



Impact of progenitor rotation on gravitational waveforms from core-collapse supernovae

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CCSNE

- Core collapse supernova (CCSN): bright astrophysical phenomenon
- It is caused by the explosion of massive star ($M_{\text{ZAMS}} \geq 8 M_{\odot}$) \Rightarrow PROGENITOR;
- Phases:
 - Fe core collapses reaching nuclear densities
 - Proto-neutron star (PNS) formation + shockwave \Rightarrow GRAVITATIONAL WAVES (GWs) EMISSION BEGINS
 - Shock stall
 - Shock revival
 - Explosion (Hopefully)

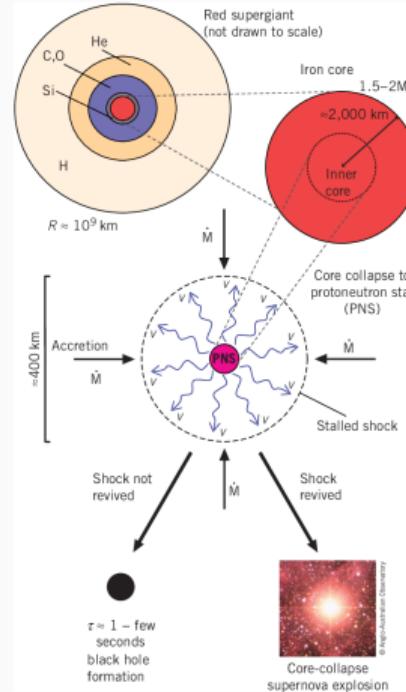


Figure 1: Ott, C.D. (2016). Massive Computation for Understanding Core-Collapse Supernova Explosions. Computing in Science & Engineering, 18, 78-92.

SIMULATION SETUP

- Axisymmetric (2D) simulations of CCSNe;
- Different progenitors with initial masses spanning $\geq 5 M_{\odot}$
 - product of 1D stellar evolution calculations;
- Central rotation from moderate ($\leq 0.5 \text{ Hz}$) to fast ($\geq 2 \text{ Hz}$);
- Two kinds of rotation profiles
 - coming with the progenitor
 - added as $\Omega = \Omega_c \frac{1}{1 + \left(\frac{R}{R_{diff}} \right)^2}$

ROTATION IMPACT: BOUNCE SIGNAL

- Loudest component of the GWs in the very early postbounce;
- Amplitude increases with rotation.
- In particularly fast rotating CCSN rotation slow the collapse \Rightarrow softer bounce \Rightarrow lower GW amplitude.

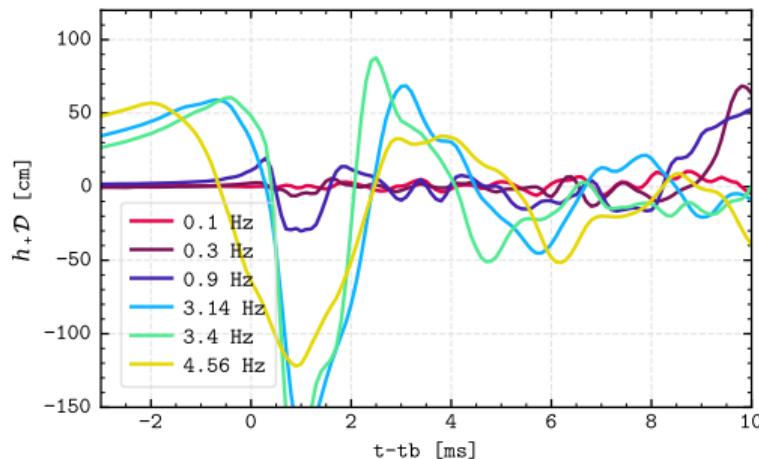


Figure 2: Bounce signal for S20 model with different central rotation.

ROTATION IMPACT: BOUNCE SIGNAL II

- GW amplitude increases linearly with innercore $T/|W|$ (quantity directly rotation);
- Deviation from relation due to fast rotation and differential rotation radius.

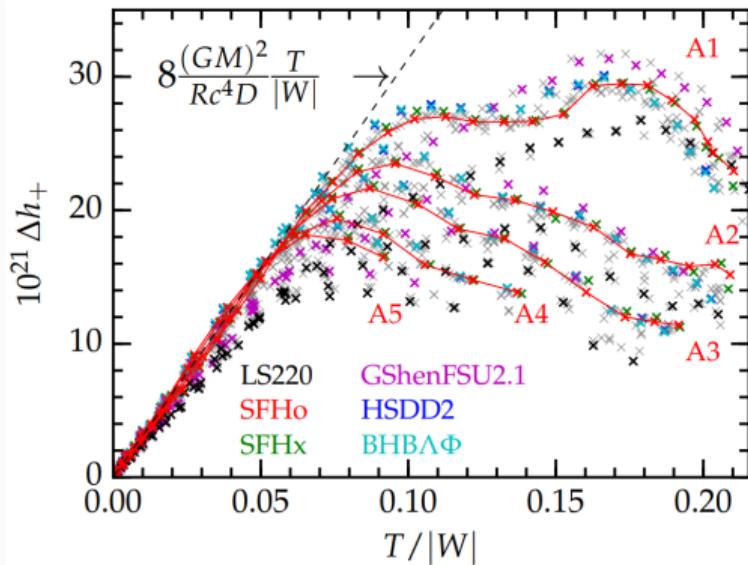


Figure 3: Richers, S. et al.. Equation of state effects on gravitational waves from rotating core collapse. Phys. Rev. D 95, 063019

SUMMARY AND OUTLOOK

CONCLUSION:

- Rotation greatly impacts the bounce signal, changing the amplitude of the waveform;
- Expand from the work of Richers *et al.* 2017 using different progenitor models both with a rotation profile deriving from stellar evolution and added later.

PROSPECTS FOR THE INFERENCE OF INERTIAL MODES FROM HYPERMASSIVE NEUTRON STARS

[ARXIV:2302.04553](https://arxiv.org/abs/2302.04553)

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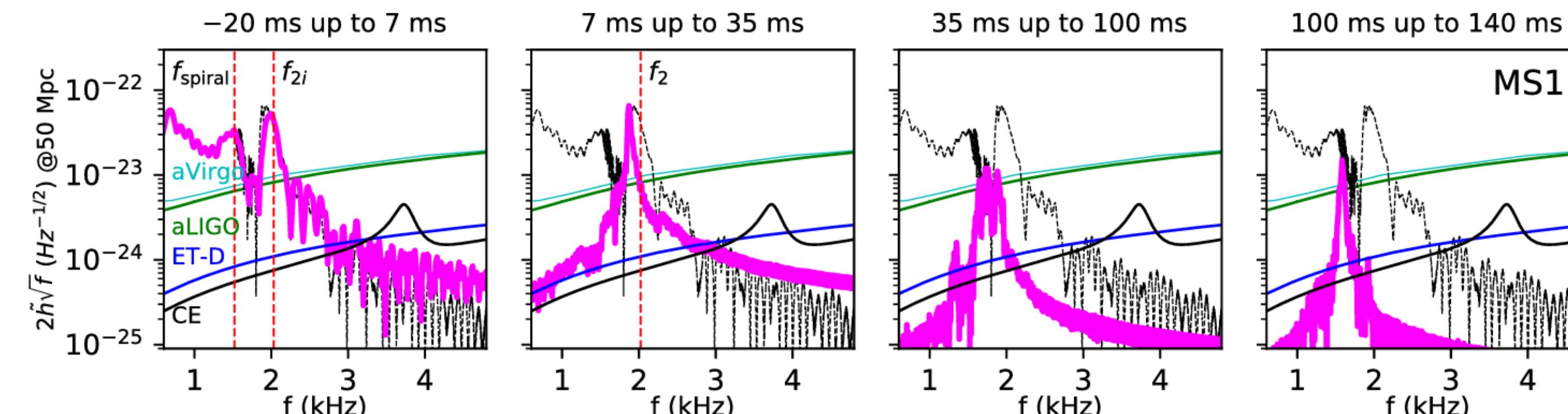
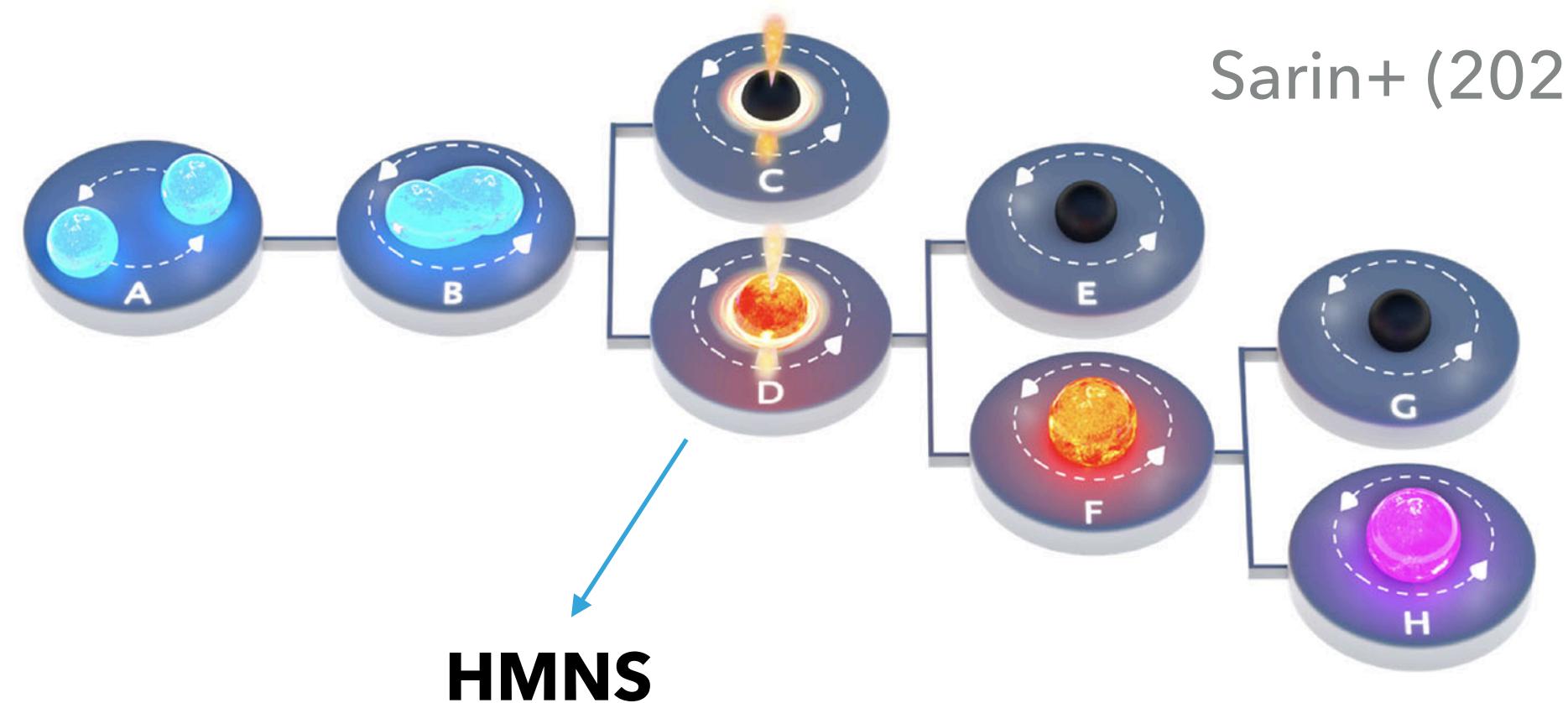
GWSNS SCHOOL, AUSSOIS (FRANCE)

JUNE 5, 2023



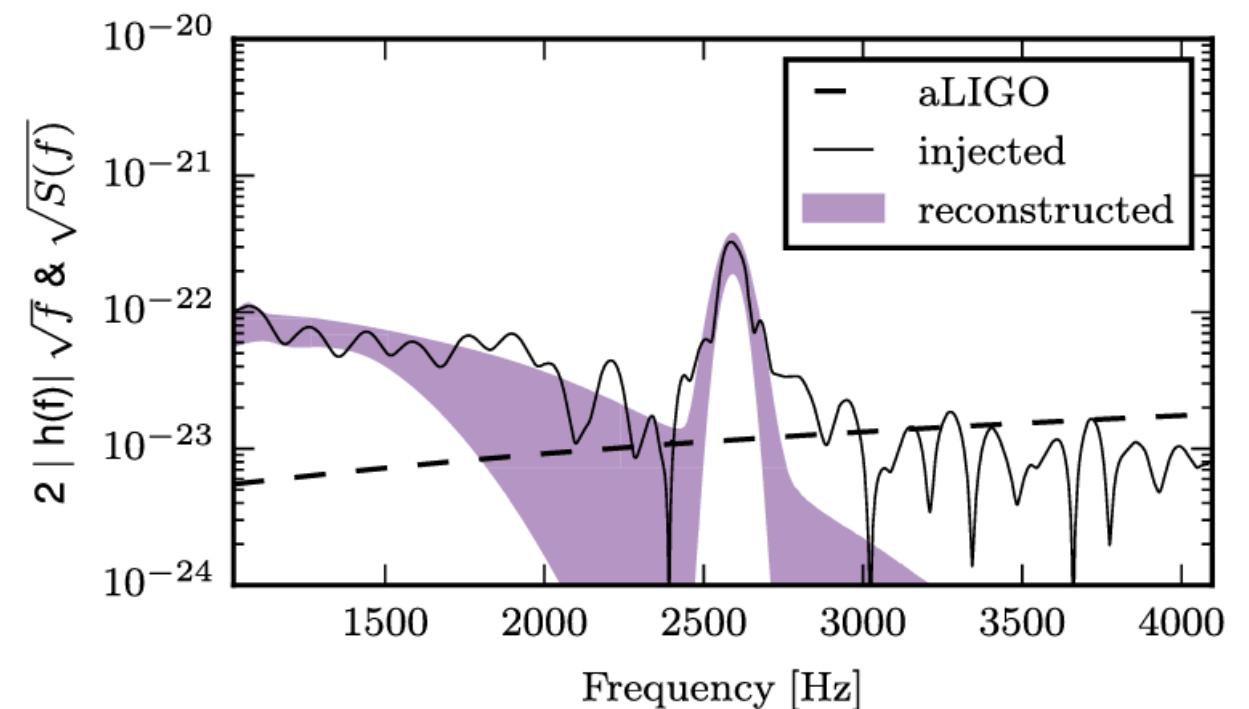
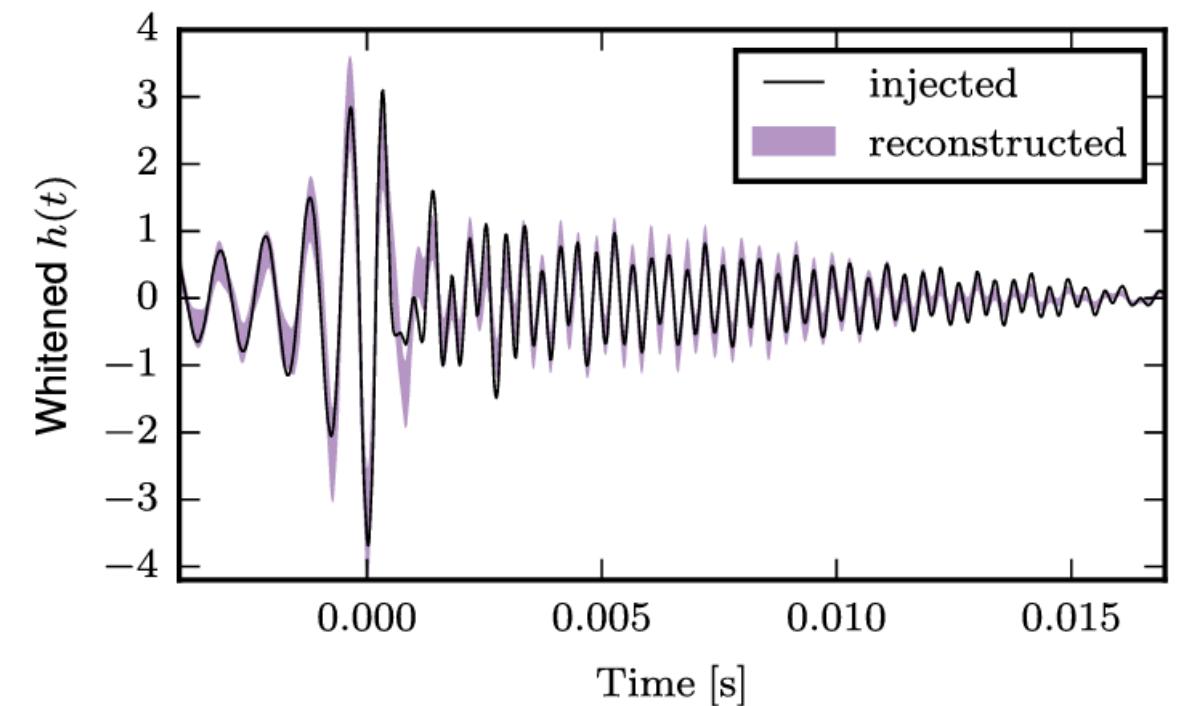
HYPERMASSIVE NEUTRON STARS

- ▶ Compact remnants of BNS mergers.
- ▶ Many distinct peaks in the GW spectrum of HMNS.
- ▶ Strong axisymmetric deformations and non-linear oscillations at few ms after merger.
- ▶ At timescales longer than ~ 50 ms after merger → **Appearance of convective instabilities**
- ▶ They trigger the so-called **inertial modes** → **New distinctive peaks in the GW spectrum**



WAVEFORM RECONSTRUCTION

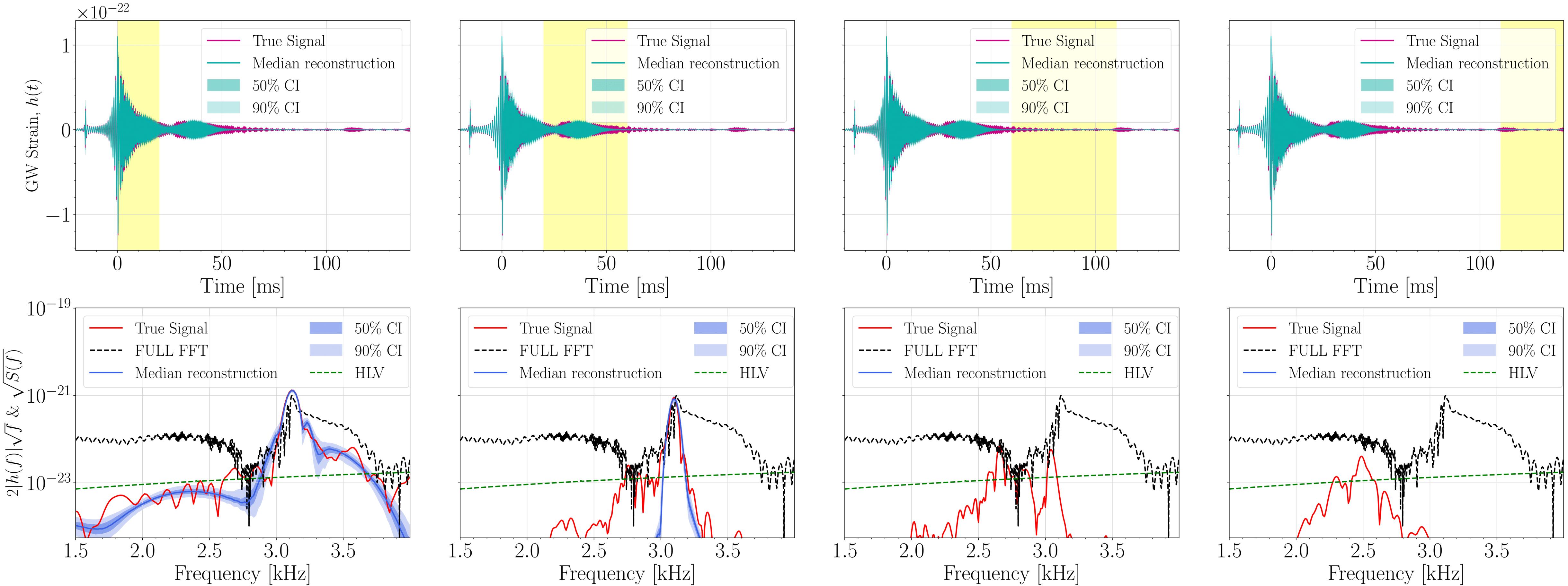
- ▶ In this work we reconstruct the long GW signals using **BAYESWAVE** .
- ▶ It is a Bayesian data-analysis algorithm that recovers the signal using series of sine-Gaussian wavelets.
- ▶ **PLAN:**
 - ▶ Perform injections into the Gaussian noise of different detectors (**HLV, ET**) from sources at different distances.
 - ▶ Check the dependence of our results on the NS equation of state (EOS) by using two different EOS: **APR4** and **SLy**.



Chatzilioannou+ (2017)

RESULTS: ET, SOURCE AT 3 MPC

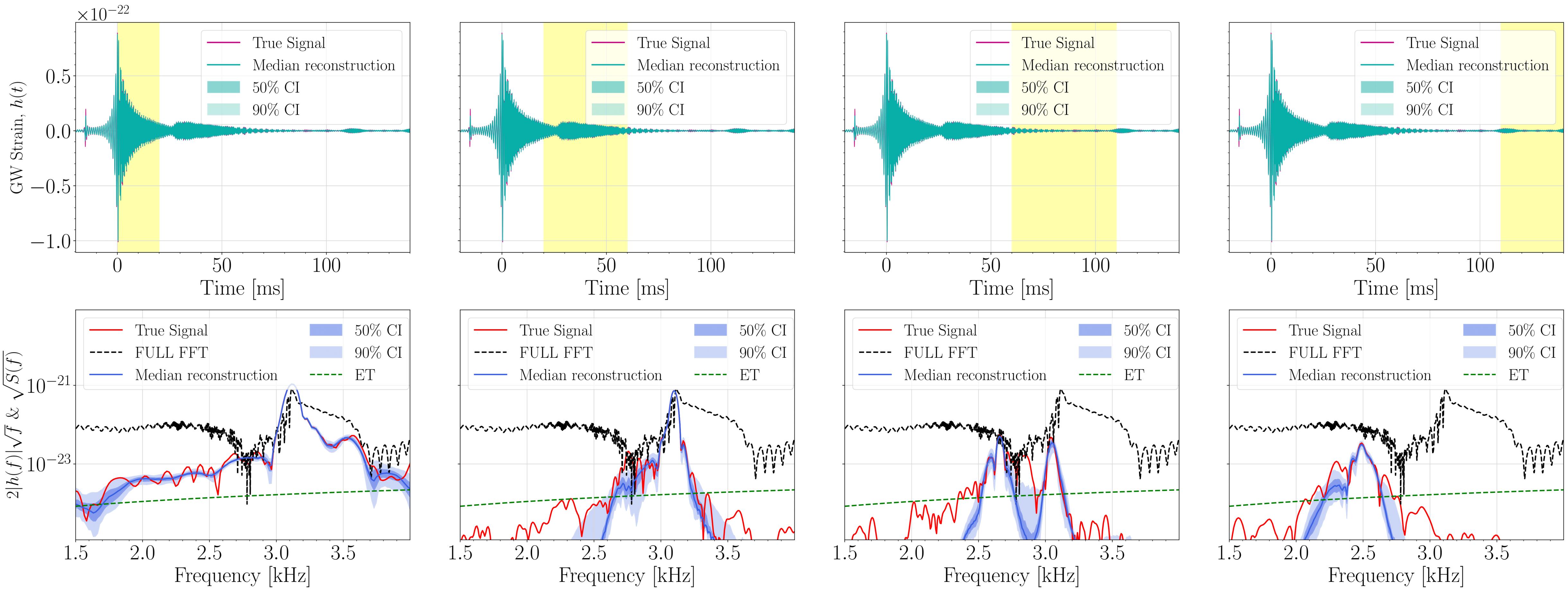
APR4 EOS



Miravet-Tenés+ (2023)

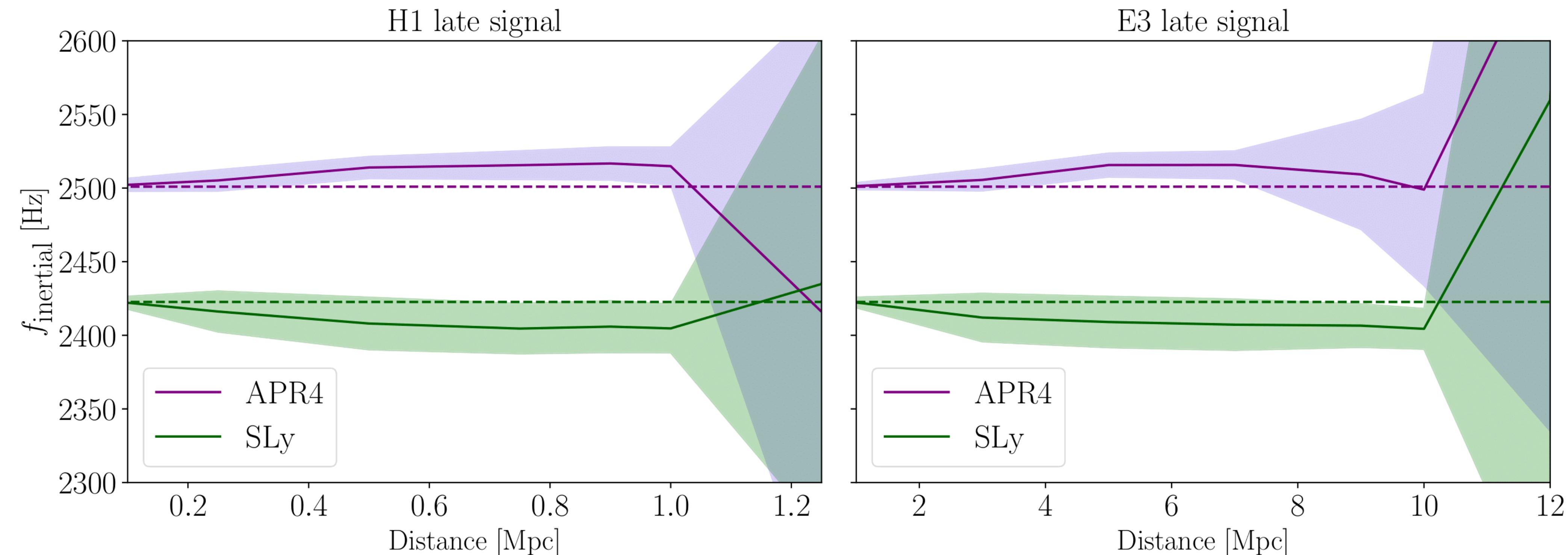
RESULTS: ET, SOURCE AT 3 MPC

APR4 EOS



Miravet-Tenés+ (2023)

FREQUENCY PEAKS



Miravet-Tenés+ (2023)

CONCLUSIONS

- ▶ Current GW interferometers (HLV network) are able to recover the inertial modes only if the BNS merger occurs at $\lesssim 1$ Mpc, which is unlikely to happen.
- ▶ Future detectors, such as ET, the range of detection increases by a factor of ~ 10 .
- ▶ A future detection of these late post-merger modes could give us more insight into the internal matter and structure of a neutron star.
- ▶ The excitation of inertial modes in long-lived remnants of BNS mergers depends on the rotational and thermal properties of the remnant and also impacts its dynamical evolution.

ACKNOWLEDGEMENTS

- Work supported by the Spanish Agencia Estatal de Investigación (Grants No. PGC2018-095984-B-I00 and PID2021-125485NB-C21) and by the Generalitat Valenciana (Grant No. PROMETEO/2019/071). MMT acknowledges support by the Ministerio de Universidades del Gobierno de España (Spanish Ministry of Universities) through the "Ayuda para la Formación de Profesorado Universitario" No. FPU19/01750.





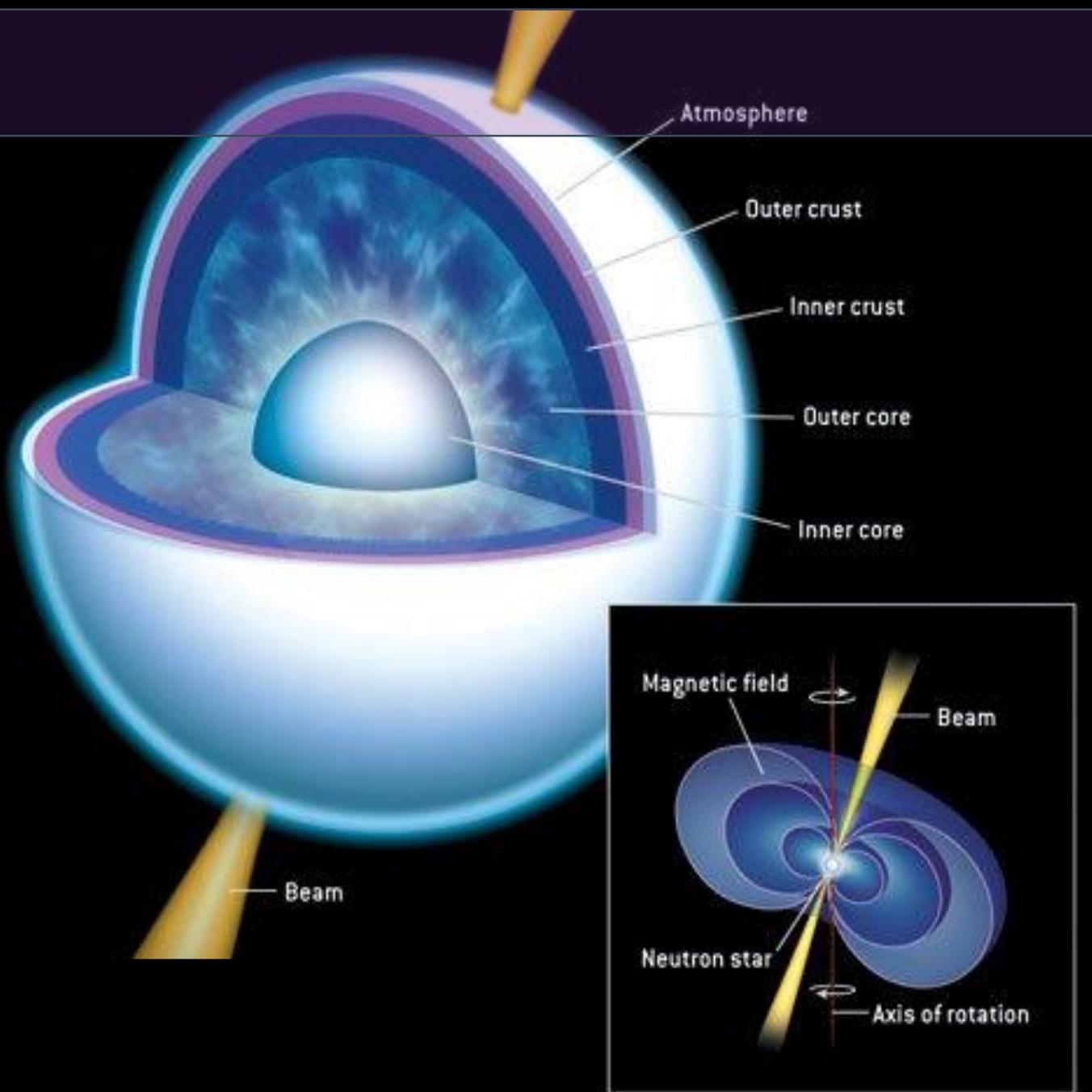
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Neutron stars as natural physics laboratories

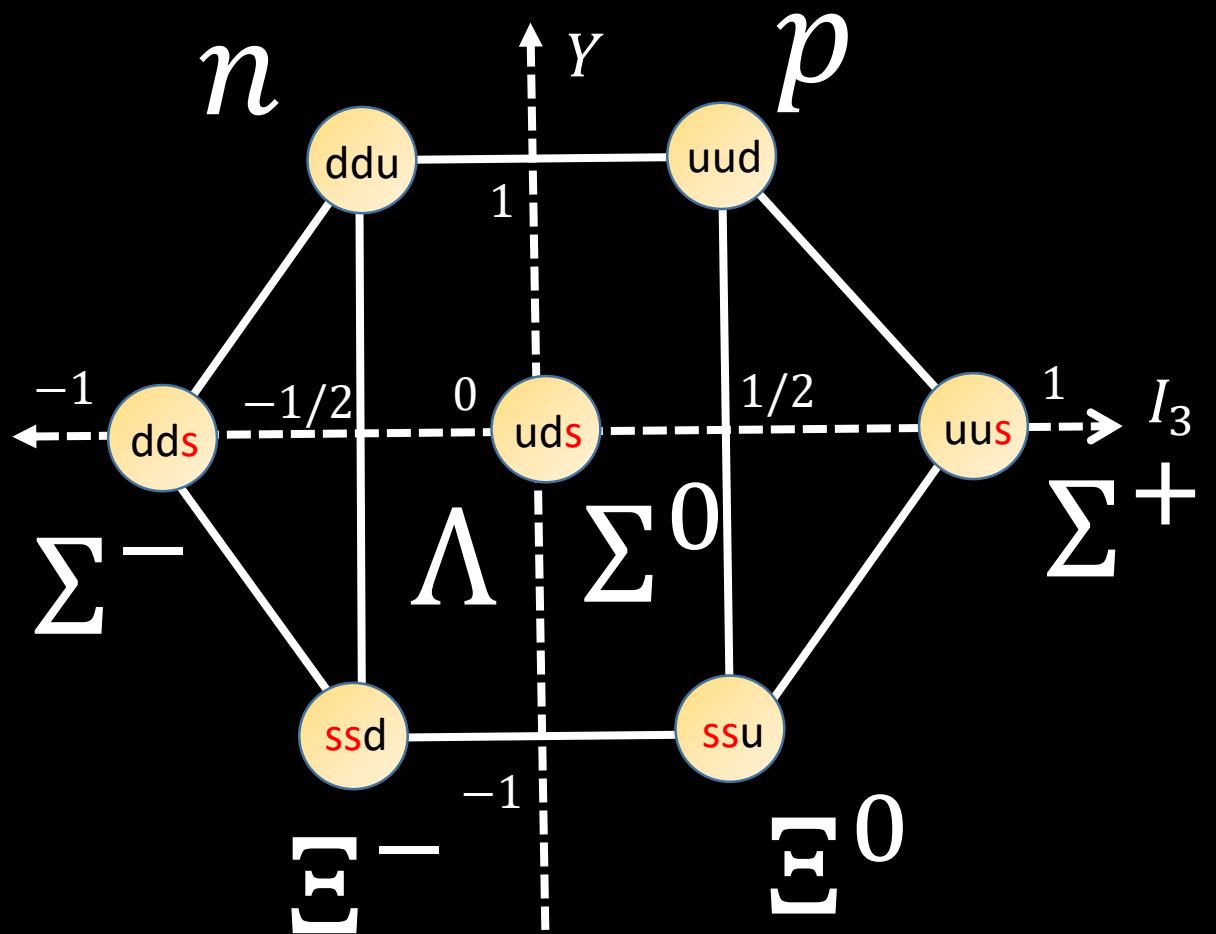


Neutron stars properties

- Exotic properties
 - Masses that can exceed $2M_{\text{Sun}}$
 - Radii of around 10-15 km
 - Densities in the center that can reach
 $\approx 10^{18} \text{ kg/m}^3 (\approx 1 \text{ fm}^{-3})$
- **=> Nuclear forces come into play**
- The composition of the **homogenous matter** in the inner core is unknown
 - Hyperons
 - Pion condensation
 - Kaon condensation
 - Quark matter



Hyperons in the neutron stars?

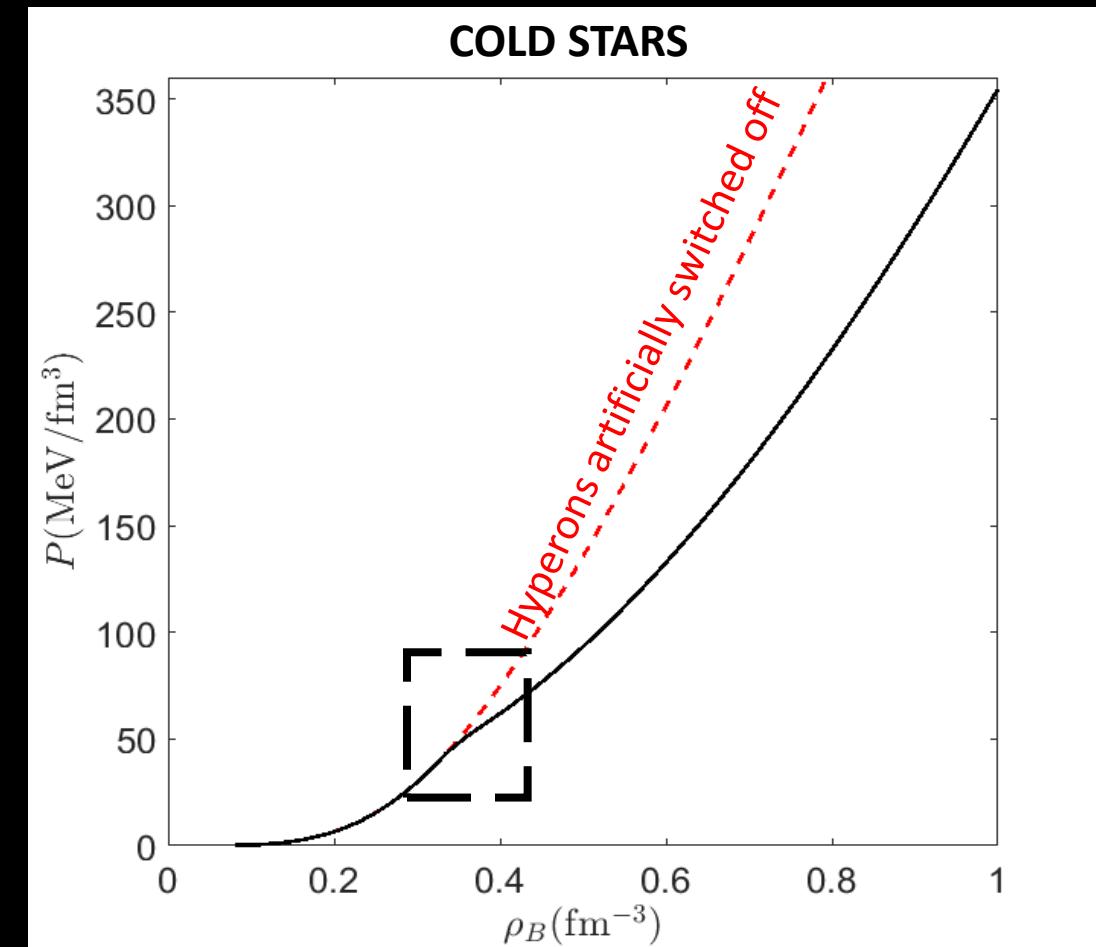
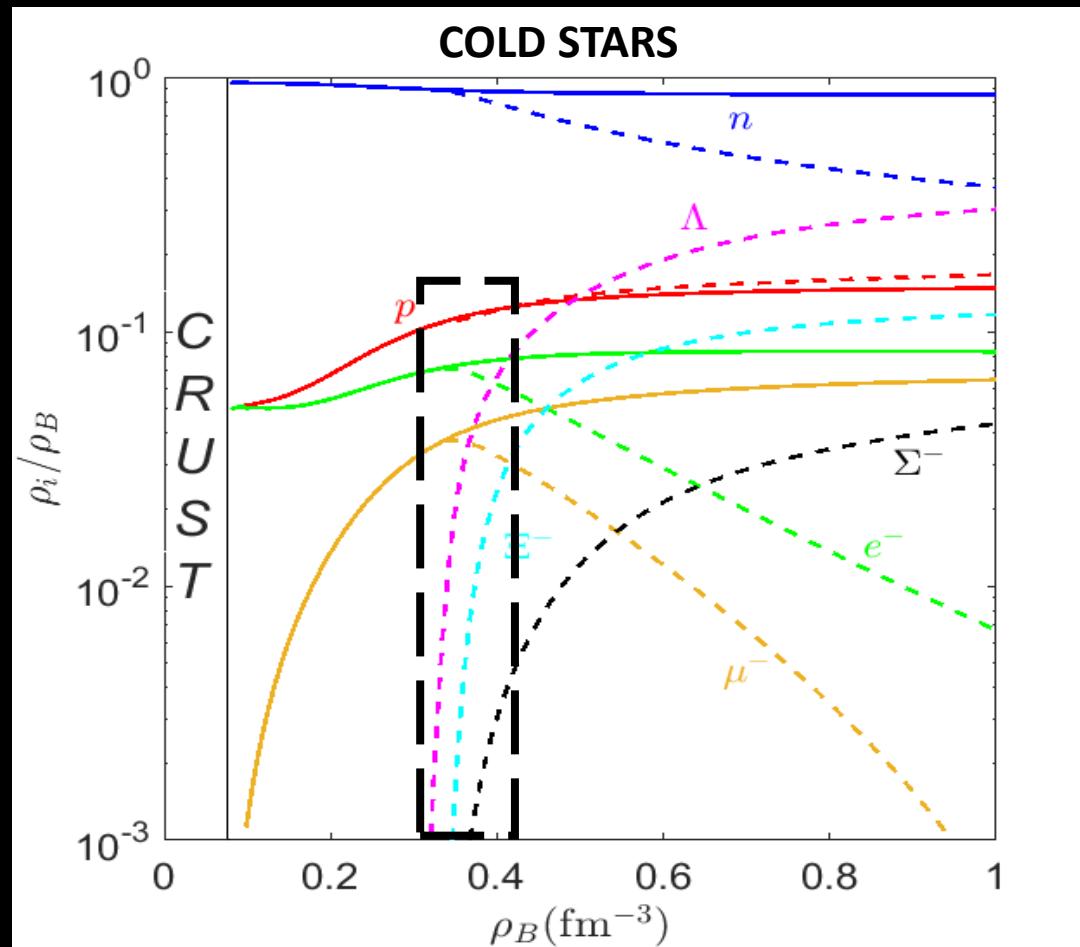


- Hyperons are baryons made of one or more strange quarks
- They can decay to nucleons via electroweak force
$$\Lambda \rightarrow p + \pi^-$$
$$\Lambda \rightarrow n + \pi^0$$
- But they can also be created in the neutron stars, if the nucleons have enough energy

$$\mu_n > m_{Y^0}$$

Hyperons signatures on the Equation of State (EoS) I

Can we identify whenever hyperons exist in
the core of the neutron stars?

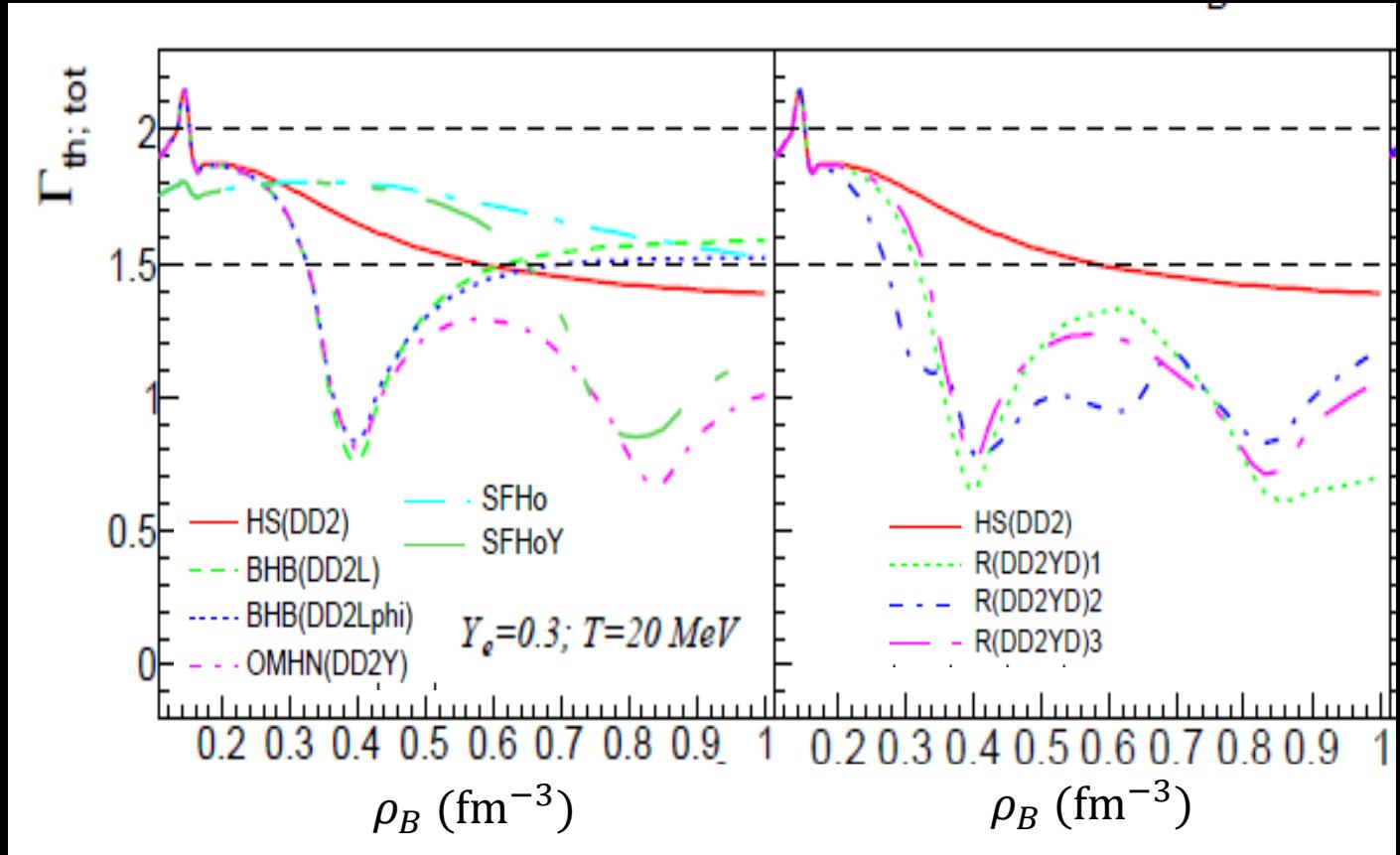


Hyperons signatures on the Equation of State (EoS) II

- Different thermal behavior between the hyperonic and the nucleonic EoSs
- We define a quantity that is known as thermal index:

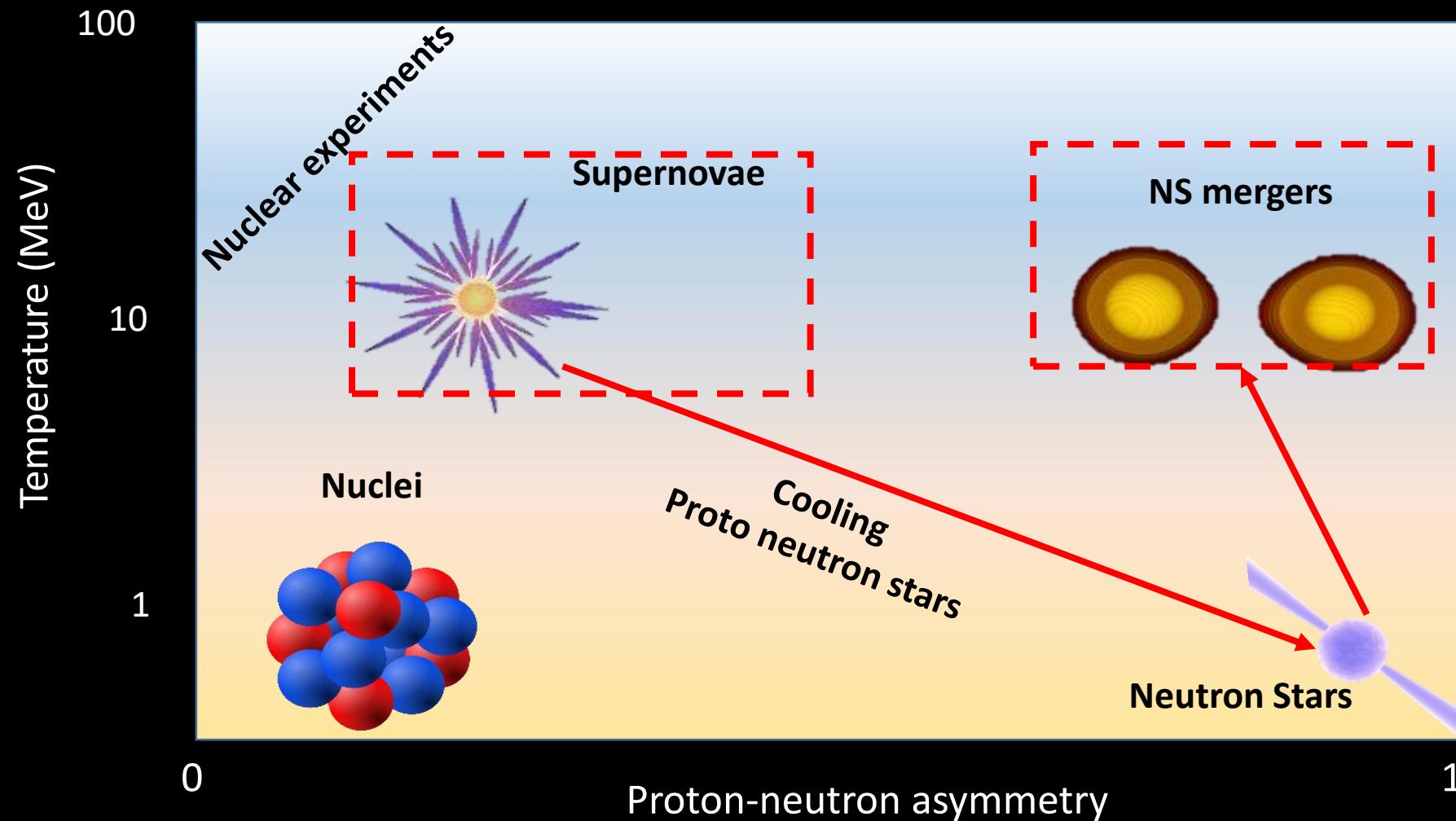
$$\Gamma_{th} = 1 + \frac{P_{th}}{\epsilon_{th}}$$

- The introduction of the hyperons induces a drop in the thermal index – **MODEL INDEPENDENT FEATURE**



Raduta et al, 2022, EPJA

Playgrounds for probing the hyperon hypothesis



Instead of a summary ☺

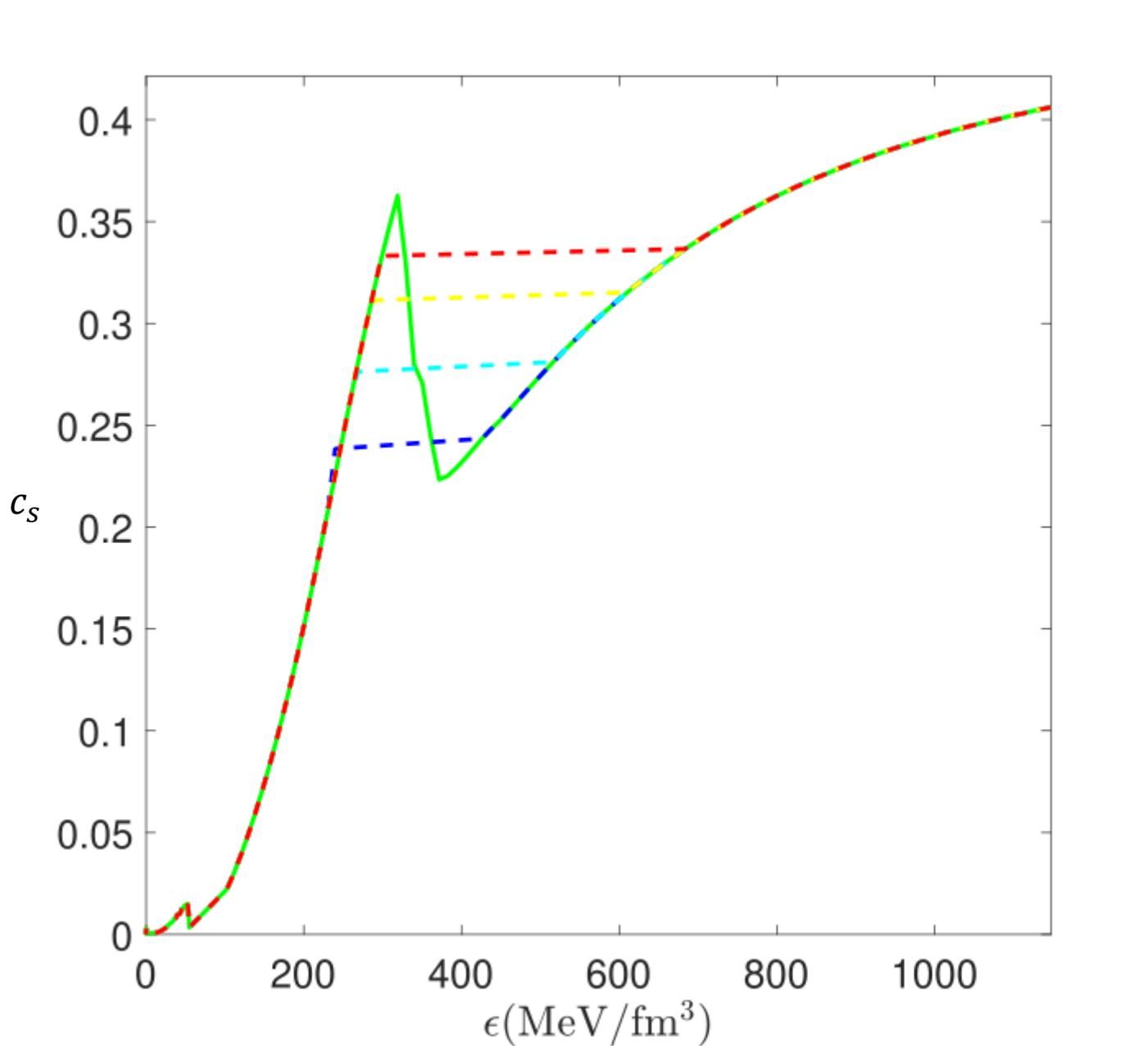


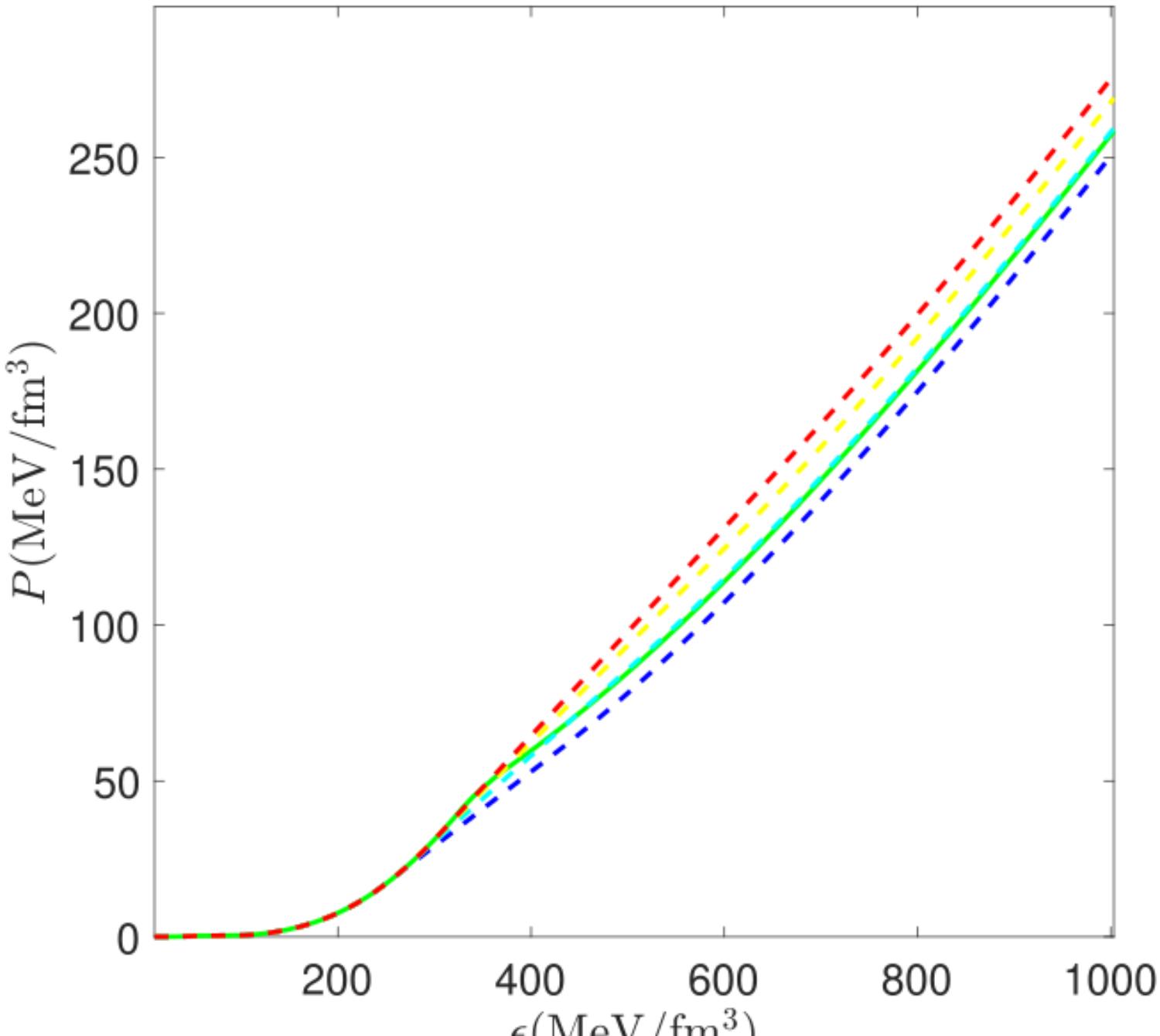


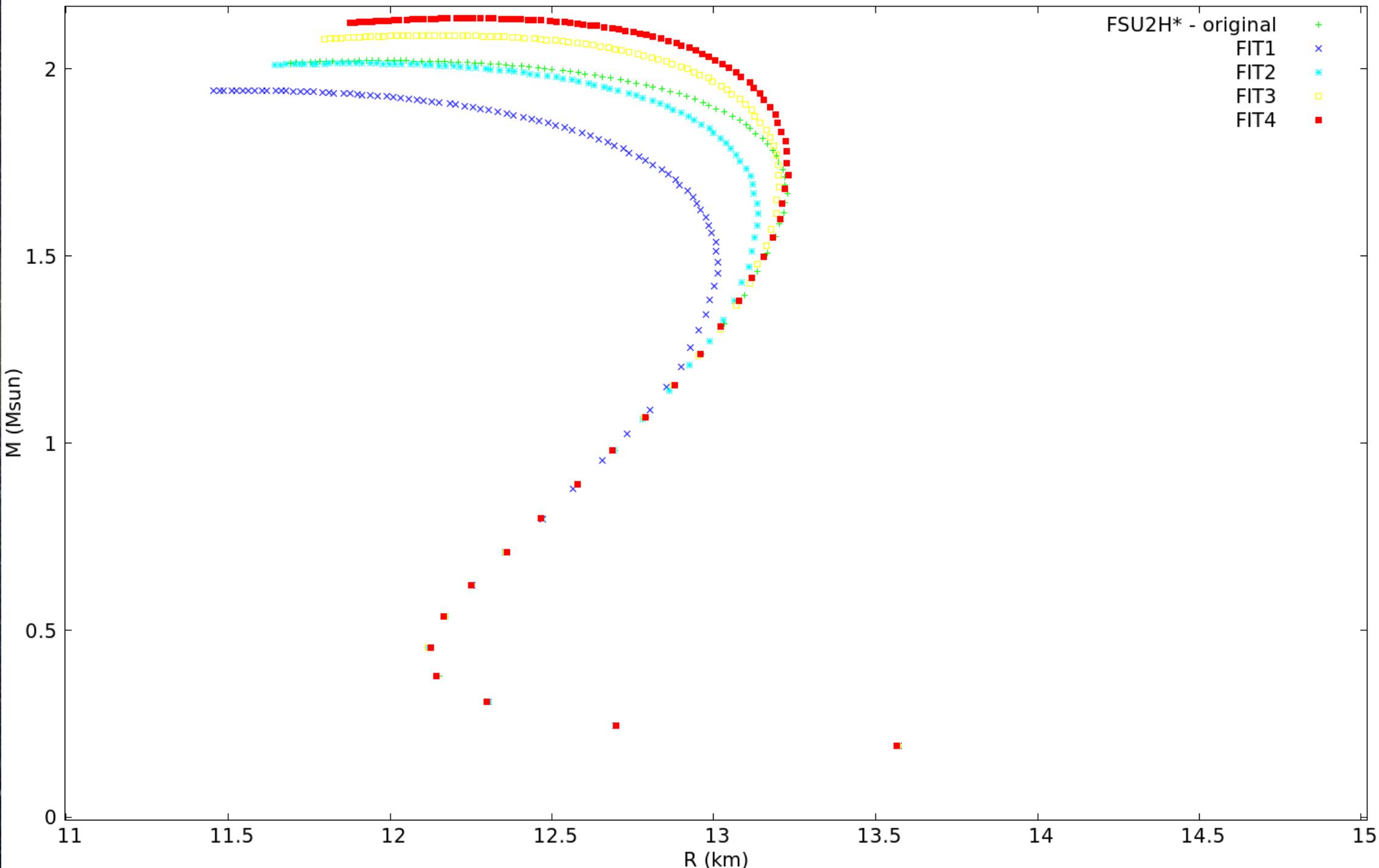
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Thank you for the attention







Neutron stars, multimessenger and very dense matter



K. Haring, Star

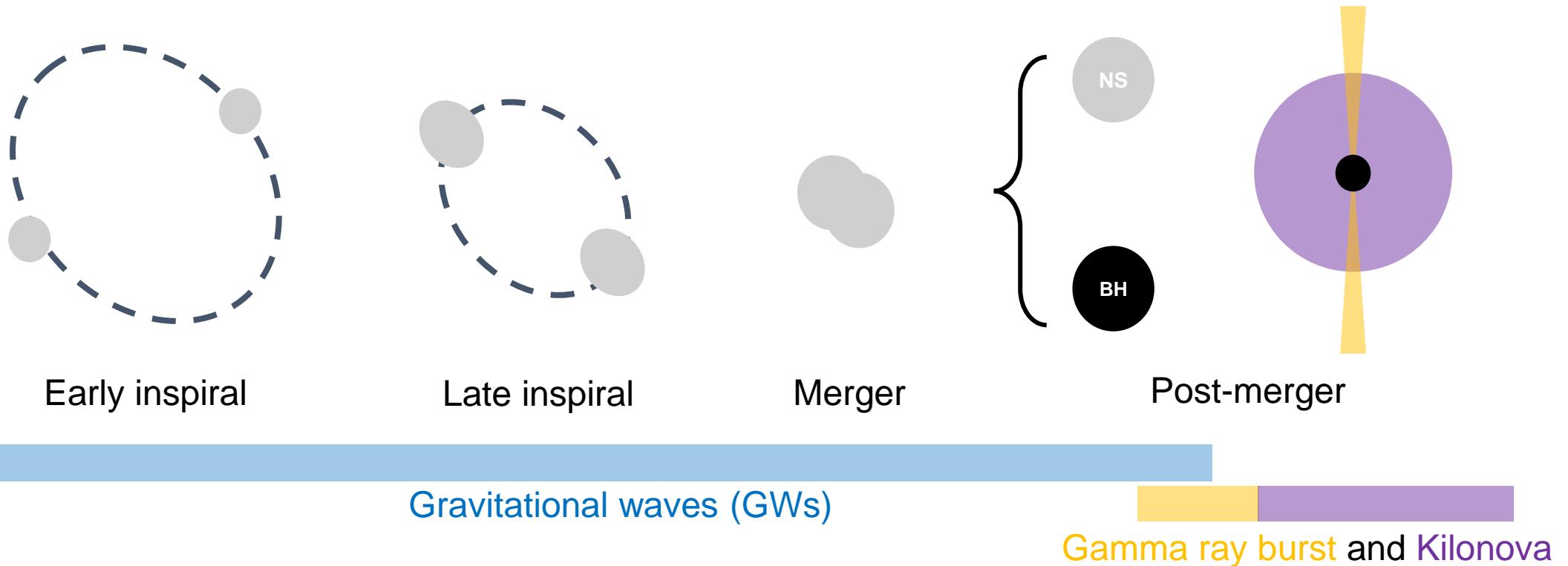


Lavinia Paiella, PhD Astroparticle Physics GSSI

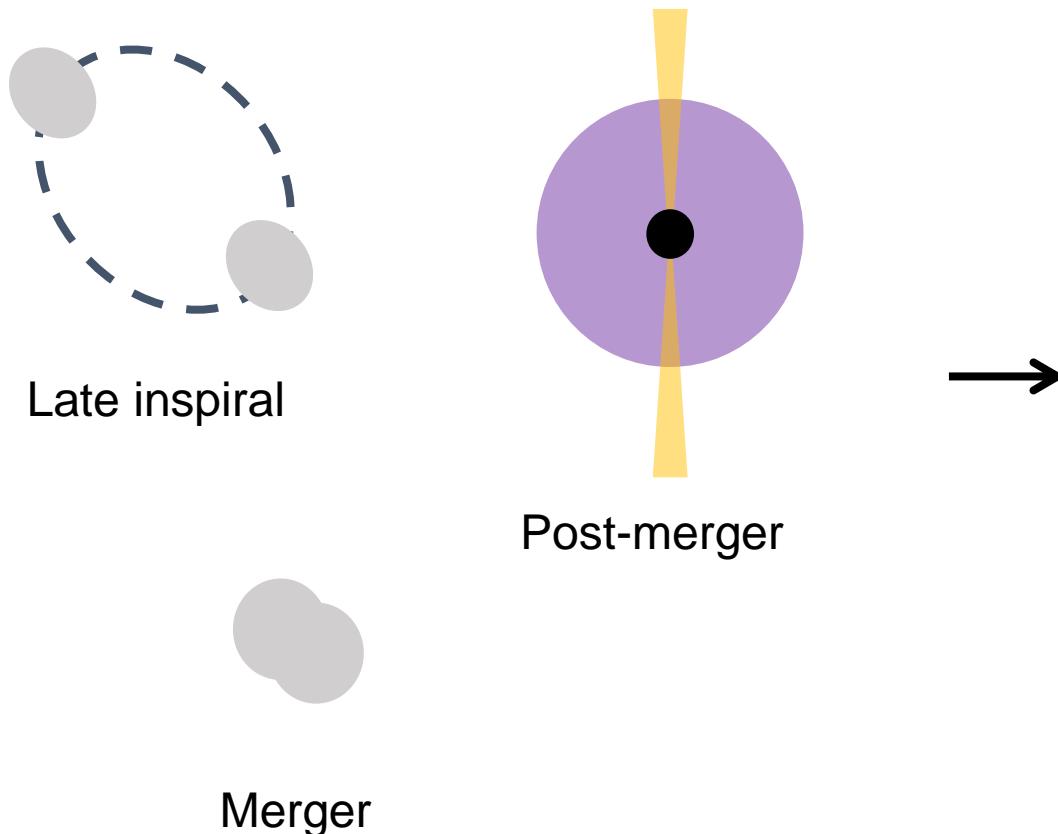
Thesis Supervisor: Andrea Maselli

G S
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Multimessenger emission of neutron star binaries



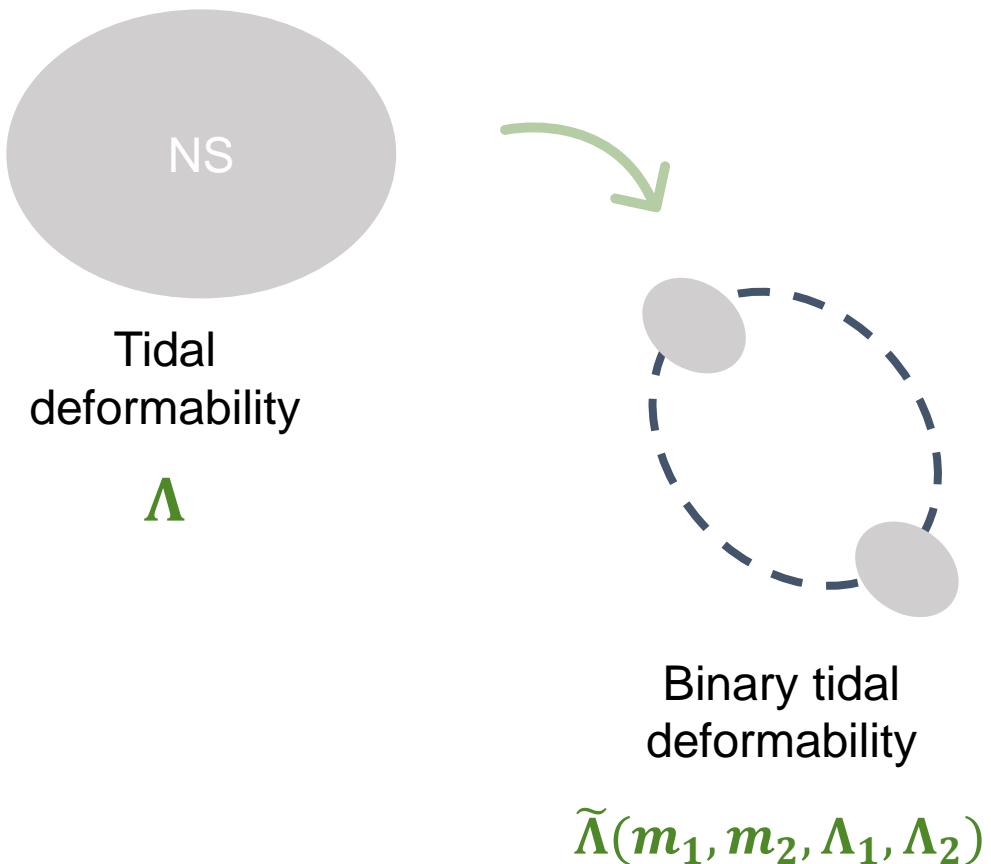
Multimessenger emission of neutron star binaries



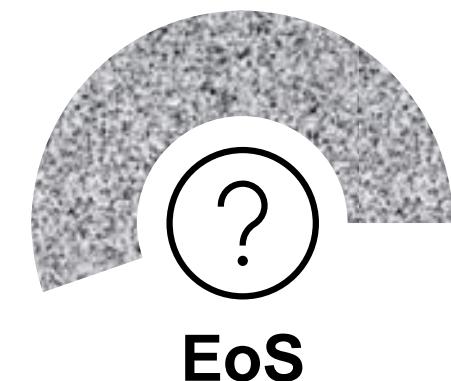
- Finite-size effects become relevant in the last stages of the coalescence;
- Tidal effects depend upon neutron stars interiors;
- Affect the phase of GWs + ejecta in the kilonova;

Multimessenger analysis!

Micro to macro



- The tidal deformability describes the NS response under an external gravitational field;
- It strongly depends on the neutron star equation of state (EoS) which encodes the microscopic behaviour of NS matter;



Probing a «simple» nuclear model

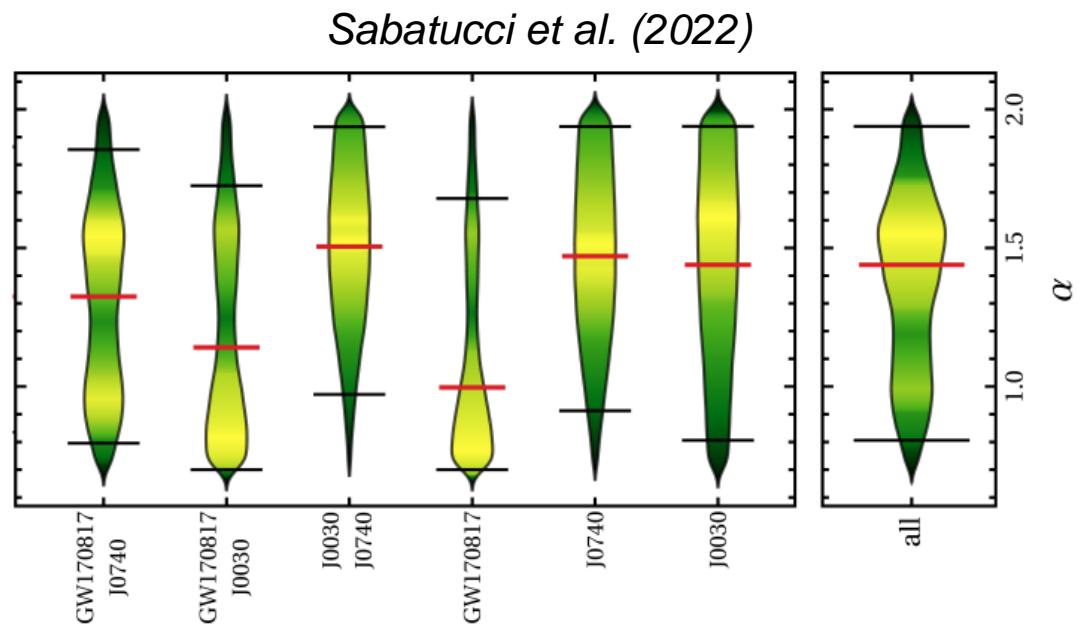
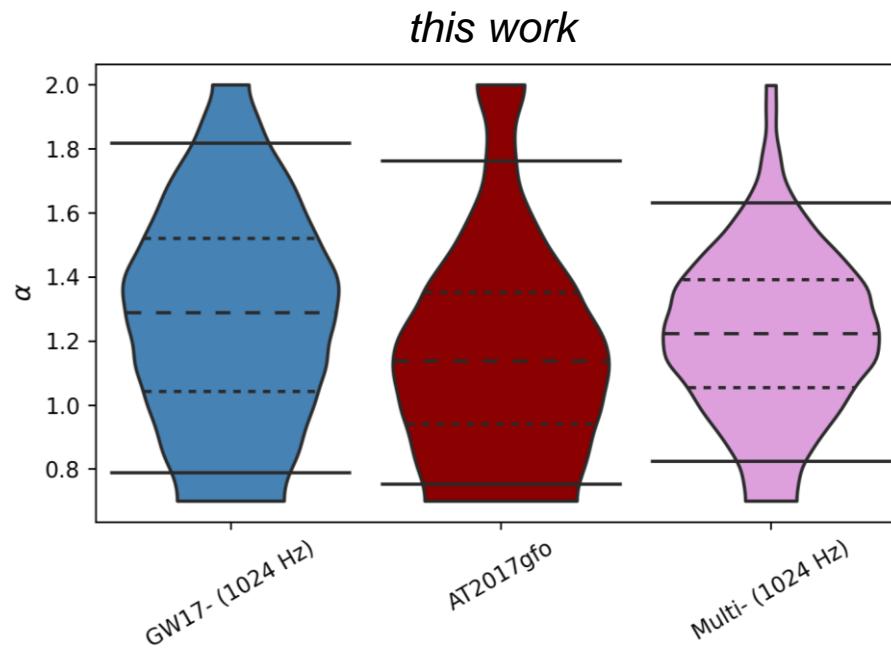
- Point-like nucleons interacting through two- and three-body forces;
- Strength of three-body repulsive interactions parametrized by adding a multiplying constant (Maselli 2021):

$$V_{ijk}^R \rightarrow \alpha \cdot V_{ijk}^R$$

$\alpha = 1$ base-line model

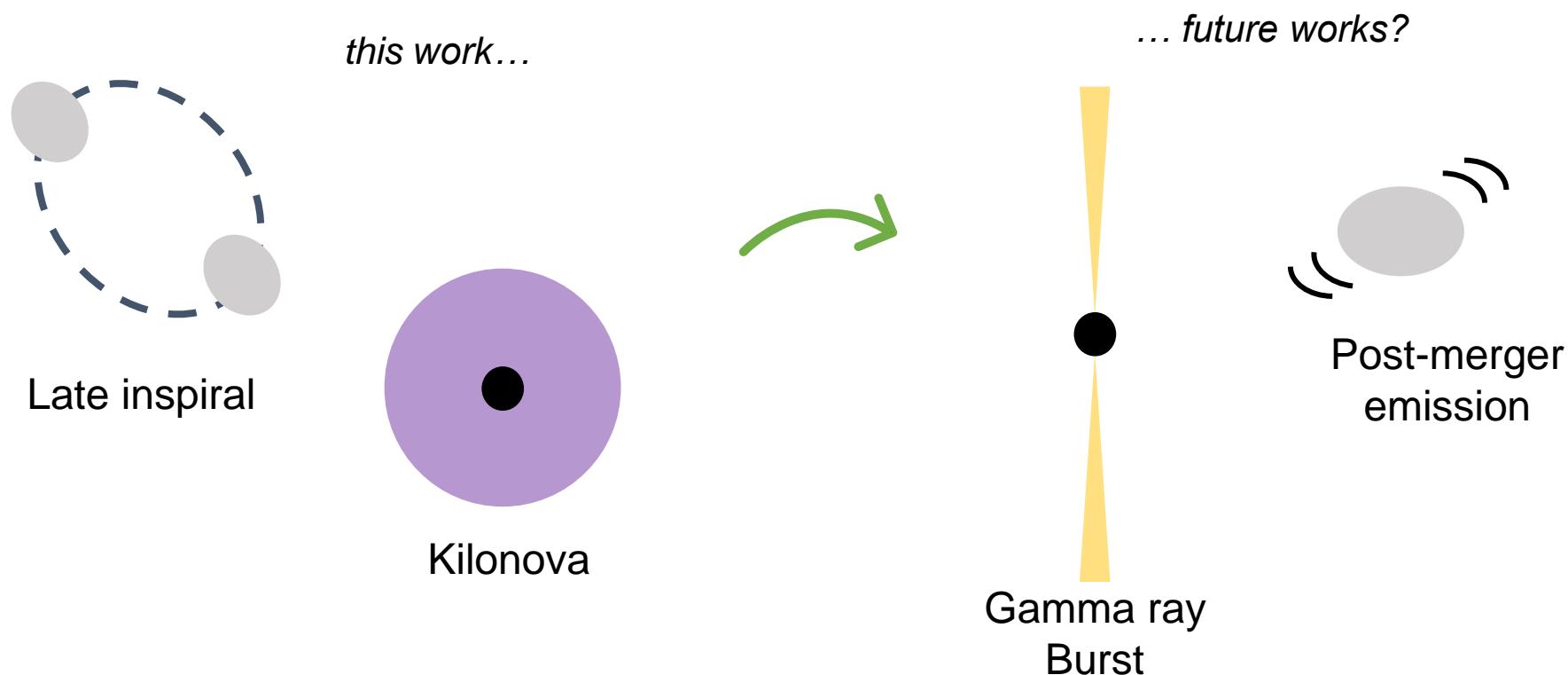
- **Goal:** constraining this parameter from data of GW170817 and AT2017gfo

Results (multi.)



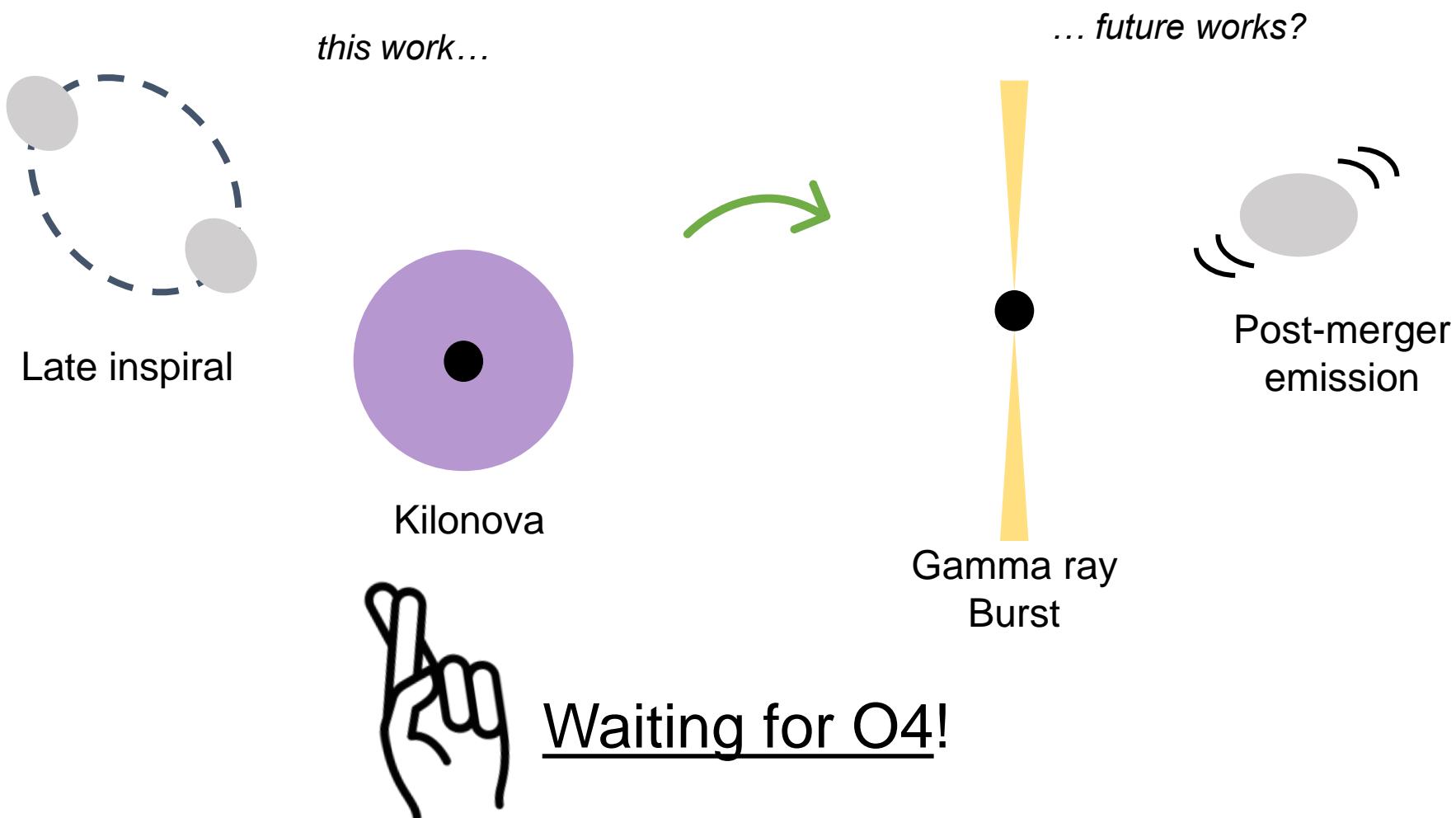
- Observations point at $\alpha \approx 1.3$ (larger values of $\alpha \rightarrow$ stiffer EoS);
- Compatible within 68% interval with PDFs from analysis of NICER pulsar data (Maselli 2021, Sabatucci 2022)

Future perspectives



- Extend pipeline to include other signatures sensitive to the NS interior → *Complete and accurate anatomy of binary neutron star mergers!*

Future perspectives

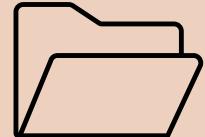


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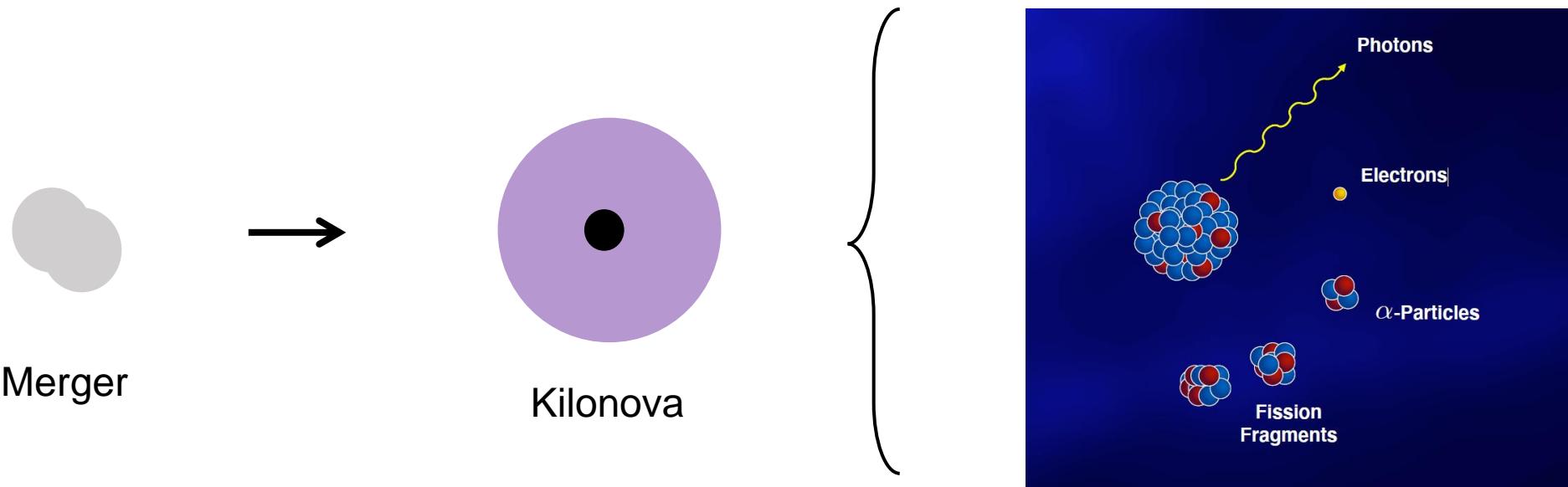
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Backup slides

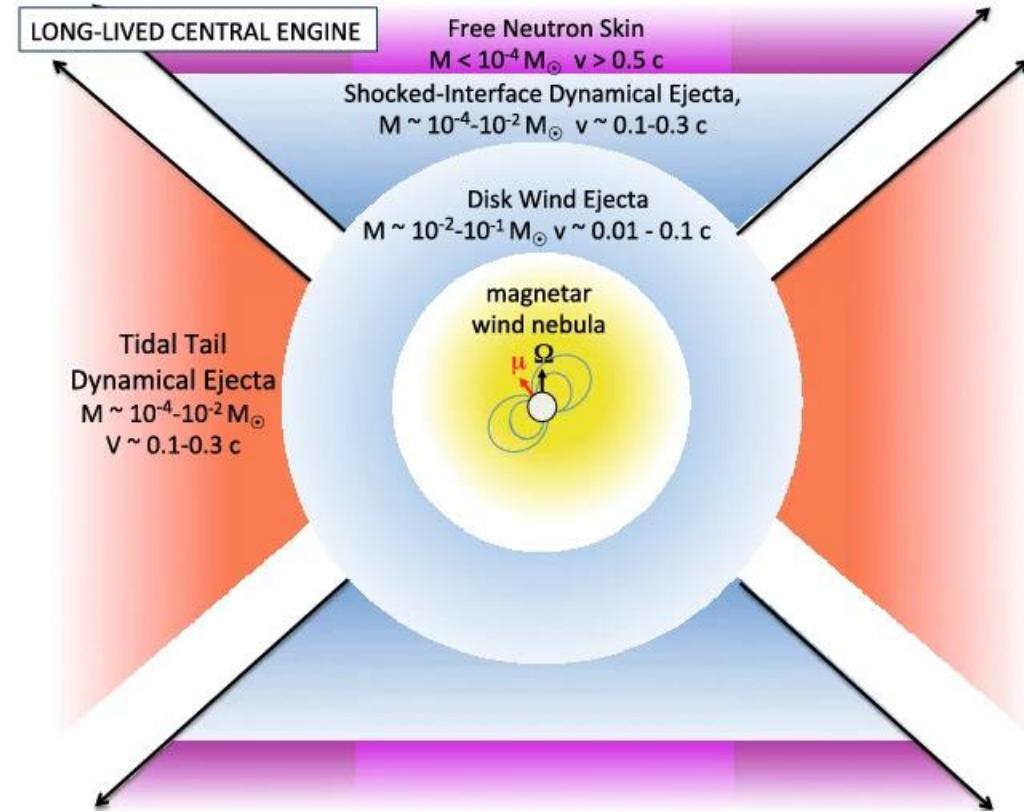
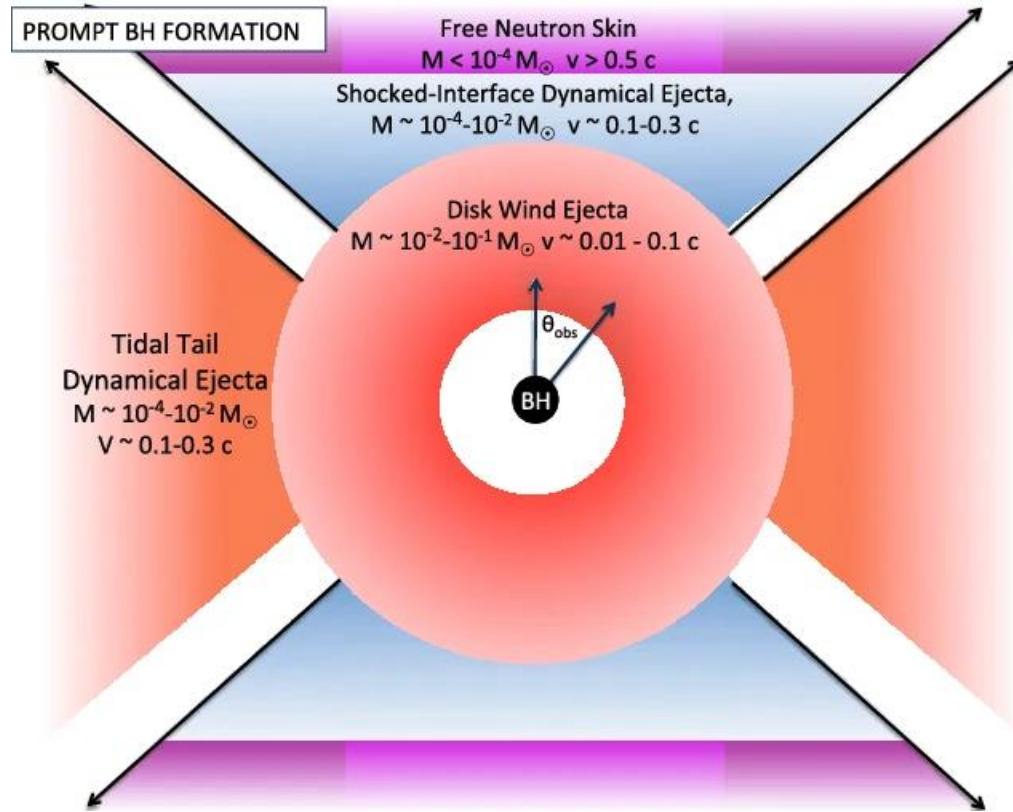


Kilonova

- **Thermal emission** produced by the **radioactive decay** of neutron-rich matter synthesized from the ejecta of the **compact binary coalescence** at **optical, near-infrared, and ultraviolet** wavelengths.

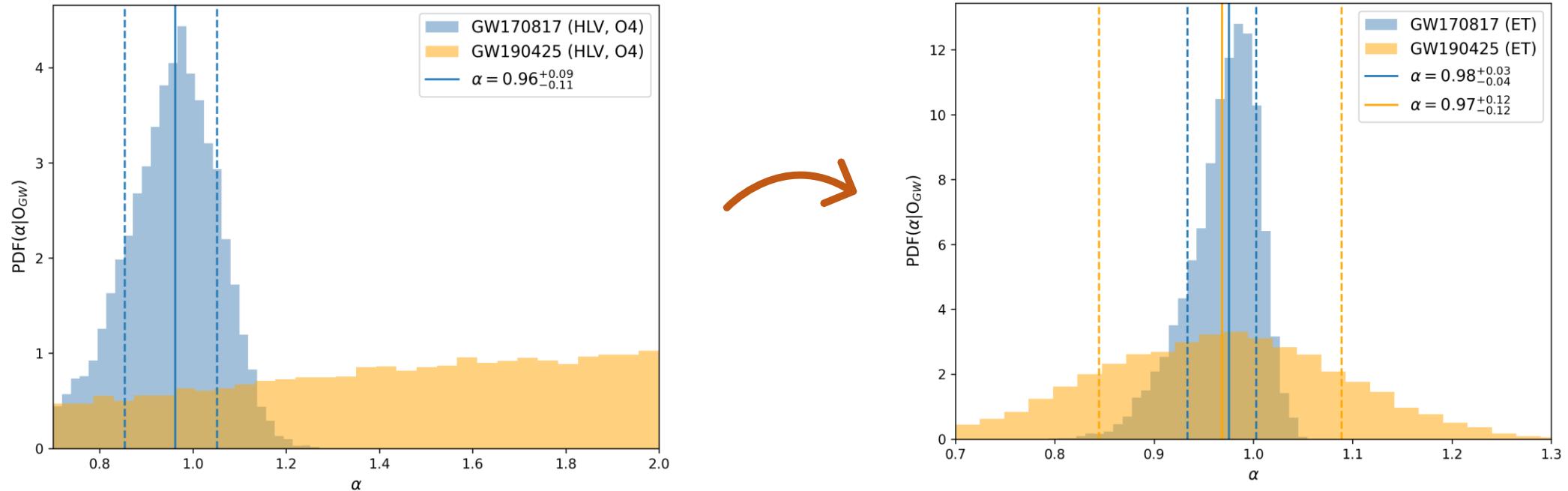


Kilonova



Metzger et al. (2020)

Results (GWs)



- Assessed the capability of current (Ligo-Virgo) and future (ET) interferometers of being sensitive to three-body interactions strength;
- Measurements of GW190425- and GW170817-like events in ET improve significantly constraints on α (3% and 10% uncertainty at 68% intervals)



Utrecht
University

Nikhef



*Unraveling information about supranuclear-dense
matter from the complete binary
neutron star coalescence process using future
gravitational-wave detector networks*

arxiv:2210.09259

GWsNS-2023

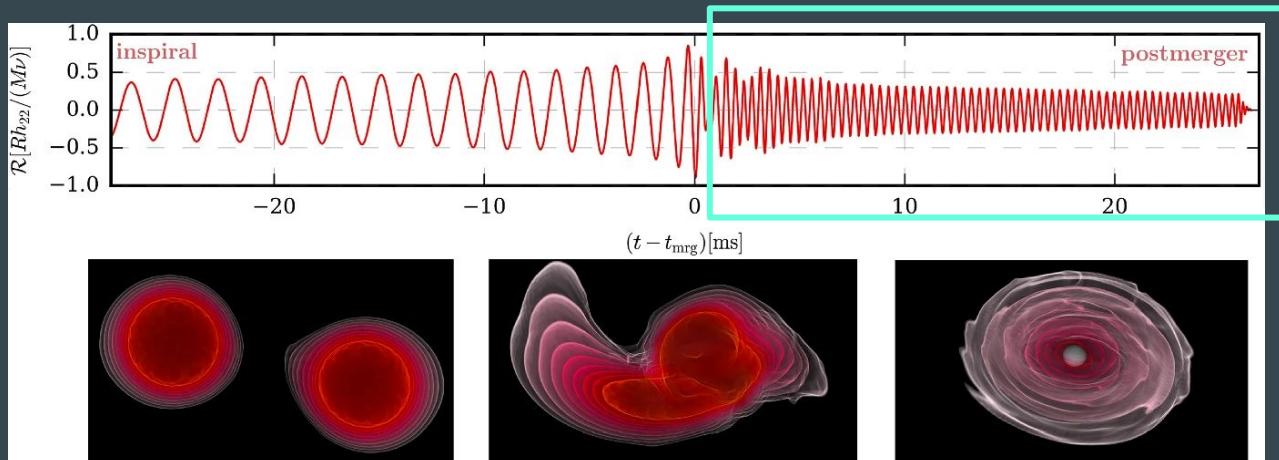
T.Dietrich, K.W. Tsang, C. Kalaghatgi, Y. Setyawati, S.Roy, C. Van Den Broeck

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Anna Puecher*

Gravitational waves from binary neutron stars

Inspiral: tidal deformability measurements (GW170817)



Postmerger

- different density and temperature regime
- remnant?

Inspiral-merger-postmerger model

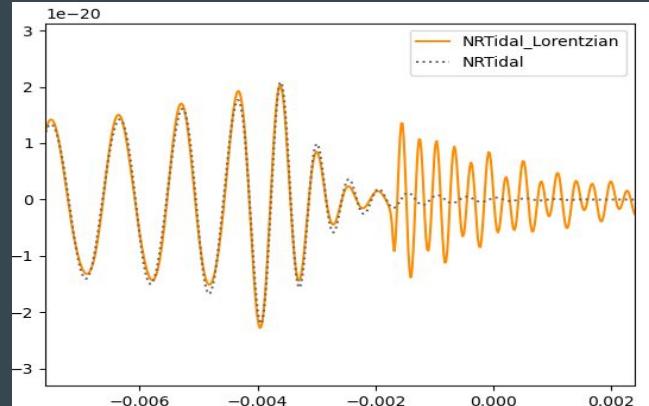
- Inspiral-merger: IMRPhenomD_NRTidalv2
- Postmerger: main emission peak \Rightarrow 3-parameters Lorentzian
(previous work: [Tsang et al. PhysRevD.100.044047](#))

$$h_{22}(f) = \frac{c_0 c_2}{\sqrt{(f-c_1)^2 + c_2^2}} e^{-i \arctan\left(\frac{f-c_1}{c_2}\right)}$$

c_0 : amplitude
 c_1 : dominant emission frequency
 c_2 : width

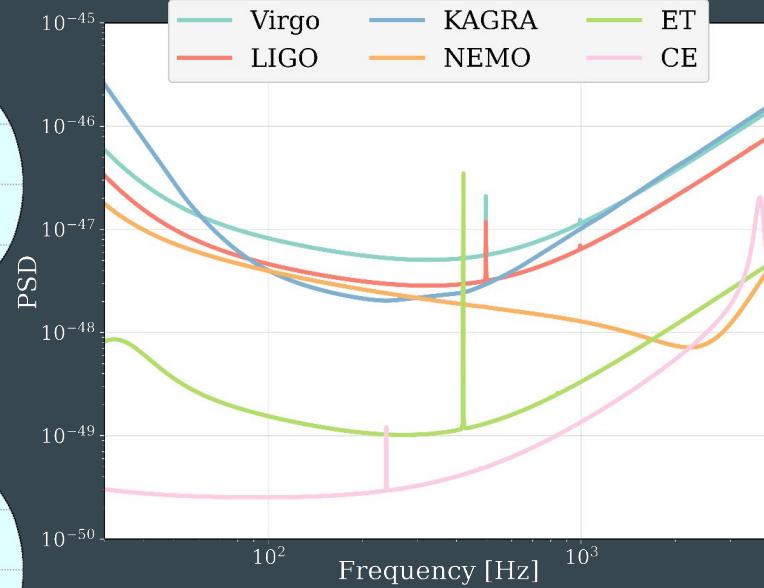
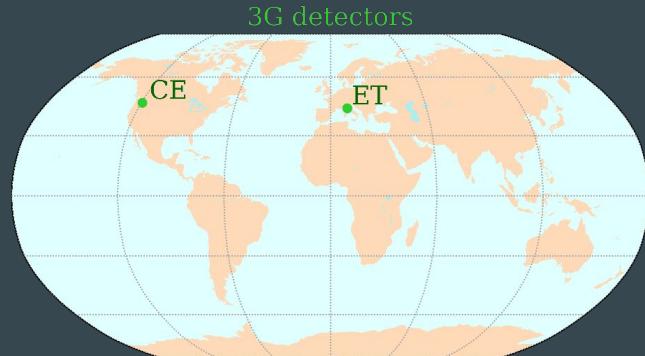
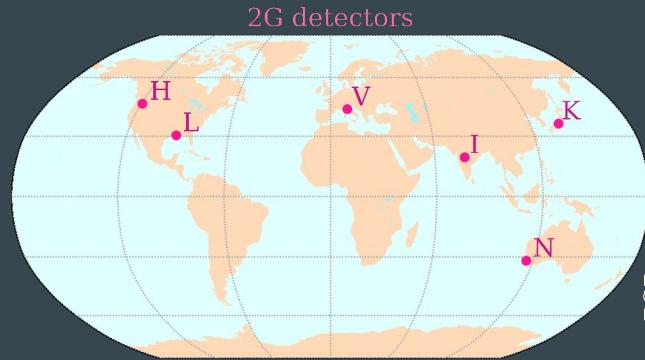
Postmerger Lorentzian described in two ways:

- c_0, c_1, c_2 as free parameters recover c_1
- Quasi-universal relations:
improvements in $\tilde{\Lambda}$ measurements



Detector networks

H: Adv LIGO+ Hanford	V: Adv Virgo+	ET: Einstein Telescope
L: Adv LIGO+ Livingston	K: KAGRA	CE: Cosmic Explorer
I: Adv LIGO+ India	N: NEMO	



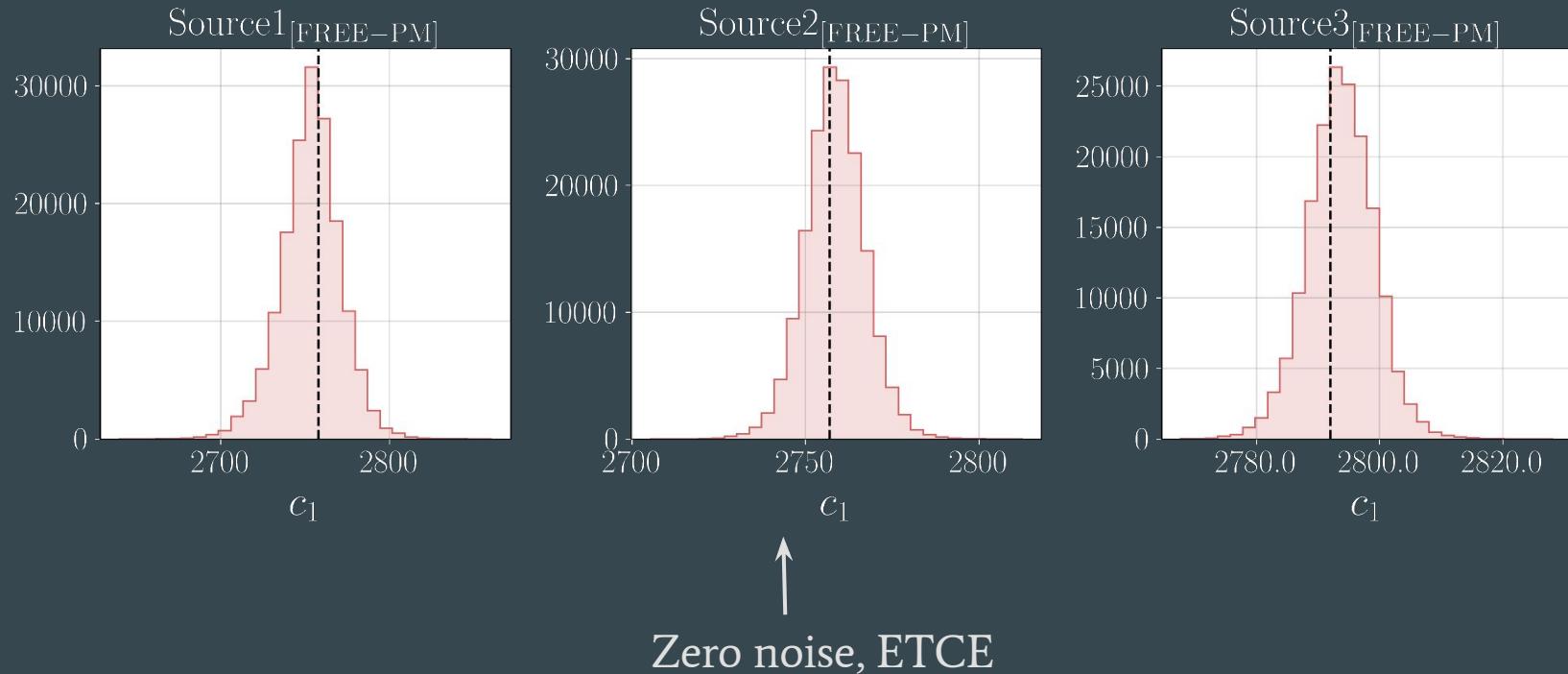
Network1:[LHV](#)

Network2:[LHVKI](#)

Network3:[LHVKIN](#)

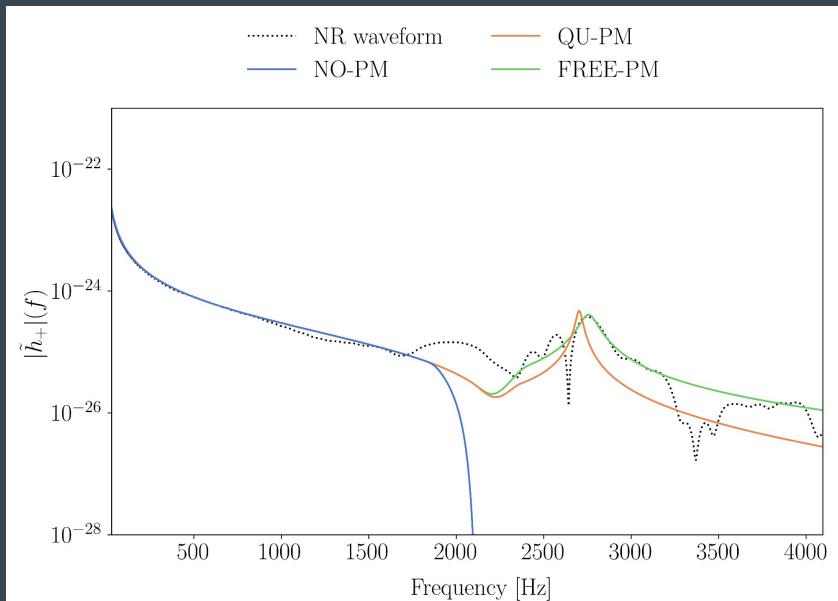
Network4:[ETCE](#)

Results

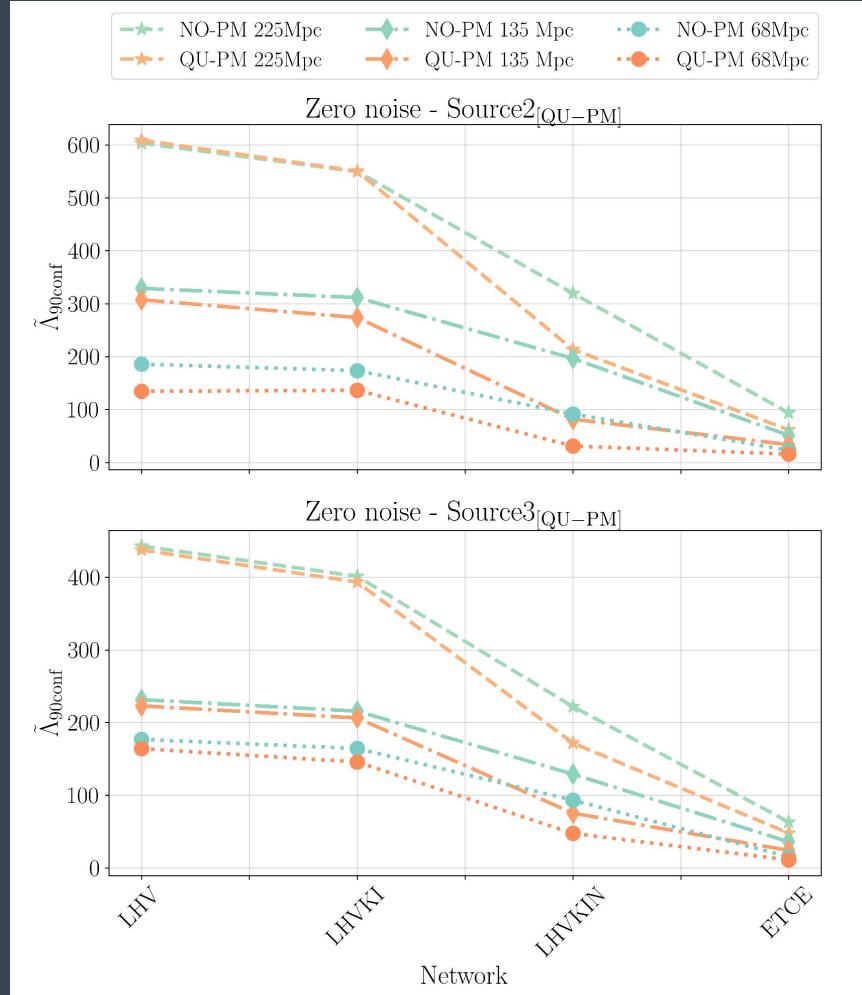


Results

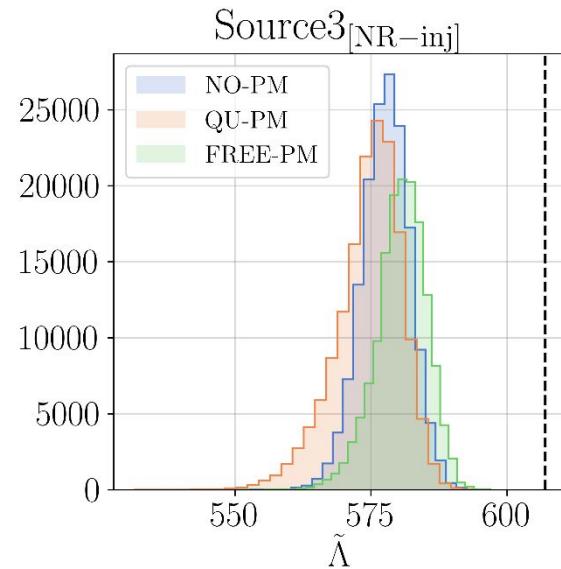
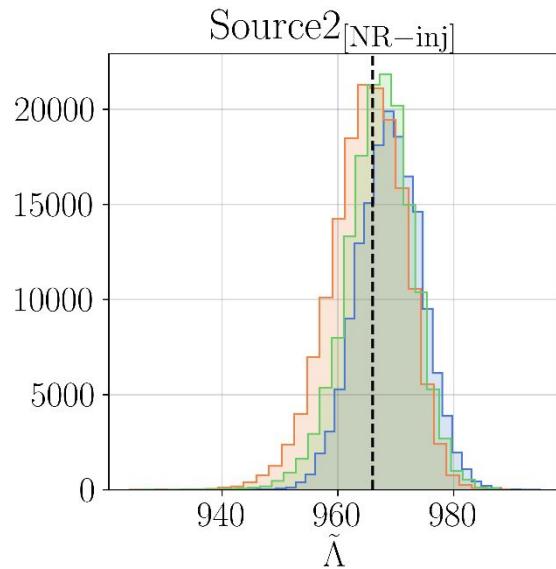
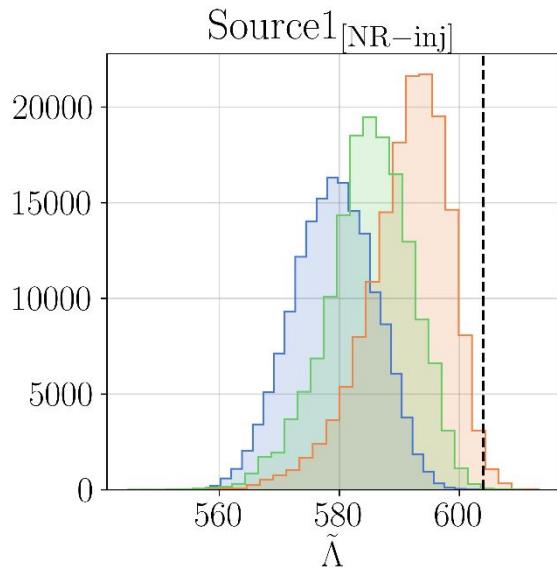
Zero noise
(Gaussian noise \Leftrightarrow large fluctuations)
NEMO strong improvement



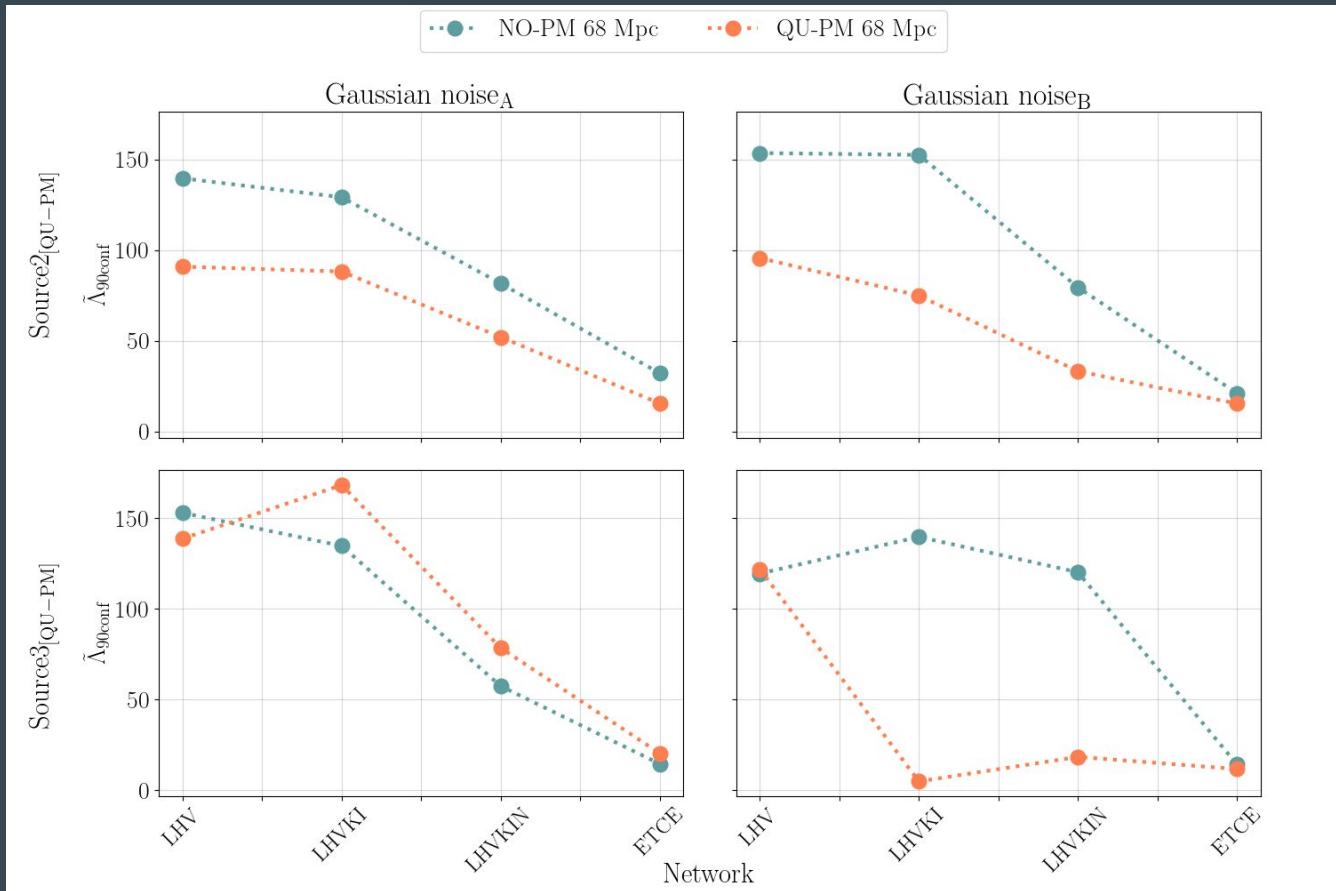
Need to improve the model!



Backup slides - Numerical relativity waveforms



Backup slides - Gaussian noise



Backup slides - Gaussian noise

	Model	$\tilde{\Lambda}_m$ noise _A	$\tilde{\Lambda}_m$ noise _B	$\tilde{\Lambda}_{\text{inj}}$
Source2 _[qu-pm]	QU-PM	$956.68^{+7.08}_{-8.37}$	$959.93^{+6.87}_{-8.71}$	966
	NO-PM	$966.35^{+9.35}_{-11.82}$	$953.10^{+13.11}_{-19.11}$	966
Source3 _[qu-pm]	QU-PM	$608.04^{+11.65}_{-6.27}$	$602.36^{+7.86}_{-12.49}$	607
	NO-PM	$611.76^{+6.68}_{-7.51}$	$604.35^{+6.84}_{-7.70}$	607