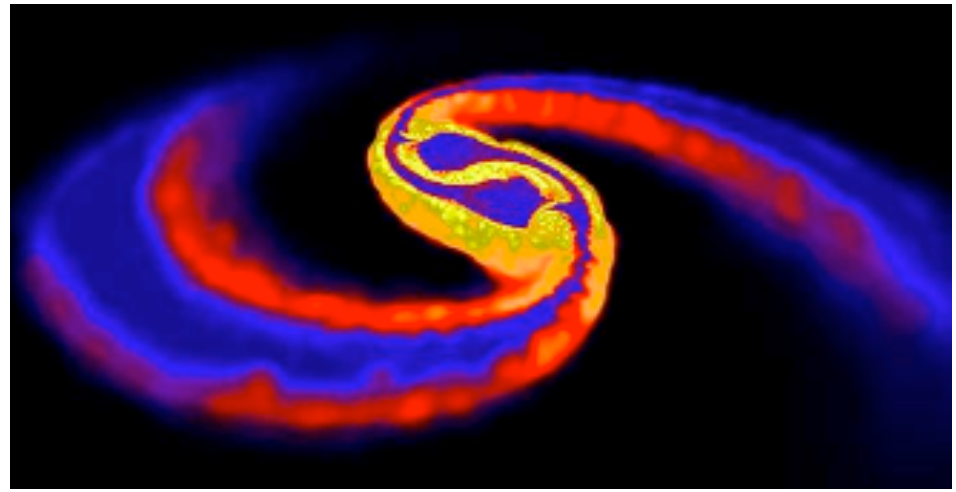
Compact Binary Mergers, Nuclear EOS, and LIGO

- GWs and LIGO
- Compact binary mergers
- prospects for LIGO GW detection and EM counterparts
- Neutron stars
- Nuclear EOS
- Neutron star mass & radius
- BNS mergers
- BNS r-process nucleosynthesis
- BNS merger constrains on NEOS

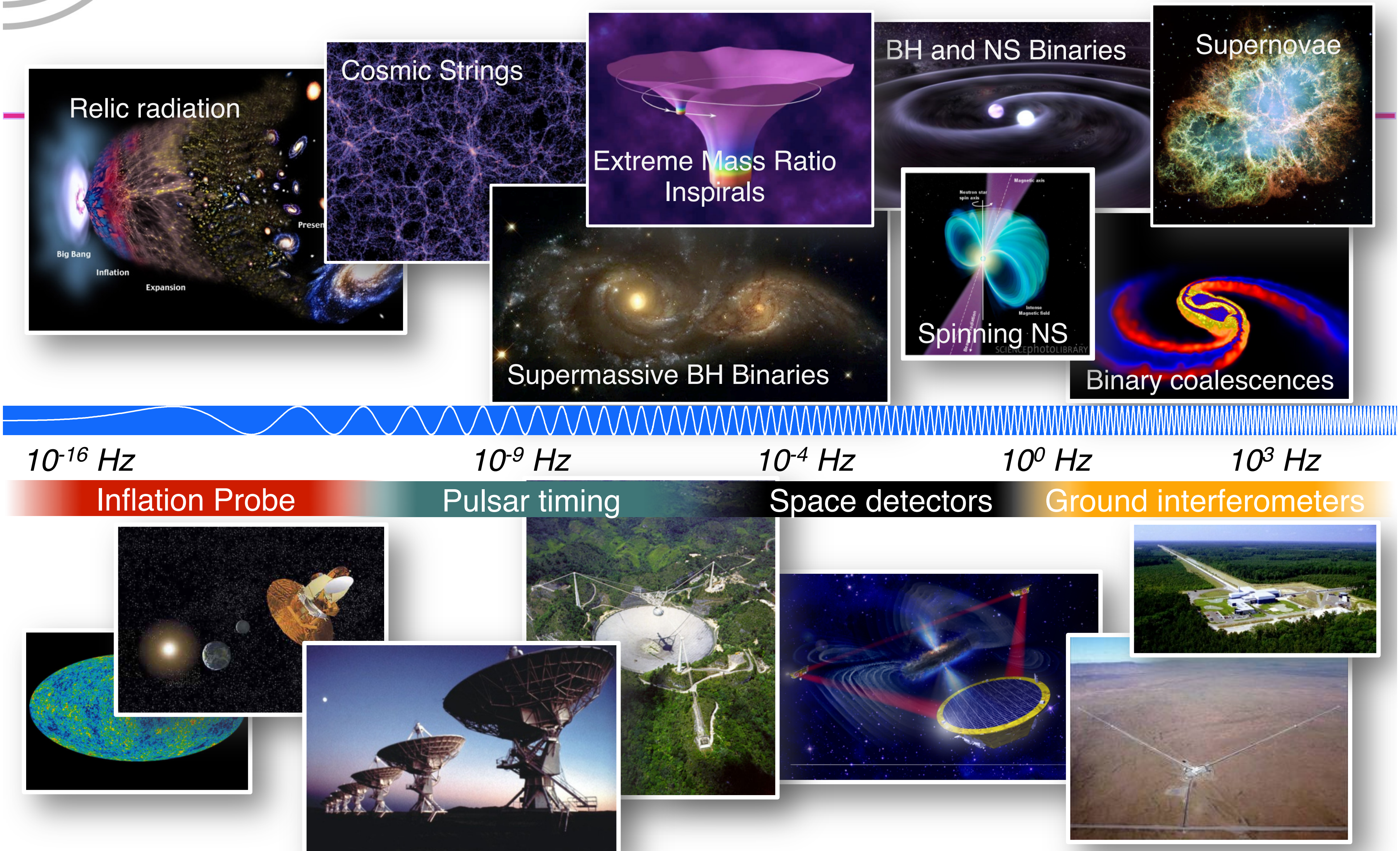


"Merging Neutron Stars" (Price & Rosswog)

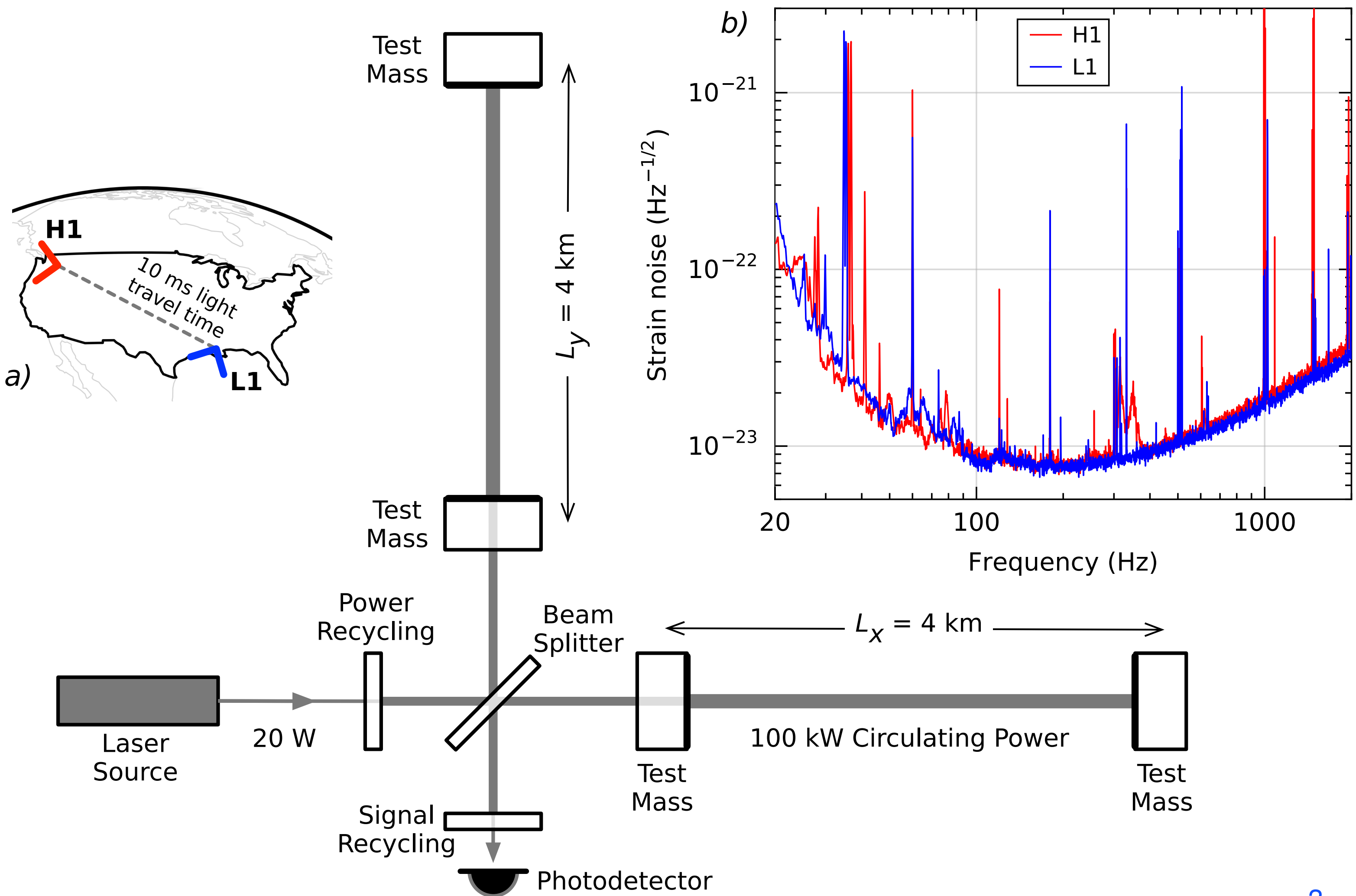
Alan Weinstein, Caltech
for the LIGO Scientific Collaboration

DOE/NSF NSAC Meeting,
Bethesda, March 23, 2016
LIGO-G1600723

The GW Spectrum



The Advanced LIGO detectors



https://dcc.ligo.org/LIGO-P1500237/public/main

LIGO

LSC

LIGO Scientific Collaboration

TRINITY UNIVERSITY

University of Maryland

Andrews University

Washington State University

California State University Fullerton

The University of Alabama in Huntsville

Sonoma State University

indigo

Montclair State University

University of Glasgow

Australian National University

Whitman College

American University Washington, DC

University of the West of Scotland UWS

Texas Tech University

Tsinghua University

R·I·T

Max Planck Institute for Gravitational Physics Albert Einstein Institute

University of Strathclyde

Michigan

Massachusetts Institute of Technology

NASA Goddard Space Flight Center

ICTP SAIFR

The University of Western Australia

PAH

ACU

CITA | ICAT

Università degli Studi del Sannio

University of Cambridge

The University of Chicago

Montana State University

The University of Mississippi

The University of Adelaide Australia

Southern University and Agricultural & Mechanical College

Columbia University in the City of New York

Caltech

University of Minnesota

University of Birmingham

The University of Melbourne

GEO 600

UIB Universitat de les Illes Balears

University of Washington

UTRGV

University of Wisconsin UW Milwaukee

Syracuse University

Cardiff University Prifysgol Caerdydd

Northwestern

Universität Hamburg

Monash University

INPE

UF University of Florida

Georgia Institute of Technology

Korean Gravitational-Wave Group

LSU Louisiana State University

ACIGA

University of Southampton

Charles Sturt University

Embry-Riddle Aeronautical University

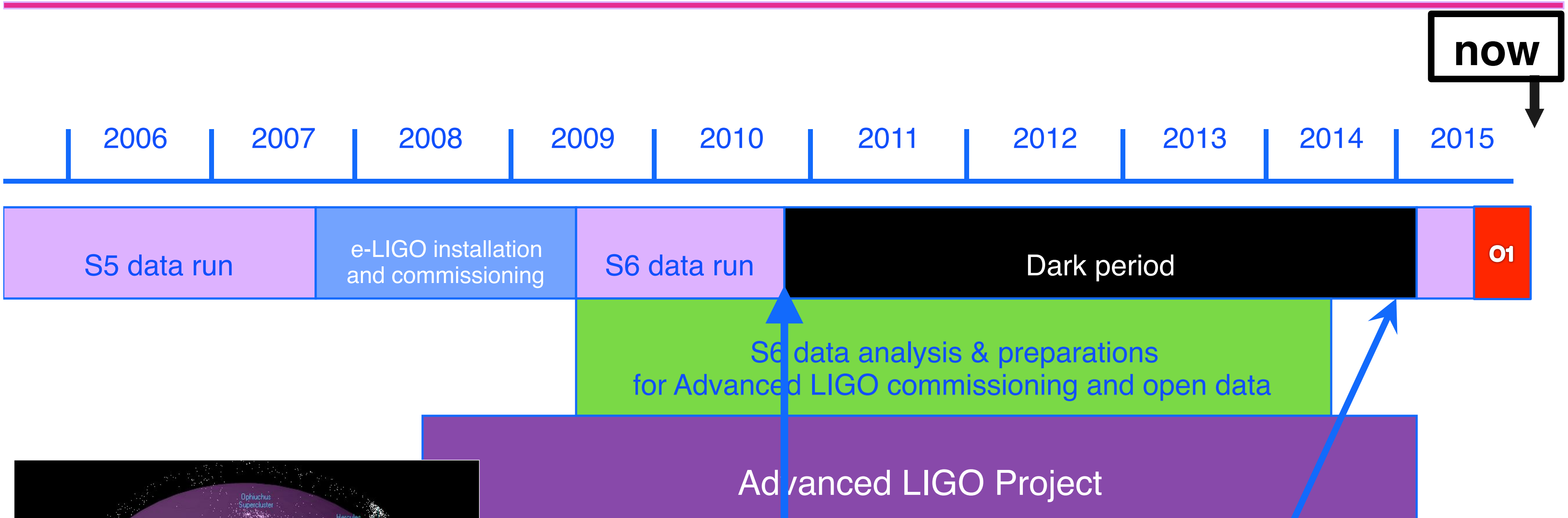
Leibniz Universität Hannover

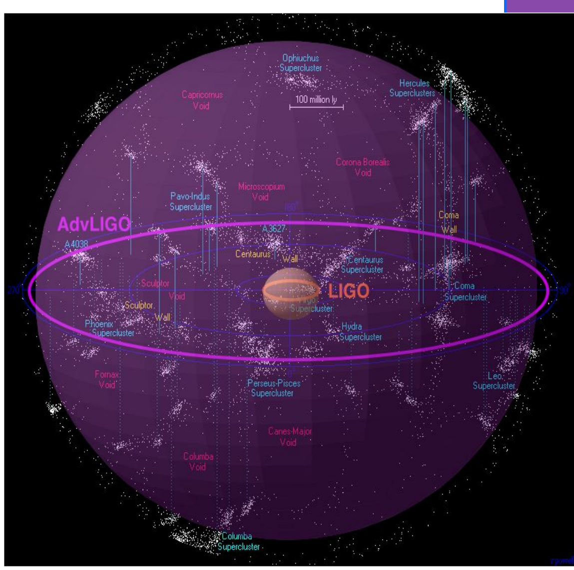
PennState

Hobart and William Smith Colleges

Science & Technology Facilities Council Rutherford Appleton Laboratory

iLIGO → eLIGO → aLIGO



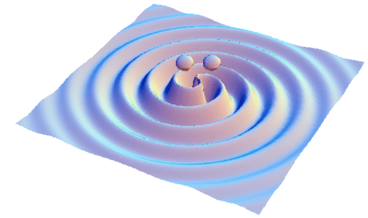


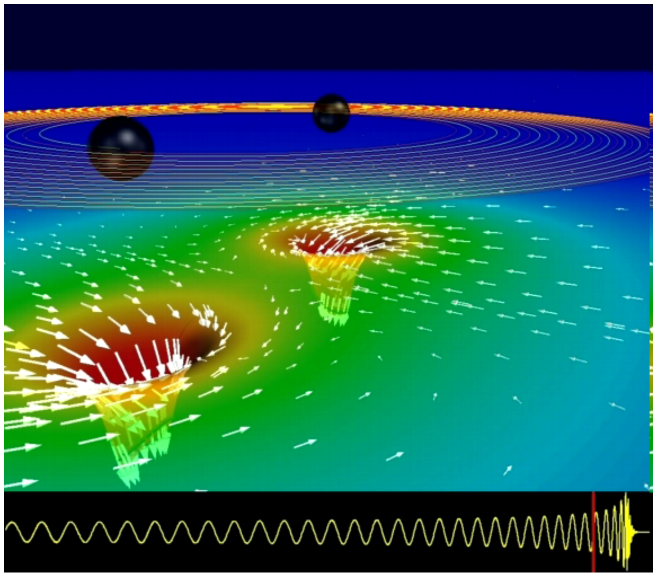
Improve amplitude sensitivity by a factor of 10x, and…

⇒ Number of sources goes up 1000x!

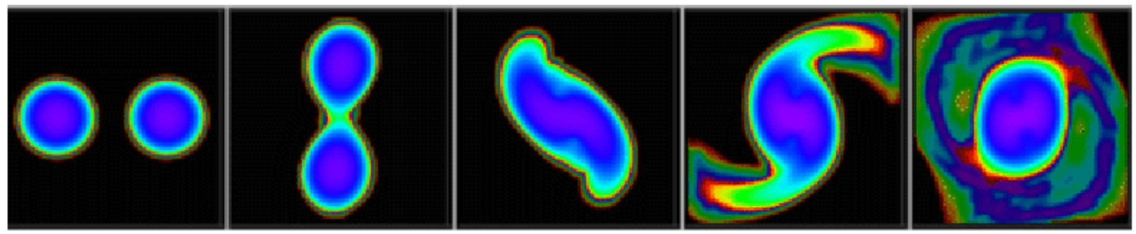
LIGO

GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)





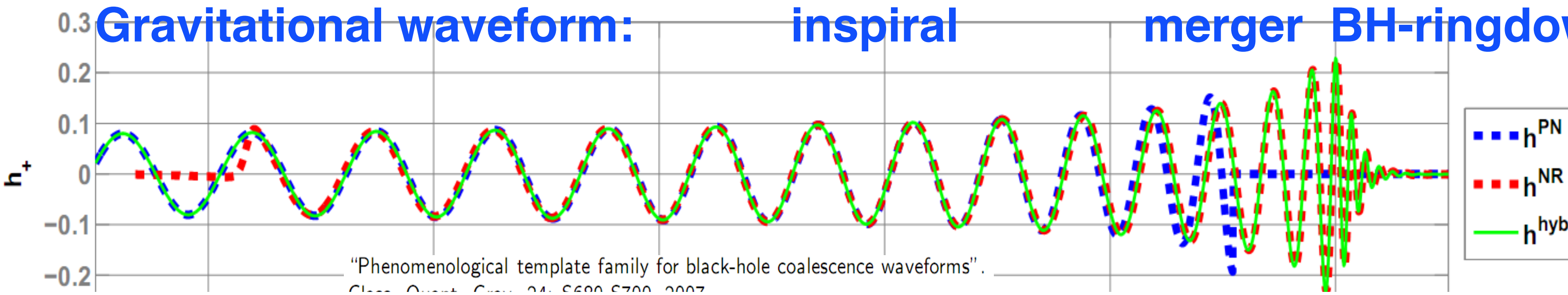
- Neutron star – neutron star (Centrella et al.)



Tidal disruption of neutron star

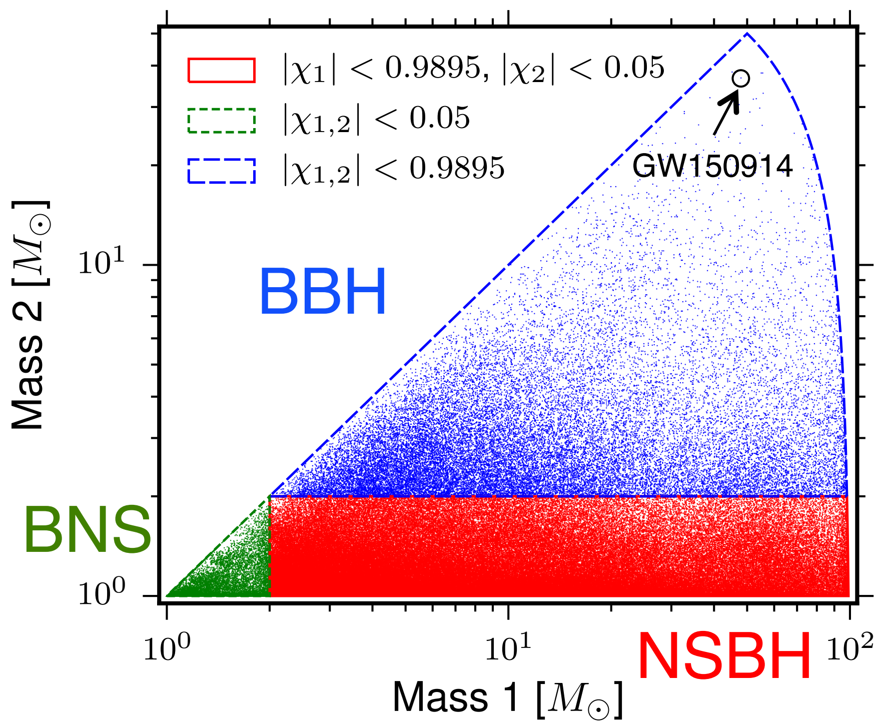
A unique and powerful laboratory to study strong-field, highly dynamical gravity and the structure of nuclear matter in the most extreme conditions

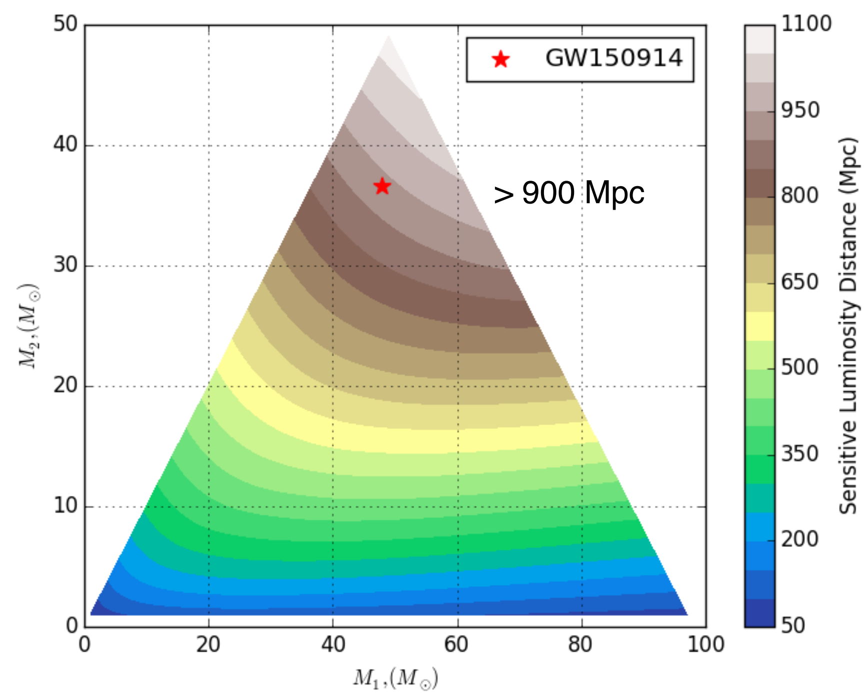
Gravitational waveform: inspiral merger BH-ringdown



Waveform carries lots of information about binary masses, orbit, merger

Template-based searches





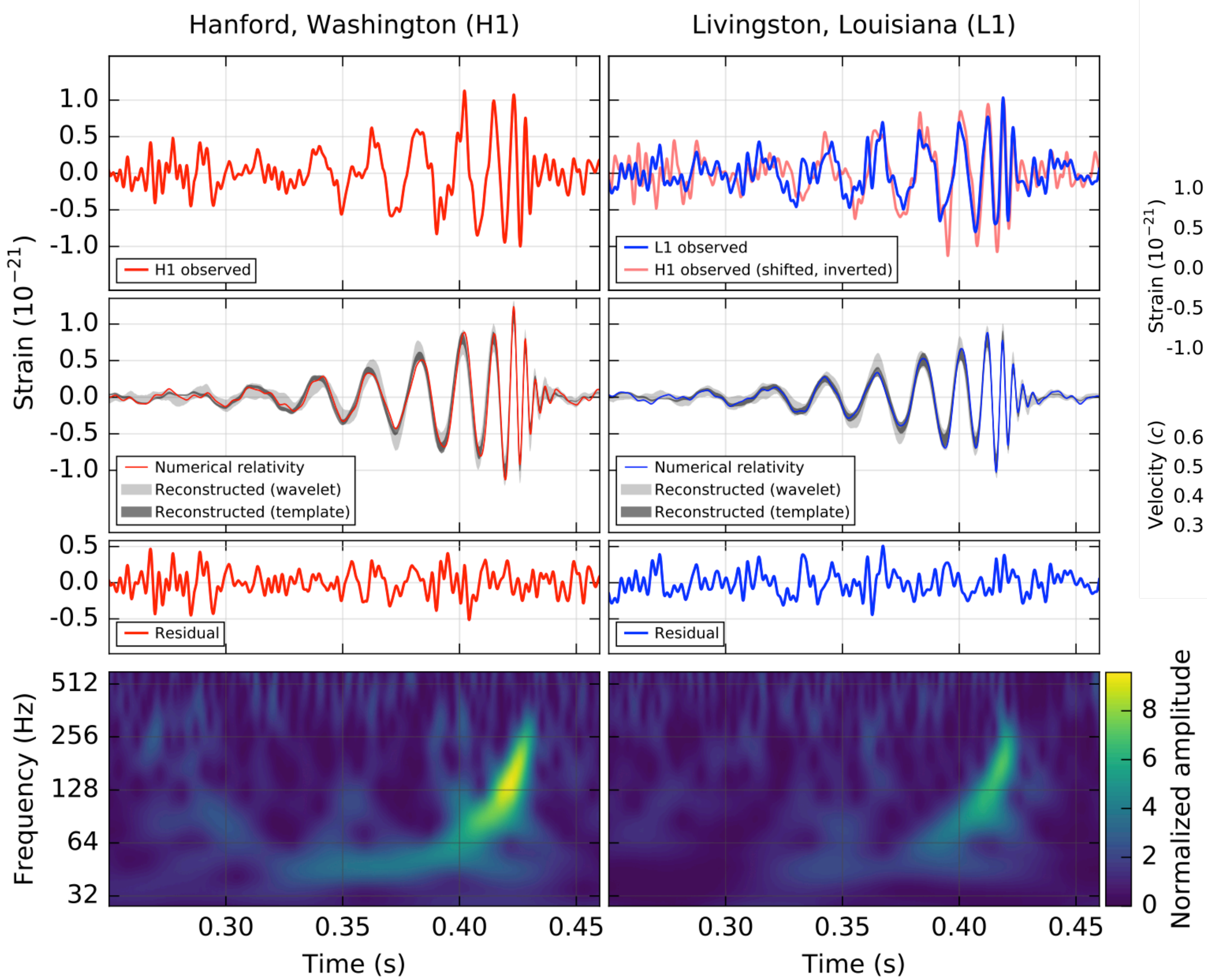
Masses and (aligned) spins
Templates spaced for < 3%
loss of SNR: 250K templates.

Sensitive distance in Mpc

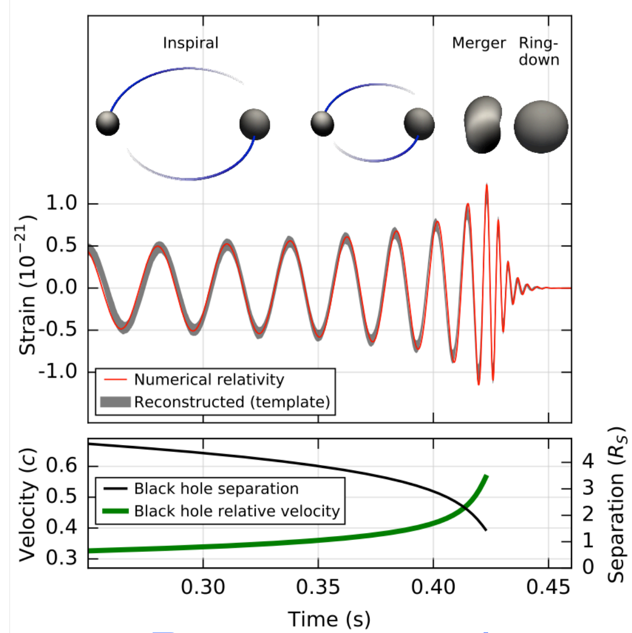
https://dcc.ligo.org/LIGO-P1500269/public/main

GW150914

Phys. Rev. Lett. 116, 061102 – Published 11 February 2016
https://dcc.ligo.org/LIGO-P150914/public/main



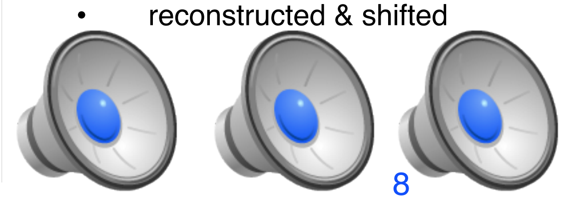
Whitened and band-passed [40-300] Hz



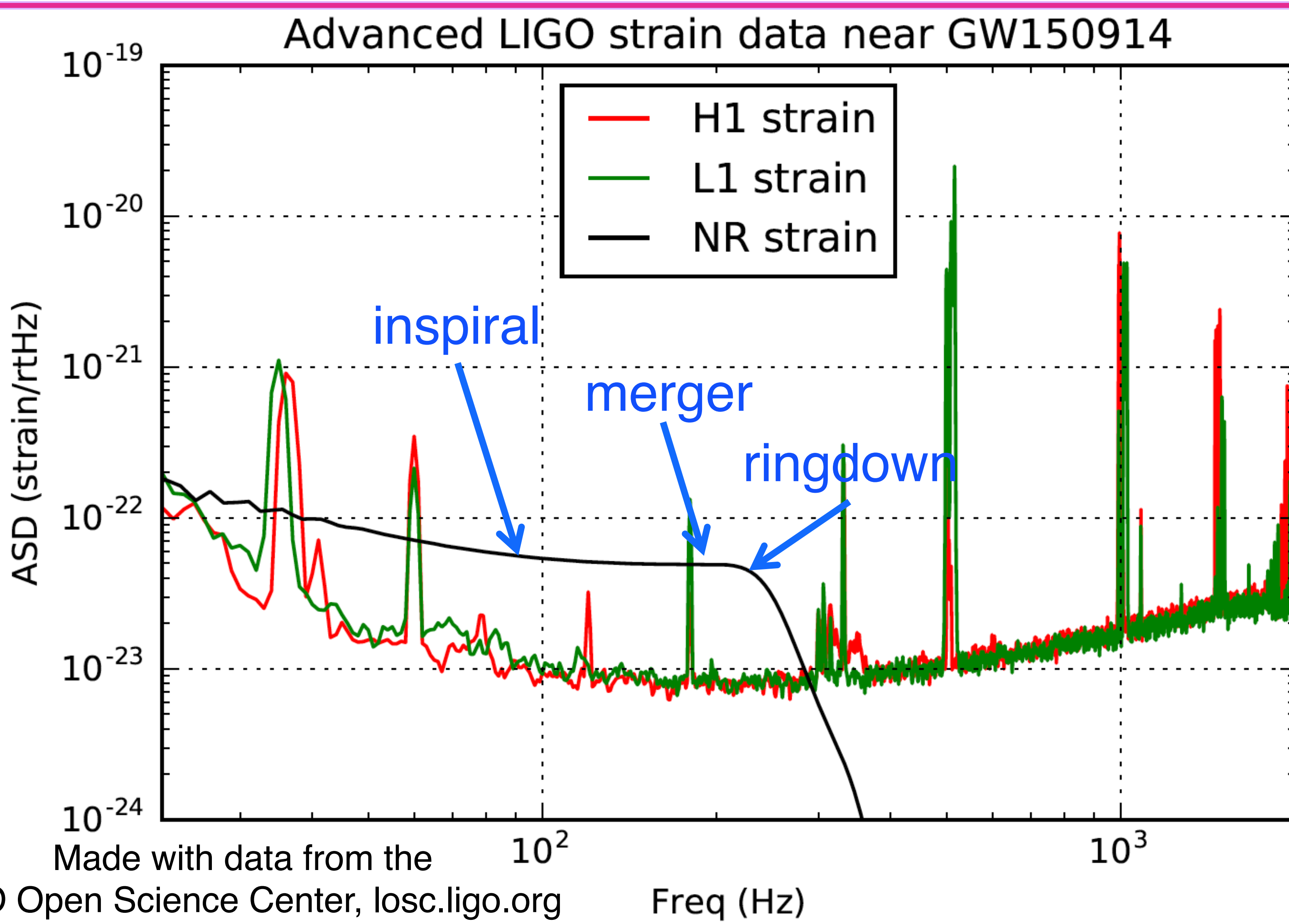
Reconstructed (no whitening)

Audio:

- filtered data
- freq-shifted data
- reconstructed & shifted



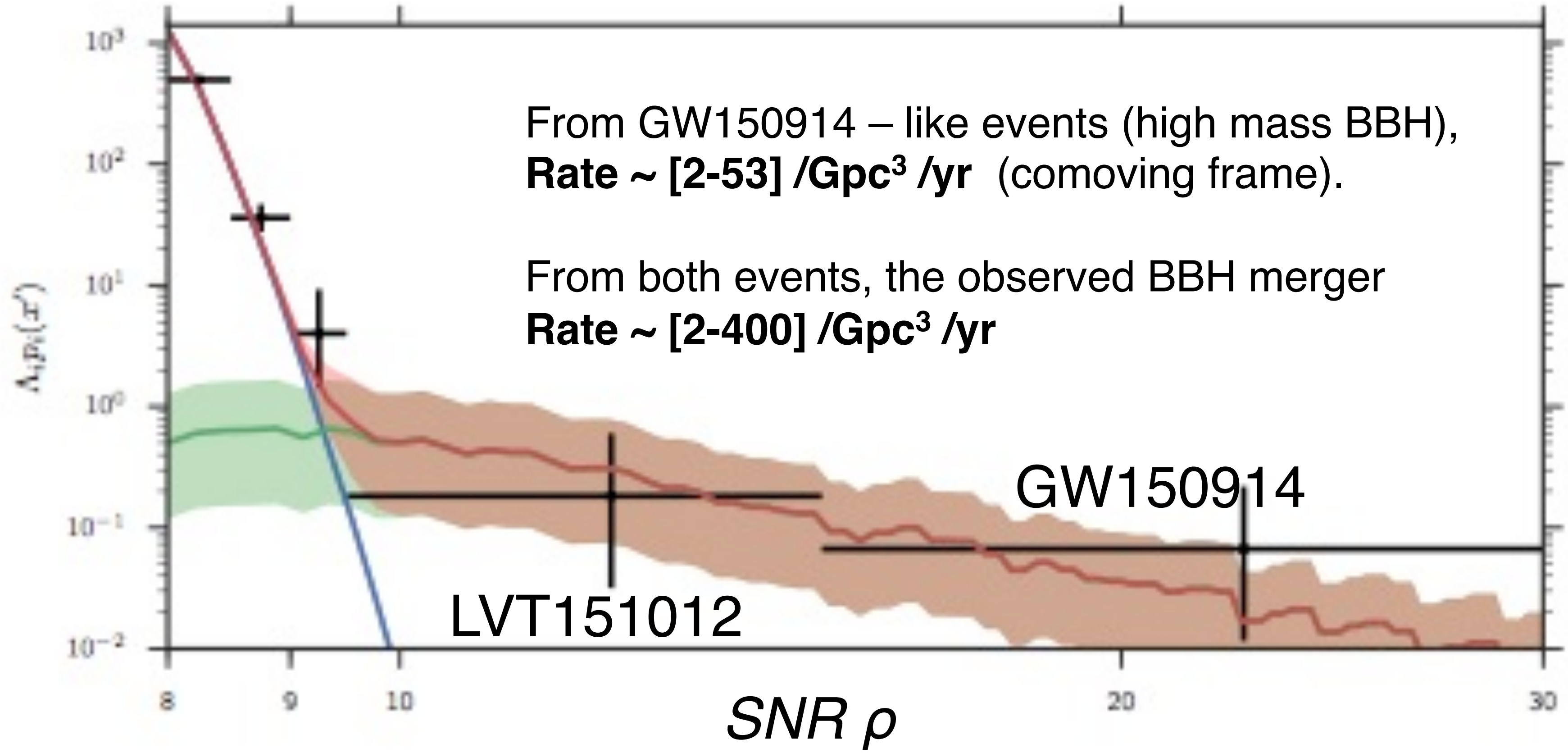
GW150914 in the frequency domain



Made with data from the LIGO Open Science Center, losc.ligo.org

Observed BBH merger rate

https://dcc.ligo.org/LIGO-P1500217/public/main

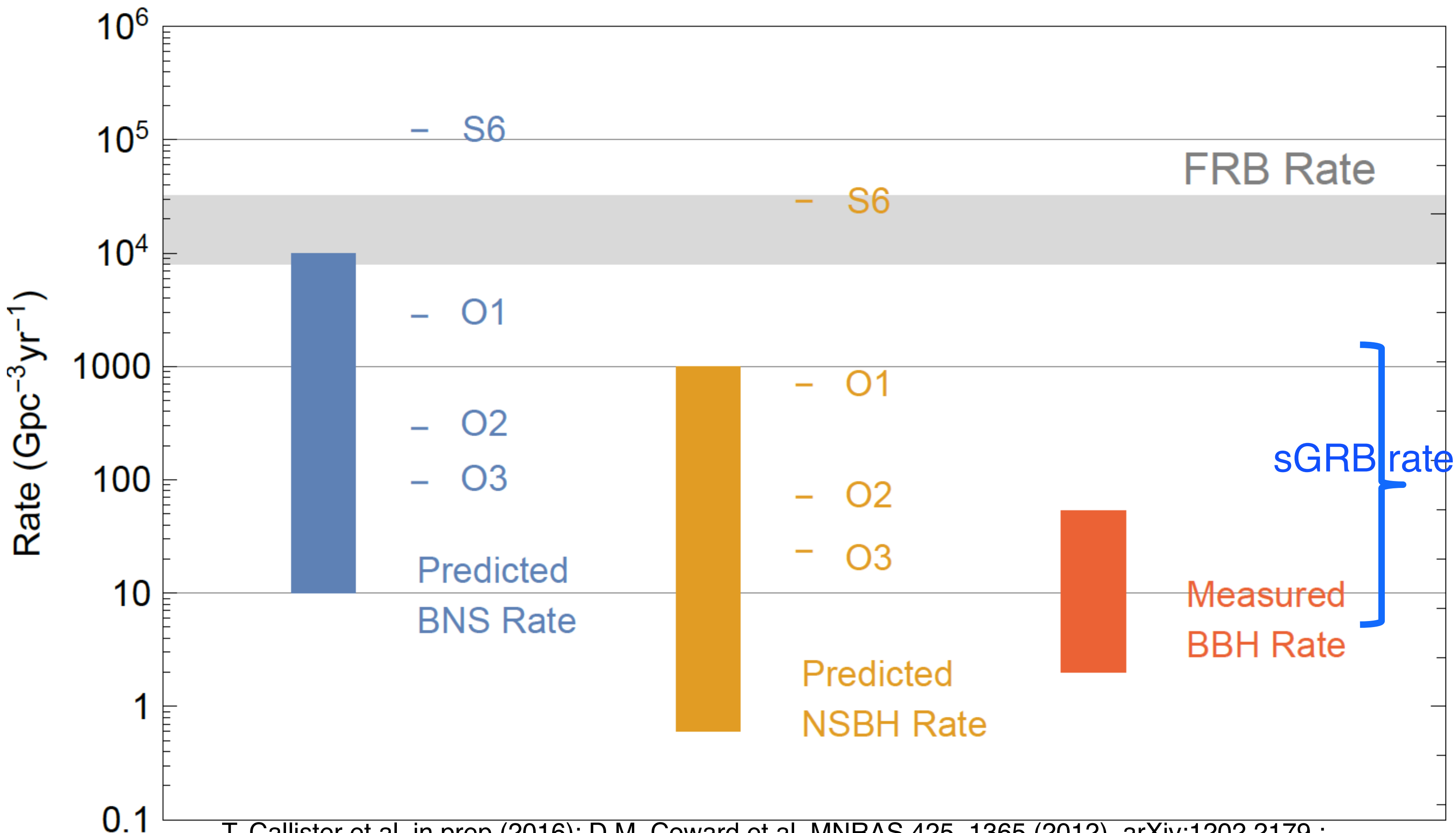


Same ballpark as population synthesis models, CCSN rate, etc

iLIGO+eLIGO BBH rate upper limit: ~< 420 Gpc^{-3} yr^{-1}

Aasi, J. et al. 2013, Phys. Rev. D, 87, 022002, arXiv:1209.6533

Expected (and measured!) compact binary merger rates

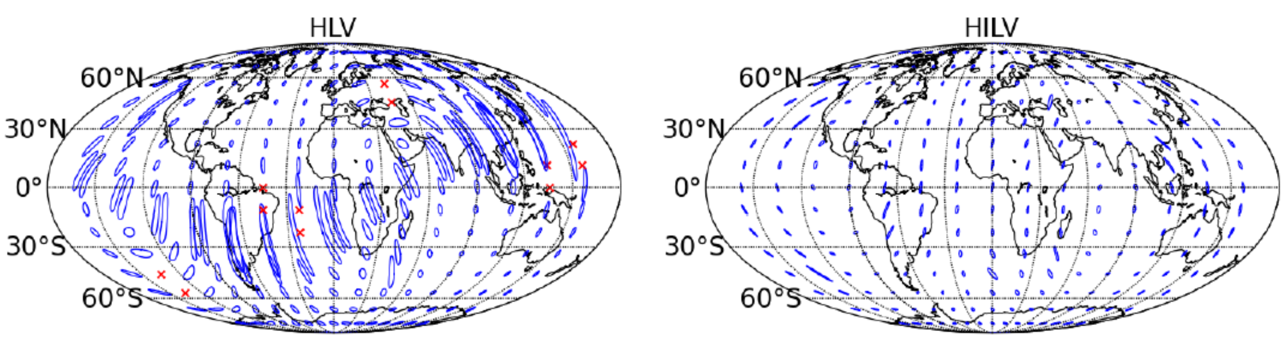


T. Callister et al, in prep (2016); D.M. Coward et al, MNRAS 425, 1365 (2012), arXiv:1202.2179 ; B. Abbott et al, Living Rev. Relativity, 19, 1 (2016) arXiv:1304.0670.

Expected ranges of binary neutron star merger rates and detections

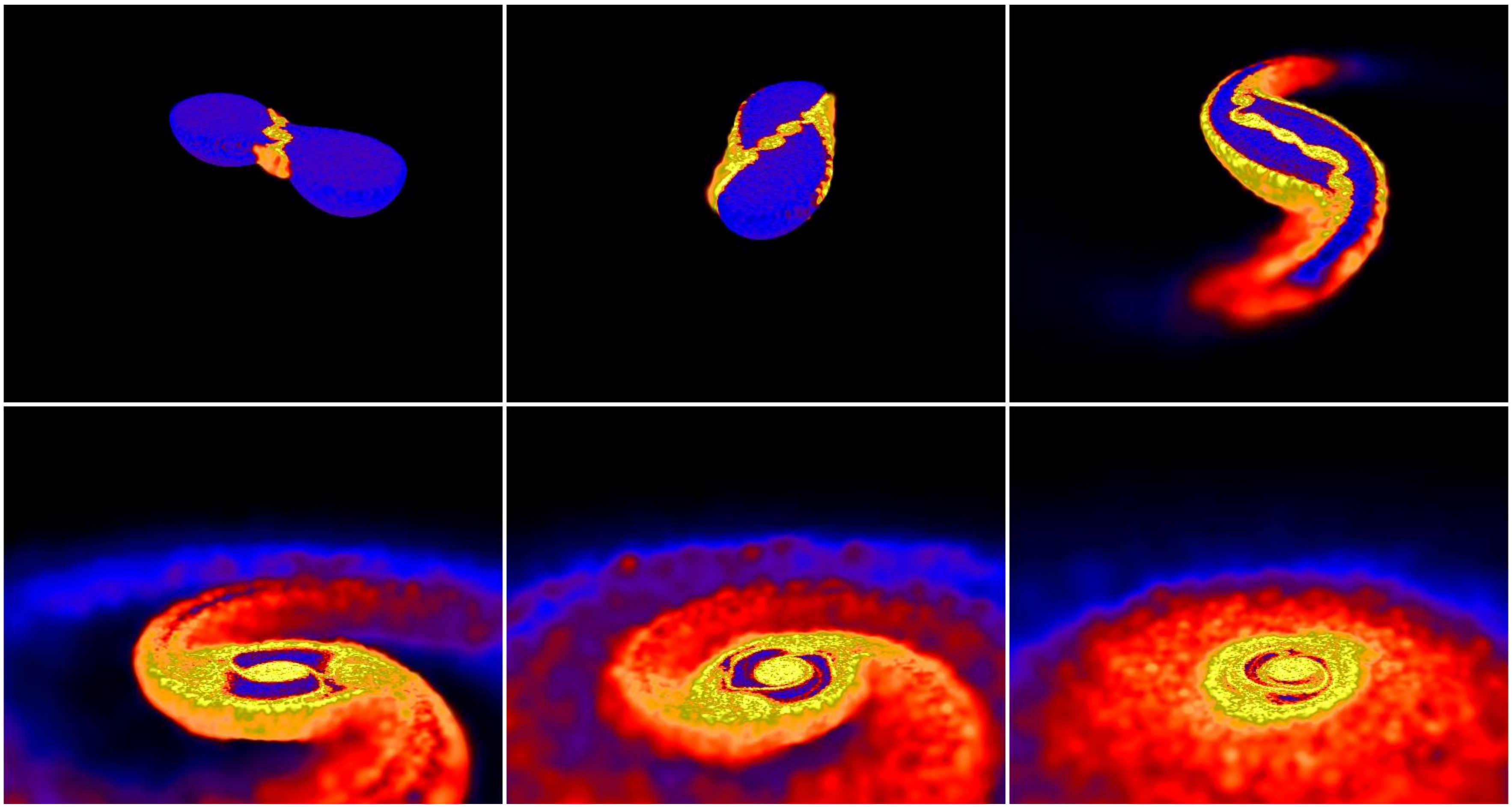
- **"It's tough to make predictions, especially about the future"** (Yogi Berra)
- Estimated BNS rate: $[10^1 - 10^4]$ $Gpc^{-3}yr^{-1}$

Epoch	Estimated Run Duration	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections
2015	3 months	40 – 80	–	0.0004 – 3
2016–17	6 months	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	120 – 170	60 – 85	0.04 – 100
2019+	(per year)	200	65 – 130	0.2 – 200
2022+ (India)	(per year)	200	130	0.4 – 400



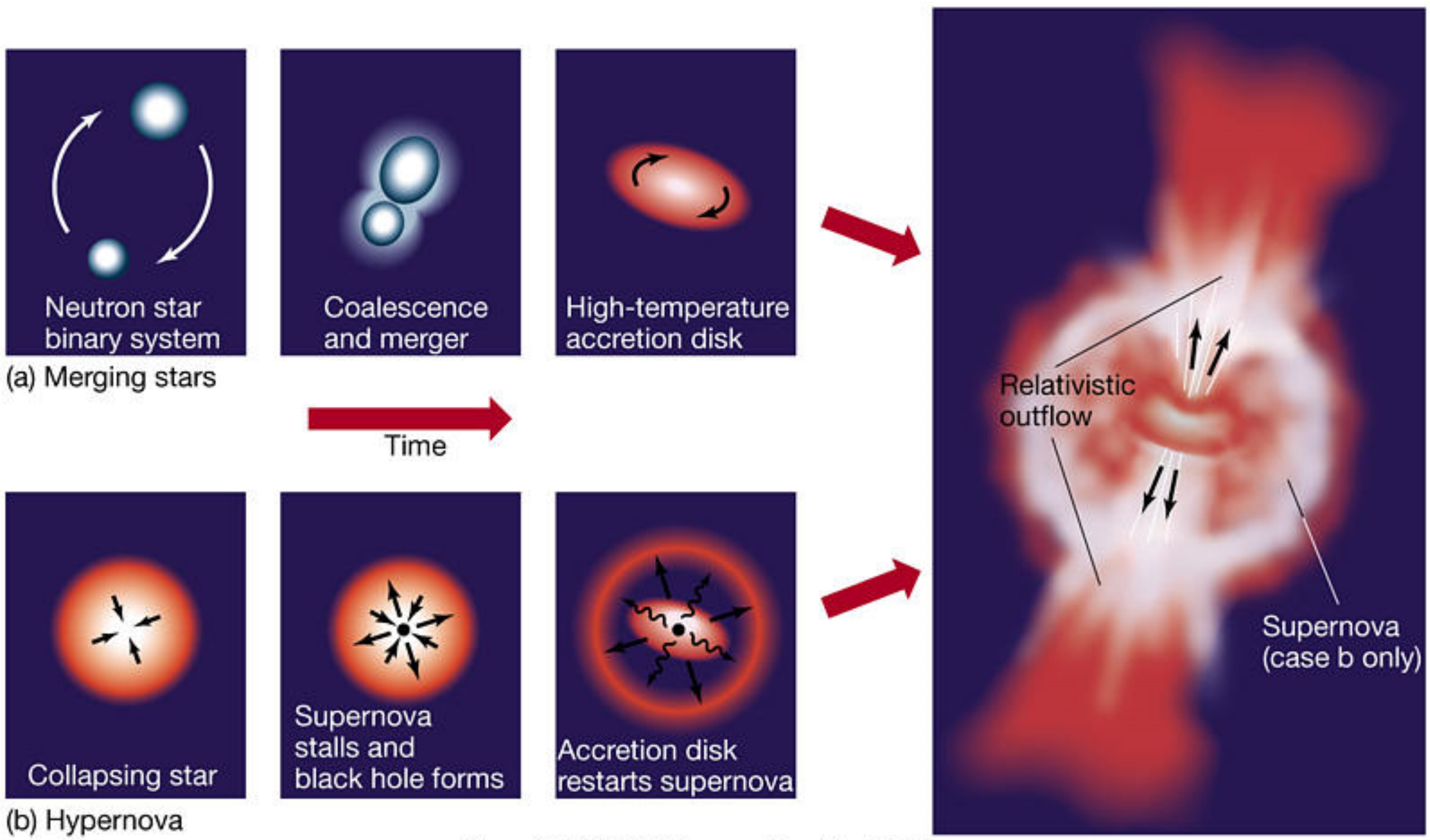
LIGO and Virgo Collaborations, "Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo" Living Rev. Relativity, 19, 1 (2016)

Binary neutron star mergers are a unique laboratory for nuclear (astro)-physics



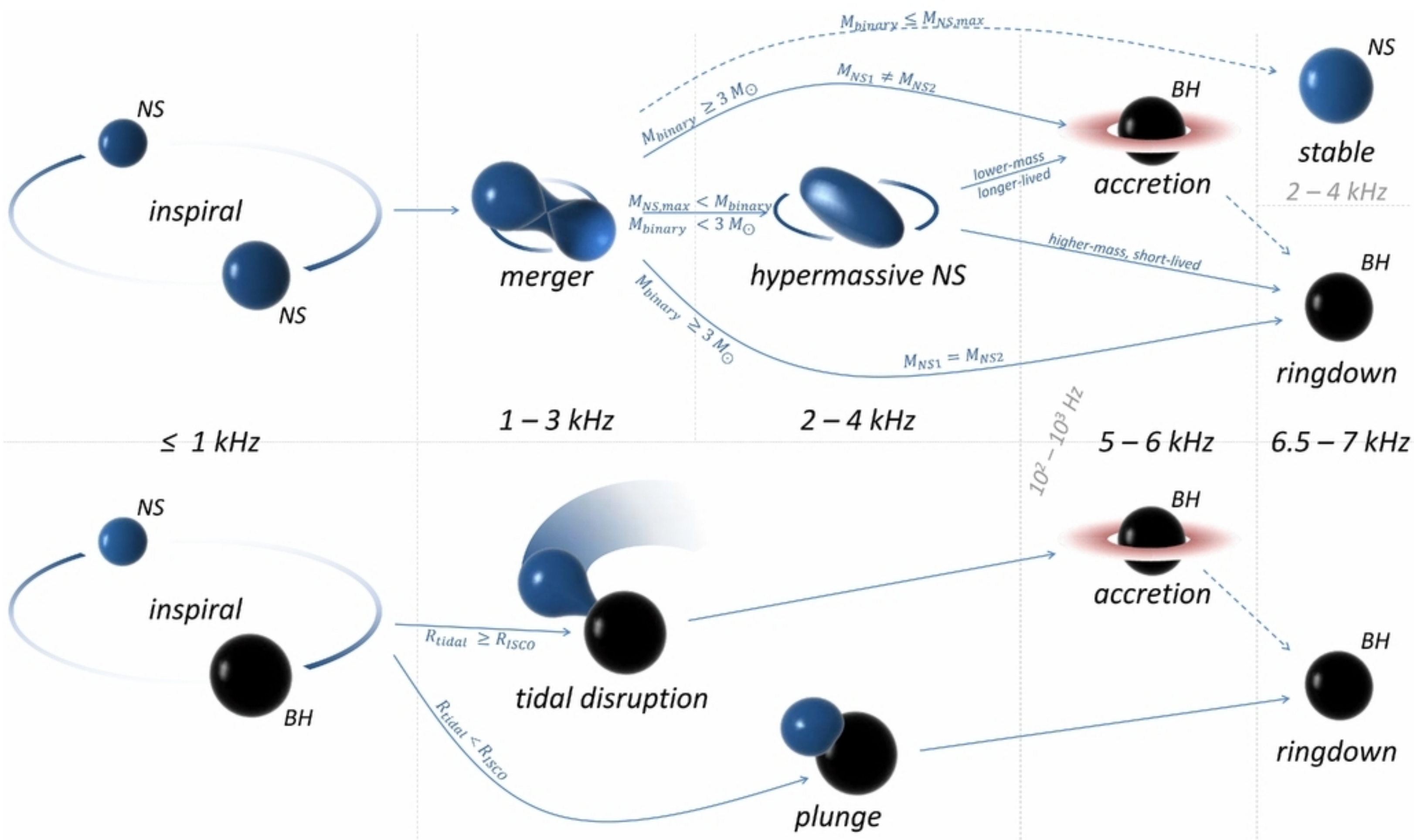
Daniel Price and Stephan Rosswog

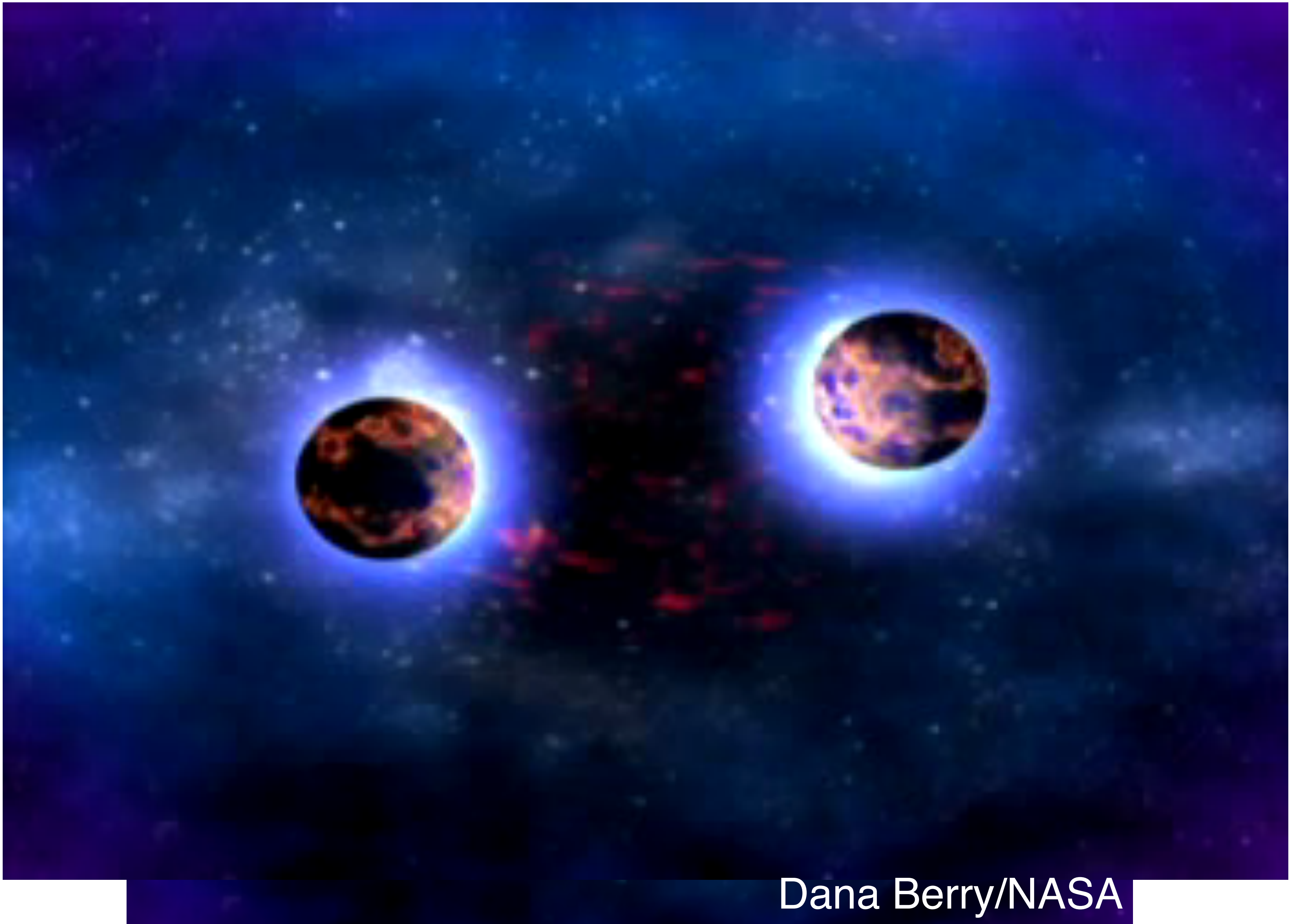
Short-hard and Long-soft GRBs



BNS and NSBH mergers

Figure 1 from I Bartos et al 2013 Class. Quantum Grav. 30 123001

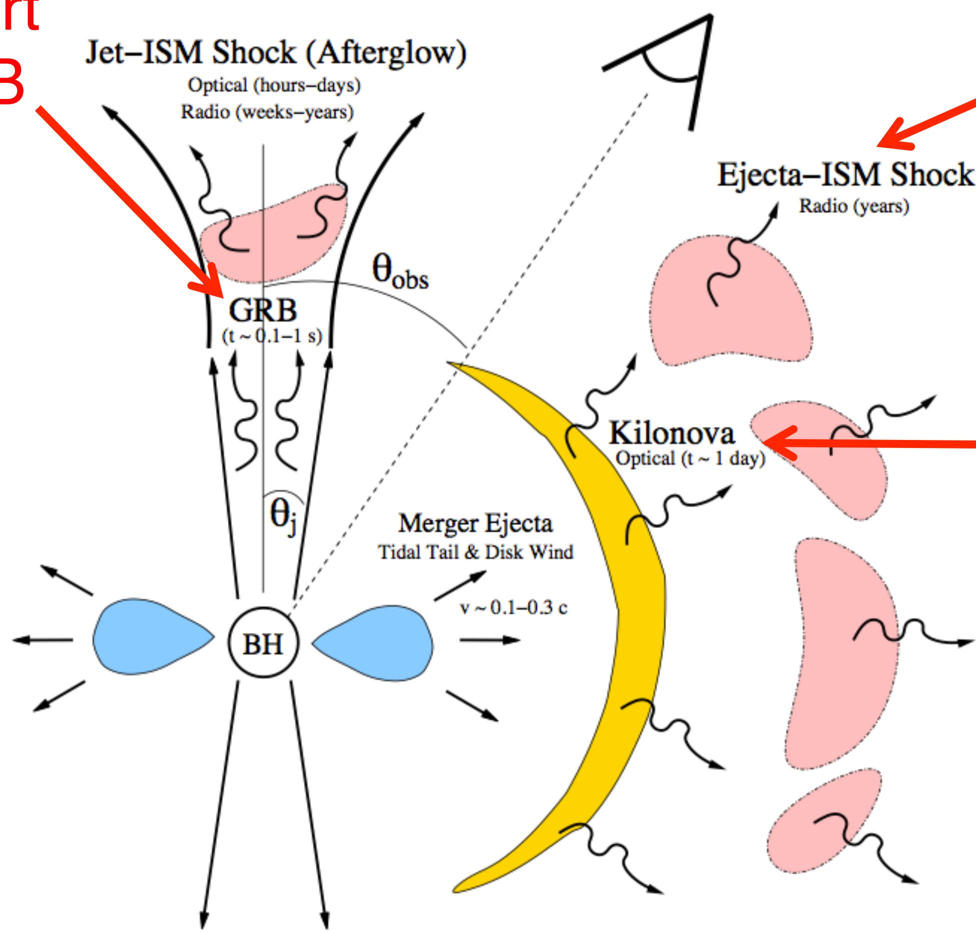




http://www.nasa.gov/mission_pages/swift/bursts/short_burst_nsu_multimedia.html

Electromagnetic radiation from sGRB progenitors

Short GRB



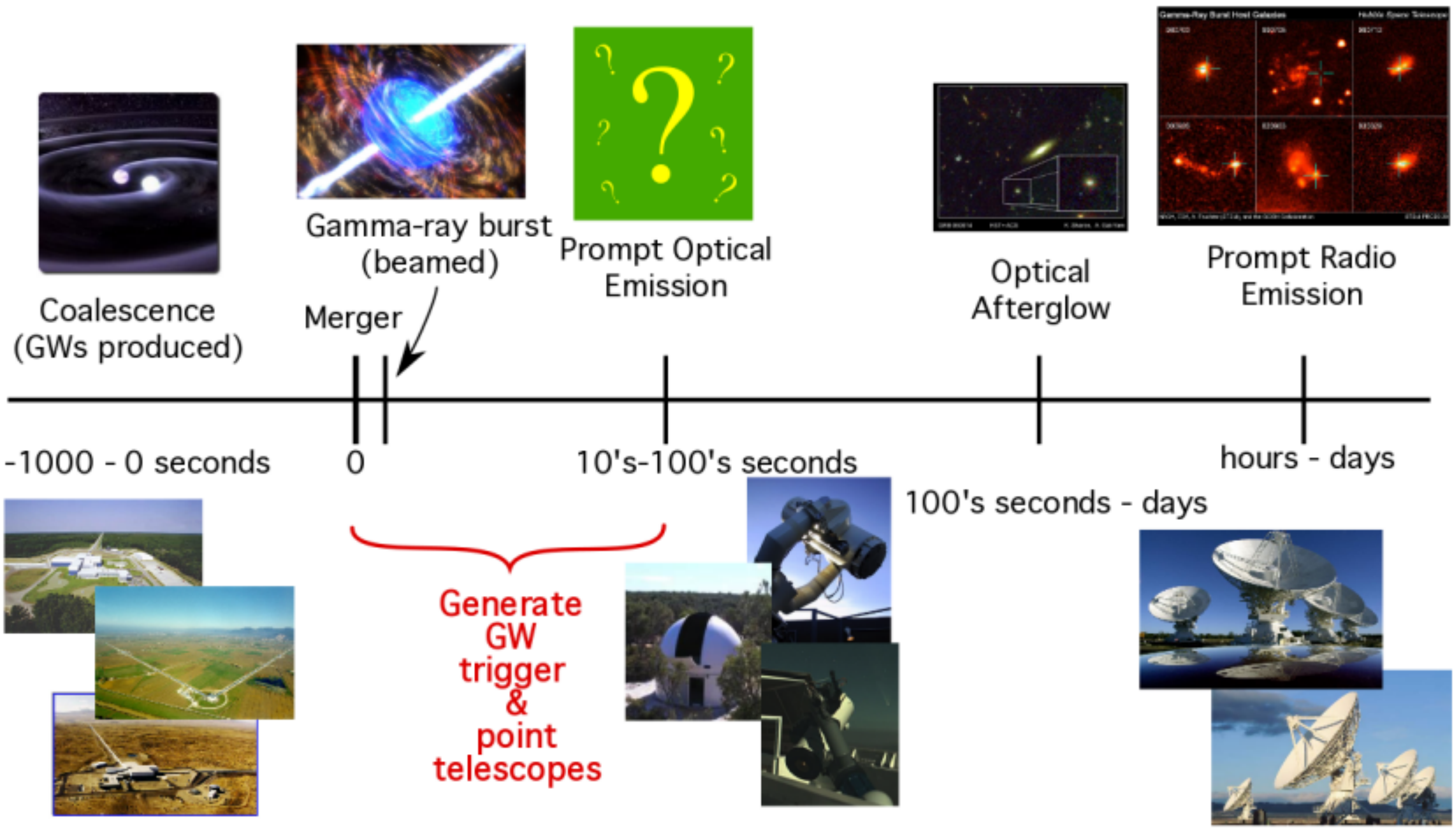
Ejecta-ISM shock radio emission from days to years

"kilonova"
Prompt optical emission from seconds to days

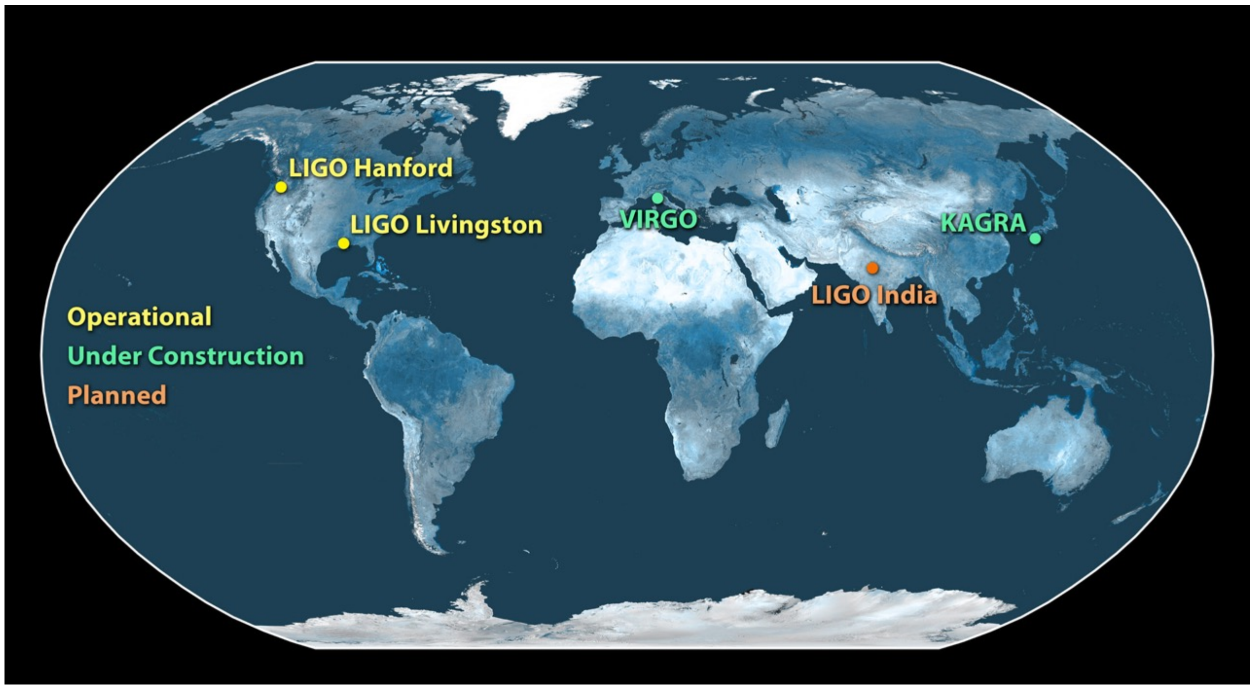
Metzger & Berger 2011

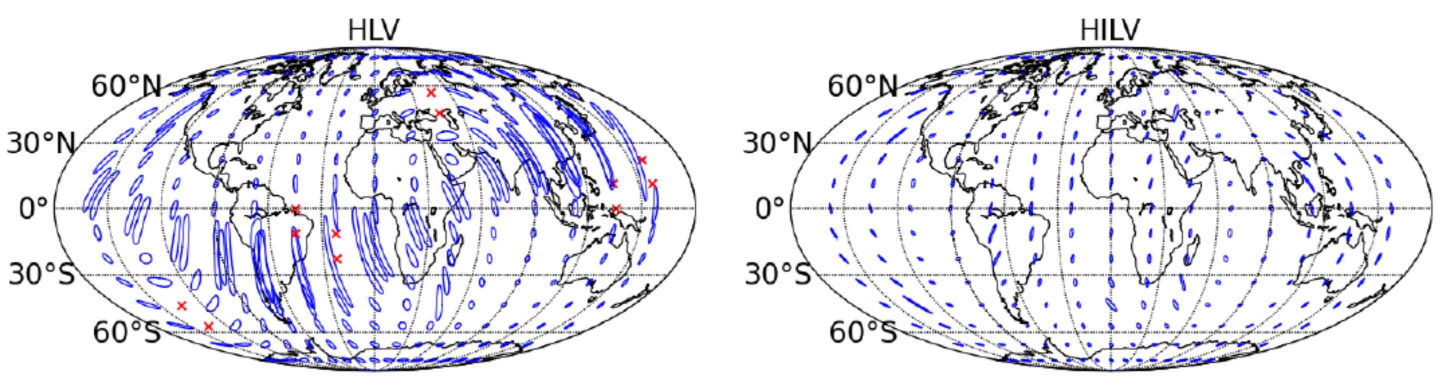
Low-latency identification of transients for rapid (< ~100s) followup

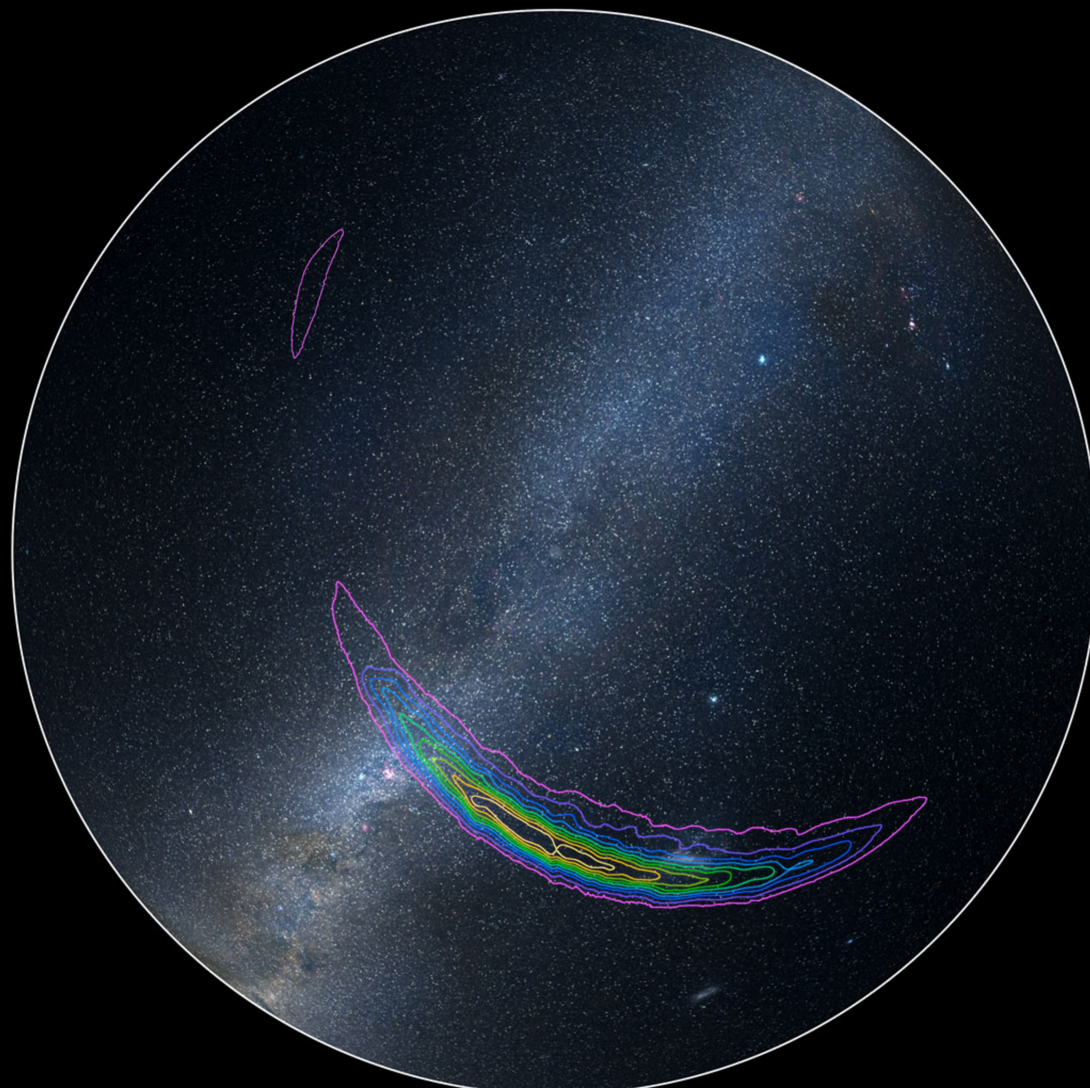
EM counterparts to GW sources (if any) are short-lived and faint



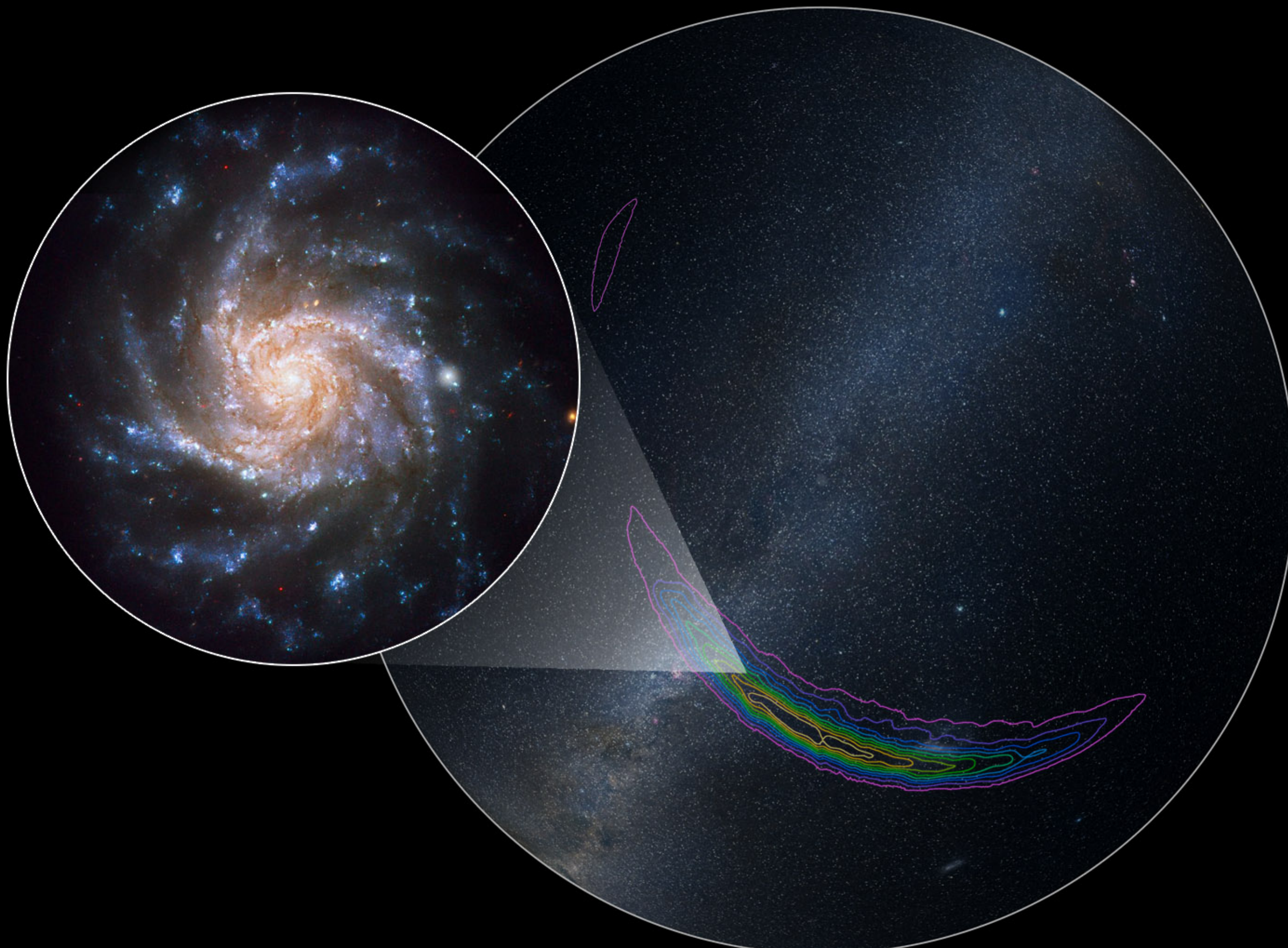
sky localization with the GW detector network



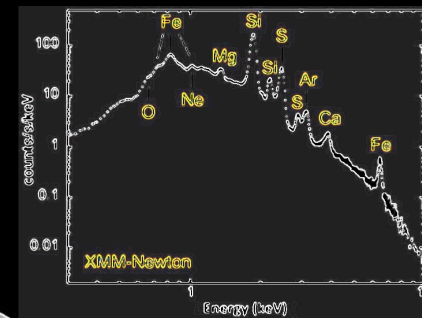


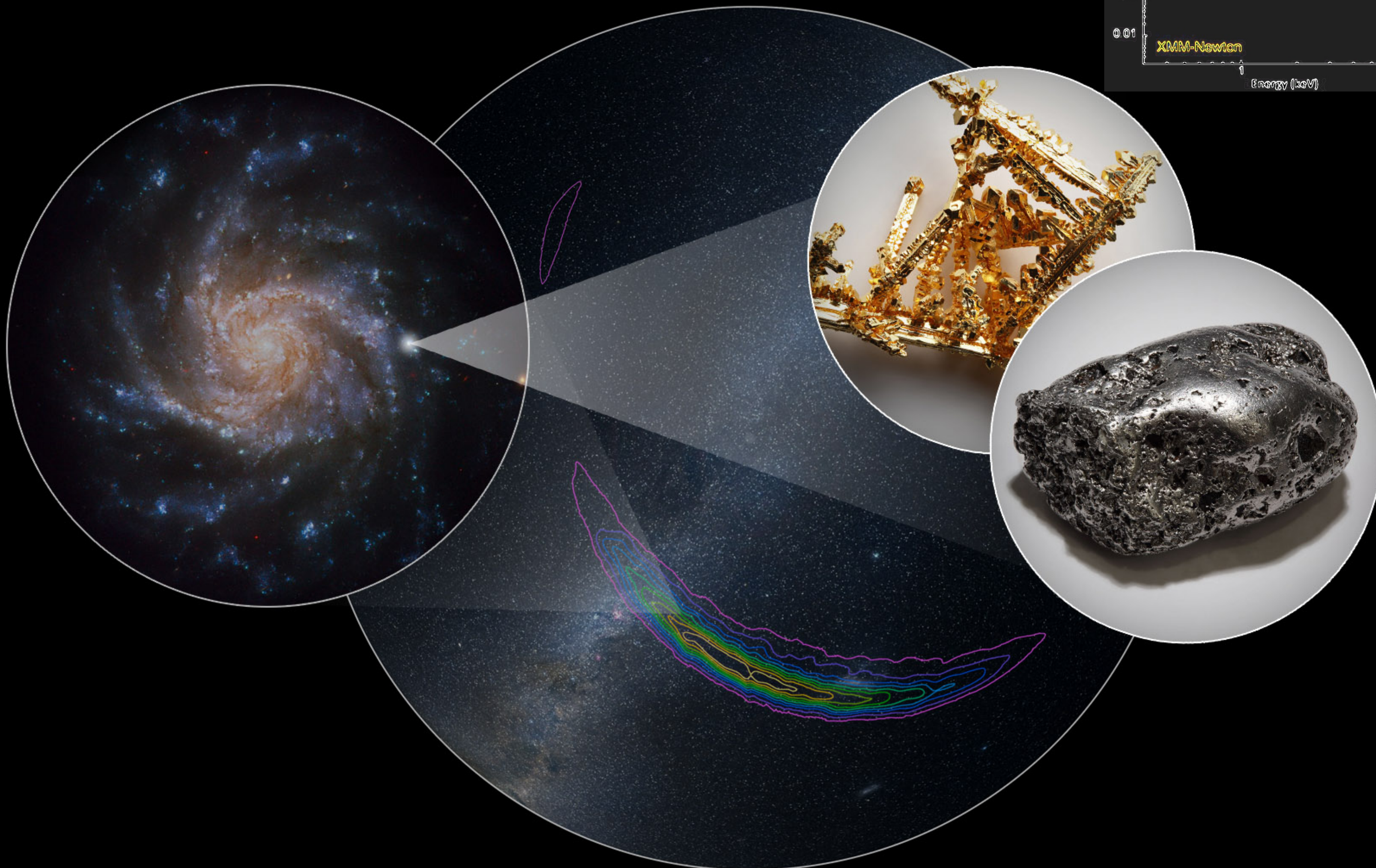


Kasliwal (2016)



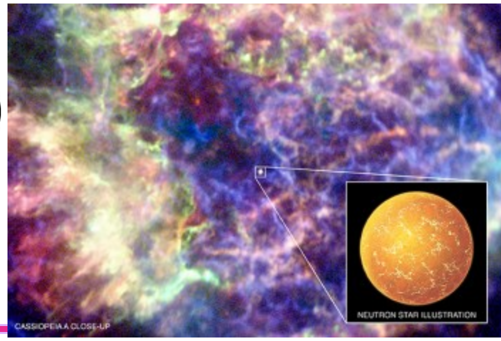
Kasliwal (2016)





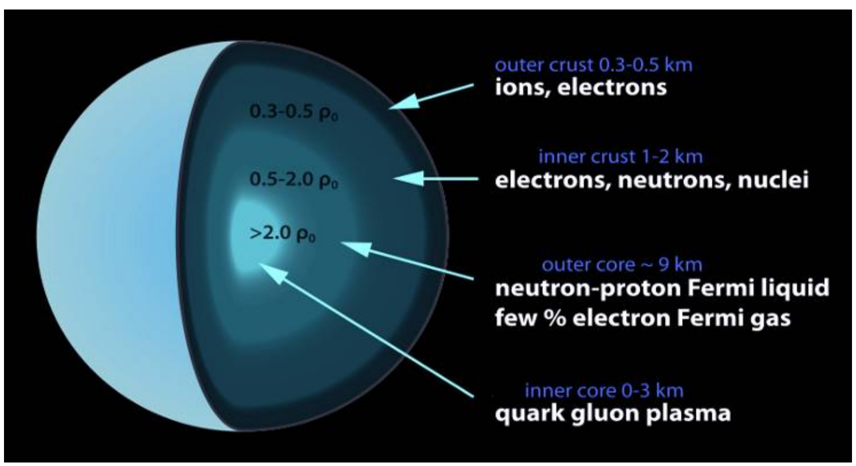
Kasliwal (2016)

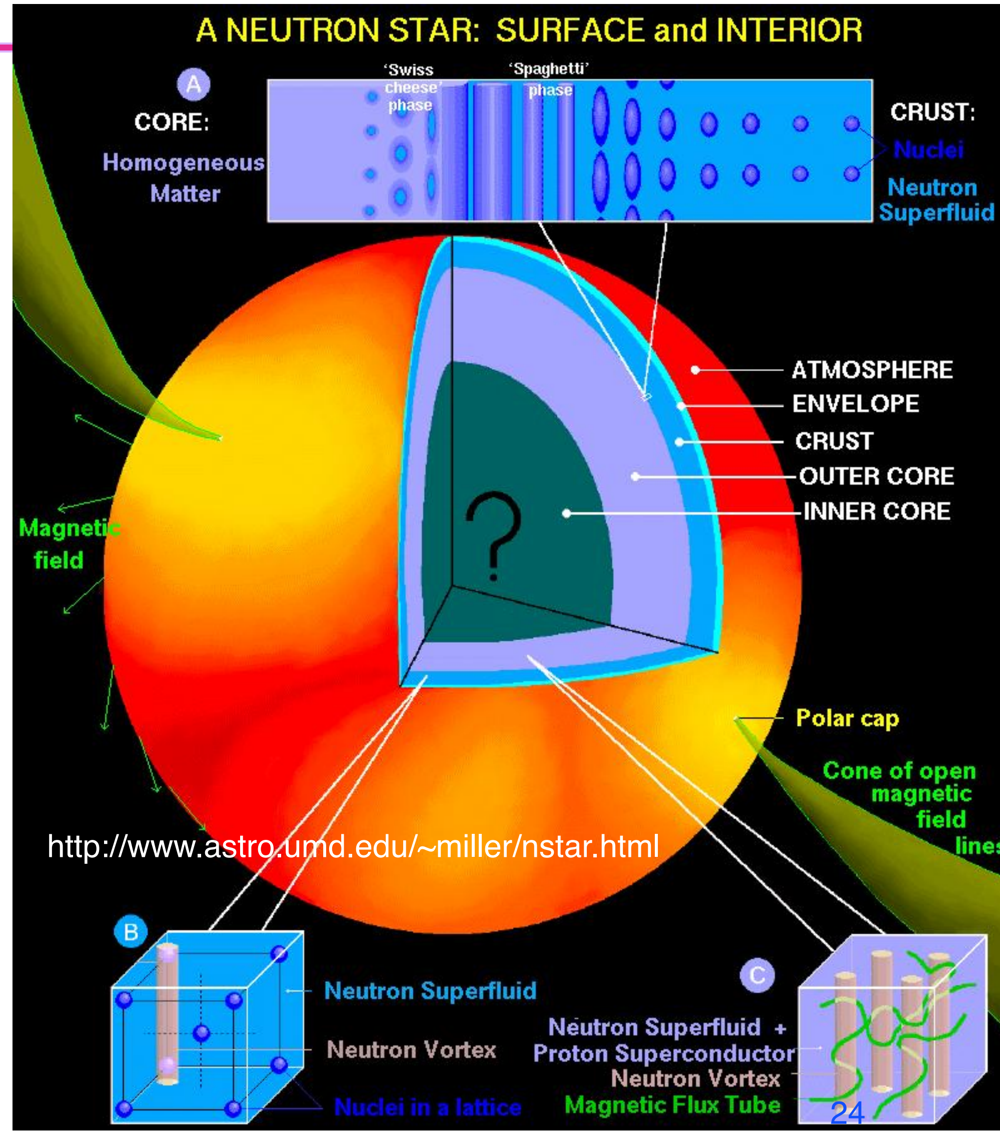

USA
USA
USA
UK
Italy
Japan
Taiwan
India
Israel
Sweden
Global Relay
of Observatories
Watching Transients Happen
Kasliwal (2016)



Neutron stars

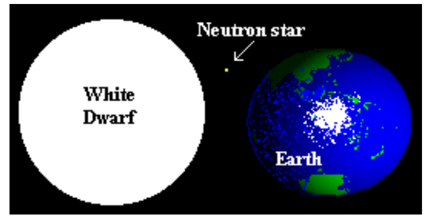
- Remnants of core collapse supernovae
- A unique laboratory for fundamental physics
- Strong, Weak, EM, gravity – all under the most extreme conditions
- Structure can be revealed through binary mergers

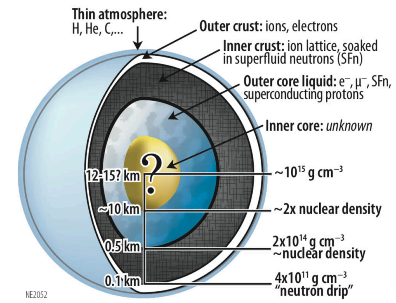


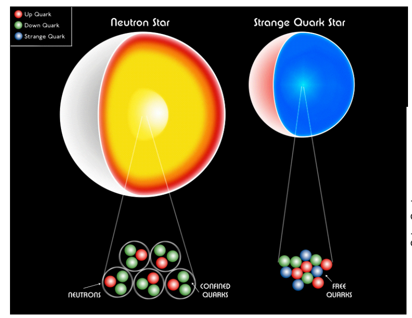


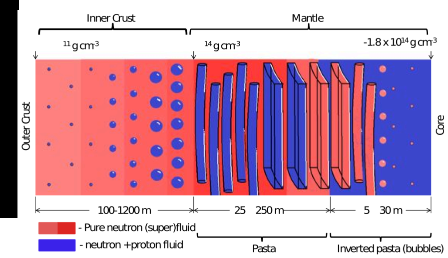
All four fundamental forces under the most extreme conditions

- Gravity: Compact stars have gravitational fields $GM/c^2R \sim O(1)$, strong tidal effects, strong curvature, highly relativistic
- Strong interaction at > 2x nuclear density in core
  - » Hard repulsive core of nucleon-nucleon interaction plays crucial role
  - » Potential transition to hyperonic matter, strange quark matter, QGP
  - » Complex ionic crystal lattice structure in crust: "nuclear pasta"
- Weak interaction under extreme conditions with neutrino trapping -> beta equilibrium
- EM: Superfluid core supporting extreme magnetic fields (perhaps > 10^{15} Gauss at surface), flux tube pinning in core

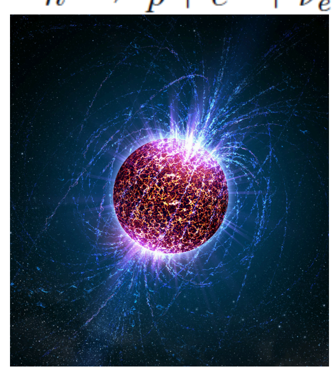


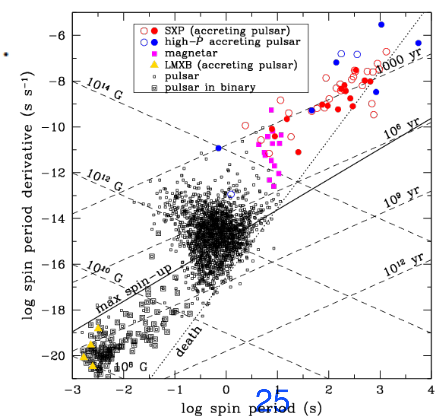






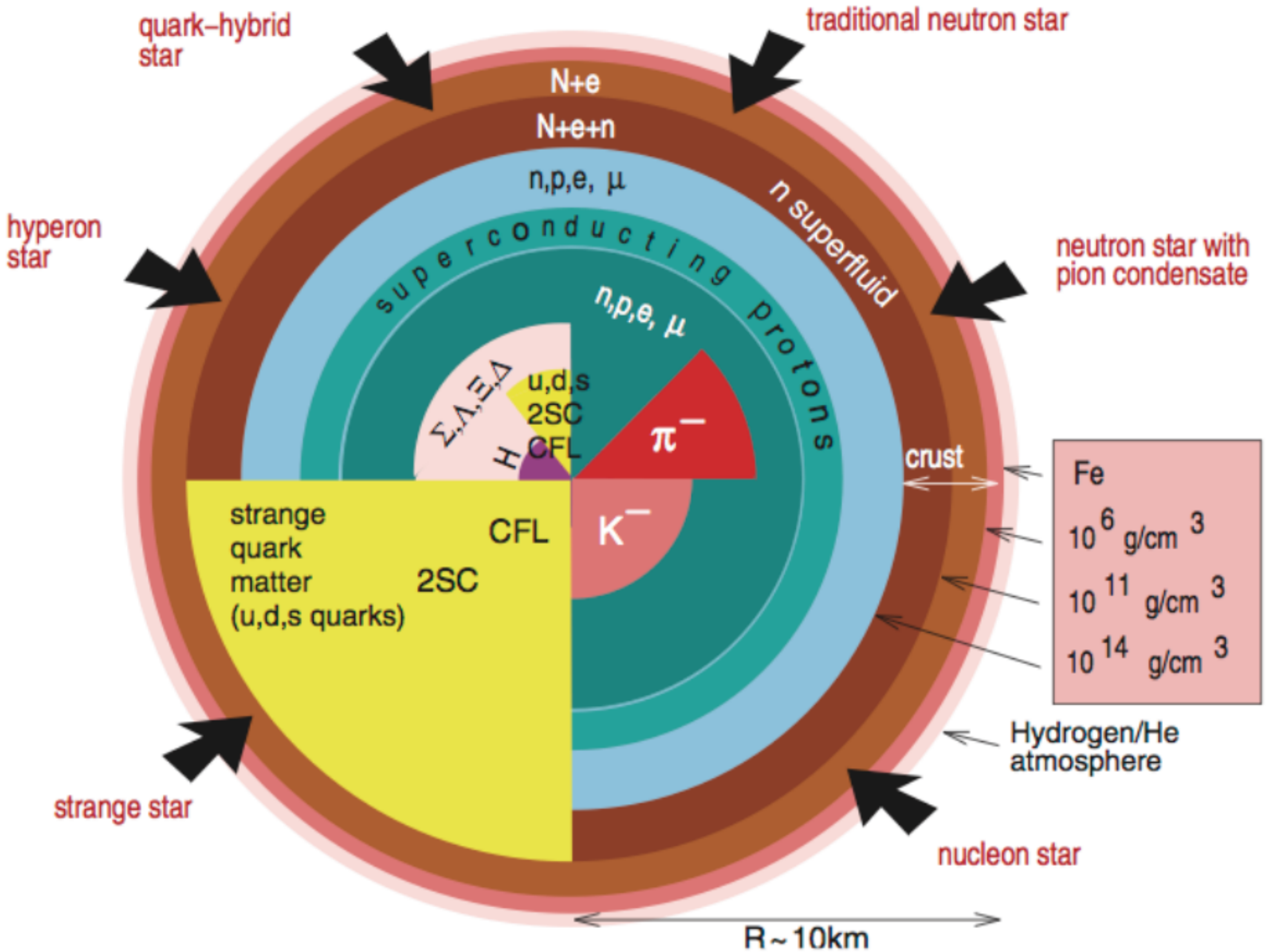
$$e^- + p \rightarrow n + \nu_e,$$
$$e^+ + n \rightarrow p + \bar{\nu}_e,$$
$$n \rightarrow p + e^- + \bar{\nu}_e.$$



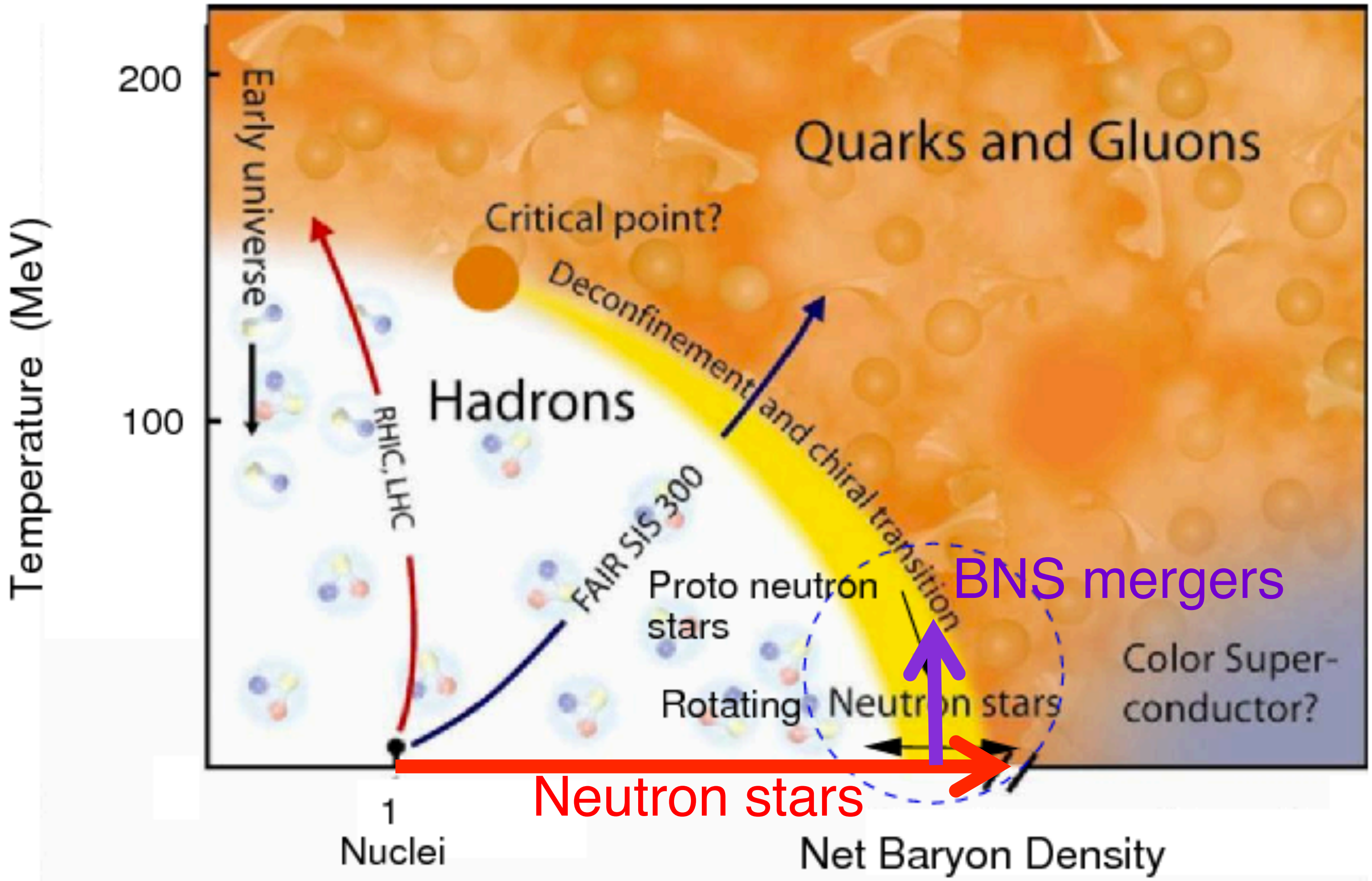


Neutron Star Equation of State

- Simplification: T=0, pure neutron & proton gas. Appropriate (?) for interior of cold neutron stars.

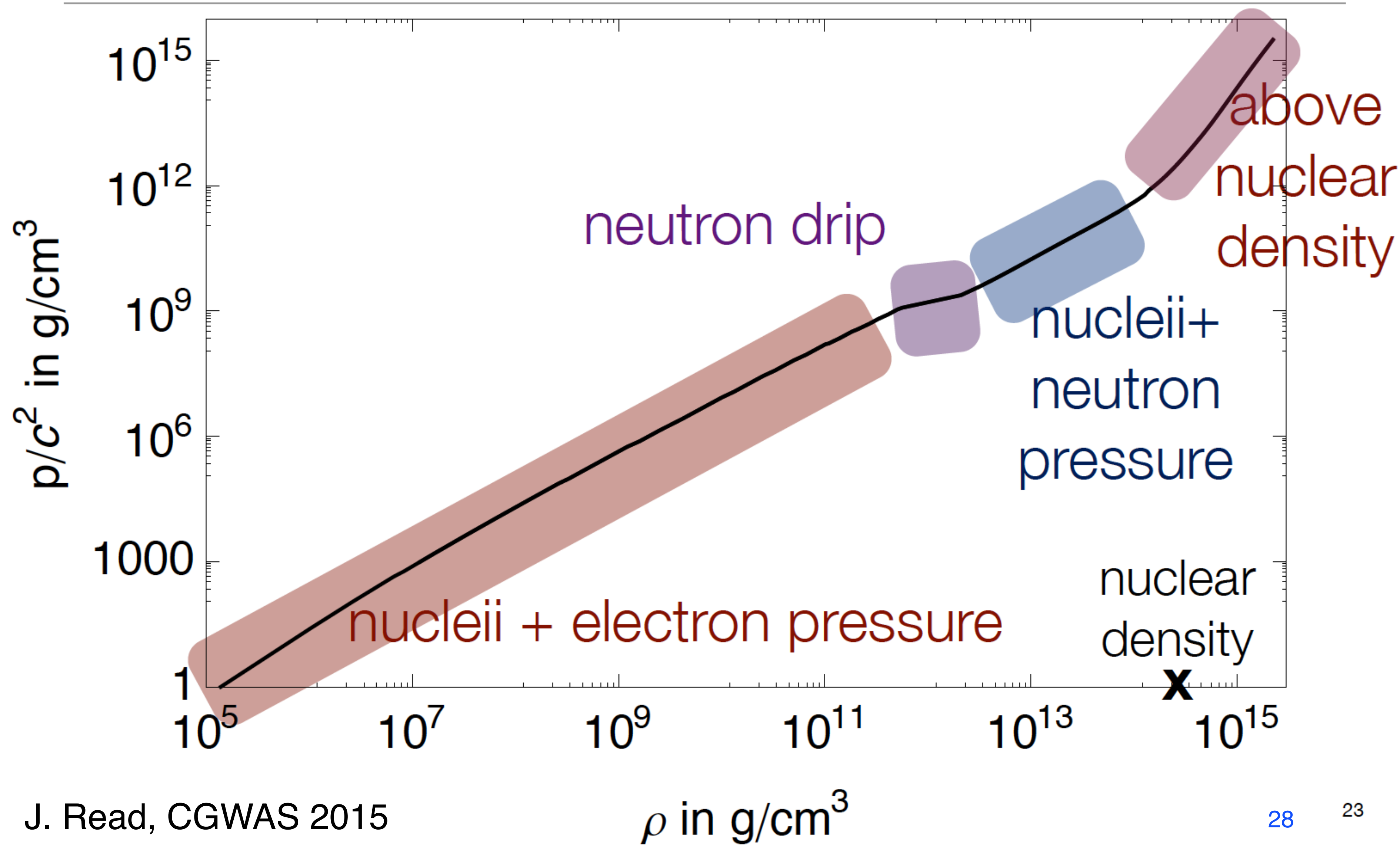


Phase diagram of ground state



Weber, Fridolin et al. Acta Phys.Polon.Supp. 3 (2010) 701-710 arXiv:0911.5164

Cold equation of state: pressure vs density



J. Read, CGWAS 2015

Neutron Star Equation of State

- T=0, pure neutron & proton gas. $f = \epsilon$

$$\epsilon(n_n, n_p) = \frac{3}{5}\frac{p_{F,n}^2}{2m_n}\frac{n_n}{n} + \frac{3}{5}\frac{p_{F,p}^2}{2m_p}\frac{n_p}{n} \quad p_F = (3\pi^2\hbar^3)^{1/3} n^{1/3}$$

$$P = n^2 \frac{\partial \epsilon}{\partial n} \propto n^{5/3}$$

$$\Gamma = \left.\frac{d\ln P}{d\ln \rho}\right|_s = \frac{5}{3}$$

$$P = K\rho^{\Gamma}$$

"polytrope"

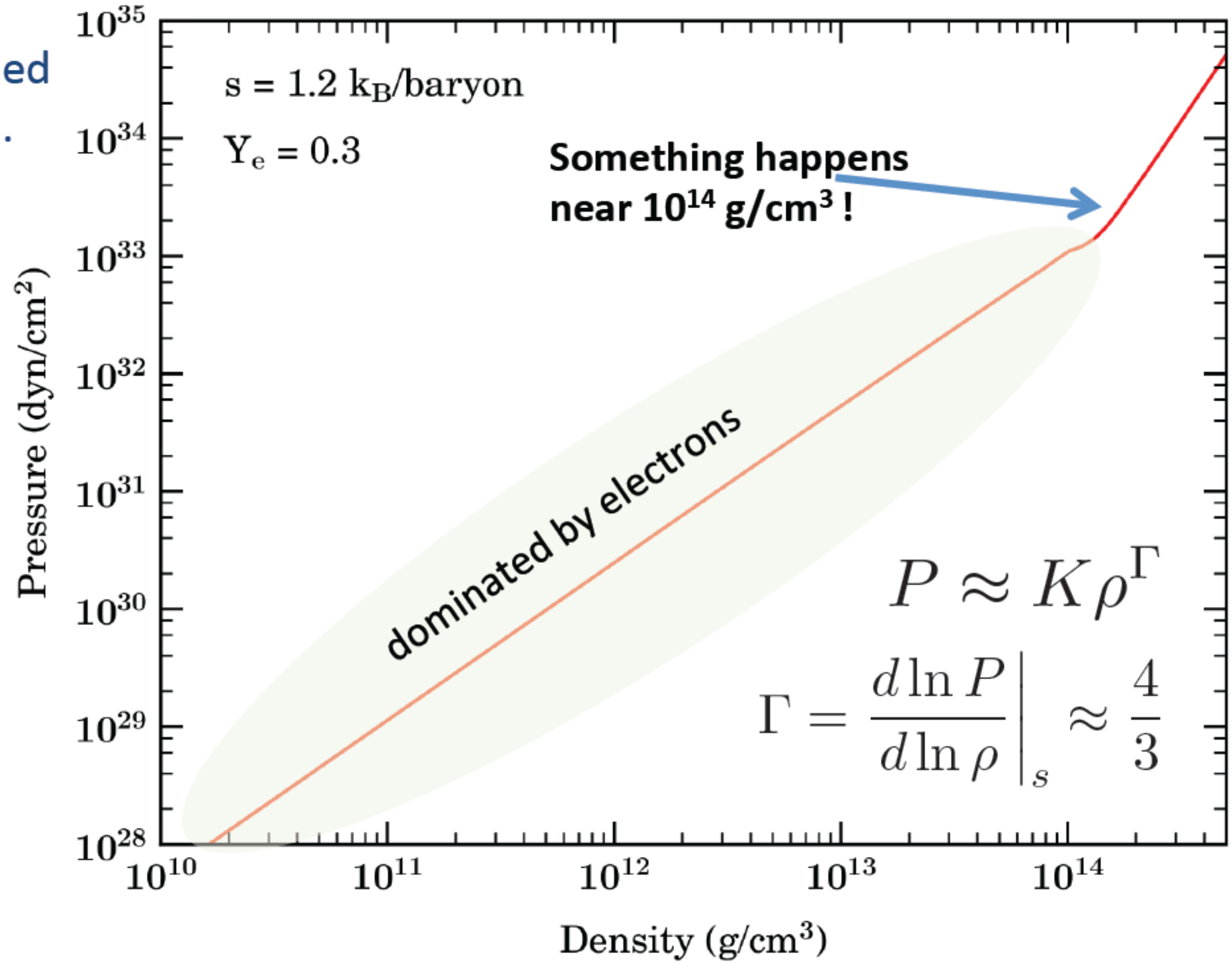
$\Gamma = 5/3$ corresponds to a non-relativistic gas.
A relativistic gas has $\Gamma = 4/3$, which is unstable to collapse.
Note that (unlike ideal gas law $P = nkT$)
the result is independent of temperature.
In general, $pv^n = const$ is polytropic, with $\Gamma = 1+1/n$; here,
n = polytropic index (NOT $n = \rho/m_N$)

Neutron Star Equation of State

Nuclear Statistical Equilibrium ($\rho > 10^7$ g/cm^3, T > 0.5 MeV)

-> $P = P(\rho, T, Y_e)$

Composition determined by Saha-type equation.



C. Ott, 2012

Neutron Star Equation of State

Nuclear Physics:

$$R_{\rm nuc} = A^{1/3} r_0$$

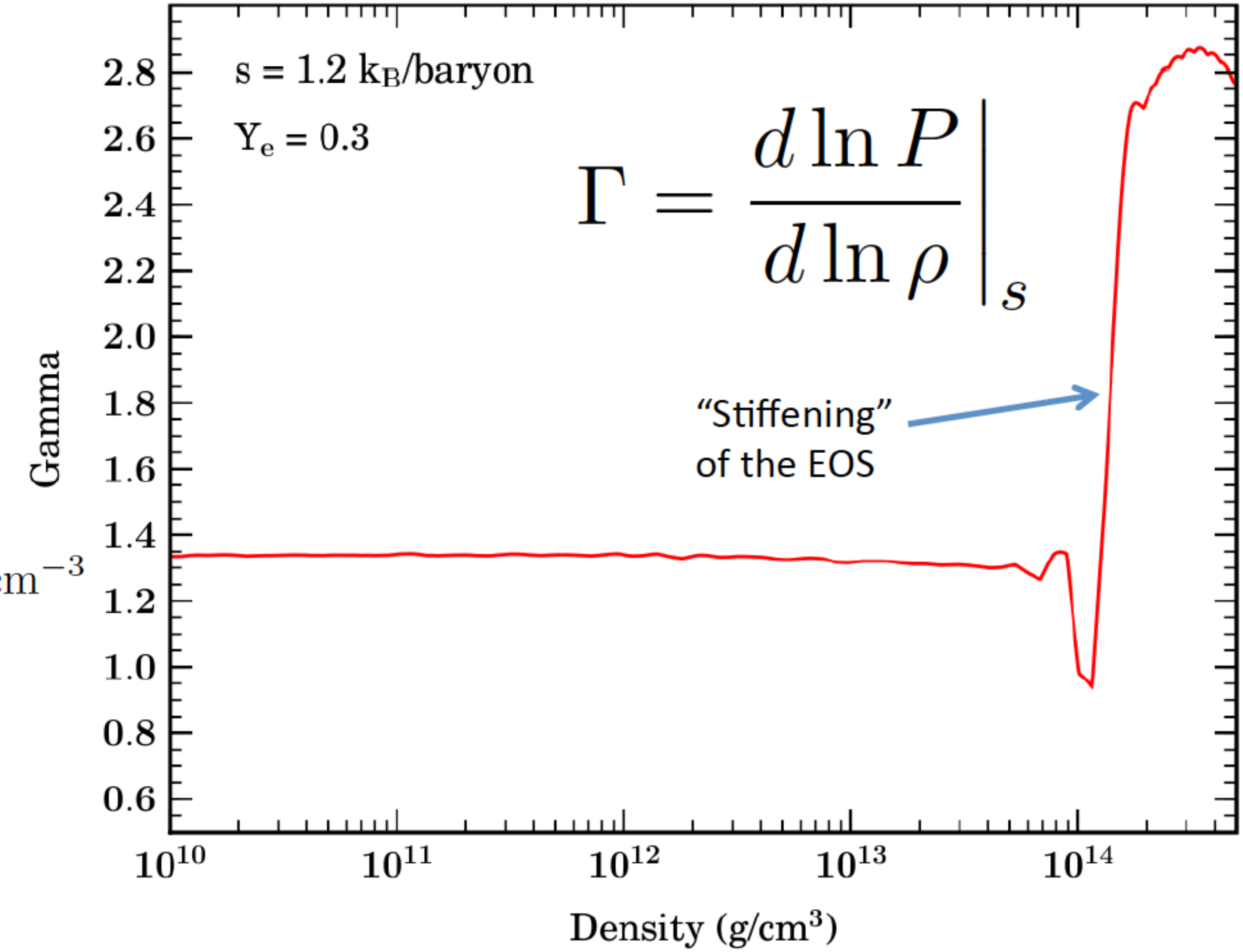
$$r_0 = 1.25\,\mathrm{fm}$$

Nuclear Density:

$$\bar{\rho}_{\rm nuc} = \frac{A\,m_b}{\frac{4}{3}\pi R_{\rm nuc}^3}$$

$$\rho_{\rm nuc} \sim 2.7 \times 10^{14}\,\mathrm{g\,cm^{-3}}$$

$$n_{\rm nuc} \sim 0.16\,\mathrm{fm^{-3}}$$



C. Ott, 2012

Neutron Star Equation of State

Nuclear Physics:

$$R_{\rm nuc} = A^{1/3} r_0$$

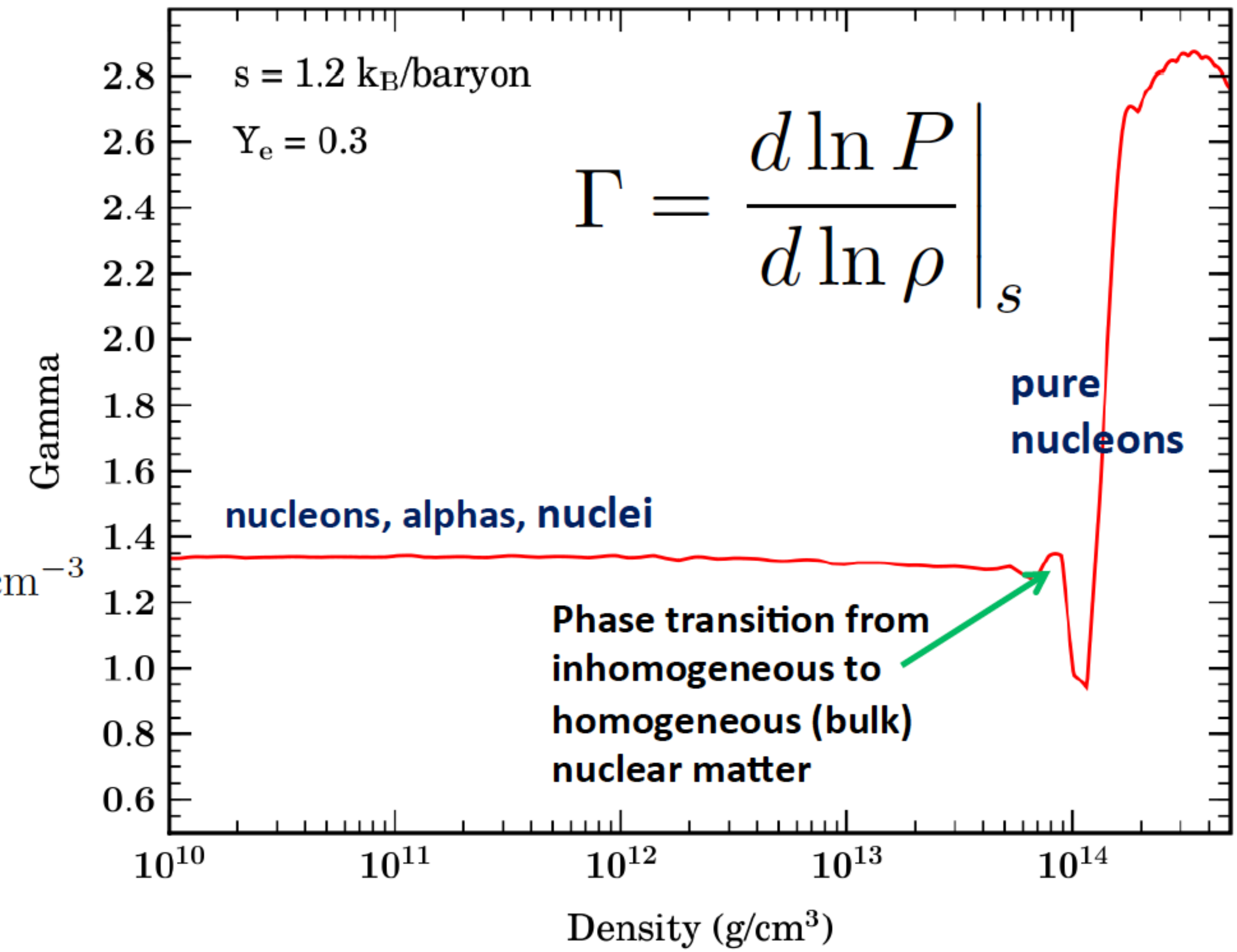
$$r_0 = 1.25\,\mathrm{fm}$$

Nuclear Density:

$$\bar{\rho}_{\rm nuc} = \frac{A\,m_b}{\frac{4}{3}\pi R^3_{\rm nuc}}$$

$$\rho_{\rm nuc} \sim 2.7\times10^{14}\,\mathrm{g\,cm^{-3}}$$

$$n_{\rm nuc} \sim 0.16\,\mathrm{fm^{-3}}$$



What is causing the stiffening of the nuclear EOS?

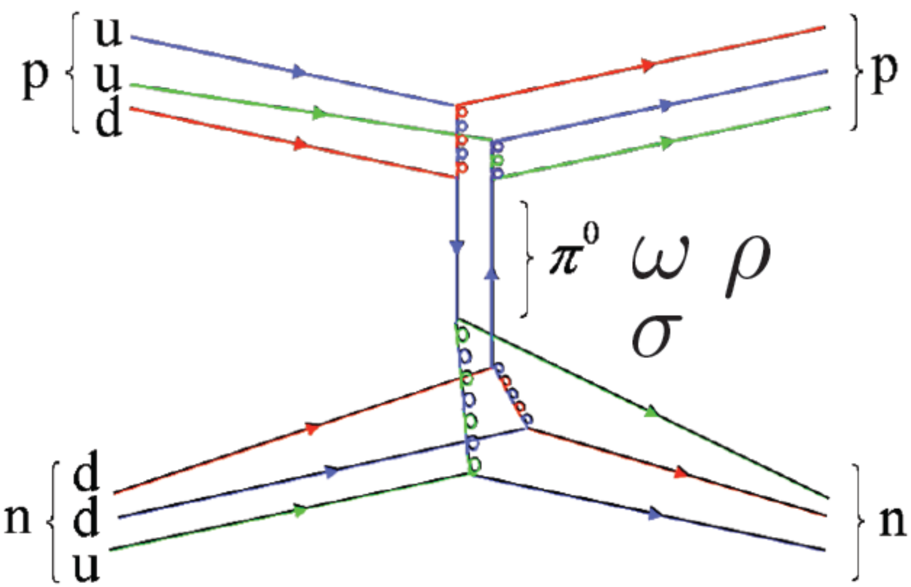
C. Ott, 2012

Nuclear Equation of State

- T=0, interacting pure neutron & proton gas.

$$\epsilon(n_n, n_p) = \frac{3}{5}\frac{p_{F,n}^2}{2m_n}\frac{n_n}{n} + \frac{3}{5}\frac{p_{F,p}^2}{2m_p}\frac{n_p}{n} + \frac{V_{np}(n_n, n_p)}{n}$$

nucleon-nucleon (NN) potential energy density



- Nuclear force is NN many-body interaction = "effective" strong force interaction.
- Mediated by mesons: π (s=0), σ (s=0), ω (s=1), ρ (s=1)
- Dependent on separation and spin orientation. **Scalar**, **vector**, and **tensor** components.
  Vector component is repulsive.

C. Ott, 2012

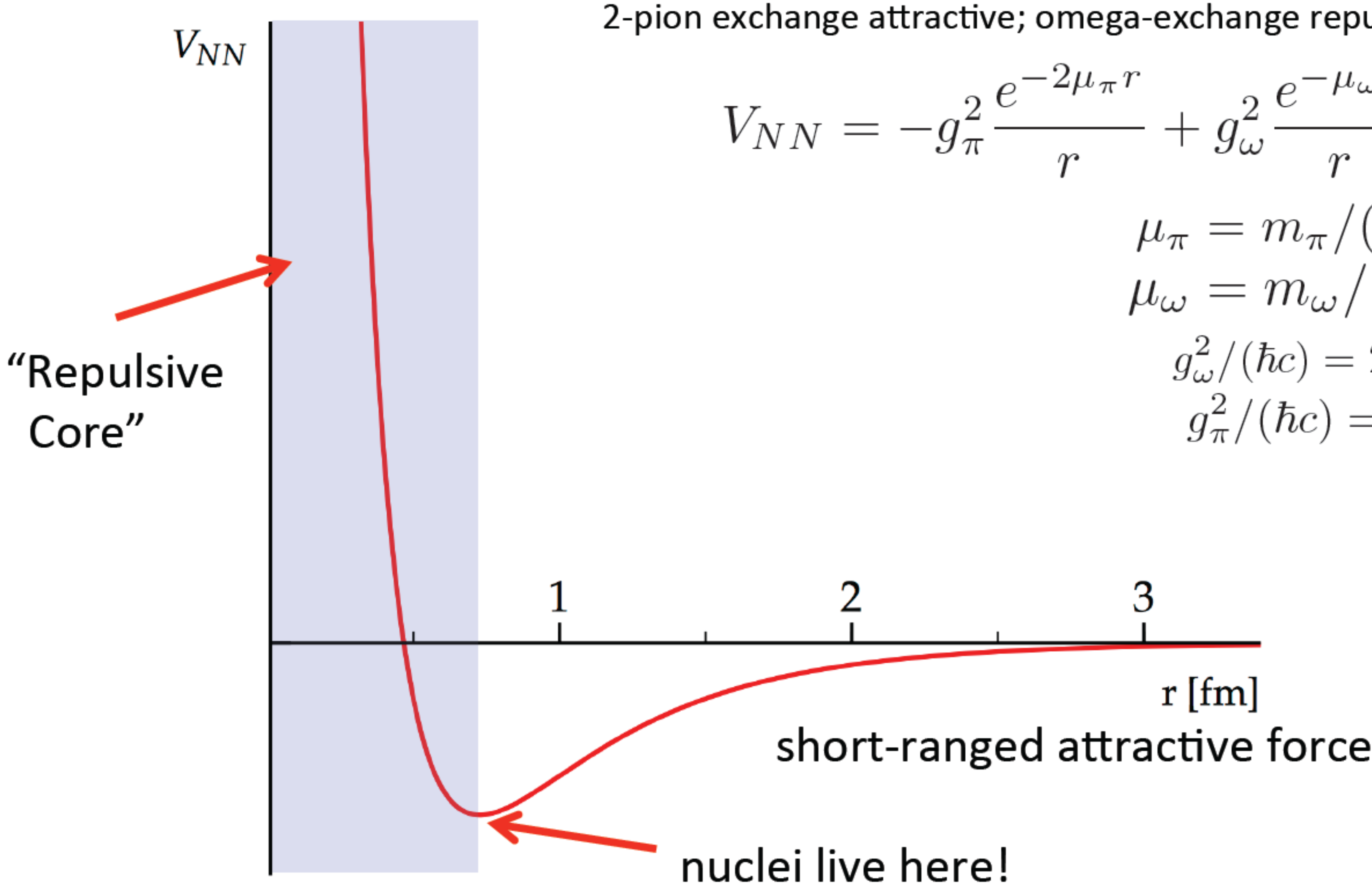
Nucleon-Nucleon Interaction

Example: Bethe & Johnson 74

2-pion exchange attractive; omega-exchange repulsive

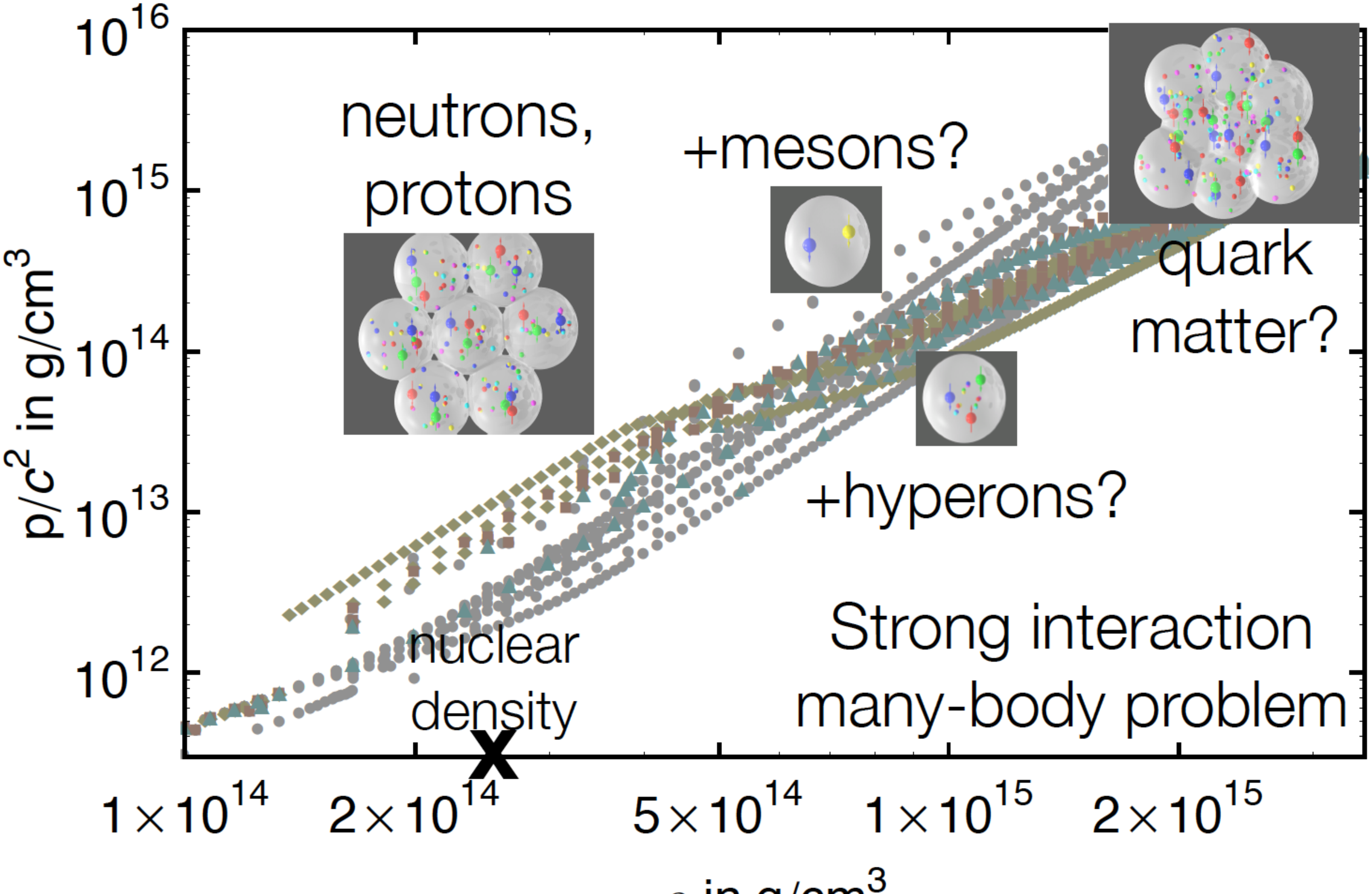
$$V_{NN} = -g_\pi^2 \frac{e^{-2\mu_\pi r}}{r} + g_\omega^2 \frac{e^{-\mu_\omega r}}{r}$$

$$\mu_\pi = m_\pi/(\hbar c)$$
$$\mu_\omega = m_\omega/(\hbar c)$$
$$g_\omega^2/(\hbar c) = 29.6$$
$$g_\pi^2/(\hbar c) = 10$$



C. Ott, 2012

What happens above nuclear density?
Inside neutrons: quarks



J. Read, CGWAS 2015

images: S. Scherer

Neutron Star Structure

Newtonian: $$\frac{dP}{dr} = -\frac{GM\rho}{r^2} \qquad \frac{dM}{dr} = 4\pi r^2 \rho$$ (no maximum mass!)

GR: Tolman-Oppenheimer-Volkov (TOV) eqns

$$\frac{dP}{dr} = -G(\rho(1+\epsilon/c^2) + P/c^2)\frac{M + 4\pi r^3 p/c^2}{r(r - 2GM/c^2)}$$

$$\frac{dM_g}{dr} = 4\pi r^2 \rho(1+\epsilon/c^2)$$ gravitational mass

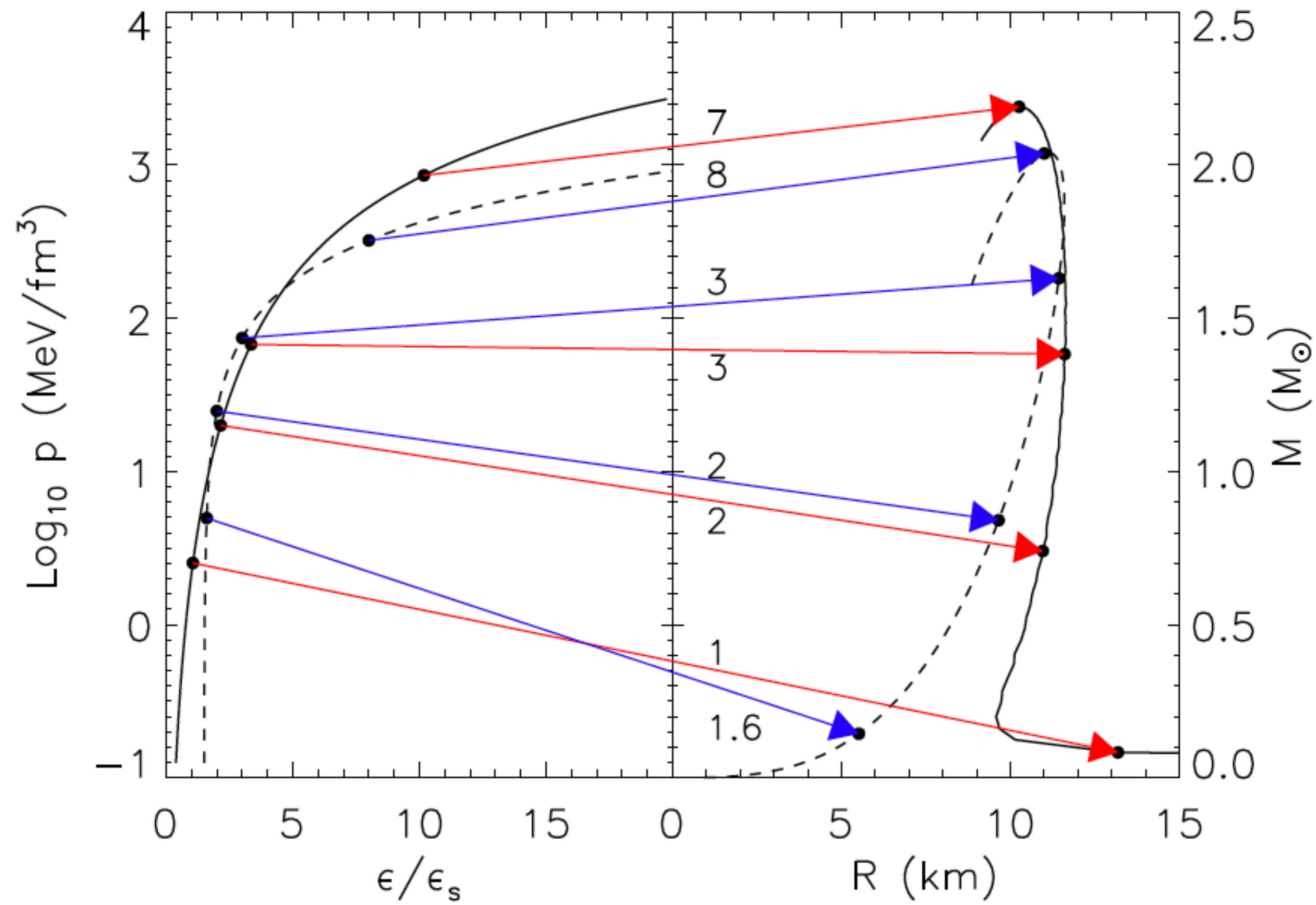
$$\frac{dM_b}{dr} = \frac{4\pi r^2}{\sqrt{1-\frac{2GM}{rc^2}}}\rho$$ baryonic mass

Radius is circumferential radius!

- Solve by ODE integration from r=0, invert P(ρ) at each step to obtain ρ.

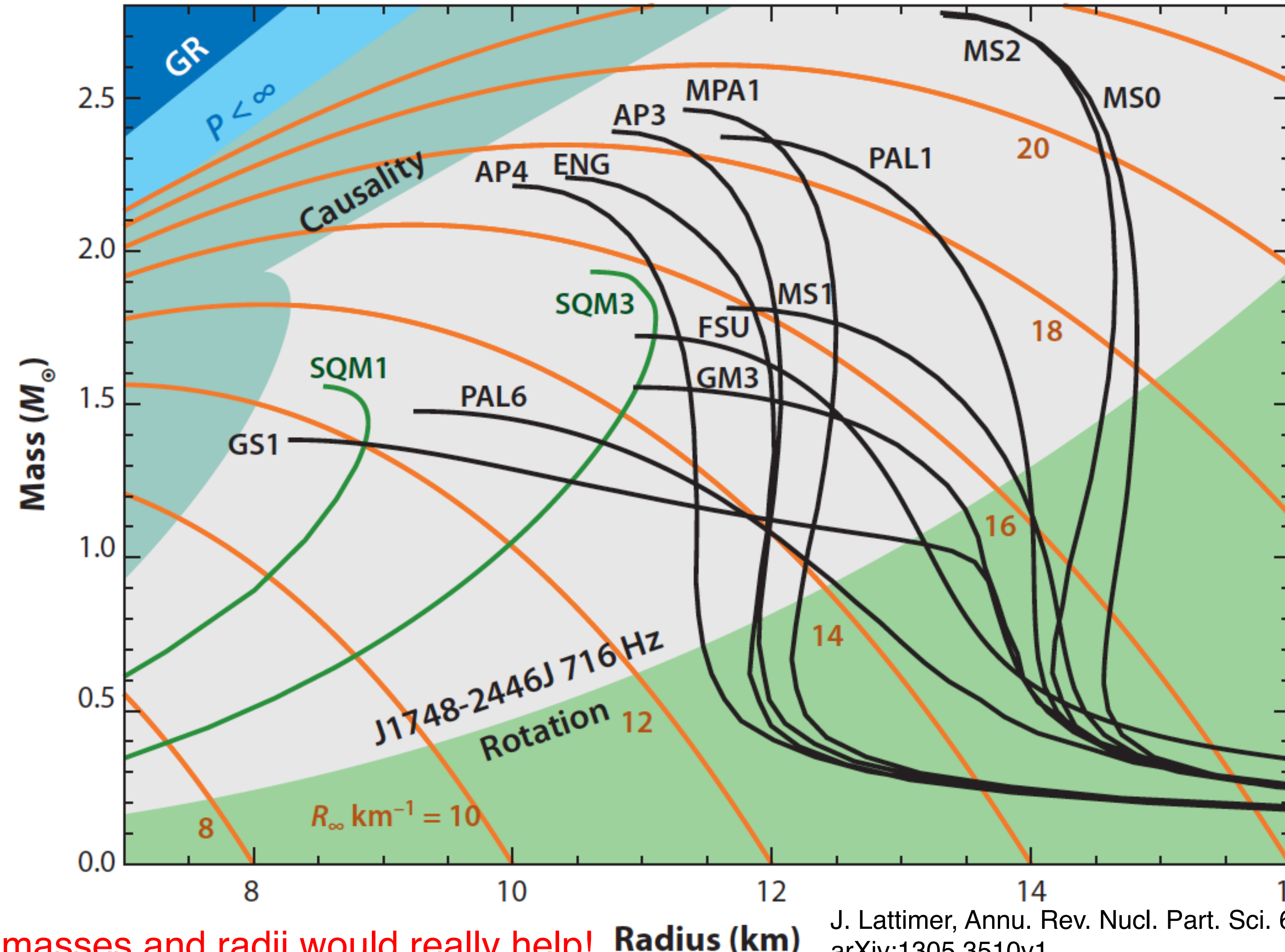
C. Ott, 2012

Building neutron star mass-radius relation with TOV and NEOS



J. Lattimer, Annu. Rev. Nucl. Part. Sci. 62, 485 (2012)

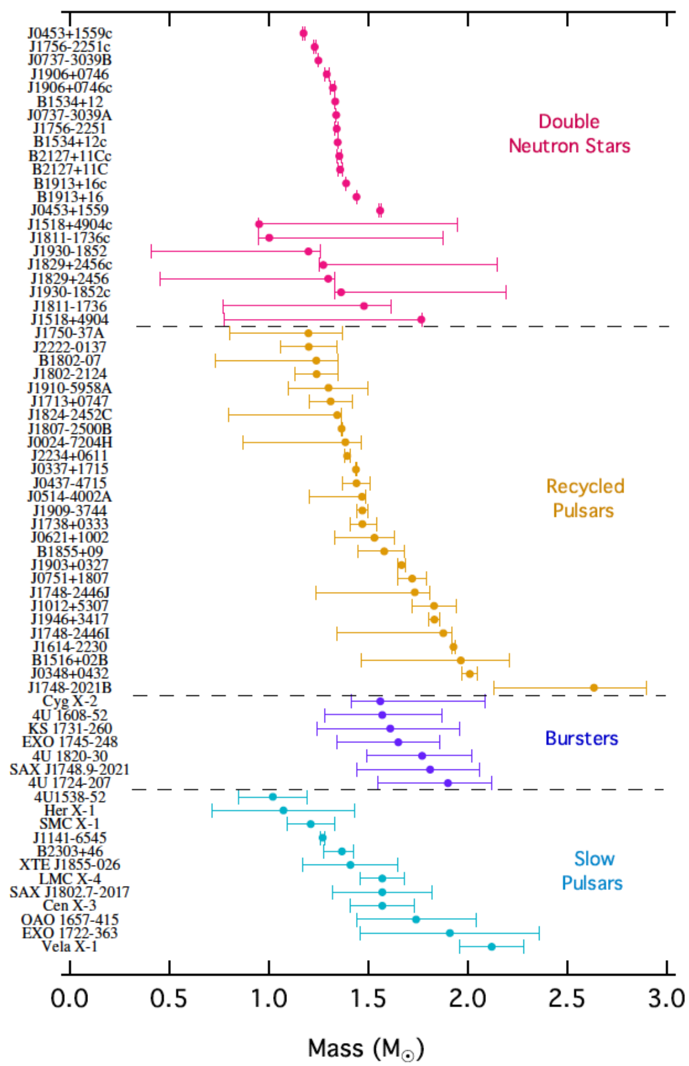
EOS and Neutron star structure

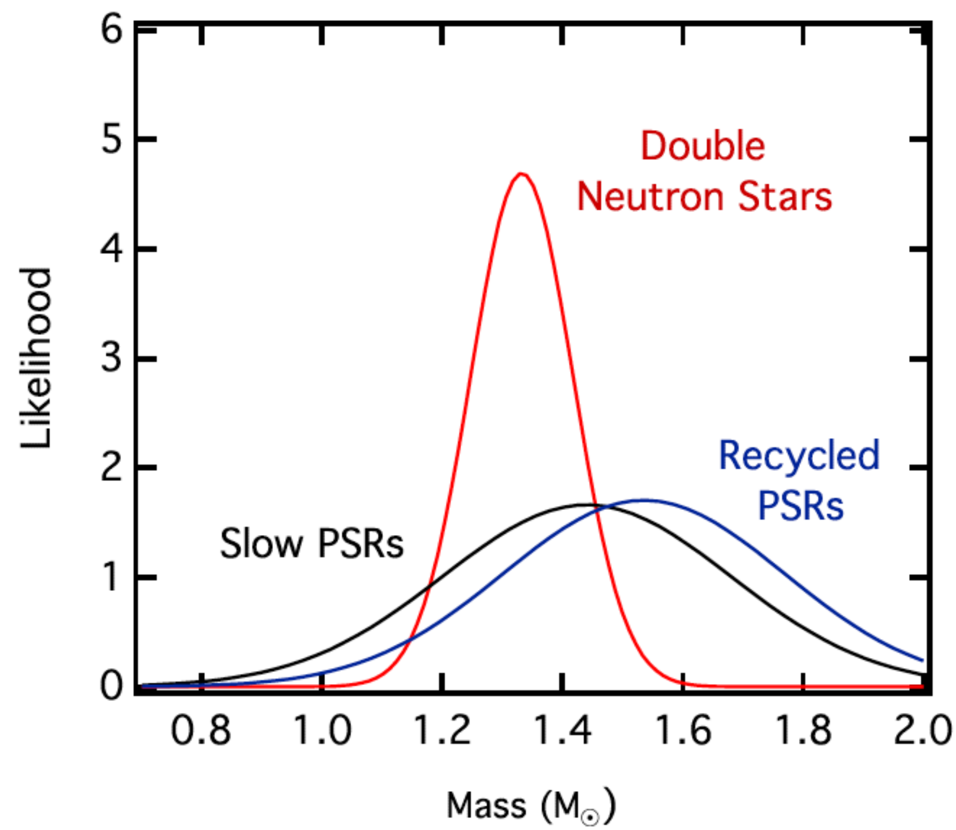


Knowing masses and radii would really help!

J. Lattimer, Annu. Rev. Nucl. Part. Sci. 62, 485 (2012)
arXiv:1305.3510v1

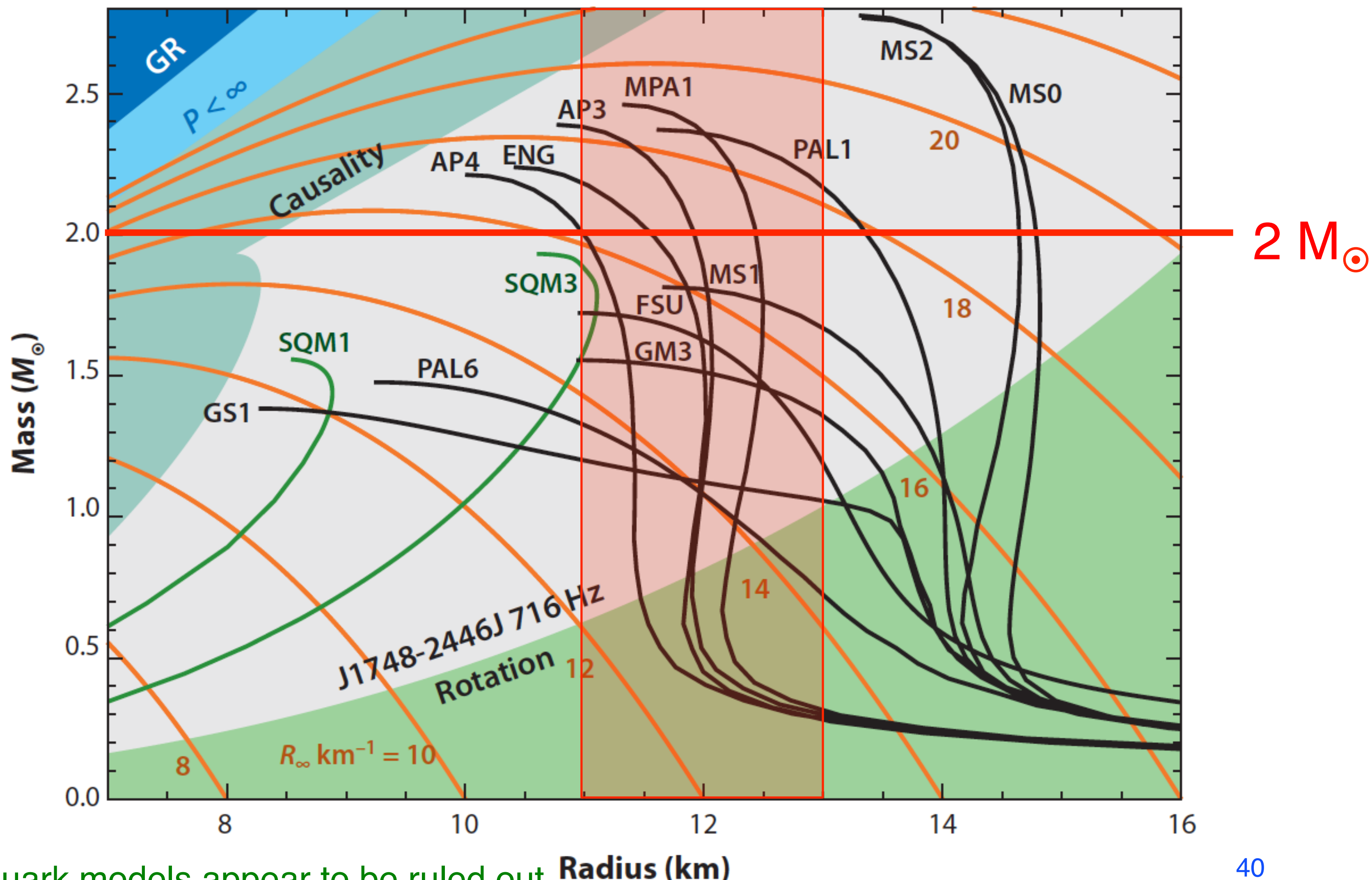
Neutron star masses





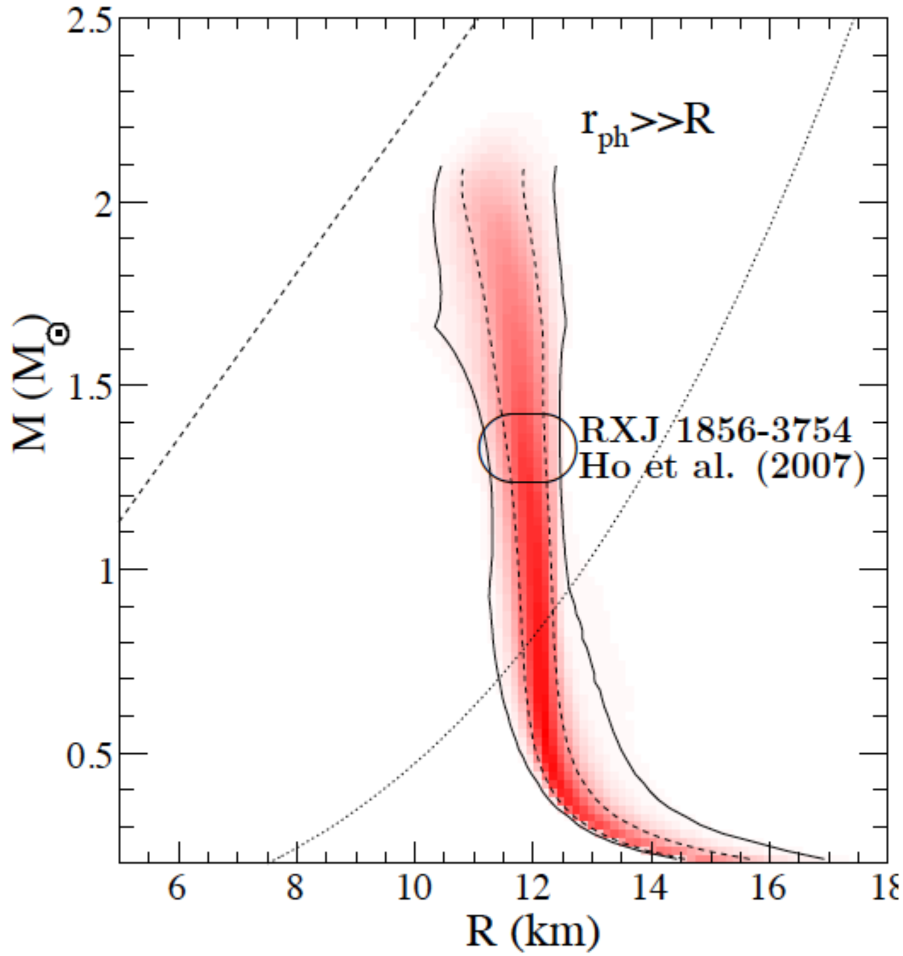
Feryal Ozel, Paulo Freire, http://arxiv.org/abs/1603.02698v1

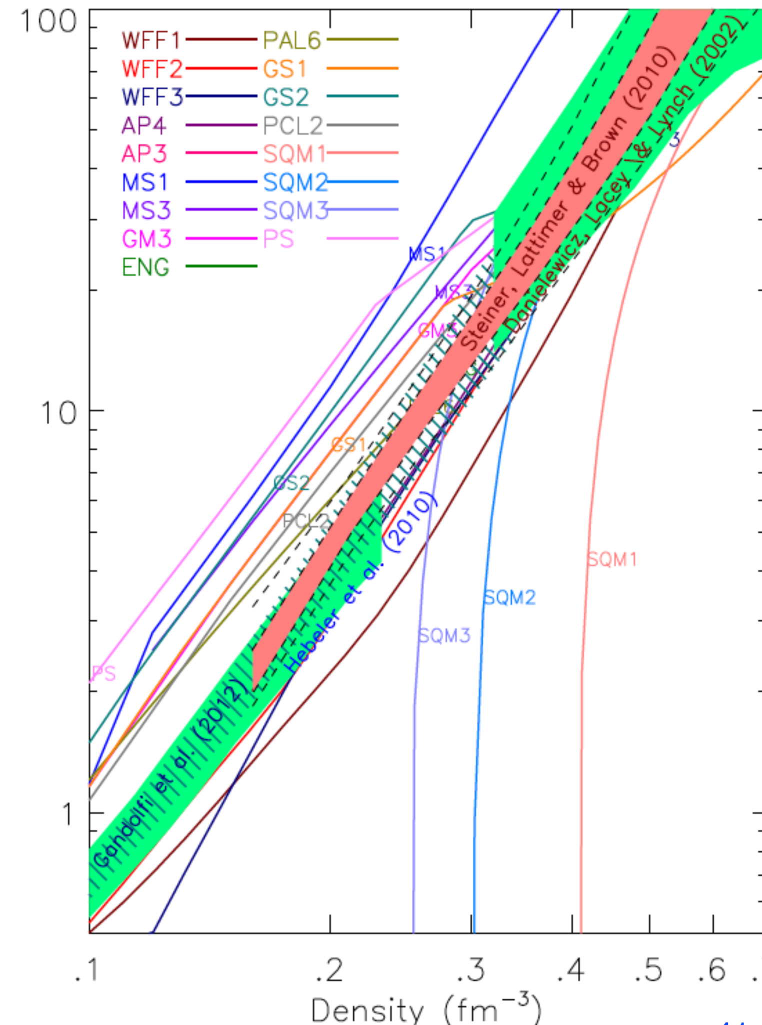
Mass and radius constraints



Strange quark models appear to be ruled out…

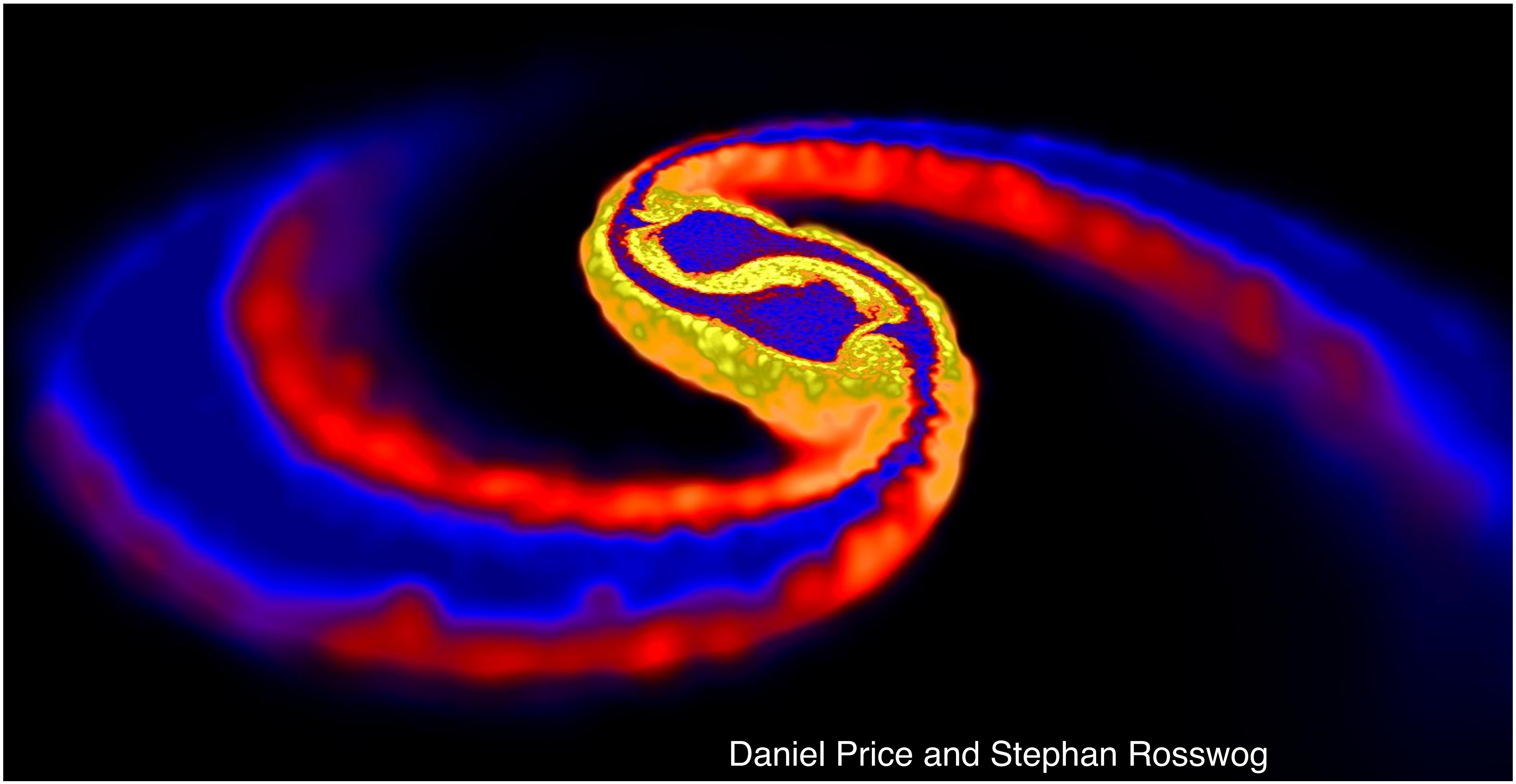
Astrophysical constraints on masses and radii of NSs



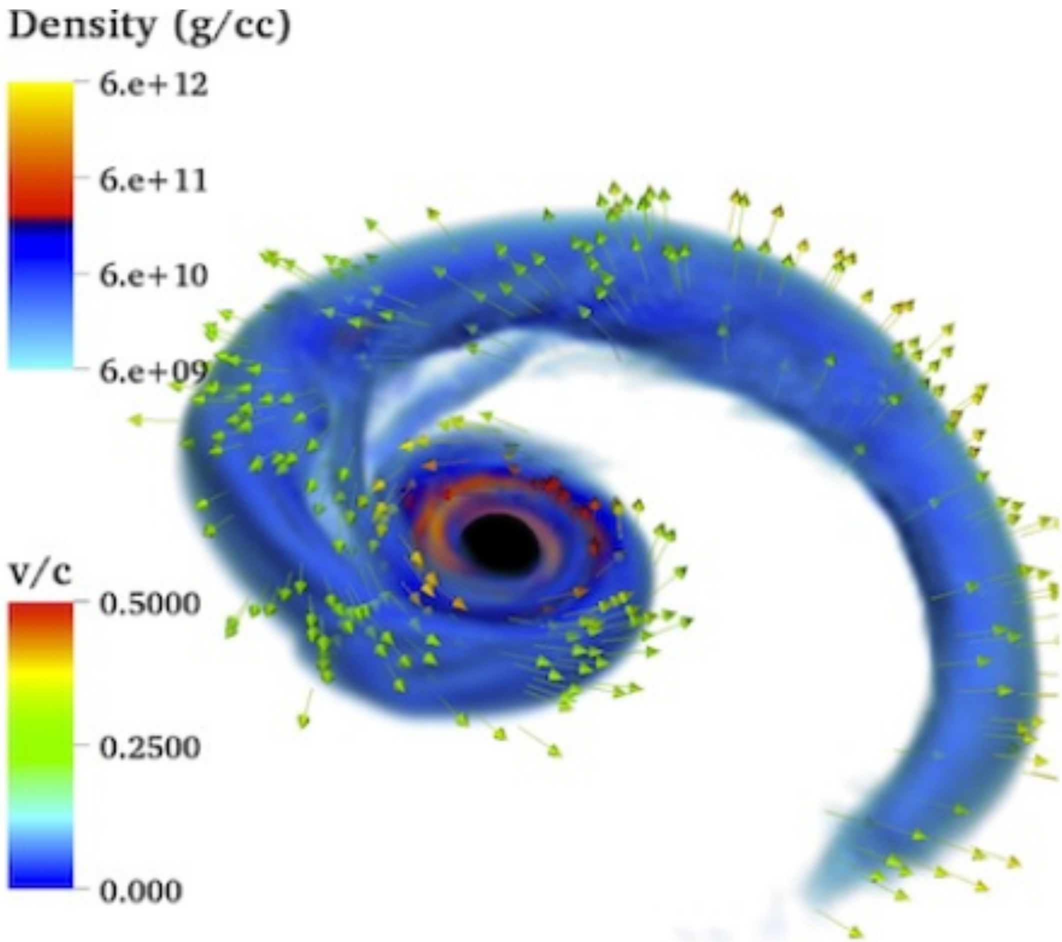


AW Steiner, JM Lattimer, EF Brown. Astrophys. J. 722:33 (2010)
J. Lattimer, Annu. Rev. Nucl. Part. Sci. 62, 485 (2012), arXiv:1305.3510v1

Binary neutron star mergers



Matter distribution during the disruption of the neutron star

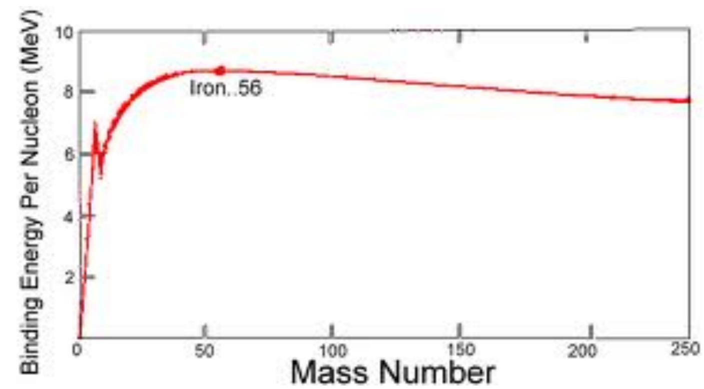


About half of the remnant material is unbound,
while a relatively low mass hot disk forms.

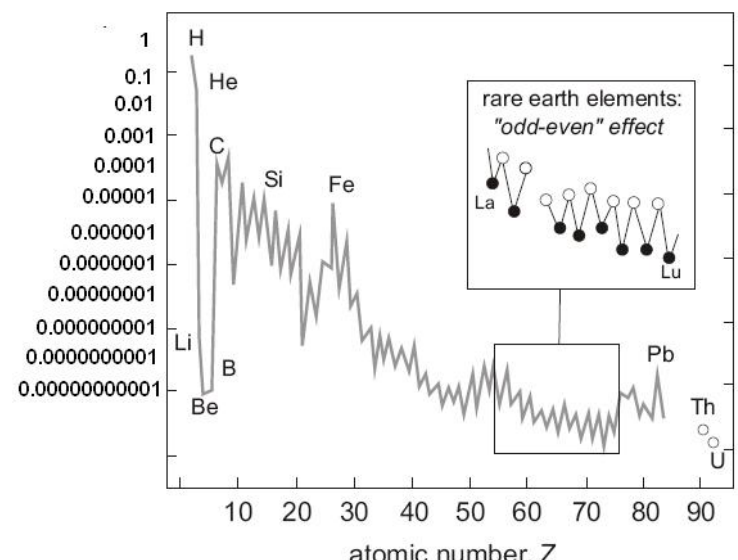
F. Foucart et al, Phys. Rev. D 90, 024026 (2014) arXiv:1405.1121

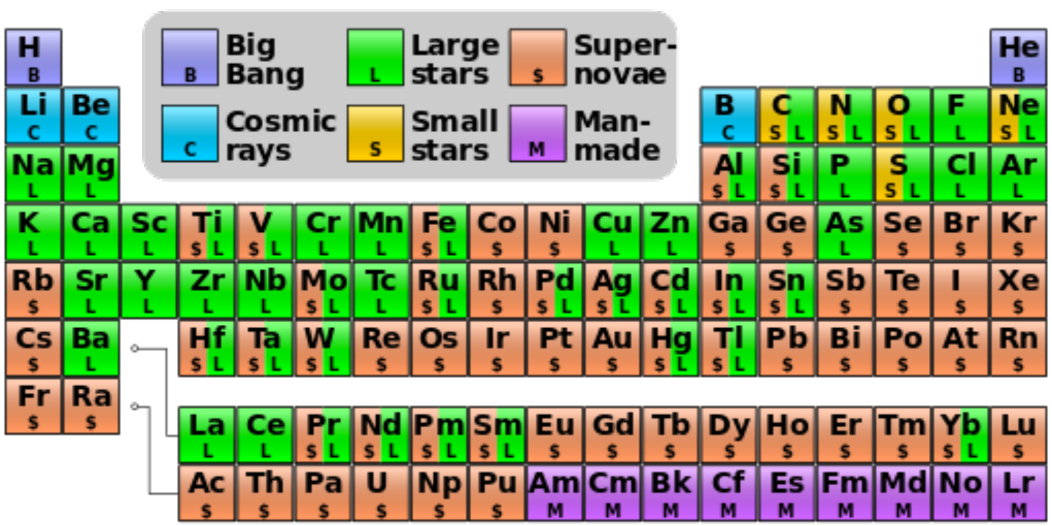
The origin of the elements – astrophysical nucleosynthesis

- **Lightest elements (H, He, Li) forged in Big Bang**
- **Heavier elements (C, O, N, … Fe) forged in the core of massive stars, distributed to ISM by core-collapse supernovae (star-death)**
- **Elements beyond Fe (like Cu, Au, Pb, Pt, U…) are forged during the SN (“r-process”)**
- **but many/most of them might come from binary neutron star mergers (second-death)**

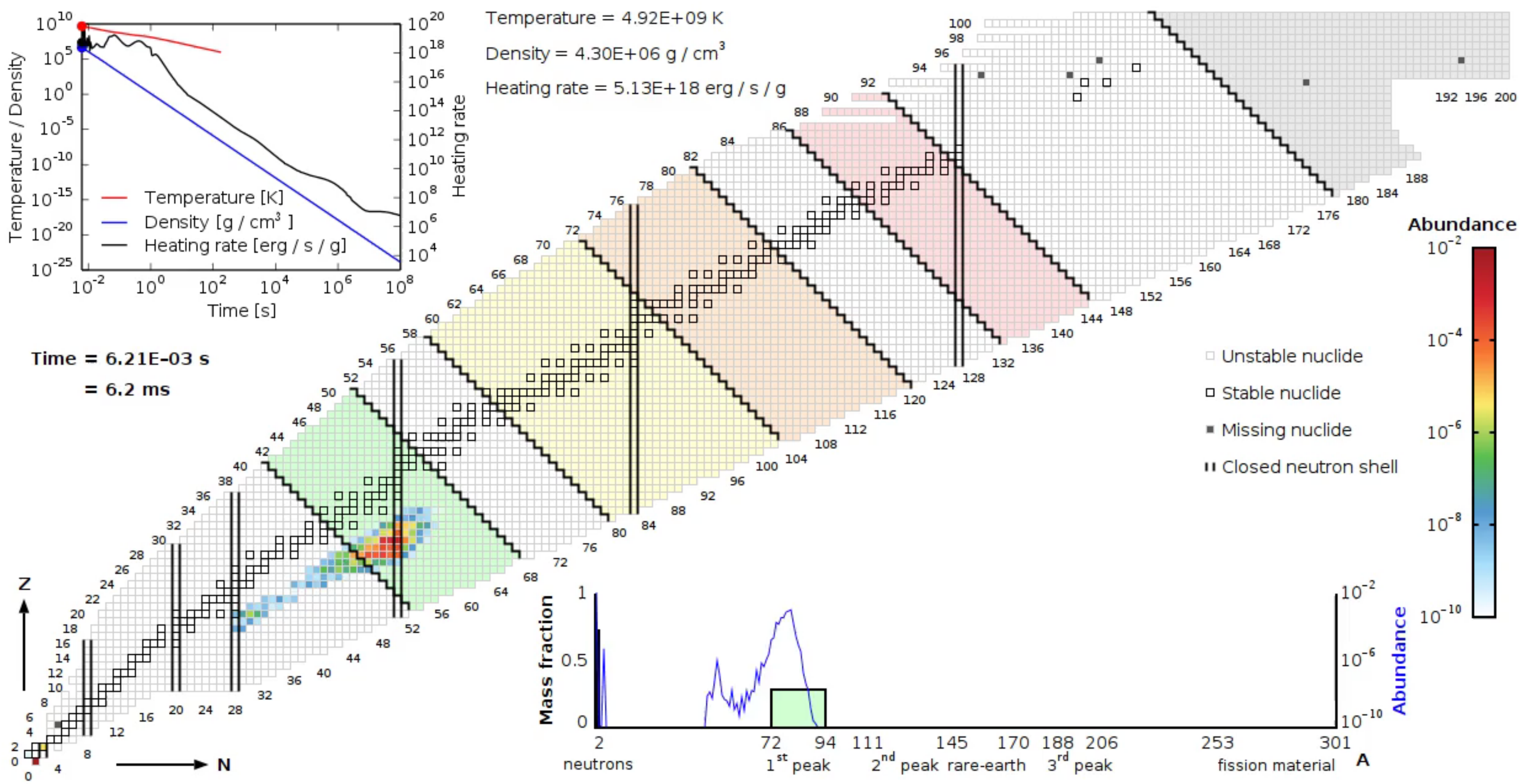


COSMIC ABUNDANCES of the elements



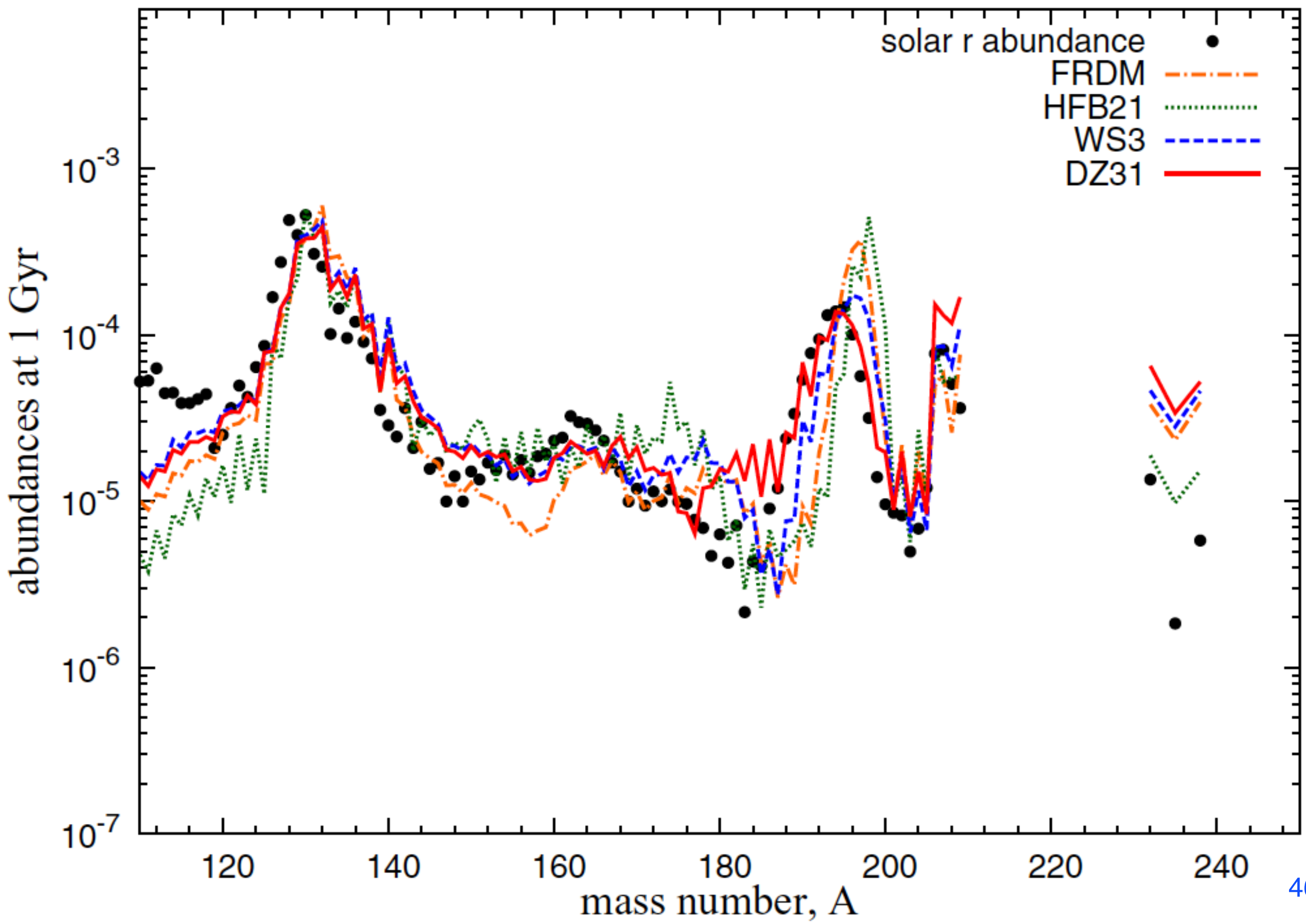


Nucleosynthesis in binary neutron star collisions

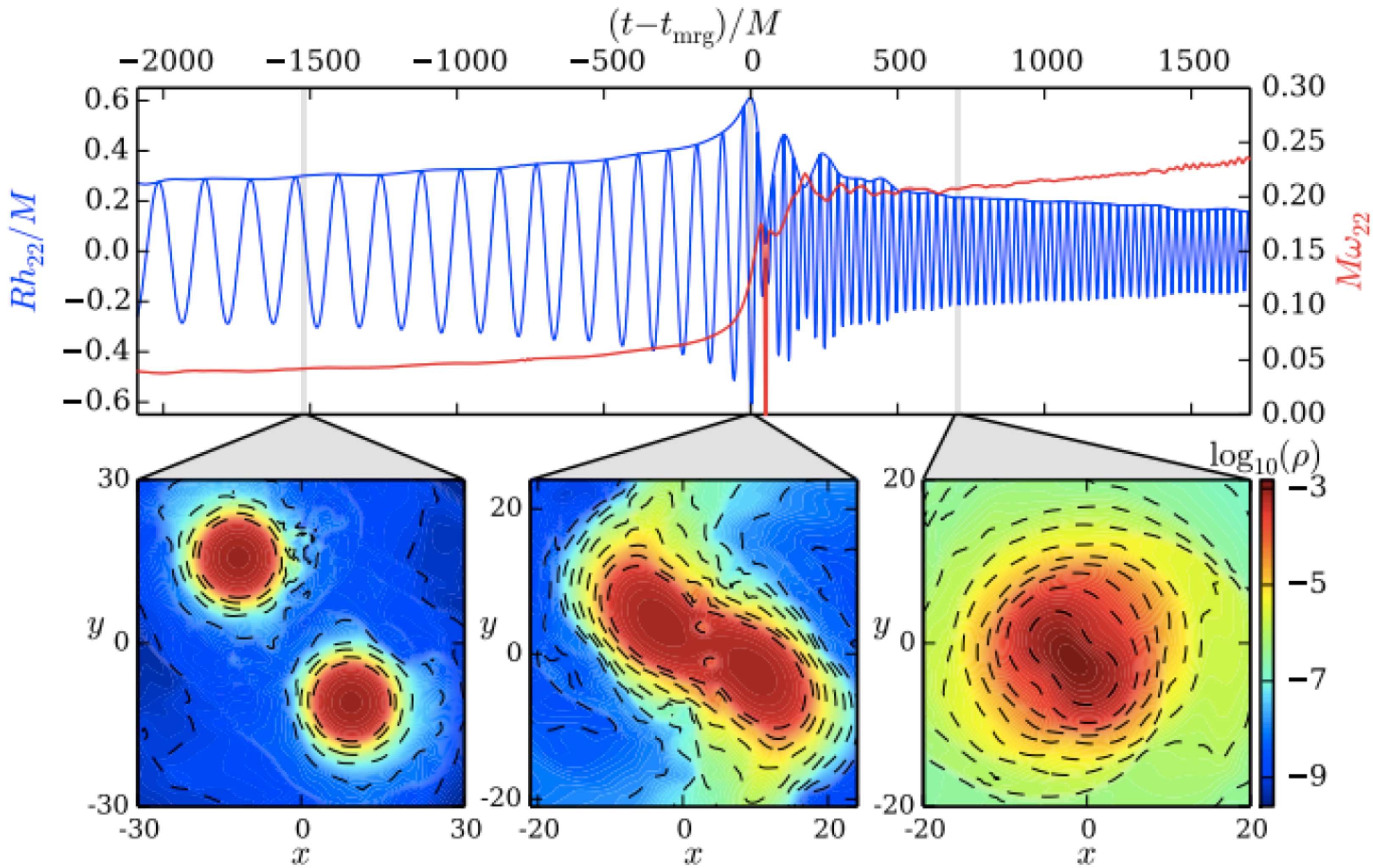


C. Ott; http://www.lippuner.ca/files/nucleosynthesis_000_med.mp4

Nuclear abundances from detailed simulations on BNS mergers

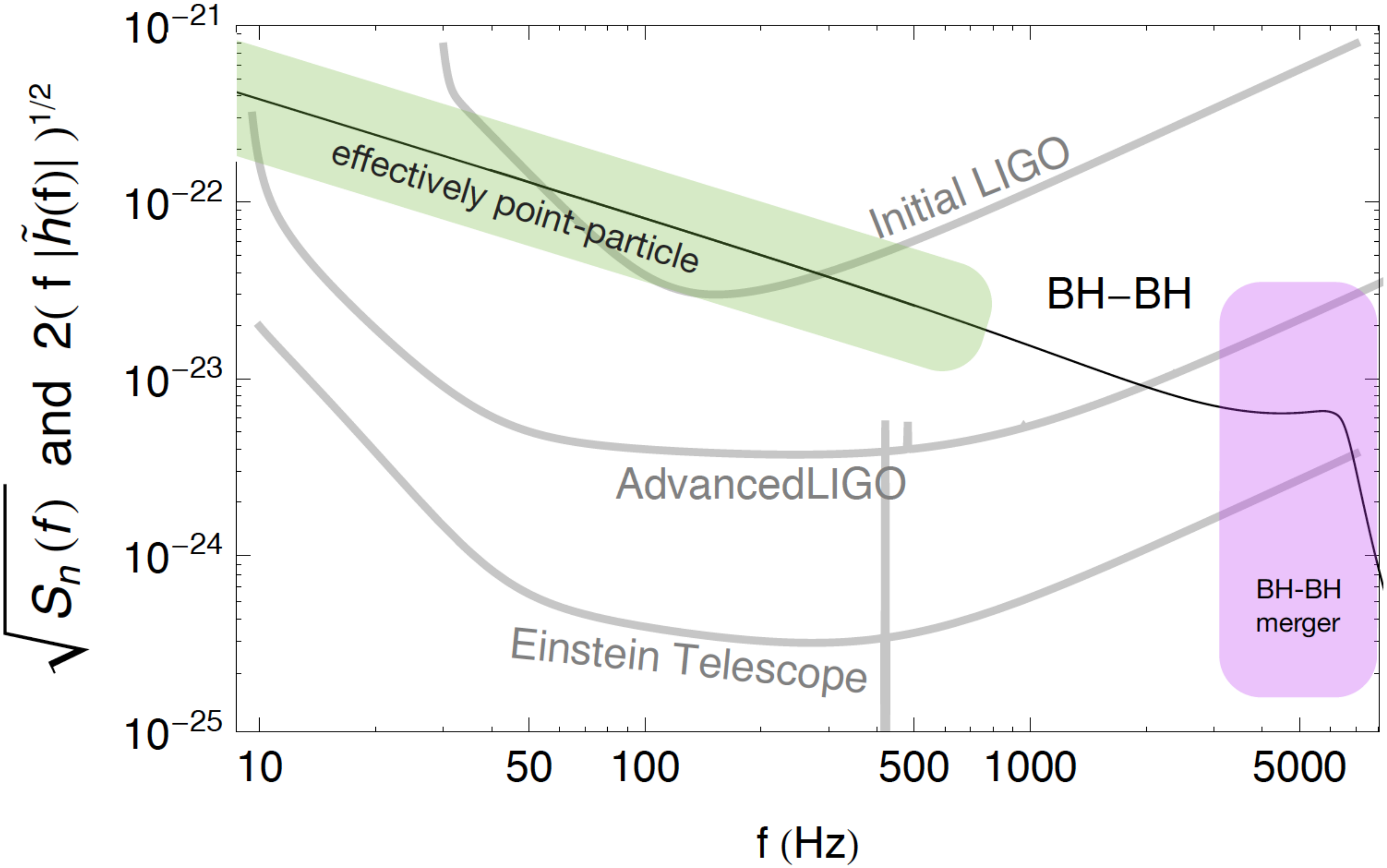


GWs from BNS mergers



S Bernuzzi, T Dietrich, A Nagar, Phys Rev Lett 115, 091101 (2015) arxiv.org:1504.01764

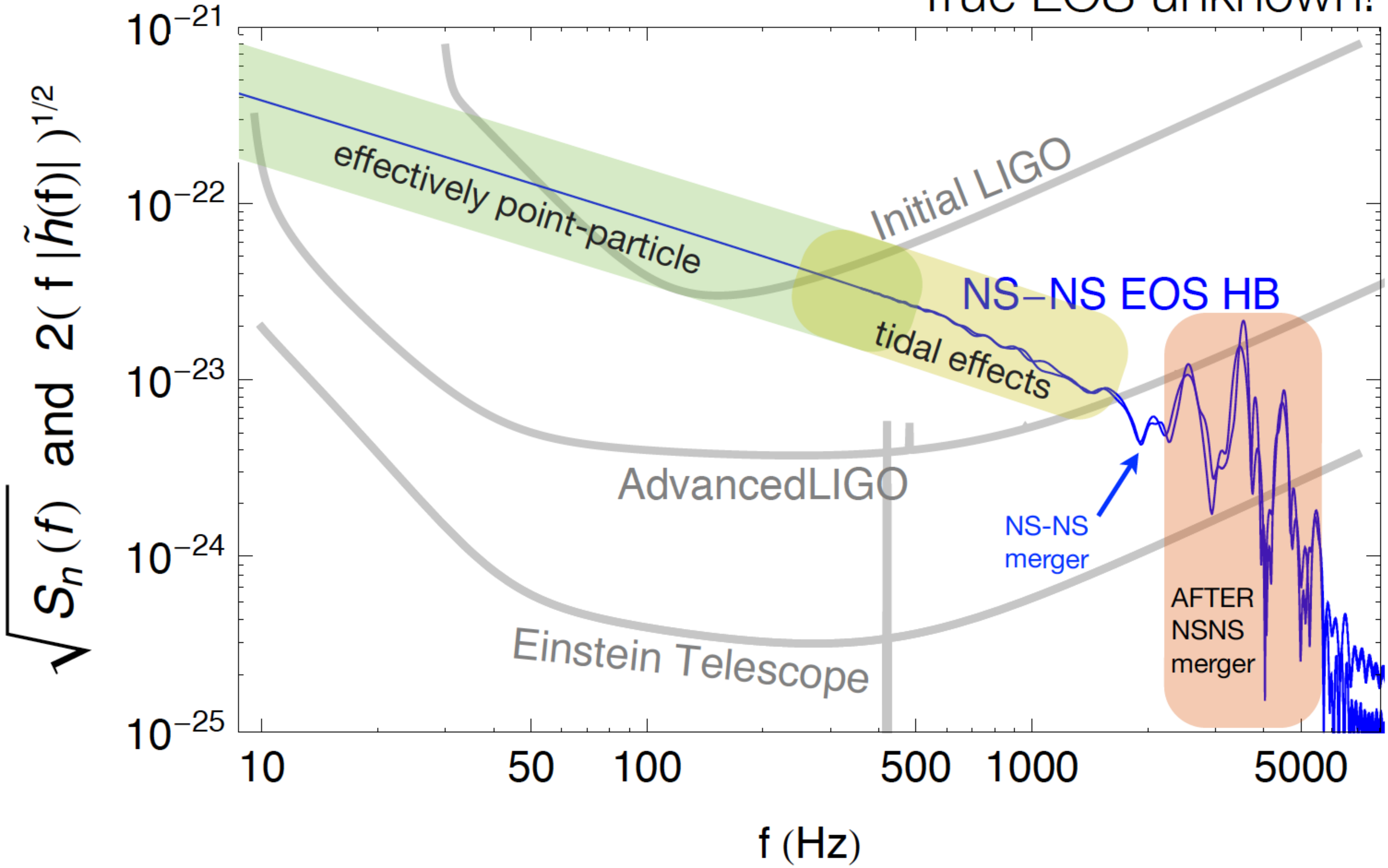
Spectrum of BBH inspiral, scale to 1.35-1.35, 45 Mpc



J. Read, CGWAS 2015

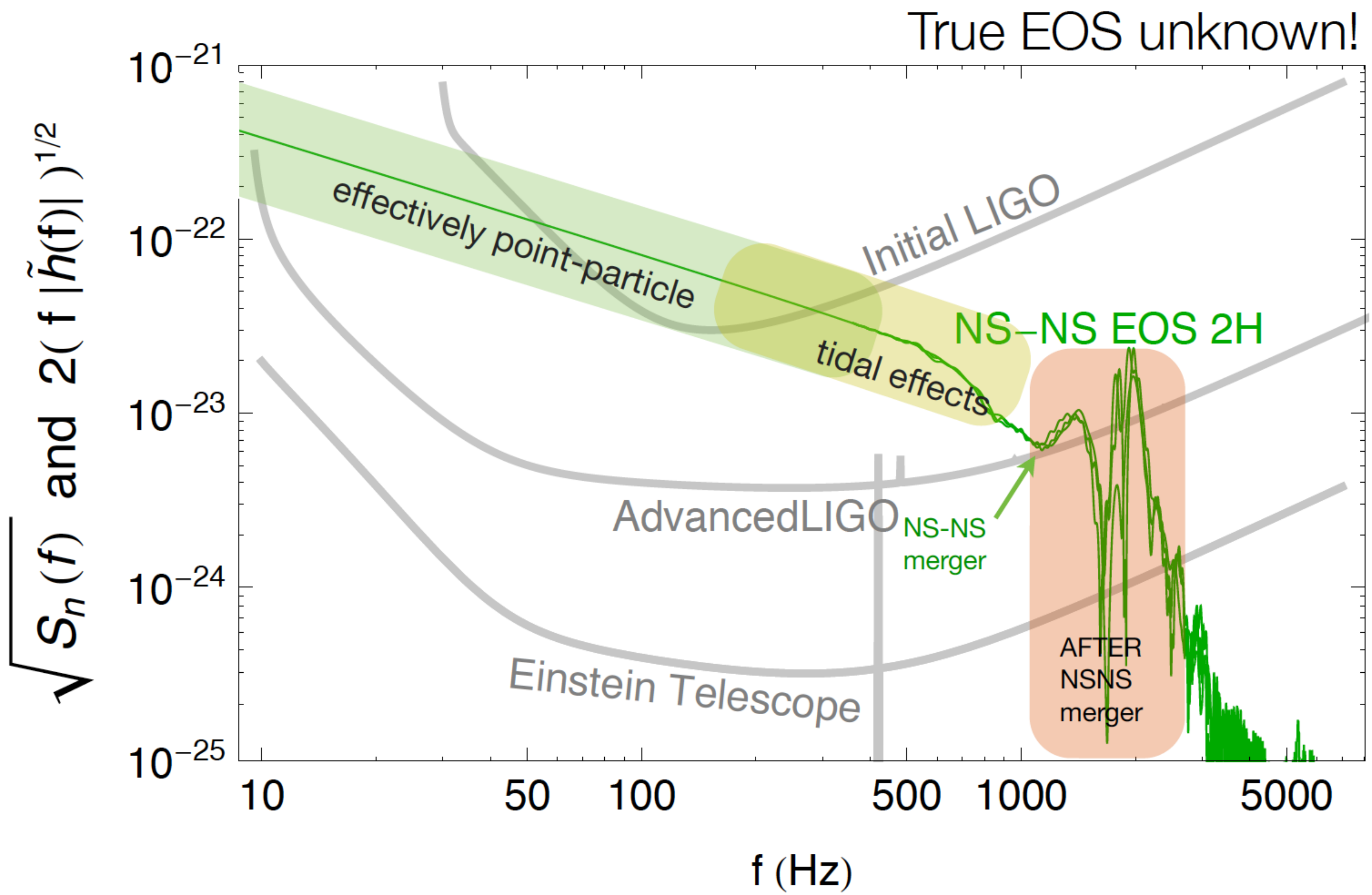
Spectrum of NS-NS inspiral, 1.35-1.35, 45 Mpc

True EOS unknown!



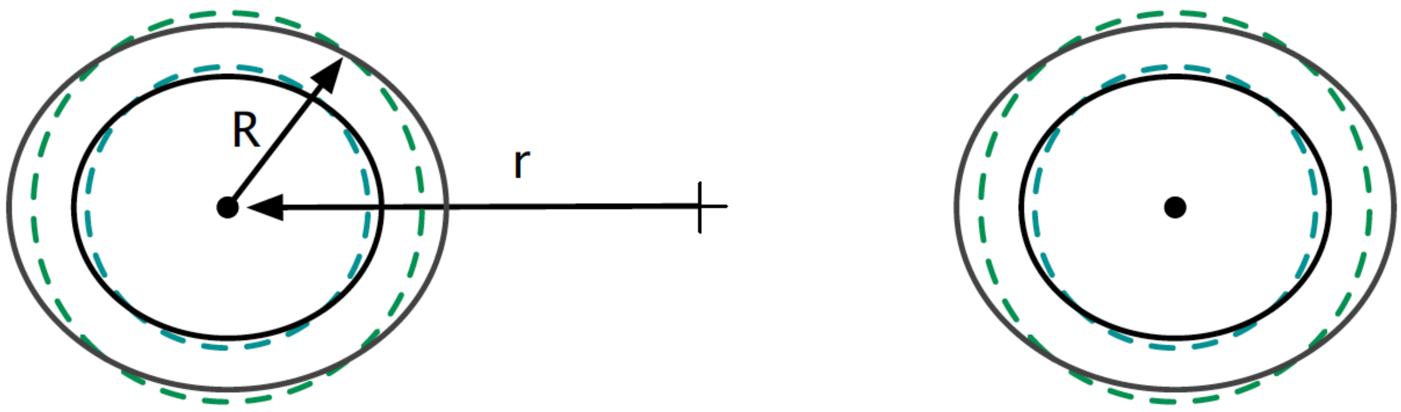
J. Read, CGWAS 2015

Spectrum of NS-NS inspiral, 1.35-1.35, 45 Mpc



J. Read, CGWAS 2015

Consider two extended bodies in orbit or free-fall:

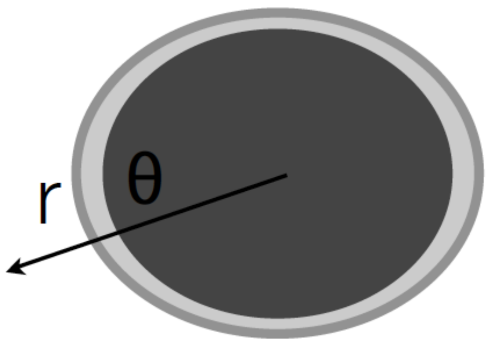


Residual gravitational effect is **tide**.

Amount of deformation depends on size and matter properties.

Deformation induces change in gravitational potential.

Tides and the Quadrupole moment Q



mass M radius R
Love number k
deformed by mass m
distance a away

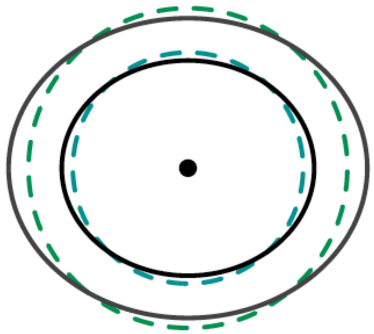
$$Q = \frac{2}{3} k R^5 \left(\frac{m}{d^3} \right)$$

gives the gravitational potential around a deformed body

$$U = -\frac{M}{r} - \frac{3}{2} \frac{Q(\cos^2\theta - 1)}{r^3}$$

This tells us about things like satellite movement, tidal locking (“back-reaction” on bulges), and **orbital dynamics in binary systems**

Calculate in GR:



Perturb a spherically symmetric neutron star
impose quadrupole angular dependence
look at scaling with distance from star r

(0711.2420, 0906.1366, 0906.0096)

$$\lambda = \frac{Q}{\mathcal{E}} = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}} \quad \begin{matrix} (\sim r^{-3}) \\ (\sim r^{2}) \end{matrix}$$

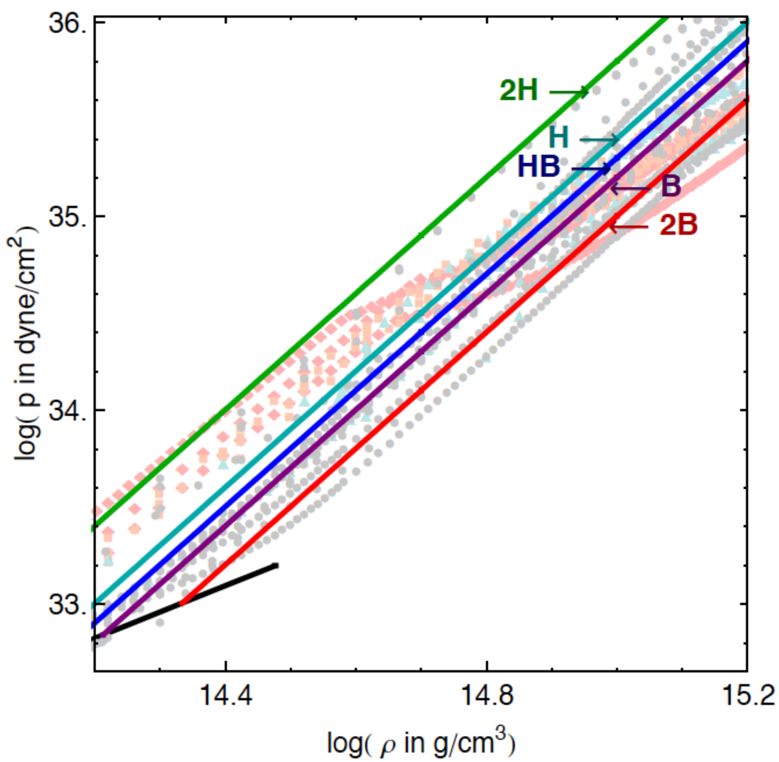
Love number k_2

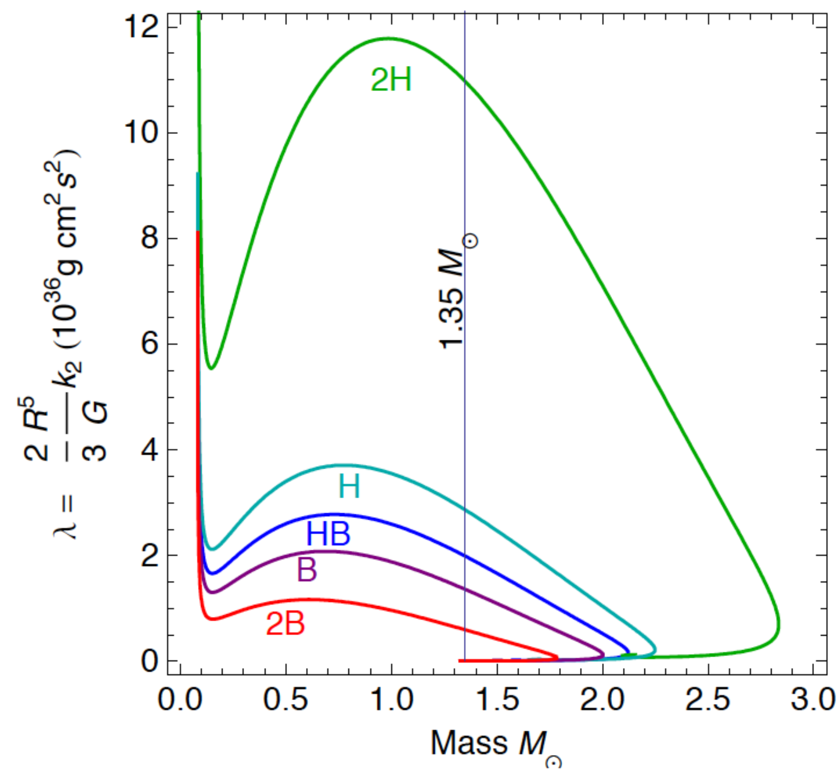
Radius R

$$\lambda = \frac{2}{3} k_2 R^5 \quad (G = c = 1)$$

J. Read, CGWAS 2015

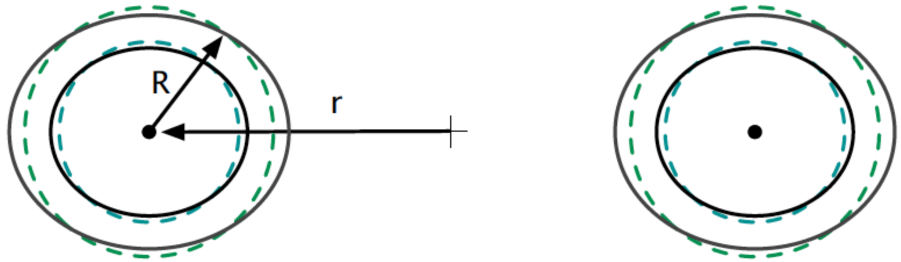
Equation of state determines λ for each M





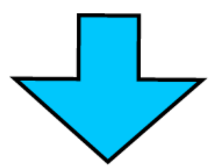
J. Read, CGWAS 2015

Effect of tides on orbit:



some energy into tides as stars come closer together

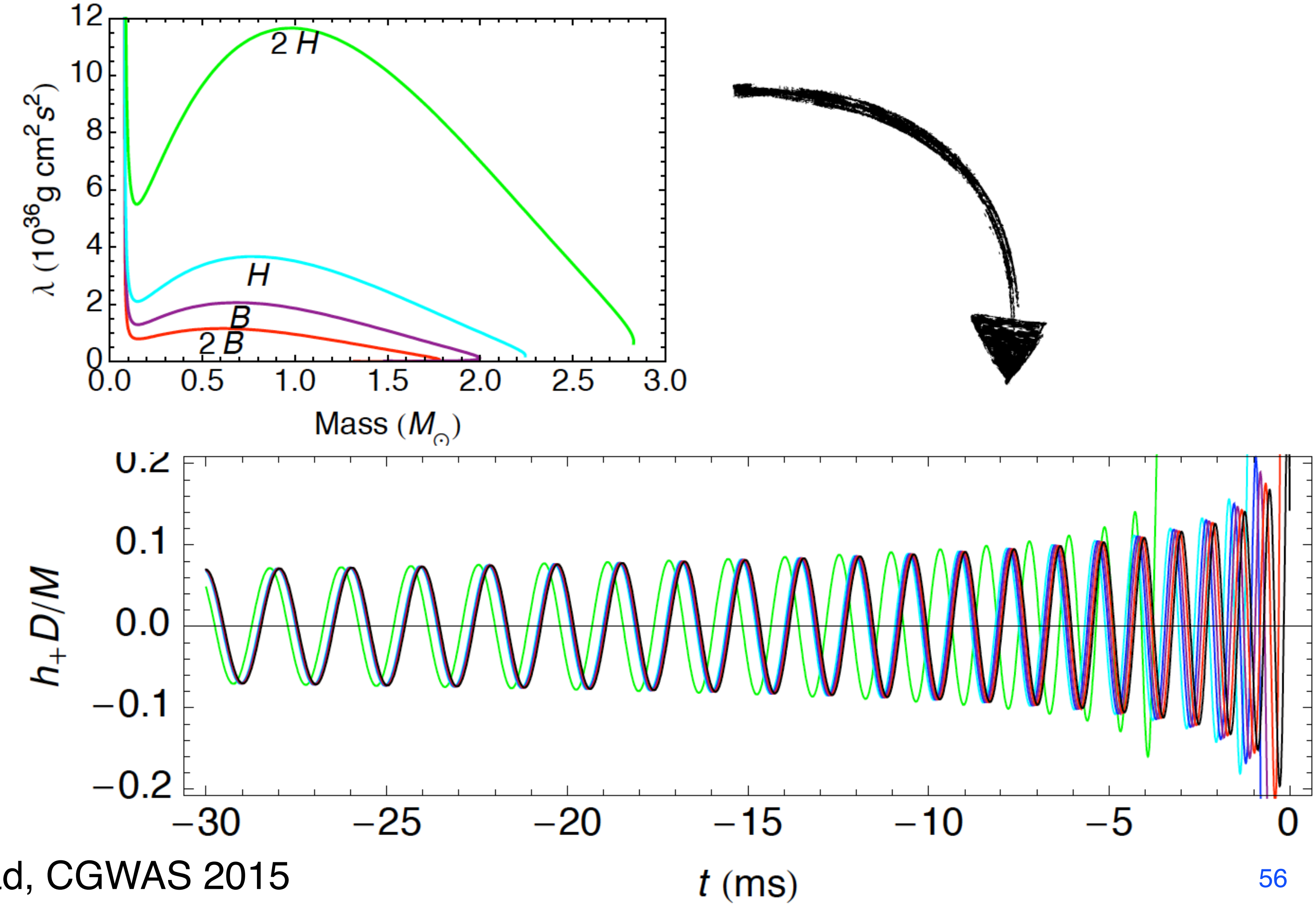
a bit of extra GW luminosity from rotating quadrupoles



stars merge earlier

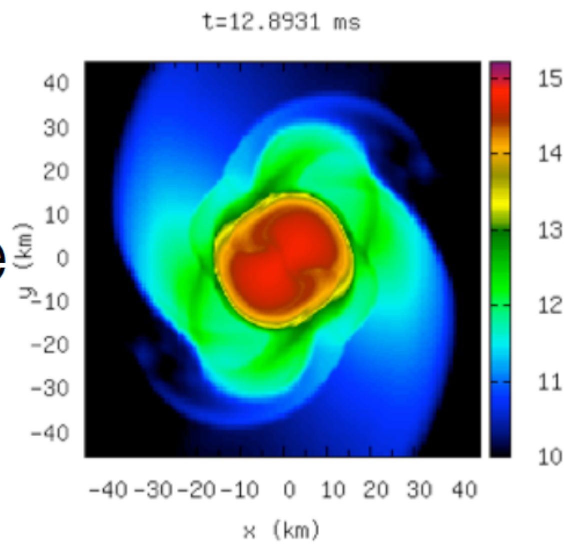
J. Read, CGWAS 2015

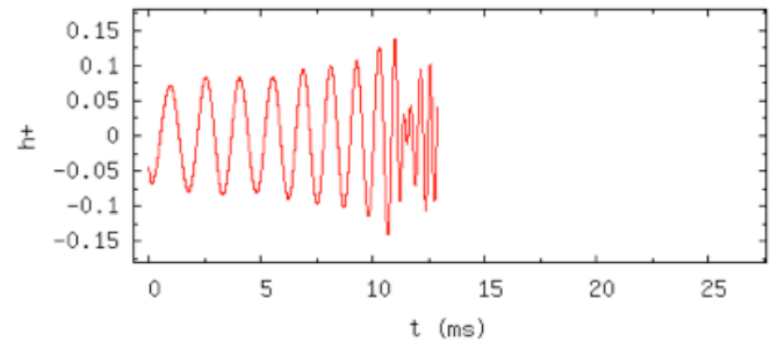
Tidal effect on PN waveforms



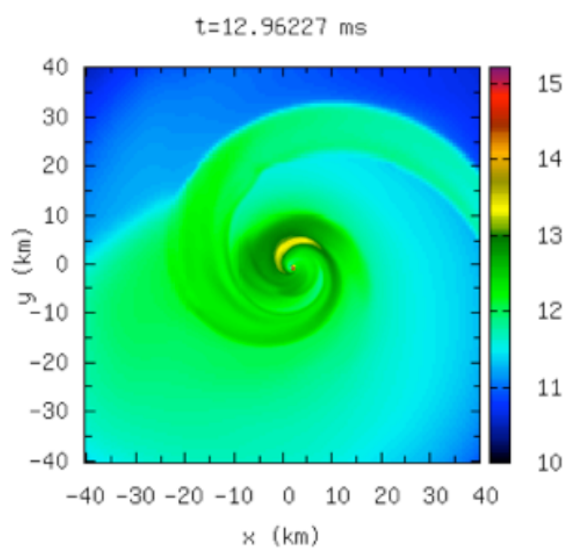
J. Read, CGWAS 2015

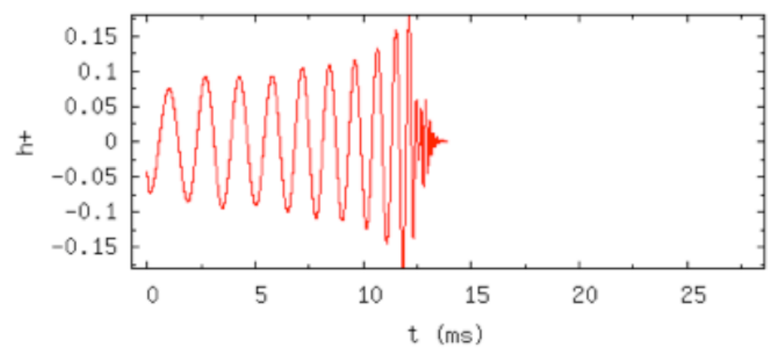
Large stars, Hypermassive Remnant





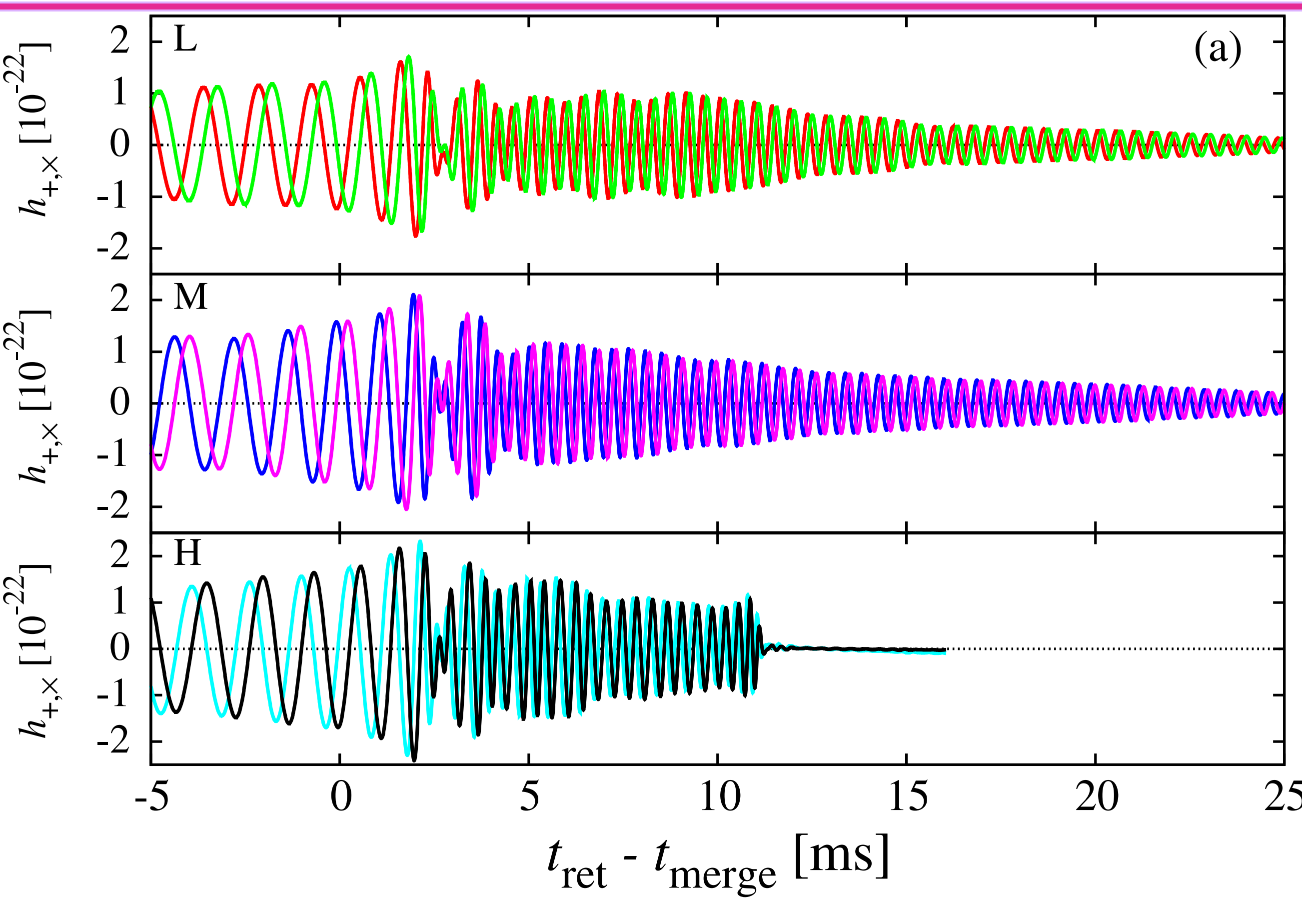
Compact stars, Prompt Collapse





Simulations & animations by K Hotokezaka

Nuclear Astrophysics: NS-NS Mergers



Mass [M_{Sun}]

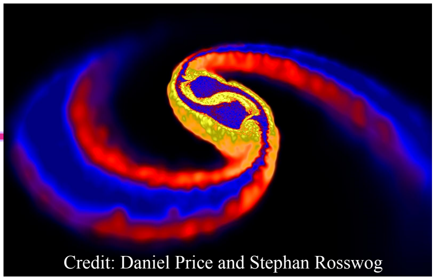
1.35 + 1.35

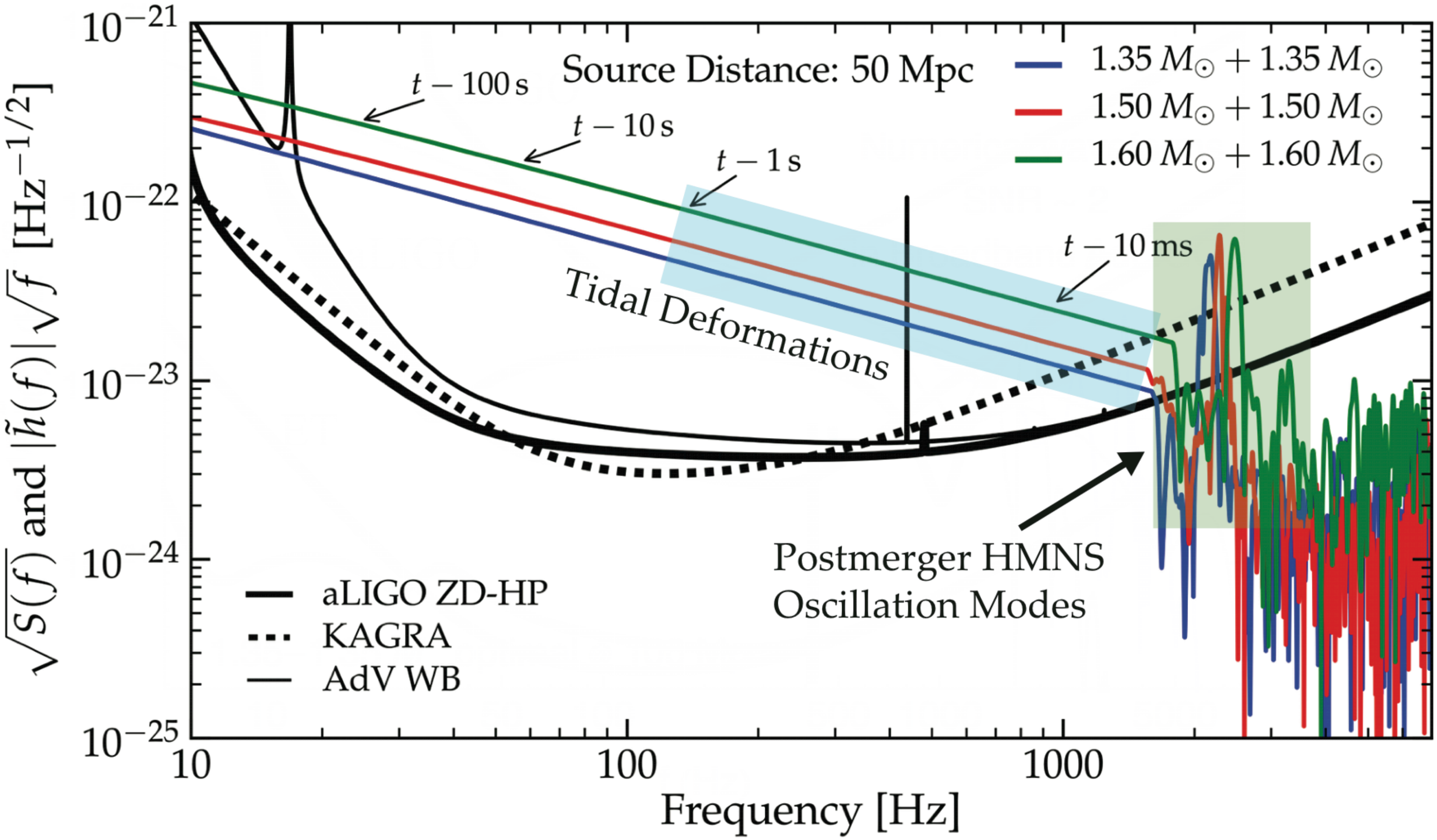
1.50 + 1.50

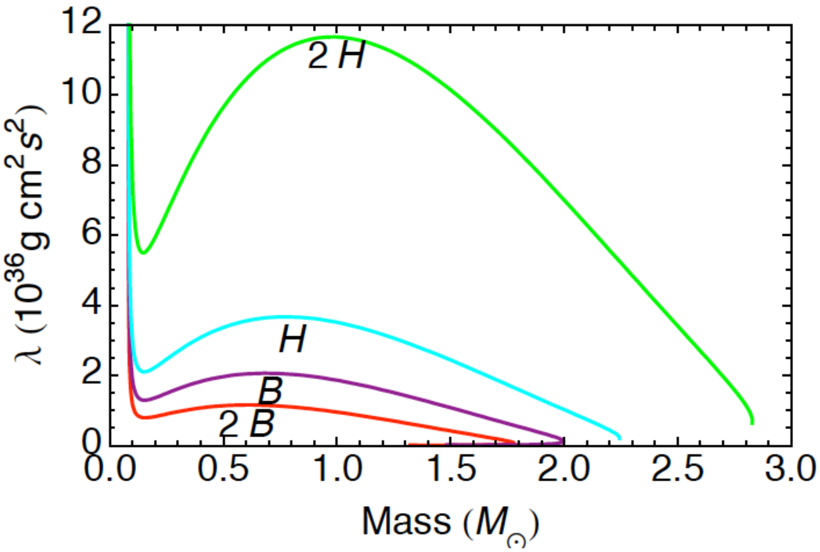
1.60 + 1.60

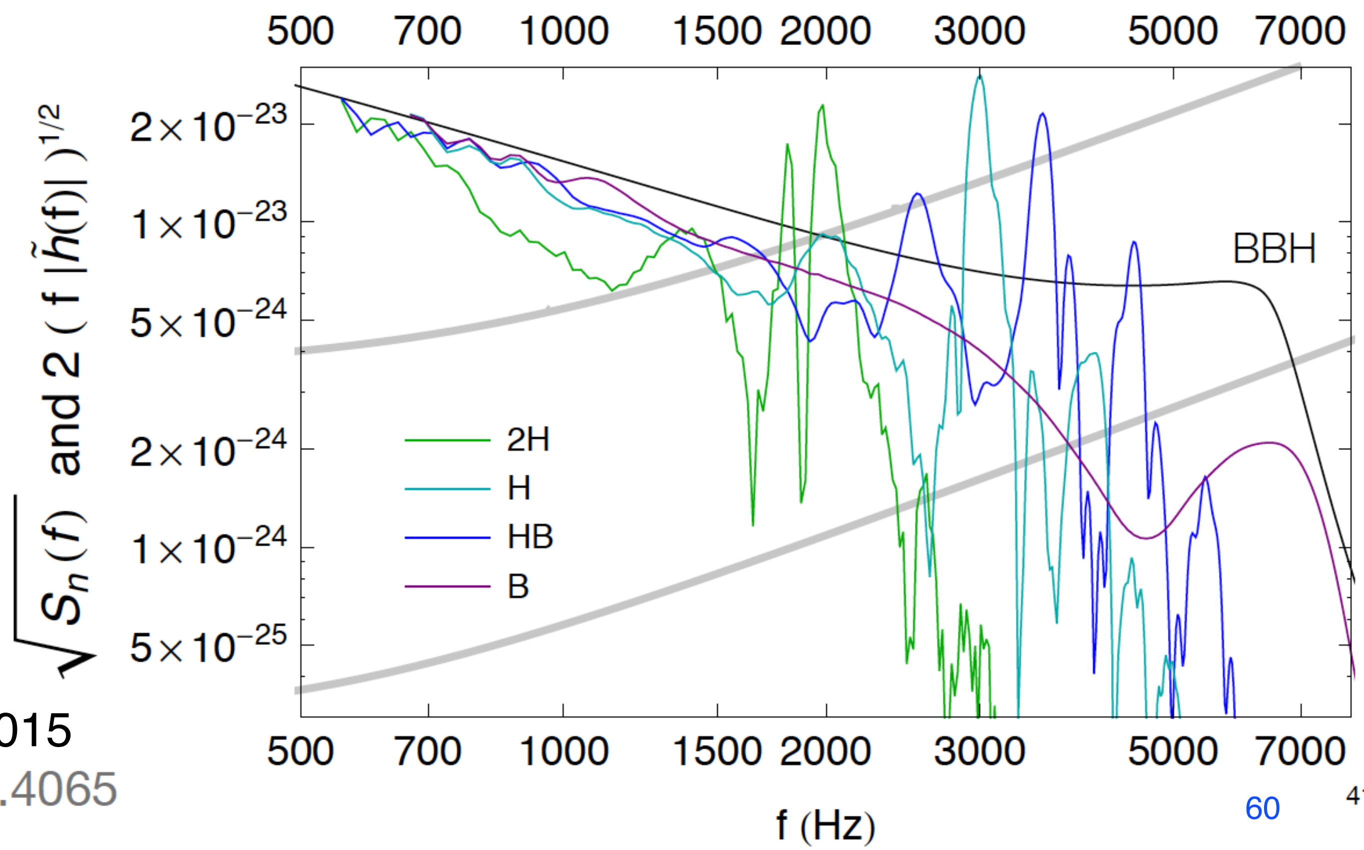
Sekiguchi+ 11: First full GR NS-NS simulation with realistic microphysics, finite-temperature nuclear EOS of H. Shen+ '98,'11

Effects of tidal disruption of neutron stars near merger





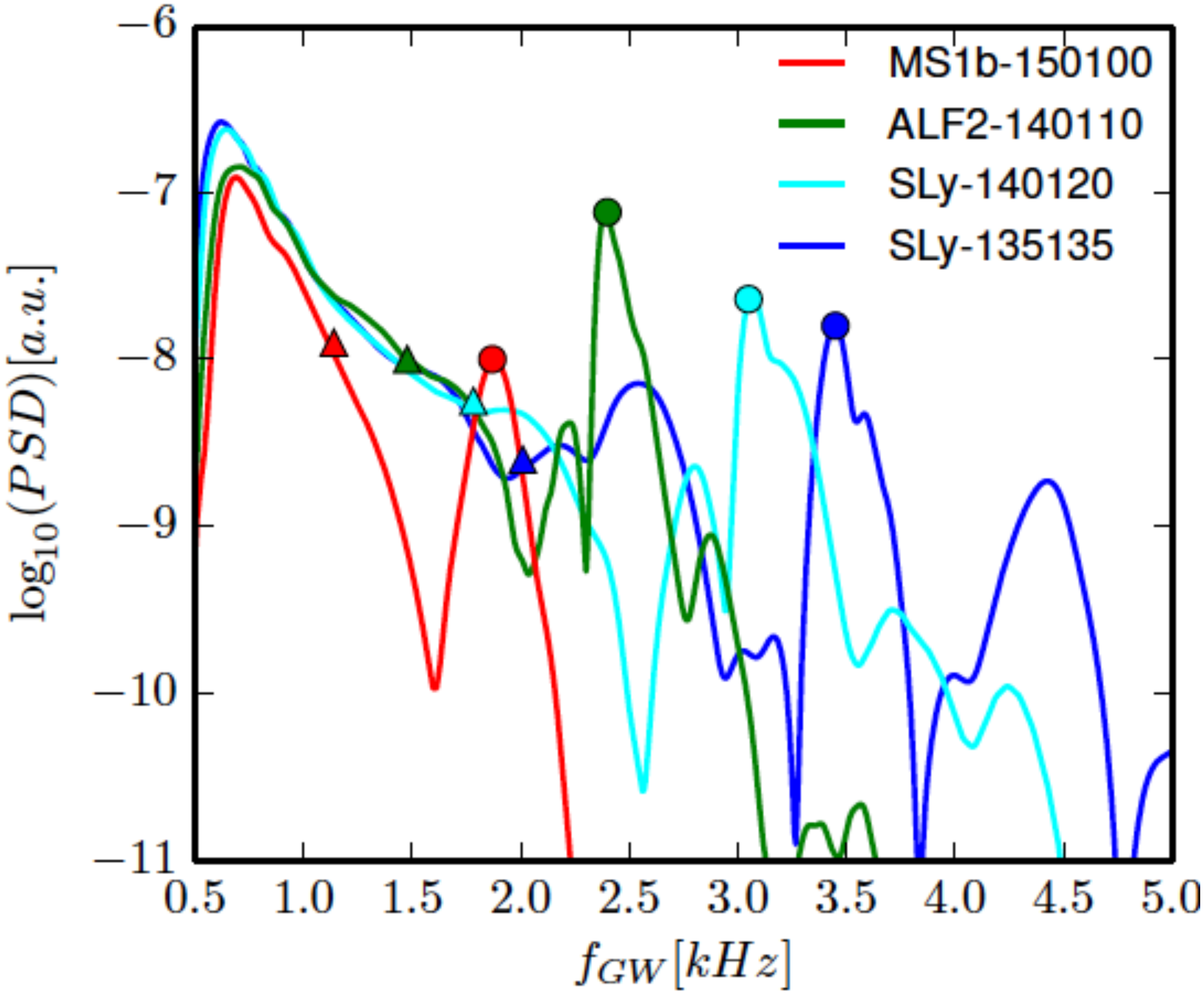




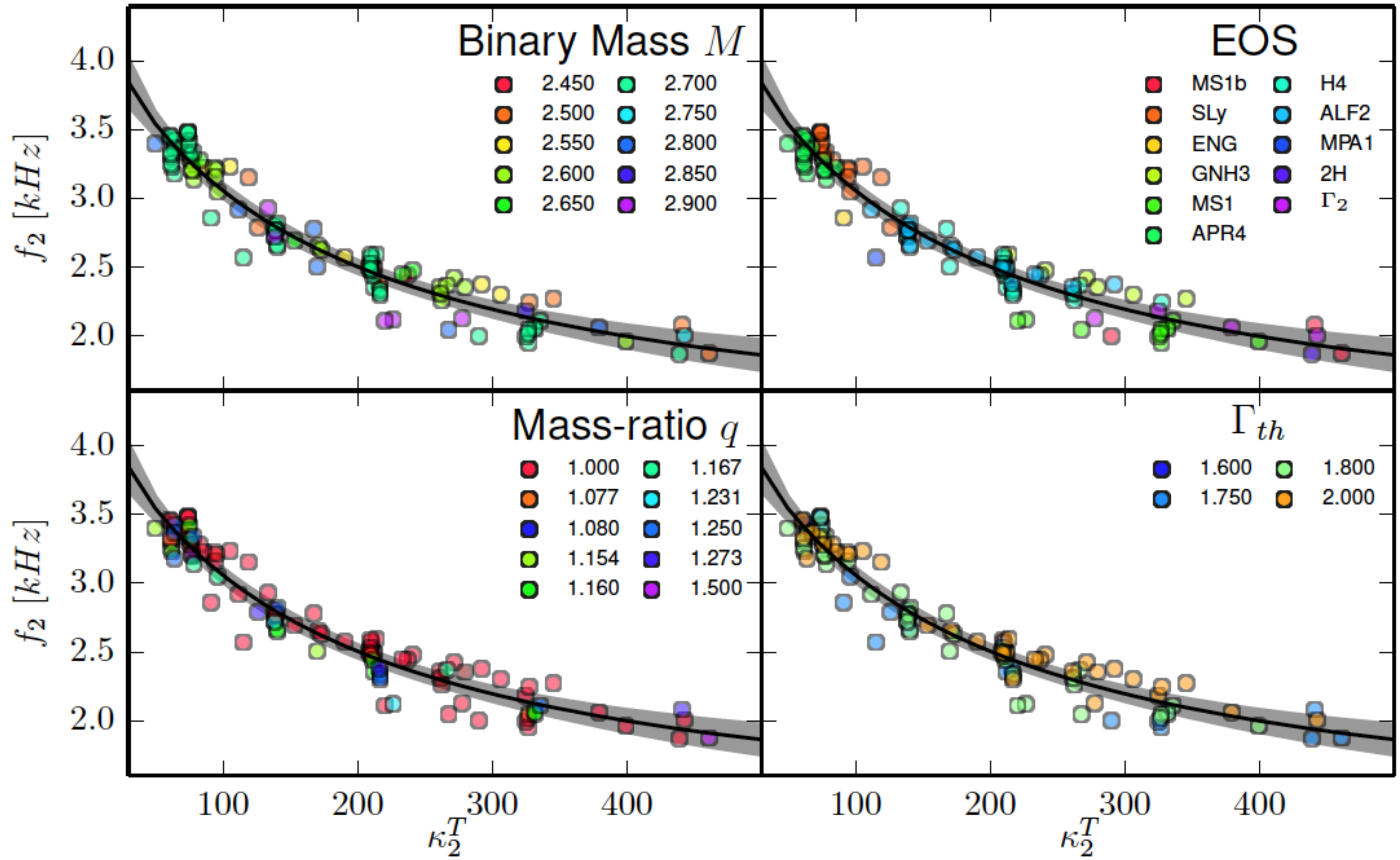
J. Read, CGWAS 2015

- arxiv.org/abs/1306.4065

Frequency of peak of final hyper-massive NS resonance



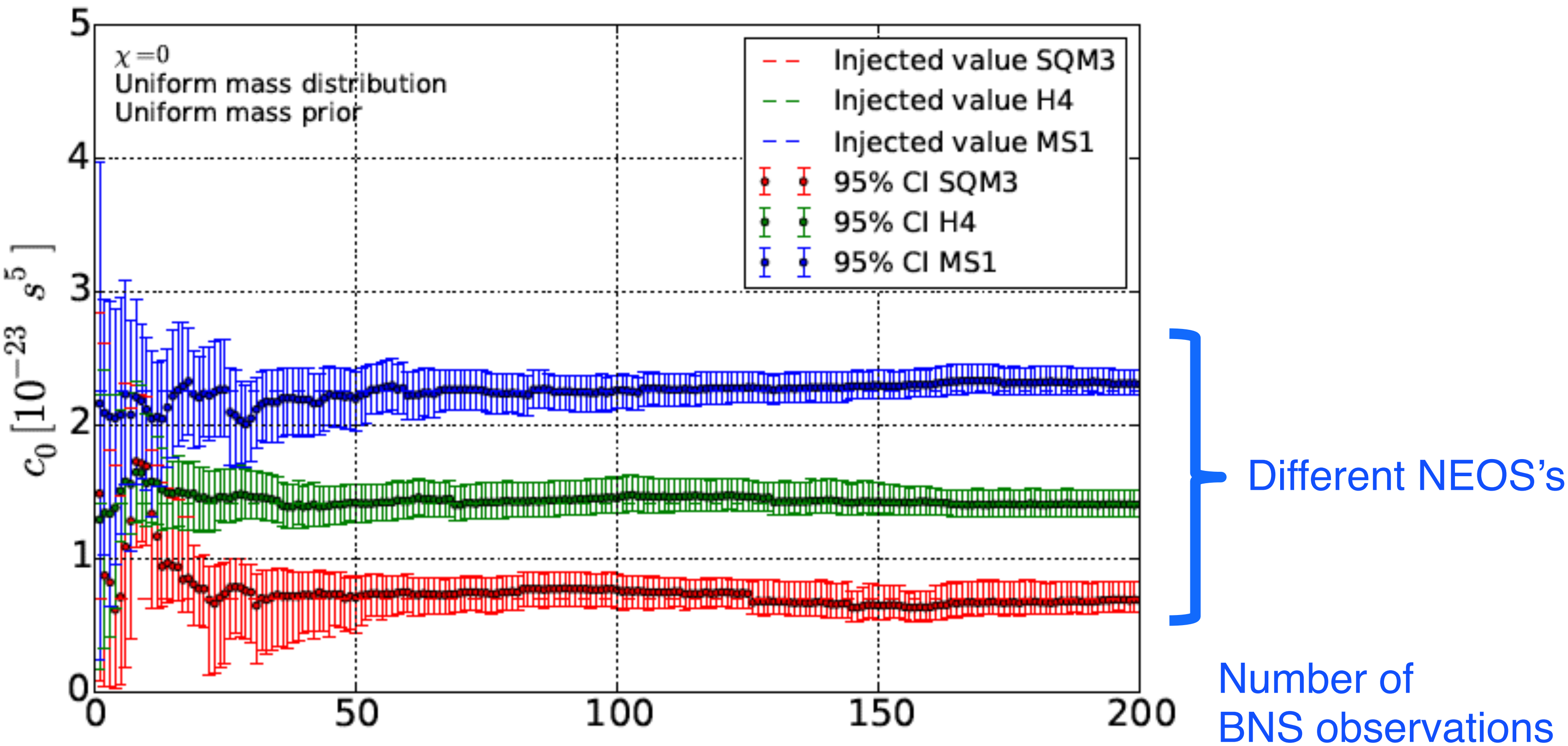
Universality of peak frequency



$$\kappa_2^T = 2\left(\frac{q^4}{(1+q)^5}\frac{k_2^A}{C_A^5} + \frac{q}{(1+q)^5}\frac{k_2^B}{C_B^5}\right)$$

S Bernuzzi, T Dietrich, A Nagar,
Phys Rev Lett 115, 091101 (2015) arxiv.org:1504.01764

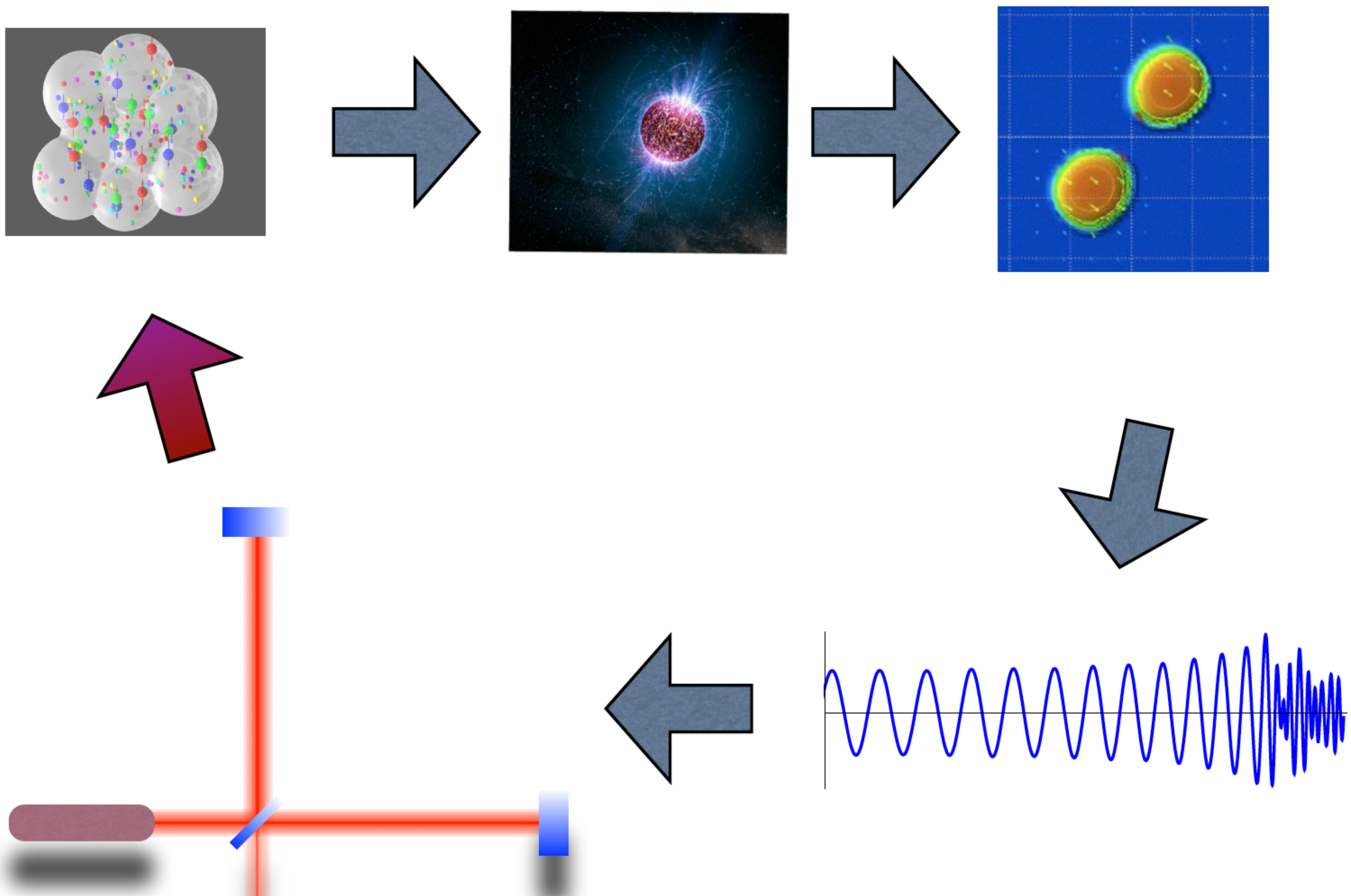
Many observations required to constrain NEOS



$$Q_{ij} = -\lambda(\mathrm{EOS}; m)\,\mathcal{E}_{ij} \qquad \lambda(m) = (2/3)k_2(m)R^5(m)$$

M. Agathos et al (LVC), Phys. Rev. D 92, 023012 (2015), arXiv:1503.05405v1

Constraining the NEOS using GWs from BNS



THANK YOU!

Questions?