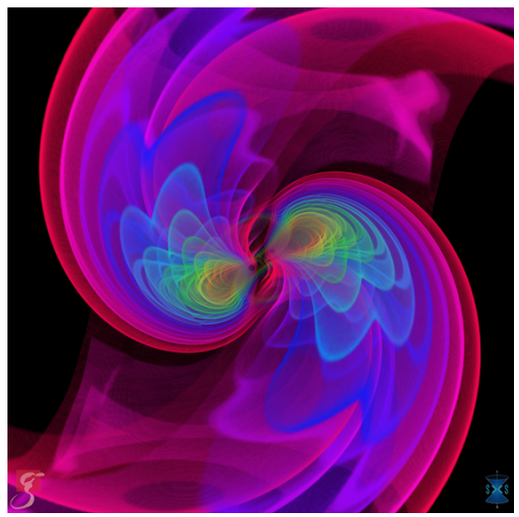
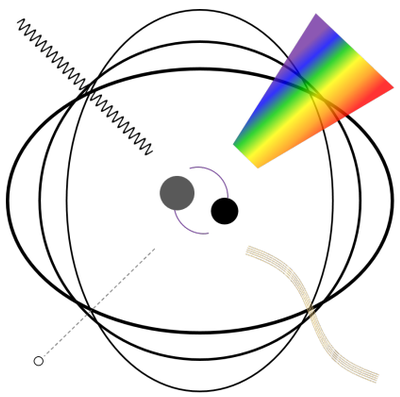




The New Era of Precision Gravitational-Wave (astro)Physics

Alessandra Buonanno

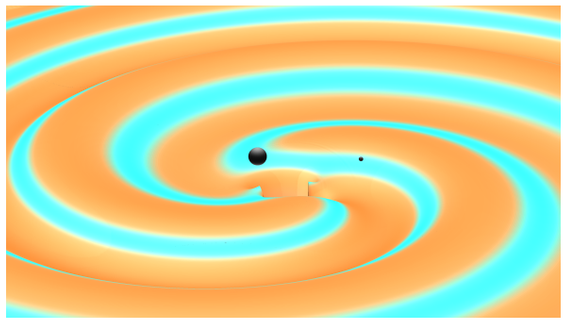
Max Planck Institute for Gravitational Physics

(Albert Einstein Institute)

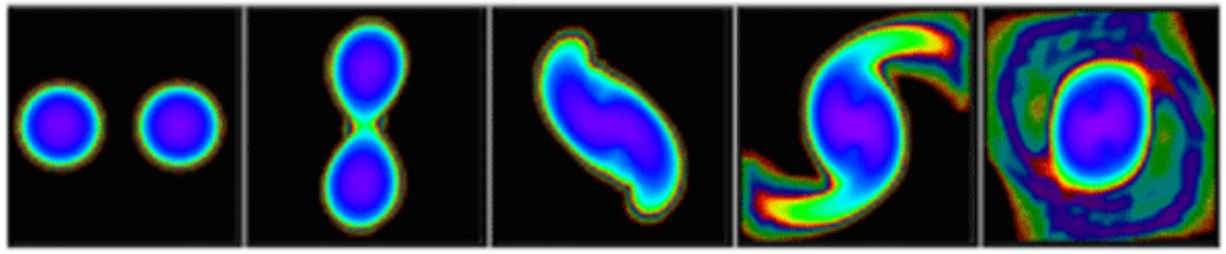
Department of Physics, University of Maryland

"Joint Gravitational Waves & CERN Meeting", CERN Sep 1, 2017

The Transient & Persistent Gravitational-Wave Sky



binary black hole

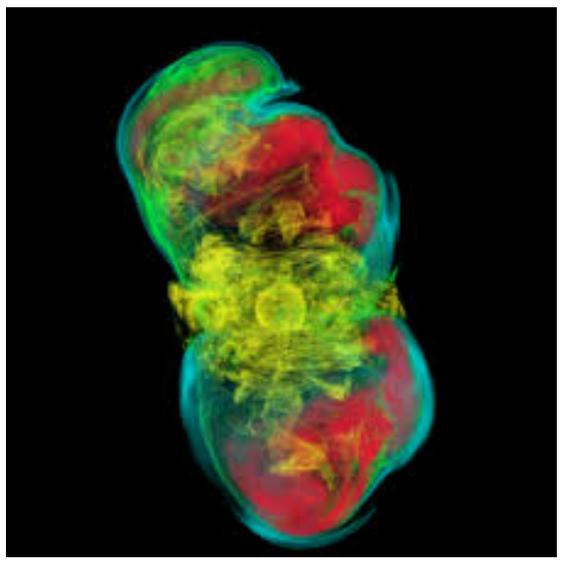


binary neutron star

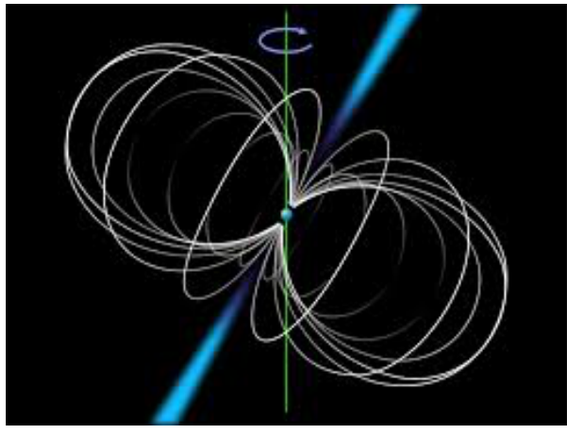
- GW frequency: 10^{-9}–10^{3} Hz

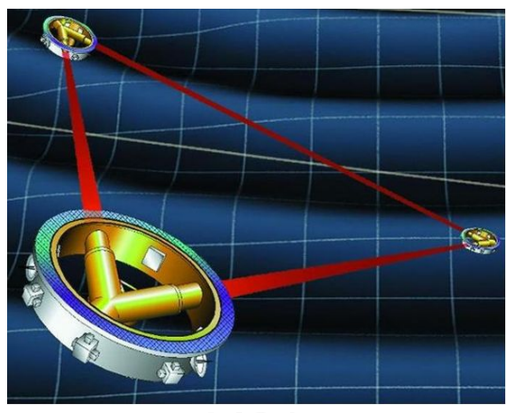
LIGO

- GWs from **binaries** are in band for **tens of msec/mins** in **LIGO/Virgo, months/years** in **Einstein Telescope/LISA** and are **continuous signals** in **Pulsar Timing Arrays**.

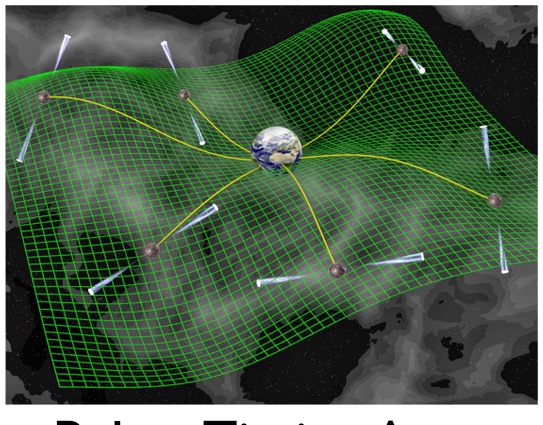


- **Periodic** GW signals from **pulsars**.





LISA



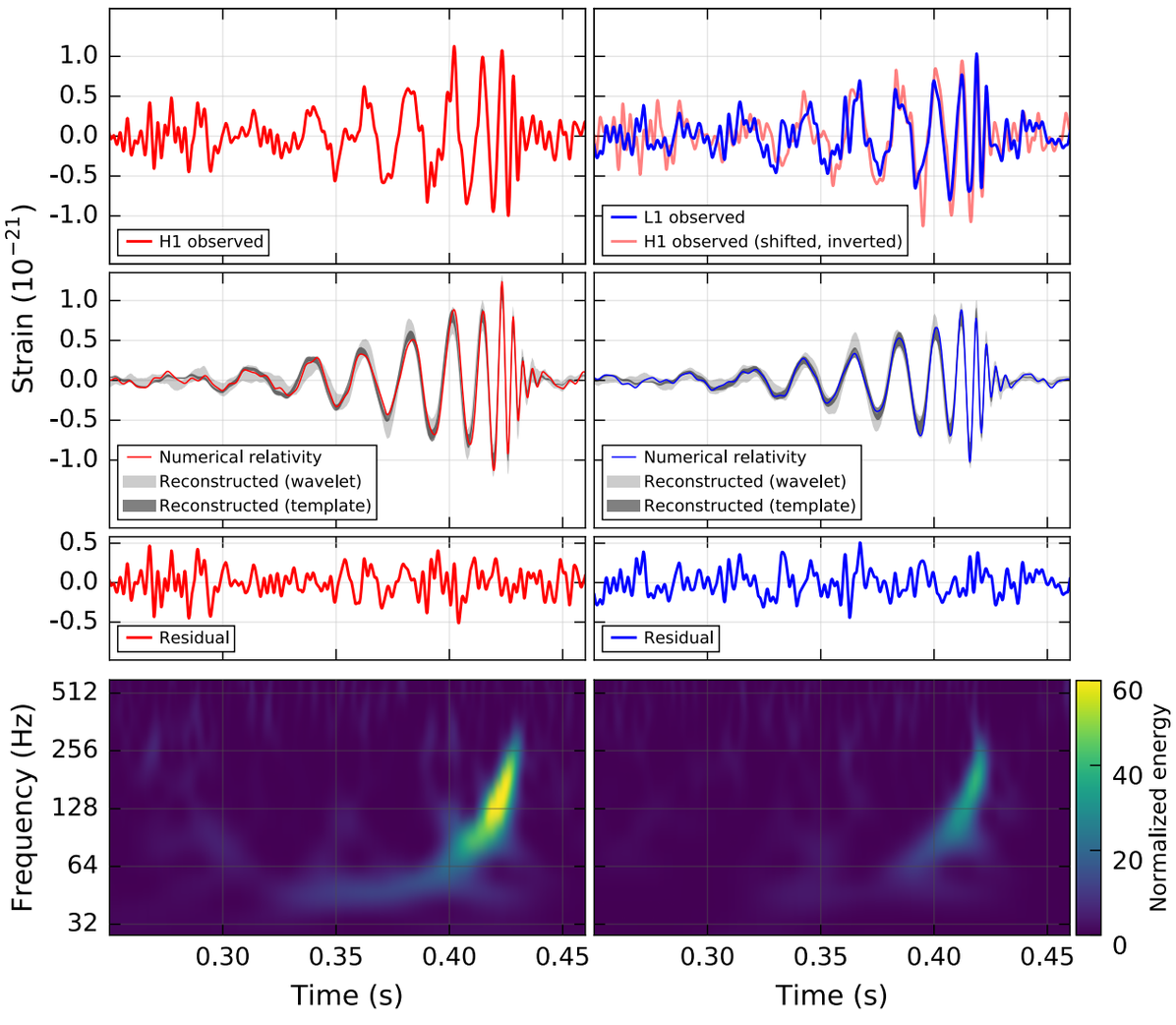
Pulsar Timing Array

- GW-bursts from **supernovae** are in band for **tens of msec**.

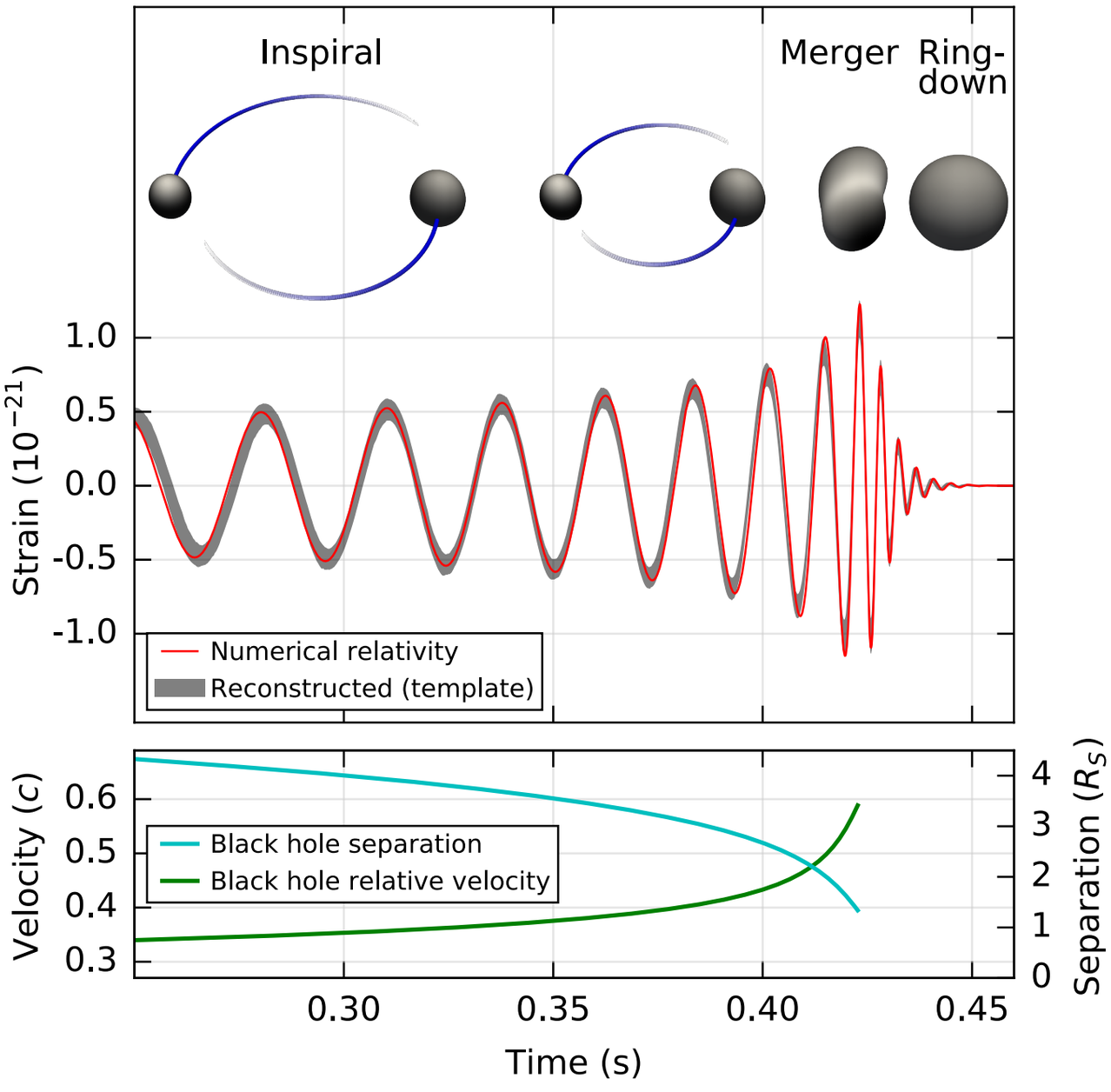
- **Stochastic** GW backgrounds from **early Universe**.

First LIGO Detection: GW150914

(Abbott et al. PRL 116 (2016) 061102)

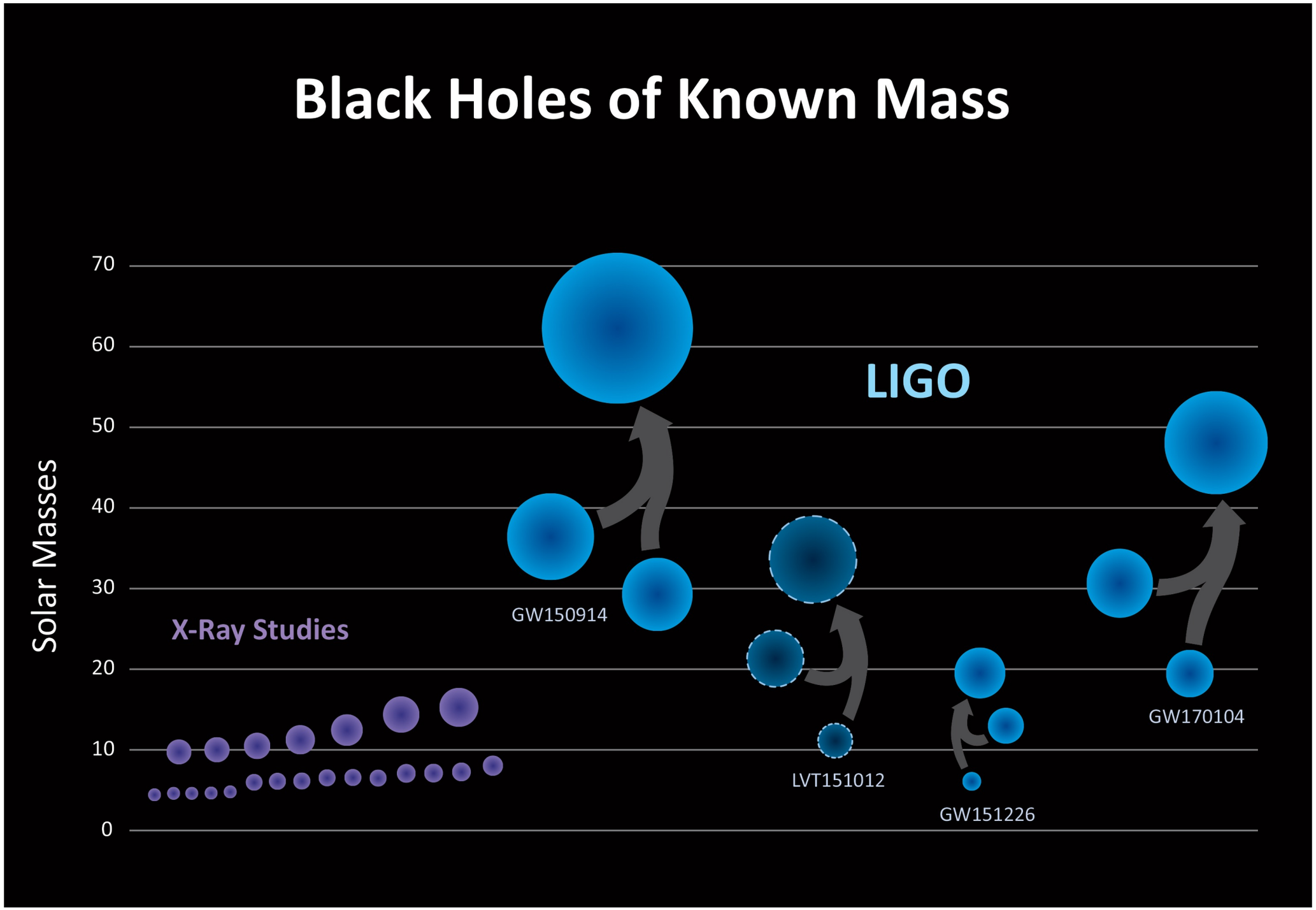


- **Black holes** of radius of 90 km at separation of 350 km are **making 75 orbits** per second **before merging**.
- **Black holes** collide at (almost) speed of light, like **fundamental particles.**



- **Gravitational waves** carry **fingerprints** of **source**.

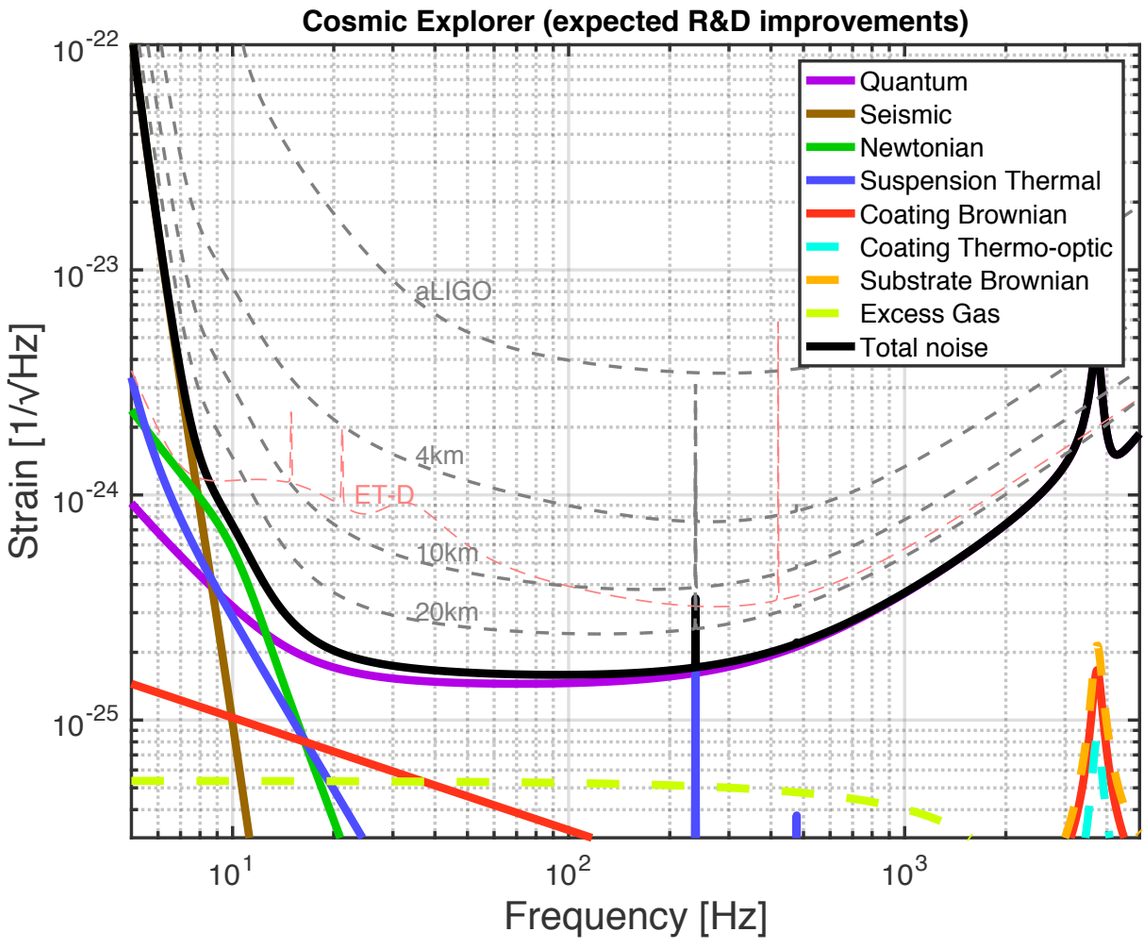
Black Holes Discovered through GWs during O1 & O2 (so far)



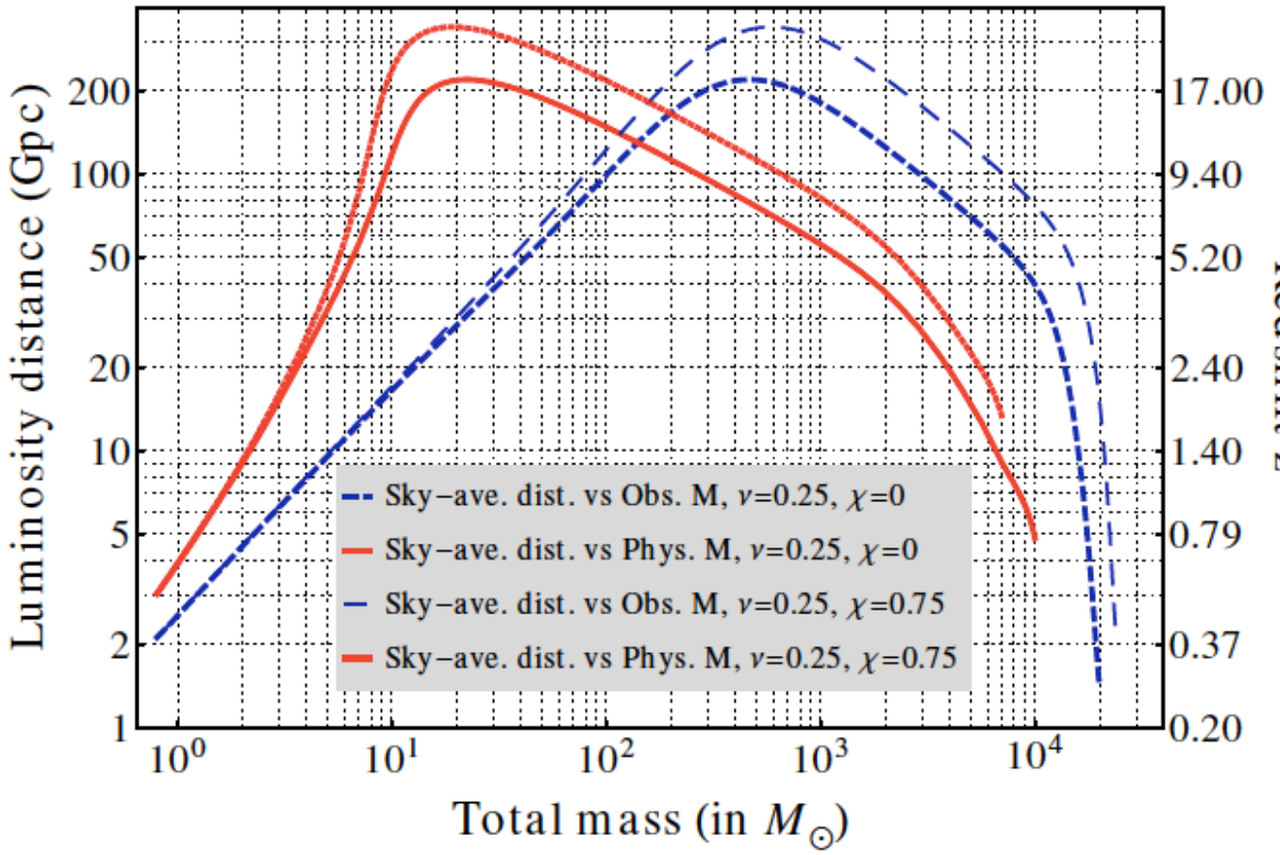
(credit: *Simonnet*)

Looking ahead: Einstein Telescope (ET) & Cosmic Explorer (CE)

(Abbott et al. CQG. 34, 2017, Punturo et al. 2010)



(Abernathy et al. 2011, ET Science Team)



- We will detect **binary black holes** in **all** observable **Universe,** … and observe many other **gravitational-wave sources dominated** by strong **gravity**.

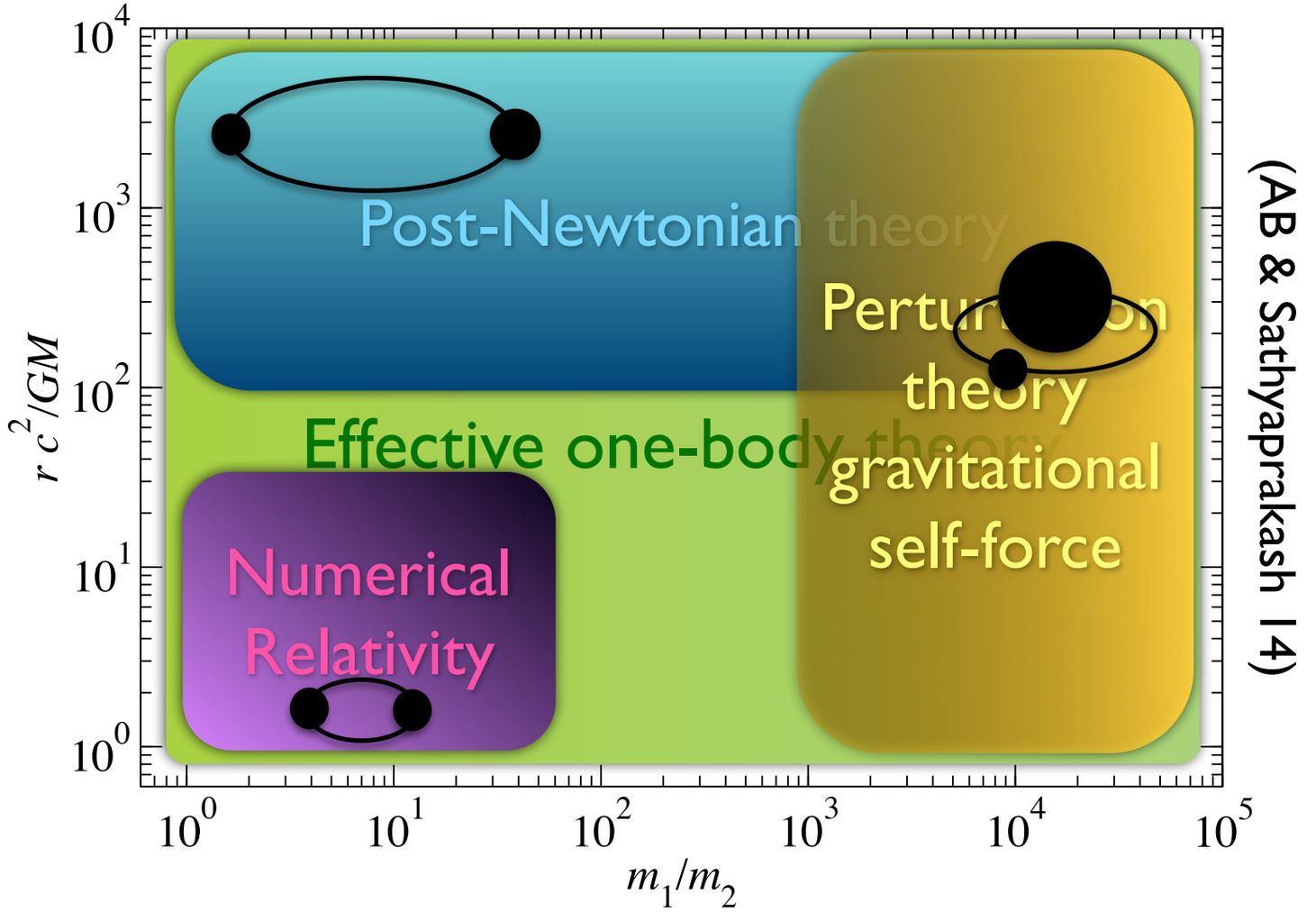
Some Outstanding Questions in Fundamental Physics

- What are the **properties** of **dynamical spacetime** (gravitational waves)?
- Is **General Relativity still valid** in the highly dynamical, strong-field regime?
- Are **Nature's black holes** the black holes in the theory of **General Relativity**?
- How **matter behaves** under **extreme density and pressure**? Can **dark matter** make compact objects?
- What's the **origin** of the **most energetic phenomena** in our Universe?
- Which physical phenomena took place in the **primordial dark age** of the **Universe**?

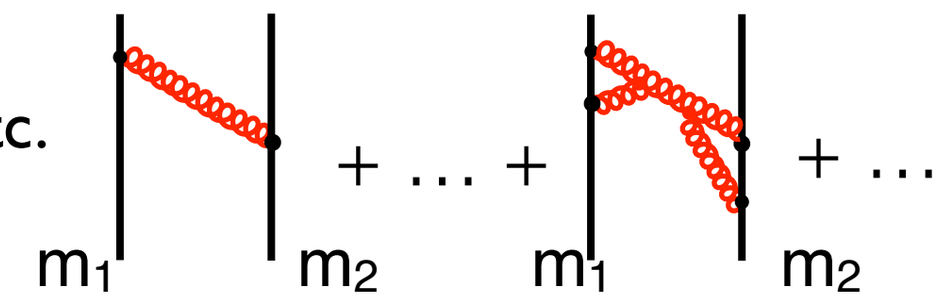
Solving Two-Body Problem in General Relativity (including Radiation)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- **GR** is **non-linear theory**. Complexity similar to QCD.
- Einstein's field equations can be solved:
  - **approximately,** but **analytically** (**fast** way)
  - **exactly**, but **numerically** on supercomputers (**slow** way)



- **Analytical methods**: post-Newtonian/post-Minkowskian expansions, gravitational self-force, effective-one-body theory
  - **effective field-theory**, **dimensional regularization**, etc.
  - **diagrammatic** approach to organize expansions



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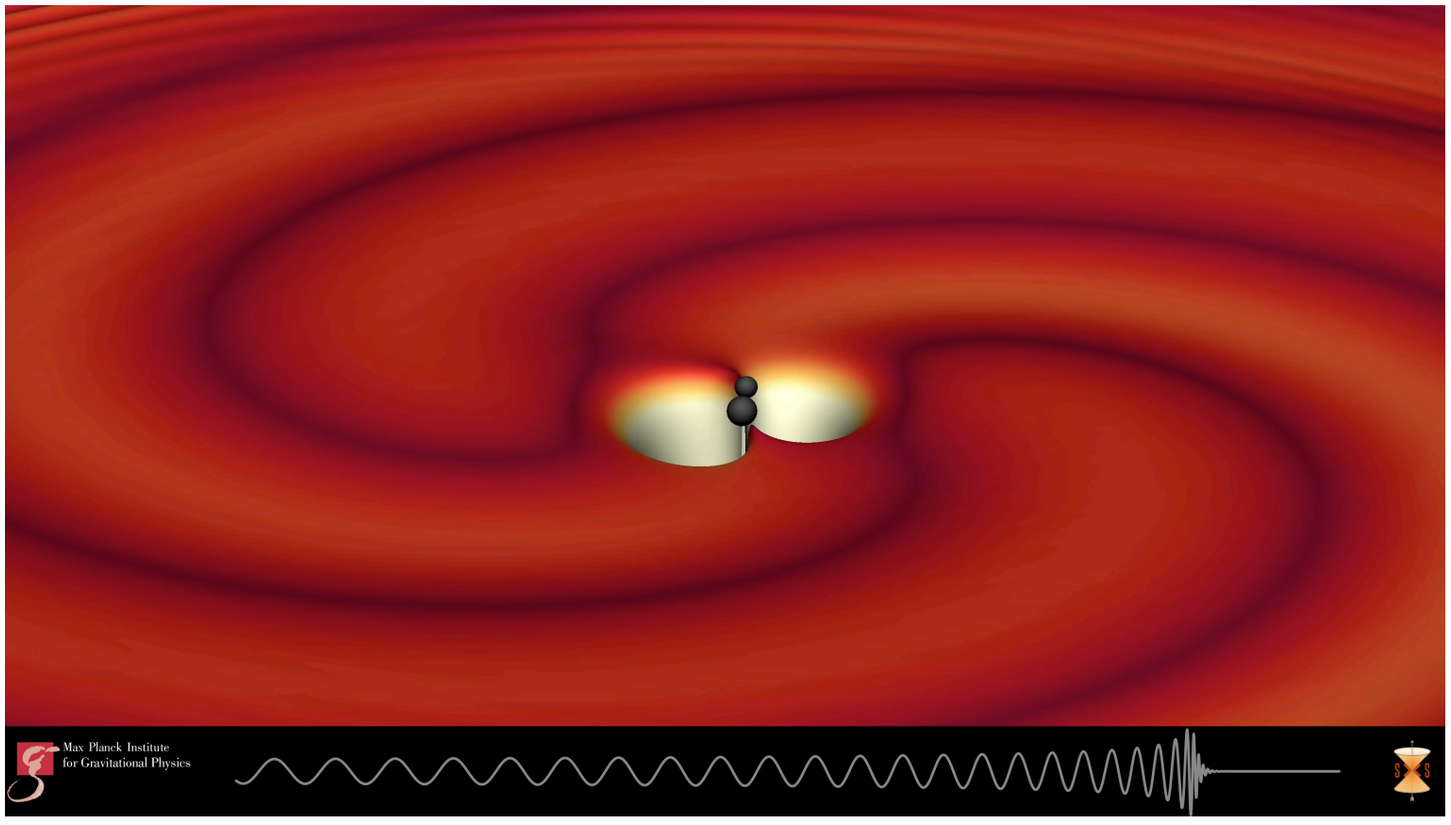

(visualization: *Haas, Ossokine @AEI)*

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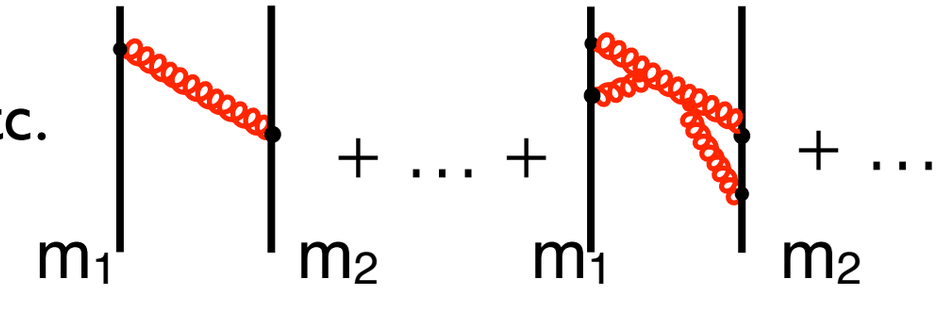
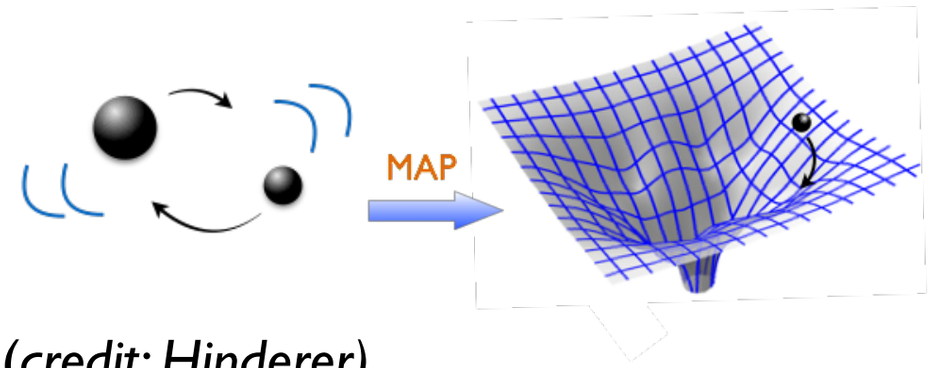
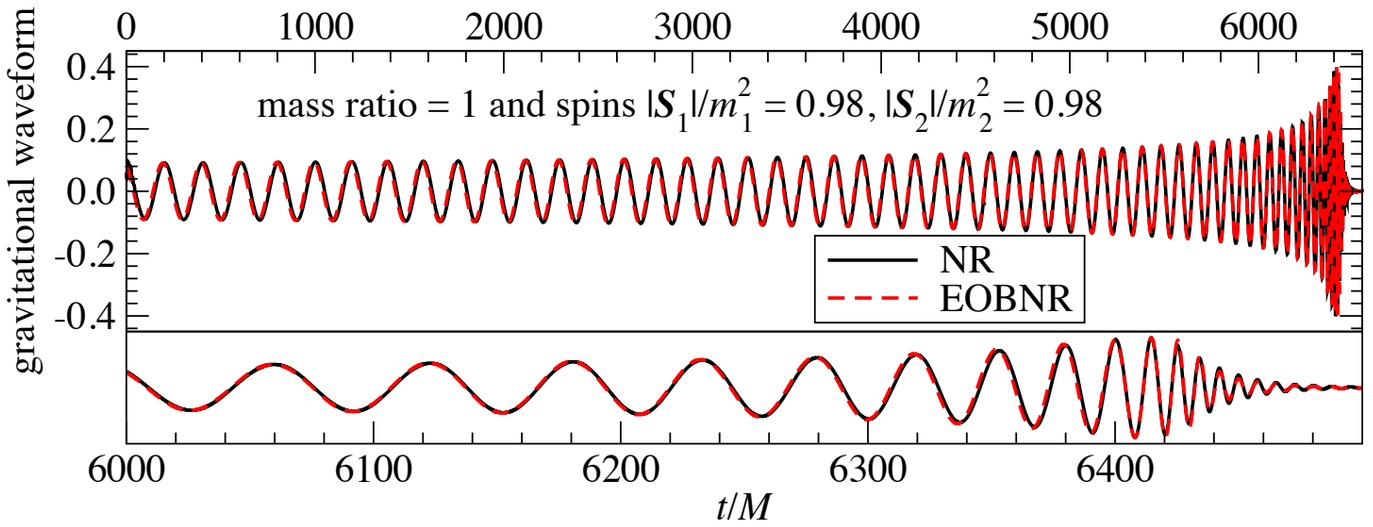


More Accurate Modeling, new Synergies within Theorists

- **Effective-one-body theory:** re-sum and re-organize PN/PM/GSF expansions to improve accuracy and include strong-field effects close to merger.



(credit: Hinderer)



(credit: Taracchini)

- Some key **ideas** of EOB theory were **inspired by quantum** field **theory results.**

- Can **gravitational waveforms be obtained more efficiently** with **modern scattering amplitude techniques**?
  - **scattering amplitudes** in **GR** from **non-abelian gauge theories**
  - are **non-perturbative results foreseeable** in this framework?
  - is it a more straightforward way of **including modified theories to GR?**

(Bern et al. 10, Monteiro et al. 15, Luna et al. 16, Bjerrum-Bohr et al. 15, Goldberger et al. 16, Guevara 17)

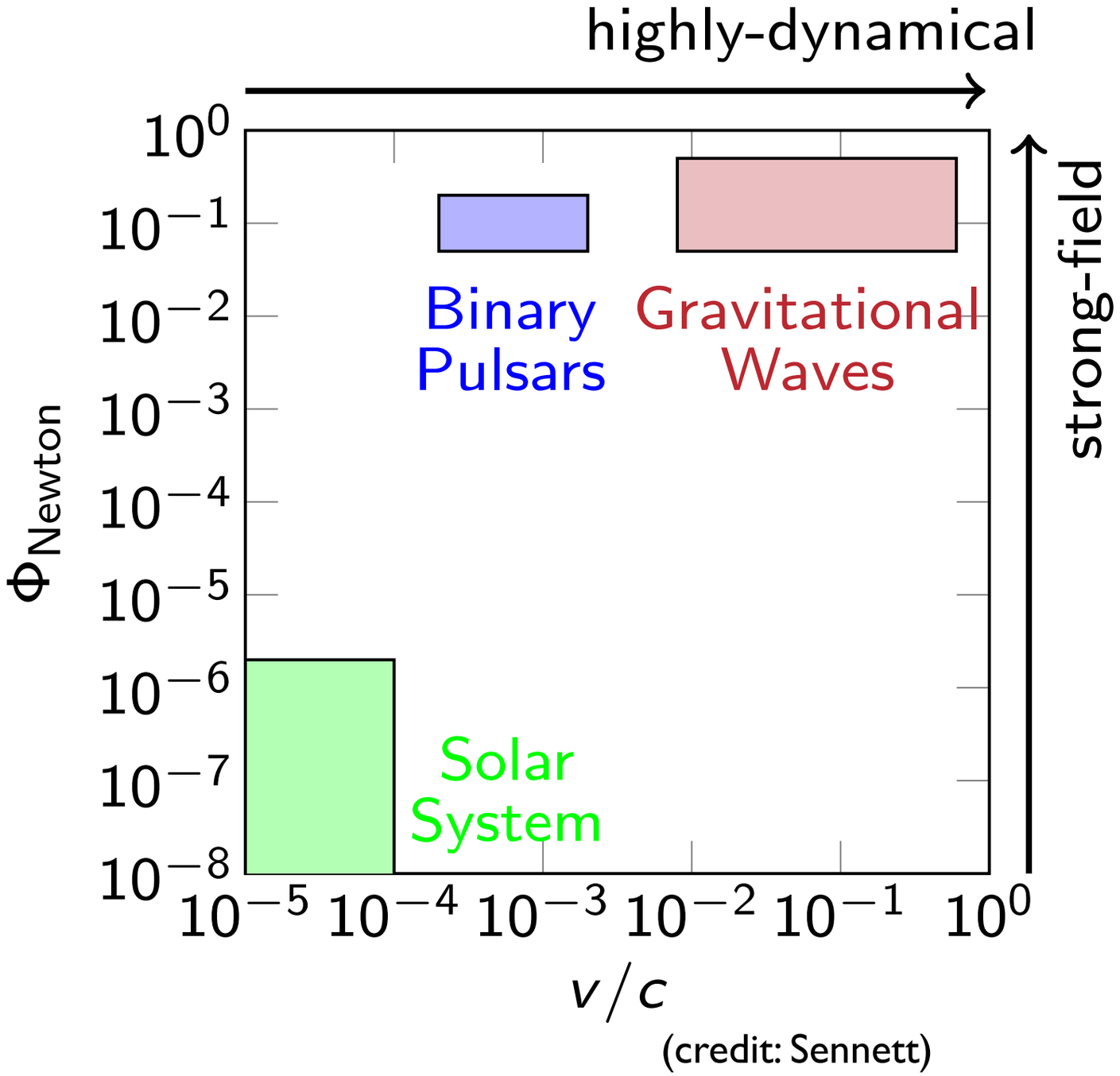
Extreme Gravity, Dynamical Spacetime: Tests of General Relativity

Solar system: $\frac{v}{c} \sim 10^{-5} - 10^{-4}$

Binary pulsars: $\frac{v}{c} \sim 10^{-3}$

LIGO/Virgo: $\frac{v}{c} \geq 0.1$

- Given **current tight constraints** on GR (e.g., Solar system, binary pulsars), can **any GR deviation be observed with GW detectors**?



(credit: Sennett)

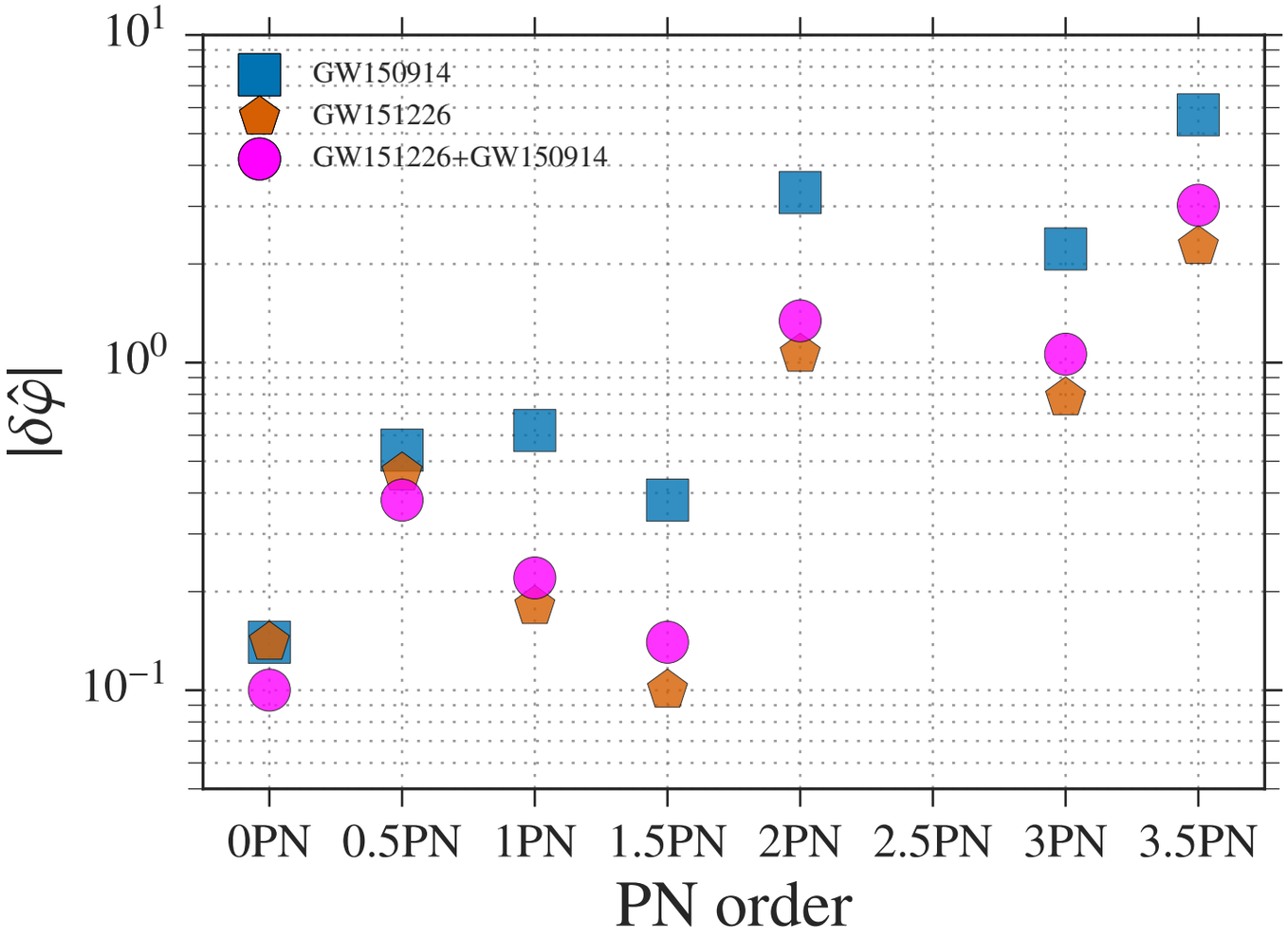
First Tests of General Relativity in Dynamical, Strong Field

- GW150914/GW122615's **rapidly varying orbital periods** allow us to **bound higher-order PN coefficients** in gravitational phase.

$$\tilde{h}(f) = \mathcal{A}(f)e^{i\varphi(f)}$$

$$\begin{aligned}\varphi(f) =& \varphi_{\rm ref} + 2\pi f t_{\rm ref} + \varphi_{\rm Newt}(Mf)^{-5/3} \\ &+ \varphi_{\rm 0.5PN}(Mf)^{-4/3} + \varphi_{\rm 1PN}(Mf)^{-1} \\ &+ \varphi_{\rm 1.5PN}(Mf)^{-2/3} + \cdots\end{aligned}$$

(Abbott et al. PRX6 (2016))



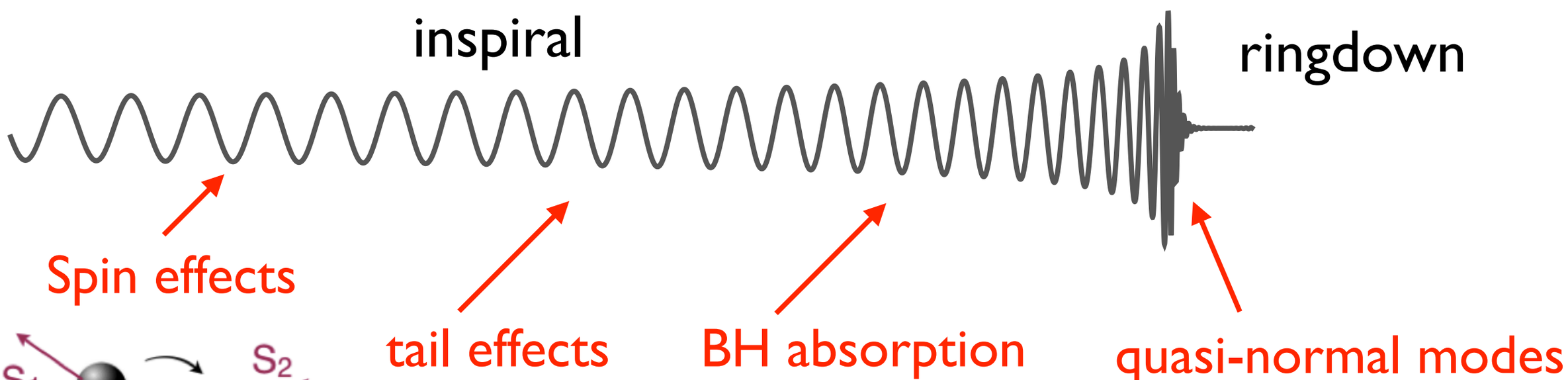
(Arun et al. 06 , Mishra et al. 10, Yunes & Pretorius 09, Li et al. 12)

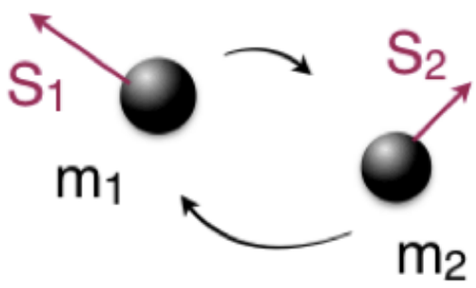
- **PN parameters** describe: **tails** of radiation due to backscattering, **spin-orbit** and **spin-spin** couplings.

- **PN parameters** take **different values** in **modified theories** to GR.

Waveforms Encode Plethora of Physical Effects

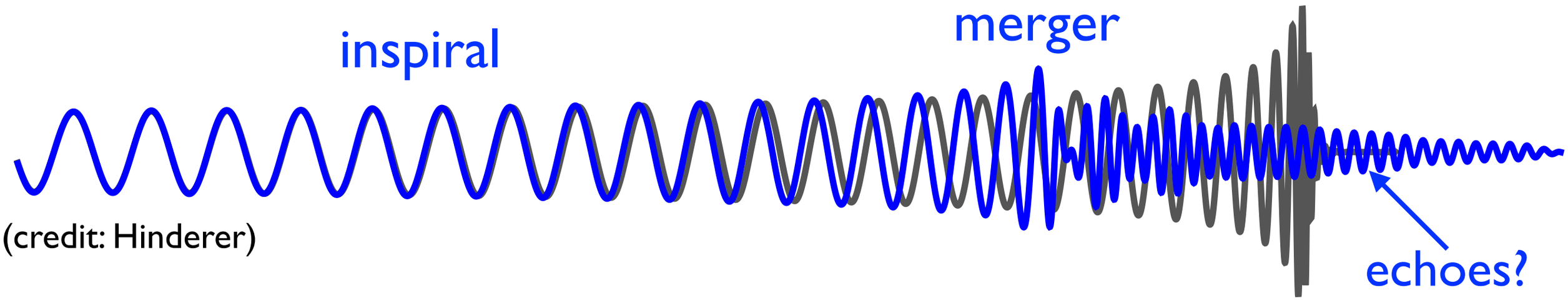
- Binary black hole





(credit: Hinderer)

- **Compact-object binary** with **matter** or in **modified theory** to GR?



(credit: Hinderer)

Some Modified Theories to GR

Theory	$\alpha_{\rm ppE}$	$a_{\rm ppE}$	$\beta_{\rm ppE}$	$b_{\rm ppE}$
Jordan–Fierz–Brans–Dicke	$-\frac{5}{96}\frac{S^2}{\omega_{\rm BD}}\eta^{2/5}$	-2	$-\frac{5}{3584}\frac{S^2}{\omega_{\rm BD}}\eta^{2/5}$	-7
Dissipative Einstein-Dilaton-Gauss–Bonnet gravity	0	·	$-\frac{5}{7168}\zeta_3\eta^{-18/5}\delta_m^2$	-7
Massive Graviton	0	·	$-\frac{\pi^2 D\mathcal{M}_c}{\lambda_g^2(1+z)}$	-3
Lorentz Violation	0	·	$-\frac{\pi^{2-\gamma_{\rm LV}}}{(1-\gamma_{\rm LV})}\frac{D_{\gamma_{\rm LV}}}{\lambda_{\rm LV}^{2-\gamma_{\rm LV}}}\frac{\mathcal{M}_c^{1-\gamma_{\rm LV}}}{(1+z)^{1-\gamma_{\rm LV}}}$	$-3\gamma_{\rm LV}-3$
$G(t)$ Theory	$-\frac{5}{512}\dot{G}\mathcal{M}_c$	-8	$-\frac{25}{65536}\dot{G}_c\mathcal{M}_c$	-13
Extra Dimensions	·	·	$-\frac{75}{2554344}\frac{dM}{dt}\eta^{-4}(3-26\eta+24\eta^2)$	-13
Non-Dynamical Chern–Simons Gravity	$\alpha_{\rm PV}$	3	$\beta_{\rm PV}$	6
Dynamical Chern–Simons Gravity	0	·	$\beta_{\rm dCS}$	-1

(Yunes & Siemens 2013)

Tests of Lorentz Invariance/Bounding Graviton Mass

- Phenomenological approach: **modified dispersion relation.** GWs travel at speed different from speed of light. (Will 94, Mirshekari, Yunes & Will 12)

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha$$

$$\alpha \geq 0$$

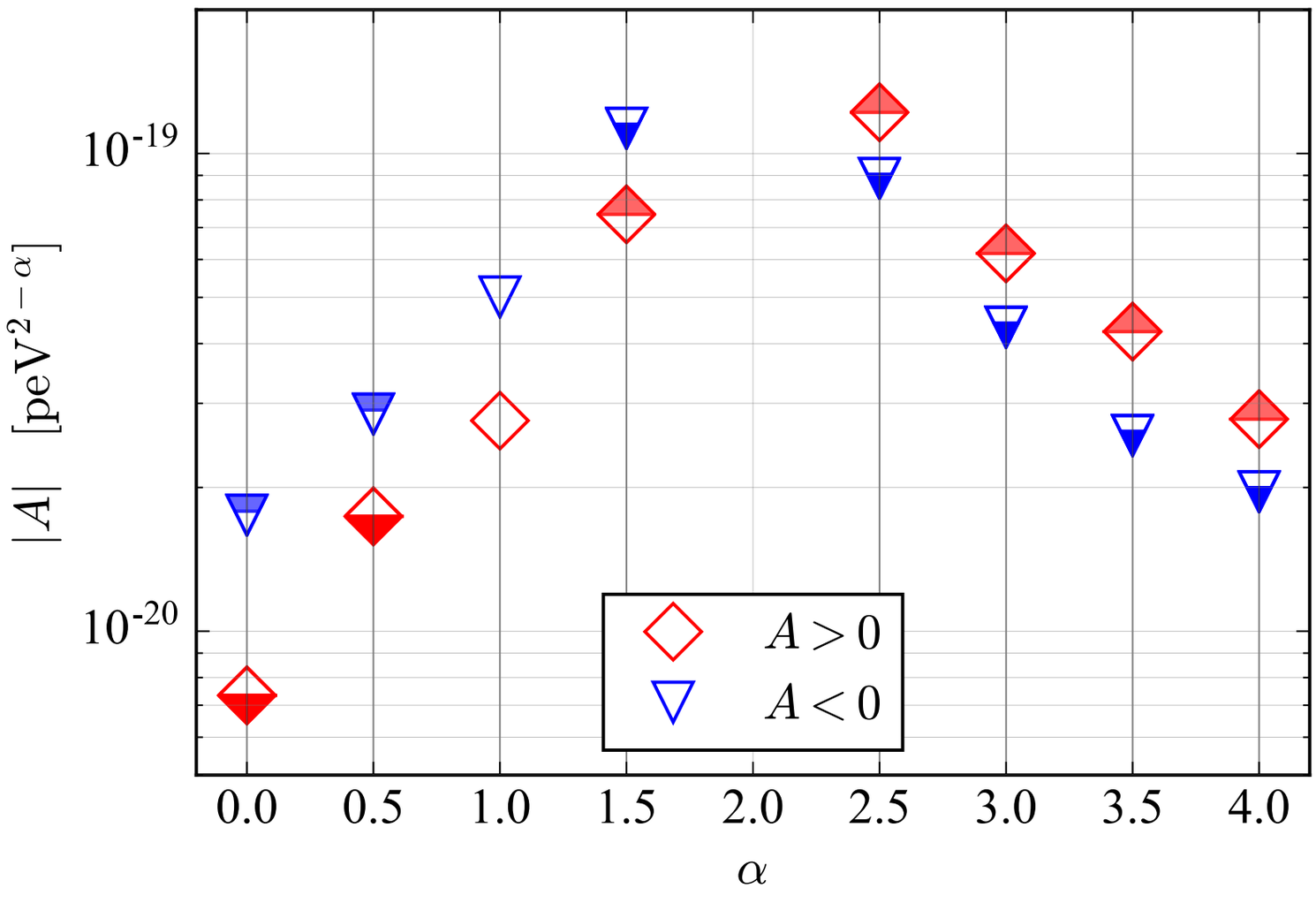
$$\frac{v_g}{c} = 1 + (\alpha - 1)\frac{A}{2}E^{\alpha-2}$$

$$m_g \leq 7.7 \times 10^{-23}\mathrm{eV/c^2}$$

$$\alpha = 0, A > 0$$

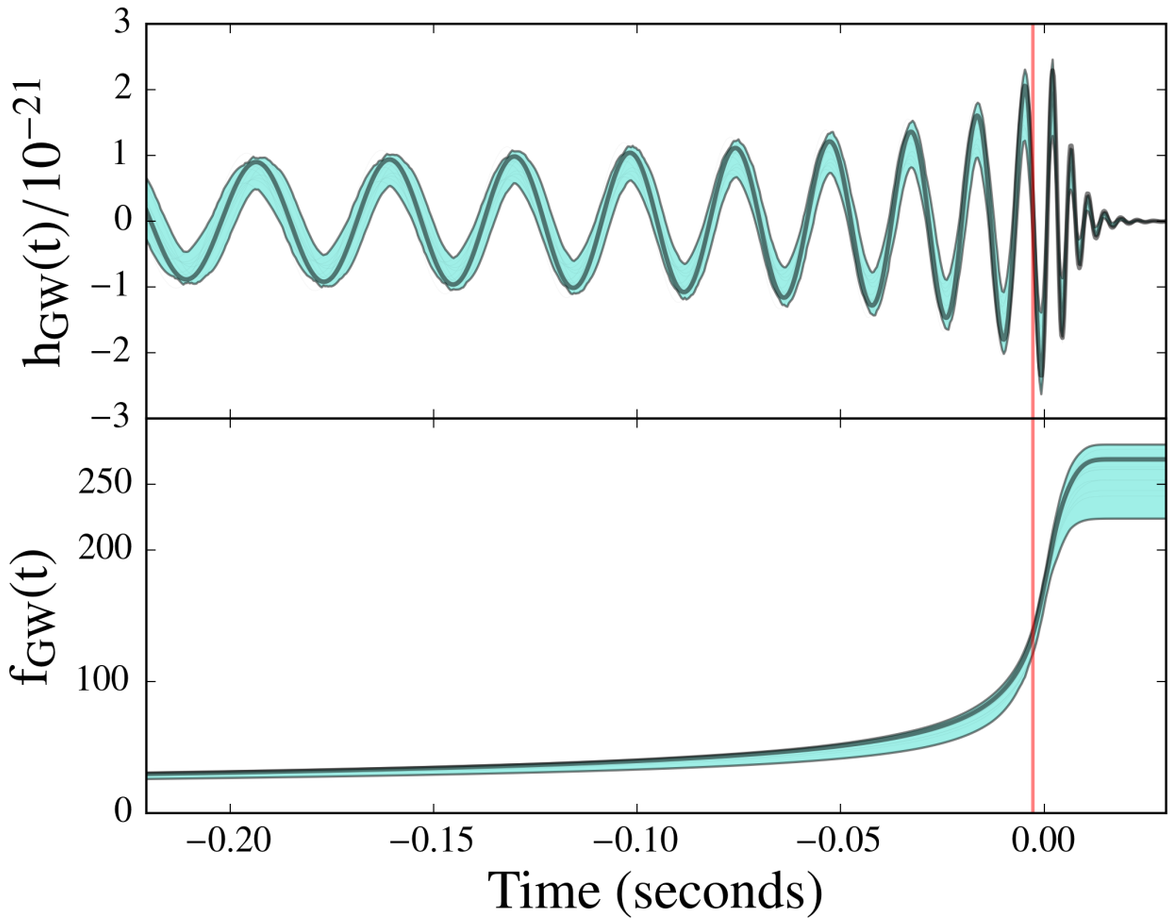
$$\lambda_g = \frac{h}{m_g c}$$

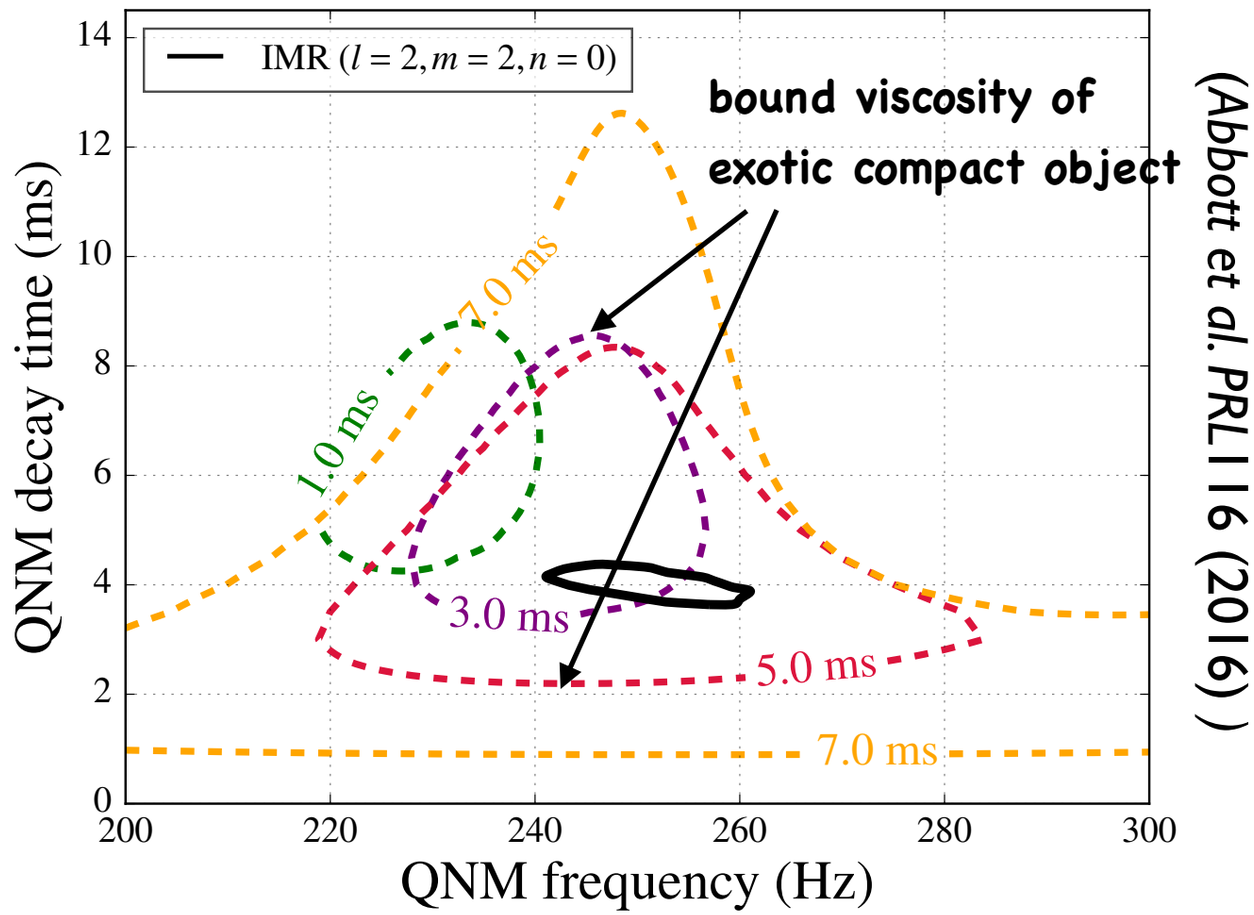
(Abbott et al. PRL118 (2017))



Probing Remnant: Quasi Normal Modes (QNMs)

- **Deformed black holes** emits **quasi-normal modes**.
- **Measuring** at least two modes will be **smoking gun** that **Nature's black holes** are black holes of **General Relativity**.



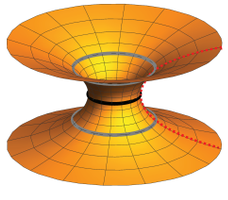


- **Multiple QNMs** can be measured with future detectors, thus testing **no-hair theorem** and **second-law black-hole mechanics** *(Israel 69, Carter 71; Hawking 71, Bardeen 73).*

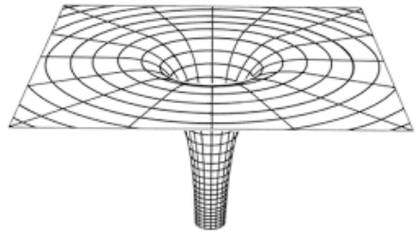
Remnant: Black Hole or Exotic Compact Object (ECO)?

horizonless objects

wormhole



boson stars, fermion stars, etc.
(e.g., Giudice et al. 16)

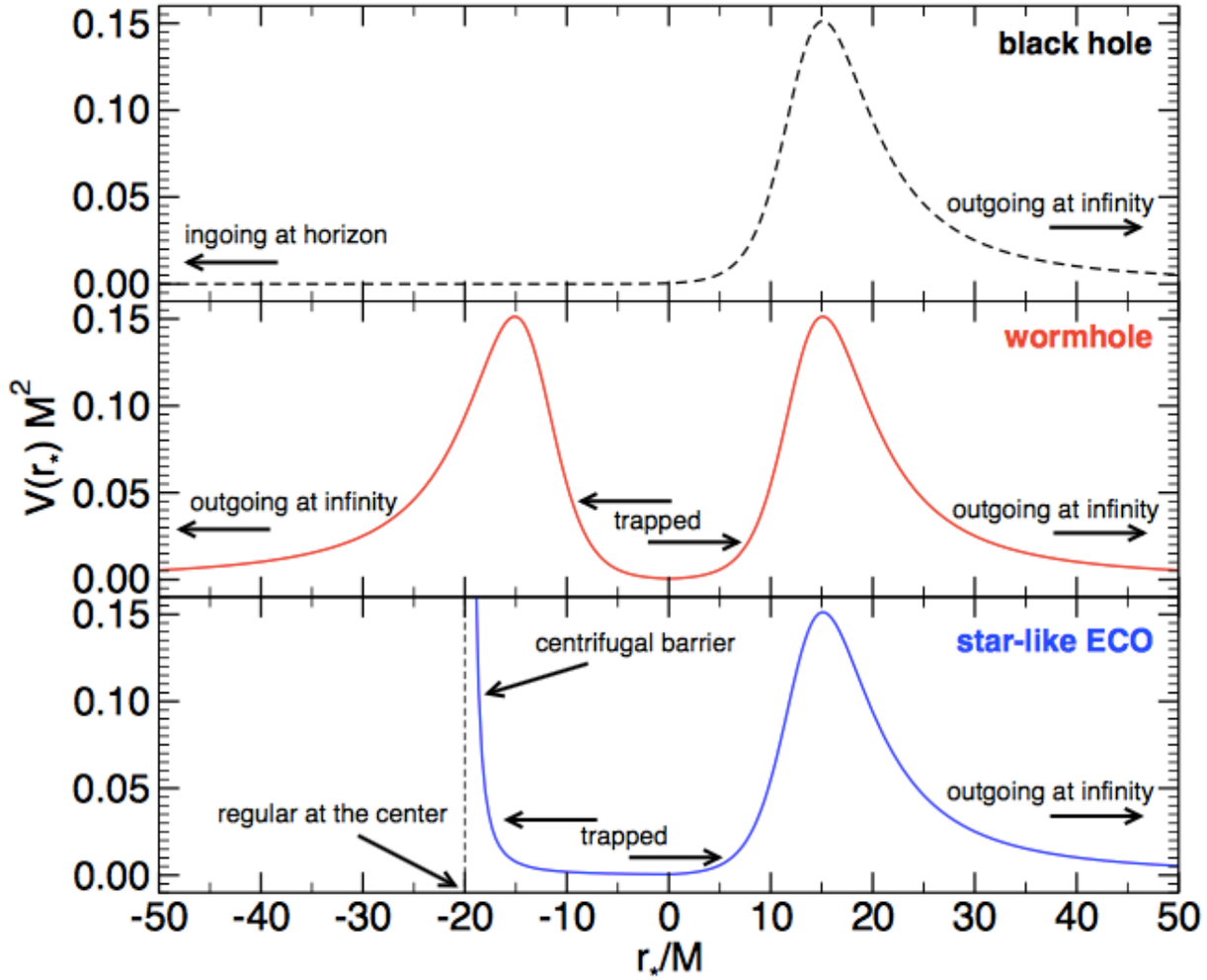


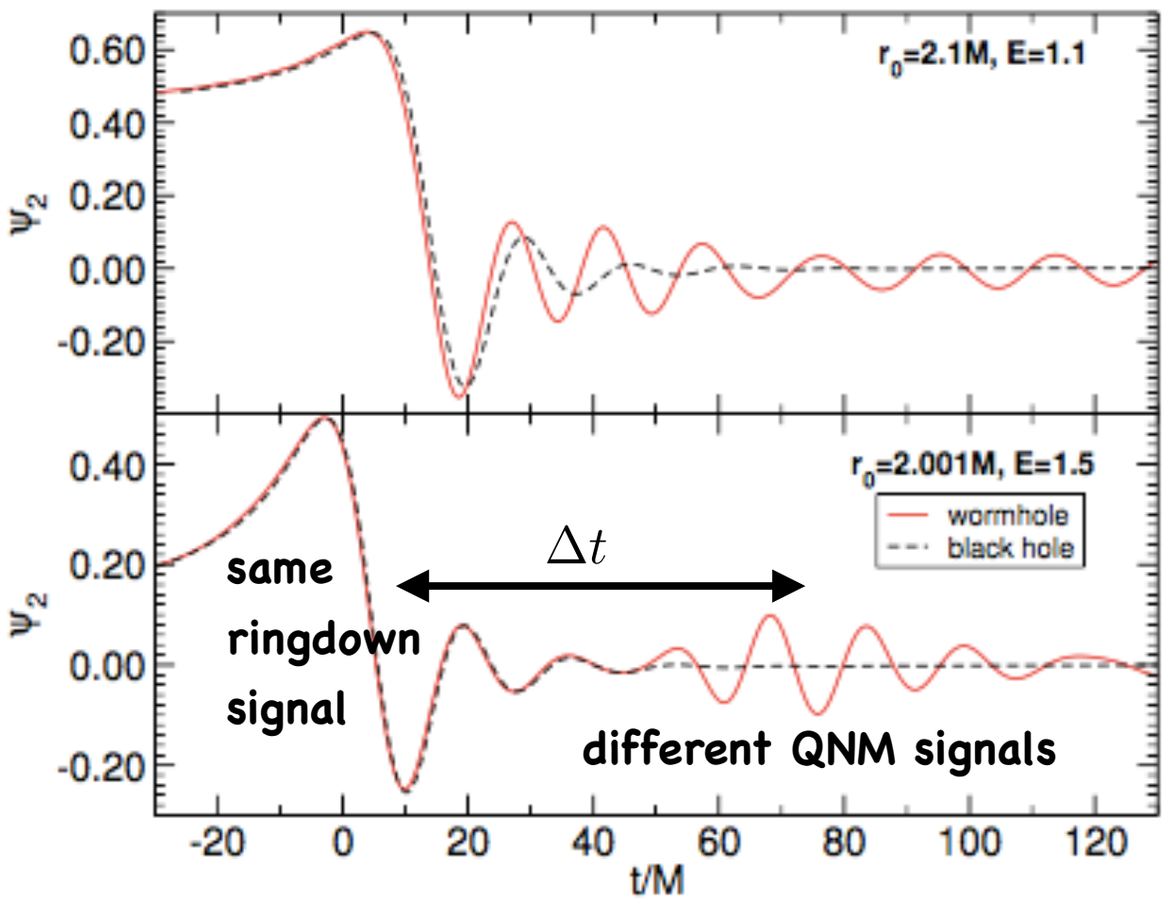
black hole

(Cardoso et al. 16)

- If **remnant** is **horizonless,** and/or **horizon is replaced** by **"surface"**, new modes in the spectrum, and ringdown signal is modified: **echoes signals emitted after merger.**

(Damour & Solodukhin 07, Cardoso, Franzin & Pani 16)



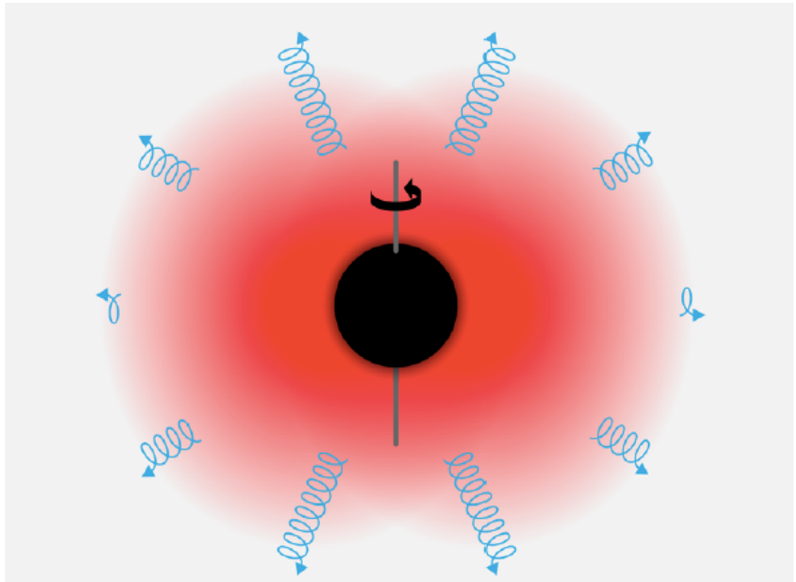


Unveiling Ultralight Bosonic Particles with GWs

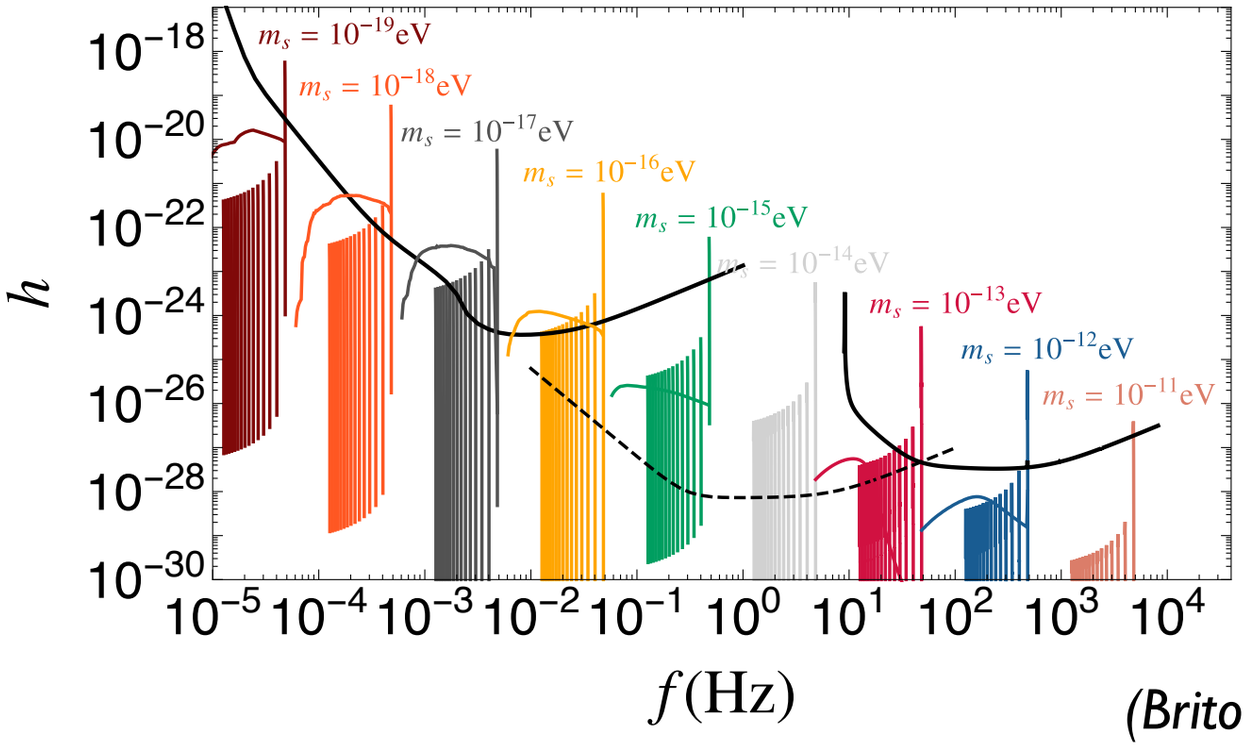
- Ultralight scalar fields around spinning BHs can **trigger superradiant instabilities**, forming a **long-lived bosonic condensate outside horizon.** *(Arvanitaki et al. 2015)*

- Bosonic condensate rotates, emitting **continuous monochromatic GW.**

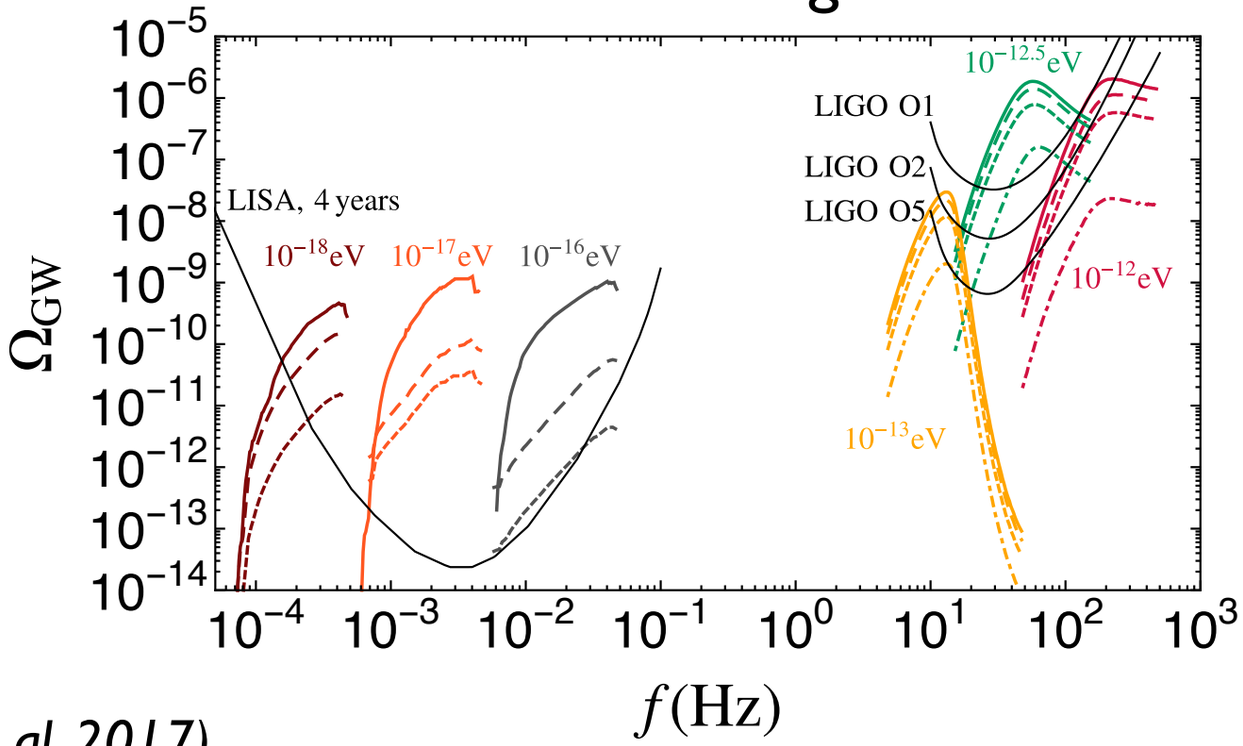
- Spinning BHs can grow hair



resolvable signals



stochastic background



(Brito et al. 2017)

Are we observing Primordial Black Holes?

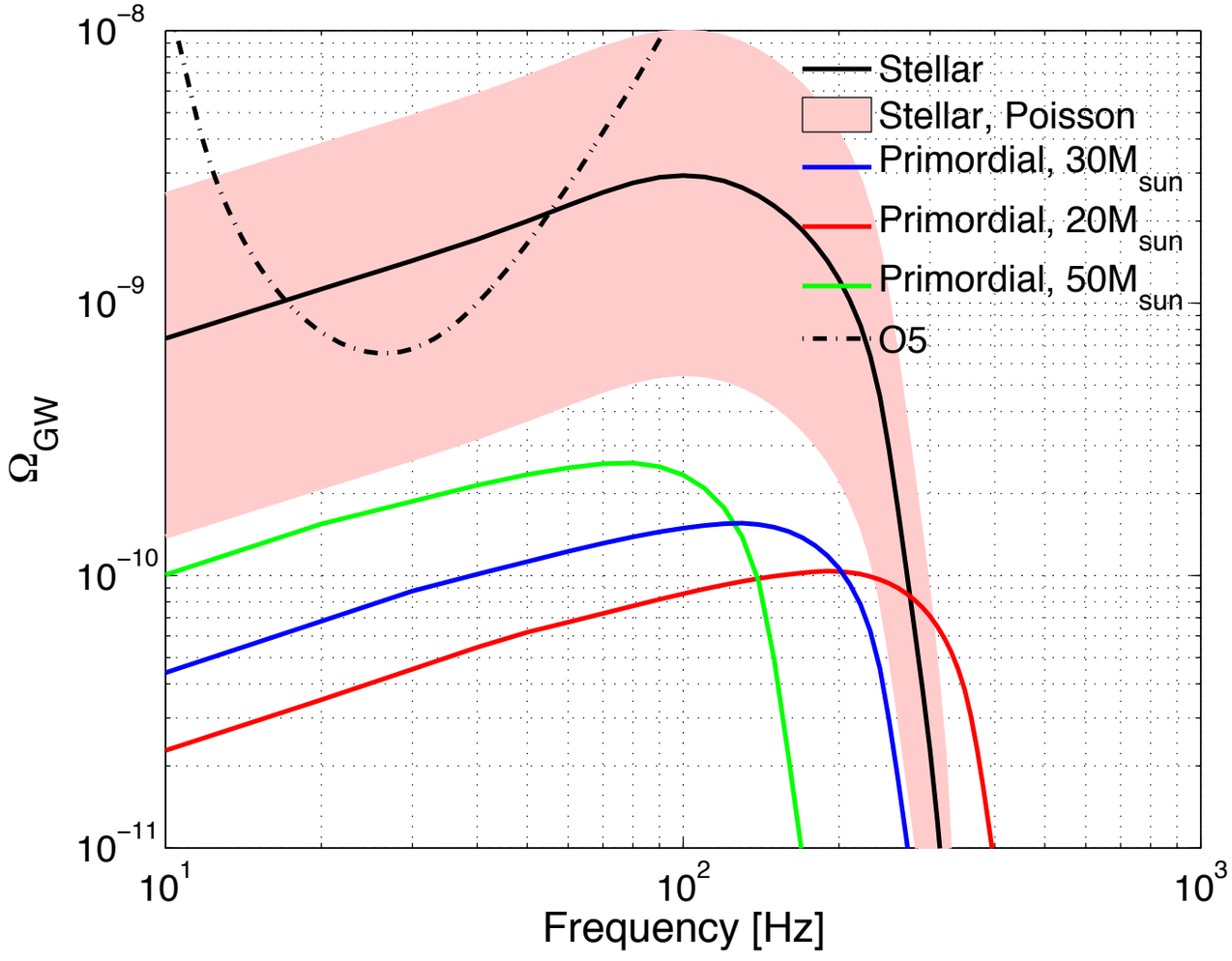
- Was GW150914 of **primordial origin**?
  If so, is GW150914 **evidence for dark matter** in form of black holes?
  (Cholis et al. 2016)

- PBHs accrete primordial gas, converting a fraction of accreted mass to radiation, leading to **distortions of CMB power spectra**.
  (Ricotti et al. 2008)

- PBHs with masses > 100 Msun are **ruled out as dominant dark-matter component**.
  (Ali-Haimond et al. 2017)

- PBHs could be dominant dark matter if **masses are 20-100 Msun**.

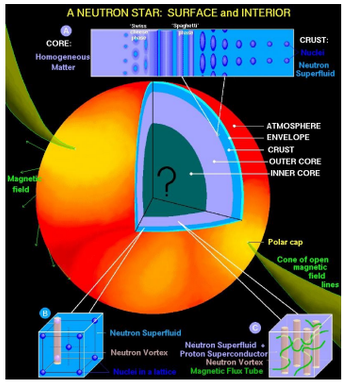
stochastic background of PBHs



(Mandic et al. 2017)

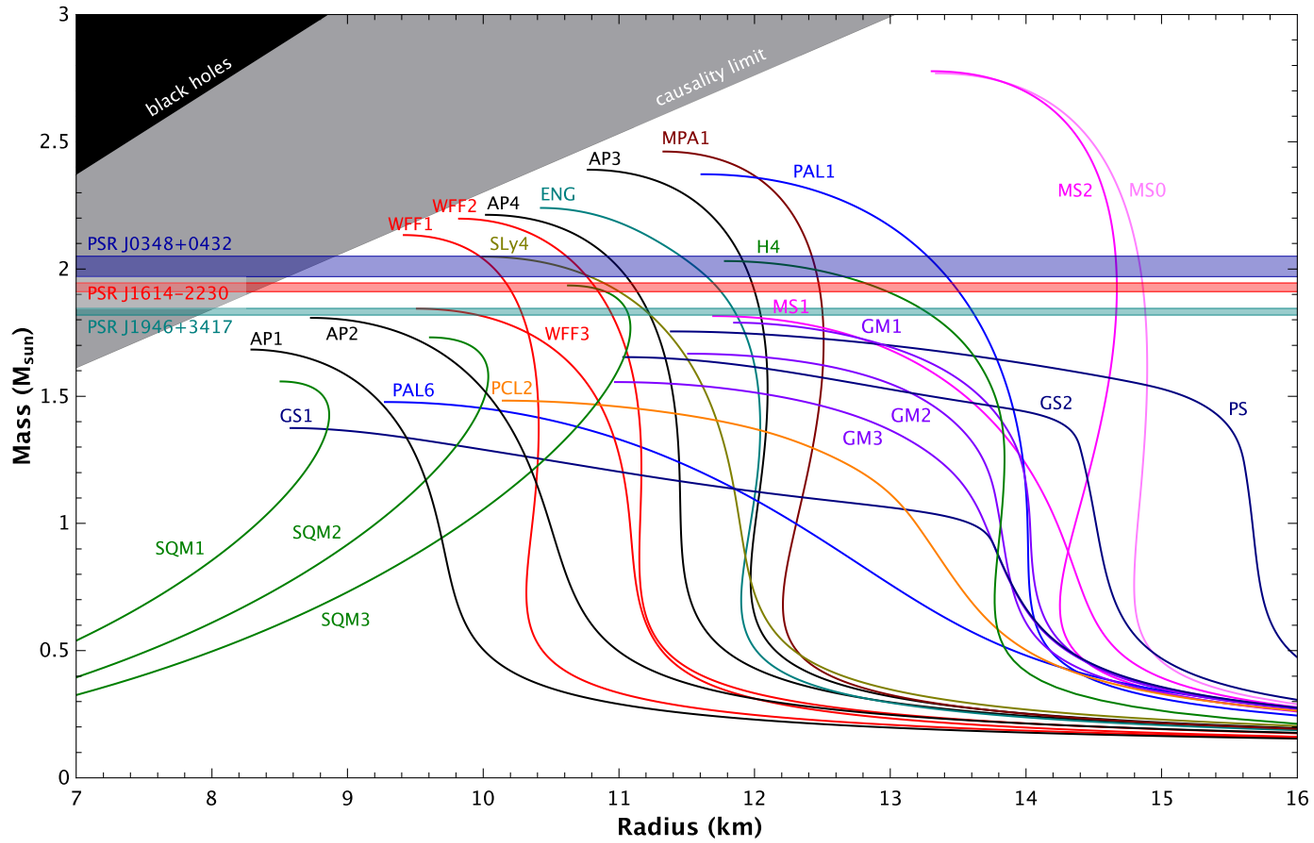
Probing New Physics with GWs and Neutron Stars

(Baade & Zwicky 1934, Gamow 1937, Landau 1938, Oppenheimer & Volkoff 1939, Cameron 1959, Wheeler 1966)

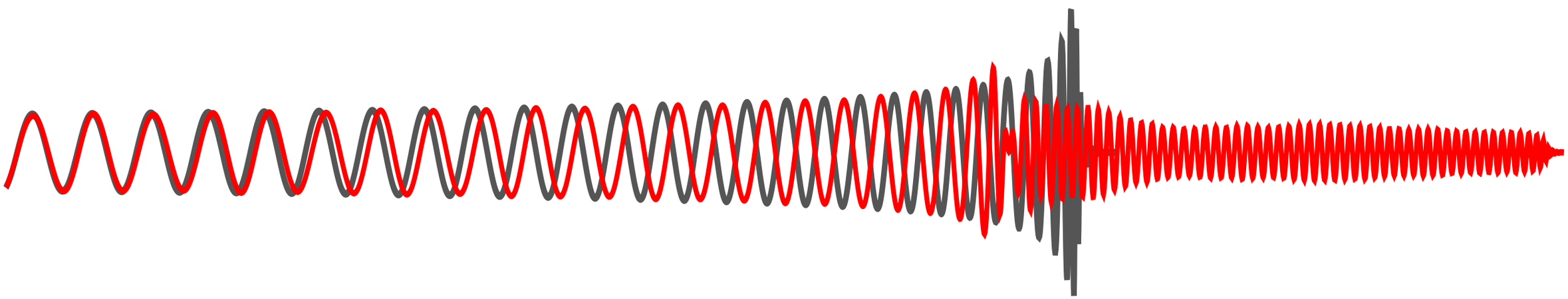


Neutron Star:

- mass: 1-3 Msun
- radius: 9-15 km
- core density > 10^{14}g/cm^3



(Antoniadis et al. 2016)

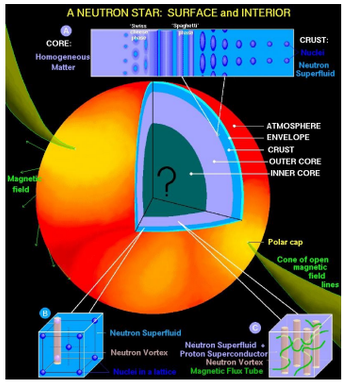


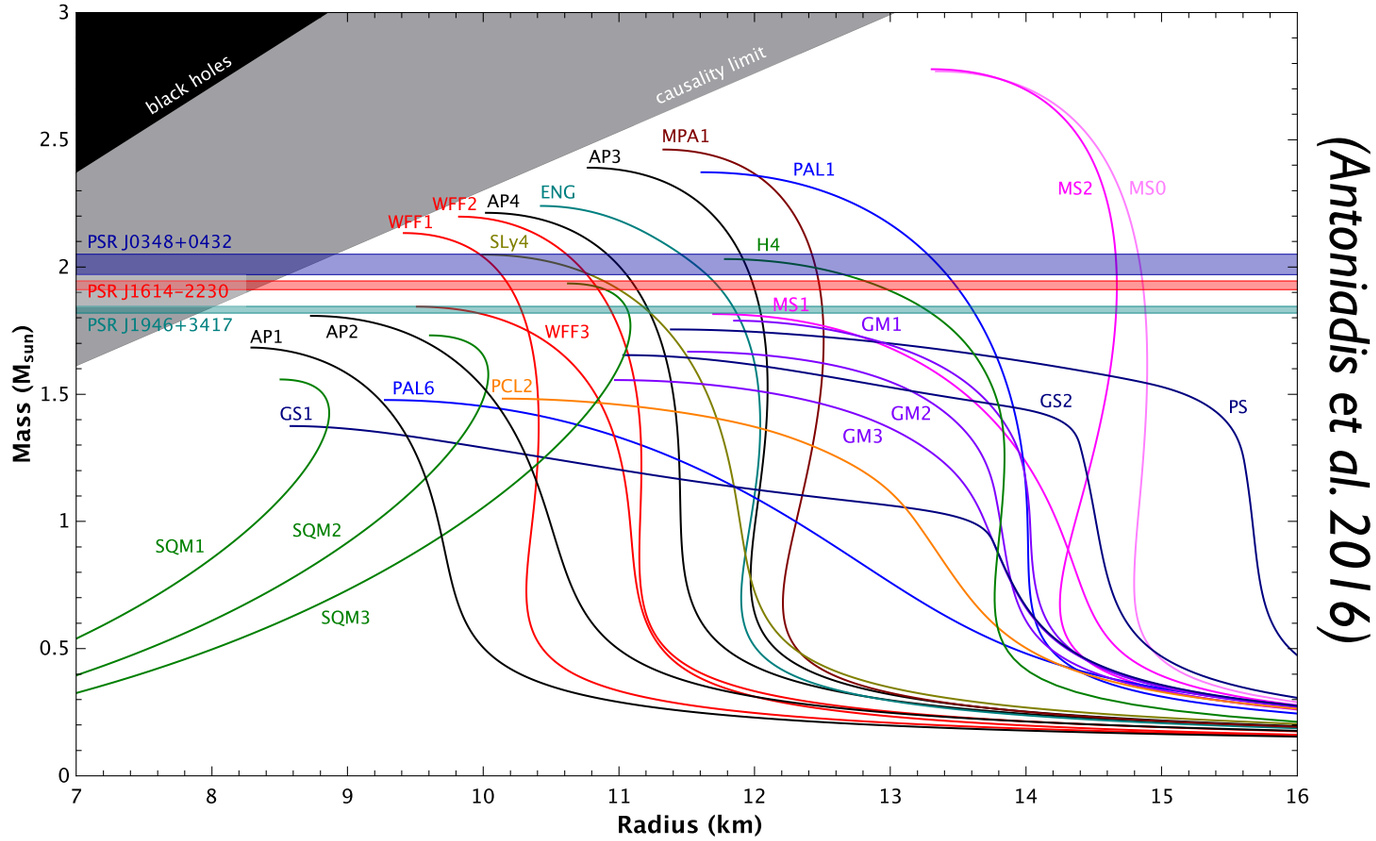
tidal interactions

(credit: Hinderer)

Inferring Equation of State of Dense Matter

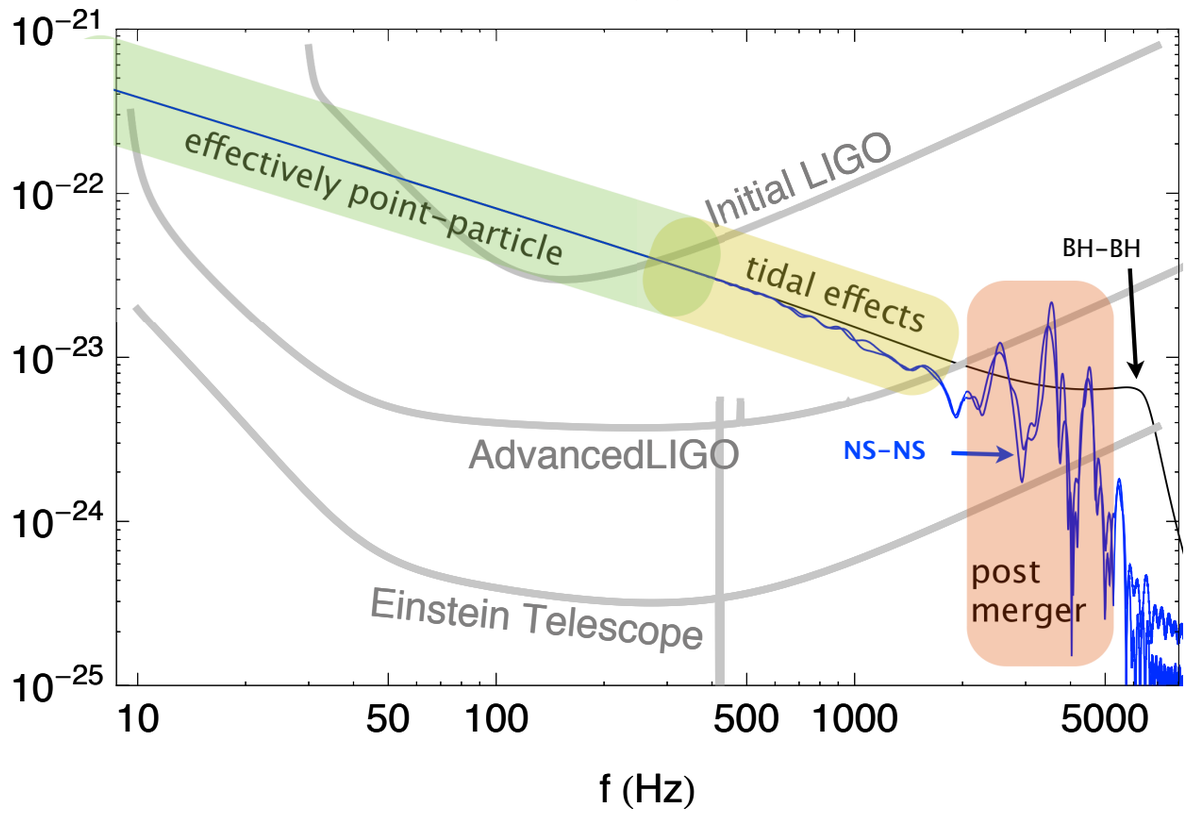
(Baade & Zwicky 1934, Gamow 1937, Landau 1938, Oppenheimer & Volkoff 1939, Cameron 1959, Wheeler 1966)





(Antoniadis et al. 2016)

- **NS equation of state** (EOS) affects gravitational **waveform** during **late inspiral, merger** and **post-merger**.



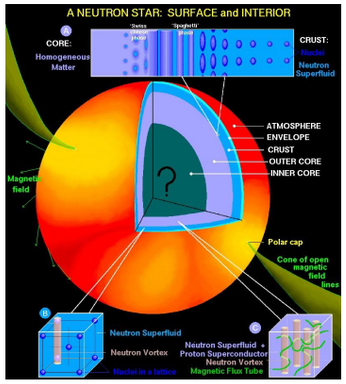
(credit: Read)

Neutron Star:

- mass: 1-3 Msun
- radius: 9-15 km
- core density > 10^{14}g/cm^3

Extracting Information on EOS from Late Inspiral

(Baade & Zwicky 1934, Gamow 1937, Landau 1938, Oppenheimer & Volkoff 1939, Cameron 1959, Wheeler 1966)



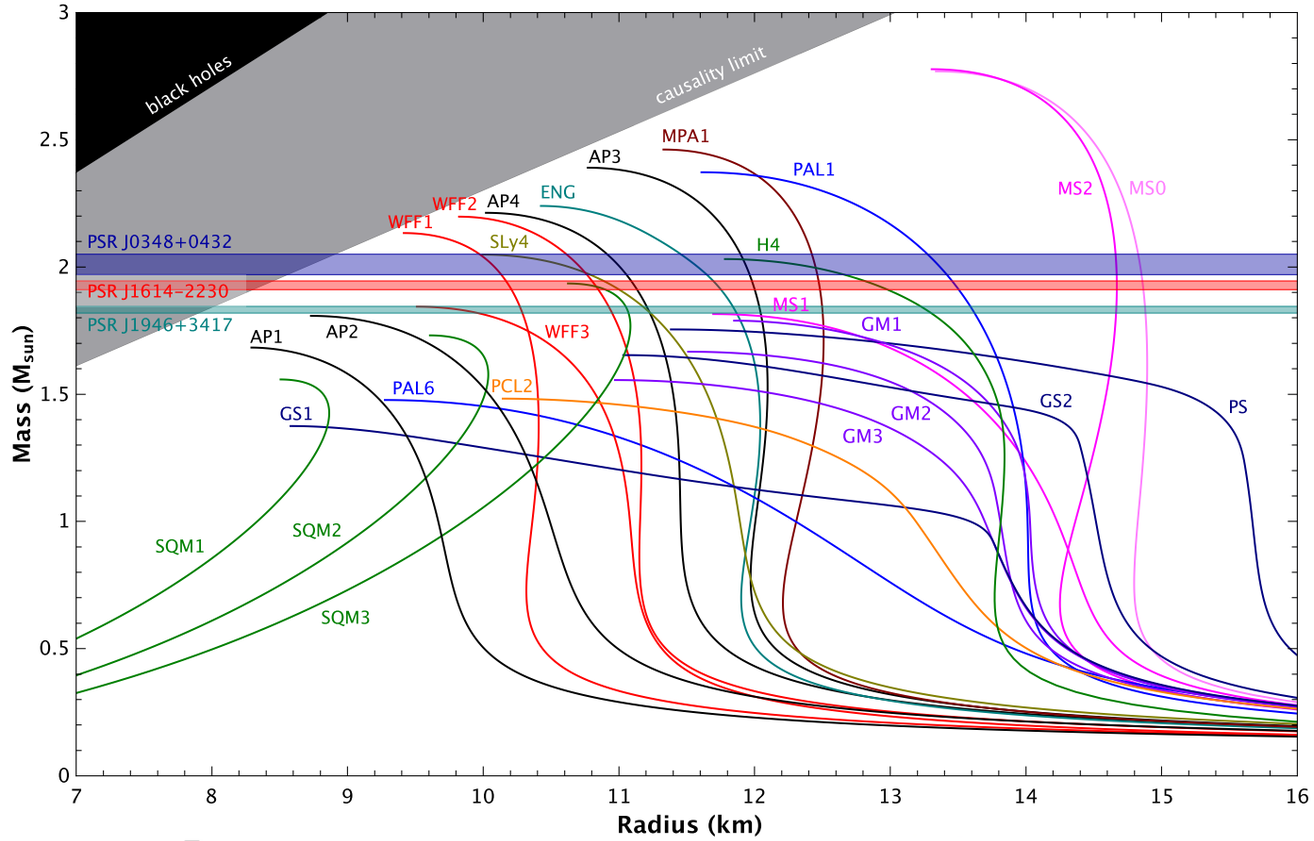
Neutron Star:

- mass: 1-3 Msun
- radius: 9-15 km
- core density > 10^{14}g/cm^3

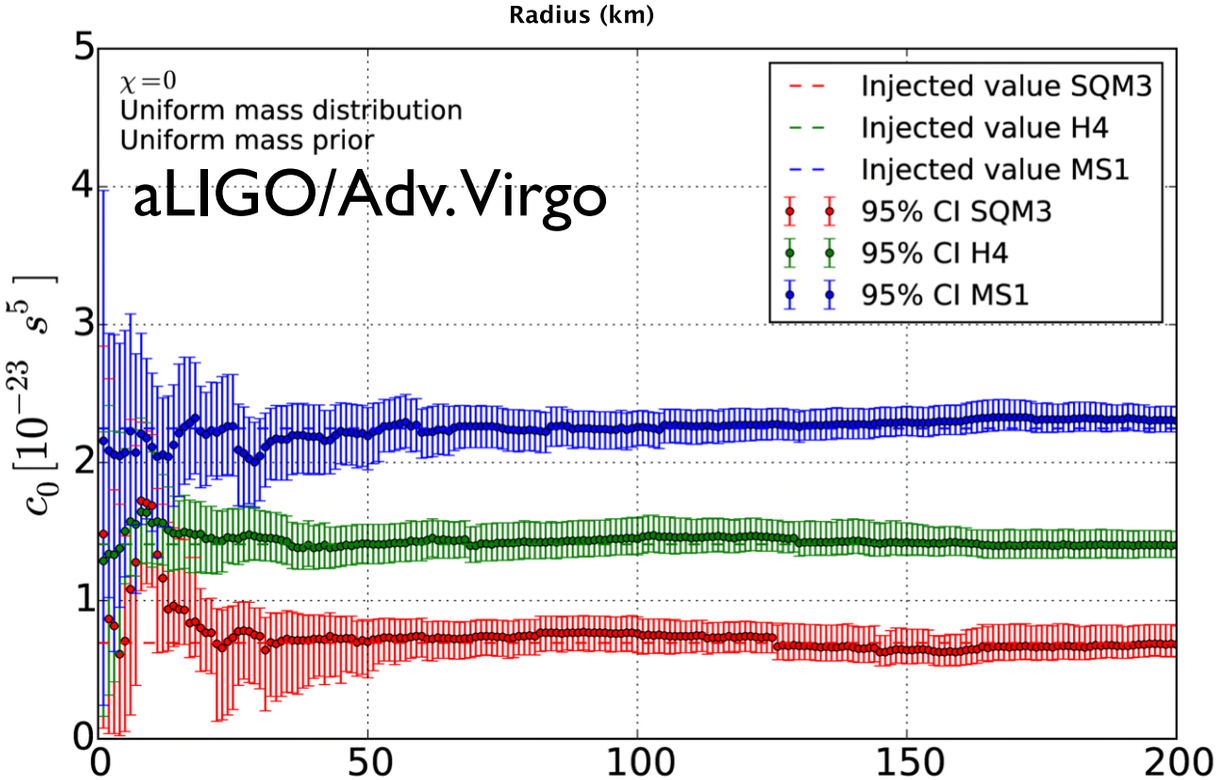
- **Tidal effects imprinted** on gravitational waveform during inspiral through **parameter** λ.

- λ **measures** star's **quadrupole deformation** in response to companion **perturbing tidal field:**

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$



(Antoniadis et al. 2016)



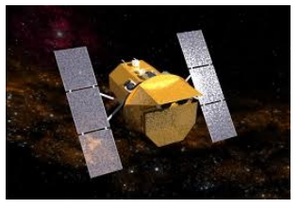
(Agathos et al. 2015)

Multi-Messenger AstroPhysics with GW & EM

- 95 **astronomical groups** part of **GW-EM** campaign

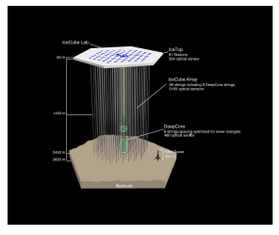
Integral

Swift

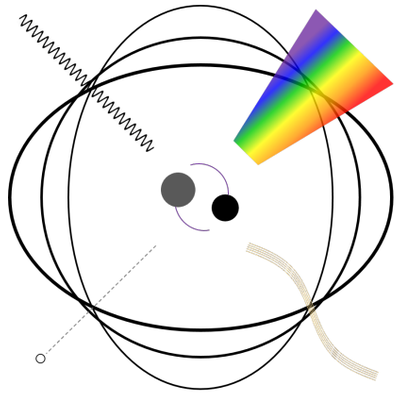


Fermi

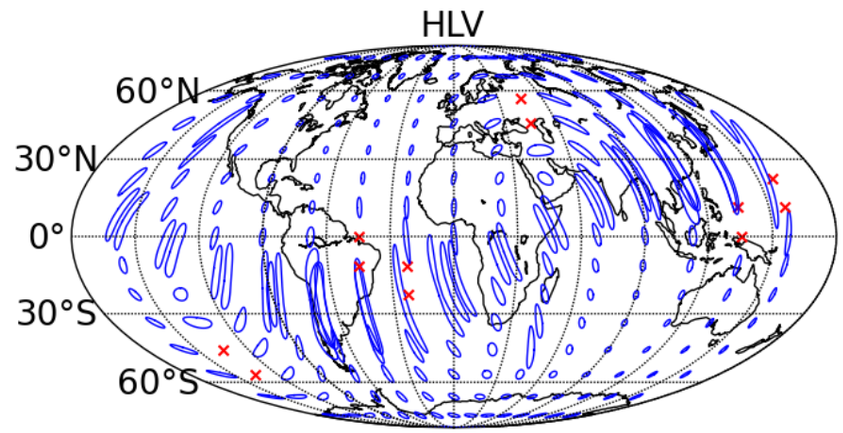
Icecube



PTF

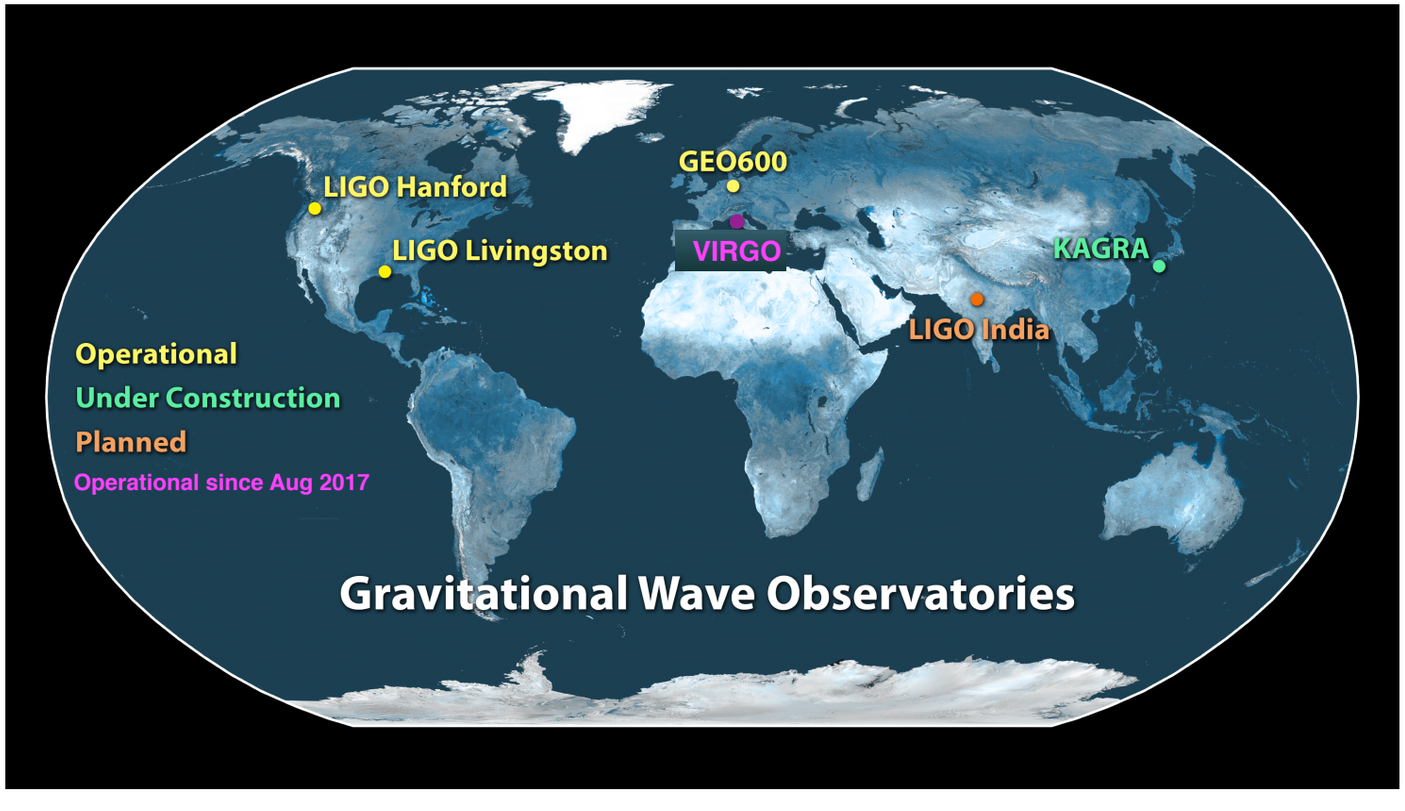


(Aasi et al. arXiv:1304.0670)



- Few tens or hundred square degrees

- What is the **physics of gravitational collapse** (supernovae)?
- What is the nature of **NS crust,** and how it interacts with **NS core**?
- What are the **true luminosity distances** of cosmological sources?
- Do **GWs** propagate at **speed of light**?



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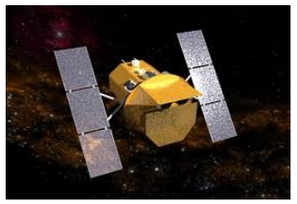

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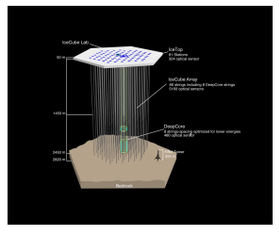

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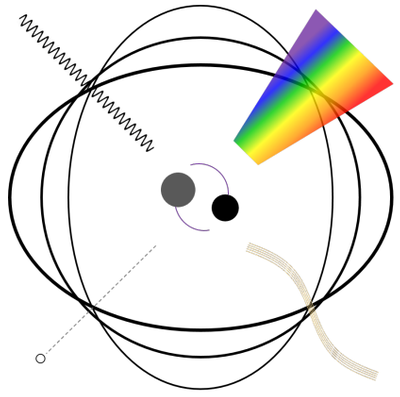

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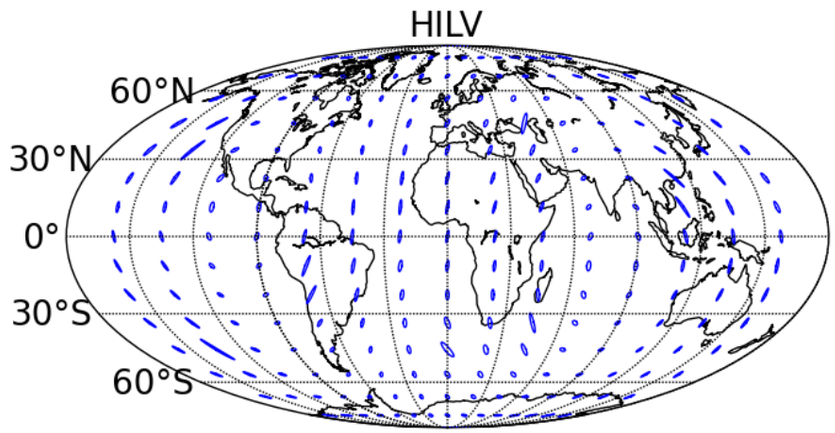
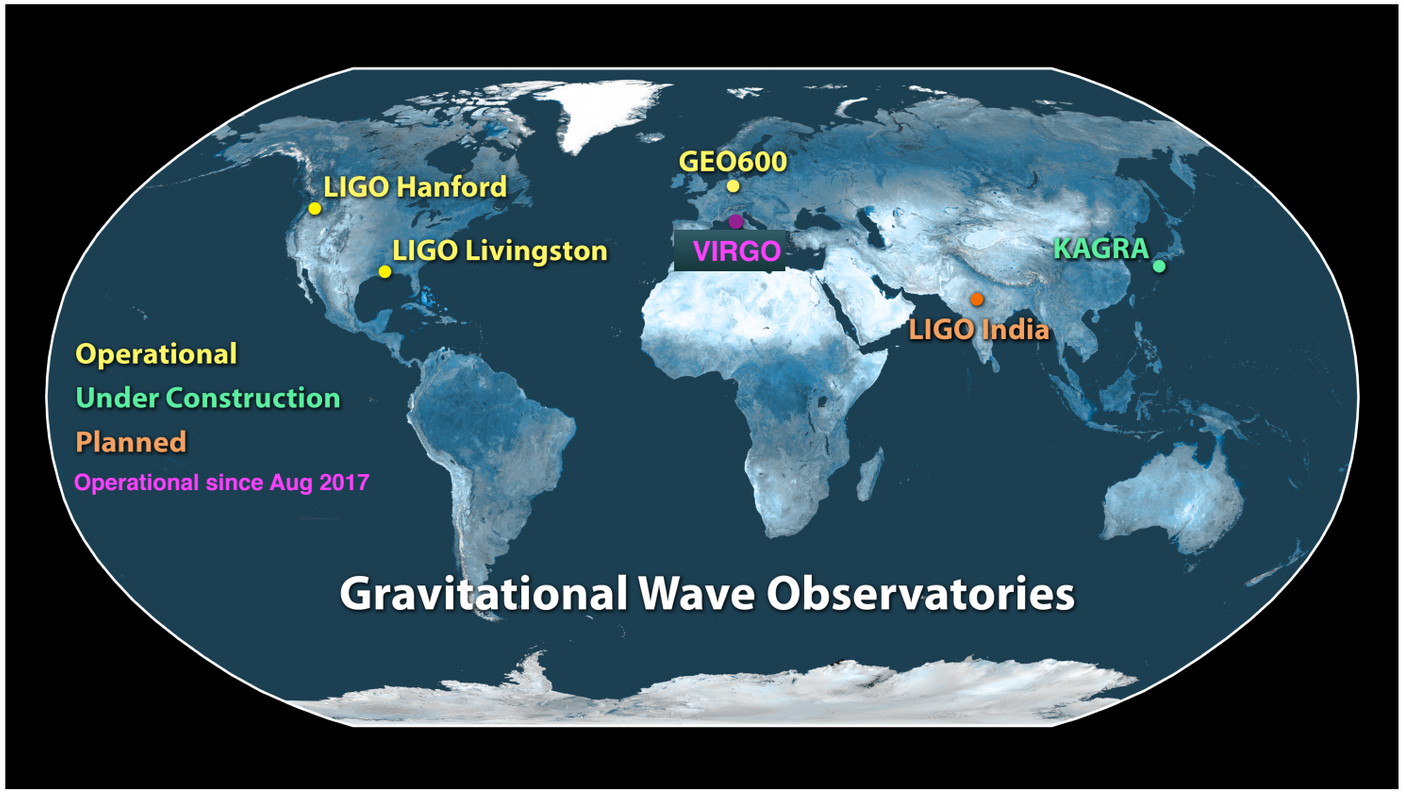


- Few square degrees!



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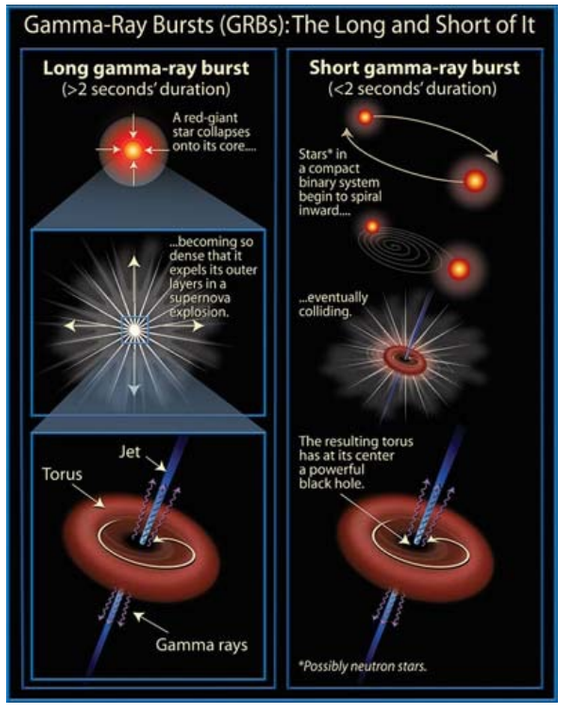
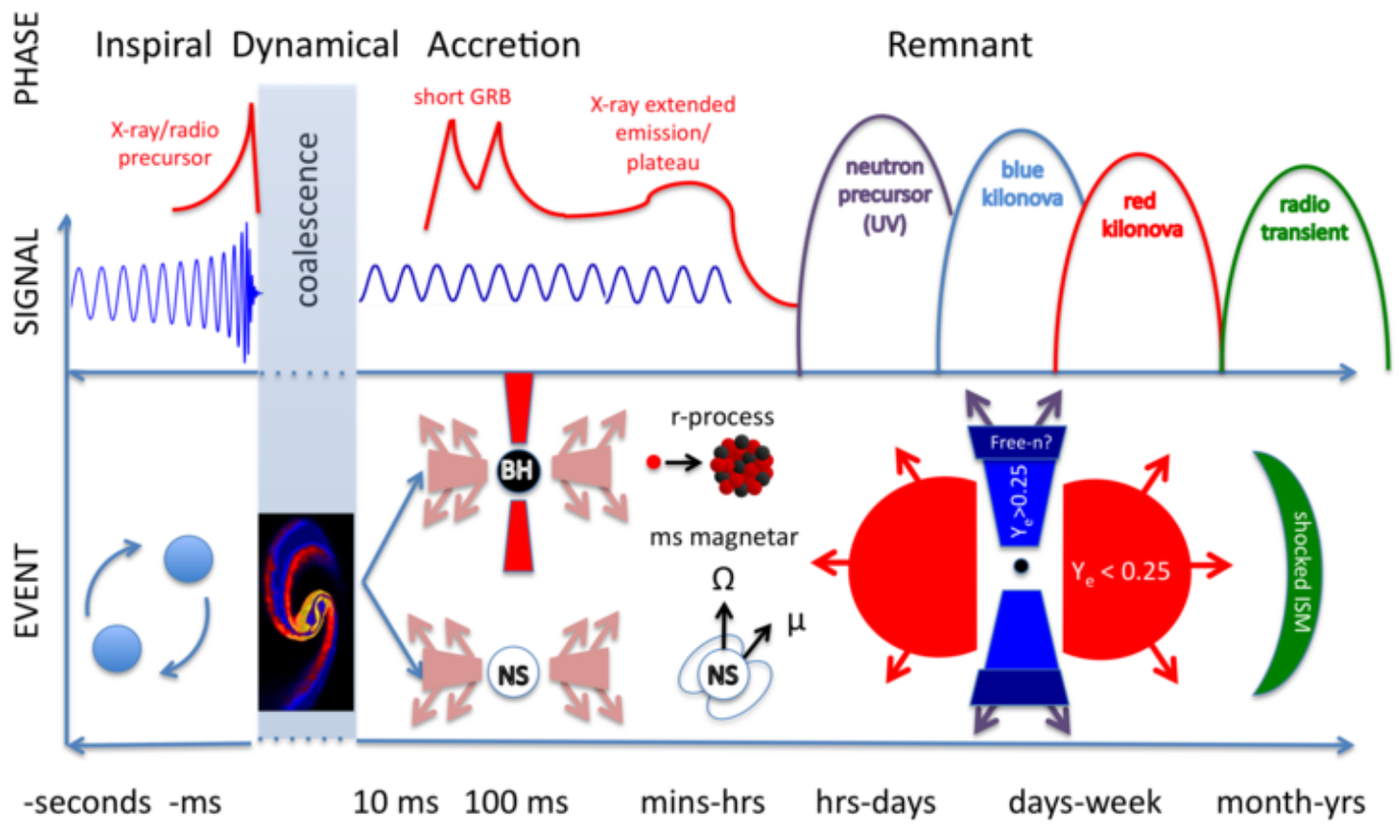
Disclosing the Origin of Most Energetic Phenomena in Universe

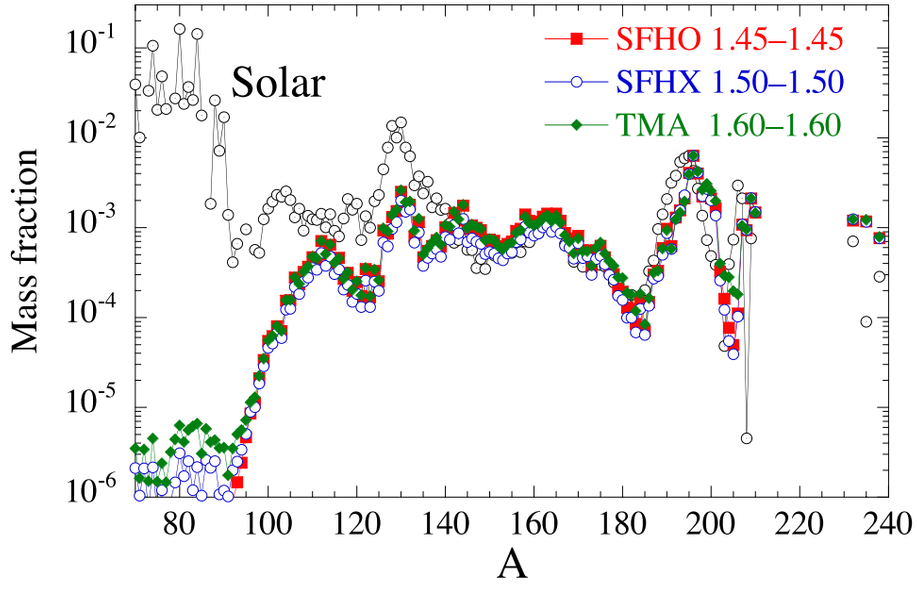


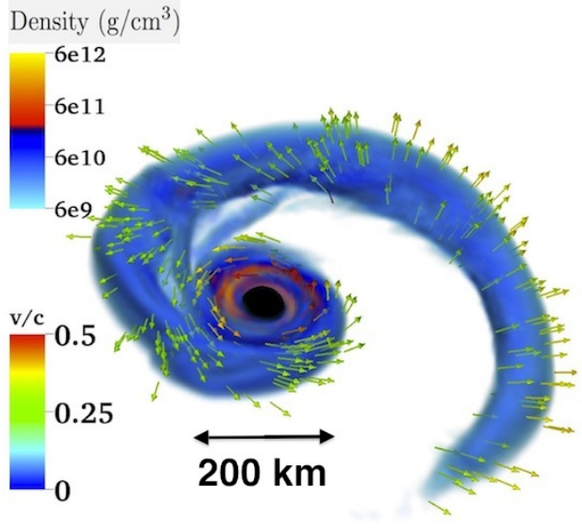


(Fernandez & Metzger 2016)

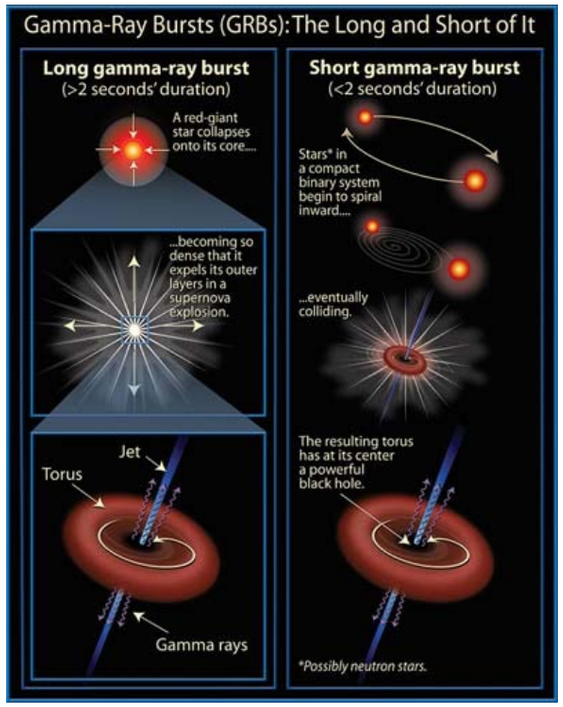
- Solving the **enigma** of short-hard **GRBs progenitors.**
- Understanding **matter and geometry** in **extreme conditions** of density, temperature, magnetic fields and relativistic motion.
- What's matter **EOS** at **supra-nuclear density**?

- **r-processes** (**nucleosynthesis**) in **neutron-star mergers**.



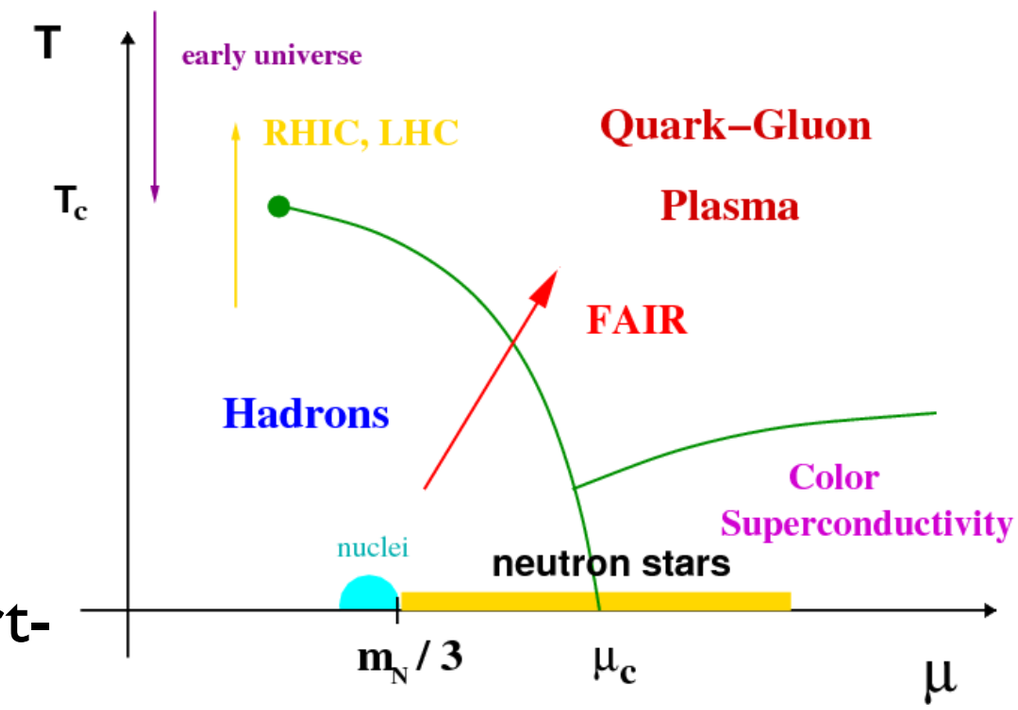


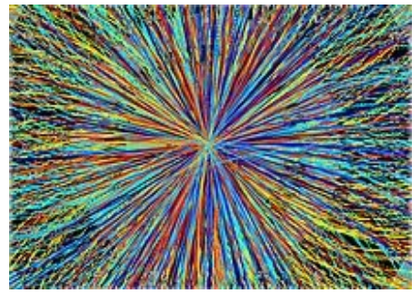
Sheding Light on Phase Diagram of Quark Matter



- Solving the **enigma** of short-hard **GRBs progenitors.**
- Understanding **matter and geometry** in **extreme conditions** of density, temperature, magnetic fields and relativistic motion.
- What's matter **EOS** at **supra-nuclear density**?

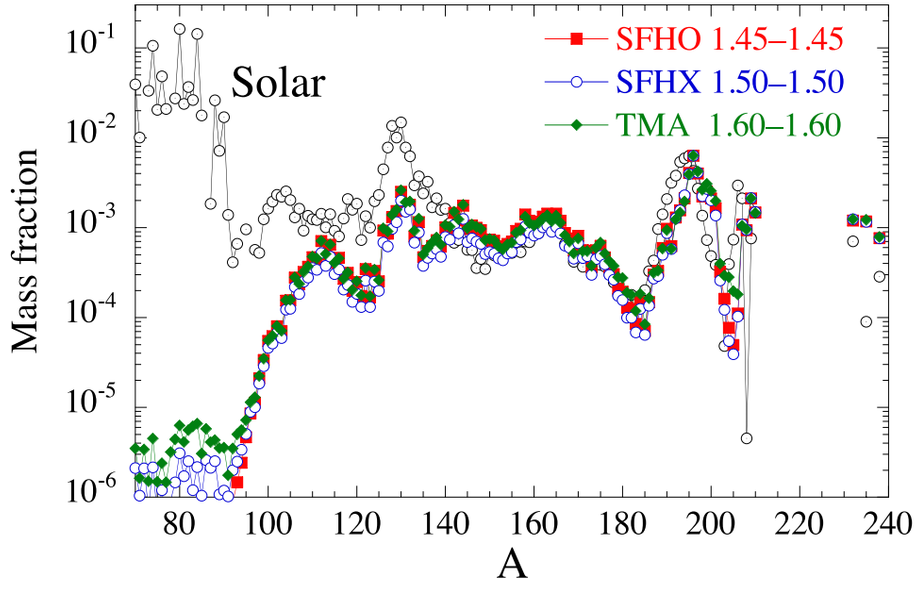
- **Conjectured** phase diagram of **quark matter.**

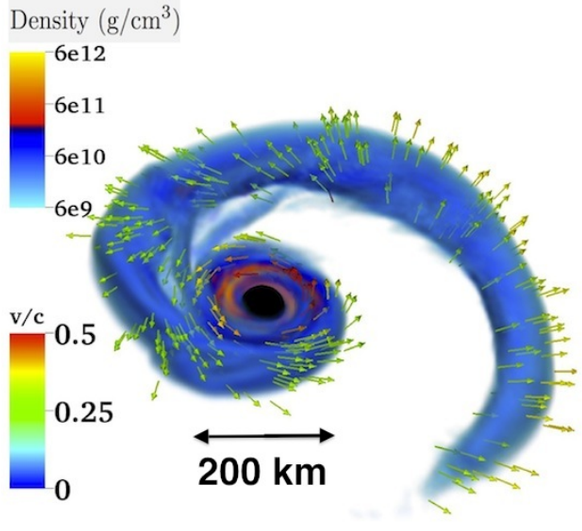




A Large Ion Collider Experiment (ALICE) @ CERN

- **Nucleosynthesis** from binary **neutron stars**.

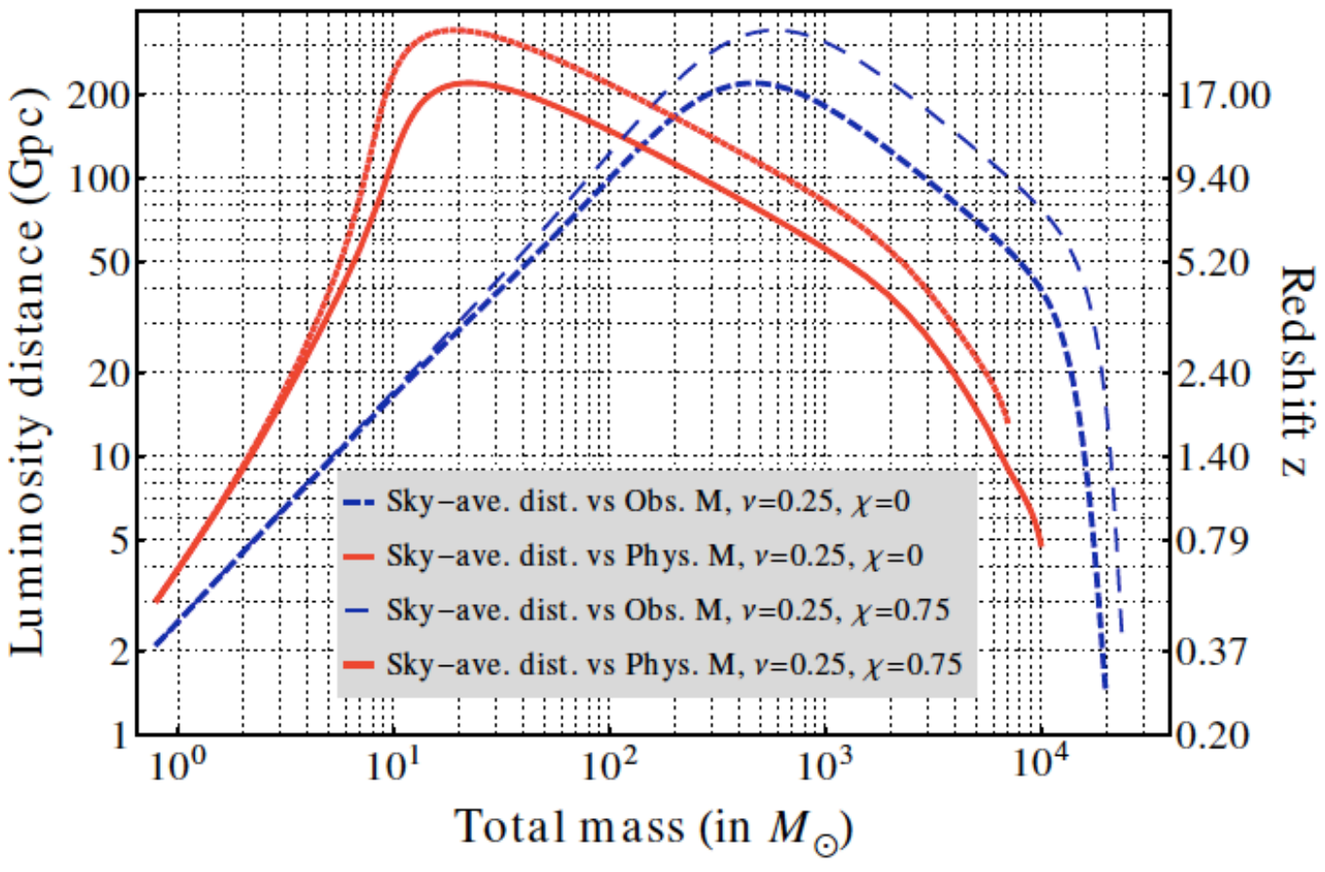


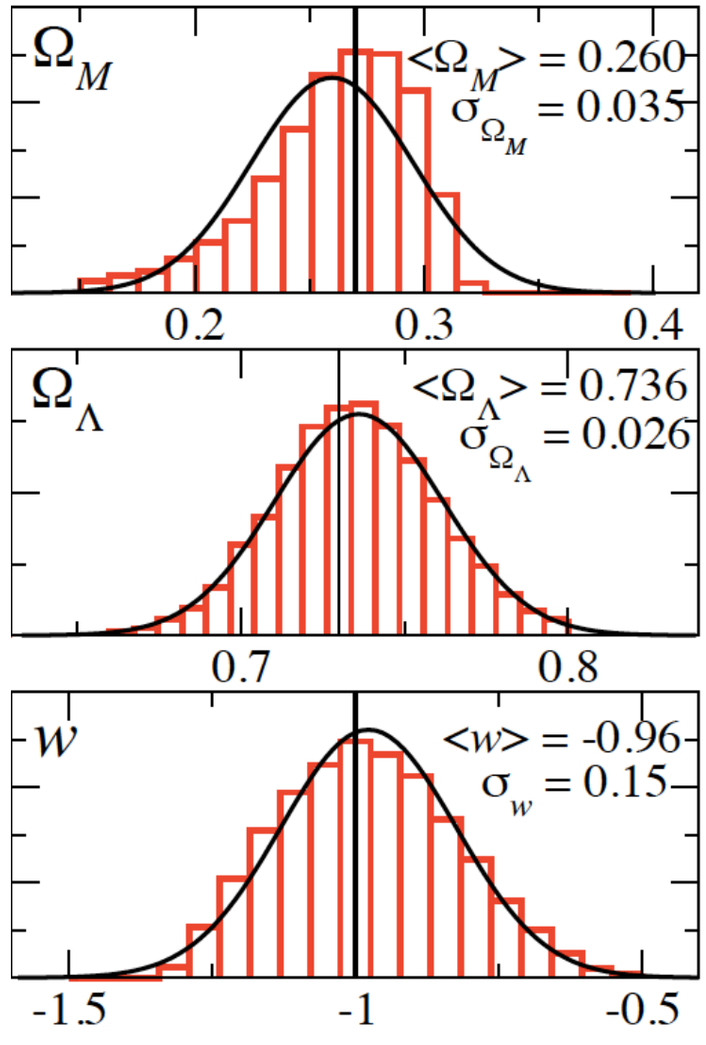


Cosmography: Inference of Cosmological Parameters with BNSs

- Compact-object **binaries are standard candles** (sirens). (Schutz 1986)
- **Standard candles** are **sources whose distance** from Earth can be **inferred from** their **luminosity**.

(Abernathy et al. 2011, ET Science Team)





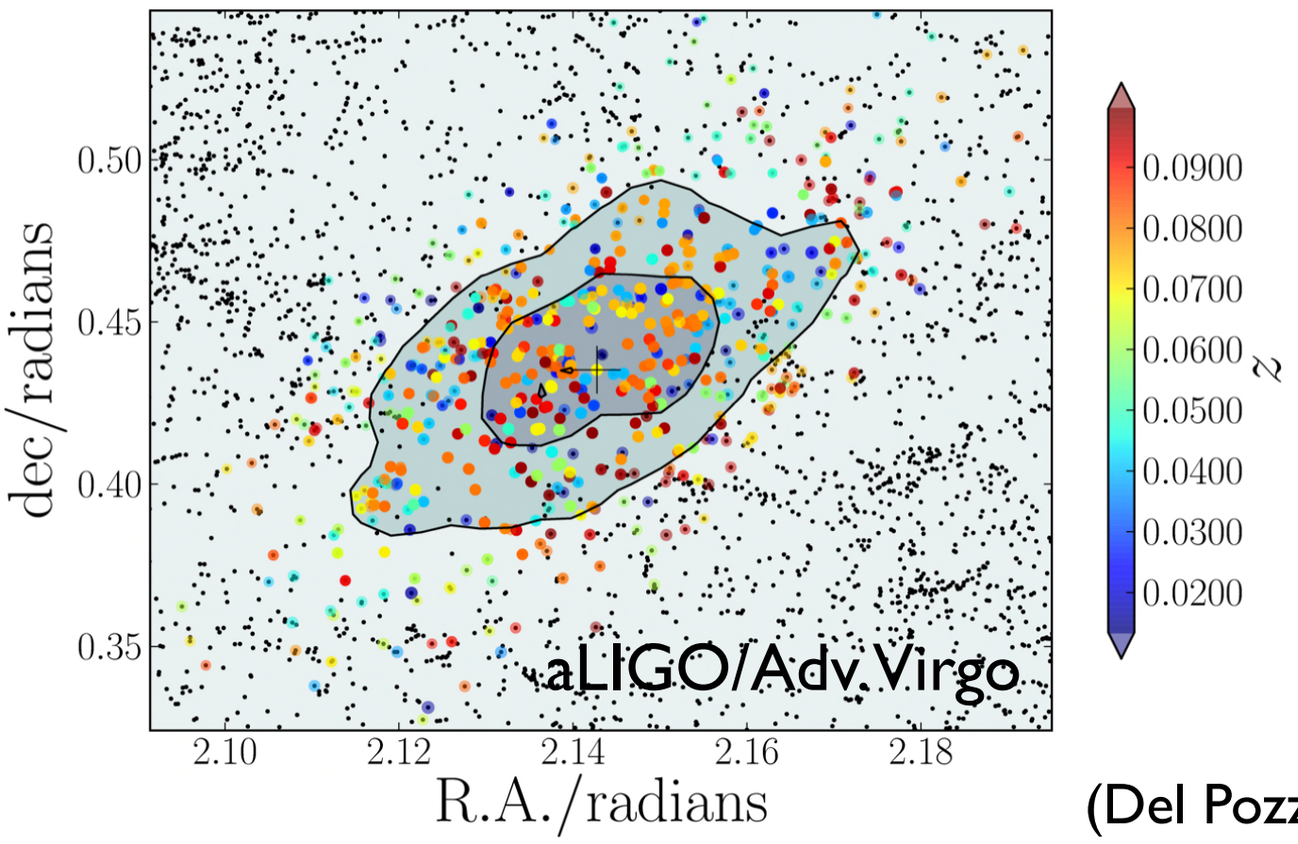
- Einstein Telescope/Cosmic Explorer:
  - **BNS** up to a redshift of **z ~ 2**
  - All **BBHs** in **all** observable **Universe** (z ~ 20)

- BNS population & **assuming EM** counterpart.

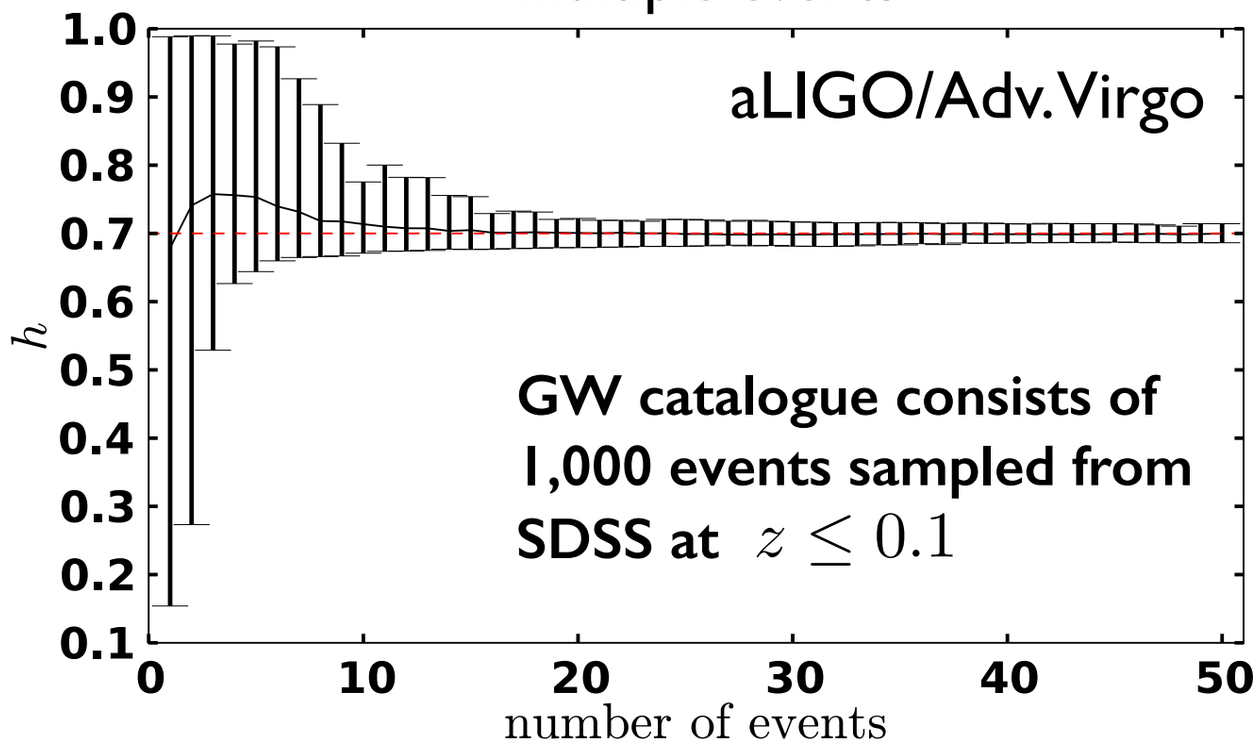
Cosmography: Inference of Cosmological Parameters with BBHs

- **Wide-field galaxy surveys** can provide (**sky positions** and) **redshifts.** (Schutz 1986)

single GW event



multiple events



(Del Pozzo 2012)

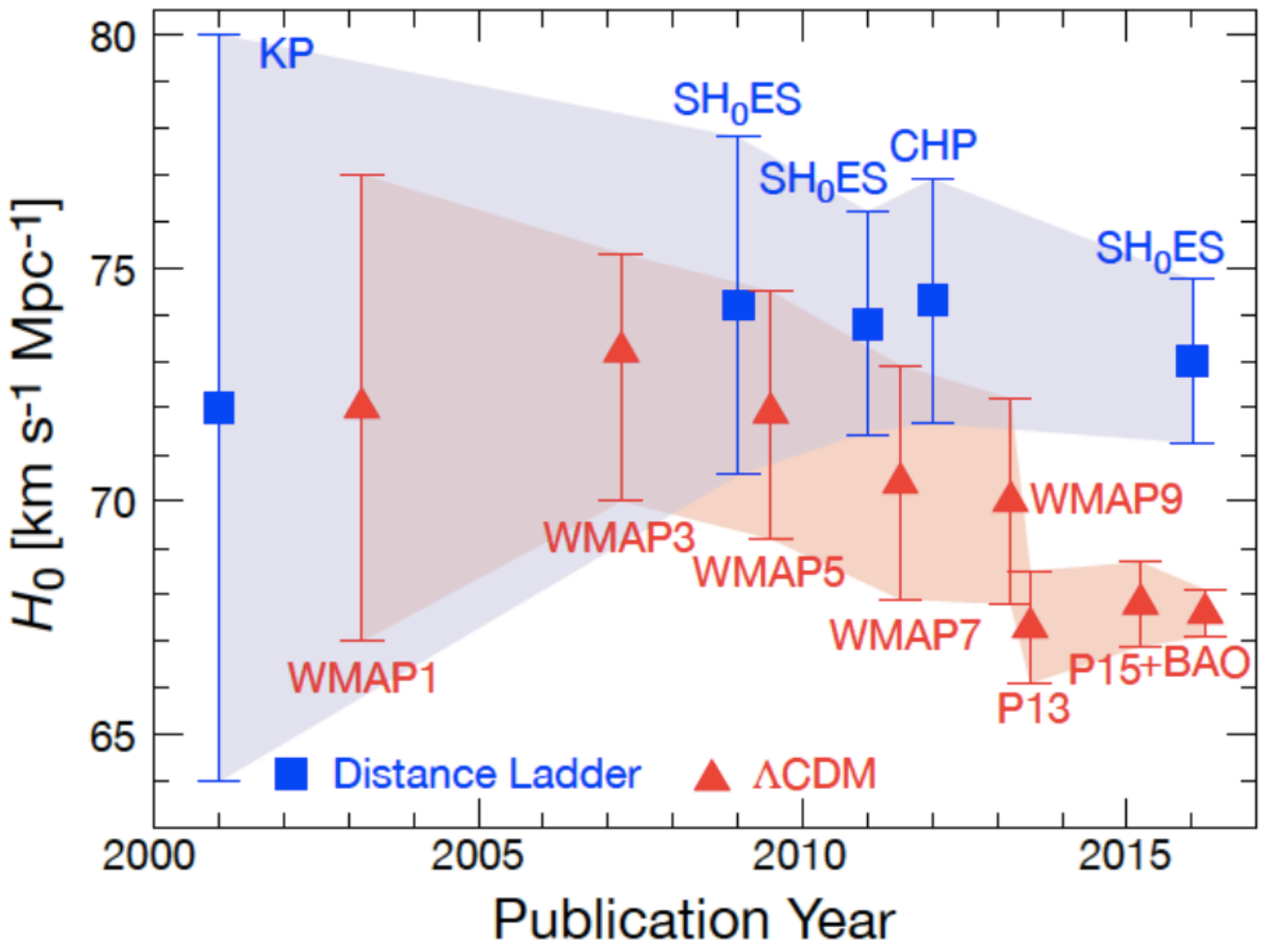
- aLIGO/Adv.Virgo: measurement of **Hubble constant** H_0 with accuracy of **5%** at 95% confidence **after 40-50 GW observations with 3 detectors.**

- Results will **depend on knowledge of clusters' catalogues** at redshifts larger than 1.

Cosmography with Spacetime Sirens: other considerations

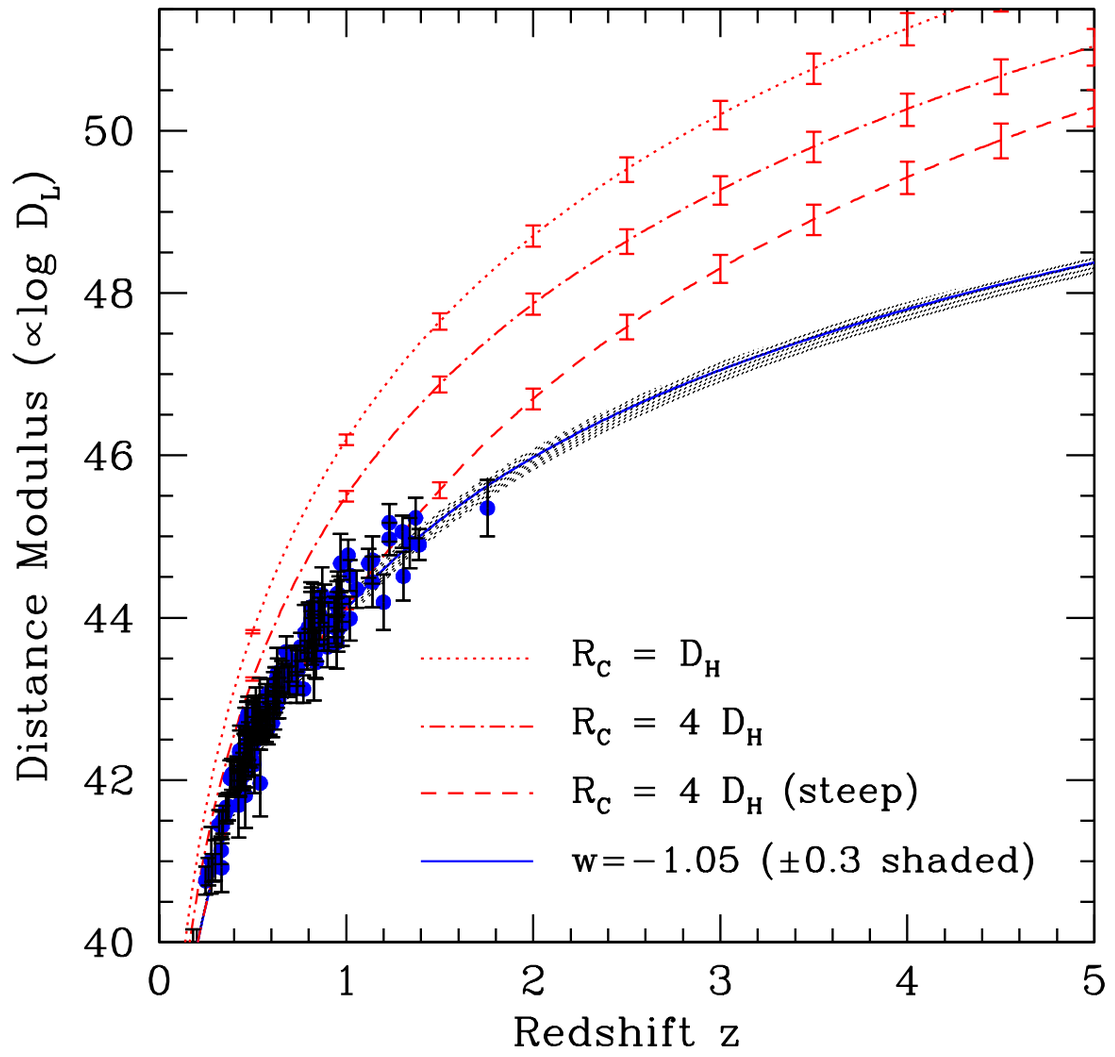
- **Current measurements** of H_0 show some **tension**.

(Freedman 2017)



- Testing **extra-dimensions** with GW standard sirens.

(Deffayet & Menou 2007)



- Mapping **expansion rate of Universe** on scales of **hundreds Mpc** will **provide** a **completely independent estimate** of **Hubble parameter**.

Disclosing the *primordial* dark age of the Universe

- **What is currently measured?**

$$- \ \rho_\gamma, \rho_m, \rho_b, \frac{(n_b - n_{\bar{b}})}{s}, \rho_\Lambda, \dots$$

$$- \ (\Delta^2_{\mathcal{R}})_{|_{k_\bullet}}, n_s, \left(\frac{d\log\Delta^2_{\mathcal{R}}}{d\log k}\right)_{|_{k_\bullet}}, \dots$$

- **Particles as probes**

$\gamma \rightarrow$ free-streaming at $\sim 1\text{eV}$

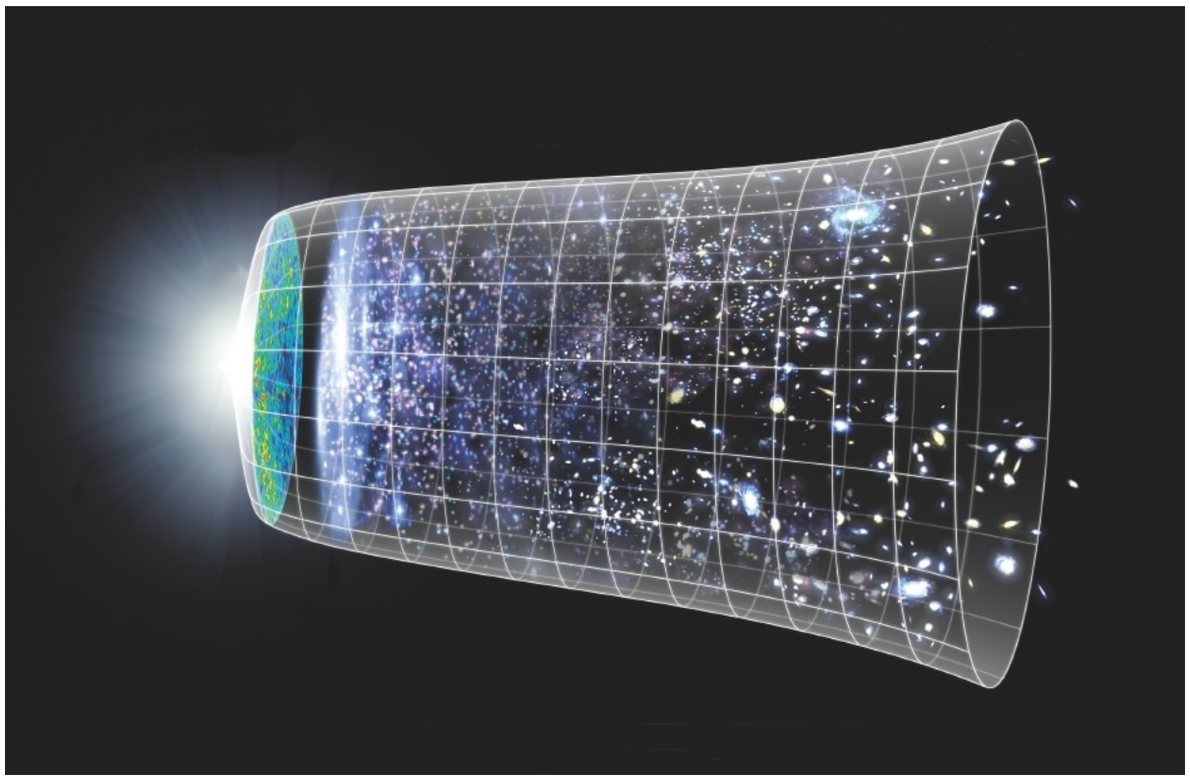
$\nu \rightarrow$ free-streaming at $\sim 1\text{MeV}$

$h \rightarrow$ free-streaming since inflation

$\sim 10^{?}\text{TeV}$

- ***Very clean* cosmological probes**

$$ds^2 = a^2\left[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j\right]$$



- **What can we probe by detecting primordial GWs?**
  - inflation (energy scale, how it ends)
  - reheating
  - Universe equations of state
  - phase transitions
  - cosmic & fundamental strings

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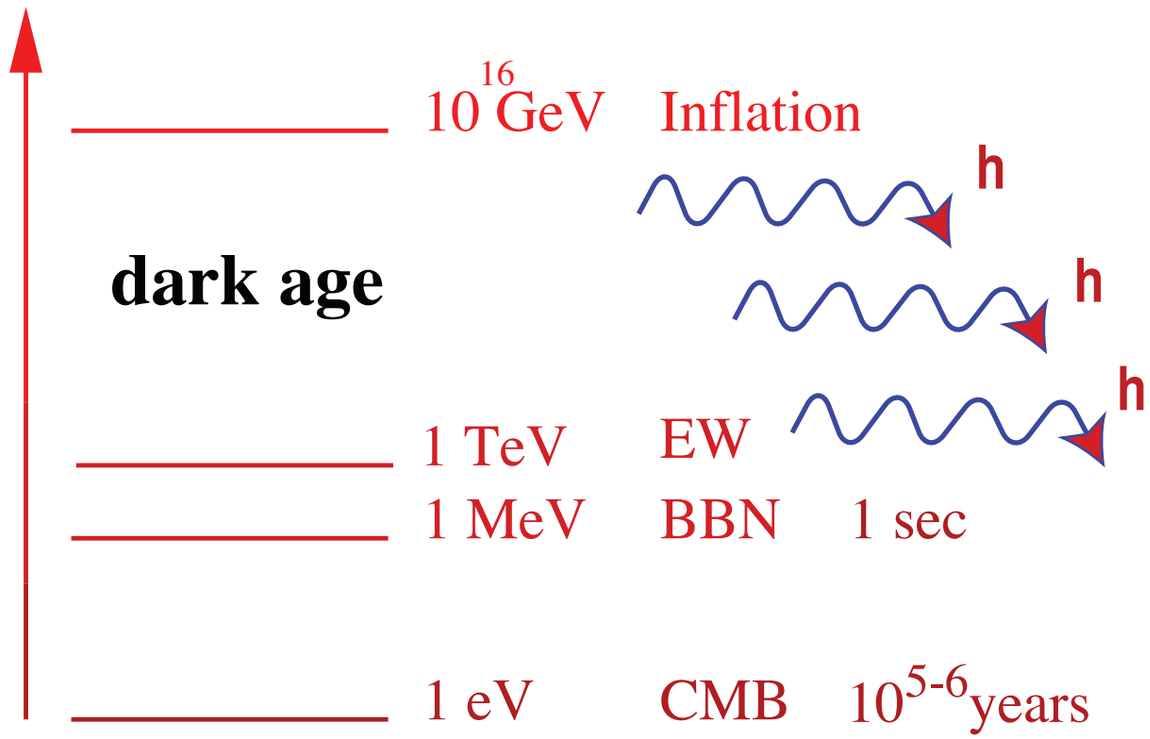

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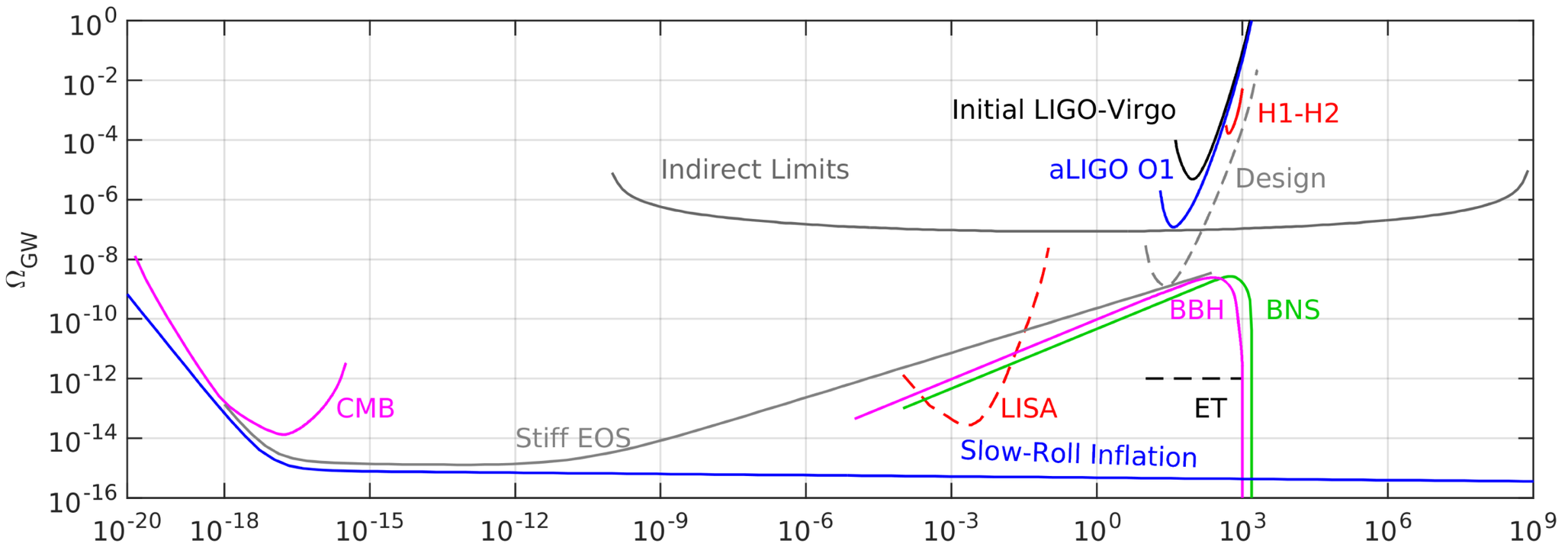
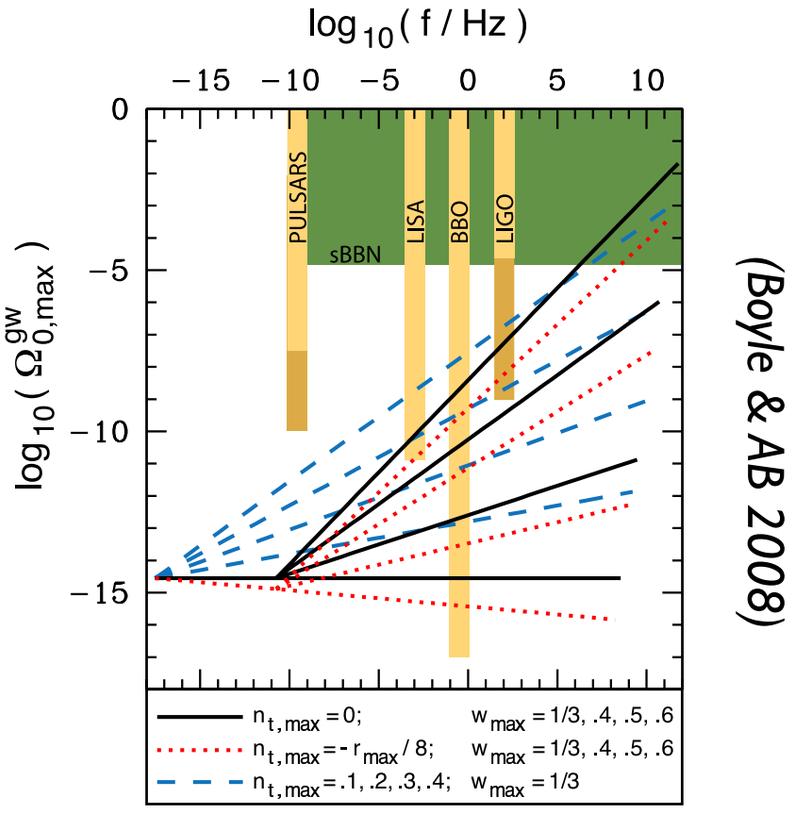


(Abbott et al. PRL 118 (2016))

(credit: Matas)

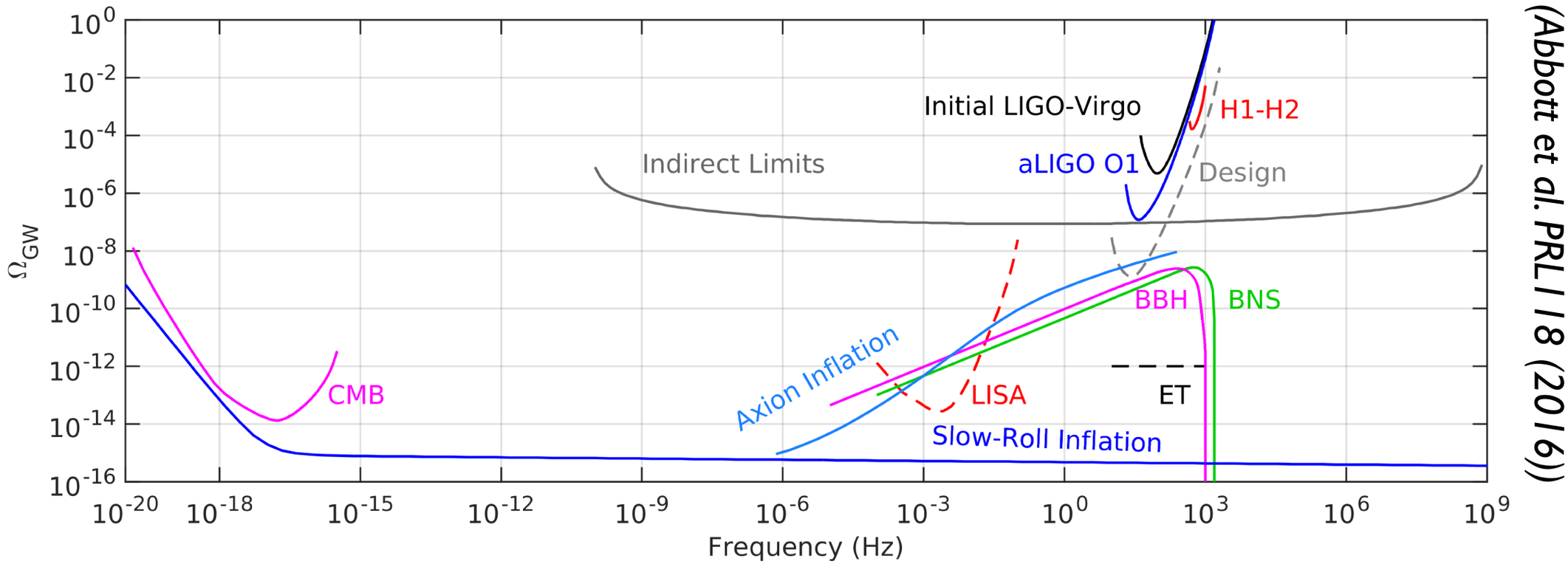


(Boyle & AB 2008)

(Starobinsky 79, Grischuck 74 & 93)

(Grischuck 75, Peebles & Vilenkin 98, Sahni et al. 98)

Disclosing the *primordial* dark age of the Universe

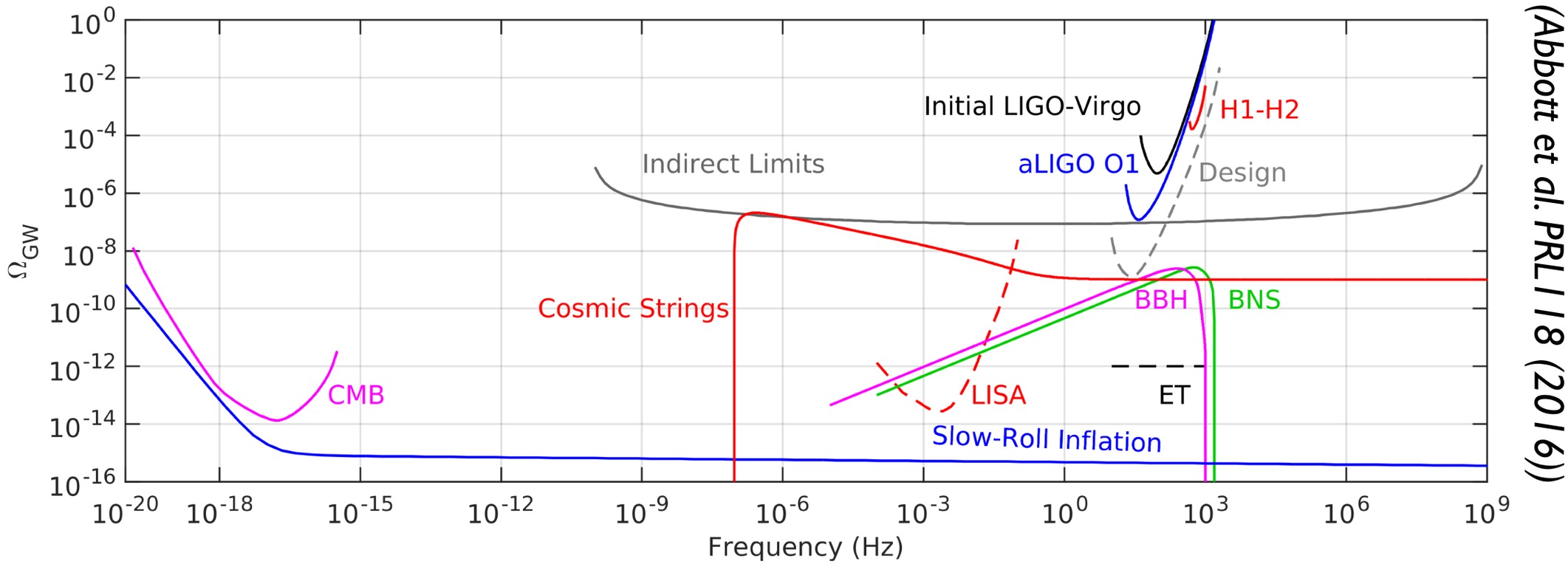


(Abbott et al. PRL 118 (2016))

(credit: Matas)

(Barnaby et al. 2012, Cook & Sorbo 2012)

Disclosing the *primordial* dark age of the Universe



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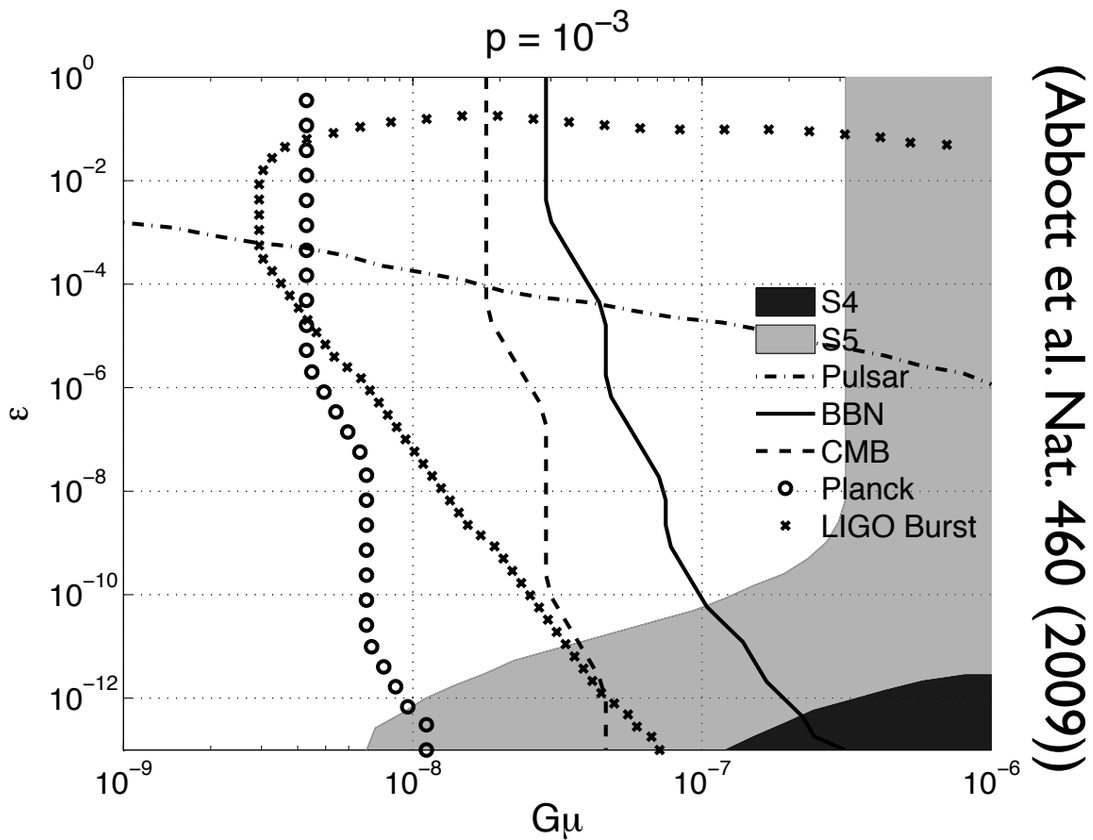
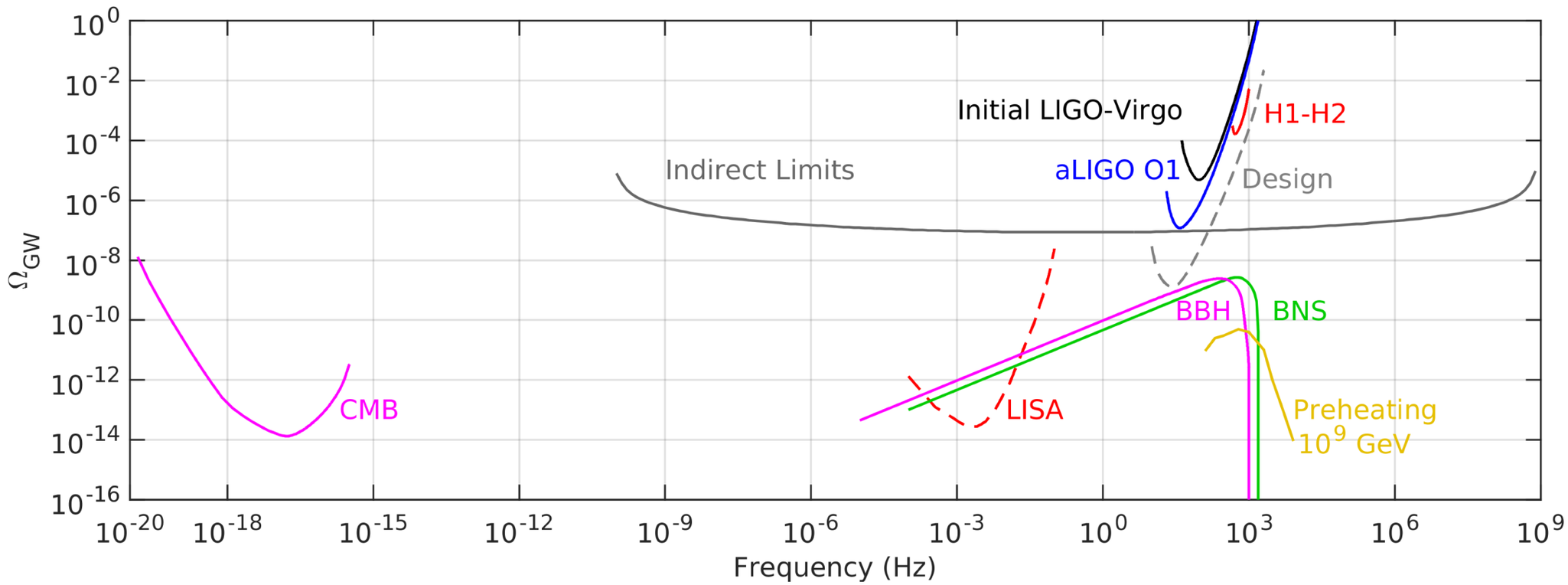


(Abbott et al. Nat. 460 (2009))

(Damour & Vilenkin 2000, 2001; Berezinsky 2000)

(Copeland et al. 2004, Jackson et al. 2005)

Disclosing the *primordial* dark age of the Universe



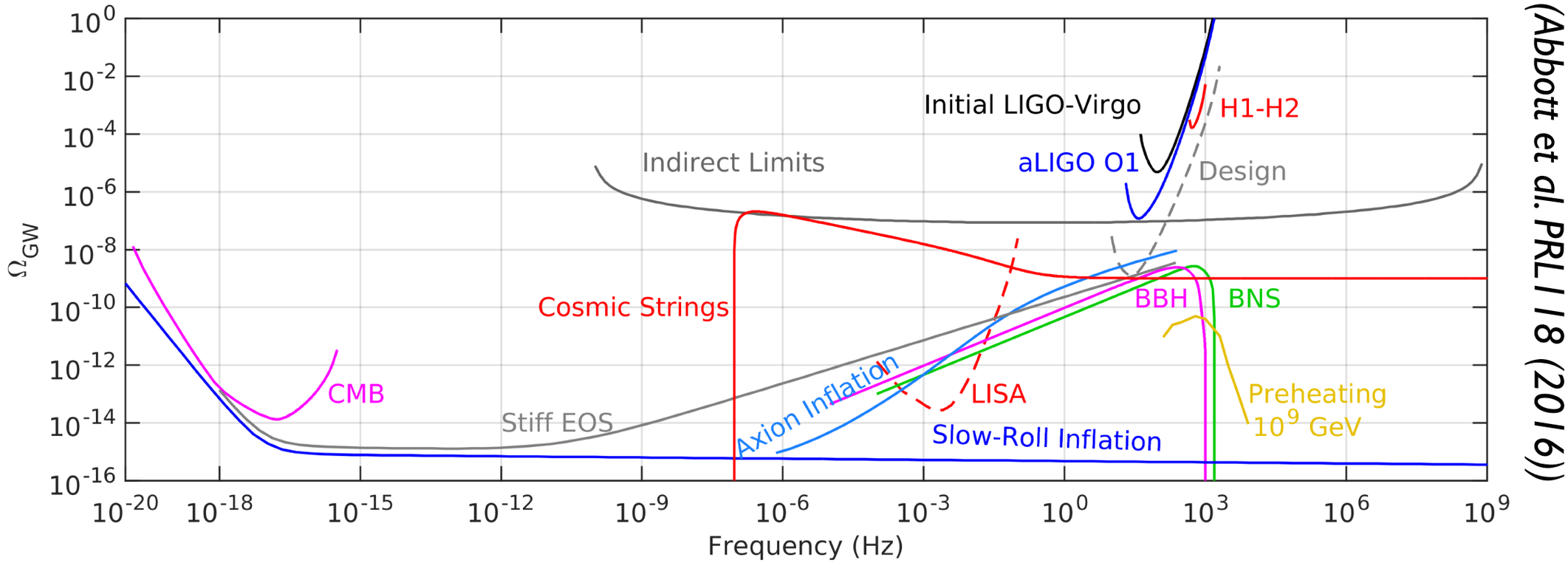
(Abbott et al. PRL 118 (2016))

(credit: Matas)

(Khlebnikov and I.Tkachev 1997)

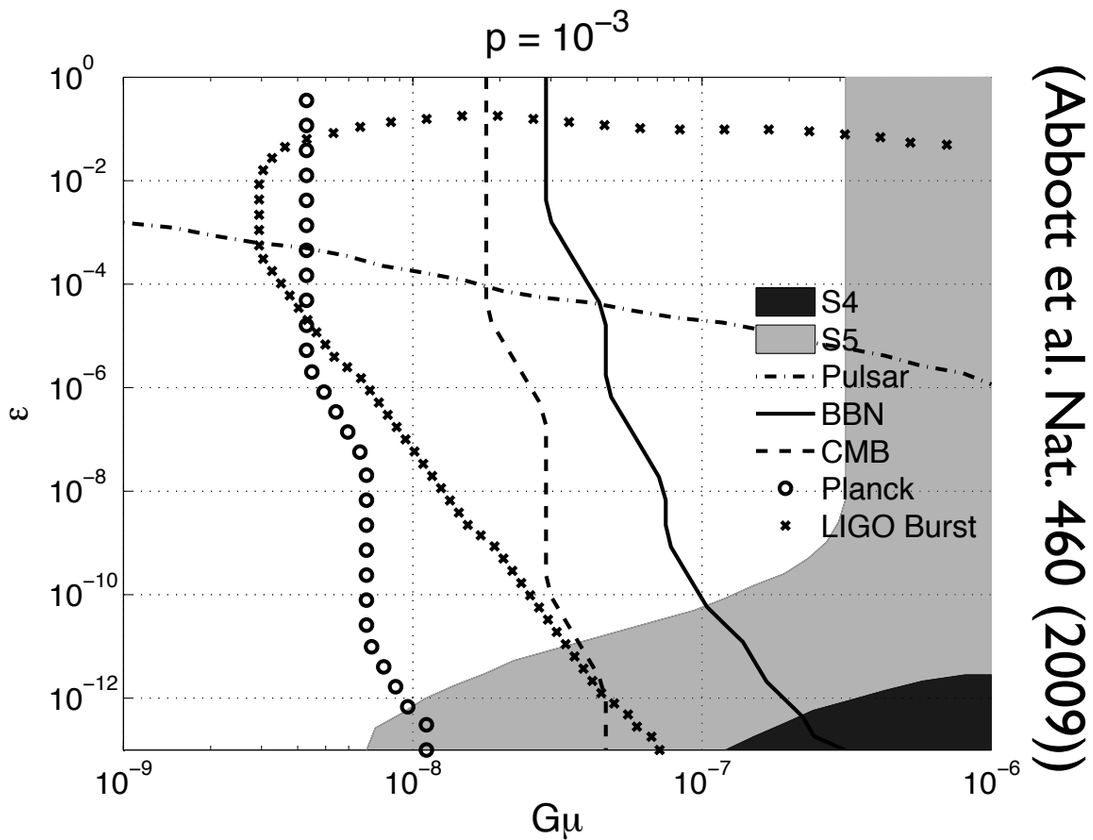
(Easther & Lim 2006, Easther et al. 2007)

Disclosing the *primordial* dark age of the Universe



(Abbott et al. PRL I 18 (2016))

(credit: Matas)



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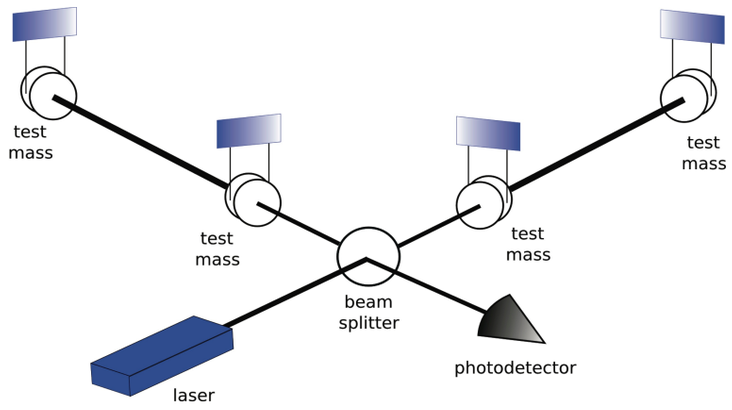
(Khlebnikov and I.Tkachev 1997)

(Easther & Lim 2006, Easther et al. 2007)

GW Detectors: Quantum Mechanics & Fundamental Physics



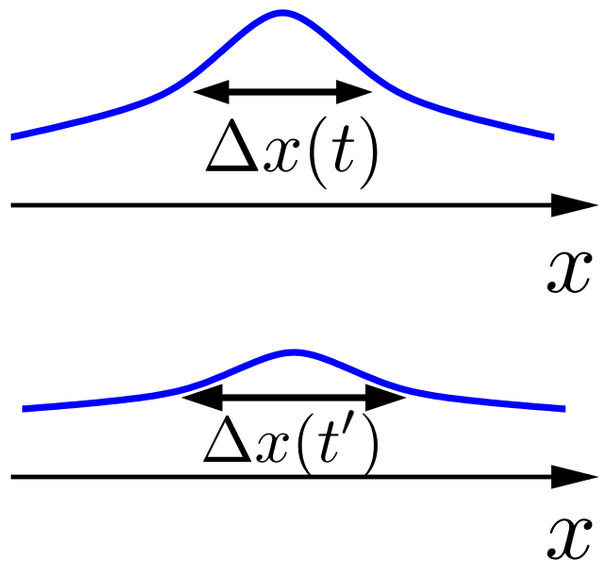
- LIGO/Virgo **measures positions** of mirrors **with high accuracy.**

- In quantum mechanics the **Heisenberg uncertainty principle prevents positions** to be **measured** with **infinite** precision.
  (Braginsky & Khalili 1992)

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

- If test-mass positions are measured with high precision, then test-mass **momenta are perturbed** (back action).

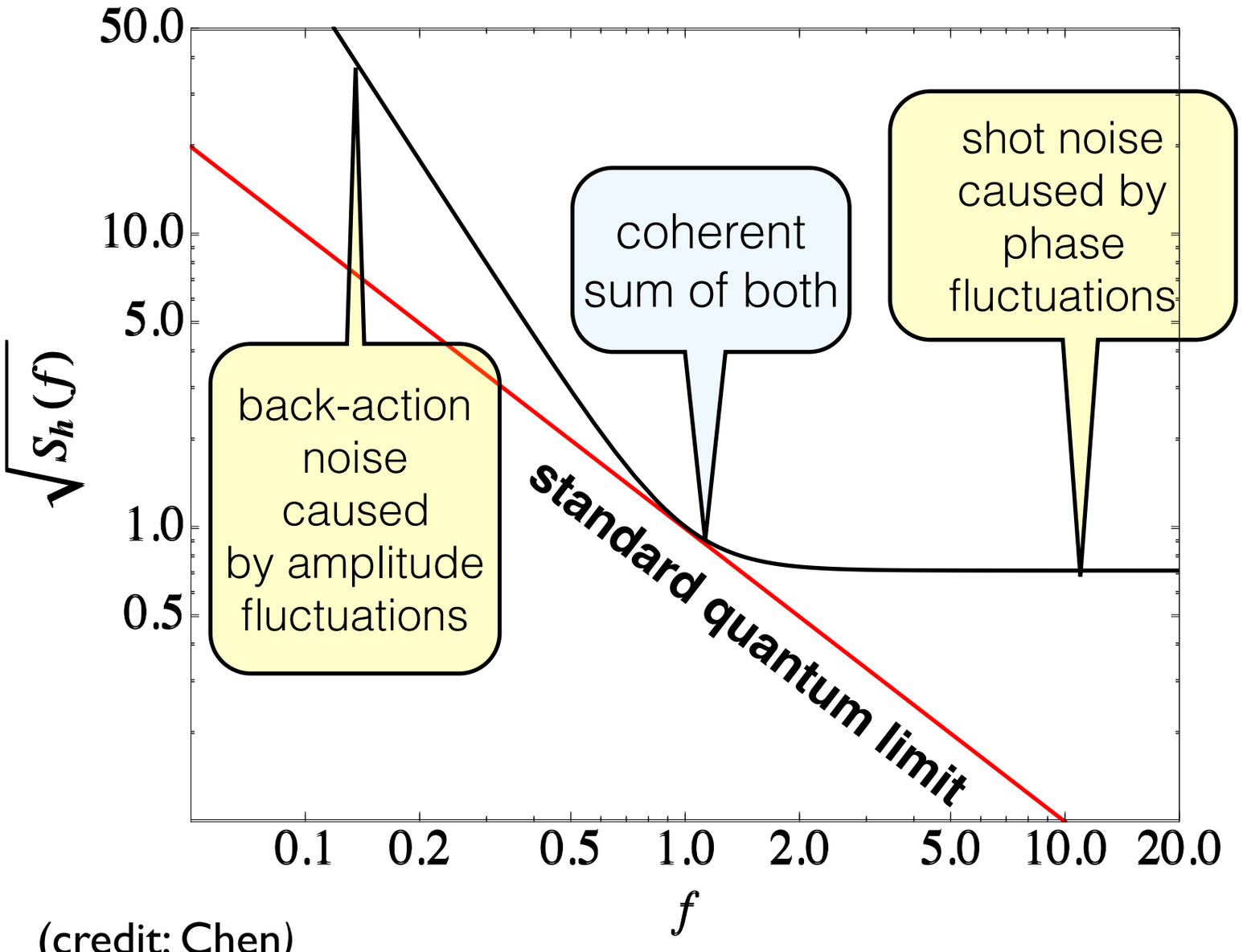
- As time passes ($t' > t$), **momentum perturbations produce position uncertainties**: standard-quantum limit on position measurements.



- This holds **if position** and **momenta** are **not correlated!**

- … In this process, test mass is projected into **quantum state** with **~ minimum uncertainty product** (pure state). *(Müller-Ebhardt et al. 2009)*

Quantum Non-Demolition Techniques for Future Detectors

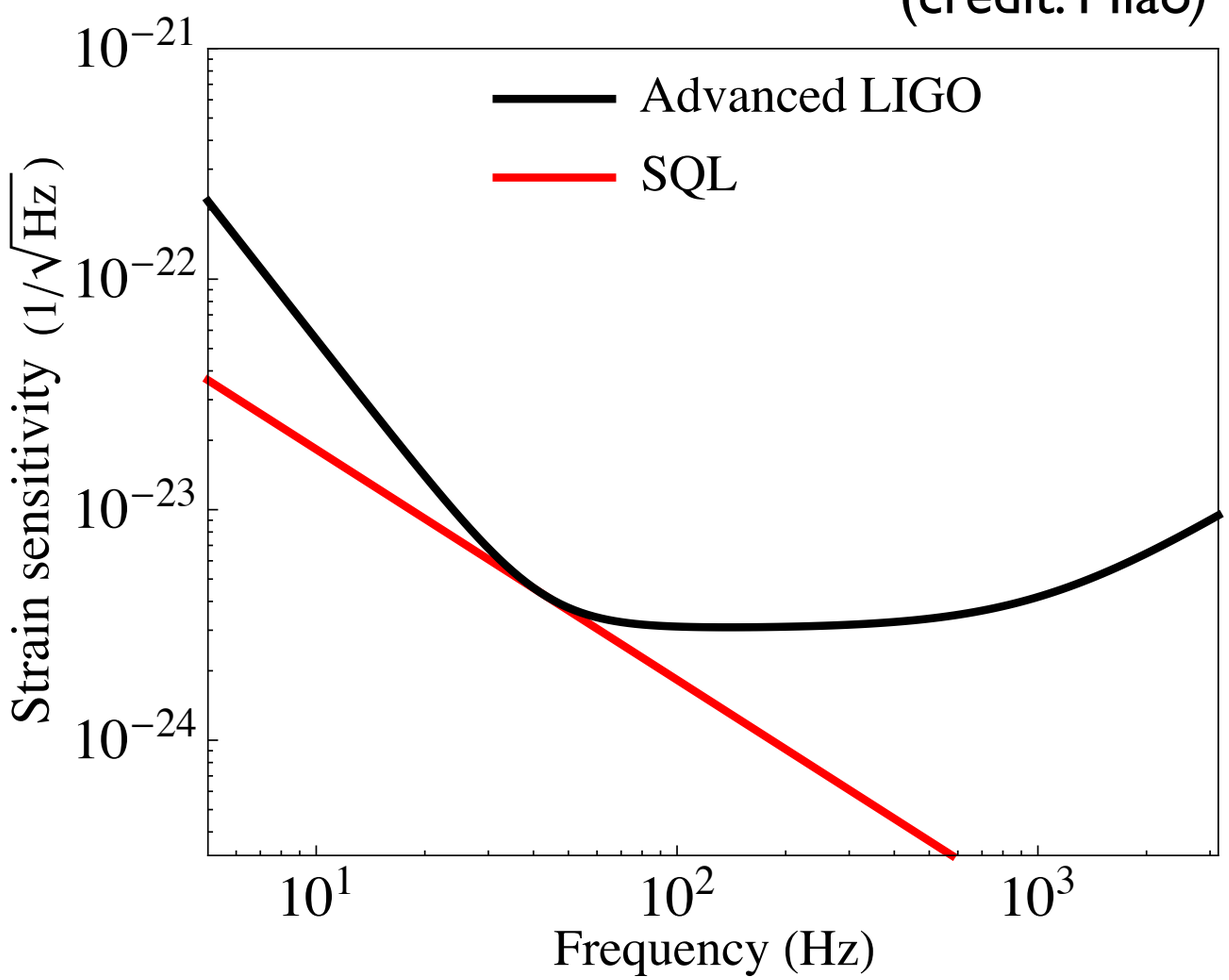


(credit: Chen)

- High frequencies, **shot noise**: **improved** by increasing power.
- Low frequencies, **radiation-pressure noise**: **made worse** by increasing power (back action).
- **Standard Quantum Limit: Heisenberg Uncertainty Principle** applied on **40 kg** test masses.
- **Circumvented by** building **correlations** between measuring device (**light**) and **test mass**
  (Braginsky & Khalili 1992)

Quantum Non-Demolition Techniques for Future Detectors

(credit: Miao)



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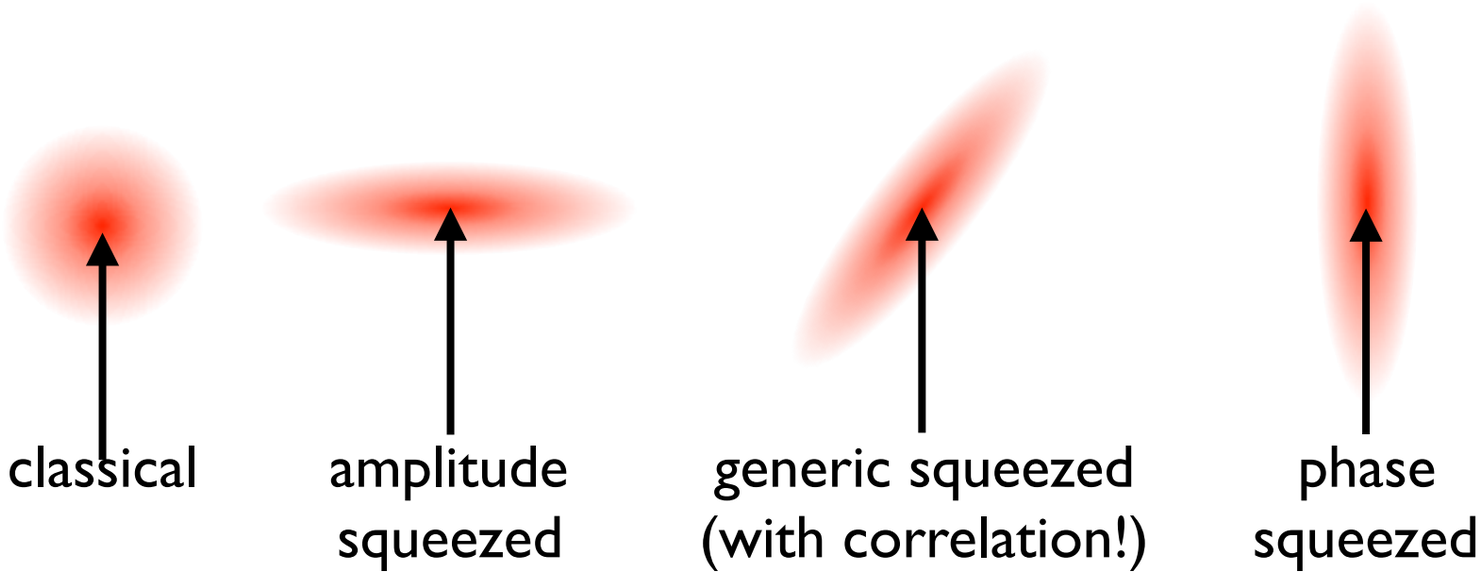

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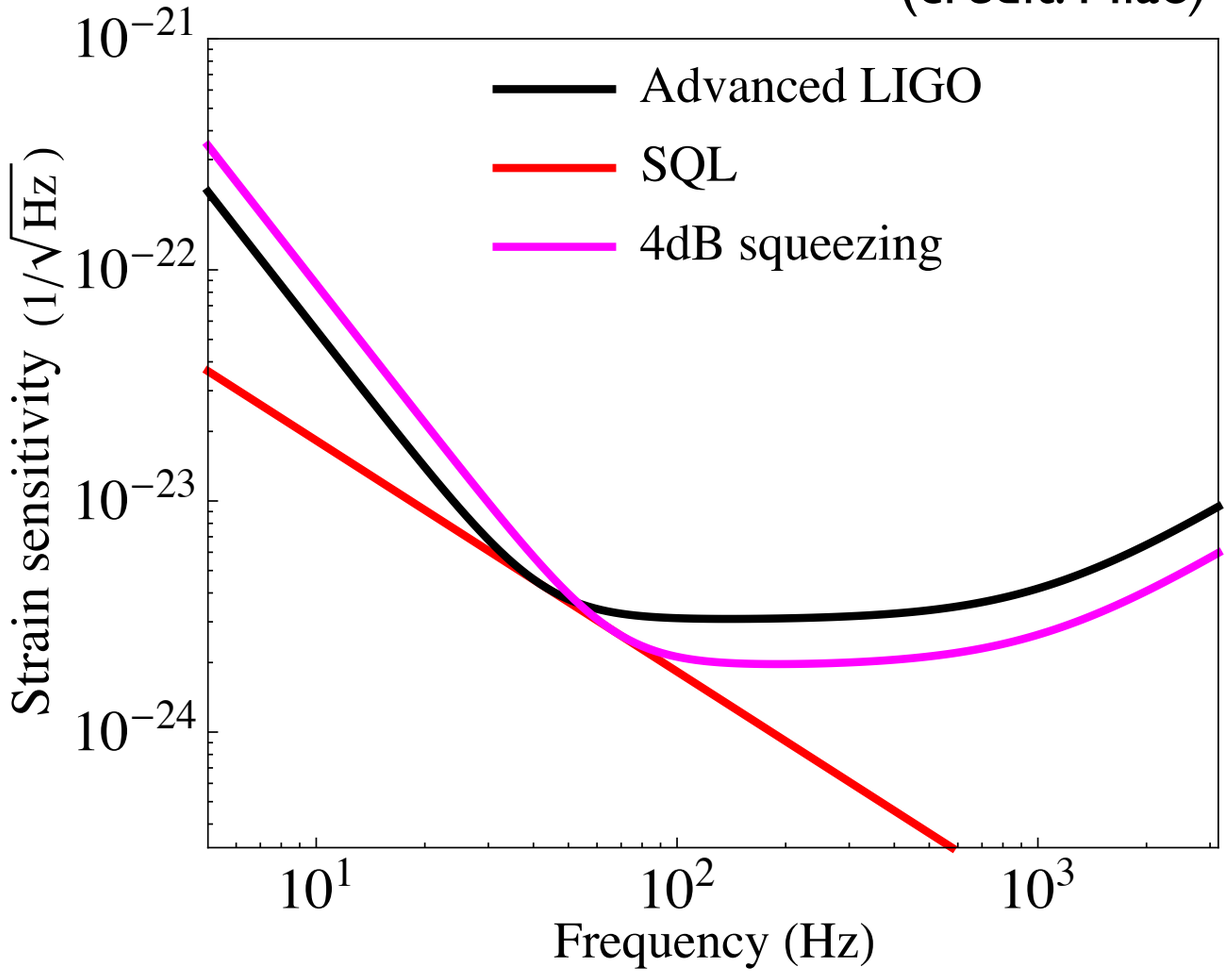

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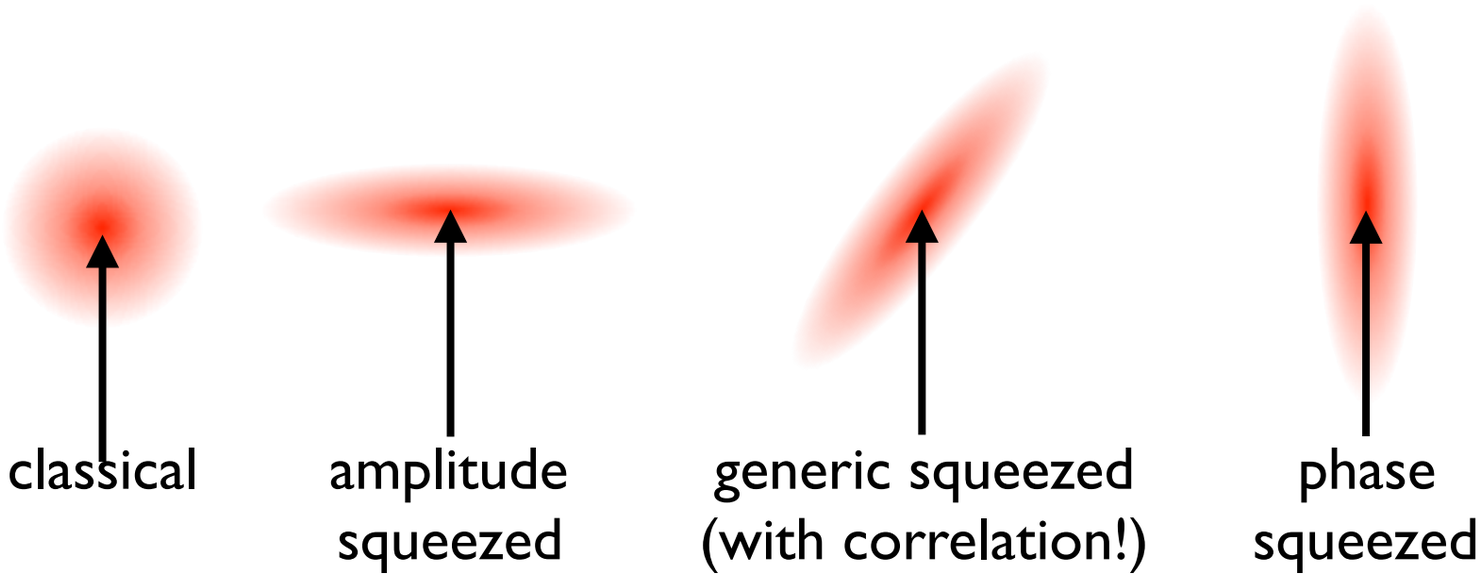
- Frequency-independent **squeezed vacuum injected in LIGO detectors.**
  (Grote et al. 2013, Aasi et al. 2013, Dooley et al. 2015, Oelker et al. 2016)



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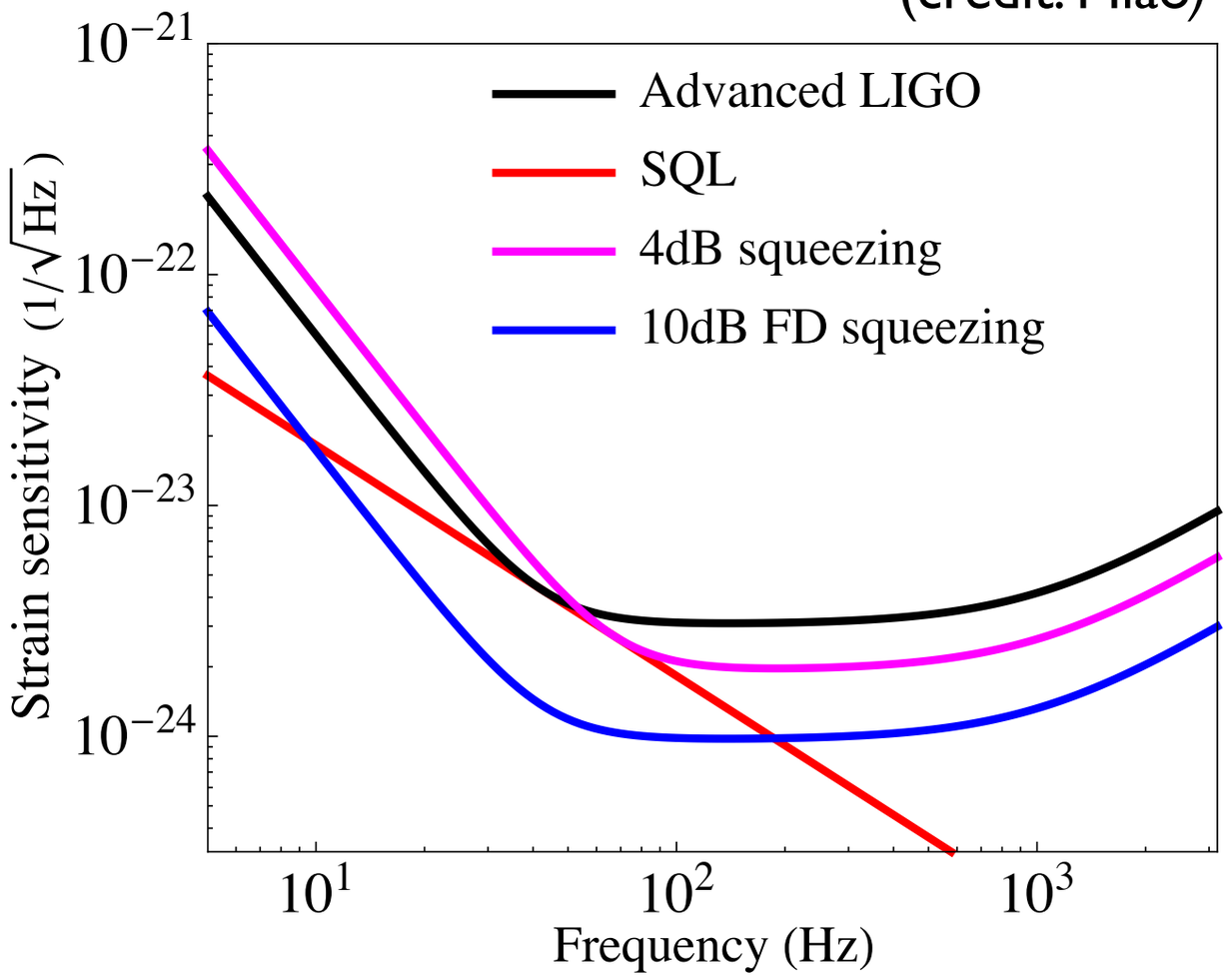

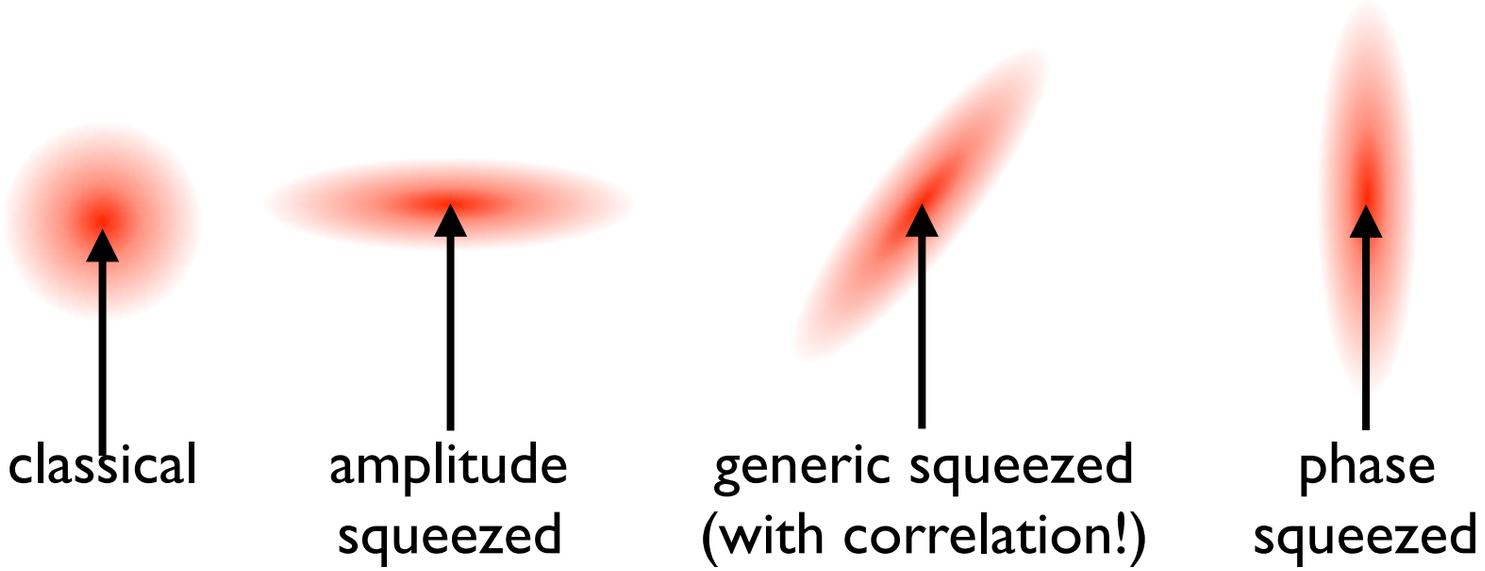

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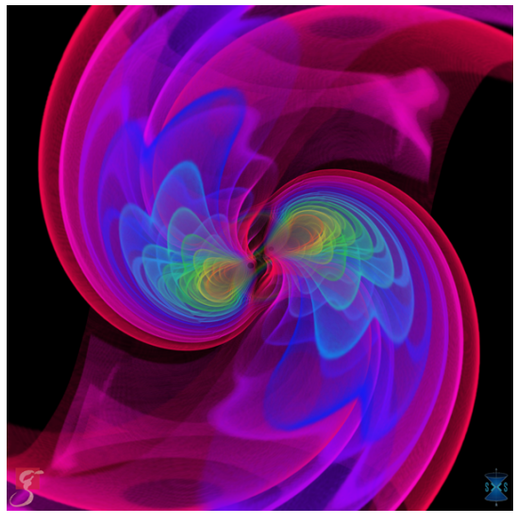
- Frequency-dependent **squeezed vacuum**:
  - **Filter cavity**
    (Kimble et al. 2001, Evans et al. 2013)
  - **EPR entangled beams** (use arm cavity as filter cavity)
    (Ma et al. 2017)

New Era of Precision Gravitational-Wave (astro)Physics

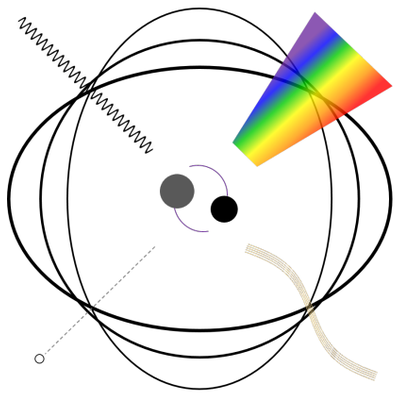


- **GW observations** by LIGO/Virgo opened a **new era** of **scientific discovery**.

- **Gravitational interaction** powers **most luminous, spectacular objects** and **phenomena** (GRBs, pulsars, supernovae, black-hole and neutron-star mergers, and evolution of early Universe).

- We will **probe extreme** gravity and astrophysics.

- We will **solve outstanding questions** in fundamental physics and cosmology.

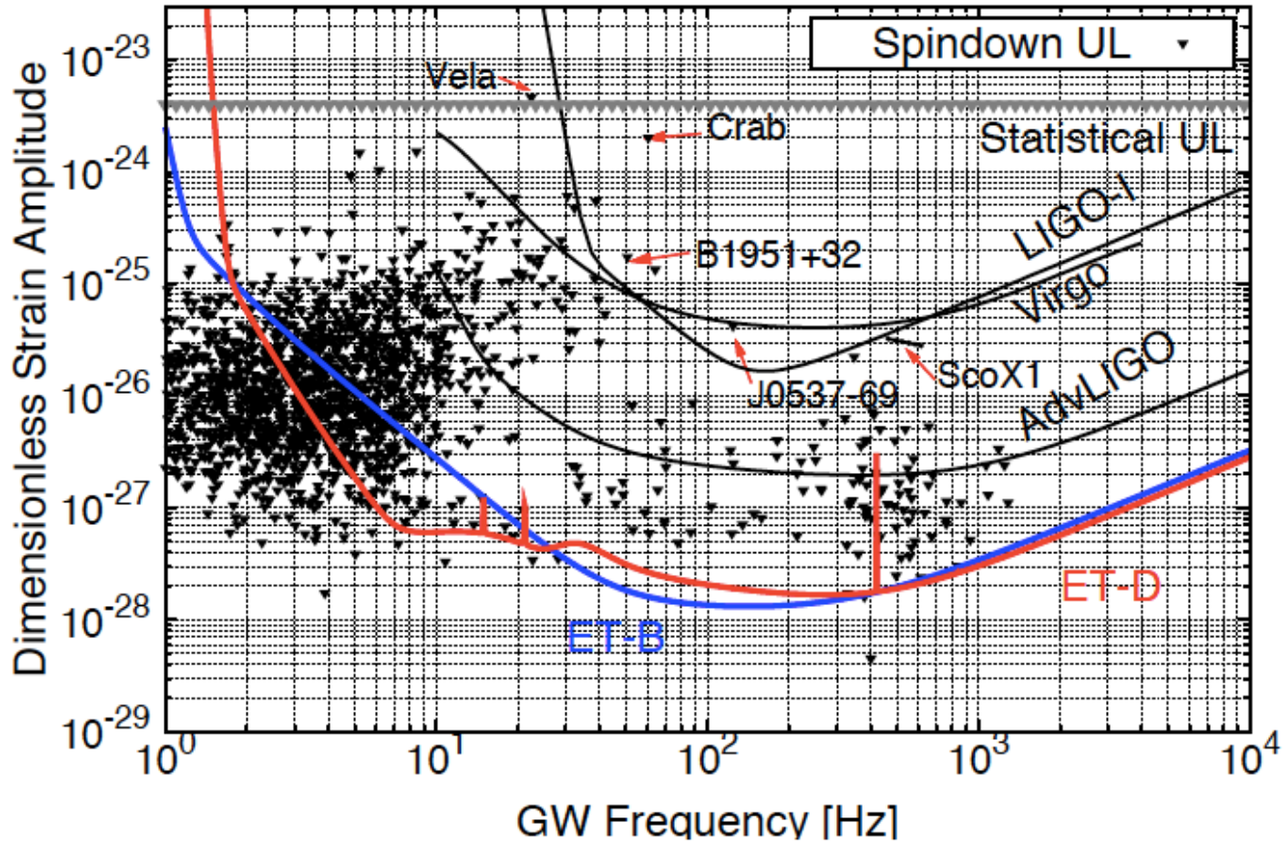


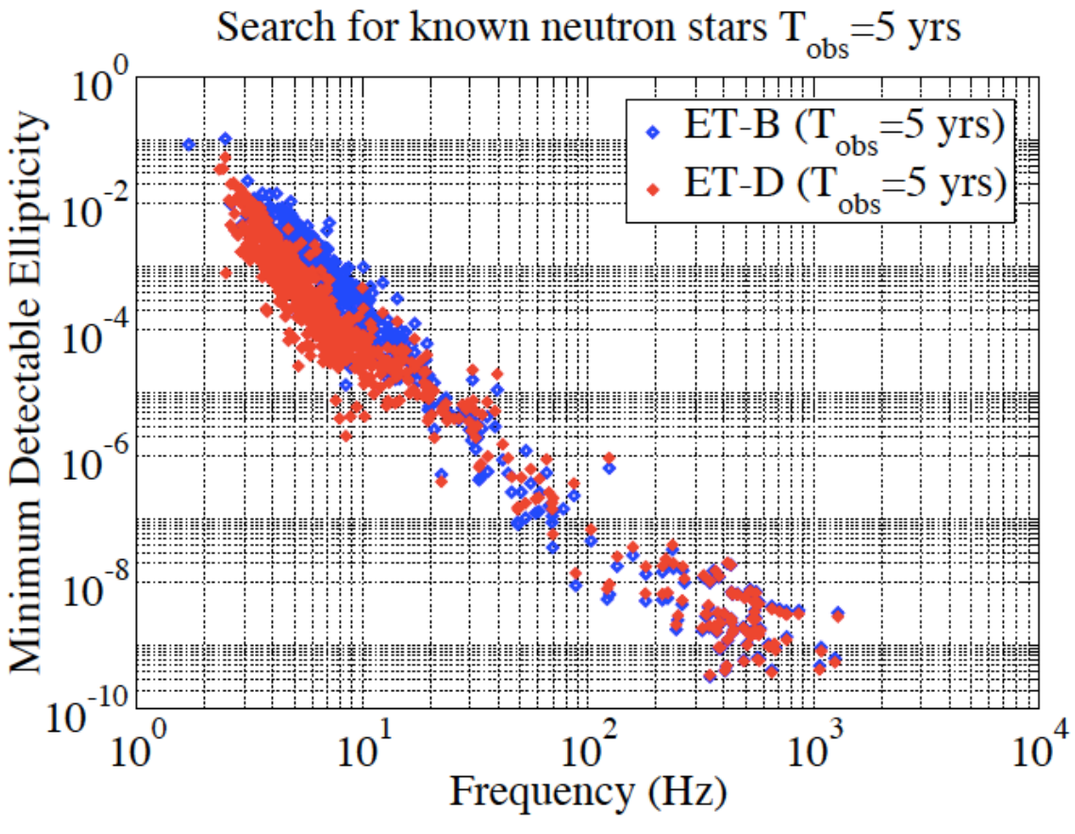
- As for any new observational tool, gravitational (astro)physics will likely **unveil phenomena** and **objects never imagined** in **wildest theories**.

Neutron-Star Physics from Pulsars

- **Probing NSs** in **stationary instead** of **dynamical** conditions:
  - what is the nature of **NS**?
  - what causes **glitches?**
  - is there **consistency in spin-rate observation** from GW & EM emission?

(Abernathy et al. 2011, ET Science Team)

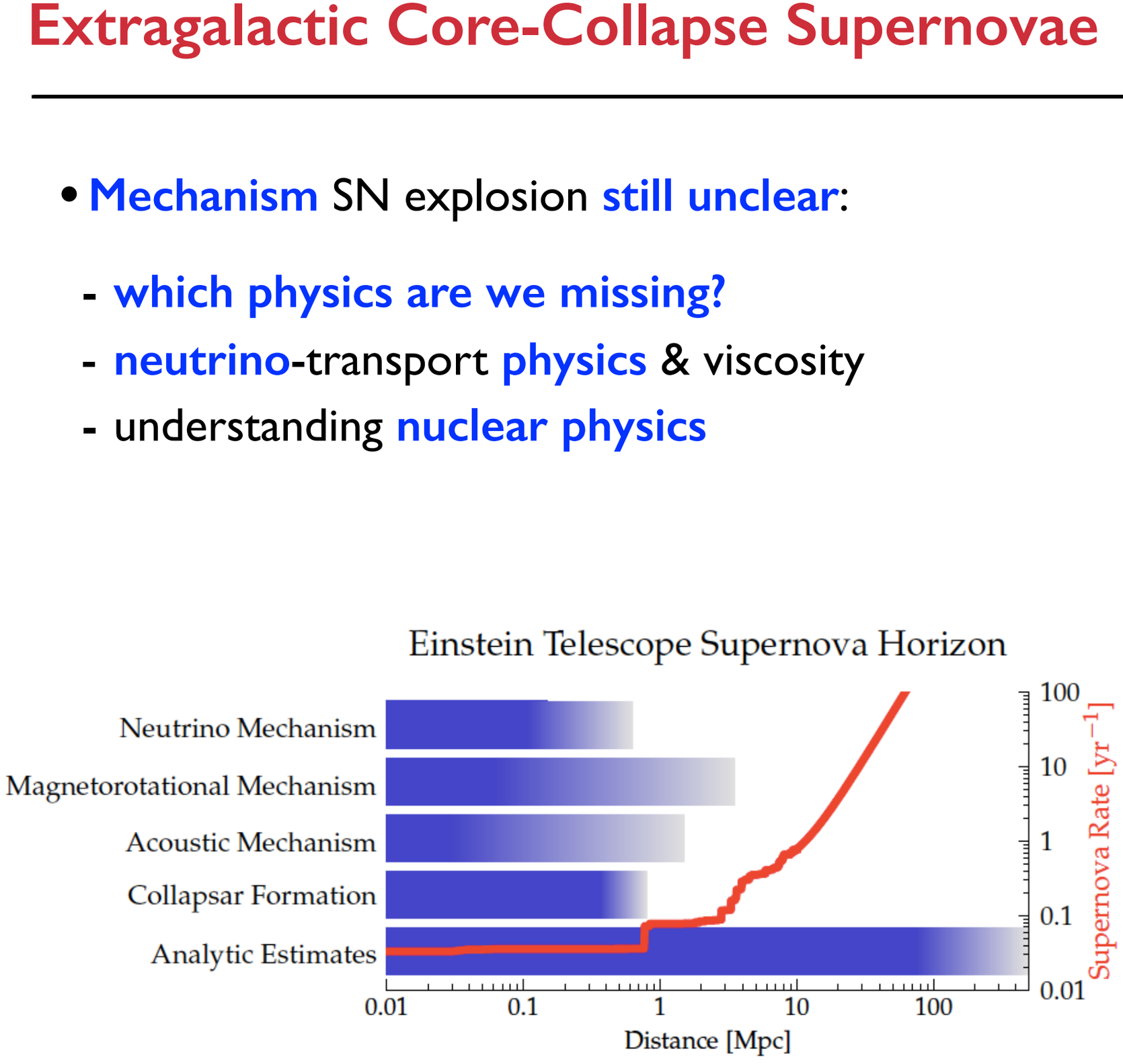




- **Pulsar's ellipticity** depends on:
  - **EOS** (max deformation)
  - deformability due to **rotation & magnetic fields**
  - **accretion, glitches**
- If ellipticity **> 10^{-5}**, EOS could point to **strange quarks or hyperons.**

Extragalactic Core-Collapse Supernovae

- **Mechanism** SN explosion **still unclear**:
  - **which physics are we missing?**
  - **neutrino**-transport **physics** & viscosity
  - understanding **nuclear physics**



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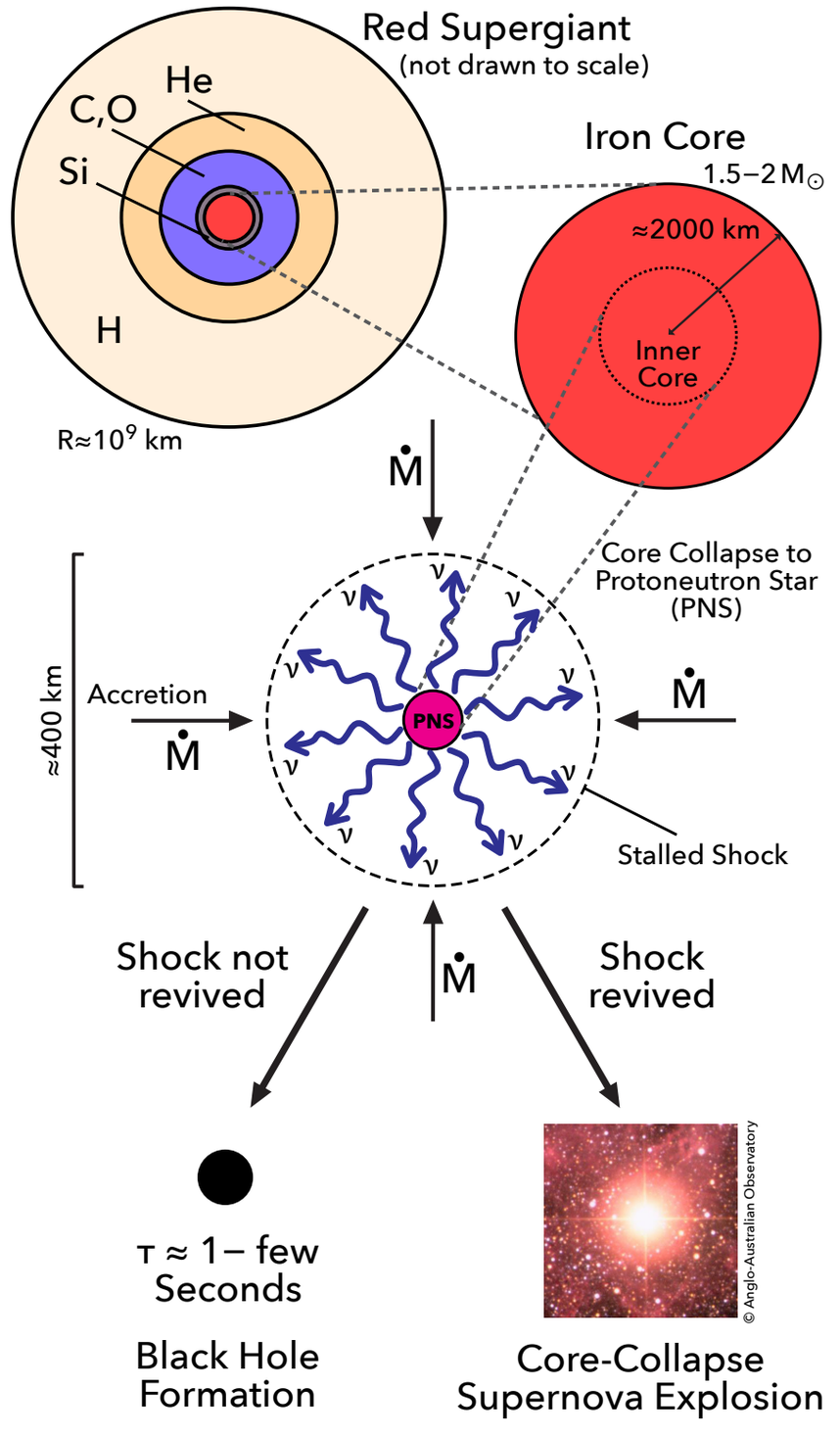
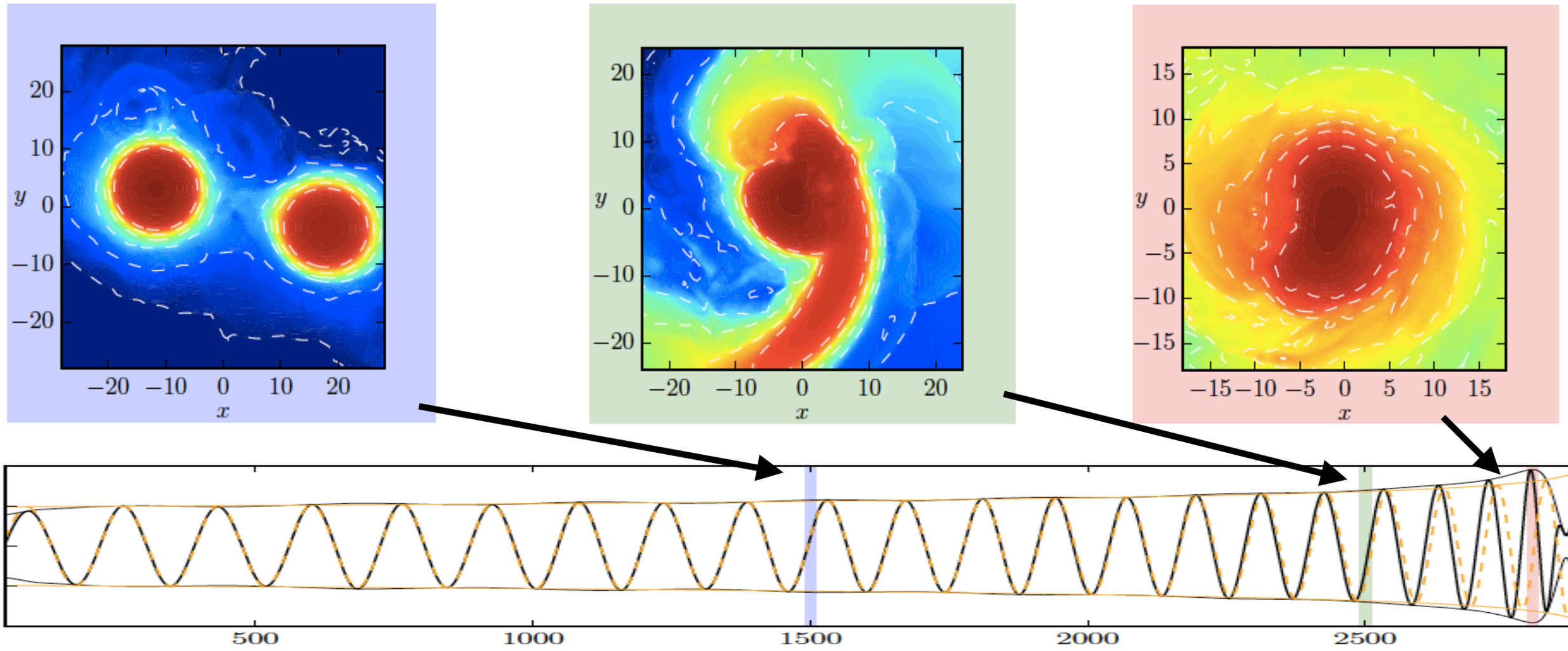


(credit: *Ott*)

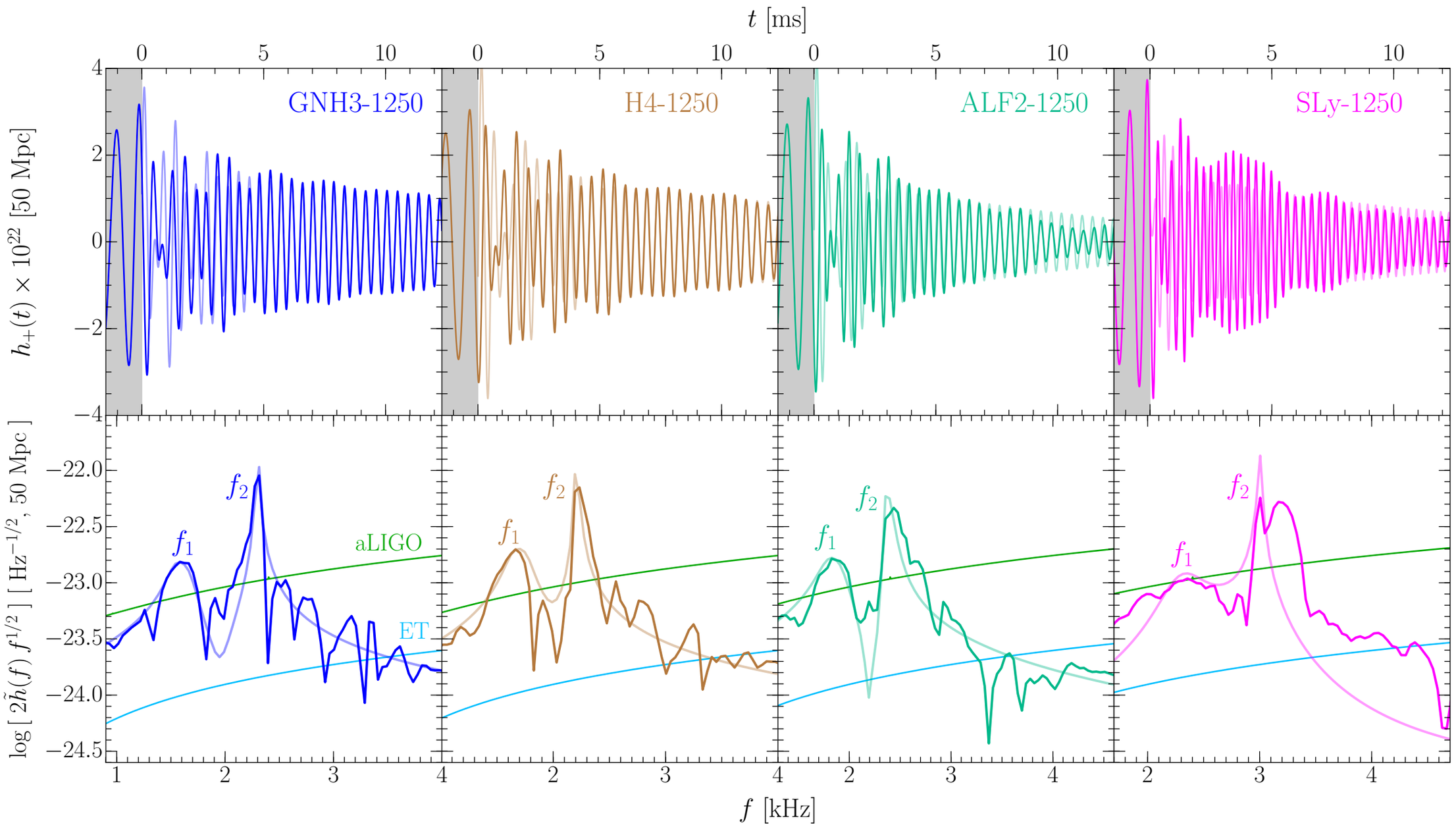
Extracting Information on EOS from Late Inspiral: Accurate Modeling



(Dietrich & Hinderer 2017)

- **Synergy** between **Numerical** & **Analytical Relativity: modeling** is **crucial** to **extract science.**

Extracting Information on EOS from Post-Merger



(Bose et al. 2017)