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Continuous gravitational waves from ultraluminous X-ray pulsar

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Based on: Li et al., ApJ, 2026

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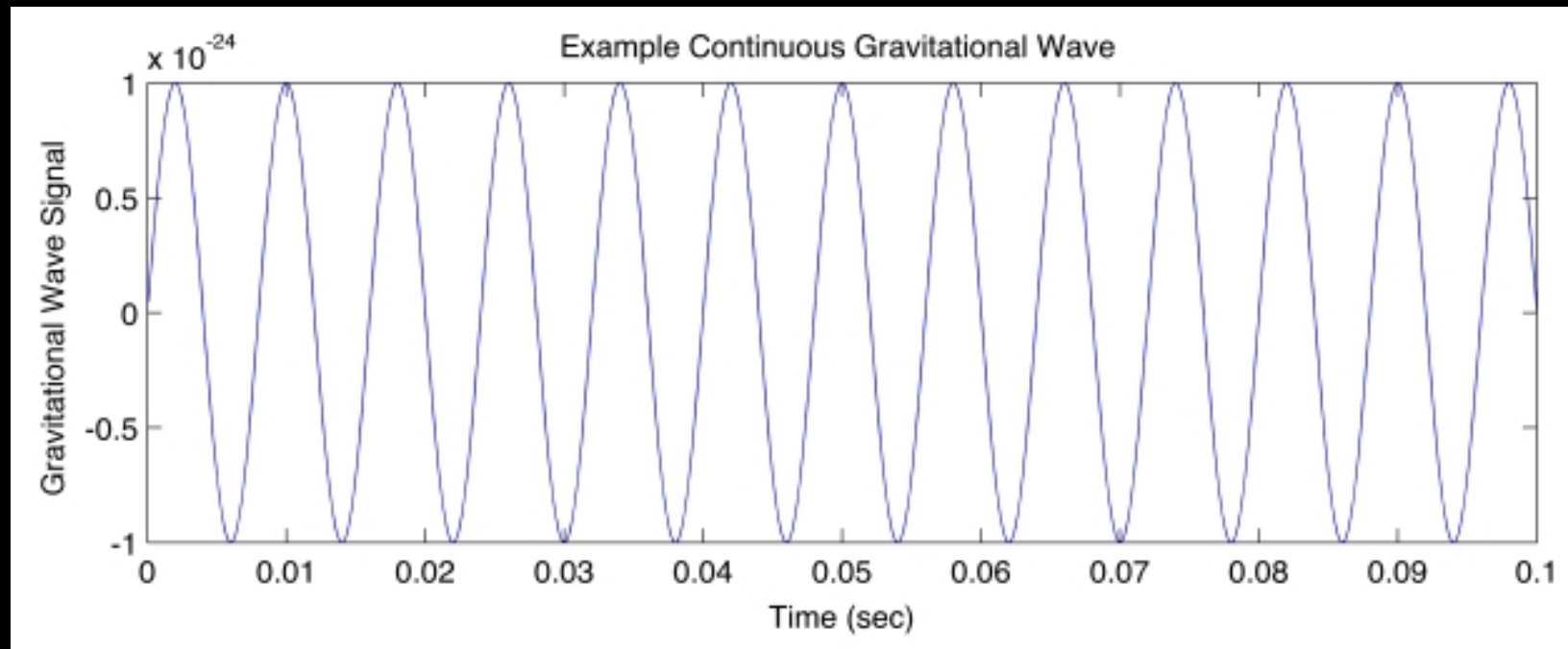
Outline

- Introduction
 - Continuous gravitational waves
 - Formation of NS deformations
 - Searches for CGW from NS deformations
- Continuous gravitational waves from ULXPs
 - Ultraluminous X-ray Sources
 - Temperature perturbation and quadrupole moment
- Summary

Continuous gravitational waves:

- (Nearly) constant frequency and amplitude
- Emitted from rapidly rotating NSs with asymmetries
- Emission mechanisms:
 - Mountains on the NS surface
 - Precessing NSs
 - r-mode instability

Credit: LIGO



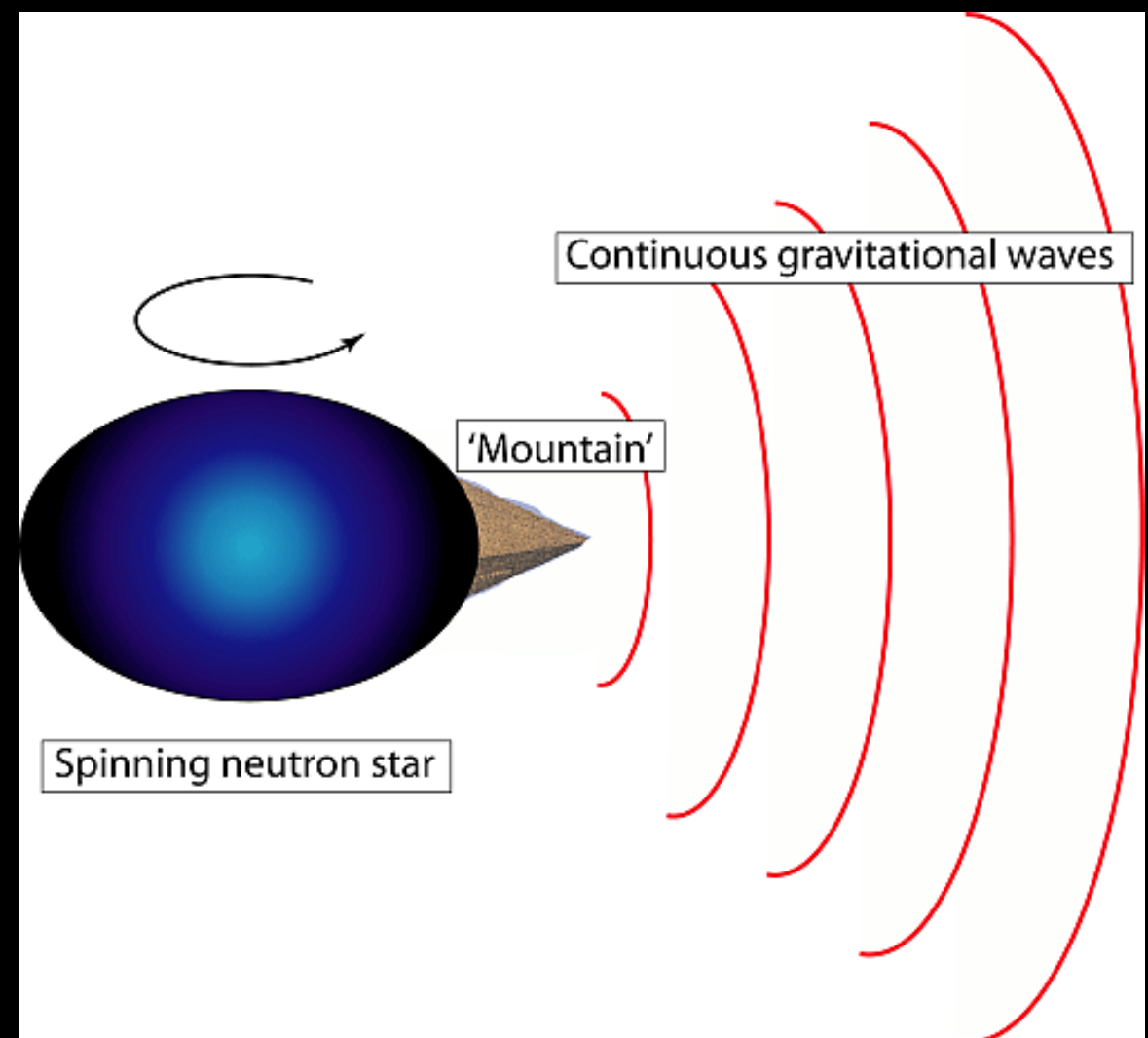
Continuous gravitational waves from neutron-star deformations

Amplitude

$$h_0 = \frac{4\pi^2 G}{c^4} I_{zz} \frac{f_{\text{GW}}^2}{d} \epsilon = 1.1 \times 10^{-24} \left(\frac{\epsilon}{10^{-6}} \right) \left(\frac{I_{zz}}{10^{45} \text{ g cm}^2} \right) \left(\frac{f_{\text{GW}}}{1 \text{ kHz}} \right)^2 \left(\frac{1 \text{ kpc}}{d} \right)$$

$\epsilon \equiv (I_{xx} - I_{yy})/I_{zz}$: ellipticity (the size of “mountain”)

If we know distance (d) and moment of inertia (I_{zz}), one can obtain ϵ , which may probe thermal or magnetic structures



Formation of NS deformations

1. Isolated NSs

- Magnetic mountains (Haskell et al. 2008; Lander et al. 2012, ...)
- Elastic mountains (Ushomirsky et al. 2000; Haskell et al. 2006; Gittins et al. 2020; 2021; Fujisawa et al. 2022; Morales & Horowitz 2022; 2024)
- Electric fields variation in magnetosphere (Kouvaris 2024)

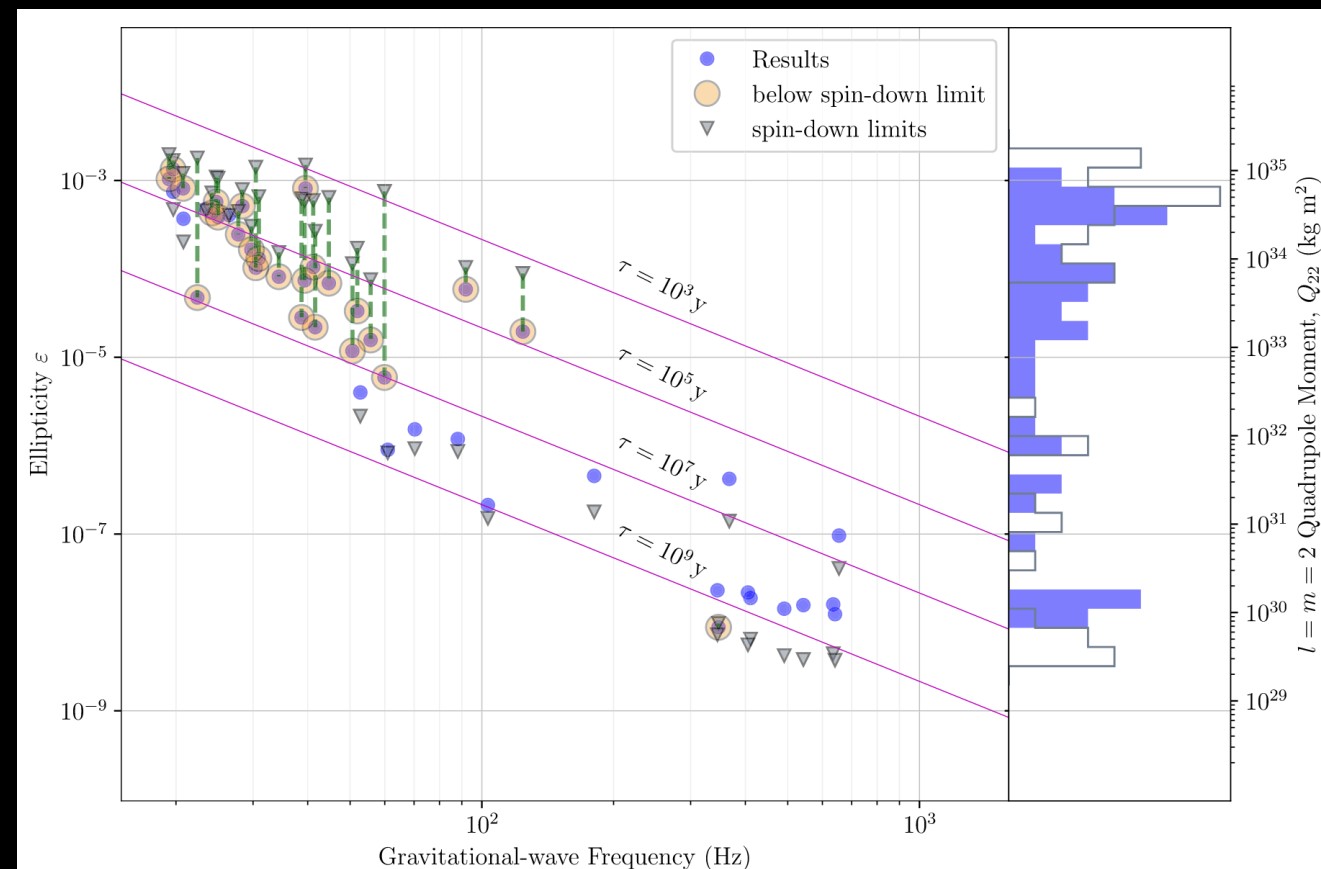
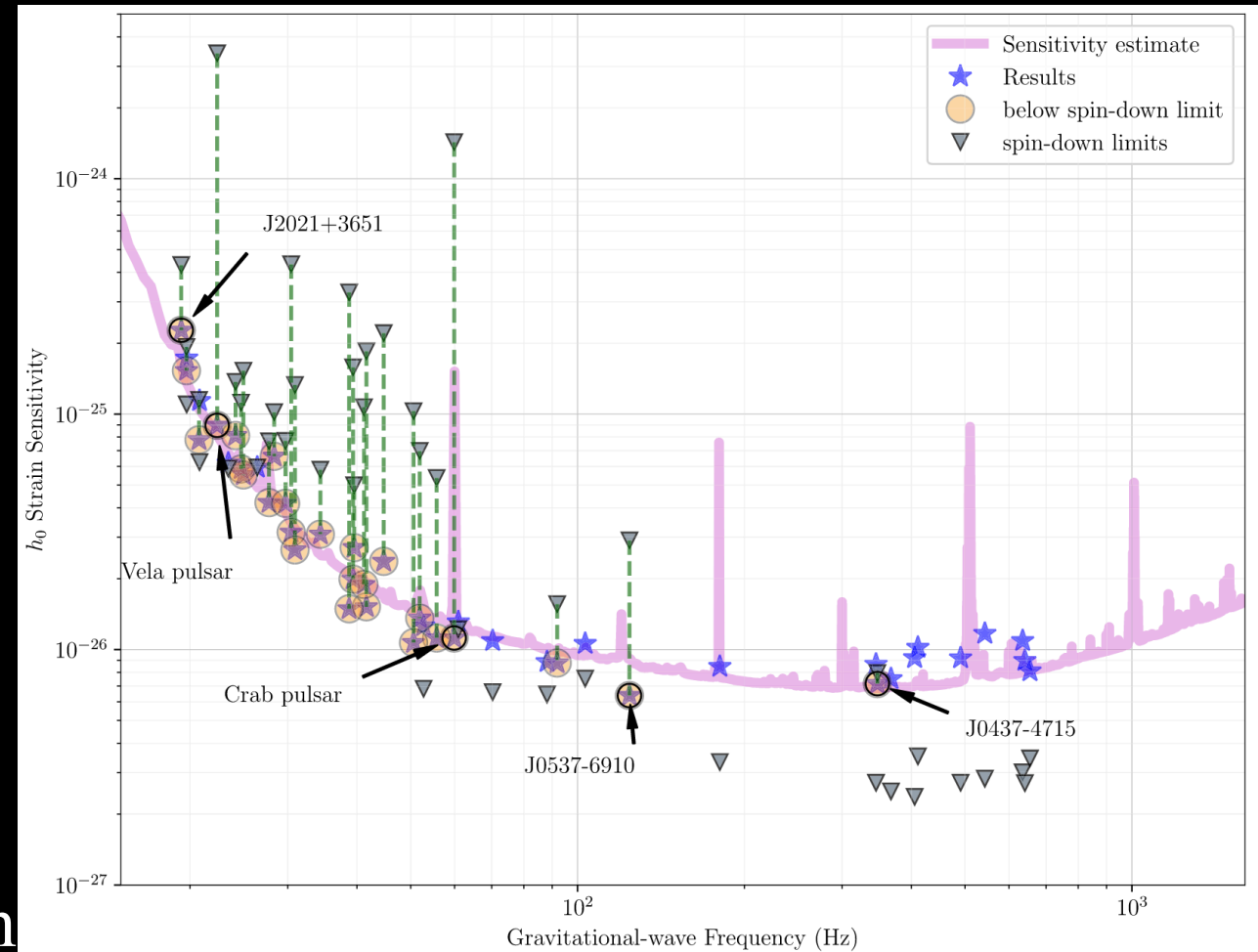
2. NSs in binary system (accreting NSs)

- Magnetically confined mountains (Payne & Melatos 2004; Priymak et al. 2011; Fujisawa et al. 2022; Rossetto et al. 2025)
- Thermal mountains (Bildsten 1998; Osborne & Jones 2020; Hutchins & Jones 2024; [Li et al. 2025](#))

Searches for CGW from NS deformations

- For 45 known pulsars, not detected (O4a)
- The lowest constraint is
 - $\epsilon_{\min} = 8.8 \times 10^{-9}$ (PSR J0437-4715)
- The scenario with $\epsilon > \epsilon_{\min}$ is testable from future GW detectors

LVK collaboration, ApJ, 2025



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- Ultraluminous X-ray Sources (ULXs) are defined by the two conditions:

$$(1) L_X > L_{\text{Edd}} \approx 10^{38} \left(\frac{M}{M_{\odot}} \right) \text{ erg s}^{-1}$$

(2) locations away from galaxy centres

- The three candidates of compact object:

1. stellar-mass black hole

$$10 M_{\odot}$$

Kaaret, Feng, and Roberts, 2017

2. intermediate-mass black holes

$$(10^2 - 10^5) M_{\odot}$$

Farrell et al. 2009

3. X-ray pulsar

ULX M82 X-2

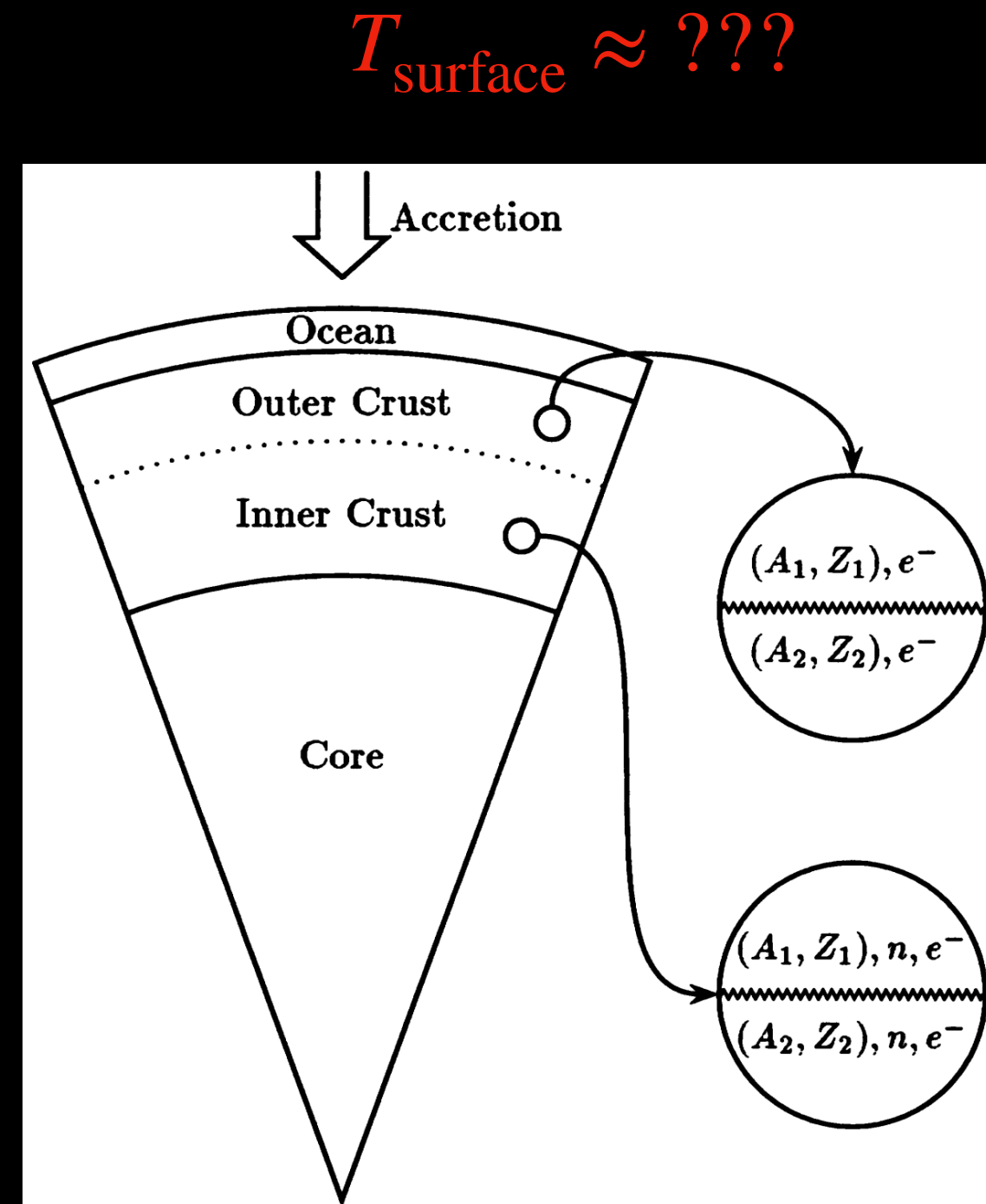
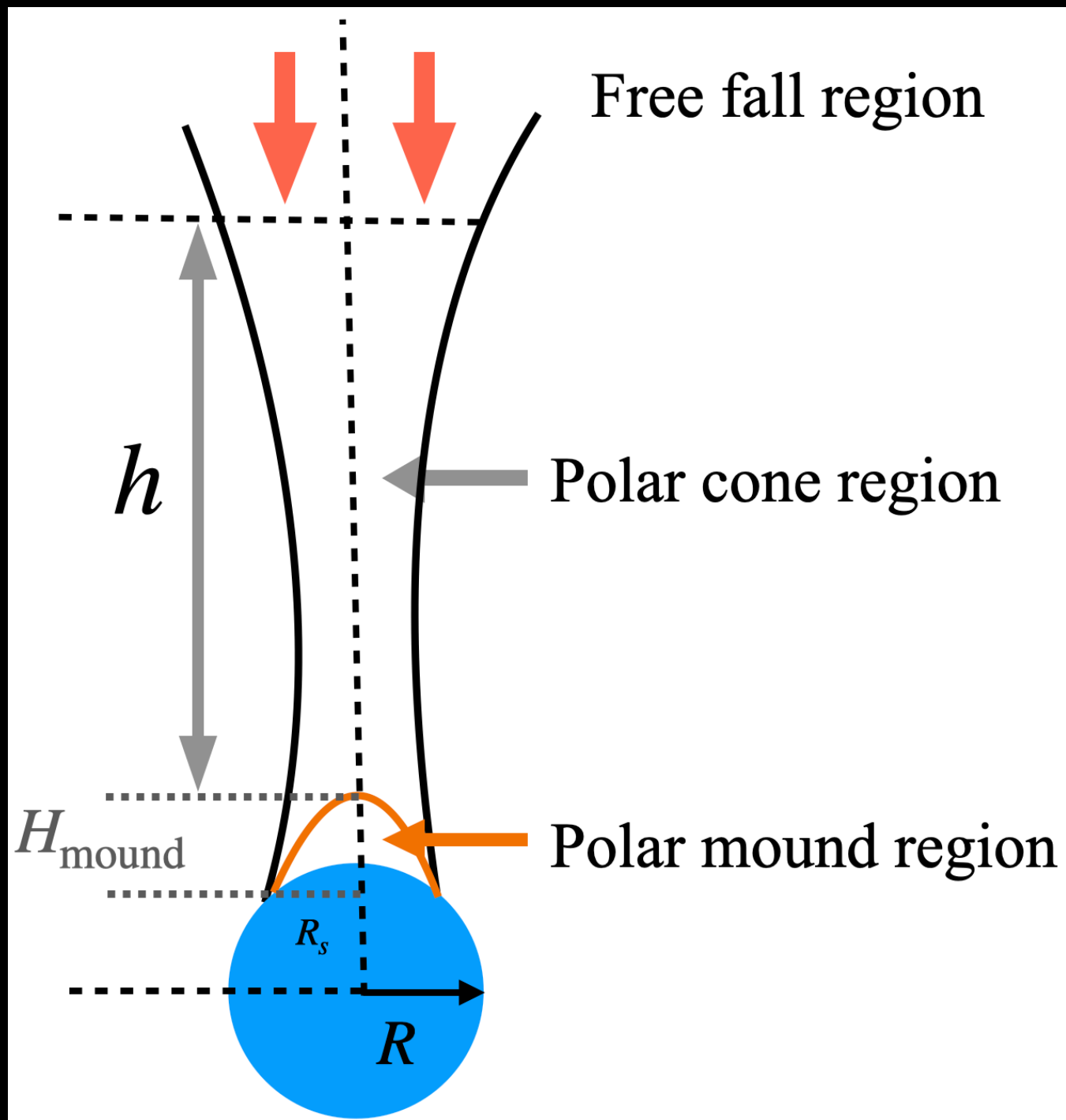
Bachetti et al. 2014

From Li et al., MNRAS, 2026

Source	P (s)	$\dot{P}$ (10^{-9} s s^{-1})	L_X ($10^{39} \text{ erg s}^{-1}$)	d (Mpc)	Ref.
M82 X-2	1.37	−0.2	18	3.6	[1]
NGC 5907 ULX-1	1.13	−3.8	~ 100	17.1	[2]
NGC 300 ULX-1	16.6	−556	4.7	2	[3]
NGC 1313 X-2	1.5	−13.8	~ 20	4	[4]
NGC 2403 ULX	18	−100	1.2	3.2	[5]
NGC 7793 P13	0.417	−0.04	~ 10	3.6	[6]
NGC 7793 ULX-4	0.4	−35	3.4	3.9	[7]
NGC 4559 X-7	2.6	+1	20	7.5	[8]
Swift J0243.6+6124	9.86	−22	2	0.007	[9]
SMC X-3	7.8	−6.46	1.2	0.062	[10]
RX J0209.6−7427	9.29	−17.5	1.6	0.06	[11]
M51 ULX-7	2.8	−0.15	4	8.6	[12]
M51 ULX-8	−	−	2	8.58	[13]
NGC 4559 X7	2.6	−1	5	7.5	[14]

Issues:

How to effect of the super-eddington magnetized neutron stars (ULXPs) on CGW ???



Dynamical properties of magnetic polar regions

Dynamical equations (steady state):

Mass conservation

$$\nabla \cdot (\rho \vec{v}) = 0$$

Euler equations

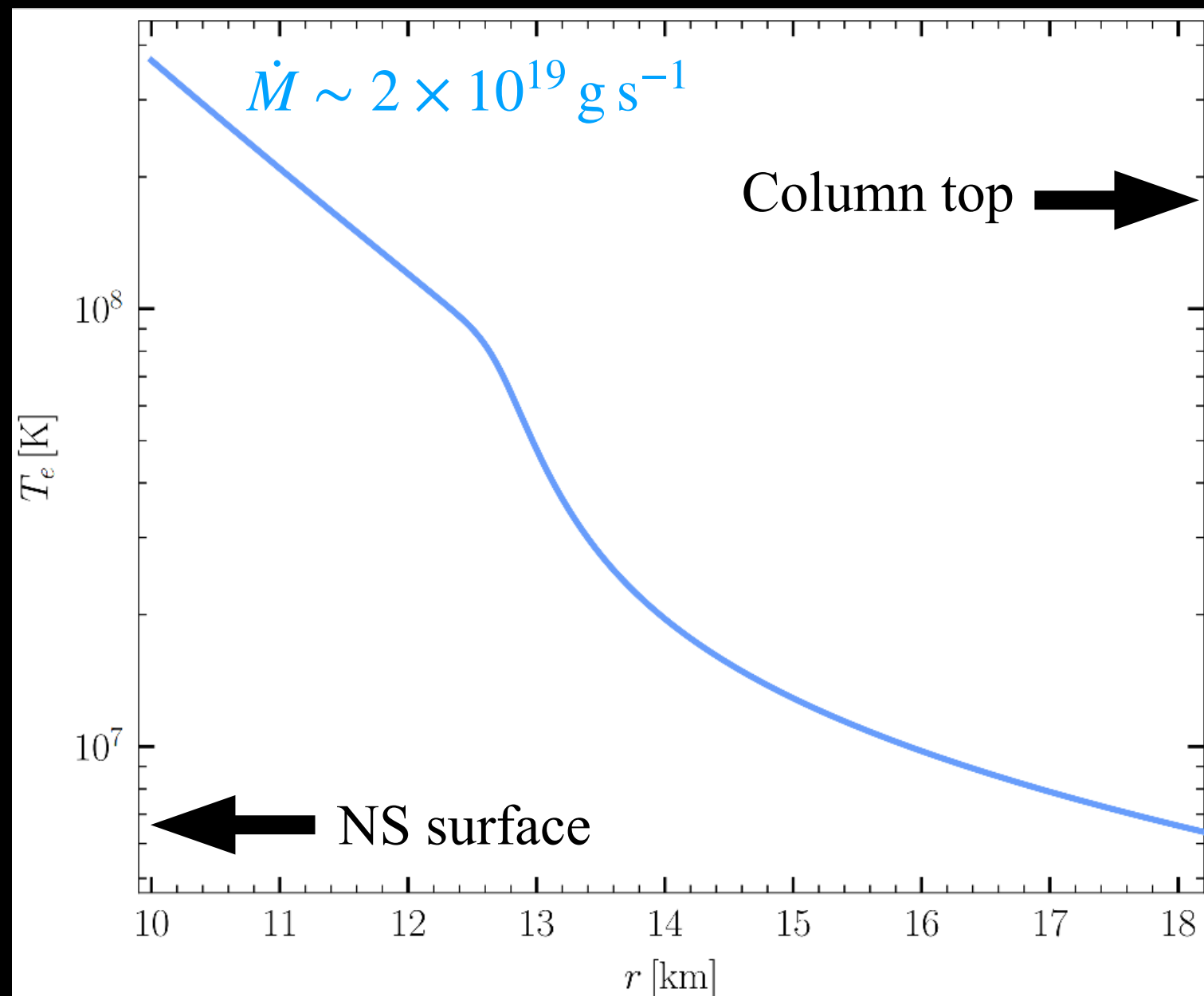
$$\rho \frac{d\vec{v}}{dt} = -\nabla P - \rho \nabla \Phi$$

Energy conservation

$$\nabla \cdot (U \vec{v}) + P \nabla \cdot \vec{v} = -\nabla \cdot \vec{F}$$

Photon diffusion equation

$$\vec{F} = -D \nabla U_{\text{rad}}$$

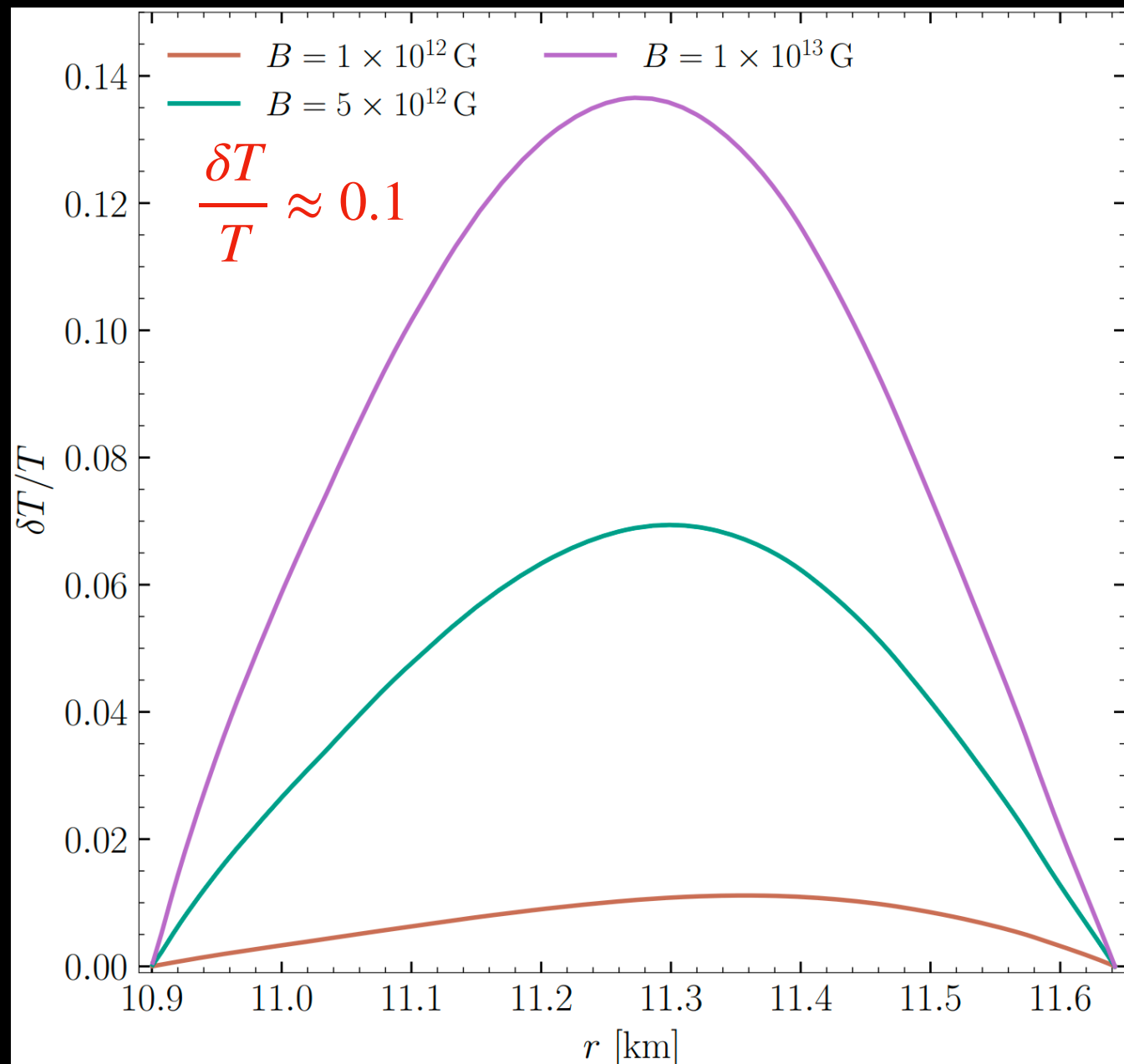
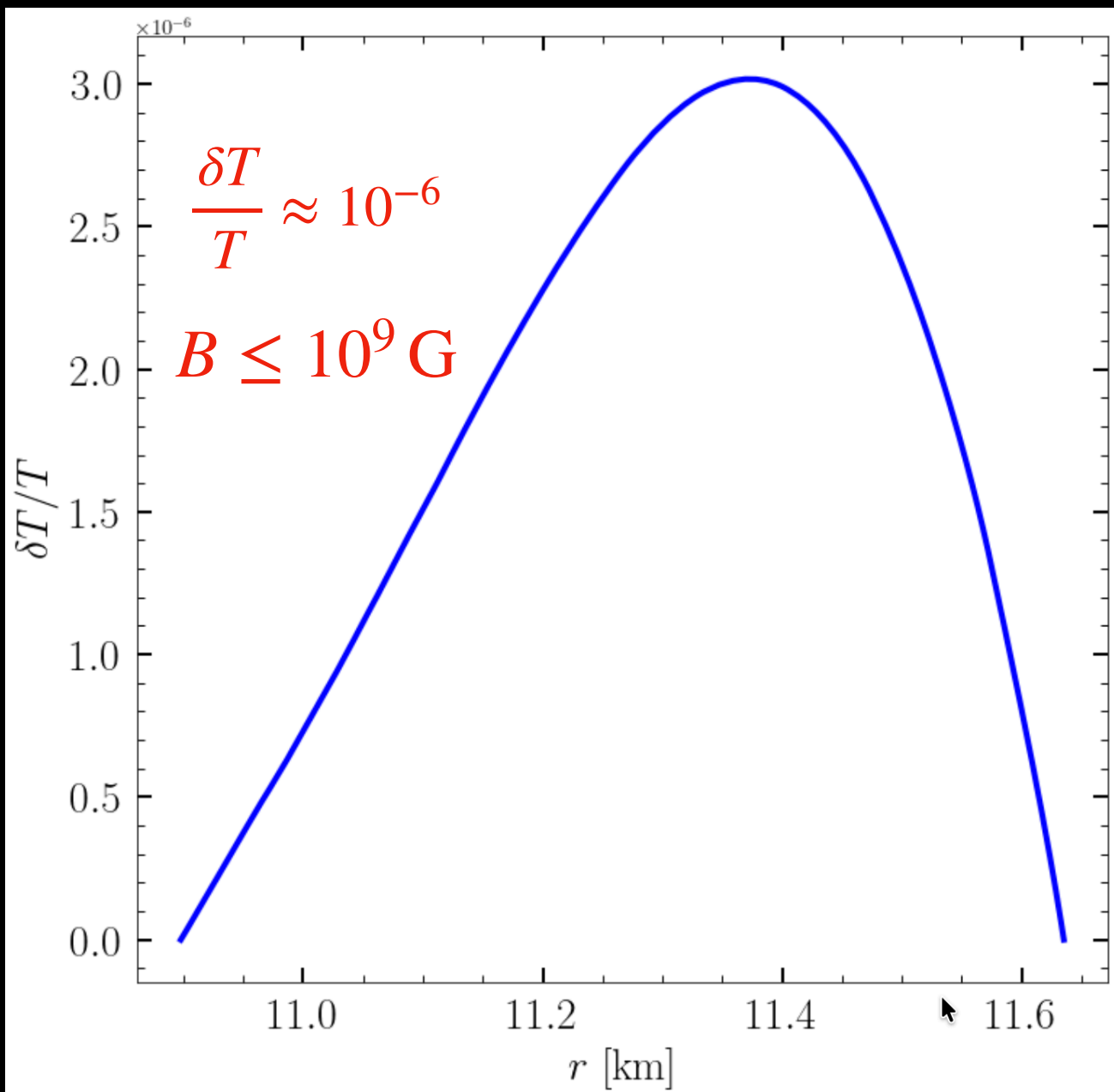


Temperature perturbation and quadrupole moment

$$Q_{22} \equiv \int \left. \frac{\partial \ln \rho}{\partial \ln T} \right|_p \frac{\delta T}{T} \rho r^4 dr$$

LMXBs

ULXPs



Detectability of CGWs

known ULXPs

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} \epsilon f_{\text{GW}}^2}{d}$$

$$I_{zz} \simeq 10^{45} \text{ g cm}^2$$

Ellipticity resulting from the temperature-induced asymmetry:

$$\epsilon \simeq 2 \times 10^{-7} B_{12}$$

CGW strain amplitudes from these sources **lie below the sensitivity** of LIGO's O5 run

Source	P (s)	$\dot{P}$ (10^{-9} s s^{-1})	L_X ($10^{39} \text{ erg s}^{-1}$)	d (Mpc)	Ref.
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Prospects for future detection

Ultraluminous X-ray sources with He star companions

Li et al. 2024, MNRAS

(1) NS+He star system evolves into NS ULXs (pulsar+CO WD system)

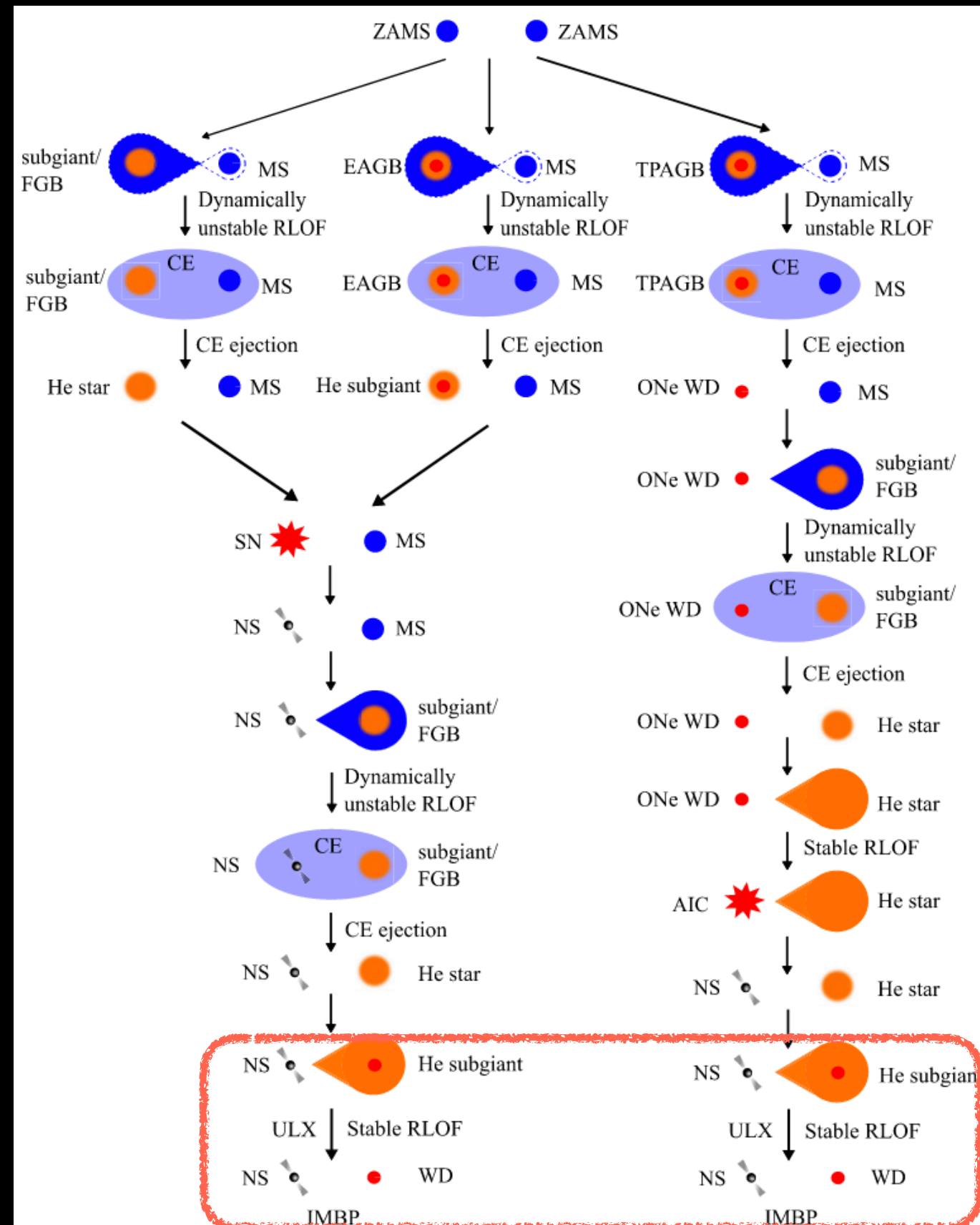
PSR J1614-2230: $P \simeq 3$ ms

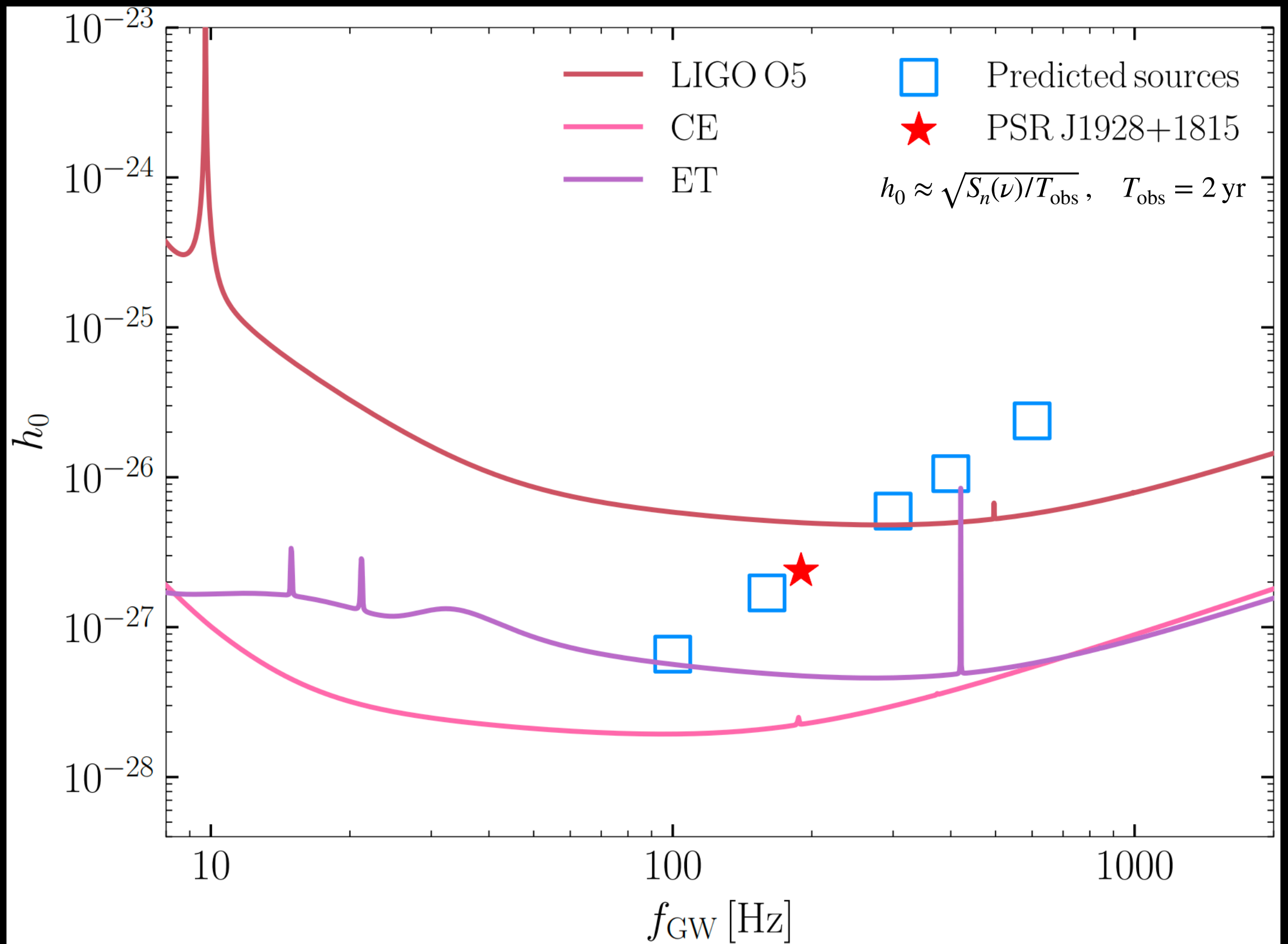
Exist 7-20 detectable NS ULXs with He donor stars in the Galaxy

(2) Galactic detached pulsar + helium star binary, PSR J1928+1815

Yang et al. 2025, Science

$P = 10.55$ ms





Summary

- Super-Eddington accretion can produce strong thermal asymmetries in magnetized neutron-star crust

The high base temperature of the accretion column, together with **magnetically induced anisotropic heat conduction**, leads to significant crustal temperature perturbations

- These thermal perturbations can generate sizable neutron-star deformations

$$\epsilon \sim 10^{-8} - 10^{-7}$$

- Galactic fast-spinning NS ULXs are promising continuous gravitational-wave sources

ET and CE could detect systems with spin periods $P \lesssim 20$ ms, while LIGO O5 may detect only very fast systems with $P \lesssim 6$ ms



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Thank you for your attention!