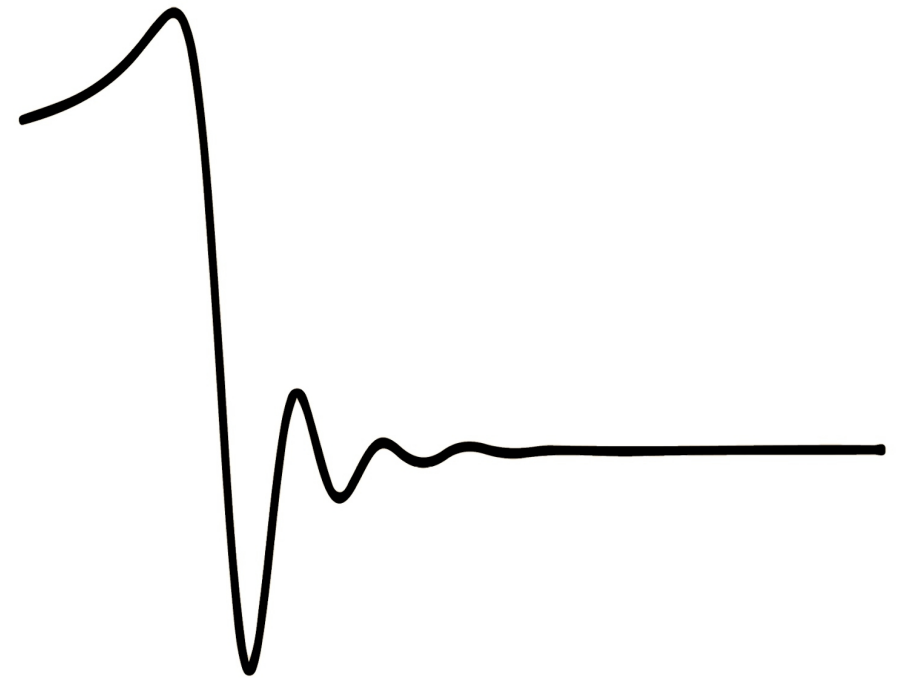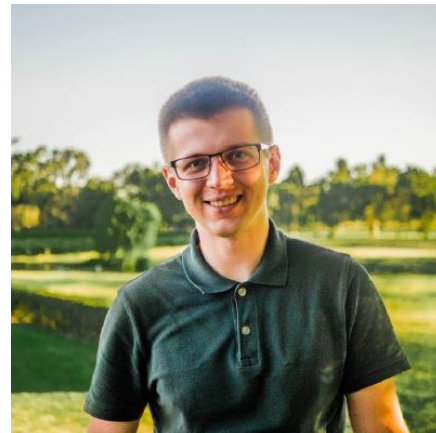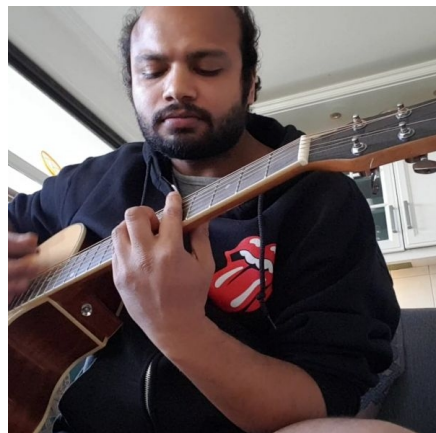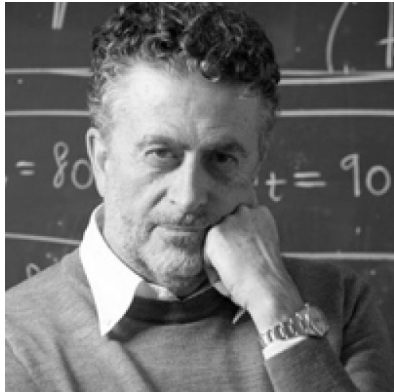# *General introduction on* **GC** *activities: Theory*

@ 7th Astroparticle Physics Scientific Fair 2020/2021
Mar 3rd 2021

Andrea Maselli

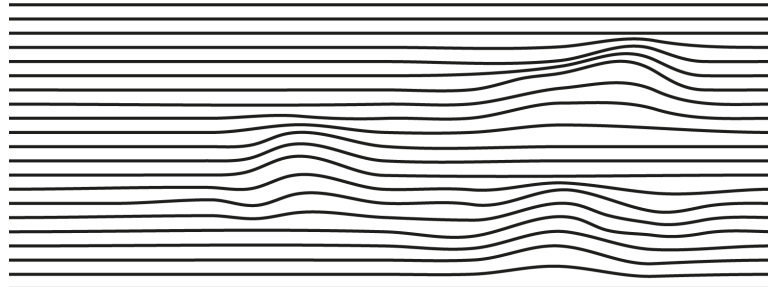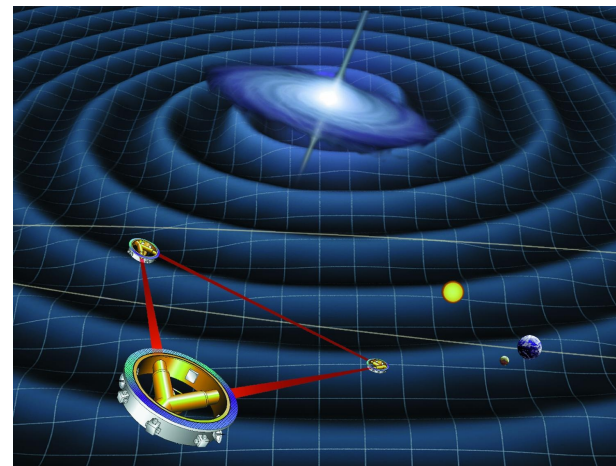# The GravGroup

The GravLinks
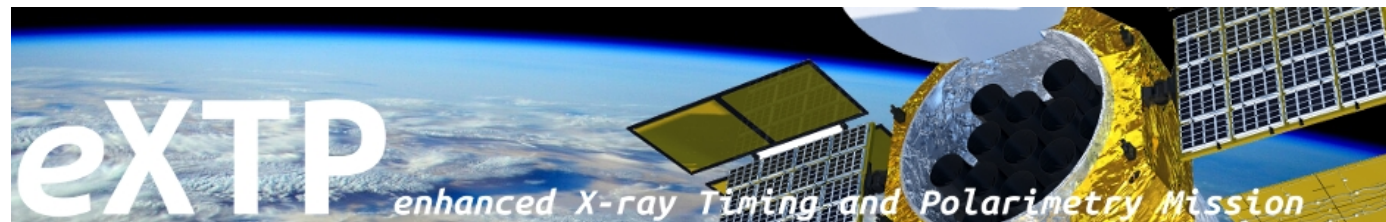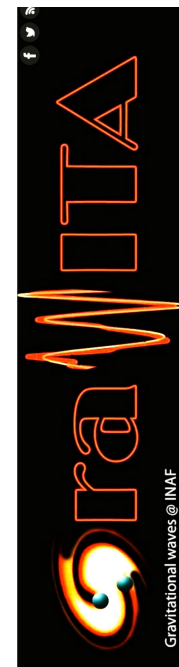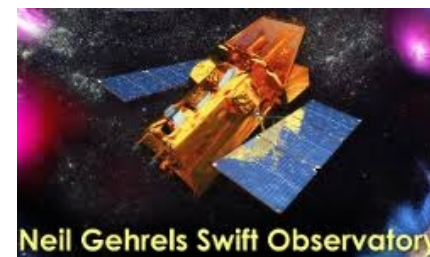
EM counterparts

Observational resources

- ○ **X-Ray***: XMM, Swift*
- ○ **Optical***: VST@ESO, REM, TNG, NOT, LBT, Asiago, Campo Imperatore*
- ○ **Radio***: SRT, EVN, VLBI*

PRIN PI (E. Cappellaro)
Local Coordinator M. Branchesi

ENGRAVE - Electromagnetic counterparts of gravitational wave
sources at the Very Large Telescope

Image Credit: ESO

About 200 astronomers

- ○ *European major group for follow-up study of the EM counterparts of GWs*
- ○ *Observations, data analysis and theory*
- ○ *Large amount of ToO on the*
  - **VLT instruments** *(X-shooter, MUSE, FORS)*
  - **Hubble Space Telescope**
  - **ALMA**

The Grav**A**ctivities

Radioactively powered transients
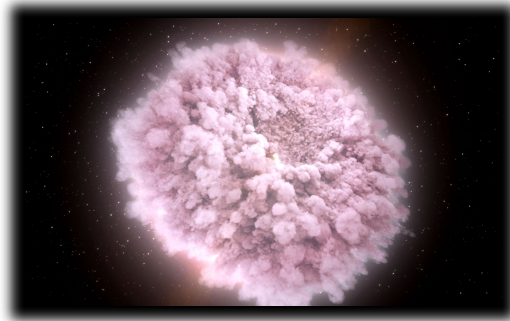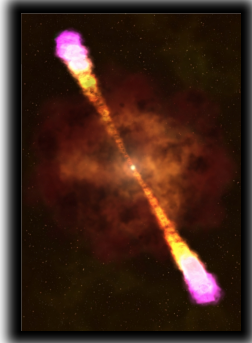
Nucleosynthesis and enrichment of the Universe

Relativistic astrophysics
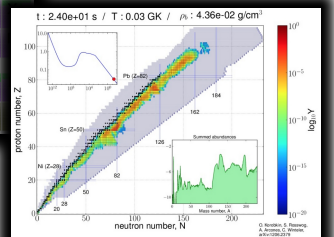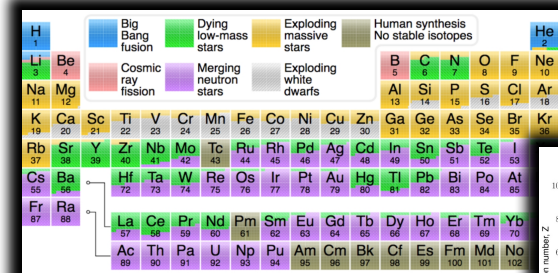
Tests of gravity
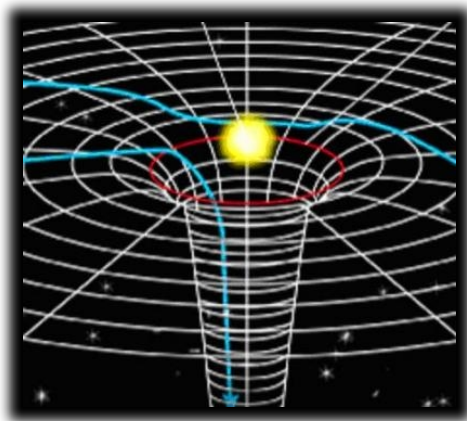
Cosmology
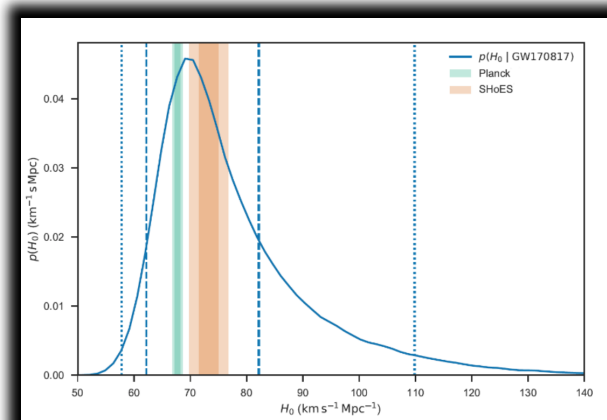
Nuclear matter physics
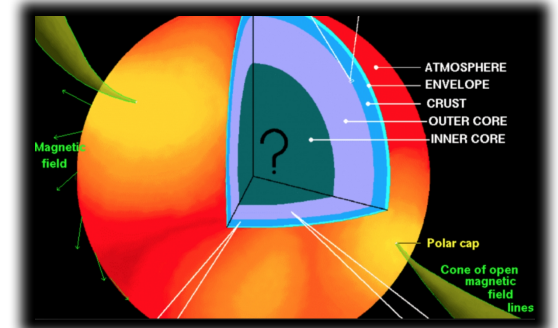
Relativistic Astrophysics

Modelling GRB emission

Structured

HLE from a structured jet
Oganesyan et al. 2020, Ascenzi et al. 2020
Arrival times
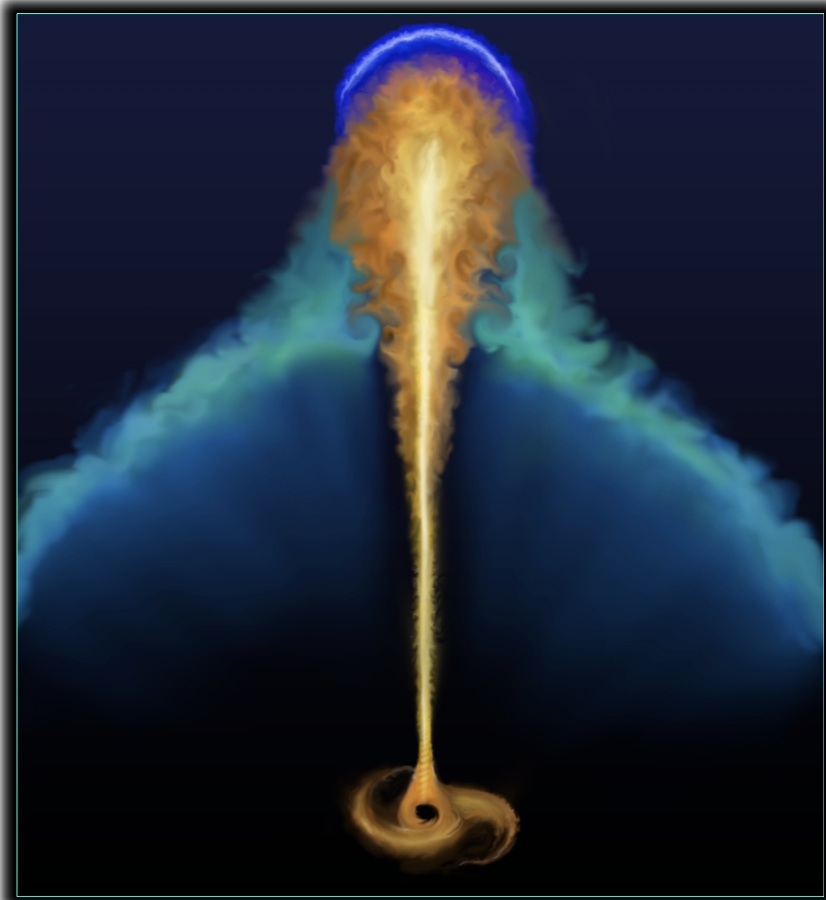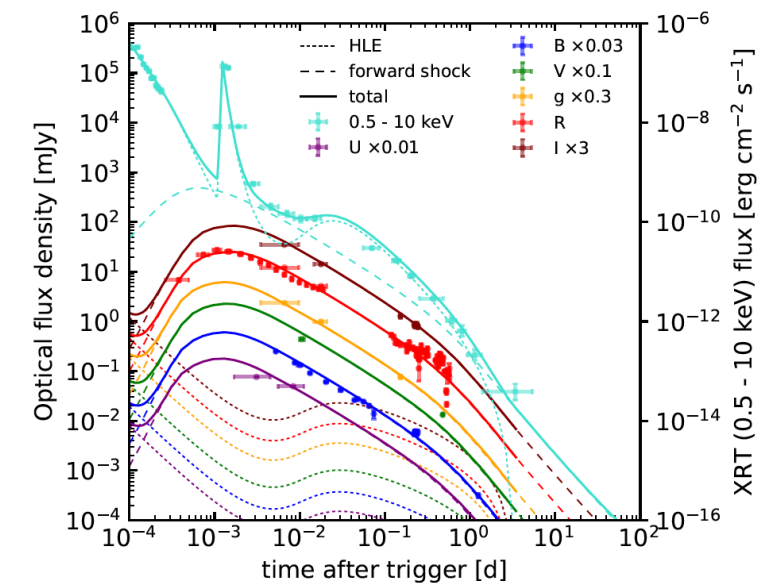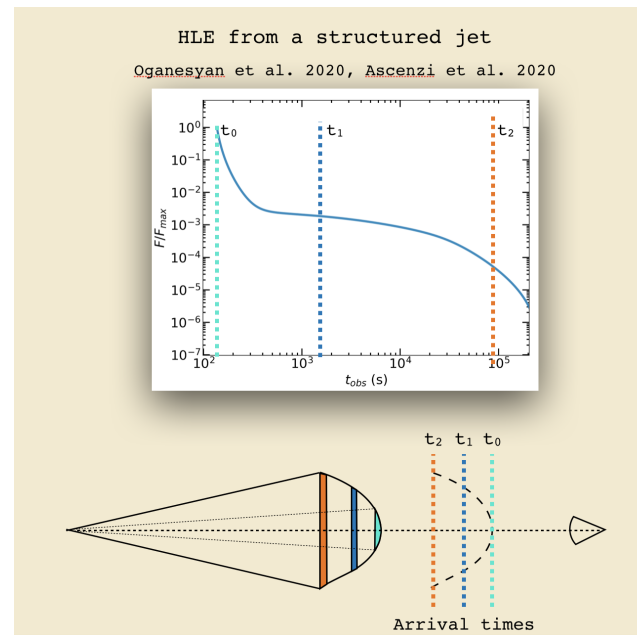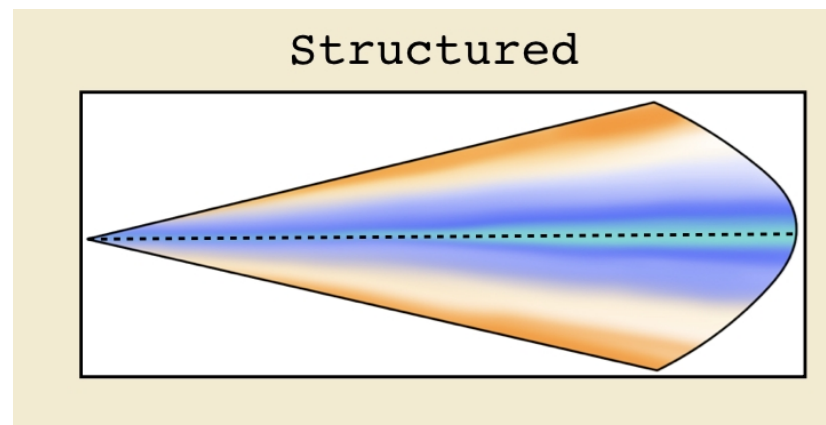
Oganesyan +, Astroph. J, 2020

○ *Predictions on EM emission testable by current/future detectors*
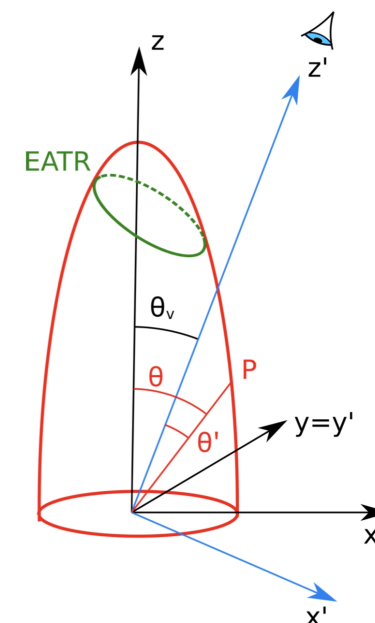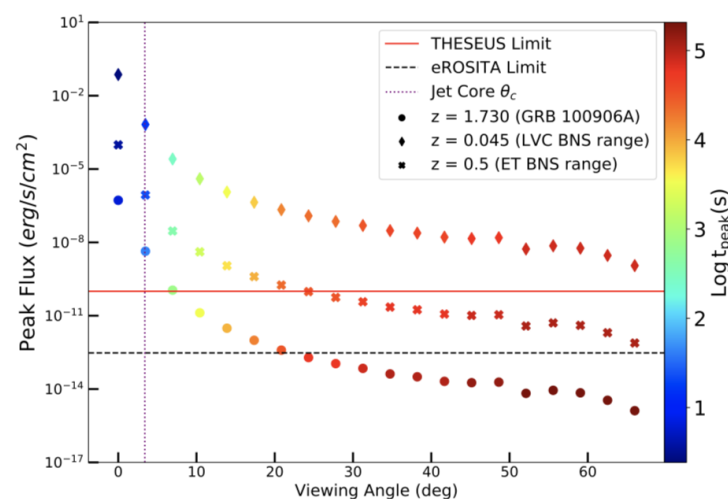
What happens **Off-axis** ?

Ascenzi +, Astron &. Astroph 641, 2020

Modelling GRB emission

Ronchini, Oganesyan, MB +, astrop-ph: 2009.03913
Nature Communication (under review)
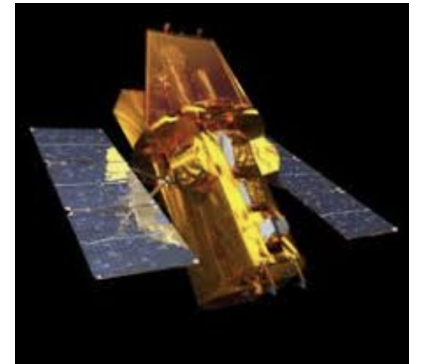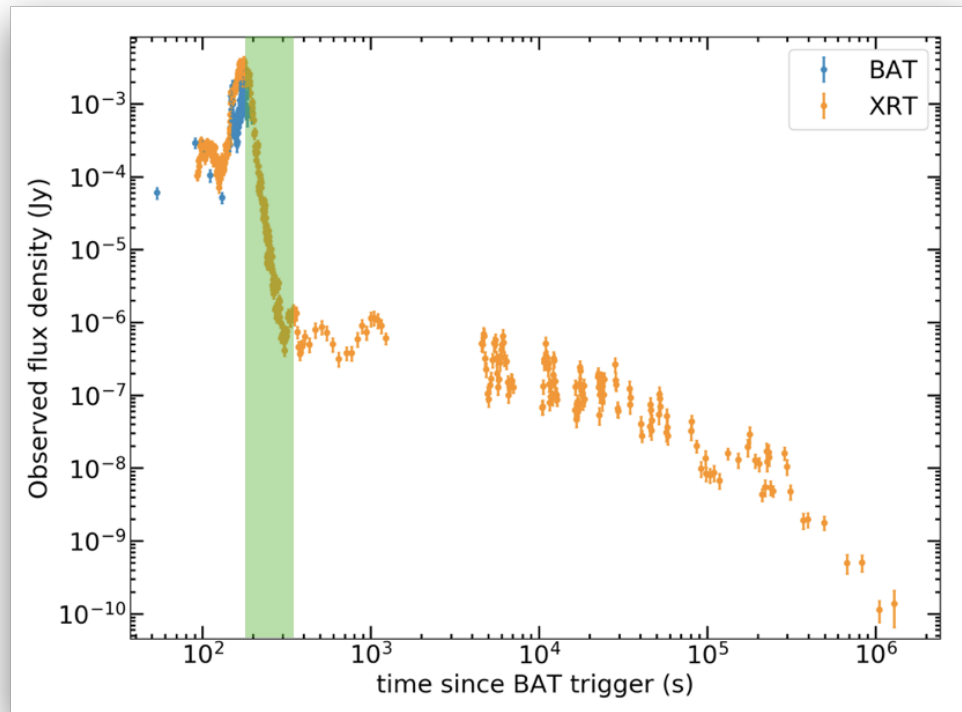
Unique relation among flux decrease and spectral properties!

- ○ *Adiabatic cooling!*

- ○ *Protons (slower cooling wrt electrons)*

Ghisellini+, Astron. & Astroph. 636, 2020

The E̱instein Ṯelescope

Detection horizon for black-hole binaries

ET science cases

EXTREME GRAVITY, DYNAMICAL SPACETIMES
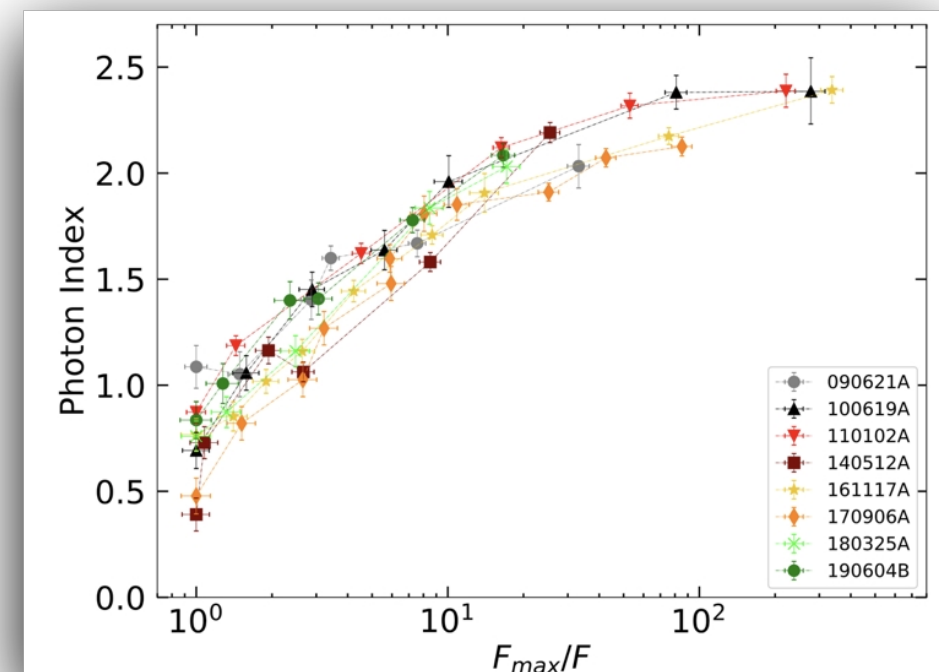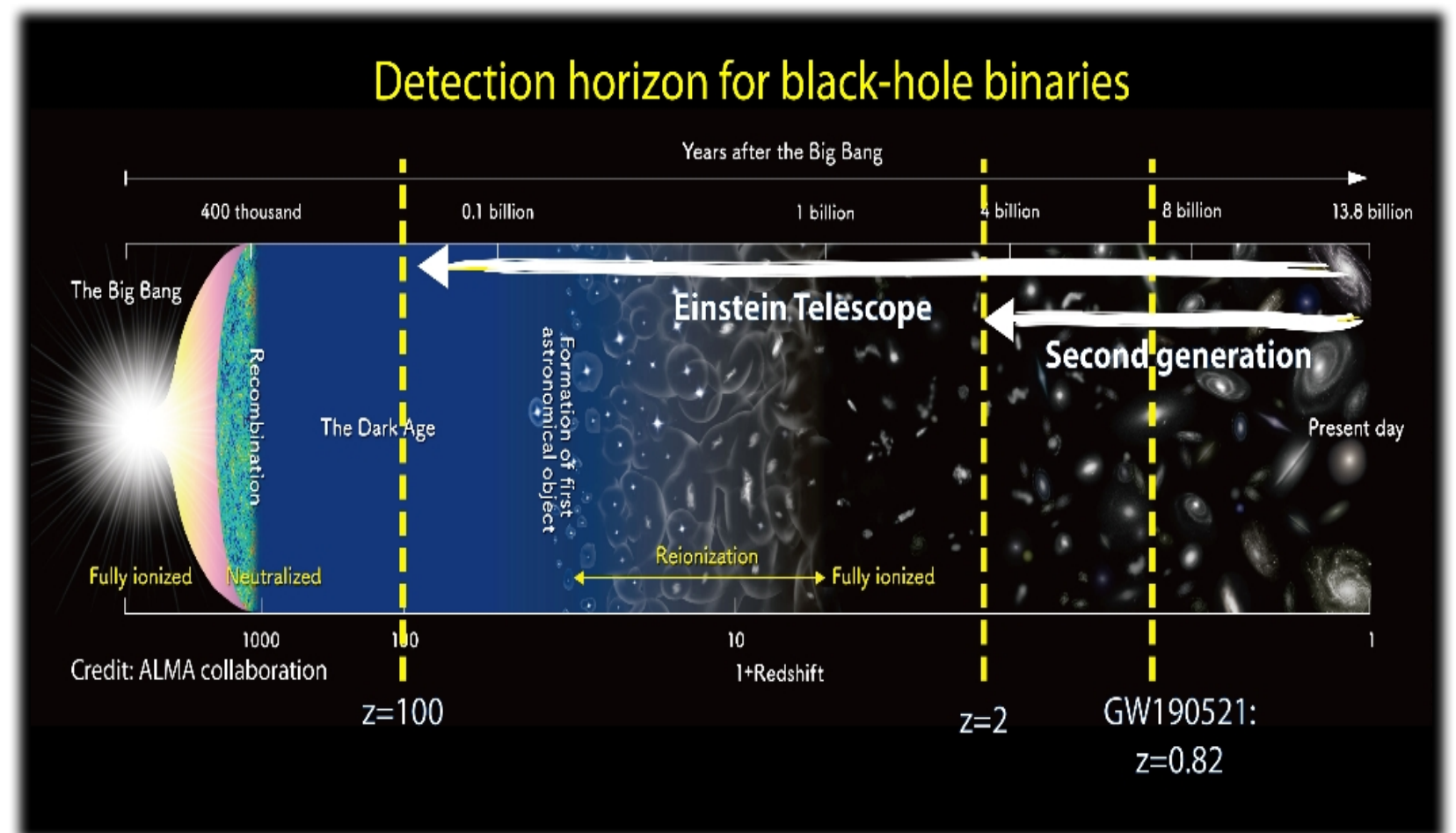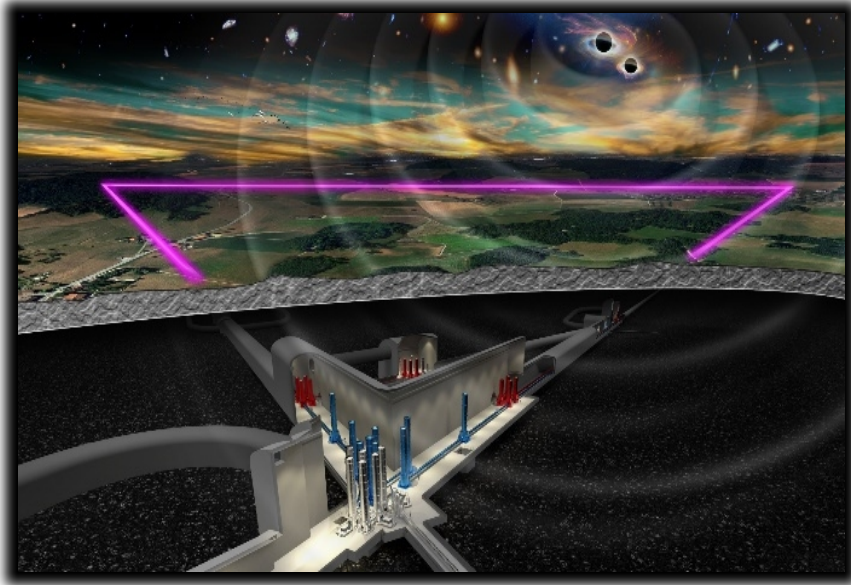
FORMATION AND EVOLUTION OF COMPACT BINARIES

Credit: Sathyaprakash

EQUATION OF STATE OF DENSE NUCLEAR AND OTHER EXTREME MATTER
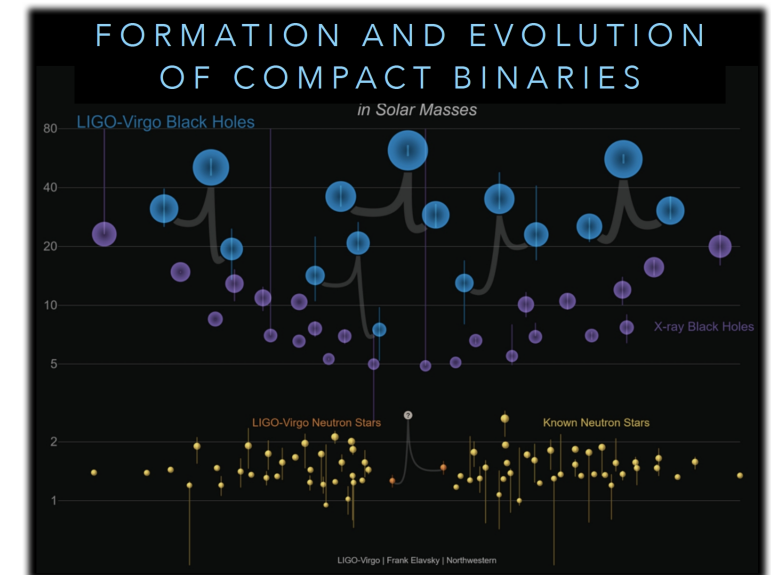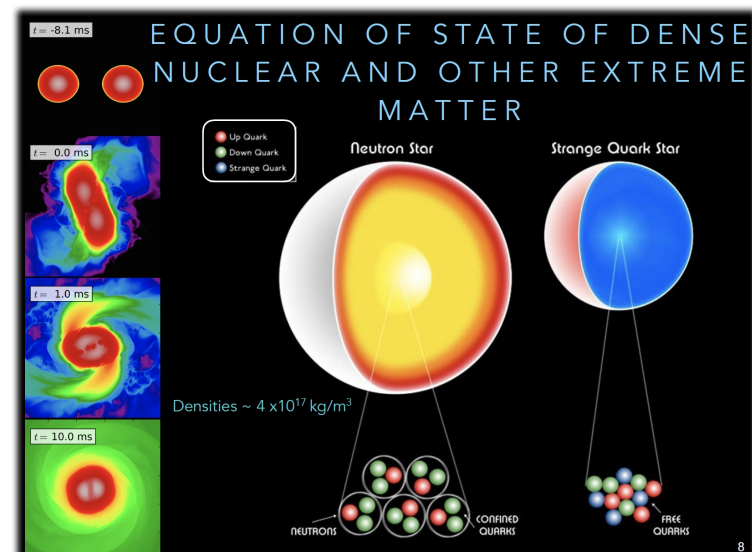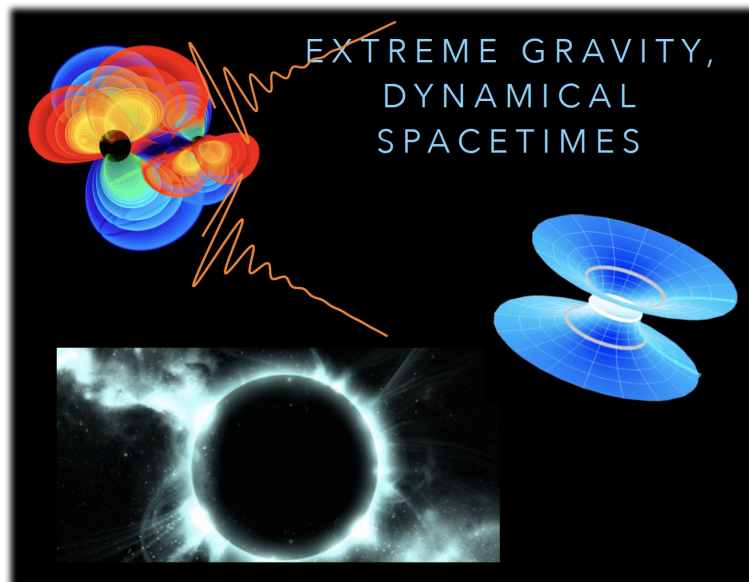
STANDARD SIREN COSMOLOGY

- Compact binaries are standard sirens; GW observations can measure the luminosity distance
- Can measure distance and redshift from GW observations of binary neutron stars

ASTROPHYSICS OF STELLAR COLLAPSE AND SUPERNOVAE

- Energy reservoir
  - few x 10^{53} erg
- Explosion energy
  - 10^{51} erg
- Time frame for explosion
  - 300 - 1500 ms after bounce
- Formation of black hole
  - At baryonic mass > 1.8-2.5 M
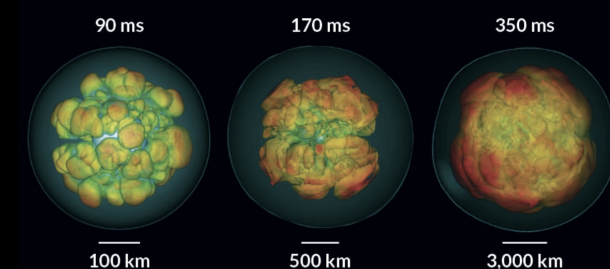
ET/THESEUS predictions for ESA

Aligned short GRBs

Aligned+misaligned short GRBs
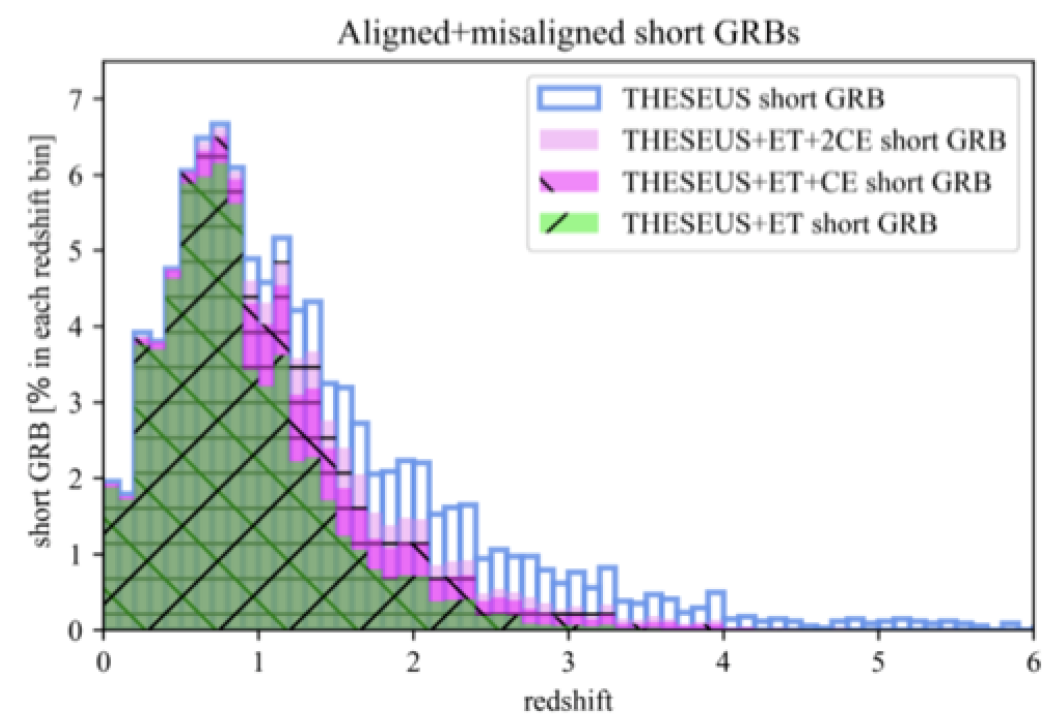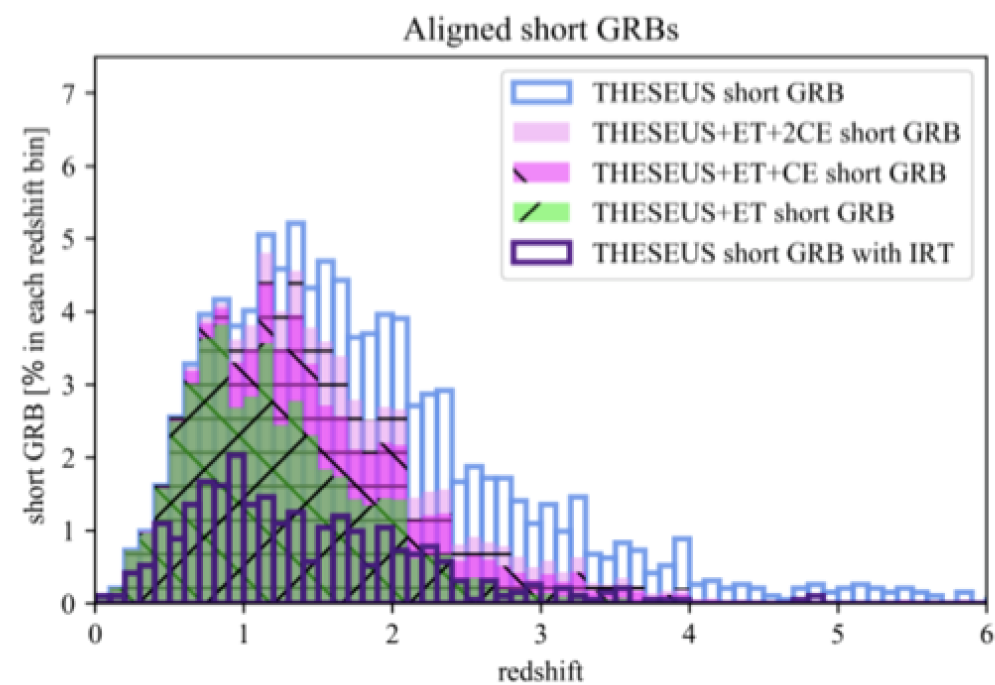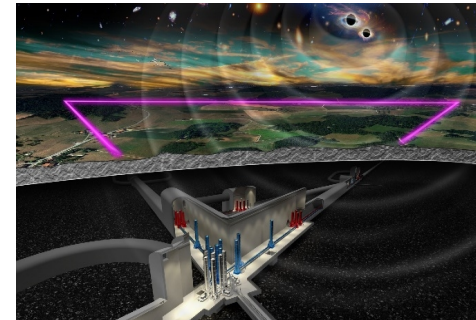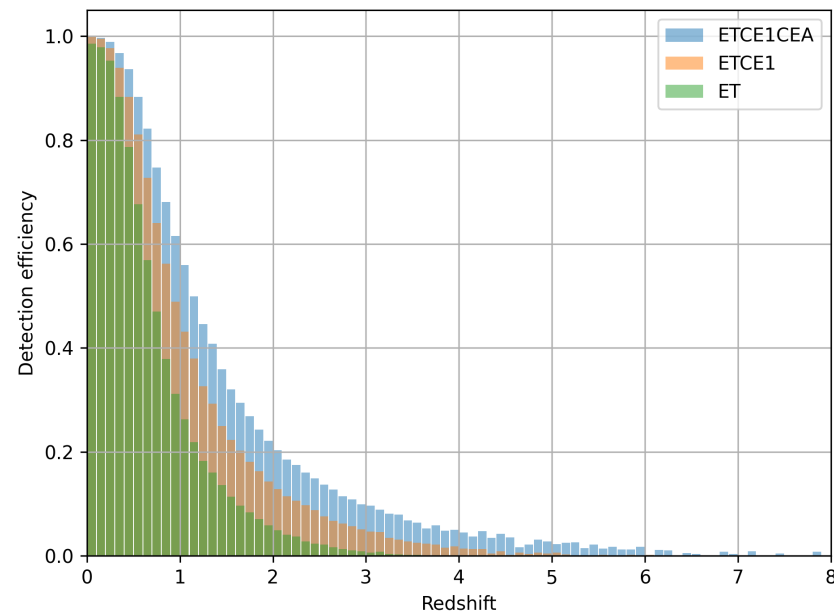
THESEUS Yellow Book just submitted to ESA

Radioactively powered transient

- Nucleosynthesis and enrichement of the Universe

- Nuclear matter physics

Main collaborator: A. Perego (Uni Trento), S. Cristallo (INAF)

Kilonovae

ESO-VLT/X-Shooter
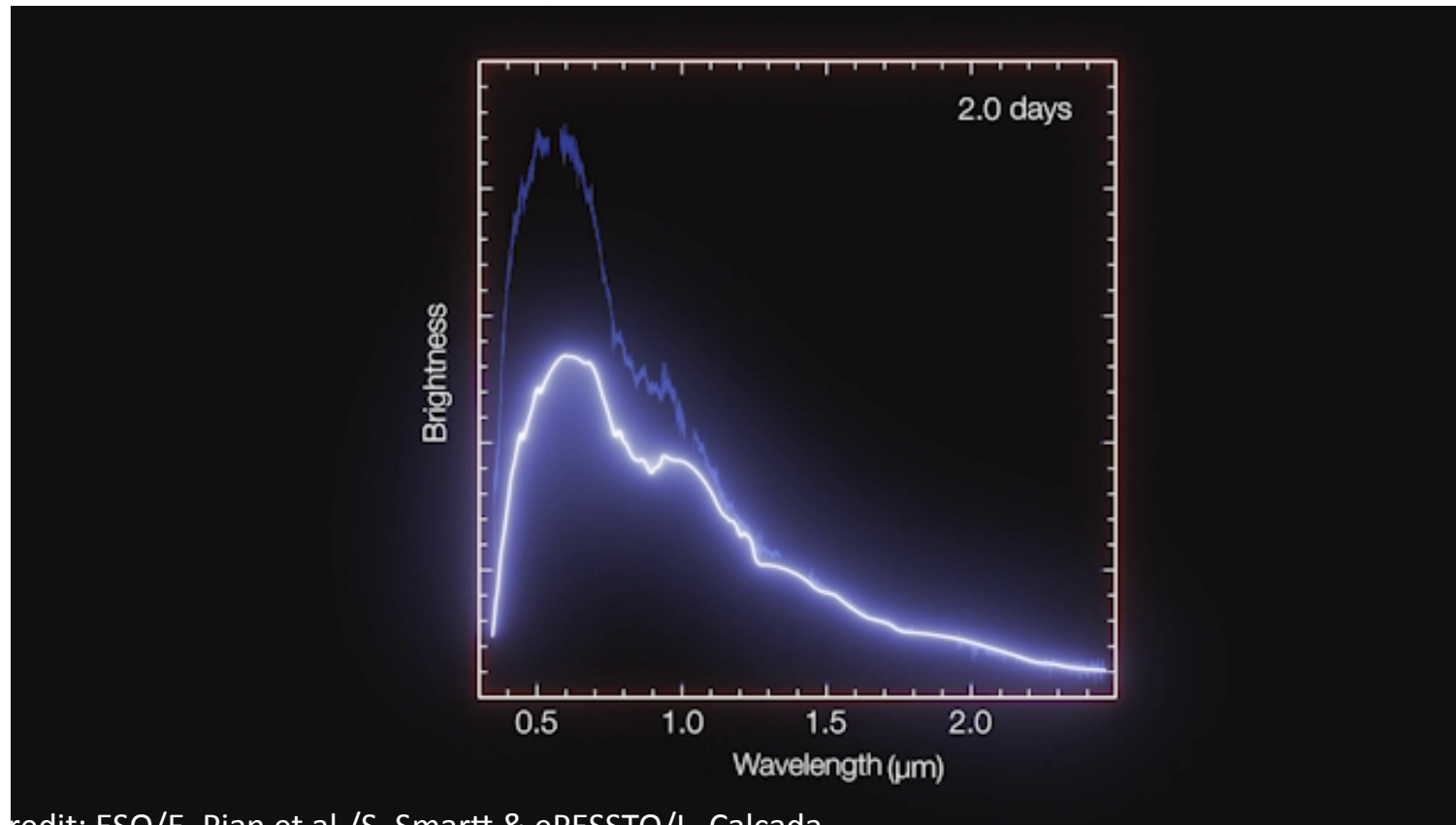
EJECTED MASS $\sim 0.03 - 0.05\ M_{\odot}$

EXPANSION VELOCITY $\sim 0.1 - 0.3\ c$

- ○ *First spectral identification of the kilonova emission*

  - ○ *the data revealed signatures of the radioactive decay of* **r-process nucleosynthesis** *(Pian + 2017, Smartt + 2017)*

  - ○ *BNS merger* **site for heavy element production in the Universe!** *(Cote et al. 2018, Rosswog et al. 2017)*

Credit: ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada

Kilonovae

Light elements (Z<20) in the ejecta of binary neutron star mergers

Abundances at 2 days for $\tau = 1.0$ ms (top) and $\tau = 11.4$ ms (bottom) trajectories
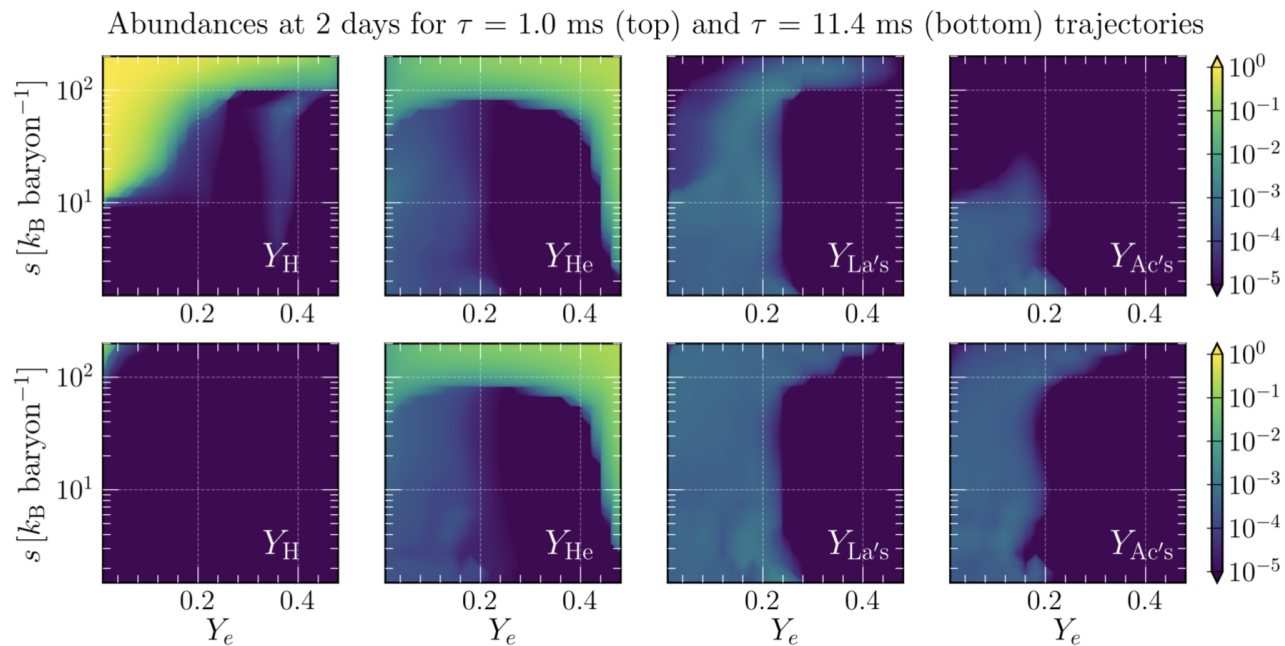
Perego,Vescovi +, astro-ph 2009.08998
Phys. Rev. Lett. (under review)

Large amount of He and H produced during the BNS merger
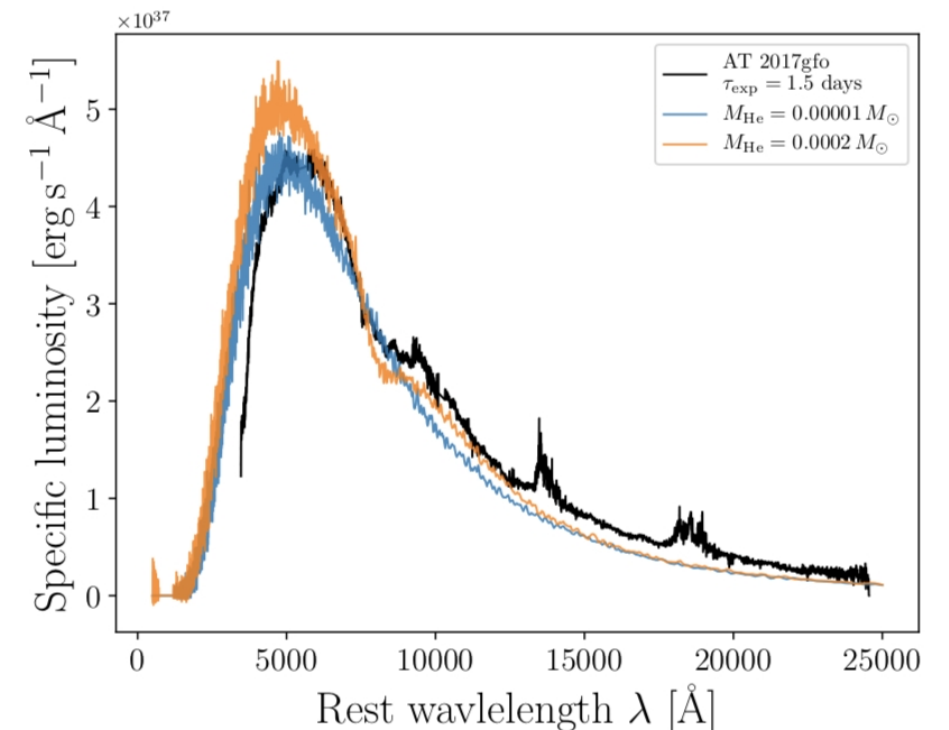
Kilonovae

- *Numerical relativity merger simulations*

- *Nucleosynthesis calculations*

Synthetic spectra for different viewing angles

Interaction jet-kilonova ejecta

Ultra-relativistic outflow

Low electron fraction
low Ye~ 0.1
Tidal Ejecta

GRB jet

remnant

Shock-heated Disk Winds

low Ye > 0.1
Higher electron fraction

GRB jet

Merger shock breakout

Cocoon

Dynamical ejecta

Wind
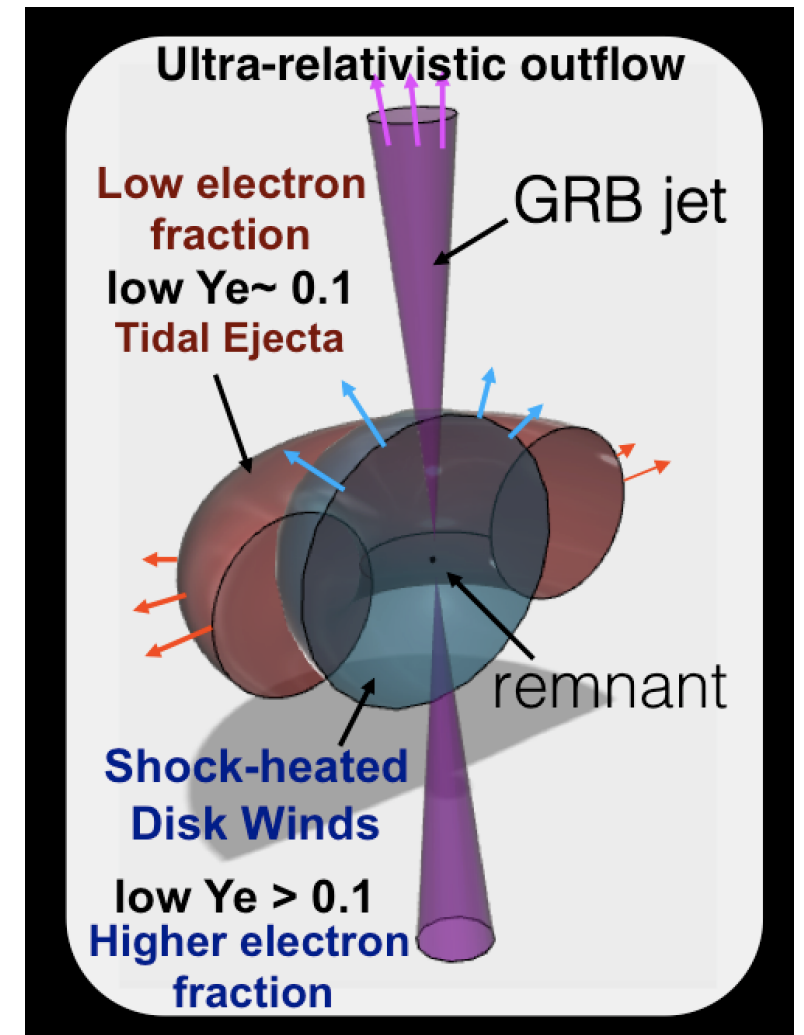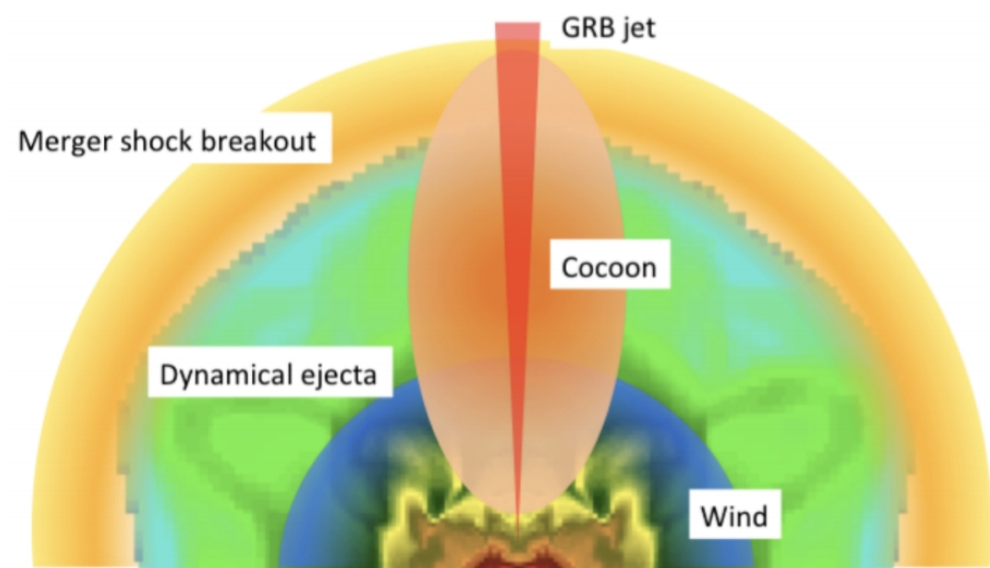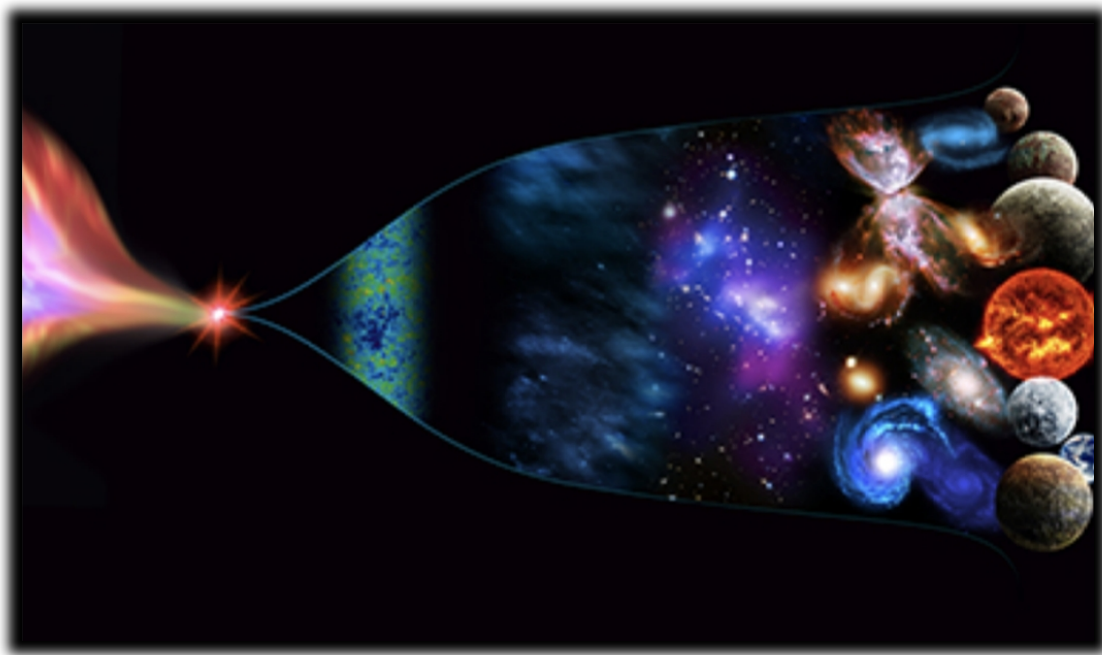
Cosmology

Main collaborators: L.Izzo (DARK), M. Cantiello (INAF)

GW cosmology with GW170817

CMB
By Plank

Cepheids and
type Ia SN

GW data
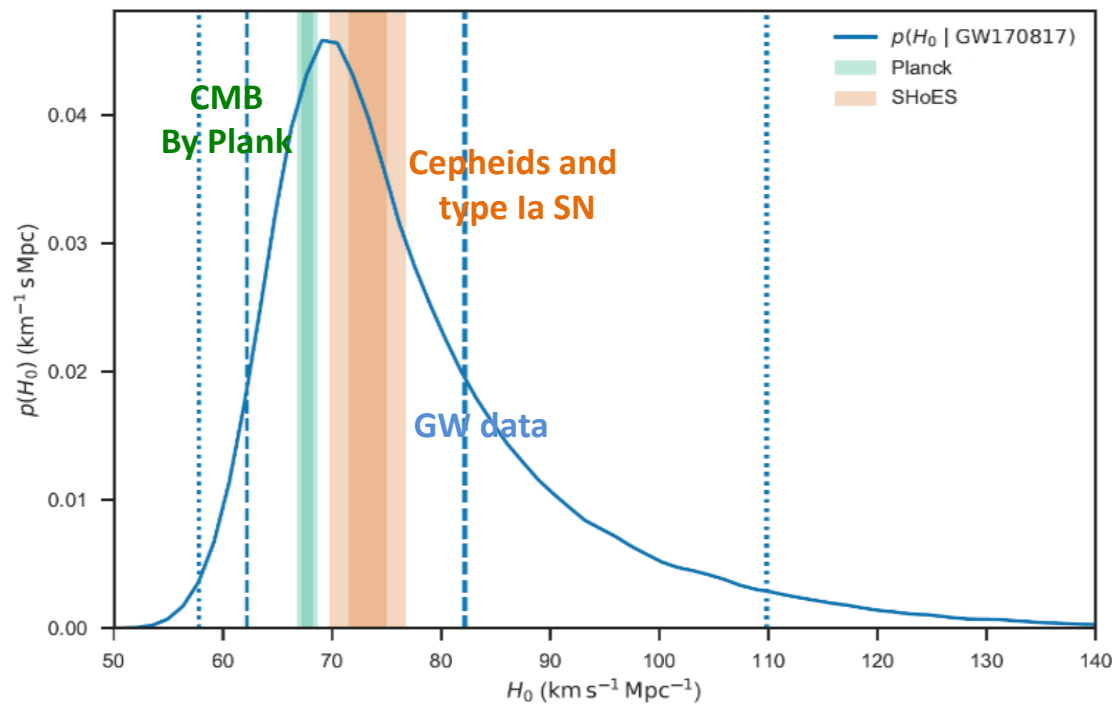
Recession velocity /redshift
GW distance

$v_H = H_0 d$ *combining the distance*

measured from GWs $d = 43.8^{+2.9}_{-6.9}\,\mathrm{Mpc}$

and NGC4993 recession velocity

$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Abbott +, Nature 551, 2017
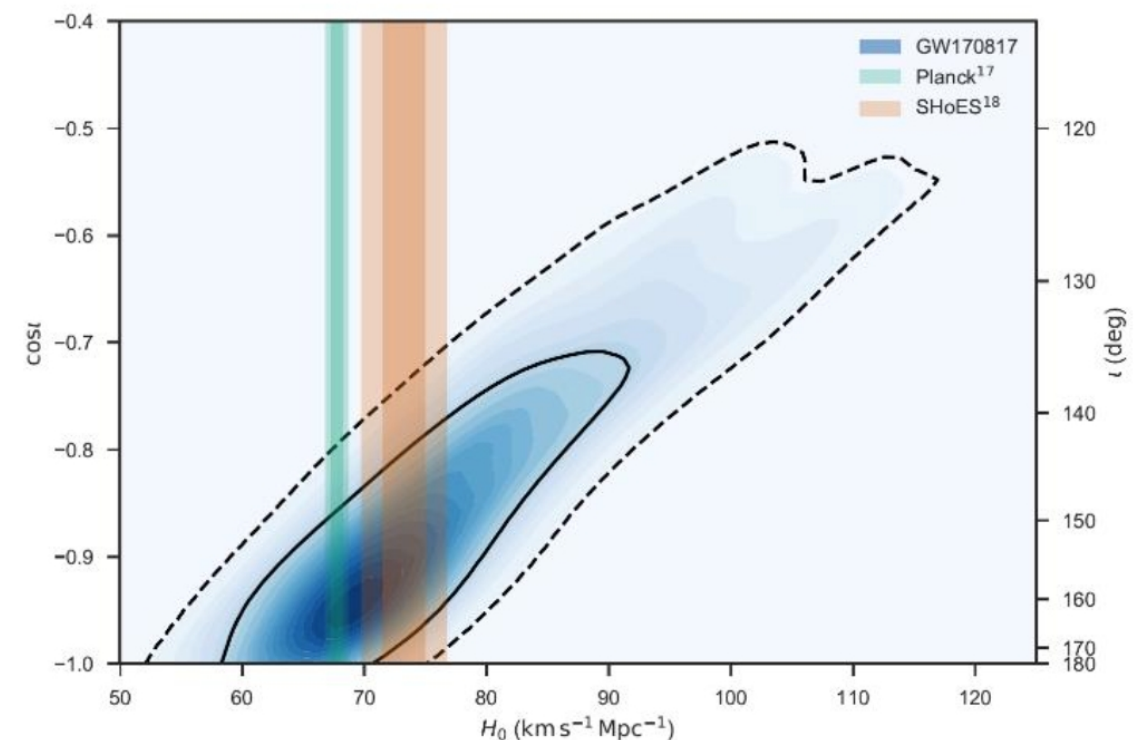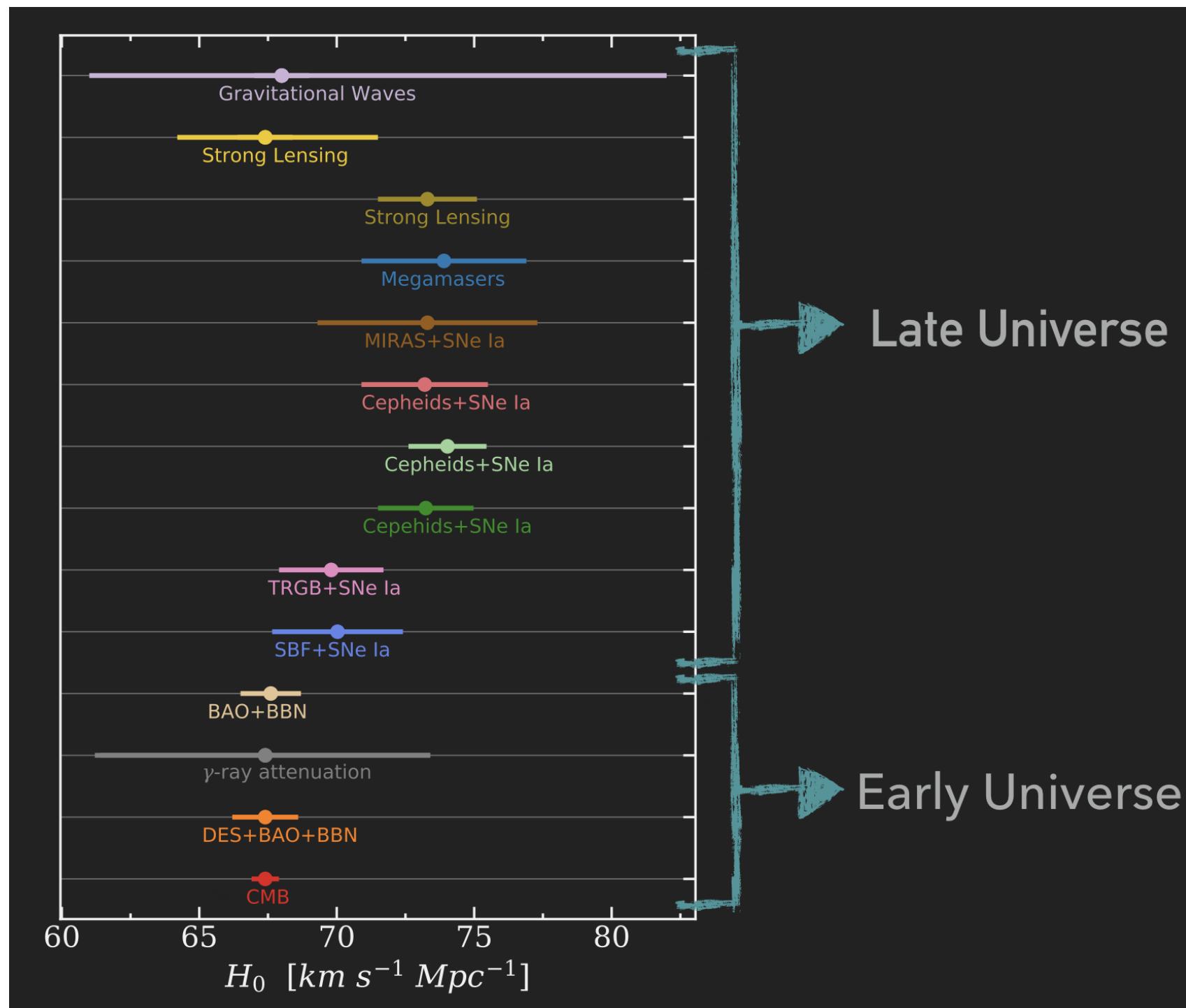
Hubble tension!

Hubble tension!

*Precise local distances to calibrate distant SN **G**alaxy **S**urface **B**rightness fluctuations*

- *SBF can be used as SNe Ia calibrators*

- *H_0 between tension range*

- *SNe Ia luminosity correlates with the host type, the ones hosted in early types seem to be brighter compared to the ones in late types*

Promising Future with JWST and LSST!

Khetan+, astrp-ph: 2008.07754
A&A in press
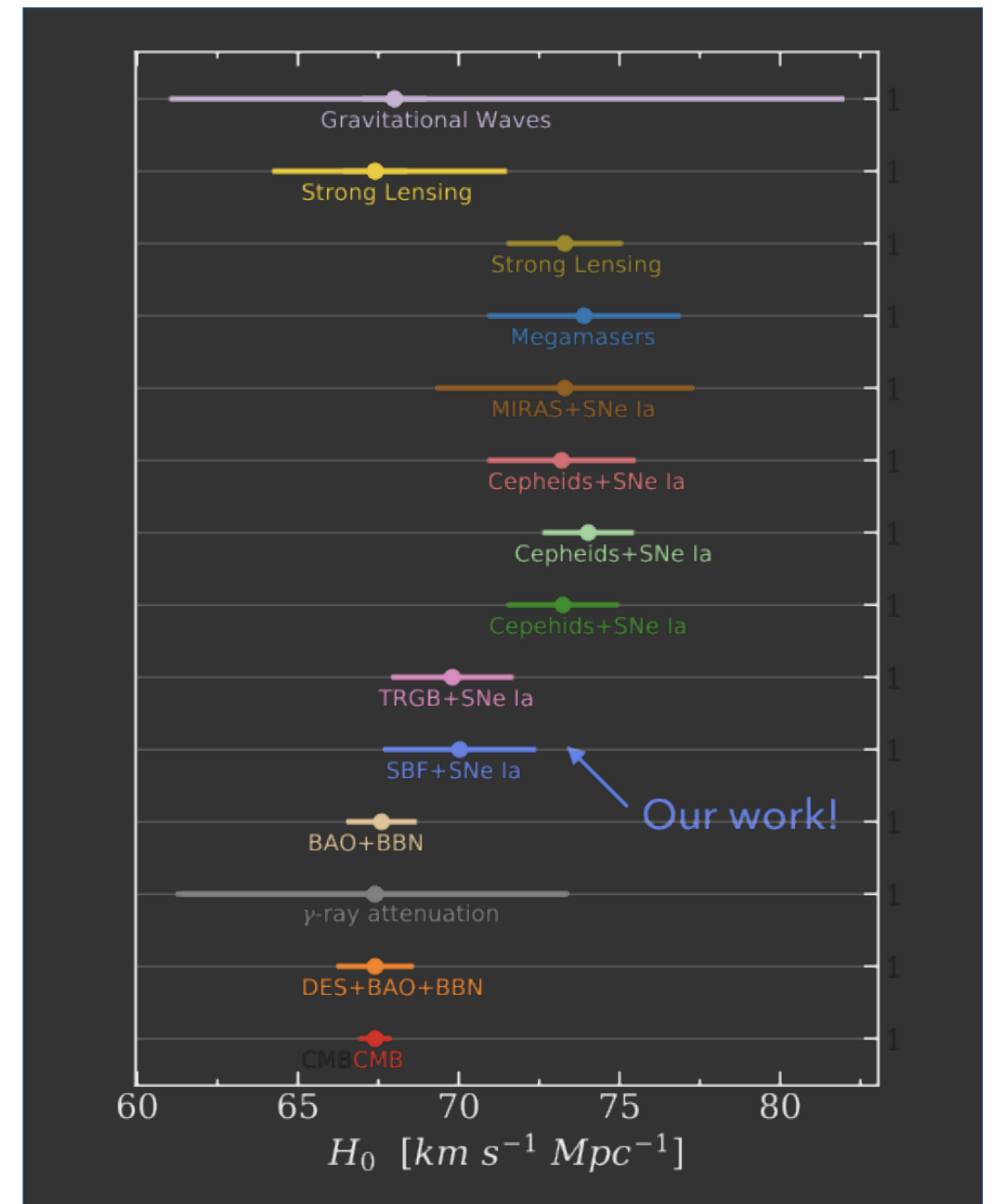
Hubble tension!

SBF in the LSST era
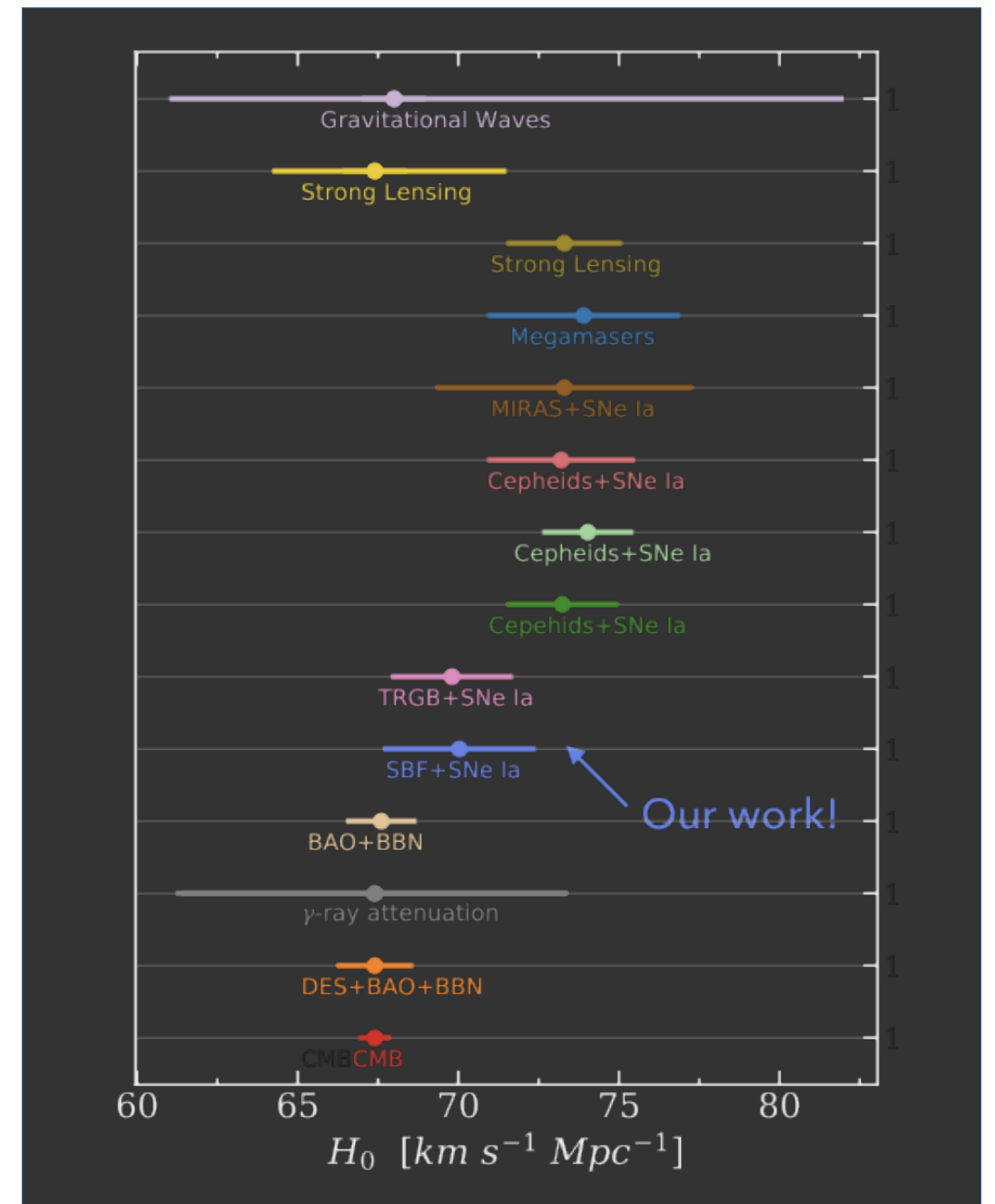
Super*NS*tars

- **Super**dense objects

- **Super**gravity

- **Super**fast rotators

- **Super**fluid and **super**conducting

- **Super**strong magnetic fields

- **Super**precise clocks

- **Super**accelerators of high energy particles

Unique laboratory to test

- *General Relativity*

- *Modified theories of Gravity*

- *Microphysics under extreme conditions*

- *Gravitational wave emission*

- *Stellar evolution*

The astro-Lab

Magnifying lenses of fundamental forces
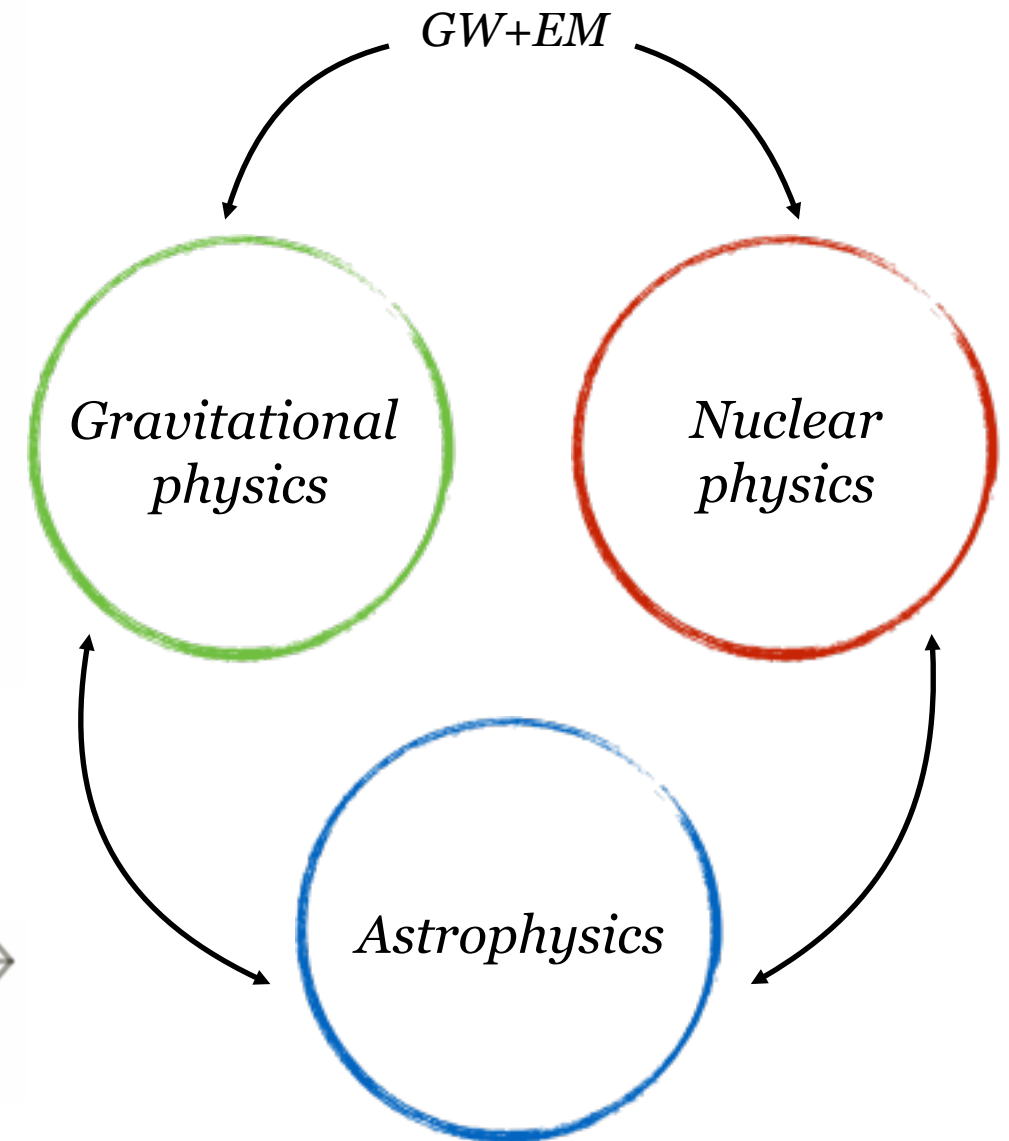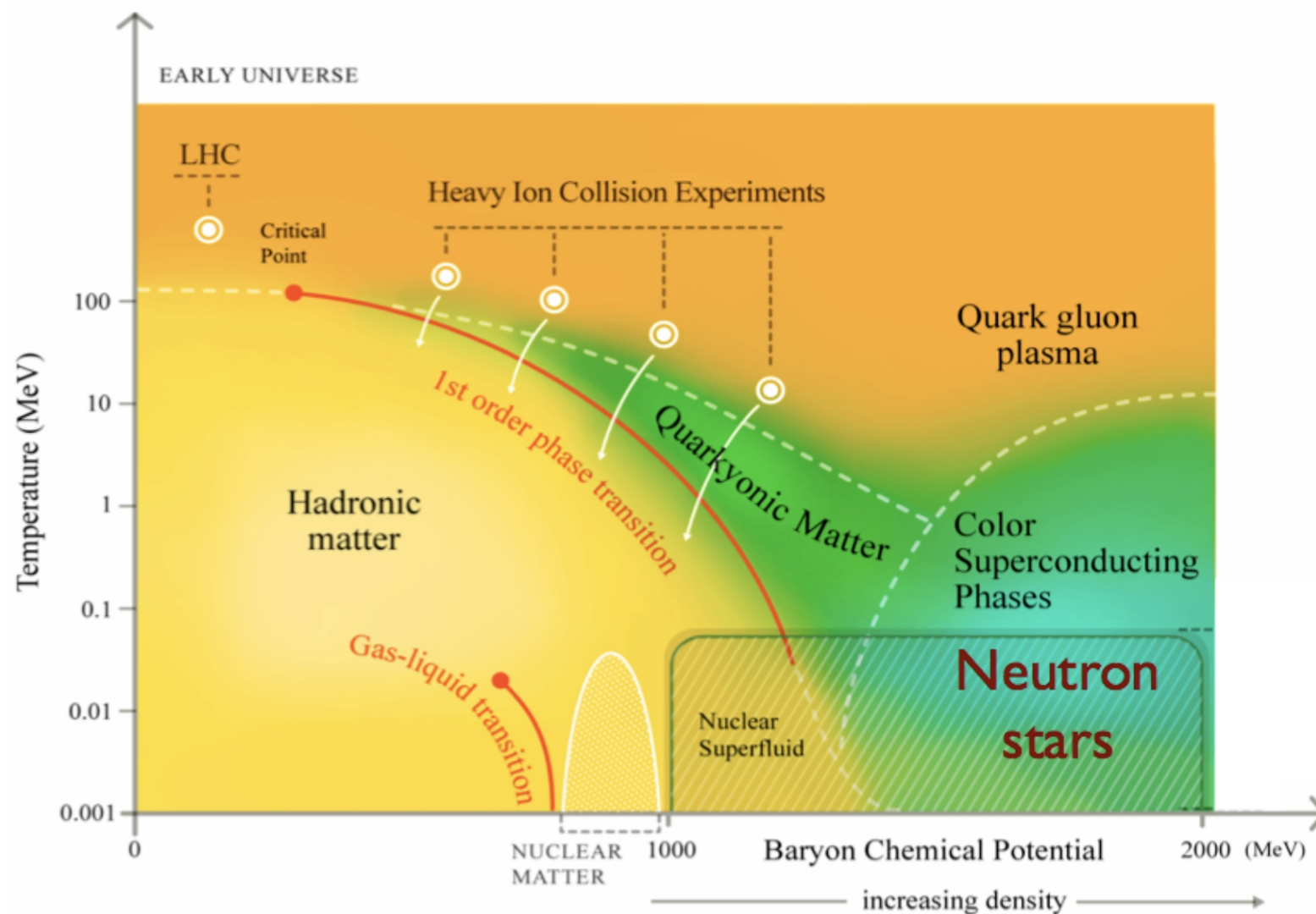
How nuclear matter behaves under extreme conditions?

From macro to micro

- *(too) many models describing the NS interior*

- *How do we identify the correct one?*

microscopic **E**quation **of** **S**tate...

GWs
from binary NS

$$p = p(\epsilon, \dots)$$

EM *(pulsar, LMXB..)*
+
Labs

macroscopic observables $(M, R, I, \dots)$

EM and **GW** observations

The power of co-working

○ *Combining EM and GW observations of **different** sources helps us to understand the features of NS composition*

EM - Mass radius
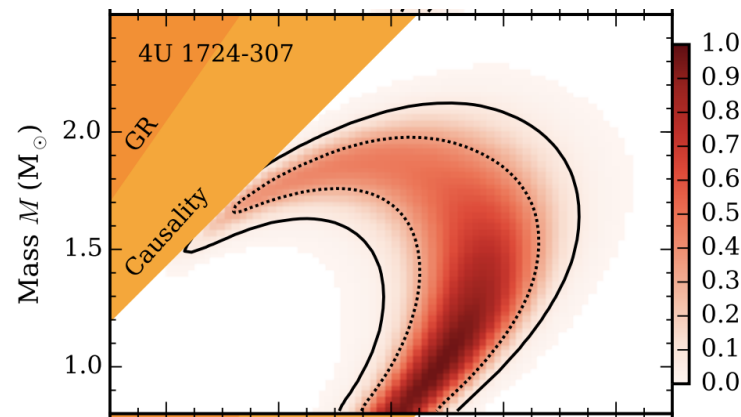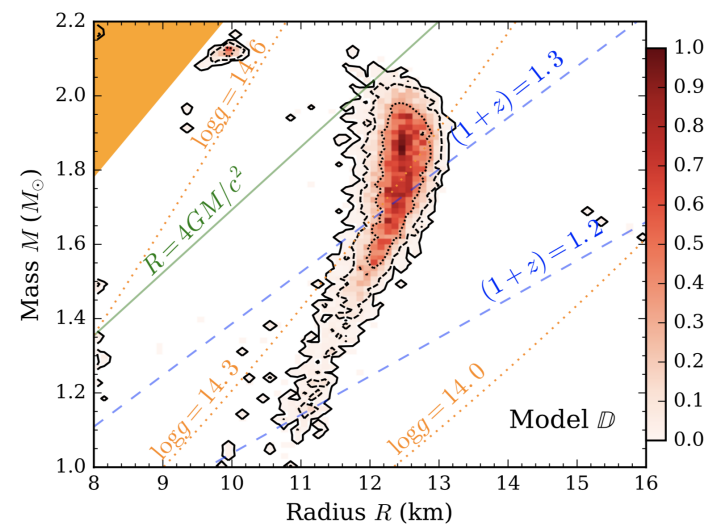
Nattila +, Astrop J. 2017

GW - Love numbers
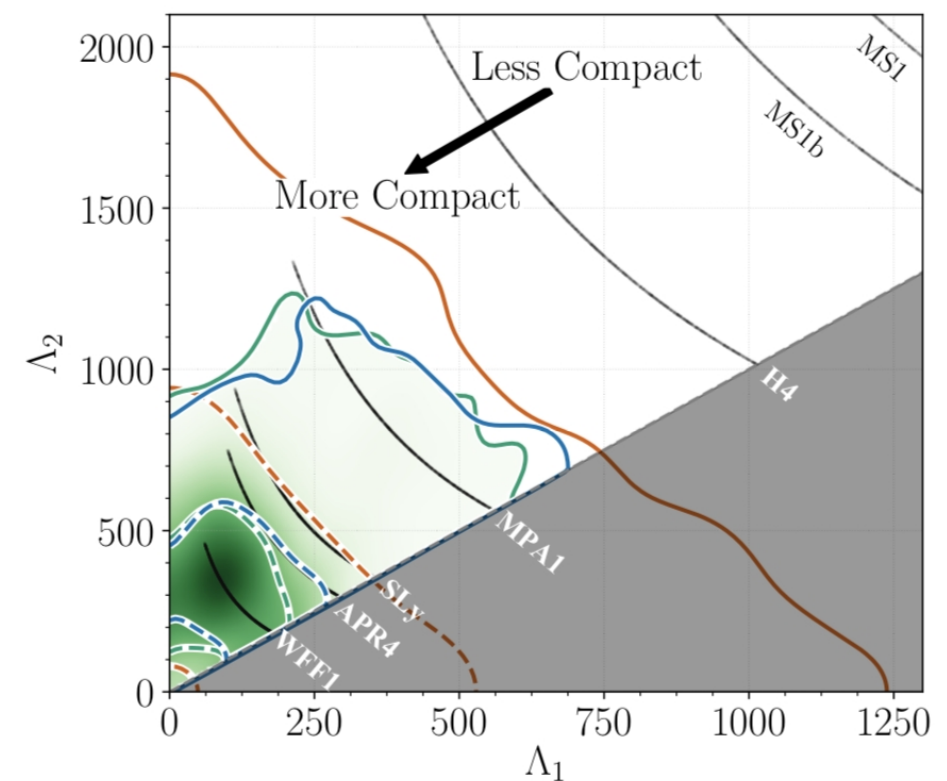
Abbott +, Phys. Rev. Lett. 2018

A new look at the radius

Constraints on the GW170817 neutron stars radii
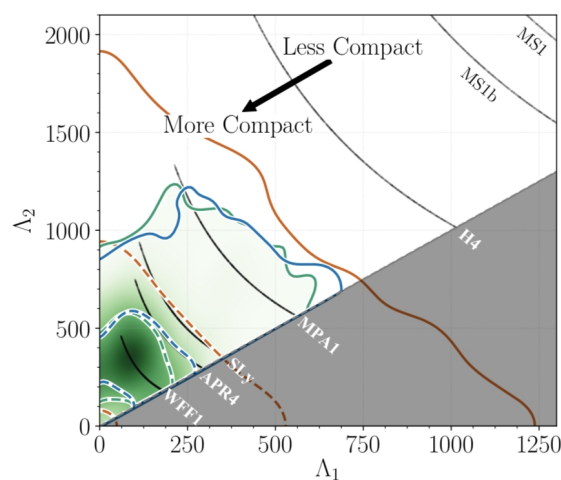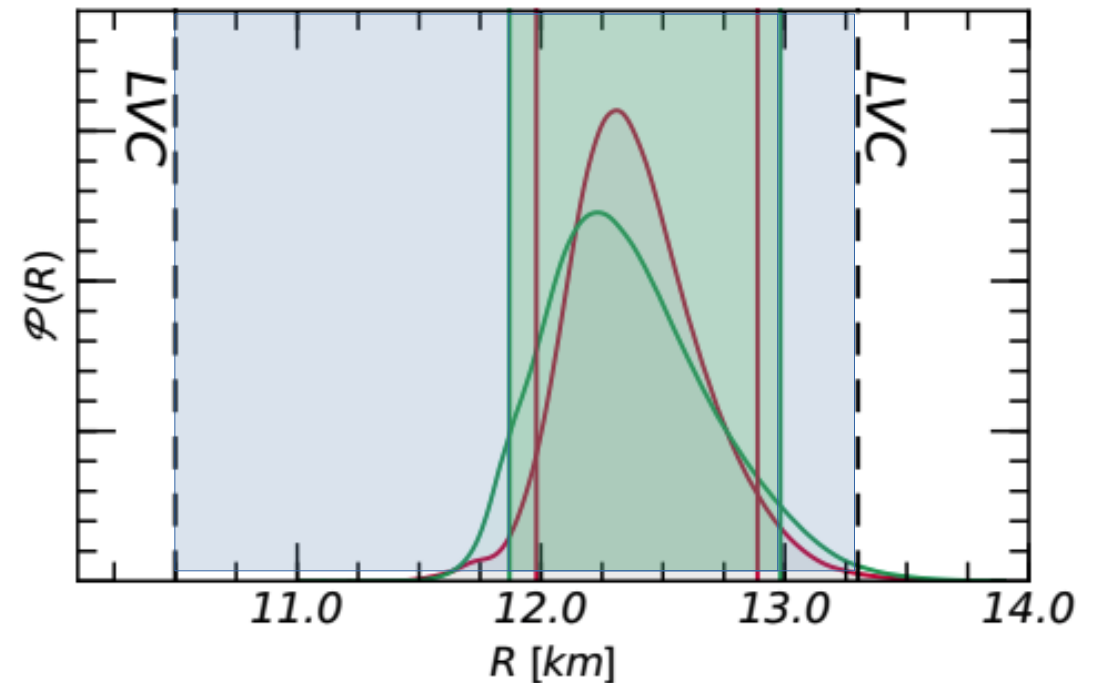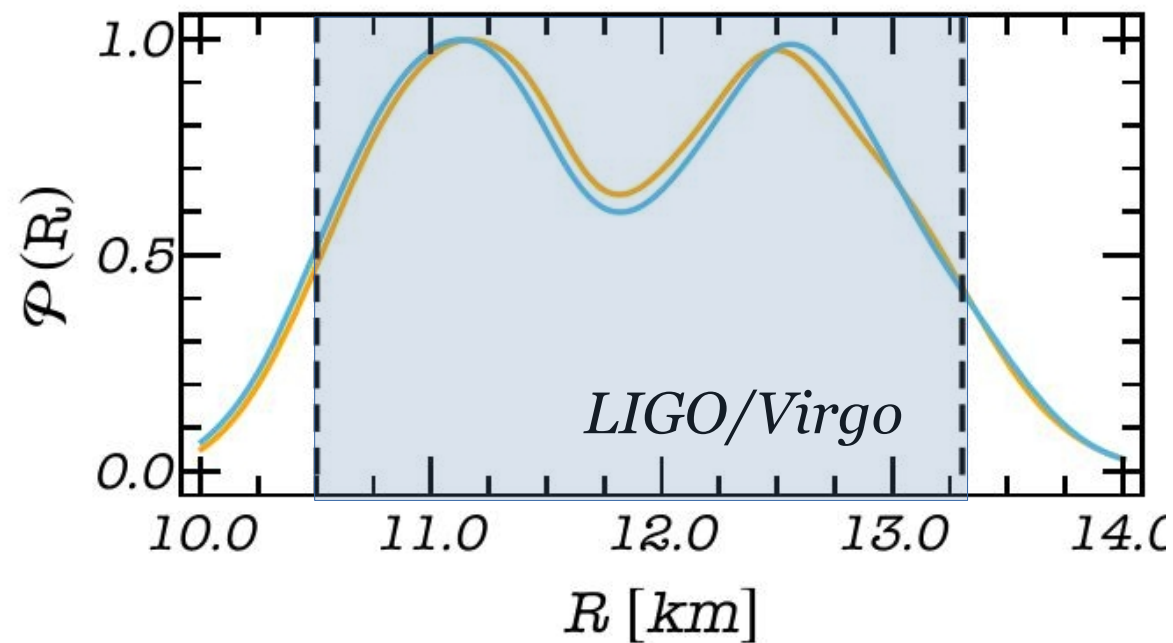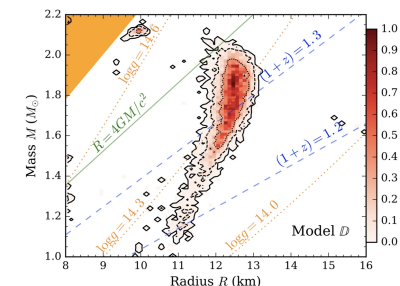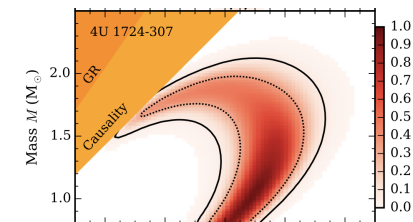
○ *Final measurement benefit from the **M**ulti-**B**and analysis*

Nucleon interactions

Can we directly constrain properties of hadron interactions from observations? (beside mass, radius.... measurements)

- *Parametrize nucleon dynamics for a given EoS based on non-relativistic many body theory*

$$\mathcal{H} = \sum_i \frac{p_i^2}{2m} + \sum_{j>i} v_{ij} + \sum_{k>i>j} V_{ijk}$$

2-body

3-body

- *__3-body__ nucleon potential*

$$V_{ijk}^{2\pi} + \alpha V_{ijk}^{R}$$

- *Unconstrained at $\rho \gg \rho_0$*

GW170817 + NICER

Multi-messenger constraints from GW binaries + accreting pulsar
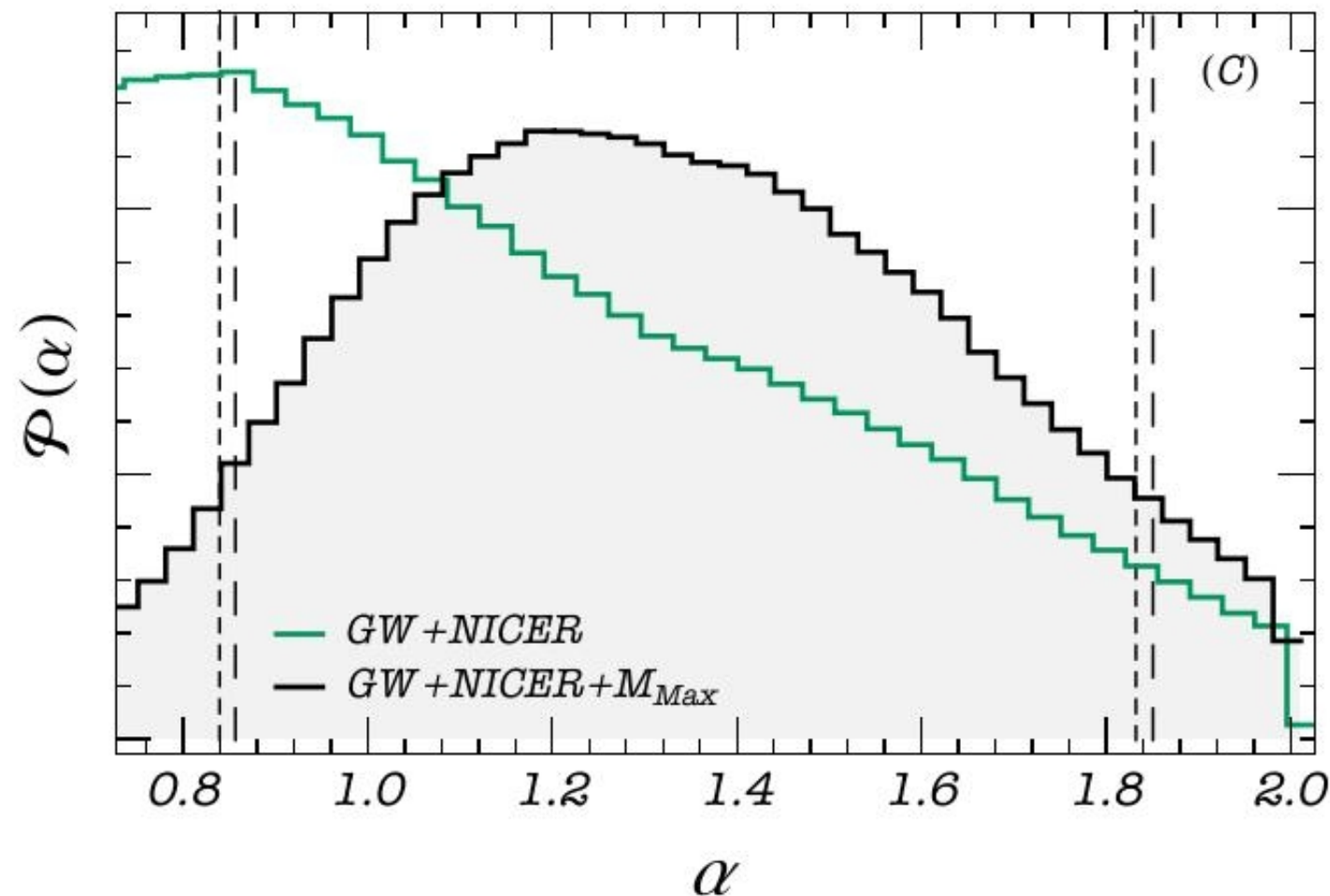
$$\alpha_{\text{GW+EM}} = 1.32^{+0.48}_{-0.51}$$

*Direct constraint on **NNN** interactions*

observations sensitive to microphysical properties of fundamental forces

Why challenge Einstein? (why not?)

Mechanics ~1700ish | **QED ~1920s** | **QCD ~1950s** — Length-scale [m]

10^{-3} meters | 10^{-9} meters | 10^{-15} meters

6 orders of magnitude

Newton ~1700ish | **Classical tests of GR ~1920s** | **Compact objects ~2010s-2020s** — Potential [GM/(c*r)]

10^{-11} | 10^{-7} | 0.1-1
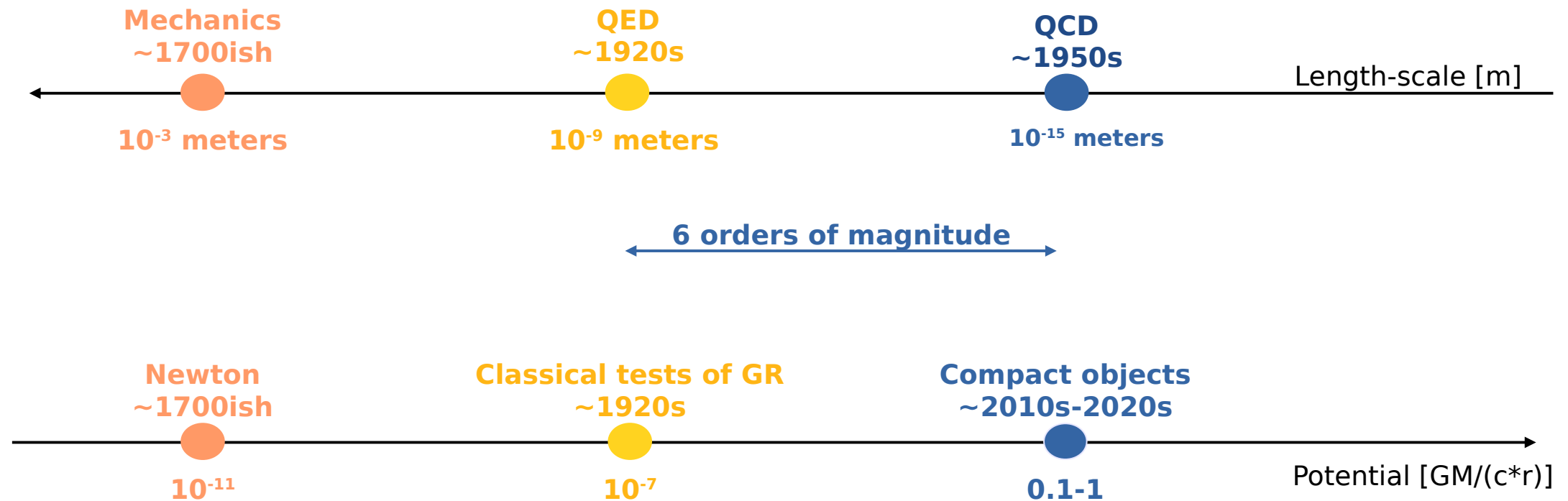
*We can test GR in a genuine **strong-field** regime*

- ○ *Test pillars of General Relativity*

- ○ *Test specific predictions of alternative theories of gravity*

The Kerr hypothesis

Test no-hair theorems from rotating BHs

○ *Track deviations from GR predictions in the frequencies of oscillations of newly born Bhs modelled in alternative theories*
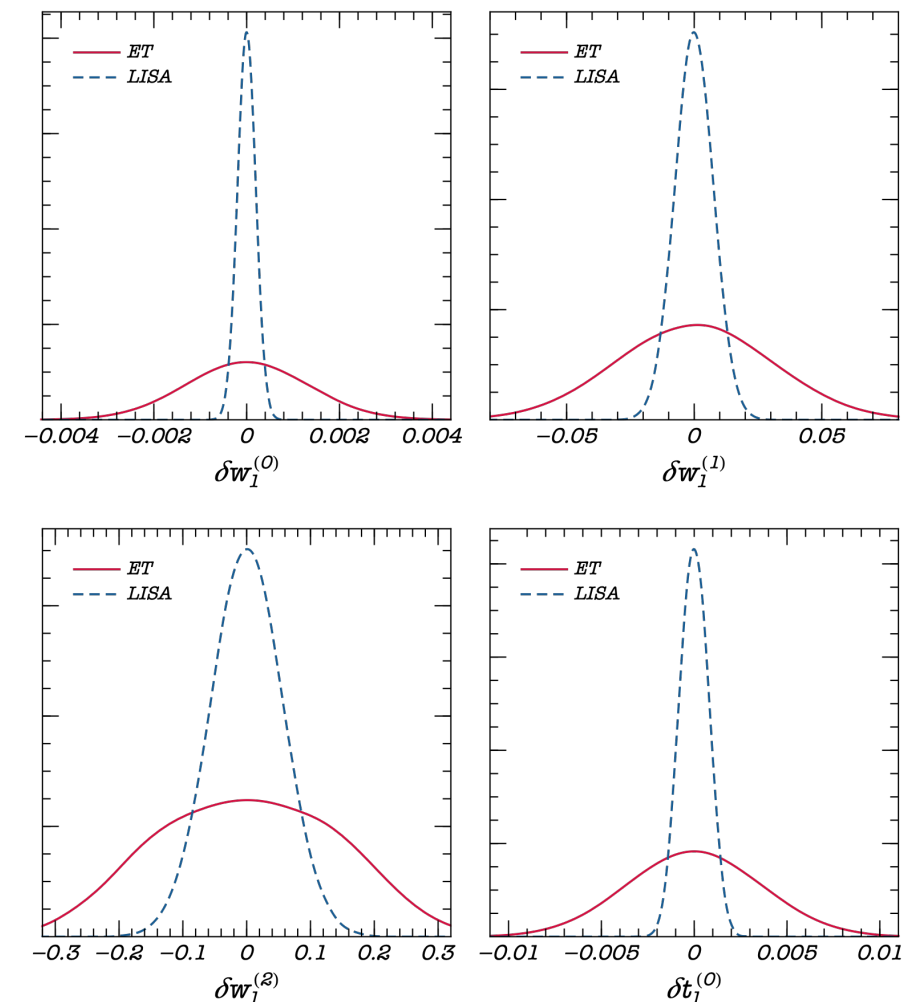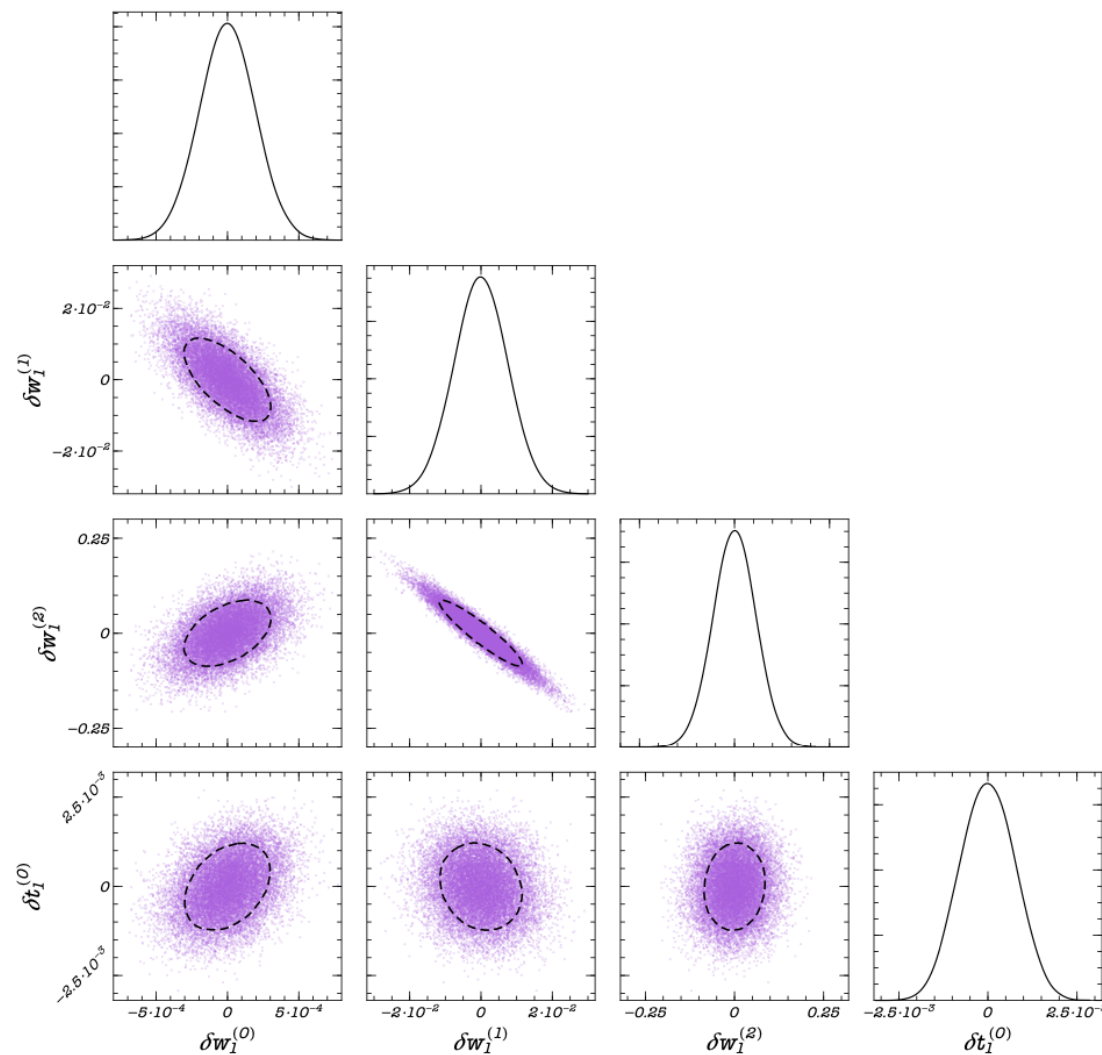
LISA & the EMRIs

Binary systems with a stellar-mass body inspiralling into a more massive black hole

- *Primary with $M \sim (10^4 - 10^7) M_\odot$*

- *Secondary such that the mass ratio $q = m_p/M \sim (10^{-6} - 10^{-3})$*

- *Emit GWs in the mHz, and are golden targets for LISA*

- *Rich phenomenology: non equatorial, eccentric orbits, resonances...*
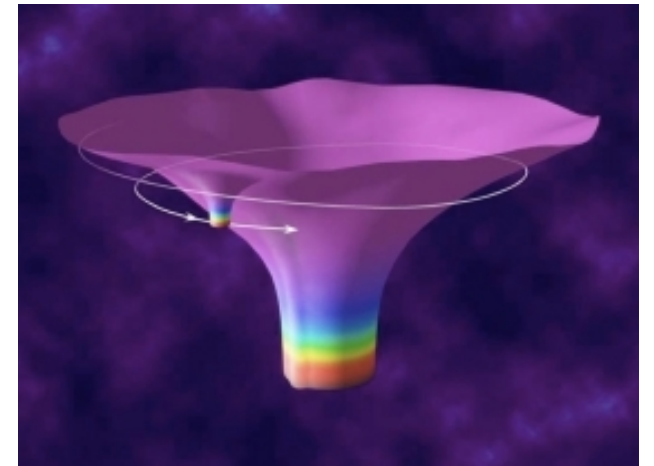
Very appealing to test fundamental physics

- *Complete $\sim (10^4 - 10^5)$ cycles before the plunge:* **bless** *and* **disguise**

> *Precise space-time map and accurate binary parameters*

LISA & the EMRIs

*With EMRI you can test the existence of **extra scalar fields**, and deviations from no-hair theorem in alternative theories of gravity*

Changes in the GW phase

dephasing >> 1 radians are **detectable** by LISA

Change in the EMRI dynamics universally captured by the scalar charge

Backup

*G*rants

AHEAD 2020
Integrated activities for the High Energy Astrophysics Domain

Funded with 10 milion euro!

Funded by the Horizon 2020
Framework Programme of the European
Union
Grant Agreement No. 871158

ADVANCED COMMUNITIES

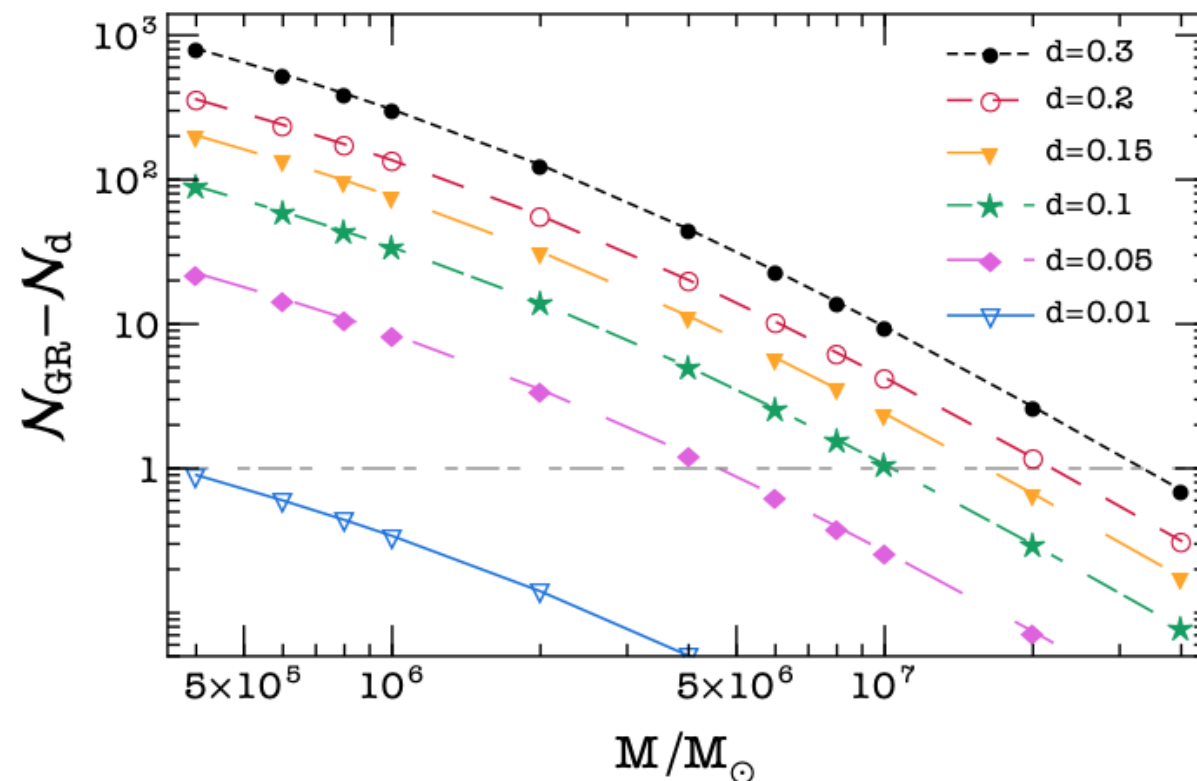## *Multimessenger Astronomy exploitation & tools*

WP12 GOALS

○ *develop tools and procedures to optimize observative programmes to rapidly detect and send alerts, and to improve the counterpart searches*

○ *build multi-messenger database and tools to access and analyse multi-messenger data*

○ *develop models and make them accessible to enable the multi-messenger and multi-wavelength interpretation of large data sets;*

○ *develop pilot science studies for the new generation of multi-messenger observatories able to drive the design of new facilities and their operation*

Test of the BH nature

BH as endpoint of stellar evolution?

○ Unexpected processes may **E**xotic **C**ompact **O**bjects, **without** an event horizon

$R = 2M (1 + \delta)$

ECO radius
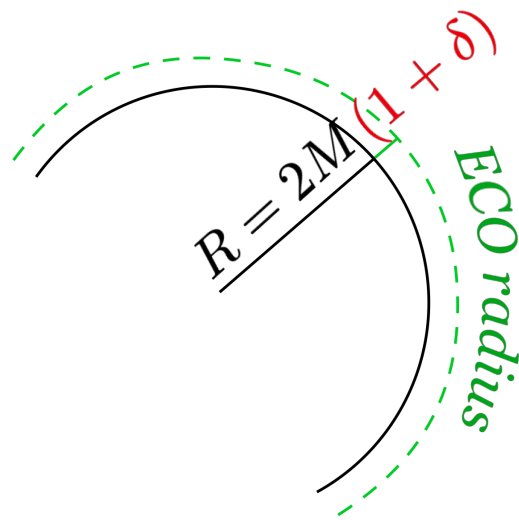
can we distinguish ECOs compact to mimic a BH?

BH limit

| **Exotic Compact objects** | **Neutron Stars** |

$2 \qquad\qquad 2.25 \qquad 3 \qquad\qquad 6 \qquad r_0/M$

Buchdahl   Photosphere   ISCO

$2(1 + \delta)$

10^{-30}

GW from binaries may provide new answers
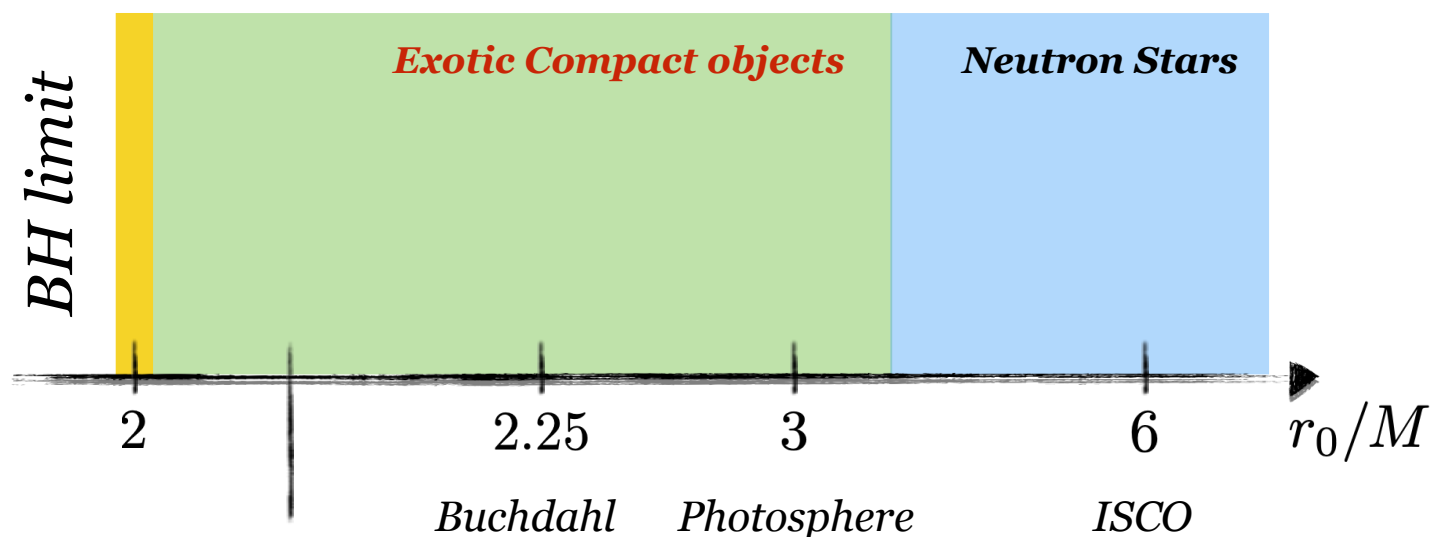
$M_{\mathrm{BH}}/R_{\mathrm{BH}} = 0.5 \quad v.s. \quad M_{\mathrm{ECO}}/R_{\mathrm{ECO}} = 0.49(99\ldots)$

ECO Love numbers

○ k_2 (or λ) depends on the compactness $\mathcal{C} = M/R$, only

Neutron stars

$$\mathcal{C} \in [0.1 \div 0.2]$$

$$k_2 \neq 0$$

GW170817

constrain the NS
equation of state

(rotating) black holes

$$\mathcal{C} = 1/2$$

$$k_2 = 0$$

Phys, Rev. D 92, 2015

ECOs

$$\mathcal{C} < 0.5 \qquad k_2 \neq 0$$

$$\mathcal{C} \to 0.5 \qquad k_2 \to 0$$

signature to distinguish
ECO and BH's inspiral

Phys, Rev. D 95, 2017
Phys, Rev. Lett. 120, 2018
Cass. Quant. Grav. 36, 2019

ECO Love numbers

k_2 translates in distance of the ECO surface from its Schwarzschild radius

$$\delta \equiv r_0 - 2M \sim 2M e^{-1/k_2}$$

$$k_2 \simeq 0.005$$

$$\delta \simeq 10^{-33} \text{cm} \sim \ell_P$$

$M = 10^6 M_\odot$