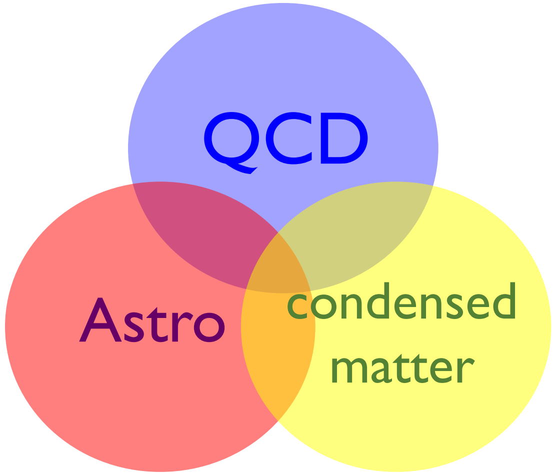
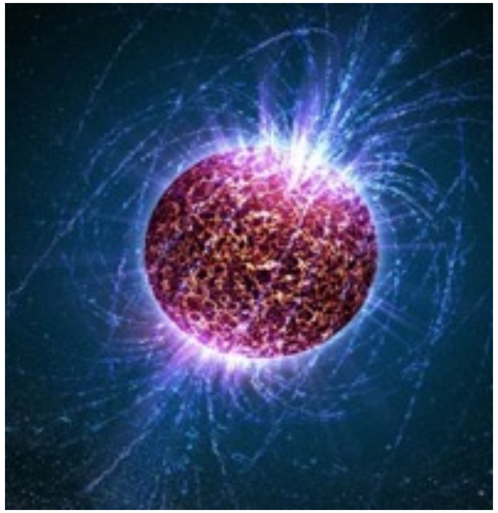
Neutron stars & multi-messenger physics

Toru Kojo

(**Tohoku Univ.**)





Plan

Lect 1) Overview

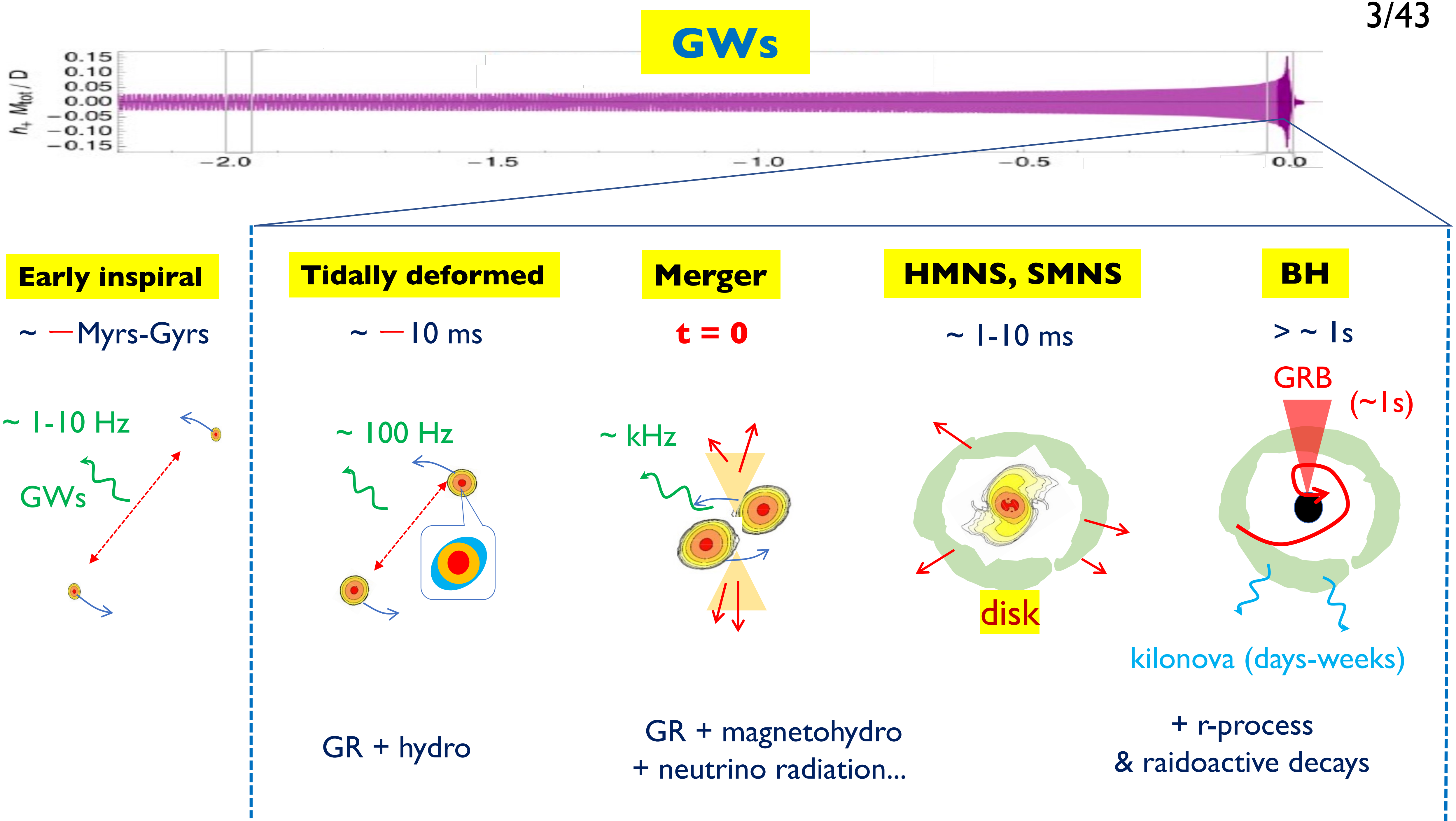
- glancing at NS properties
- M-R relation and EOS
- $R_{1.4}$ & low density EOS

Lect 2) NS-NS mergers

- gravitational waves
- pre-mergers [inspiral & tidal deformation]
- post-mergers [EM-counterparts]

Lect 3) From hadrons to quarks in NS

- quark matter
- 3-window modeling
- stiffening of matter in quark-hadron continuity


GWs
$h_+ M_{tot} / D$
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0.05
0.00
−0.05
−0.10
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HMNS, SMNS
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disk
BH
> ~ 1s
GRB
(~1s)
kilonova (days-weeks)
GR + hydro
GR + magnetohydro
+ neutrino radiation...
+ r-process
& raidoactive decays

References (reviews)

- L. Baiotti and L. Rezzolla, [arXiv:1607.03540]
  "Binary neutron-star mergers: a review of Einstein's richest laboratory"
- M. Shibata and K. Hotokezaka, [arXiv: 1908.02350]
  "Merger and Mass Ejection of Neutron-Star Binaries"
- D. Radice, S. Bernuzzi, and A. Perego, [arXiv: 2002.03863]
  "The Dynamics of Binary Neutron Star Mergers and of GW170817"
- K. Chatziioannou, [arXiv: 2006.03168]
  "Neutron star tidal deformability and equation of state constraints"
- N. Sarin and P. D. Lasky, [arXiv: 2012.08172]
  "The evolution of binary neutron star post-merger remnants: a review"

Gravitational Waves (GWs)

Einstein eq. $$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Riemann tensor

Ricci tensor $$R_{\alpha\beta} = R^{\rho}{}_{\alpha\rho\beta} = \partial_\rho \Gamma^{\rho}{}_{\beta\alpha} - \partial_\beta \Gamma^{\rho}{}_{\rho\alpha} + \Gamma^{\rho}{}_{\rho\lambda}\Gamma^{\lambda}{}_{\beta\alpha} - \Gamma^{\rho}{}_{\beta\lambda}\Gamma^{\lambda}{}_{\rho\alpha}$$

Ricci scalar $$R = g^{\alpha\beta}R_{\alpha\beta}$$

metric

Christoffel $$\Gamma^{\alpha}{}_{\beta\gamma} = \frac{1}{2}g^{\alpha\sigma}\left(\partial_\gamma g_{\sigma\beta} + \partial_\beta g_{\gamma\sigma} - \partial_\sigma g_{\beta\gamma}\right)$$

highly nonlinear eq. for strong large curvatures

flat metric small pert.

simplified for weak field regime: $$g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x)$$

Gravitational Waves (GWs)

Einstein eq. $$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

1) linearized in metric

2) use the general covariance for coordinates:

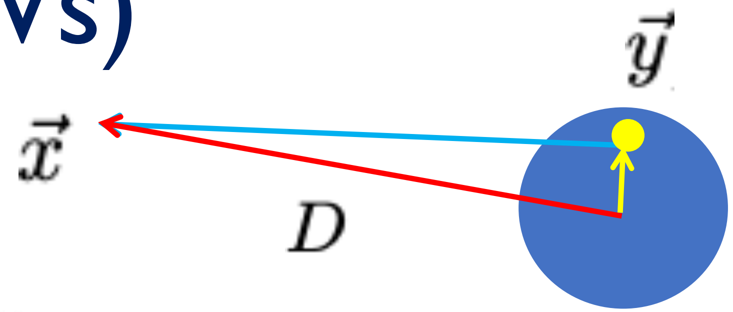
gauge fixing:
4 + 4 conditions (Lorentz gauge)

10 d.o.f → 2 physical d.o.f in *h*

Now we define: $$\psi_{\mu\nu} \equiv h_{\mu\nu} - \frac{1}{2} \eta_{\mu\nu} \eta^{\alpha\beta} h_{\alpha\beta}$$

Einstein eq. is reduced to: $$\partial^2 \psi_{\mu\nu} = -16\pi G T_{\mu\nu}$$ wave-eq.

Gravitational Waves (GWs)



$$\partial^2 \psi_{\mu\nu} = -16\pi G T_{\mu\nu}$$

retardation time

$$\Rightarrow \psi_{\mu\nu}(t, \vec{x}) = 4G \int_{\vec{y}} \frac{T_{\mu\nu}(t - |\vec{x} - \vec{y}|, \vec{y})}{|\vec{x} - \vec{y}|} \simeq \frac{4G}{D} \int_{\vec{y}} T_{\mu\nu}(t_{\rm ret}, \vec{y})$$

$$t_{\rm ret} \equiv t - D/c$$

formal solutions

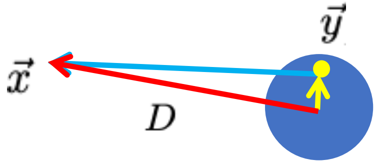
$$\partial_\mu T^{\mu\nu} = 0 \quad \Rightarrow \quad T^{0i} = \partial_k(T^{k0} x^i) + x^i \partial_0 T^{00}$$

$$T^{ij} = \frac{1}{2}\left[\partial_k(T^{ki} x^j + T^{kj} x^i) + \partial_0(T^{0i} x^j + T^{0j} x^k)\right]$$

$$= \partial_k(\cdots) + \partial_0^2(T^{00} x^i x^j)$$

total derivative

2nd time derivative of energy quadrupole



Gravitational Waves (GWs)

fluctuating quadrupole

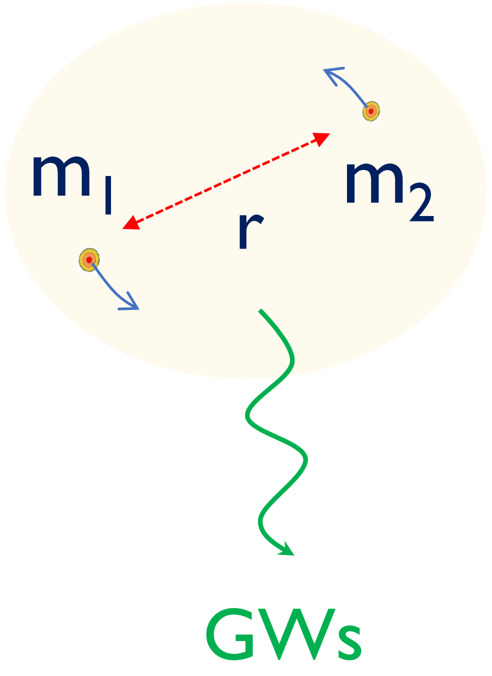
$$\psi_{ij}(t,\vec{x}) \simeq \frac{4G}{D}\int_{\vec{y}} T_{ij}(t_{\rm ret},\vec{y}) = \frac{4G}{D}\partial_0^2\int_{\vec{y}} \varepsilon y_i y_j = \frac{4G}{D}\ddot{I}_{ij}(t_{\rm ret})$$

e.g.) binary

$$I_{xx} = \mu r^2 \cos^2 \omega t$$
$$I_{yy} = \mu r^2 \sin^2 \omega t$$

$\omega = [GM_{tot}/r^3]^{1/2}$ [Kepler]

$$\mu = m_1 m_2/M$$



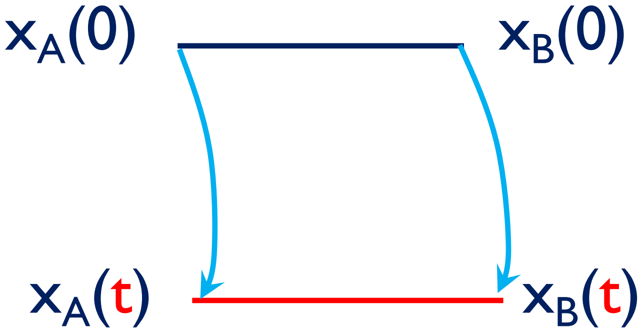
eliminate r

$$h_{\max} = \frac{4G}{D}\mu r^2\omega^2 = \frac{4G^{5/3}}{D}\mu M^{2/3}\omega^{2/3}$$

$$\mu M^{2/3} \equiv \mathcal{M}_{\rm chirp}^{5/3}$$ "*chirp mass*" (observable)

the signals are large for large M_{chirp}, ω, and small D

Geodesic deviation



grav. pot.

$$\ddot{x}^i_A = -\partial^i \Phi(x_A)$$

$$\ddot{x}^i_B = -\partial^i \Phi(x_B)$$

Newtonian

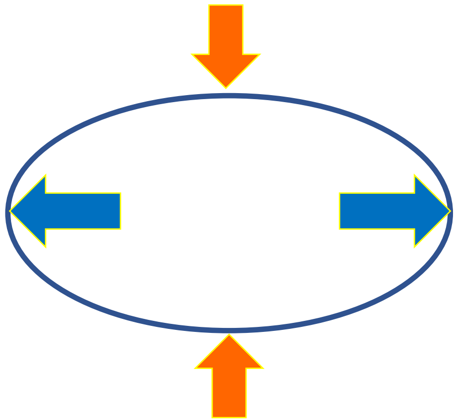
$$\delta \ddot{x}^i = -\left(\partial^i \partial_j \Phi_A\right) \delta x^j$$

GR version:

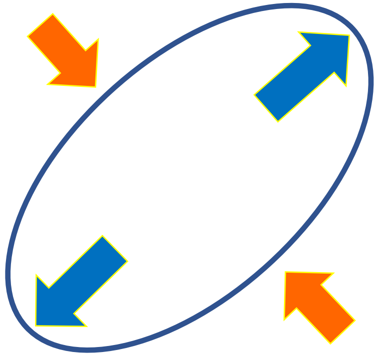
$$\delta \ddot{x}^i = R^i{}_{00j} \delta x^j = R_{i00j} \delta x^j = \frac{\ddot{h}_{ij}}{2} \delta x^j$$

For GWs:

+ mode



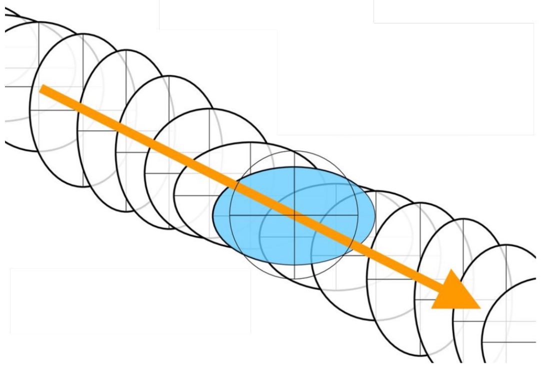
X mode



GW170817

Detecting GWs from NS-NS mergers

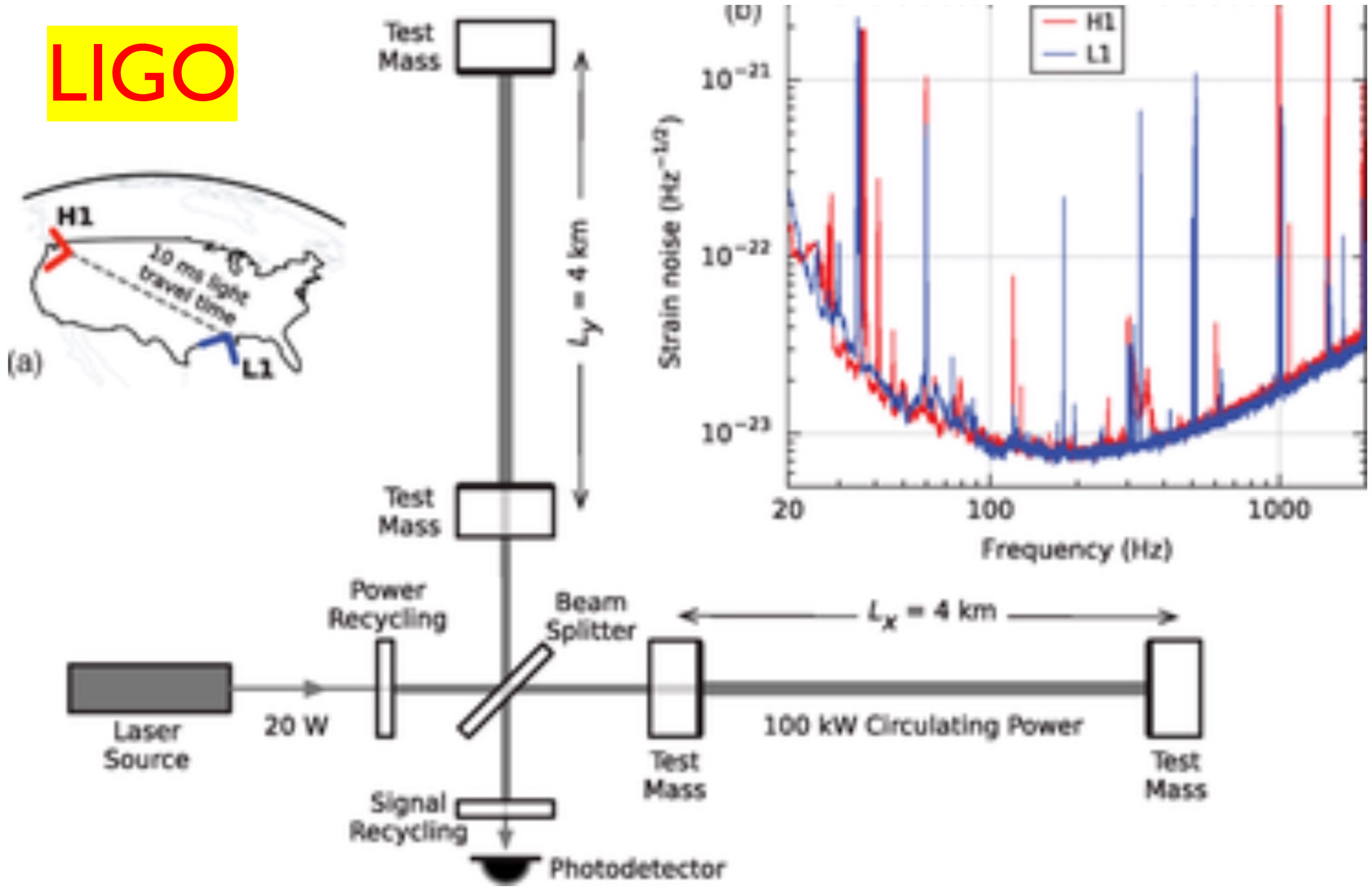
distortion of space-time



$$g_{\mu\nu} \simeq \eta^{\text{flat}}_{\mu\nu} + \underline{h_{\mu\nu}}$$

$\Delta L/L \sim 10^{-23}$!!

LIGO



magnitude

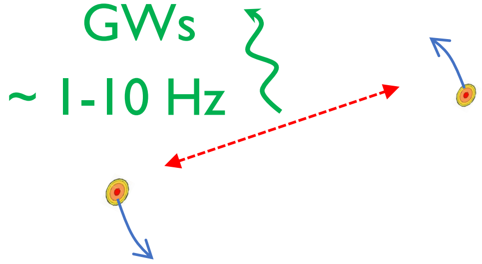
$$h \simeq \underline{10^{-23}} \left(\frac{M_{\rm NS}}{M_\odot}\right)^{5/3} \left(\frac{f}{200\,{\rm Hz}}\right)^{2/3} \left(\frac{100\,{\rm Mpc}}{R}\right)$$

distance to the NS-NS

How long do we have to wait?

$$t_{\text{merge}} - t \approx \underline{7\times10^6\,\text{yr}} \left(\frac{T}{\underline{1\,\text{hr}}}\right)^{8/3} \left(\frac{M_c}{1.21 M_\odot}\right)^{-5/3} \approx 3\times10^{10}\,\text{yr} \left(\frac{T}{1\,\text{day}}\right)^{8/3} \left(\frac{M_c}{1.21 M_\odot}\right)^{-5/3}$$

orbit



NS-NS binaries in **our galaxy**

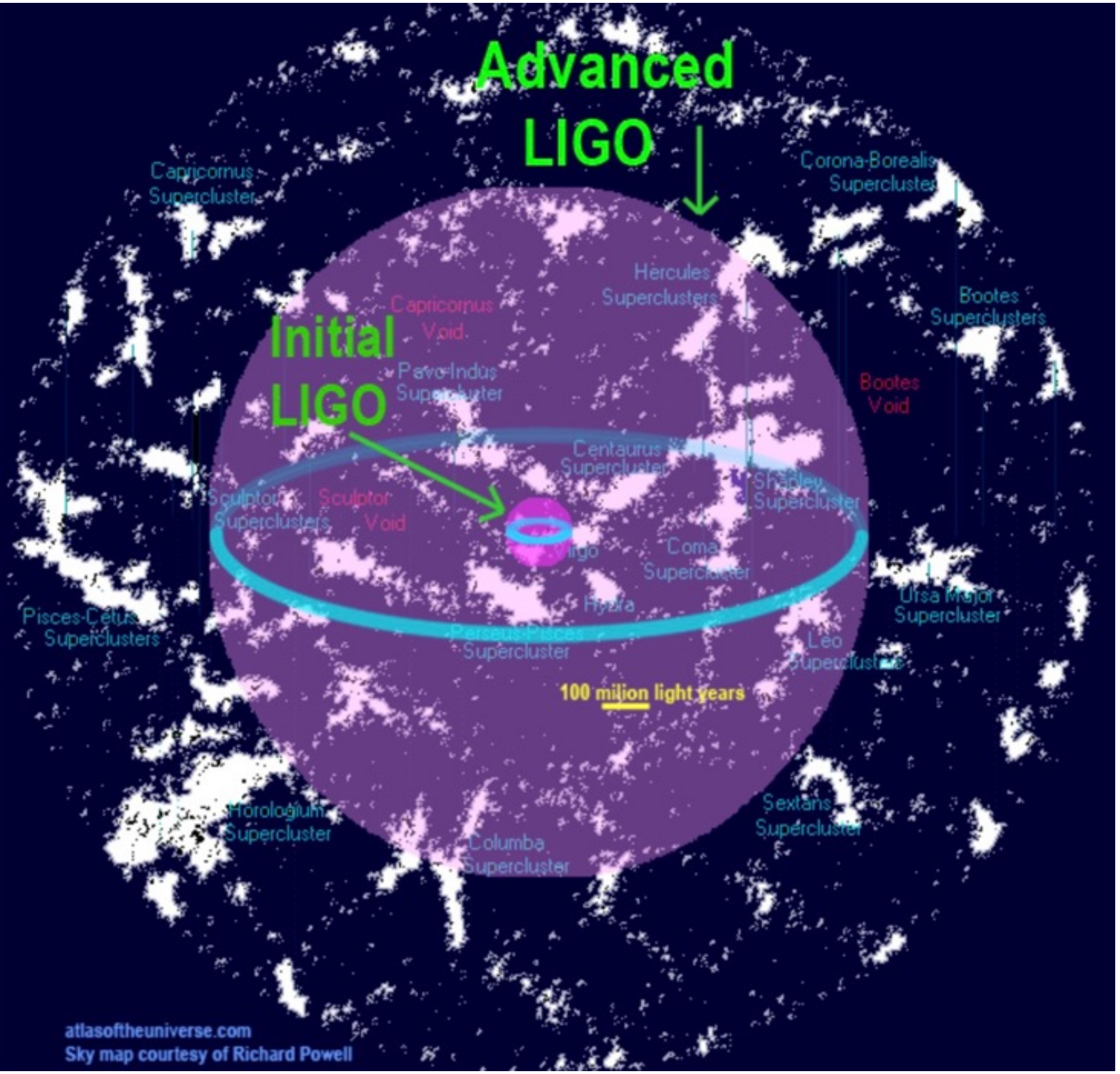
T_{orbit} ~ hr -day

will **NOT** be merged in next ~10^6 yrs

Name	M_{tot} [$M_\odot$]	M_A [$M_\odot$]	M_B [$M_\odot$]	q	T_{orb} [days]	R [light s]	e_{orb}	D [kpc]	f_s [Hz]	B_{surf} [G]
J0453+1559 [8]	2.734	1.559	1.174	0.75	4.1	14	0.11	1.8	22	9.3E+09
J0737-3039 [9]	2.587	1.338	1.249	0.93	0.10	1.4	0.088	1.1	44	6.4E+09
J1518+4904 [10]	2.718	<1.766	>0.951	>0.54	8.6	20	0.25	0.7	24	9.6E+08
B1534+12 [11]	2.678	1.333	1.345	0.99	0.42	3.7	0.27	1.0	26	9.6E+09
J1753-2240 [12]	–	–	–	–	14	18	0.30	3.5	10	9.7E+09
J1756-2251 [13]	2.577	1.341	1.23	0.92	0.32	2.8	0.18	0.73	35	5.4E+09
J1807-2500B [14]	2.571	1.366	1.21	0.89	1.0	29	0.75	–	239	≤9.8E+08
J1811-1736 [15]	2.571	<1.478	>1.002	>0.68	19	35	0.83	5.9	9.6	9.8E+09
J1829+2456 [16]	2.59	<1.298	>1.273	>0.98	1.2	7.2	0.14	0.74	24	1.5E+09
J1906+0746 [17]	2.613	1.291	1.322	0.98	0.17	1.4	0.085	7.4	6.9	1.7E+12
J1913+1102 [18]	2.875	<1.84	>1.04	>0.56	0.21	1.8	0.090	13	1.1	2.1E+09
B1913+16 [19]	2.828	1.449	1.389	0.96	0.32	2.3	0.62	7.1	17	2.3E+10
J1930-1852 [20]	2.59	<1.199	>1.363	>0.88	45	87	0.40	2.3	5.4	6.0E+10
B2127+11C [21]	2.713	1.358	1.354	1.0	0.34	2.5	0.68	13	33	1.2E+10

To detect rare events

1pc = 3.26 lyr

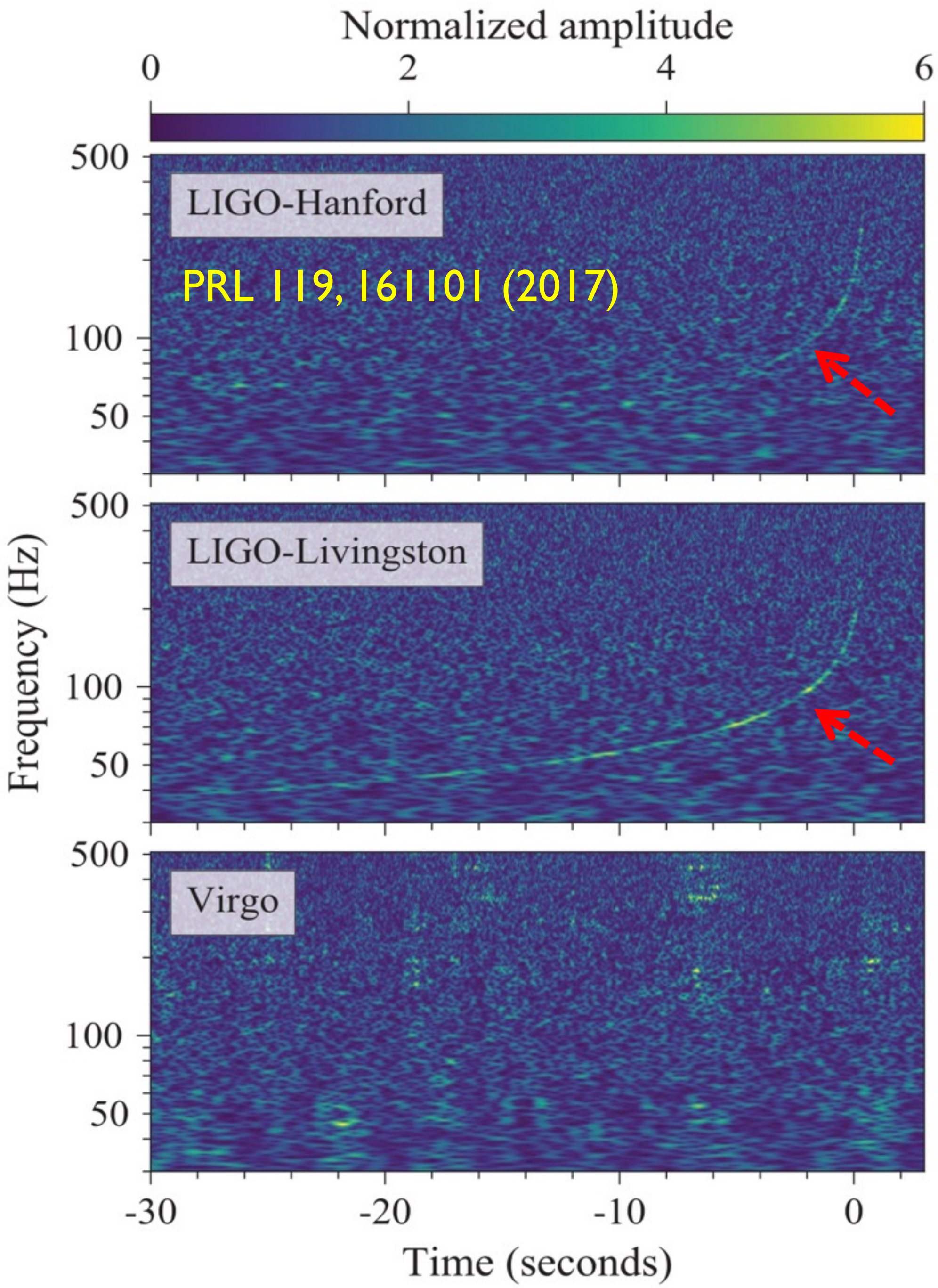


- our **galaxy** (milky-way) ~ 31-55 **kpc**
- to **the edge of universe** ~ 14 **Gpc**
- detector horizon
  - **aLIGO**
    Livingston ~ 218 **M**pc
    Hanford ~ 107 **M**pc
  - **Virgo** ~ 58 **M**pc

→ expected detection rate

0.1 – 100 events/year

- GW170817 happened at 40^{+8}_{-14} Mpc



On Aug. 17, 2017

- aLIGO: signal-to-noise = 32.4 !
- Virgo did not find it

  GWs from the blind spot of Virgo

  → strongly constrain the location

  → trigger follow-up EM studies

- clear signal 20 Hz - 1kHz

  inspiral – tidal deformed phases

- NOT measured for > ~1**k**Hz

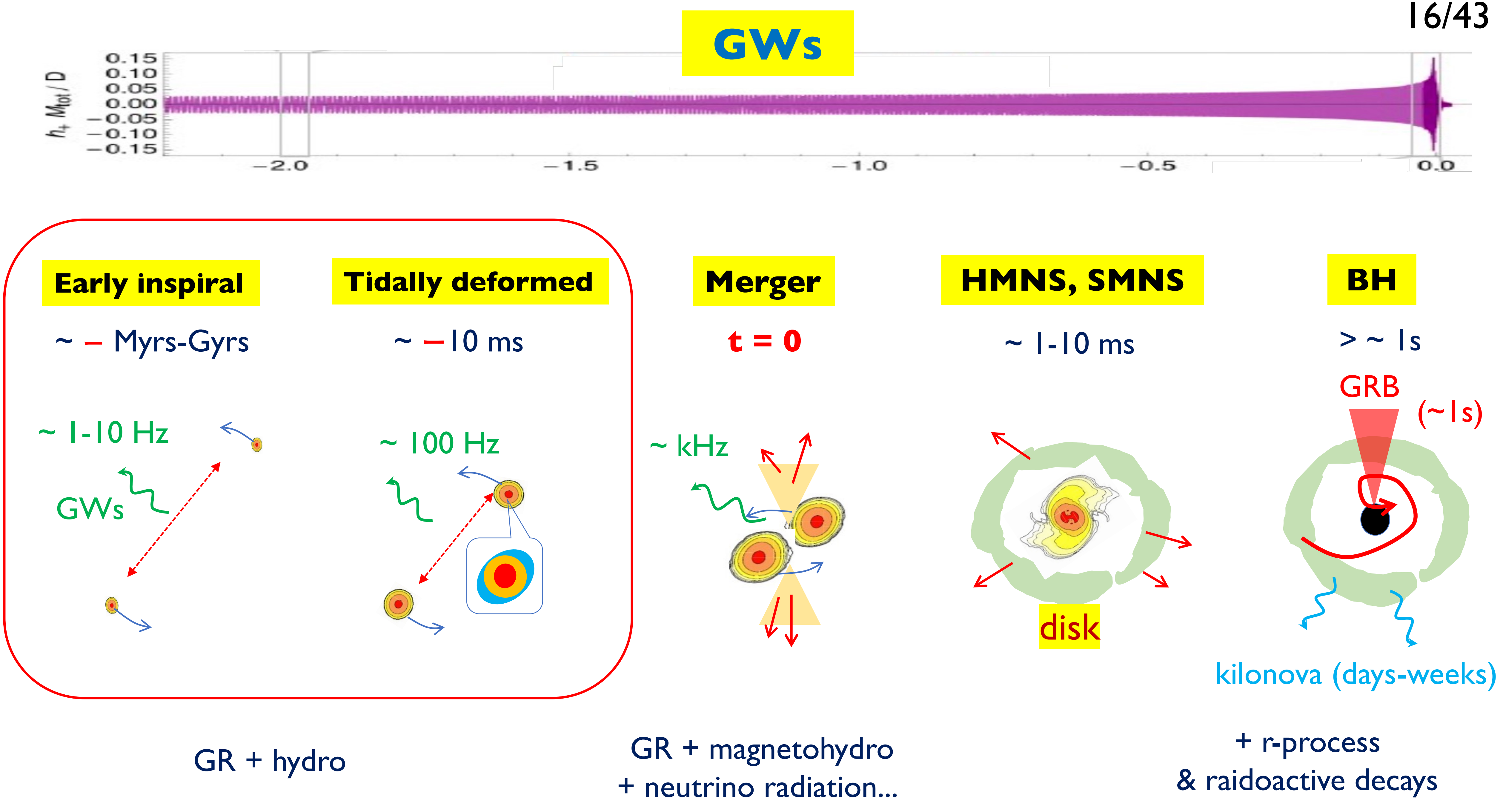
  larger noise at higher frequency

- EM signals from objects just after merger

  but neutrino signals too small

Pre merger

inspiral & tidally deformed phases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Early inspiral
~ – Myrs-Gyrs
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~ –10 ms
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Merger
t = 0
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GRB
(~1s)
kilonova (days-weeks)
GR + hydro
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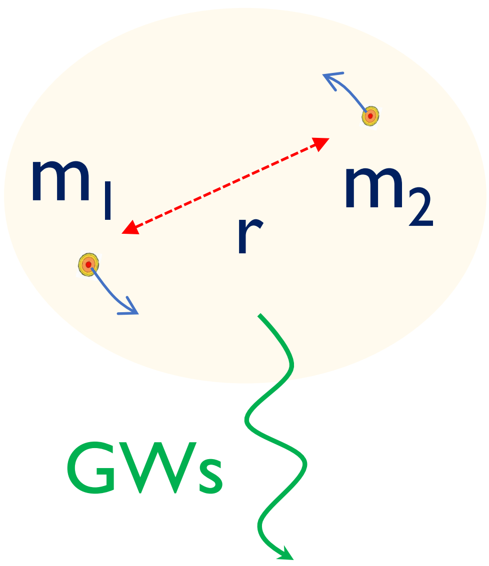
+ neutrino radiation...
+ r-process
& raidoactive decays

Inspiral phase



chirp mass $\mathcal{M} := (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$

$$\approx 1.188^{+0.004}_{-0.002} M_\odot$$ (well constrained)

mass ratio: $q = m_2/m_1 = 0.7 - 1.0$ (not well constrained)

Nevertheless, $m_{tot} = m_1 + m_2$ is well constrained:

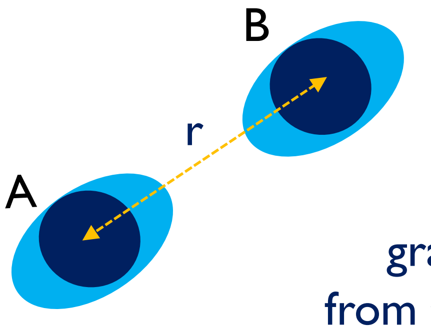
(insensitive to details of q)

$$m_{tot} = 2.74^{+0.04}_{-0.01} M_\odot$$

$m_{1,2} = 1.3 - 1.5\ M_\odot$

(typical)

Tidally deformed phase



quadrupole moment

polarizability

$$Q_{ij} = -\lambda(M) E_{ij}$$

external field

$$E_{ij} = -\frac{\partial^2 V}{\partial x_i \partial x_j}$$

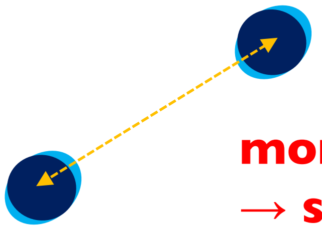
grav. pot. from the star A

$$V_A(r) \simeq -\frac{GM_A}{r} - \frac{GQ_{AB}}{r^3}$$

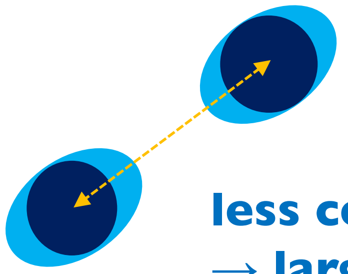
deformation of A by B

additional **attraction**

→ **NSs approach faster**



more compact
→ smaller Q



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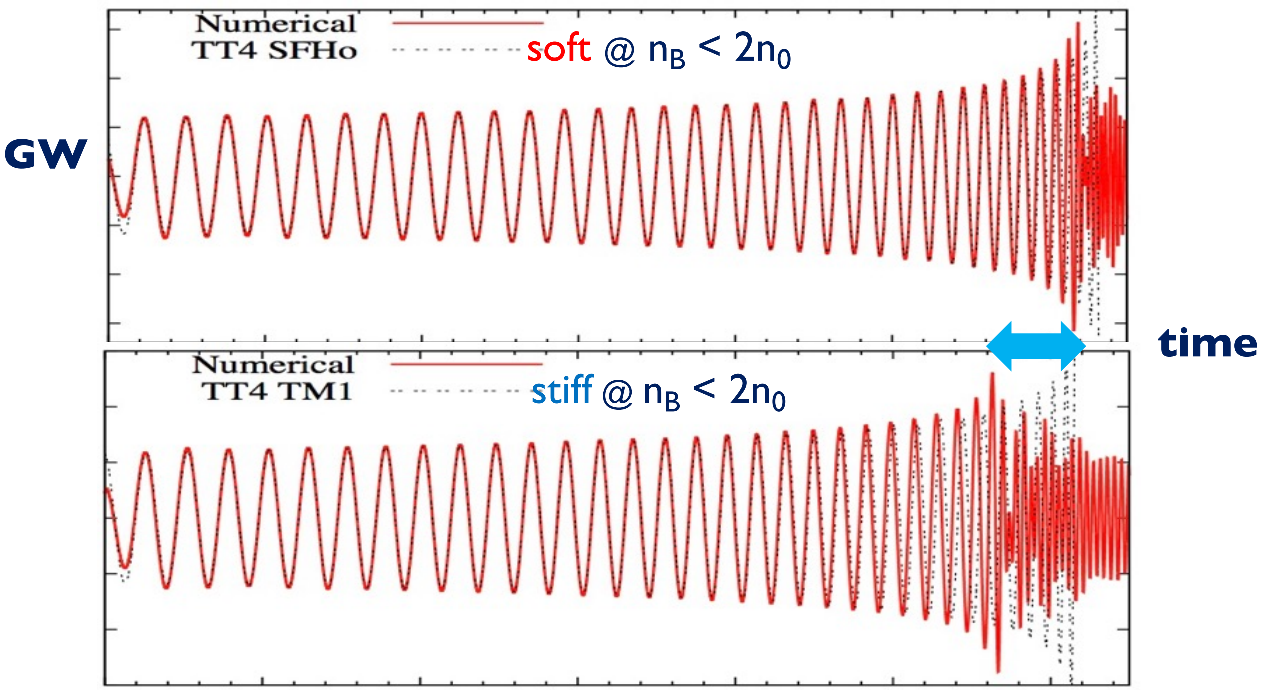
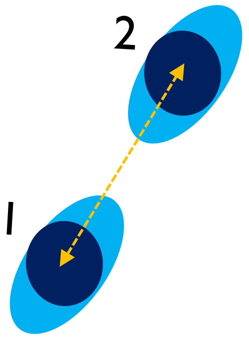


Dimensionless tidal deformability → R_{NS}



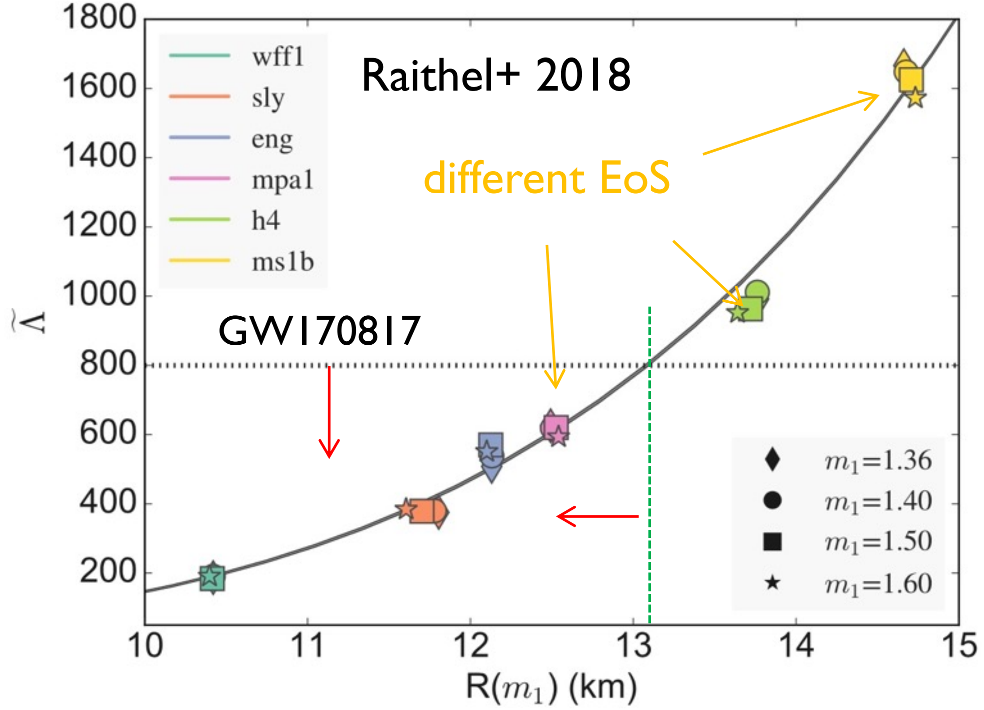
more common to use $$\Lambda(M) = 32\frac{\lambda G}{R^5}$$ ← R^{-5} (!)

What GW analyses measure: combination of Λ for star 1 & 2 :

$$\tilde{\Lambda} = \frac{16}{13}\frac{(M_1+12M_2)M_1^4\Lambda_1 + (M_2+12M_1)M_2^4\Lambda_2}{(M_1+M_2)^5}$$

(measured)

2-parameters: M_1 & M_2



For **GW170817** :

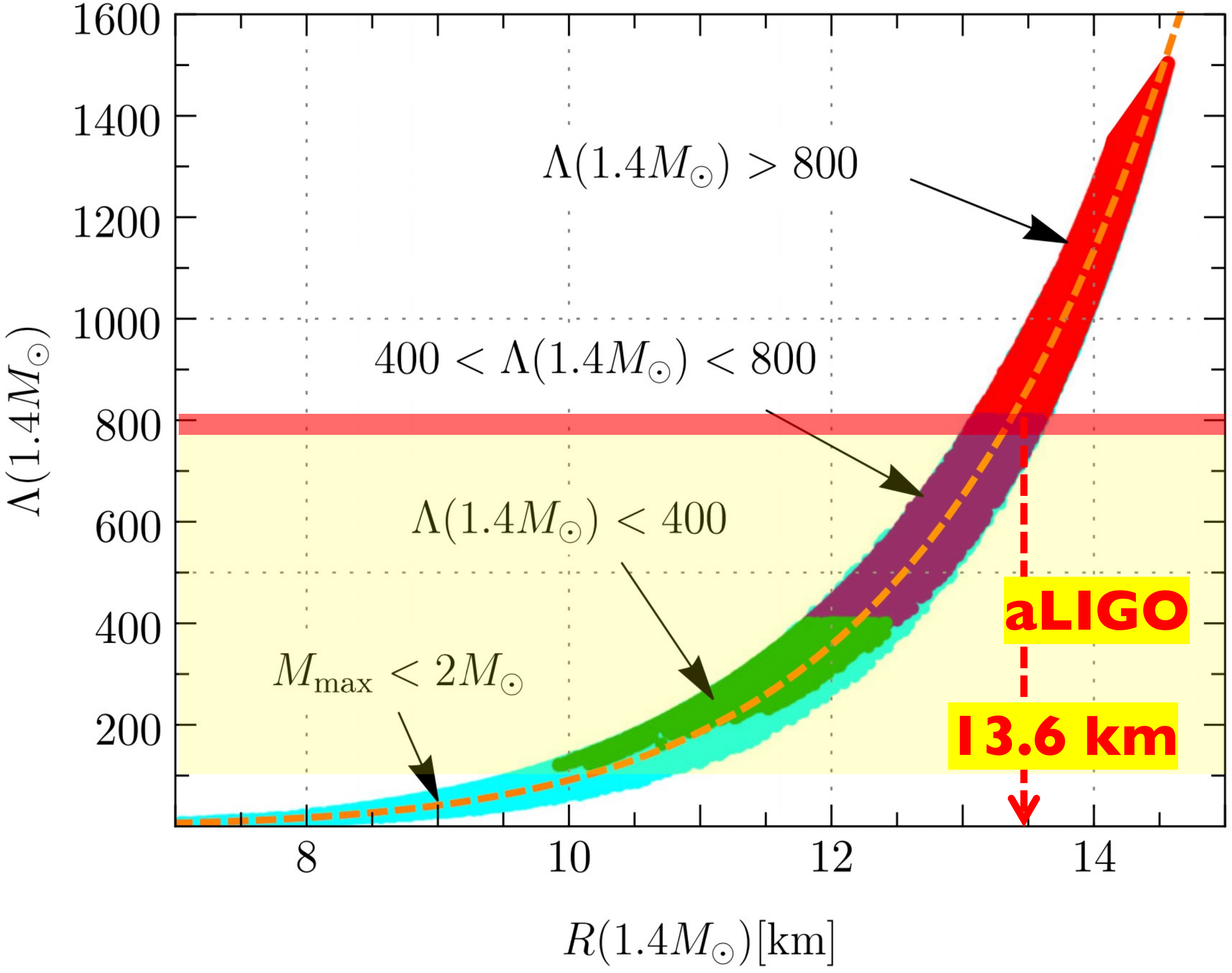
chirp mass (1.188 M_{sun}) (determined)

$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = m_1 \frac{q^{3/5}}{(1+q)^{1/5}}$$

mass ratio $q = M_2/M_1$ (undetermined)

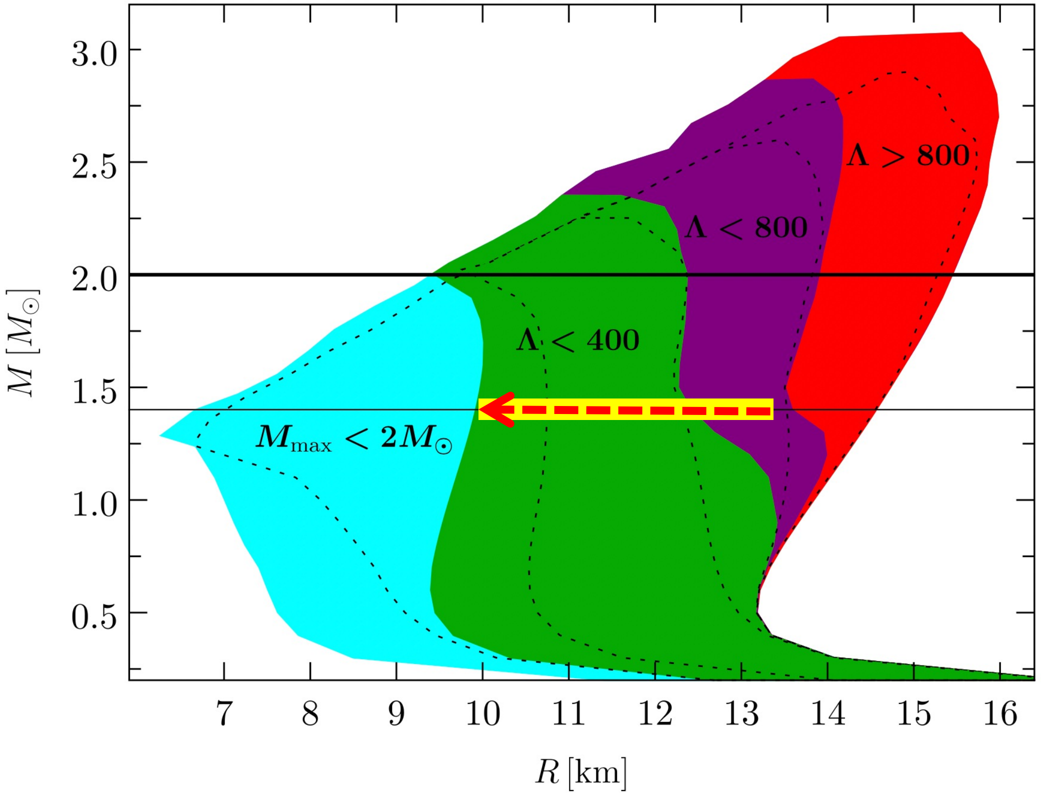
→
- different q degenerate !
- R < ~ 13 km

Constraints on $R_{1.4}$ [e.g., Annala+ '18]



with ChEFT constraint up to $1.1n_0$

& pQCD constraint down to $40n_0$

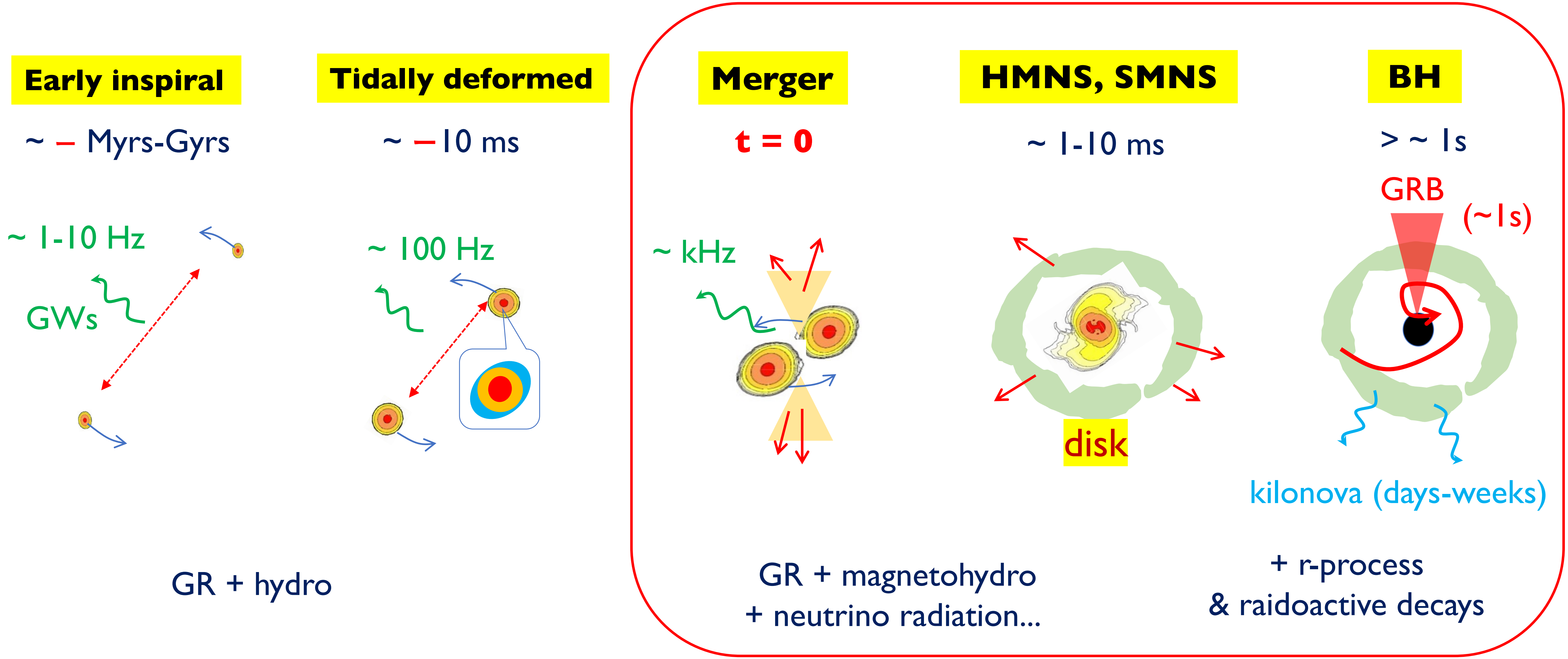


Post merger

short-lived vs long-lived NS remnants

GWs


$h_+ M_{tot} / D$
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−2.0
−1.5
−1.0
−0.5
0.0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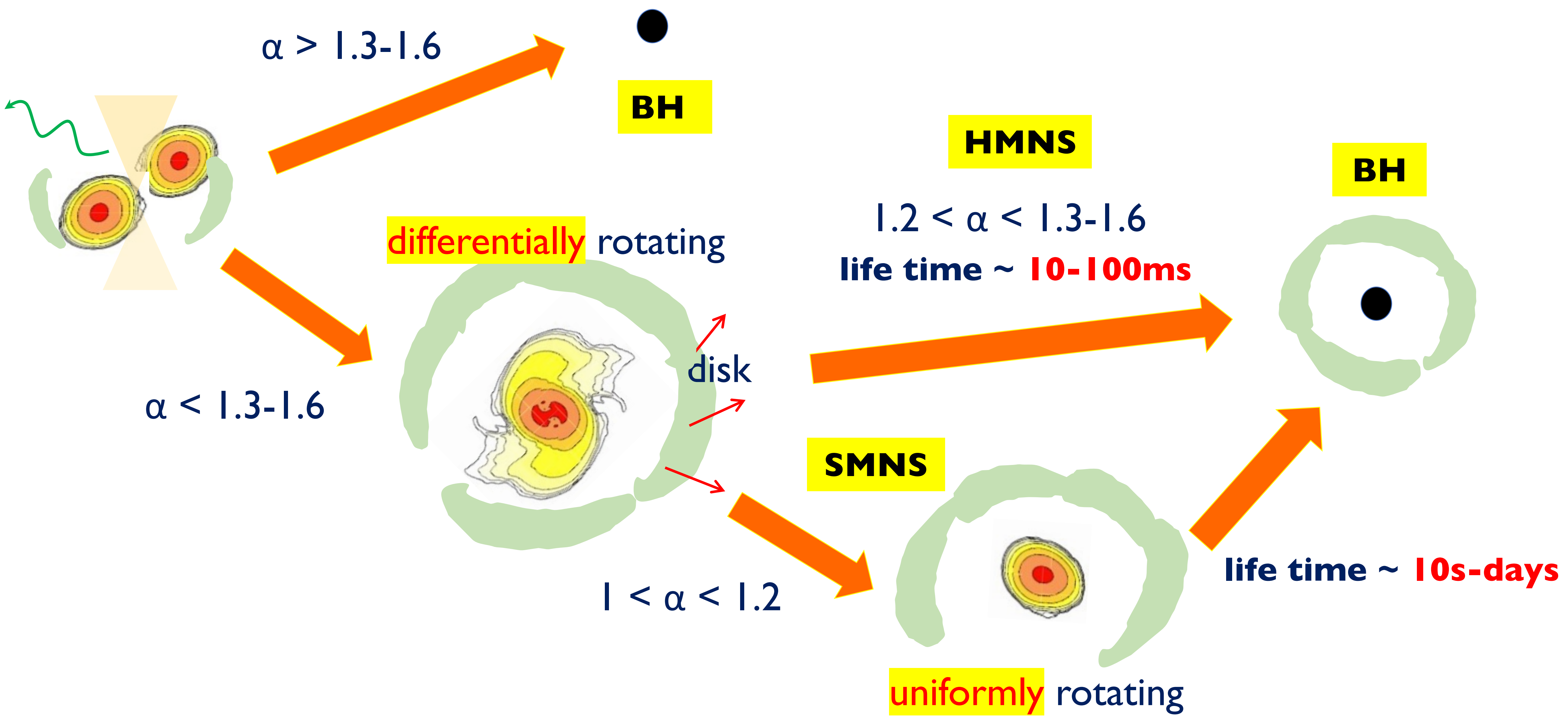
Fate of post-merger depends on $\alpha = M/M_{TOV}$



Supports for threshold masses

$$M_{thre} = M_{TOV}^{max} + \Delta M_{rot,\,rigid} + \Delta M_{rot,\,diff} + \Delta M_{therm}$$

$\Delta M_{rot,\,rigid}$: additional support from rigid rotation, ~ 0.2 M_{TOV}^{max}

→ for long time:

$\Delta M_{rot,\,diff}$: additional support from differential rotation, ~ 0.1-0.4 M_{TOV}^{max}

→ only for short time: viscosity & magnetic field braking

ΔM_{therm} : additional thermal support

→ only for short time: neutrino emissions remove thermal support

➡ need sophisticated "*numerical GR* + *magnetohydro* + *microphysics*"

Life time → constraints on M_{TOV}

If the merger in GW170817 (M_{tot} = 2.73-2.78M_{sun})

1) promptly collapsed to BH [unlikely, see below]

M_{tot}/M_{TOV} > 1.3-1.6 → M_{TOV} < 1.71-2.14

2) is **HMNS** (life time ~ 10-100 ms → diff. rot. stops)

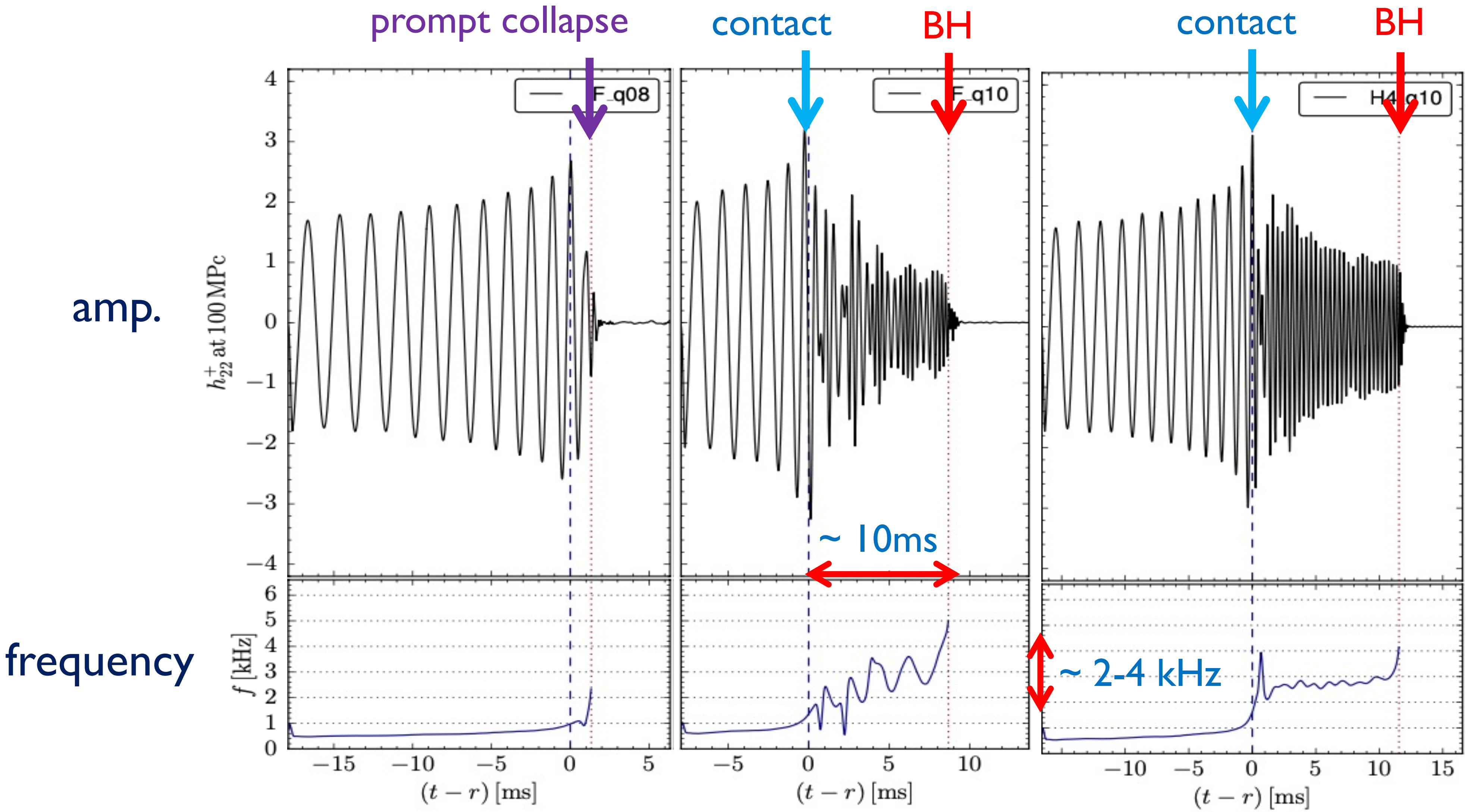
1.2 < M_{tot}/M_{TOV} < 1.3-1.6 → 1.71-2.14 < M_{TOV} < 2.28-2.32

3) is **SMNS** (life time ~10s - days → loss of angular mom.)

M_{tot}/M_{TOV} < 1.2 → M_{TOV} > 2.28-2.32 (!?)

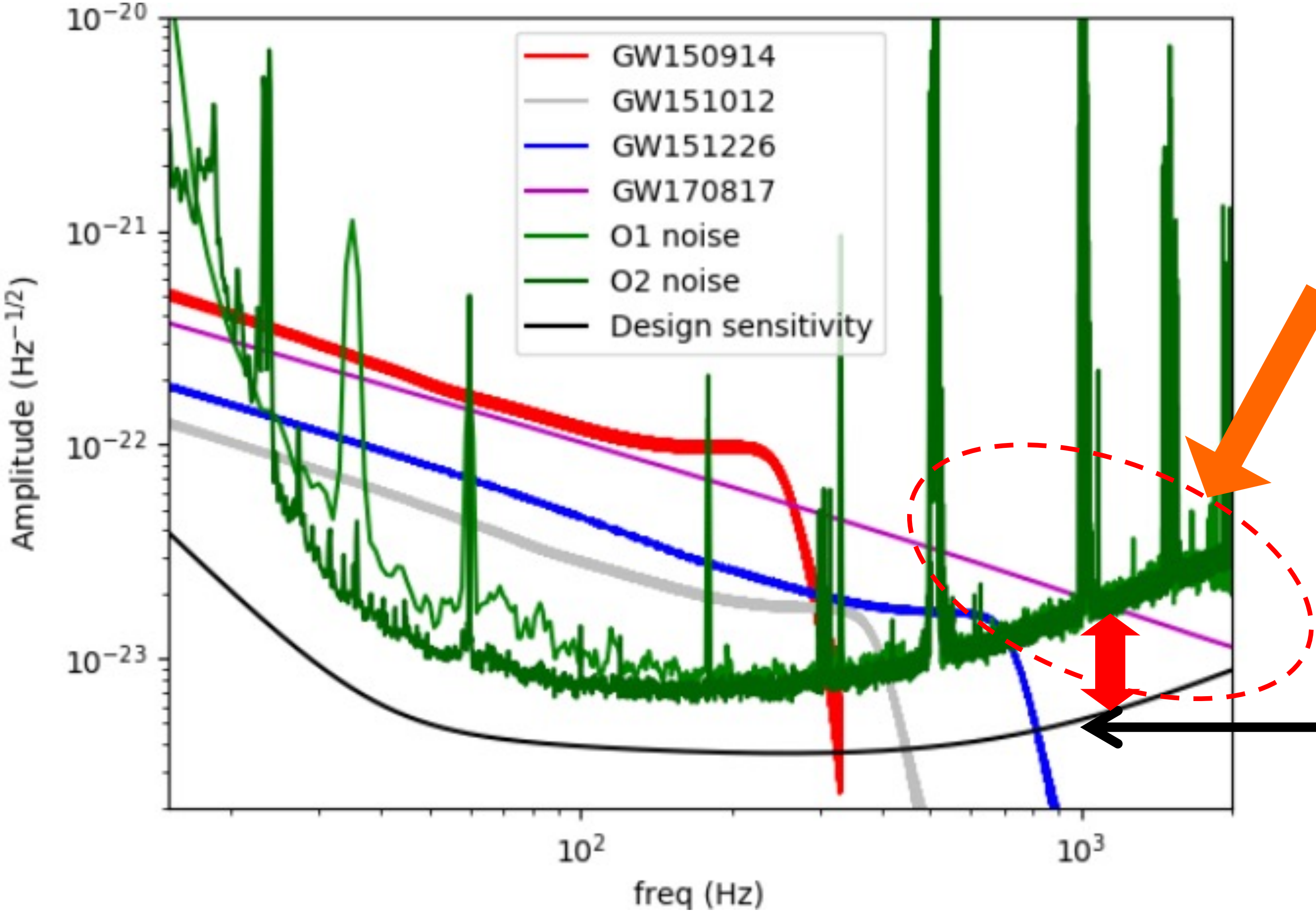
GWs from HMNS: life time

[Fig. from Kawamura+ '16]



GWs from post-mergers ??

ideal to determine the life time, but not measured yet (!)



GWs from post-mergers
with > ~ **1kHz**
are difficult to measure

- smaller signals for f with less cycles
  (as in usual Fourier analyses)
- noises in detectors are large

design sensitivity

Alternative signals for post-mergers

electromagnetic (EM) counterparts

- Gamma Ray Burst (GRB170817A)
- kilonova light curves (AT 2017gfo)
- heavy r-process nuclei (solar-abundance)

key quantities: ejecta mass M_{ej} & proton fraction Y_p

(sensitive to short- vs long-lived NS)

Y_p again (see also lect.1, page 12)

cold NS (wo neutrinos) $(p_F^n)^2 = 2M_N\, p_F^p + \ldots$ (large scale: M_N) $(p_F^n \gg p_F^p)$ **neutron rich !**

we used:

charge neutrality → $n_p\ (= Y_p\, n_B) = n_e$ or $p_F^p = p_F^e$

β-equilibrium → $m_N + (p_F^n)^2/2M_N = m_N + (p_F^p)^2/2M_N + p_F^p + \ldots$ (small: $(p_F^p)^2/2M_N$; $p_F^p\ (= p_F^e)$)

with neutrinos equilibrated: $\mu_n + \mu_\nu = \mu_p + \mu_e$

β-equilibrium → $(p_F^n)^2/2M_N + p_F^\nu = (p_F^p)^2/2M_N + p_F^p + \ldots$

$(p_F^n)^2 = 2M_N\,(p_F^p - p_F^\nu) + \ldots$ (large scale: M_N) **p_F^p needs not be small**

Ejecta mass & proton fraction Y_p

1) **dynamical** ejecta

t ~ 1-10 ms

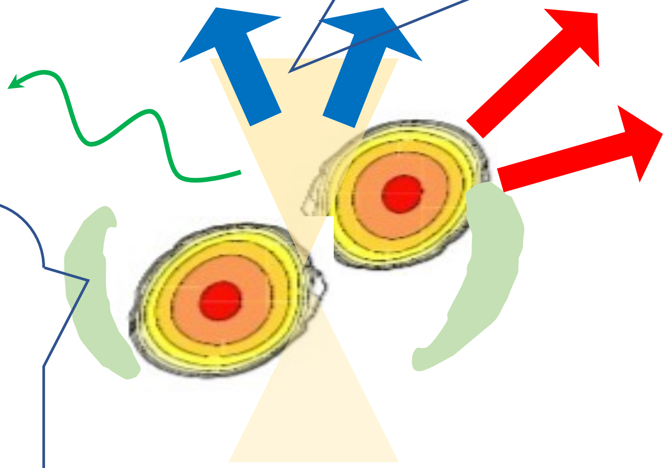
shock **heated** ejecta $Y_p \uparrow$

(T > 10 MeV, positron capture by n)

tidal ejecta

$Y_p \sim 0.05$-

(as in NS)

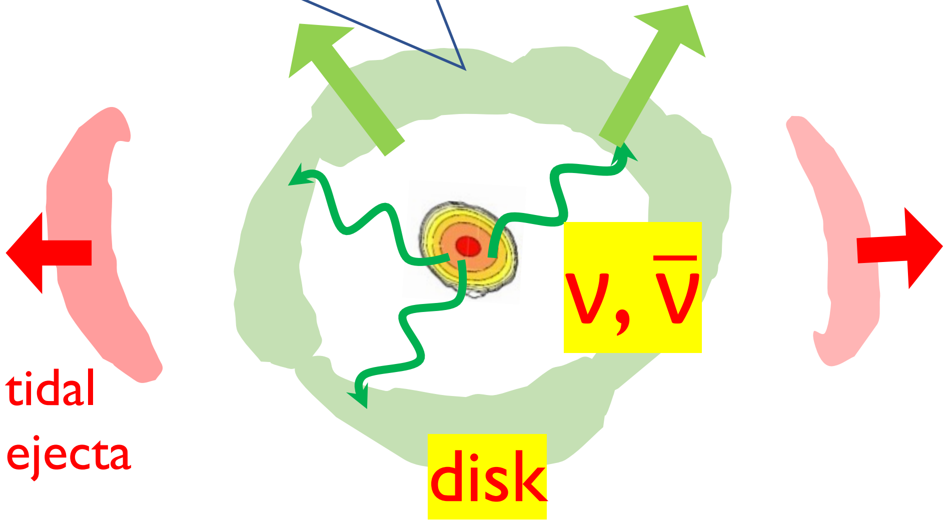


2) **post merger** ejecta

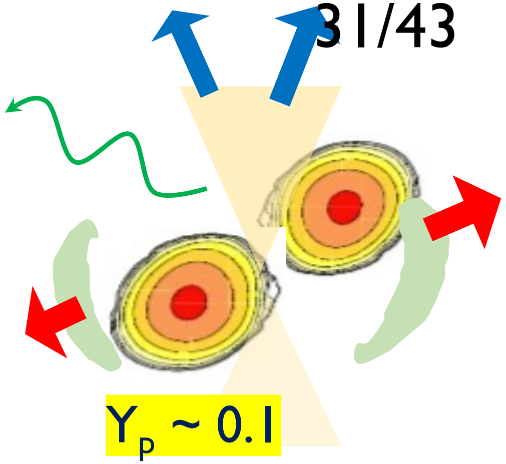
t > ~ 100 ms

post-merger ejecta $Y_p \uparrow$ in disk

$$n + \nu_e \rightarrow p + e^-$$



1) Dynamical ejecta (~10 ms)



many GR simulations → mechanical, well-understood

key factors: binary parameters (m_1, m_2) & **EOS**

1) $M_{ej} = 10^{-4} - 10^{-2}\, M_{sun}$ ➡ compactness of NSs; mass ratio: q = m1/m2 [Hotokezaka, Sekiguchi, Foucart, Radice,...]

2) average velocity = 0.15-0.25c [Hotokezaka, ...]

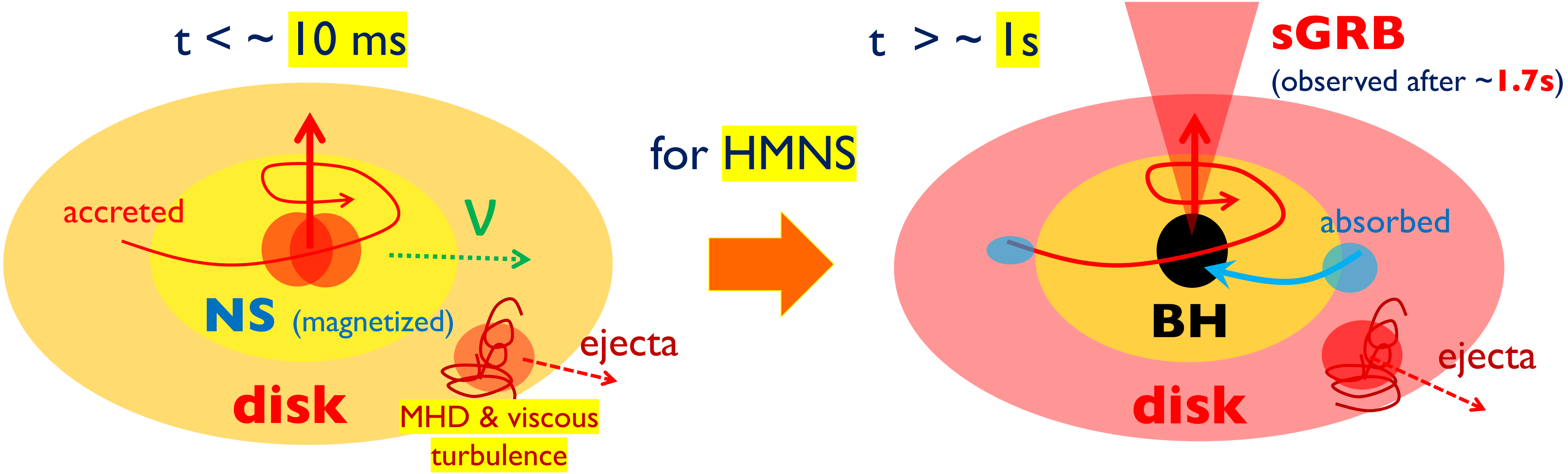
[Wanajo, Sekiguchi, Roberts,...]

3) Y_p = **0.05** – 0.4 ➡
- polar direction (shock heated) → $Y_p >\sim 0.2$, T > 10 MeV
- equatorial direction (tidal + ...) → $Y_p \sim$ **0.05-**

important for r-process nuclei & kilonova light curves (see below)

2) Post-merger ejecta (> ~100 ms)

complicated, long time duration → less-understood (difficult to simulate)



MHD instabilities → eB ~ $10^{14\text{-}16}$ G

neutrino irradiation → Y_p↑

Temp. at NS core ~ 10 MeV

BH + accretion → Gamma Ray Burst

ejecta powered by dynamics

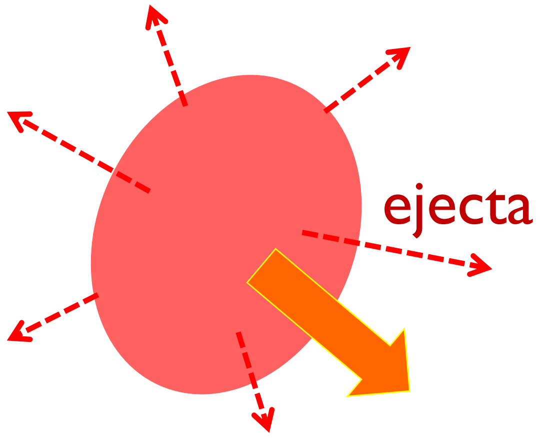
M_{ej} depends on the life time of HMNS

Processes in ejecta

1) decompression: $M_{ej} \ll M_{sun}$

→ weaker grav. attraction
→ expand (matter becomes dilute)

nuclear liquid → nuclei + neutrons & $Y_p \uparrow$



2) r-process: seed nuclei travel through neutron rich environment

depends on entropy, density, and Y_p (HMNS vs SMNS)

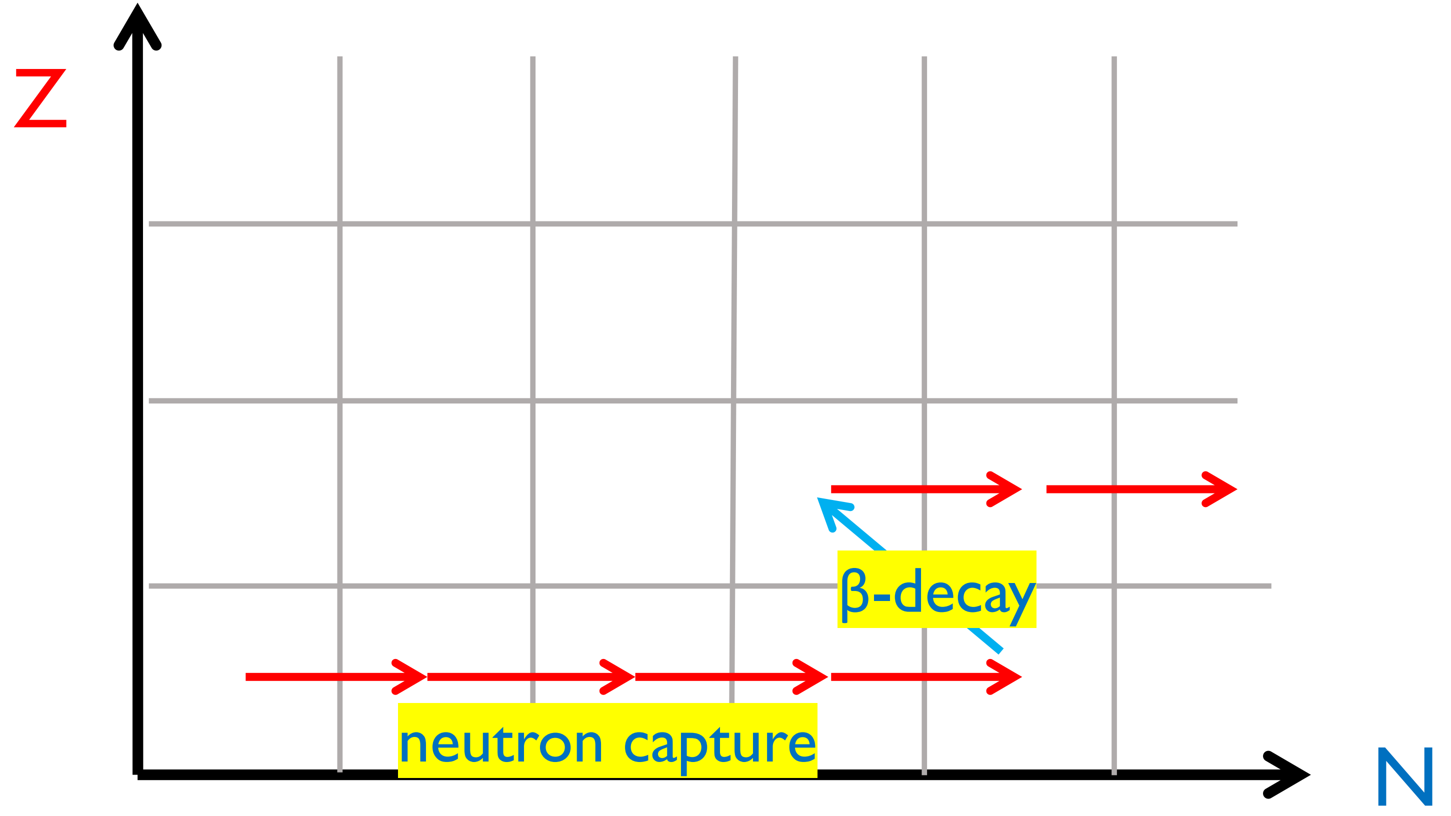
3) radioactive decay: decays of r-processed nuclei

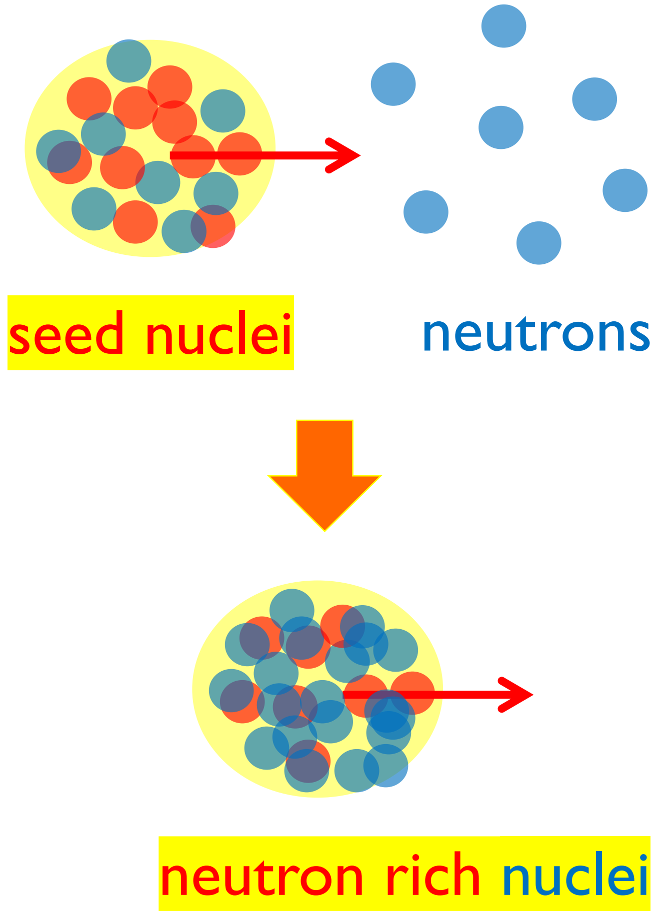
thermal emission of photons → kilonova

(colors & time scales)

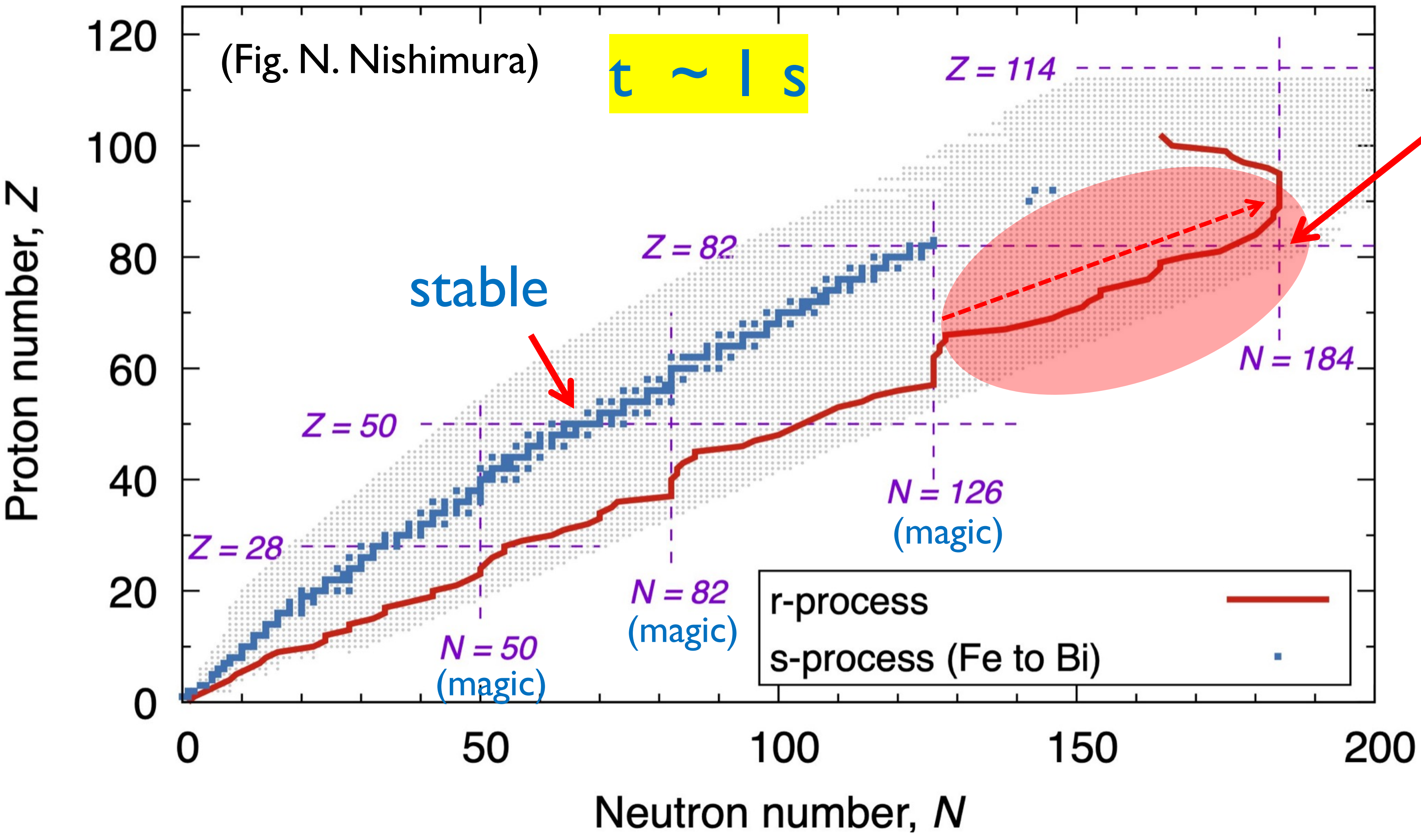
r-process (rapid neutron capture)

neutron capture rate >> β-decay rate





r-process (rapid neutron capture)



to reach high mass

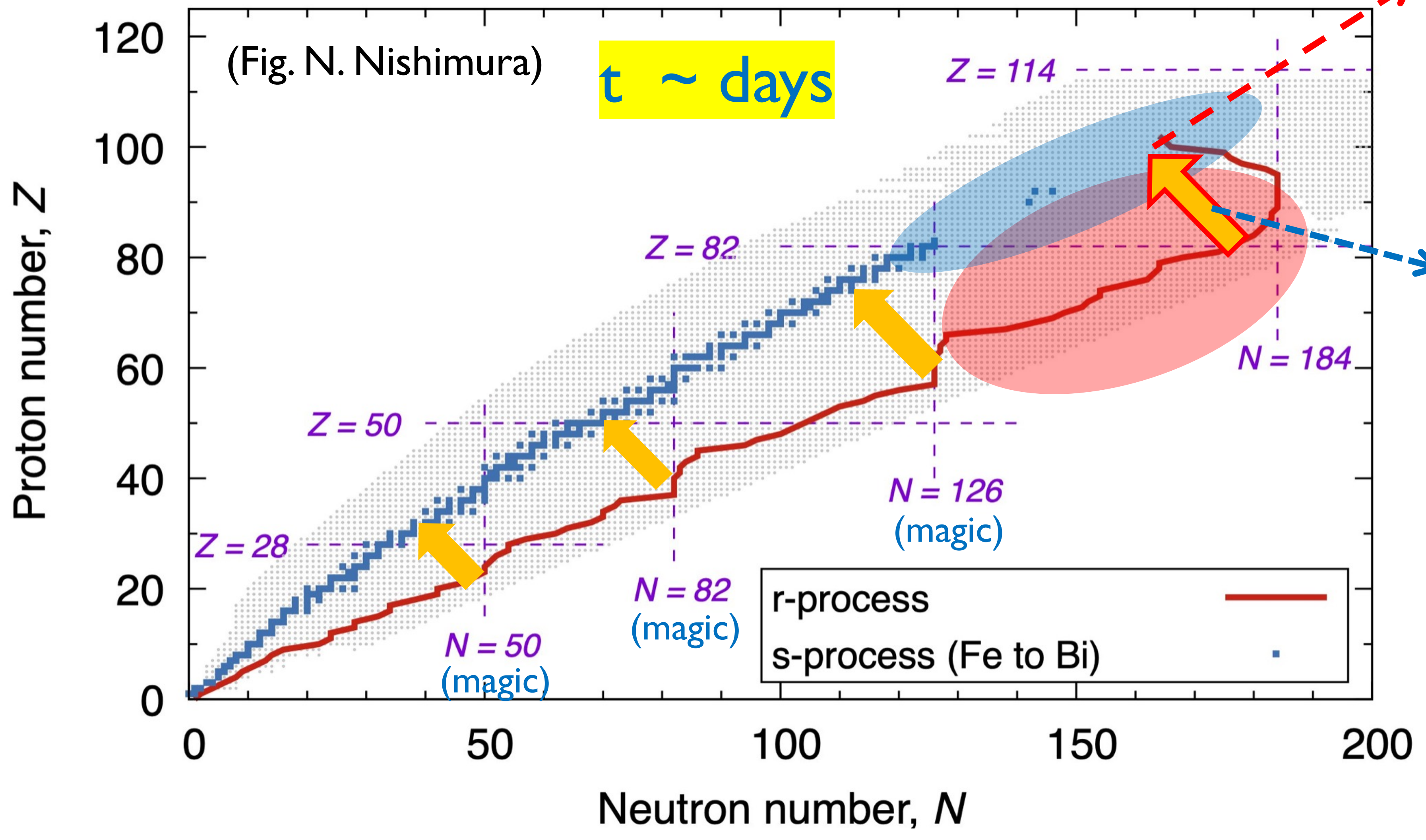
$Y_p < \sim 0.1$ needed

unique in NS mergers!

(not in supernovae)

caveats: magic num. in neutron rich regime ?

radio active decays



heavy elements !

1) β-decay
2) α-decay (A>210)
3) fission (A>250)

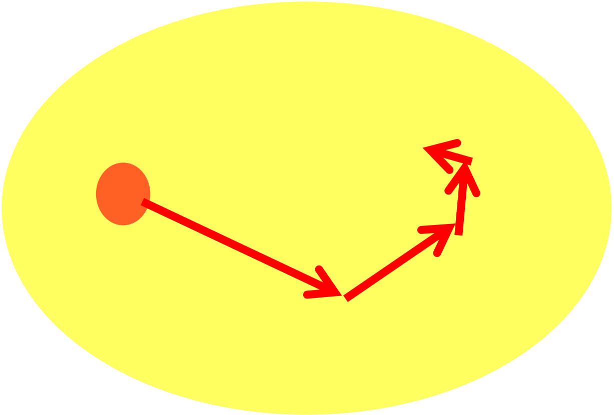
power
“kilonova”

kilonova 1) kinetic E to thermal E

decay products: electrons with E ~ 0.1-1 MeV

α-particles with E ~ 5 MeV

fission fragments with E ~ 100 MeV



time scale
to **deposit kin. E**

(thermalization time scale)

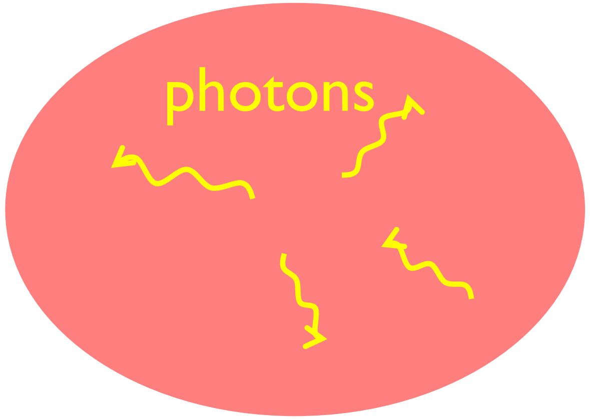
stopping power ↓ density of ions ↓

$$t_{\rm th} \approx \left(\frac{\sigma_{\rm st}(E_i) N v_i}{E_i} \right)^{-1}$$

→ time scale ~ days

kilonova 2) opacity for photons

The thermalized ejecta have **thermal photons**



How do photons go out of the ejecta and reach us?

small Y_p (< ~0.1) ejecta

heavy r-processed nuclei

more open channels for the final states

→ **more** absorption of photons

Red kilonova (slow: ~ weeks)

large Y_p (> 0.2-0.3) ejecta

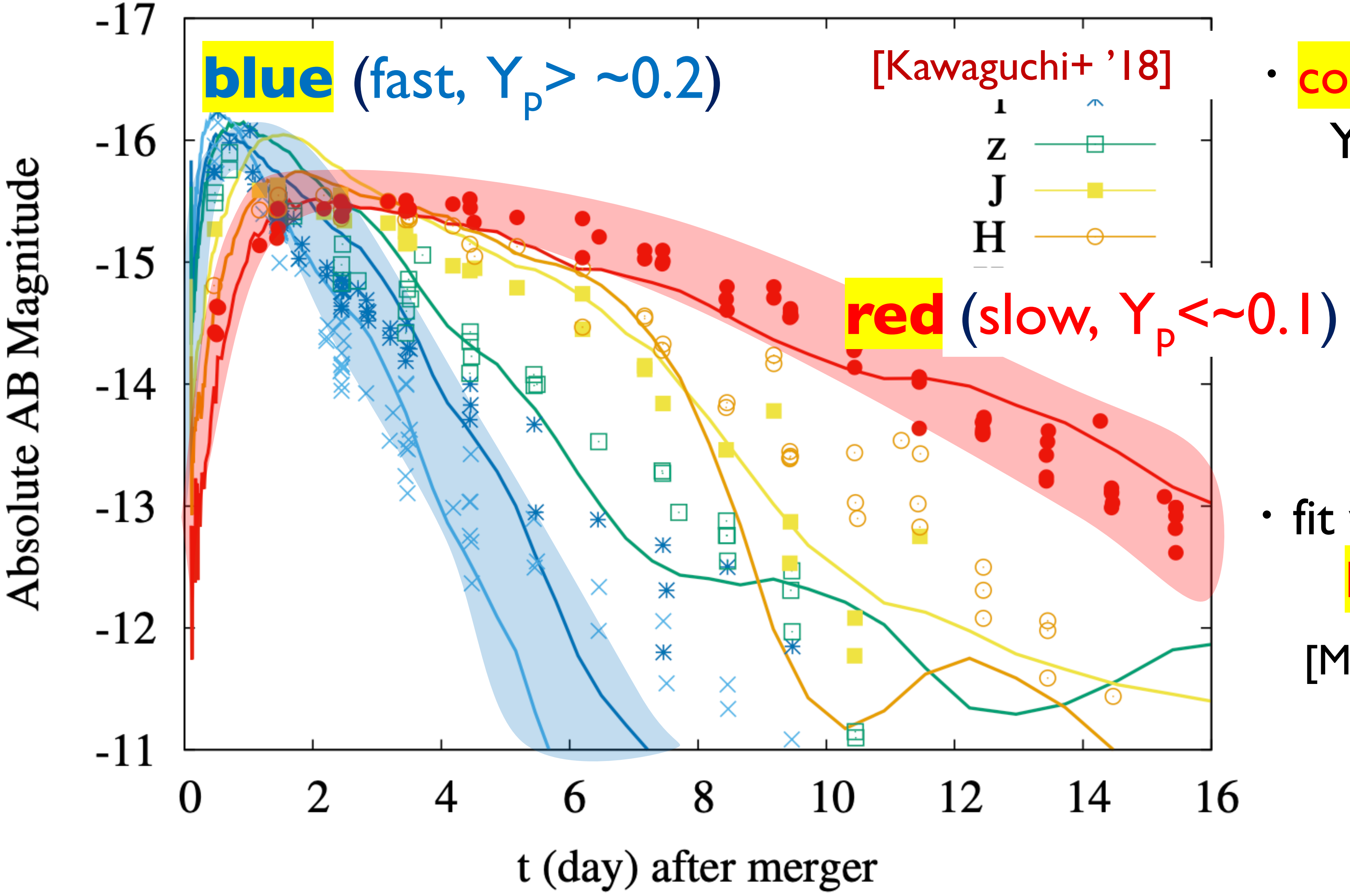
light r-processed nuclei only

less open channels for the final states

→ **less** absorption of photons

Blue kilonova (fast: ~ days)

kilonova light curves of GW170817

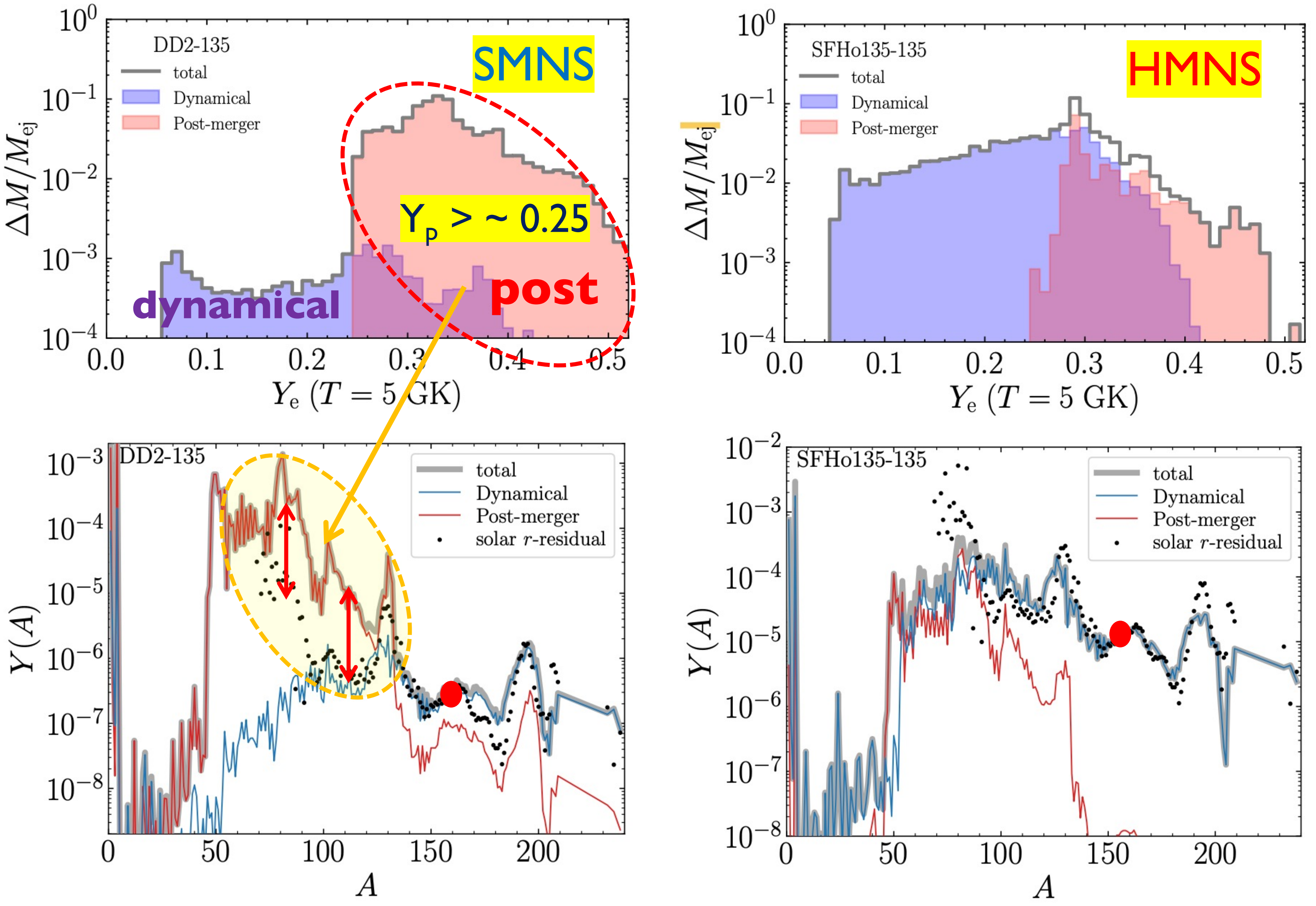


- confirmed the diversity of Y_p: Y_p from ~ **0.01** to ~ 0.4
- fit well with predictions of HMNS + kilonova

[Metzger+, Kasen+, Tanaka+,..]

Abundance of r-processed nuclei

[Fujibayashi+ ’22]



observations

solar abundance

(known to be universal)

normalized at A = 153

(abs. values are not universal)

SMNS:

ejecta: post >> dynamical

too much light elements

HMNS:

better agreement

& systematics

Short- vs long-lived NS (HMNS vs SMNS)

In HMNS scenarios for GW170817,

sGRB, kilonovae, r-process nuclei,...

can be described *within* standard mechanisms

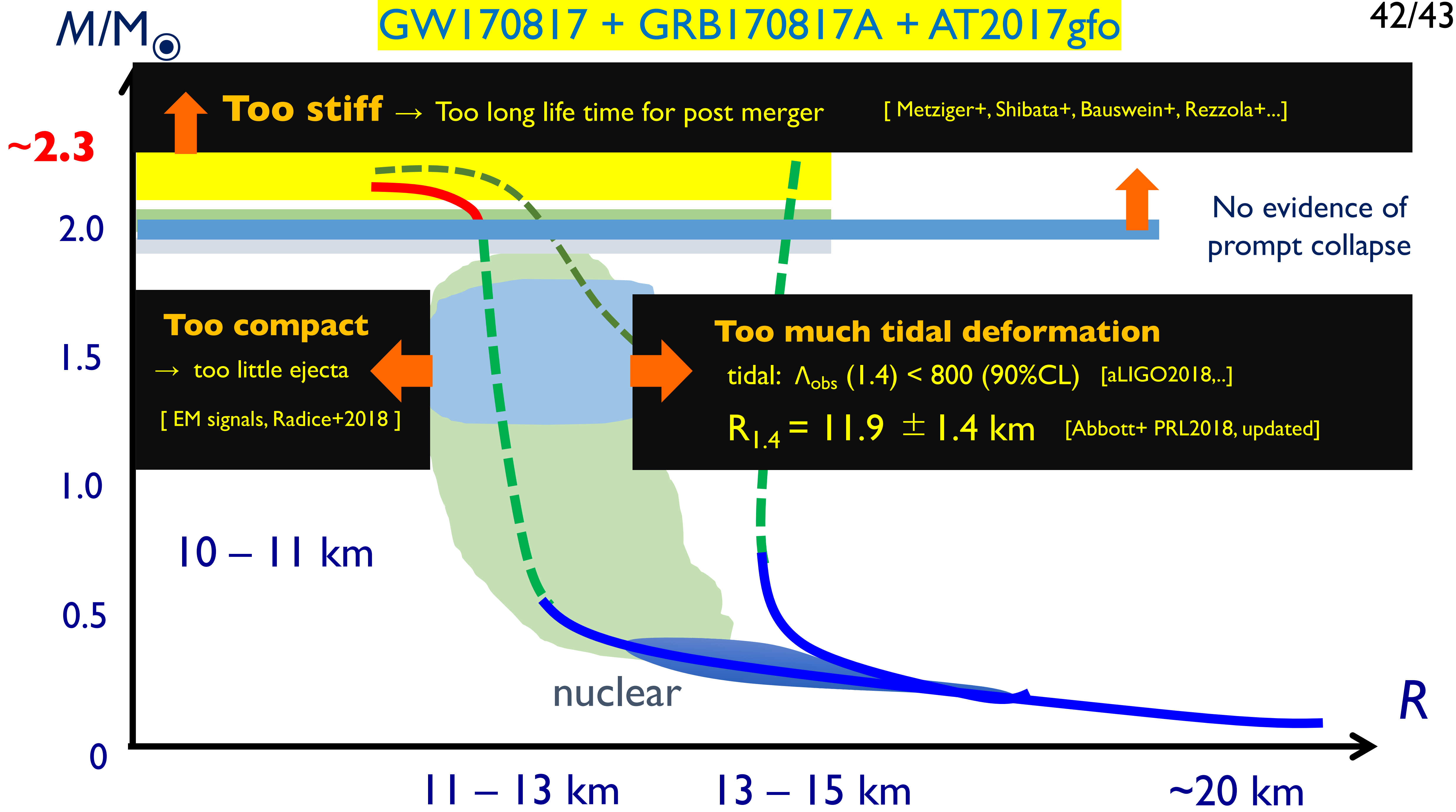
In SMNS scenarios, one needs to introduce extra discussions for each of them to explain GW170817

(not covered in this lecture)

For now, the HMNS scenario seems more likely for GW170817:

→ $M_{TOV} < 2.28\text{-}2.32$ (But if HMNS is incorrect, a real big deal !)

GW170817 + GRB170817A + AT2017gfo



Summary of Lecture 2

- Gravitational waves from fluctuating energy quadrupole
- GW170817, pre-mergers, tidal deformability → $R_{1.4}$
- GW170817, post-mergers, EM-counterparts

Single event already yields a lot of info

in next 10 years, detections will be daily events

Lect. 3 : From hadrons to quarks in NS