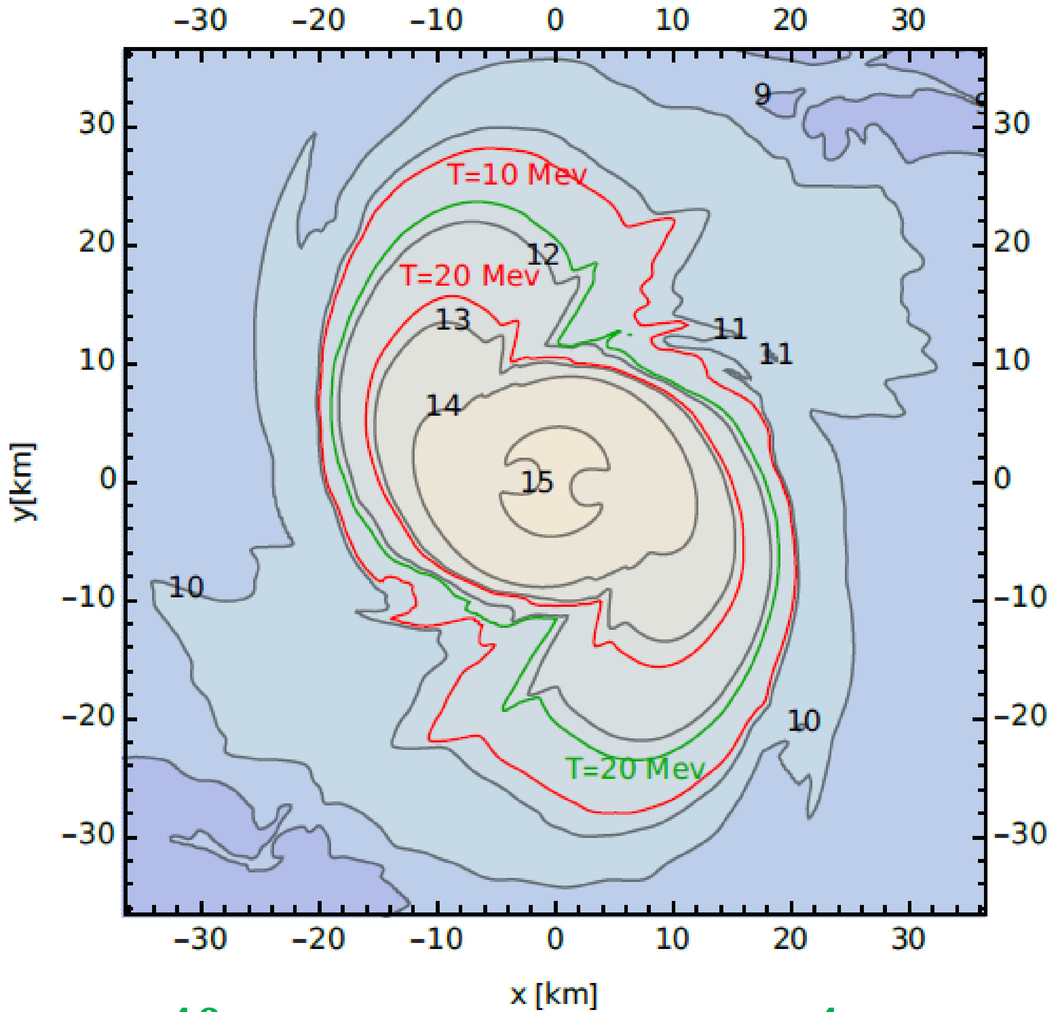
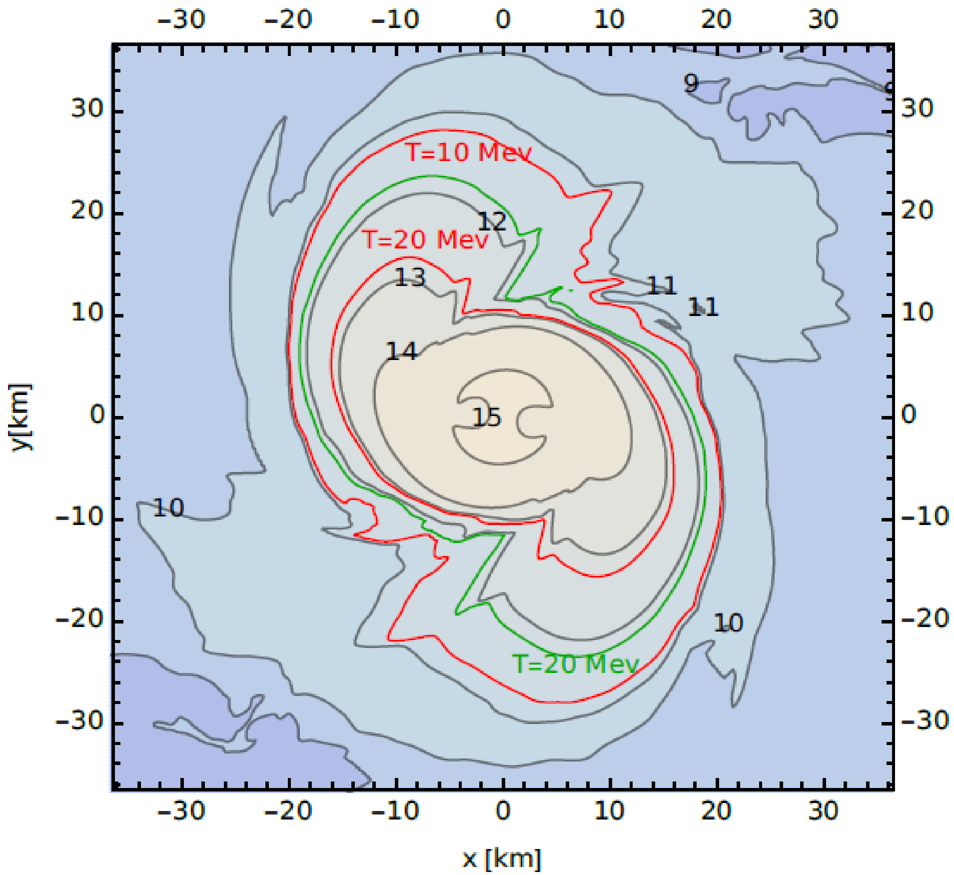


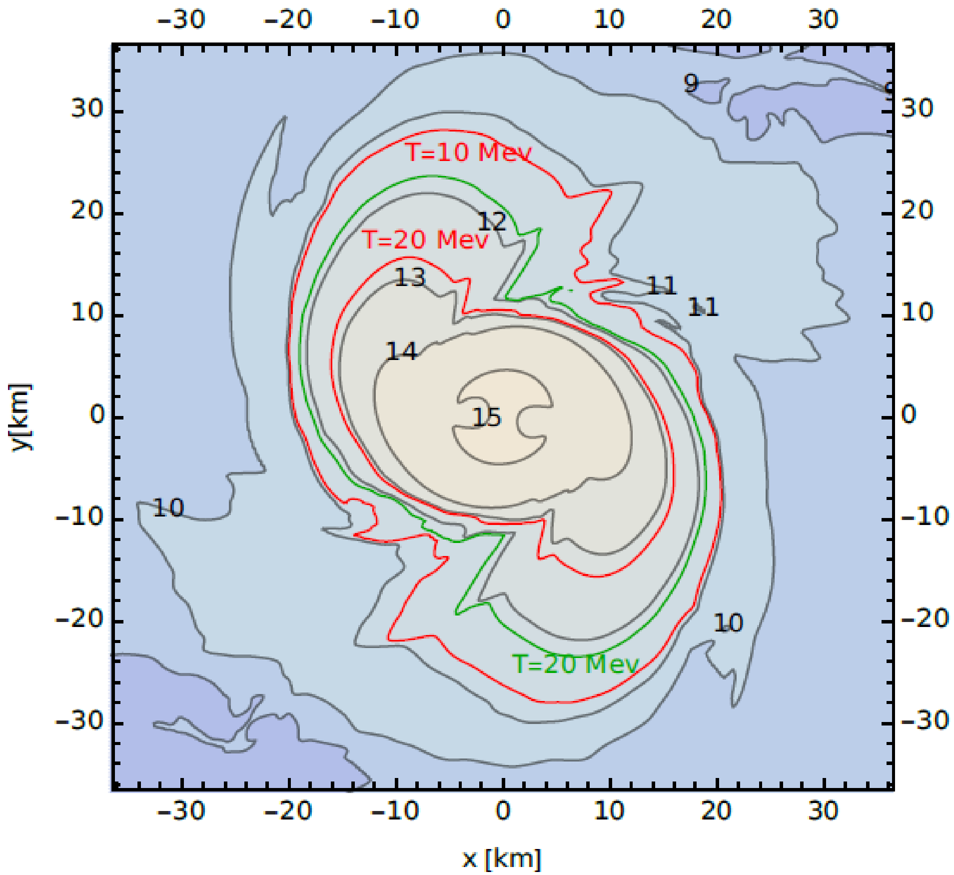


Outside the contours all the strangelets with $A \leq 10^{40}$ **evaporate in few $10^{-4}s$**

green contour: $T_u = 20\ MeV$, re-heating source = **neutrinos** ⟹ $T_s < T_u,\ \rho \sim 6 \cdot 10^{11}\ g/cm^3$



red contours: $\boldsymbol{T_u = T_s = 10, 20\ MeV}$,
more efficient re-heating source $\Rightarrow$ $T_s = T_u$,
$\boldsymbol{\rho \sim 1.6 \cdot 10^{11}\ {}^{g}/_{cm^3}}$, $\boldsymbol{\rho \sim 5.9 \cdot 10^{12}\ {}^{g}/_{cm^3}}$



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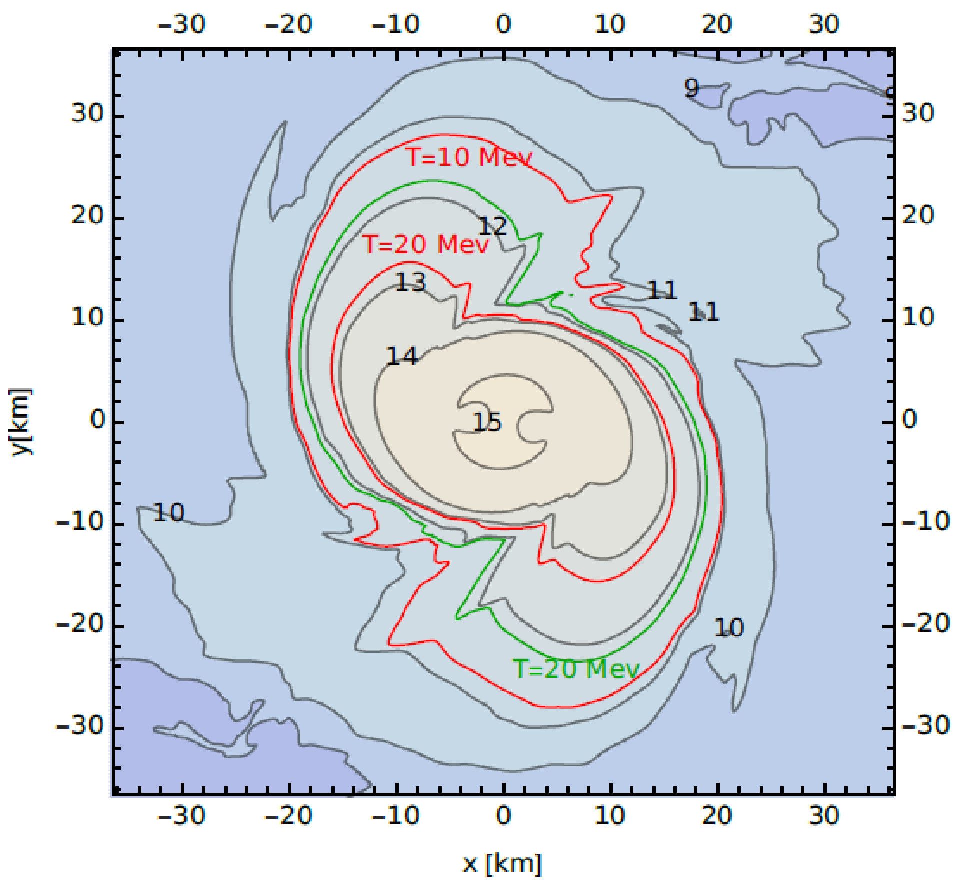
distances ~ $\boldsymbol{20, 30\ km}$

from the center of the merger



Evaporation raises the strangeness fraction on the surface

red contours: $\boldsymbol{T_u = T_s = 10, 20\ MeV}$,

more efficient re-heating source ⇨ $T_s = T_u$,

$\boldsymbol{\rho \sim 1.6 \cdot 10^{11}\ g/cm^3}$, $\boldsymbol{\rho \sim 5.9 \cdot 10^{12}\ g/cm^3}$

distances ~ **20, 30 *km***
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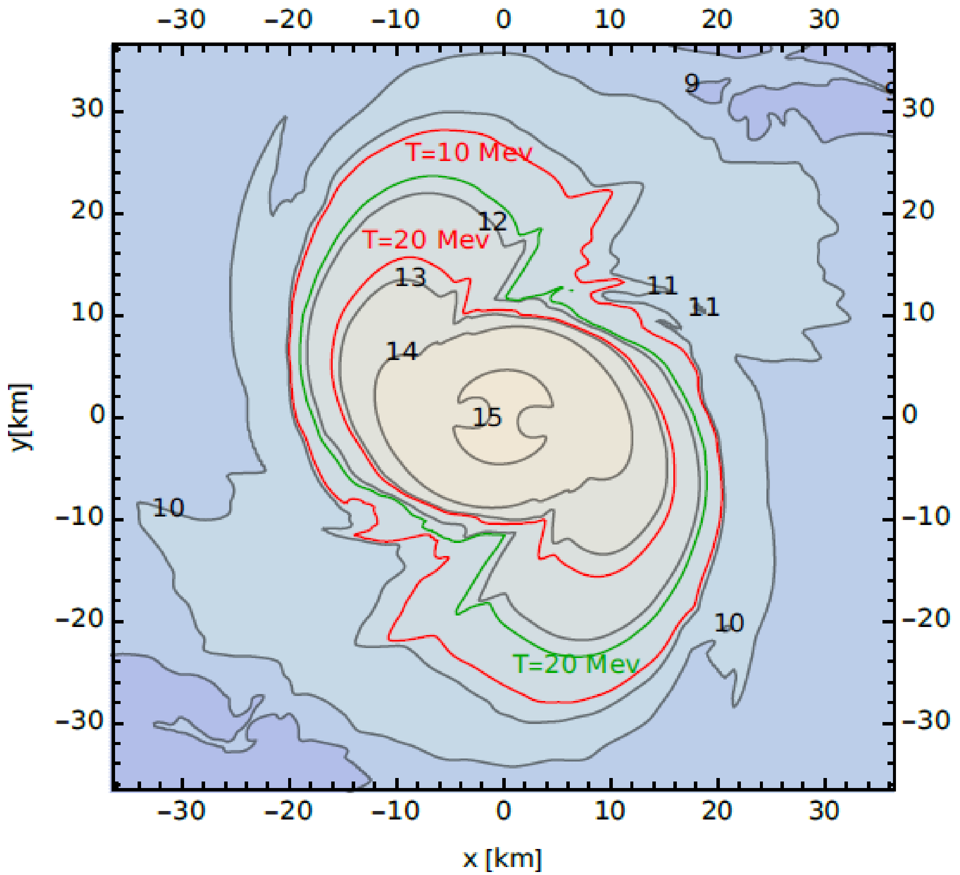

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Weak reactions need time to re-equilibrate $\frac{dA}{dt} < kG_F^2\mu_q^5 \sin\theta_c{}^2 A$

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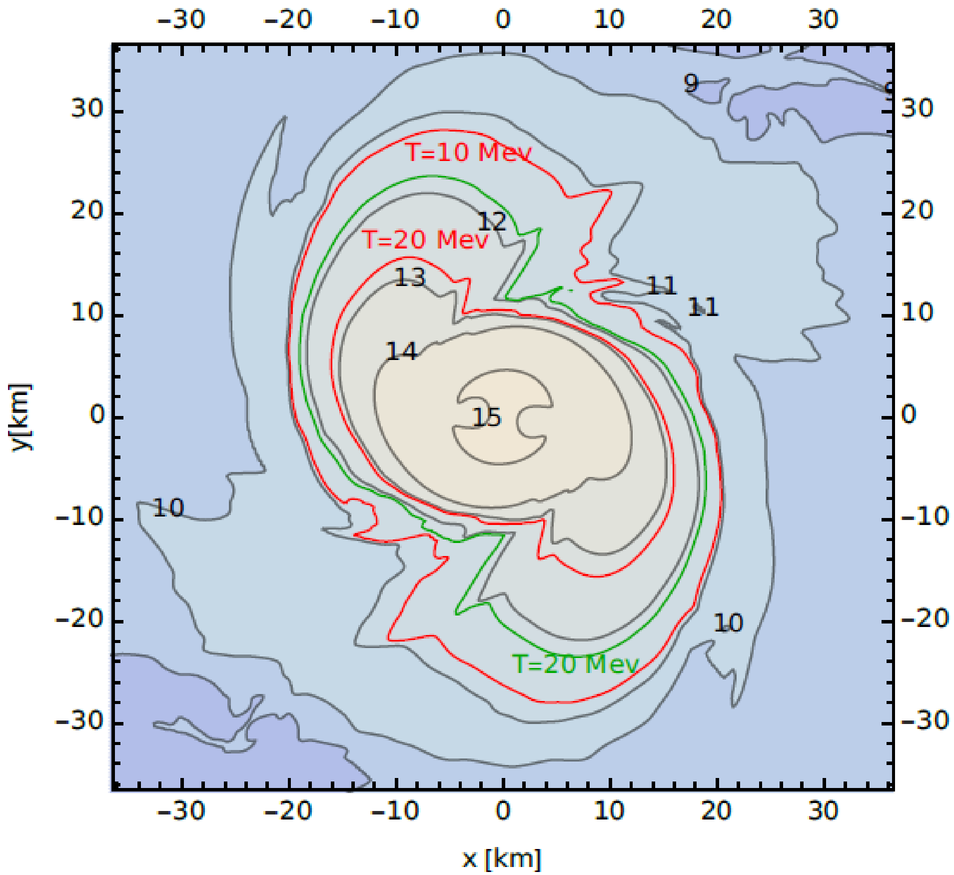

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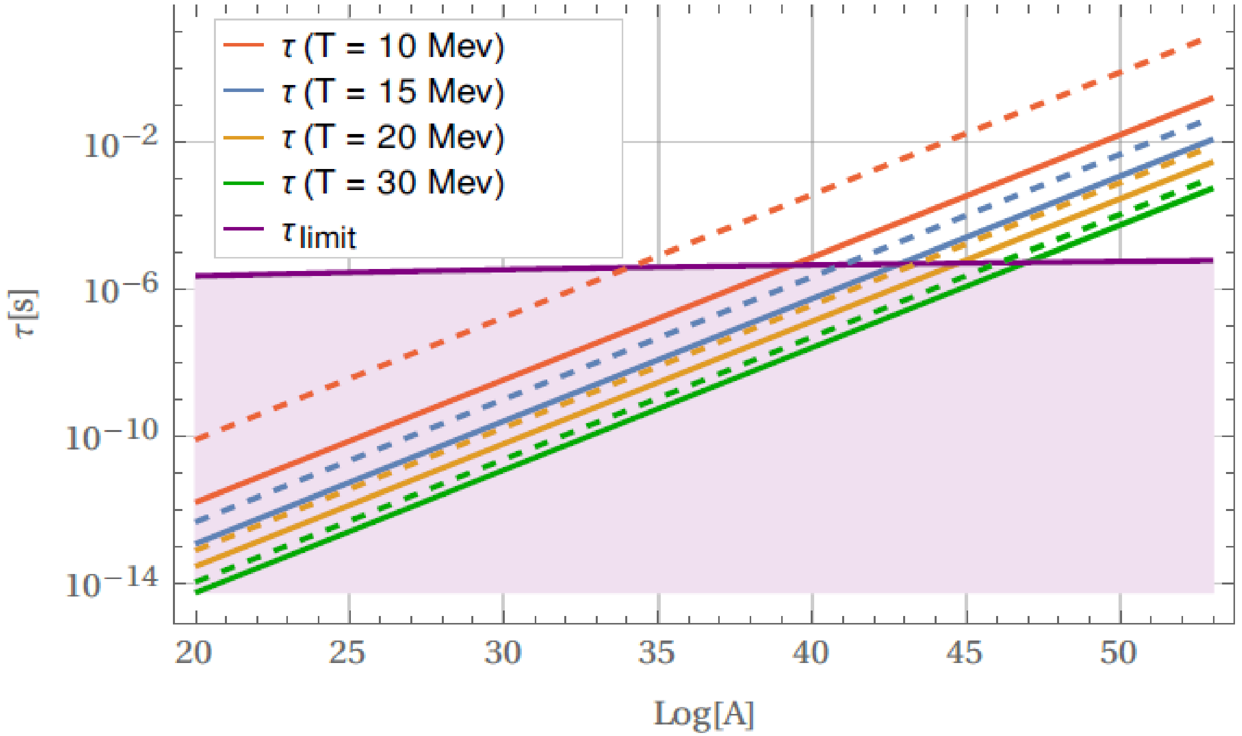

Negligible lower limit on the timescale

$\boldsymbol{\tau > 10^{-6} - 10^{-5}\ s}$

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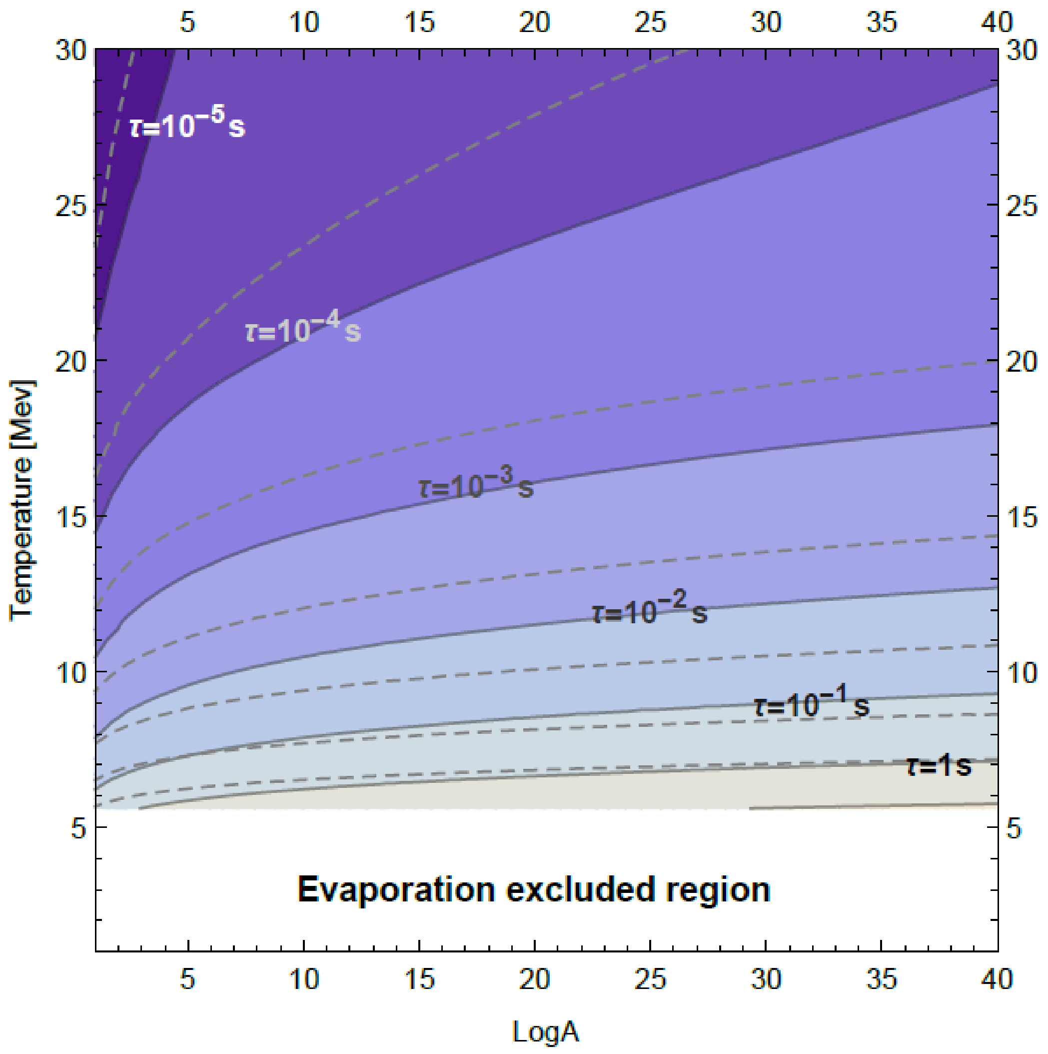

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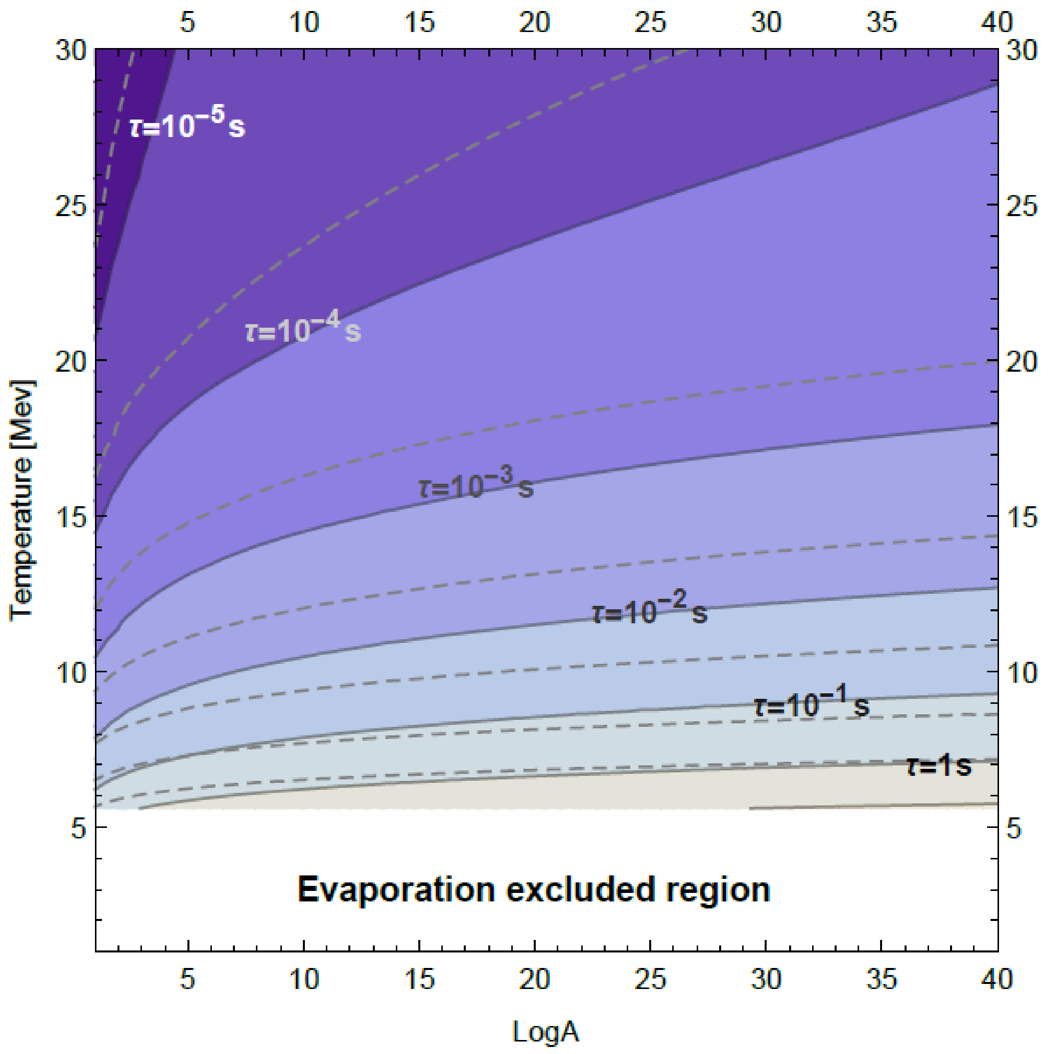
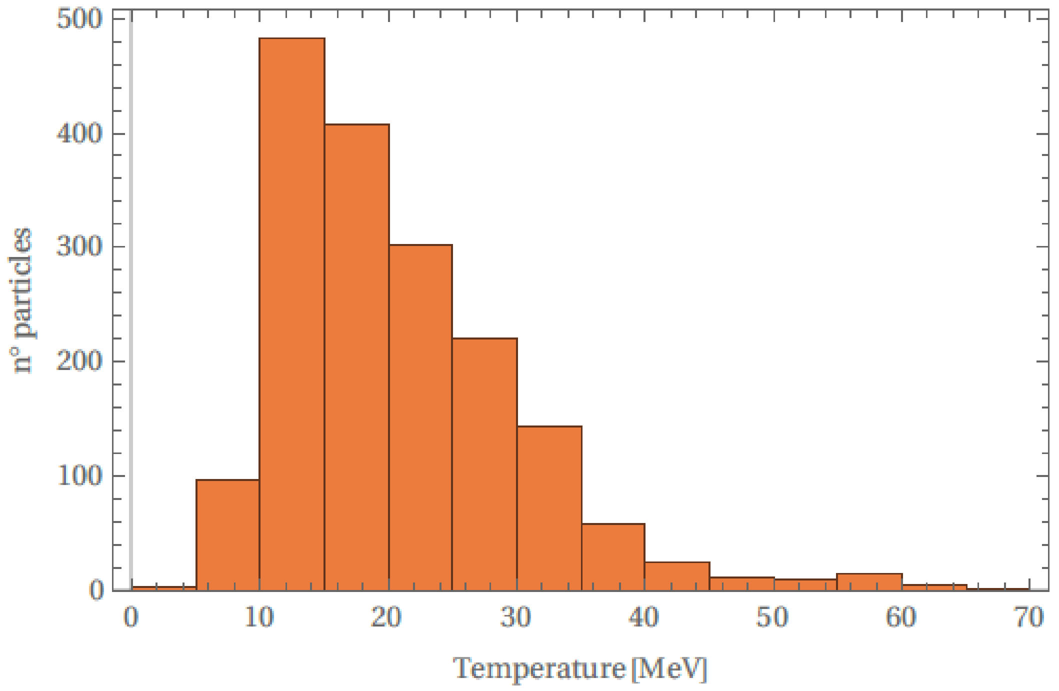
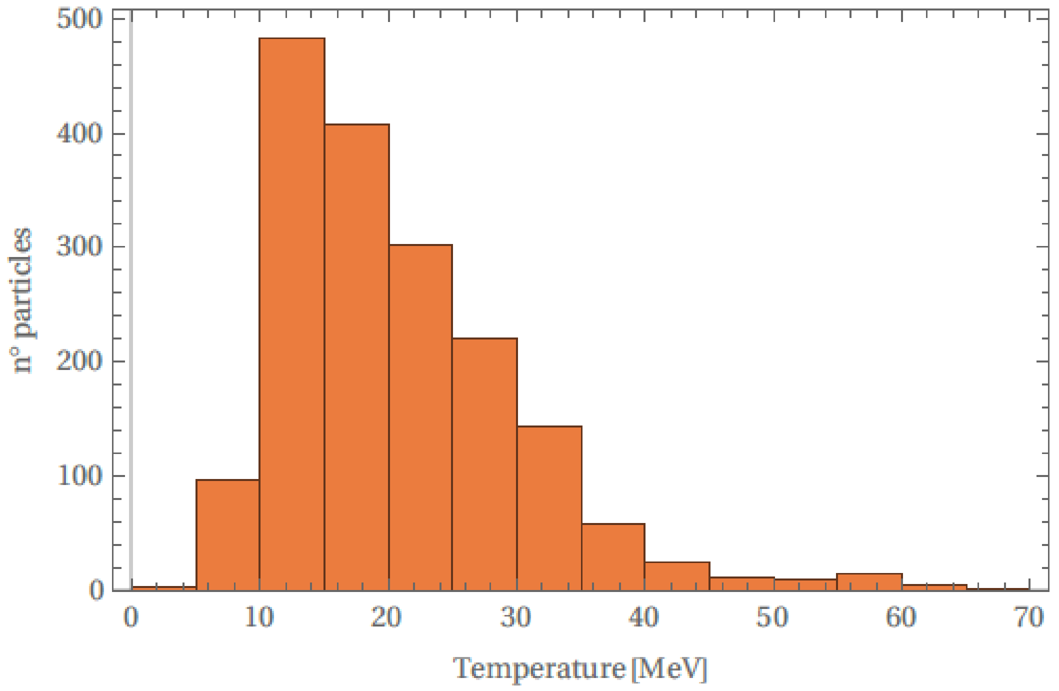


Some fragments with $\boldsymbol{A \sim 10^{30}}$ could **survive**



From quark – star quark star simulation:

(A. Bauswein, R. Oechslin, and H.-T. Janka, Phys. Rev. D 81 (2010) 024012)



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How many strangelets … ?

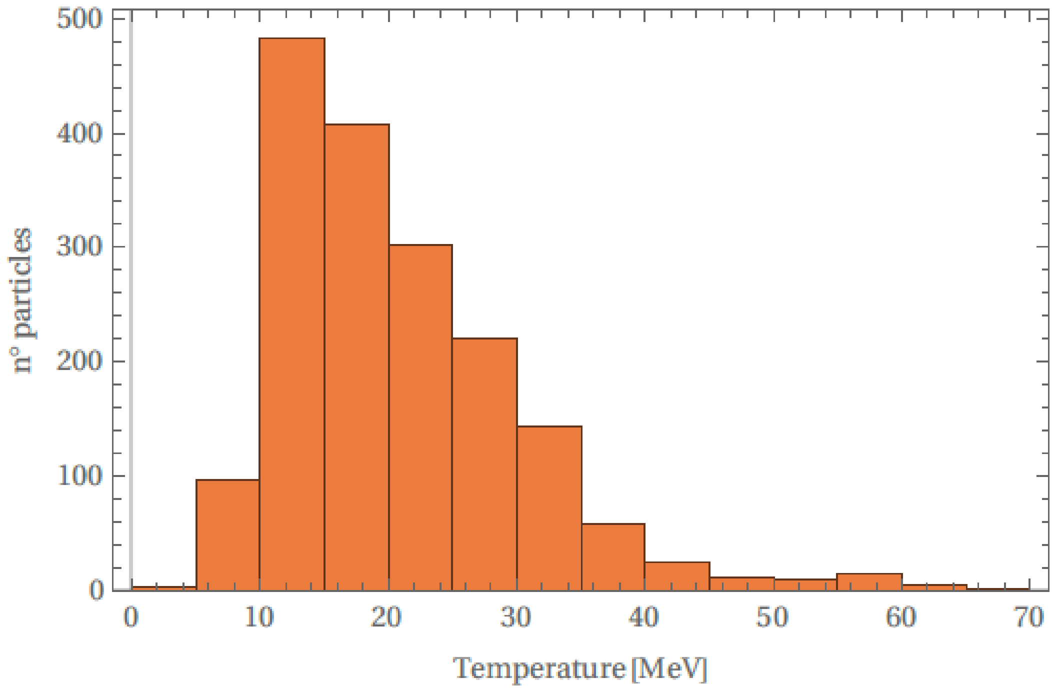
- keep $T > 13\ MeV$ for $t > 8\ ms$ or
  $T > 16\ MeV$ for $t > 1\ ms$
  evaporated
- do not fulfill any of the two conditions
  remain
- have a temperature that is still increasing at end of the simulation
  increasing

	100 % evaporated	99.9 % evaporated	99 % evaporated	total evaporated mass
I=50 MeV	0.64-0.73	0.83-0.91	0.85-0.92	0.88-0.94
I=70 MeV	0.57-0.65	0.78-0.86	0.81-0.88	0.83-0.90

ν-heating: **≈70%** evaporate

$T_u = T_s$: **94%** evaporate

(total ejecta = $6.6 \cdot 10^{-3} M_{\odot}$)



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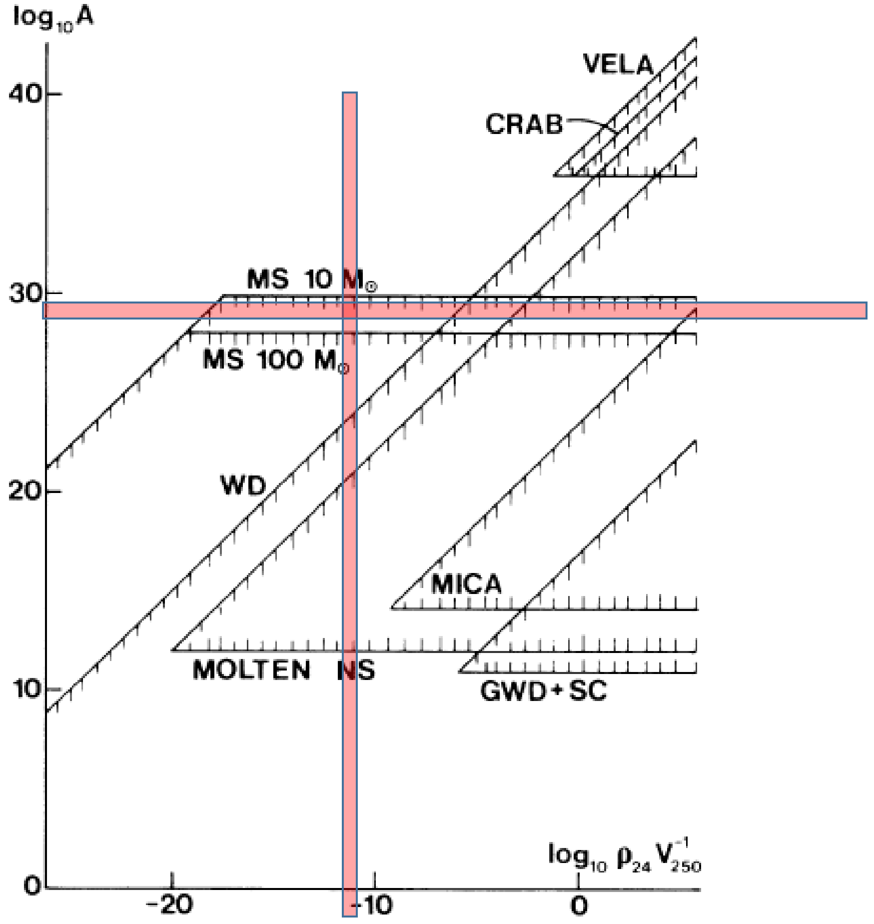
Some strangelets evaporate partially: **≈90% of the mass** evaporates

Conclusions

- Most of the strangelets ejected during the merger evaporate
- non-evaporating strangelets are massive $A \sim 10^{30}$ and their number is small and so they are very unlikely to be detected in experiments
- evaporation is dominated by neutrons and therefore the initial electron fraction of the material is really low: same KN as NS-NS



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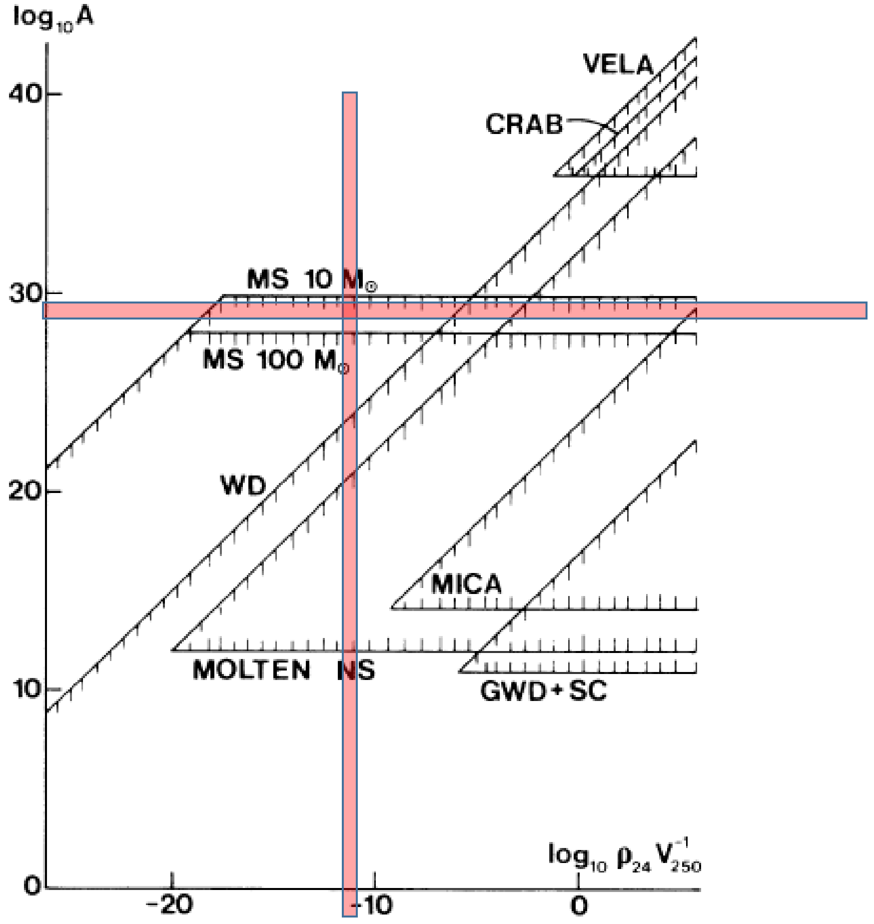

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THANK YOU