Image: OzGrav | Carl Knox

Hunting for Humming Continuous Wave Signals
—— Neutron Stars, Dark Matter, New Physics

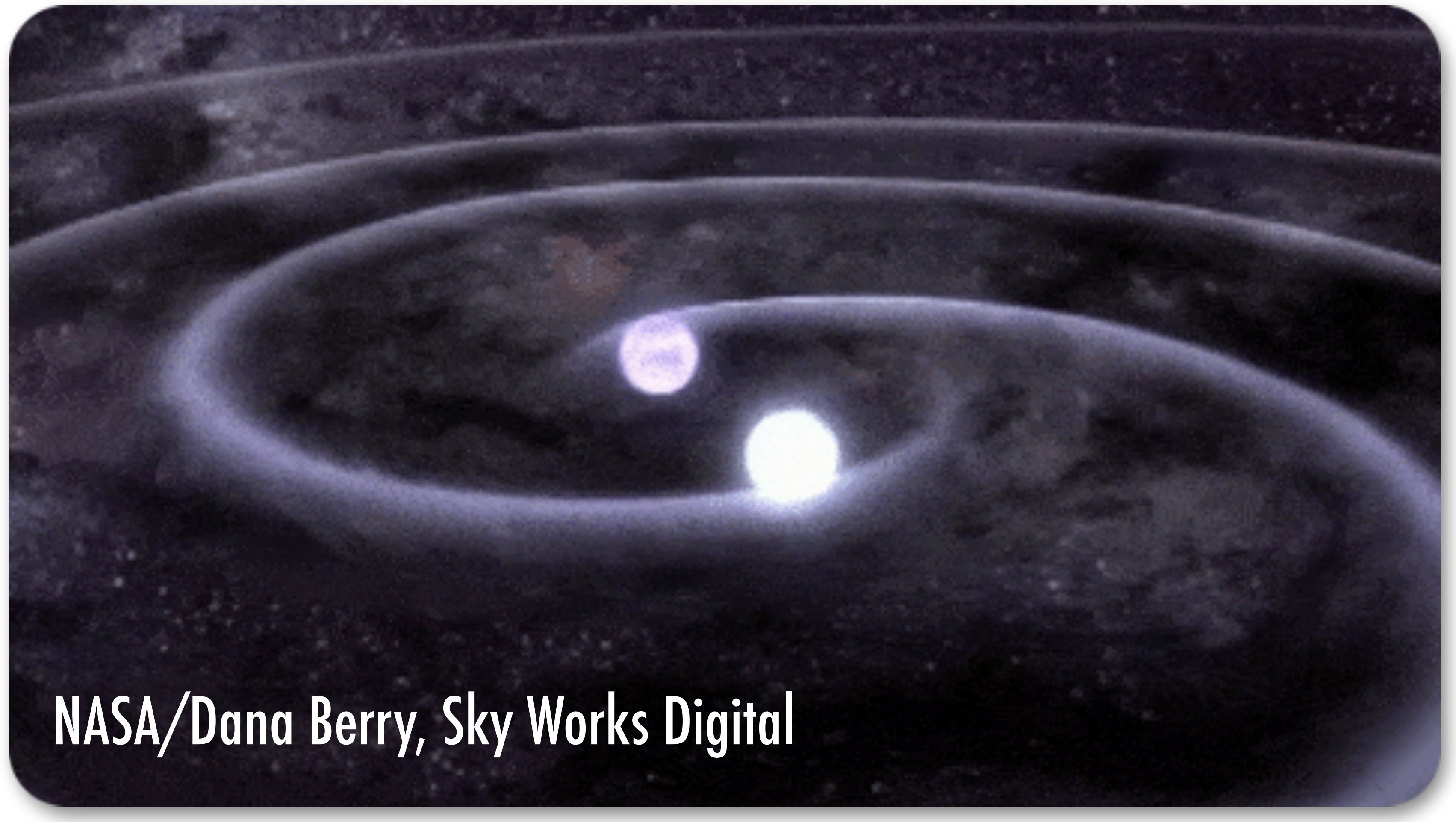
Australian National University

ANU CENTRE FOR GRAVITATIONAL ASTROPHYSICS

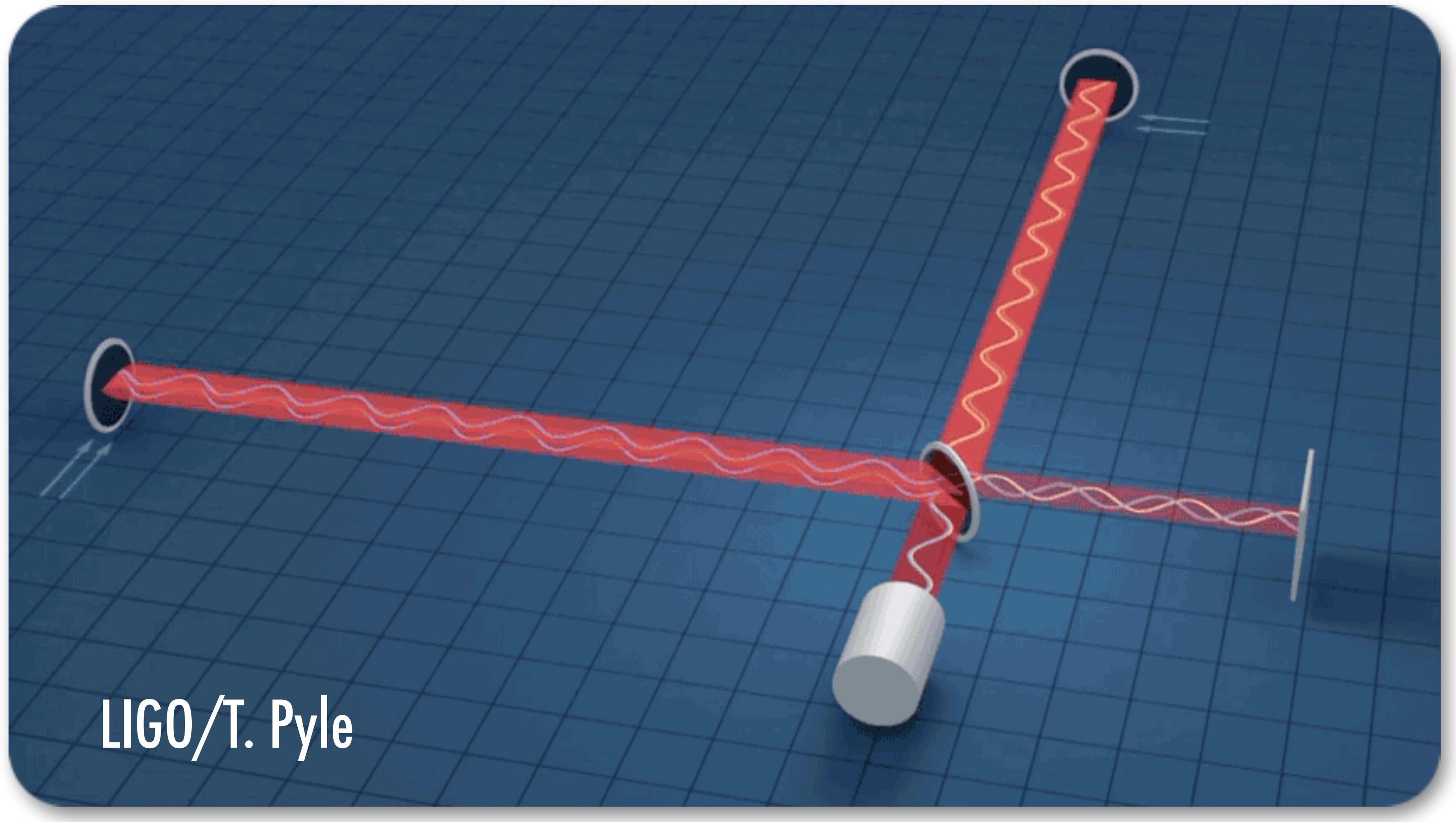
OzGrav

Dr Ling Sun, OzGrav-ANU
INT Workshop 2024, Seattle WA

Gravitational wave detections



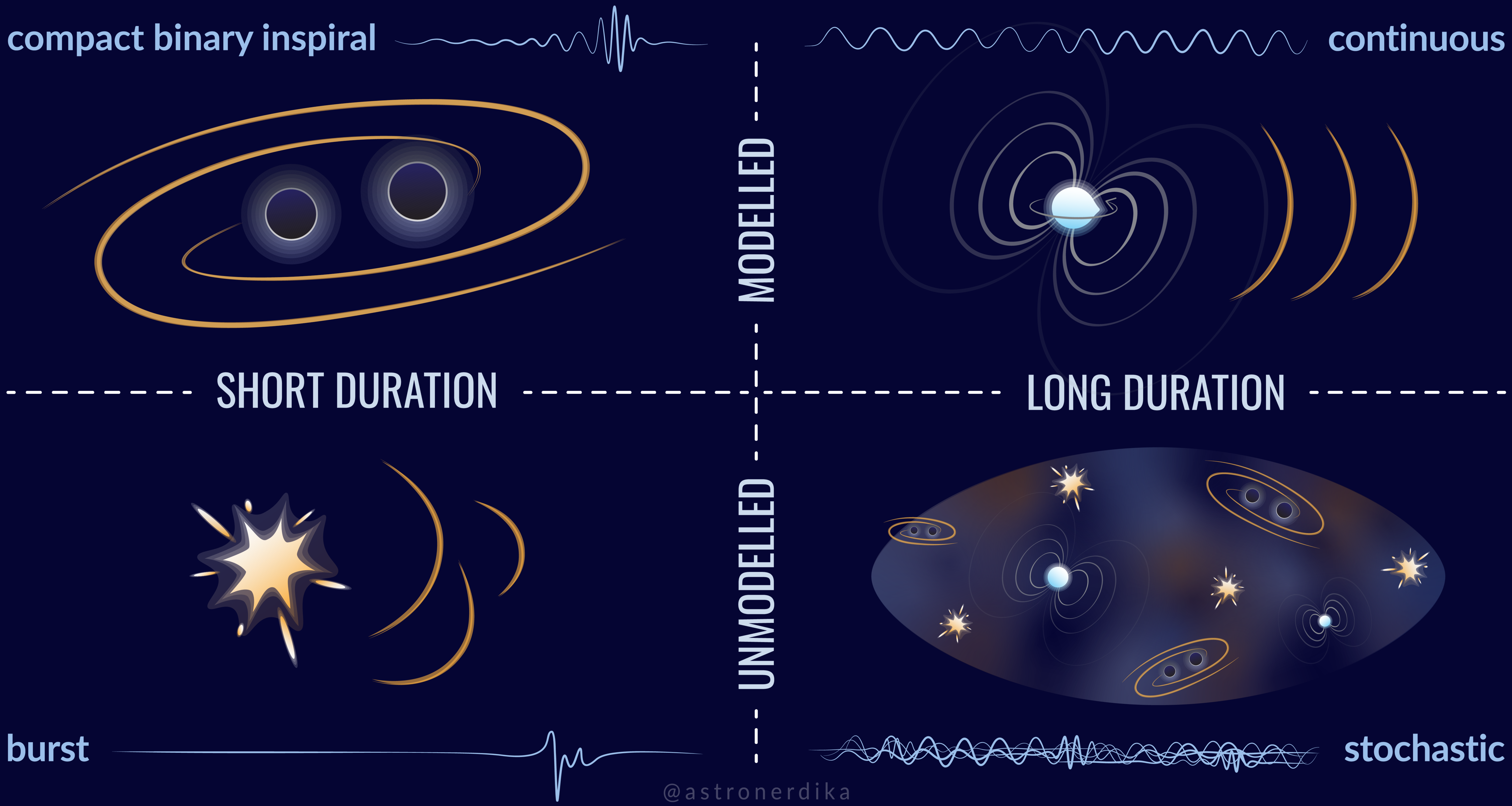
NASA/Dana Berry, Sky Works Digital



LIGO/T. Pyle

ICRR, Univ. of Tokyo/LIGO Lab/Caltech/MIT/Virgo Collaboration

* This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.



compact binary inspiral

continuous

MODELLED

SHORT DURATION

LONG DURATION

UNMODELLED

burst

stochastic

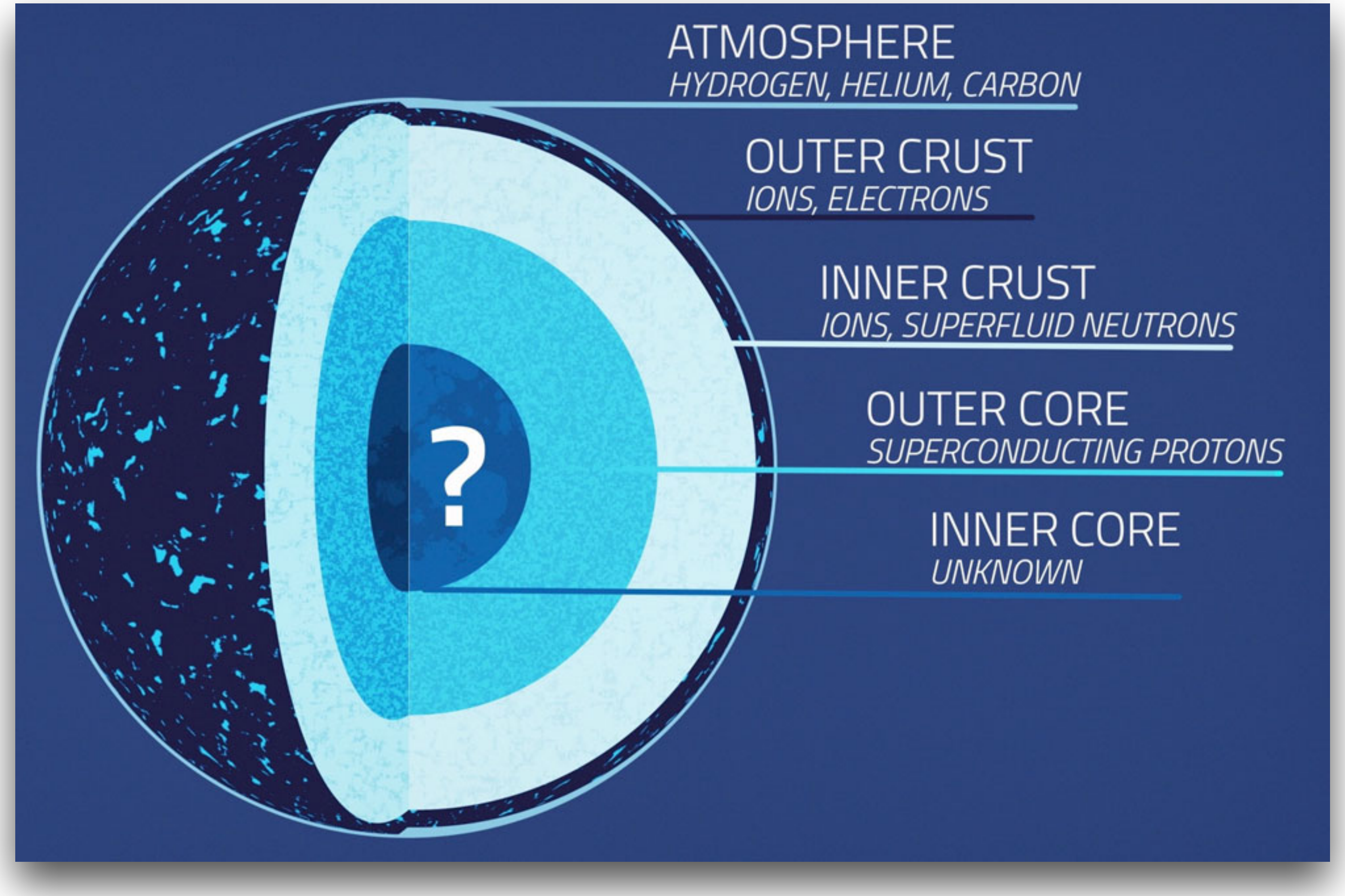
Image: Shanika Galaudage / LIGO-Virgo-KAGRA collaboration

Continuous Waves from Neutron Stars

Image: OzGrav | Carl Knox

See recent reviews:
Piccinni, Galaxies 10(3) (2022)
Riles, Living Reviews in Relativity 26, 3 (2023)
Wette, Astroparticle Physics 153, 102880 (2023)

What can we learn from continuous waves?

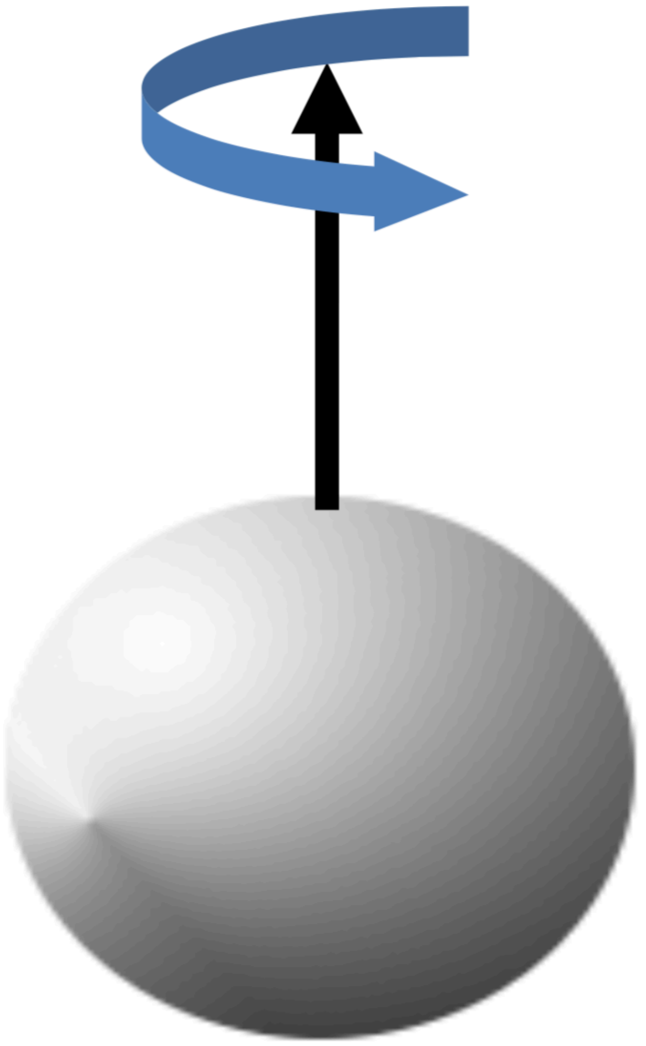


NASA's Goddard Space Flight Center / Conceptual Image Lab

- *Interior structure of neutron star*
- *Neutron star properties, e.g., mass, spin, ellipticity*
- *Nuclear equation of state*
- *May discover exotic states of matter*
- *Multi-messenger studies, e.g., mass and magnetic field structure inferred from GW/EM relative phase*
- *Testing General Relativity*
- *… and so on*

Continuous waves from neutron stars

- *Non-axisymmetric deformation due to elastic stresses or magnetic field –– tiny* ***"mountains"***
- *Signal is weak but persistent*



$$\boxed{f_{\mathrm{GW}} = 2 f_{\mathrm{rotation}}}$$

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

$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

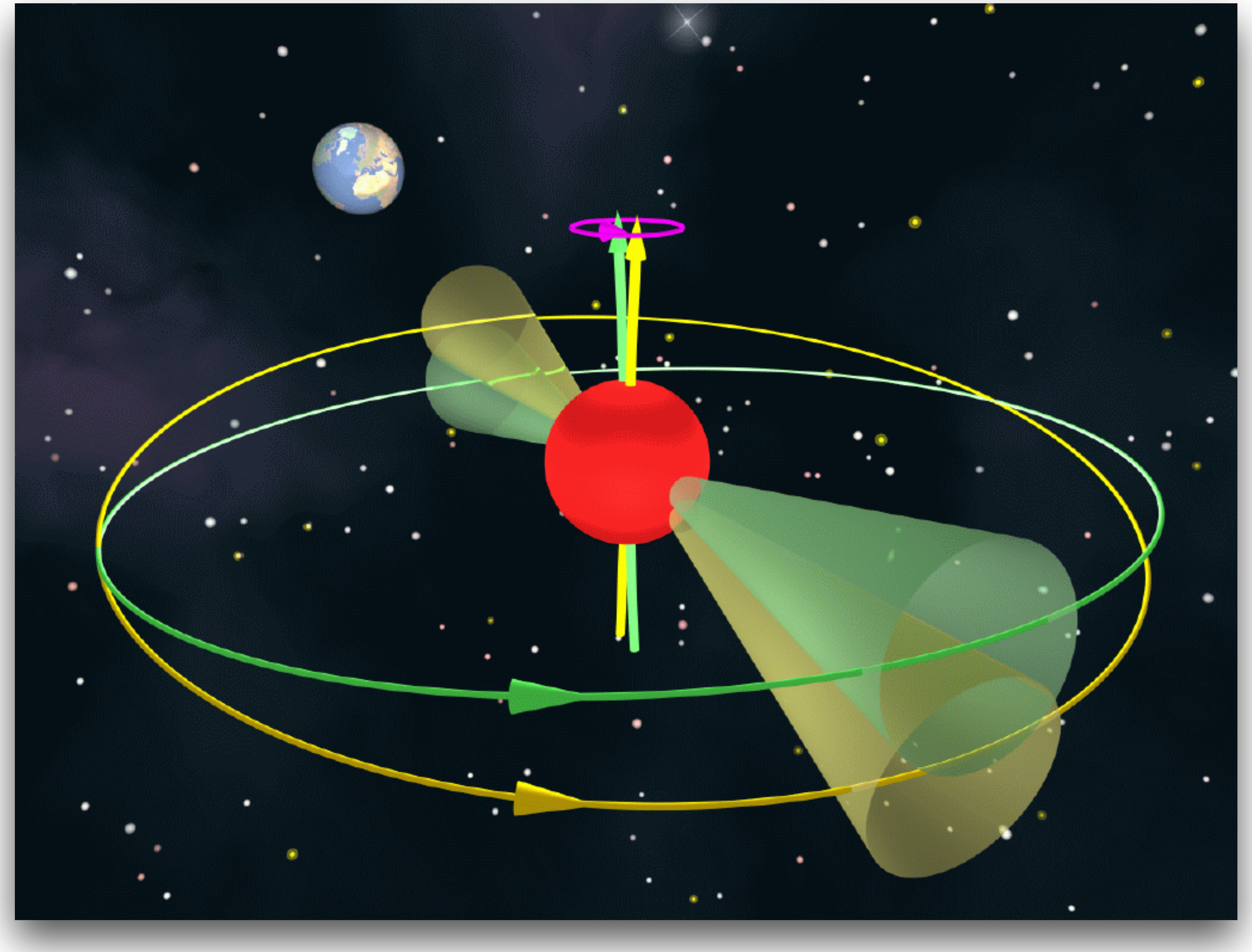
ellipticity

cf. GW150914 peak ***$h_0 \sim 10^{-21}$***

$$h_0 \approx 10^{-25} \left(\frac{\epsilon}{10^{-5}}\right) \left(\frac{I_{zz}}{10^{45}\,\mathrm{g\,cm^2}}\right) \left(\frac{f_{\mathrm{GW}}}{100\,\mathrm{Hz}}\right)^2 \left(\frac{1\,\mathrm{kpc}}{D}\right)$$

Continuous waves from neutron stars

- *Free precession around the rotation axis*



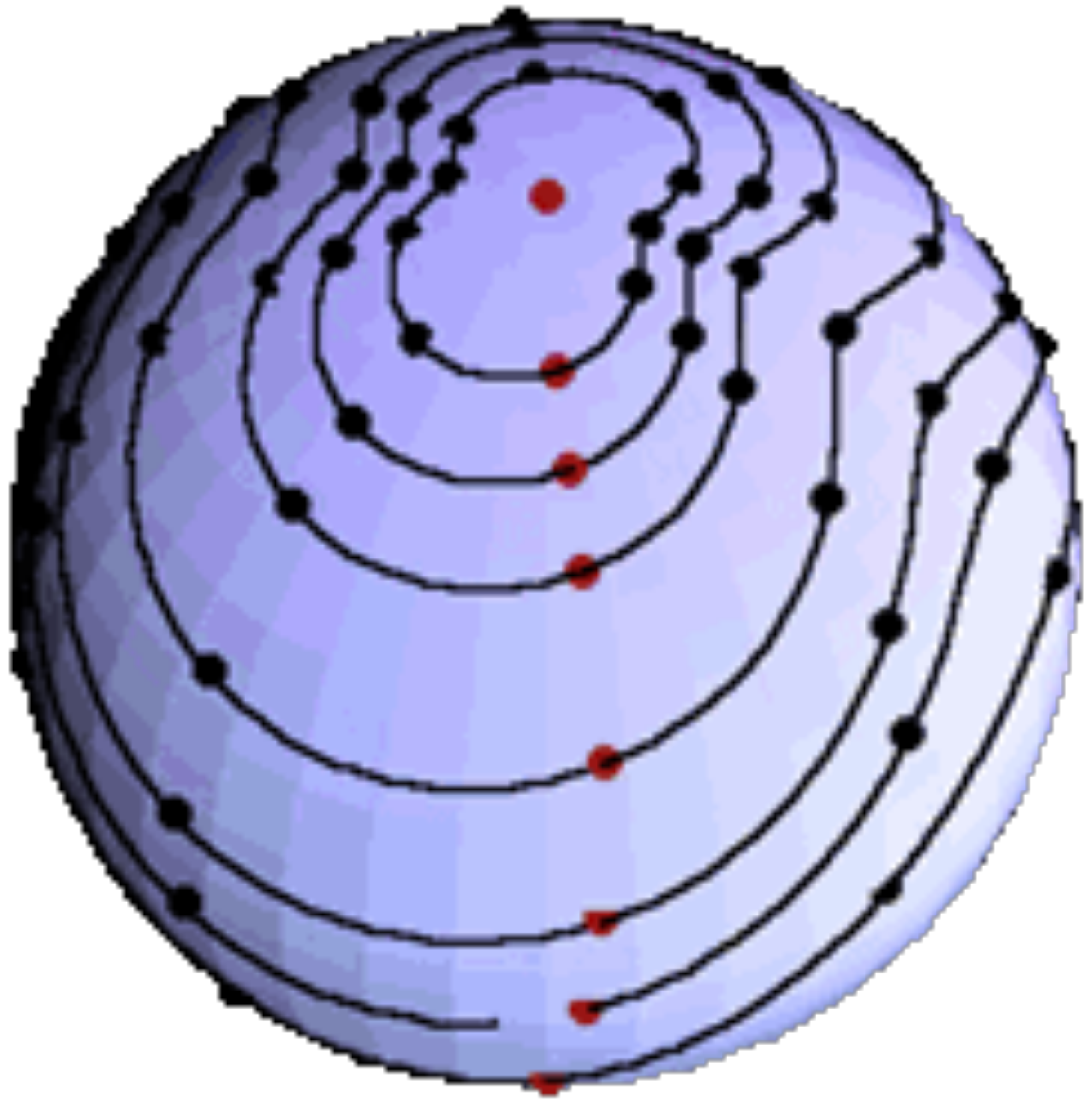
Credit: M. Kramer

$$f_{\mathrm{GW}} \sim f_{\mathrm{rotation}} + f_{\mathrm{precession}}$$

$$f_{\mathrm{GW}} \sim 2f_{\mathrm{rotation}} + 2f_{\mathrm{precession}}$$

Continuous waves from neutron stars

- ***r-modes*** *–– long-lasting oscillations in the fluid that makes up most of the star –– a fluid wave travelling around the star and driven by the Coriolis force due to rotation (see Rossby waves)*



Credit: C. Hanna and B. Owen

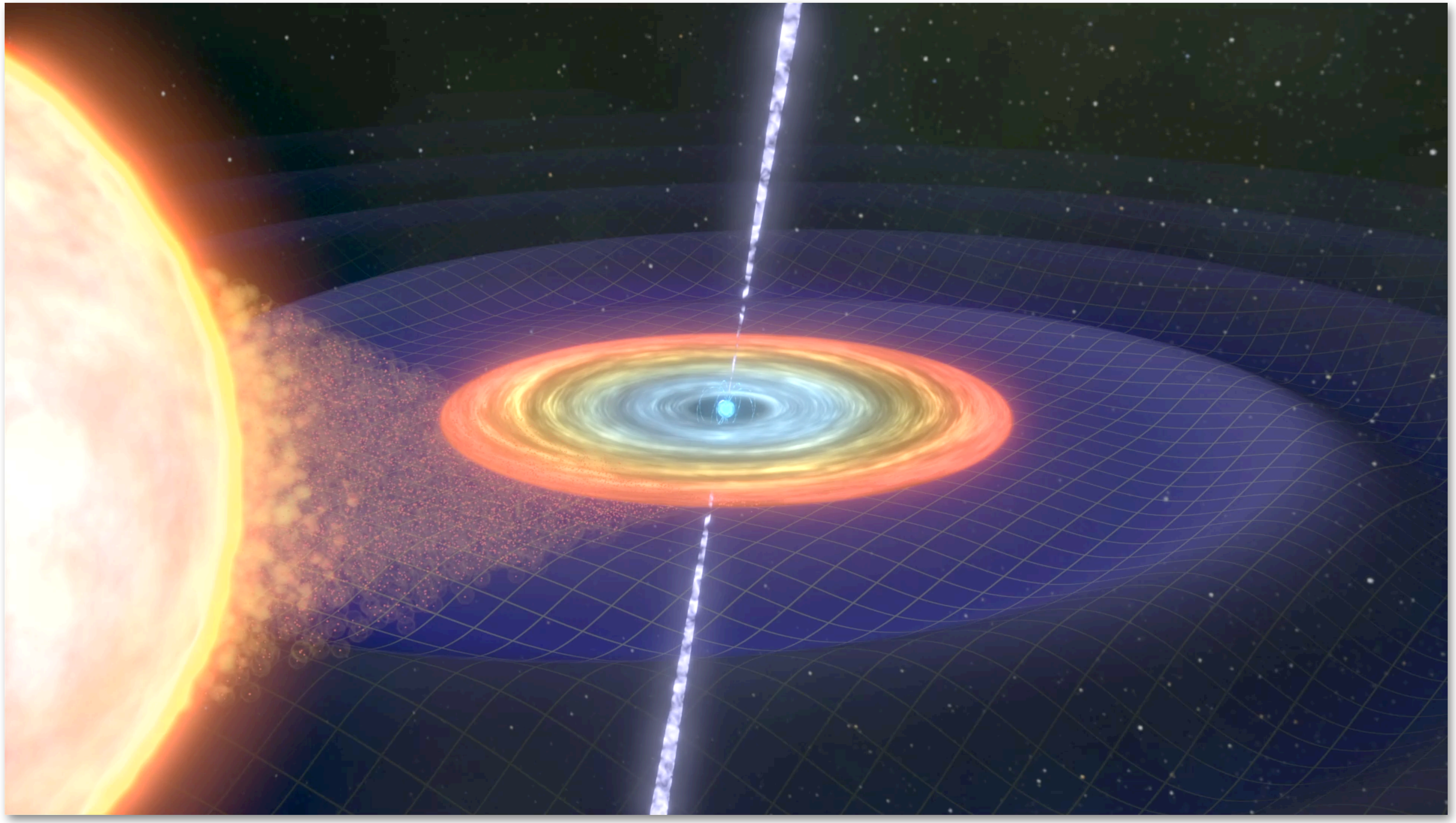
$$f_{\mathrm{GW}} \sim 4 f_{\mathrm{rotation}}/3$$

r-mode amplitude

$$h_0 \simeq 3.6 \times 10^{-26} \left(\frac{\alpha}{10^{-3}}\right) \left(\frac{f_{\mathrm{GW}}}{100\,\mathrm{Hz}}\right)^3 \left(\frac{1\,\mathrm{kpc}}{D}\right)$$

Continuous waves from neutron stars

- *Deformation due to matter accretion in the binary system*



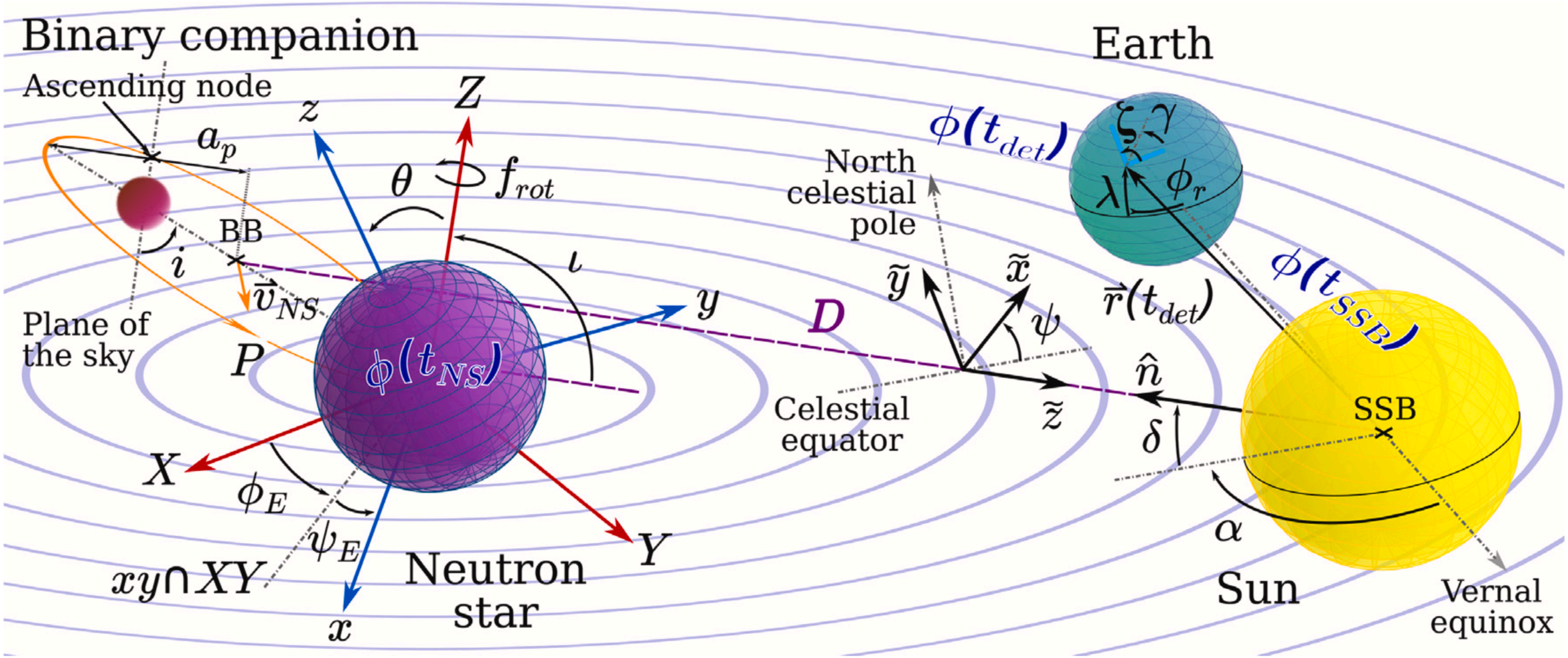
Credit: Mark Myers, OzGrav-Swinburne

$$\boxed{f_{\mathrm{GW}} \sim 2 f_{\mathrm{rotation}}}$$

- *Accretion is a natural method of powering GW emission*
- *Torque-balance theory –– accretion spins the star up; GW emission slows it down*
- *Signal frequency might be wandering slightly due to accretion*

Continuous waves signal models

- *Intrinsic parameters, e.g., spin frequency, time derivatives of the frequency*
- *Extrinsic parameters, e.g., sky location, orientation, orbital motion (if applicable), etc.*



Wette, Astroparticle Physics 153, 102880 (2023)

Modulation of continuous wave signals

- *Rotation of the Earth (daily cycle)*

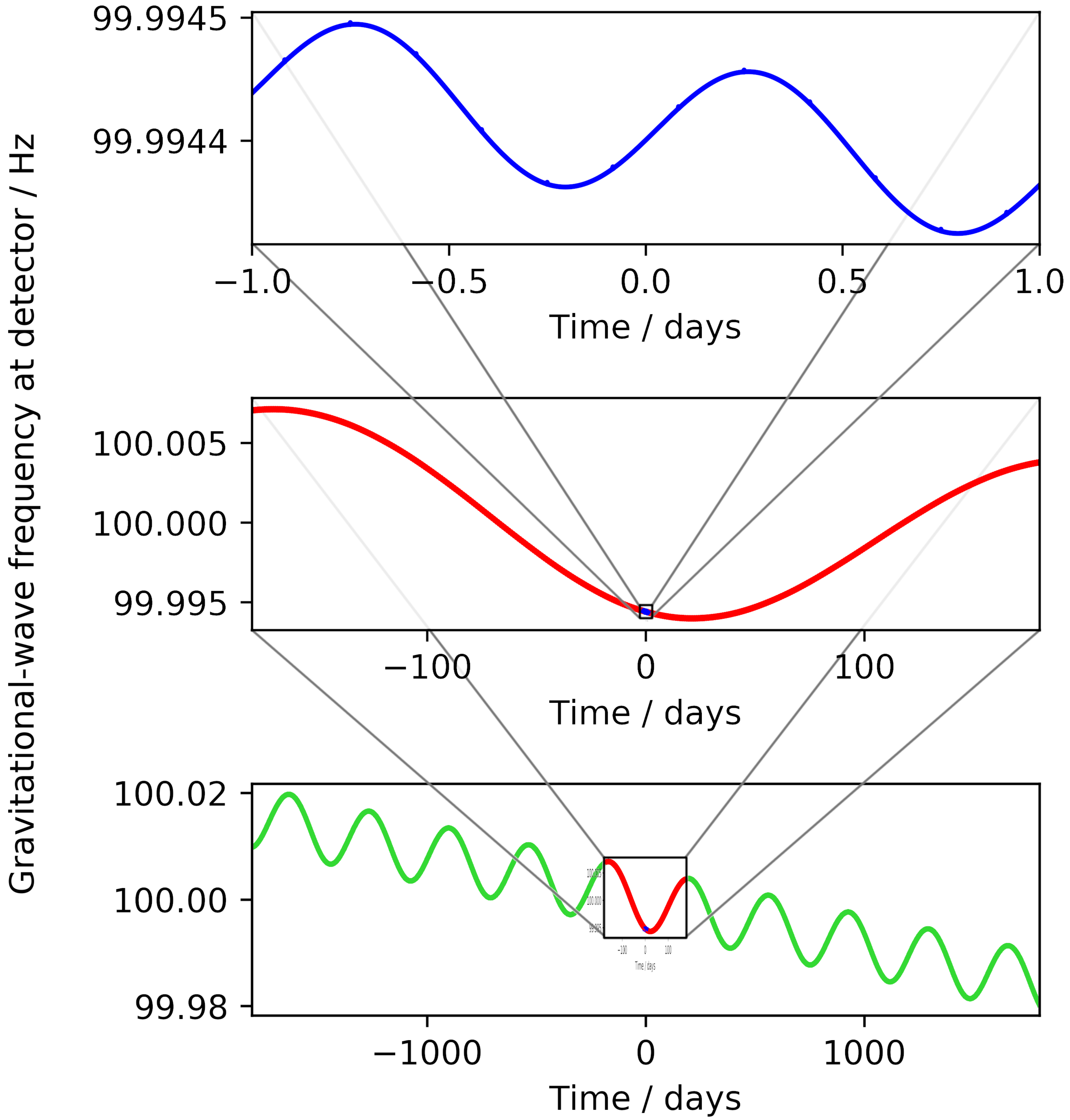
$$\frac{\delta f}{f} \approx 4 \times 10^{-6}$$

- *Earth orbiting the sun (yearly cycle)*

$$\frac{\delta f}{f} \approx 2.6 \times 10^{-4}$$

- *Secular spin down of the neutron star*
  - *EM (n~3)*
  - *GW (n=5)*
  - *r-mode (n=7)*

$$\dot{f}_{\mathrm{gw}} \propto f_{\mathrm{gw}}^{n}$$

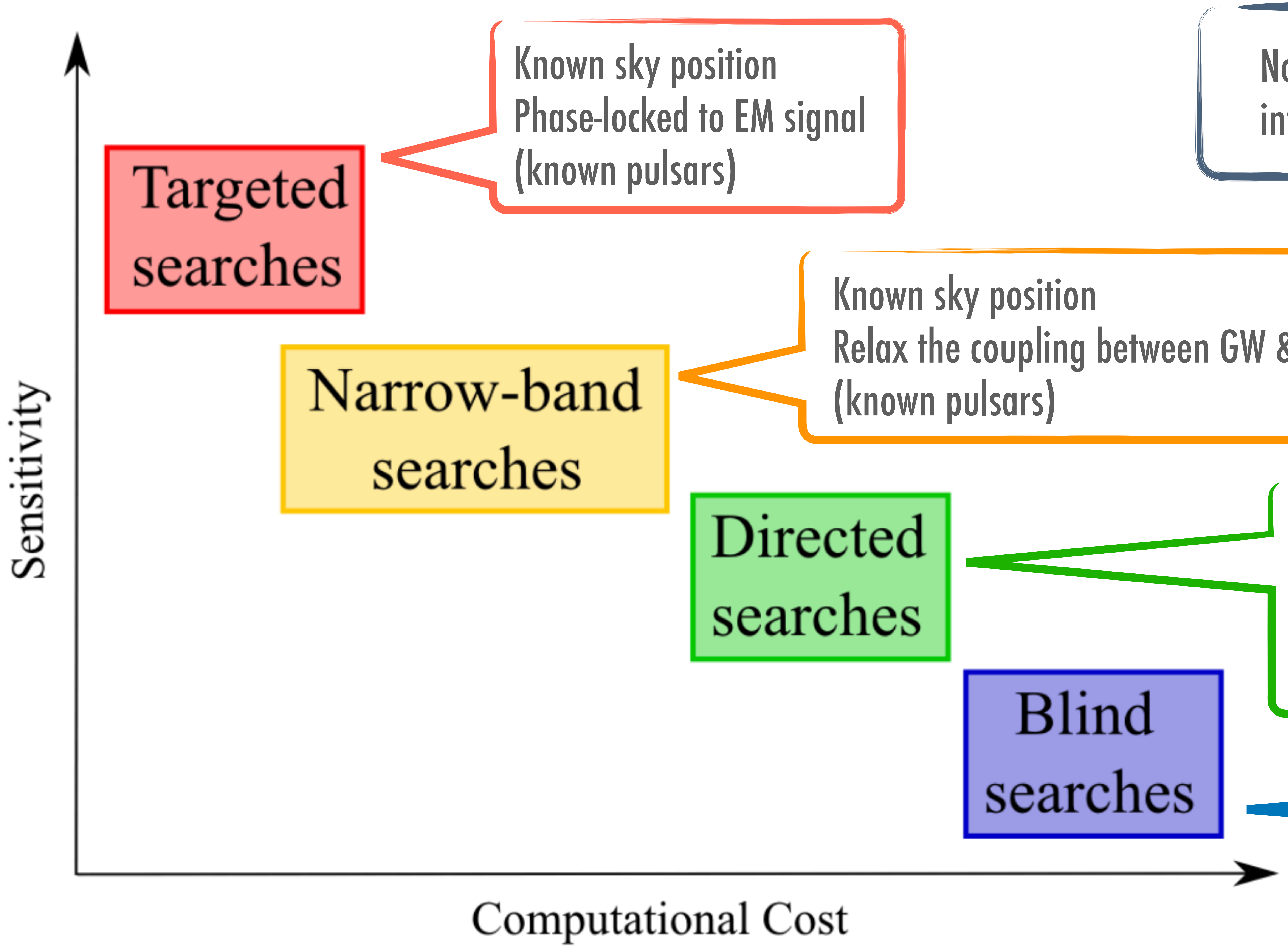


Wette, Astroparticle Physics 153, 102880 (2023)

- *Signal frequency is modulated by the motion of the detector*
- *Signal amplitude is modulated by the antenna pattern*

(There is extra modulation if the source is in a binary orbit)

Continuous waves search types



Known sky position
Phase-locked to EM signal
(known pulsars)

No continuous-wave detection yet, but interesting implications are obtained

Known sky position
Relax the coupling between GW & EM signals
(known pulsars)

Known sky position
Unknown frequency
(NSs without ephemerides; boson clouds around known BHs)

Unknown sky position
Unknown frequency
(any possible emitters)

Sieniawska & Bejger, Universe 2019, 5(11), 217

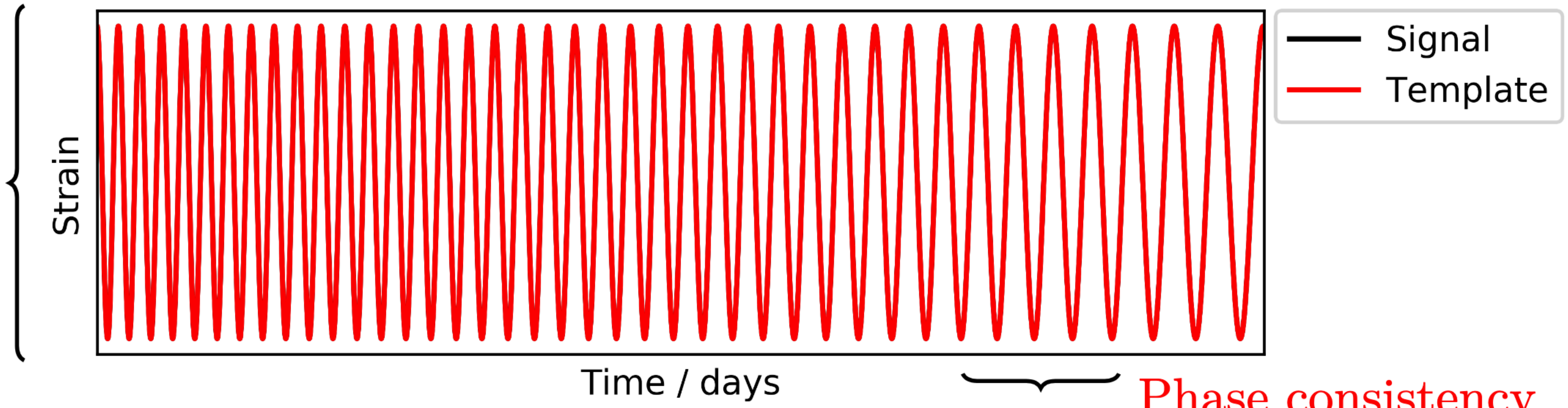
Continuous waves search methods

- ***Fully coherent*** *searches provide the best sensitivity but allow for least flexibility in signal models; also most expensive*

- ***Semi-coherent*** *methods sacrifice some sensitivity but are more computationally efficient and can allow for more flexible signal models*

Fully coherent filter

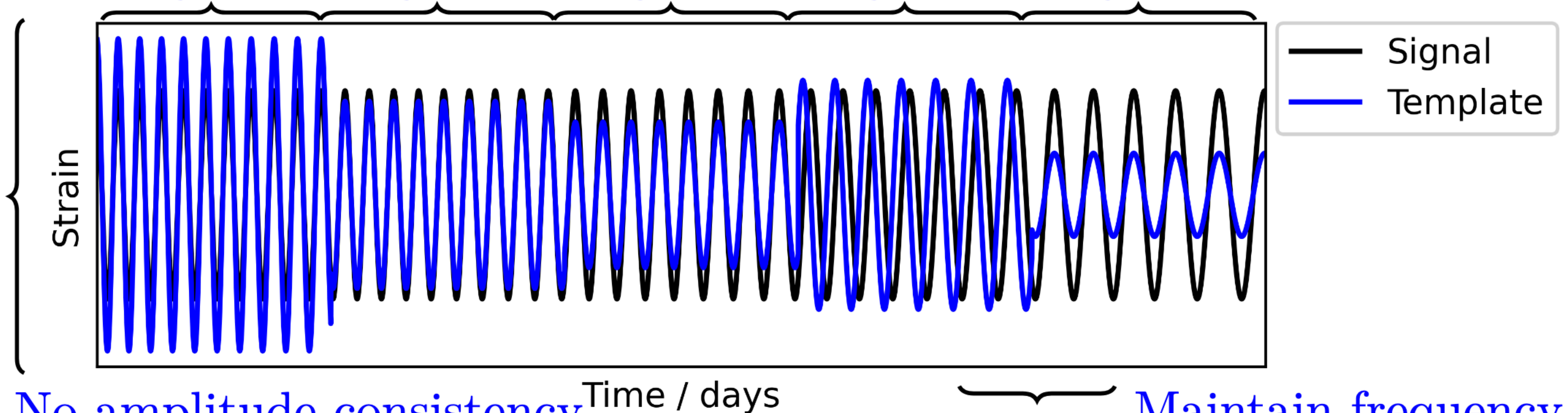
Amplitude consistency



Phase consistency

Semi-coherent filter

Segment Segment Segment Segment Segment



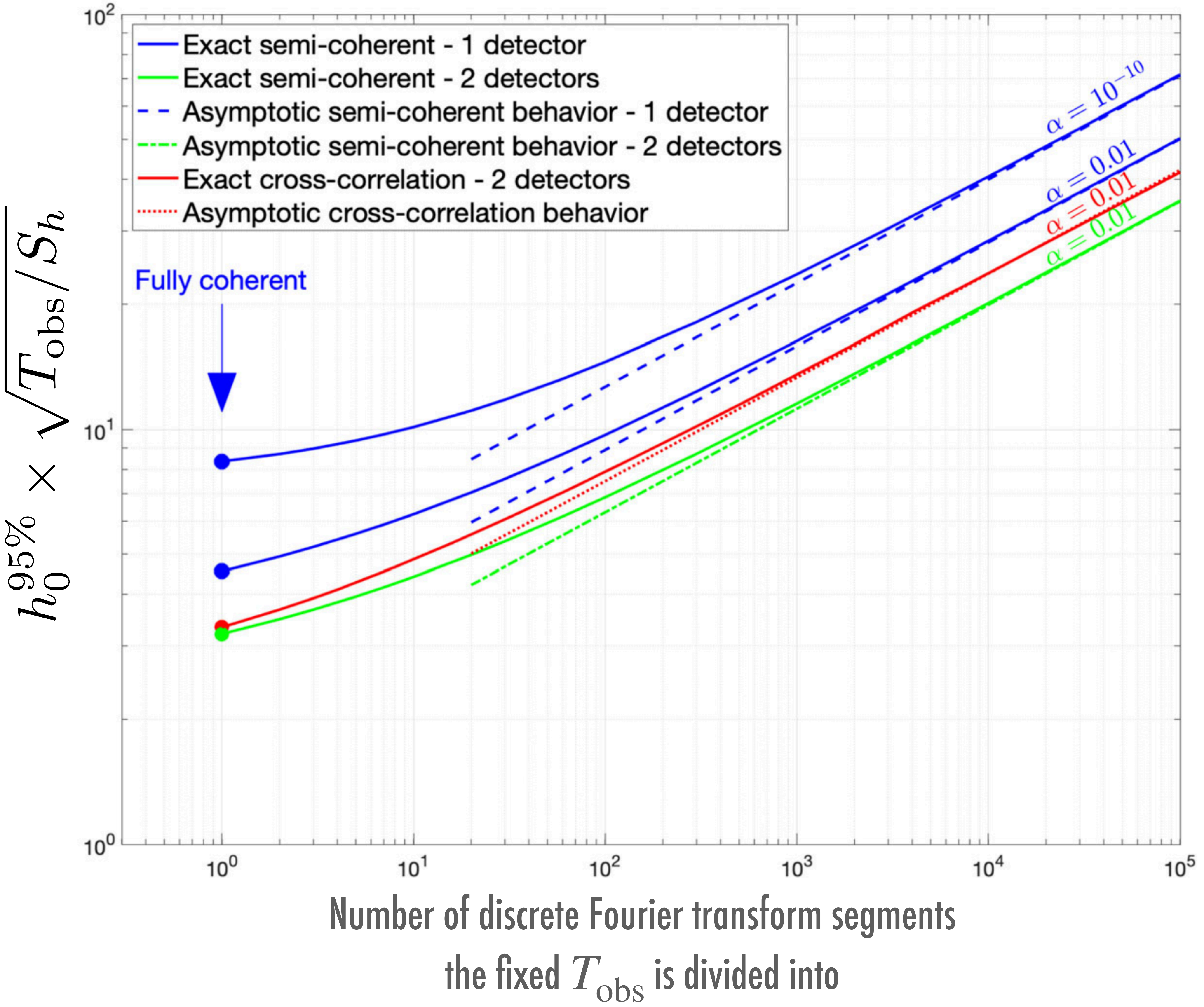
No amplitude consistency
☞ constant phase jumps

Maintain frequency consistency

Credit: K. Wette, G2401246

Continuous waves search methods

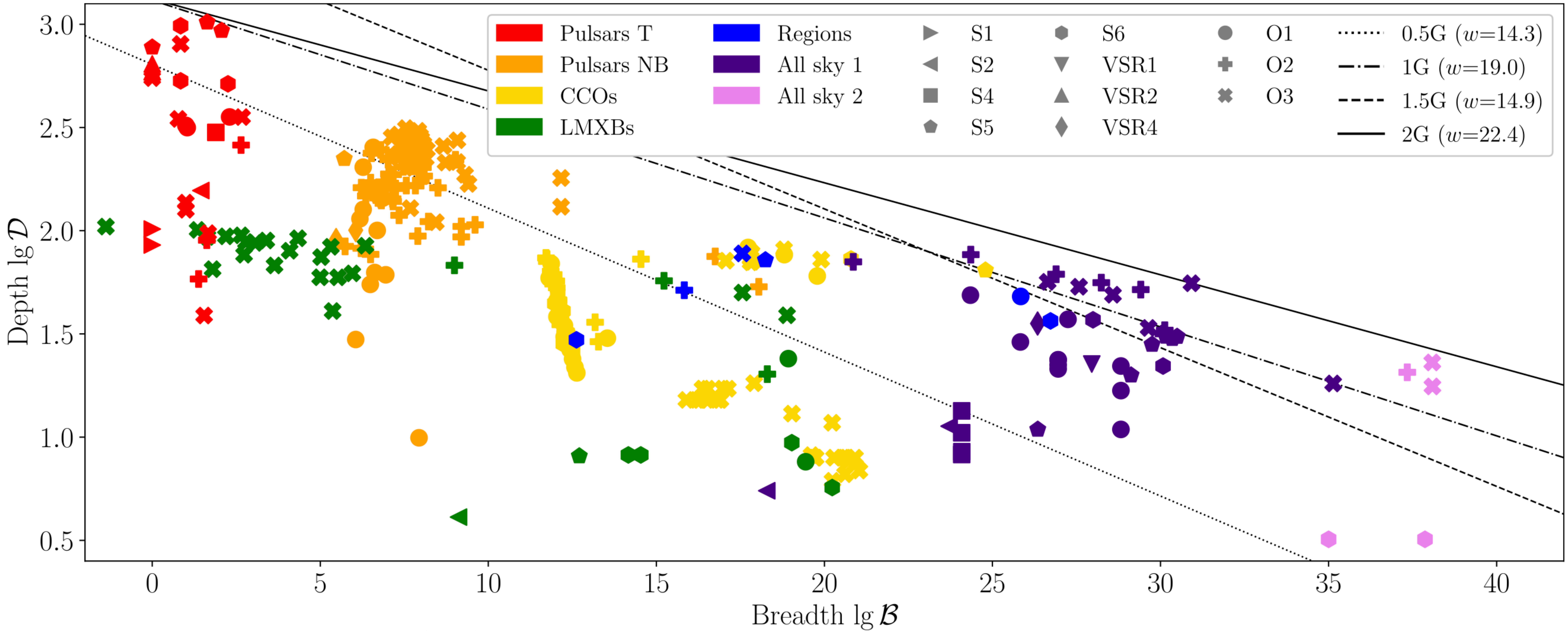
- *Can increase the coherent time as follow-ups in hierarchical searches to balance sensitivity vs computing cost*
- *But there are difficulties with different signal model assumptions, e.g., spin-wandering effect*



See Riles, Living Reviews in Relativity 26, 3 (2023) for a comprehensive review of search methods

Continuous waves search sensitivities

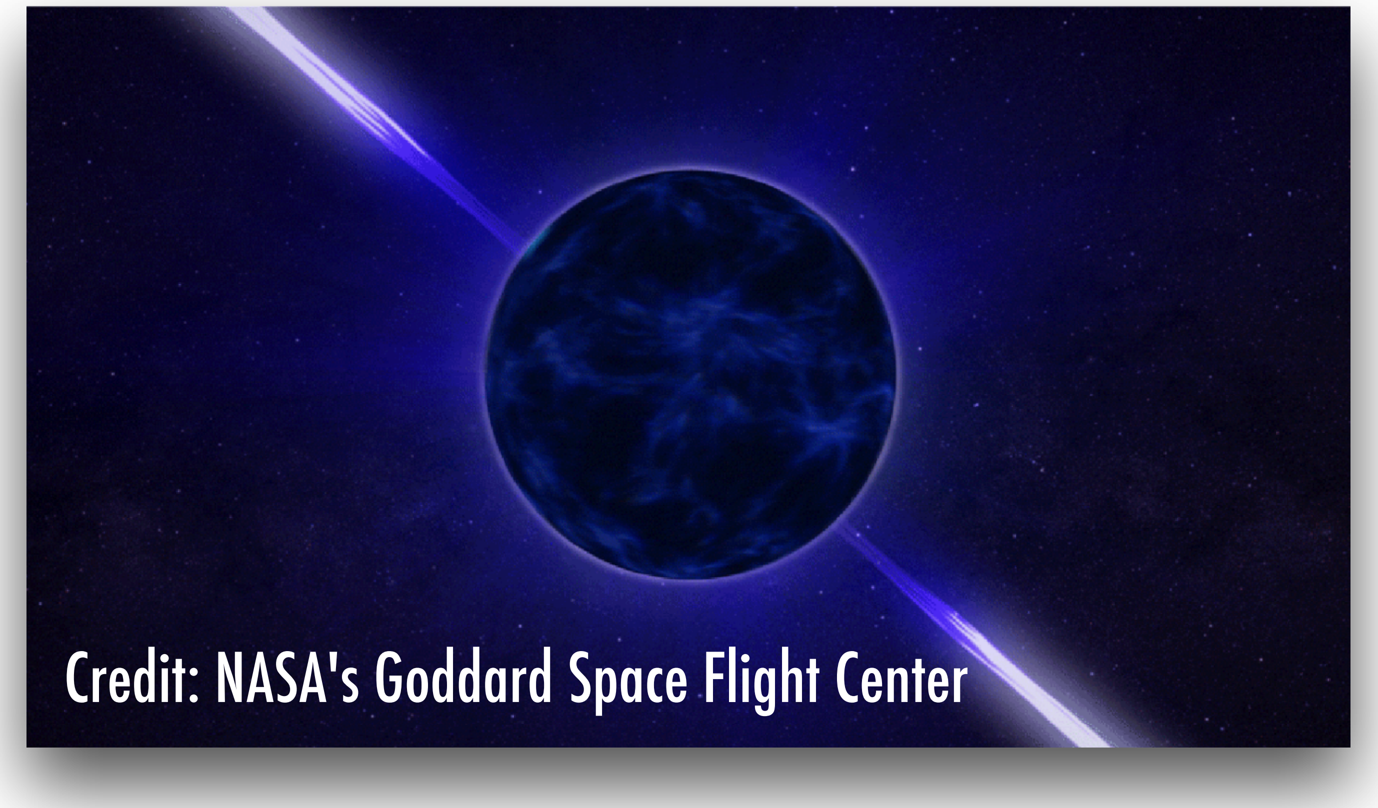
- *Trade-off between breadth and depth*
- *297 searches from 80 published articles (performed by LVK and other CW research groups)*



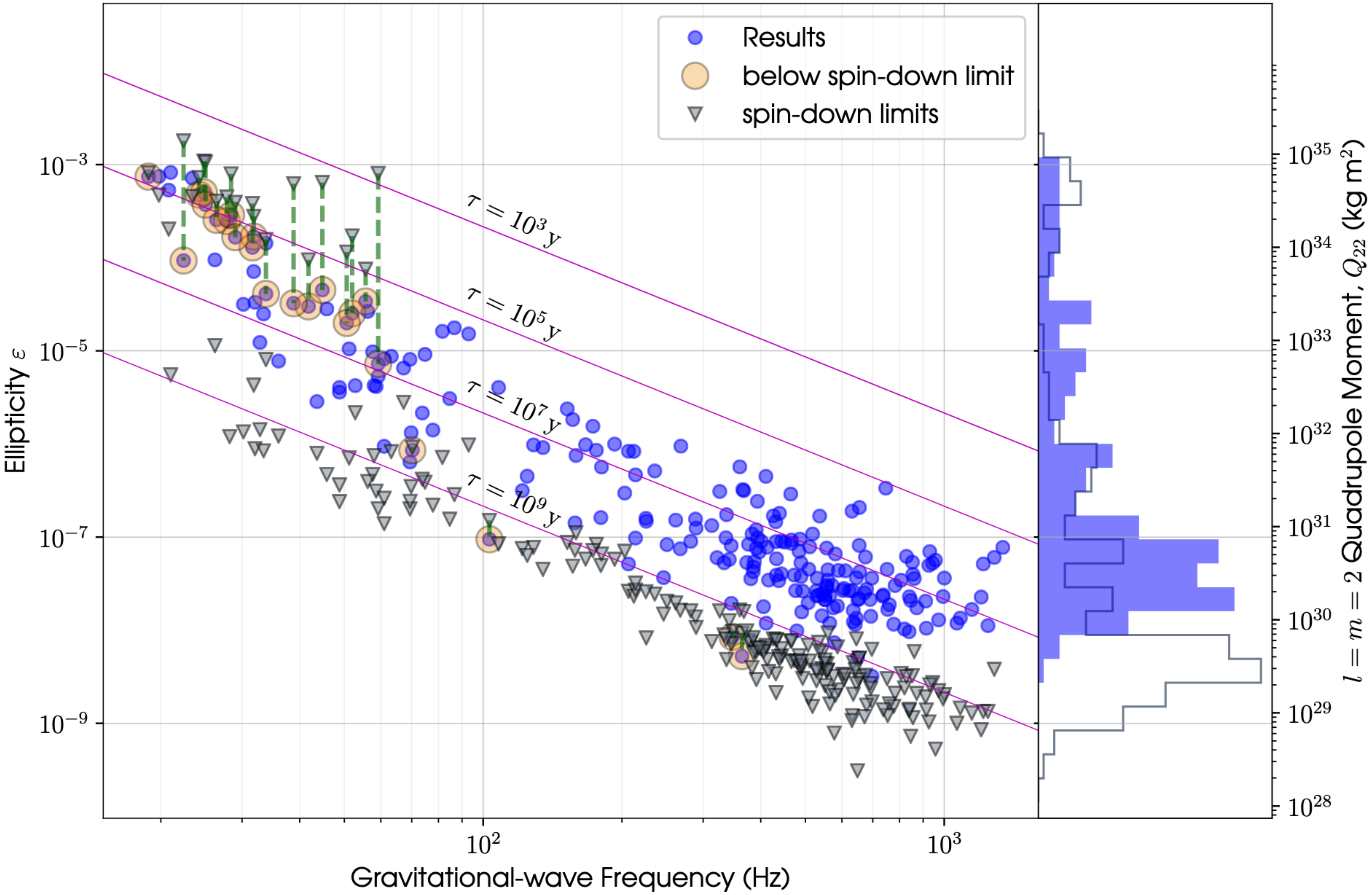
Wette, Astroparticle Physics 153, 102880 (2023)

TARGETED: 236 known pulsars

- *For **23** pulsars, resulting upper limits have surpassed EM measured spin-down limits.*
- *For **9** pulsars, their spin-down limits have been surpassed for the first time.*
- *For **Crab** & **Vela**, our limits are factors of **~100** and **~20** more constraining than the spin-down limits, respectively.*



Credit: NASA's Goddard Space Flight Center



O2+O3 HLV, Abbott+ (LVK) ApJ 935, 1 (2022)

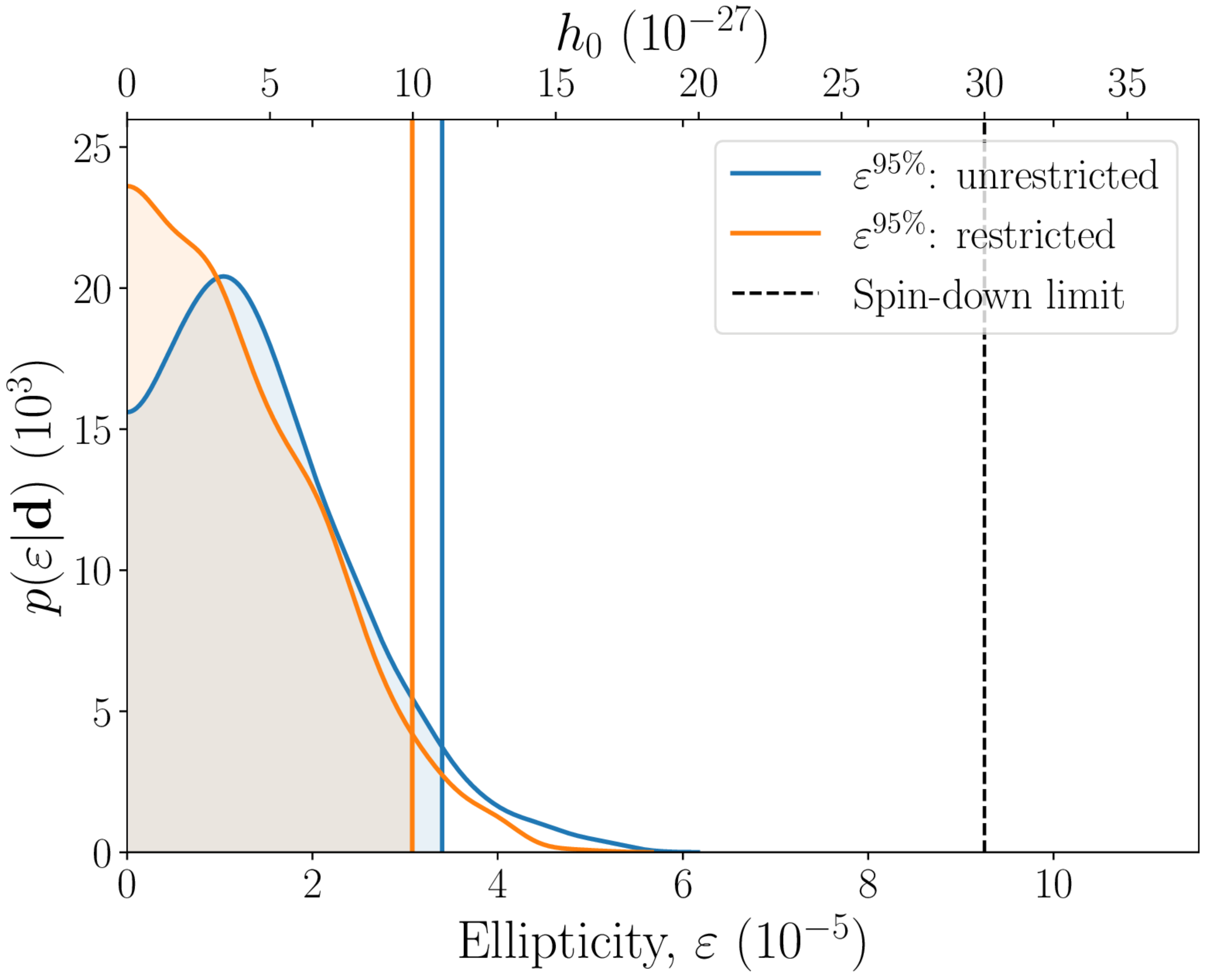
Also see O3 narrowband search:
O3 HLV, Abbott+ (LVK) ApJ 932, 133 (2022)

TARGETED: Energetic young pulsar PSR J0537-6910

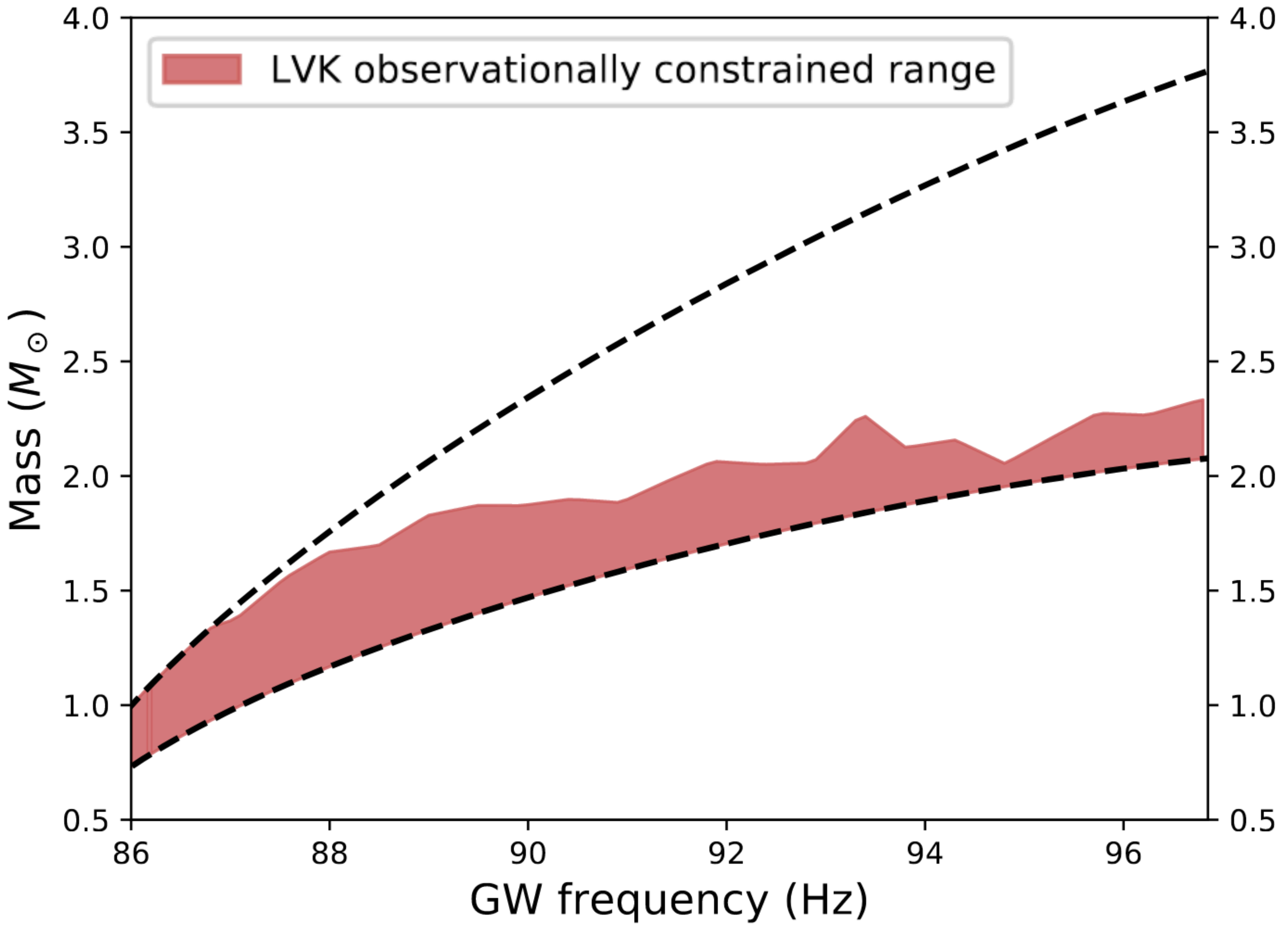
X-ray pulsar, largest spin-down luminosity, frequent and strong glitches; Use a NICER timing ephemeris

[NICER — Neutron star Interior Composition Explorer]

- *Searched at once and twice the spin frequency 62 Hz*
- *First time reach* ***below GW spin-down limit*** *for this star by more than* ***a factor of 2*** *and limit GWs (l=m=2 mode) to account for* ***<14%*** *of the spin-down energy budget.*



O2+O3 HLV, Abbott+ (LVK), ApJL 913, L27 (2021)

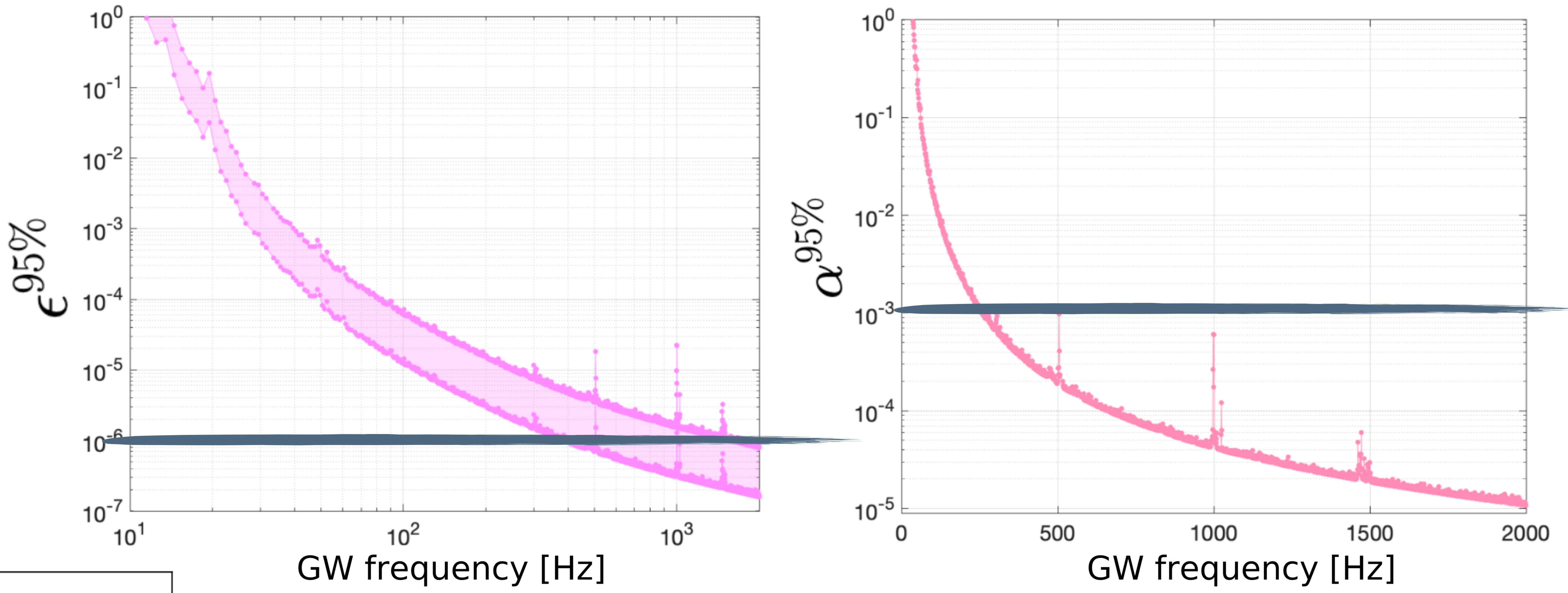


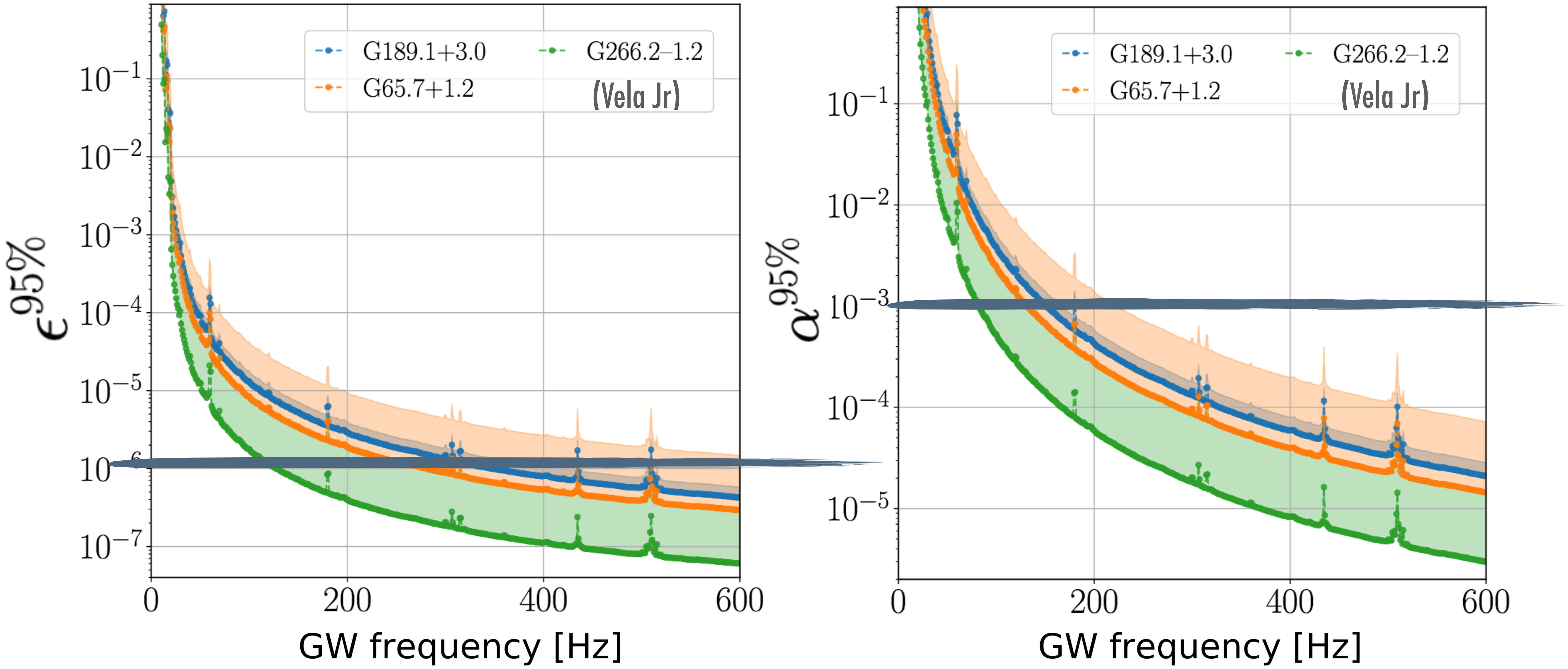
- *Inter-glitch braking index suggests that* ***r-mode*** *oscillations may be important to GW emission.*
- *Search in a narrow band 86–97 Hz*
- *Allow for the* ***r-mode driven*** *spin-down scenario for a* ***lower-mass*** *neutron star with* ***soft EoSs***

O3 HL, Abbott+ (LVK), ApJ 922, 71 (2021)

DIRECTED: Young supernova remnants & Milky Way center

- *Young supernova remnants may have larger ellipticity and are promising targets*





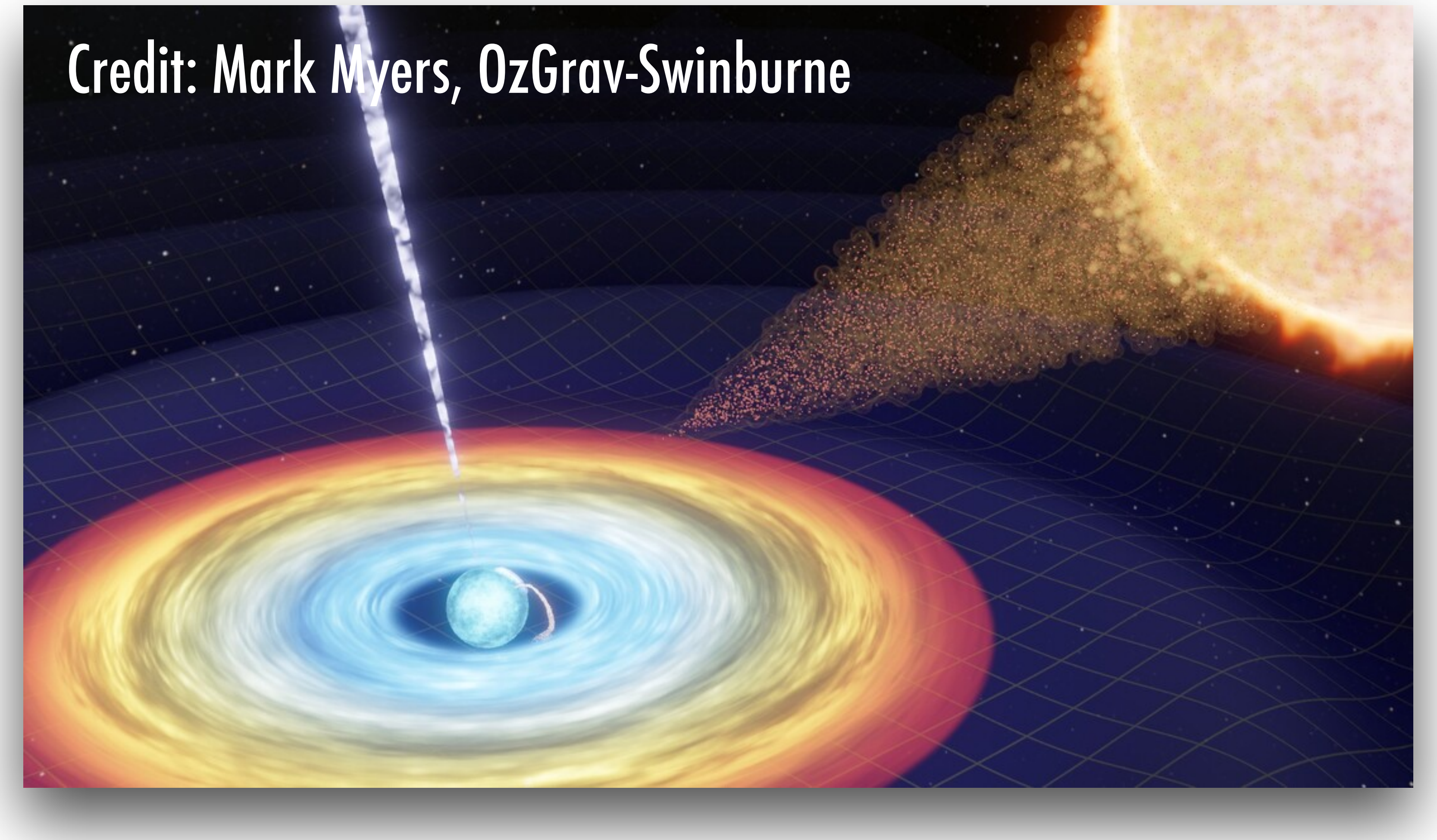
O3a HLV, Abbott+ (LVK), ApJ 921, 80 (2021), O3a HL, Abbott+ (LVK), PRD 105, 082005 (2022)
[Also see open data searches, e.g., Ming et al., 2024]

- *Compelling evidence shows a large population of neutron stars in the Galactic Center*

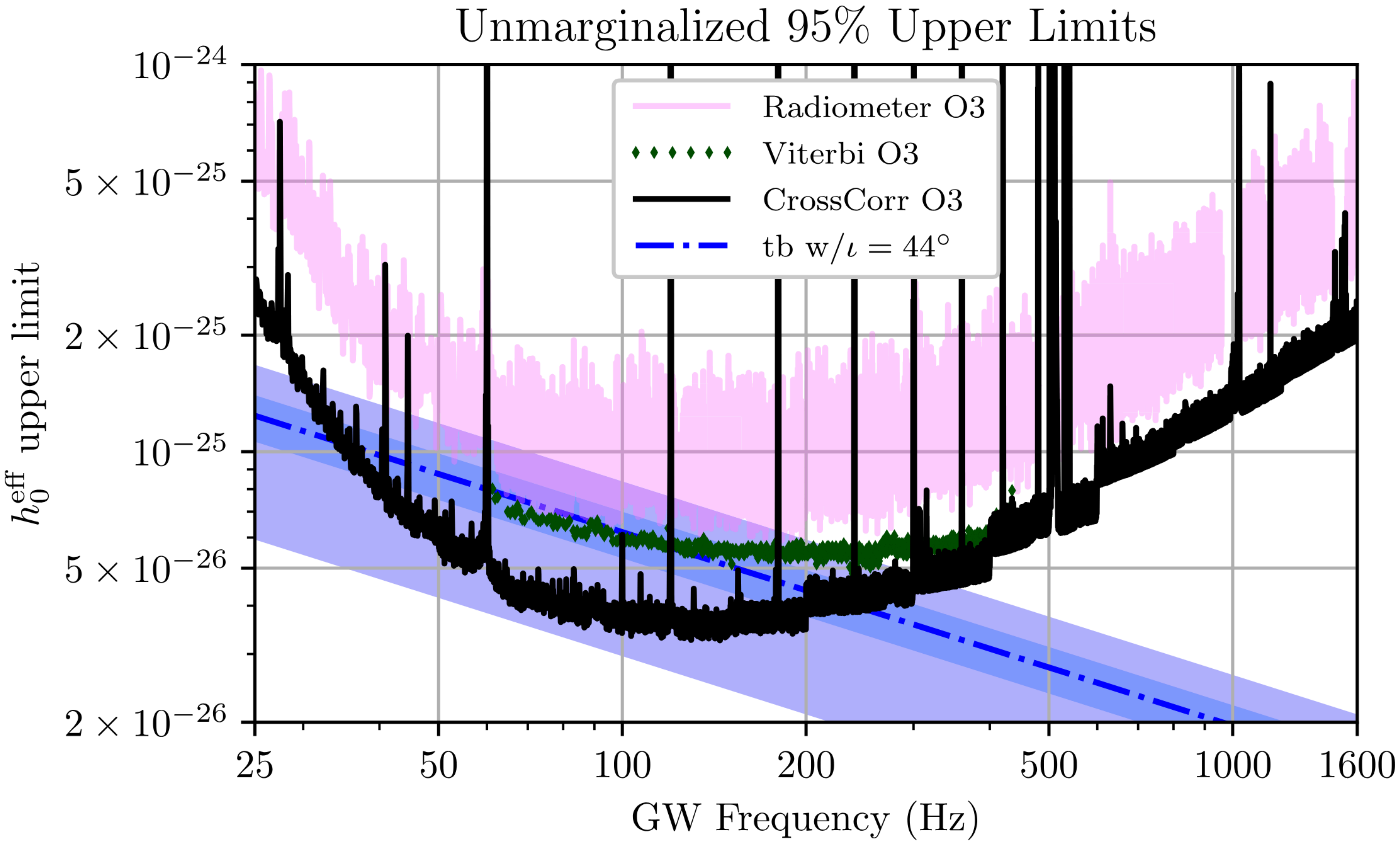
O3 HLV, Abbott+ (LVK), PRD 106, 042003 (2022)

DIRECTED: Scorpius X-1

- *Scorpius X-1 is the most X-ray-luminous low-mass X-ray binary*
- *Several methods have been used, reaching physically interesting regimes*
- *Better understanding of the spin-wandering effect can facilitate more sensitive searches*



Credit: Mark Myers, OzGrav-Swinburne



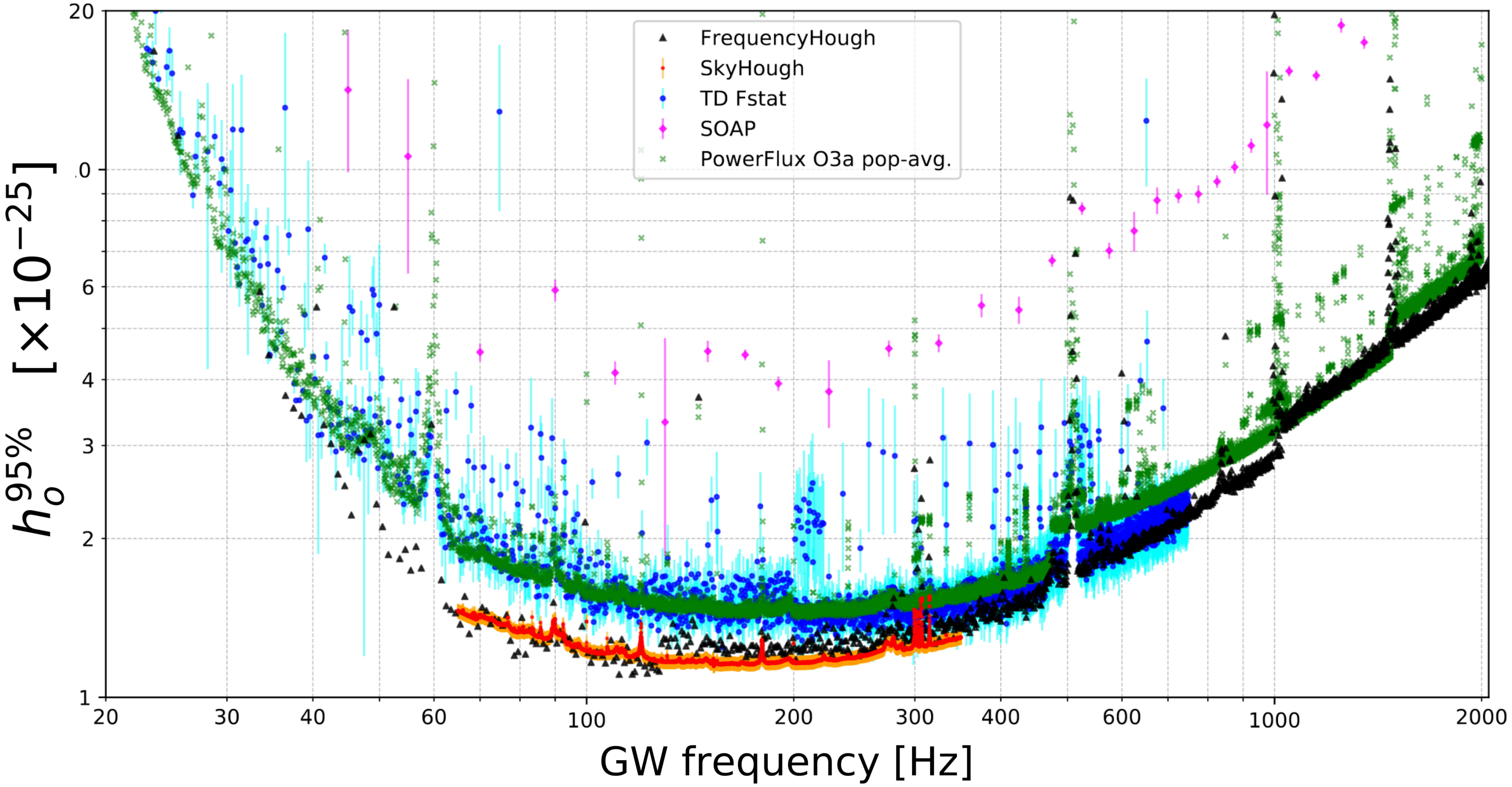
O3 HL, Abbott+ (LVK), PRD 106, 062002 (2022)
O3 HL, Abbott+ (LVK), ApJL 941, L30 (2022)

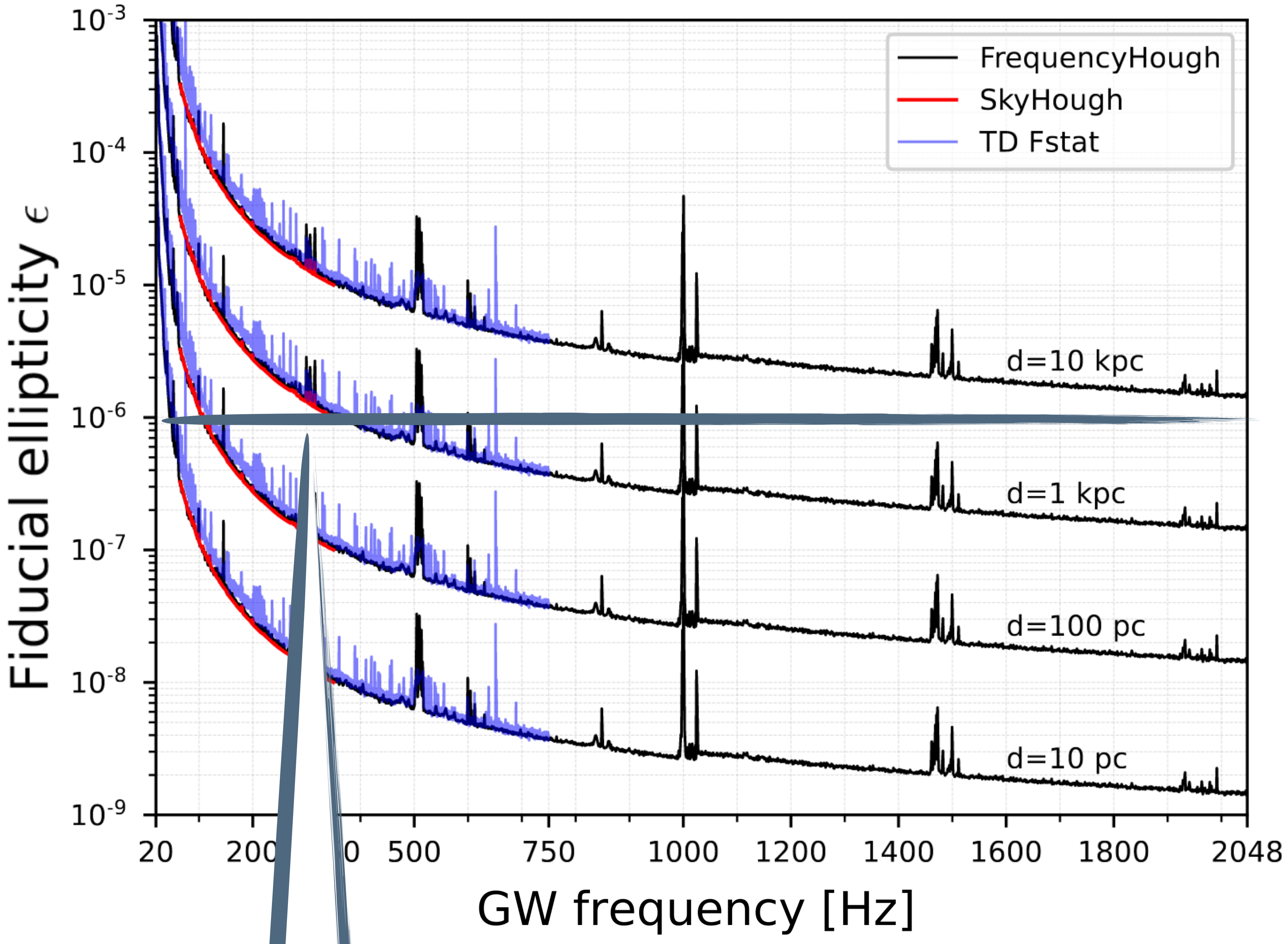
Re-analyses with corrected orbital ephemeris:
Whelan+ ApJ 949 117 (2023)
Vargas+Melatos arXiv:2310.19183 (2023)

BLIND ALL-SKY: Isolated neutron stars

- *Use model-based & unmodeled algorithms*

O3a HL, Abbott+ (LVK), PRD 104, 082004 (2021)
O3 HLV, Abbott+ (LVK), PRD 106, 102008 (2022)





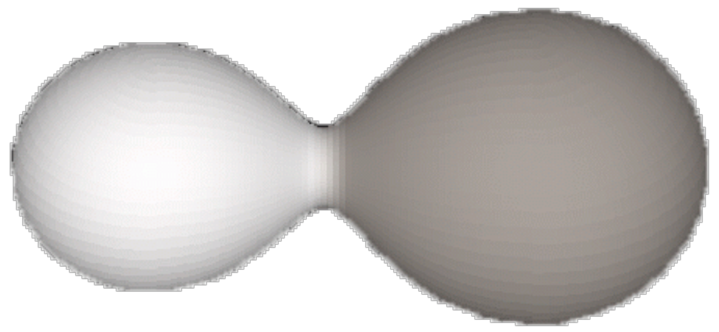
Frequency band: [10, 2048] Hz
Frequency derivative: $[-1.0, +0.1] \times 10^{-8}\ \mathrm{Hz/s}$

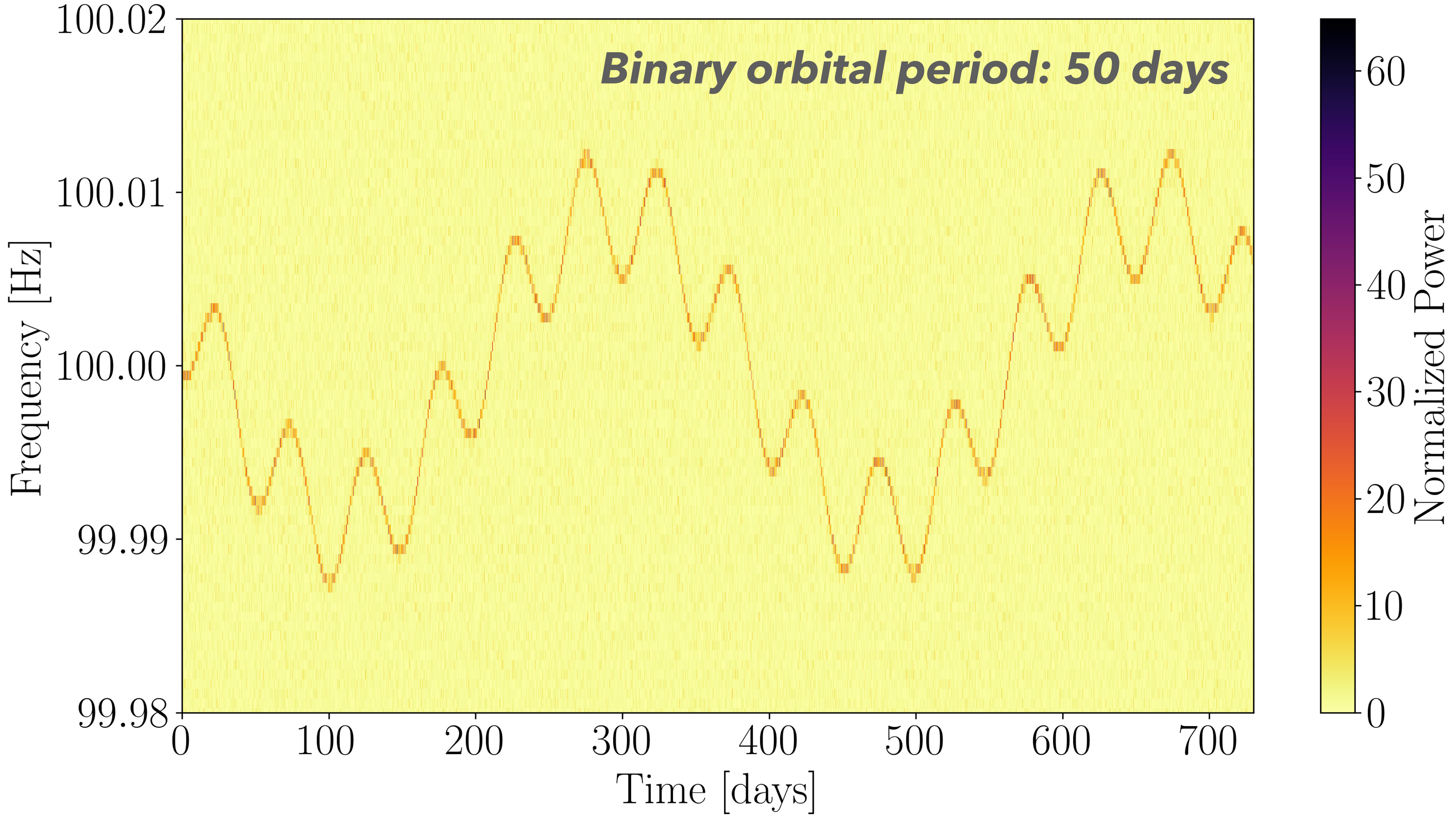
- *Can probe the ellipticity that may be supported by the crust of a NS described by a realistic equation of state within ~1 kpc*

[Also see deep all-sky searches with open data, e.g., Dergachev & Papa (2022), Steltner et al., (2023)]

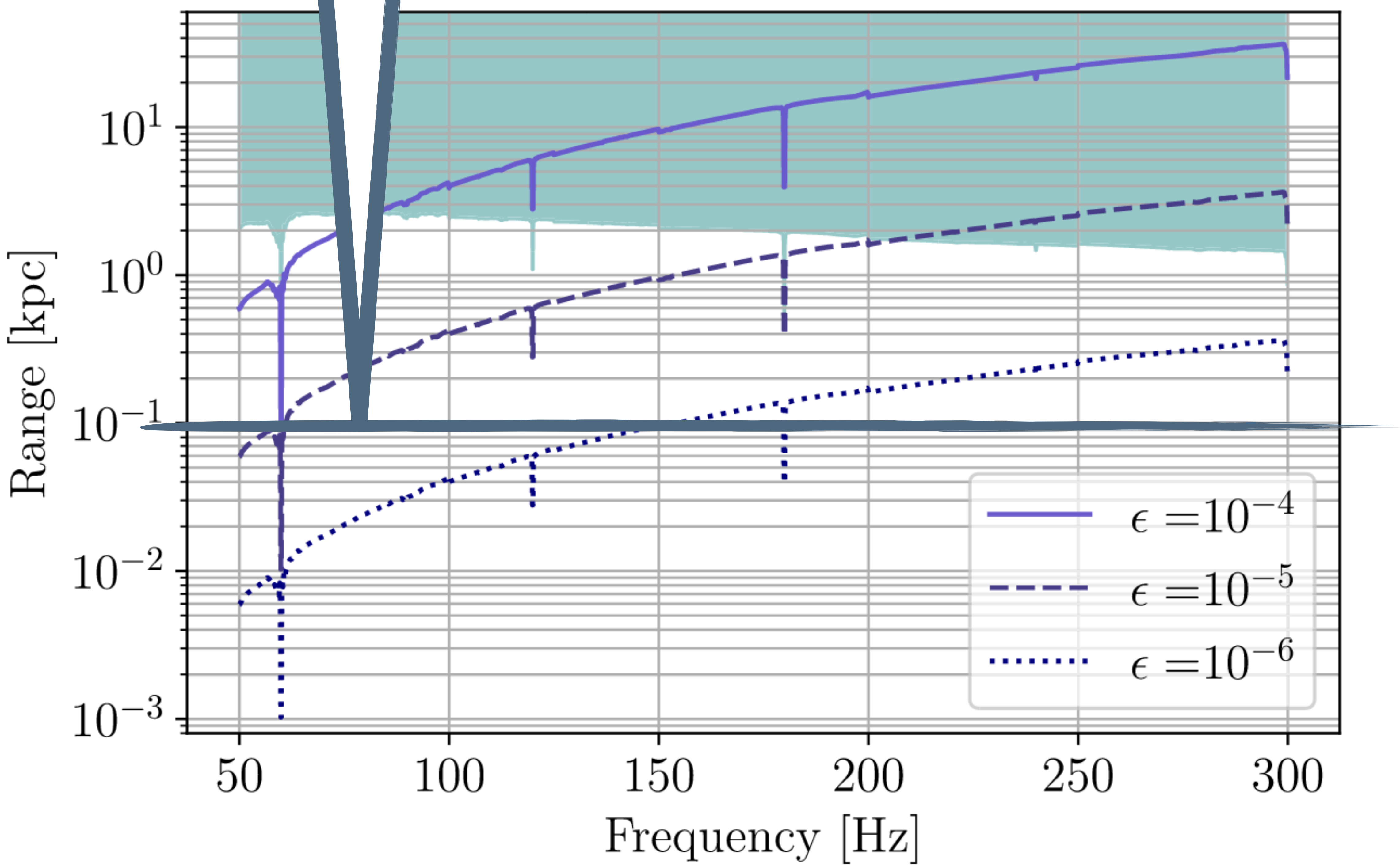
BLIND ALL-SKY: Neutron stars in binary systems

- *Need to account for the modulation due to the binary orbit*
- *Binary orbital parameters: orbital period* **[3, 45] days** *and projected semimajor axis* **[2, 40] light-sec**





The closest known NS is 0.1 kpc away.



O3a HL, Abbott+ (LVK), PRD 103, 064017 (2021)
[Also see open data analyses, e.g., Covas et al., (2022), Covas et al., (2024)]

Challenges in searches and interpretations

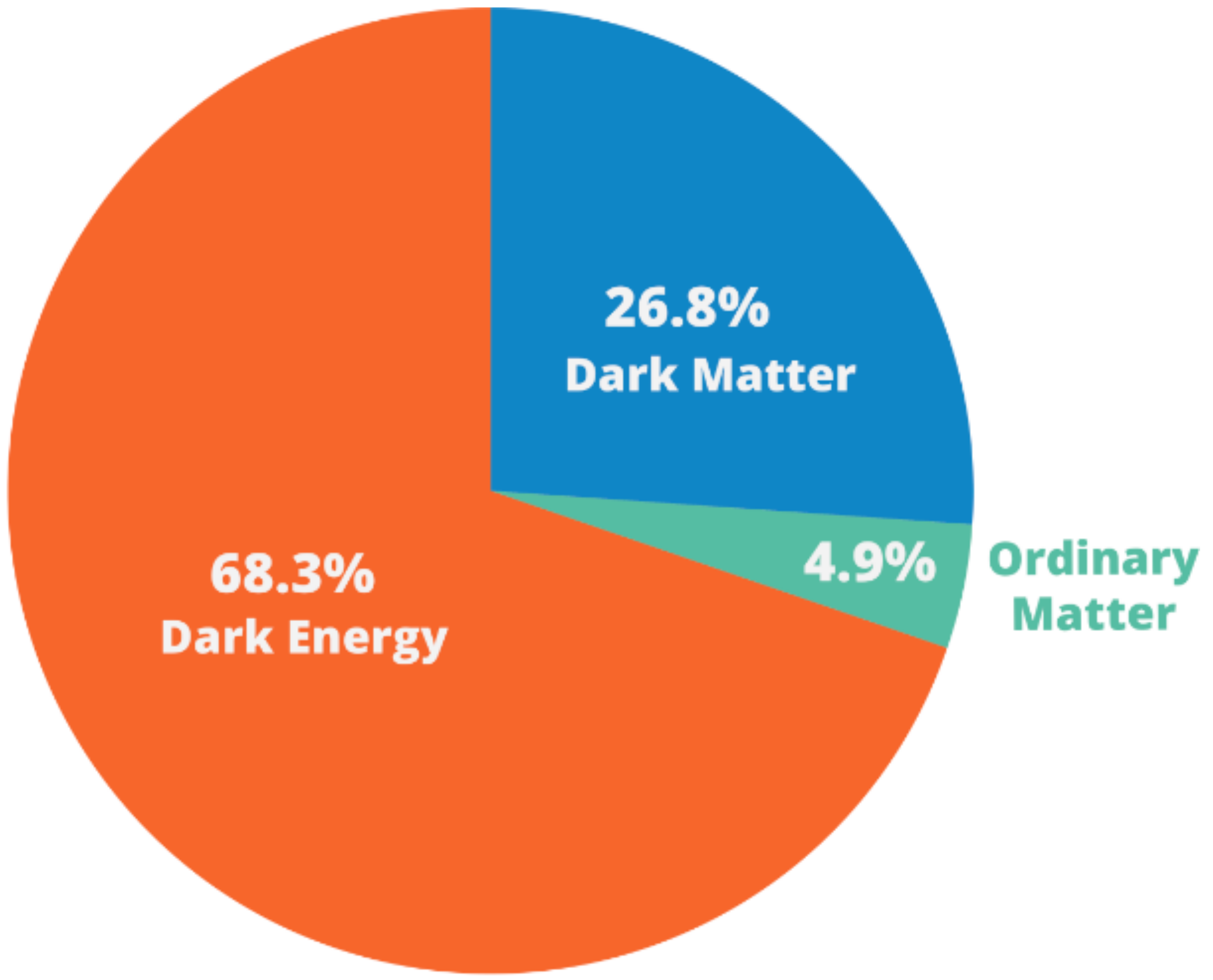
- ***Long-duration integration***
  - *Computationally challenging*
- ***Large parameter space***
  - *The full possible frequency range, and/or sky positions*
  - *Large range of frequency time derivatives*
  - *Breadth vs depth trade-off*

- ***Uncertainty in signal models***
  - *Spin-wandering has been seen in EM observations —— fluctuation of magnetospheric or superfluid torques; fluctuation of accretion torque in binaries*
  - *Glitches*
  - *Other imperfectness in signal models*
  - *Unknown effects*
- ***Uncertainty in interpretations***
  - *Uncertainties associated with the source properties, e.g., distance, orientation, age, and signal models*
- ***Need better theoretical understanding, e.g.***
  - *Lower limit of neutron star ellipticity*
  - *Improved theoretical modelling of r-modes*
  - *Better nuclear physics informed models*

Image: OzGrav | Carl Knox

Probe the Dark Sector with GW Detectors

Probes of dark matter with GW detectors



Credit: ATLAS Experiment, CERN

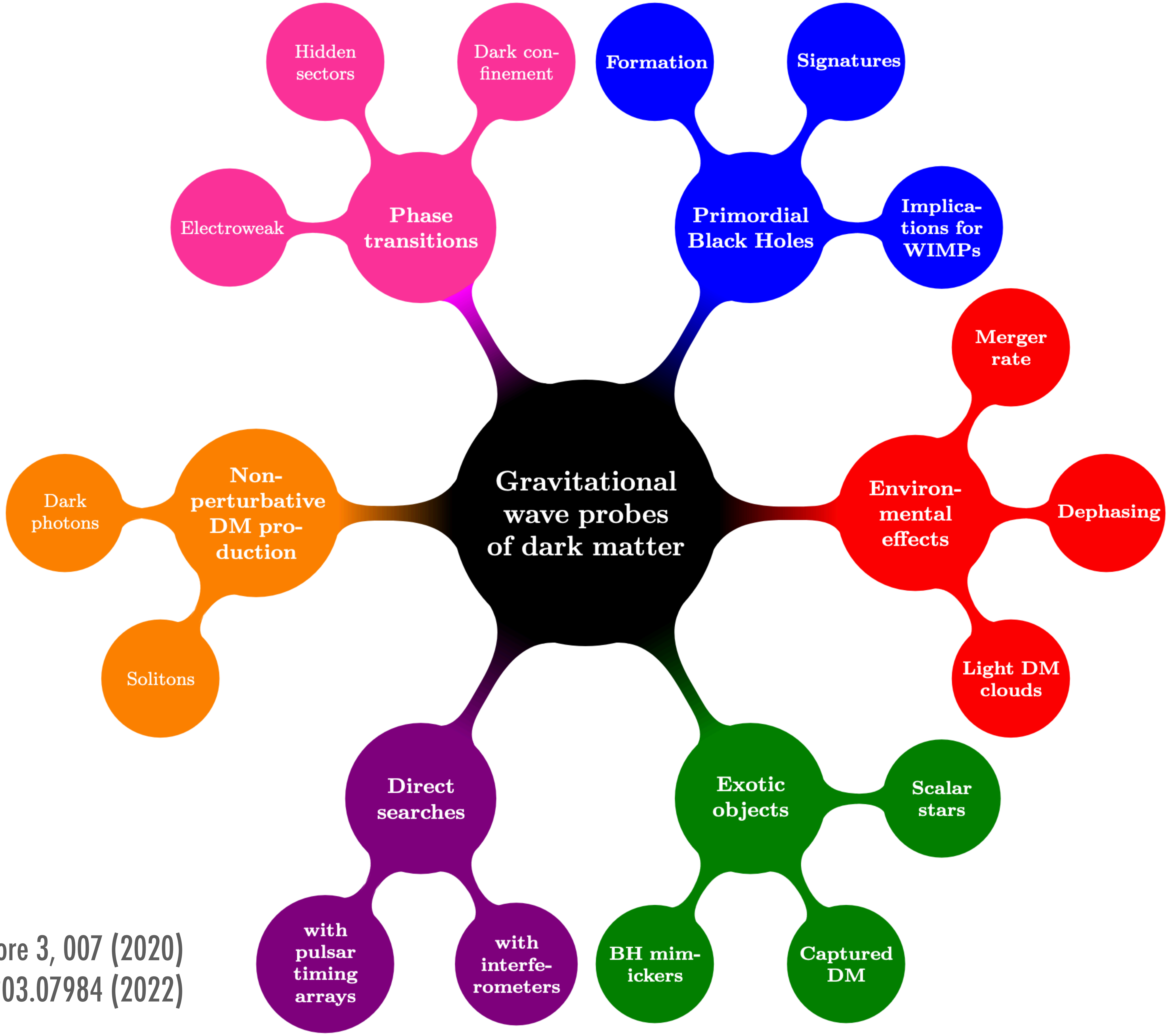


Figure from Bertone et al., SciPost Phys. Core 3, 007 (2020)
Also see Snowmass review: Baryakhtar et al., arXiv:2203.07984 (2022)

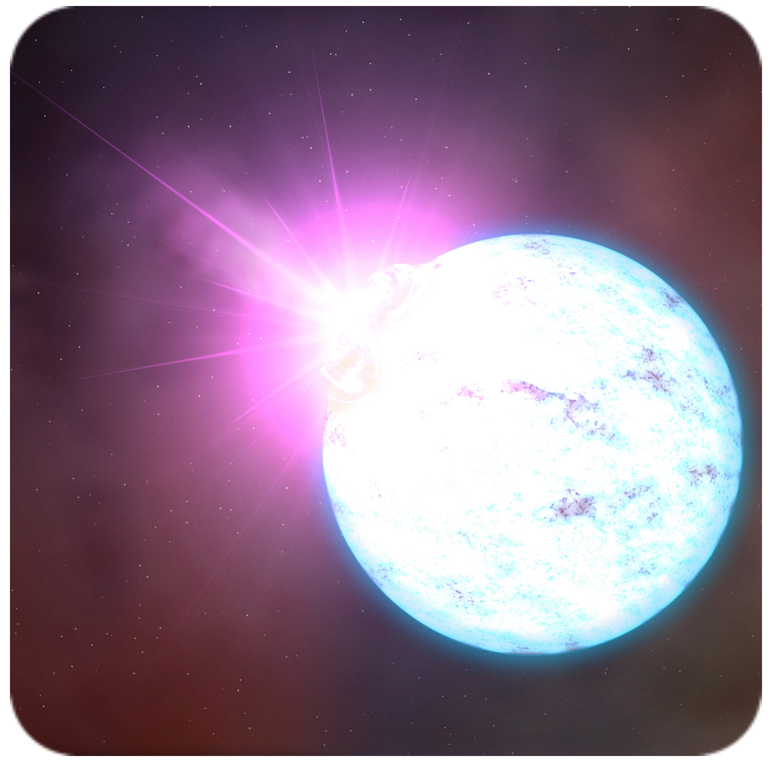
Astrophysical probes via GW observations

- *If neutron stars were to contain dark matter, there would be imprints in the star's tidal deformability, which may be accessible to GW observation.*

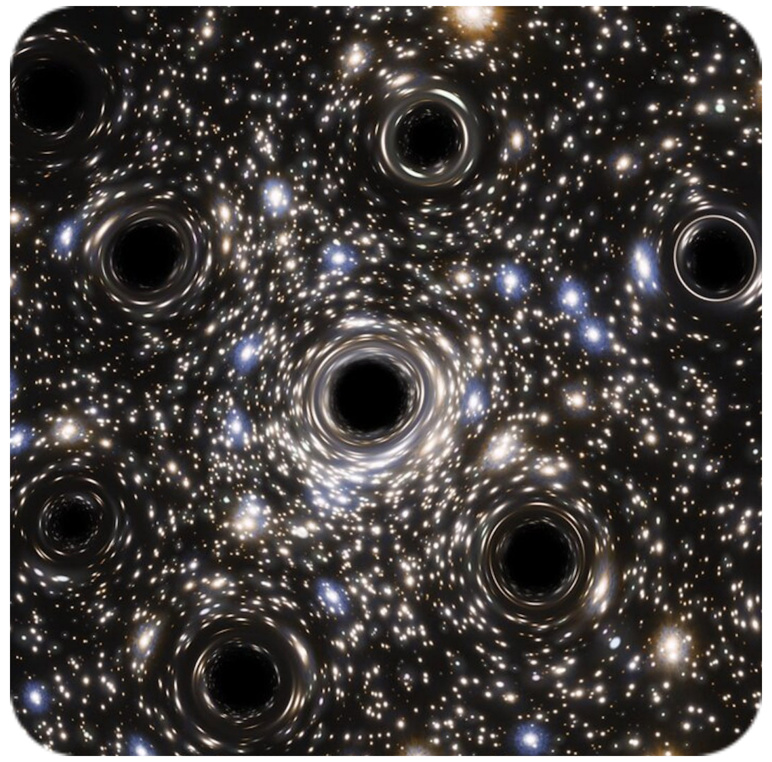
- *Compact objects can form with an astrophysical or dark matter origin. Dissipative dark matter can allow new formation channels for compact objects.*

- *Primordial black holes are also dark matter candidates. Sub-solar-mass black hole inspirals are continuous GW sources.*

- *Astrophysical probes of ultralight boson condensates around black holes become possible via GW observation, by only assuming a coupling through gravity.*



Goddard Space Flight Center/NASA

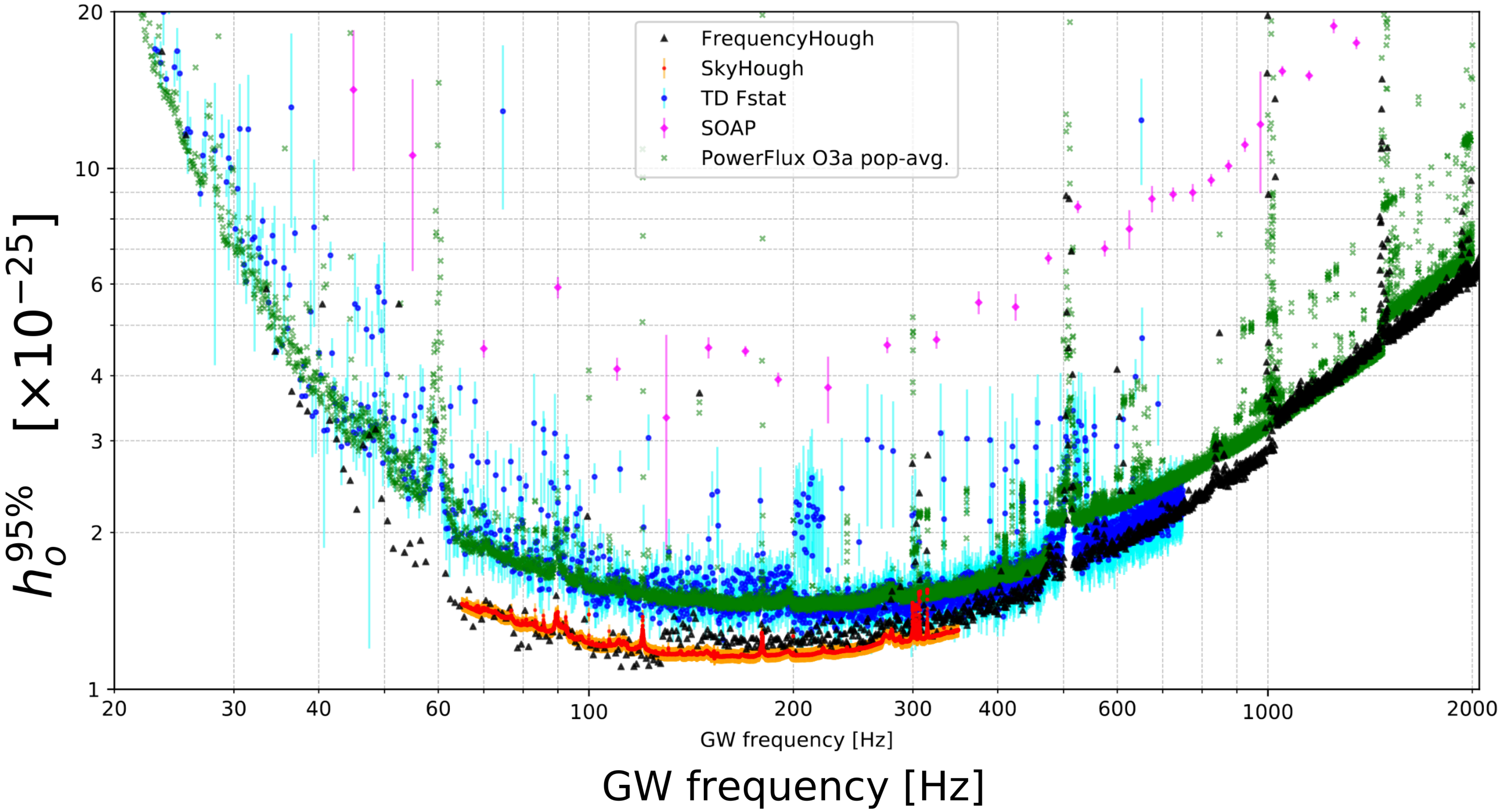


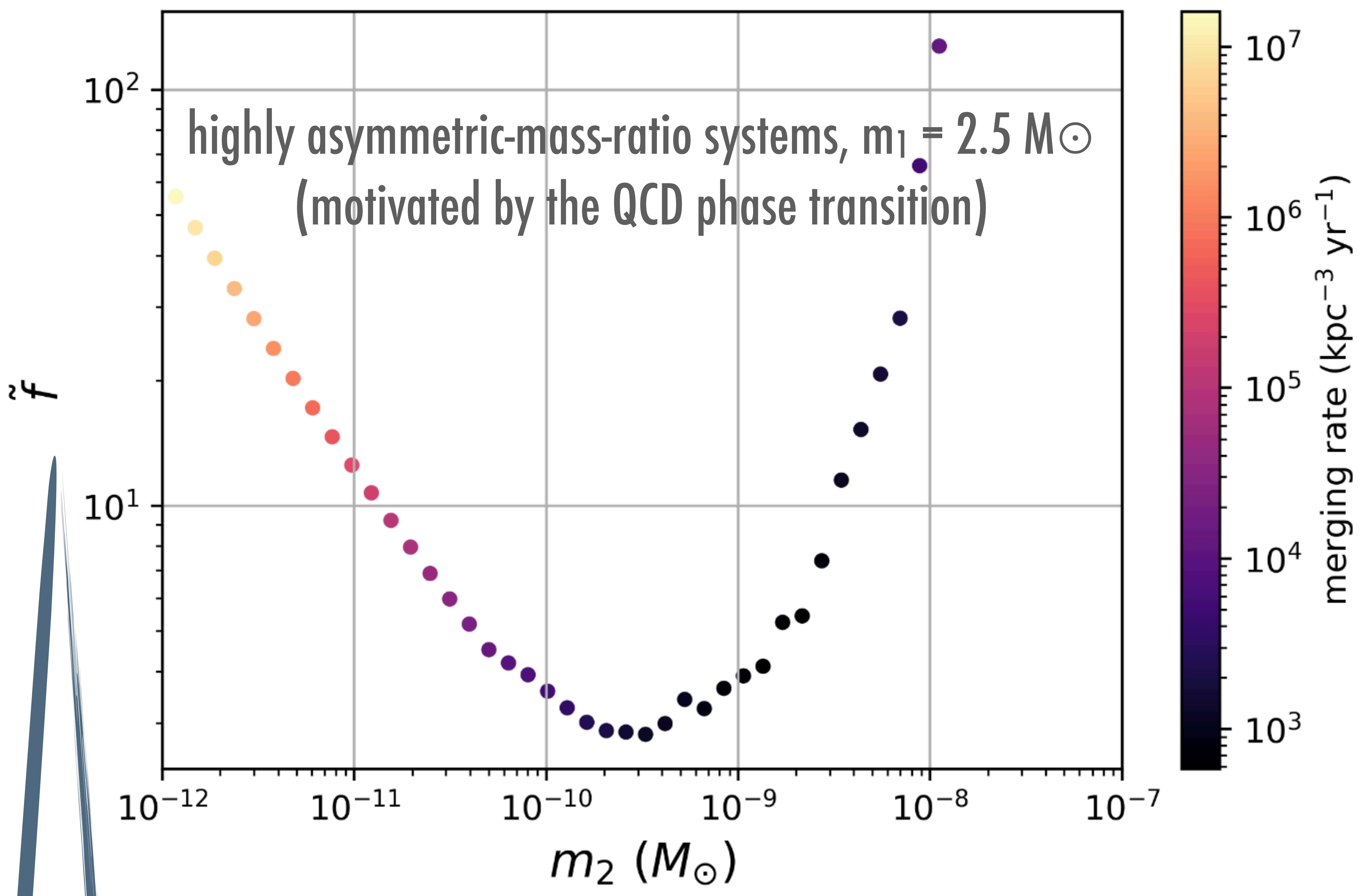
ESA/Hubble, N. Bartmann

Superradiance: Brito, Cardoso, Pani

Searches and constraints on primordial black holes

Abbott+ (LVK), PRD 106, 102008 (2022)





highly asymmetric-mass-ratio systems, $m_1 = 2.5\ M_\odot$
(motivated by the QCD phase transition)

If < 1, indicates the sensitivity to the fraction of dark matter that PBHs could compose

- *Can make statements about the rate and abundance of inspiraling planetary-mass and asteroid-mass primordial black holes with CW search constraints*

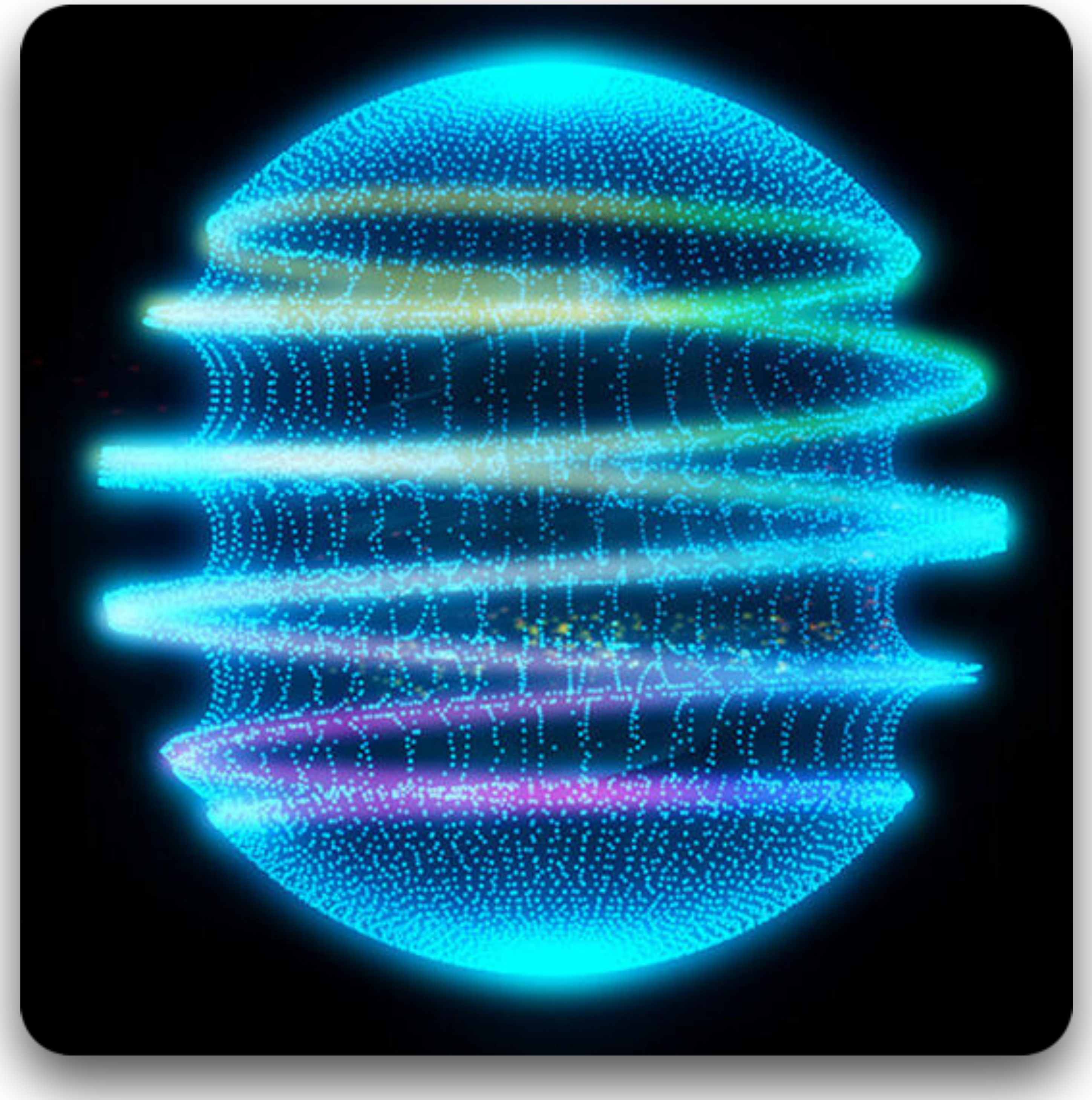
- *Quasi-continuous-wave search methods are being developed and improved to carry out more sensitive searches to primordial black hole inspirals.* e.g., [Horowitz+ 2020, Miller+ 2021, Alestas+ 2024, Andres-Carcasona+ 2024, Velcani 2024]

Ultralight bosons

- *Alternative beyond Standard Model theoretical frameworks predict the existence of new ultralight boson particles, including scalar (spin 0), vector (spin 1), and tensor (spin 2) fields.*

- *QCD axion (well motivated to solve the strong CP problem), string axion, dark photon, etc. —— They are also dark matter candidates.*

- *Their model-dependent weak couplings to the Standard Model (if at all) and the vanishingly small mass make them extremely difficult to detect by conventional lab experiments.*

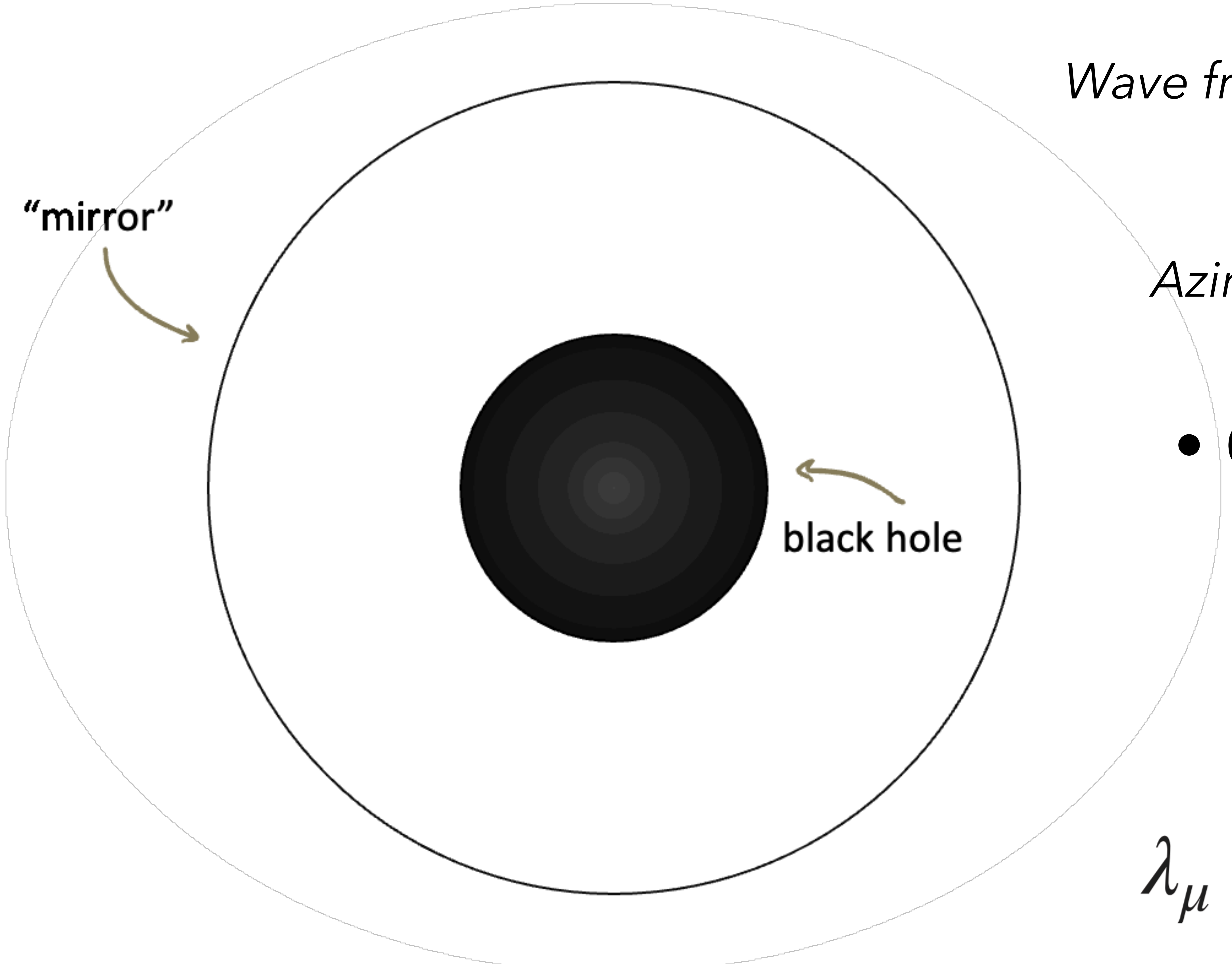


Artist's impression of an axion. Image: Science Photo Library / Andrade, Ramon / 3dciencia

- *Now we can appeal to the new experimental field and use GW detectors to search for them, taking advantage of their universal character of gravitational couplings.*

Superradiant instability

BH bomb (Press and Teukolsky)
Superradiant Instability



Credit: Dana Jones

- **Superradiance condition:**

Wave frequency

Frequency of BH horizon

$$\boxed{\omega/m < \Omega_H}$$

Azimuthal quantum number

- **Confinement condition:**

Compton wavelength ~ BH characteristic length

$$\boxed{\lambda_\mu \sim r_g}$$

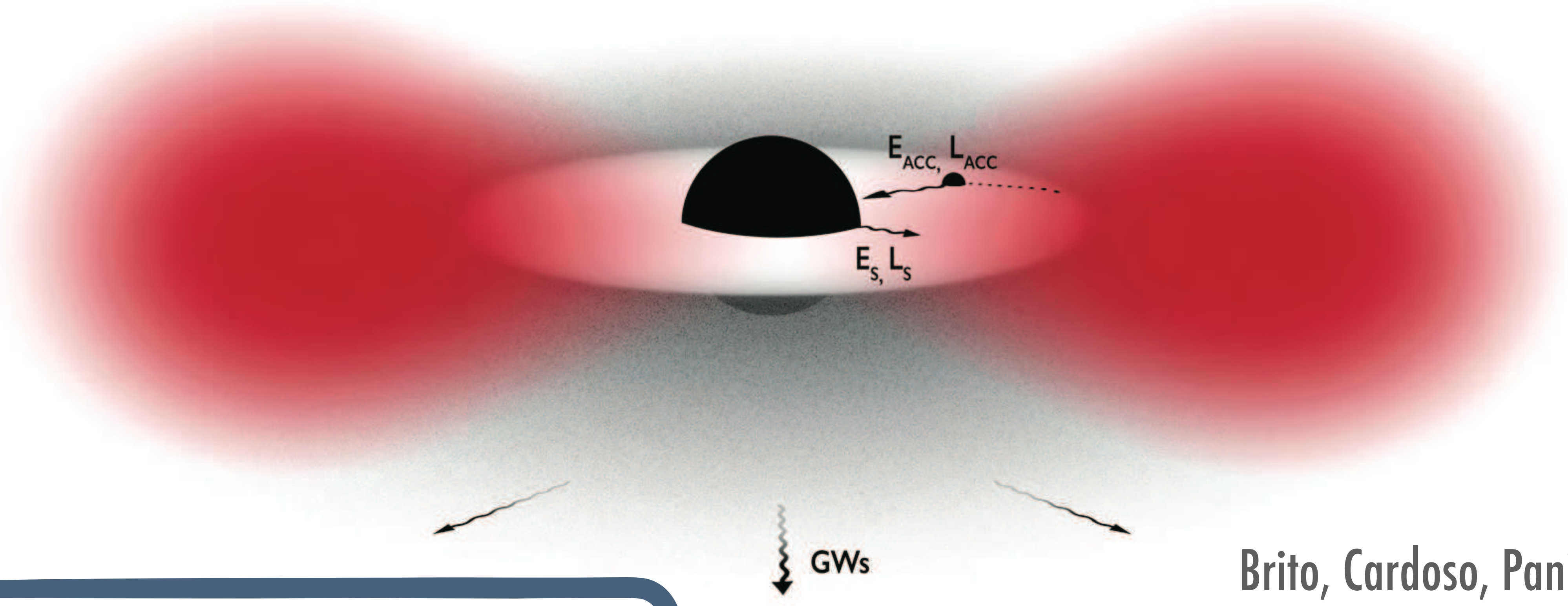
$$\lambda_\mu \equiv 2\pi\bar{\lambda}_\mu \equiv h/(m_b c) \qquad r_g \equiv GM/c^2$$

Boson mass

BH mass

[Arvanitaki+ (2010), Arvanitaki & Dubovsky (2011)]

Continuous waves from boson clouds



Brito, Cardoso, Pani (2015)

- *A massive vector boson cloud oscillates around a black hole and produces gravitational waves*

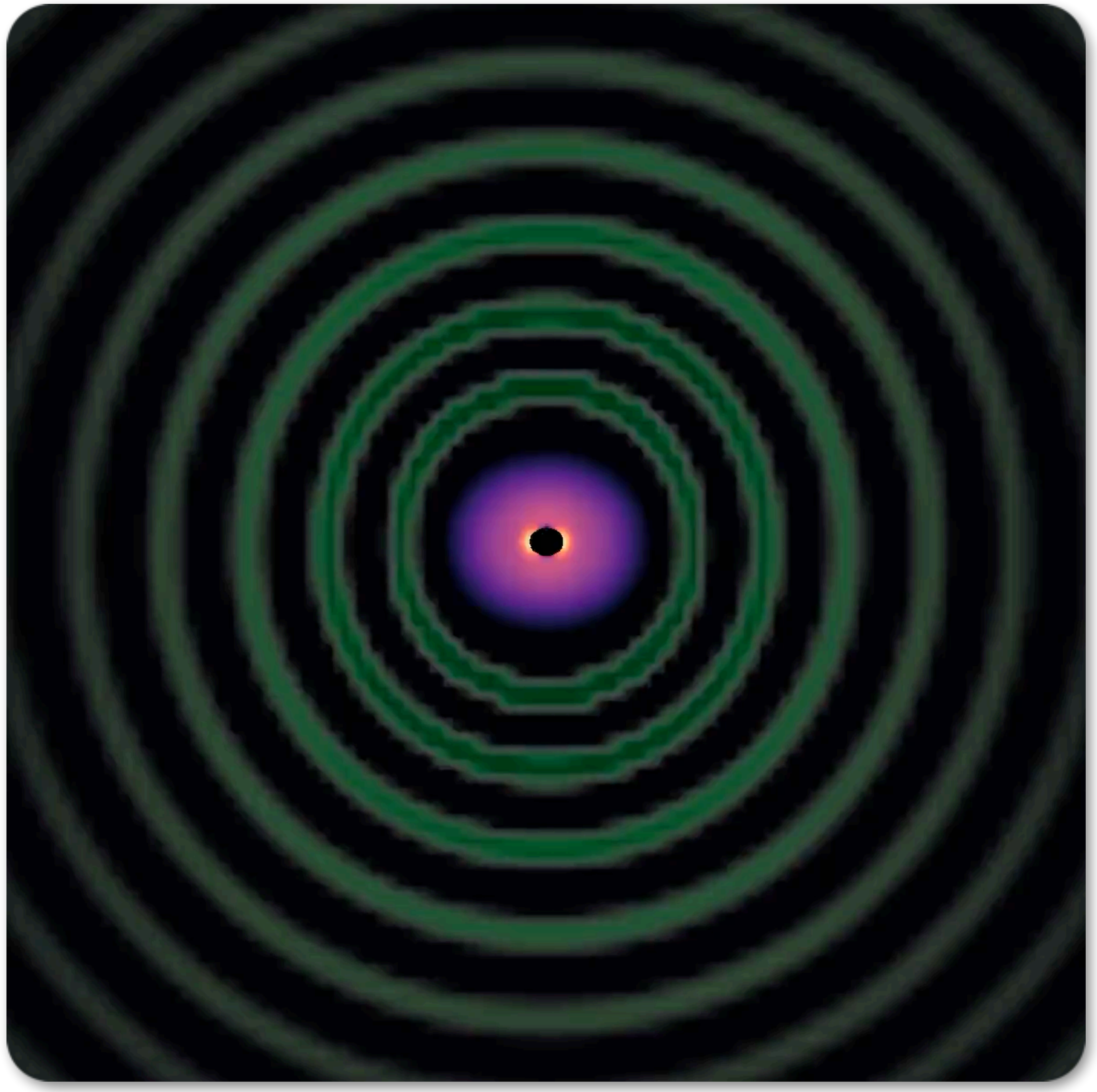
Credit: W. East (https://www2.perimeterinstitute.ca/personal/weast/research.html)

$$\omega_{\mathrm{GW}} = 2\omega_{\bar{n}}$$

Quasi-monochromatic signals (small positive $\dot{f}$)

Scalars –– conventional CW signals

Vectors –– long-transient signals



- ***What can we learn?***

–– Probe a parameter space that is inaccessible by conventional lab particle physics experiments; may detect new particles

Ground-based detector

$$10^{-14} \lesssim \mu/\mathrm{eV} \lesssim 10^{-11}$$

Space-based detector

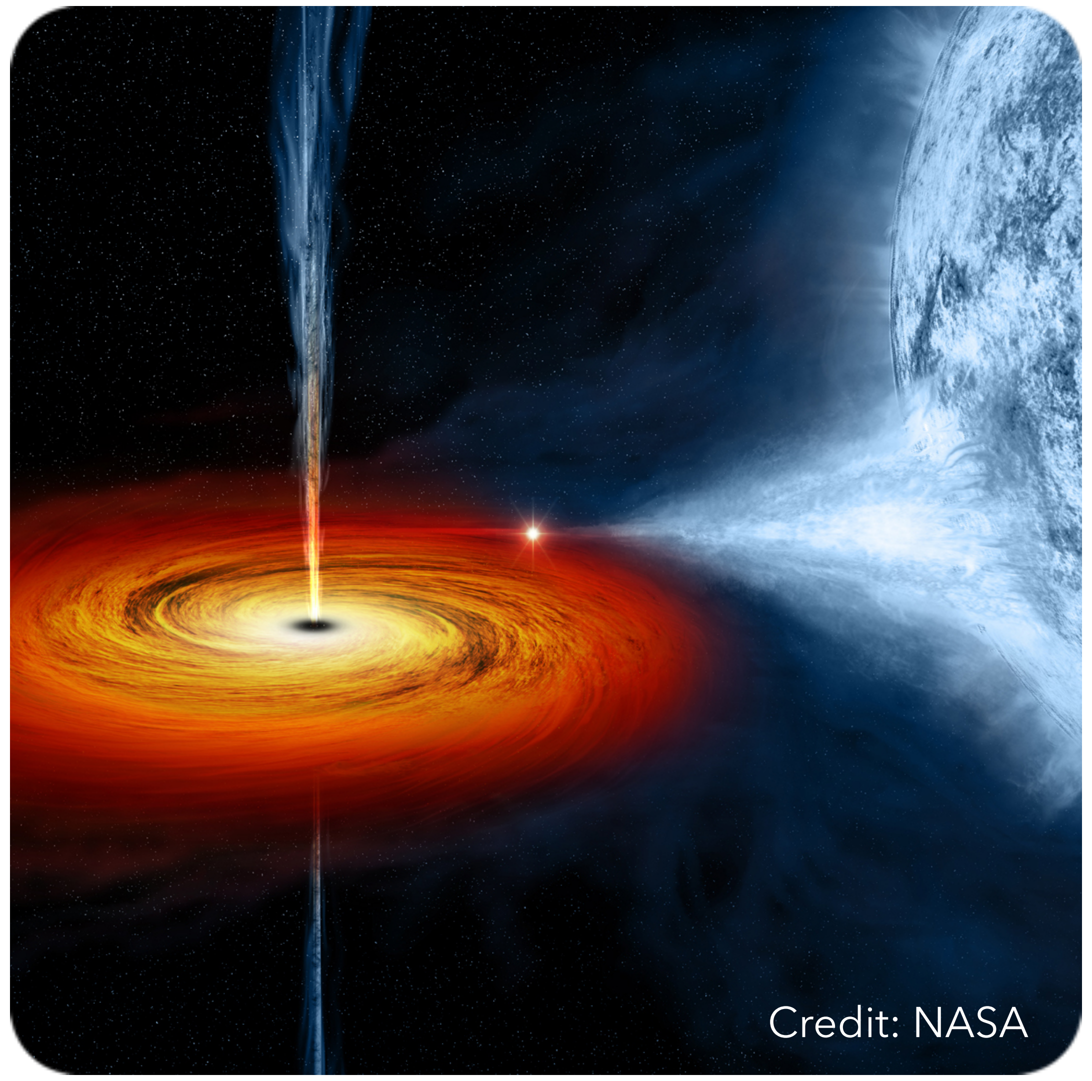
$$10^{-19} \lesssim \mu/\mathrm{eV} \lesssim 10^{-15}$$

See e.g., [Arvanitaki+ (2010), Yoshino & Kodama (2014), Arvanitaki+ (2015), Arvanitaki+ (2017), Brito+ (2017), Baryakhtar+ (2017), East (2018)]

Searches for individual galactic sources (examples)

- ***Searches for boson clouds around unknown BHs***
  - ***An all-sky search tailored for scalars in O3 data*** [Abbott+ PRD 105, 102001 (2022)] –– *semiquantitative constraints on the possible presence of emitting boson clouds in our Galaxy, e.g., systems* ***younger than*** $\sim 10^3$ ***yrs*** *are disfavored in the whole Galaxy for* ***boson masses*** $\sim [2.5,\ 10] \times 10^{-13}\,\mathrm{eV}$ *for a maximum BH mass of* $50M_\odot$ *and* $\sim [1.2,\ 10] \times 10^{-13}\,\mathrm{eV}$ *for a maximum BH mass of* $100M_\odot$ *(using Kroupa mass distribution with PDF* $\propto m^{-2.3}$*)*
  - ***Constraints derived from all-sky/Milky Way center continuous wave searches****, e.g.,* [Dergachev+ (2019), Palomba+ (2019), Abbott+ PRD 106, 042003 (2022)]


Credit: NASA


Credit: NASA

- ***A dedicated search for scalars targeting Cygnus X-1 in O2***

  [Sun+ PRD 101, 063020 (2020), PRD 102, 089902 (2020), Collaviti+ (2024)]

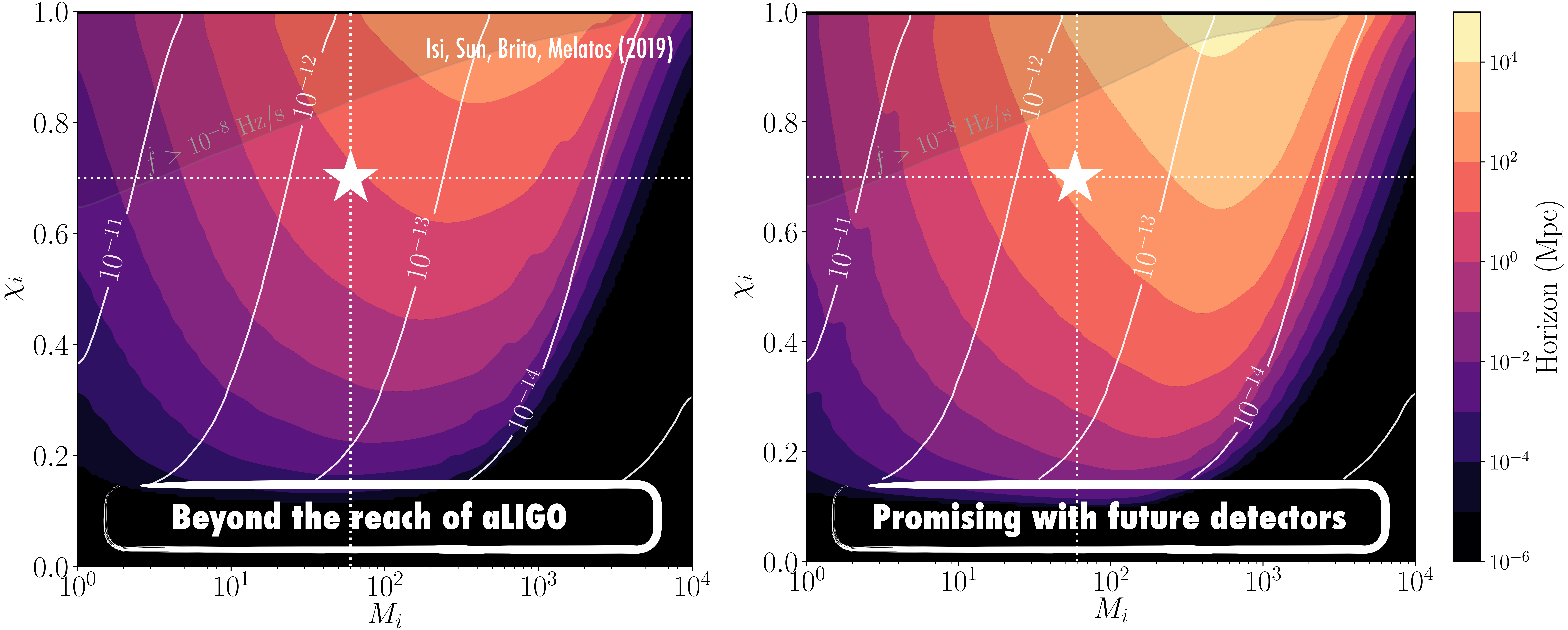
  - *E.g.,* ***boson masses*** $[6.4,\ 8.0] \times 10^{-13}\,\mathrm{eV}$ *are disfavored assuming a BH age of* 5×10^6 ***yrs*** *and* $[6.3,\ 13.2] \times 10^{-13}\,\mathrm{eV}$ *assuming a BH age of* 10^5 ***yrs***

Unknown black holes or black holes with unknown history are not ideal in order to obtain robust constraints
Remnant black holes in GW merger events are better targets!

[Arvanitaki+ (2017)]

CBC remnant black holes — Horizon distance (scalar)

Sensitivity estimates based on latest numerical relativity studies [assuming 1 detector with a full year's observing time]



Beyond the reach of aLIGO

Promising with future detectors

$M_i = 60\ M_\odot \quad \chi_i = 0.70$

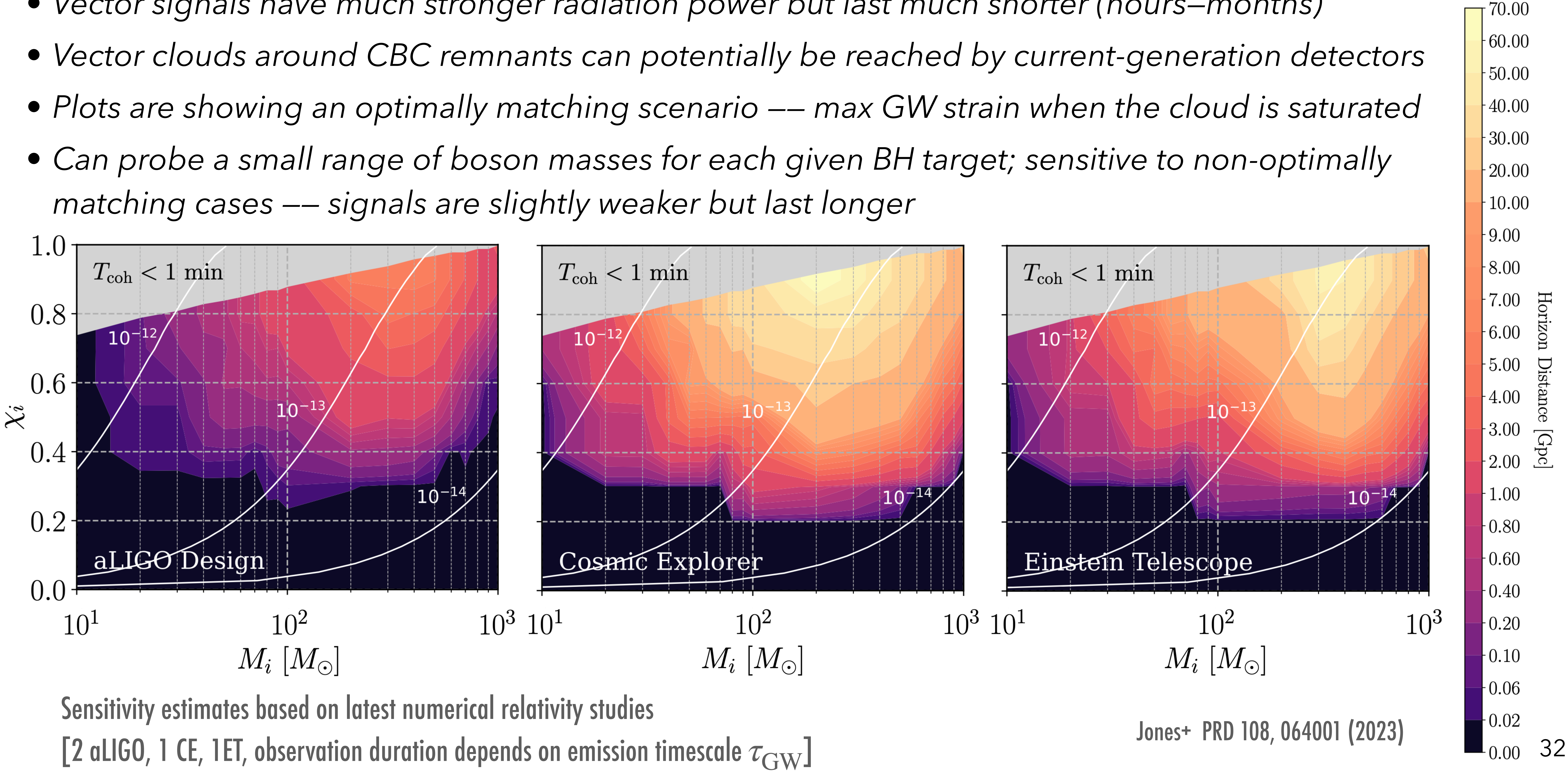
[GW150914] can reach ~10 Mpc

$M_i = 60\ M_\odot \quad \chi_i = 0.70$

[GW150914] can reach ~160 Mpc

CBC remnant black holes — Horizon distance (vector)

- *Vector signals have much stronger radiation power but last much shorter (hours–months)*
- *Vector clouds around CBC remnants can potentially be reached by current-generation detectors*
- *Plots are showing an optimally matching scenario –– max GW strain when the cloud is saturated*
- *Can probe a small range of boson masses for each given BH target; sensitive to non-optimally matching cases –– signals are slightly weaker but last longer*

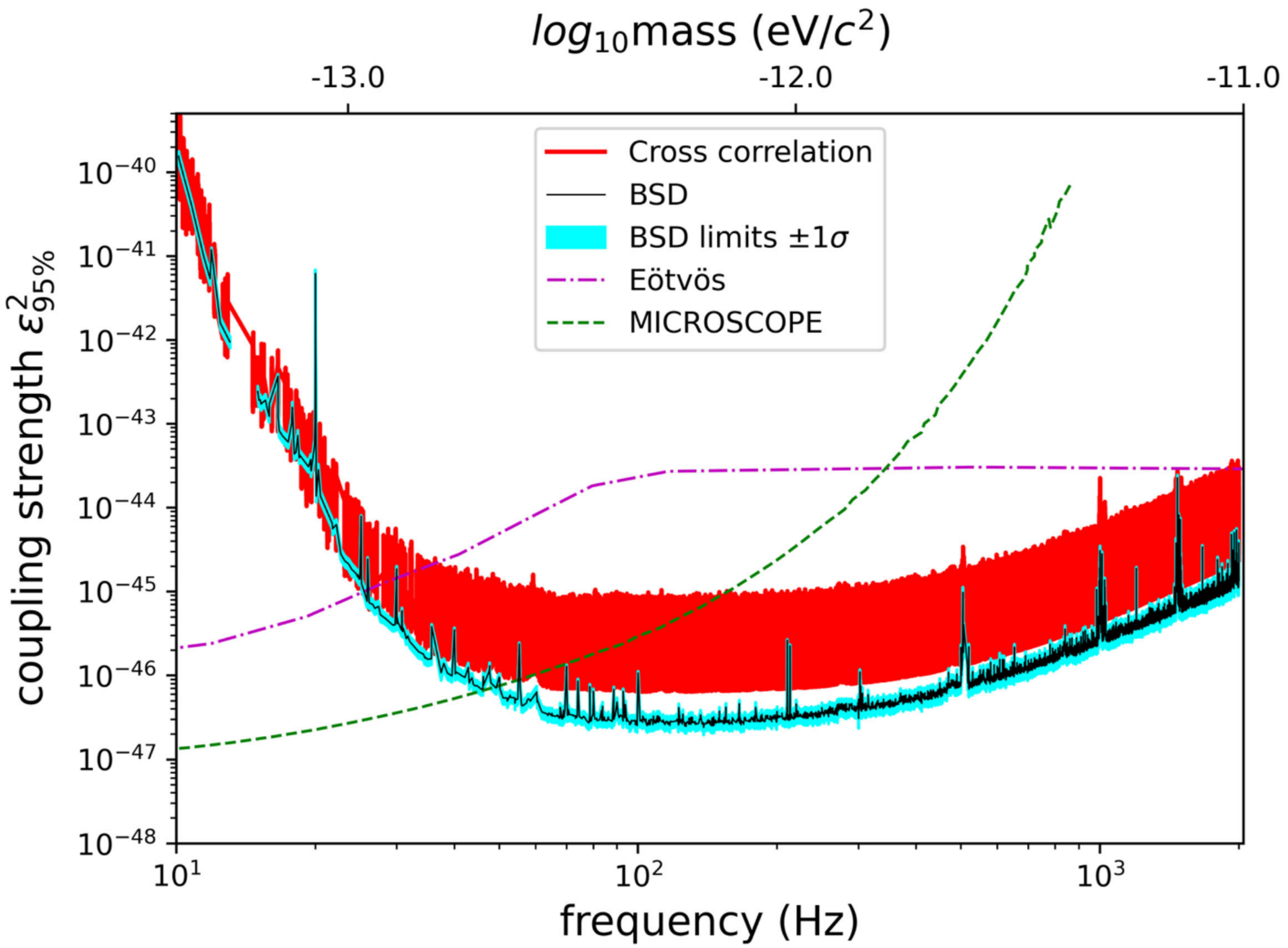


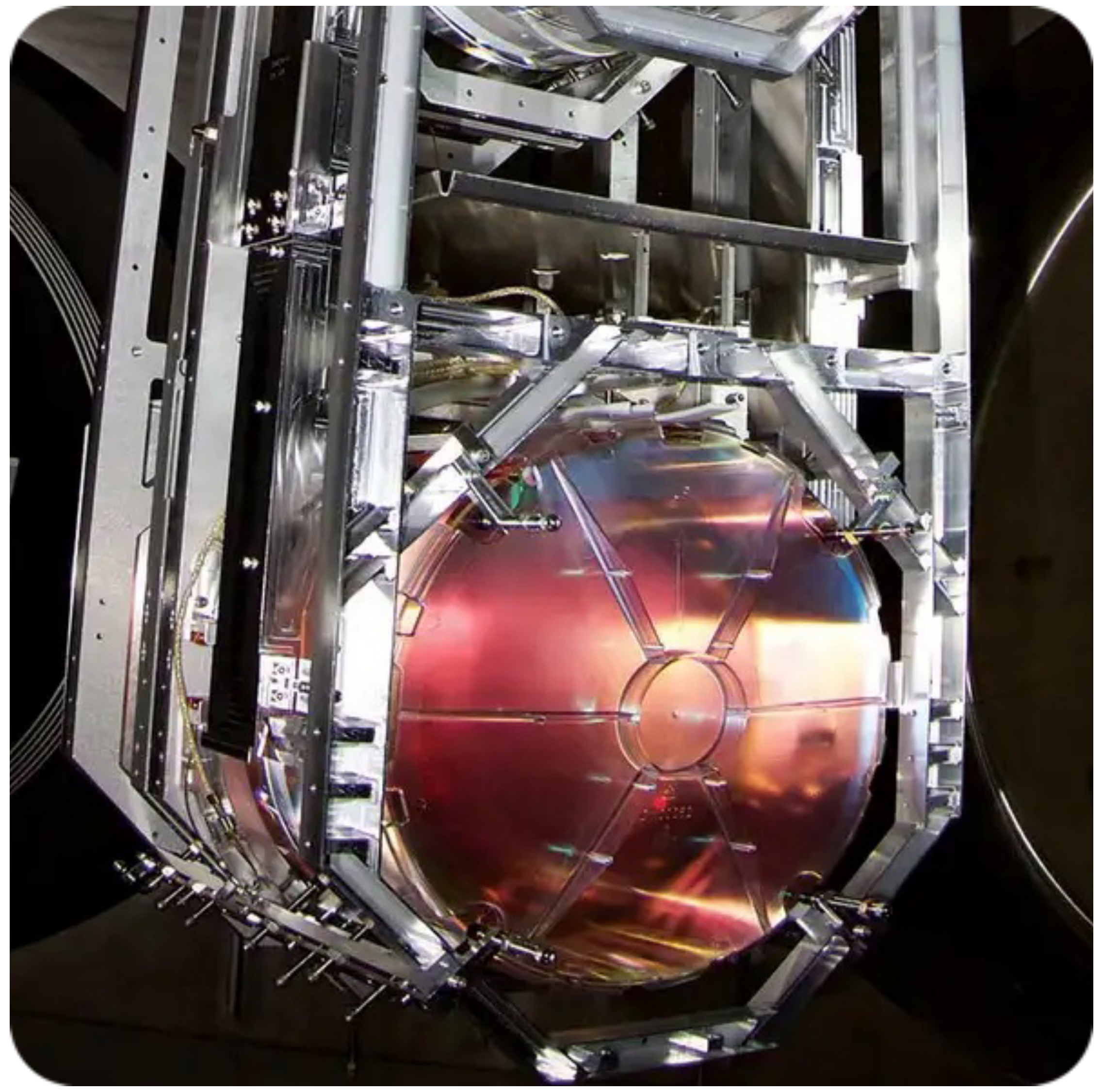
Sensitivity estimates based on latest numerical relativity studies
[2 aLIGO, 1 CE, 1ET, observation duration depends on emission timescale $\tau_{\rm GW}$]

Jones+ PRD 108, 064001 (2023)

Searches via Direct Interactions

- *GW detectors are extremely sensitive to displacements —— can be used as direct dark matter detectors through the field's weak coupling to normal matter.*



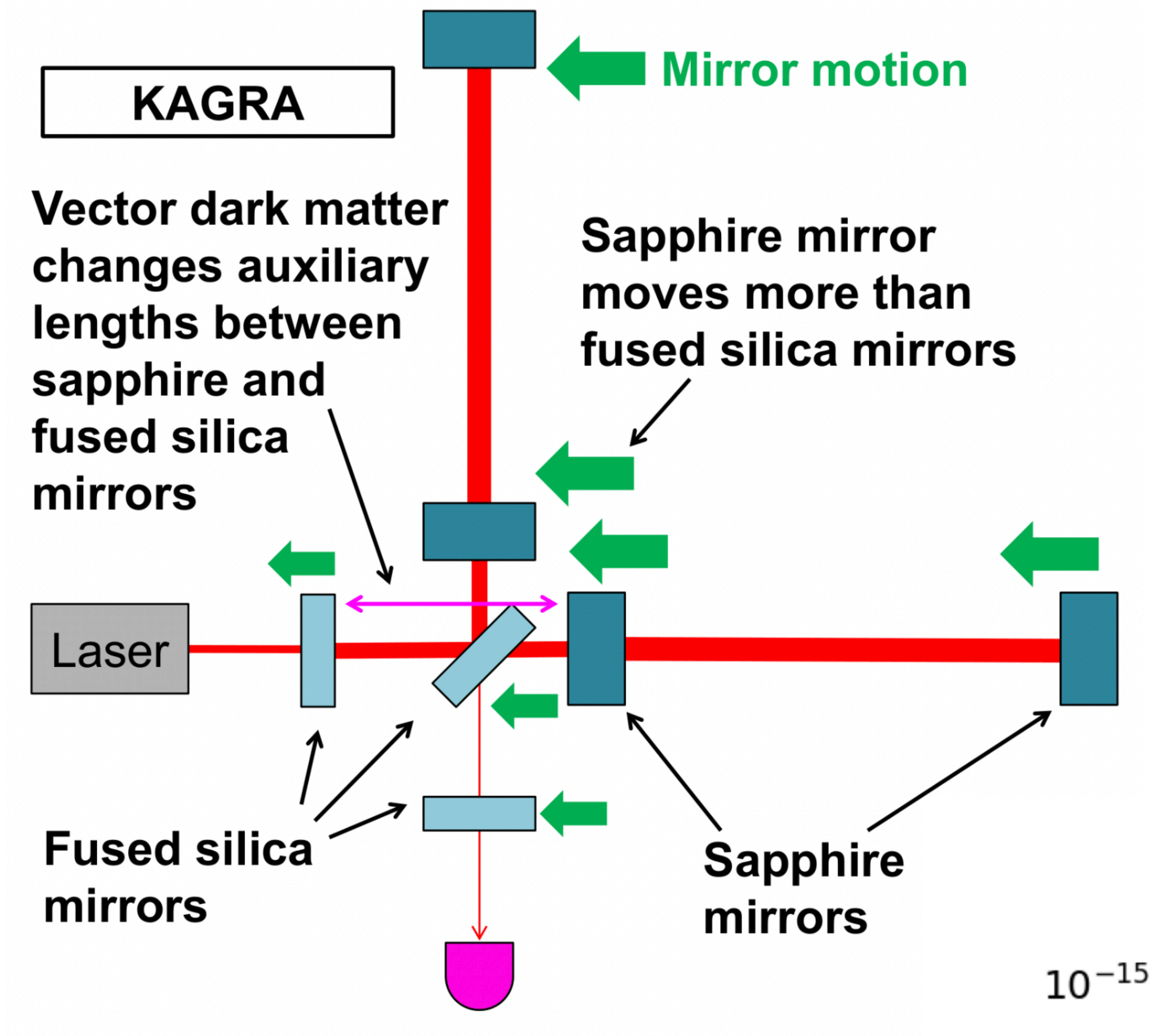


Caltech/MIT/LIGO Lab

- *Dark photons may directly couple to the baryons in the test masses and cause an oscillatory force on the detector*
- *Constraints on the coupling strength of dark photons to baryons in the mirrors using two methods*

O3LHV, Abbott+ (LVK), PRD 105, 063030 (2022)
PRD 109, 089902 (2024)

Searches via Direct Interactions



Vector dark matter changes auxiliary lengths between sapphire and fused silica mirrors

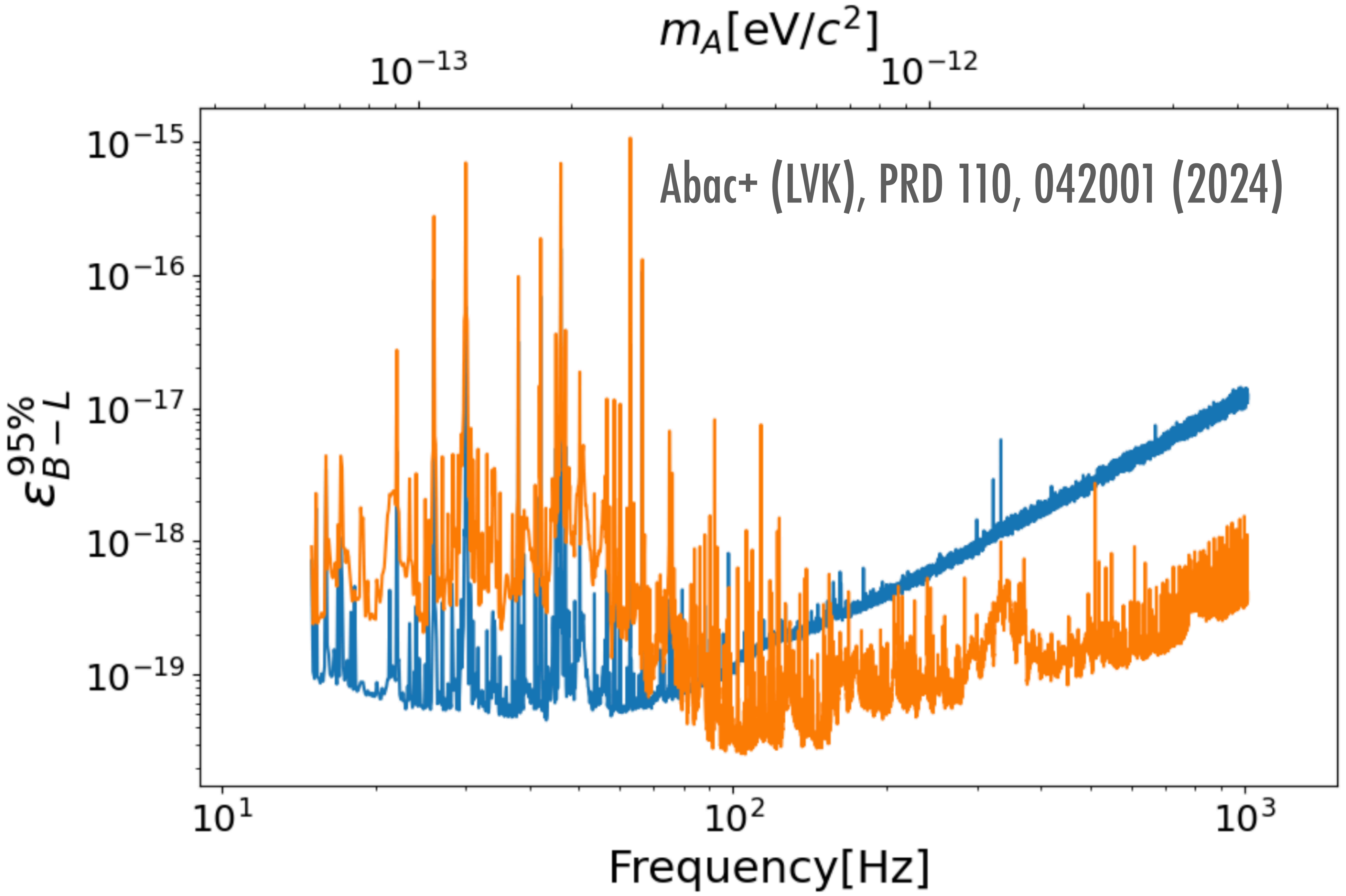
Sapphire mirror moves more than fused silica mirrors

Fused silica mirrors

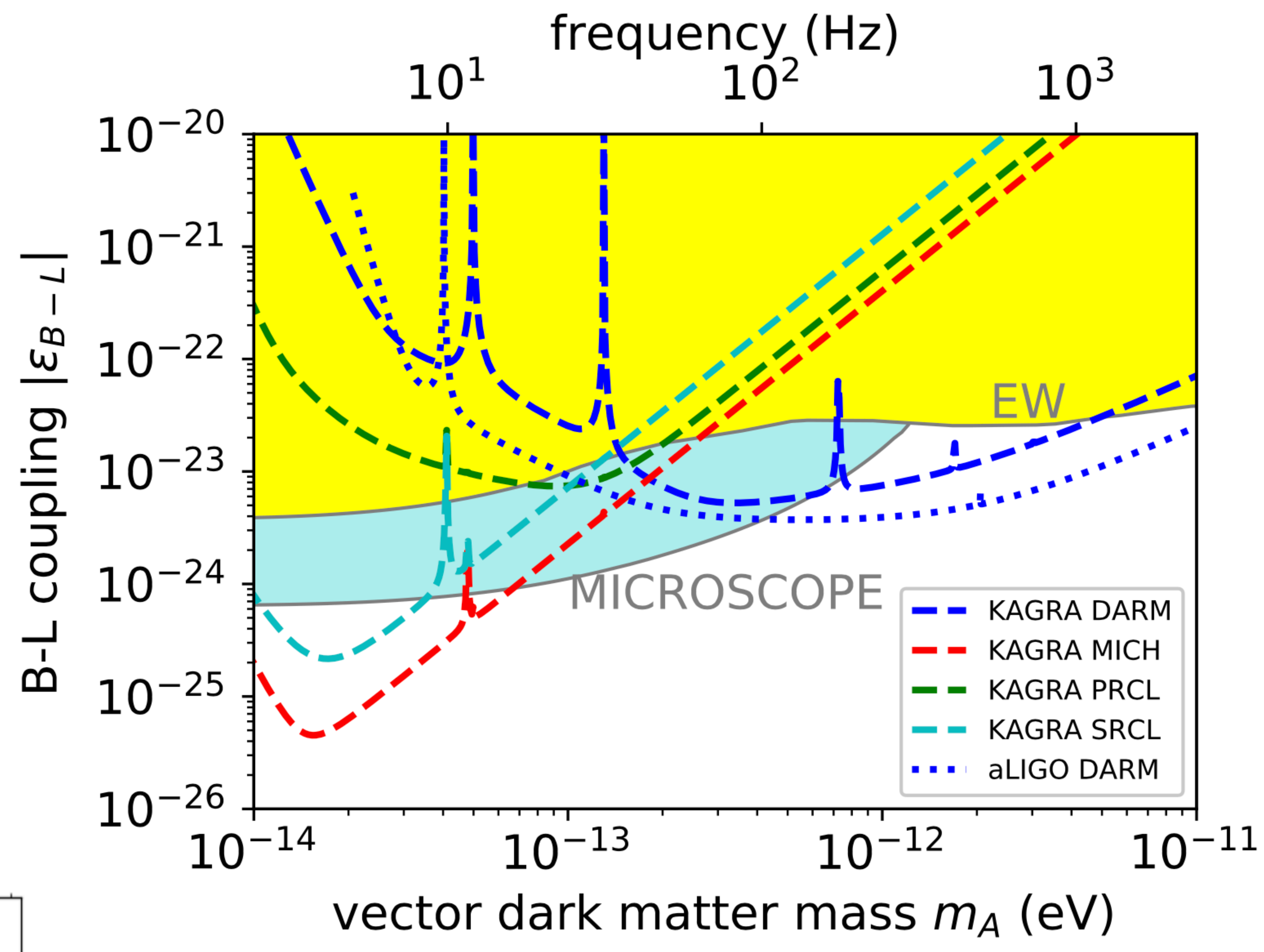
Sapphire mirrors

- *KAGRA mirrors are made from different materials (sapphire test masses and fused silica auxiliary mirrors), enhancing a potential vector DM signal*

- *Constraints are less stringent than those derived from previous experiments (limited by current noise level and measurement time) –– demonstrating the applicability of the method to the lower-mass vector DM search*



Abac+ (LVK), PRD 110, 042001 (2024)



Michimura+ PRD 102, 102001 (2020)

- *Projected sensitivity for 1-year observation –– KAGRA is more sensitive than LIGO/Virgo in low mass range (< 10Hz) by using auxiliary length channels for the B-L coupling*

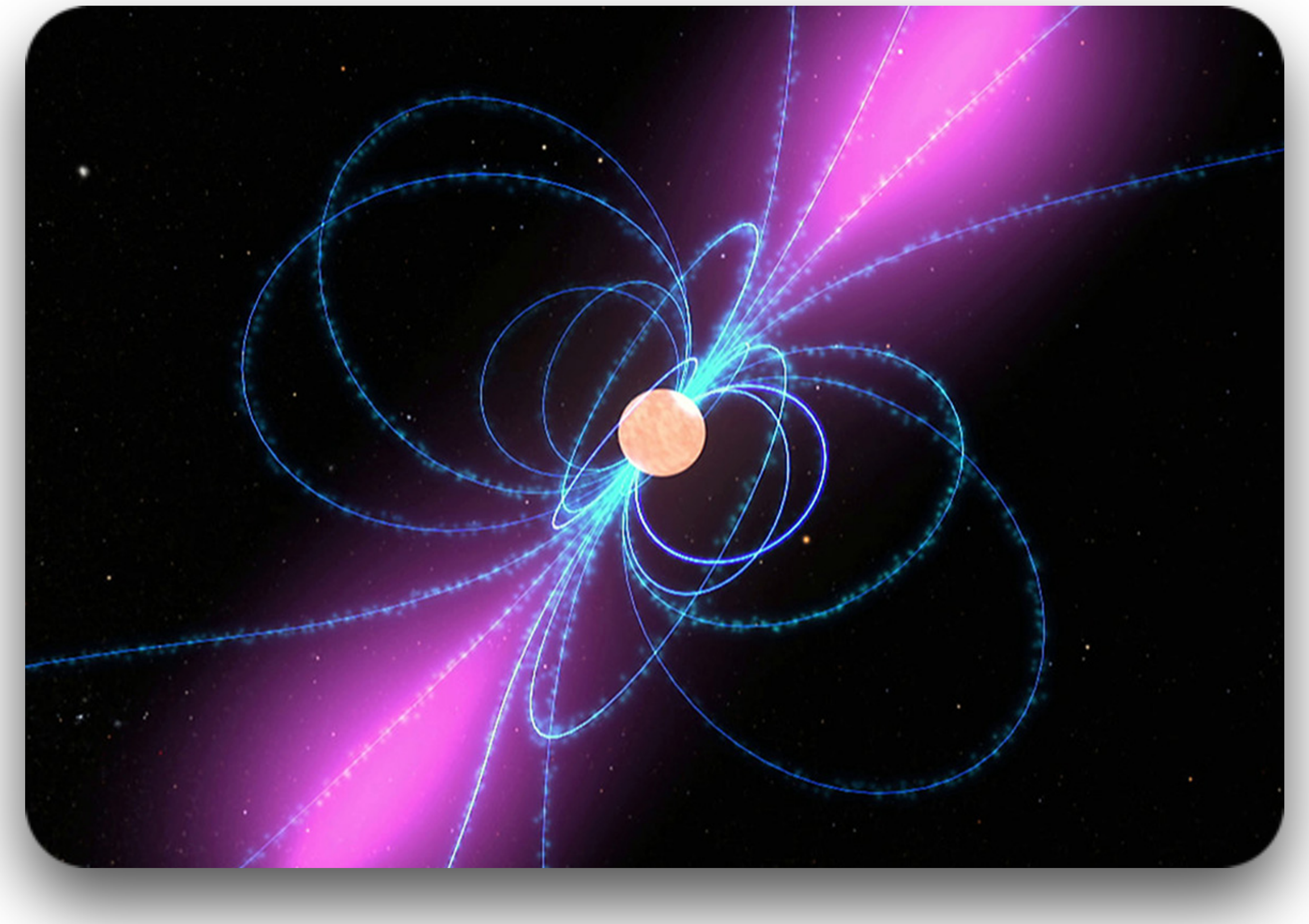
Challenges in searches and interpretations

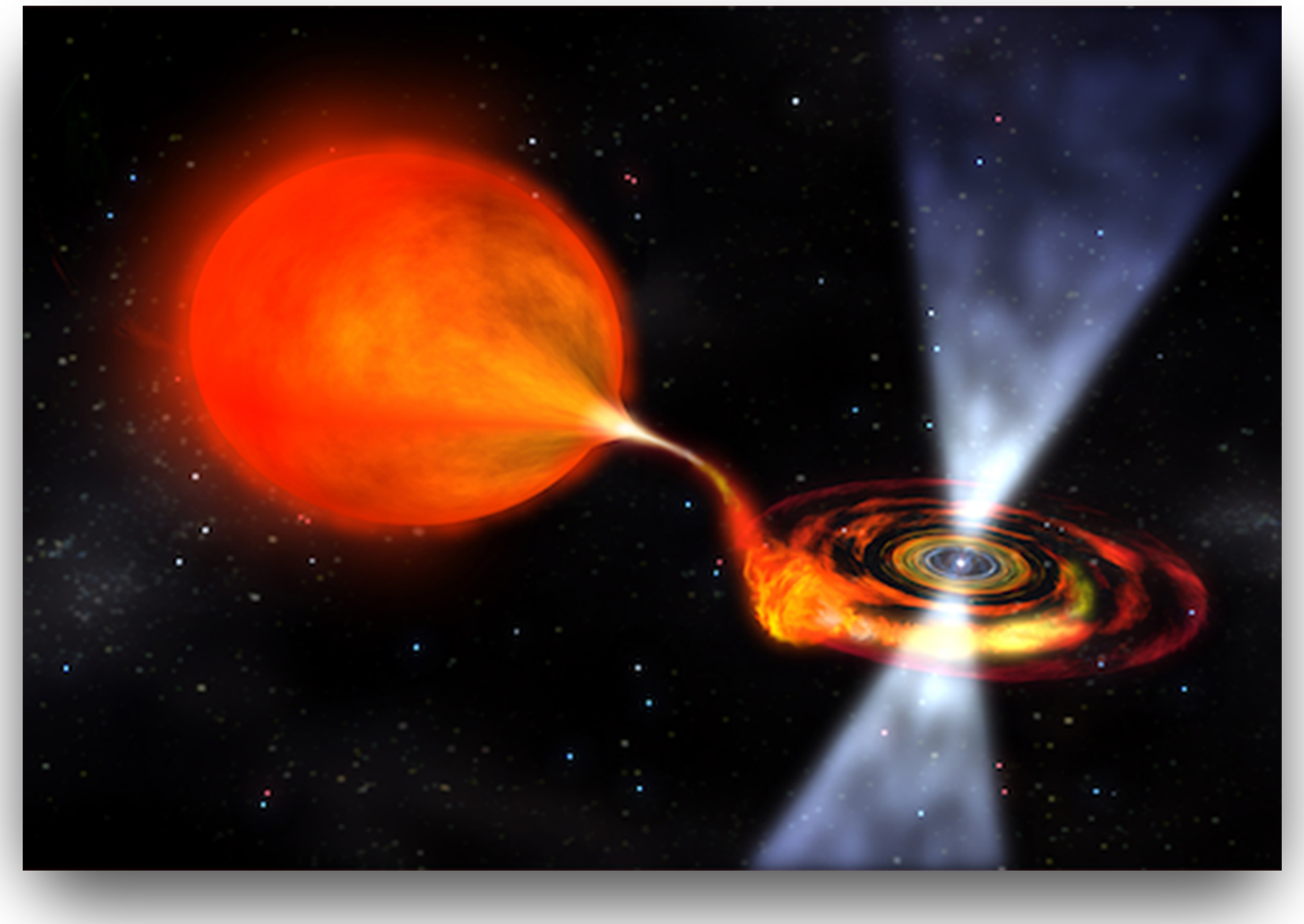
- ***Long-duration integration***
  - *Computationally challenging*
- ***Large parameter space***
  - *The full possible frequency range, and/or sky positions*
  - *Large range of frequency time derivatives*
  - *Breadth vs depth trade-off*

- ***Uncertainty in signal models***
  - *Signal morphology highly depends on theories*
  - *Minor features not taken into account in simplified signal models*
  - *Uncertainties and approximations in theoretical and numerical studies*
  - *Not well-understood effects*
- ***Uncertainty in interpretations***
  - *Uncertainties associated with the source properties, e.g., black hole age and spin, PBH systems*
  - *Uncertainties of the property distribution in the population (more relevant for blind search and stochastic background studies)*
- ***Need better theoretical understanding, e.g.***
  - *Coupling and self-interaction strength*
  - *More accurate waveforms*
  - *Theoretically preferred parameter space*

Summary

- *Multiple types of searches for multiple types of continuous-wave signals*
- *Opened up new avenues for studying dark matter and new physics*
- *No detections yet but probing physically interesting regions*
- *Continuous-wave signal processing techniques continue to develop and improve*
- *Inputs from astronomers and theorists are essential to improve future studies*
- *With further improved detectors in the near future, new discovery is at the horizon!*





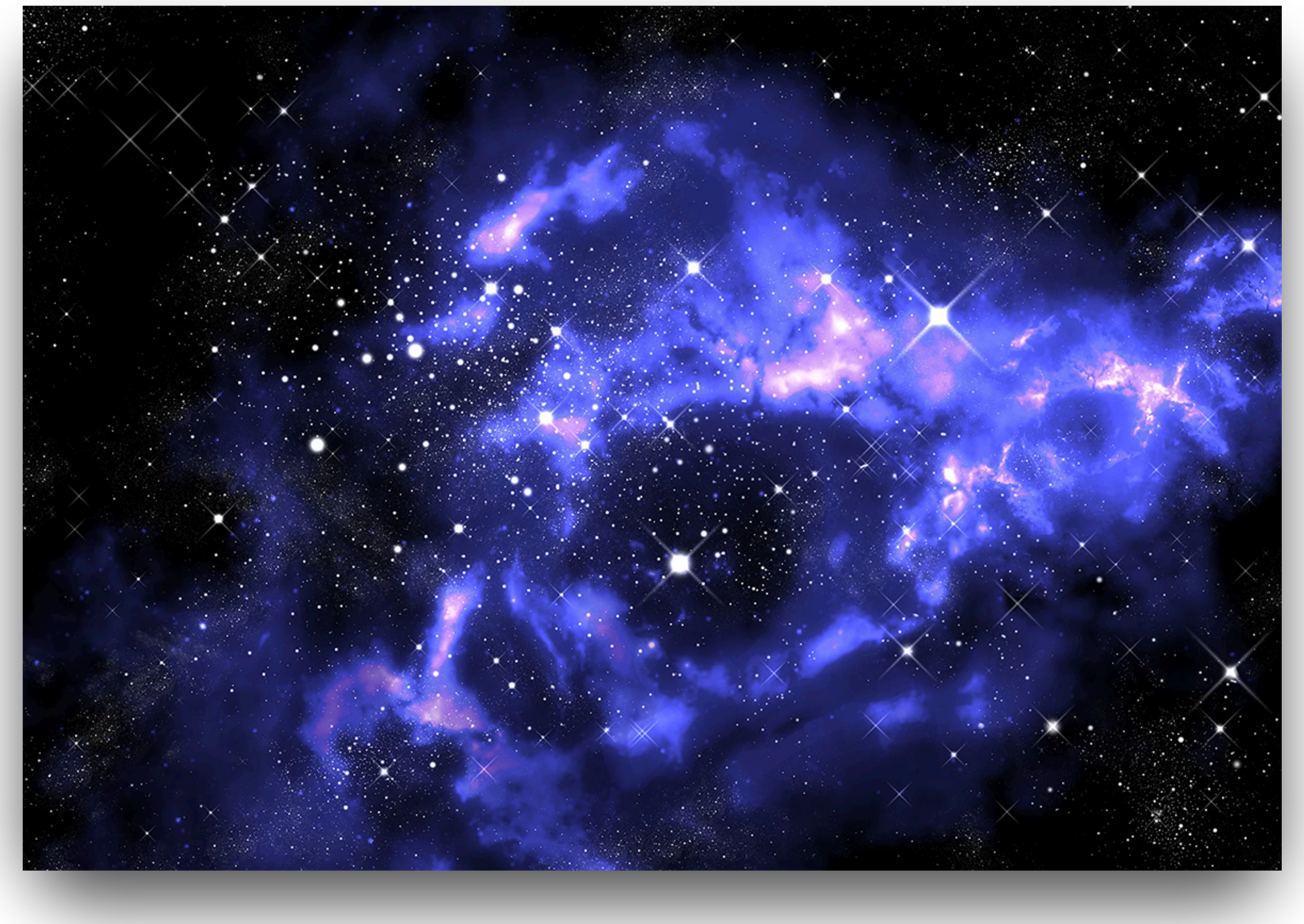


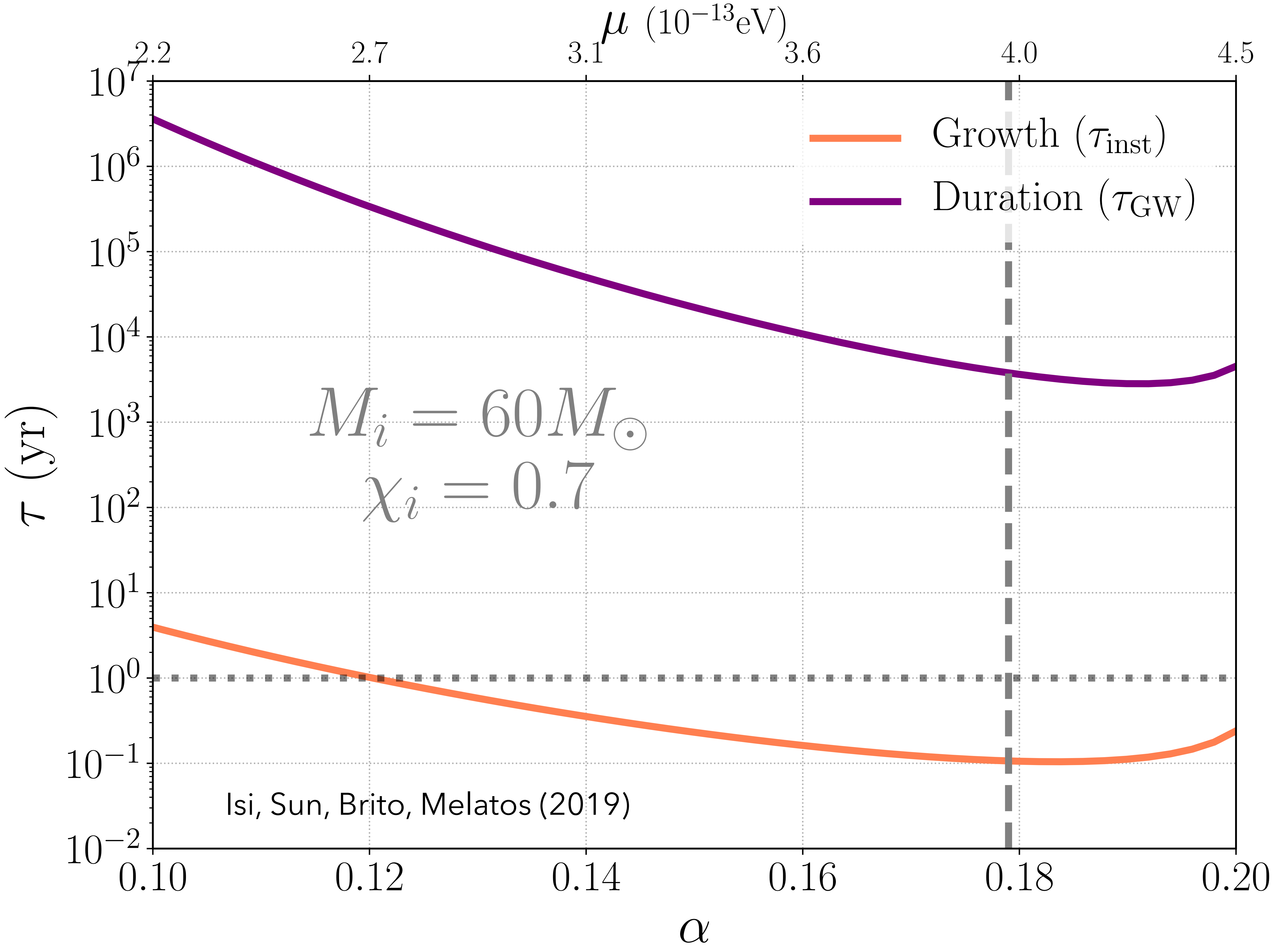
Image: OzGrav | Carl Knox

Thanks!

Questions?

GW signal timescales (scalar)

- *Fastest growing scalar level (s = n = 0, j = l = m =1)*



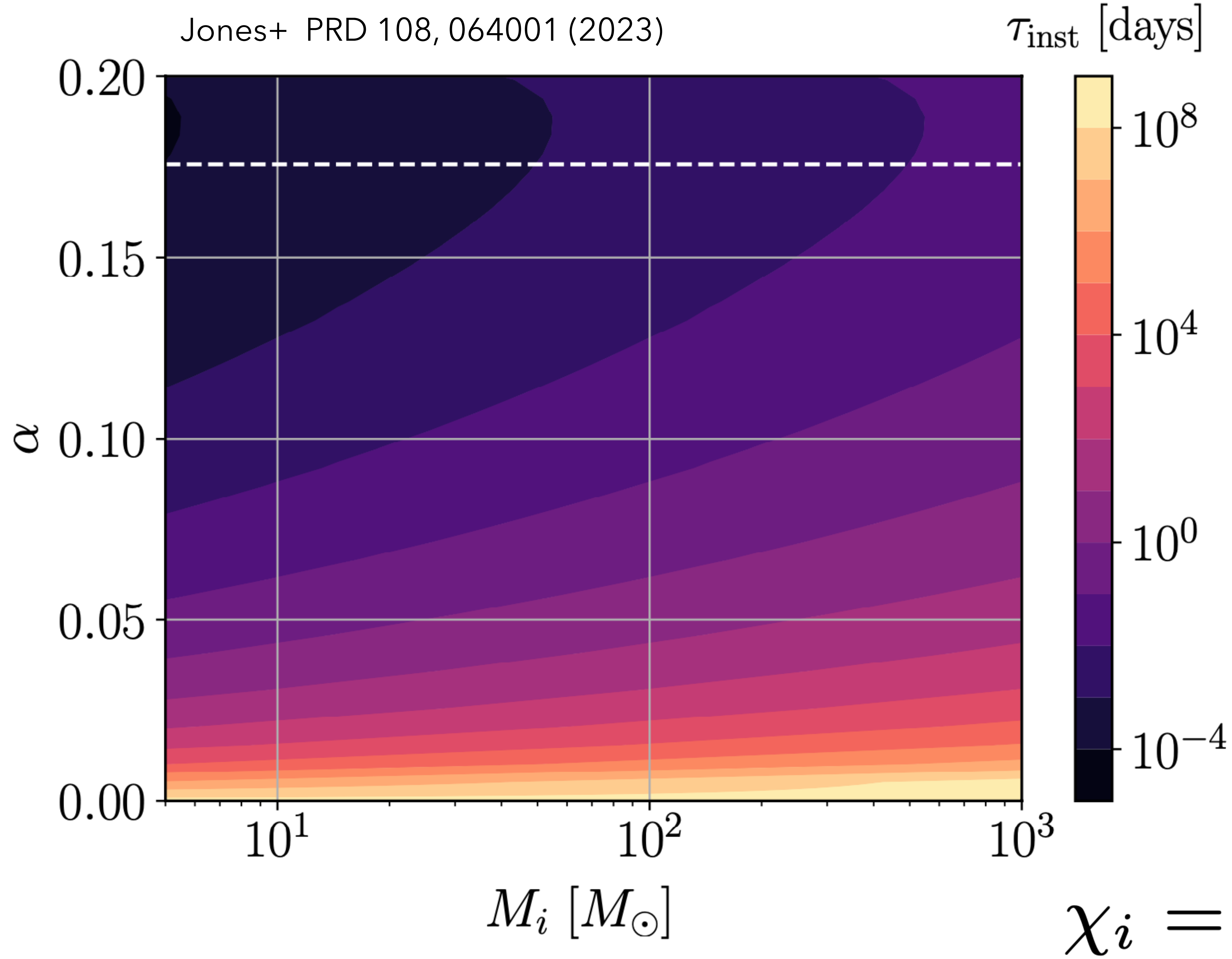
Isi, Sun, Brito, Melatos (2019)

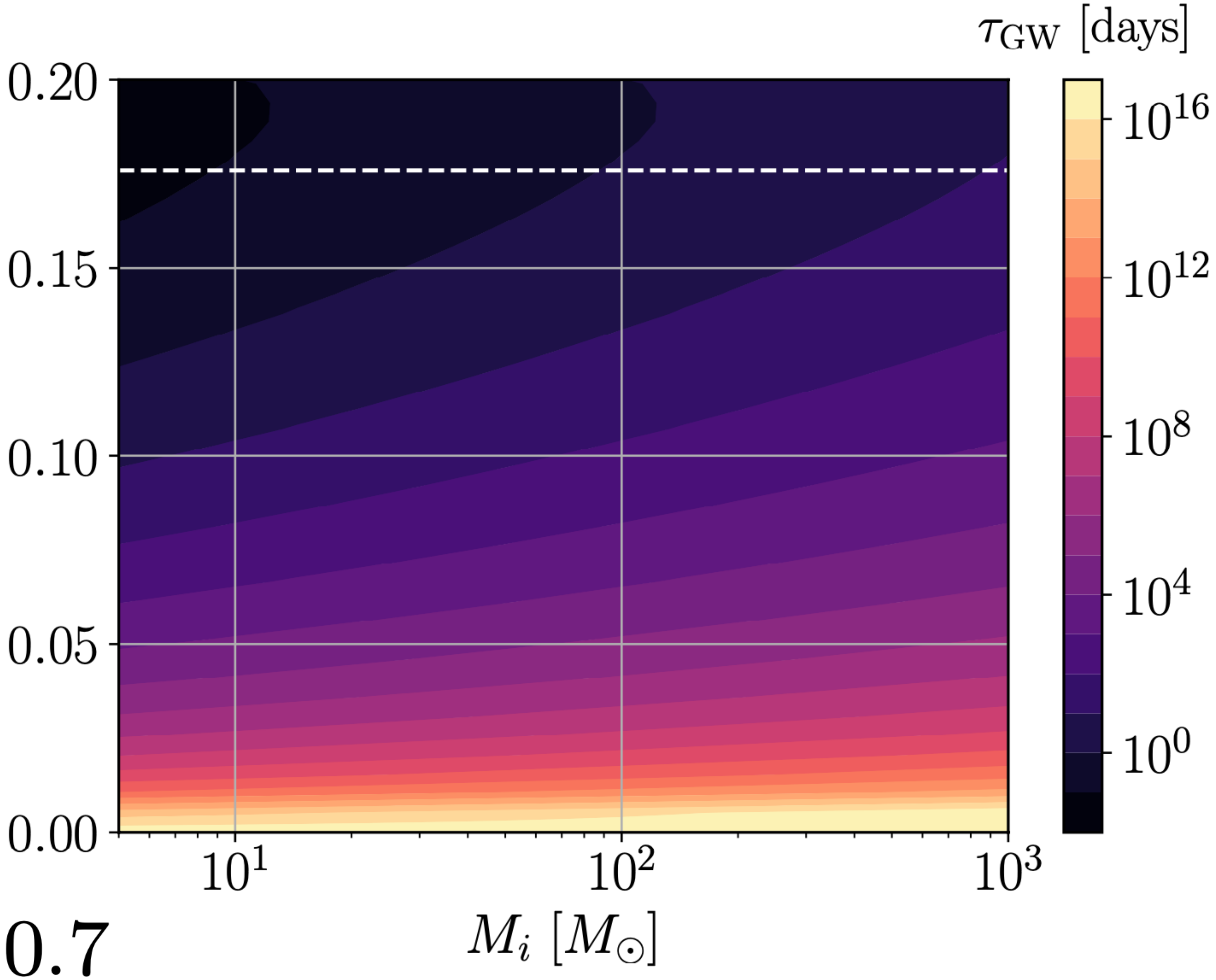
$$\alpha \equiv \frac{r_g}{\lambdabar_\mu} = \frac{GM}{c}\frac{m_b}{\hbar}$$

$$\tau_{\rm inst}^{(\rm s)} \approx 27\,\mathrm{days}\left(\frac{M}{10\ M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^9\frac{1}{\chi_i}$$

$$\tau_{\rm GW}^{(\rm s)} \approx 6.5\times 10^4\ \mathrm{yr}\left(\frac{M}{10\ M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^{15}\frac{1}{\chi_i}$$

GW signal timescales (vector)


Jones+ PRD 108, 064001 (2023)



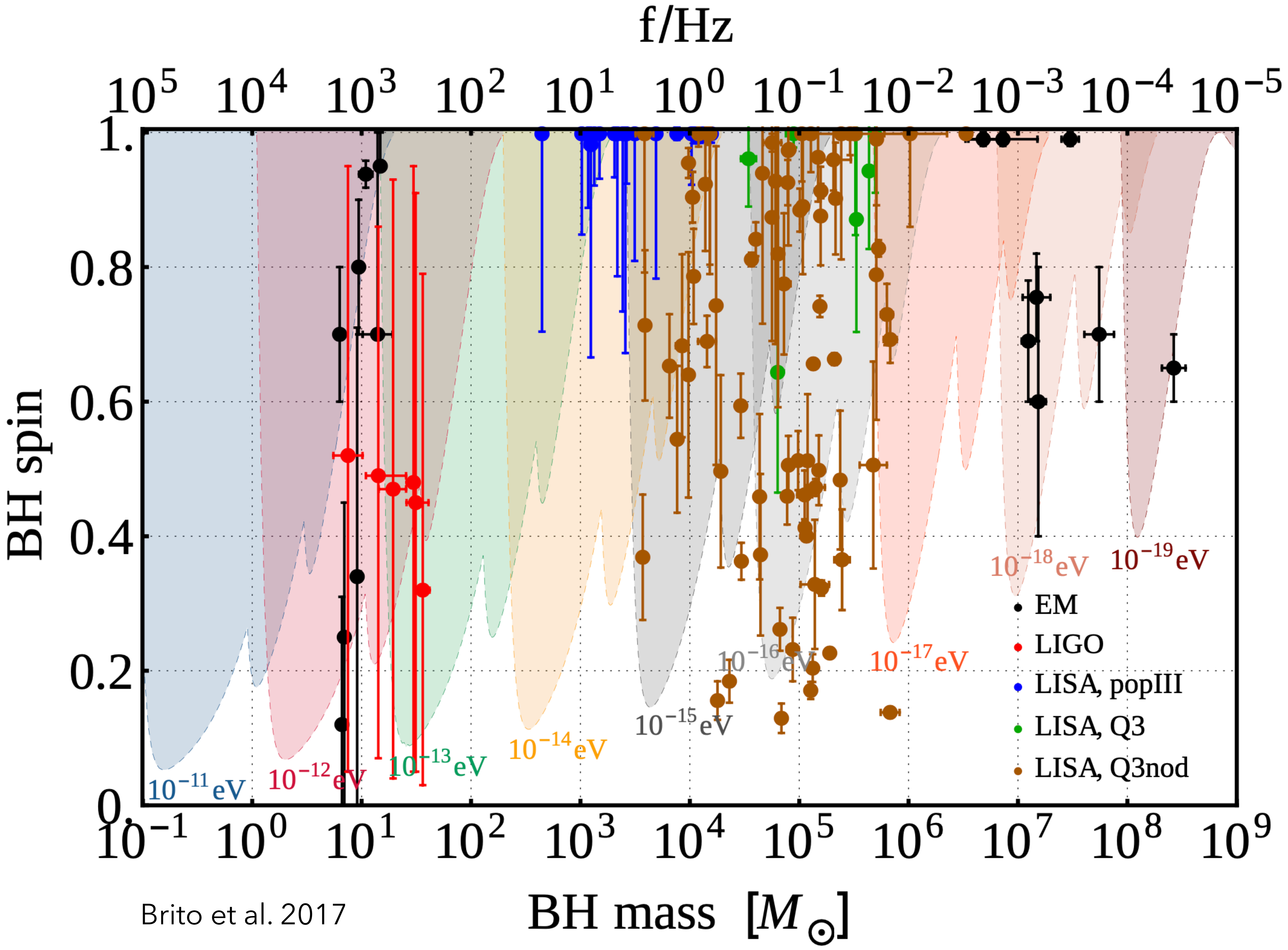
$$\chi_i = 0.7$$

$$\tau_{\rm GW} \approx 33 \text{ days} \left(\frac{M}{10 M_\odot}\right) \left(\frac{0.1}{\alpha}\right)^{11} \left(\frac{0.1}{\chi_i - \chi_f}\right)$$

Population and stochastic background studies

- ***Constraints obtained from black hole spin measurements***

e.g. [Arvanitaki et al. 2017, Brito et al. 2017, Baryakhtar et al. 2017, Cardoso et al. 2018, Ng et al., PRD 2021, Ng et al. PRL 2021]



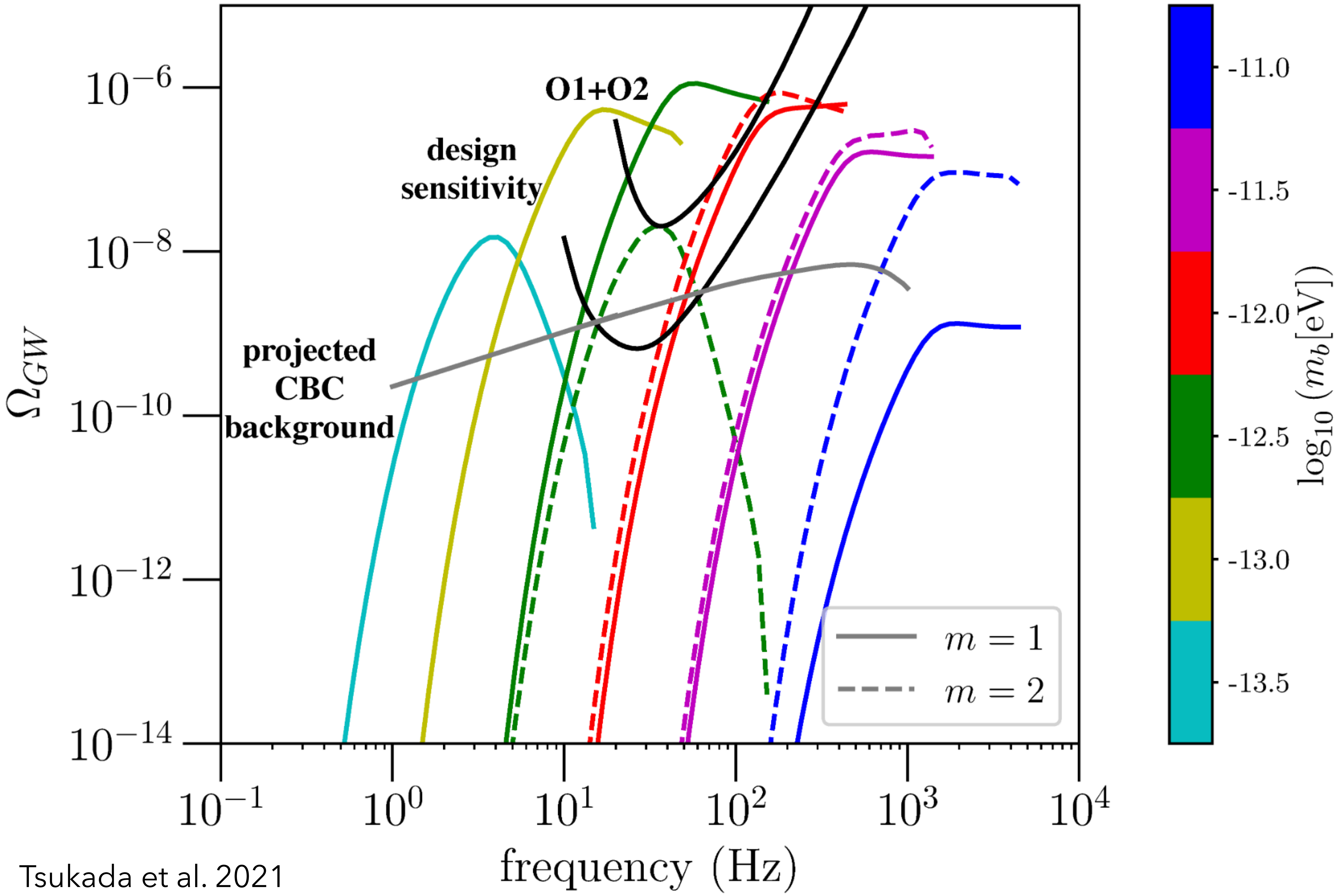
Brito et al. 2017

- *Exclusion regions in the BH mass-spin plane for a massive scalar field (l=m = 1,2,3) for a time scale of 50 Myr*
- *There are systematics and uncertainties associated with spin measurements*

Population and stochastic background studies

- ***Constraints from searches for stochastic GW background***

e.g. [Tsukada et al. 2019, Tsukada et al. 2021, Yuan et al. 2022]



Tsukada et al. 2021

- *Constraints on vectors (O1+O2 aLIGO data) –– excluding vector boson mass ~10^{-13} eV*
- *Assumptions are made for BH population and spin distribution*

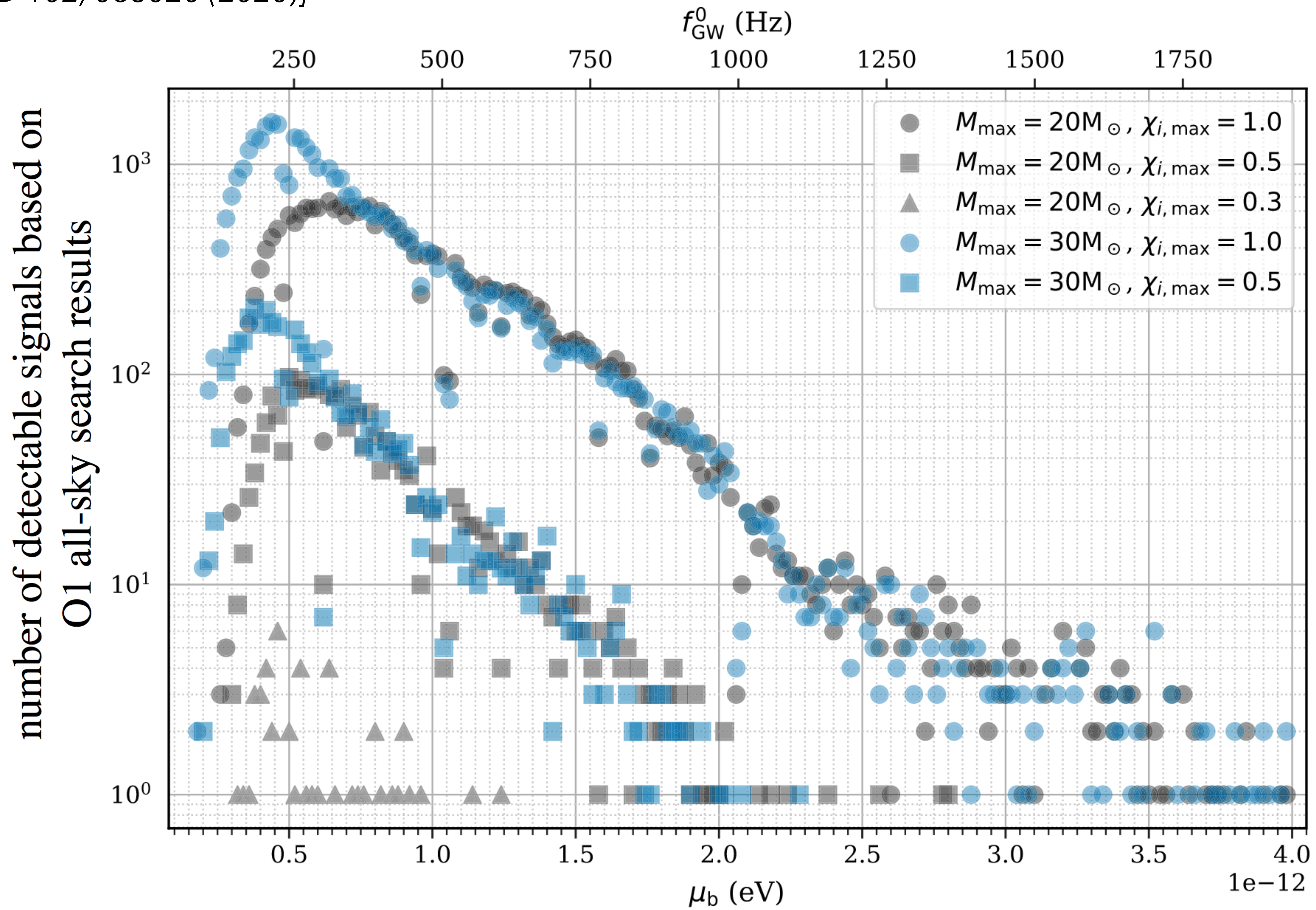
Searches for individual galactic sources

BHs in galactic X-ray binaries e.g., [Sun+ PRD 101, 063020 (2020)]	• *Well-localized* • *Unknown age and history* • *Systematics affecting the spin measurements* • *Not well understood impact from the active environment* • *Relatively low BH mass* • *Search challenges due to the binary motion*
Isolated galactic BHs e.g., [Abbott+ PRD 105, 102001 (2022), Abbott+ PRD 106, 042003 (2022)]	• *Clean environment, no impact from binary motion* • *Unknown location (need an all-sky blind search)* • *Contingent on BH populations* • *Unknown age, spin, etc.*

Searches for individual galactic sources

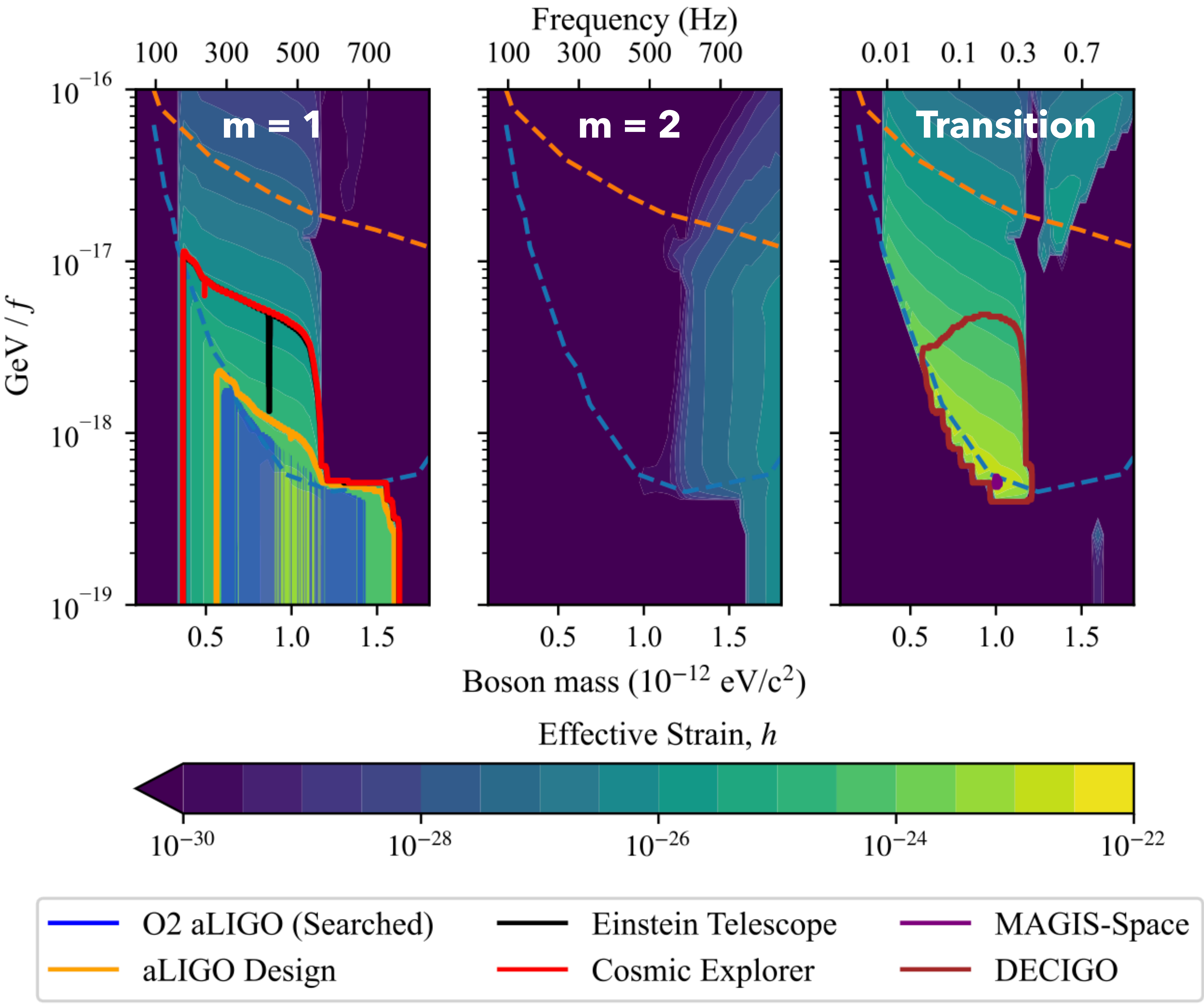
- ***There may be plenty of detectable sources in our galaxy (if the bosons exist)***

[Zhu et al., PRD 102, 063020 (2020)]



Relax the assumption — consider self interactions (scalar)

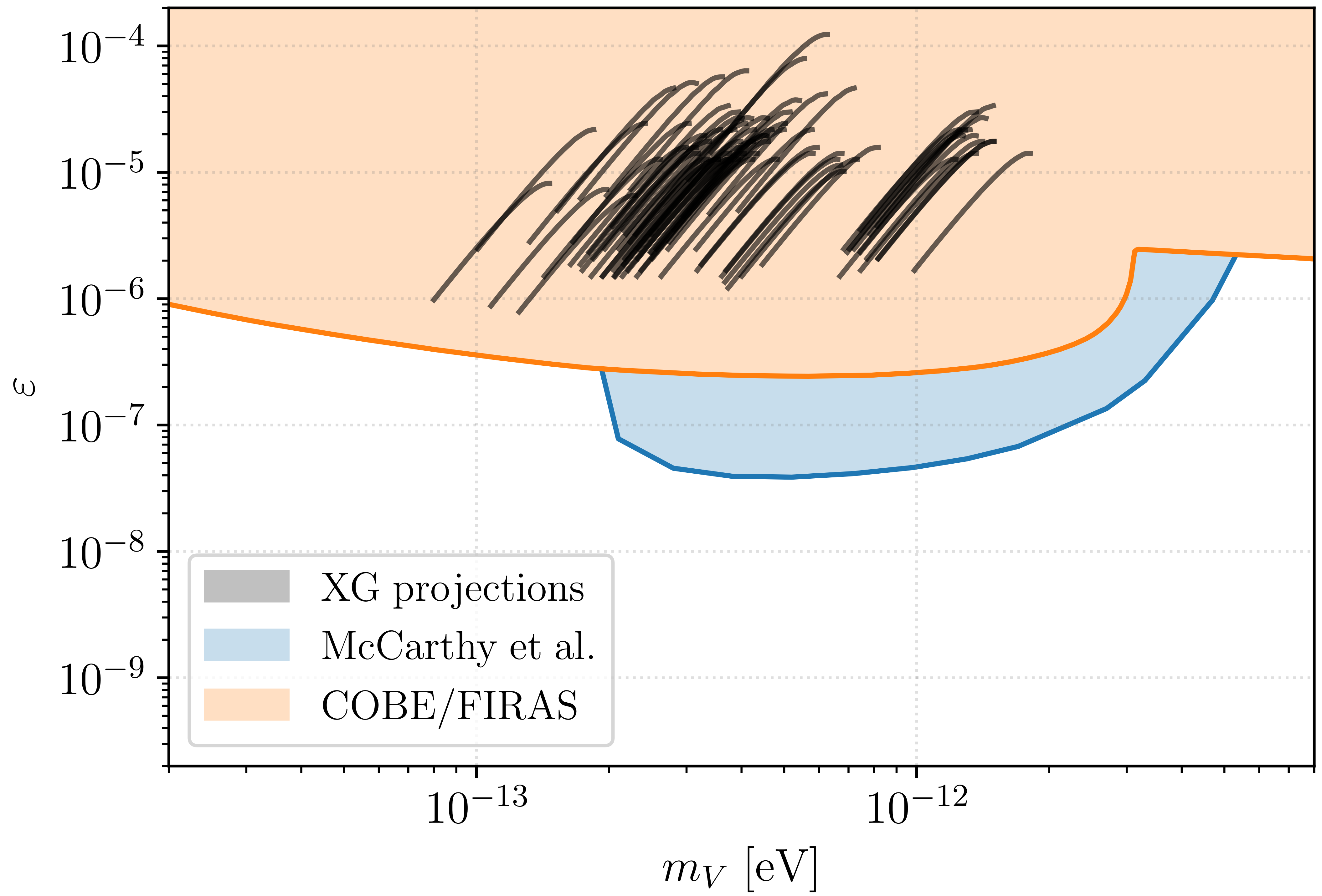
- *Self-interaction leads to smaller clouds and faster growth of the next level*
- *Constraints from Cygnus X-1 O2 search and future prospects considering boson self-interaction (assuming a BH age of 10^5 year)*
- *There are potential observational prospects of level transition signals*
- *Further numerical studies in high boson mass regime that capture full dynamics of the cloud will facilitate future searches*

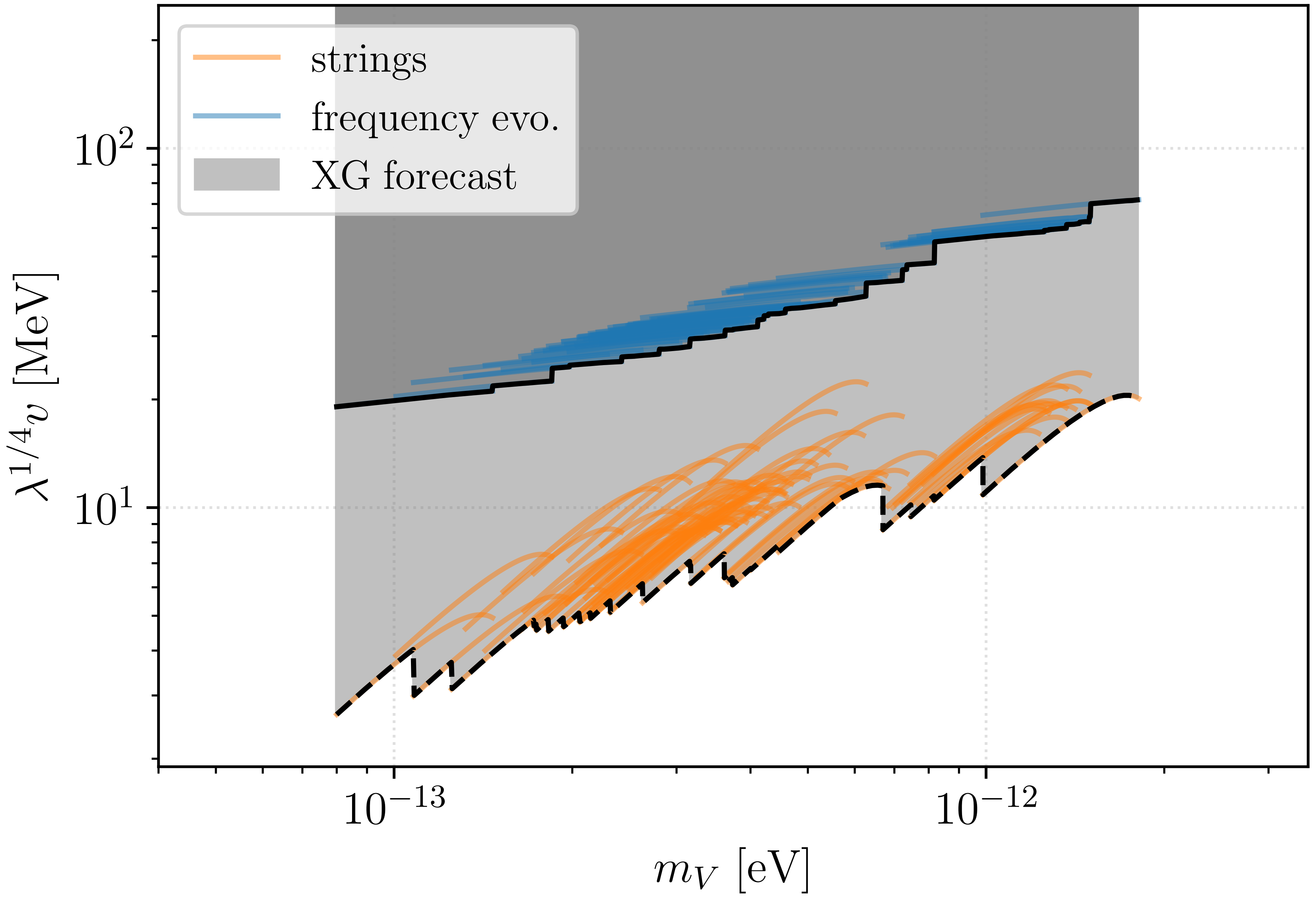


Collaviti+ (2024), Baryakhtar+ (2021)

Relax the assumption — consider weak couplings (vector)

Jones+ in prep (2024)





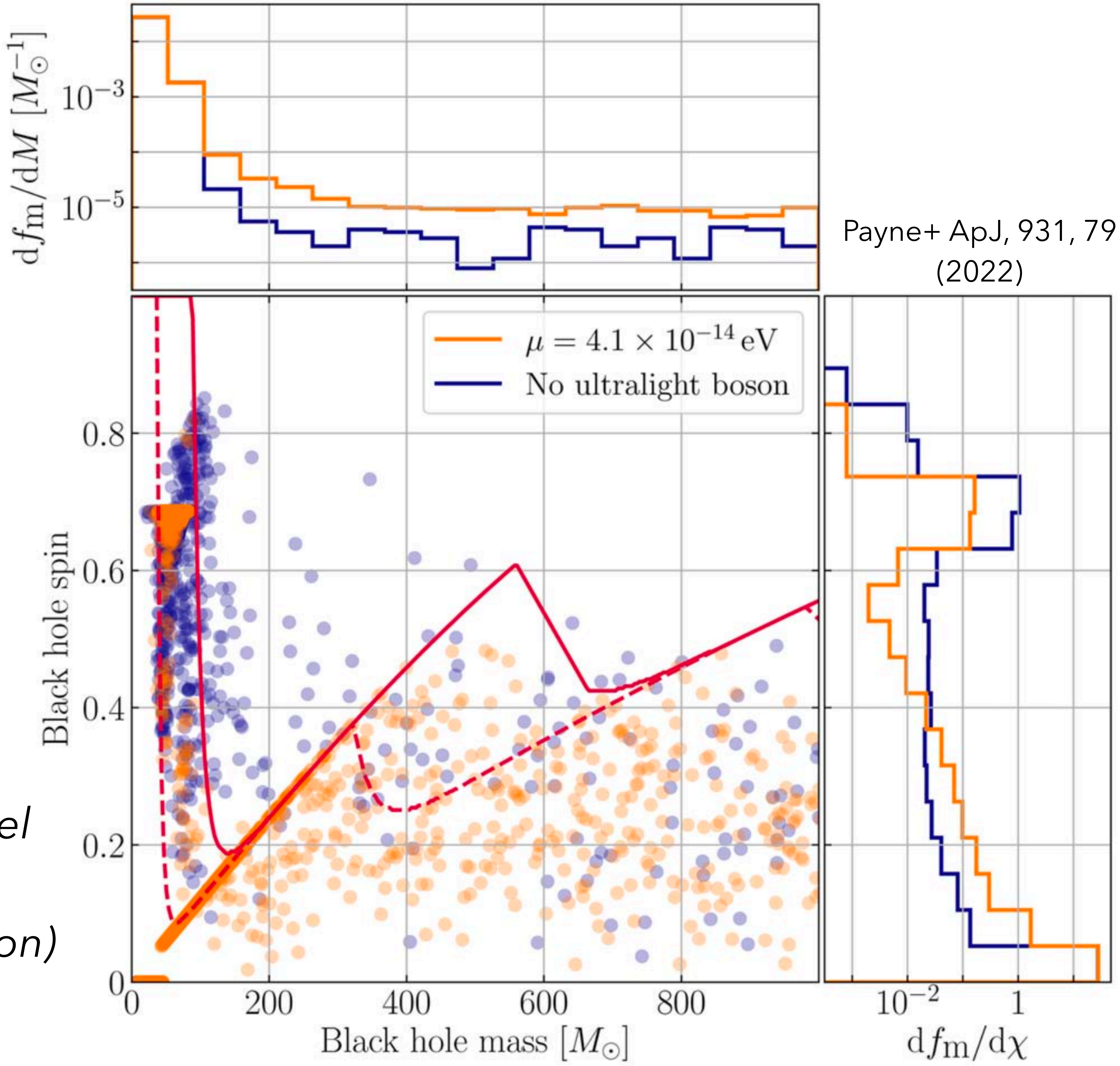
- *Test weak coupling of kinetically mixed dark photon —— With a non-vanishing kinetic mixing, the superradiant cloud also dissipates energy through electromagnetic radiation.*

- *Test the dark Higgs-Abelian sector —— Depending on the relevant coupling strengths, the presence of the Higgs boson may lead to additional frequency evolution/dark radiation or an explosive bosenova forming strings*

Imprints on hierarchical mergers

- *Hierarchical mergers in dense stellar clusters can create intermediate/massive BHs*
- *Recoil velocity can kick the remnant BH out of the dense stellar environment*
- *Low-spin progenitor BHs lead to lower recoil velocity of the remnant*
- *Superradiance can rapidly spin down BHs and may keep more BHs in the dense stellar environment*

- *Simulate merging BH populations by evolving a model cluster population (such that it visually matches the observed nuclear star cluster population after evolution)*



Payne+ ApJ, 931, 79 (2022)