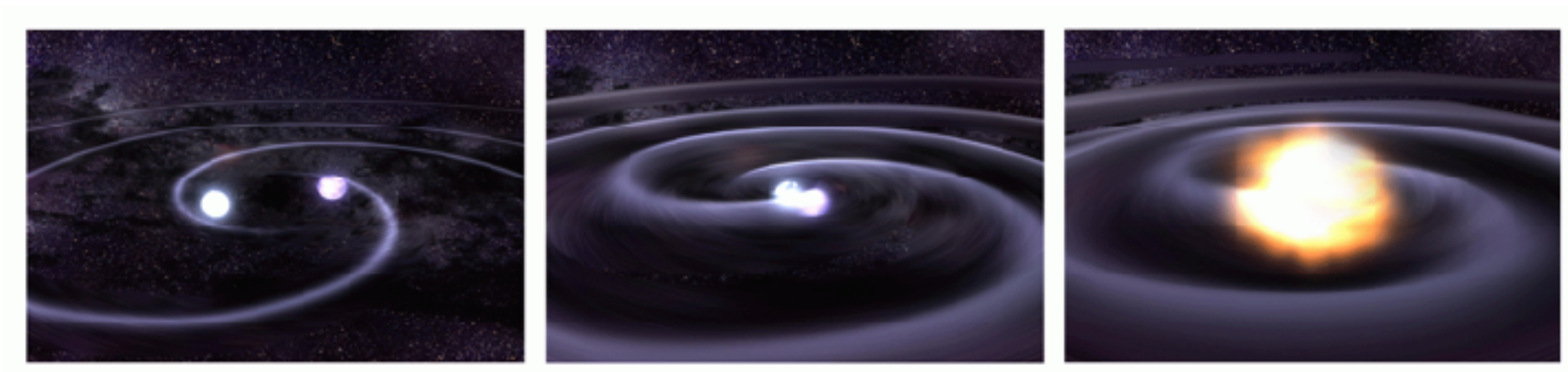
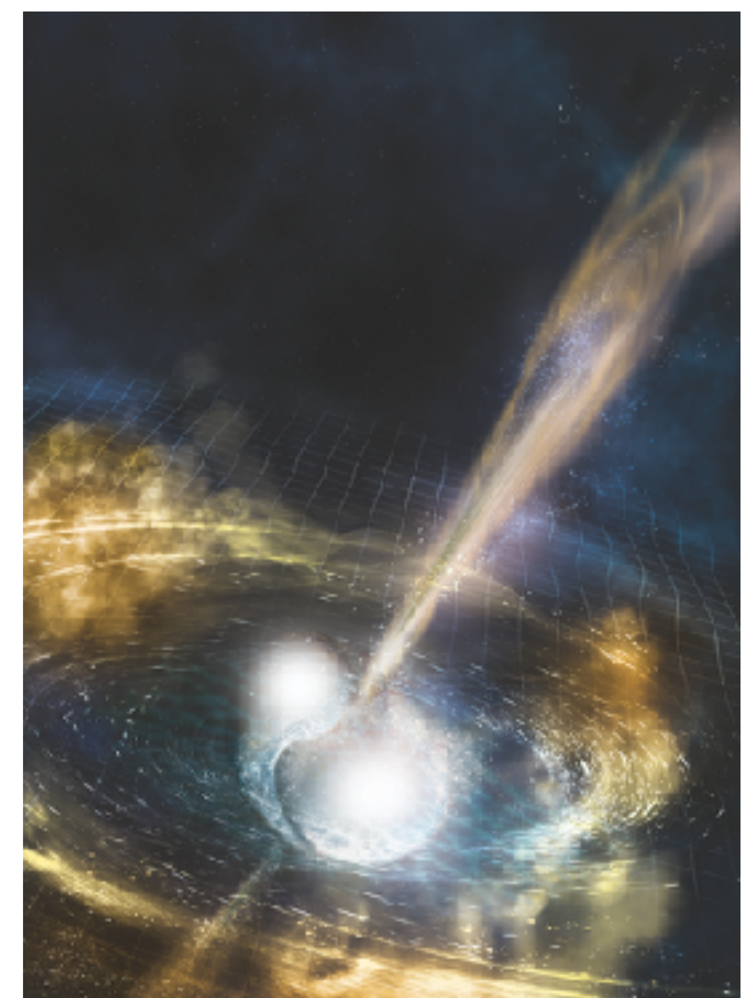
Astrophysical GW sources cont:

1. GW signatures of non-black-hole objects

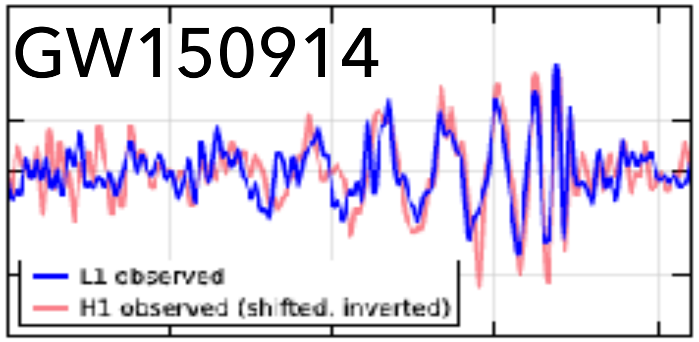
2. Multi-messenger observations of GW170817

3. Outlook



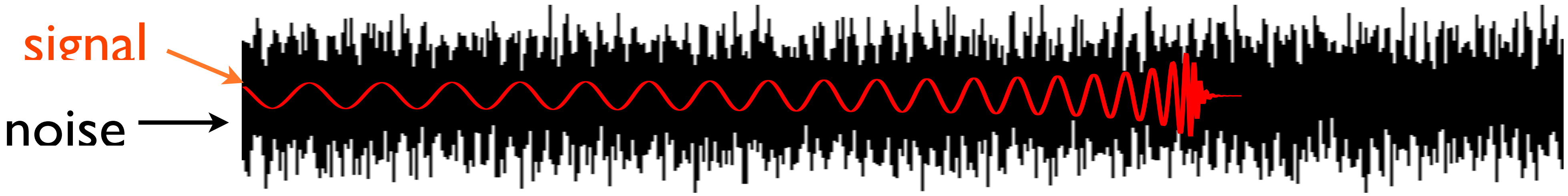


Last time: GWs from binary black holes



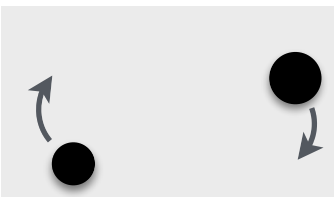
Data and tutorials available at: https://losc.ligo.org/

Weak signals (e.g. GW151226) buried in the noise:



- Detection: cross-correlate data with template bank
- Extracting information (e.g. source parameters): Bayesian analysis (MCMC), need accurate templates
  - phase evolution to better than 1 rad over entire signal

Last time: Effective One-Body (EOB) templates

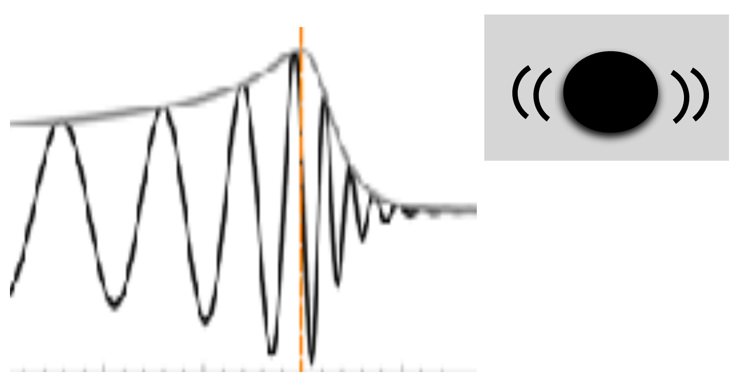


$$H_{\rm EOB} = M\sqrt{1+2\nu\left(\frac{H_{\rm eff}}{\mu}-1\right)}$$

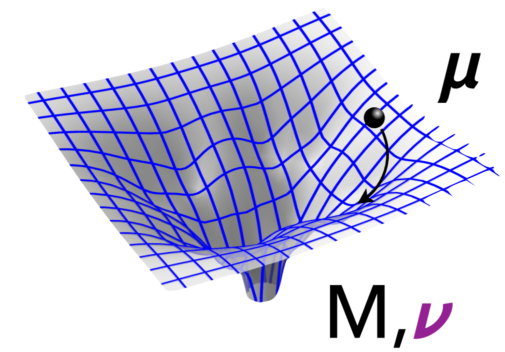
$$\frac{dP_i}{dt} = \{P_i, H^{\rm EOB}\} + \mathcal{F}_{\rm rr}$$

+

Merger & Ringdown



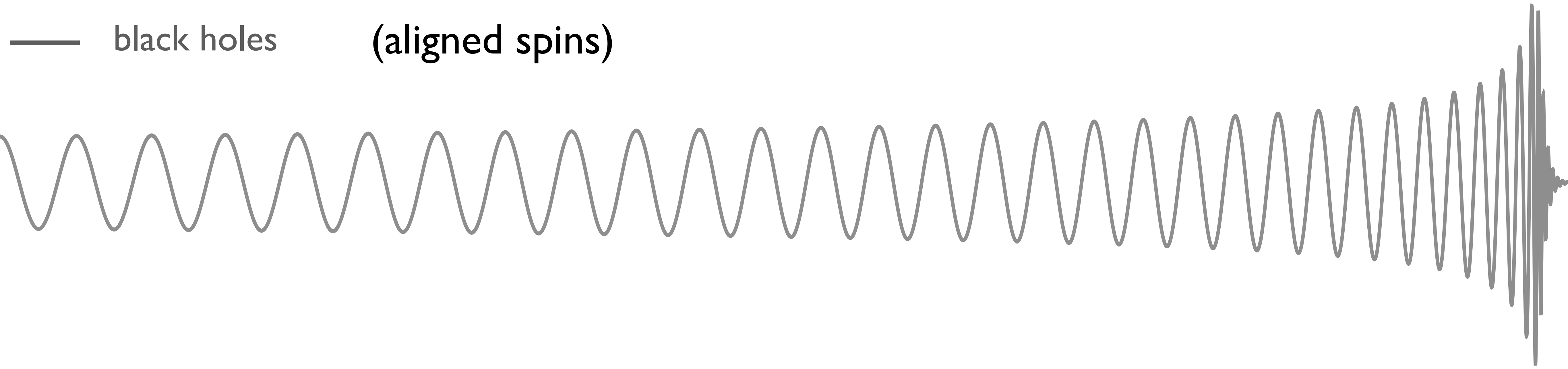
Effective description



$$\nu = \mu/M \ \in [0, 1/4]$$

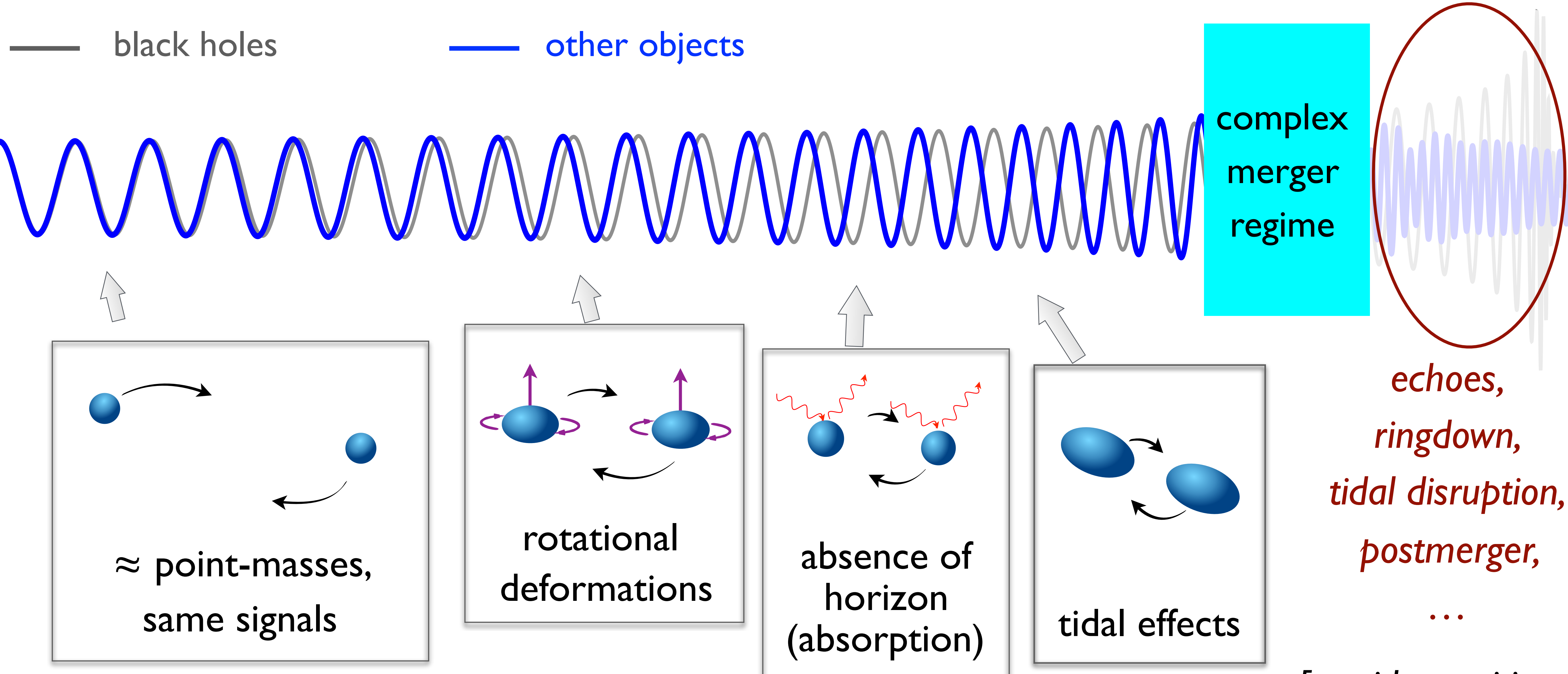
Uncalibrated EOB re-summation of PN information also used in alternative "Phenom" template models for frequency-domain GW signals

Imprints of objects' internal structure on GWs



What changes for non-black hole objects (comparable masses)?

Imprints of objects' internal structure on GWs



[~10³ cycles for few-Msun objects in LIGO]

+ tidal excitation of internal oscillation modes / resonances

[outside sensitive band for few-Msun objects in LIGO]

Tidal effects in nonspinning binaries

- Are there new, non-tidal interactions in GR that impact the early inspiral?

[Wilson+ 1995 ``Instabilities in Close Neutron Star Binaries'' & 4 follow-up papers;
Sociological account: Kennefick 2000 ``Star crushing: theoretical practice & the theoretician's regress'']

- Rigorous analysis: [Flanagan 1998: ``GR coupling between orbital motion & internal degrees of freedom for inspiraling binary neutron stars'']

Dimensionless parameters characterizing the system:

$$\epsilon = \frac{M}{R} \qquad \alpha = \frac{R}{D} \qquad \epsilon_{\rm orbit} = \frac{M}{D}$$

Internal gravity *Tidal expansion* *PN expansion*

Tidal effects in nonspinning binaries

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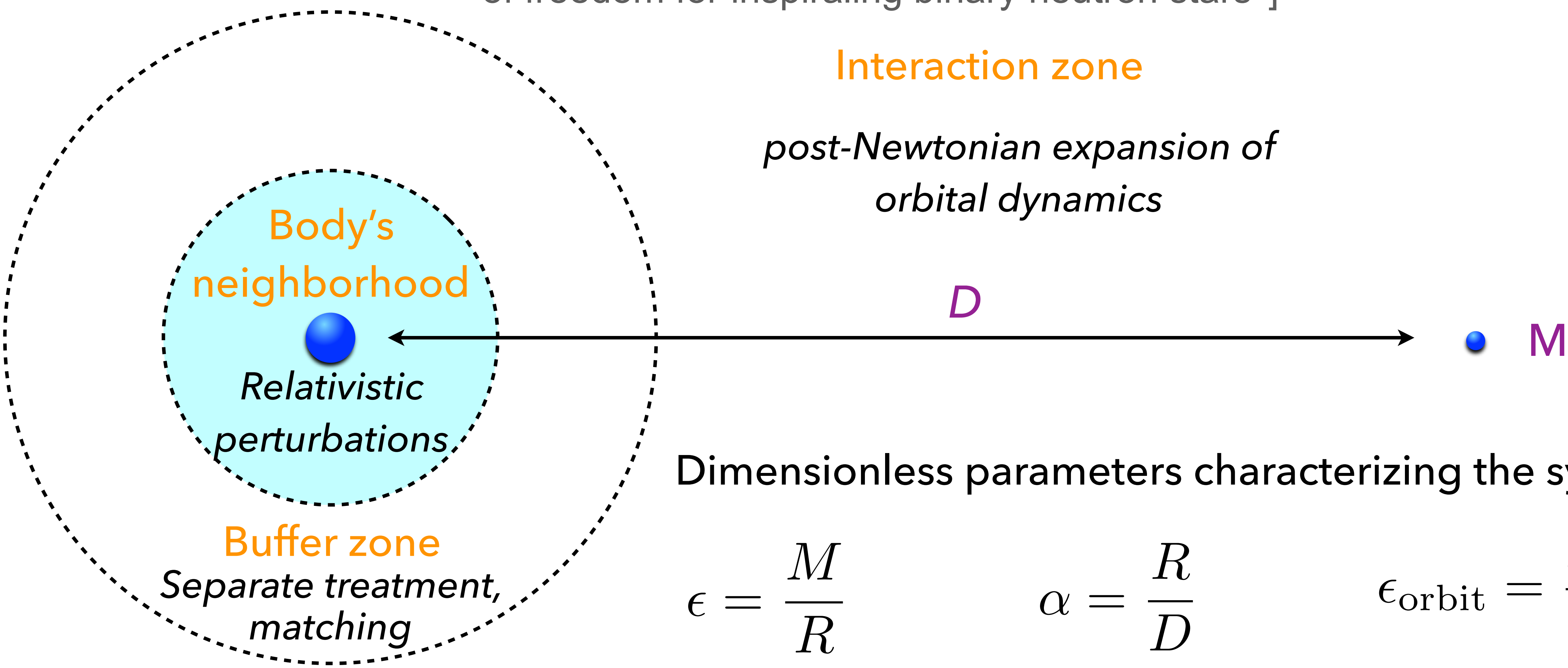


Dimensionless parameters characterizing the system:

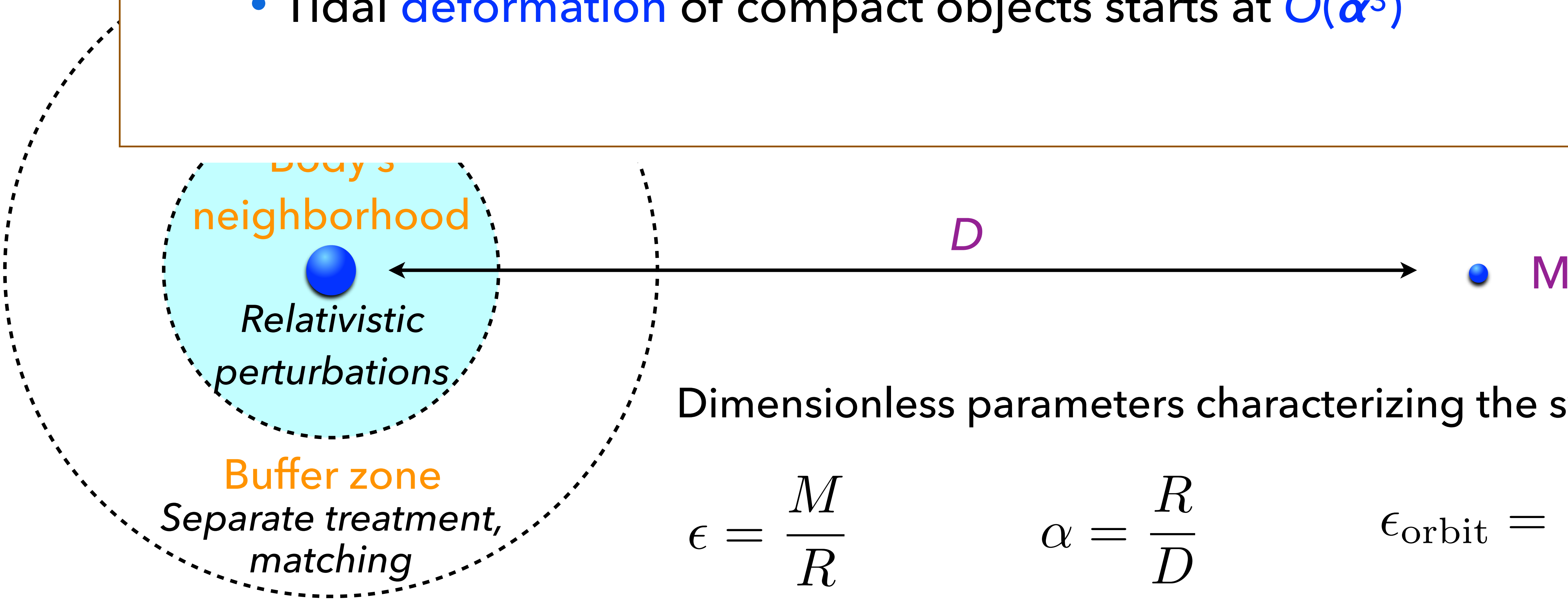
$\epsilon = \frac{M}{R}$	$\alpha = \frac{R}{D}$	$\epsilon_{\rm orbit} = \frac{M}{D}$
Internal gravity	*Tidal expansion*	*PN expansion*

Tidal effects in nonspinning binaries

- Matched asymptotic expansions (for $D >> R$, to all orders in ϵ):

  [Flanagan 1998]

  - There are NO GR non-tidal interactions
  - Body-dependence of the equations of motion starts at $O(\alpha^5)$
  - Tidal deformation of compact objects starts at $O(\alpha^3)$



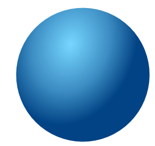
Dimensionless parameters characterizing the system:

$$\epsilon = \frac{M}{R} \qquad \alpha = \frac{R}{D} \qquad \epsilon_{\rm orbit} = \frac{M}{D}$$

Internal gravity   *Tidal expansion*   *PN expansion*

Tidal effects (nonspinning objects, leading order)

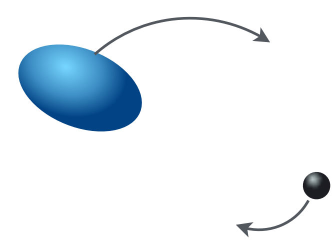
- Isolated object in equilibrium



- In a binary: tidal field due to curvature produced by distant companion

$$\mathcal{E}_{ij} = R_{titj}$$ in object's rest frame

- linear response: object deforms



- Limit where variations in tidal field are much faster than object's internal timescales:

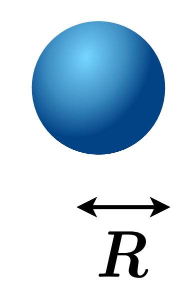
induced quadrupole

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

tidal deformability parameter

$$\lambda = \frac{2}{3} k_2 R^5$$

dimensionless Love number

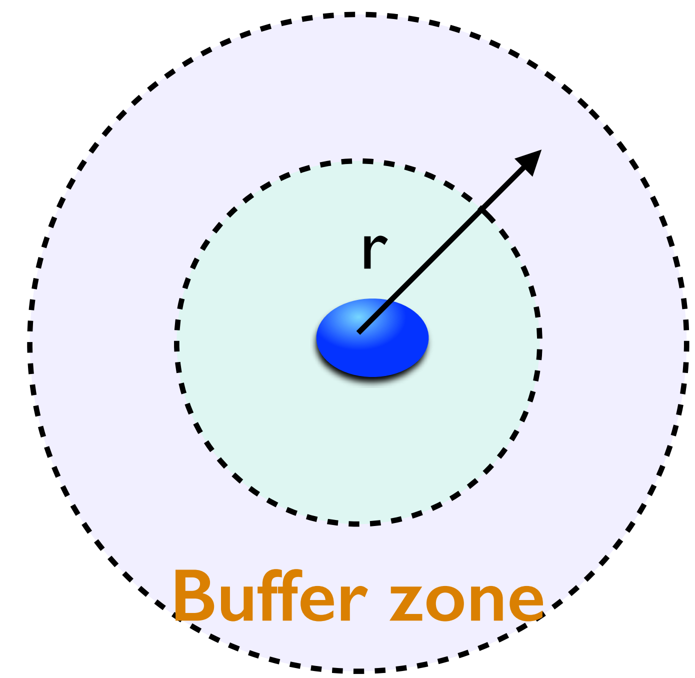


[Flanagan, Hinderer 2008]

Tidal deformability parameter

- Convert tensors to spherical harmonic decomposition, sufficient to consider (l,m)=(2,0)

$$\mathcal{Q} = -\lambda\, \mathcal{E}$$



- quantities defined by the asymptotic metric (buffer zone) e.g. in the object's local rest frame:

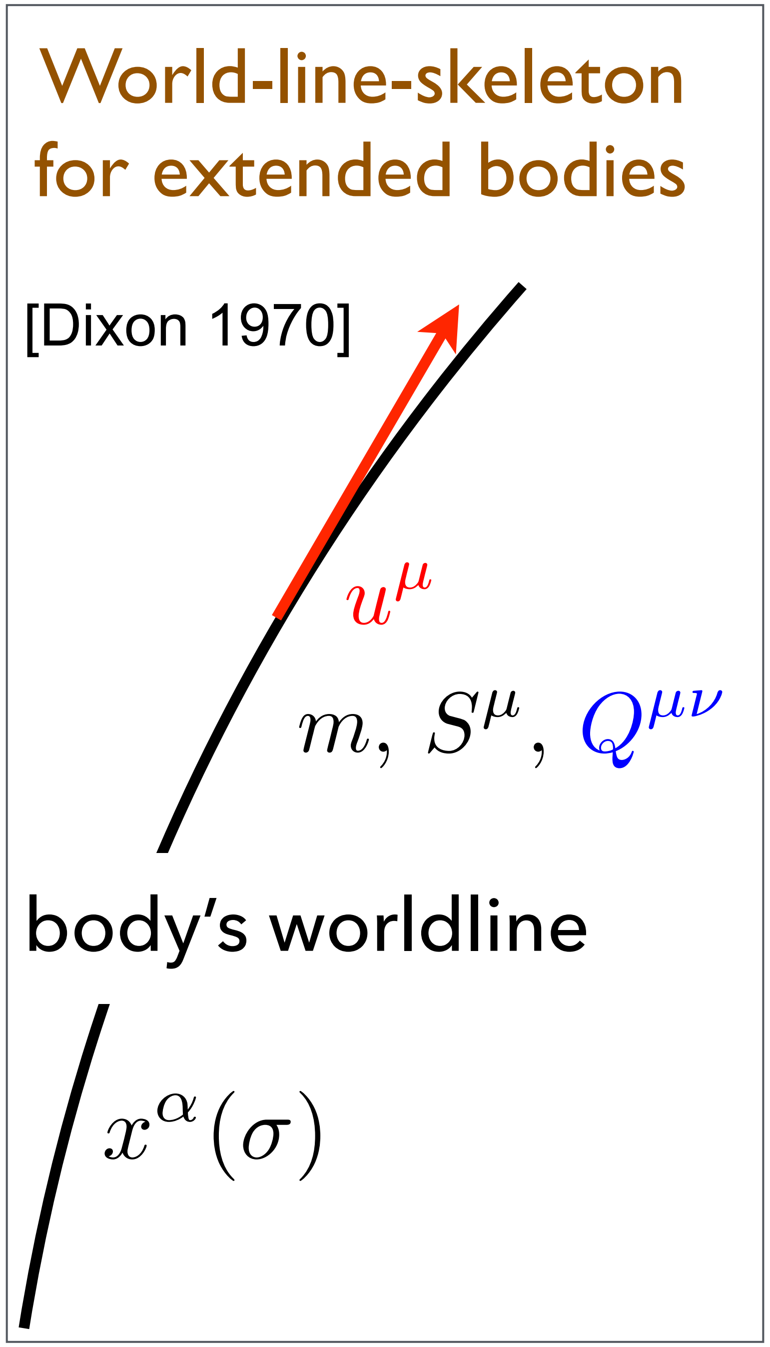
$$\frac{(1+g_{tt})}{2} = -\frac{\mathrm{m}}{r} - \frac{3\,\mathcal{Q}\,Y_{20}(\theta,\phi)}{2\,r^3} + \ldots + \frac{1}{2}\,\mathcal{E}\,r^2\,Y_{20}(\theta,\phi) + \ldots$$

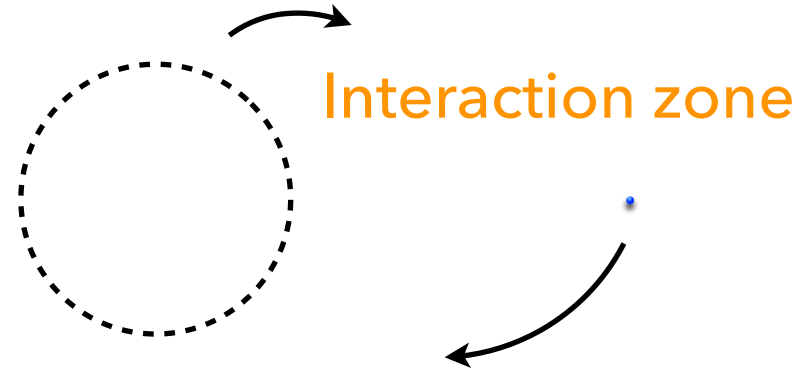
- Determined from Einstein's equations: linear static perturbations to equilibrium [Hinderer 2008]

- $\boldsymbol{\lambda}$=0 for a nonspinning BH [e.g. Kol & Smolkin 2011]

Similar method for higher multipoles [Damour, Nagar 2009, Binnington, Poisson 2009]

Tidal effects on the dynamics in the interaction zone





Two-body dynamics described by an effective action:

$$S = S_{\rm pp} + \int d\sigma\ [L_{\rm tidal} + L_{\rm internal}]$$

point-mass contribution

$$L_{\rm tidal} = -\frac{z}{2}\mathcal{E}_{\mu\nu}Q^{\mu\nu}$$

$$z = \sqrt{-u_\mu u^\mu}$$

dynamics of quadrupole

$Q^{\mu\nu}$

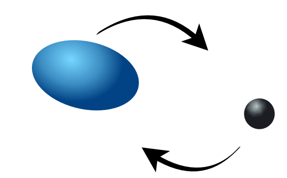
[Goldberger 2010
Steinhoff+2016]

Influence on the GWs

- Energy goes into deforming the NS

$$\boldsymbol{E} \sim \boldsymbol{E}_{\text{orbit}} + \frac{1}{4}\boldsymbol{\mathcal{Q}}\,\boldsymbol{\mathcal{E}}$$

$\boldsymbol{\Omega}$



$$\boldsymbol{\mathcal{Q}} = -\lambda\,\boldsymbol{\mathcal{E}}$$

- moving tidal bulges contribute to gravitational radiation

$$\dot{\boldsymbol{E}}_{\text{GW}} \sim \left[\frac{d^3}{dt^3}\left(\boldsymbol{Q}_{\text{orbit}} + \boldsymbol{\mathcal{Q}}\right)\right]^2$$

$$M = m_1 + m_2$$

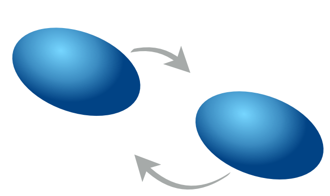
- approx. GW phase:

$$\frac{d\phi_{\text{GW}}}{dt} = 2\Omega, \qquad \frac{d\Omega}{dt} = \frac{\dot{E}_{\text{GW}}}{dE/d\Omega}$$

$$\Delta\phi_{\text{GW}}^{\text{tidal}} \sim \lambda \frac{(M\Omega)^{10/3}}{M^5}$$

- for two extended objects, tidal analogue of the chirp mass is:

$$\tilde{\Lambda} = \frac{1}{26}\left[\left(1 + 12\frac{m_2}{m_1}\right)\lambda_1 + \left(1 + 12\frac{m_1}{m_2}\right)\lambda_2\right]$$



[Flanagan, Hinderer 2008]

Neutron stars (NSs)

- densest stable material objects known in the universe
- 1939: theoretical description *[Oppenheimer & Volkoff]*
- thousands observed to date

debris from a supernova explosion in 1054

Crab Pulsar
(NS rotating at 30 rev/sec)

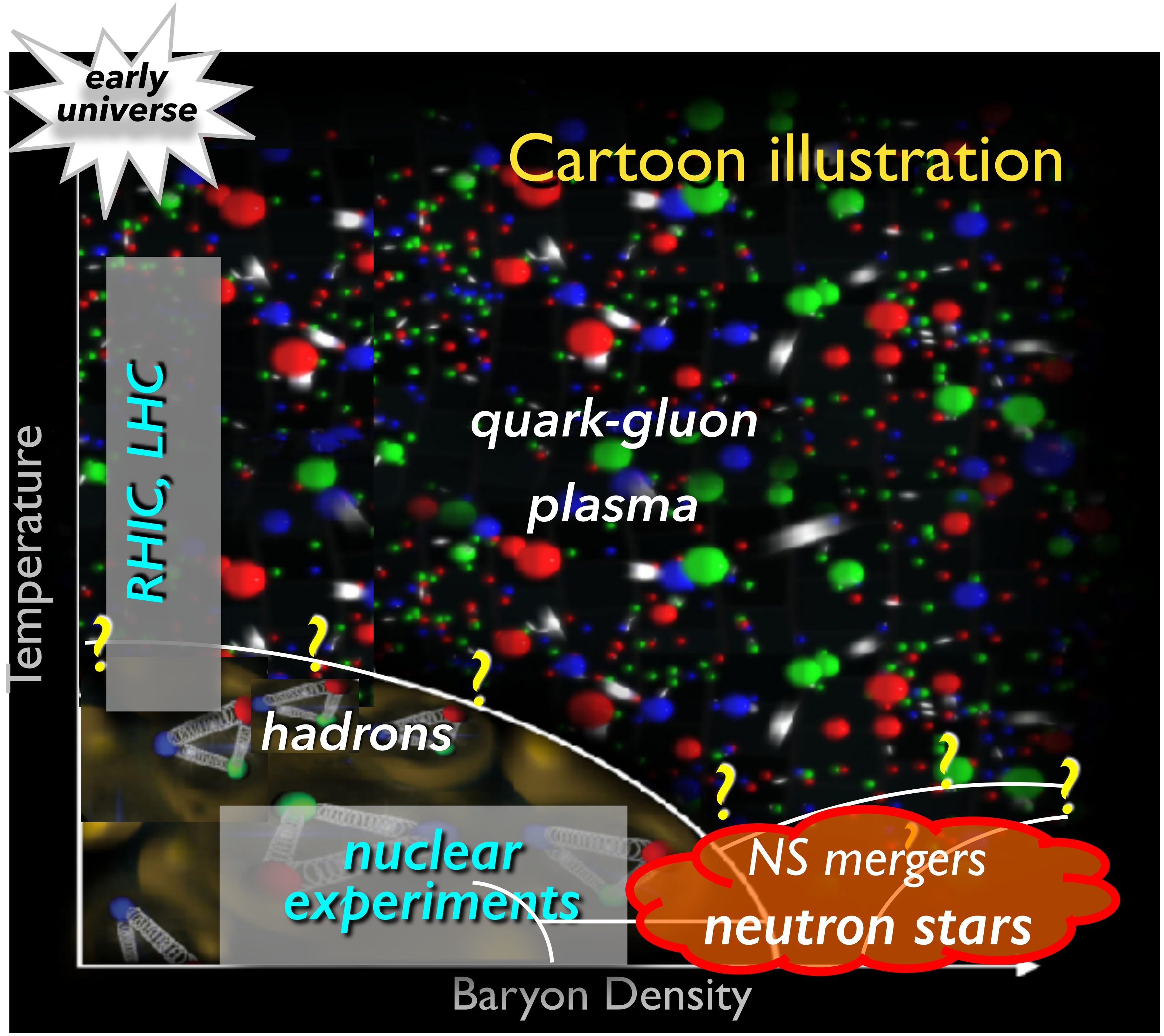
crushed to neutron-star compactness

crushed

Black hole

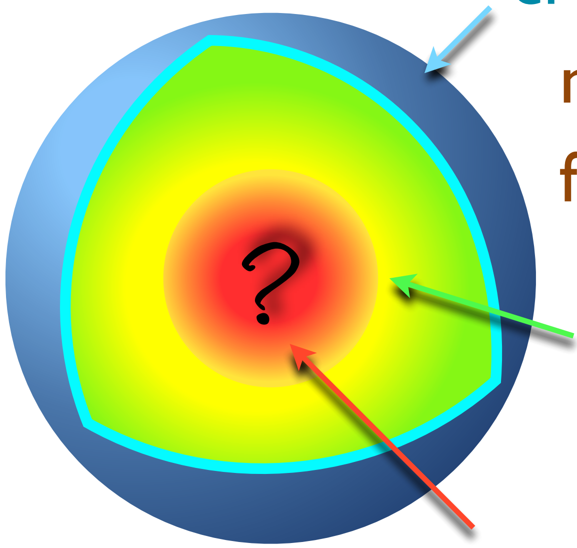
What is the nature of matter in such extreme conditions?

Phases of QCD



Credit: F. Linde

Conjectured Neutron Star (NS) structure



[iron ~ **10** g/cm^3]

crust ~ *km*

neutron rich ions,

free neutrons

~10^6 g/cm^3 inverse β-decay

~10^{11} g/cm^3 neutron drip

outer core

uniform liquid

deep core

~2-10x nuclear density

exotic states of matter?

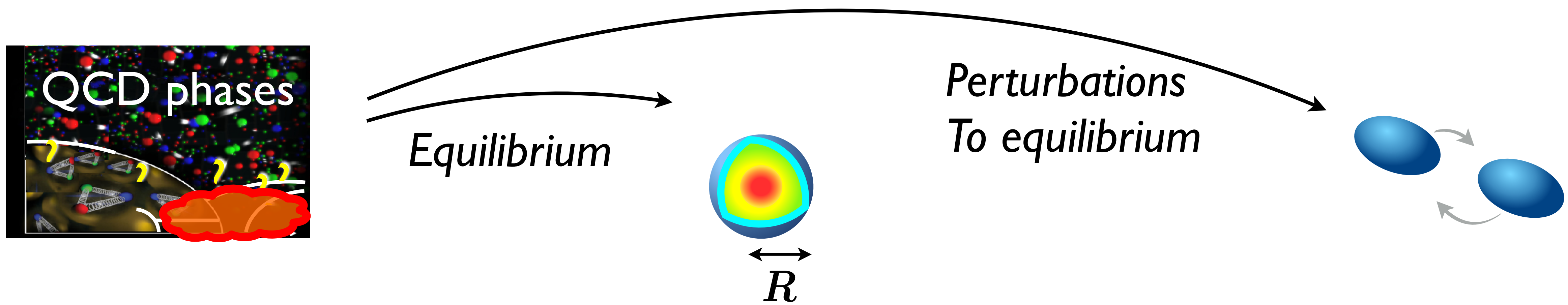
deconfined quarks?

signatures of new physics?

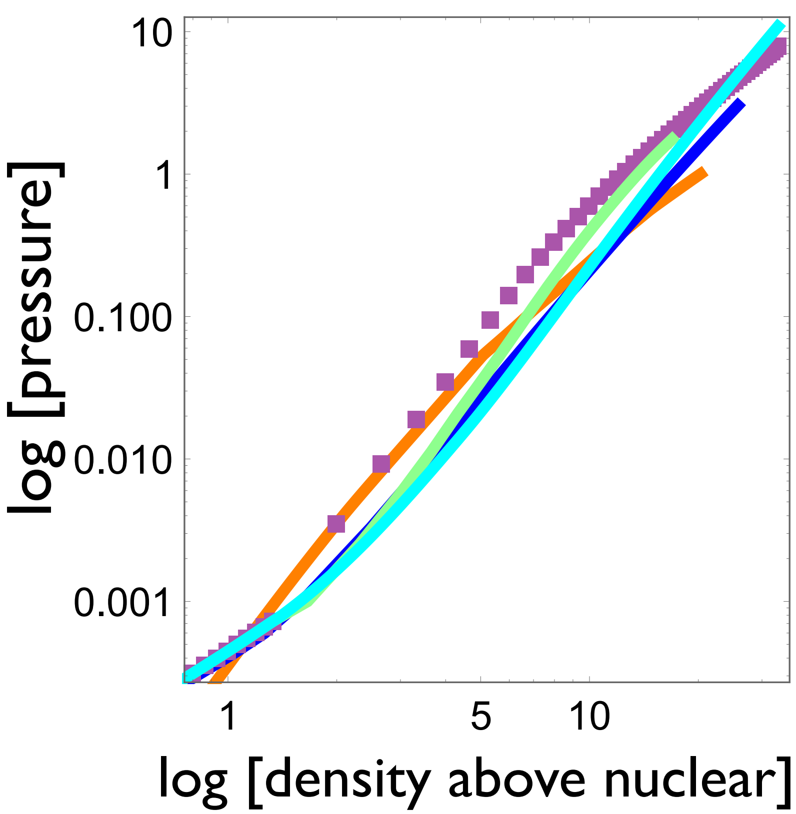
~10^{15} g/cm^3

- many theoretical difficulties
- far extrapolations from known physics

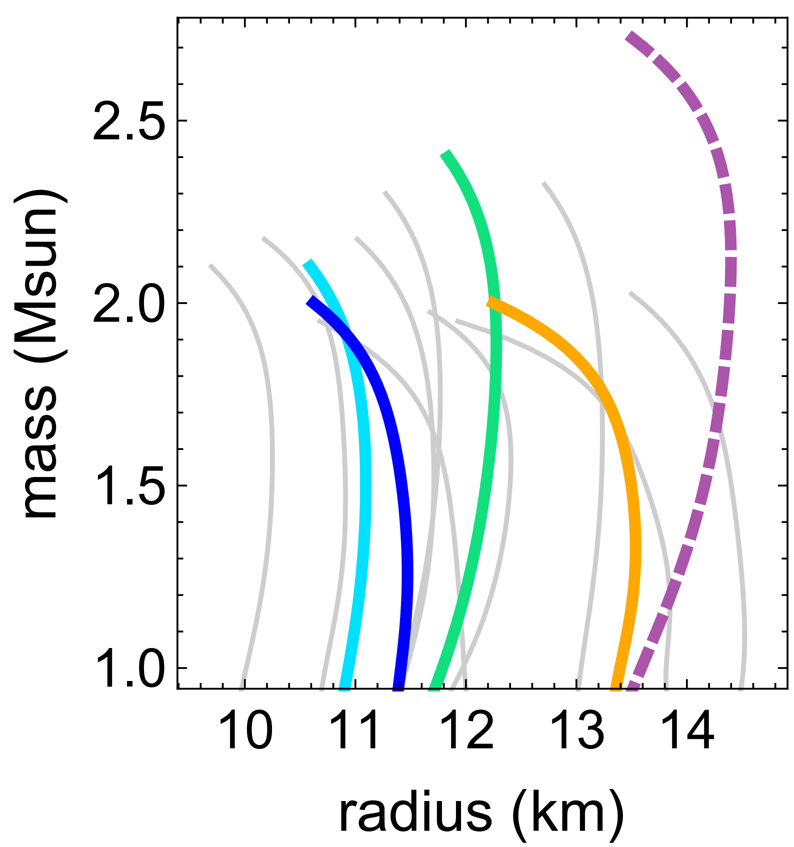
Properties of NS matter reflected in global observables



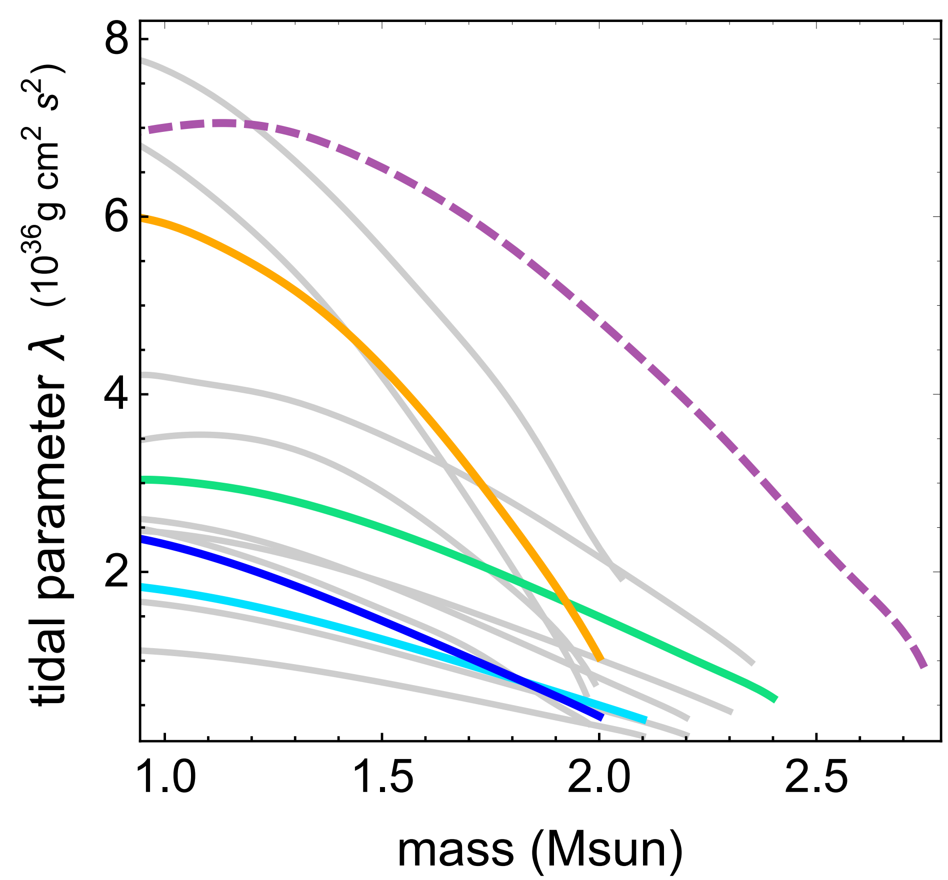
NS matter models
(equations of state)



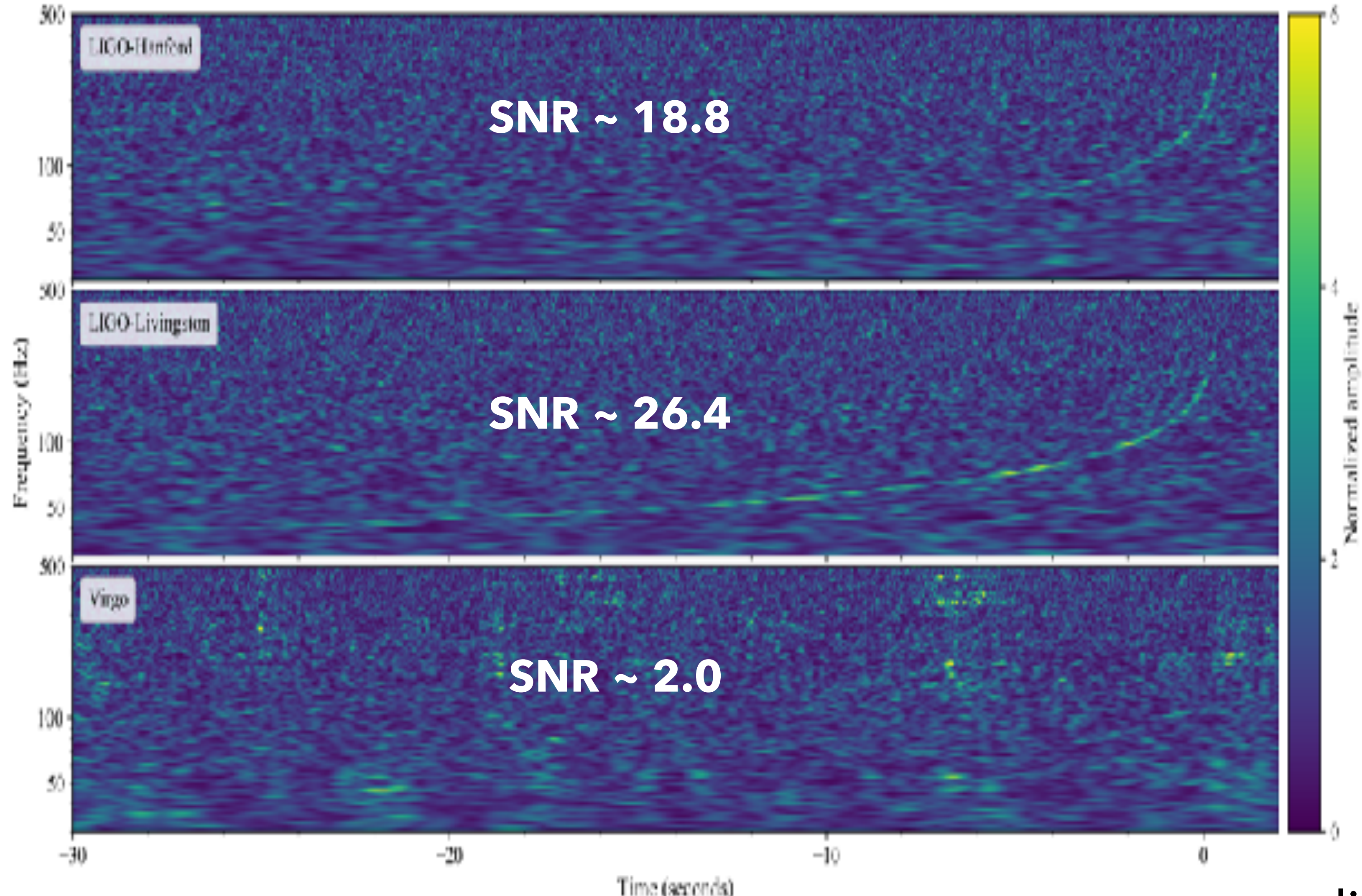
Mass vs. radius



tidal deformability λ vs. mass



Aug. 17, 2017: binary neutron star merger GW170817



credit:LVC

Distance: ~40 Mpc

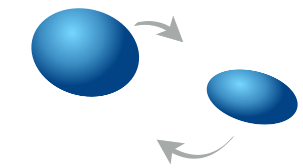
Total mass: ~ 2.74 Msun

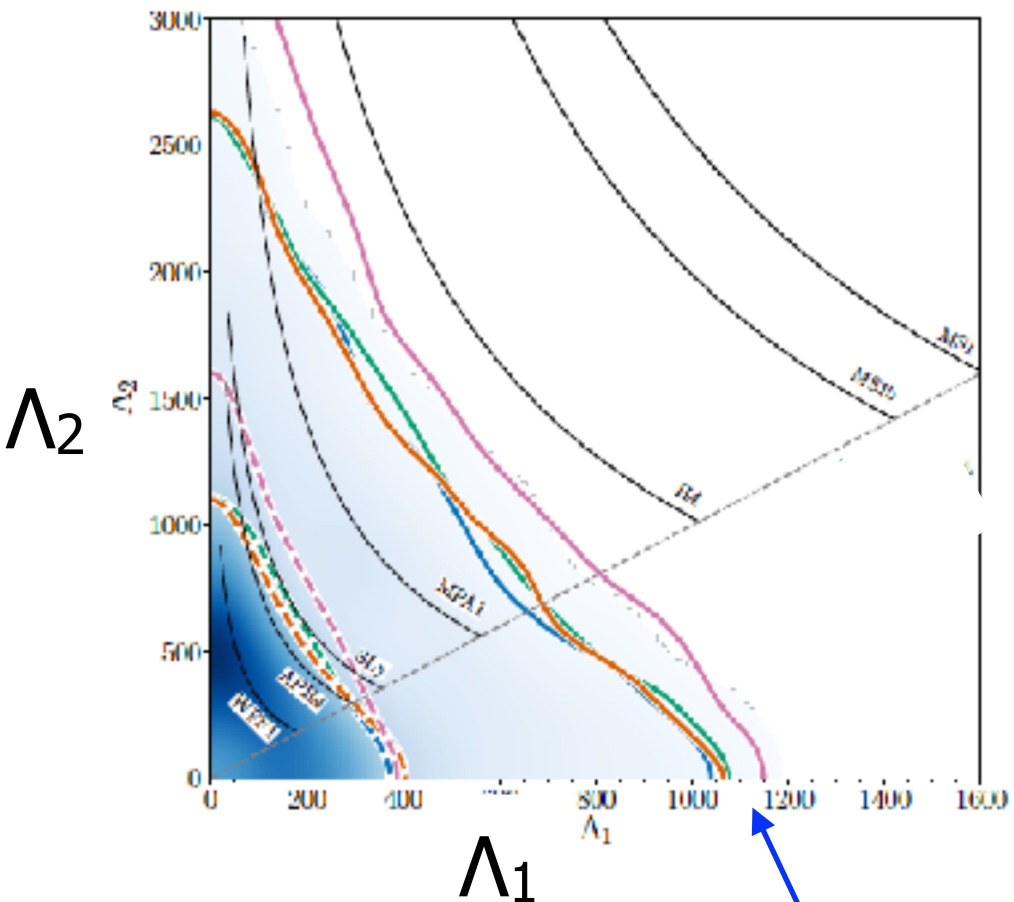
Loudest, closest, richest in science

Longest:~100 s (c.f. <2 s for GW151226)

Measurements of tidal deformability for GW170817

- Results for dimensionless tidal deformability $\Lambda = \frac{\lambda}{m_{\mathrm{NS}}^5}$ allowing for high spins:

Λ_1  Λ_2



LVC arXiv:1805.11579

Measurements of tidal deformability for GW170817

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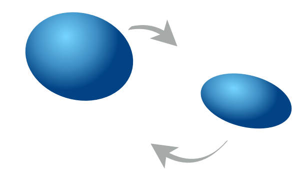
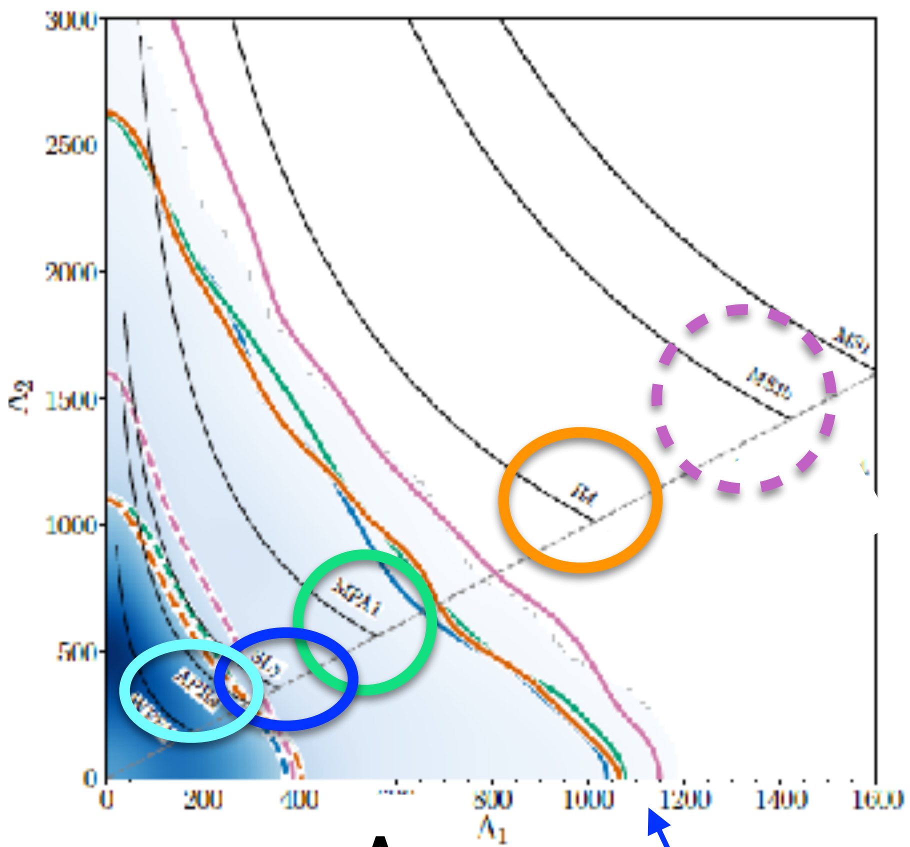
Λ_1  Λ_2

Λ_2

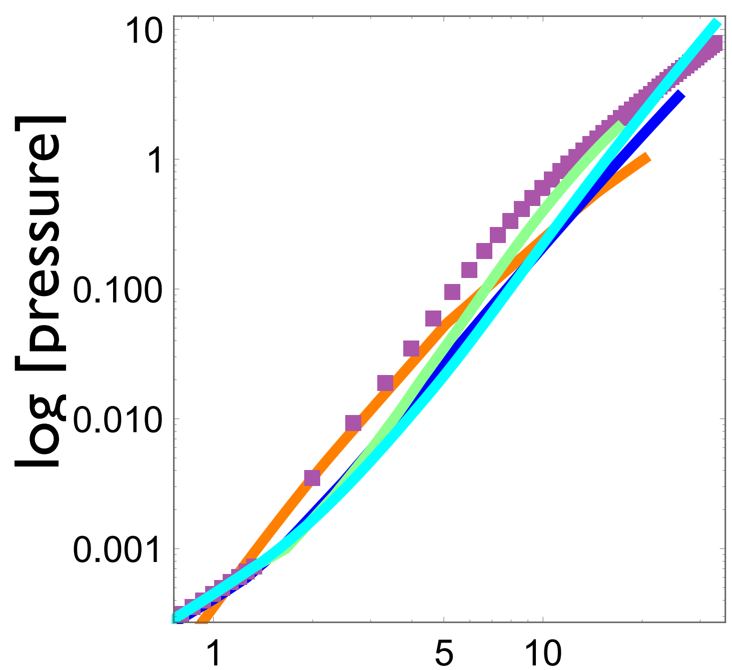


Λ_1

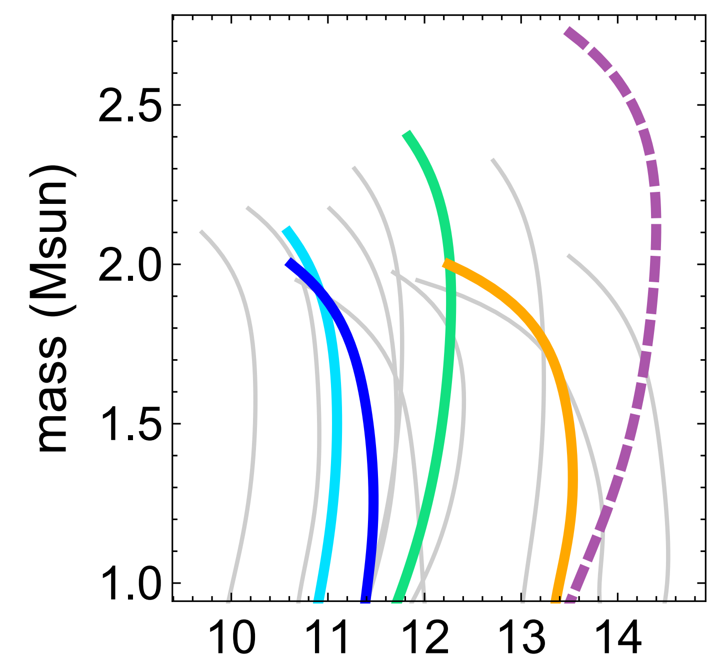
90% contours with different GW models

if two NSs:

Equation of state



Mass vs. radius



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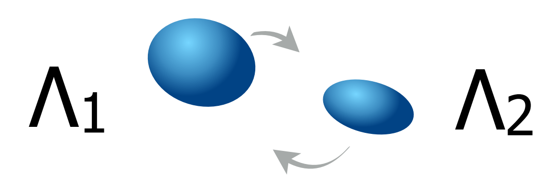
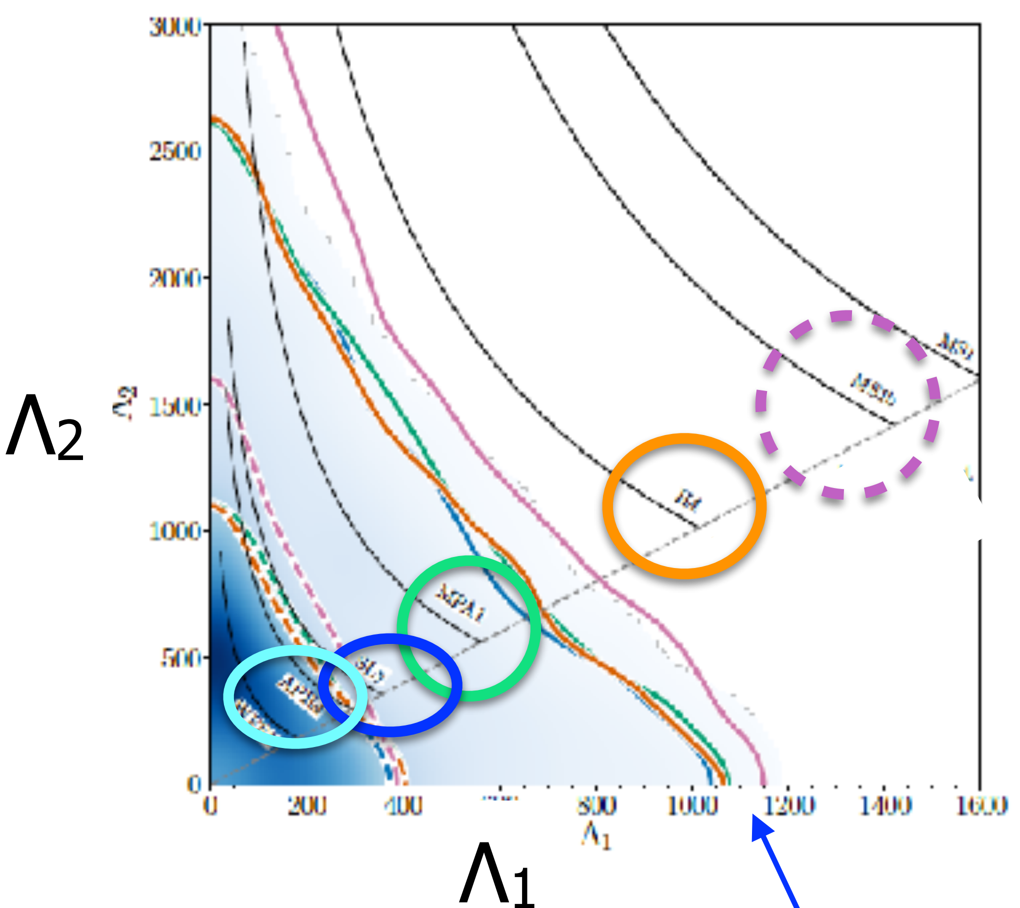
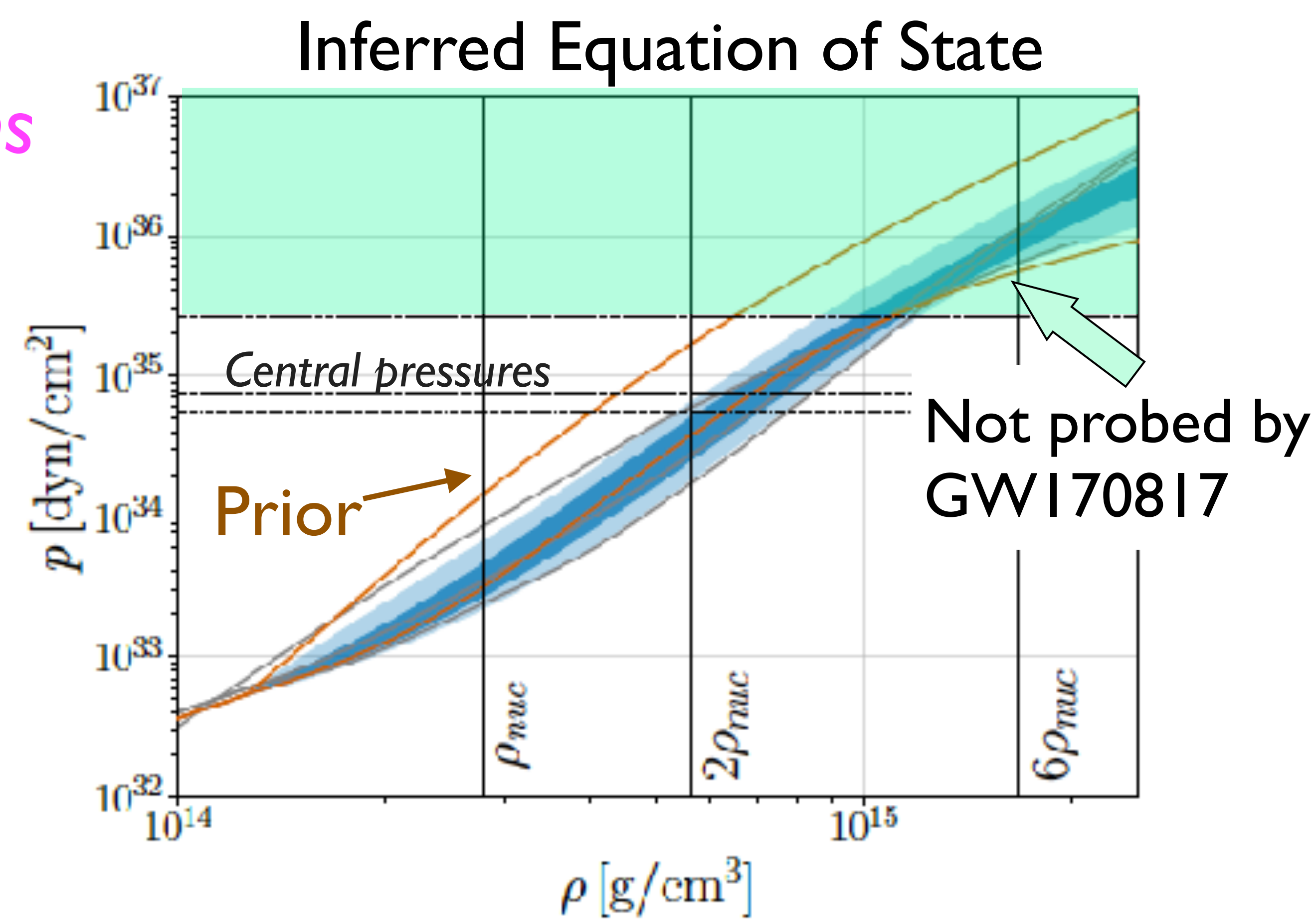




90% contours with different GW models

Further assumptions

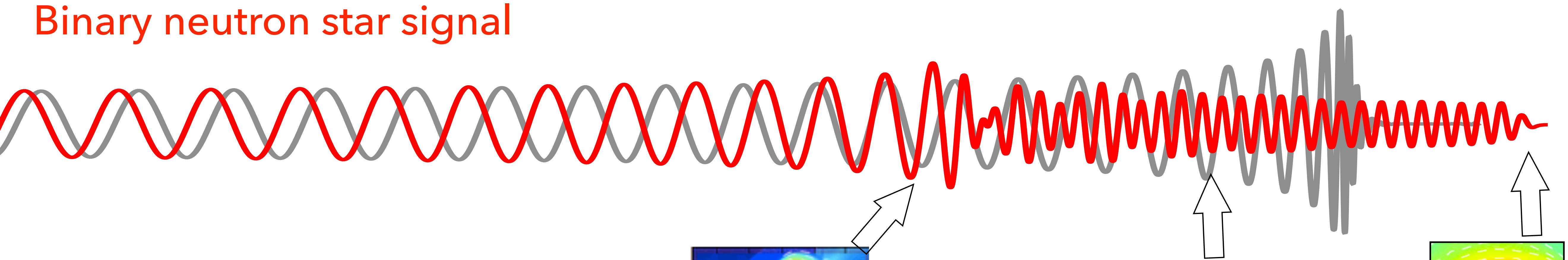


LVC arXiv:1805.11579

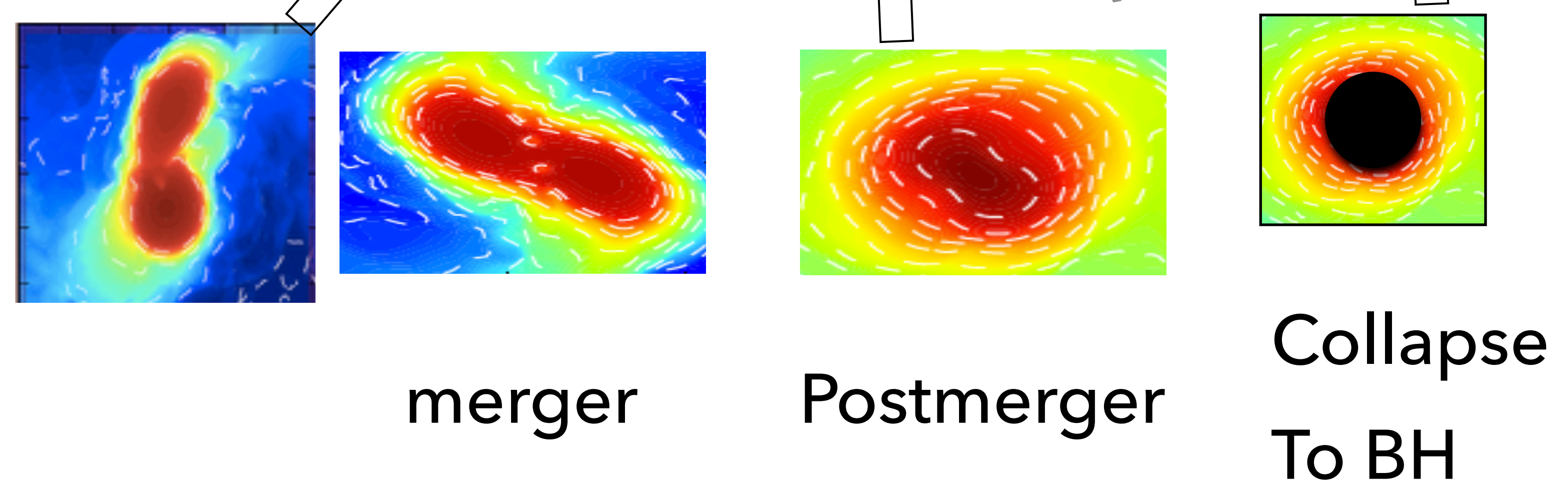
What happened post-inspiral? If a NS-NS system

NR data: T. Dietrich

Binary neutron star signal



Example of a plausible scenario :

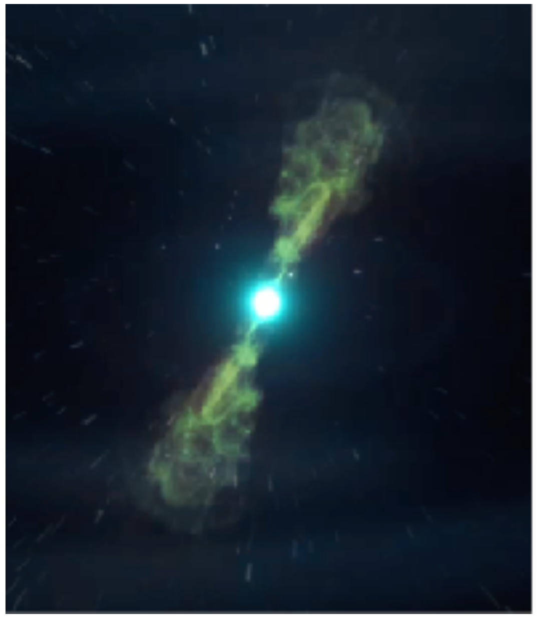


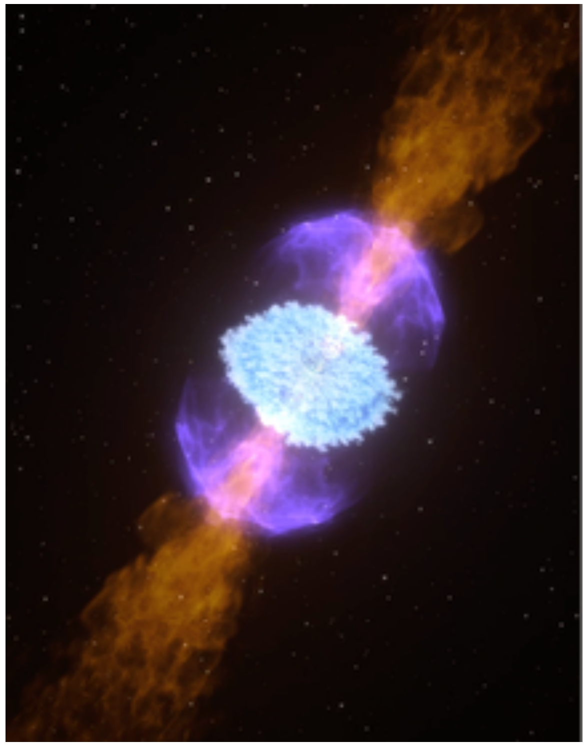
Couldn't tell anything about their fate from GWs ……

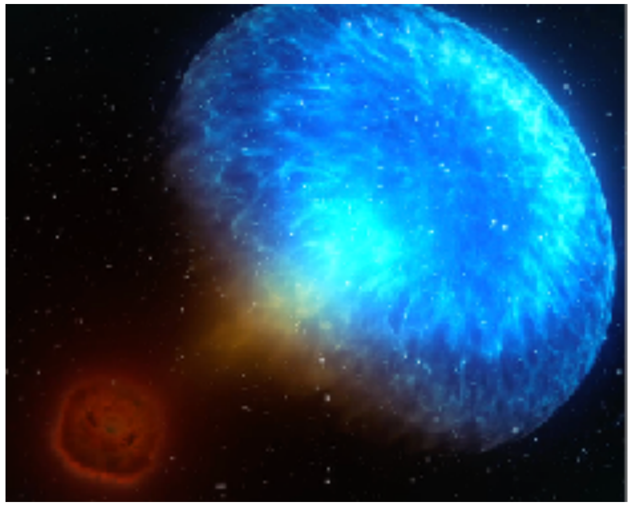
…. but lots of information from spectacular electromagnetic counterparts at all wavelengths

Relativistic outflows of neutron-rich material

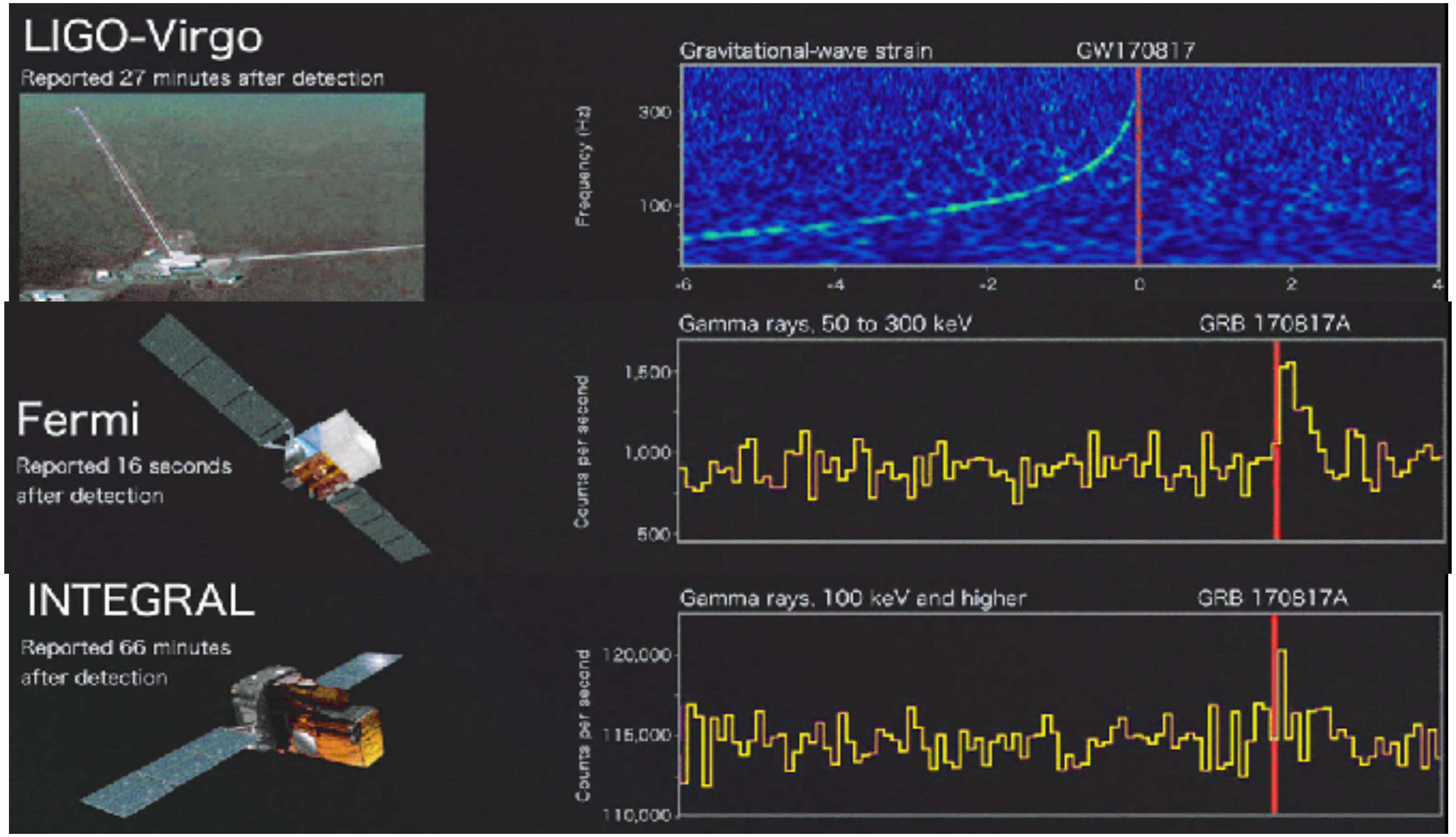
Shocks, collision with interstellar medium, and nuclear reactions : wide range of electromagnetic signals (+neutrinos)







Multimessenger observations of GW170817

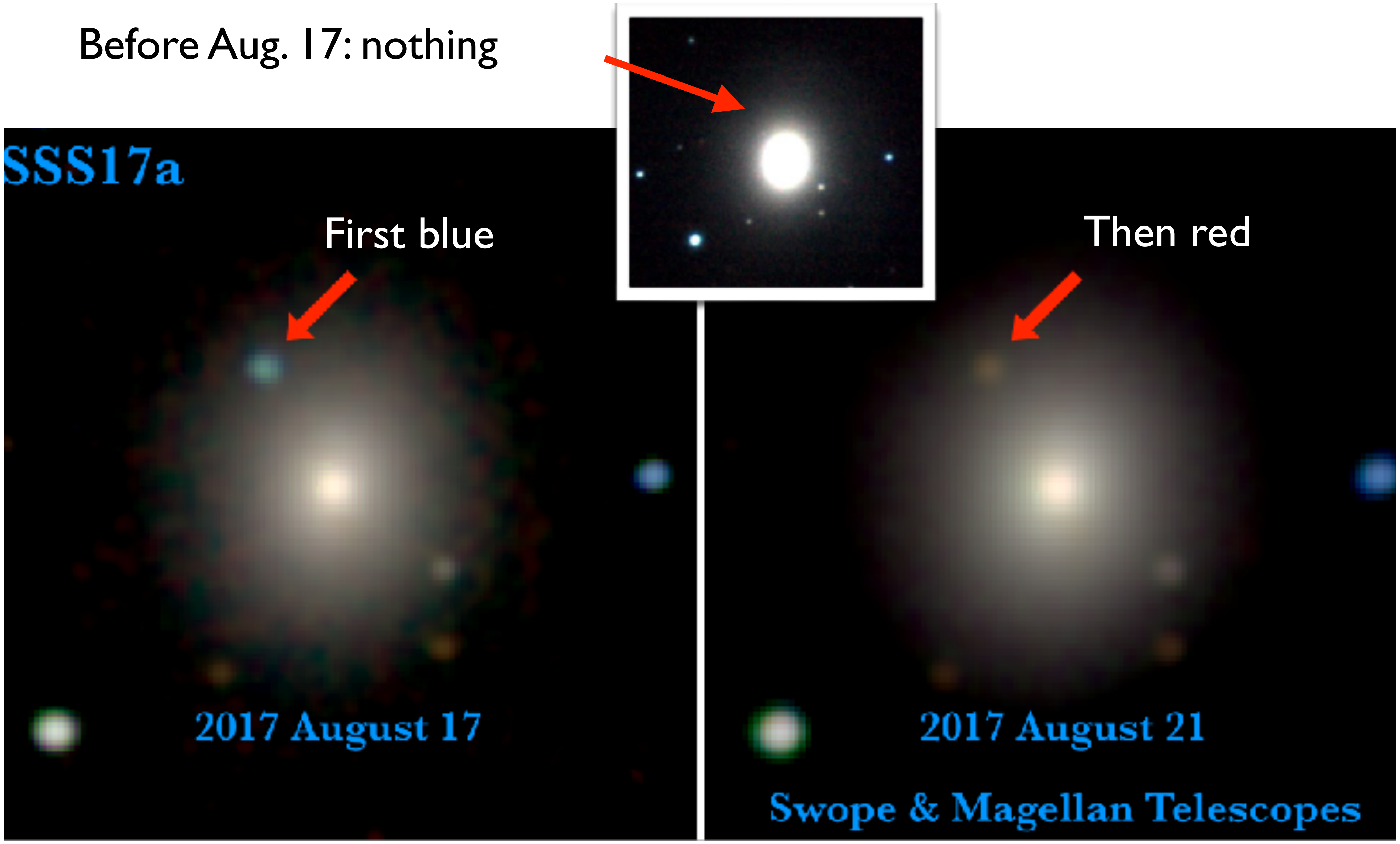


1.7 s after signal in LIGO ended:

Short gamma-ray burst

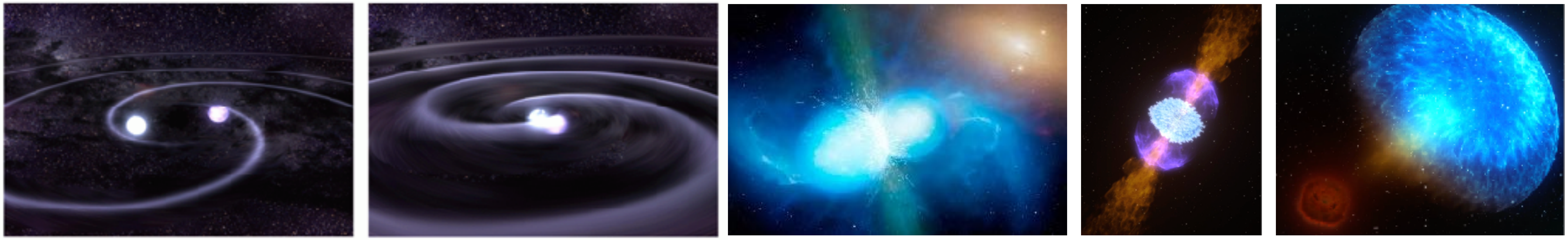
- Observed arrival times (travel over 130 million light years):
  - test speed of gravity, Lorentz invariance, and equivalence principle

Optical observations



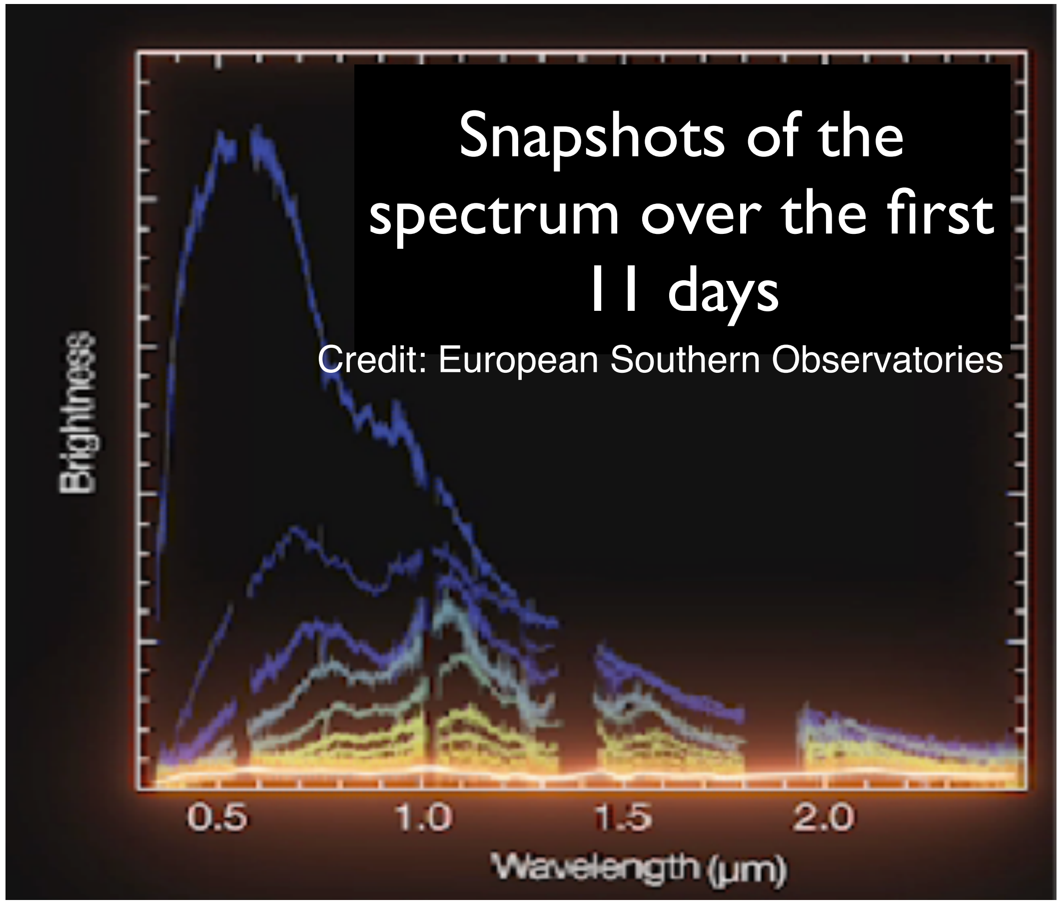
Credit: NASA

EM counterpart



Credit: NASA

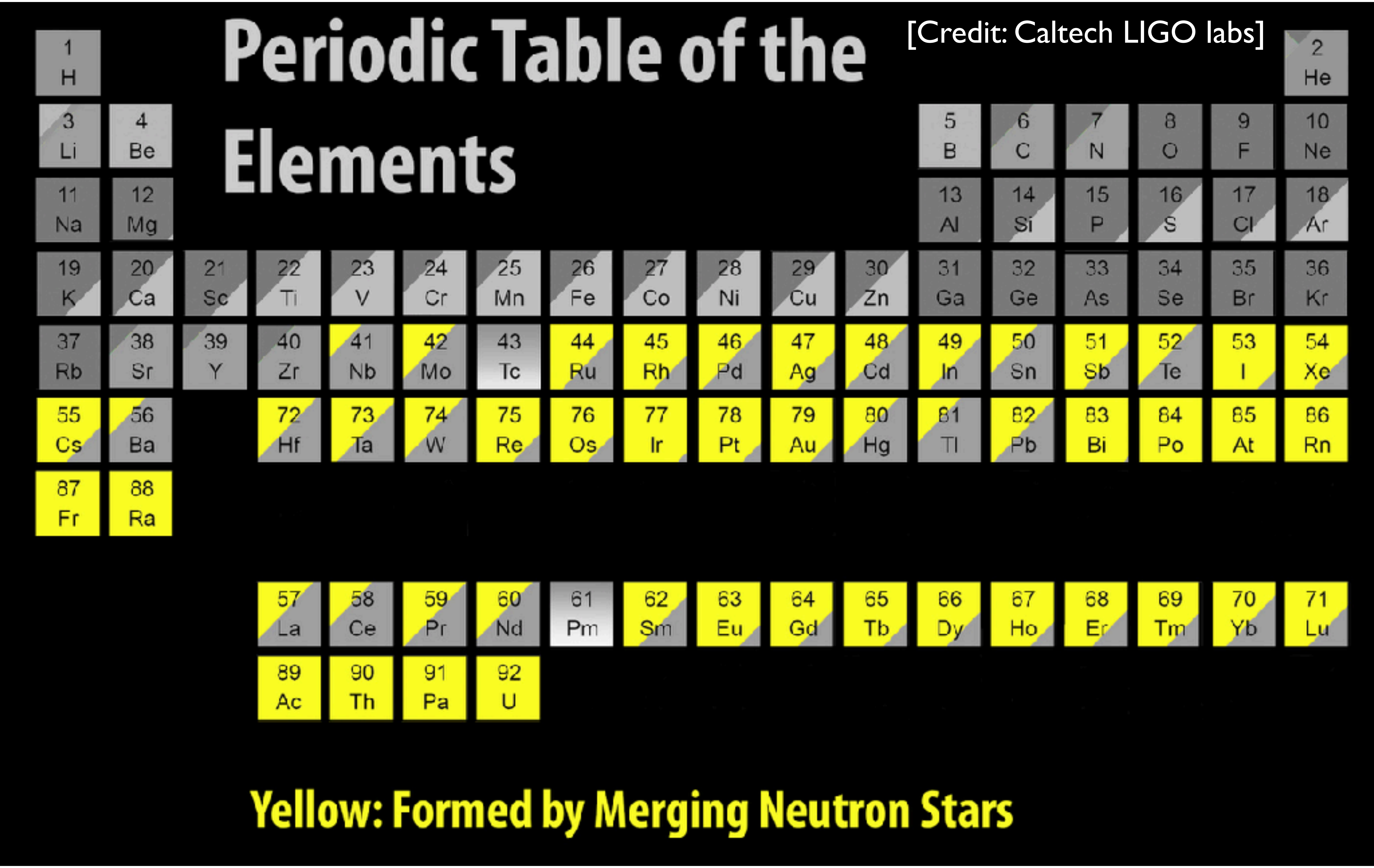
- Numerous multiwavelength EM observations
- Focus on UVOIR:



Credit: ESO

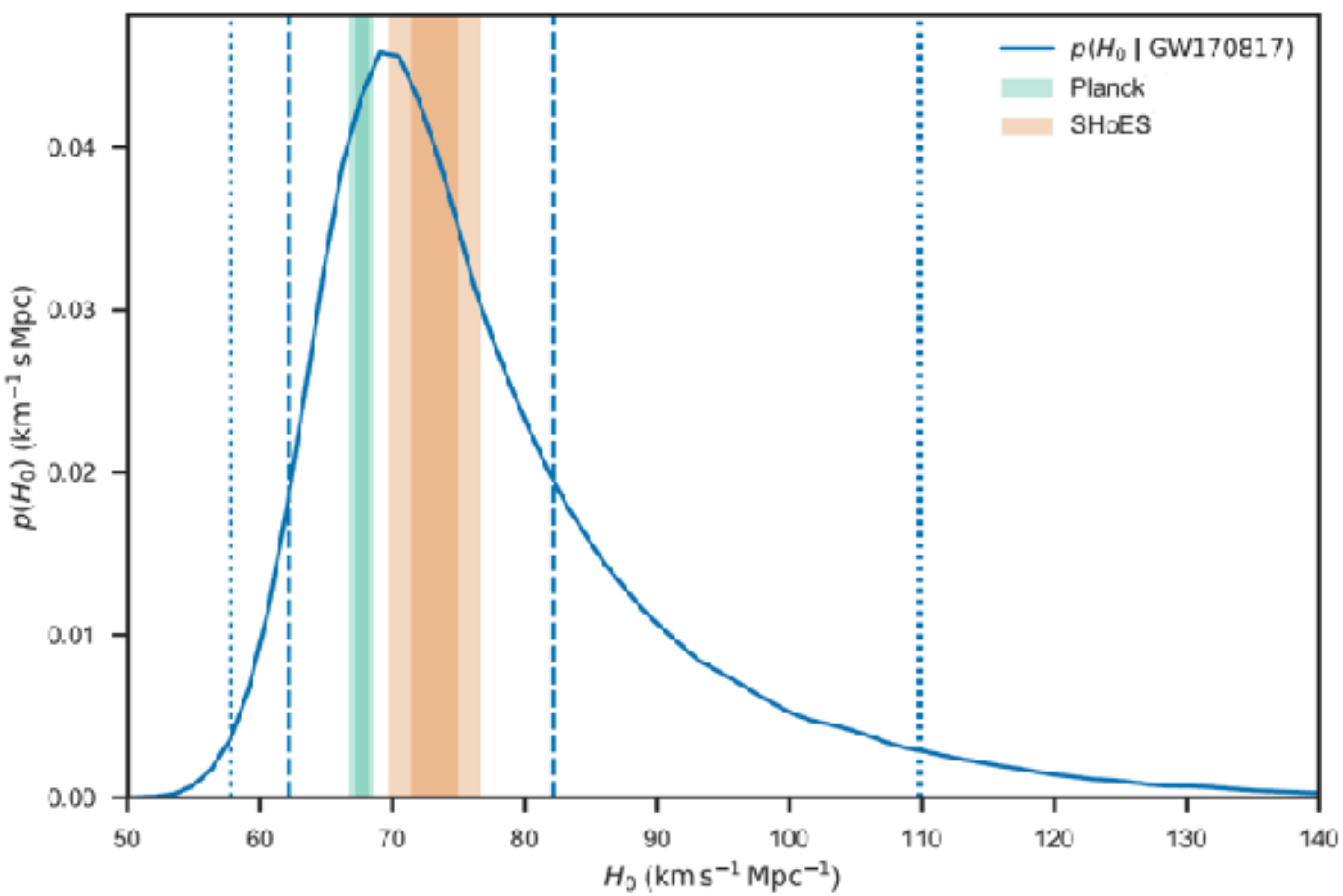
Kilonova characteristic of r-process nucleosynthesis

Production site of heavy elements



More combined GW & EM science

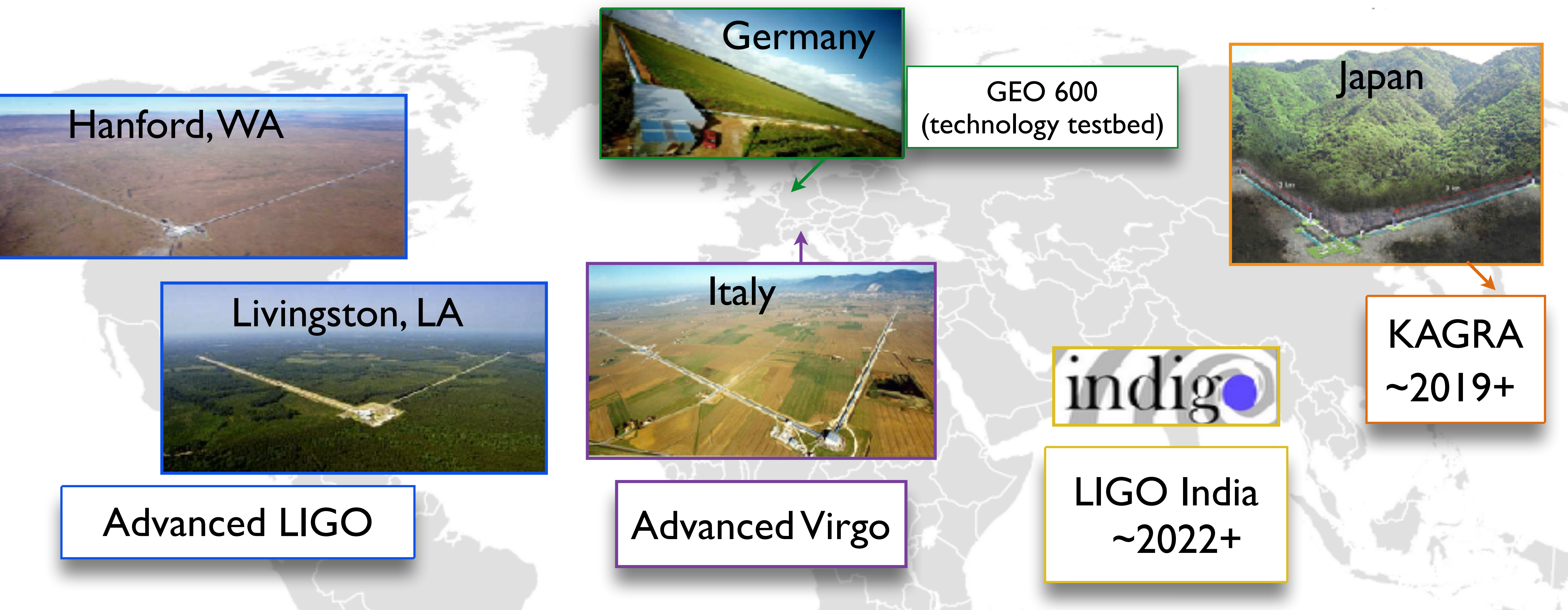
- Source localized to NGC 4993 (Elliptical galaxy ~130 million light years away)
- From GWs: luminosity distance to source
- Combine to infer Hubble constant:



LVC 2017

Outlook

Upcoming worldwide network of GW detectors

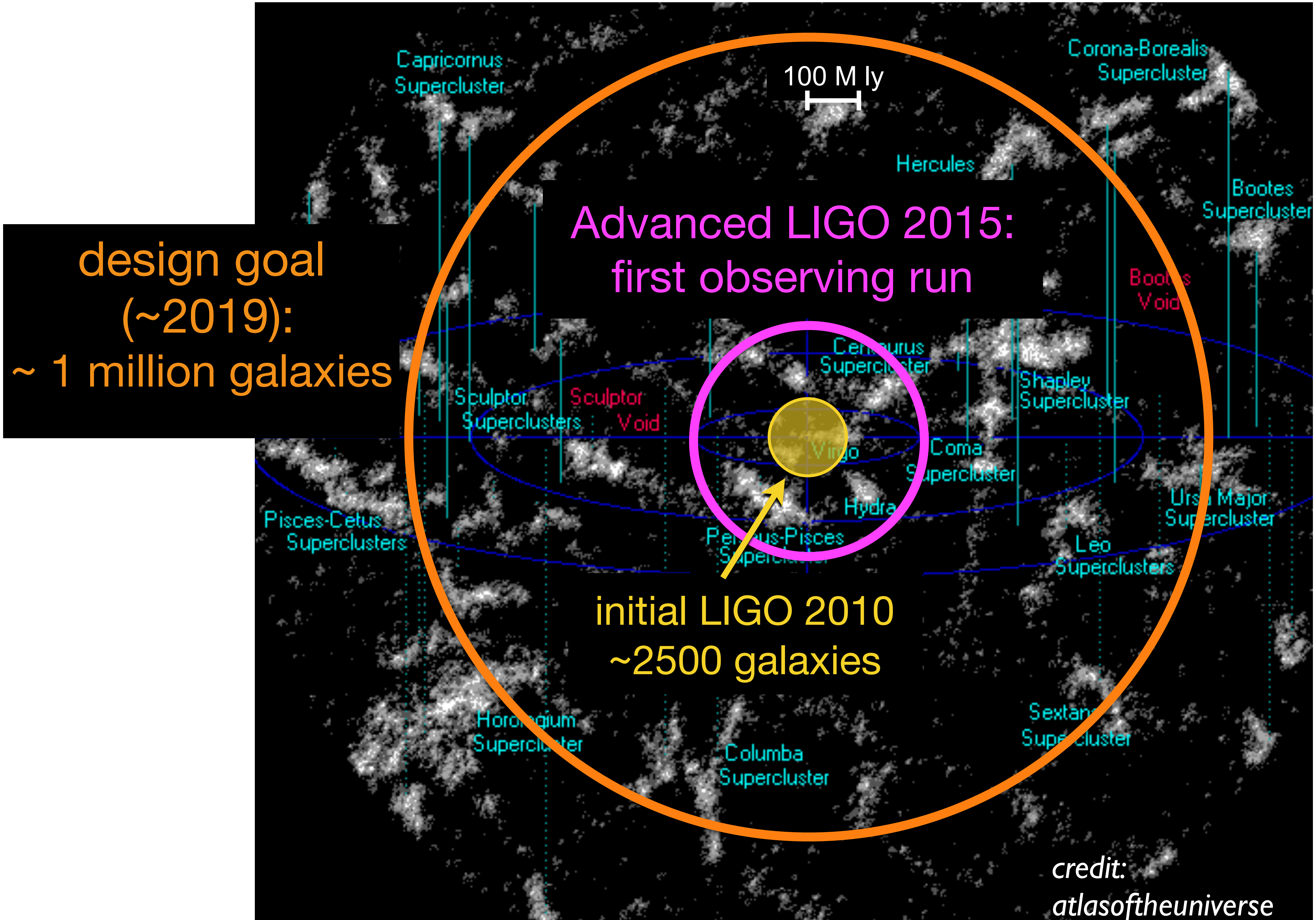


Future upgrades, new detectors (?) e.g. Einstein Telescope, Cosmic Explorer

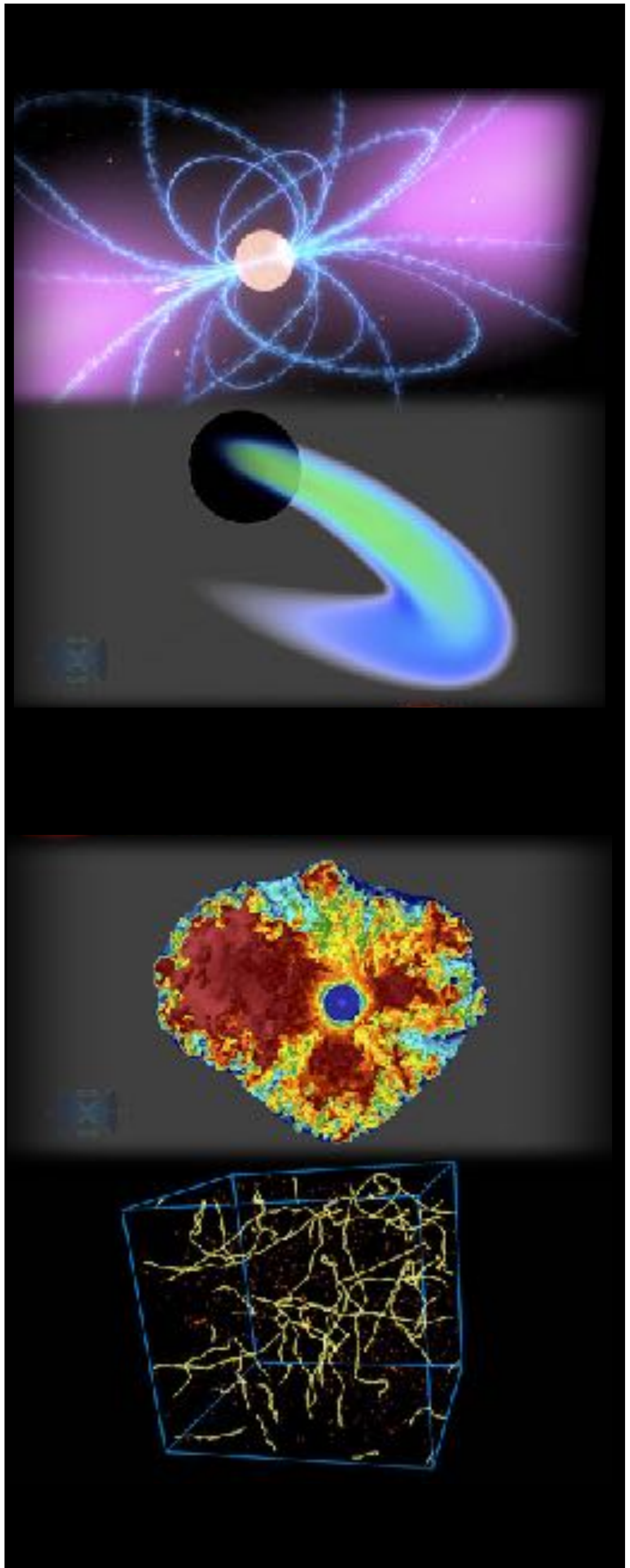
- *preparatory studies (experimental, site selection, …) underway,*
- *international team currently preparing 3G science case document*

Pulsar timing arrays: GWs in nanoHertz window

Visible volume of the universe (for binary neutron stars)



Other sources for ground-based detectors: a few examples



Binaries:

- inspirals of neutron stars into BHs

Continuous, nearly monochromatic signals

- single neutron stars
  - Distortions (mountains, accretion)
  - wobbles
  - unstable modes

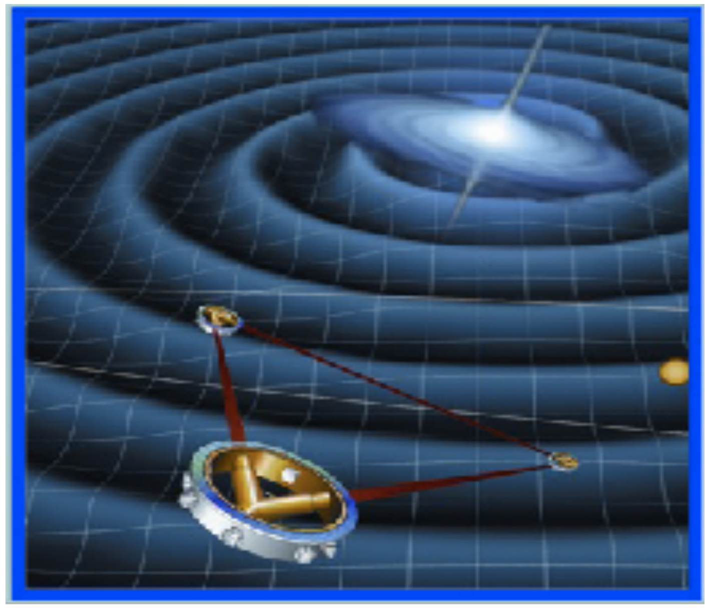
Burst signals:

- supernovae [$h \sim 10^{-20}$ if at D=10kpc]

Stochastic background:

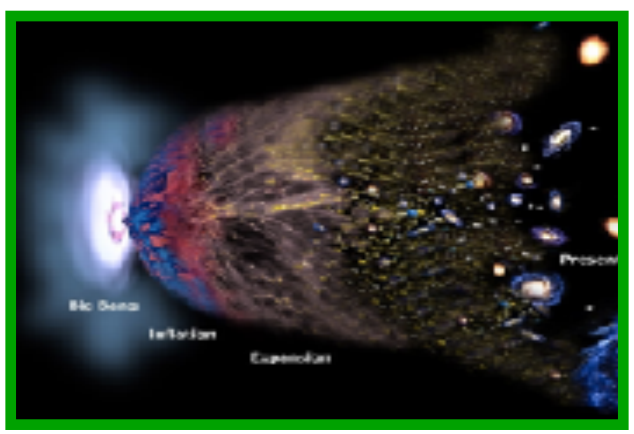
- cosmic strings, early universe physics

Next step: LISA (lower frequency window than LIGO)

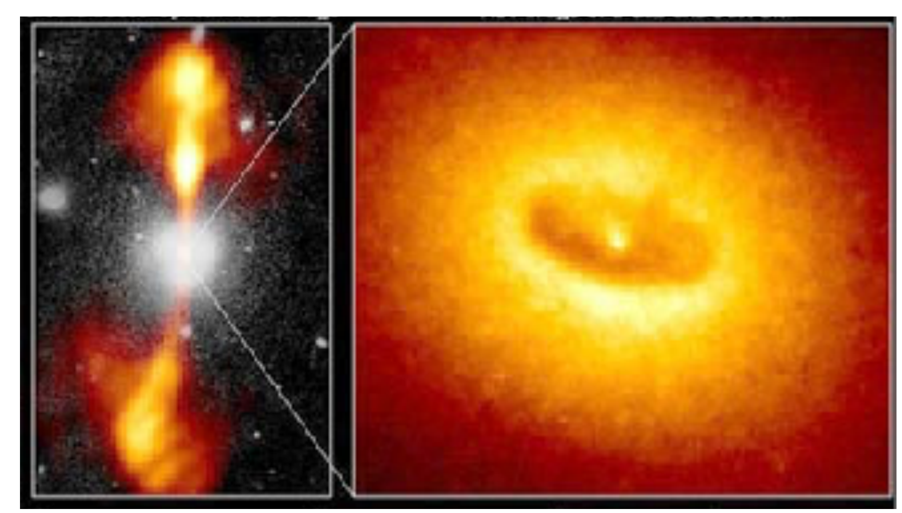


ESA-led mission, scheduled launch date in 2034:

new era of discoveries: mHz GW window

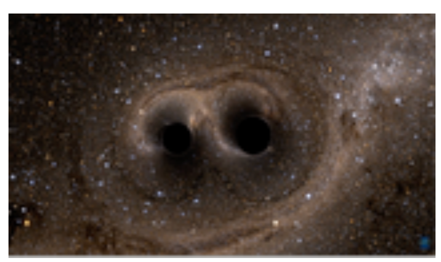


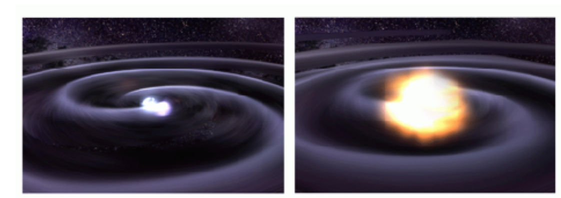
- formation, growth history of massive black holes
- stellar populations and dynamics in galactic nuclei
- exquisitely accurate tests of General Relativity and black holes
- cosmology
- multimessenger studies



Outlook

- gravitational waves now available as a channel of information about the universe
- even more science gains with joint electromagnetic/neutrino observations
- Much remains to be studied, further developments needed, progress underway





Expect a wealth of new insights in the coming years - decades