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Numerical studies of the imprints of thermal effects in the gravitational wave signals of long-lived remnants of BNS mergers

Davide Guerra

With the collaboration of Toni Font, Pablo Cerda-Duran, Milton Ruiz, Michele Pasquali

ASFAE 2024 workshop – University of Alicante

Going to talk about…

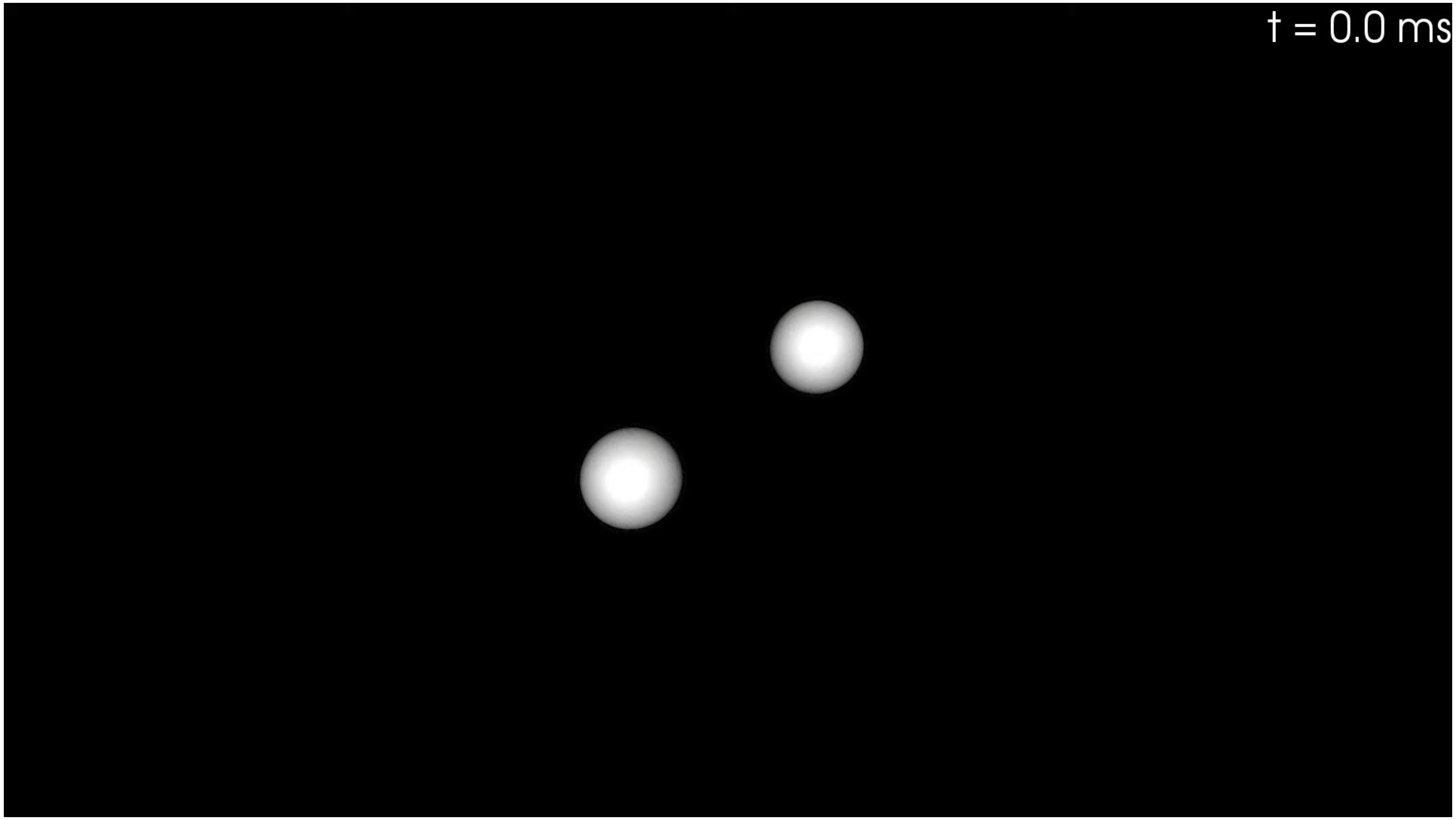
I. Binary Neutron Stars (BNSs) mergers
   - GW signal: main frequencies and where to find them
   - Long-term simulations

II. Neutron Star Equation of States (EOS)
   - Different approaches: hybrid vs tabulated
   - Thermal effects and imprints in the GW signal
   - Defining Temperature

III. Conclusions and future projects

Binary Neutron Stars mergers

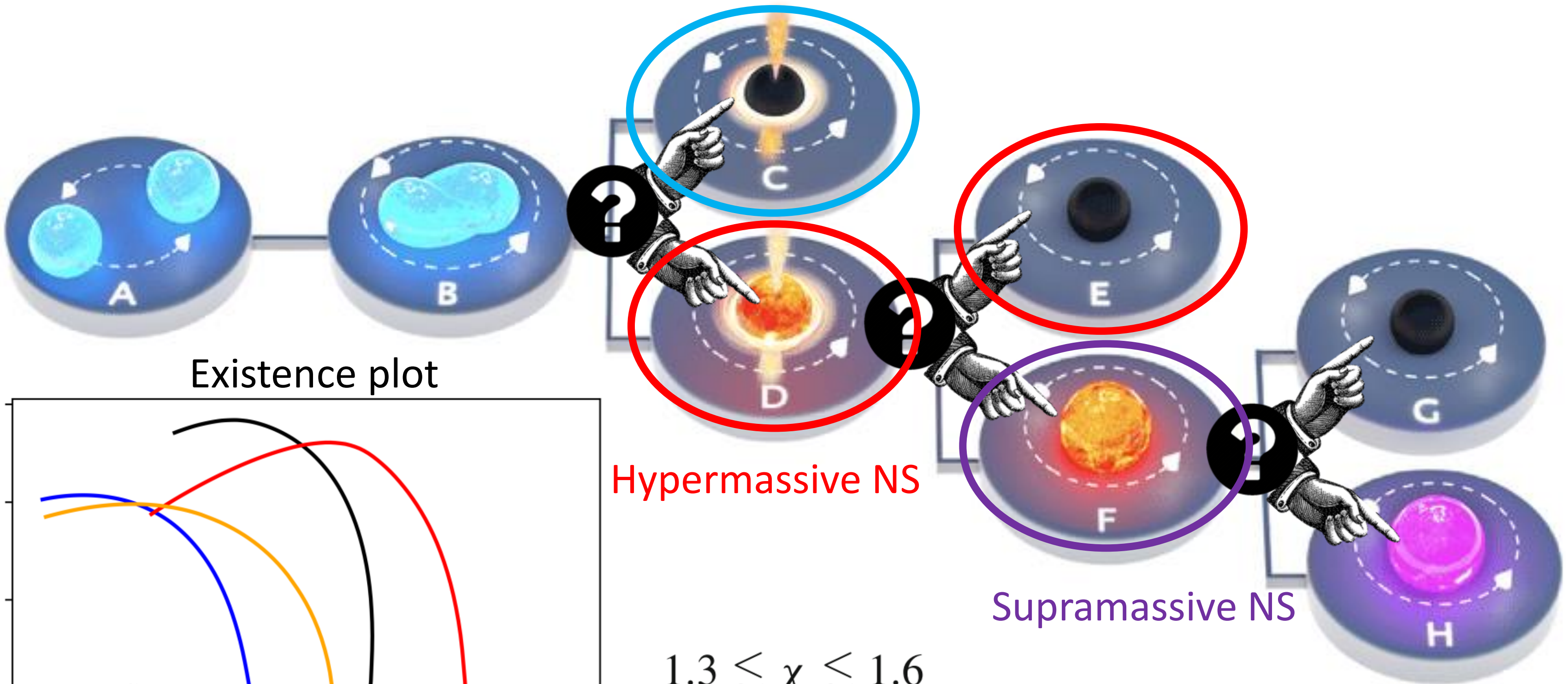
BNSs mergers



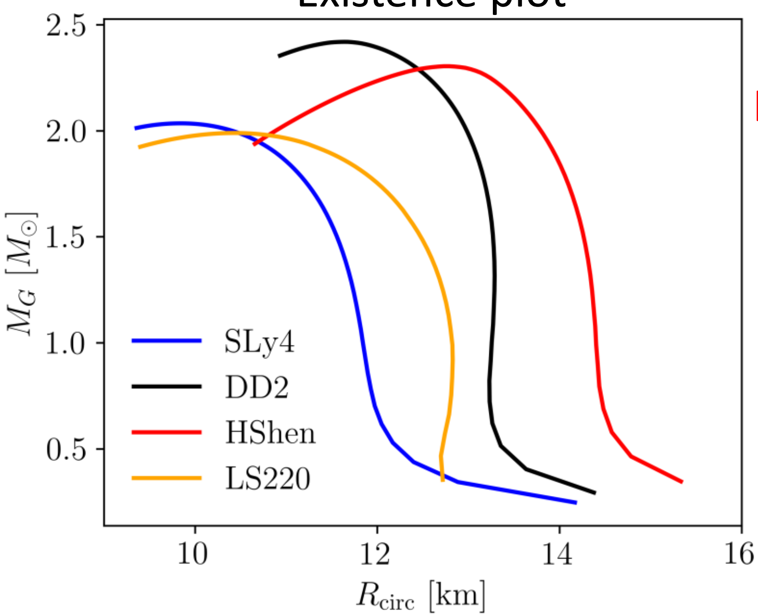
[T. Kawamura et al - Phys. Rev. D 94, 064012 (2016)]

BNSs mergers

[N.Sarin, P.D.Lasky -DOI:10.1007/s10714-021-02831-1]



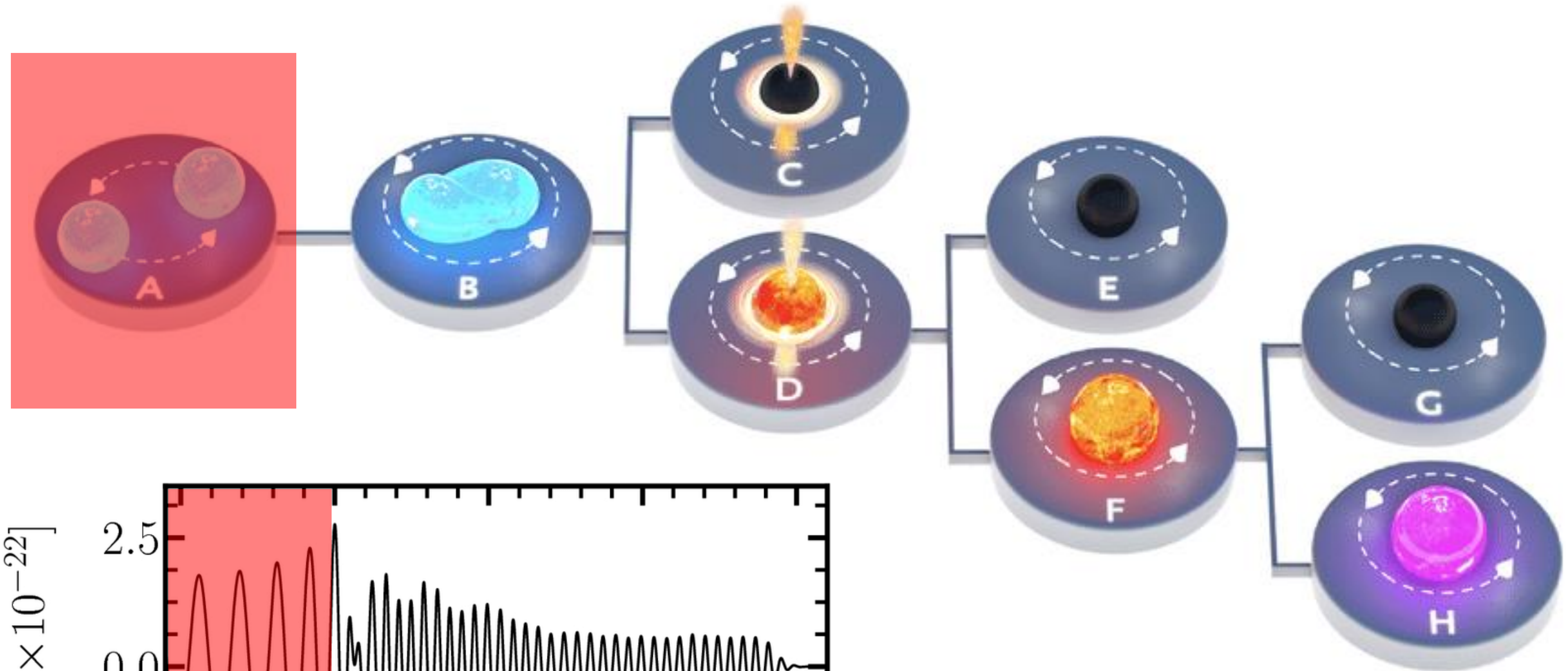
Existence plot

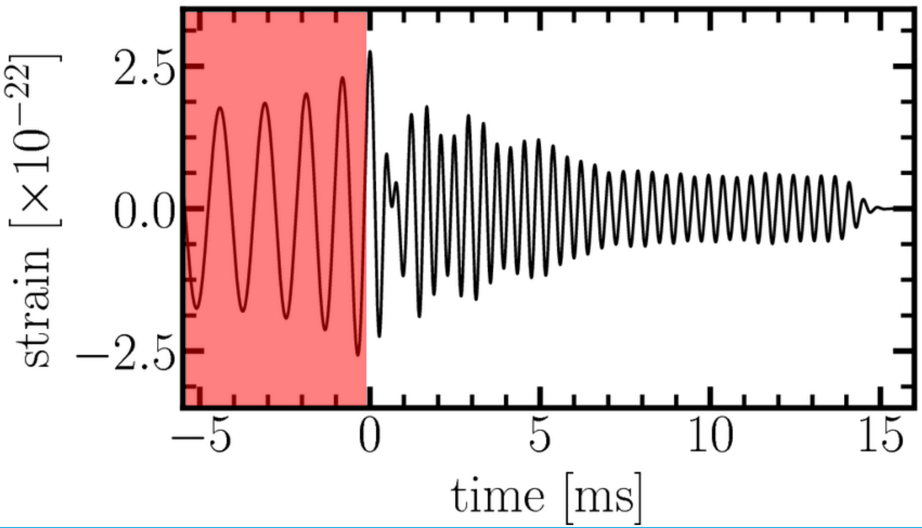


$$1.3 \lesssim \chi \lesssim 1.6$$

- $M \gtrsim \chi\, M_{\rm TOV}$
- $1.2\, M_{\rm TOV} \lesssim M \lesssim \chi\, M_{\rm TOV}$
- $M_{\rm TOV} < M \lesssim 1.2\, M_{\rm TOV}$

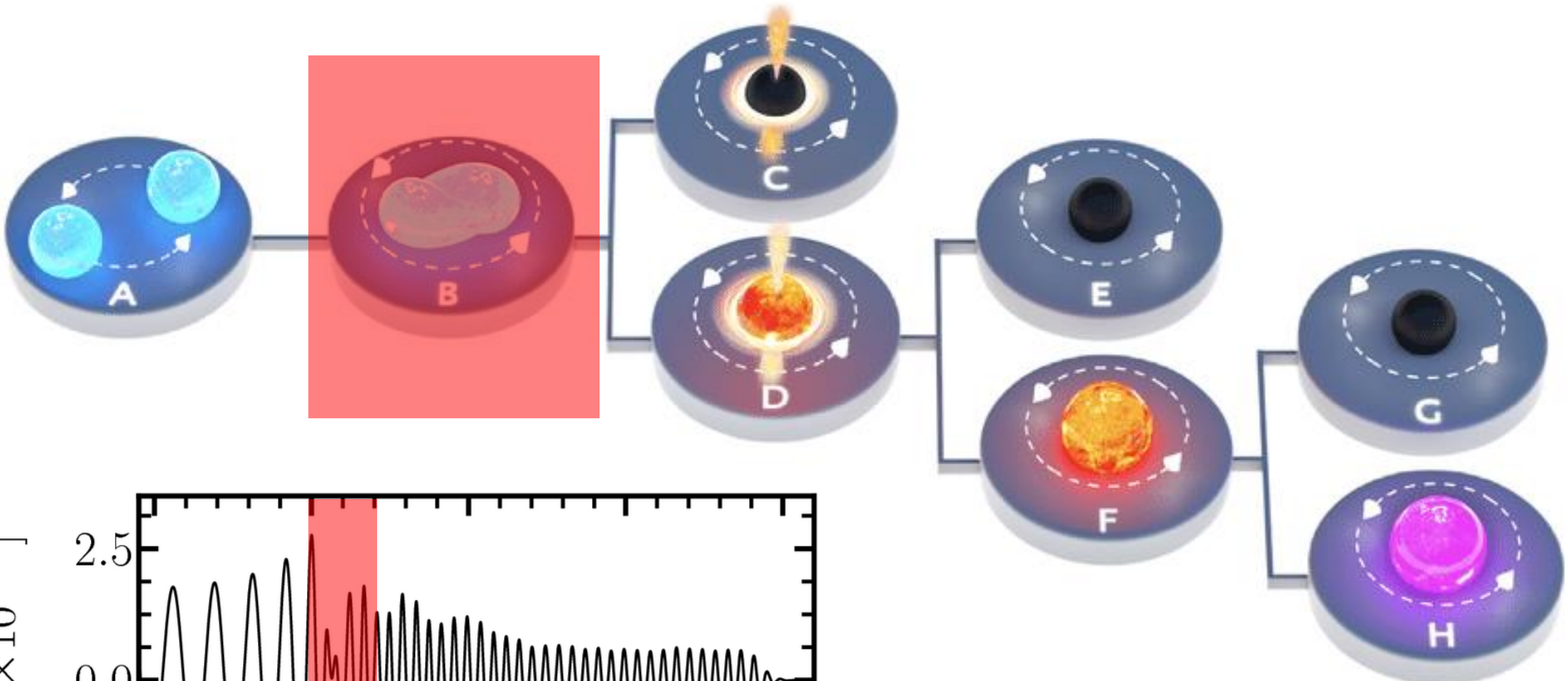
BNSs mergers

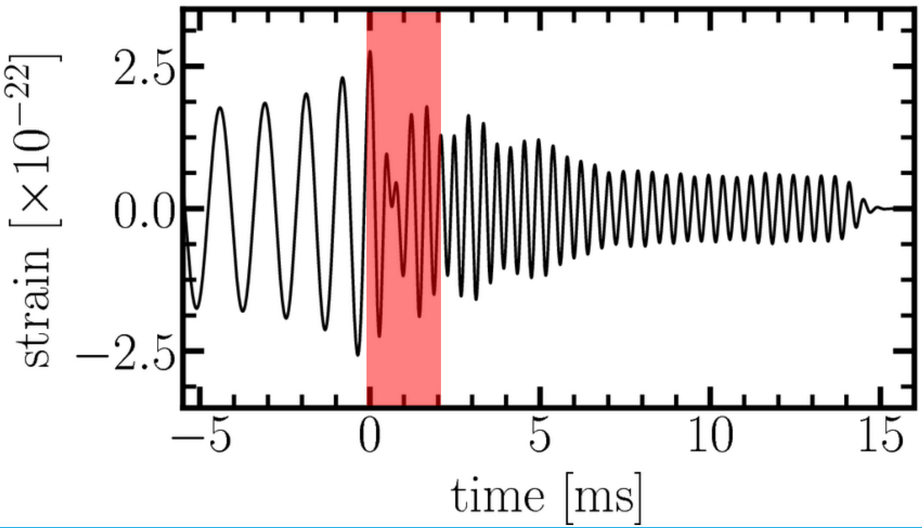




Chirp signal

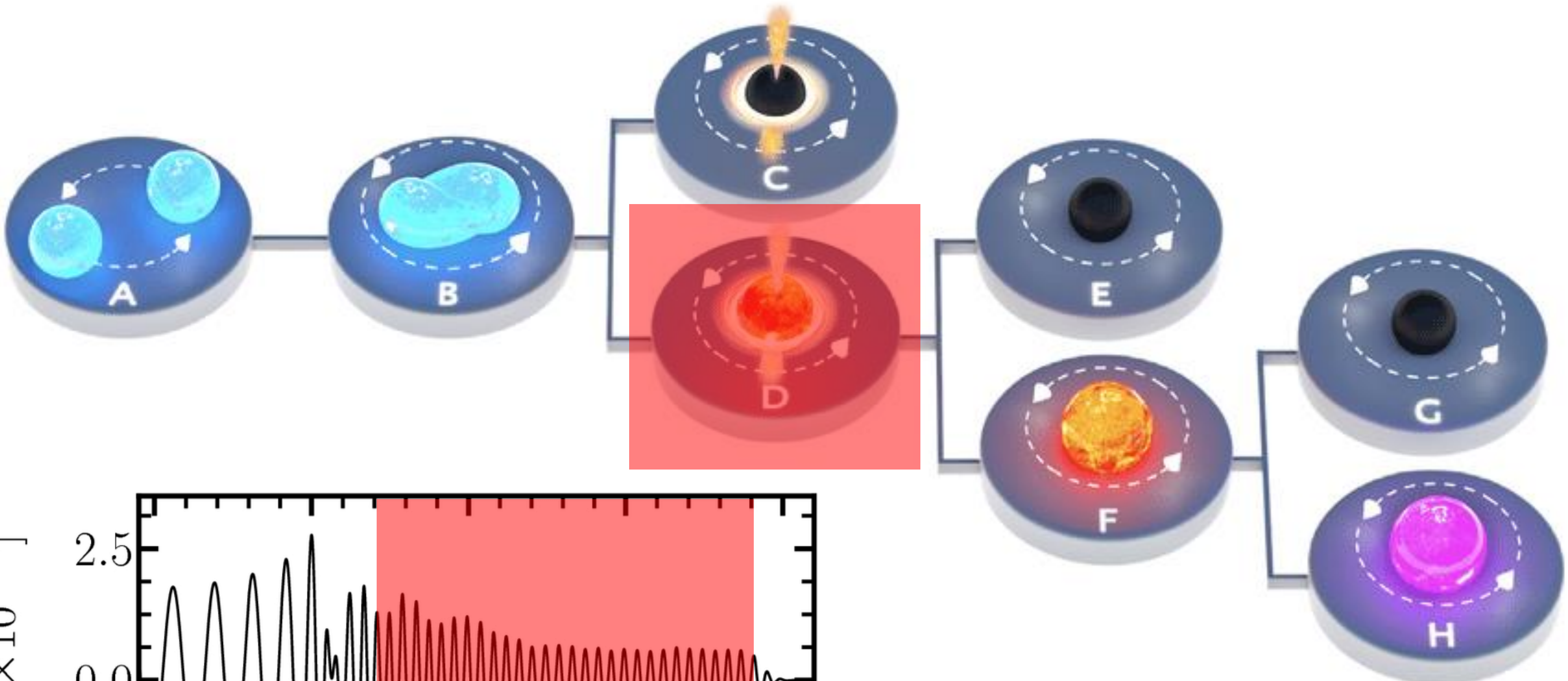
BNSs mergers

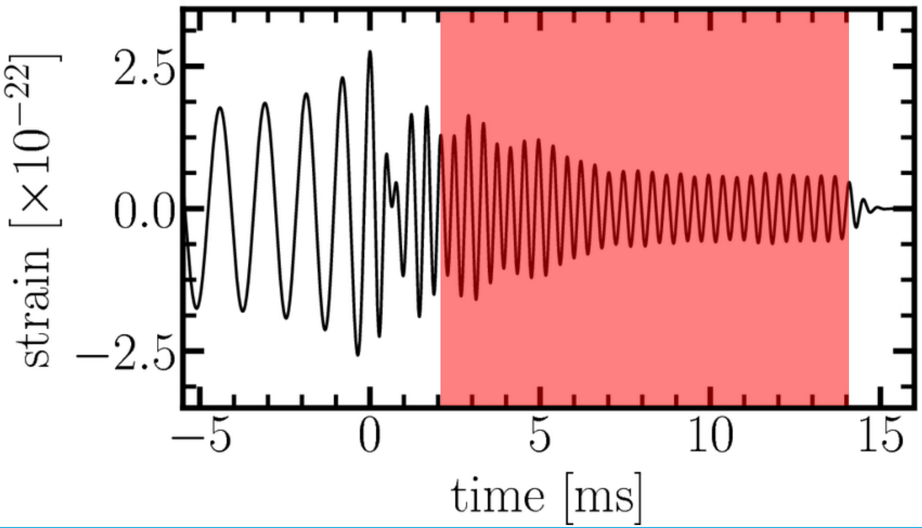




Transient

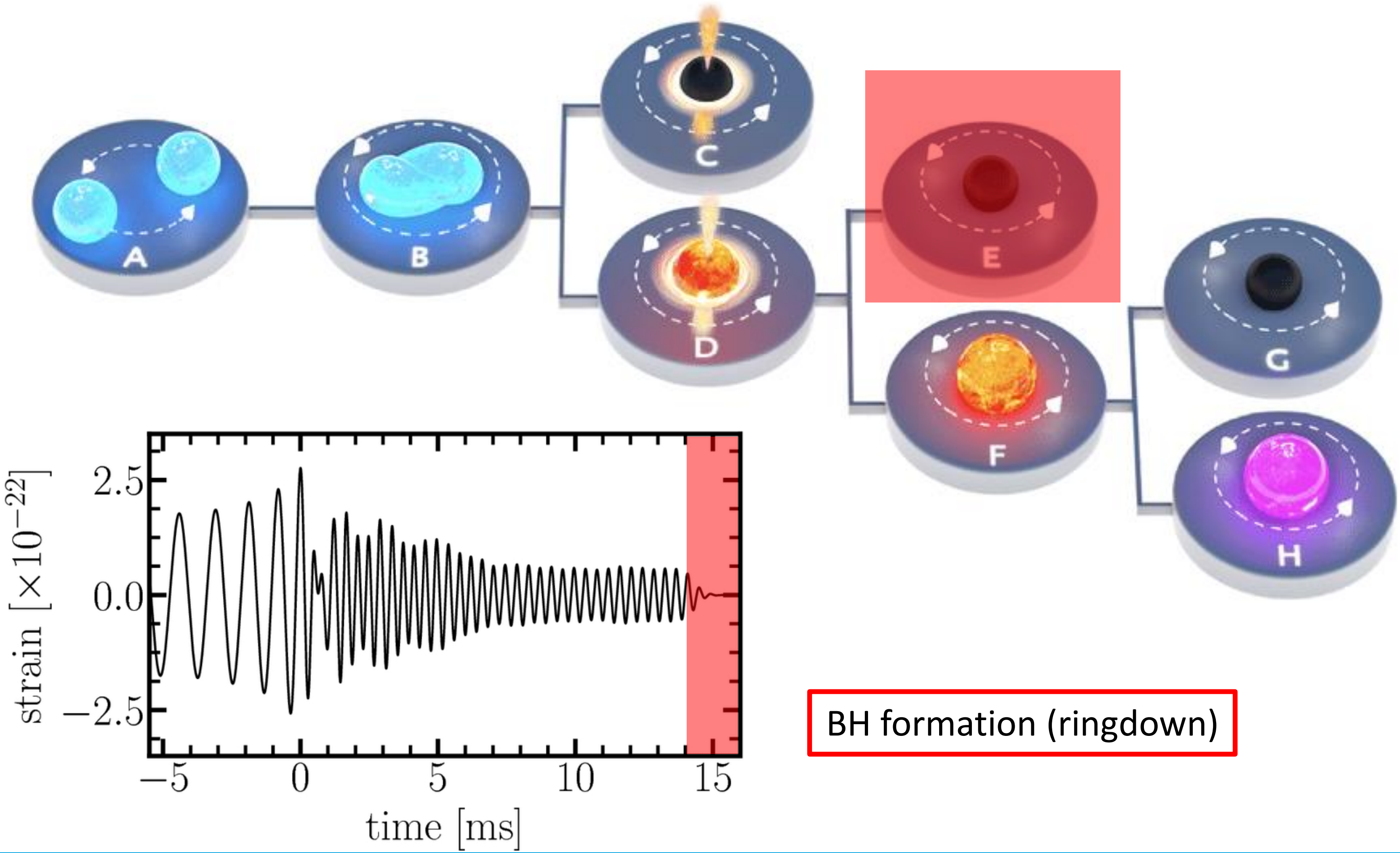
BNSs mergers





Post-merger (HMNS)

BNSs mergers

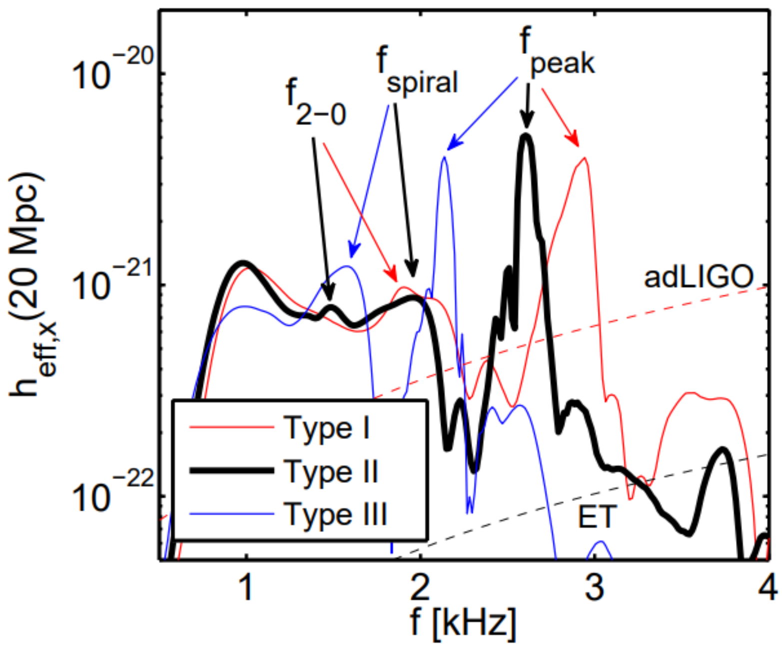


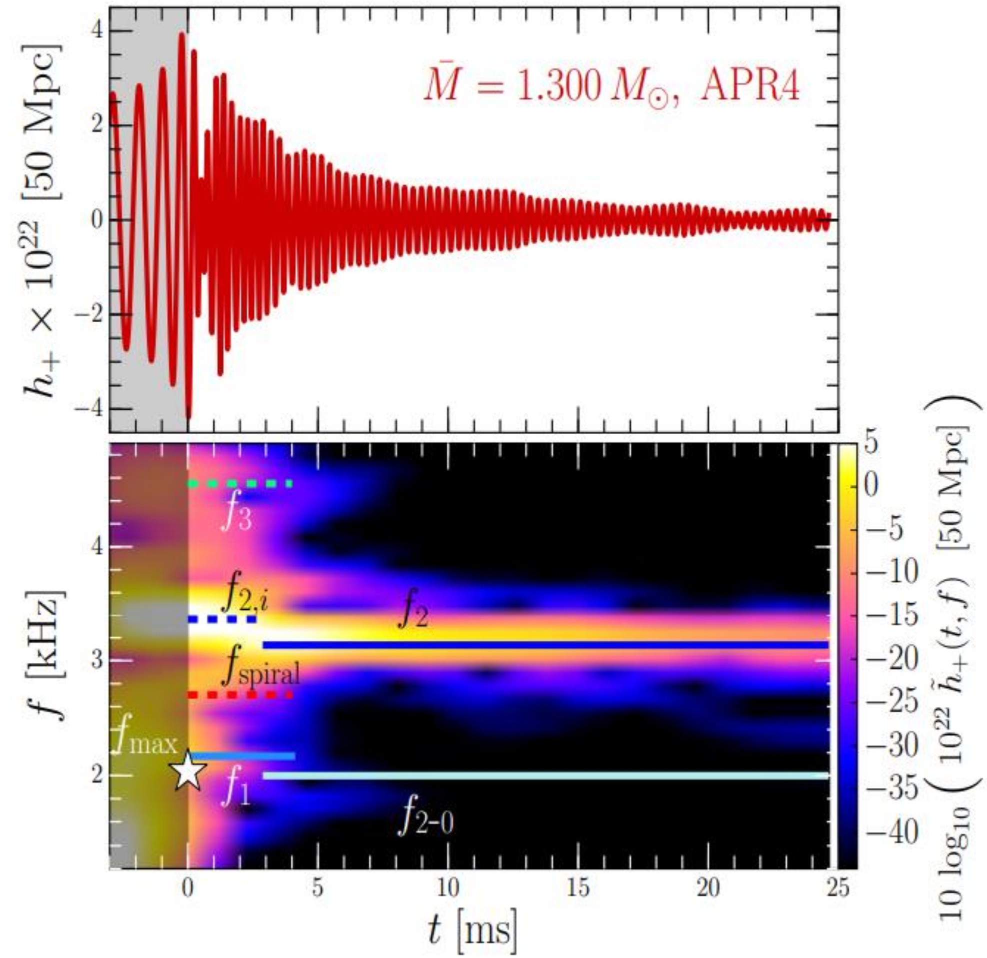
BH formation (ringdown)

GW spectroscopy

[L.Rezzolla and K.Takami (2016)]

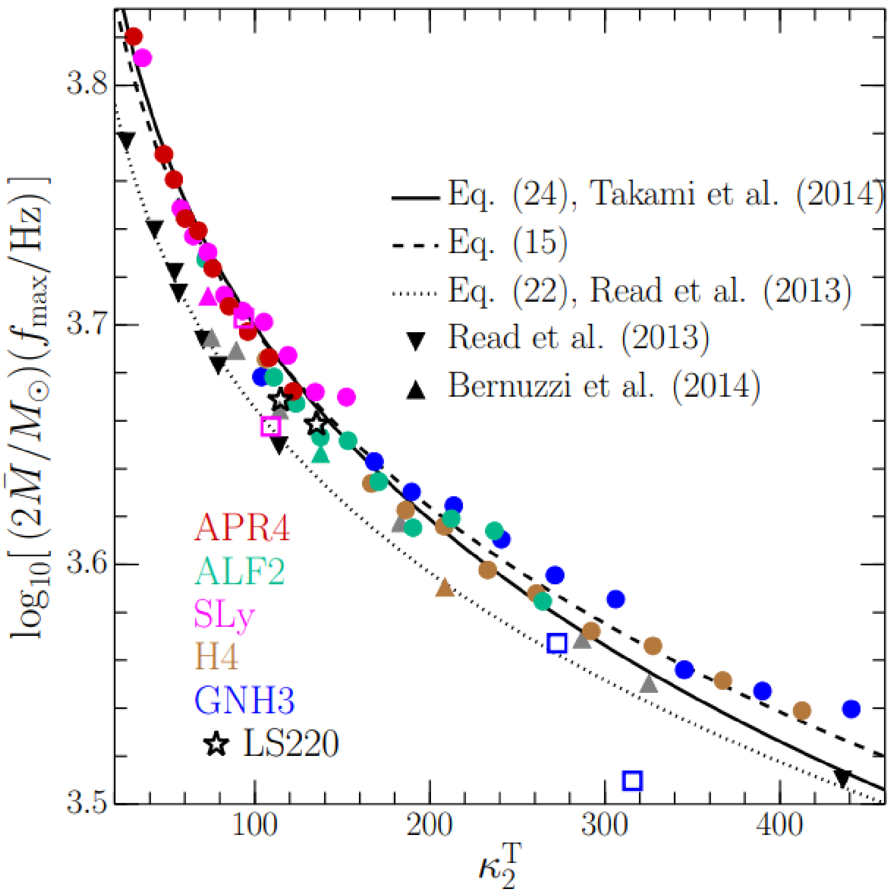
[A.Bauswein and N.Stergioulas (2018)]





GW spectroscopy: quasi-universal relations

[L.Rezzolla and K.Takami (2016)]



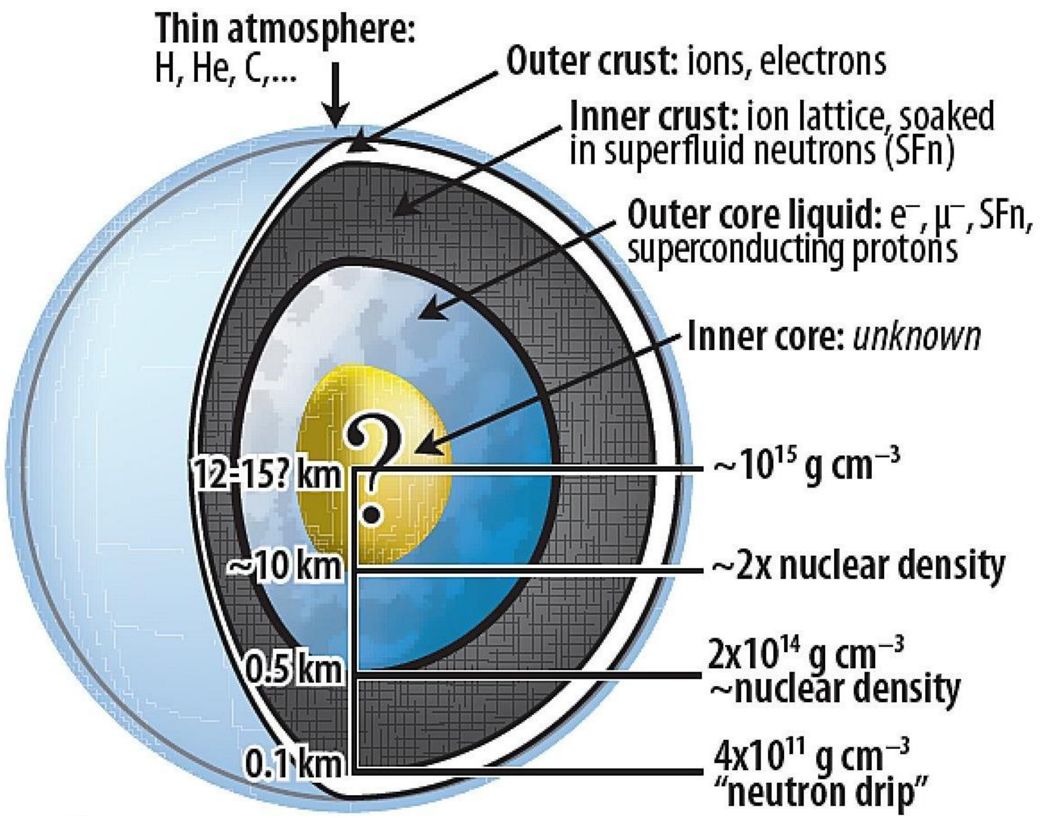
$$\log_{10}\left(\frac{f_{\rm max}}{\rm kHz}\right) \approx a_0 + a_1 \left(\kappa_2^T\right)^{1/5} - \log_{10}\left(\frac{2\bar{M}}{M_{\odot}}\right)$$

$$\kappa_2^T \equiv \frac{1}{8}\bar{k}_2\left(\frac{\bar{R}}{\bar{M}}\right)^5 = \frac{3}{16}\Lambda = \frac{3}{16}\frac{\lambda}{\bar{M}^5}$$

Neutron Stars EOSs

Neutron Star EOSs

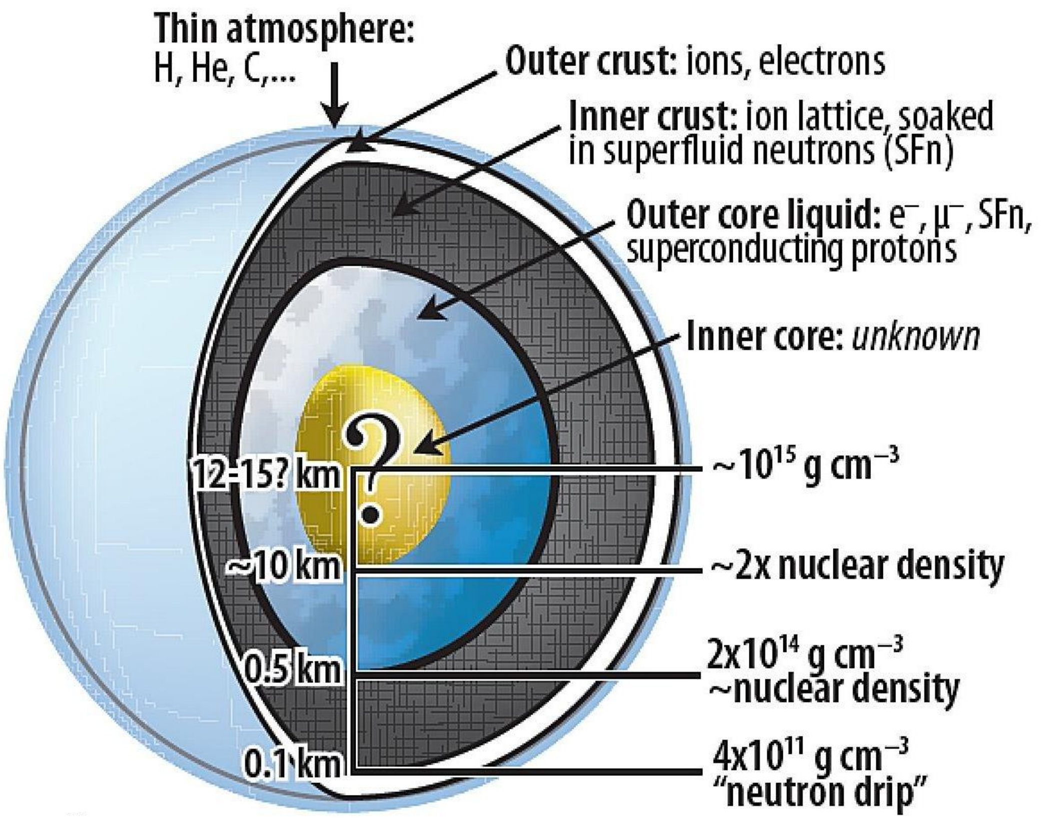
[credits: eoPortal, NASA, NICER Team]



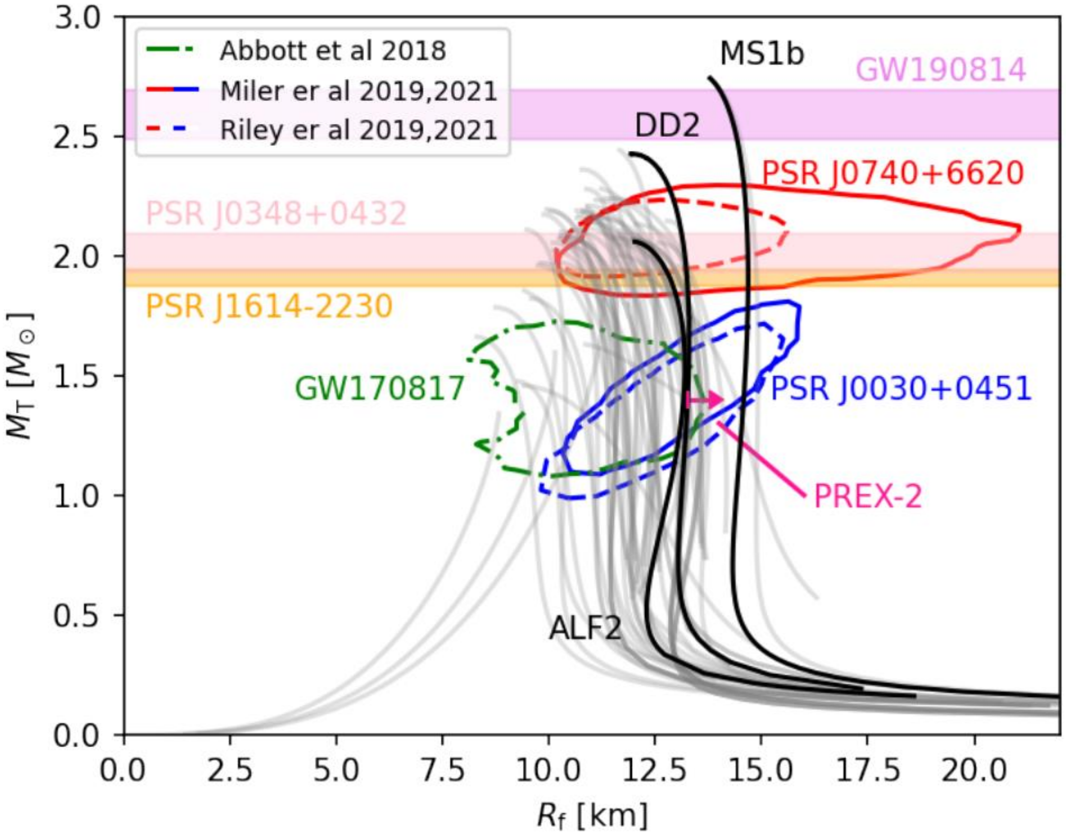
Neutron Star EOSs

- Which are the correct thermodynamic EOSs for cold matter above nuclear saturation density? (hyperon, kaon, pion condensates, strange quark matter…)
- And for hot matter?
- Can relativistic astrophysics help with NS measurements to contrain the nuclear EOS?

[credits: eoPortal, NASA, NICER Team]



Neutron Star EOSs



[F.Di Giovanni et al, Phys. Rev. D 105, 063005 (2022)]

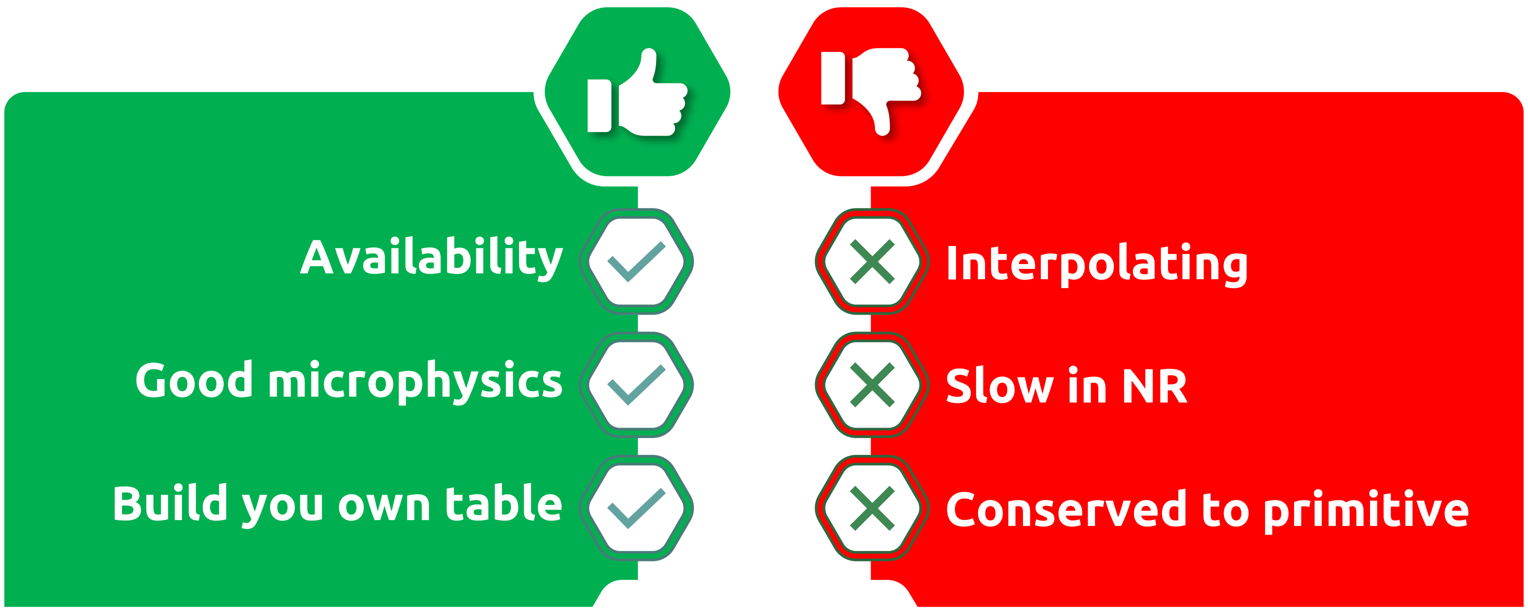
Construct static spherically symmetric star:

- TOV solver (own one, Lorene, RNS)
- Tabulated Cold EOS in beta-equilibrium

Tabulated EOSs

- Building EOSs (we don't do it here)

- User point of view:



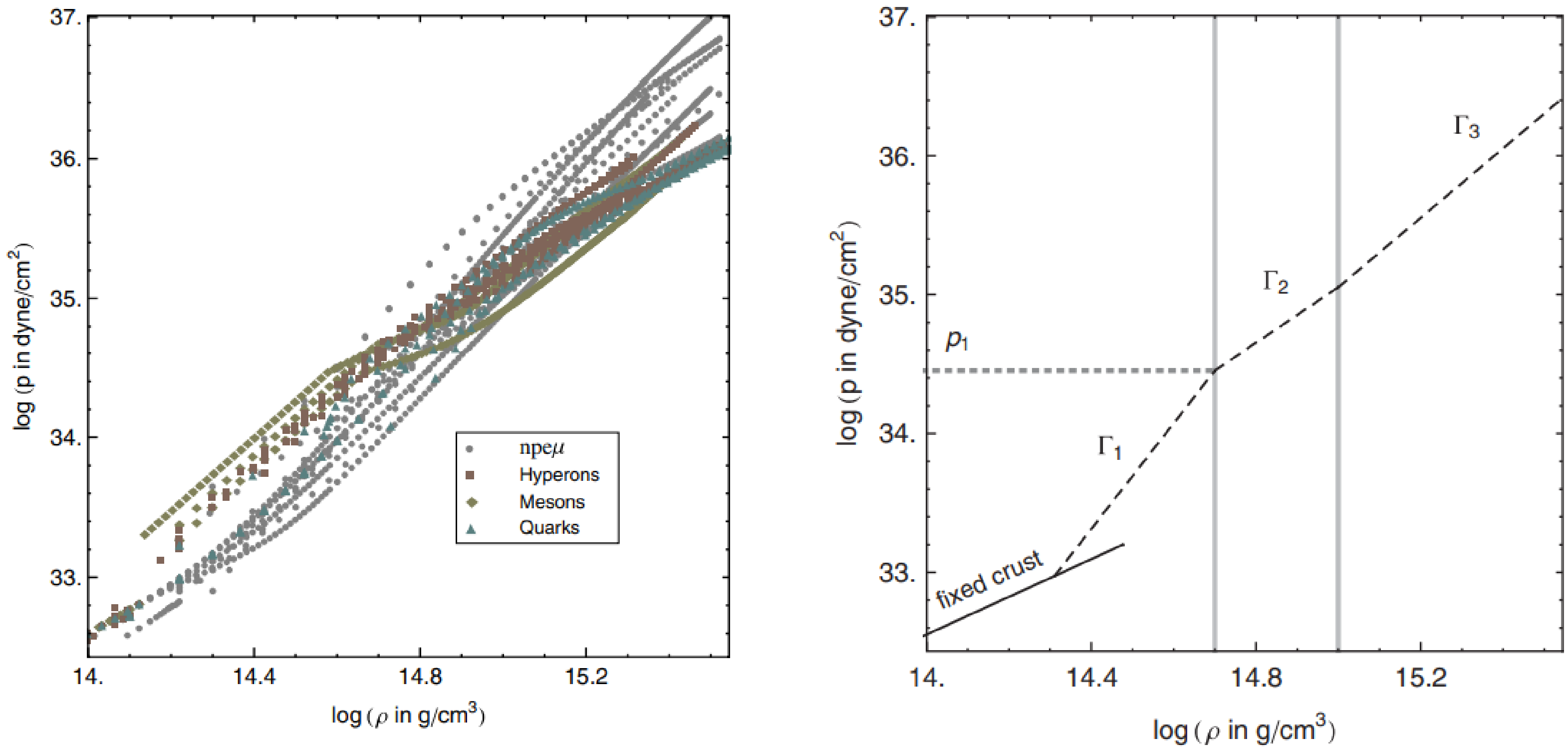
FIT: piecewise polytropic EOSs

PHYSICAL REVIEW D **79,** 124032 (2009)

Constraints on a phenomenologically parametrized neutron-star equation of state

Jocelyn S. Read,[1] Benjamin D. Lackey,[1] Benjamin J. Owen,[2] and John L. Friedman[1]

[1]*Department of Physics, University of Wisconsin-Milwaukee, P.O. Box 413, Milwaukee, Wisconsin 53201, USA*
[2]*Center for Gravitational Wave Physics, Institute for Gravitation and the Cosmos, and Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802-6300, USA*
(Received 22 January 2009; published 22 June 2009)



FIT: piecewise polytropic EOSs

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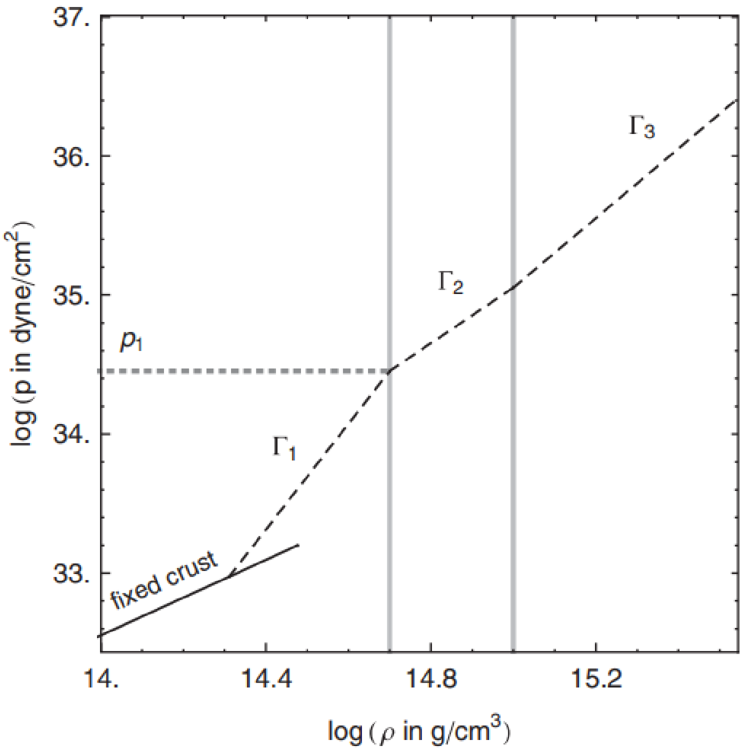
$$p(\rho) = K\rho^{\Gamma},$$

$$\frac{\epsilon}{\rho} = (1+a) + \frac{1}{\Gamma - 1}K\rho^{\Gamma-1},$$

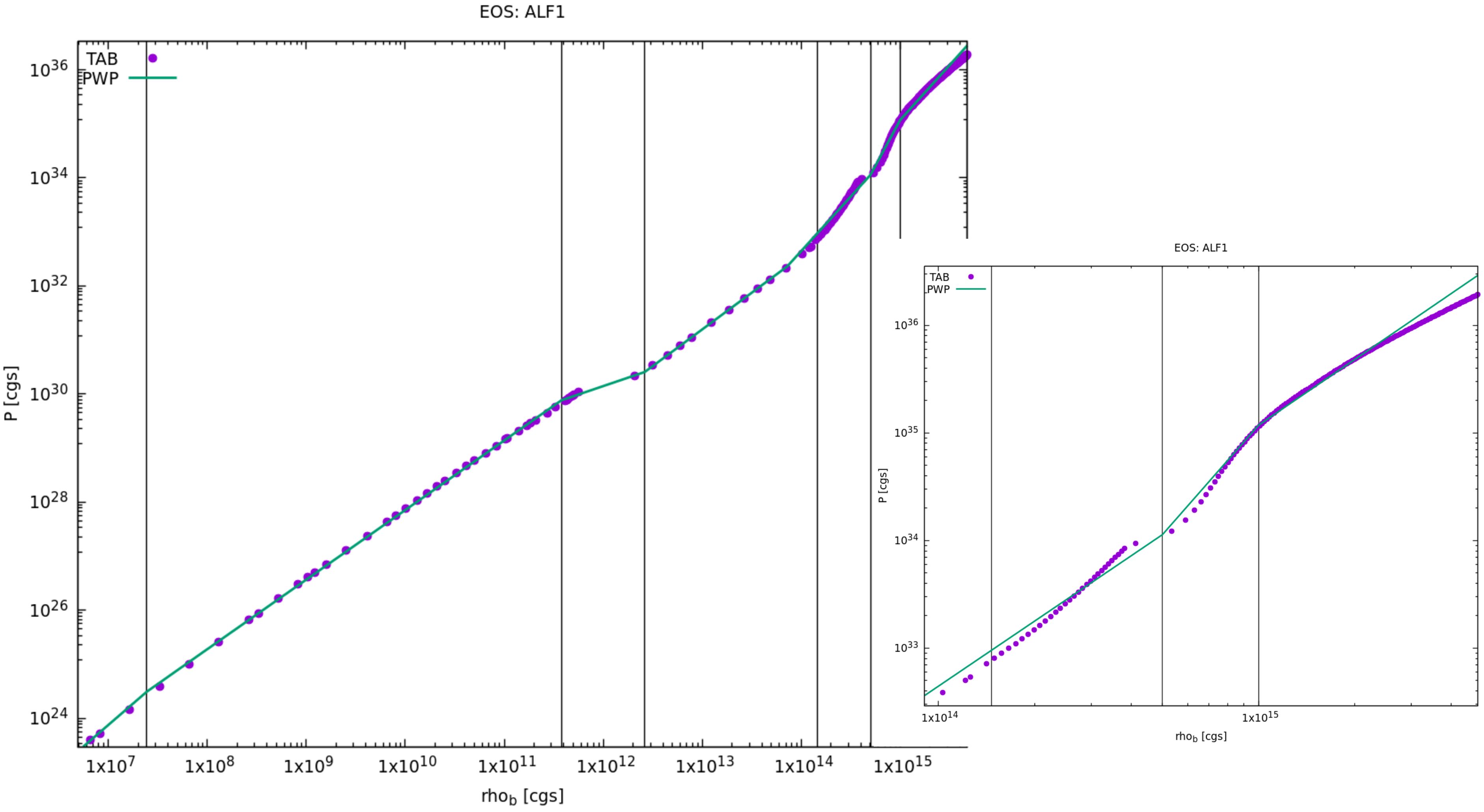


Piecewise Politropic fit

$$p(\rho) = K_i\rho^{\Gamma_i} \qquad \rho_{i-1} \le \rho \le \rho_i$$

$$d\frac{\epsilon}{\rho} = -p\,d\frac{1}{\rho} \qquad K_{i+1} = \frac{p(\rho_i)}{\rho_i^{\Gamma_{i+1}}}$$

FIT: piecewise polytropic EOSs



FIT: piecewise polytropic EOSs

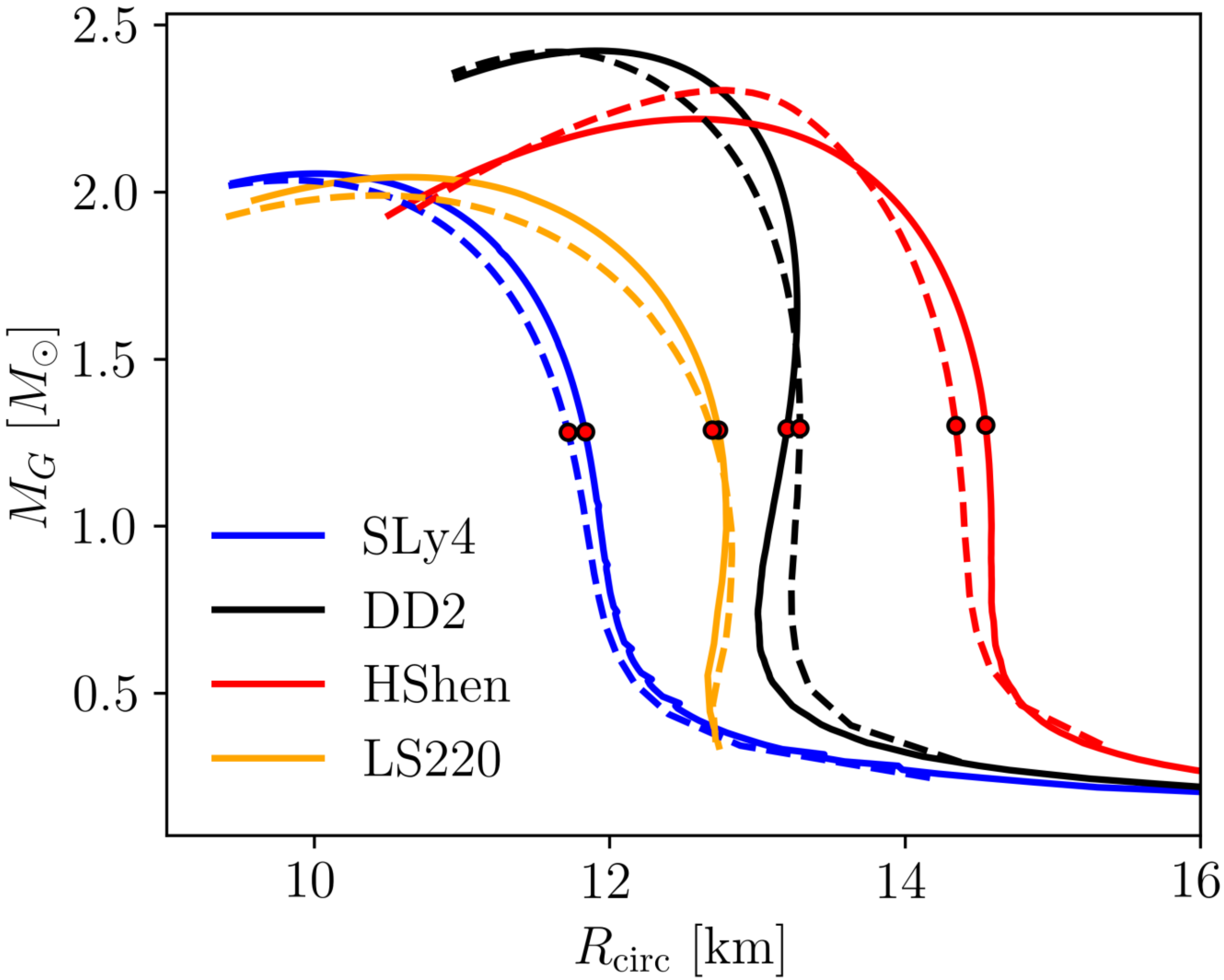
Pros

- Analytical expression
- Conserved to primitive
- Evaluating

Cons

- Approximation
- Trust results
- Matching points

Tabulated VS Piecewise



Tabulated VS Hybrid

- Differences: evolution!

Hybrid EOS

$$P_{TOT} = P_{cold} + P_{th} = P_{pwp} + K\rho^{\Gamma_{th}}$$

- computationally faster
- not the best physics

$$T = (\Gamma_{th} - 1)\epsilon_{th}$$

Tabulated EOS

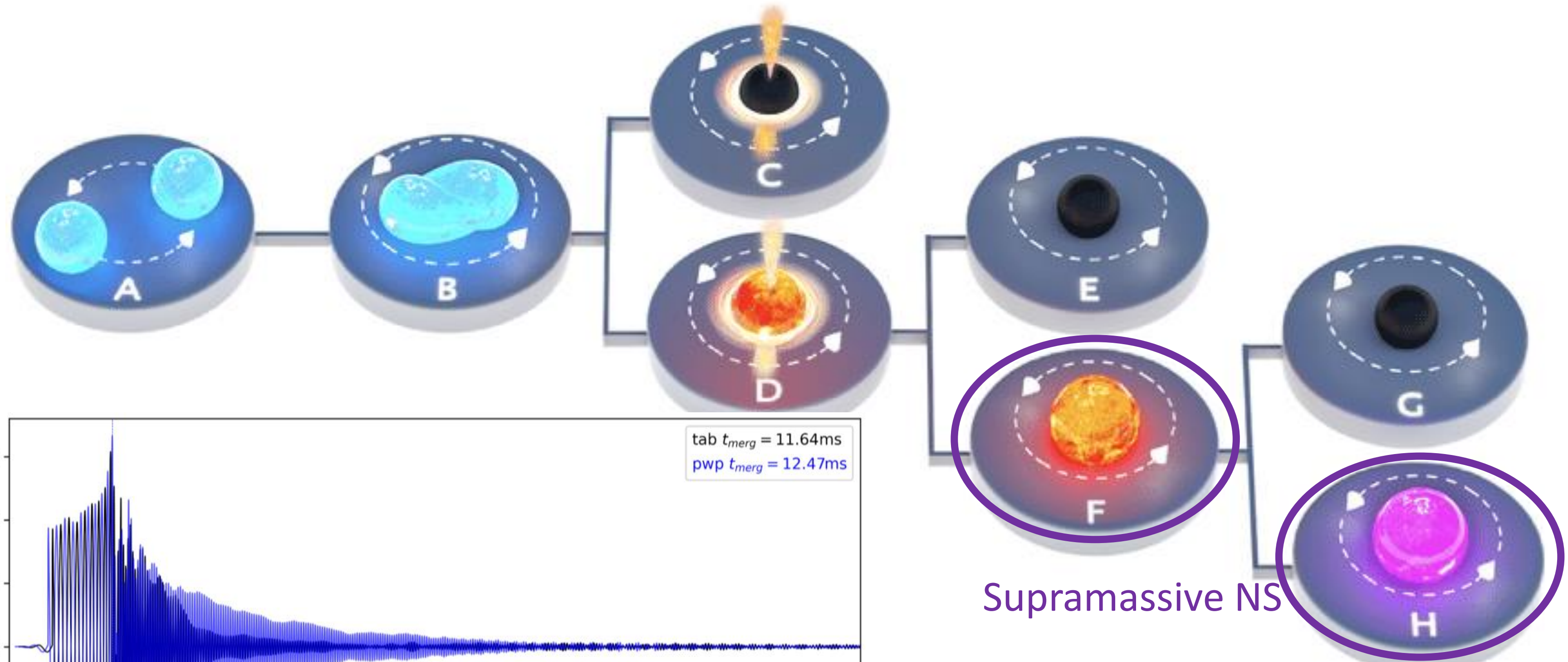
$$P_{TOT} = P(\rho, T, Y_e)$$

- interpolation for every point at every time
- good microphysics

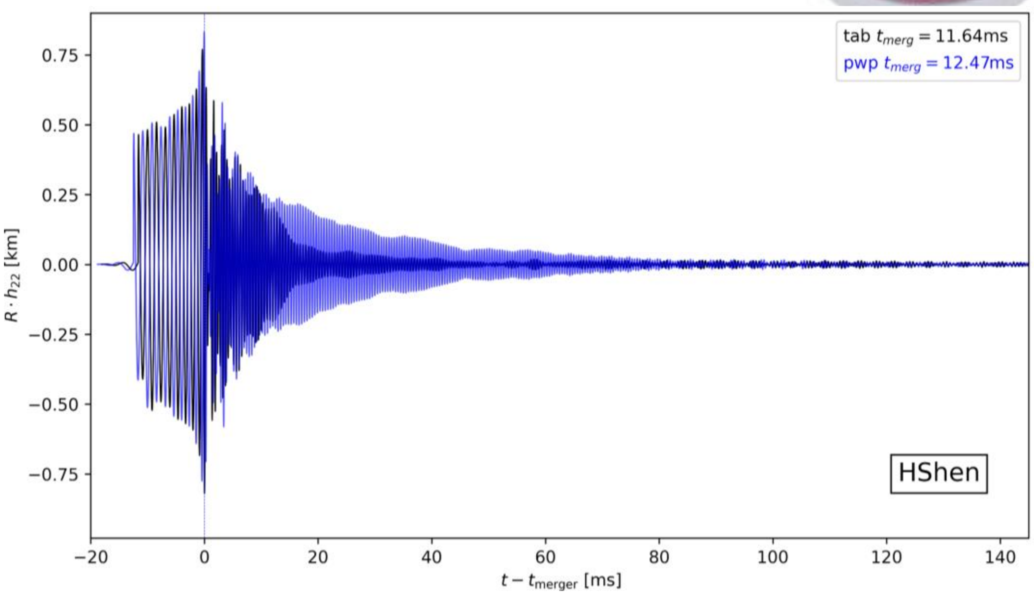
Imprinting in the GW signal?
Modes in long-remnant?

Long-term simulations

[N.Sarin, P.D.Lasky DOI:10.1007/s10714-021-02831-1]



Supramassive NS



Simulation up to $\sim 140\ ms$ after merger

Inertial modes in BNS merger remnant

Inertial Modes

Type of oscillation of matter driven by the Coriolis force due to the rotation. In the context of BNS mergers, these modes can influence the post-merger dynamics.

Emission of GW

Oscillation patters and frequencies can leave imprints on the GW spectrum, providin clues about the internal structure and dynamics of the NS

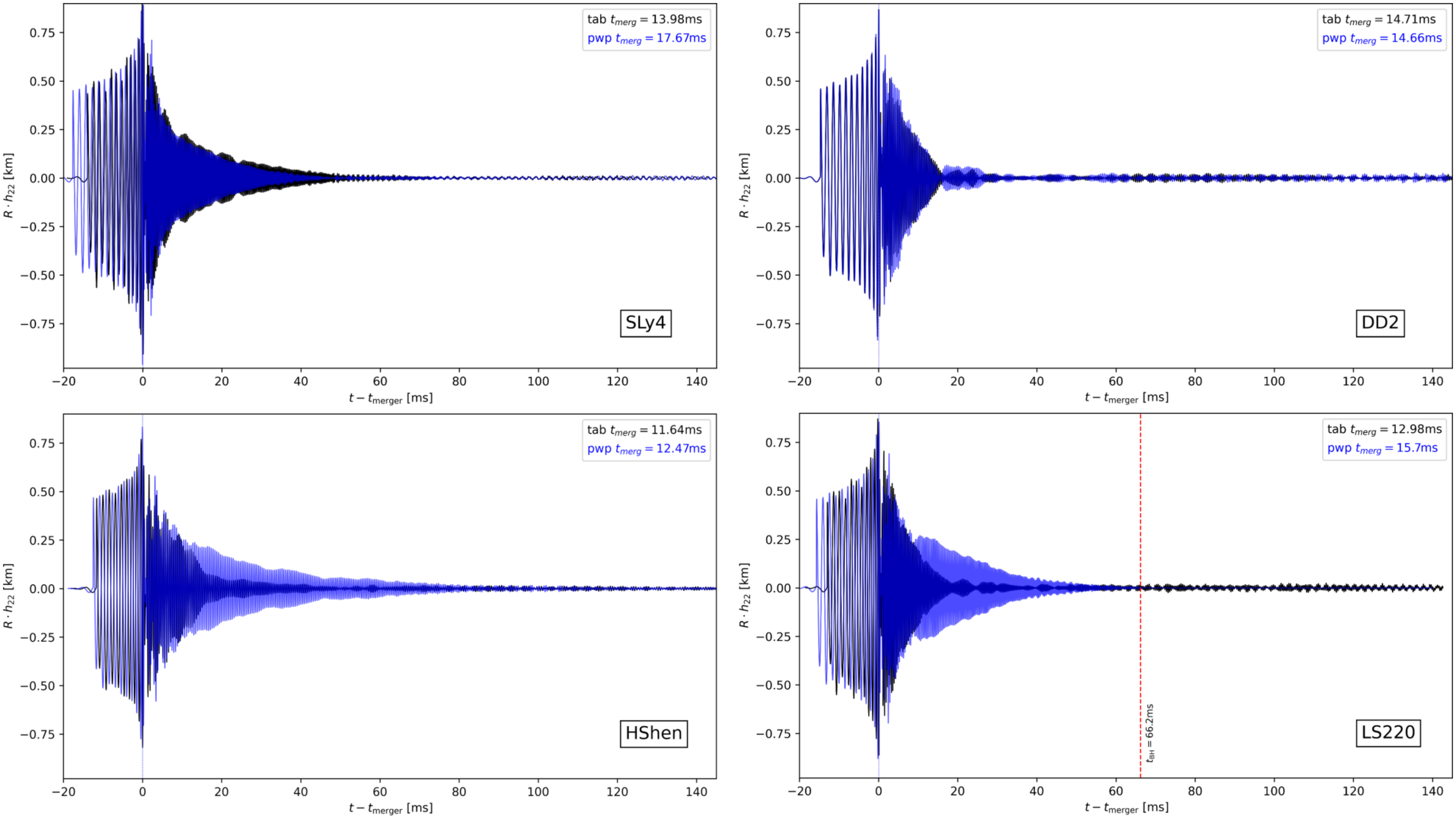
Energy dissipation

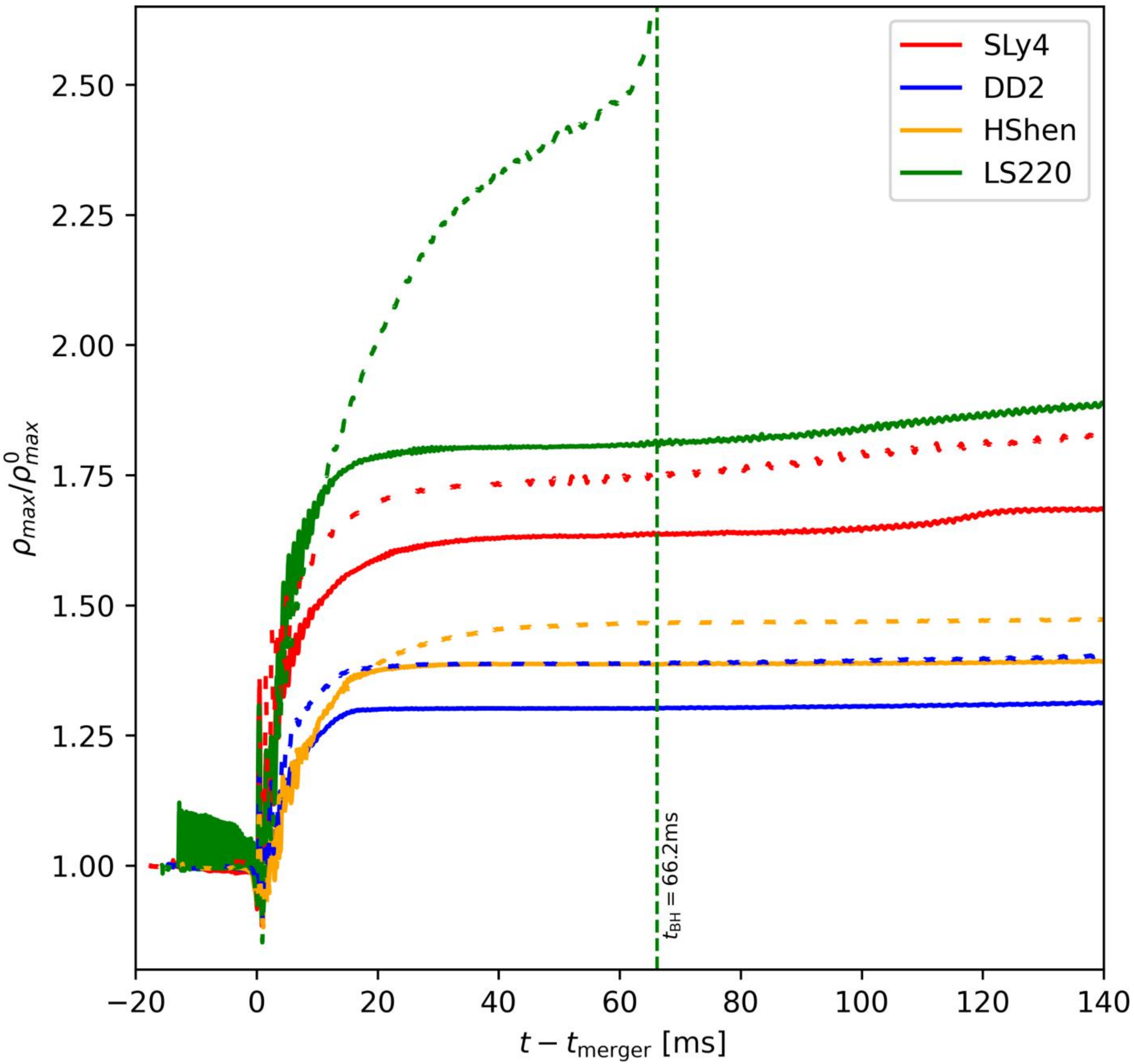
(e.g. viscous damping) can influence the thermal evolution of the merger remnant and its GW signal

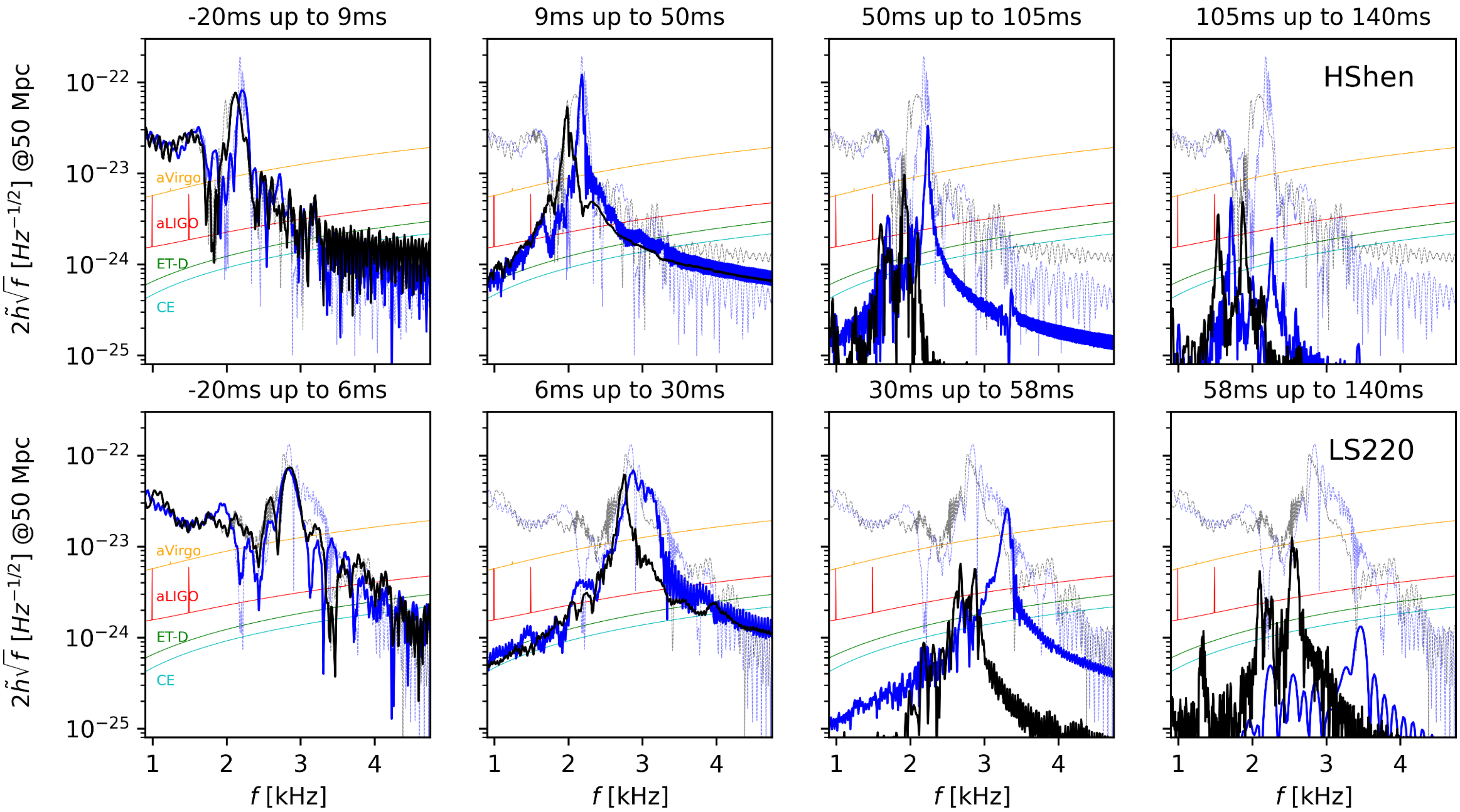
Angular momentum redistribution

Affecting the final spin state of the remnant, crucial for the sustainment of the NS

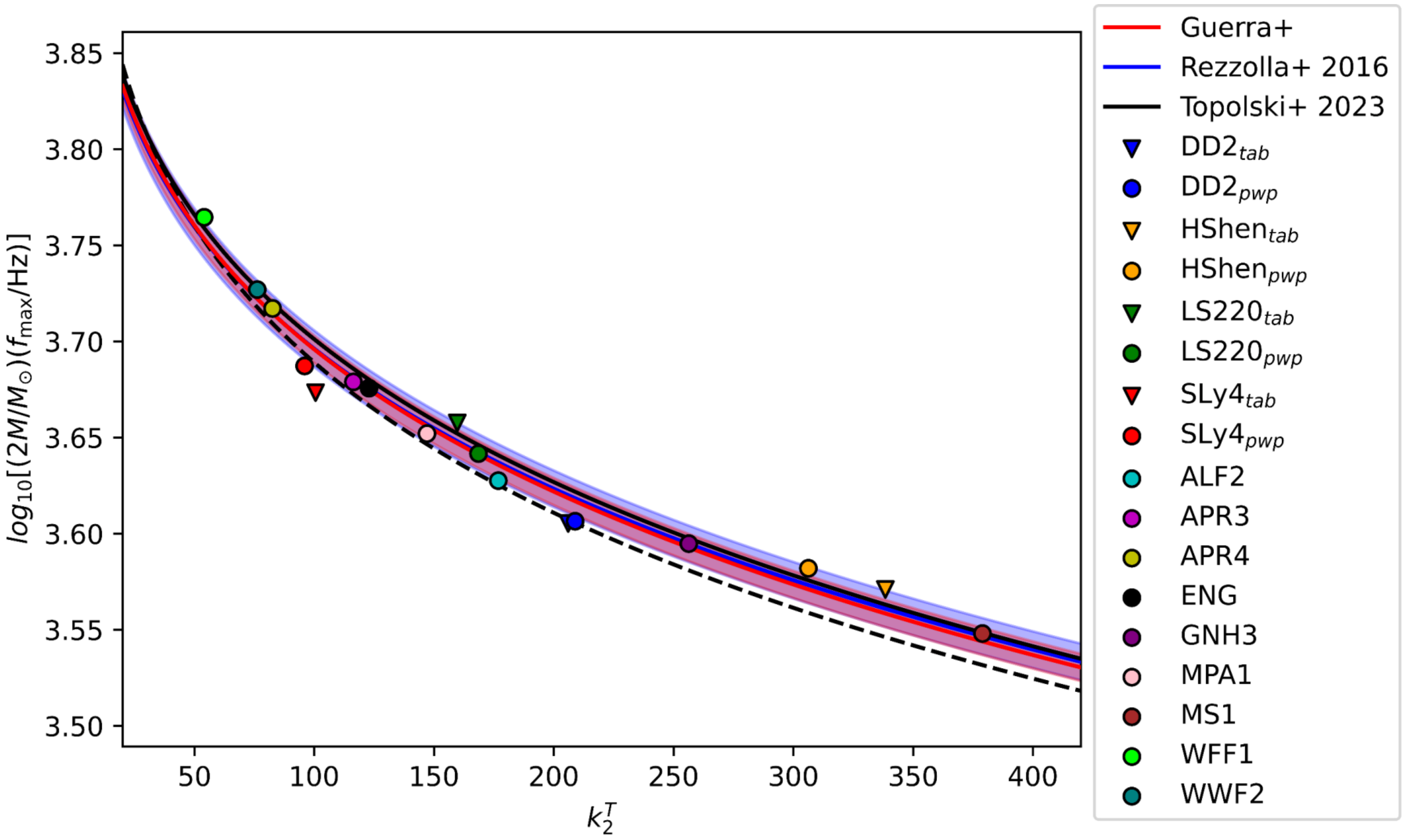
Numerical Relativity Results


tab $t_{merg} = 13.98$ms
pwp $t_{merg} = 17.67$ms
SLy4
tab $t_{merg} = 14.71$ms
pwp $t_{merg} = 14.66$ms
DD2
tab $t_{merg} = 11.64$ms
pwp $t_{merg} = 12.47$ms
HShen
tab $t_{merg} = 12.98$ms
pwp $t_{merg} = 15.7$ms
LS220
$t_{BH} = 66.2$ms
$R \cdot h_{22}$ [km]
$t - t_{merger}$ [ms]

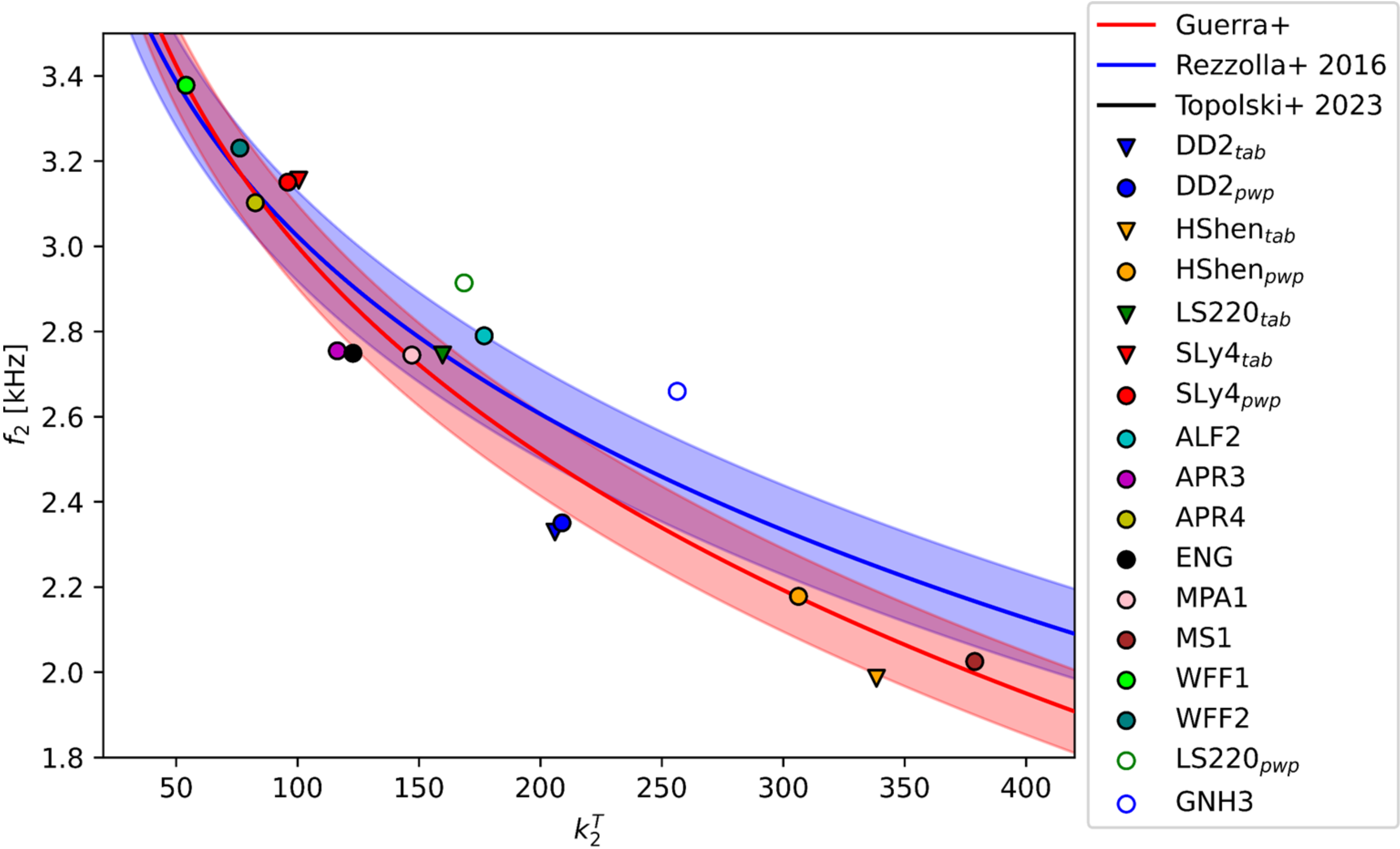

SLy4
DD2
HShen
LS220
ρ_{max}/ρ^0_{max}
$t - t_{merger}$ [ms]
$t_{BH} = 66.2$ms
2.50
2.25
2.00
1.75
1.50
1.25
1.00
−20
0
20
40
60
80
100
120
140

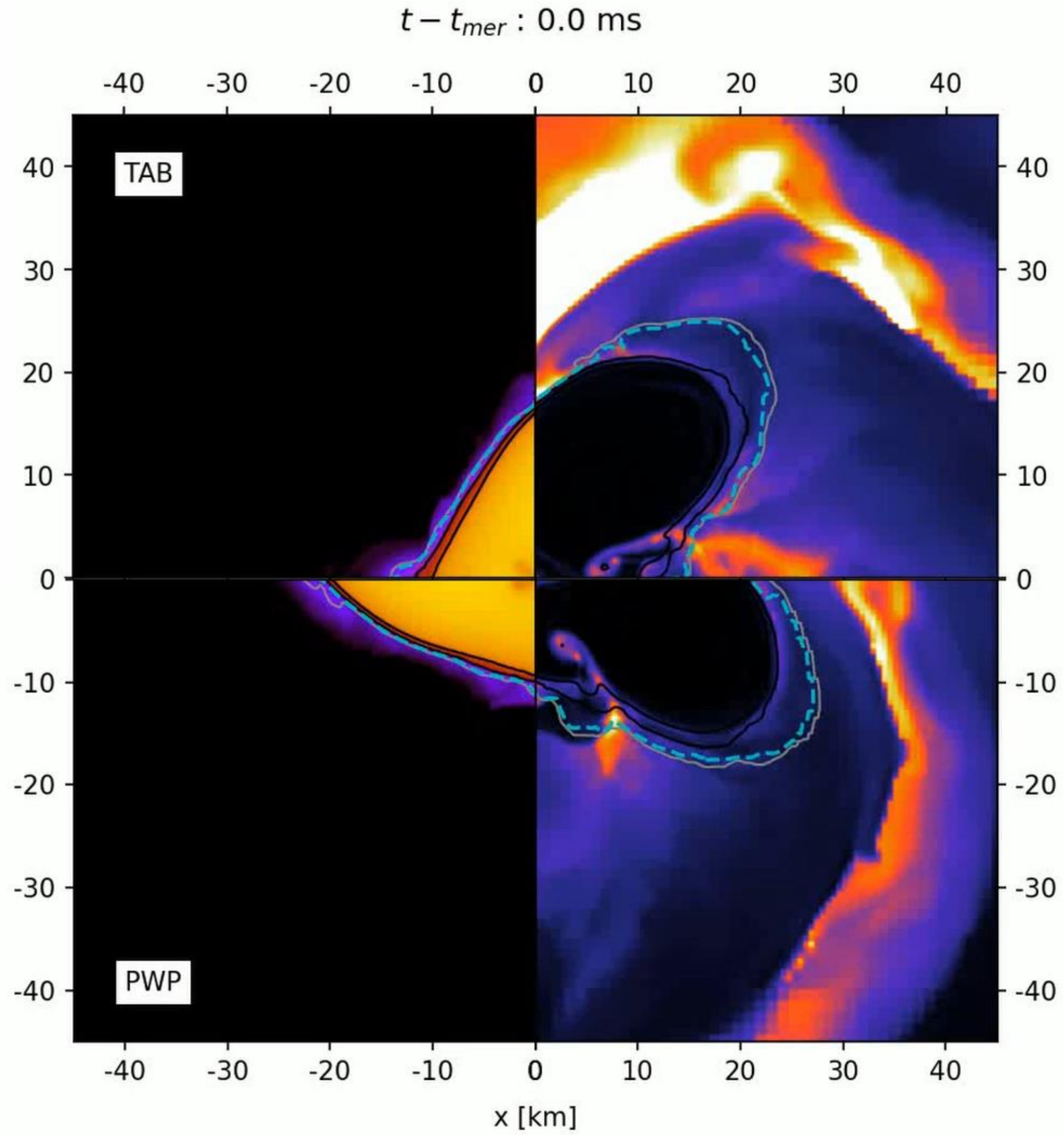


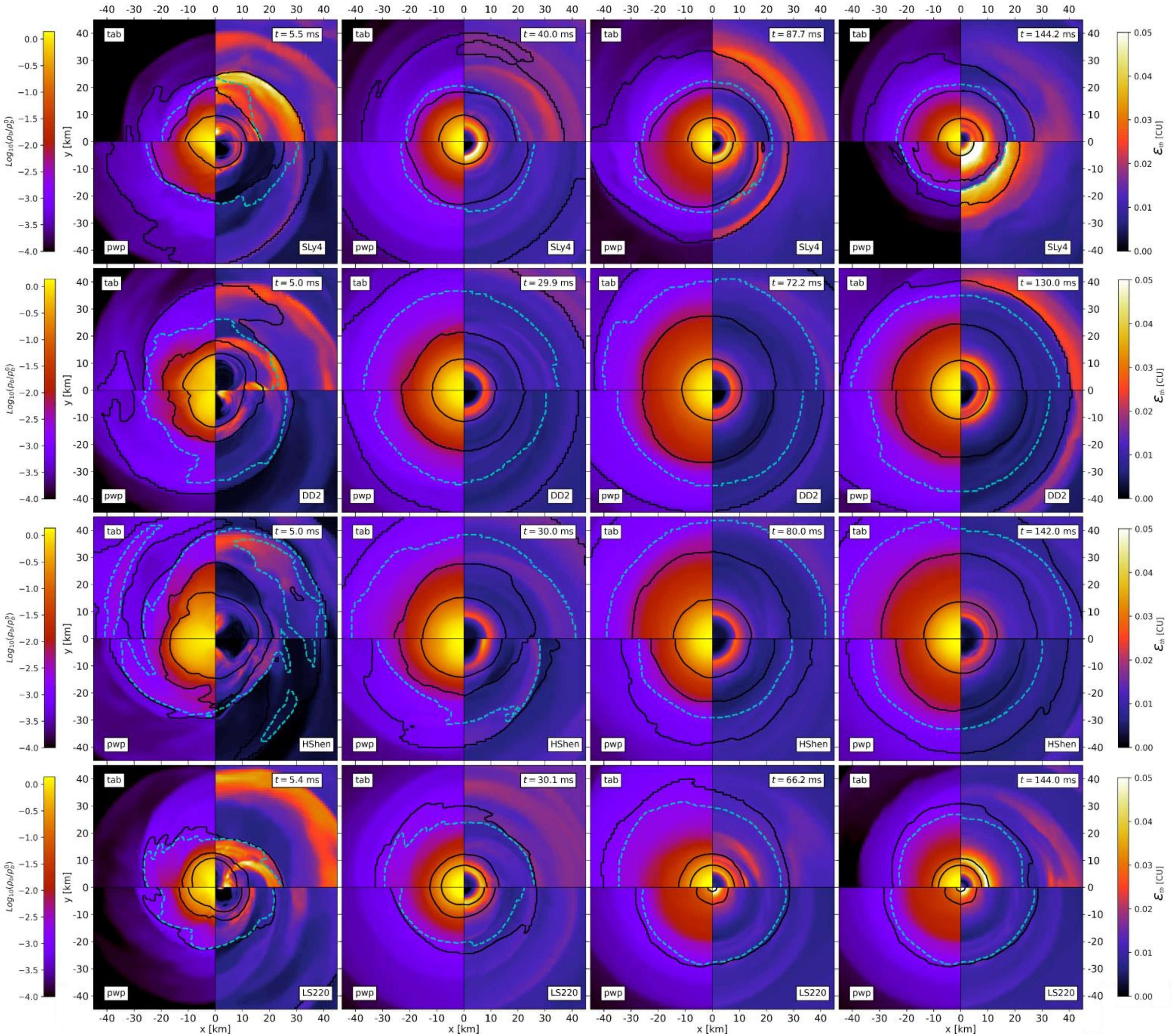
-20ms up to 9ms
9ms up to 50ms
50ms up to 105ms
105ms up to 140ms
HShen
-20ms up to 6ms
6ms up to 30ms
30ms up to 58ms
58ms up to 140ms
LS220
aVirgo
aLIGO
ET-D
CE
$2\tilde{h}\sqrt{f}\ [Hz^{-1/2}]$ @50 Mpc
f [kHz]

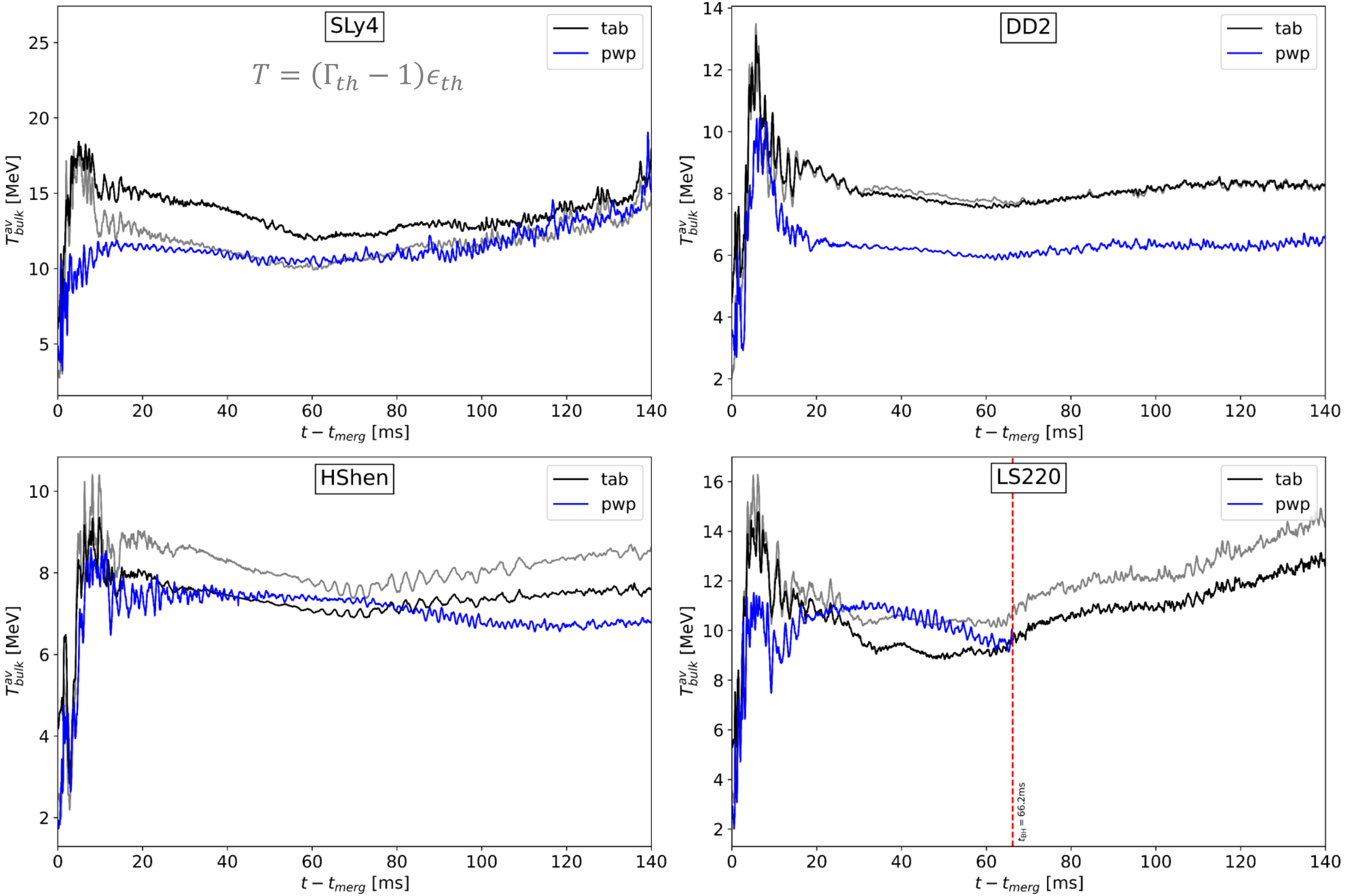


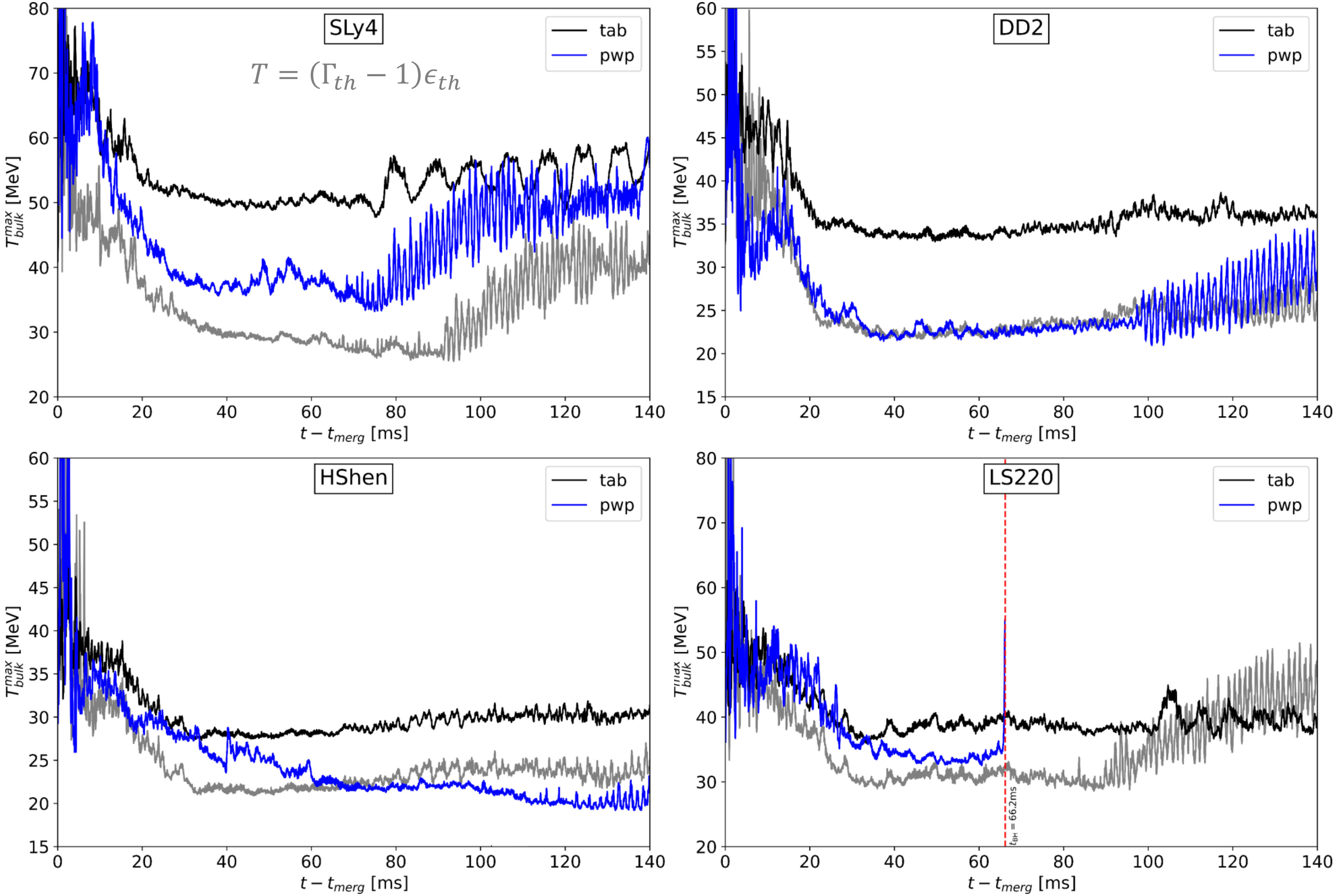
3.85
3.80
3.75
3.70
3.65
3.60
3.55
3.50
$log_{10}[(2M/M_{\odot})(f_{max}/Hz)]$
50
100
150
200
250
300
350
400
k_2^T
Guerra+
Rezzolla+ 2016
Topolski+ 2023
$DD2_{tab}$
$DD2_{pwp}$
$HShen_{tab}$
$HShen_{pwp}$
$LS220_{tab}$
$LS220_{pwp}$
$SLy4_{tab}$
$SLy4_{pwp}$
ALF2
APR3
APR4
ENG
GNH3
MPA1
MS1
WFF1
WWF2


Guerra+
Rezzolla+ 2016
Topolski+ 2023
$DD2_{tab}$
$DD2_{pwp}$
$HShen_{tab}$
$HShen_{pwp}$
$LS220_{tab}$
$SLy4_{tab}$
$SLy4_{pwp}$
ALF2
APR3
APR4
ENG
MPA1
MS1
WFF1
WFF2
$LS220_{pwp}$
GNH3
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
f_2 [kHz]
50
100
150
200
250
300
350
400
k_2^T

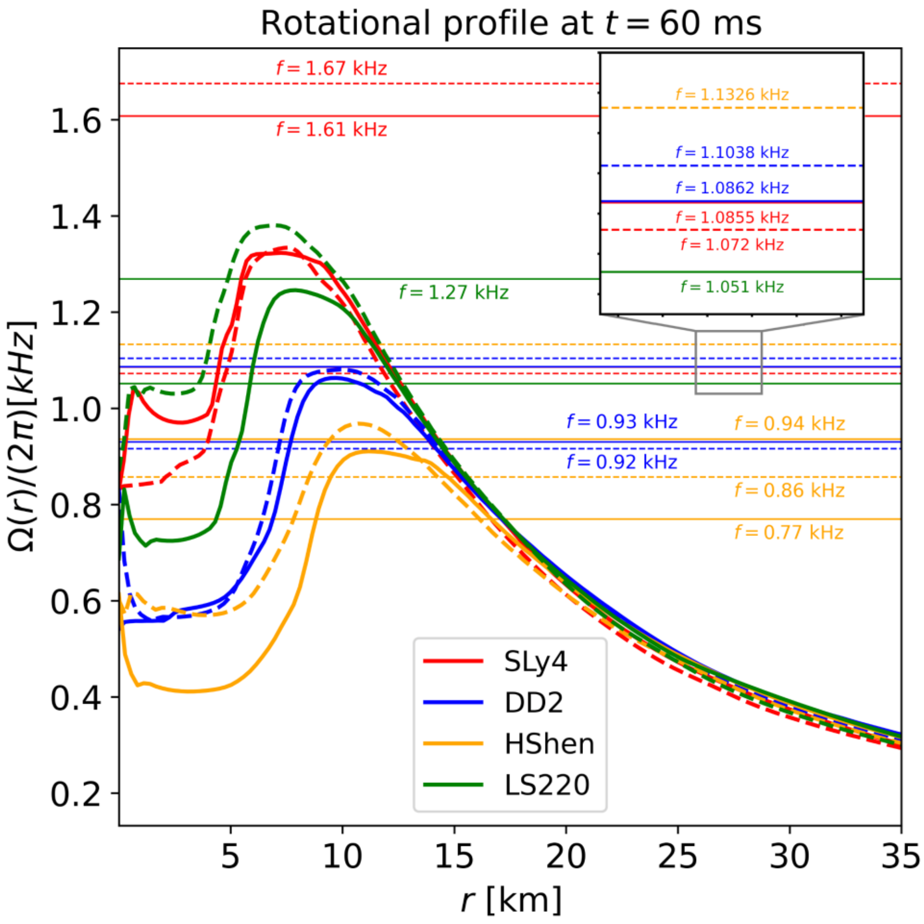

$t - t_{mer}$: 0.0 ms
TAB
PWP
x [km]
-40
-30
-20
-10
0
10
20
30
40


tab
pwp
t = 5.5 ms
t = 40.0 ms
t = 87.7 ms
t = 144.2 ms
SLy4
t = 5.0 ms
t = 29.9 ms
t = 72.2 ms
t = 130.0 ms
DD2
t = 5.0 ms
t = 30.0 ms
t = 80.0 ms
t = 142.0 ms
HShen
t = 5.4 ms
t = 30.1 ms
t = 66.2 ms
t = 144.0 ms
LS220
x [km]
y [km]
$Log_{10}(\rho_0/\rho_0^{\mathrm{max}})$
ϵ_{th} [CU]

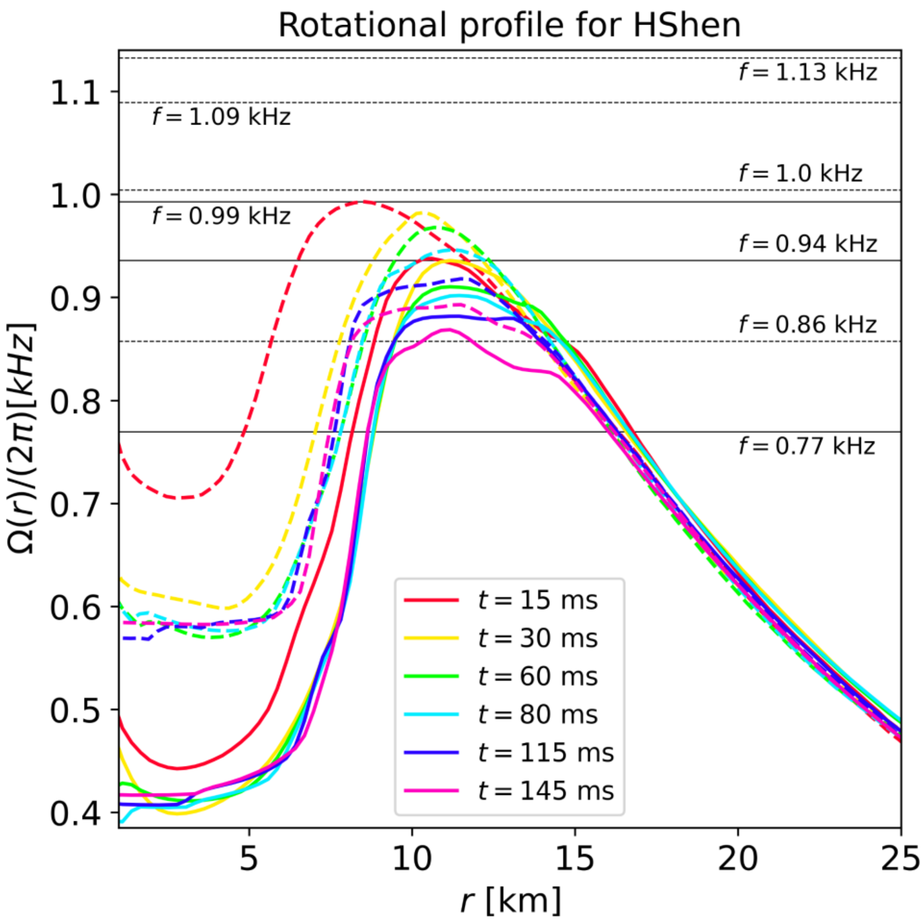

SLy4
$T = (\Gamma_{th} - 1)\epsilon_{th}$
DD2
HShen
LS220
tab
pwp
T_{bulk}^{av} [MeV]
$t - t_{merg}$ [ms]
$t_{BH} = 66.2$ms



SLy4
tab
pwp
$T = (\Gamma_{th} - 1)\epsilon_{th}$
T_{bulk}^{max} [MeV]
$t - t_{merg}$ [ms]
DD2
tab
pwp
T_{bulk}^{max} [MeV]
$t - t_{merg}$ [ms]
HShen
tab
pwp
T_{bulk}^{max} [MeV]
$t - t_{merg}$ [ms]
LS220
tab
pwp
$t_{BH} = 66.2$ms
T_{bulk}^{max} [MeV]
$t - t_{merg}$ [ms]



Rotational profile at $t = 60$ ms
$f = 1.67$ kHz
$f = 1.61$ kHz
$f = 1.27$ kHz
$f = 1.1326$ kHz
$f = 1.1038$ kHz
$f = 1.0862$ kHz
$f = 1.0855$ kHz
$f = 1.072$ kHz
$f = 1.051$ kHz
$f = 0.93$ kHz
$f = 0.94$ kHz
$f = 0.92$ kHz
$f = 0.86$ kHz
$f = 0.77$ kHz
SLy4
DD2
HShen
LS220
$\Omega(r)/(2\pi)[kHz]$
r [km]



Rotational profile for HShen
$f = 1.13$ kHz
$f = 1.09$ kHz
$f = 1.0$ kHz
$f = 0.99$ kHz
$f = 0.94$ kHz
$f = 0.86$ kHz
$f = 0.77$ kHz
$t = 15$ ms
$t = 30$ ms
$t = 60$ ms
$t = 80$ ms
$t = 115$ ms
$t = 145$ ms
$\Omega(r)/(2\pi)[kHz]$
r [km]

Conclusions and future project

- Binary Neutron Stars mergers: different final states + how to determine them + Gravitational wave spectroscopy
- Definition of EOS for NSs: different approaches as the piecewise politropic representation + tabulated VS hybrid + definition of temperature
- Numerical results: tab remnants are less compact then hyb + underestimation of temperature + shift in the GW peaks frequencies + presence of inertial modes in the long-remnant

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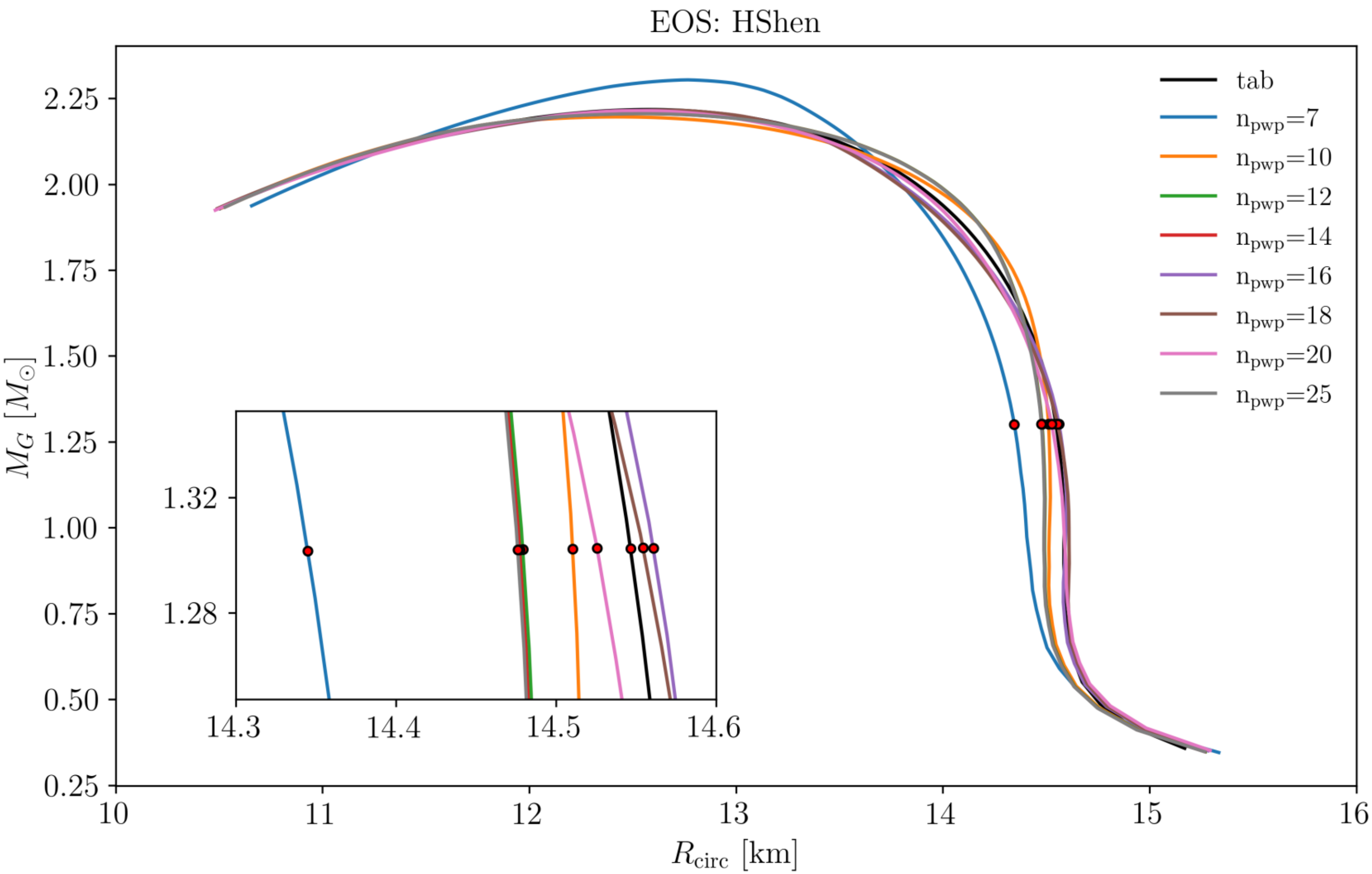
- Neutrino + Magnetic field
- Studing the matter ejecta

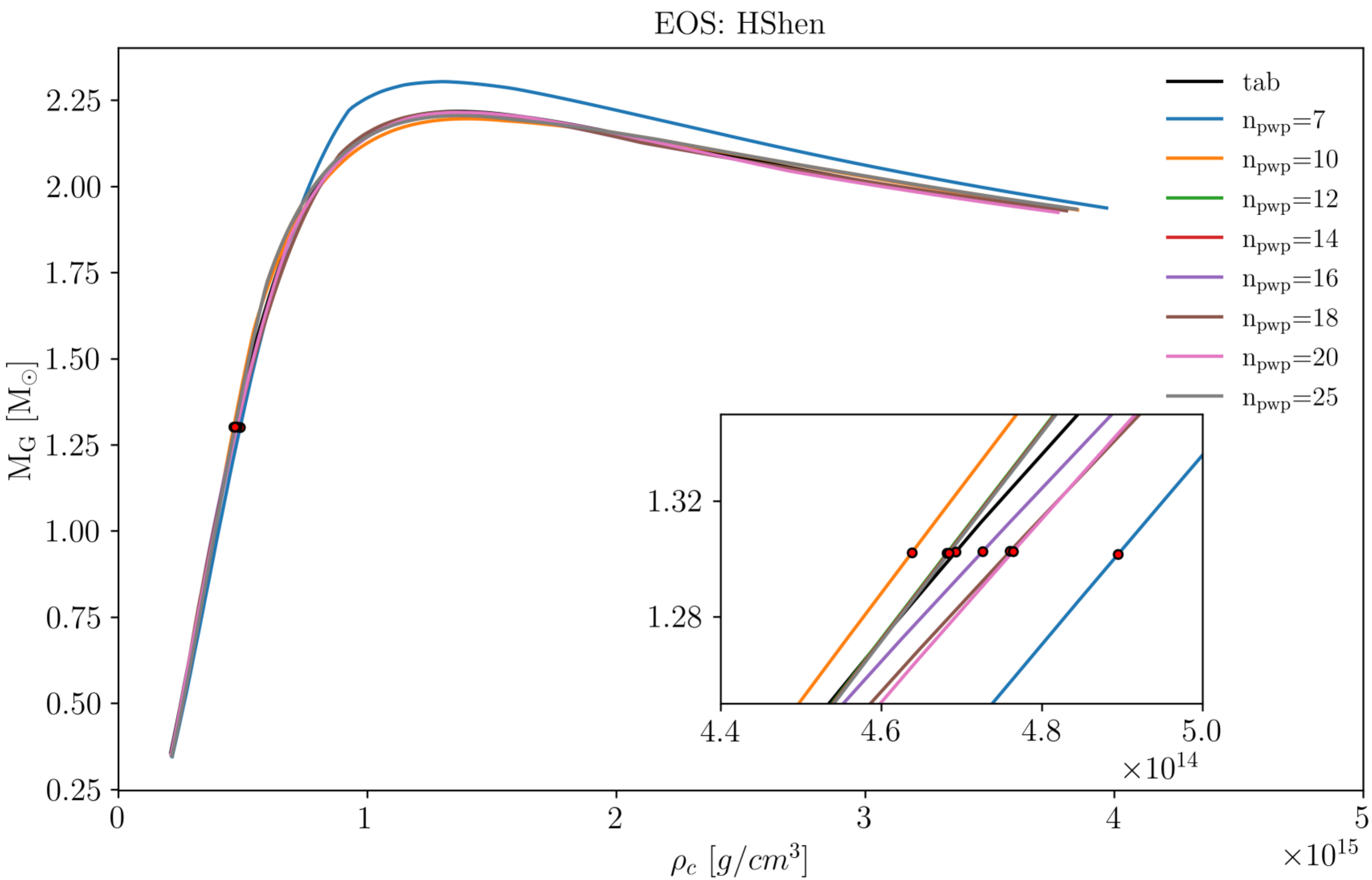
V.Villa-Ortega et al. *Self-consistent treatment of thermal effects in neutron-star post-mergers: observational implications for third-generation gravitational-wave detectors*, arXiv:2310.20378 [gr-qc]

- Check if the differences in the GW signal could be observed by the GW experiments (LVK, ET, Cosmic Explorer)

M.Miravet-Tenés, **DG** et al. *Identifying thermal effects in neutron star merger remnants with model-agnostic waveform reconstructions and third-generation detectors*, arXiv:2401.02493 [gr-qc]

Thank you for your attention


EOS: HShen
tab
n_{pwp}=7
n_{pwp}=10
n_{pwp}=12
n_{pwp}=14
n_{pwp}=16
n_{pwp}=18
n_{pwp}=20
n_{pwp}=25
M_G [$M_\odot$]
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
10
11
12
13
14
15
16
R_{circ} [km]
1.32
1.28
14.3
14.4
14.5
14.6


EOS: HShen
tab
n_pwp=7
n_pwp=10
n_pwp=12
n_pwp=14
n_pwp=16
n_pwp=18
n_pwp=20
n_pwp=25
M_G [M_⊙]
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0
1
2
3
4
5
×10^15
ρ_c [g/cm^3]
1.32
1.28
4.4
4.6
4.8
5.0
×10^14