Title: Nuclear astrophysics with gravitational wave observations

Speakers: Jocelyn Read

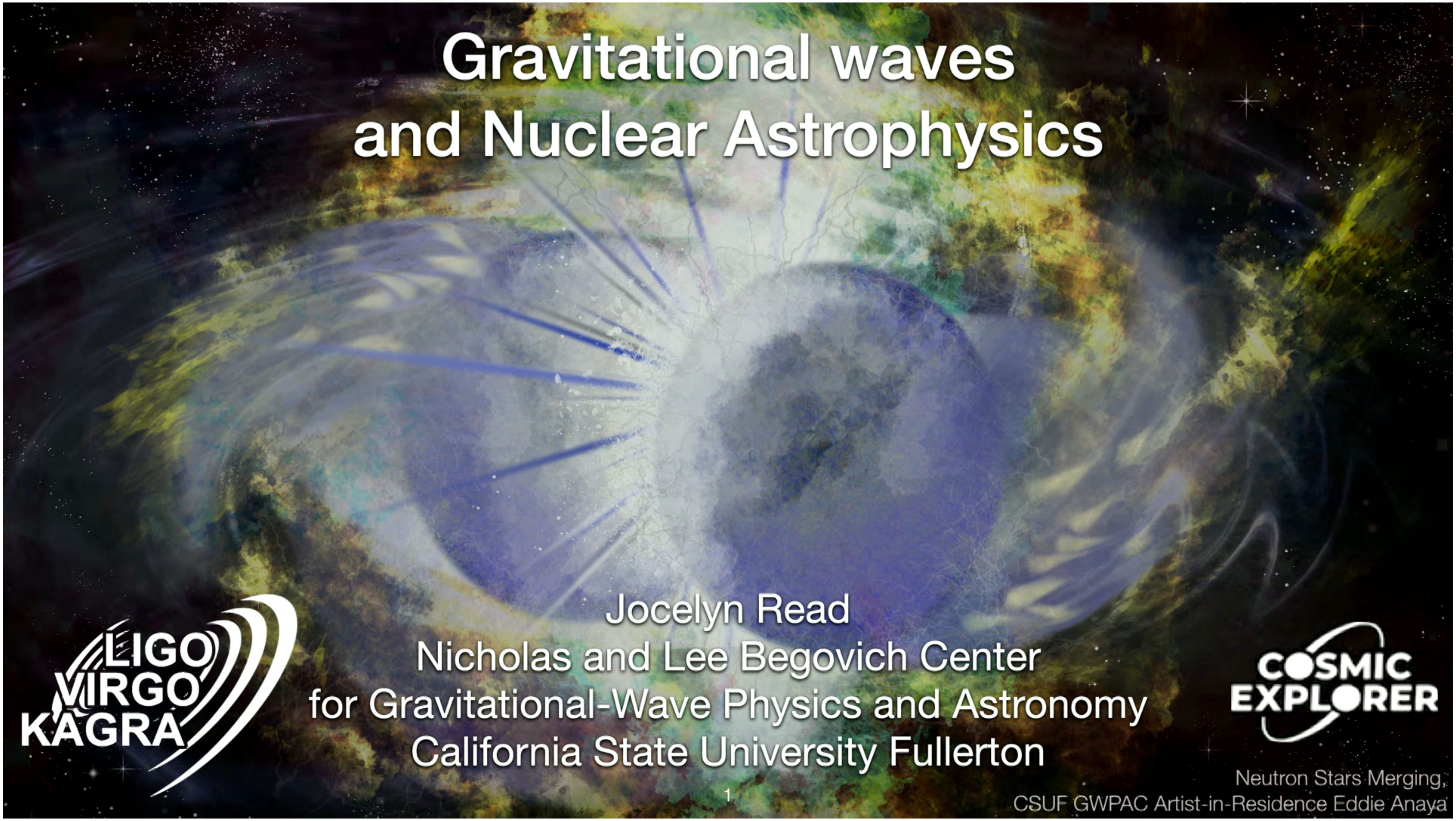
Series: Colloquium

Date: December 13, 2023 - 2:00 PM

URL: https://pirsa.org/23120019

Abstract: Gravitational-wave observatories have established a new field of transient astronomy. The most recent LIGO-Virgo-KAGRA catalog, GWTC-3, identified 90 merging binaries, which range from a double neutron star with a total mass of 2.7 at 40 Mpc (GW170817) to a double black hole with a total mass of 150 at 5.3 Gpc (GW190521). These observations have many connections to nuclear astrophysics. They are revealing the remnants of stellar evolution and supernovae in merging binary systems, they are constraining event rates and astrophysical environments for heavy-element nucleosynthesis, and they are illuminating the dense matter dynamics inside the cores of merging neutron stars. Here, I will describe the imprint of dense matter on gravitational waves, the implications of existing observations for nuclear physics, and some prospects for the coming years including the science potential of proposed next-generation observatories like Cosmic Explorer.

Zoom link https://pitp.zoom.us/j/99015121355?pwd=NStOc2srbEJXdW9aSTJJbDk4RWZhdz09



Gravitational waves and Nuclear Astrophysics

Jocelyn Read
Nicholas and Lee Begovich Center
for Gravitational-Wave Physics and Astronomy
California State University Fullerton

Neutron Stars Merging,
CSUF GWPAC Artist-in-Residence Eddie Anaya

- Fundamentals of gravitational-wave astronomy
- Using gravitational waves to learn about:
    - What physics governs the lives and deaths of stars?
    - What is the origin of the elements?
    - What's inside a neutron star?
- Going deeper: Modeling gravitational-wave sources
- Future detectors

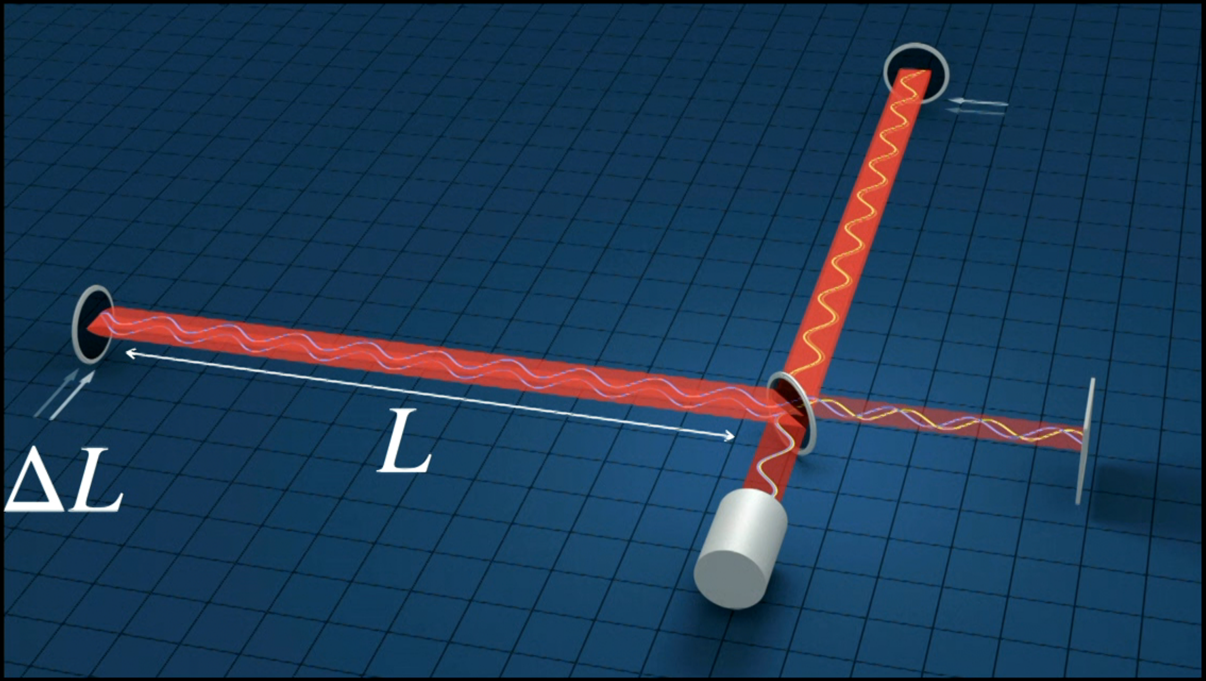
GW: Mass in motion

- Curvature of spacetime changes around moving objects → change propagates at speed of light
- Linearized Einstein Equations of General Relativity → wave equation
- Metric change modifies the distance between freely-falling objects

Moon passing Earth
as seen from NASA's DSCOVR spacecraft (NASA/NOAA)
at the L1 Point between the Earth and the Sun, 5 light seconds from Earth

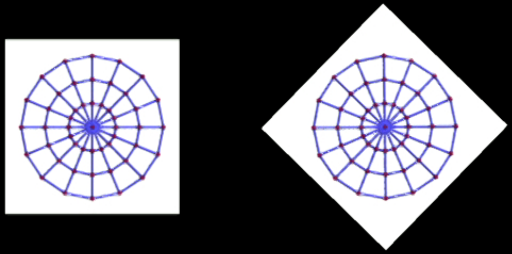
GW: Strain

Test masses follow stretch and squeeze of spacetime



Gravitational-wave strain

$$h = 2\frac{\Delta L}{L}$$



Sources of gravitational waves

Oscillatory source
mass M, size s, frequency f
Distance to source r

Quadrupole moment $Q \sim Ms^2$

$$h \sim \frac{\ddot{Q}}{r} \sim GM\frac{f^2}{c^4}\frac{s^2}{r}$$

Sources of gravitational waves

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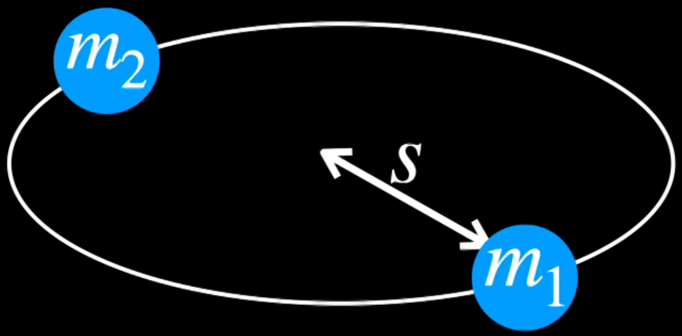
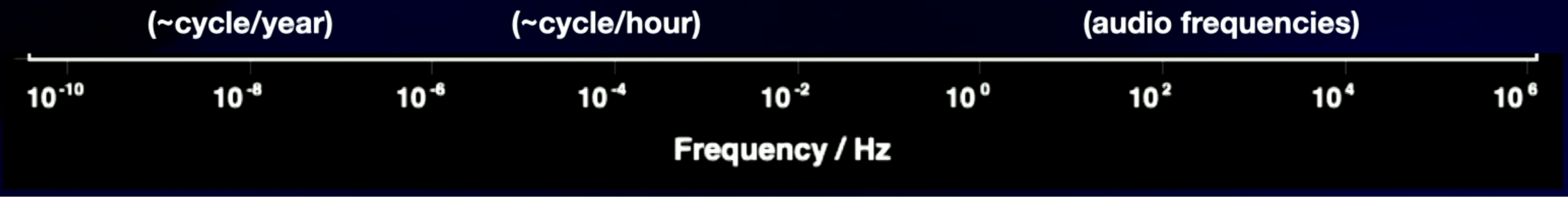


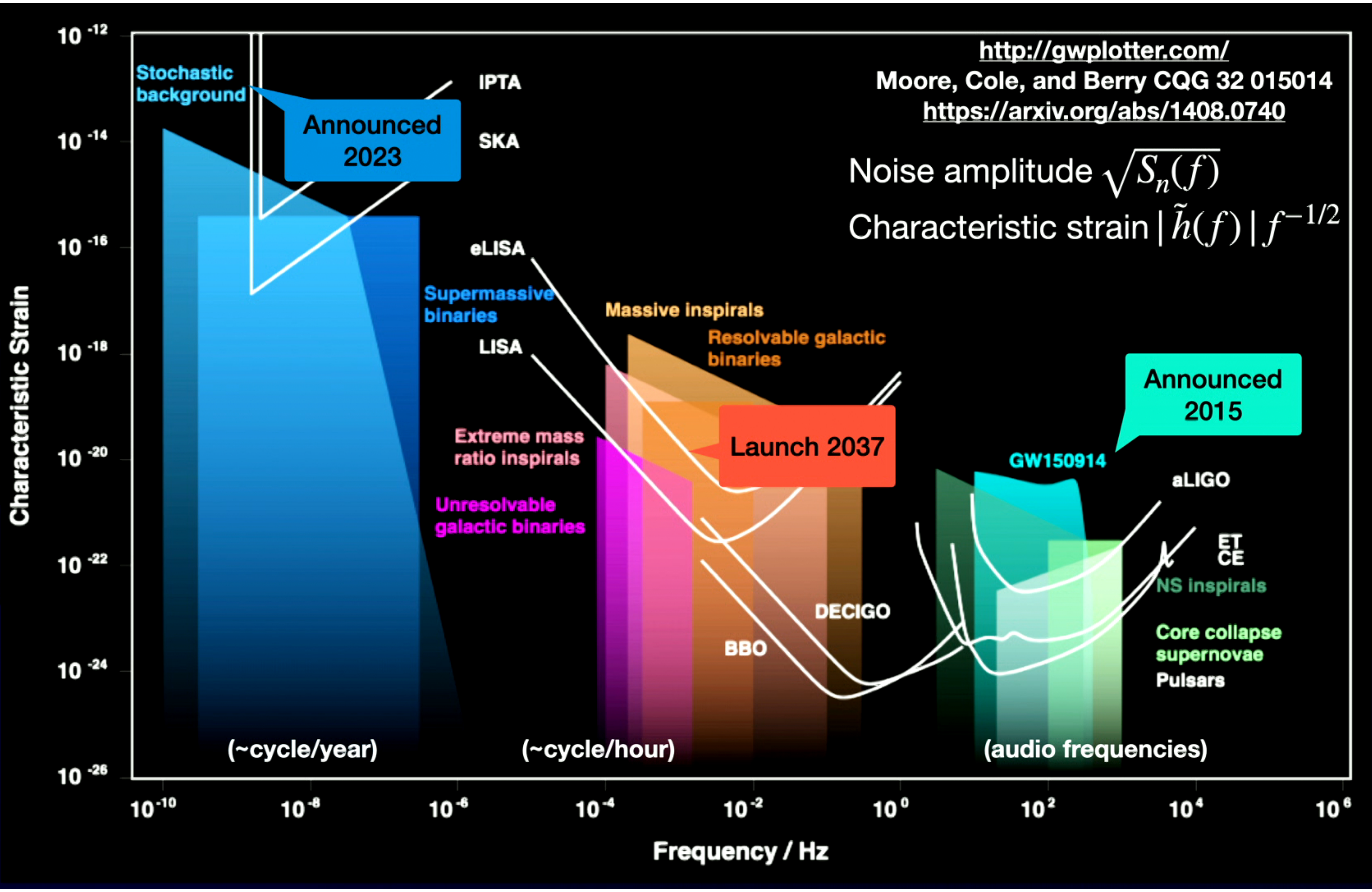
Quadrupole moment $Q \sim Ms^2$

$$h \sim \frac{\ddot{Q}}{r} \sim GM\frac{f^2}{c^4}\frac{s^2}{r} \sim \frac{G}{c^2}\frac{M}{r}\frac{v_\perp^2}{c^2}$$

e.g. binary orbit with:
mass M, size s, orbital frequency f

The Gravitational-wave Spectrum





Announced 2023

Launch 2037

Announced 2015

http://gwplotter.com/

Moore, Cole, and Berry CQG 32 015014

https://arxiv.org/abs/1408.0740

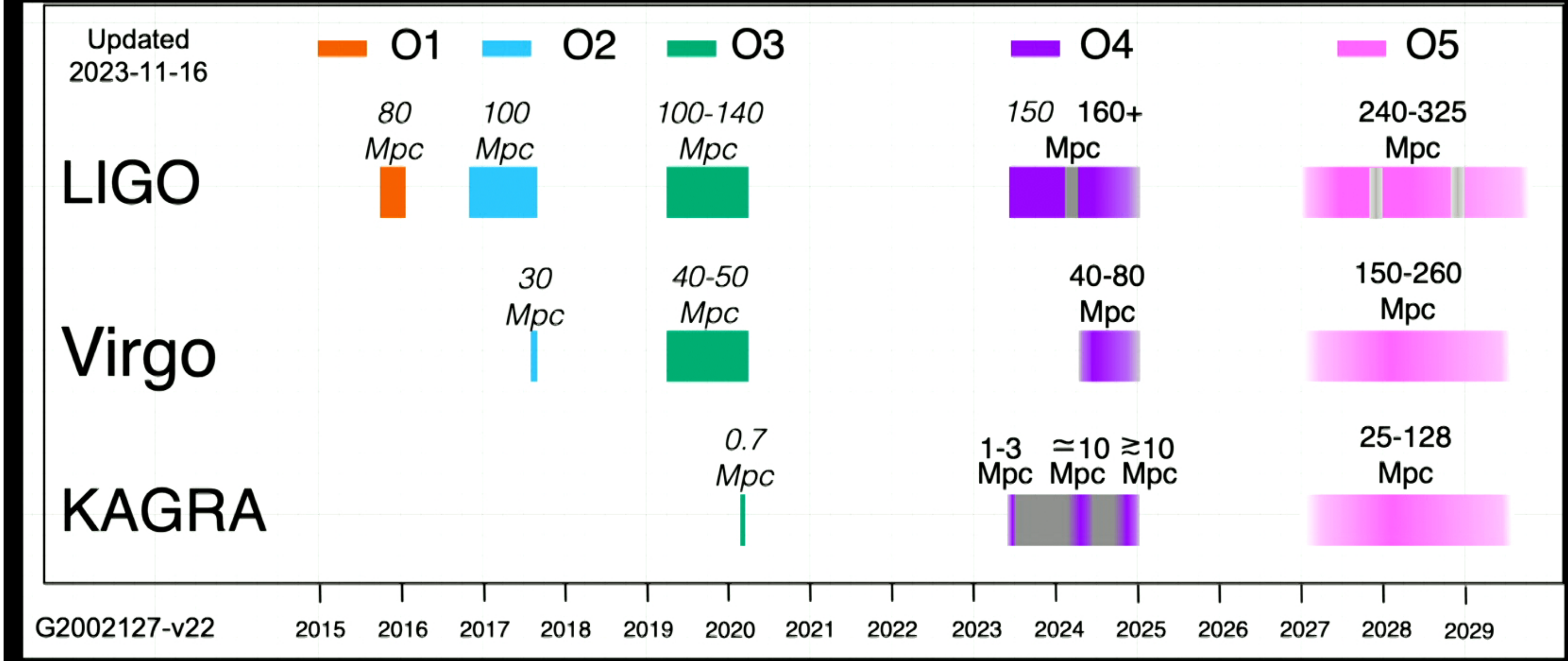
Noise amplitude $\sqrt{S_n(f)}$

Characteristic strain $|\tilde{h}(f)|\, f^{-1/2}$

Ground-based gravitational-wave observatories

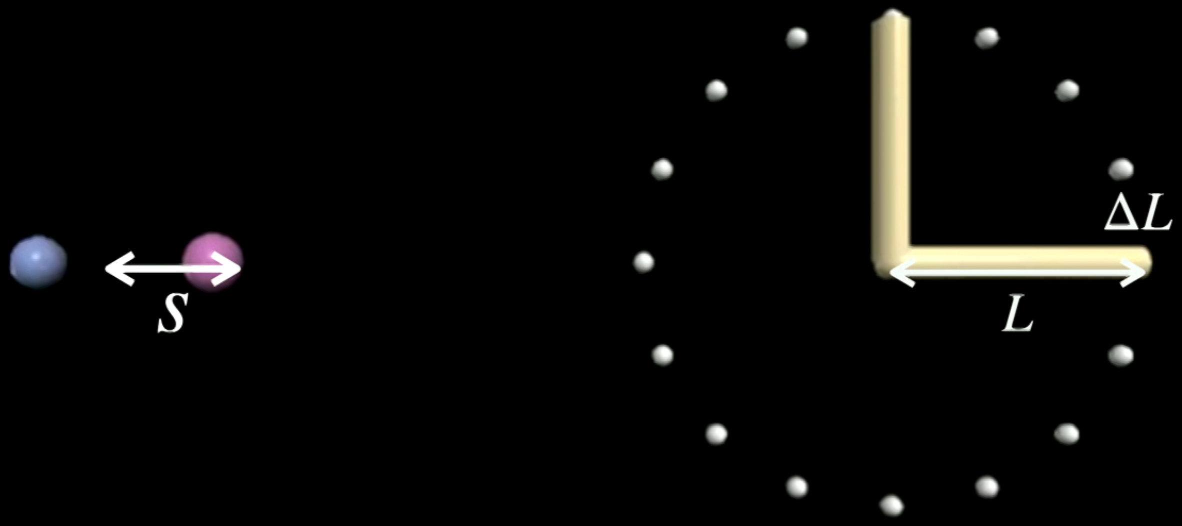
https://observing.docs.ligo.org/plan/

Observing in the “Advanced” Era

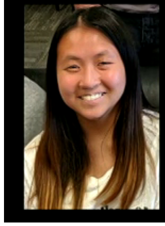


Ranges: Sky average distance to double neutron star with SNR 8

Compact binary source



$$h = 2\frac{\Delta L}{L} \sim 10^{-21}\frac{100\text{ Mpc}}{r}\frac{M}{1.4\,M_\odot}\frac{R_S}{s}$$



Movie by
Megan Loh, CSUF

https://www.youtube.com/watch?v=loZIgl

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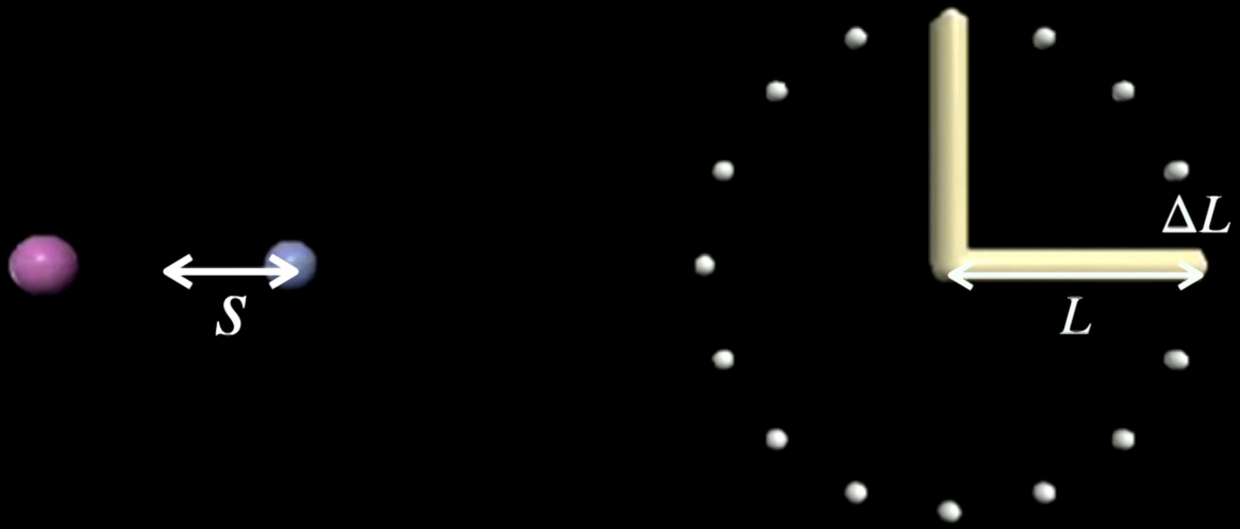
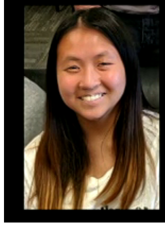


GW energy flux $\sim f^2 h^2$, integrate over sphere $\sim r^2$



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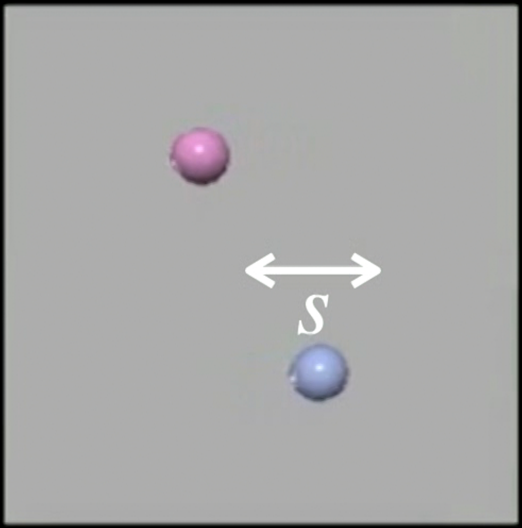
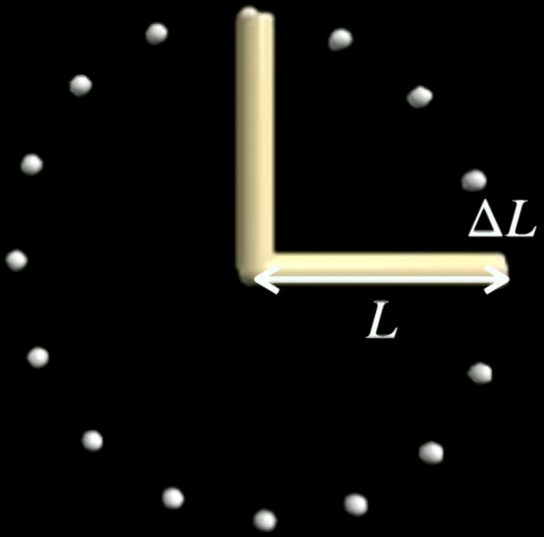
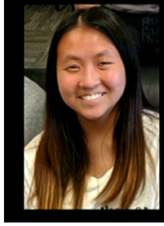




GW energy flux $\sim f^2h^2$, integrate over sphere $\sim r^2$

$$\mathscr{L}_{GW} \sim \frac{c^5}{G}\left(\frac{R_S}{s}\right)^2\left(\frac{v}{c}\right)^6 \sim 10^{59}\ \text{erg s}^{-1}\frac{R_S}{s}$$



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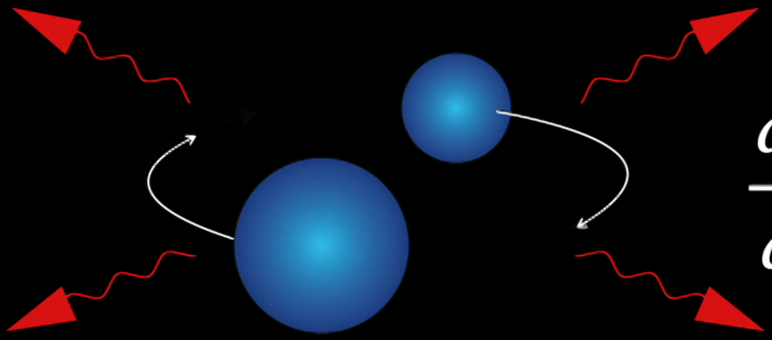
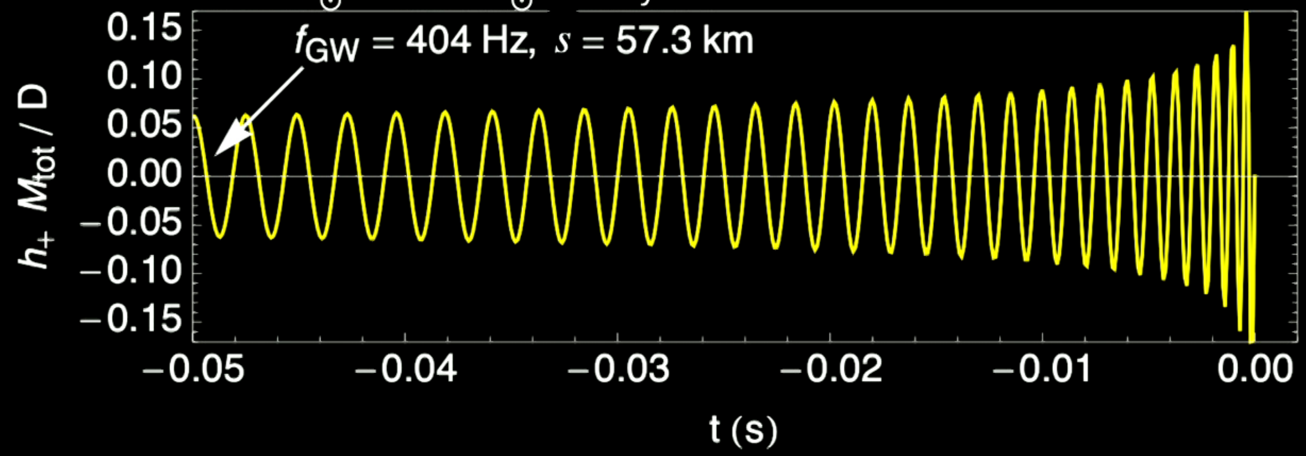
The “chirp”

$$\frac{dE}{dt} = -\mathscr{L}_{GW}$$

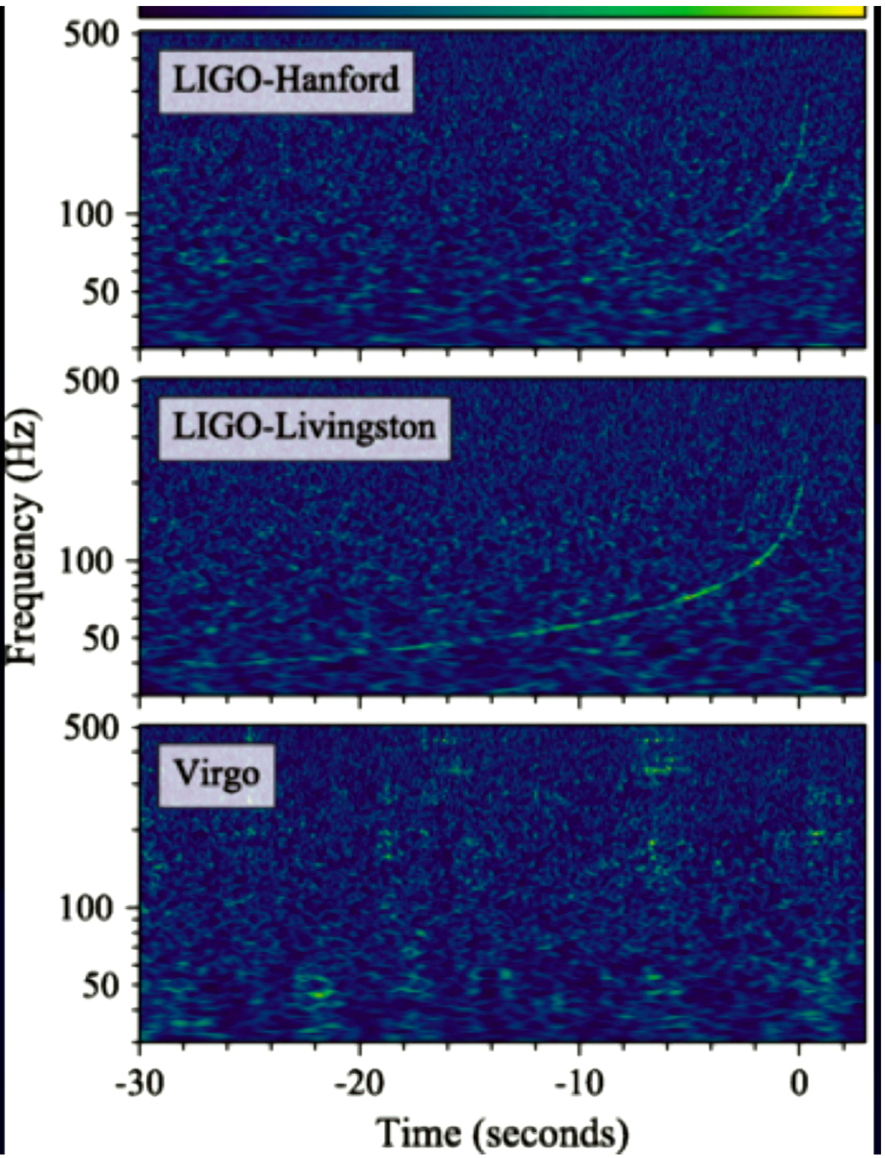


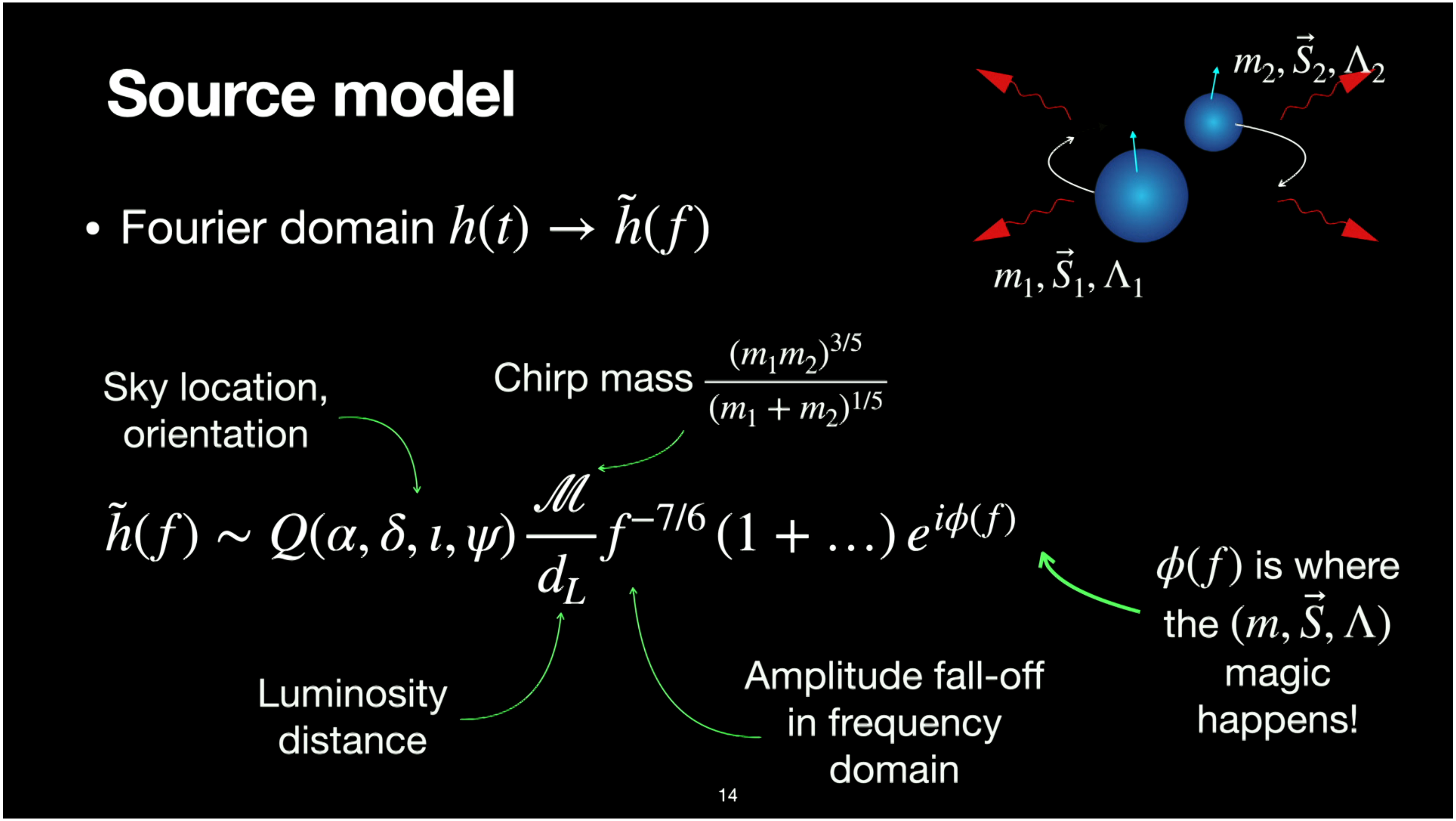
$$\frac{ds}{dt} = \frac{-\mathscr{L}_{GW}}{dE_{orb}(s)/ds}$$

$1.35\,M_\odot - 1.35\,M_\odot$ binary



How do we interpret observational data?





Source model

- Fourier domain $h(t) \to \tilde{h}(f)$

$m_2, \vec{S}_2, \Lambda_2$

$m_1, \vec{S}_1, \Lambda_1$

Sky location, orientation

Chirp mass $\frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$

$$\tilde{h}(f) \sim Q(\alpha, \delta, \iota, \psi)\,\frac{\mathscr{M}}{d_L}\,f^{-7/6}\,(1 + \ldots)\,e^{i\phi(f)}$$

$\phi(f)$ is where the $(m, \vec{S}, \Lambda)$ magic happens!

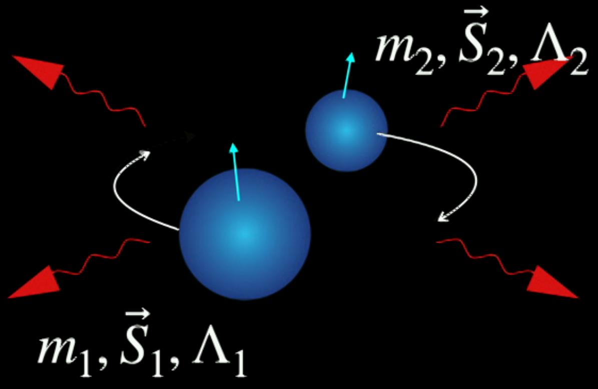
Luminosity distance

Amplitude fall-off in frequency domain

GW phase ↔ Orbital phase

$$\phi(f) = 2\pi i f t_c + \phi_c + [\text{const}]\left(\mathscr{M} f\right)^{-5/3} + \ldots$$

for inspiral a function of leading-order combinations:



- Chirp mass: $\mathscr{M} = \dfrac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$
- Mass ratio: $q = m_2/m_1$
- Effective spin: $\chi_{\text{eff}} = \dfrac{\vec{S}_1/m_1 + \vec{S}_2/m_2}{m_1 + m_2} \cdot \overrightarrow{L}$

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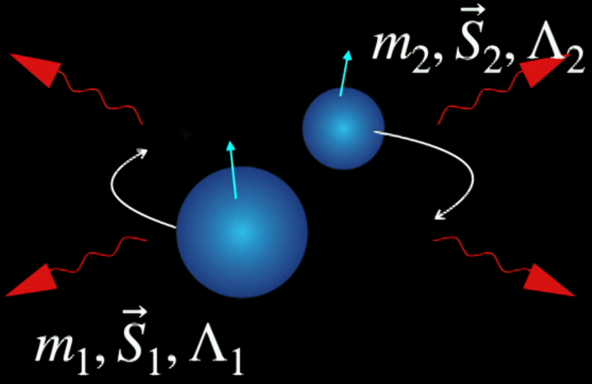

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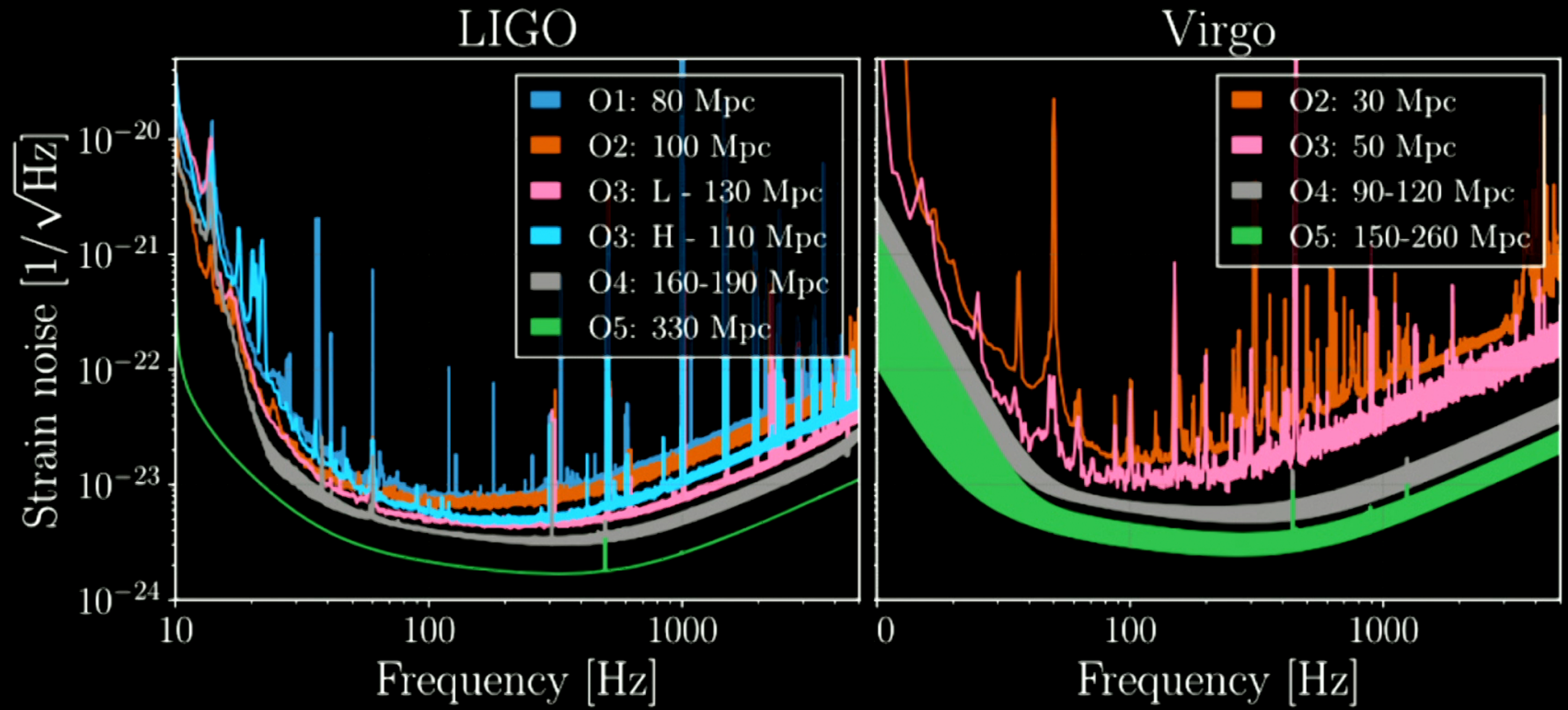
- Effective tide: $\tilde{\Lambda} = \dfrac{16}{13}\dfrac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$

Strain noise: detector spectral density $\sqrt{S_n(f)}$



LIGO-Virgo-KAGRA Observing Scenarios Living Rev Relativ 23, 3 (2020)

Template Search

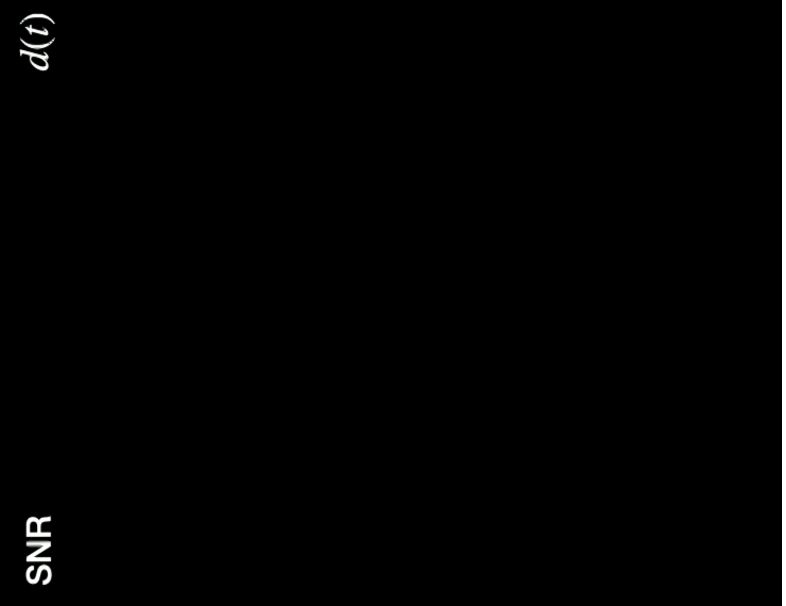
Recorded data $\tilde{d}(f)$ Candidate signal $\tilde{h}(f)$

Signal-to-noise ratio

$$\text{SNR} \propto \sum_f \frac{\tilde{d}(f)\tilde{h}^*(f)}{S_n(f)}$$

Optimal statistic in Gaussian noise

Detection pipelines build search statistics (typically some sort of χ^2 weighted SNR) to help differentiate astrophysical signal from noise transients



LIGO-Virgo-Kagra GWTC-3 Catalog, Phys. Rev. X **13**, 041039, arXiv:2111.03606, https://gwosc.org/GWTC-3/

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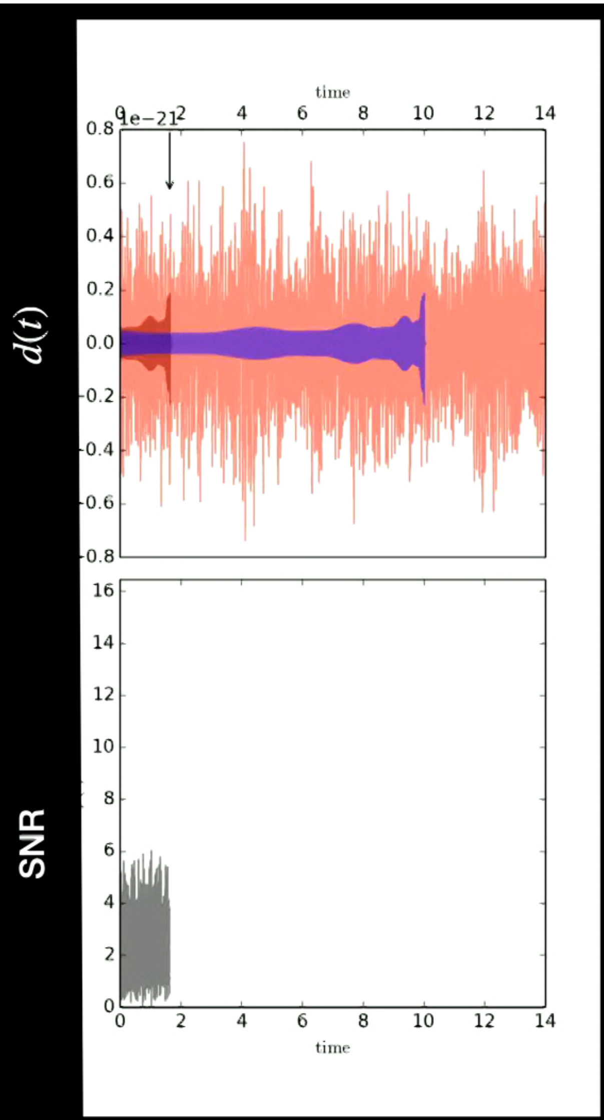
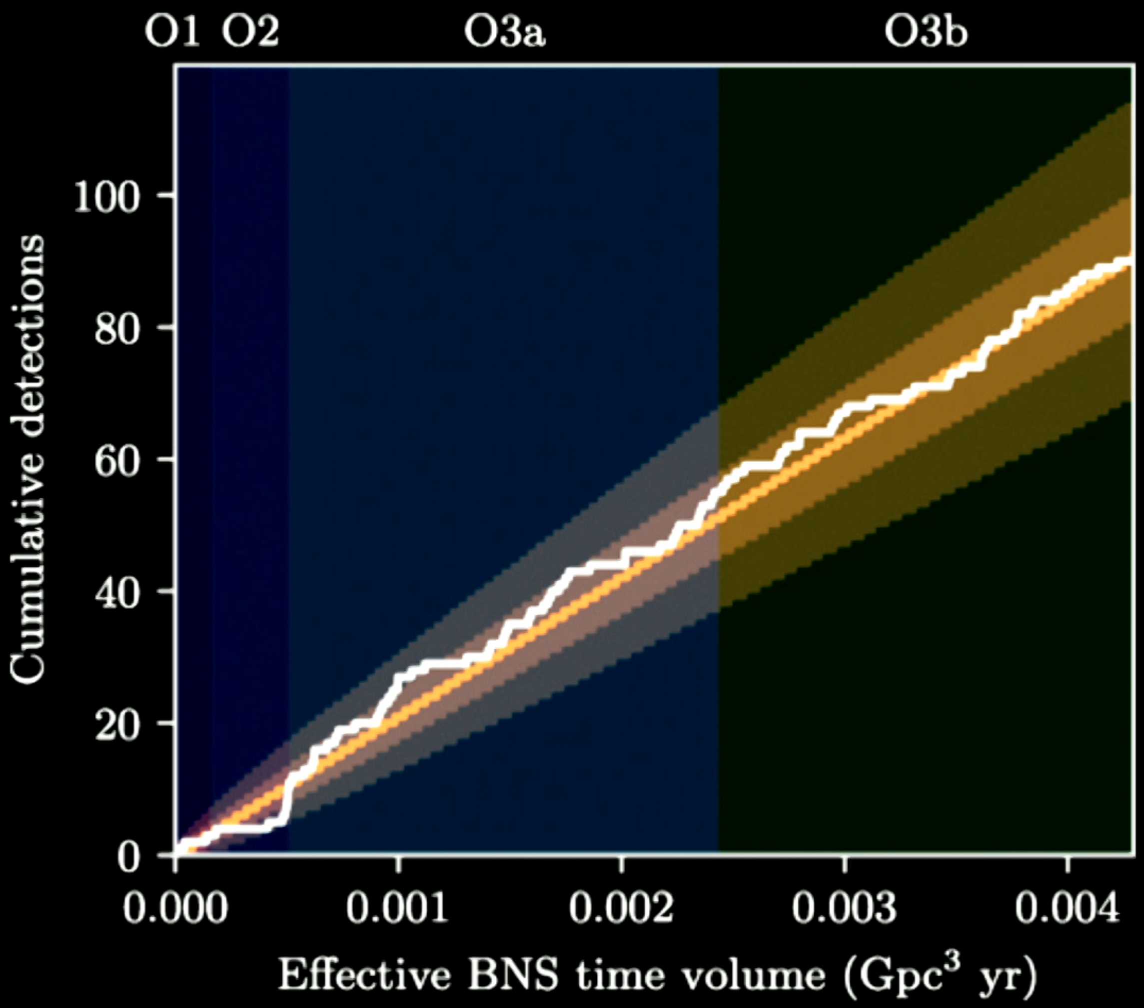


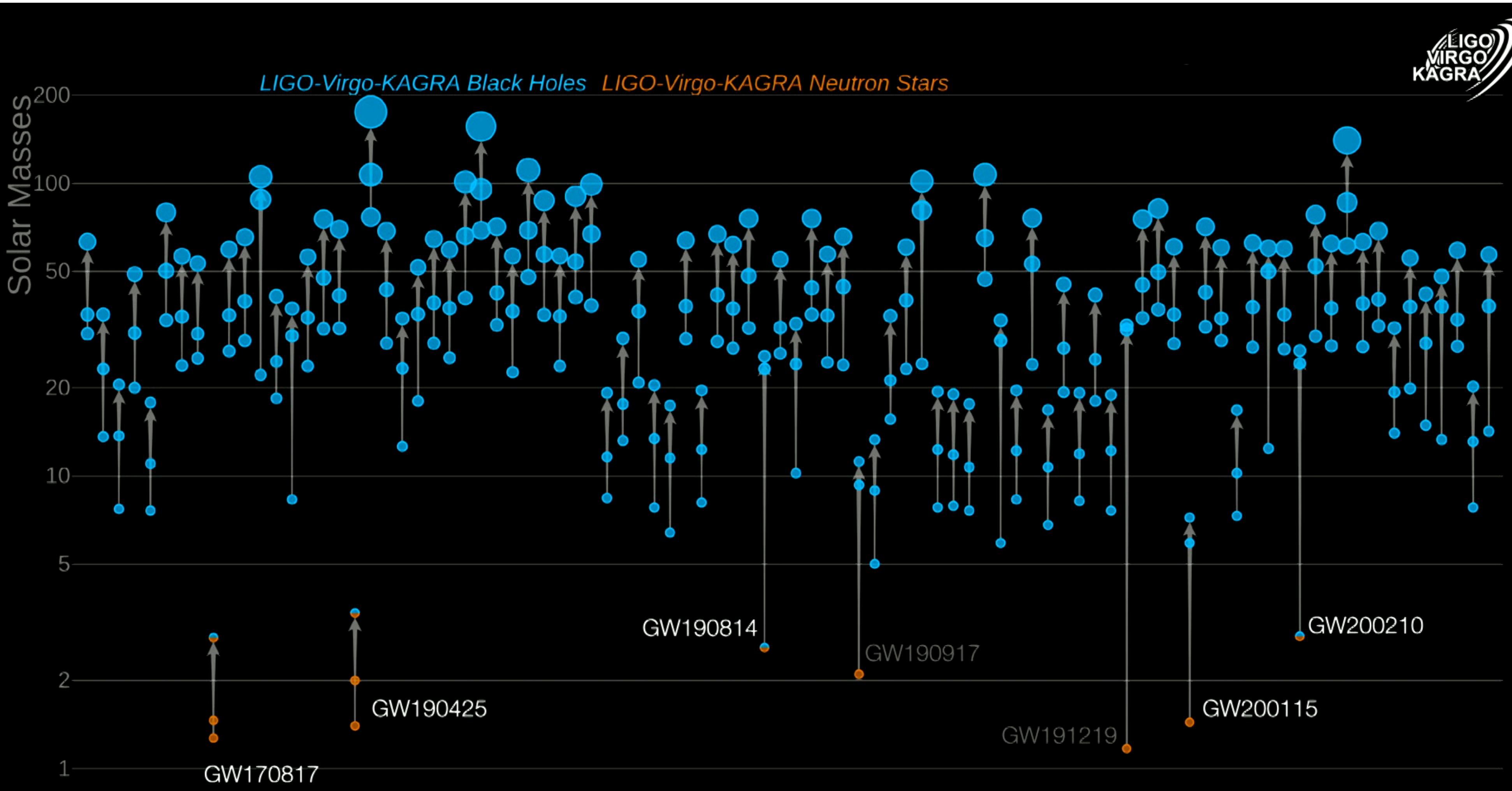
LIGO-Virgo-Kagra GWTC-3 Catalog, Phys. Rev. X **13**, 041039, arXiv:2111.03606, https://gwosc.org/GWTC-3/

Signals found

LIGO-Virgo-Kagra GWTC-3 Catalog, Phys. Rev. X **13**, 041039, arXiv:2111.03606, https://gwosc.org/GWTC-3/

Detections scale with observation time × estimated sensitive volume





LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LIGO-Virgo-Kagra GWTC-3 Catalog, Phys. Rev. X **13**, 041039,
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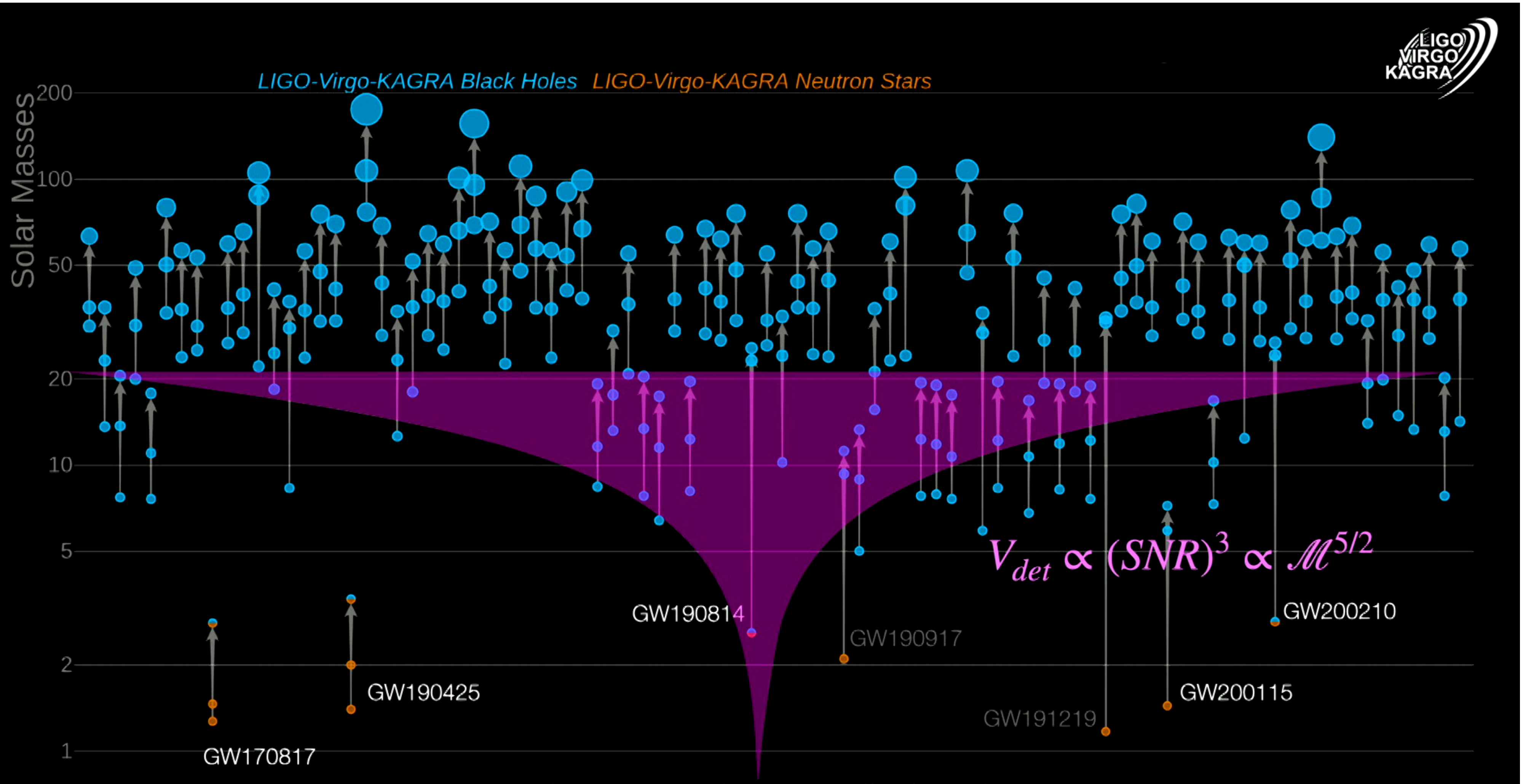
LIGO-Virgo-Kagra O3 Population, Phys. Rev. X **13**, 011048
arXiv:2111.03634 (https://dcc.ligo.org/LIGO-P2100239/)



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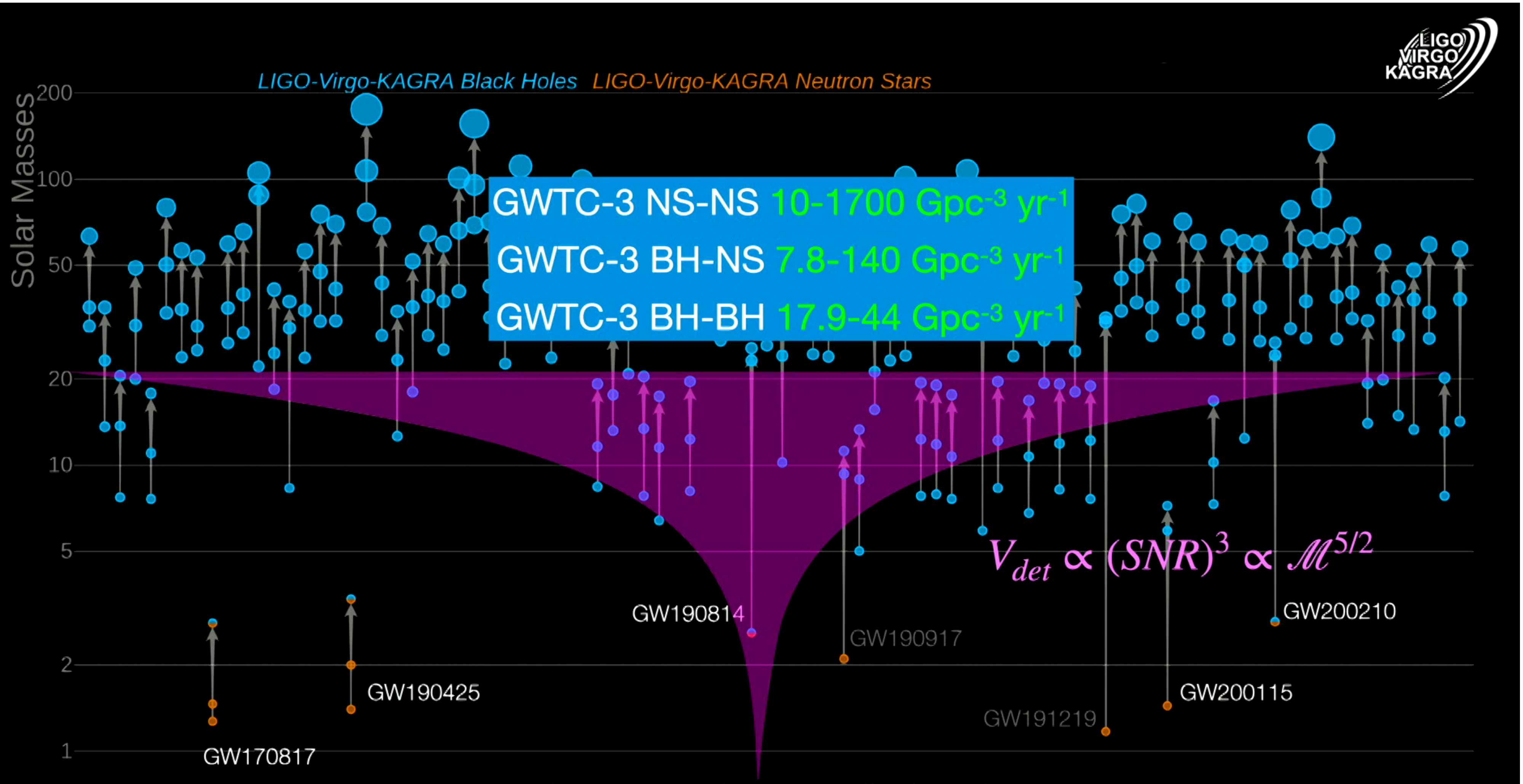

GWTC-3 NS-NS 10-1700 $\mathrm{Gpc^{-3}\,yr^{-1}}$

GWTC-3 BH-NS 7.8-140 $\mathrm{Gpc^{-3}\,yr^{-1}}$

GWTC-3 BH-BH 17.9-44 $\mathrm{Gpc^{-3}\,yr^{-1}}$

$$V_{det} \propto (SNR)^3 \propto \mathcal{M}^{5/2}$$

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LIGO-Virgo-Kagra GWTC-3 Catalog, Phys. Rev. X **13**, 041039,
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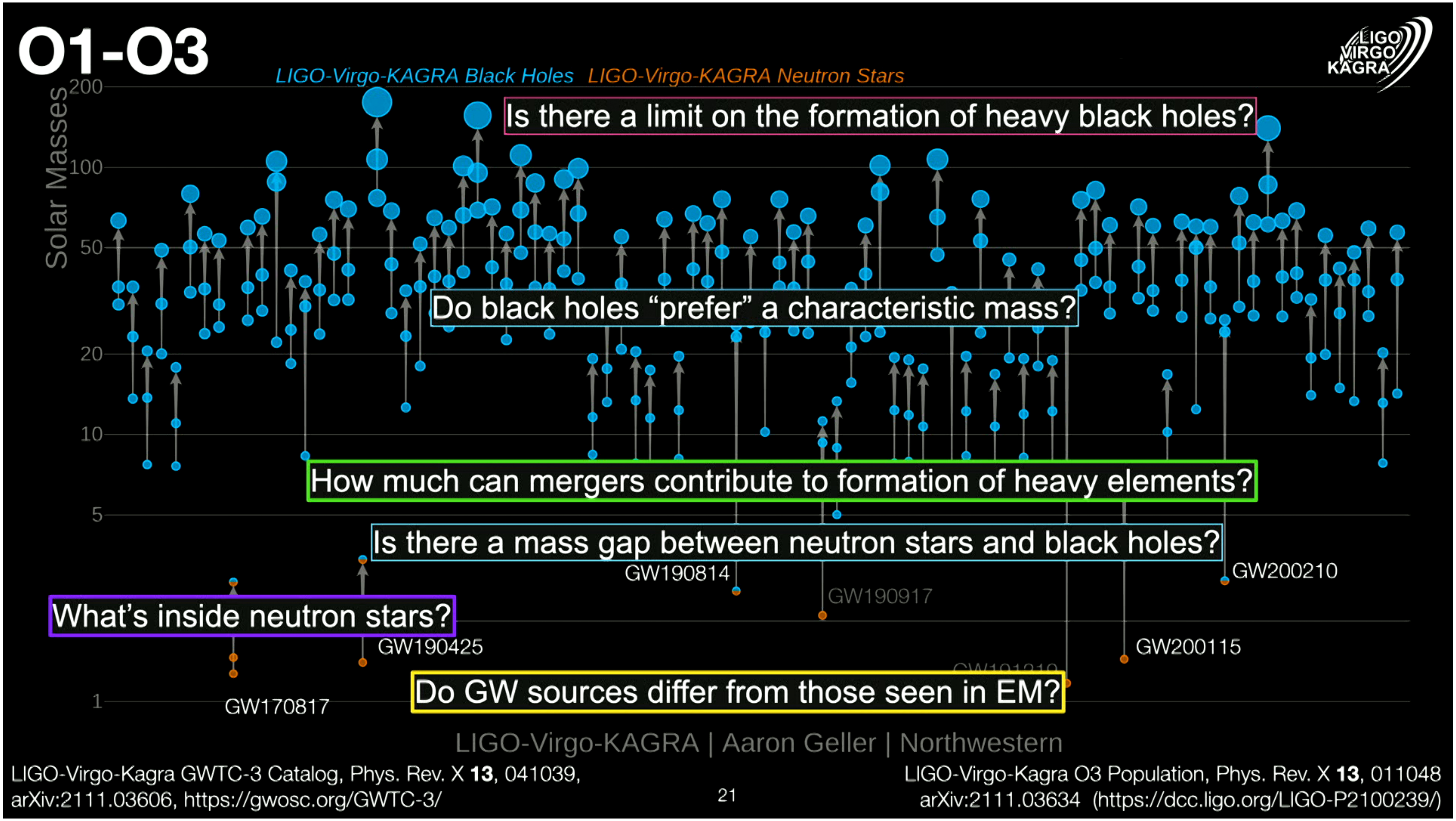
O1-O3



Is there a limit on the formation of heavy black holes?

Do black holes “prefer” a characteristic mass?

How much can mergers contribute to formation of heavy elements?

Is there a mass gap between neutron stars and black holes?

What’s inside neutron stars?

Do GW sources differ from those seen in EM?

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

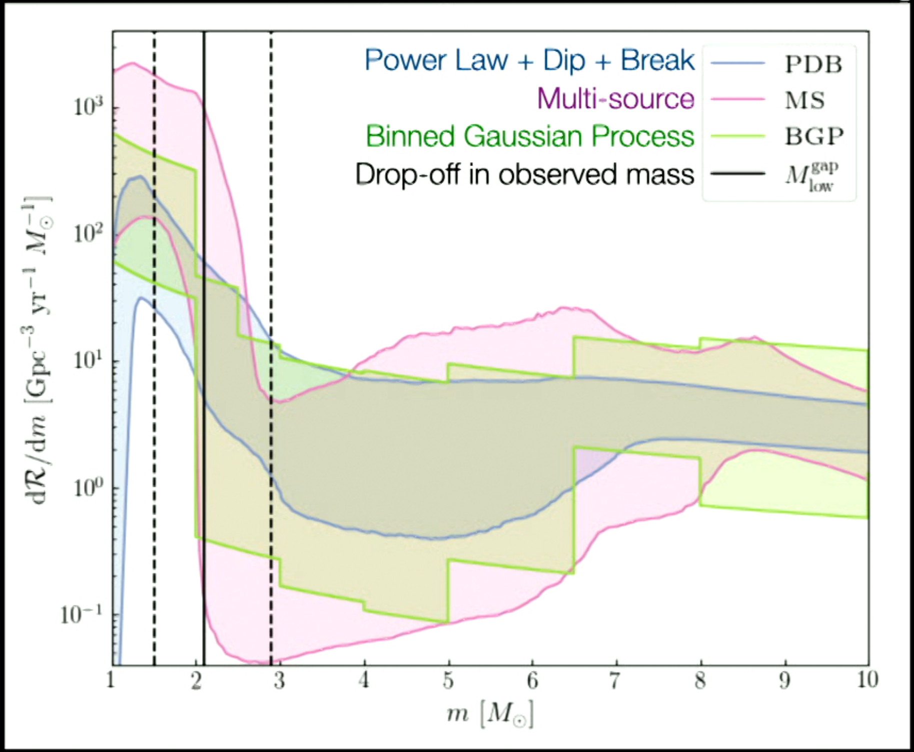
LIGO-Virgo-Kagra GWTC-3 Catalog, Phys. Rev. X **13**, 041039, arXiv:2111.03606, https://gwosc.org/GWTC-3/

LIGO-Virgo-Kagra O3 Population, Phys. Rev. X **13**, 011048 arXiv:2111.03634 (https://dcc.ligo.org/LIGO-P2100239/)

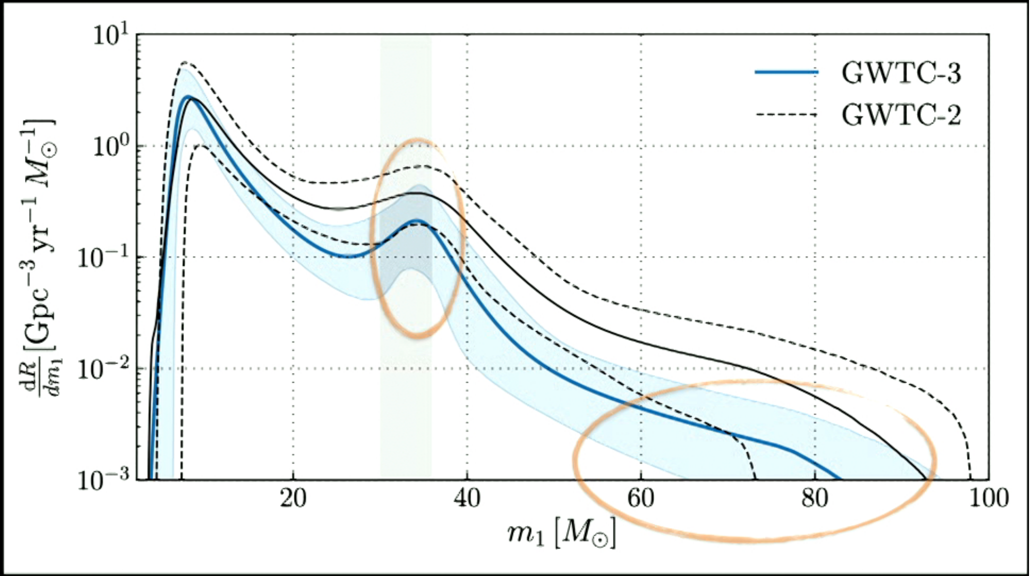
The population of merging compact binaries inferred using gravitational waves through GWTC-3

LIGO-Virgo-Kagra, Phys. Rev. X **13**, 011048
arXiv:2111.03634 (https://dcc.ligo.org/LIGO-P2100239/)

Lower mass gap above $\simeq 2.1 M_\odot$

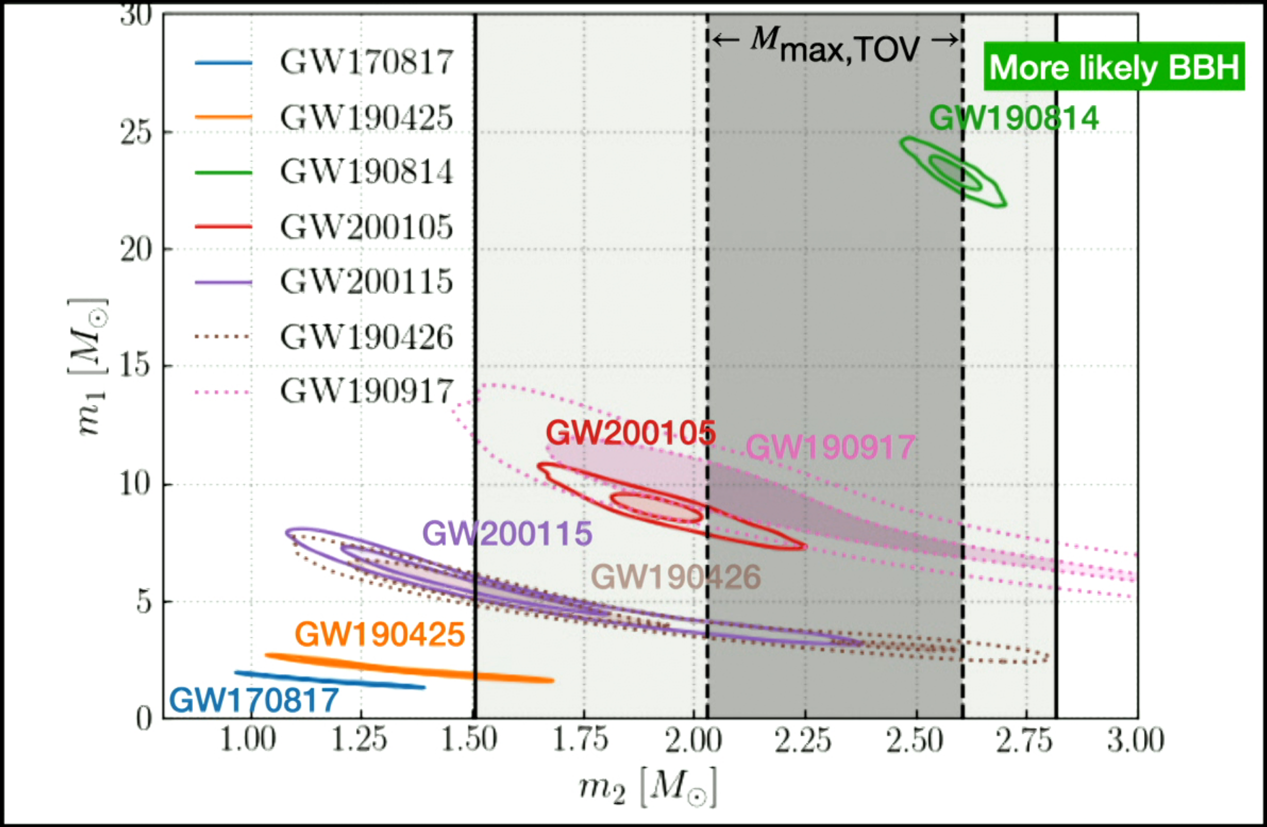


Structure in the BH mass spectrum



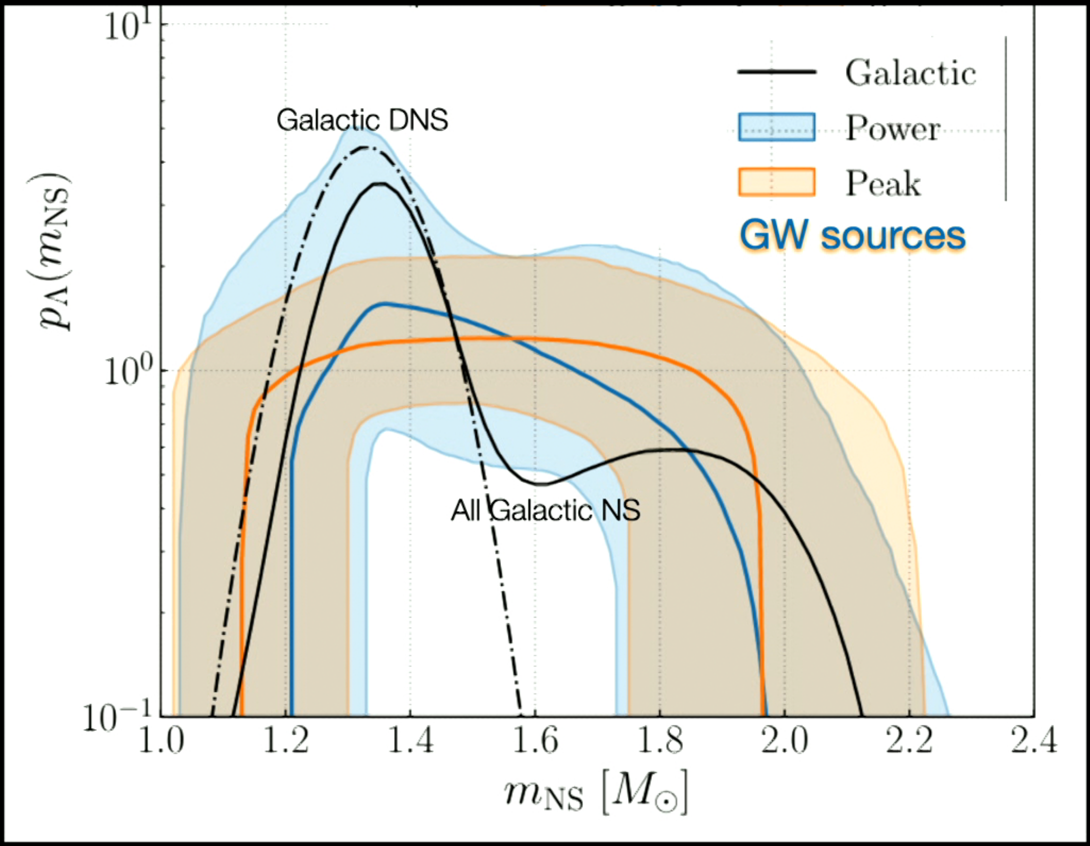
Upper mass gap above $> 60 M_\odot$

Low-mass mergers observed through O3



LIGO-Virgo-Kagra, Phys. Rev. X **13**, 011048
arXiv:2111.03634 (https://dcc.ligo.org/LIGO-P2100239/)

NS in GW extend beyond "typical" 1.4 $M_\odot$



High-mass NS in GW190425, GW200105, GW190917: flatter mass distribution than galactic radio observations

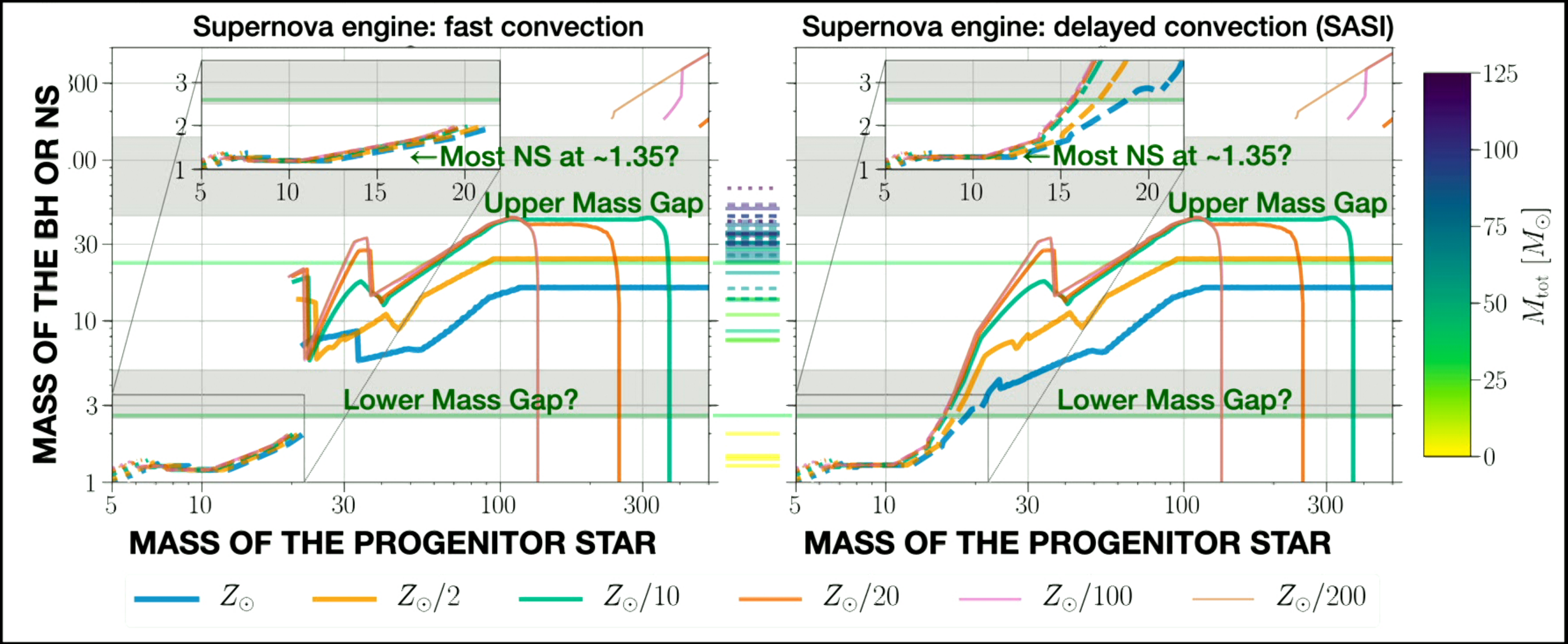
(Here: GW190814 assigned to be BH from EOS expectation)

LIGO-Virgo-Kagra, Phys. Rev. X **13**, 011048
arXiv:2111.03634 (https://dcc.ligo.org/LIGO-P2100239/)

Method and related discussion:
Landry and Read Astrophys. J. Lett. 921, L25 (2021)

Implications for supernovae, binary dynamics…

e.g. compare Fast/delayed supernova engine scenarios from Chris Fryer *et al* 2012 *ApJ* 749 91



Michael Zevin *et al* 2020 *ApJL* 899 L1

Implications for supernovae, binary dynamics...

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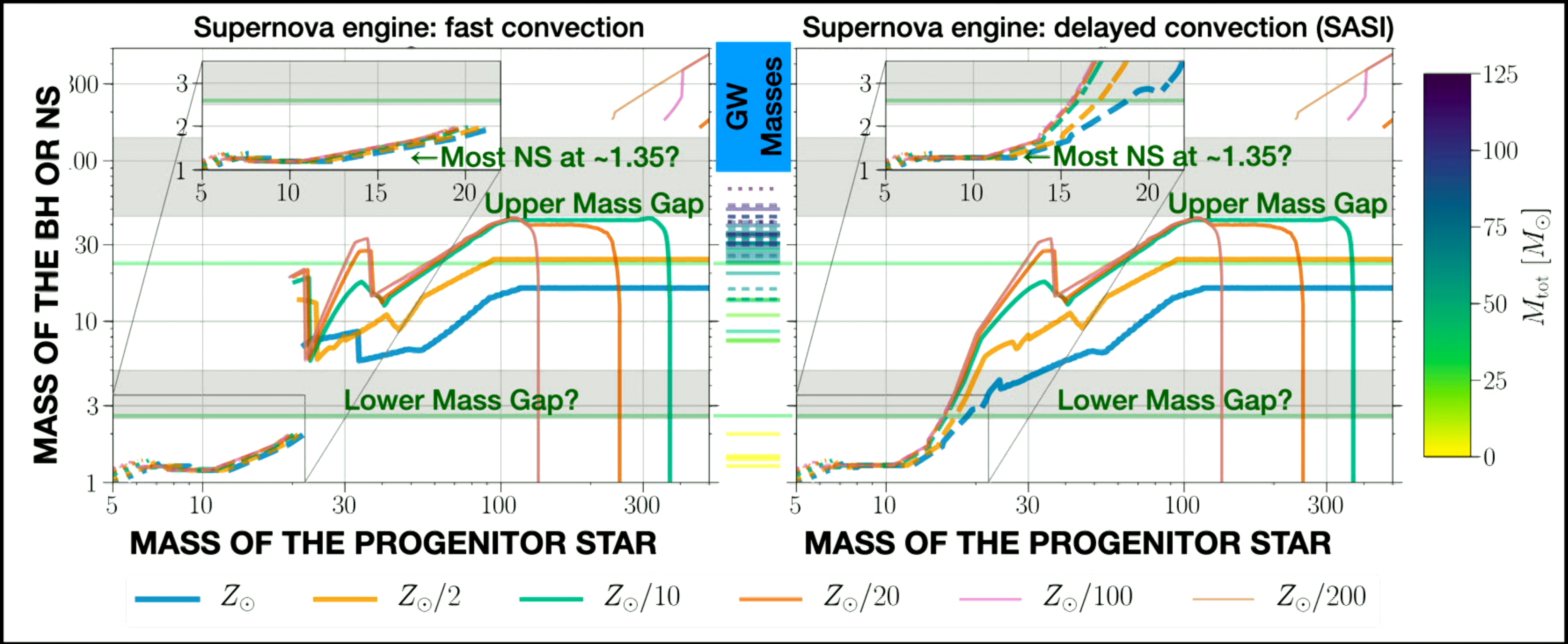
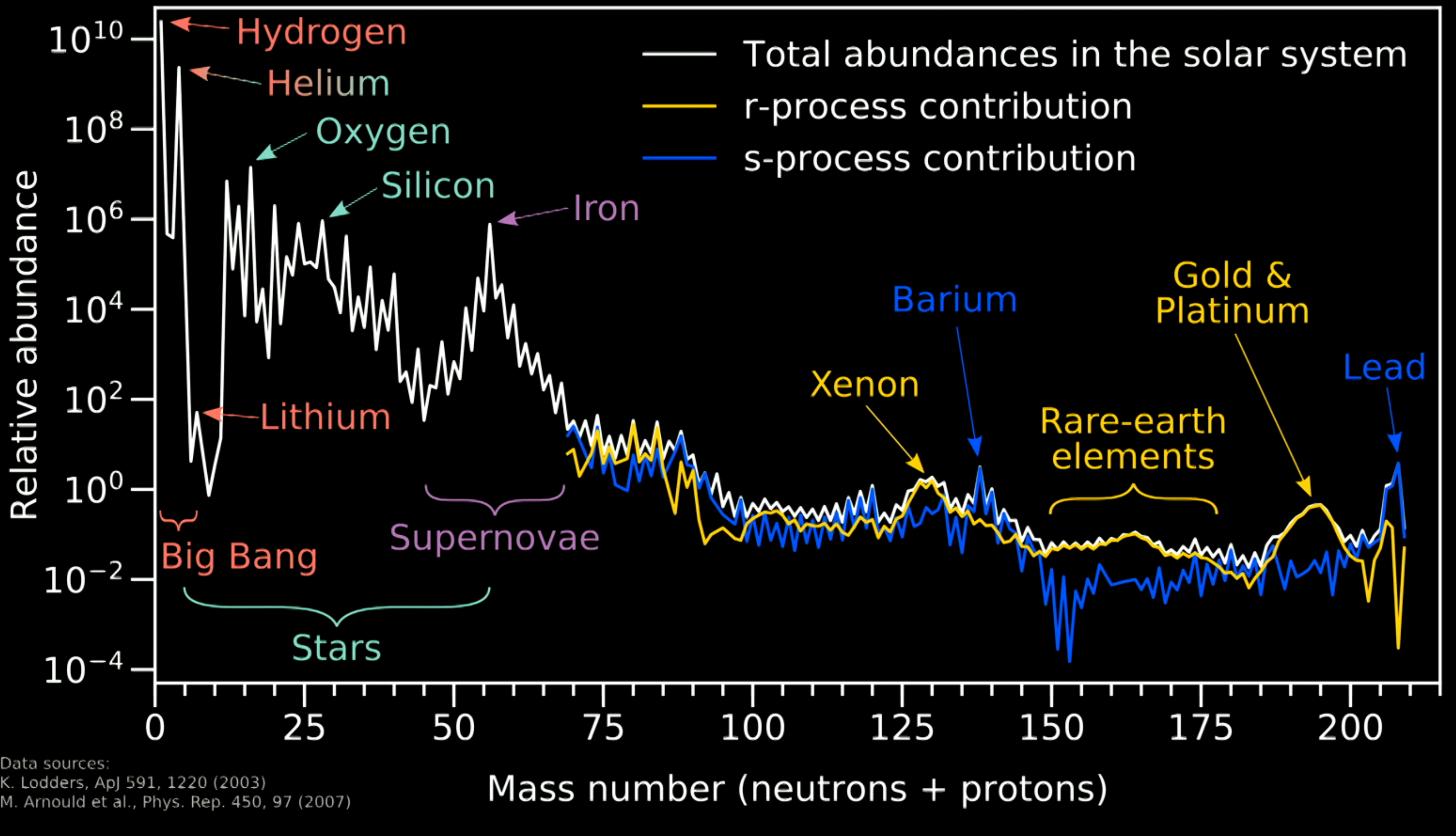


Michael Zevin *et al* 2020 *ApJL* 899 L1

Where do our elements come from?

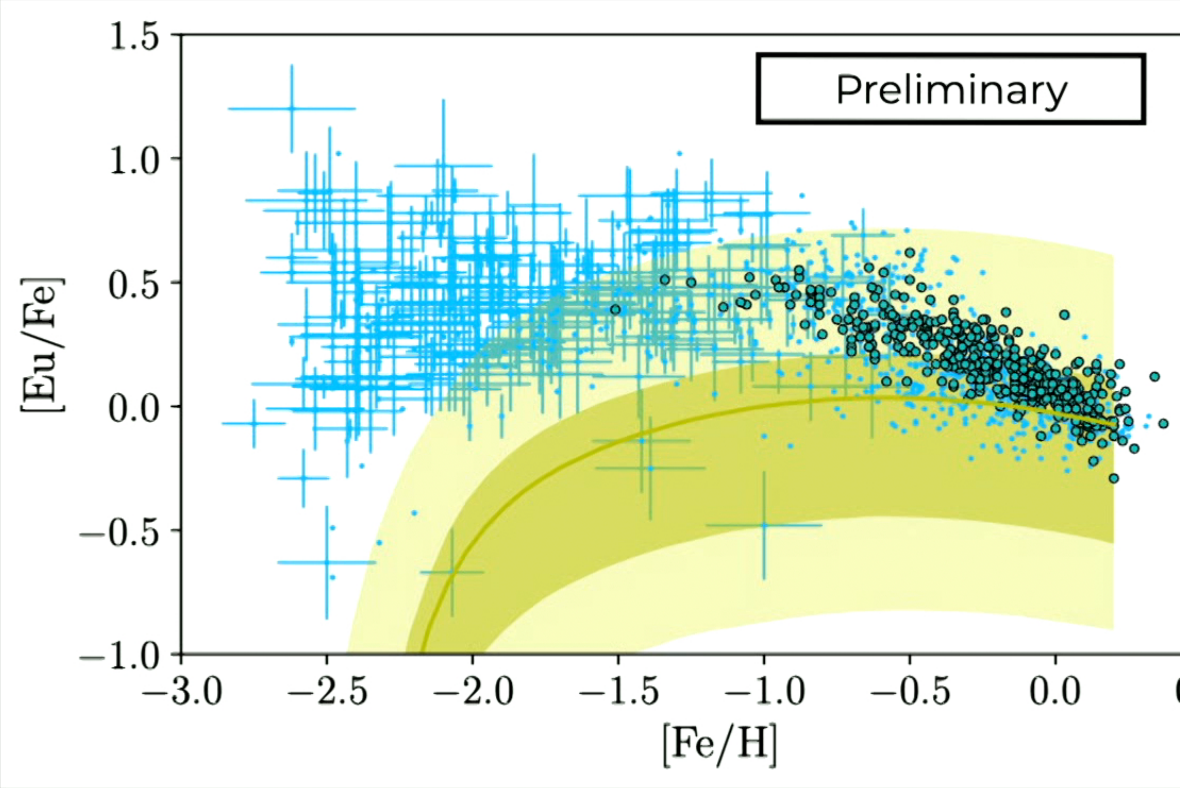


Data sources:
K. Lodders, ApJ 591, 1220 (2003)
M. Arnould et al., Phys. Rep. 450, 97 (2007)

Lippuner 2017

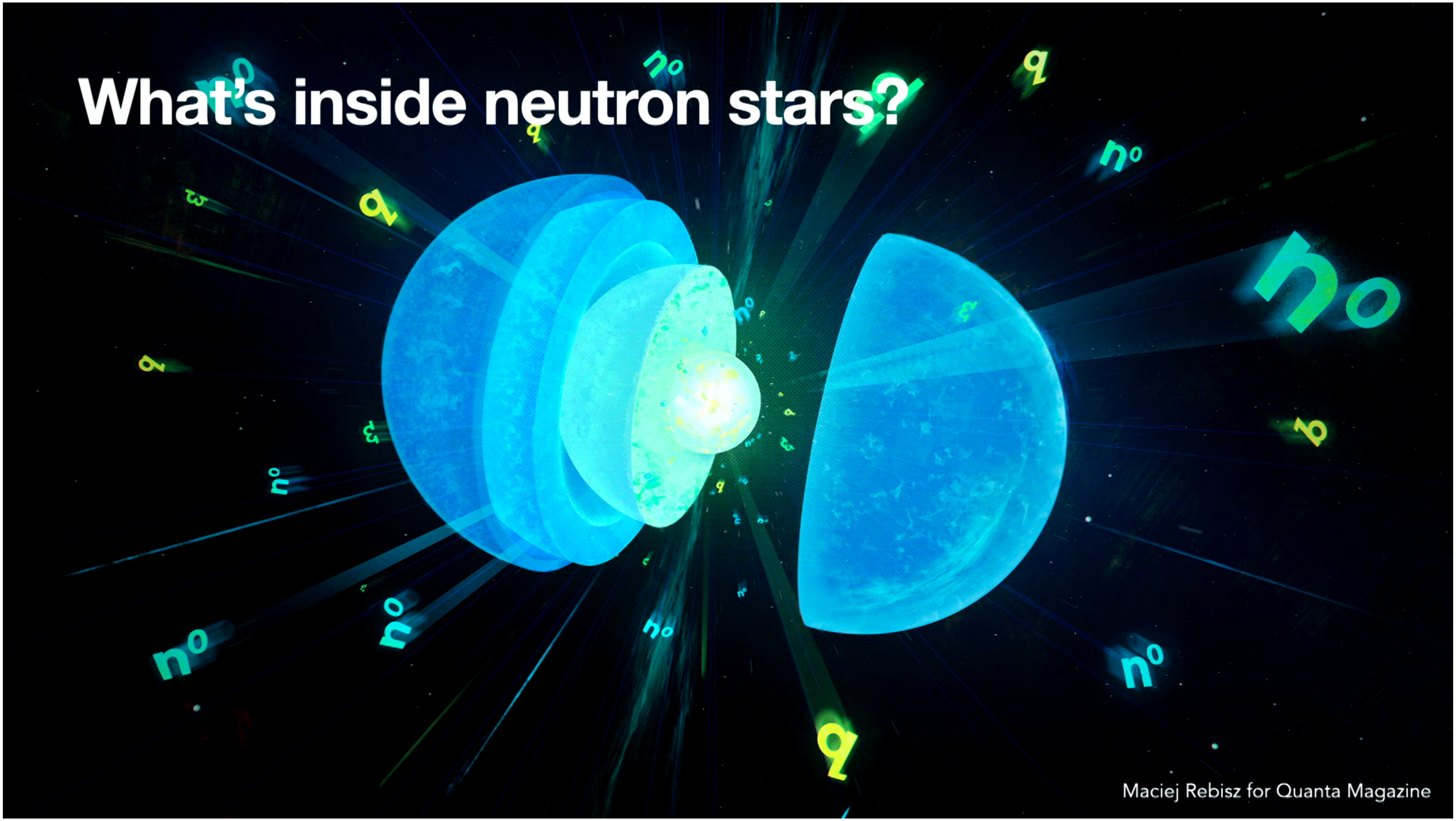
Element abundance in of metal-poor stars:

- Merger rates and masses distributions from LVK O3
- EOS distribution from nonparametric inference using LVK/NICER/Pulsar masses
- Ejecta mass per system from simulation-calibrated formulae (see Hsin-Yu Chen et al 2021 ApJL 920 L3)
- Delay from star formation following sGRB (Michael Zevin et al 2022 ApJL 940 L18)
- One-zone chemical evolution

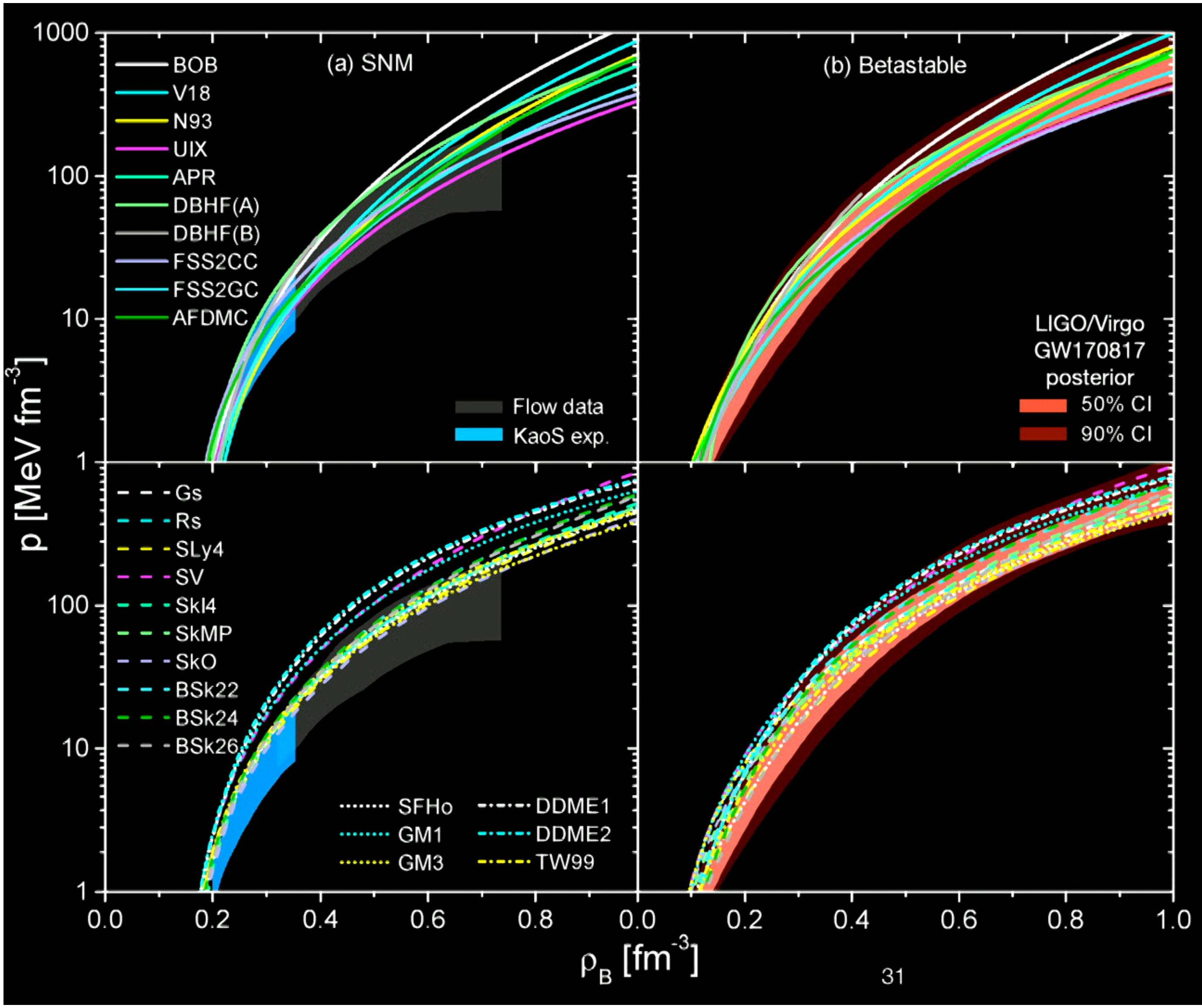


NS contribution: Hsin-Yu Chen, Phil Landry, J Read, D. Siegel, in prep

What's inside neutron stars?



Maciej Rebisz for Quanta Magazine



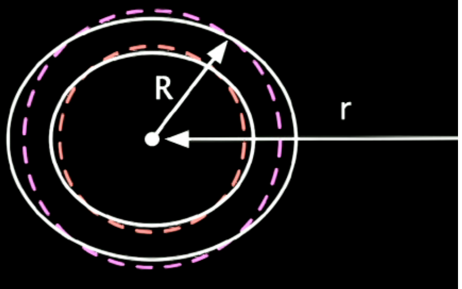
Matter above nuclear density

- Nucleon interactions plus many-body forces
- Range of methods and approximations at increasing density

*Burgio, G.F.; Schulze, H.-J.; Vidaña, I.; Wei, J.-B. A Modern View of the Equation of State in Nuclear and Neutron Star Matter. Symmetry **2021**, 13, 400.*

Changing the chirp

- Additional orbital energy lost to the deformation of the stars
- Tidal bulges add a little extra quadrupole, GW luminosity



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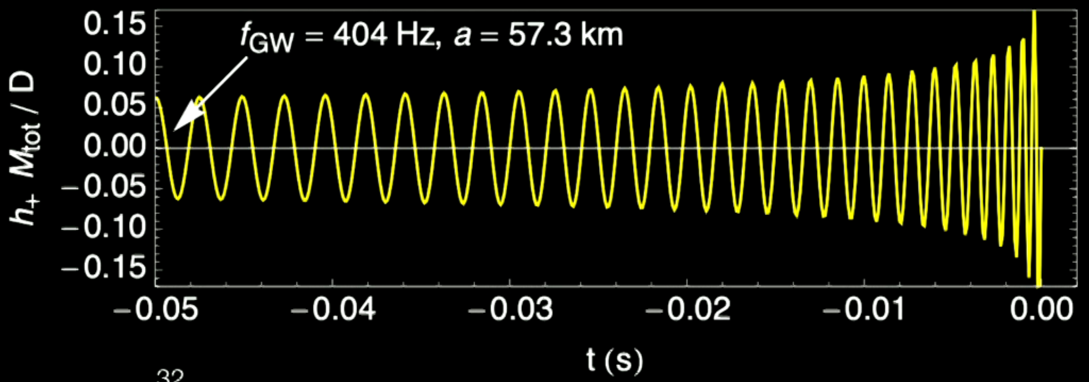
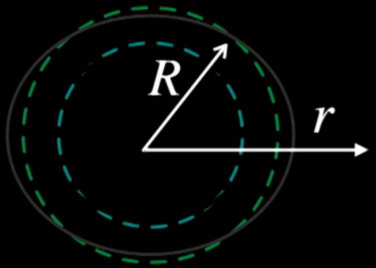


Relativistic tides

matter responds to a companion

- Deformability **defined** by linear perturbation of cold equilibrium star

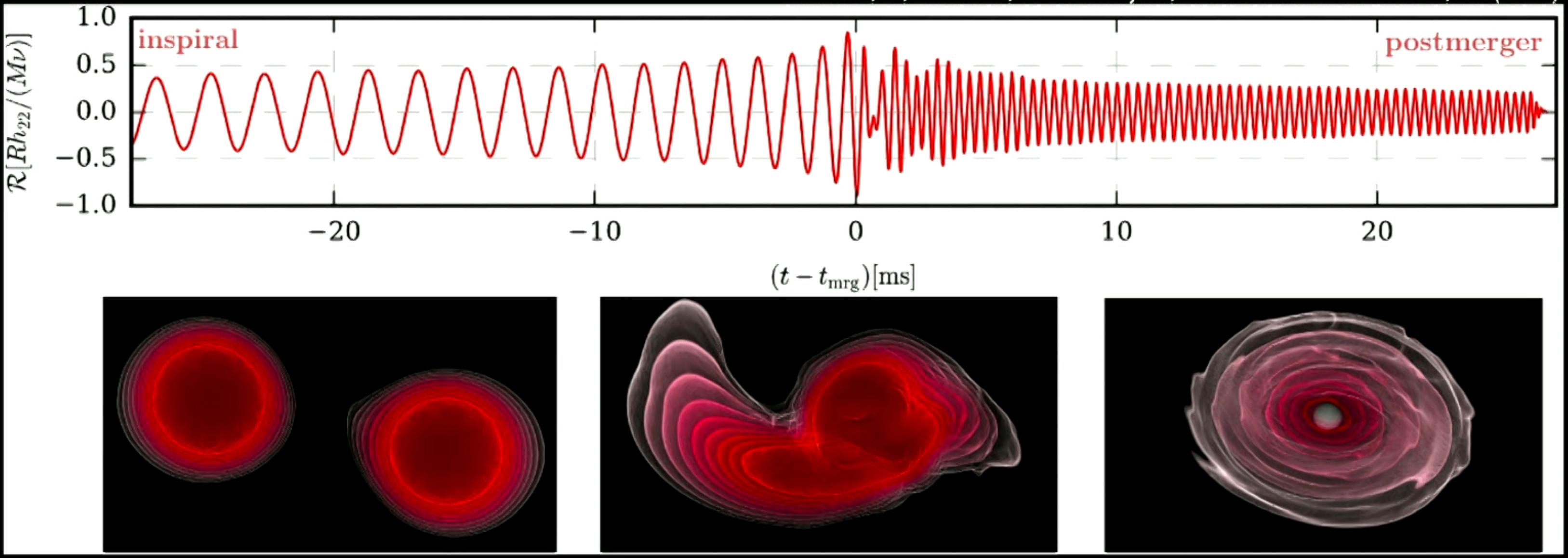
Ratio of quadrupole term $\sim \dfrac{1}{r^3}$ and external tidal term $\sim r^3$



Dimensionless form: $\Lambda_i = \dfrac{\lambda_i}{m_i^5} = \dfrac{2}{3}k_2\left(\dfrac{R_i}{m_i}\right)^5$

- *R* radius, *m* mass of star ⬅ *most EOS impact on tides*
- k_2 relativistic love number ≃ 0.05–0.15
  - Mass distribution inside the star (polarization), not surface deformation
  - $k_2 = 0$ for BH (some discussion in literature)

Dietrich, T., Hinderer, T. & Samajdar, A. Gen Relativ Gravit 53, 27 (2021)

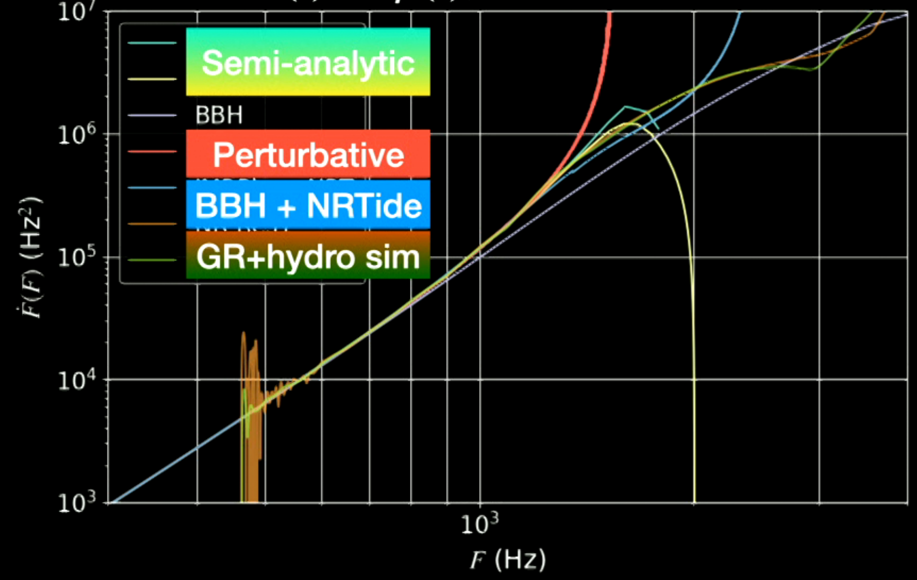


- We use a perturbative property of isolated stars (Λ_1, Λ_2) as an ***effective*** descriptor of matter effects in gravitational-wave models ***through to merger***
  (Based on GR+Hydro simulation: Read et al 1306.4065, Bernuzzi et al 1402.6244, Dietrich, & Tichy 1706.02969, …)
  (Empirical quasi-universal relation: Yagi Phys. Rev. D 89, 043011 (2014), Chan et al Phys.Rev.D90 (2014))

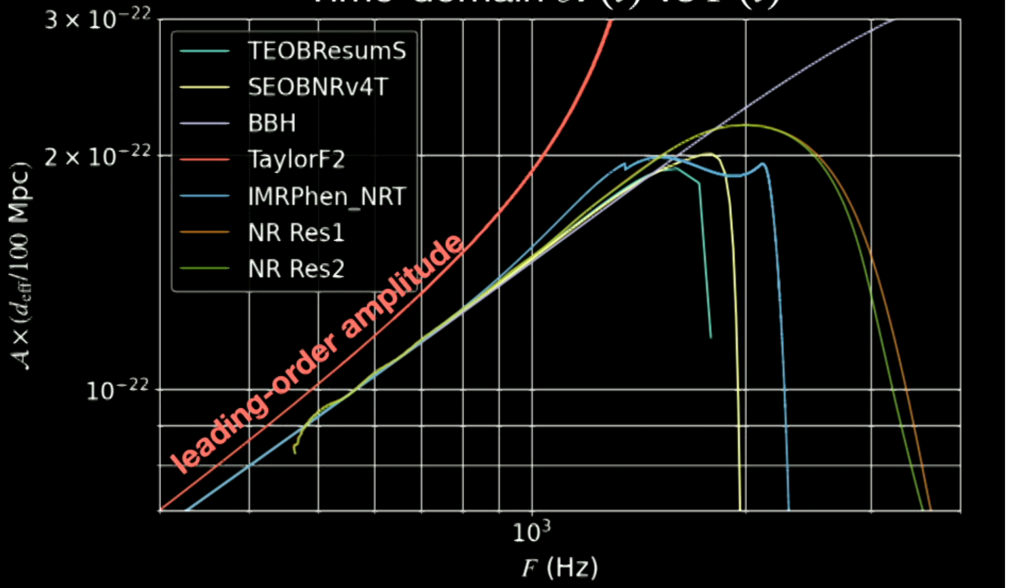
- **In XG era**: additional parameters needed to describe waveforms
  (e.g Carson et al Phys. Rev. D 99, 083016 (2019), Pratten et al Nat Commun 11, 2553 (2020).

Models of $h(t) = \mathscr{A}(t)e^{i\psi(t)}$

$2\pi F(t) = \dot{\psi}(t)$, $\dot{F} \propto \dot{\Omega}$ used in NR



Time-domain $\mathscr{A}(t)$ vs $F(t)$



NR - high-res CoRe sim ‘BAM:0095’ with SLy EOS
Spline smoothing for F before taking derivative
m_1 & m_2: 1.349998 for all waveforms shown

From Sly: Λ_1 & Λ_2 = 390.1104
used for TEOBResumS, SEOBNRv4T,
TaylorF2, and IMRPhenomPv2_NRT

Jocelyn Read 2023 Class. Quantum Grav. 40 135002

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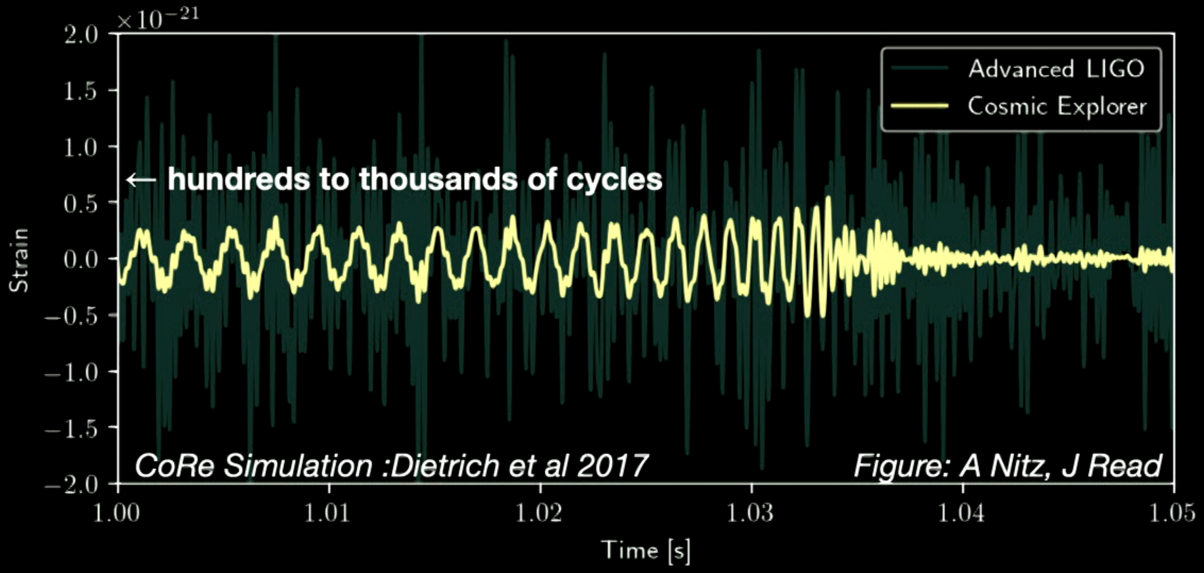
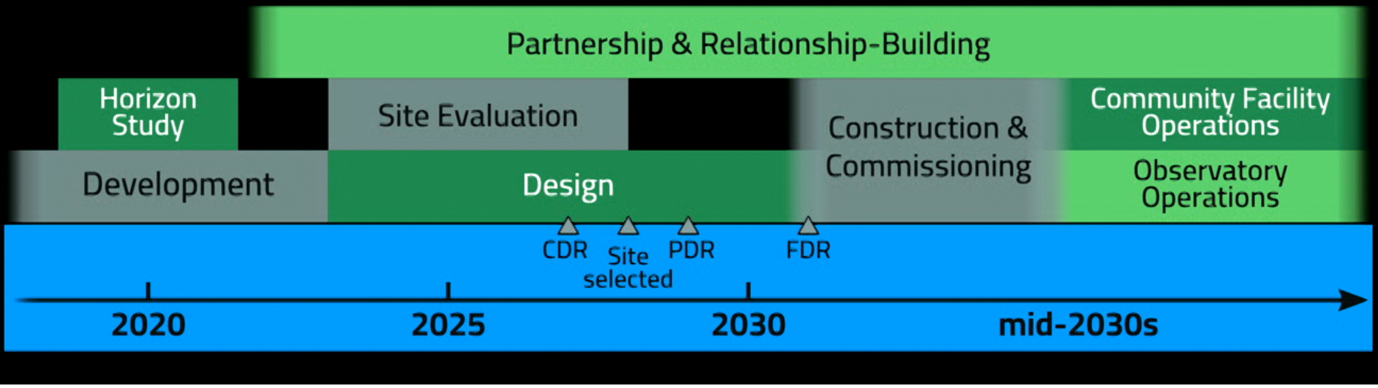


CoRe Simulation :Dietrich et al 2017

Figure: A Nitz, J Read

"Today's rare events are tomorrow's precision physics"

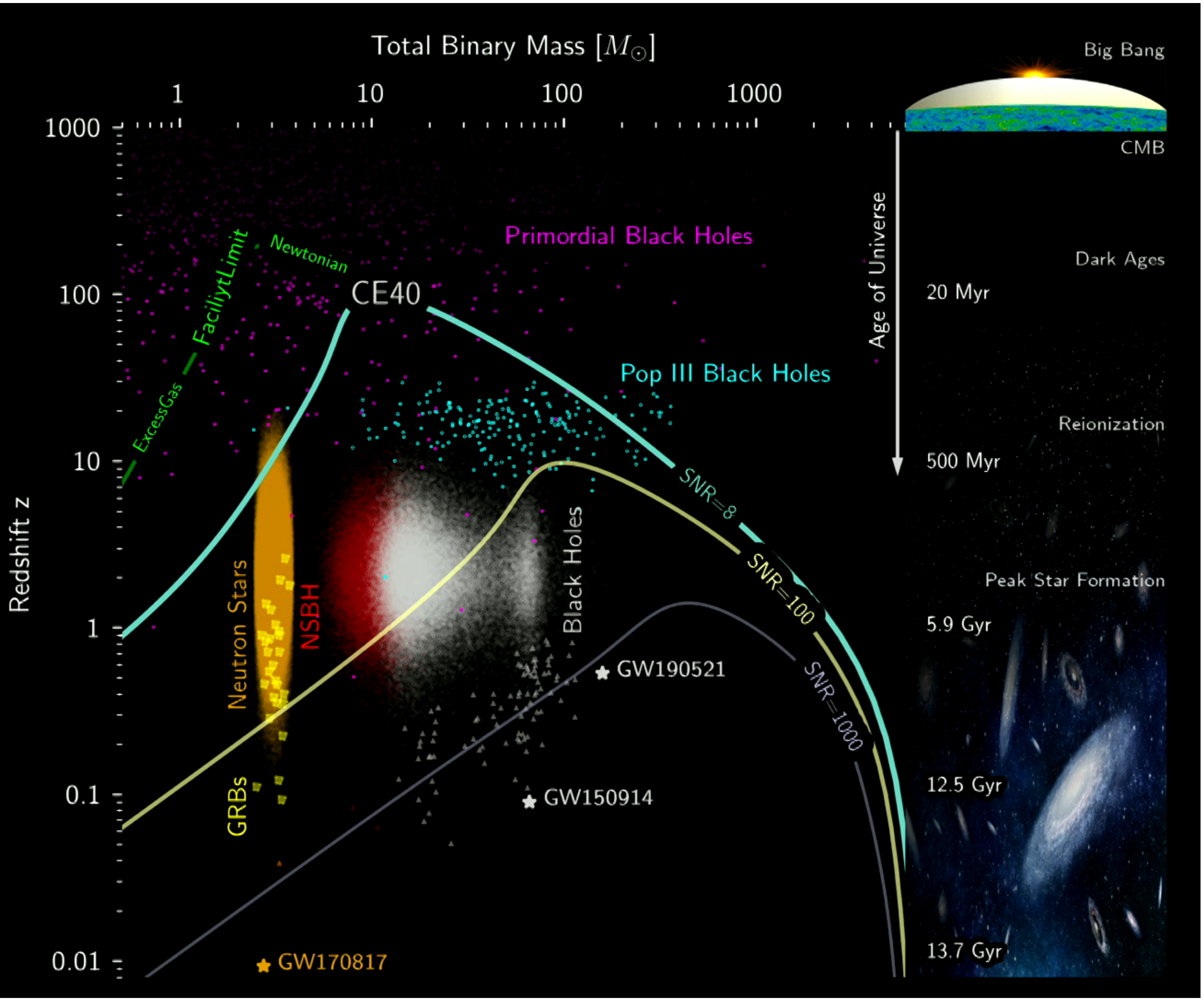
US Timeline



White Paper for NSF MSCAC ngGW ,
https://arxiv.org/abs/2306.13745
Site evaluation and design funded by NSF starting 2023

COSMIC EXPLORER

XG Universe



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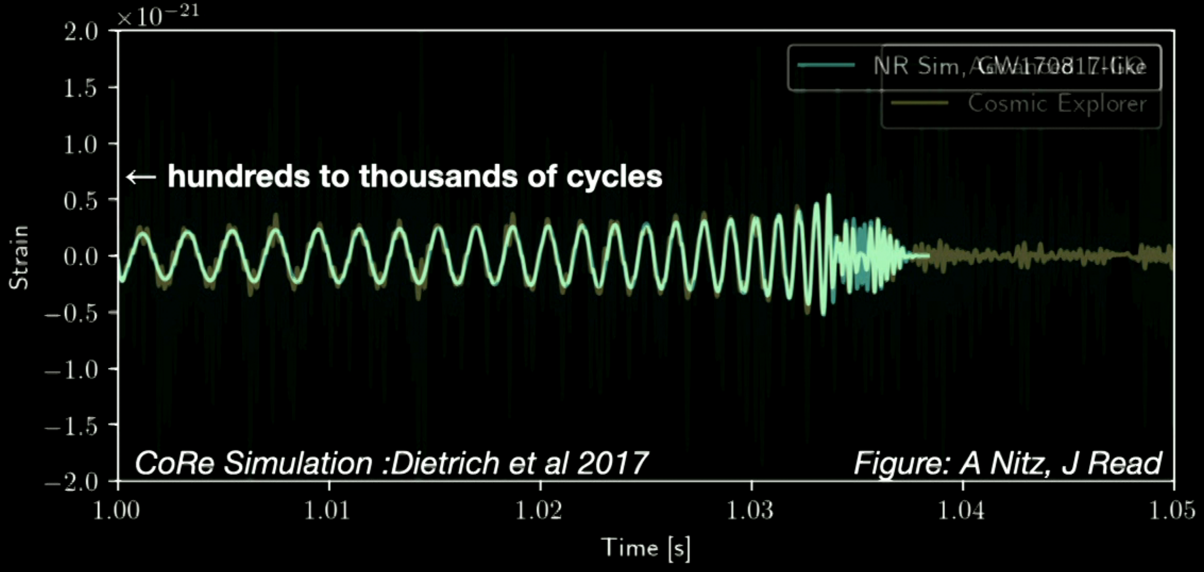


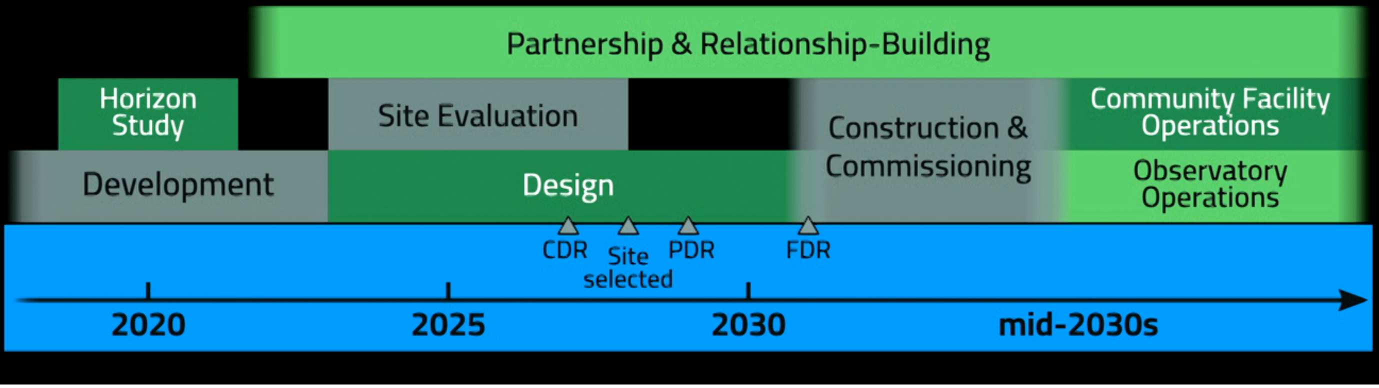
← hundreds to thousands of cycles

CoRe Simulation :Dietrich et al 2017

Figure: A Nitz, J Read

"Today's rare events are tomorrow's precision physics"

US Timeline



Partnership & Relationship-Building

Horizon Study

Site Evaluation

Construction & Commissioning

Community Facility Operations

Development

Design

Observatory Operations

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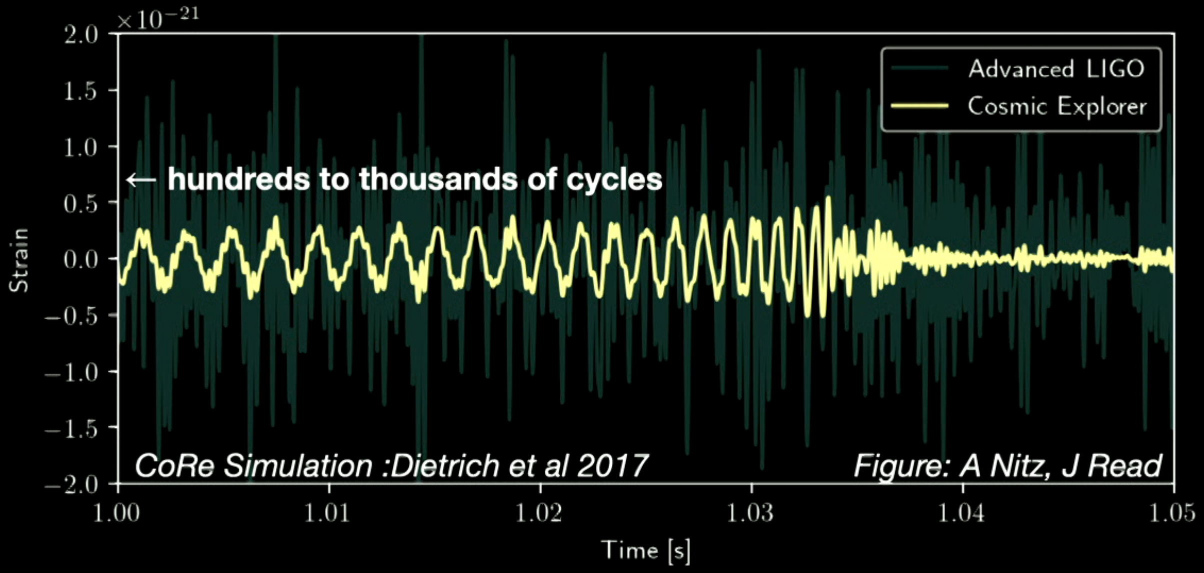

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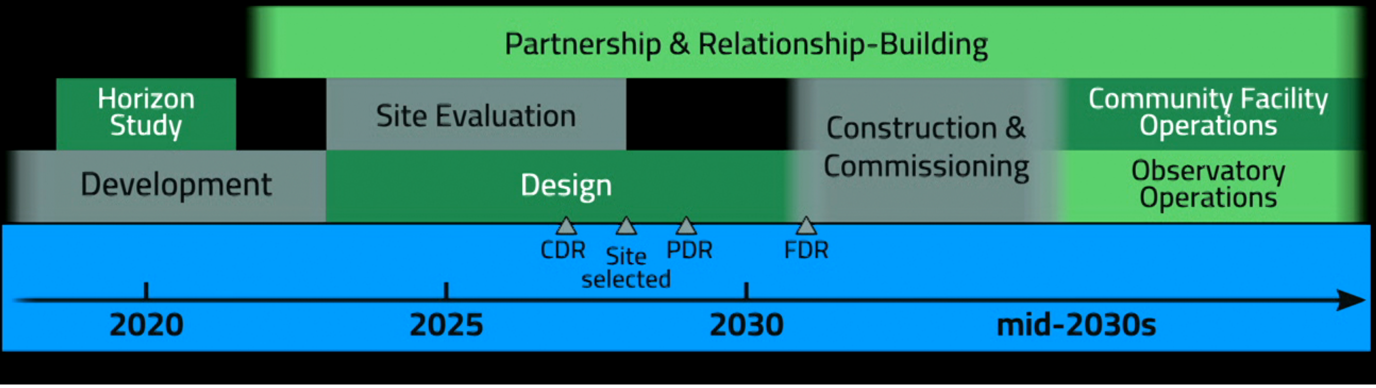

Partnership & Relationship-Building

Horizon Study

Site Evaluation

Construction & Commissioning

Community Facility Operations

Development

Design

Observatory Operations

CDR

Site selected

PDR

FDR

2020

2025

2030

mid-2030s

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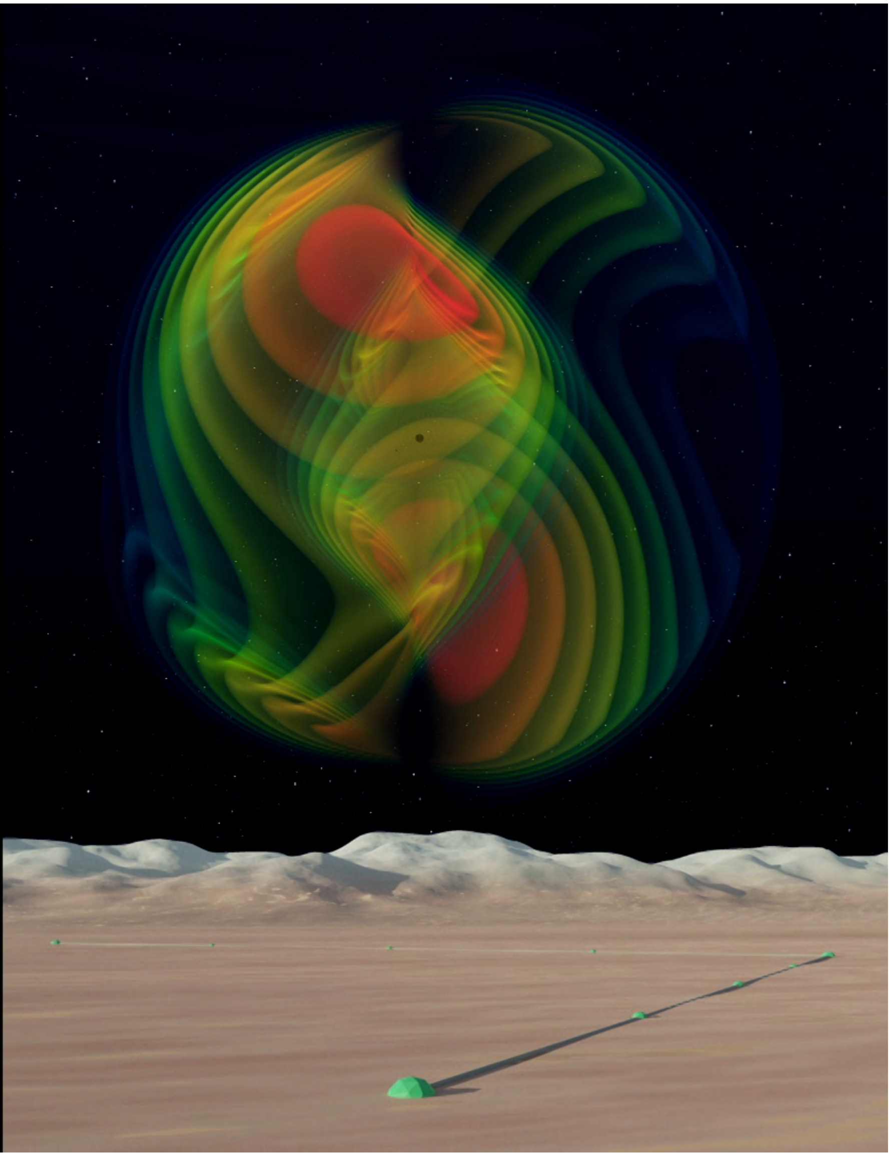

Horizon Study: arXiv:2109.09882