Constraining Dark Matter in Neutron Stars with Next-Generation Gravitational-Wave Detectors

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CoCoNUT Meeting

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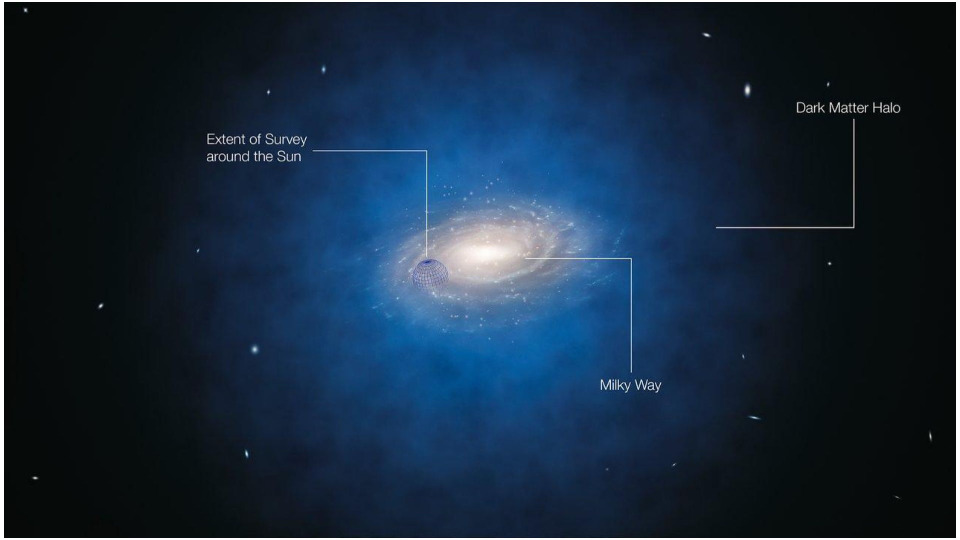
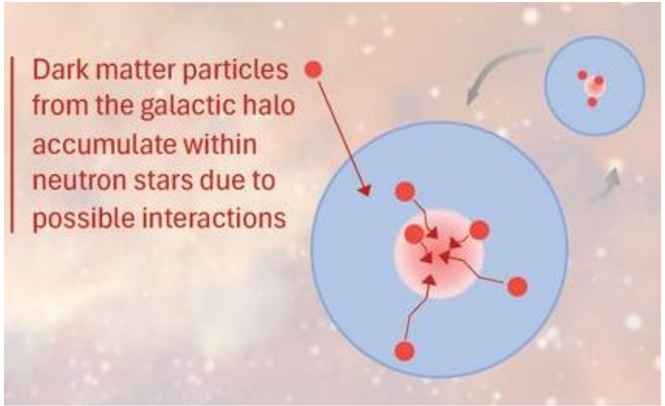
DM accretion

In the DM-dense regions, due to their strong gravity, NSs might accumulate a sizeable amount of DM in their interior [Bramante et. al, 2022].



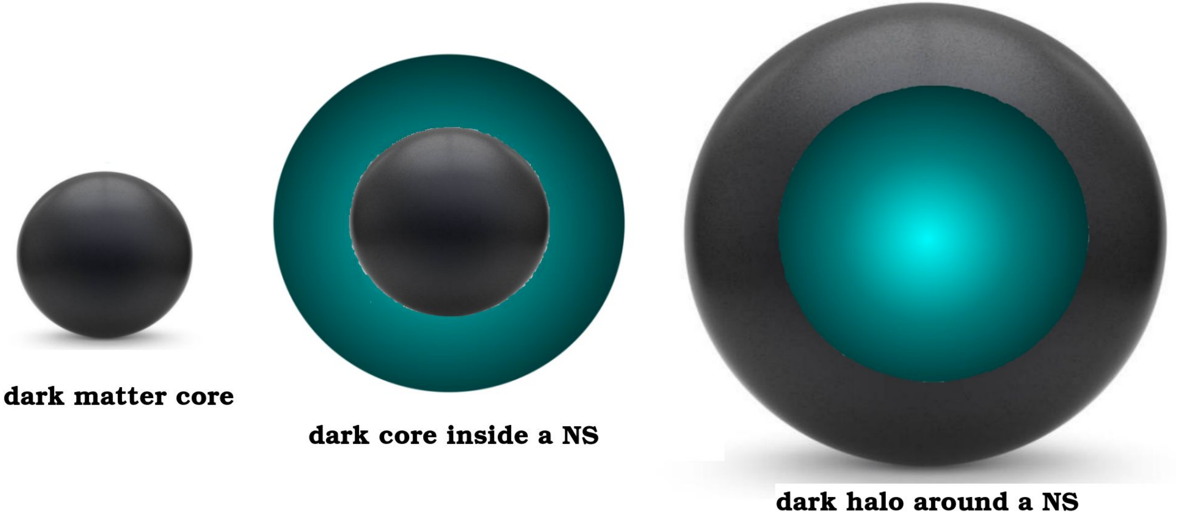


Credit: ESO/L. Calçada

Two-fluid framework

DM Core: decrease of the maximum mass and observed stellar radius.

DM Halo: increase of the maximum mass and the outermost radius.



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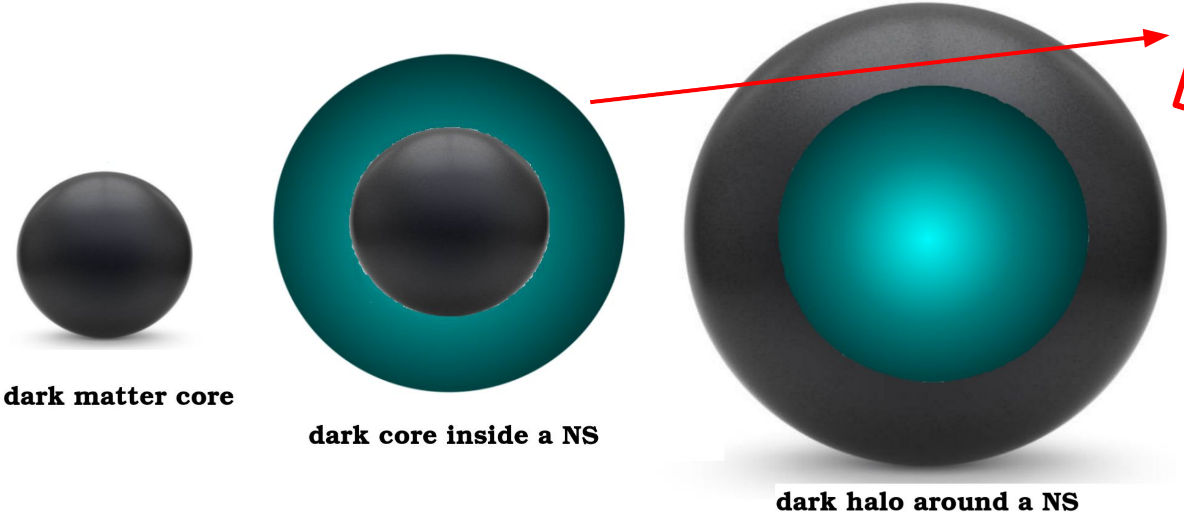
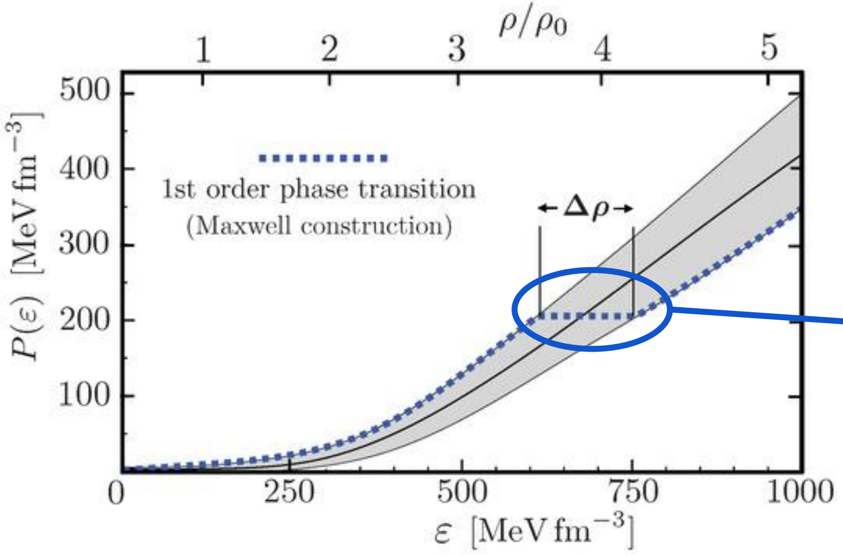


Softening of the EoS!

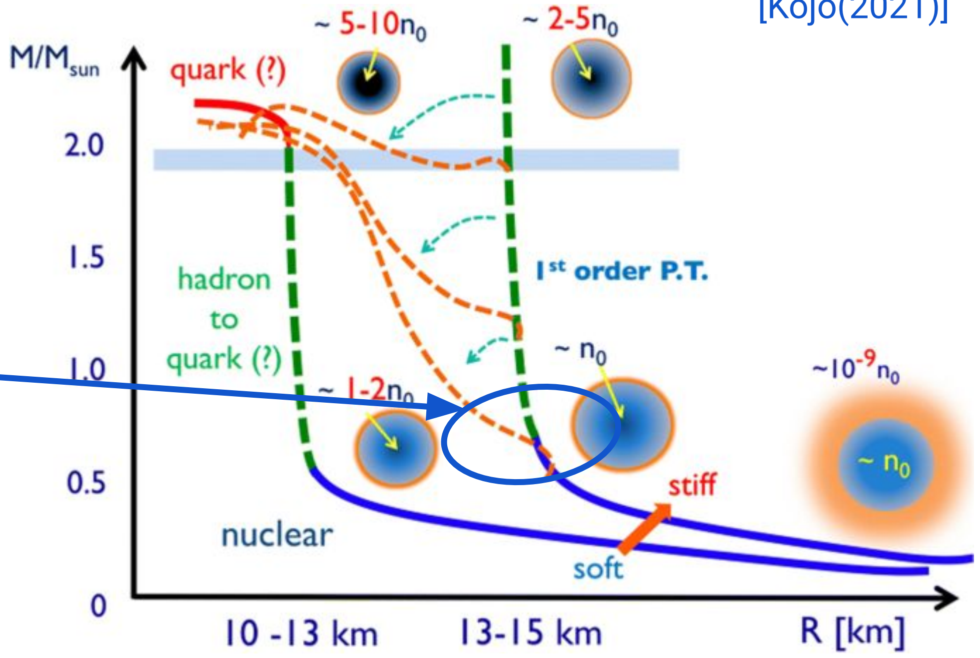
Deconfinement Phase Transition (PT)

NSs core densities may exceed nuclear saturation enough to allow for a PT between hadronic and quark matter.



[Brandes and Weise (2024)]

[Kojo(2021)]



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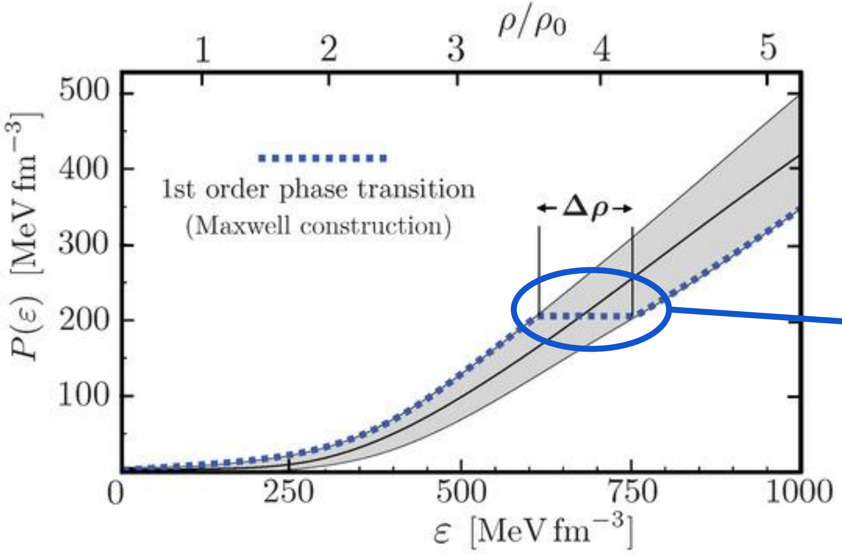

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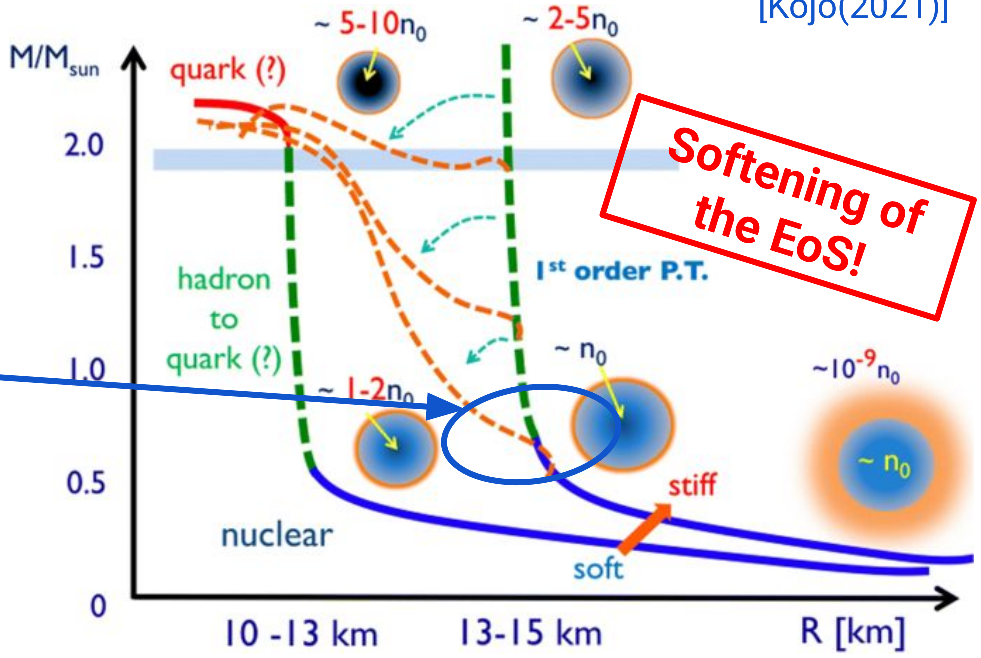
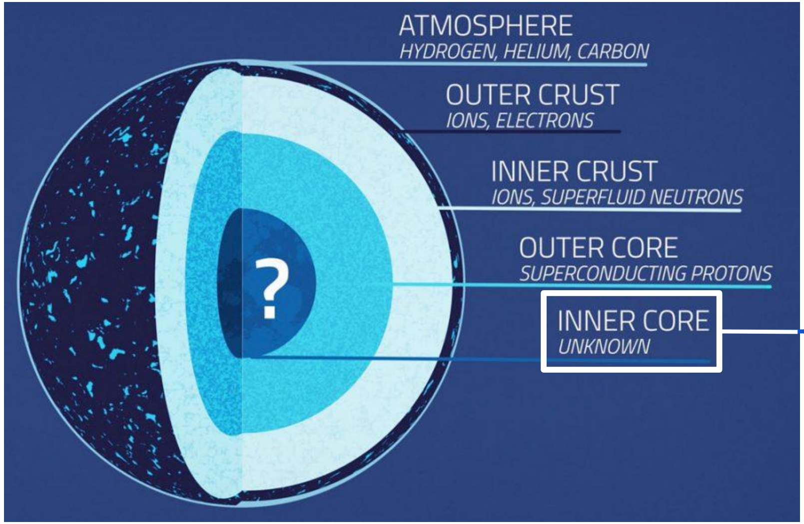
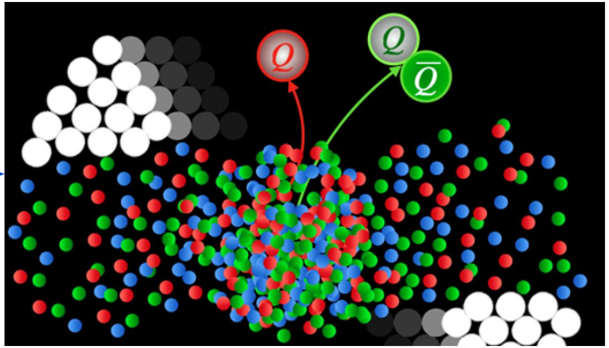


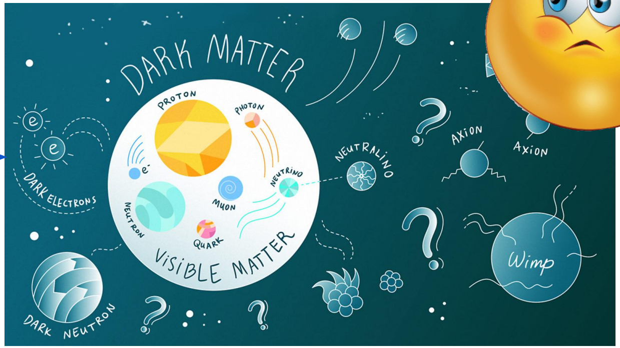
Core Idea

Both scenarios can leave similar imprints on the NS properties, resulting in a possible degeneracy!



Credit: NASA's Goddard Space Flight Center / Conceptual Image Lab



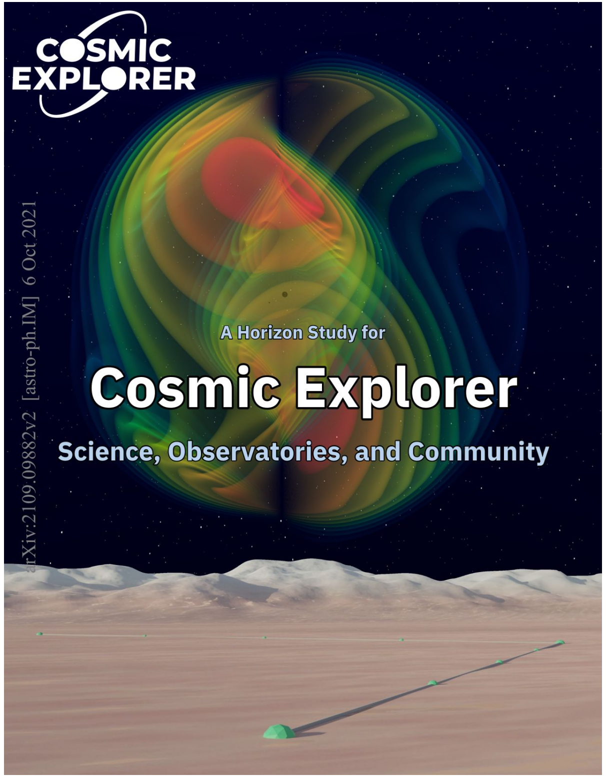


Hadronic matter

- The SFHo EoS [Steiner et al. (2012)] is adopted as the hadronic reference model, retrieved from the CompOSE database.

CompOSE CompStar Online Supernovae Equations of State

- It is used as the fiducial hadronic EoS in the Science Traceability Matrix study of the CE Consortium [Evans et al. (2021 & 2023)].



Quark matter

Quark matter is described by the 2SC EoS [Gärtlein et al. (2023)] following the analytical ABPR parametrization introduced in [Alford et al. (2005)].

For cold and β-equilibrated matter, the pressure is expressed as

$$p_Q(\mu_Q) = \frac{A_4\, \mu_Q^4}{2\pi^2} + \frac{\Delta^2 \mu_Q^2}{\pi^2} - B\,. \tag{4.1}$$

$$\mu_Q = \mu_B/3$$

Where A_4, Δ and B, are free parameters representing the stiffness of quark matter, the pairing gap and the bag pressure, respectively.

Quark matter

Based on the values listed in Table II of [Gärtlein et al. (2023)] the parameters were scanned within the ranges

$$A_4 \in [0.20, 1.00], \Delta \in [160, 280]\mathrm{MeV} \text{ and } B \in [90, 250]\mathrm{MeV/fm}^3$$

Thermodynamic consistency

$$n_B = \frac{\partial p_Q}{\partial \mu_B} = \frac{1}{3}\frac{dp_Q}{d\mu_Q}, \qquad \varepsilon = \mu_B n_B - p_Q, \qquad c_s^2 = \frac{dp_Q}{d\varepsilon}, \qquad (4.2)$$

where n_B, ε and c_s^2, are the baryon number density, energy density and squared speed of sound, respectively.

Construction of the first order PT

The hadronic and quark matter are matched through a first order PT by a Maxwell construction

$$\mu_B^H = \mu_B^Q \equiv \mu_T \,, \qquad p_H(\mu_T) = p_Q(\mu_T)\,, \tag{4.3}$$

The values of the quark EoS are found in order to achieve a earliest PT at $\sim 1\,M_\odot$, corresponding to a transition density at $n \approx 2.5\, n_0\,.$

$$A_4 = 0.595, \Delta = 251\text{MeV} \text{ and } B = 139.11\text{MeV}/\text{fm}^3$$

Hybrid EoS

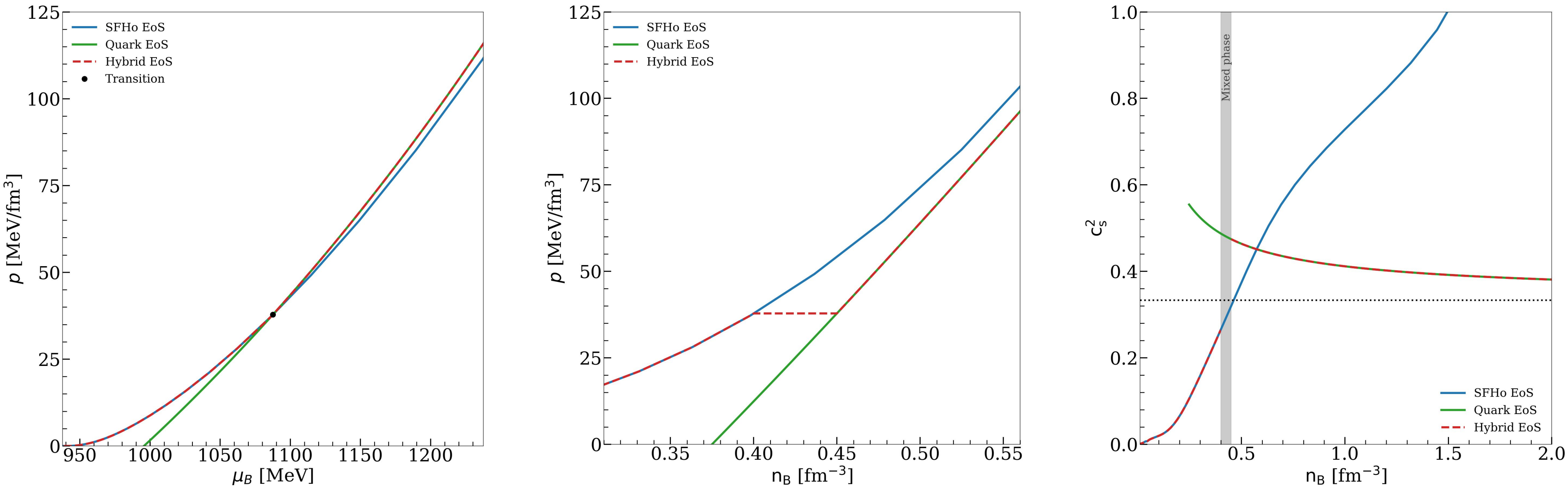
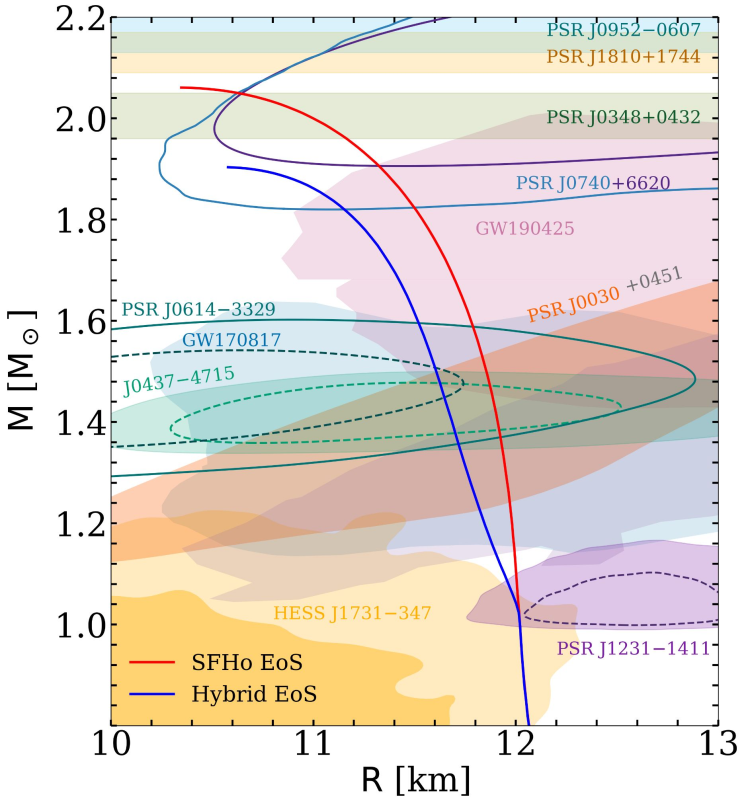


Figure 1: Pressure, p, as a function of the baryonic chemical potential, μ_B (left), and number density, n_B (middle), and squared speed of sound, c_s^2, as a function of number density (right), for the SFHo, quark and hybrid EoSs. The black dot marks the chemical potential of the phase transition; the black dotted line marks the conformal value, $c_s^2 = 1/3$.

Hybrid EoS



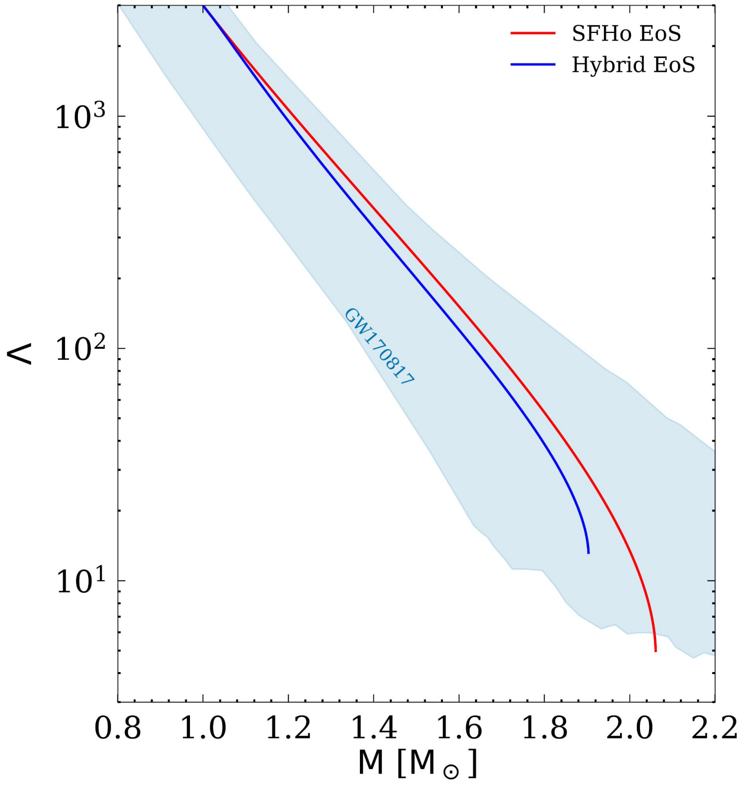


Figure 2: Gravitational mass, M, as a function of radius, R, (left) for the SFHo and hybrid EoSs. Tidal deformability, Λ, as a function of gravitational mass, M, (right) for the same EoSs.

DM EoS

DM is modelled as a relativistic Fermi gas of non-interacting particles with spin ½. The pressure and energy density take the form

$$p_{DM} = \frac{g_{DM}}{48\pi^2}\left[\mu_{DM}\, k_{DM}\left(2\mu_{DM}^2 - 5m_{DM}^2\right) + 3m_{DM}^4 \ln\frac{\mu_{DM}+k_{DM}}{m_{DM}}\right], \quad (4.4)$$

$$\varepsilon_{DM} = \mu_{DM}\, n_{DM} - p_{DM},$$

[Nelson et al. (2019), Ivanytskyi et al. (2020), Sagun et al. (2022)]

where, $g_{DM} = 2$, μ_{DM} and $k_{DM} = \sqrt{\mu_{DM}^2 - m_{DM}^2}\,\theta\left(\mu_{DM} - m_{DM}\right)$ are the DM degeneracy factor, chemical potential and Fermi momentum, respectively.

The results were obtained for $m_{DM} = 1\,\mathrm{GeV}$.

DM EoS

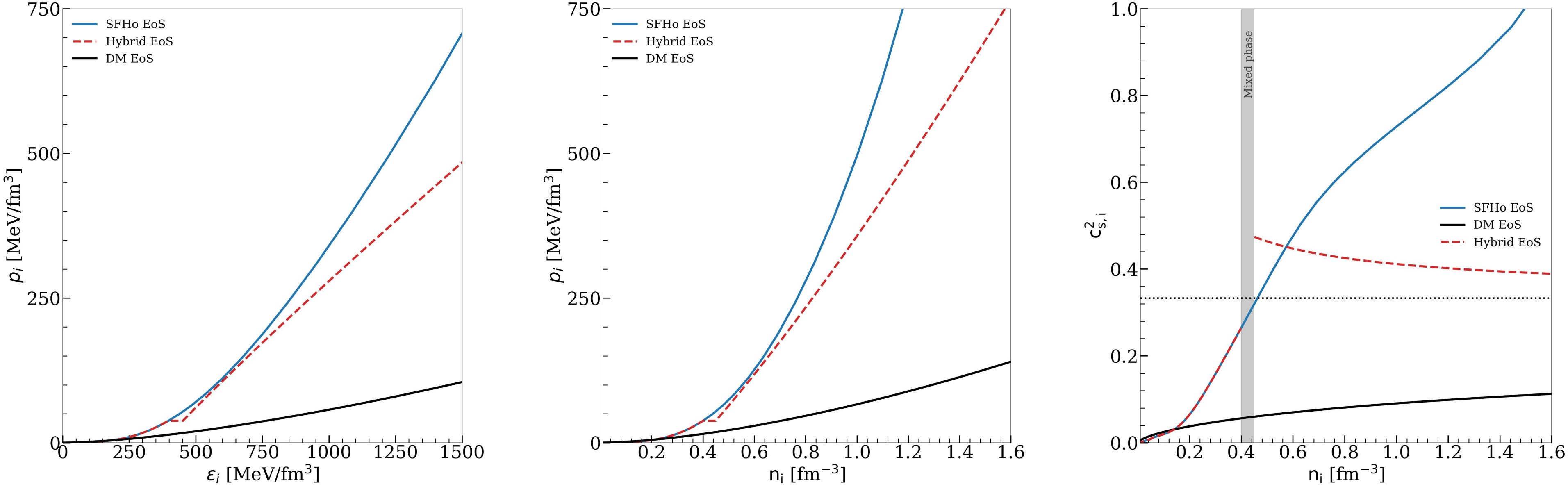


Figure 3: Pressure, p_i, as a function of the energy density, ε_i, (left) and number density, n_i, (mid), and squared speed of sound, $c^2_{s,i}$, as a function of number density (right), for the SFHo, hybrid and DM EoSs.

DM-admixed NS

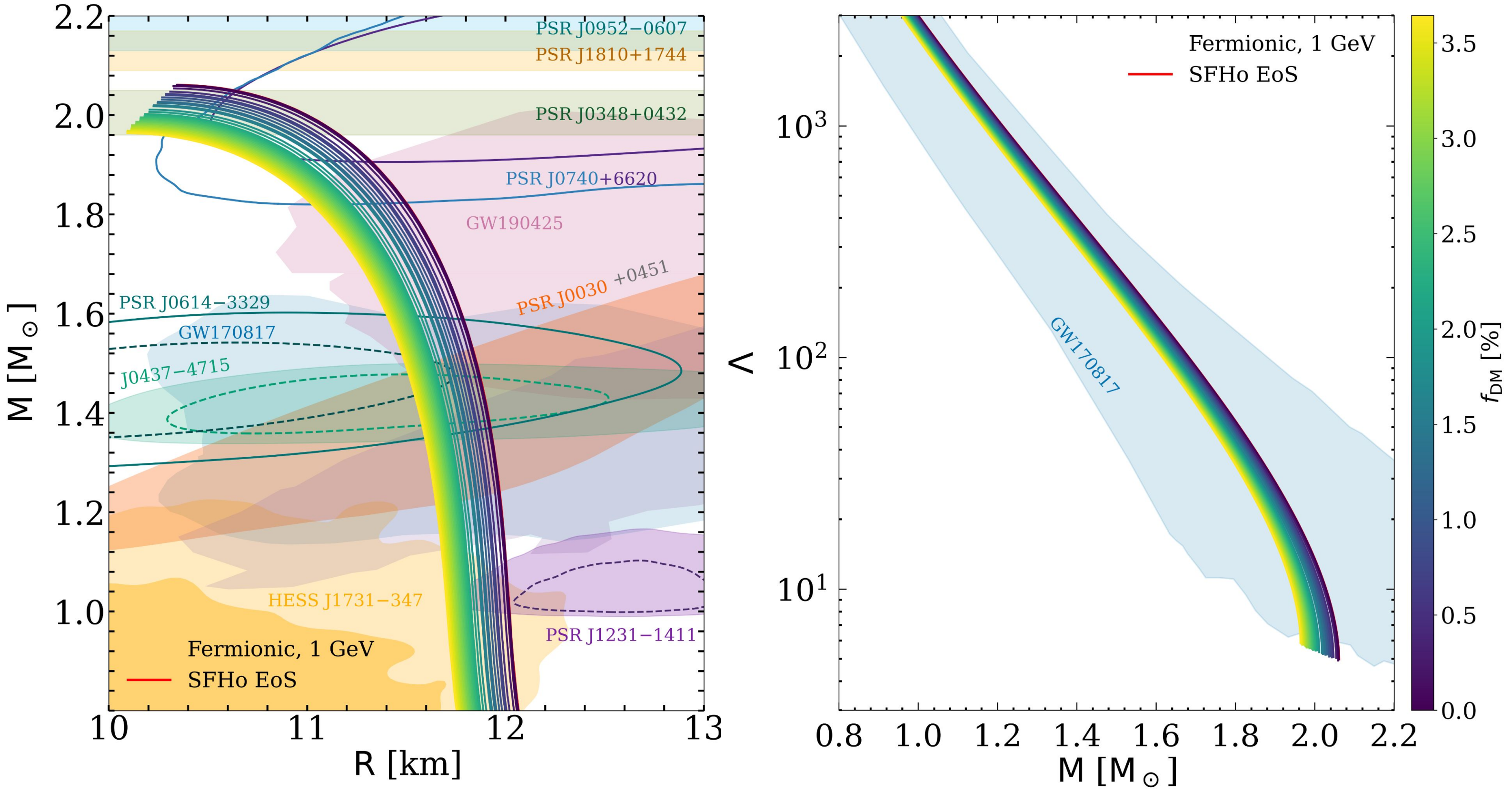
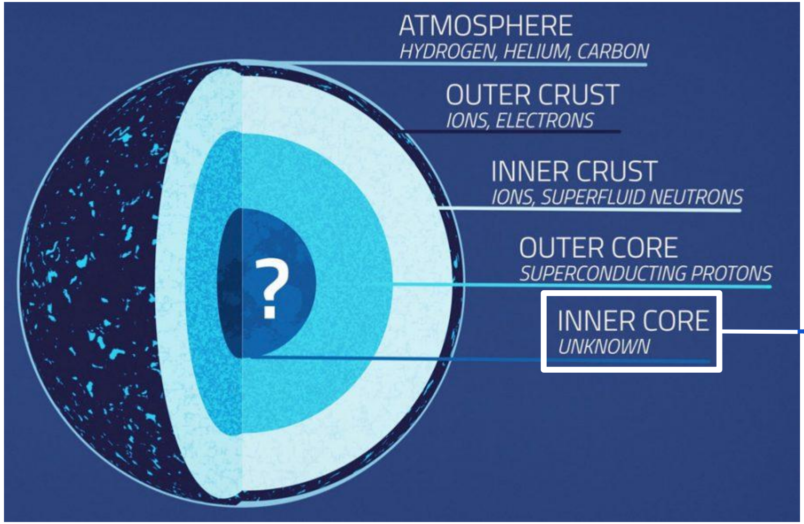
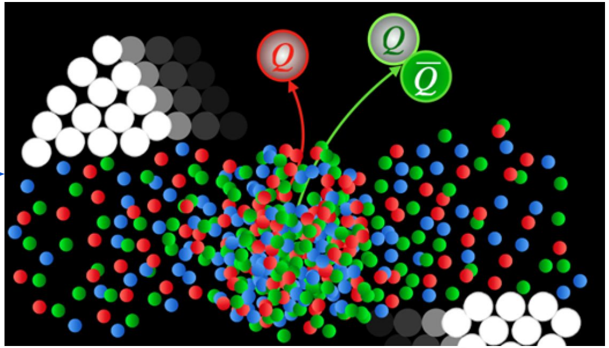


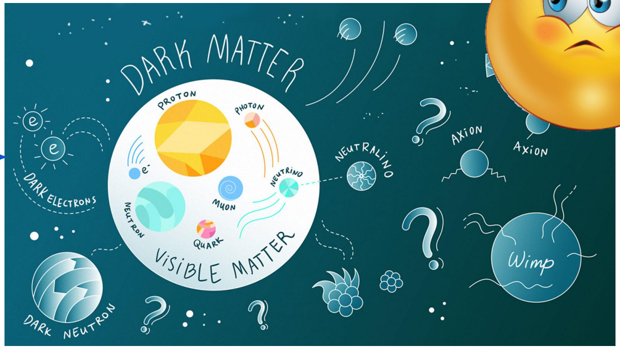
Figure 4: Gravitational mass, M, as a function of radius, R, (left) for the SFHo EoS and the DM-admixed configurations, color coded by the DM mass fraction f_{DM}. Tidal deformability, Λ, as a function of gravitational mass, M, (right).

Possible Degeneracy

Both scenarios can leave similar imprints on the NS properties, resulting in a possible degeneracy!







Credit: NASA’s Goddard Space Flight Center / Conceptual Image Lab

Degeneracy

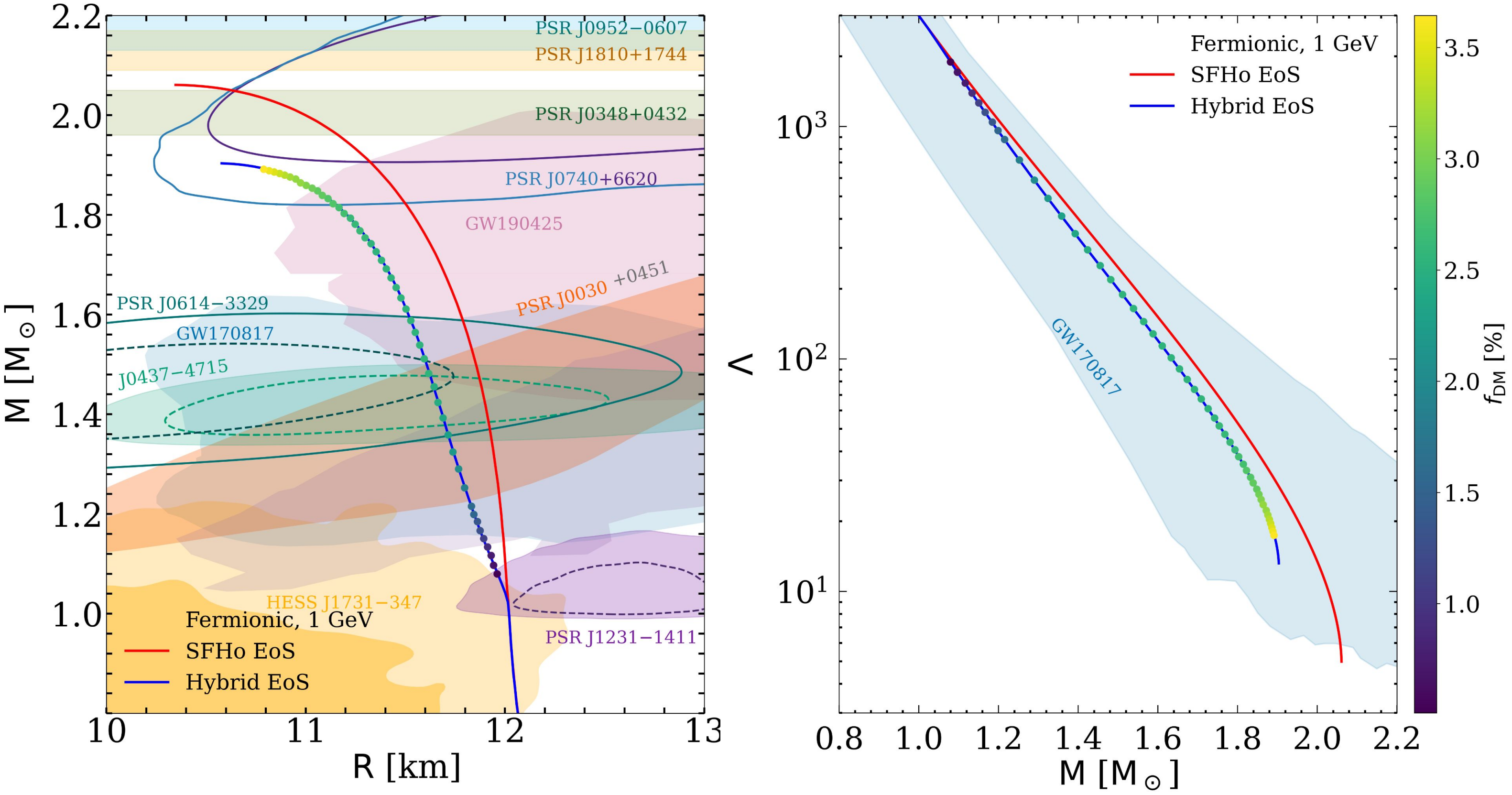


Figure 5: Gravitational mass, M, as a function of radius, R, (left) for the SFHo and hybrid EoSs. The color dots mark, along the hybrid branch, the DM-admixed configuration whose f_{DM} reproduces the same mass, radius and tidal deformability as the hybrid star. Tidal deformability, Λ, as a function of mass, M, (right).

Degeneracy

A configuration is accepted as a crossing only if,

$$|\Delta M| \leq 10^{-3}\ M_\odot,\ |\Delta R| \leq 10^{-2}\ \mathrm{km}\ \mathrm{and}\ |\Delta\Lambda| \leq 10^{-3},$$

[This will be taken from **CE and ET estimated measurement precision**]

between the DM-admixed and hybrid stars, are satisfied simultaneously.

- The degeneracy holds only up to $f_{DM} \simeq 3.5\%$, beyond which **no DM-admixed configuration** reproduces the mass, radius and tidal deformability of the hybrid EoS considered.

The results were obtained for $m_{DM} = 1\,\mathrm{GeV}$, for considered BM and DM EoSs.

Degeneracy

- Two NSs with the same mass, radius and tidal deformability but completely different internal composition

- Re-run at the precision for CE & ET can deliver

What measurement precision is needed to break the degeneracy?

Degeneracy

- Two NSs with the same mass, radius and tidal deformability but completely different internal composition

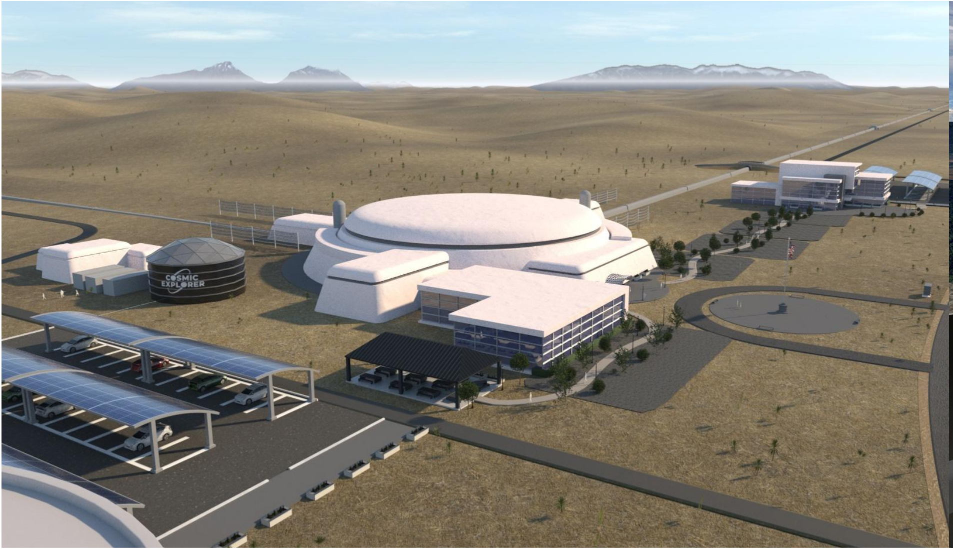
- Re-run at the precision for CE & ET can deliver

What measurement precision is needed to break the degeneracy?

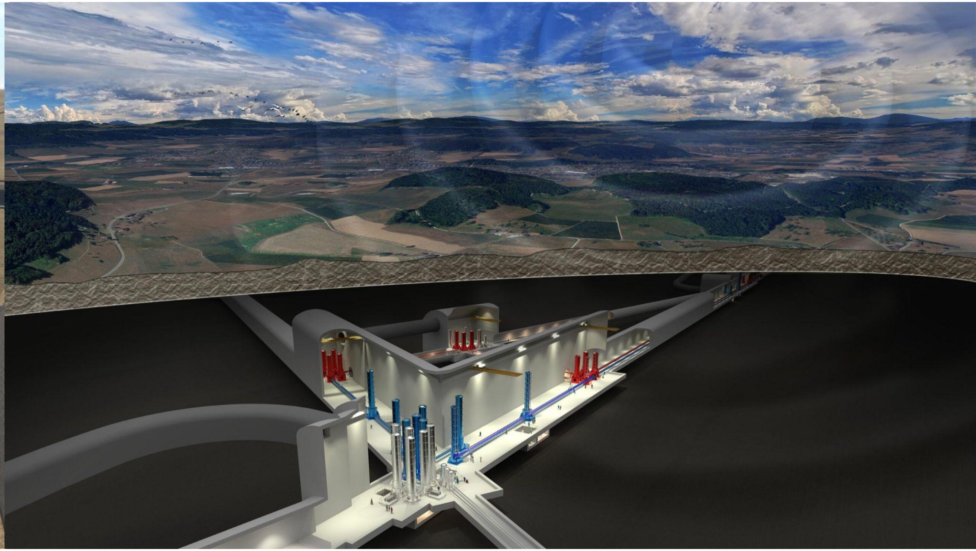
More data and precision can constraint the “hiding” space for DM

3G Detectors: Cosmic Explorer (CE) & Einstein Telescope (ET)

Cosmic Explorer (CE)

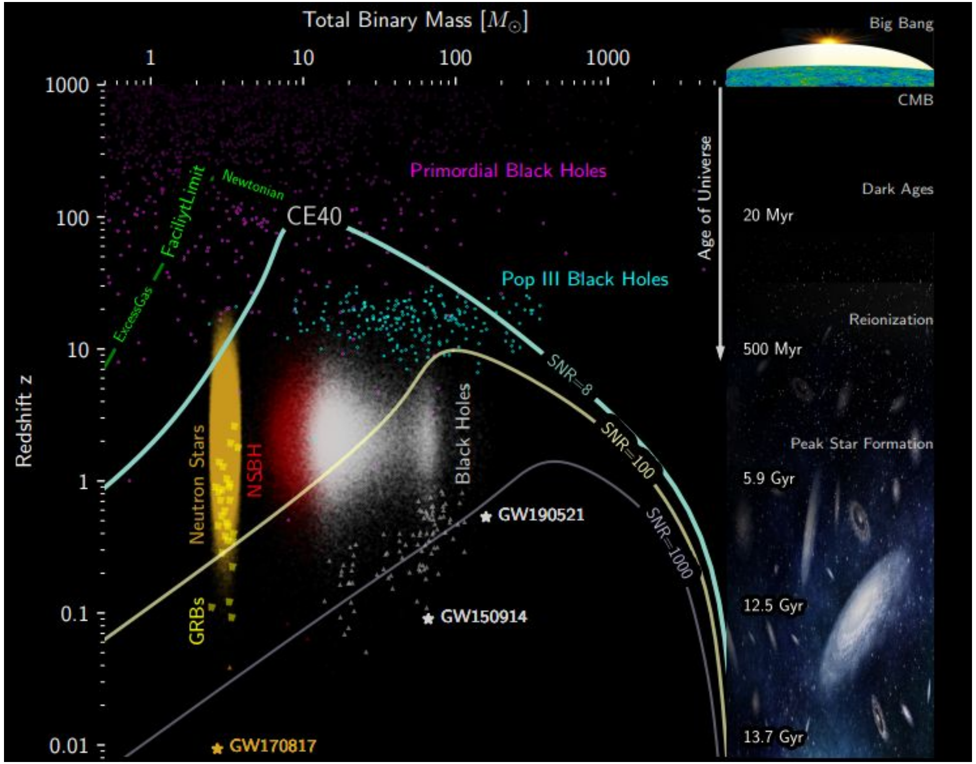


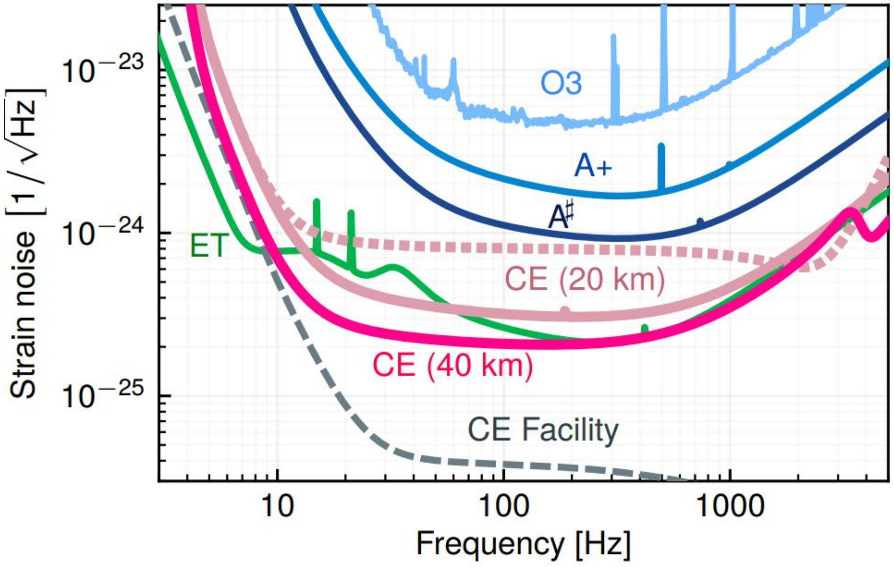
Einstein Telescope (ET)



[Cosmic Explorer, Einstein Telescope]

The next generation of GWs observations





[Cosmic Explorer, 2306.13745v1]

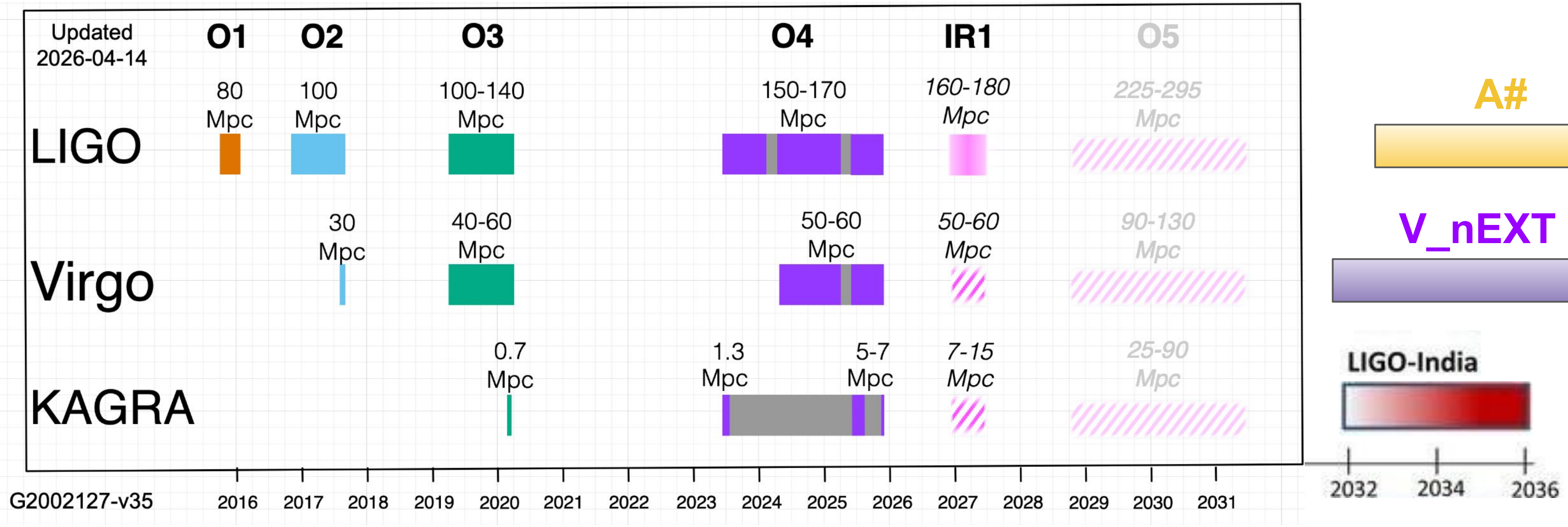
Conclusions

- DM and a deconfinement PT can leave the same imprint on mass, radius and tidal deformability , but differ in composition
- 3G detectors improve strain sensitivity, cosmological reach and SNR by orders of magnitude over LVK
- Longer inspirals and access to the post-merger will tighten the constraints on NSs properties
- The CE + ET network could deliver the precision needed to break the degeneracy and constrain the DM parameter space

Thank you!

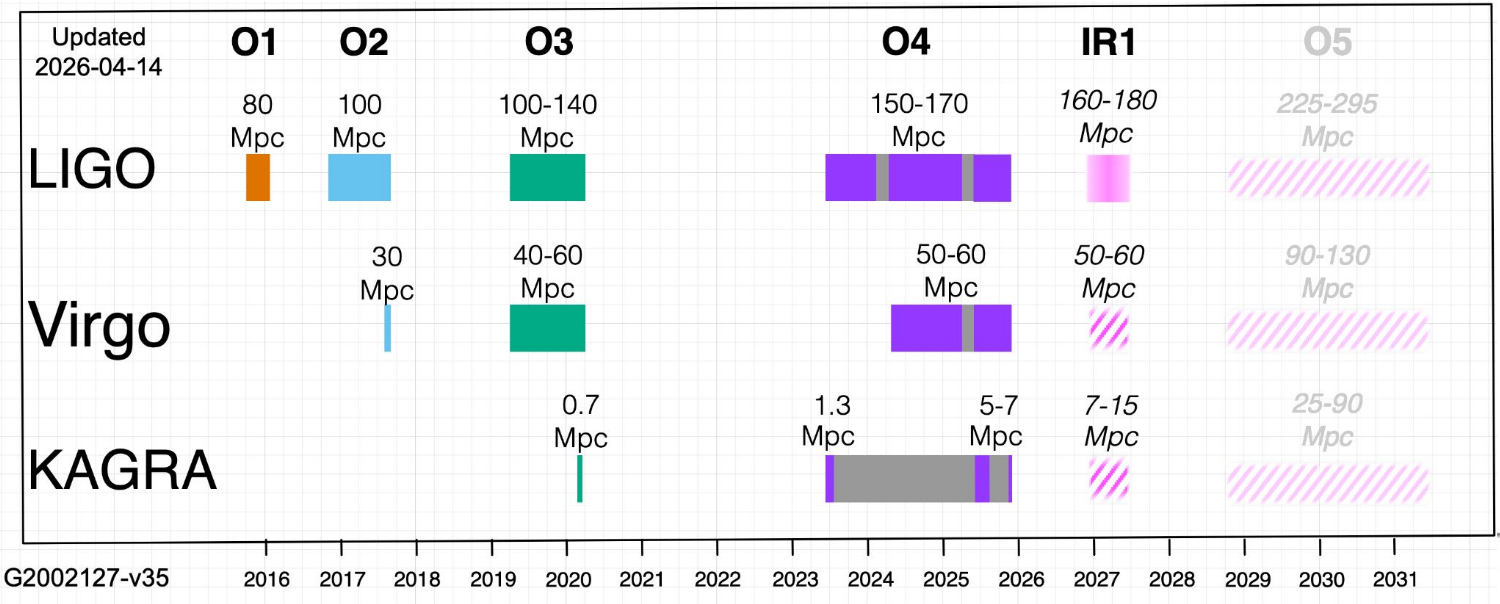
Backup Slides

2G Detectors: LIGO-Virgo-KAGRA (LVK)

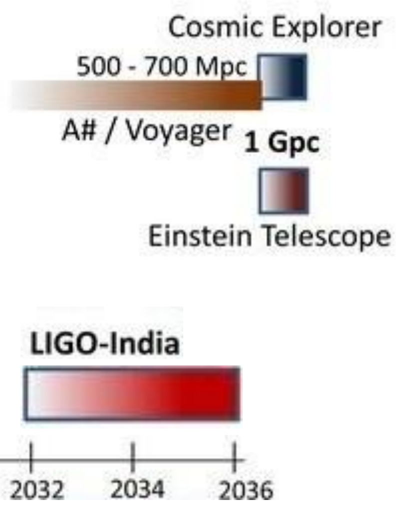


[LIGO-Virgo Collaboration]

2G Detectors: LIGO-Virgo-KAGRA (LVK)



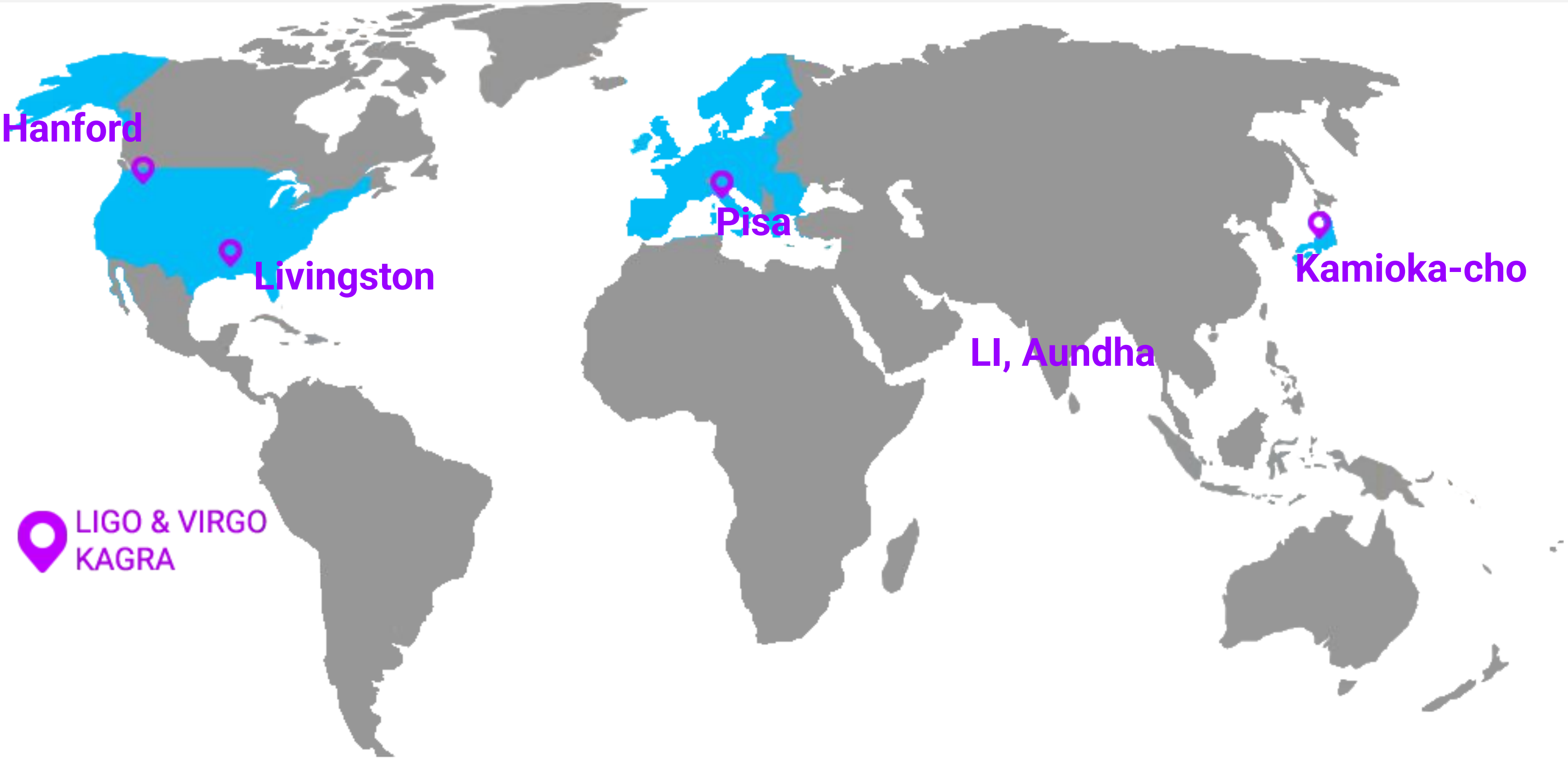
2035…



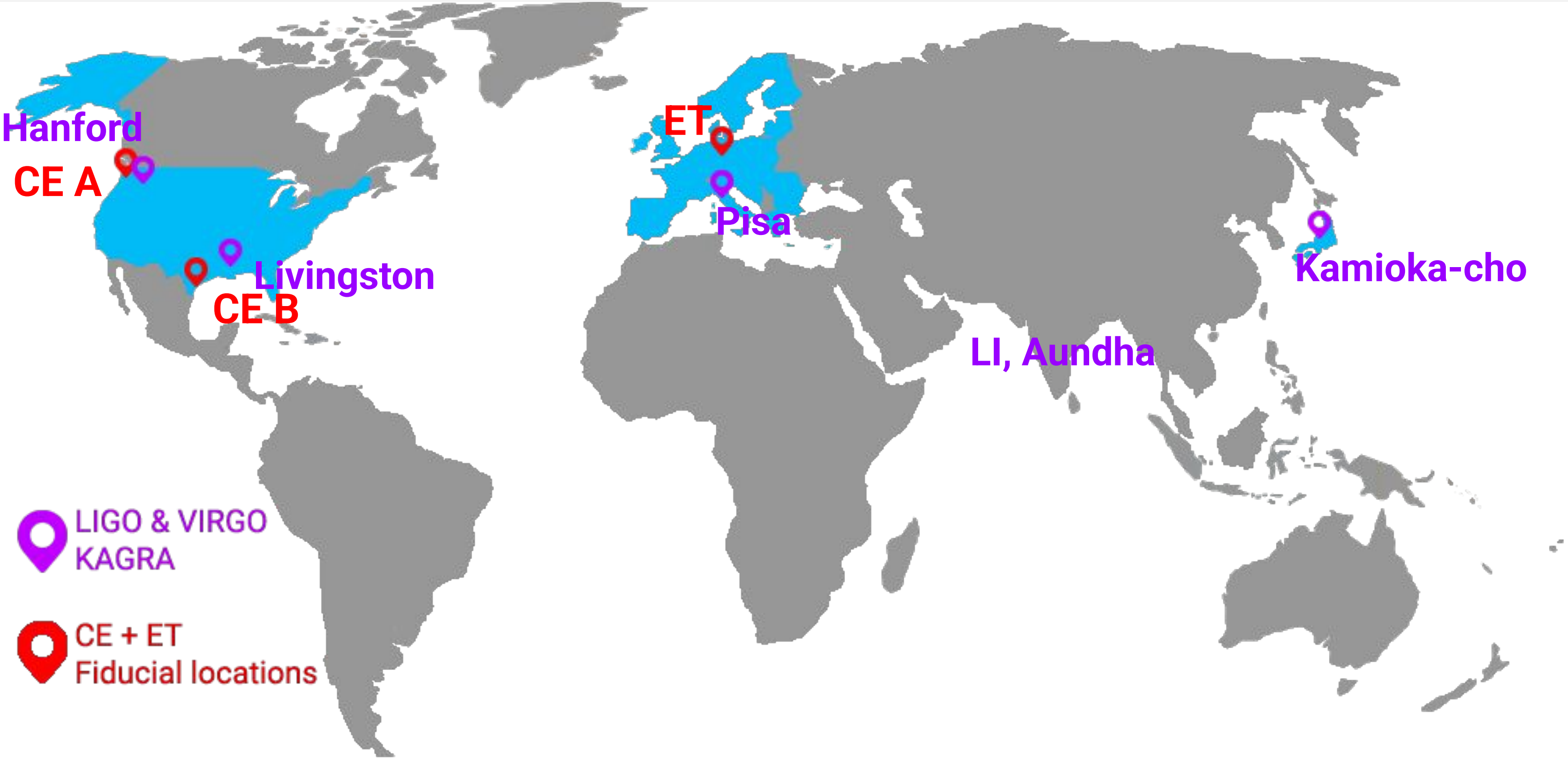
[LIGO-Virgo Collaboration]

What's next???

3G Detectors: Cosmic Explorer (CE) & Einstein Telescope (ET)



3G Detectors: Cosmic Explorer (CE) & Einstein Telescope (ET)



3G Detectors: Cosmic Explorer (CE) & Einstein Telescope (ET)

EMR site

Saxony site

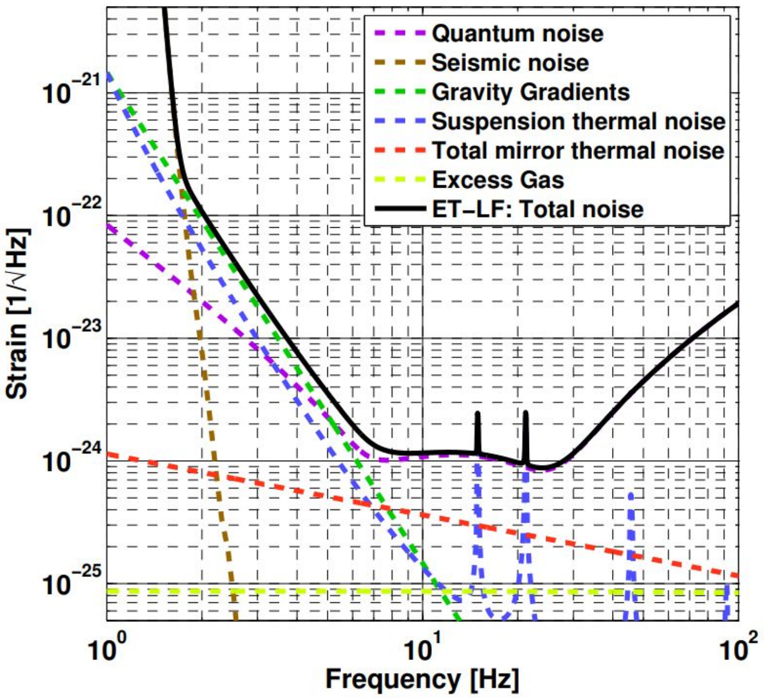
Sos Ennatos site

Potential sites:

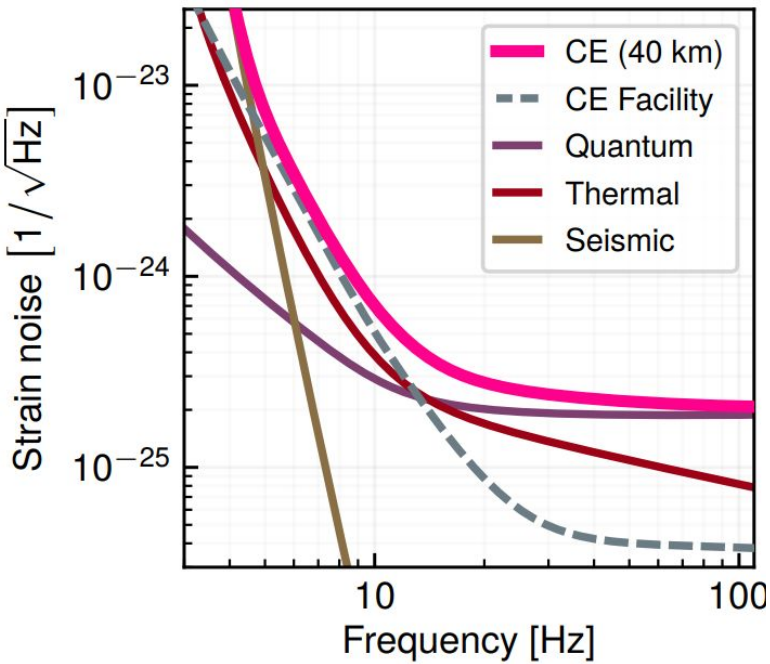
- Sardinia, Italy (Sos Enattos)
- Euregio Meuse-Rhine (Belgium/Germany/Netherlands)
- Lusatia, Germany (Saxony)

Credit: G. Bruno slides

The next generation of GWs observations



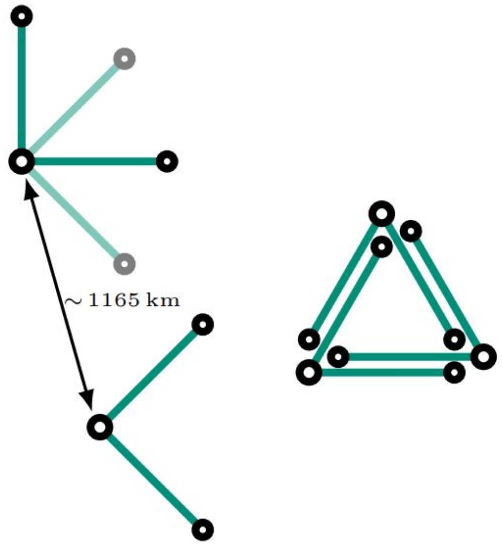
[ET Conceptual Design Study, ET-0106C-10]



[Cosmic Explorer, 2306.13745v1]

Einstein Telescope: the European 3G concept

Two widely separated L-shaped detectors or a triangle made of three nested detectors, underground.[2]



Xylophone

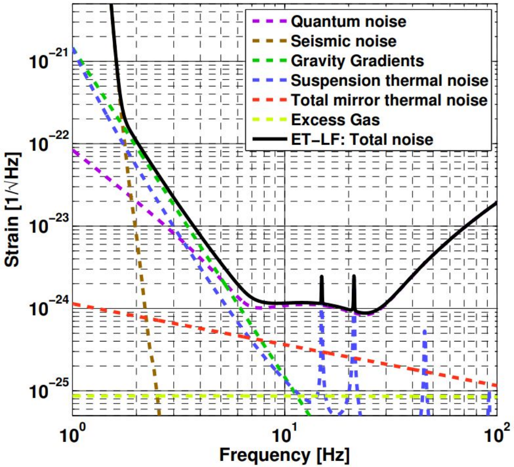
1. a triangle with 10 km arms (the current baseline ET geometry)
2. a triangle with 15 km arms
3. a 2L with 15 km arms, with parallel arms
4. a 2L with 15 km arms, with a relative orientation of 45°
5. a 2L with 20 km arms, with parallel arms
6. a 2L with 20 km arms, with a relative orientation of 45°

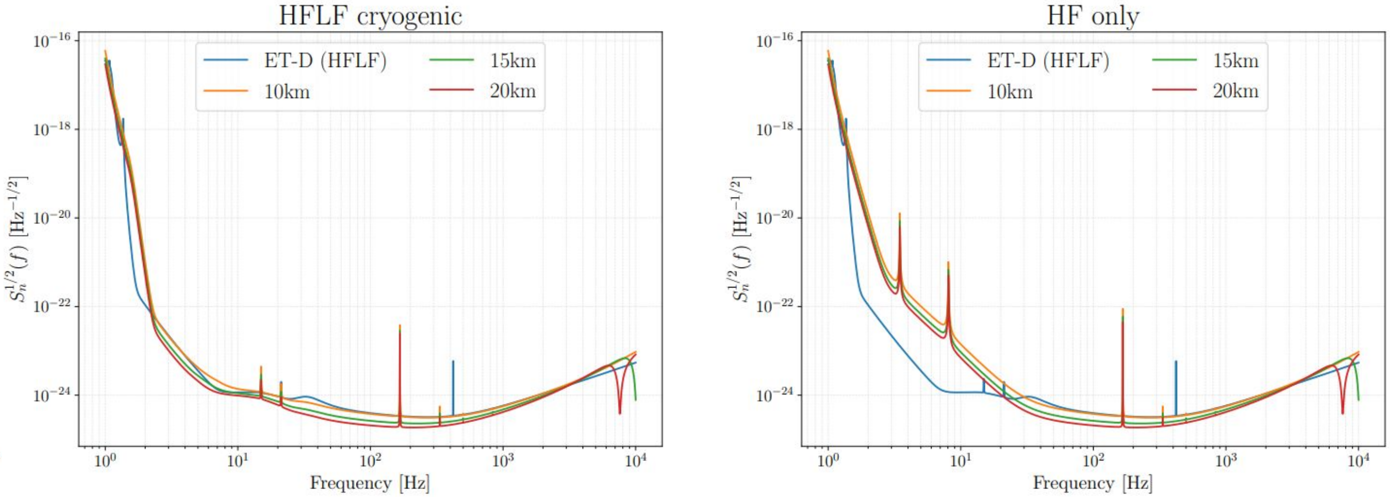
[Einstein Telescope, 2303.15923v2]

[2] Orientation with respect to the local Norths at the two detector sites.

What “xylophone” means

[ET Conceptual Design Study, ET-0106C-10]





[Thompson et al.]

[Einstein Telescope, 2503.12263v2]

$$SNR^2 = 4\int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n(f)}df$$

ET + CE as a network

1. ET as a triangle with 10 km arms, together with 2CE (20+40 km)
2. ET as a 2L of 15 km and parallel arms, together with 2CE (20+40 km)
3. ET as a 2L of 15 km and arms at 45°, together with 2CE (20+40 km)
4. ET as a triangle with 10 km arms, together with 1CE (40 km)
5. ET as a 2L of 15 km and parallel arms, together with 1CE (40 km)
6. ET as a 2L of 15 km and arms at 45°, together with 1CE (40 km)

[Einstein Telescope, 2503.12263v2]

3G Detectors: Cosmic Explorer (CE) & Einstein Telescope (ET)

Cosmic Explorer (CE)

- Long arms → High strain sensitivity
- High SNR and cosmological reach
- Excellent statistics from large BNS populations

Einstein Telescope (ET)

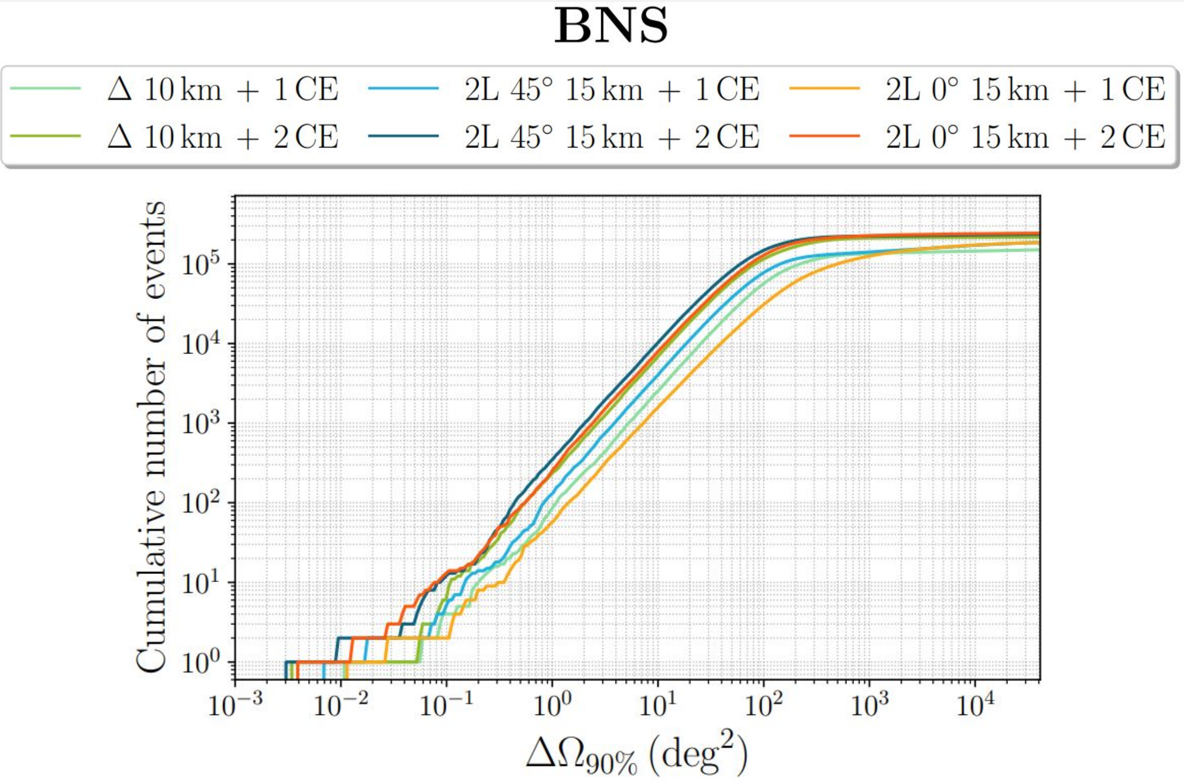
- Low-frequency sensitivity
- Xylophone configuration

  ↓

  Broadband optimization
- Triangular polarization capability

Together they maximize parameter estimation!

ET + CE as a network



[Einstein Telescope, 2303.15923v2]

Why 3G Detectors Improve Precision

- ET+CE network **(higher SNR)**

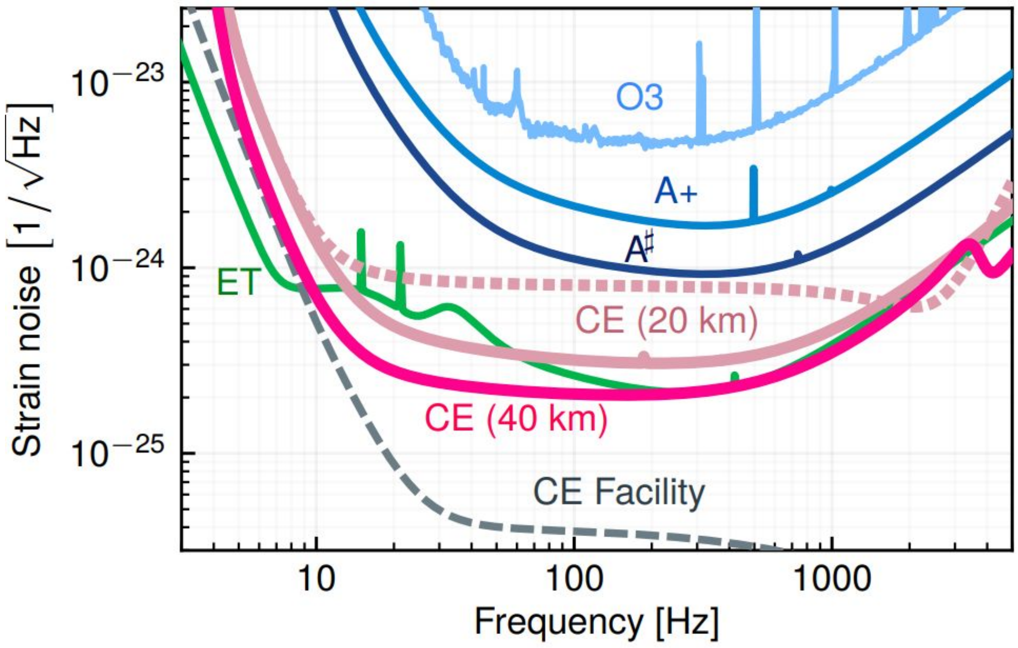
⇓

Tidal effects at low SNR to **not be buried** in noise

- Signals enter the detector band earlier **(Broader waveband)**

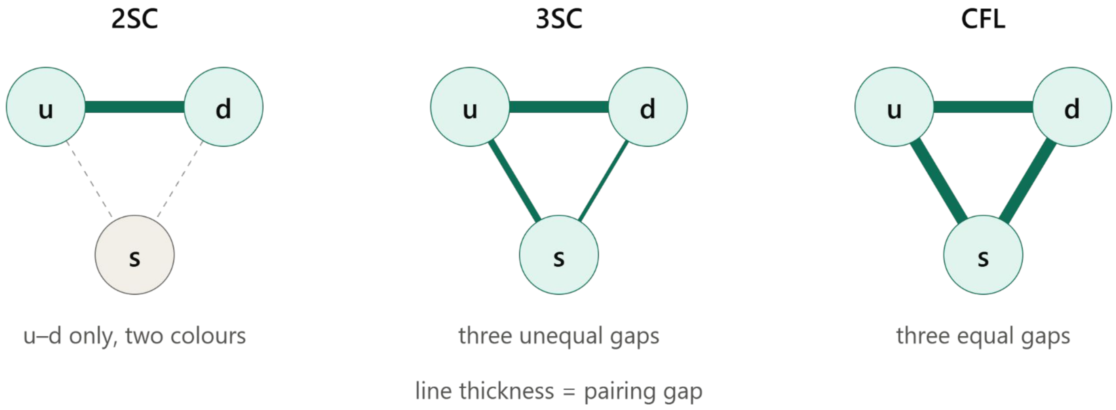
⇓

Longer inspiral duration



[Cosmic Explorer, 2306.13745v1]

ABPR: 2SC vs 3SC and CFL



$$\text{2SC:} \quad \frac{\Delta^2 \mu_Q^2}{\pi^2} \qquad \text{CFL:} \quad \frac{3\Delta^2 \mu_Q^2}{\pi^2}$$

- 2SC: only u-d pairs, and only in two of the three colours (red-green). Blue u, blue d, and all s quarks stay ungapped

- 3SC: u-d, u-s and d-s all pair, but in three separate channels with three unequal gaps

$$\Delta_{ud} \neq \Delta_{us} \neq \Delta_{ds}$$

- CFL: u-d, u-s and d-s all pair, in all three colours, with a single common gap

ABPR: 2SC vs 3SC and CFL

The pairing lowers the free energy by one term per open channel

$$\Omega_\Delta \simeq -\frac{\mu_Q^2}{\pi^2}\left(\Delta_{ud}^2 + \Delta_{us}^2 + \Delta_{ds}^2\right) + \mathcal{O}\left(\Delta^4\right)$$

$$\text{2SC:} \quad \Delta_{us} = \Delta_{ds} = 0 \qquad \Longrightarrow \qquad \Omega_\Delta = -\frac{\Delta_{ud}^2 \mu_Q^2}{\pi^2}$$

$$\text{3SC:} \quad \Delta_{ud} \neq \Delta_{us} \neq \Delta_{ds} \qquad \Longrightarrow \qquad \Omega_\Delta = -\frac{\mu_Q^2}{\pi^2}\sum_i \Delta_i^2$$

$$\text{CFL:} \quad \Delta_{ud} = \Delta_{us} = \Delta_{ds} \equiv \Delta \qquad \Longrightarrow \qquad \Omega_\Delta = -\frac{3\Delta^2 \mu_Q^2}{\pi^2}$$

LORENE (Langage Objet pour la RElativité NumériquE)

- C++ library for numerical relativity and computational astrophysics [Gourgoulhon, Grandclément, Novak et al., Observatoire Astronomique de Strasbourg]
  - Solves PDEs using multi-domain spectral methods
  - Infrastructure implemented (e.g. binary systems)
  - Allows to study BNS quasi-equilibrium sequences (elliptic PDE problem)
  - A full treatment perturbs the **fluid** and the **spacetime** together, letting the star radiate GWs

- **LORENE + Strasbourg group's hydrodynamics code** [Servignat, Novak & Cordero-Carrión 2023] provides the numerical infrastructure to solve this fully perturbed system

NMMA (Nuclear-Physics and Multi-Messenger Astrophysics)

- Open-source python Bayesian inference framework for BNS
  [Pang, Dietrich, Coughlin et al. 2022, arXiv:2205.08513]

  - Analyses GW, kilonova and gamma ray burst at the same time (Joint-Likelihood)
  - Pulsar masses and NICER (mass-radius) posteriors enter as EoS prior weights
  - *Flexible* workflow:
    - Can build its own EoS from nuclear theory, or take a catalogue of tabulated ones
    - The EoS is sampled as a label, so the data can rank the models directly

- Sampling directly over an EoS catalogue allows the hybrid and DM-admixed catalogue to be weighted against data.

The next generation of NSs observations

[Joshi et al. (2025)]

- **Radio: SKA (2027 onwards)**
  - Times pulse arrivals from binary pulsars to under a microsecond
  - **10,000 slow pulsars** and nearly **800 millisecond pulsars**, more than **doubling** the known population
  - Shapiro delay, periastron advance, orbital decay - depend on the two masses of the double NS system

  Provides both masses separately

Provides both mass and radius

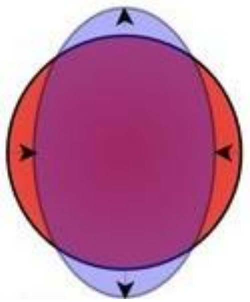
- **X-ray: NICER (now), eXTP & NewAthena (early 2030s)**
  - Observes hotspots rotate in and out of view on millisecond pulsars
  - Light bending constrains the compactness, Doppler boosting constrains the radius
  - Relative precision in radius of 10% for 4 stars today → to 5% for around 20 stars with the next generation

- **GWs: ET & CE (mid-2030s)**
  - **Today:** One confirmed event today (GW170817) → **With CE and ET:** around 300,000 mergers per year, and the 20 loudest carry the constraint
  - Post-merger oscillation frequency: a **direct look at the possible PT**
  - Relative precision on radius **below 2%** from the 20 loudest events per year

Adiabatic & Dynamic Tides

A. Adiabatic tides

$$\omega_f \gg |m|\Omega$$



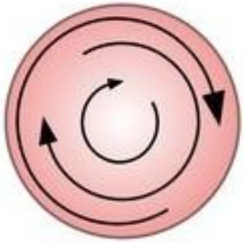
Early Inspiral

Tidal_v2 (Start)

$$\Omega = \frac{2\pi}{P_{orb}}$$

B. Dynamic tides

$$\omega_f \approx |m|\Omega$$



Late Inspiral

Tidal_v3 (LVK)

[Hinderer et al., 2016]