Binary neutron star mergers: observations and modelling in the multimessenger astronomy era

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On the behalf of the Virgo Scientific Collaboration

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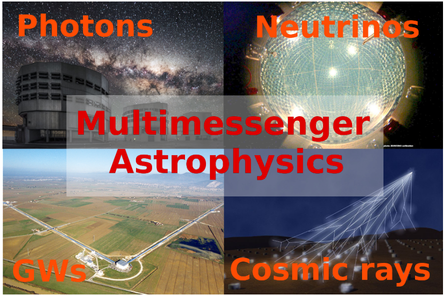
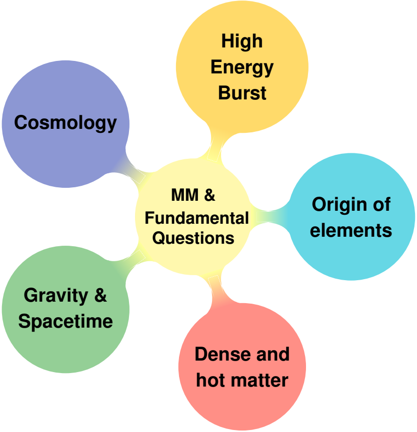
DISCRETE Conference, Vienna

Multimessenger astrophysics

MM astrophysics: detection of different radiations from one single event or source





High Energy Burst

Cosmology

MM & Fundamental Questions

Origin of elements

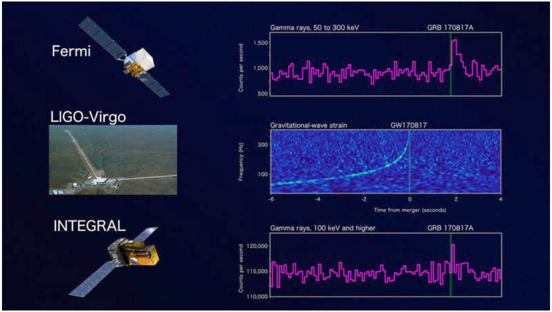
Gravity & Spacetime

Dense and hot matter

MM astrophysics: answers to many fundamental questions

Detections from GW170817 and its EM counterparts

GW170817: first MM detection from a compact binary merger



- GWs from an event compatible with BNS merger reported by LVC

LVC PRL 119 2017

- ∼1.7 seconds after, γ-ray signal compatible with short GRB

LVC, Fermi, Integral ApJ 848 L13 2017

- 11 hrs after, kilonova emission from NGC 4993 (40 Mpc): AT2017gfo

e.g., LVC+ many other astronomy and astroparticle collaborations ApJ 848 L2 2017

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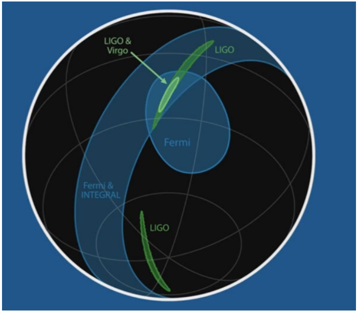

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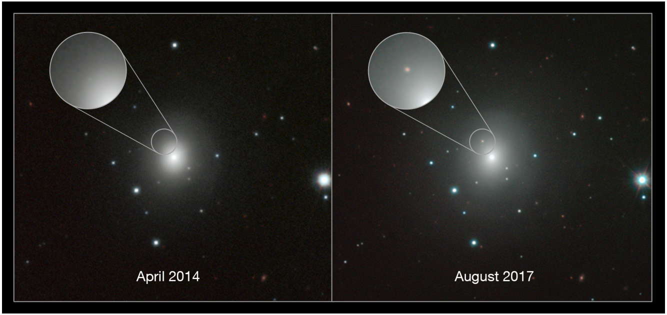

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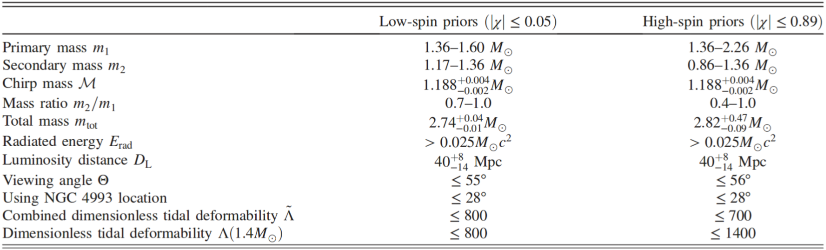
Properties of GW170817 and its kilonova detection

- GW signal
  - signal duration in GW detector network: 55 s
  - largest to date network SNR: 32.4
  - inference of many source properties



	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	$1.36–1.60\ M_\odot$	$1.36–2.26\ M_\odot$
Secondary mass m_2	$1.17–1.36\ M_\odot$	$0.86–1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	$0.7–1.0$	$0.4–1.0$
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

LVC PRL 2017. see LVC arXiv:1805.11579 for a refined analysis

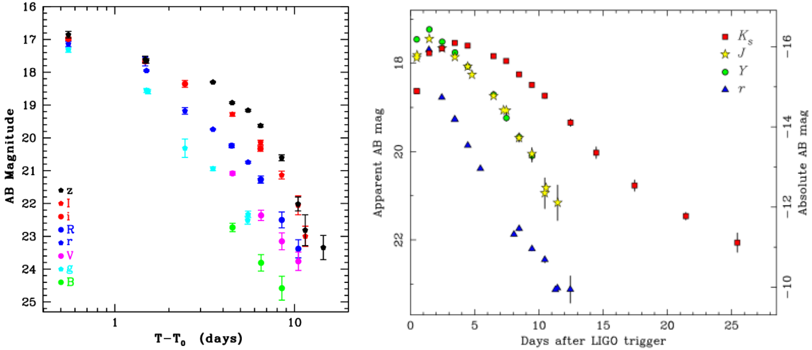
- chirp mass: $\mathcal{M}_{\rm chirp} = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$
- upper limit on $E_{\rm rad}$ only from BNS modelling:

$$E_{\rm rad} \lesssim 0.126\, M_\odot c^2$$

Zappa, Bernuzzi, Radice, Perego, Dietrich PRL 2018

Properties of GW170817 and its kilonova detection

- GW signal
- kilonova signal
  - bright, UV/O component, with a peak @ ∼ 1day (blue component)
  - rather bright, nIR component, with a peak @ ∼ 5day (red component)



Light curves; Pian, D'Avanzo *et al.* Nature 2017 (left); Tanvir *et al.* Science 2017 (right).

See also, e.g., Coulter *et al.* Science 358 2017; Troja *et al.* Nature 2017, Hallinan *et al.* Science 2017

Fundamental physics implications from GW170817 MM detection

Implications of joint GW+EM detection: v_{EM}

Speed of gravity

- if $v_{EM} \neq v_{\mathrm{GW}}$, delay in travel time Δt:

$$\frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \approx v_{\mathrm{EM}} \frac{\Delta t}{D}$$

- arrival time difference between GW and photons from GRB

$$\Delta t_{\mathrm{GRB}} = (1.74 \pm 0.05)\mathrm{s}$$

- however, uncertainties on emission sequence
  - if simultaneous emission ($\delta t = 0$), $\Delta t \geq \Delta t_{\mathrm{GRB}}$ and $v_{\mathrm{GW}} > v_{\mathrm{EM}}$
  - if EM emitted $\delta t \leq 10$s after GW, $v_{\mathrm{EM}} > v_{\mathrm{GW}}$

$$\boxed{-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\mathrm{EM}}} \leq 7 \times 10^{-16} \qquad D = 26\mathrm{Mpc}}$$

LVC PRL 119 2017

Implications of joint GW+EM detection: $(\gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}})$

Test of equivalence principle

- are EM radiation and GWs affected by background potentials in the same way?
- Shapiro delay: propagation time of massless particles larger in curved spacetimes

$$\delta t_{\mathrm{S}} \approx -\frac{1+\gamma}{c^3} \int_{\mathbf{r}_e}^{\mathbf{r}_o} U(\mathbf{r}(l))\, \mathrm{d}l$$

- Einstein-Maxwell minimal coupling: $\gamma_{\mathrm{EM}} = \gamma_{\mathrm{GW}} = 1 \to (\gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}}) = 0$
- conservative limit obtained by assuming:
  - $0 \leq \delta t \leq 10\mathrm{s}$
  - measured arrival time delay $\Delta t_{\mathrm{GRB}} = (1.74 \pm 0.05)\mathrm{s}$
  - $U(\mathbf{r})$ caused by Milky Way for distances $> 100\mathrm{kpc}$,

$$\boxed{-2.6 \times 10^{-7} \leq (\gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}}) \leq 1.2 \times 10^{-6}}$$

LVC PRL 119 2017

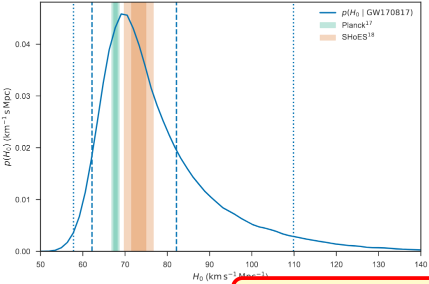
Implications of joint GW+EM detection: H_0

GW as standard sirens for H_0 measurement

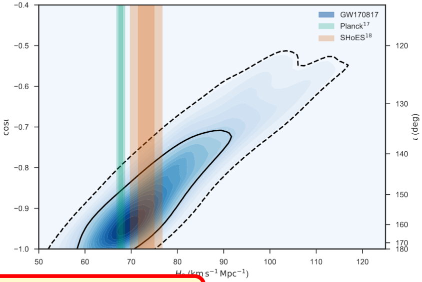
LVC, 1M2H coll, Dark Energy Camera GW-EM coll and DES coll *et al.* Nature 551 2017

- Hubble law in the local Universe: $v_{\mathrm{H}} = H_0\, d + \mathcal{O}\left(v_{\mathrm{H}}/c\right)$
- analysis of GW signal (NGC 4993 sky location):
- measurement of cosmological redshift of NGC 4993

$$d = 43.8^{+2.9}_{-6.9}\mathrm{Mpc}$$



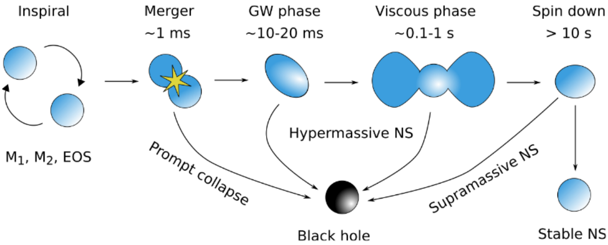
$$v_{\mathrm{H}} = 3017^{+166}_{-166}\mathrm{km\,s^{-1}}$$



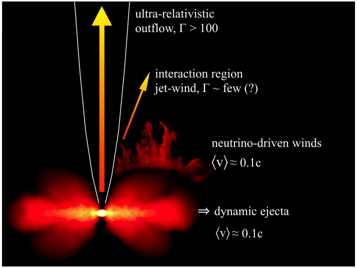
$$H_0 = 70.0^{+12.0}_{-8.0}\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

BNS merger modelling and the EOS of neutron star

BNS merger in a nutshell



Credit: D. Radice



Rosswog 2015

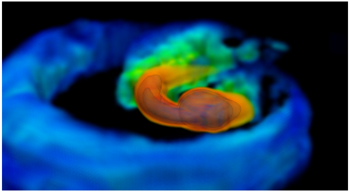
- *n*-rich matter ejected
  - *r*-process nucleosynthesis
  - different mechanisms
- decay of freshly sinthetized *r*-process element: release of nuclear energy
- kilonova: thermal photons diffuse and are emitted at photosphere

Li & Paczynski ApJL 98, for a review: Metzger LRR 17

BNS modelling and NS equation of state (EOS)

BNS merger simulations in Numerical Relativity (NR):

necessary to model highly non-linear, strong field (post-)merger phase



Volume rendering of matter density from BNS NR simulation.

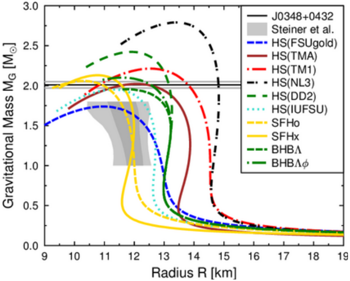
Courtesy of T. Dietrich & S. Bernuzzi

EOS of NS matter still affected by large uncertainties

e.g., Tsang *et al* 86 PRC 2012, Lattimer & Prakash Phys. Rep. 621 2016, Örtel et al. RMP 89 2017 for recent reviews

- nucleon Hamiltonian
- many-body treatment
- thermodynamical degrees of freedom (hyperons, quarks?)

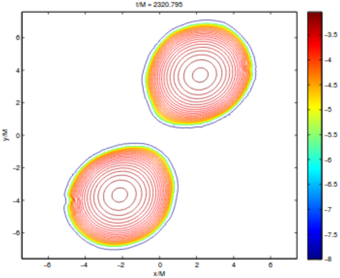
- NR: art of solving Einstein's and GR-HD equations on computer
- accurate GW waveforms, energetics, final state properties, matter dynamics
- need of NS matter EOS to close the system



Mass-radius curves for several RMF NS EOS. Courtesy of M. Hempel

Tidal deformation during the inspiral phase

NS in external, inhomegeneous gravitational field ⇒ tidal deformation



Bernuzzi et al PRD 2012

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

$$\lambda = \left(\frac{2}{3} \frac{R^5}{G} k_2 \right)$$

- $Q_{i,j}$ quadrupolar moment
- $\mathcal{E}_{i,j} = \partial^2_{i,j}\Phi$ tidal field
- k_2 quadrupolar tidal polarizability
- R radius of the star

- tidal deformation enhances GW emission
- $\geq 5^{th}$ PN order correction to point particle dynamics
- leading term $\propto \tilde{\Lambda}(M_A, M_B, \mathrm{EOS})$

$$\tilde{\Lambda} = \frac{16}{13} \left[\frac{(M_A + 12 M_B) M_A^4 \Lambda_2^{(A)}}{(M_A + M_B)^5} + (A \leftrightarrow B) \right] ; \; \Lambda_2^{(i)} = \left(\frac{c^2}{M_i} \right)^5 \lambda_{(i)} ; \quad i = A, B$$

see, e.g., Damour, Les Houches Summer School on Gravitational Radiation 1982; Flanagan & Hinderer PRD 77 2008, Bernuzzi et al PRD 2012

NS mass, radius and EOS from GW170817

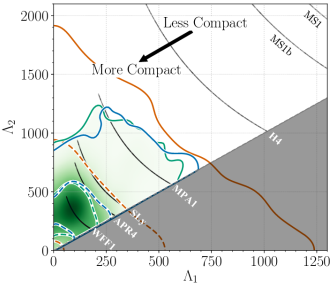
Idea:

Measure the NS tidal deformation from GW170817 inspiral signal to probe cold NS EOS above $\rho_{\rm nuc}$

LVC PRL 121 2018

Relevant assumptions:

- same parametrized EOS for the two NSs — e.g. Lindblom & Indik PRD 89 2014
- $M_{\rm max,TOV} > 1.97 M_\odot$ — Antoniadis *et al* Science 340 2013



- marginalized posteriors for $\Lambda_{1,2}$
- same EOS for the two NSs improves results compared with previous analysis

LVC PRL 121 2018

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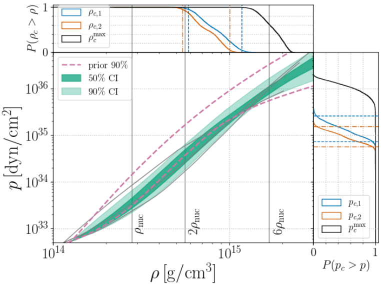

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- marginalized posteriors for $p = p(\rho)$
- GW signal favors softer EOS
- $M_{\rm TOV,max} > 1.97 M_\odot$: EOS stiffening at high density

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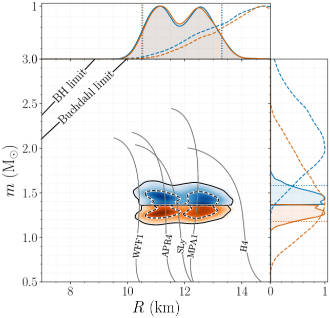

- simultaneous NS $M-R$ measurements
- $R_1 = 11.9^{+1.4}_{-1.4}$ km $m_1[M_\odot] \in [1.36, 1.58]$
- $R_2 = 11.9^{+1.4}_{-1.4}$ km $m_2[M_\odot] \in [1.18, 1.36]$

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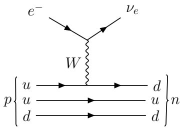
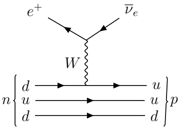
Weak interaction in BNS merger

Weak interaction in hot and dense matter

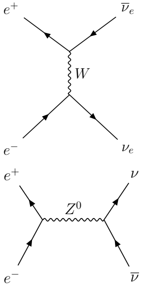
- most relevant neutrino production processes (inverse: absorption)



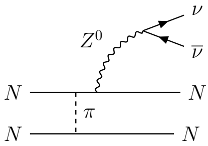
$p + e^- \rightarrow n + \nu_e$



$n + e^+ \rightarrow p + \bar{\nu}_e$

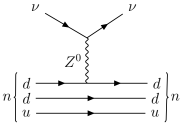


$e^- + e^+ \rightarrow \nu + \bar{\nu}$

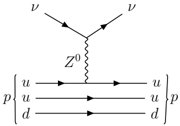


$N + N \rightarrow N + N + \nu + \bar{\nu}$

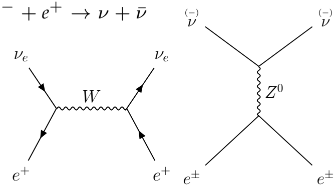
- most relevant scattering processes



$n + \nu \rightarrow n + \nu$



$p + \nu \rightarrow p + \nu$



$e^\pm + \nu \rightarrow e^\pm + \nu$

Tubbs & Schramm ApJ 75; Lamb & Pethick ApJ 76; . . . Burrows, Reddy & Thompson NuPhA 06; Bacca, Hally, Liebendörfer, Perego *et al.* ApJ 12

Reaction rates in hot and dense matter

- plasma ($n, p, e^{\pm}, \gamma$) in thermal and NSE (NS matter EOS)
- ν production rates: boosted by high temperatures & densities

$$\lambda_{\mathrm{e}^-} \propto n_p T^5 F_4(\mu_e/T) \qquad \lambda_{\mathrm{e}^+} \propto n_n T^5 F_4(-\mu_e/T)$$

$$\begin{aligned} \lambda_{\mathrm{e}-} &= \int \frac{\mathrm{d}^3 p_\nu}{(2\pi\hbar c)^3}\, j_{\nu_e}(E_\nu) \\ &\approx \left(\frac{n_n - n_p}{\exp\left(\frac{\mu_p - \mu_n + \Delta}{k_B T}\right) - 1} \right) \int_0^\infty \frac{4\pi\sigma_0 c}{(2\pi\hbar c)^3} \left(\frac{E+\Delta}{m_e}\right)^2 f_{e-}(E+\Delta)\, E^2 \mathrm{d}E \end{aligned}$$

$$\sigma_0 = \frac{4G_F^2 (m_e c^2)^2 (c_v^2 + 3c_a^2)}{\pi(\hbar c)^4} \approx 2.43 \times 10^{-44}\,\mathrm{cm}^2 \sim 2 \times 10^{-20} \sigma_{t,e}$$

$$F_k(\eta) = \int_0^\infty \frac{x^k}{1+\exp(x-\eta)}\, \mathrm{d}x$$

e.g. Bruenn ApJ 1985; Rosswog & Liebendörfer MNRAS 2003

Reaction rates in hot and dense matter

- plasma $(n, p, e^{\pm}, \gamma)$ in thermal and NSE (NS matter EOS)

- ν production rates: boosted by high temperatures & densities

$$\lambda_{\mathrm{e}^-} \propto n_p T^5 F_4(\mu_e/T) \qquad \lambda_{\mathrm{e}^+} \propto n_n T^5 F_4(-\mu_e/T)$$

- ν absorption/scattering rates: neutrino diffusion

$$\ell_{\nu_e} = \frac{c}{\kappa_{\nu_e}} \approx 2.36 \times 10^3 \mathrm{cm} \left(\frac{\rho}{10^{14}\,\mathrm{g/cm^3}} \right)^{-1} \left(\frac{E_\nu}{10\,\mathrm{MeV}} \right)^{-2} \ll R_{\mathrm{NS}}$$

$$\kappa_{\nu_e}(E_{\nu_e}) = \exp\left(\frac{E_{\nu_e} - (\mu_p + \mu_e - \mu_n)}{k_B T} \right) j(E_{\nu_e}) \approx \frac{n_{\mathrm{N}} \sigma_\nu}{c}$$

$$\sigma_\nu \sim \sigma_0 \left(\frac{E_\nu}{m_{\mathrm{e}} c^2} \right)^2$$

⇒ Radiative transfer problem

Reaction rates in hot and dense matter

- plasma ($n, p, e^{\pm}, \gamma$) in thermal and NSE (NS matter EOS)
- ν production rates: boosted by high temperatures & densities

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- ν absorption/scattering rates: neutrino diffusion

$$\ell_{\nu_e} \ll R_{\mathrm{NS}}$$

- matter composition:
  - W-mediated processes can change ratio between n and p, i.e. $\mathrm{Y_e}$:

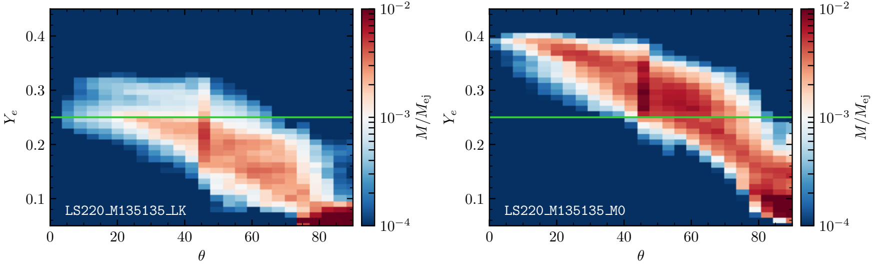
$$n + e^+ \leftrightarrow p + \bar{\nu}_e \qquad p + e^- \leftrightarrow n + \nu_e$$

$$\left(\mathrm{Y_e} = \mathrm{n_e}/\mathrm{n_B} \approx \mathrm{n_p}/\left(\mathrm{n_p} + \mathrm{n_n}\right)\right)$$

→ direct impact on nucleosynthesis

Impact of ν absorption on dynamical ejecta

- dynamical ejecta: matter promptly expelled in a BNS merger
  - $\tau_{\mathrm{ej,dyn}} \lesssim 5\,\mathrm{ms}$
  - $M_{\mathrm{ej,dyn}} \lesssim 10^{-4}$ - $10^{-3} M_{\odot}$
  - $v_{\mathrm{ej,dyn}} \sim 0.3c$
- in the past, ν-matter interactions assumed to be negligile
- however, ν-matter interactions increase $\mathrm{Y_e}$ $(n + \nu_e \rightarrow p + e^-)$



w/o neutrino absorption

w neutrino absorption

Perego, Radice, Bernuzzi ApJL 2017; Radice, Perego, Hotokezaka *et al* arXiv:1809.11161

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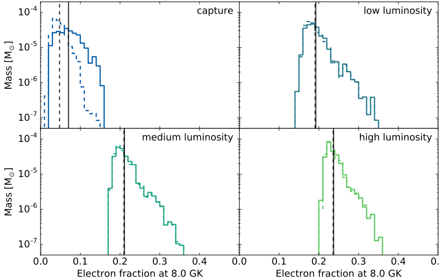
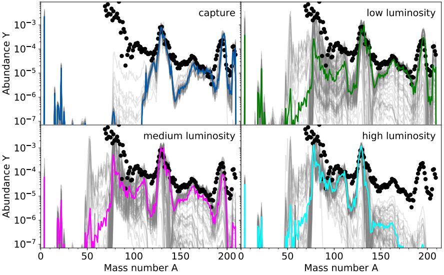
ejecta $\rm Y_e$ for increasing L_ν

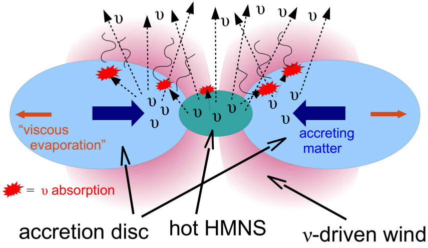


→ r-process nucleosynthesis



Martin, Perego, Kastaun & Arcones CQG 2018

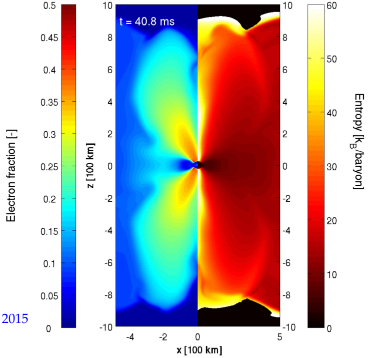
ν-driven winds from BNS merger



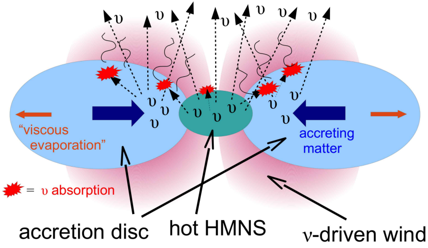
- wind ejection driven by energy & momentum deposition
- $\tau_{\mathrm{ej,wind}} \sim$ tens ms
- $M_{\mathrm{ej,wind}} \lesssim 10^{-2} M_{\odot}$
- $v_{\mathrm{ej,wind}} \lesssim 0.1c$

- first 3D radiation-hydrodynamics simulation
- ejecta analysis and nucleosynthesis calculations
- kilonova prediction: blue & red kilonova

Perego, Rosswog, Cabezon *et al* MNRAS 2014; Martin, Perego, Arcones *et al* ApJ 2015

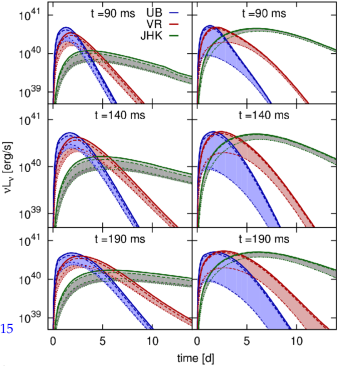


ν-driven winds from BNS merger



- wind ejection driven by energy & momentum deposition
- $\tau_{\text{ej,wind}} \sim$ tens ms
- $M_{\text{ej,wind}} \lesssim 10^{-2} M_{\odot}$
- $v_{\text{ej,wind}} \lesssim 0.1c$

- first 3D radiation-hydrodynamics simulation
- ejecta analysis and nucleosynthesis calculations
- kilonova prediction: blue & red kilonova

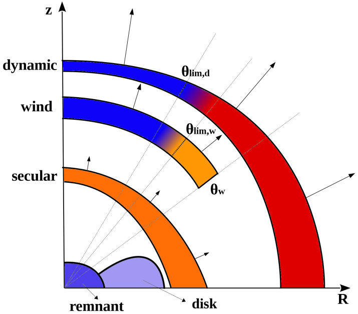


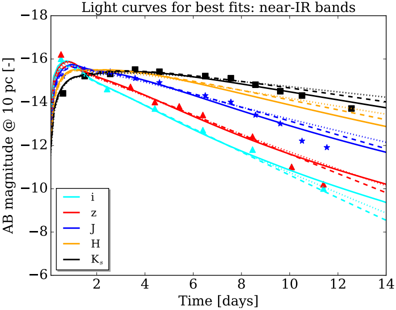
Perego, Rosswog, Cabezon *et al* MNRAS 2014; Martin, Perego, Arcones *et al* ApJ 2015

Multi-Component Anisotropic Kilonova Model

- kilonova model that includes our present knowledge about ejecta
- different ejection channels → multi-component
- explicit dependency on polar angle → anisotropic & viewing angle
- homologous expansion + γ diffusion

Perego, Radice, Bernuzzi 2017, ApjL



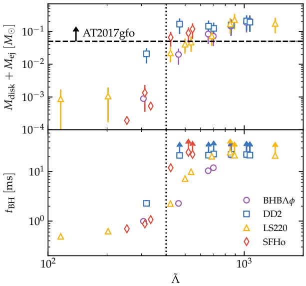


$$M_{\rm ej,tot} \sim 0.05 M_\odot, \qquad \theta_{\rm obs} \approx 30^o$$

Multimessenger constraints on nuclear EOS

- can GW signal + EM signature + NR simulations constrain NS EOS?

Radice, Perego, Zappa, Bernuzzi ApJL 17

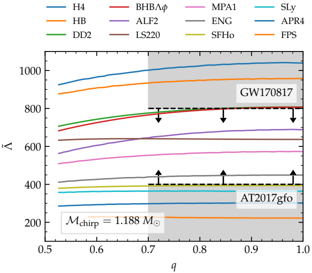


- $\tilde\Lambda$ describes BNS deformation:

$$\tilde\Lambda = \tilde\Lambda(\mathrm{EOS}, M_1, M_2)$$

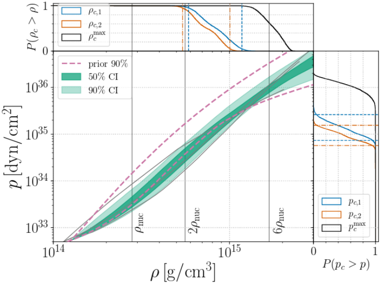
- NR results suggest $\tilde\Lambda \gtrsim 400$ to account for $0.05 M_\odot$ of ejecta

- application to GW170817/AT2017gfo
- $\tilde\Lambda(\mathrm{EOS}, \mathcal{M}_{\rm chirp} = 1.118 M_\odot, q)$
- calculation of $\tilde\Lambda$ for different EOSs
- MM constraints from GW & EM+NR exclude very stiff & soft EOSs

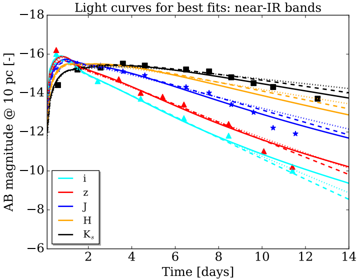


Conclusions

- MM astrophysics can answer fundamental questions: compact binary mergers as laboratory for fundamental physics
- interpretation of MM observation requires sophisticated models including all the necessary physics
- weak reactions and neutrinos play a central role in MM astrophysics
- joint GW+EM detections can set stringent limits, e.g.
  - interaction speed
  - equivalence principle
  - Hubble constant
  - EOS of nuclear matter

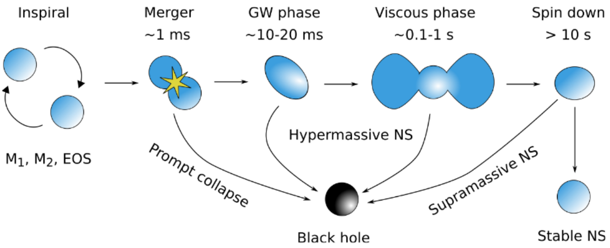


LVC PRL 121 2018

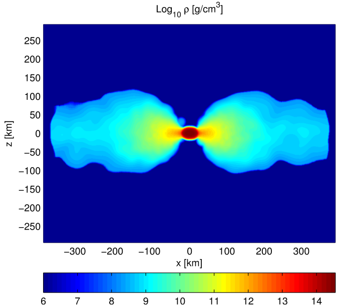


Perego, Radice, Bernuzzi, ApJL 2017

BNS merger in a nutshell



Credit: D. Radice; see Rosswog IJMP 2015 for a recent review



- Massive NS ($\rightarrow$ BH)
  $\rho \gtrsim 10^{12}\mathrm{g\,cm^{-3}}$, $T \sim$ a few 10 MeV
- thick accretion disk
  $M \sim 10^{-2} - 0.2 M_{\odot}$, $\mathrm{Y_e} \lesssim 0.20$
  $T \sim$ a few MeV
- intense ν emission
  $L_{\nu,\mathrm{tot}} \sim 10^{53} \mathrm{erg\,s^{-1}}$, $E_\nu \gtrsim 10\,\mathrm{MeV}$

$(\mathrm{Y_e} = \mathrm{n_e}/\mathrm{n_B} \approx \mathrm{n_p}/\left(\mathrm{n_p} + \mathrm{n_n}\right))$

NS radii and EOS from GW170817: basic idea

Idea:

Measure the NS tidal deformation from GW170817 inspiral signal to probe cold NS EOS above $\rho_{\rm nuc}$, assuming the same EOS for the two NSs LVC PRL 121 2018

Hypothesis:

- NS mass and spin consistent with astro constraints & expectations
- same EOS for the two NSs

Methods:

- Bayesan analysis of GW data against waveforms models generated by `PhenomPNRT` with different $\{\Lambda_1, \Lambda_2\}$ choices

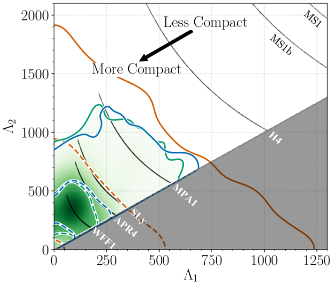
  e.g., Schmidt *et al.* PRD 86 2012; Kahn *et al.* PRD 93 2016, Dietrich, Bernuzzi, Tichy PRD 2017

- two methods to generate $\{\Lambda_1, \Lambda_2\}$:
  1. EOS-insensitive empirical relations involving $\Lambda_{1,2}$ e.g. Yanu & Yuges CQG 33 2016
  2. general, parametrized version of the NS EOS, satisfying basic constraints

     e.g. Lindblom & Indik PRD 89 2014

     - causality
     - thermodynamical stability
     - $M_{\rm TOV,max} > 1.97 M_{\odot}$ Antoniadis *et al* Science 340 2013

NS radii and EOS from GW170817: results



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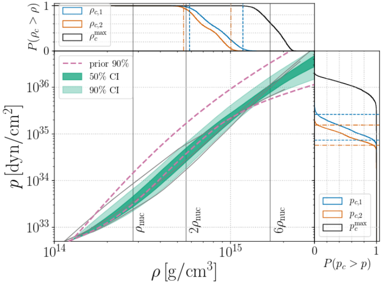
- marginalized posteriors for $\Lambda_{1,2}$
- same EOS for the two NSs improves results compared with previous analysis

- marginalized posteriors for $p = p(\rho)$
- GW signal favors softer EOS
- $M_{\mathrm{TOV,max}} > 1.97 M_{\odot}$: EOS stiffening at high density



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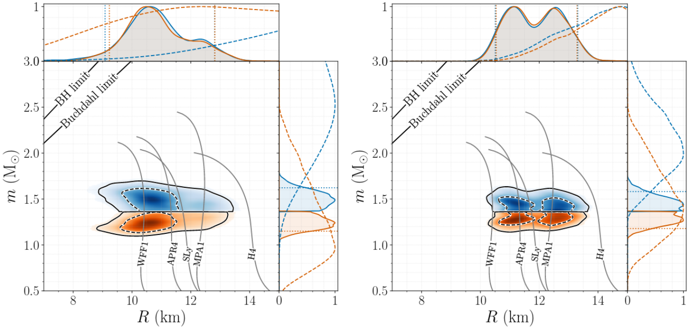
NS radii and EOS from GW170817: results

- simultaneous *M*-*R* measurments



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- EOS-independent $\Lambda_{1,2}$ relations
- $R_1 = 10.8^{+2.0}_{-1.7}$ km
  $m_1[M_\odot] \in [1.36, 1.62]$
- $R_2 = 10.7^{+2.1}_{-1.5}$ km
  $m_2[M_\odot] \in [1.15, 1.36]$

- parametrized EOS
- $R_1 = 11.9^{+1.4}_{-1.4}$ km
  $m_1[M_\odot] \in [1.36, 1.58]$
- $R_2 = 11.9^{+1.4}_{-1.4}$ km
  $m_2[M_\odot] \in [1.18, 1.36]$