Constraints on neutron star properties from GW170817

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Rezzolla, **Most** and **Weih** *ApJL 2017 852 2*

Most , **Weih** , Rezzolla and Schaffner-Bielich *submitted*

Collaborators: Luciano Rezzolla, Jürgen Schaffner-Bielich

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

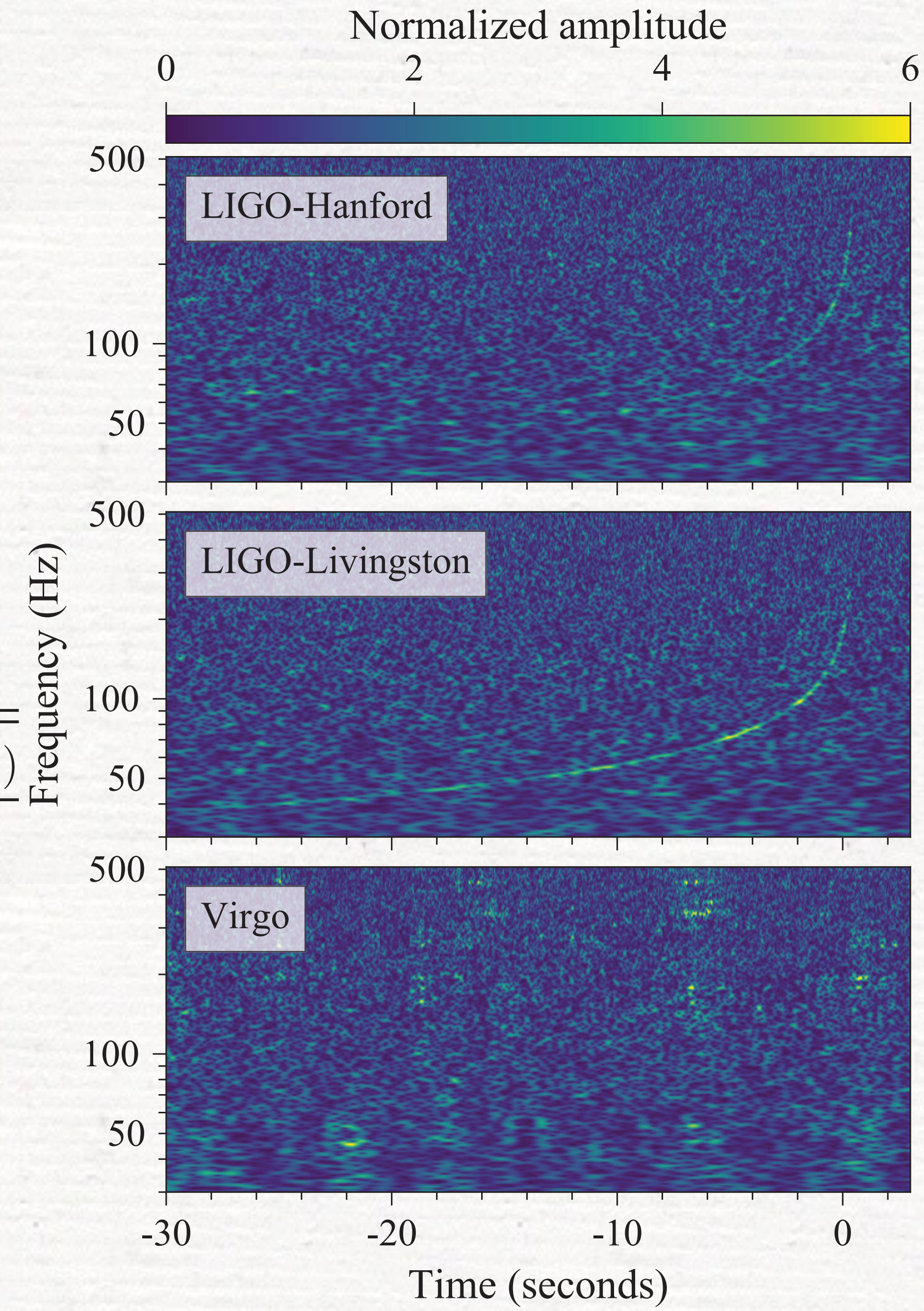
ITP Institute for Theoretical Physics

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

GW170817

	Low-spin priors ($\vert\chi\vert \leq 0.05$)	High-spin priors ($\vert\chi\vert \leq 0.89$)
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

No post-merger phase observed



Abbott et al 2017

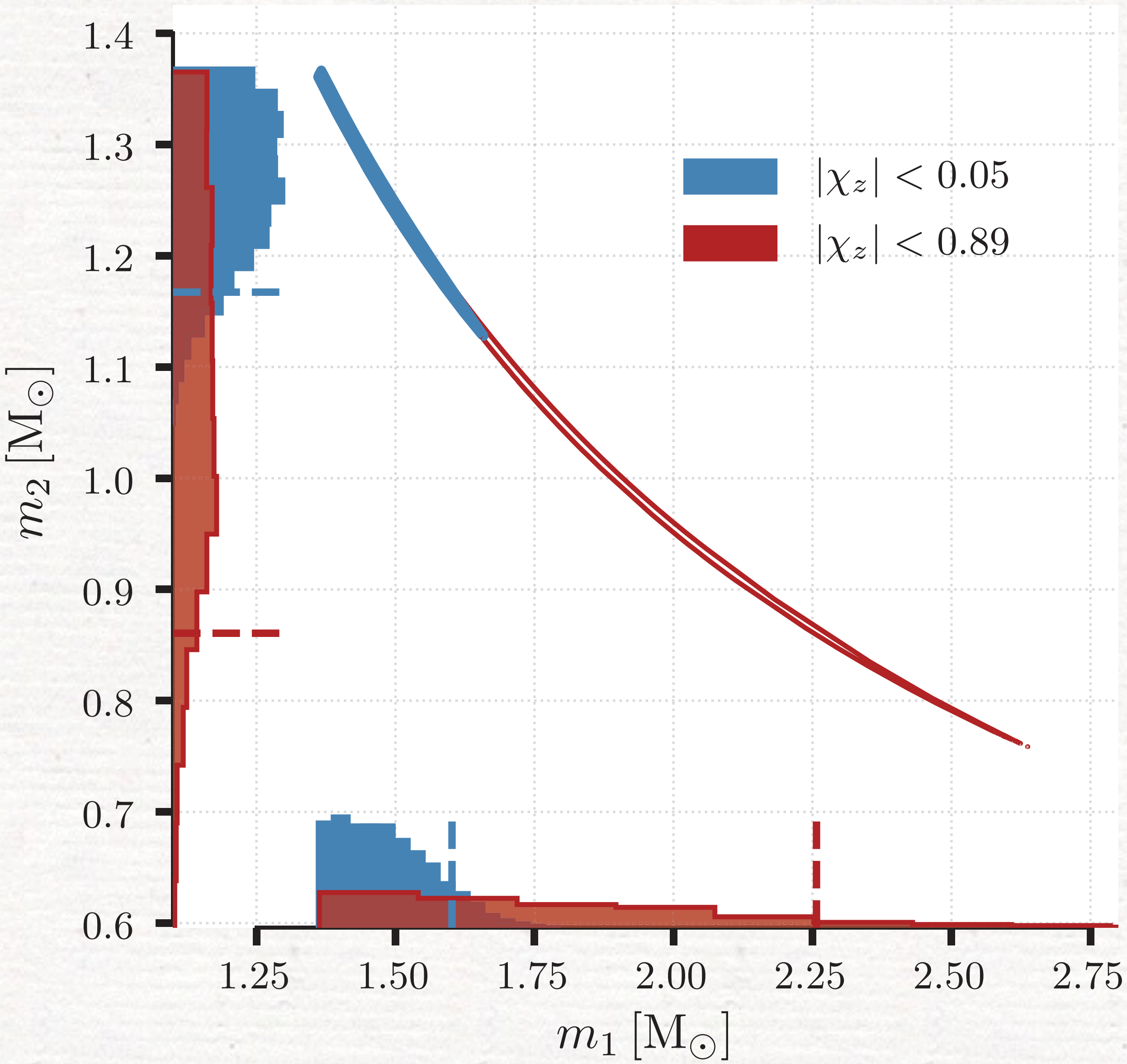
GW170817: What do we know?

- The observation of GW170817 provides information on the chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$
- Assuming low spin priors:

$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$

$$M_1 = 1.36 - 1.60 M_\odot$$

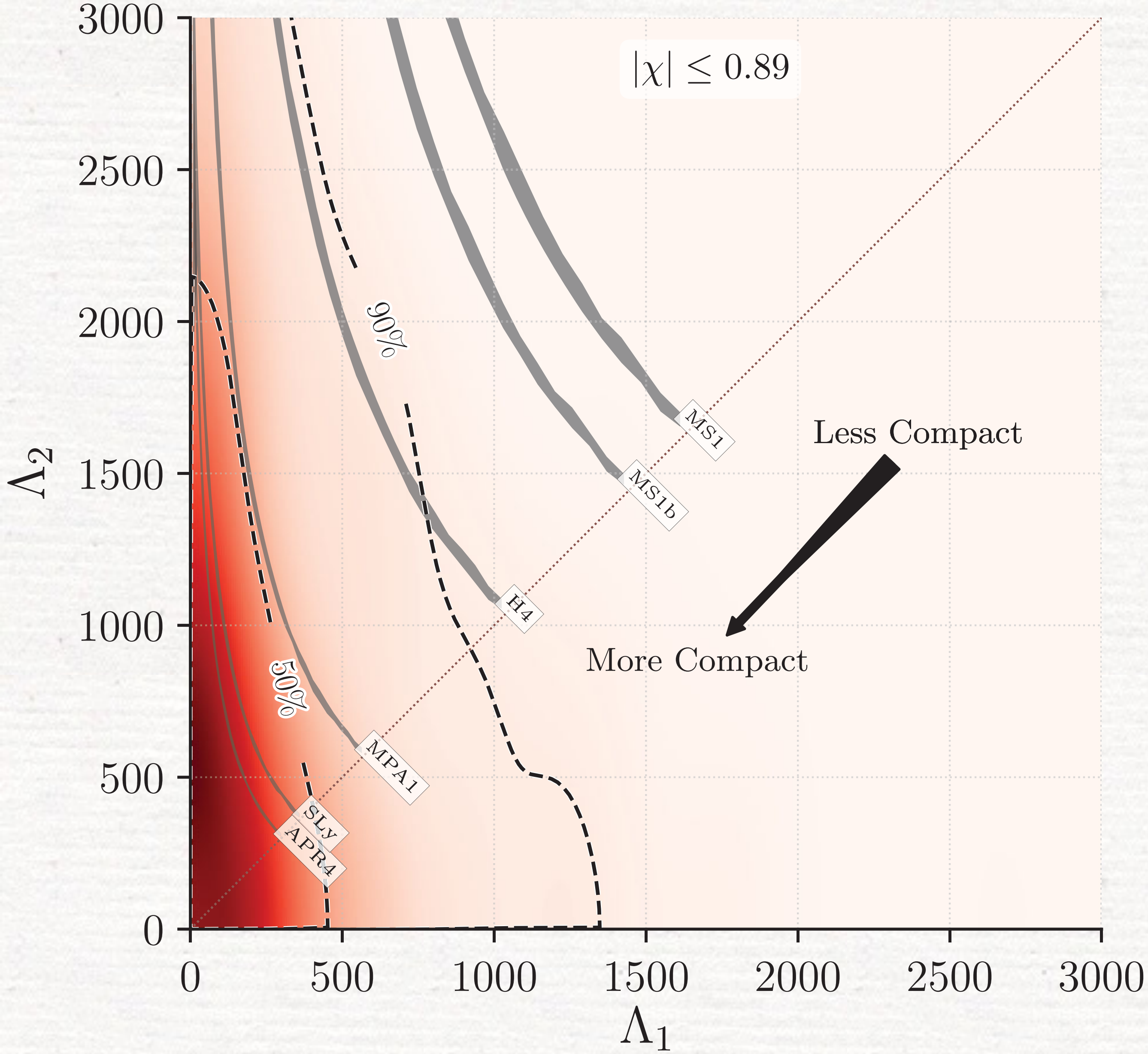
$$M_2 = 1.17 - 1.36 M_\odot$$

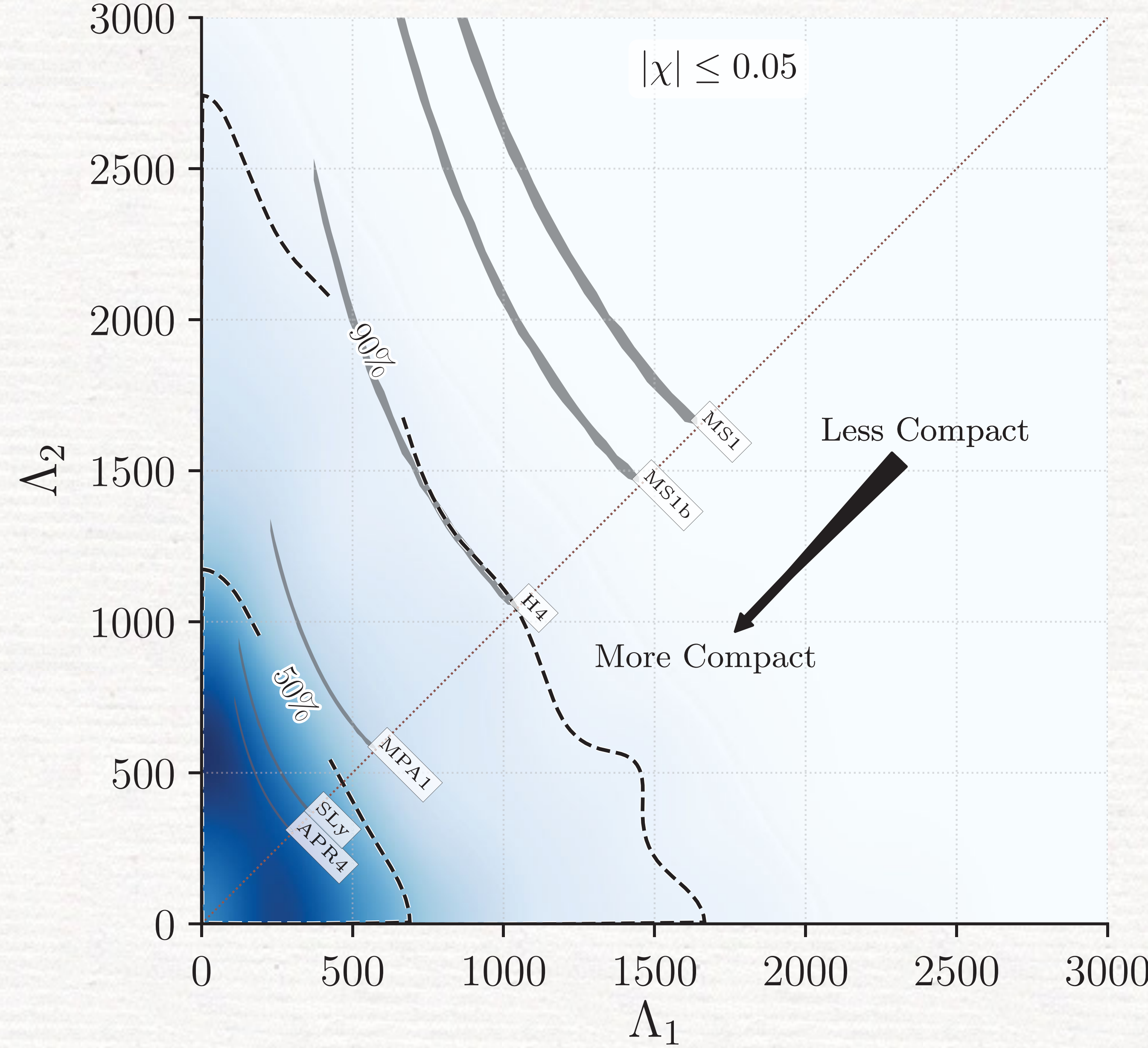


Abbott et al 2017

GW170817: What do we know?

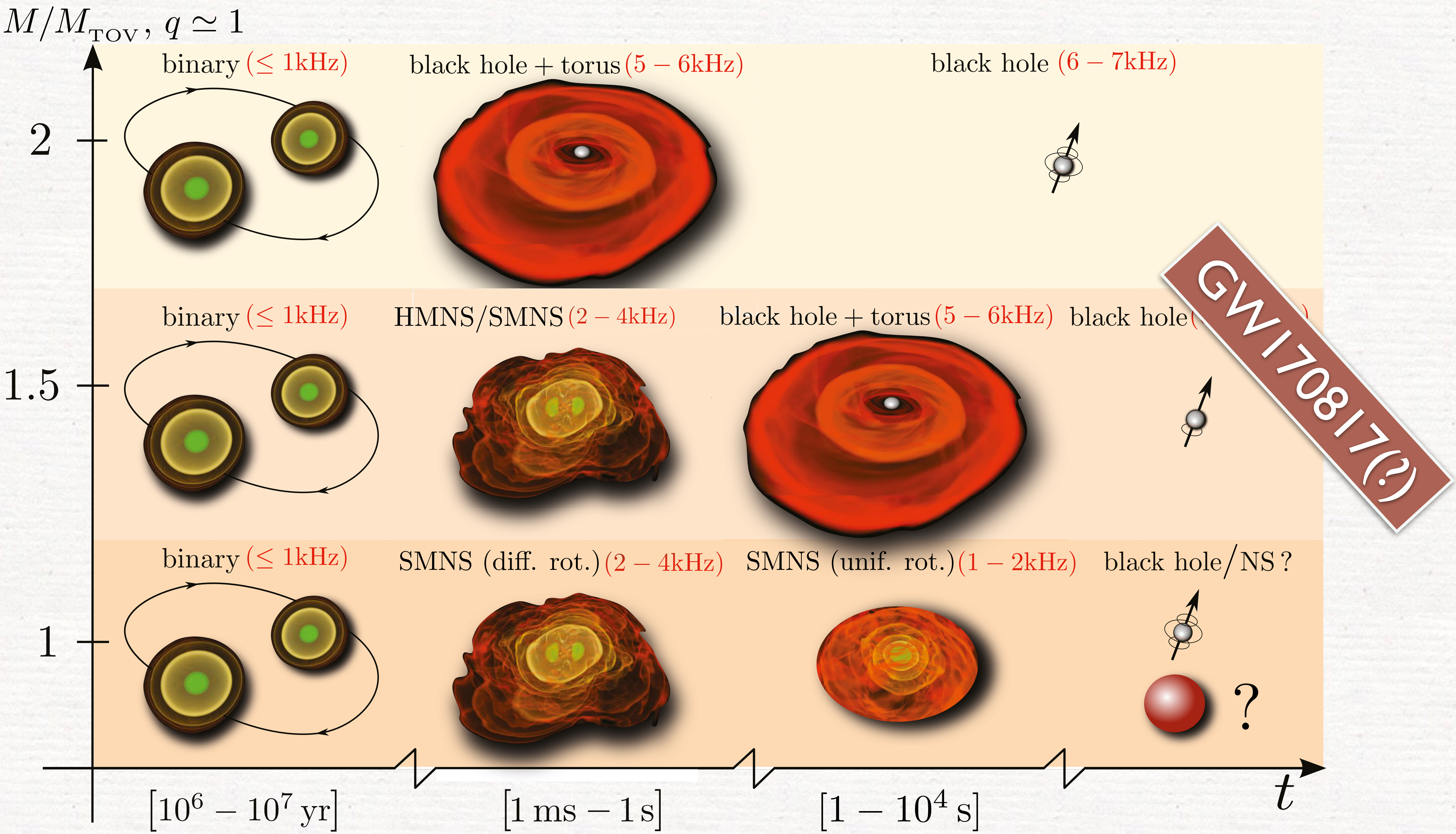
$\tilde{\Lambda} < 800$





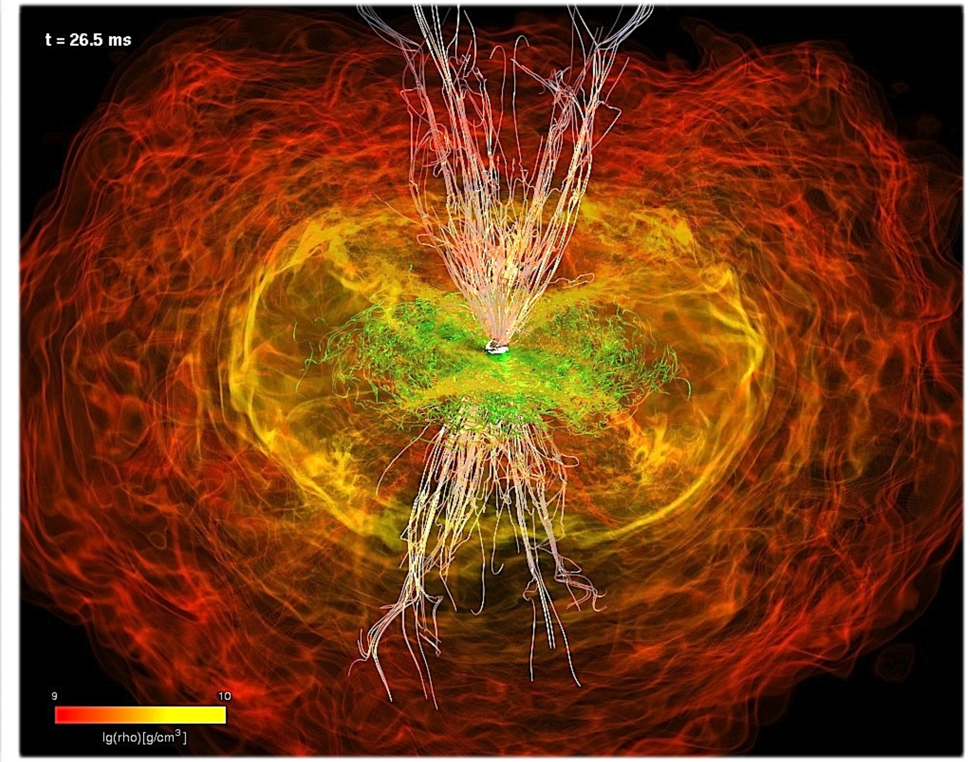
Abbott et al 2017

Binary neutron stars: general picture

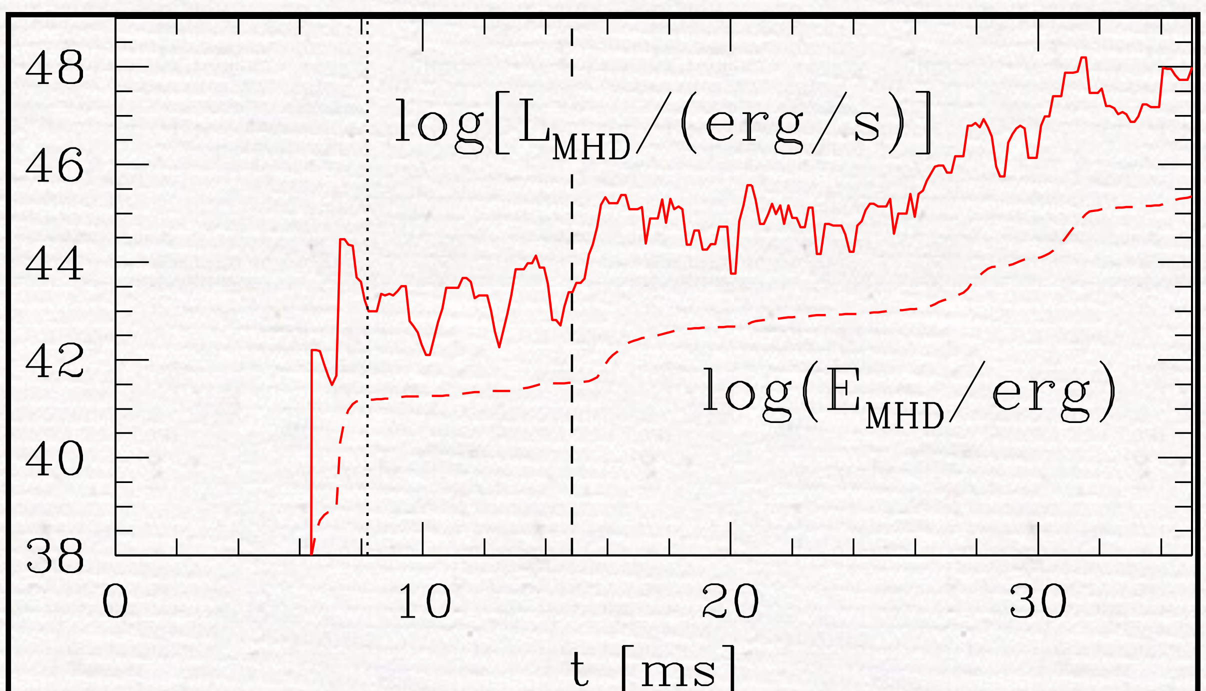


Baiotti & Rezzolla 2017

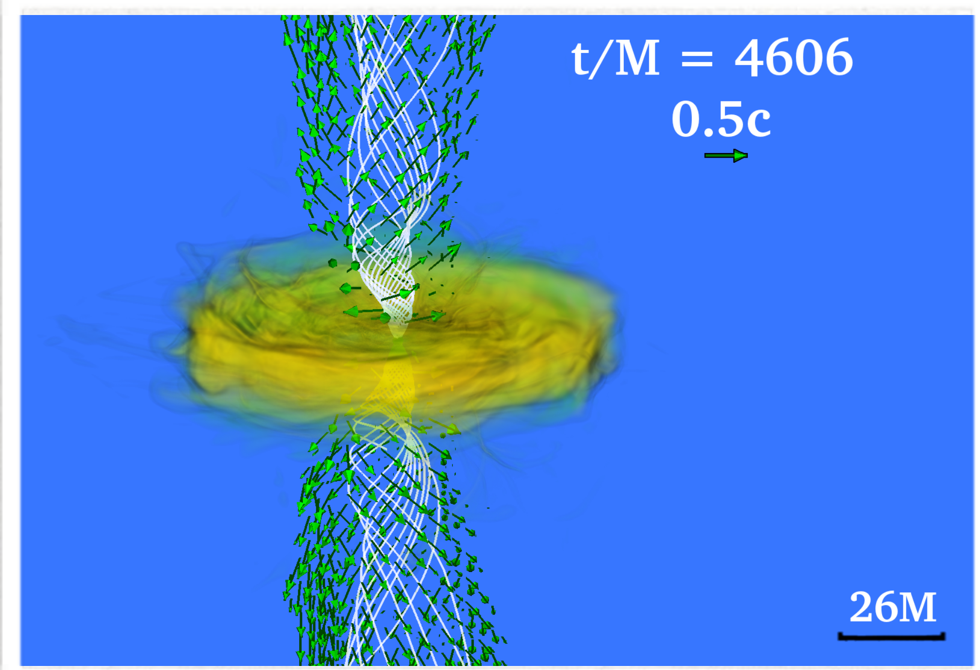
EM counterparts



Rezzolla et al 2011



Rezzolla et al 2011

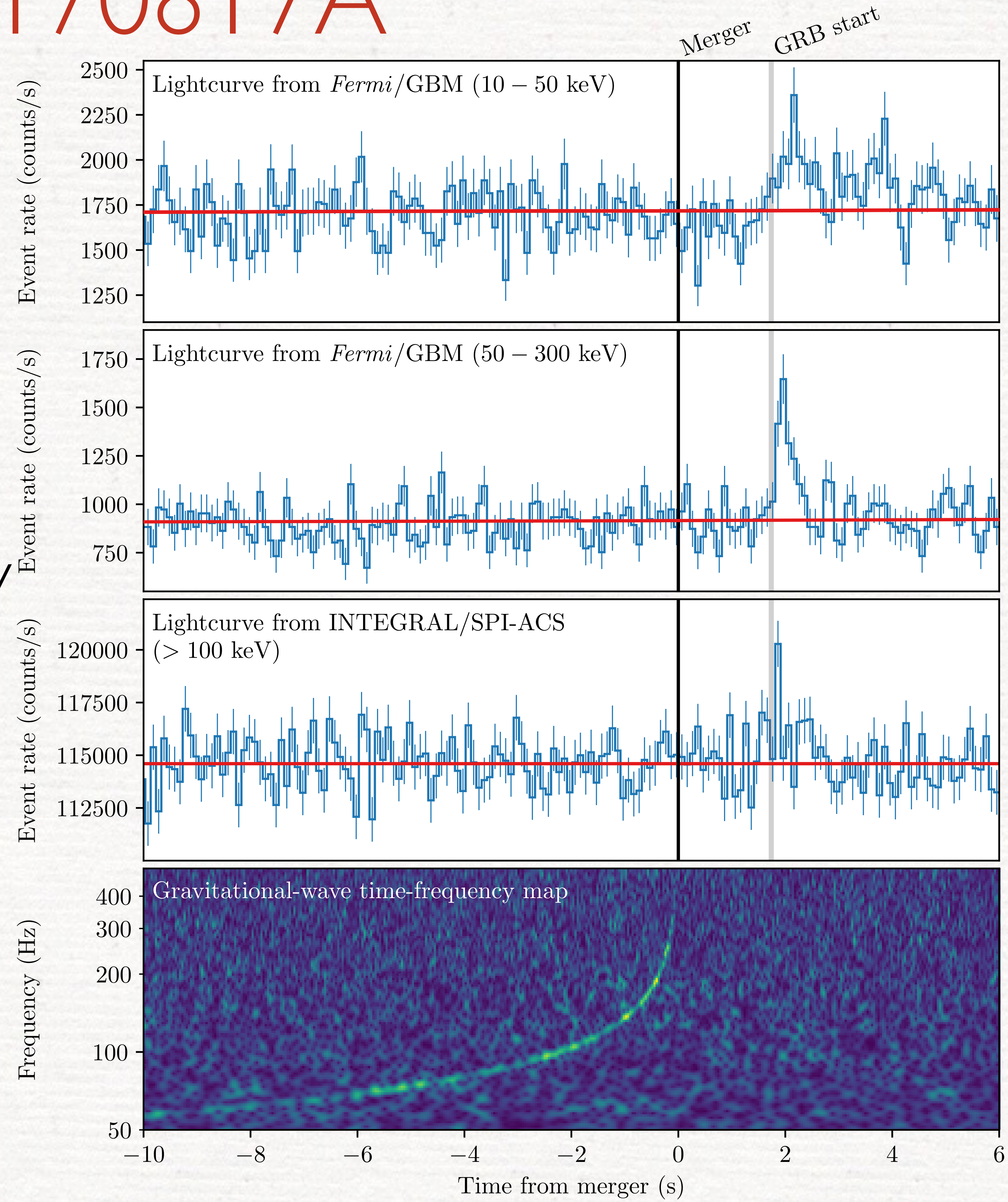


Ruiz et al 2016

GW170817A

- Coincident detection of sGRB
- Multi-messenger astronomy now possible

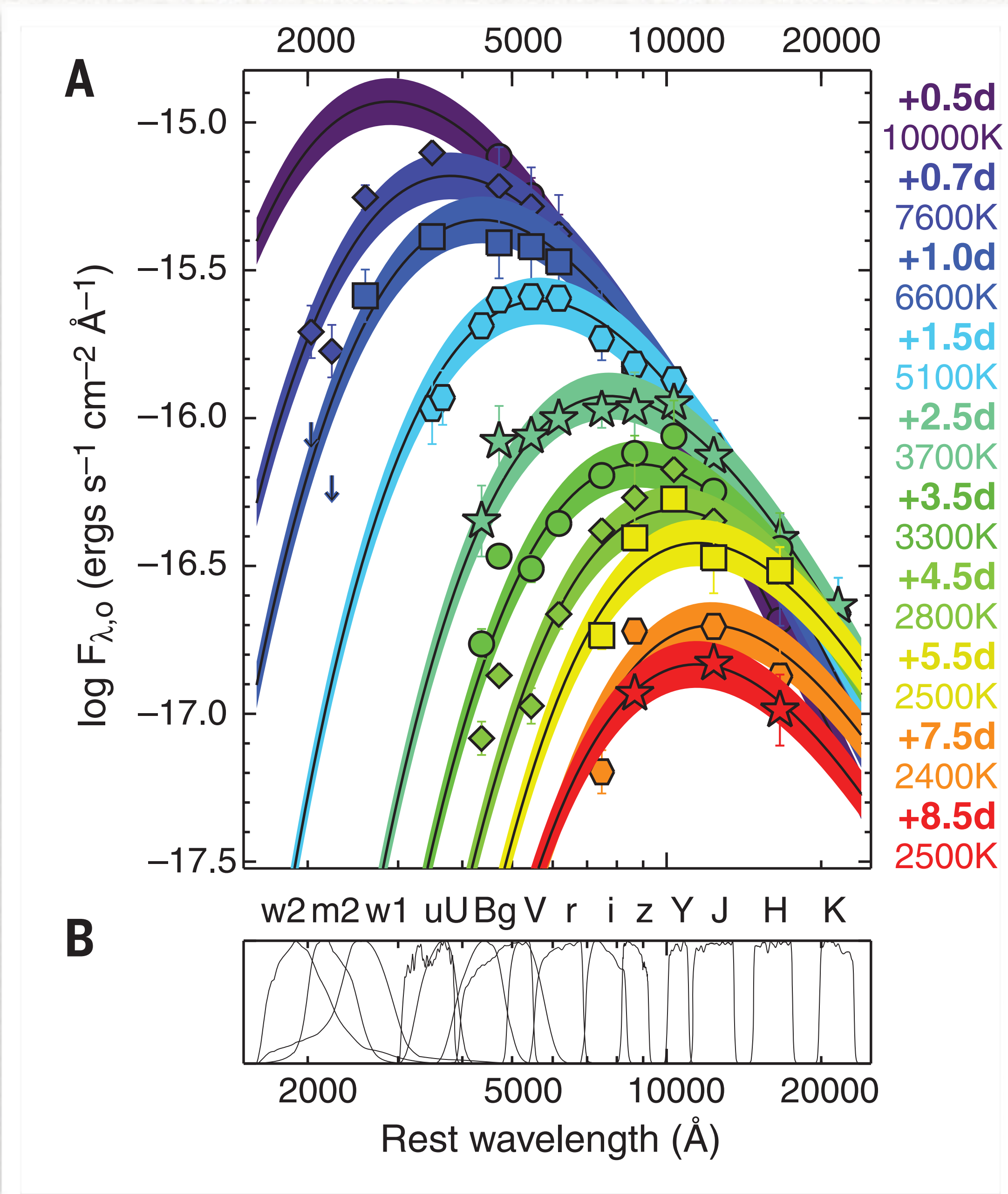
Most models of sGRBs assume the formation of a black hole!

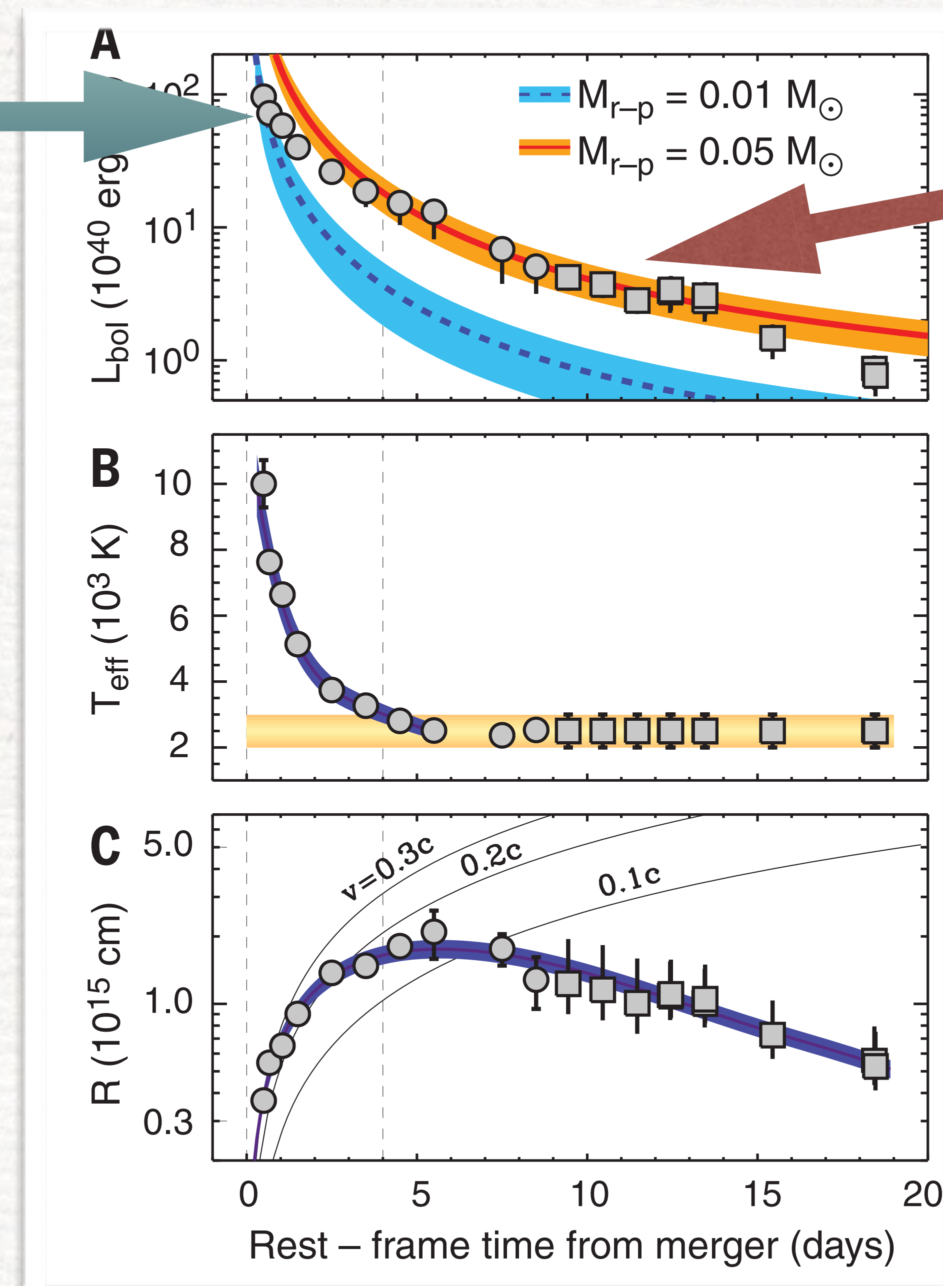


Abbott et al 2017

Light curves

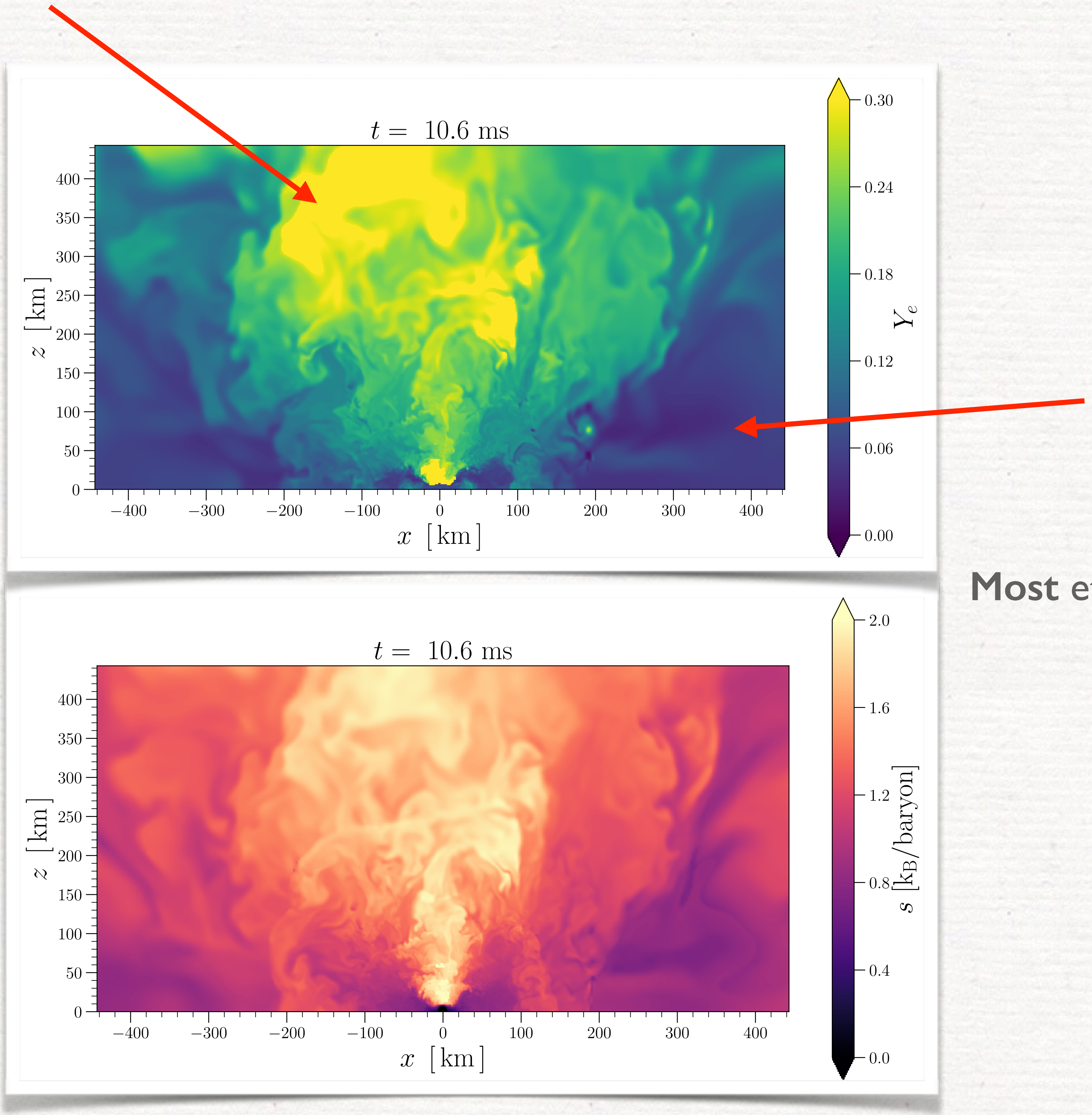
Observations consistent with two component model





Drout et al 2017

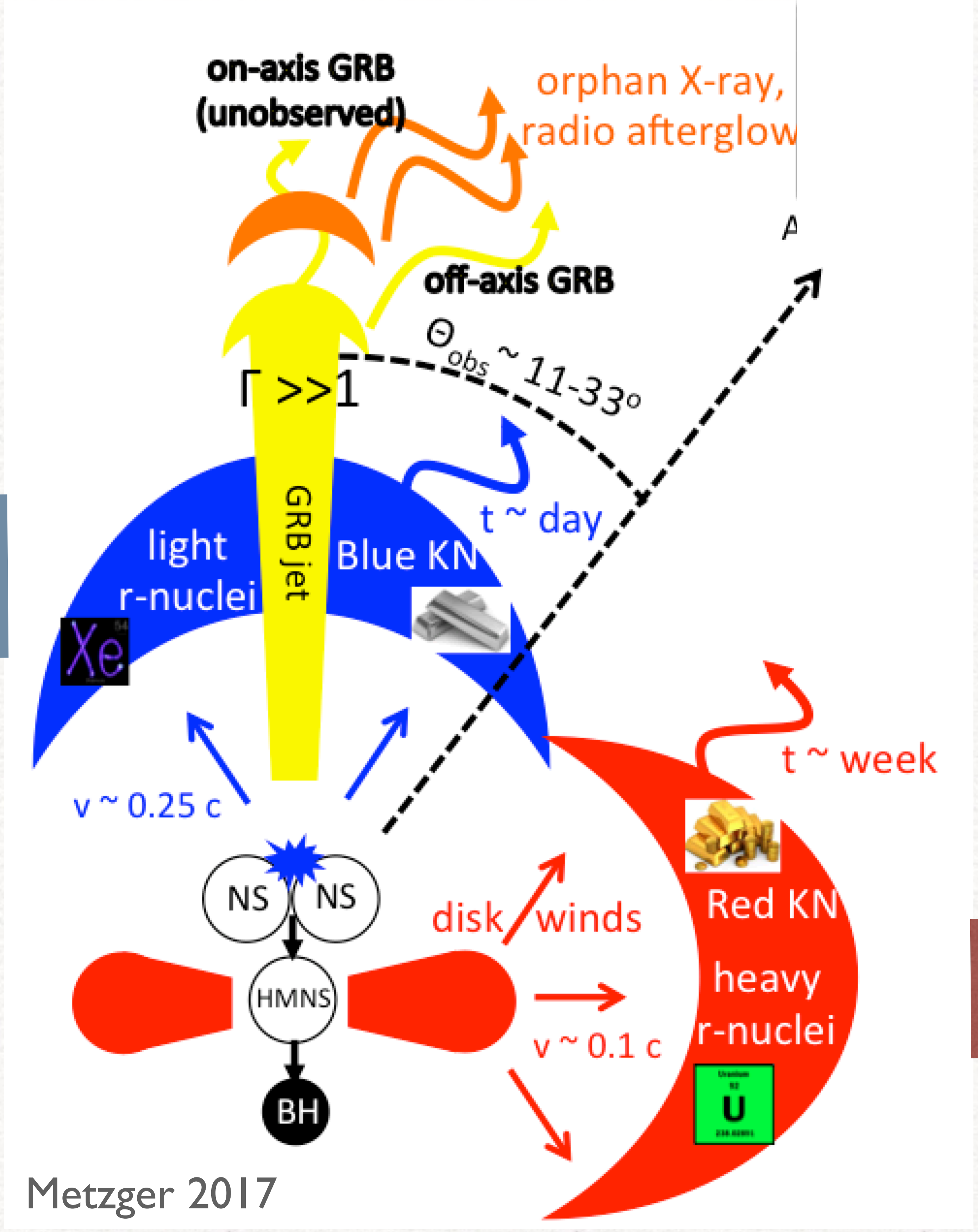
NR simulations



Most et al in prep.

AT2017gfo: Kilonova picture

Blue ejecta: ~0.01 M_{sun}



Red ejecta: ~0.04 M_{sun}

Ingredients to constrain EOS

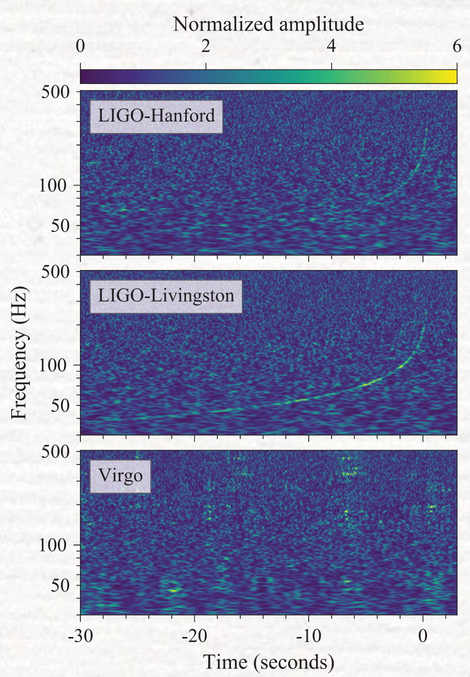
Numerical relativity | **Nuclear physics** | **Physics modelling**

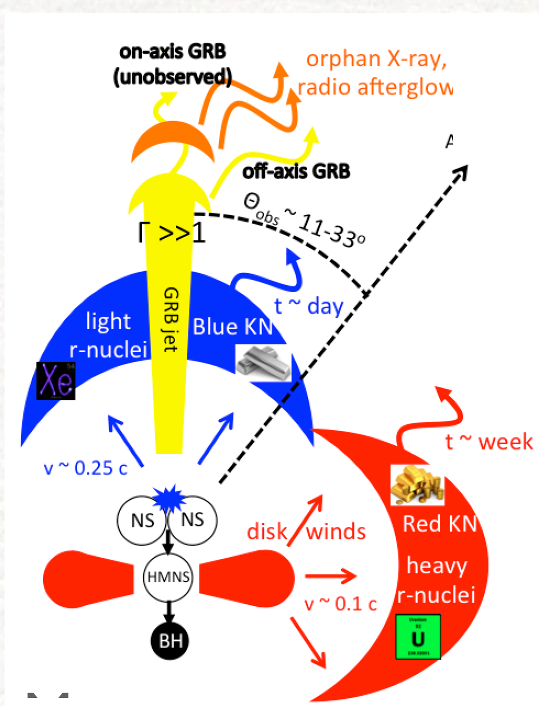
↓

EOS CONSTRAINTS

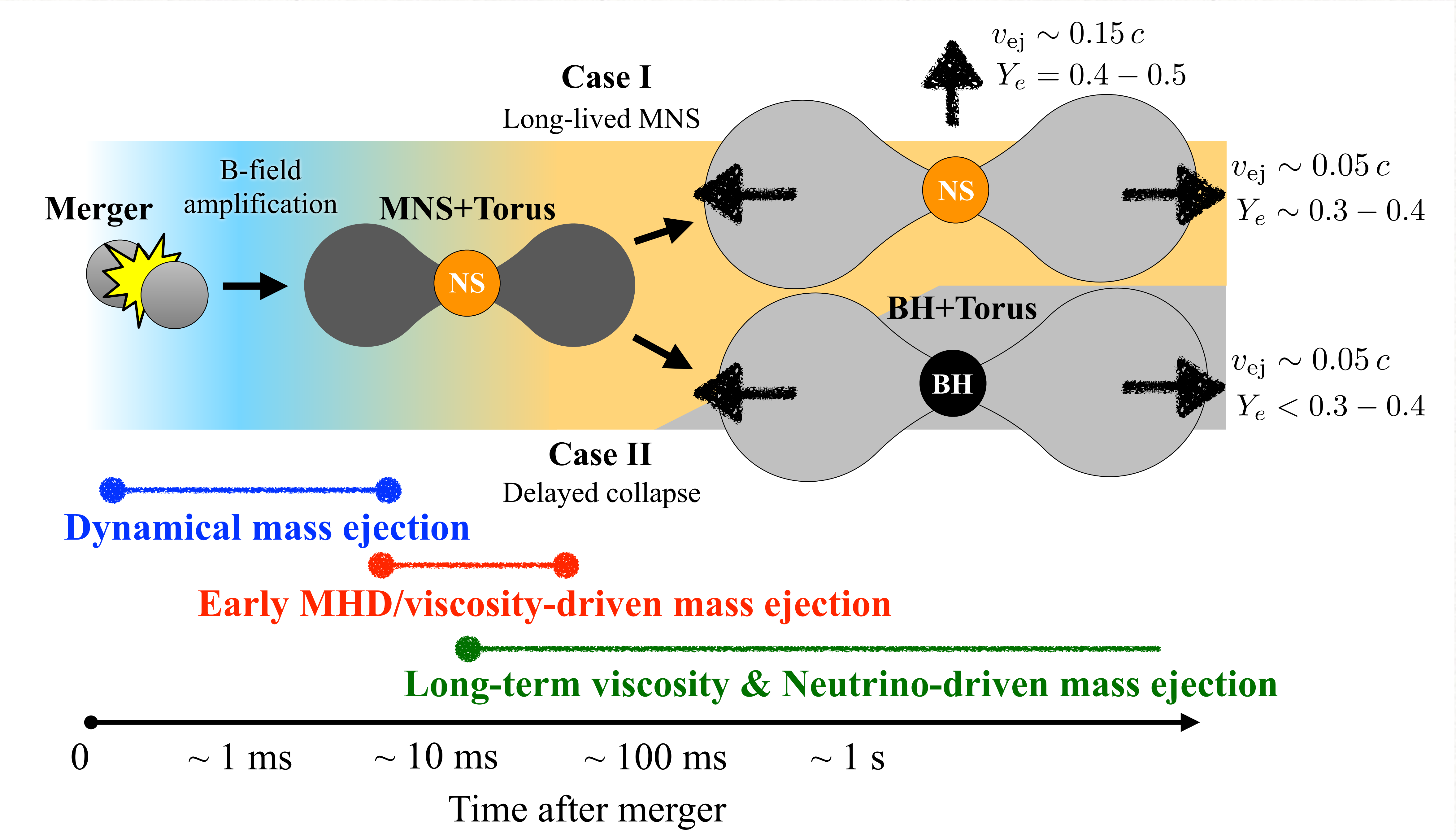
↑

Observations





Time scales - broad brush picture

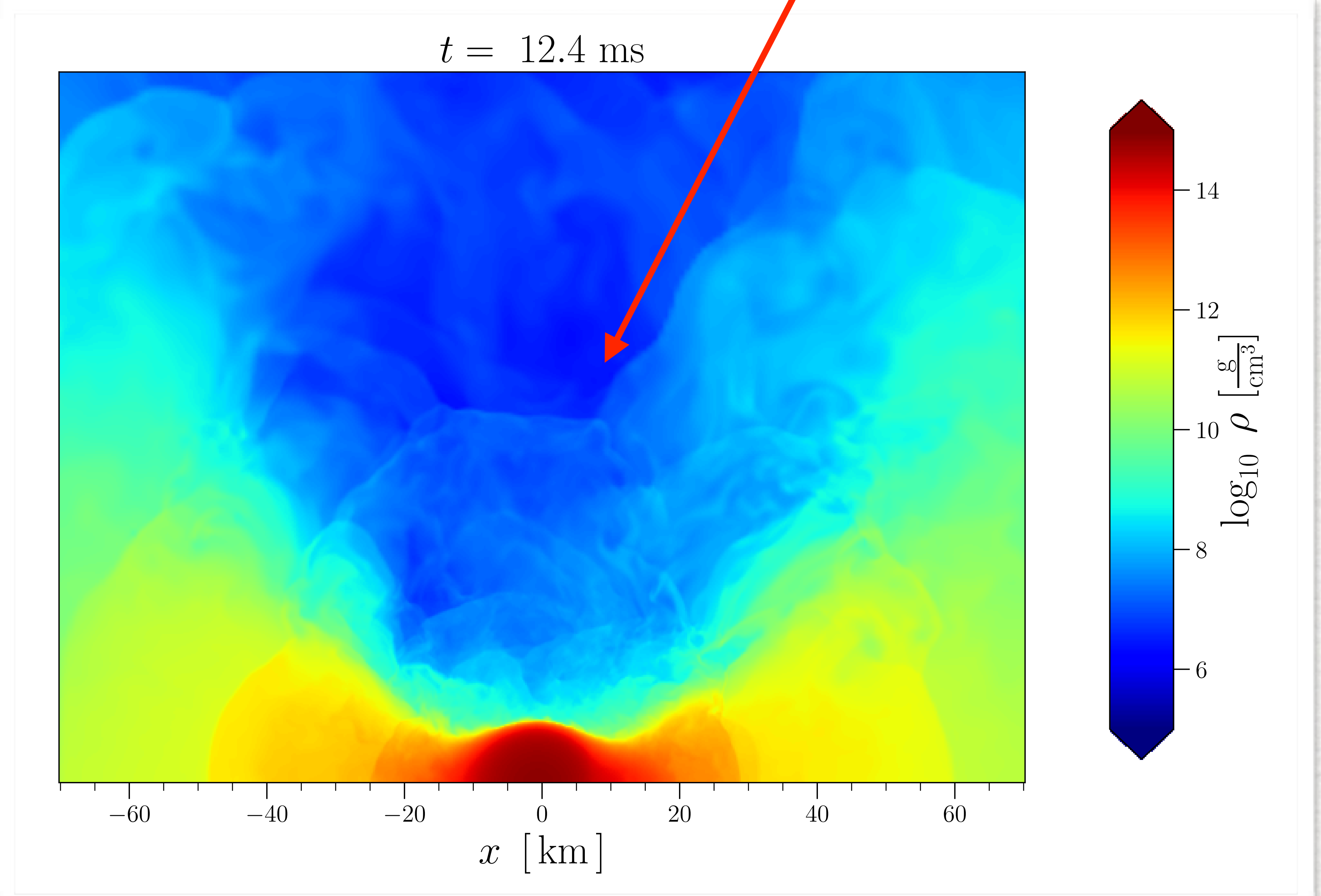


Fujibayashi et al 2017

Mass ejection

Consistency
with blue ejecta requires HMNS
to have a lifetime > 100 ms

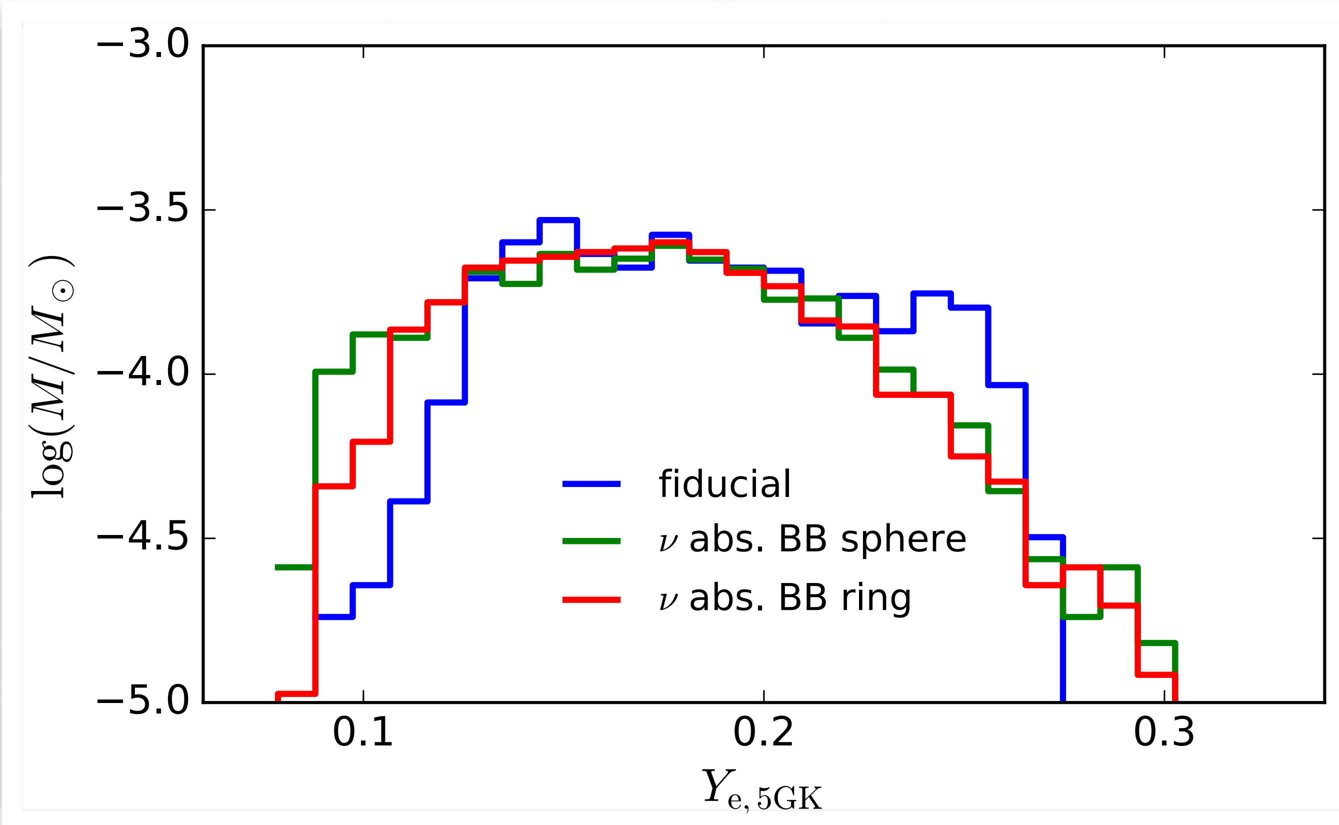
Low densities



Blue ejecta:~0.01 M_{sun}

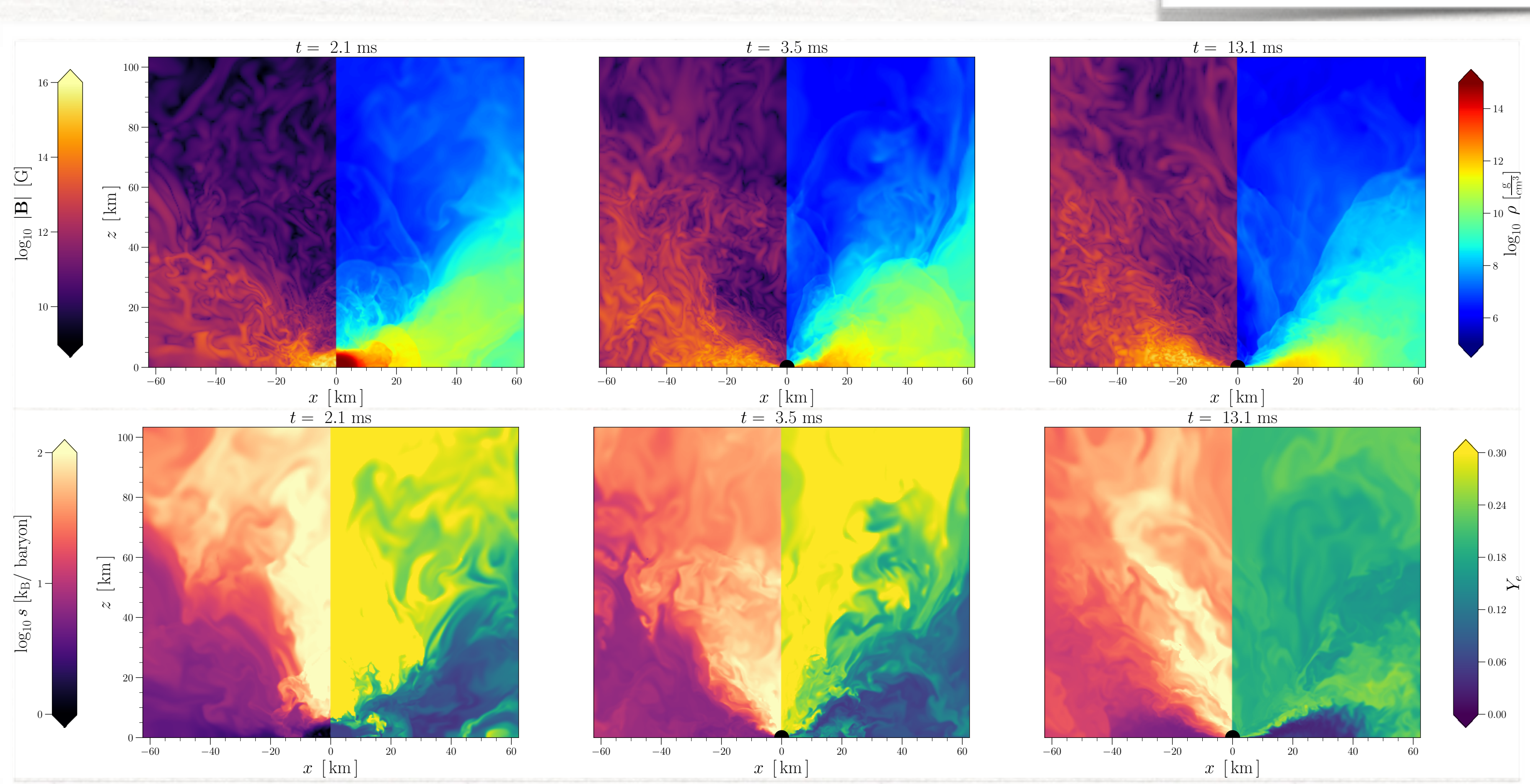
What about BH-torus systems?

Siegel et al 2017



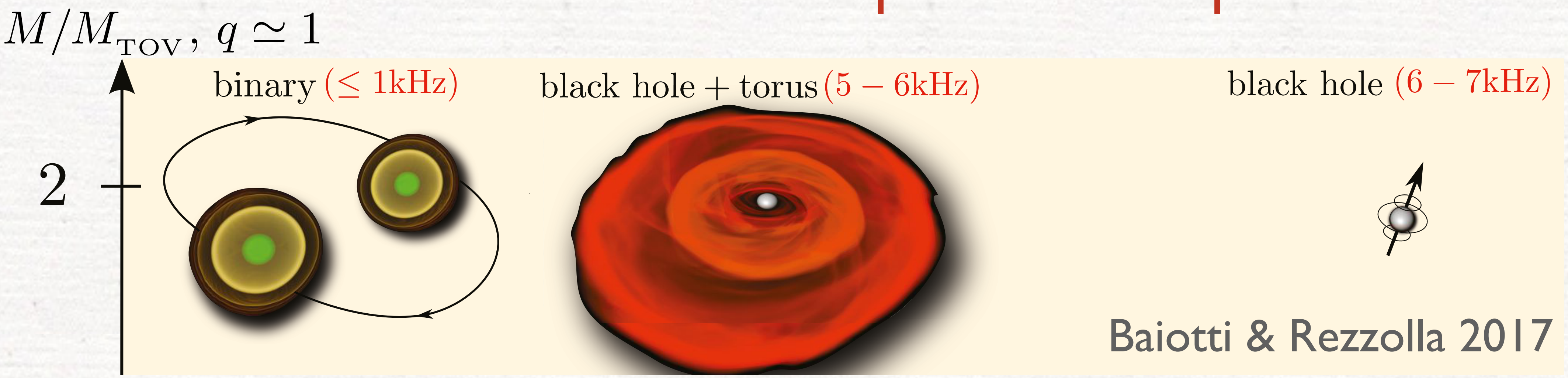
Need also to account for long term ejecta from BH-torus

Most et al in prep



no high Ye ejecta

Prompt collapse



If the two NS in a binary are too heavy, the system will undergo prompt collapse

$$M_{\rm thresh} = k M_{\rm TOV}$$

$$k = -3.606 \frac{M_{\rm max}}{c^2 R_{1.6}} + 2.38$$

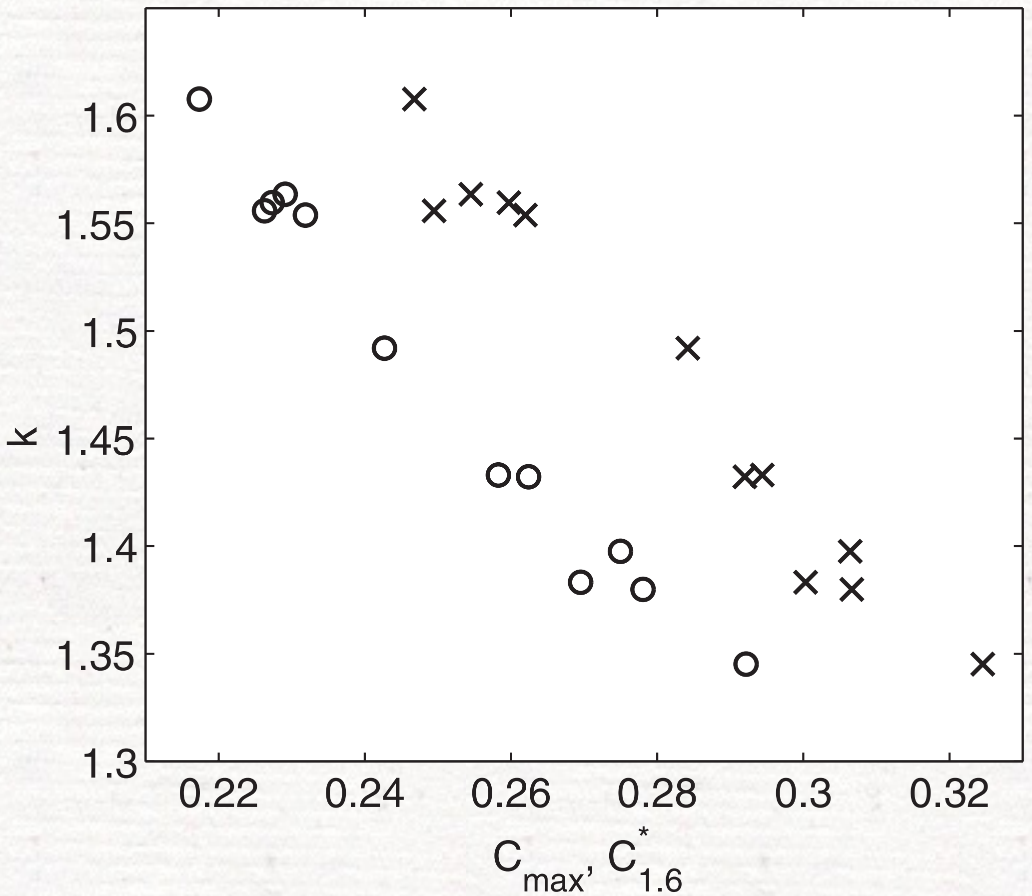


FIG. 1. Coefficient k [Eq. (1)] as a function of $C_{\rm max} = GM_{\rm max}/(c^2 R_{\rm max})$ (crosses) and $C^*_{1.6} = GM_{\rm max}/(c^2 R_{1.6})$ (circles).

Bauswein et al 2013

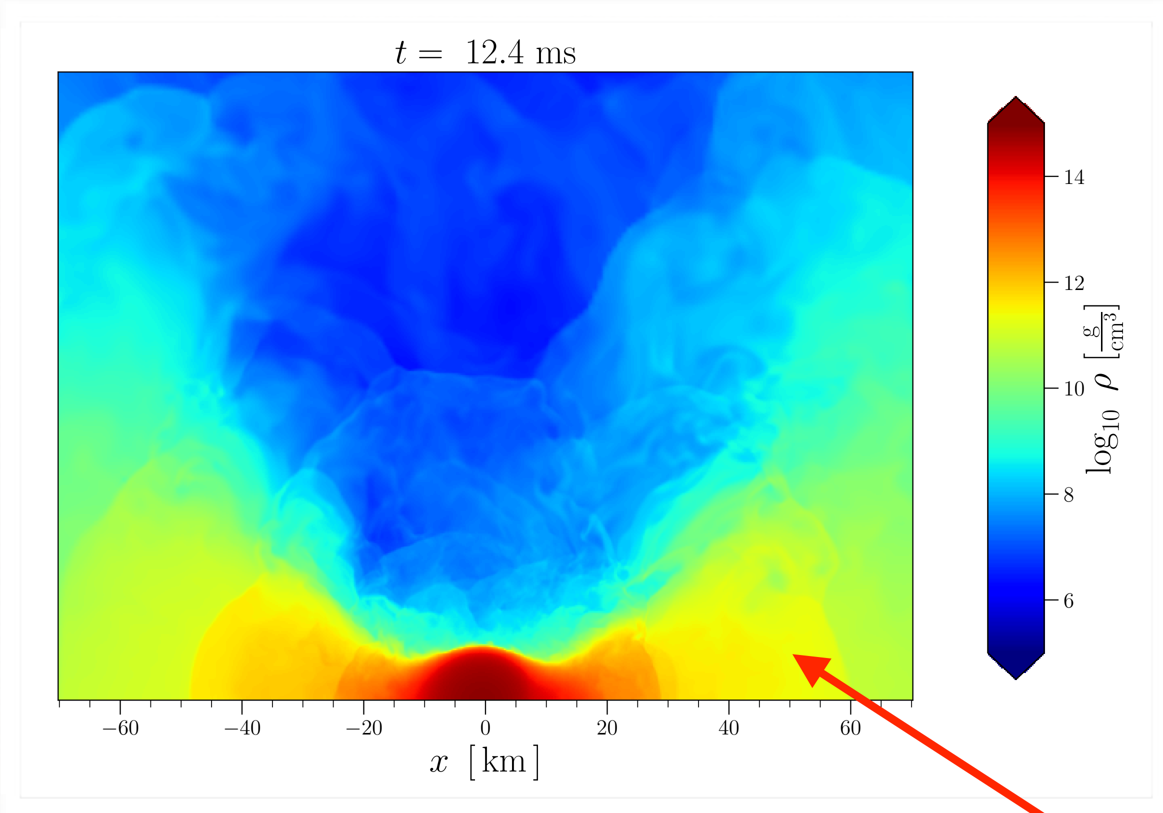
Direct life time assessment

Numerical simulations can also directly exclude EOS that lead to a rapid collapse for $M \sim 2.7\ M_{sun}$

Hotokezaka et al 2013

Model	Γ_{th}	m_1 ($M_\odot$)	m_2 ($M_\odot$)	Lifetime (ms)	Disk mass ($M_\odot$)	Final mass ($M_\odot$)
APR4-130150	1.8	1.30	1.50	30	0.12	2.69
APR4-140140	1.8	1.30	1.50	35	0.12	2.69
APR4-120150	1.6, 1.8, 2.0	1.20	1.50	—	—	2.60, 2.59, 2.59
APR4-125145	1.8	1.25	1.45	—	—	2.60
APR4-130140	1.8	1.30	1.40	—	—	2.60
APR4-135135	1.6, 1.8, 2.0	1.35	1.35	—	—	2.59, 2.61, 2.60
APR4-120140	1.8	1.20	1.40	—	—	2.52
APR4-125135	1.8	1.25	1.35	—	—	2.53
APR4-130130	1.8	1.30	1.30	—	—	2.53
SLy-120150	1.8	1.20	1.50	10	0.12	2.60
SLy-125145	1.8	1.25	1.45	15	0.14	2.60
SLy-130140	1.8	1.30	1.40	15	0.11	2.60
SLy-135135	1.8	1.35	1.35	10	0.08	2.58
SLy-130130	1.8	1.30	1.30	—	—	2.51

Disk masses



The disk
has a *mass fraction* of
~3% (Radice+ 2018)
~5% (Hanauske+ 2017)

Table 1
BH formation time and disk masses for all models. Values are given at the final simulation time.

EOS	M_A	M_B	$\tilde{\Lambda}$ [a]	M_{disk} [b]	M_{ej} [c]	t_{BH} [d]	t_{end} [e]
	$[M_\odot]$			$[10^{-2}$	$M_\odot]$	[ms]	
BHBΛφ	1.365	1.25	1028	18.73	0.06	–	23.98
BHBΛφ	1.35	1.35	857	14.45	0.07	–	21.26
BHBΛφ	1.4	1.2	1068	20.74	0.11	–	23.74
BHBΛφ	1.4	1.4	697	7.05	0.09	11.96	16.39
BHBΛφ	1.44	1.39	655	8.28	0.06	10.39	15.77
BHBΛφ	1.5	1.5	462	1.93	0.05	2.27	11.78
BHBΛφ	1.6	1.6	306	0.09	0.00	0.99	10.67
DD2	1.365	1.25	1028	20.83	0.04	–	24.24
DD2	1.35	1.35	858	15.69	0.03	–	24.41
DD2	1.4	1.2	1070	19.26	0.09	–	23.59
DD2	1.4	1.4	699	12.36	0.04	–	24.52
DD2	1.44	1.39	658	14.40	0.05	–	23.52
DD2	1.5	1.5	469	16.70	0.07	–	23.12
DD2	1.6	1.6	317	1.96	0.12	2.28	12.08
LS220	1.2	1.2	1439	17.43	0.14	–	23.22
LS220	1.365	1.25	848	16.86	0.11	–	26.71
LS220	1.35	1.35	684	7.25	0.06	20.34	23.84
LS220	1.4	1.2	893	22.82	0.19	–	23.52
LS220	1.4	1.4	536	4.58	0.14	9.93	26.95
LS220	1.44	1.39	499	3.91	0.19	7.22	14.83
LS220	1.45	1.45	421	2.05	0.16	2.26	11.83
LS220	1.6	1.6	202	0.07	0.03	0.63	10.42
LS220	1.71	1.71	116	0.06	0.03	0.49	9.94
SFHo	1.365	1.25	520	8.81	0.15	–	26.41
SFHo	1.35	1.35	422	6.23	0.35	11.96	22.88
SFHo	1.4	1.2	546	11.73	0.12	–	24.31
SFHo	1.4	1.4	334	0.01	0.04	1.07	13.91
SFHo	1.44	1.39	312	0.09	0.04	0.87	7.06
SFHo	1.46	1.46	252	0.02	0.00	0.70	9.51

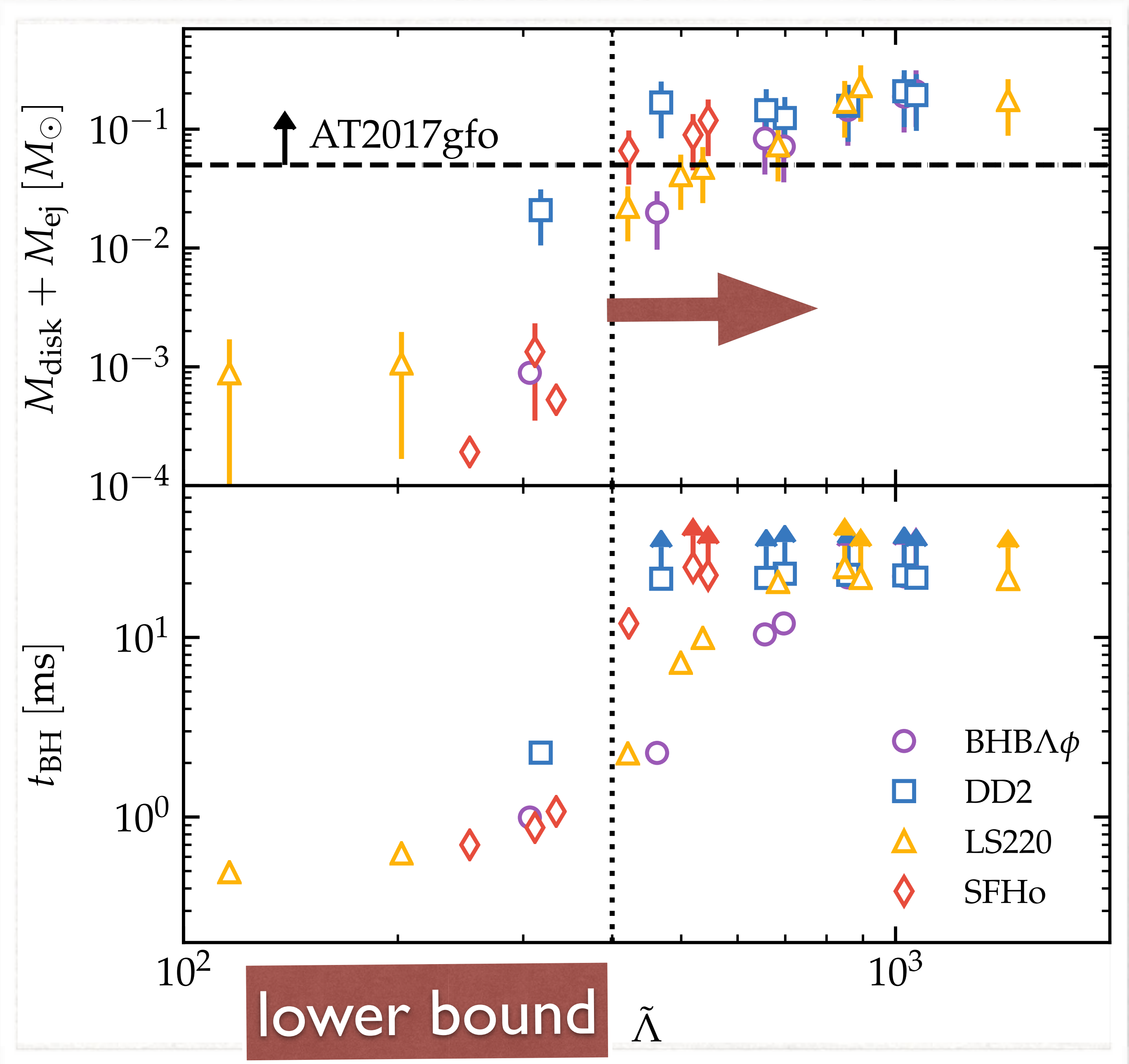
Radice et al 2018

Tidal deformability

Sufficient mass ejection seems to depend on the tidal deformability of the system

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

$\tilde{\Lambda} > 400$ (error?)



Radice et al 2018

Universal relations

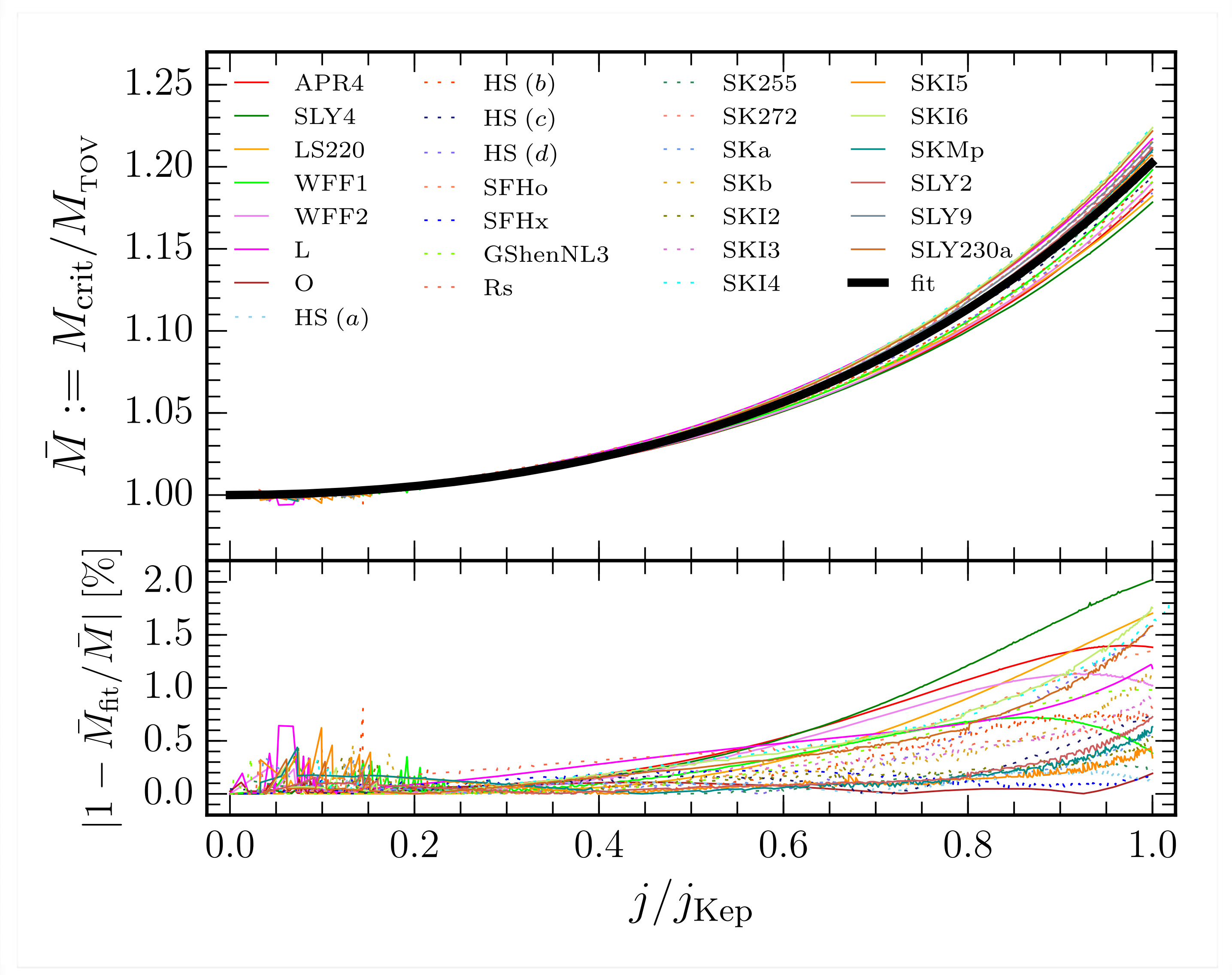
Universal relations can provide EOS independent information

$$\frac{M_{\rm crit}}{M_{\rm TOV}} = 1 + a_2 \left(\frac{j}{j_{\rm Kep}}\right)^2 + a_4 \left(\frac{j}{j_{\rm Kep}}\right)^4$$

The maximum mass of a TOV and of a maximally spinning NS are related!

$$M_{\rm max} := M_{\rm crit}(j = j_{\rm Kep}) = (1 + a_2 + a_4)\, M_{\rm TOV}$$

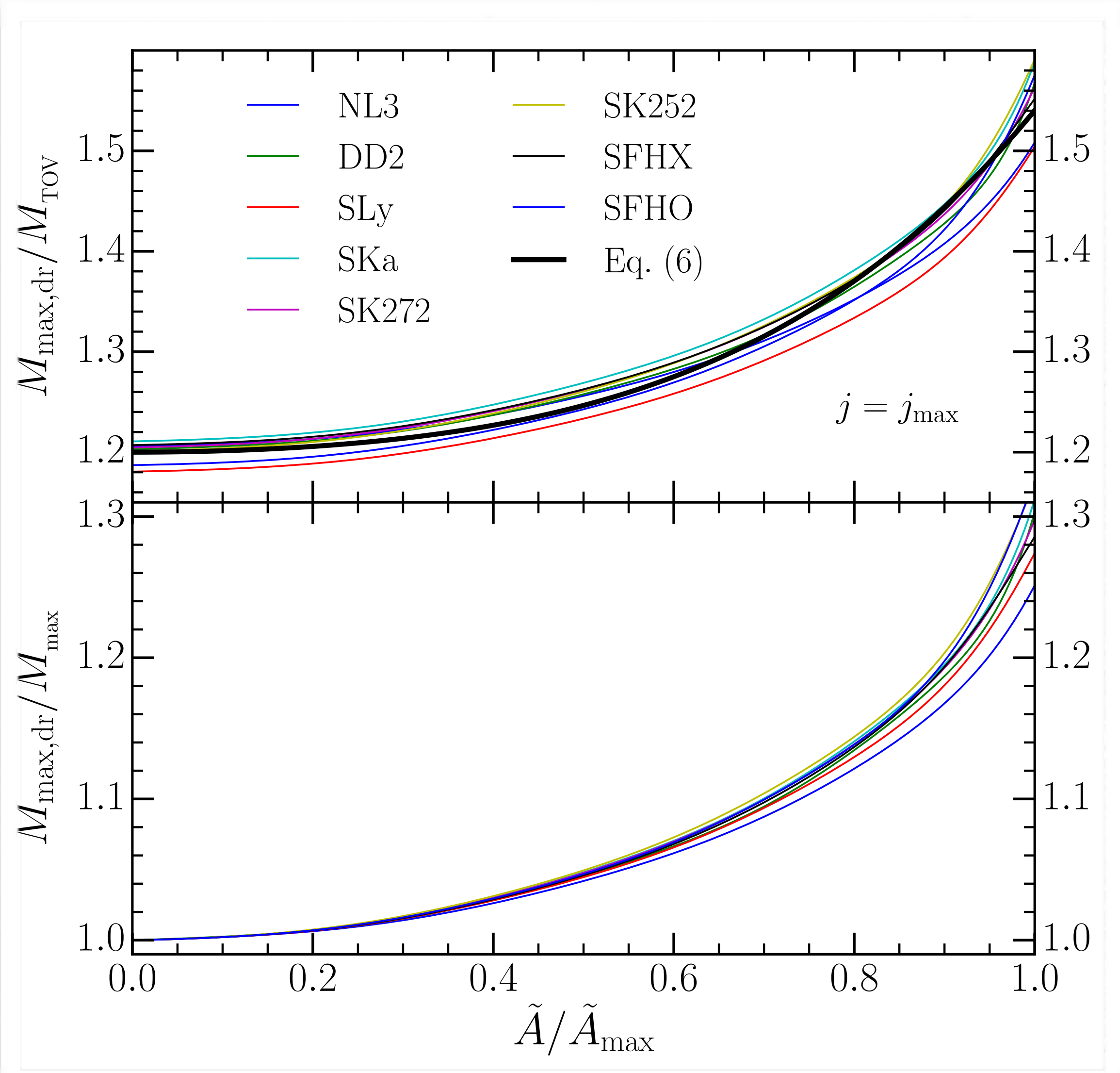
$$\simeq (1.203 \pm 0.022)\, M_{\rm TOV}\,,$$

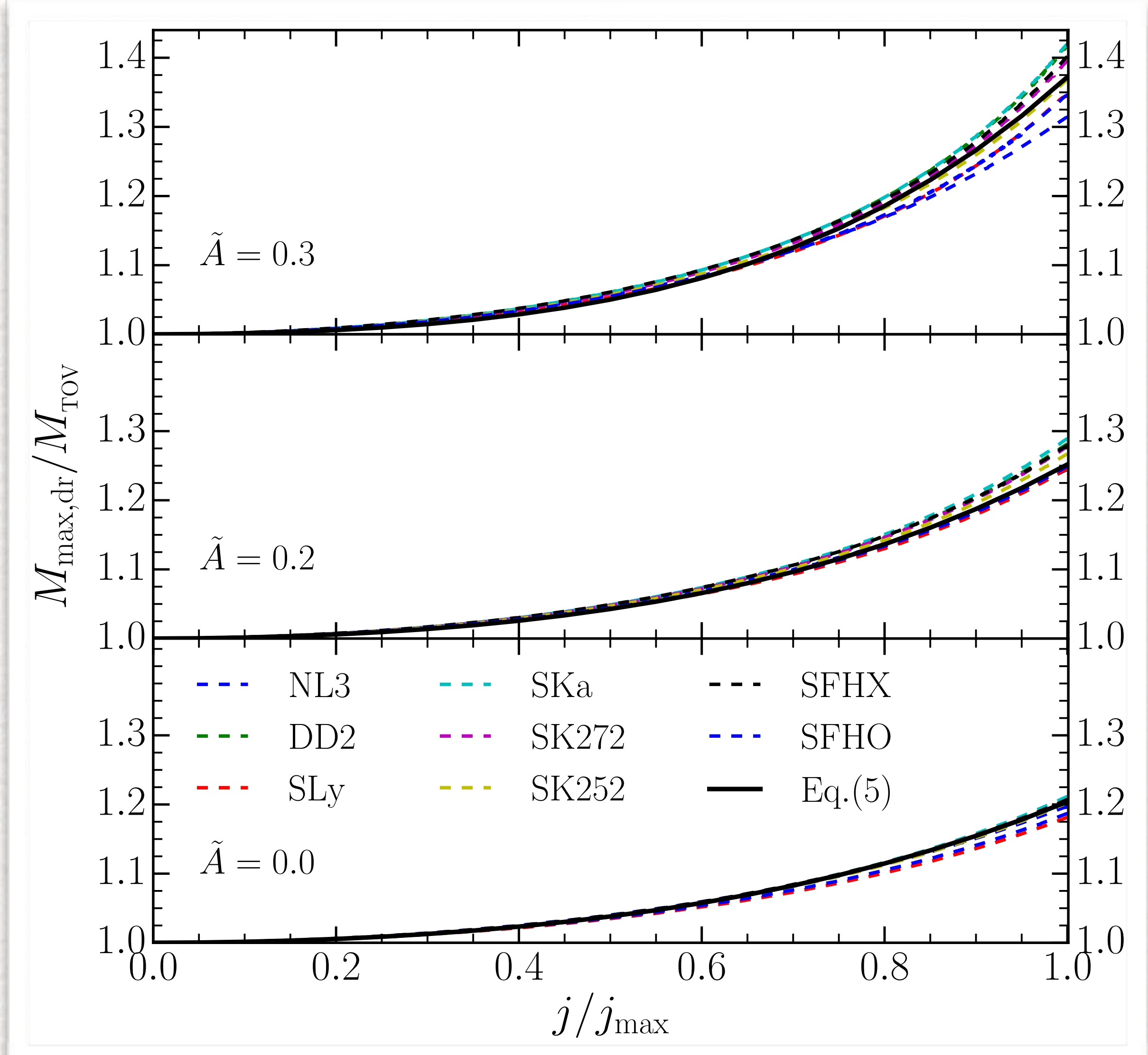


Breu and Rezzolla 2016

Universal relations

Universal relations also exist for differentially rotating NS



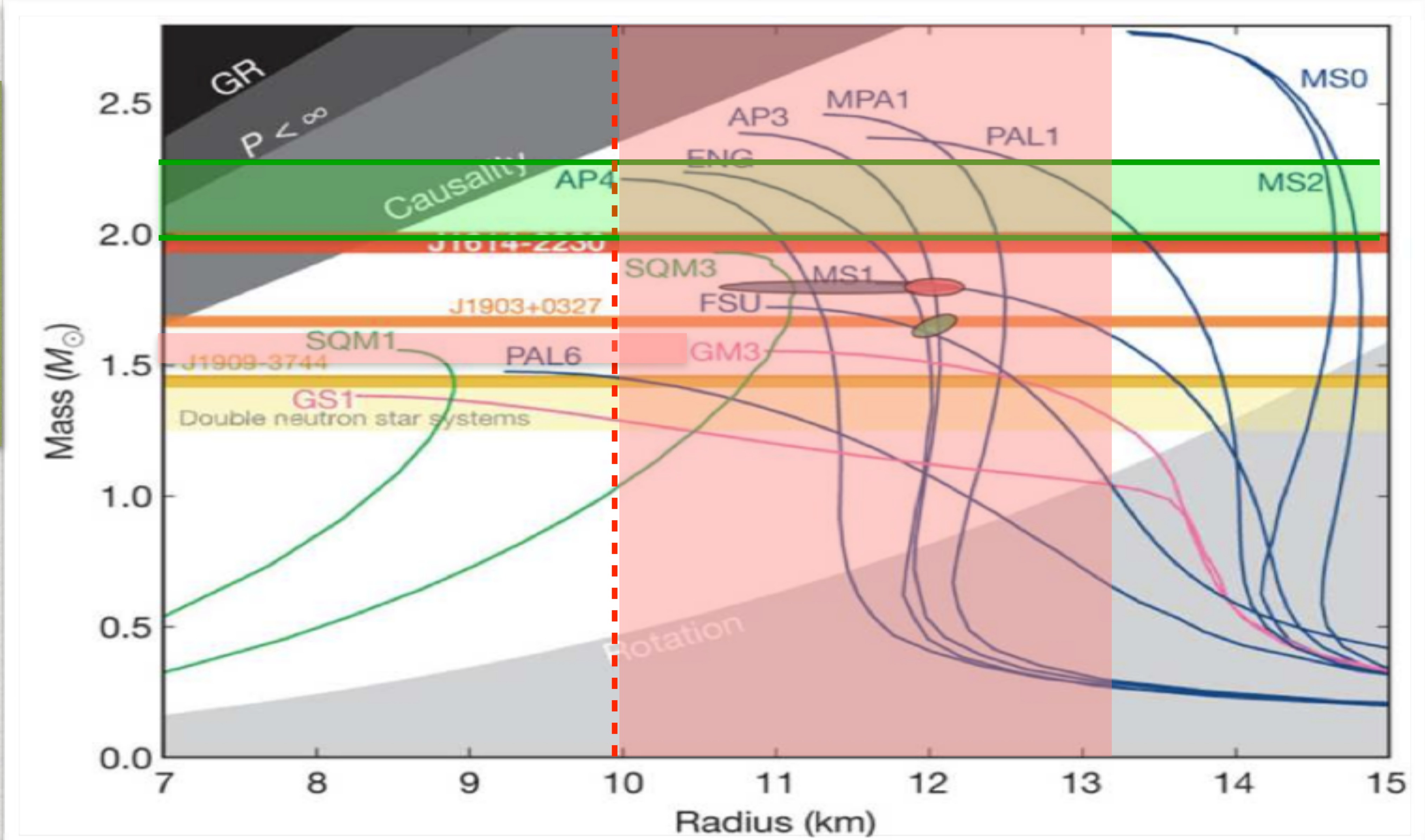


$$\frac{M_{\rm max,dr}(j,\tilde{A})}{M_{\rm TOV}} = 1 + a_1(\tilde{A})\left(\frac{j}{j_{\rm max}}\right)^2 + a_2(\tilde{A})\left(\frac{j}{j_{\rm max}}\right)^4$$

Weih, Most and **Rezzolla 2017**

Applying the constraints

maximum mass



lowest/largest radius

Part I

Constraining the maximum mass

Recent publications

CONSTRAINING THE MAXIMUM MASS OF NEUTRON STARS FROM MULTI-MESSENGER OBSERVATIONS OF GW170817

BEN MARGALIT & BRIAN D. METZGER

GW170817: Modeling based on numerical relativity and its implications

Masaru Shibata,[1] Sho Fujibayashi,[1] Kenta Hotokezaka,[2,1] Kenta Kiuchi,[1] Koutarou Kyutoku,[3,1] Yuichiro Sekiguchi,[4,1] and Masaomi Tanaka[5]

USING GRAVITATIONAL-WAVE OBSERVATIONS AND QUASI-UNIVERSAL RELATIONS TO CONSTRAIN THE MAXIMUM MASS OF NEUTRON STARS

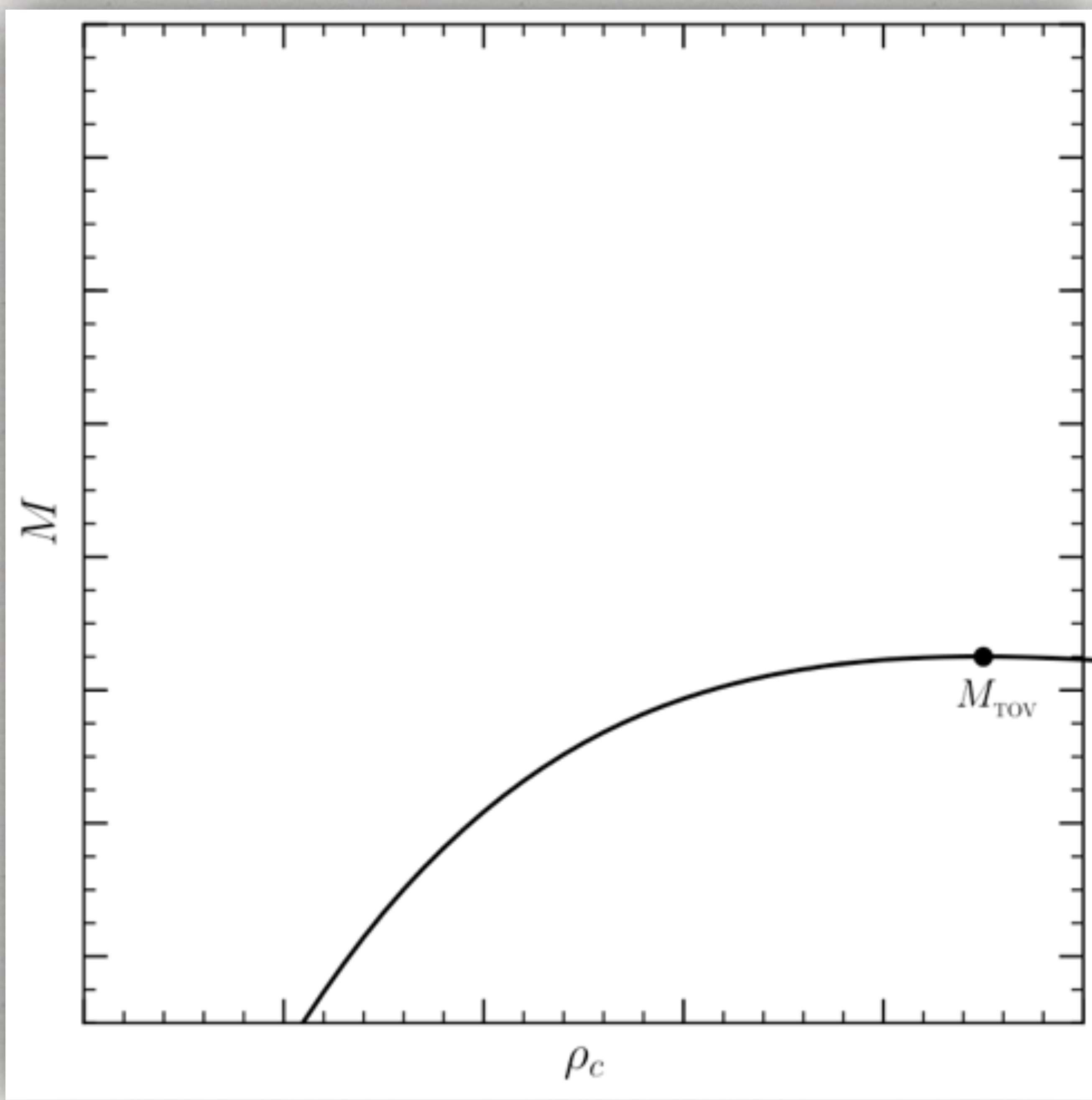
LUCIANO REZZOLLA[1,2], ELIAS R. MOST[1], AND LUKAS R. WEIH[1]

GW170817, General Relativistic Magnetohydrodynamic Simulations, and the Neutron Star Maximum Mass

Milton Ruiz,[1] Stuart L. Shapiro,[1,2] and Antonios Tsokaros[1]

The outcome of GW170817

- The product of GW170817 was likely a hypermassive star, i.e. a differentially rotating object with initial **gravitational** mass $M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$



- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$

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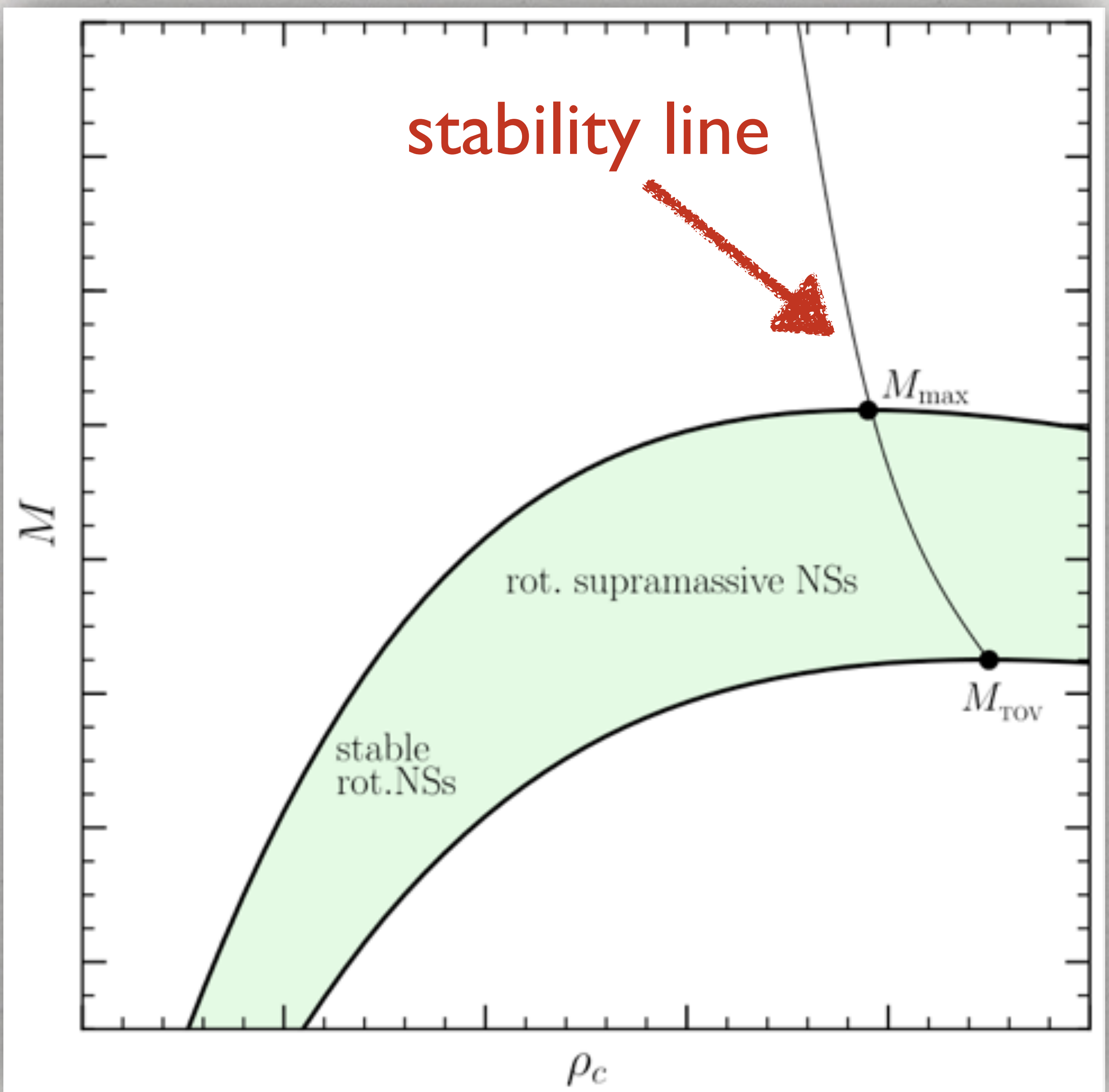

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\rm max}$
- $M_{\rm max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & Rezzolla 2016)

$$M_{\rm max} = \left(1.20^{+0.02}_{-0.05}\right) M_{\rm TOV}$$

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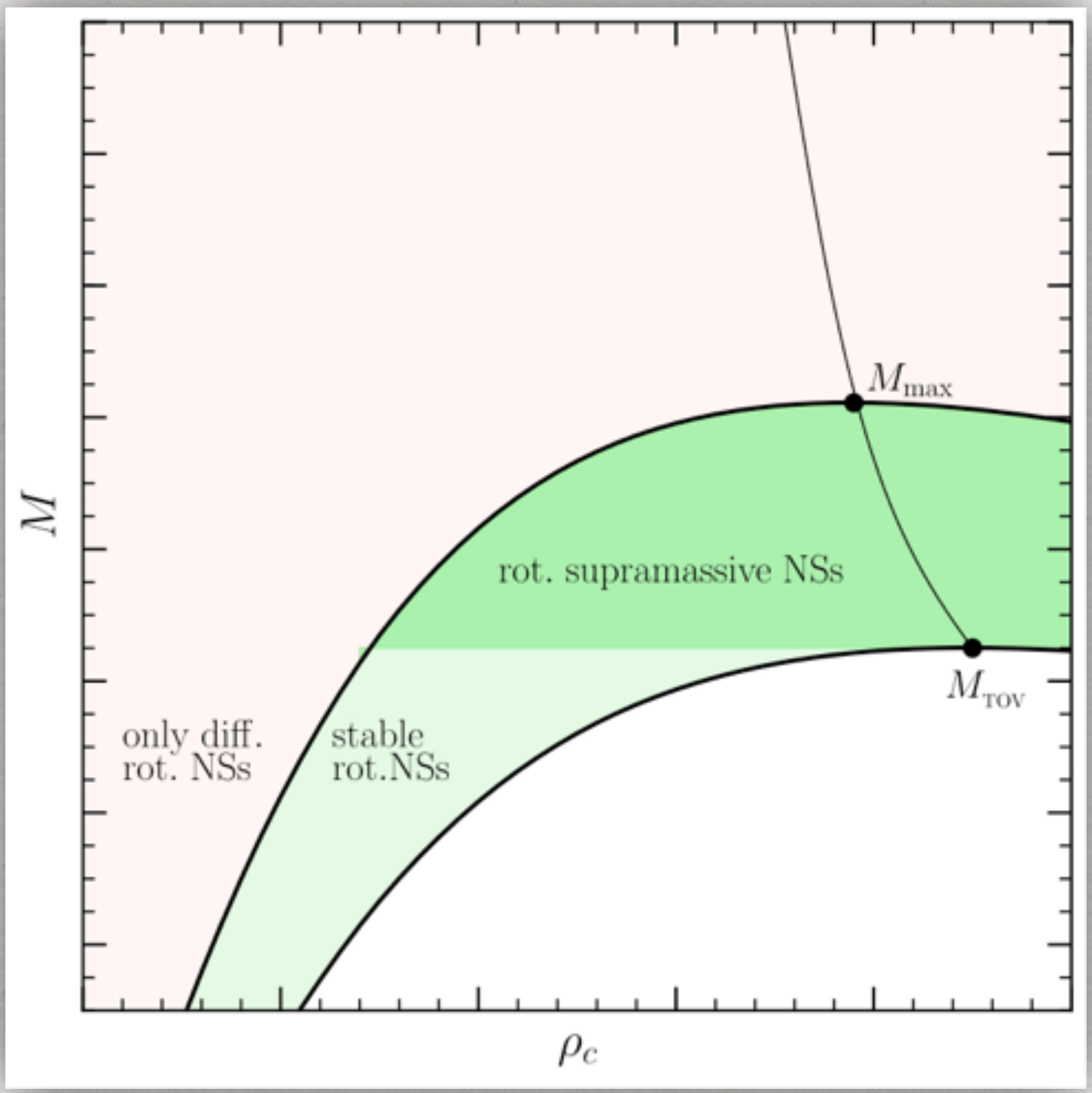
$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$



- Green region is for **uniformly** rotating equilibrium models.
- Salmon region is for **differentially** rotating equilibrium models.

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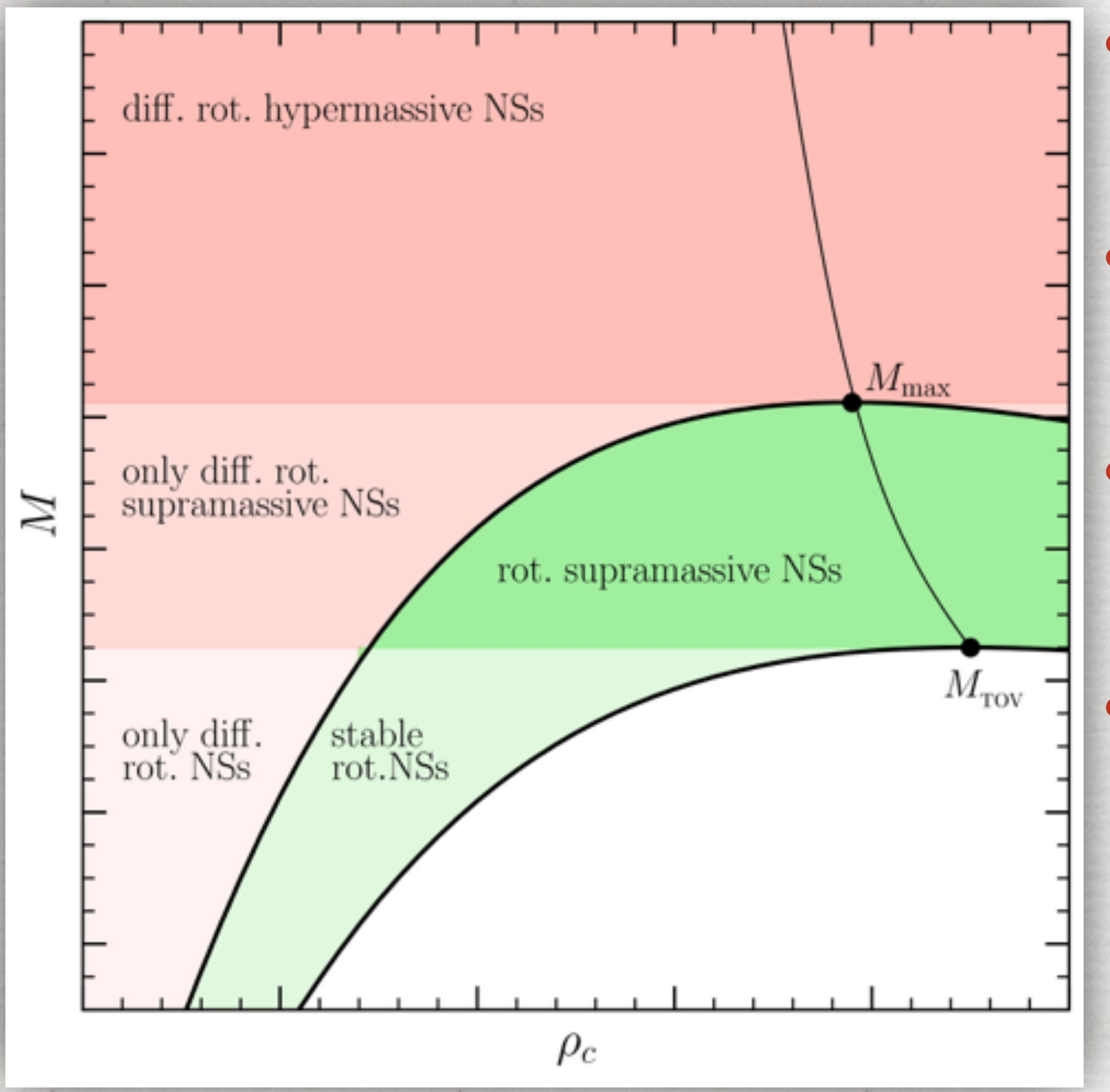


- Green region is for **uniformly** rotating equilibrium models.
- Salmon region is for **differentially** rotating equilibrium models.
- **Supramassive** stars have

$$M > M_{\rm TOV}$$

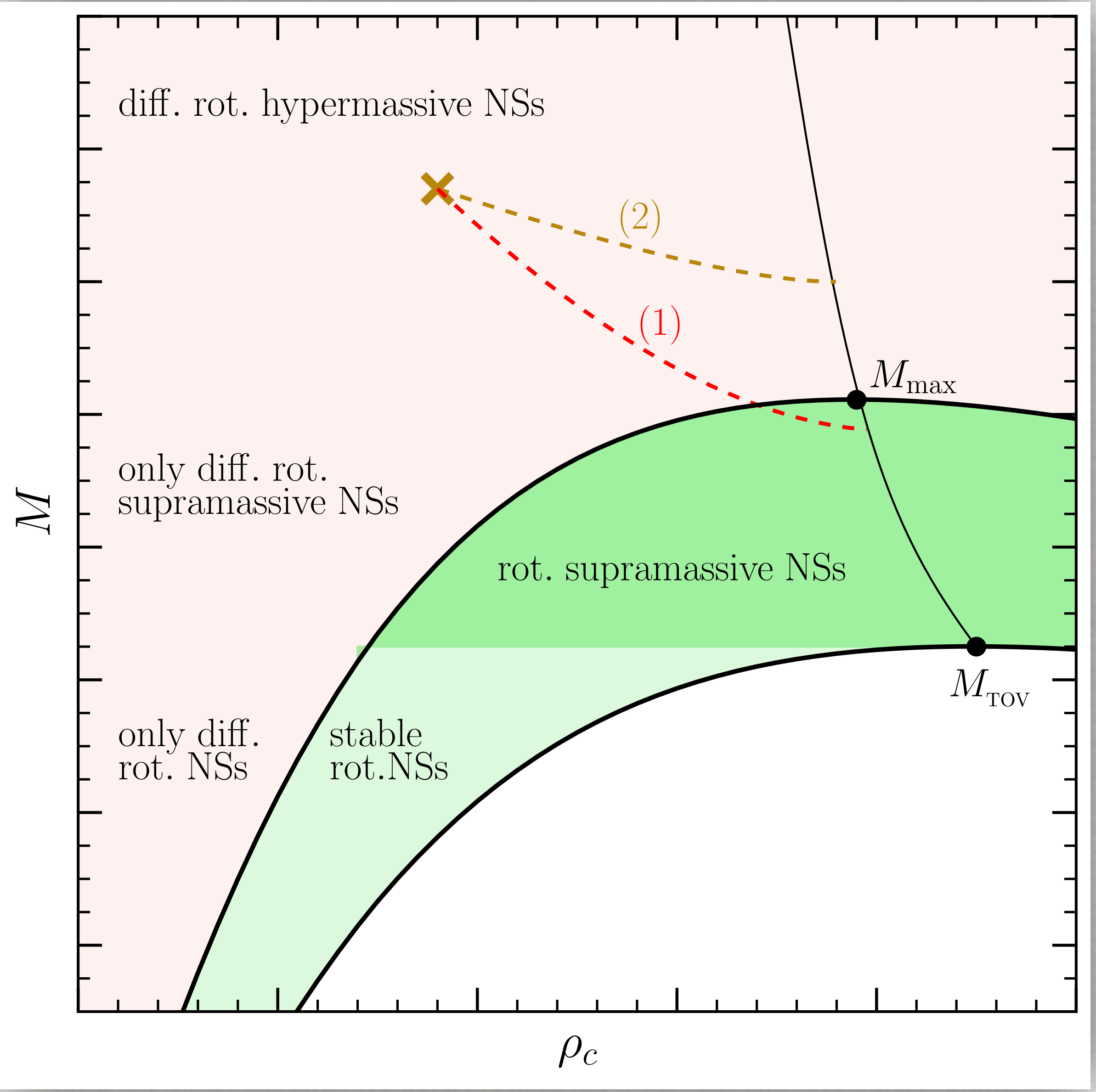
- **Hypermassive** stars have

$$M > M_{\rm max}$$

The outcome of GW170817

- Merger product in GW170817 could have followed two possible tracks in diagram: **fast (2)** and **slow (1)**

- It rapidly produced a BH when still **differentially** rotating **(2)**
- It lost differential rotation leading to a **uniformly** rotating core **(1)**.
- **(1)** is more likely because of large ejected mass (long lived).
- Final mass is near $M_{\max}$ and we know this is universal!



Rezzolla, **Most** and **Weih** 2017

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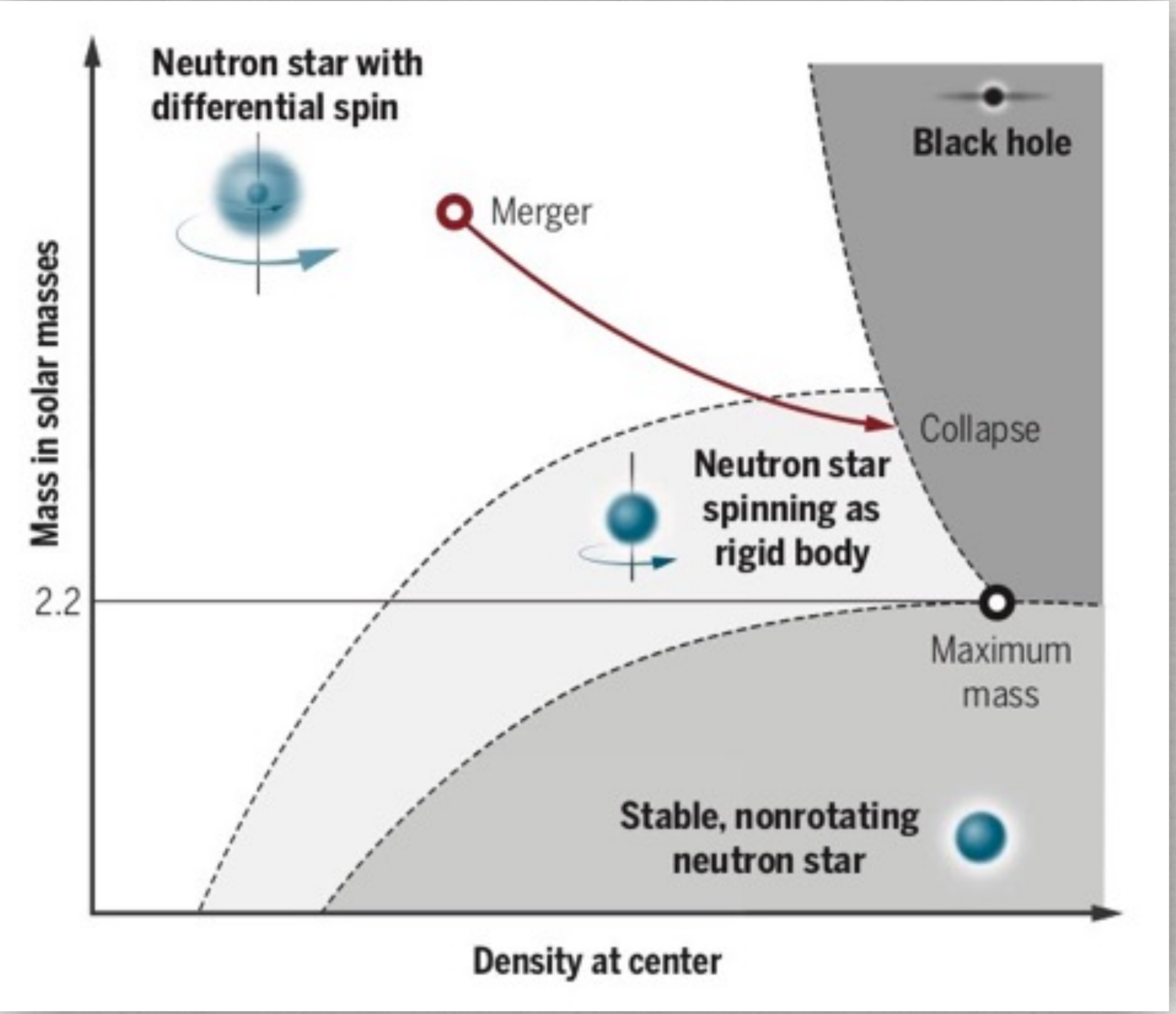
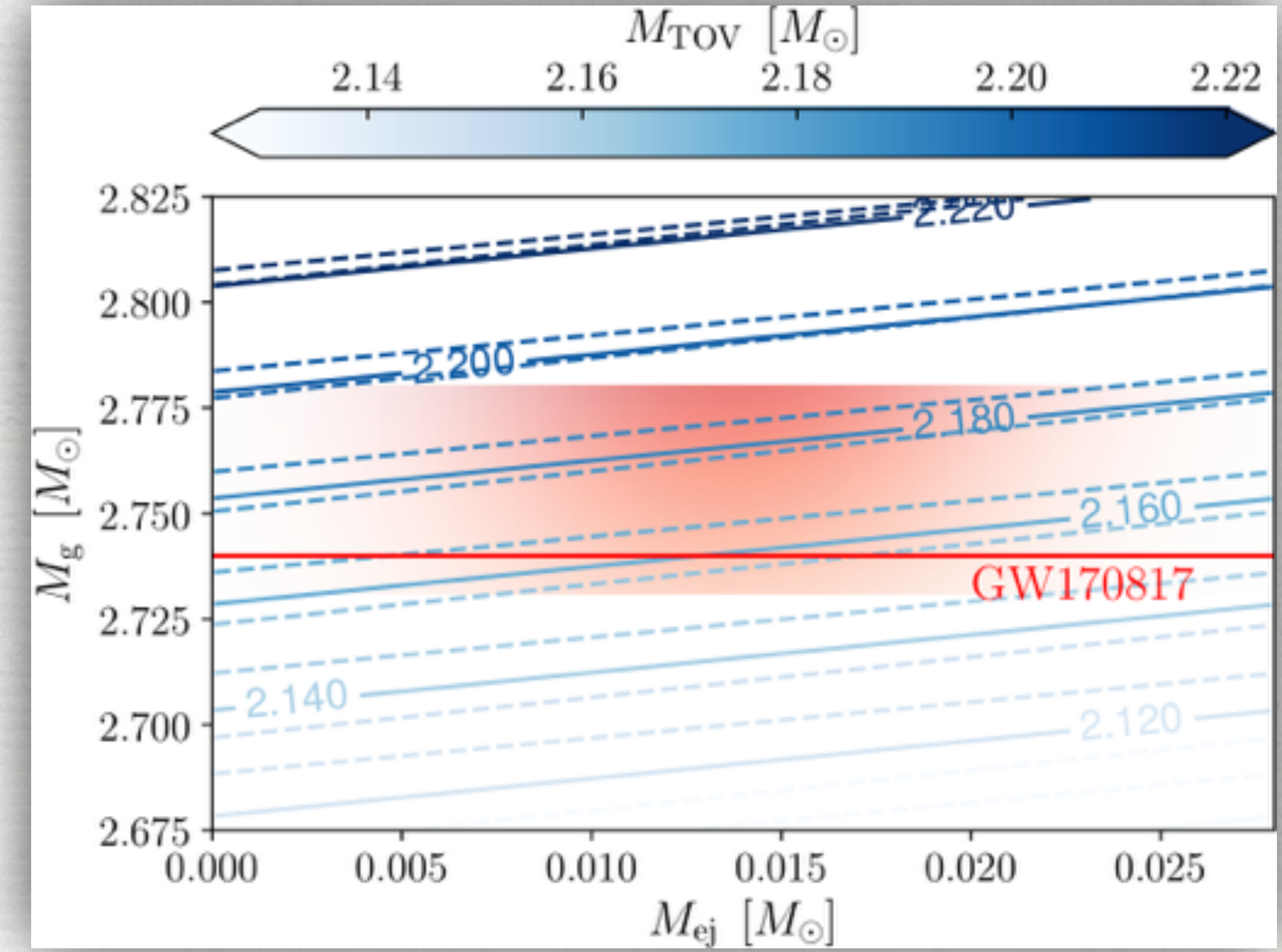


Cho, Bicknell, Science 2018

Rezzolla, **Most** & **Weih** 2017

- The merger product of GW170817 was initially **differentially** rotating but collapsed as a **uniformly** rotating object.
- HMNS core has about 95% **gravitational** mass of GW170817

$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$



- Ejected **rest mass** deduced from kilonova emission

$$M_{\rm ej}^{\rm blue} = 0.014^{+0.010}_{-0.010} M_\odot$$

- Use **universal relations** and account errors to obtain

pulsar timing

$$2.01^{+0.04}_{-0.04} \leq M_{\rm TOV}/M_\odot \lesssim 2.16^{+0.17}_{-0.15}$$

universal relations and GW170817; similar estimates by other groups

Overview of different results

MARGALIT+	Baysian analysis + threshold mass	$< 2.17\ M_{sun}$
SHIBATA+	numerical simulations	$< 2.25\ M_{sun}$
REZZOLLA+	universal relations	$< 2.16\ M_{sun}$
RUIZ+	Rhoades-Ruffini	$< 2.17\ M_{sun}$

Note: All groups use input from kilonova modelling

Bottom line:
$M_{max} \sim 2.2\ M_{sun}$

Part II

Constraining radii and tidal deformabilities

Recent publications

Neutron-star Radius Constraints from GW170817 and Future Detections

Andreas Bauswein[1], Oliver Just[2], Hans-Thomas Janka[3], and Nikolaos Stergioulas[4]
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Gravitational-wave constraints on the neutron-star-matter Equation of State

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New constraints on radii and tidal deformabilities of neutron stars from GW170817

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Neutron star tidal deformabilities constrained by chiral effective field theory

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(Dated: March 8, 2018)

TIDAL DEFORMABILITY FROM GW170817 AS A DIRECT PROBE OF THE NEUTRON STAR RADIUS

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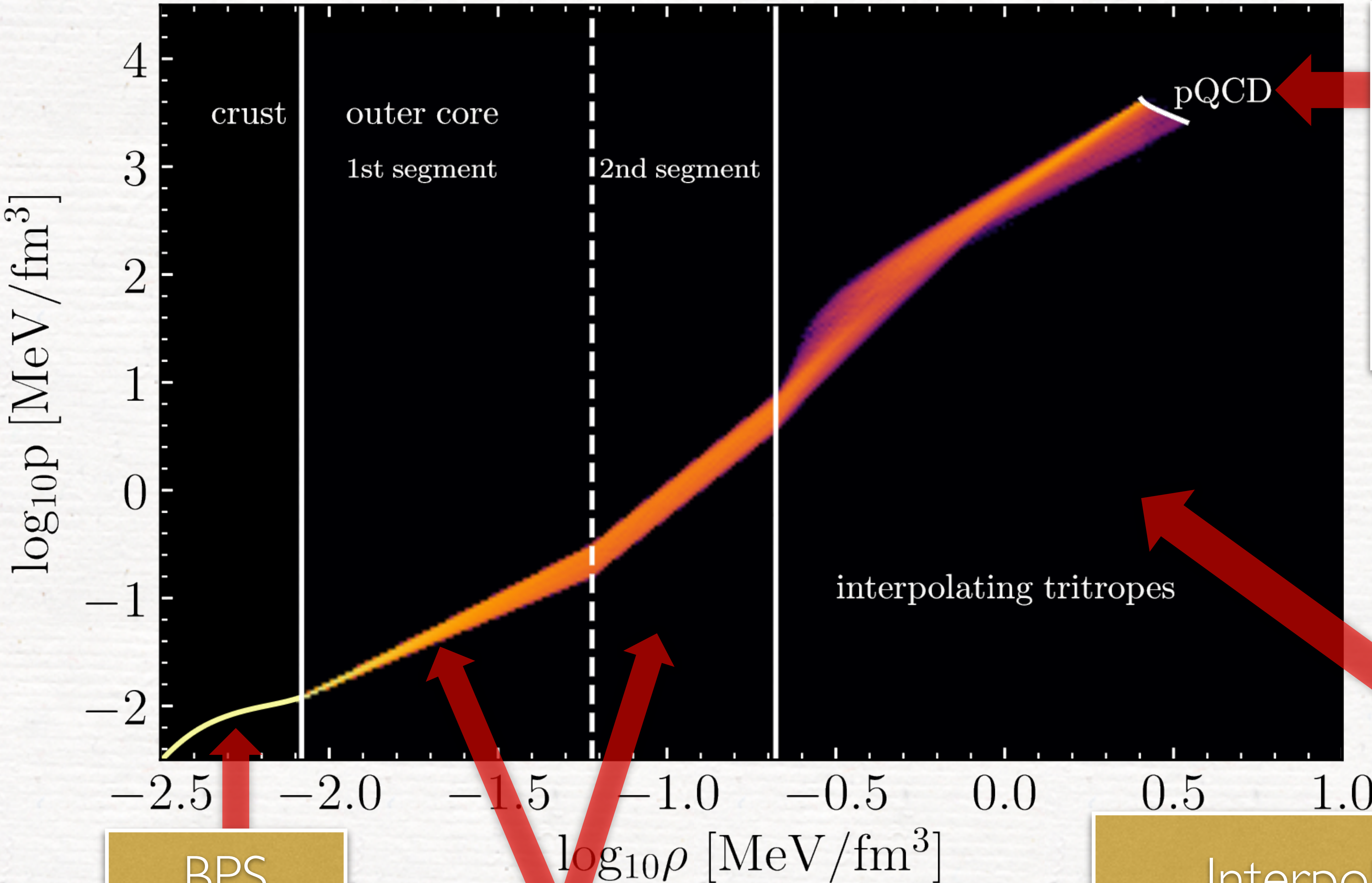
Draft version March 22, 2018

Setup for the EOSs

- Construct most generic family of NS-matter EOSs



From μ_b =2.6GeV on:

NNLO pQCD results of Kurkela+ (2014) / Fraga+ (2014)

BPS

Polytropic fit of Drischler+ (2016) (results strongly depend on the prescription here)

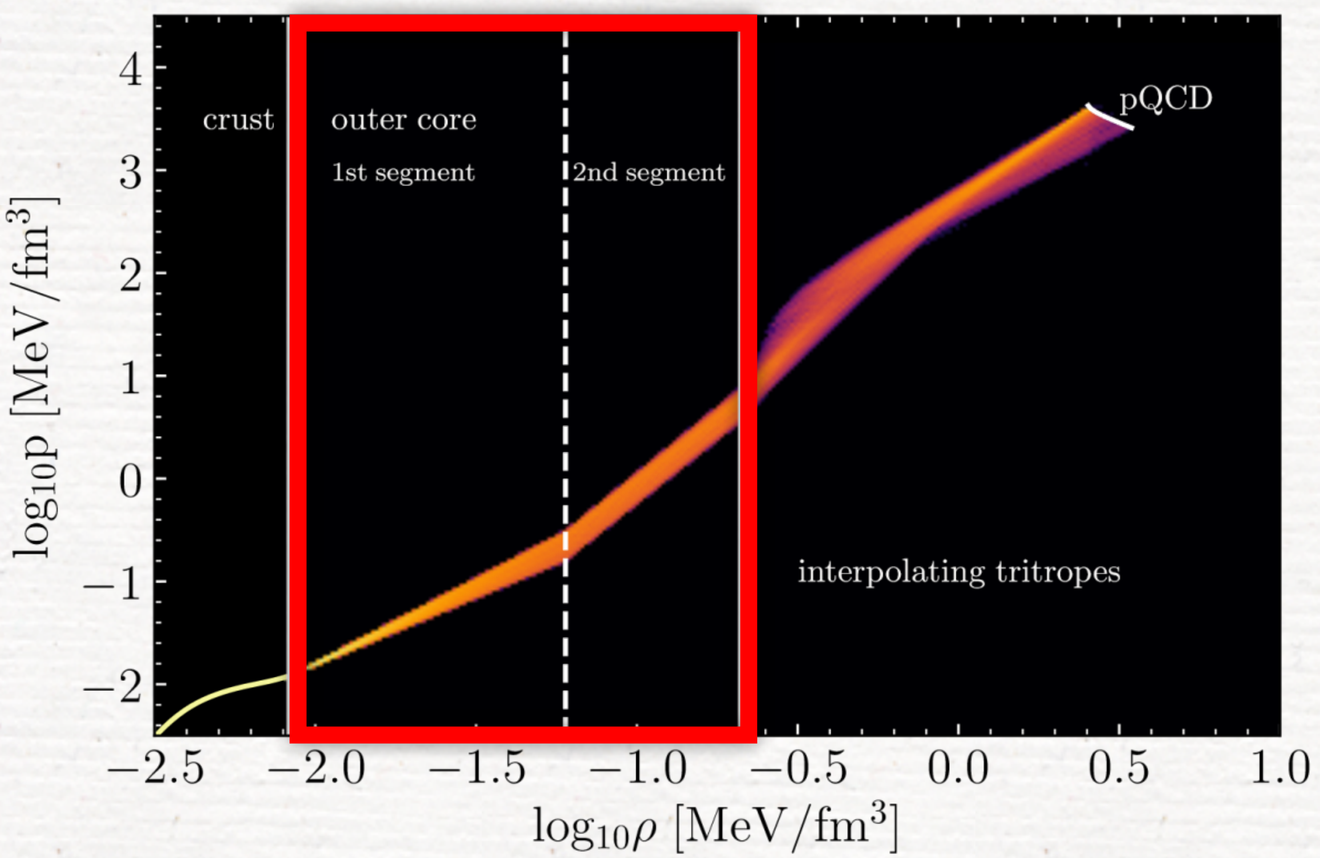
Interpolating by matching 3 polytropes (4 or more polytropes have only weak influence)

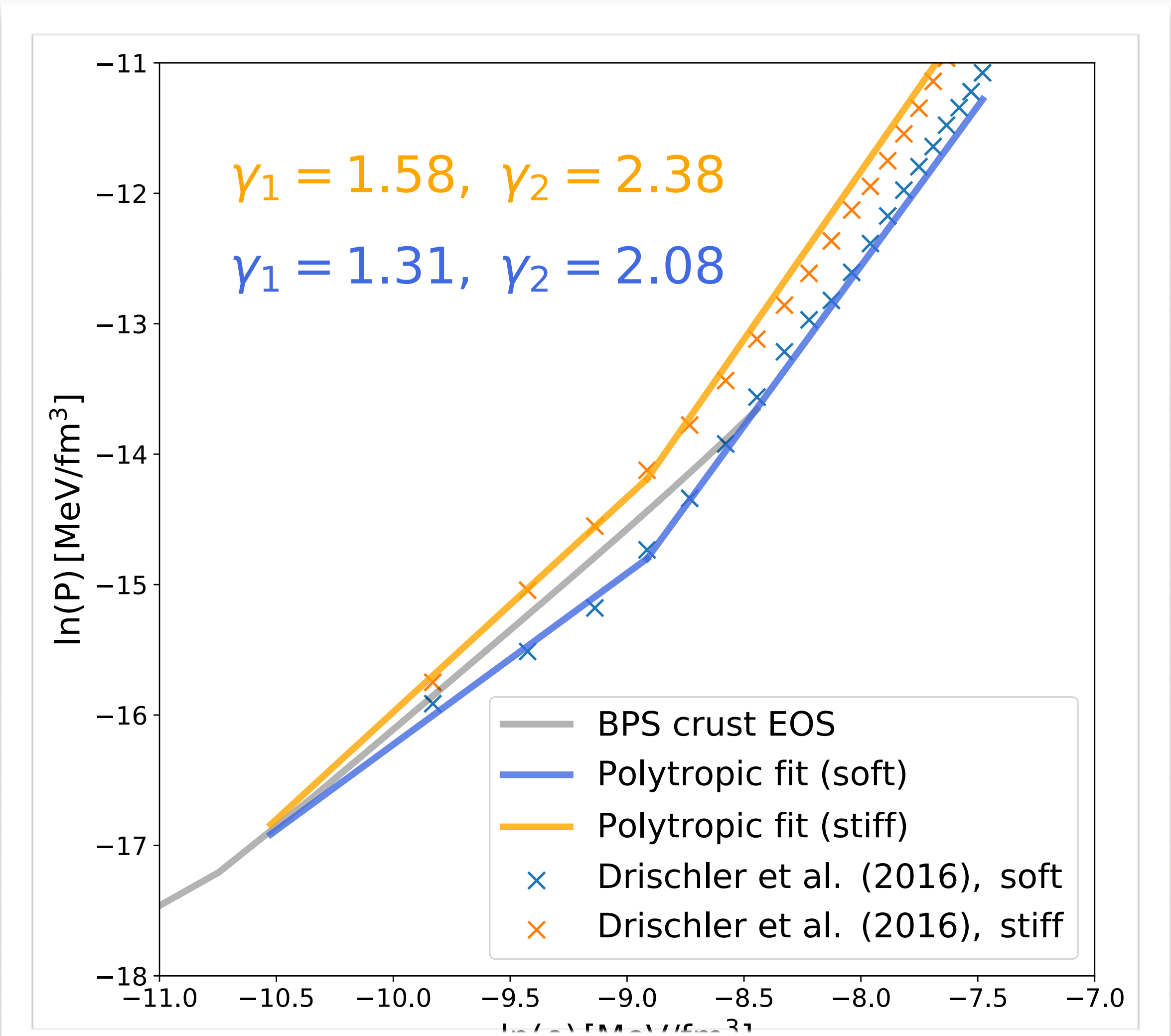
Setup for the EOSs

- EOS based on chiral expansion at N3LO of 2N and 3N chiral interactions

- Fit with two polytropes yields: $\gamma_1 \in [1.31, 1.58]$, $\gamma_2 \in [2.08, 2.38]$

- Varying polytropic exponents yields softest/stiffest limit and everything in between





Setup for the EOSs

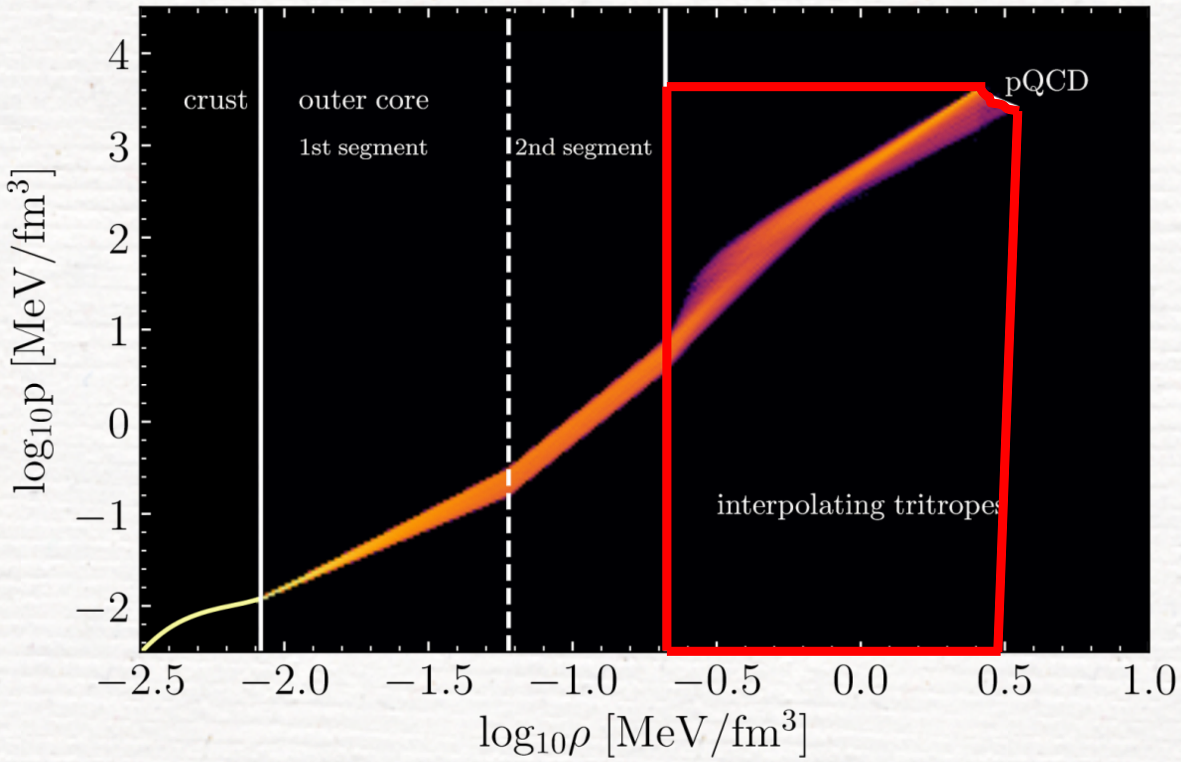
- Interpolate between low- and high-density regime with piecewise polytropes:

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

- Vary polytropic indices: $\gamma_{2+i} \in [1.0, 10.0]$

- Ensure continuity of pressure and density by matching the polytropic constant K via

$$P_i(\rho_i) = P_{i+1}(\rho_i)$$



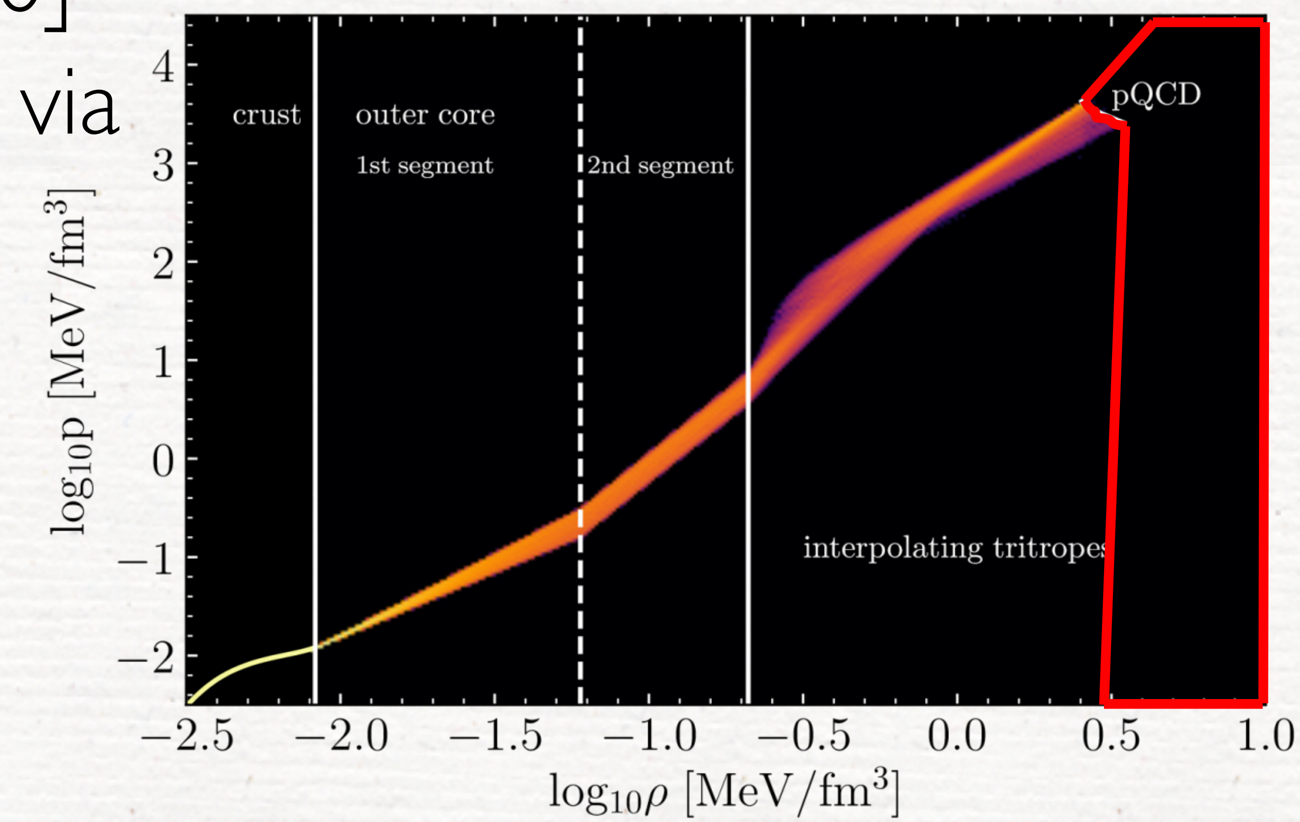
Setup for the EOSs

- High-density regime: fitting formula from Fraga et al. (2014) for numerically derived pQCD EOS from Kurkela et al. (2014)

$$P_{QCD} = \frac{3}{4\pi^2}\left({}^{\mu_b}/_3\right)^4\left(c_1 - \frac{a(X)}{\mu_b/GeV - b(x)}\right)$$

- Vary scale parameter X ϵ [1.0, 4.0] and match to last polytropic piece via

$$P_{poly}(\mu_b = 2.6GeV) = P_{QCD}(\mu_b = 2.6GeV)$$



Constraints

- Causality: $c_s < 1$
- Antoniadis et al. (2013): $M_{max} > 2.01 M_\odot$
- Thermodynamic stability criteria automatically satisfied for PW polytropes

→ 10^6 EOSs with a total of $\sim 10^9$ TOV-models

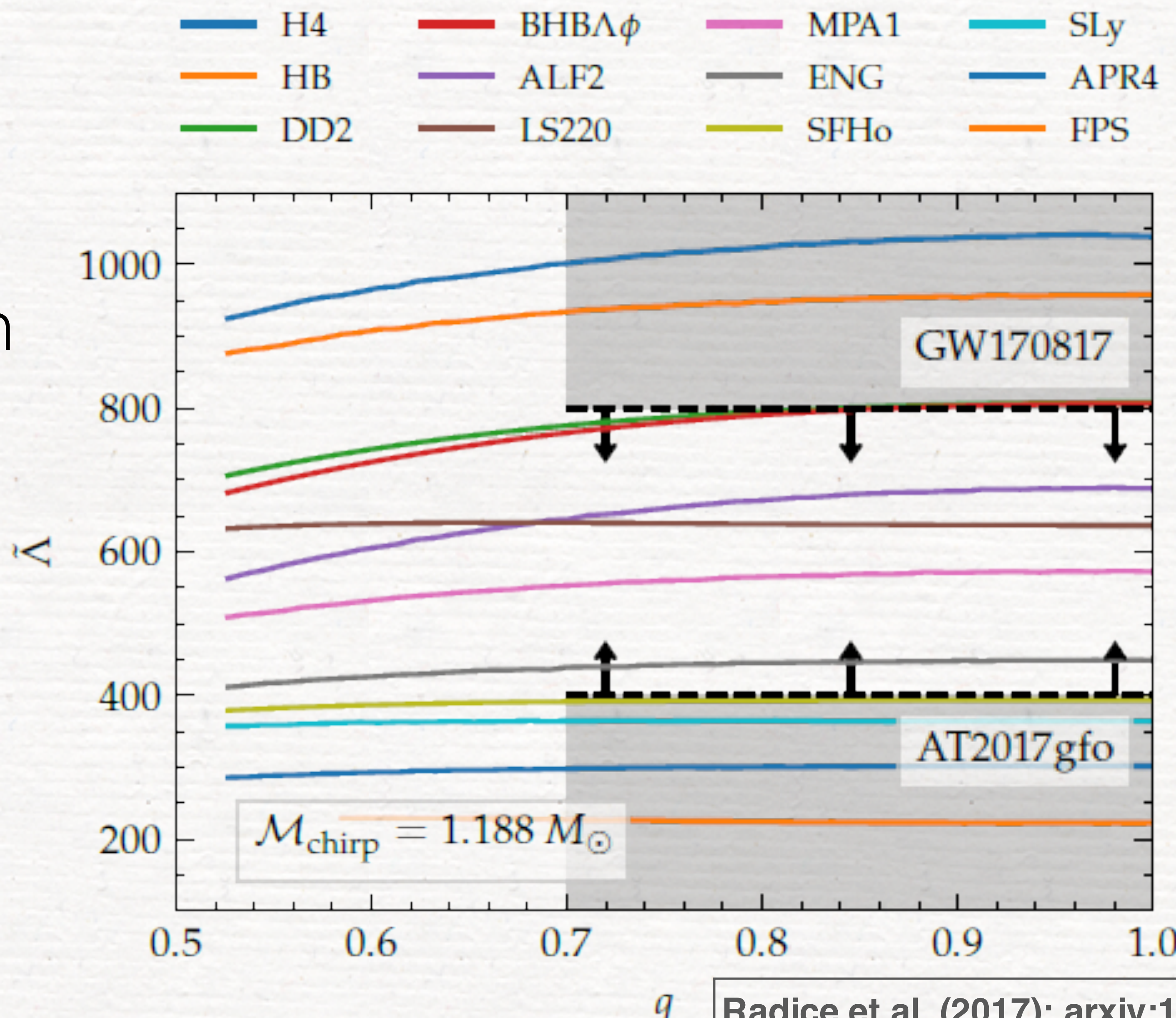
Constraints from GW170817

- $M_{max} < 2.16\ (2.33) M_{\odot}$ (Rezzolla, **Most** and **Weih** (2018))

- $\Lambda < 800\ (1000)$ (Abbott+ (2017))

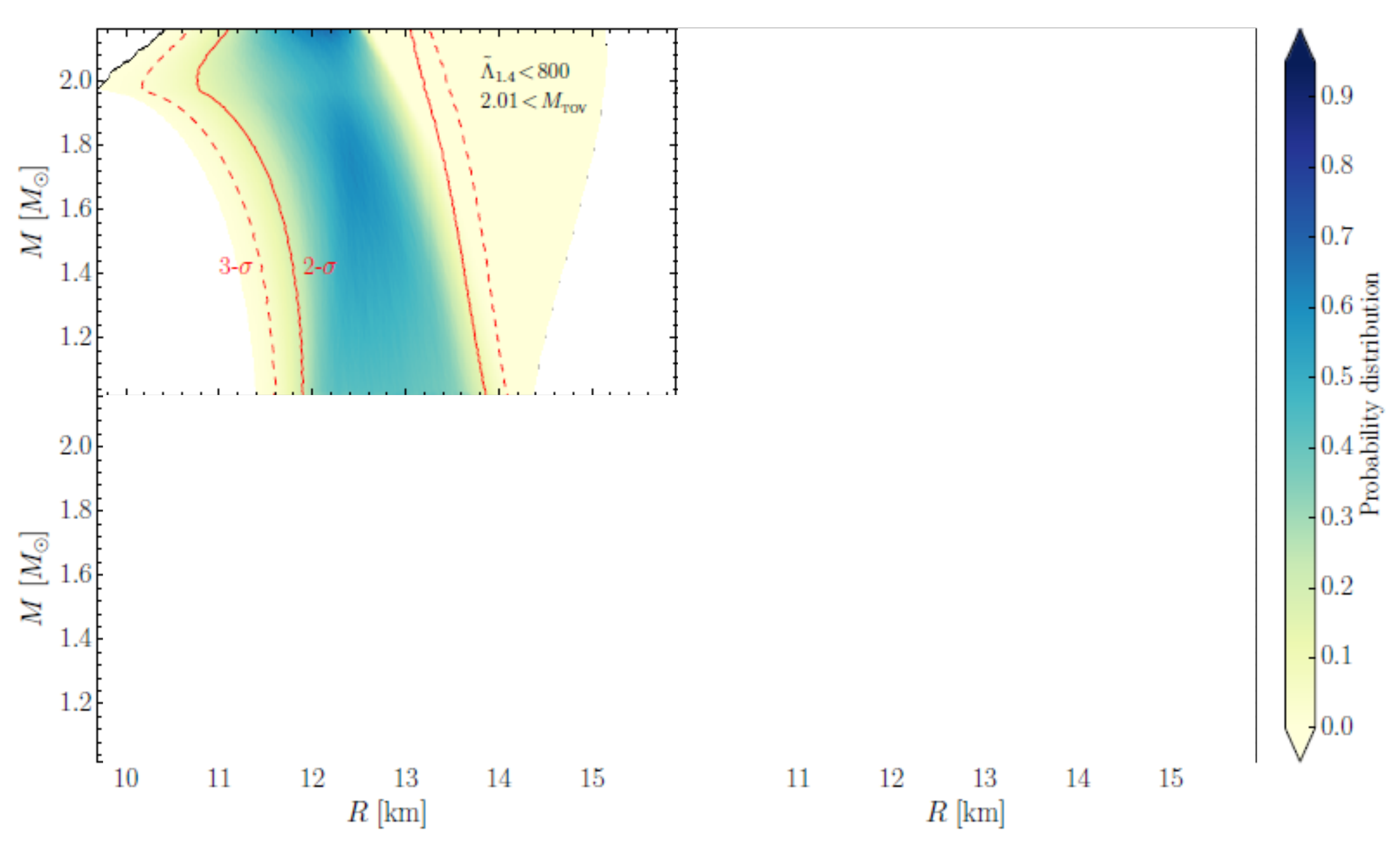
- Numerical simulations suggest only binaries with $\Lambda > 400$ can produce enough mass ejection (Radice+ (2017))

Caution: Based only on 4 EOSs

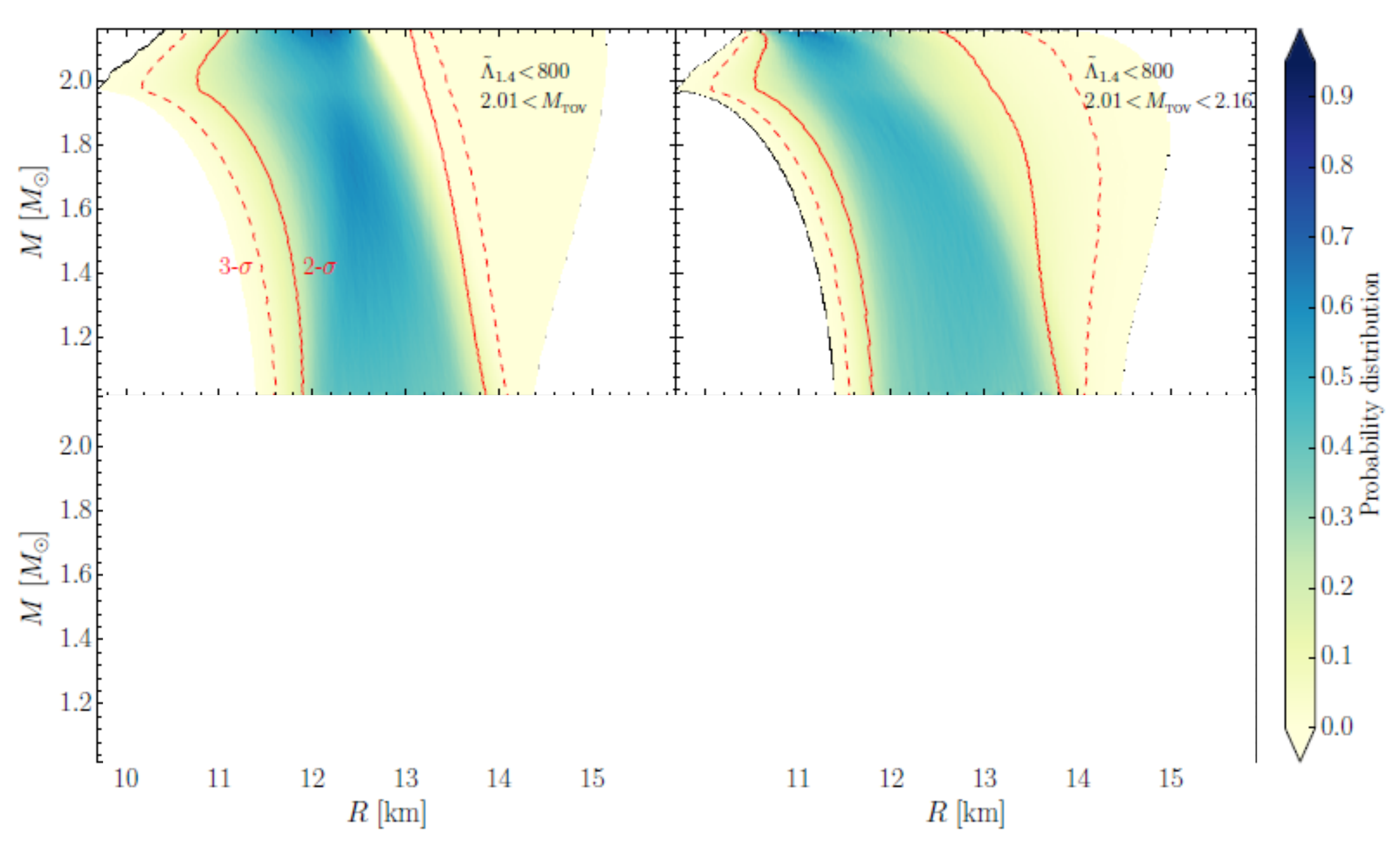


Radice et al. (2017): arxiv:1711.03647v3

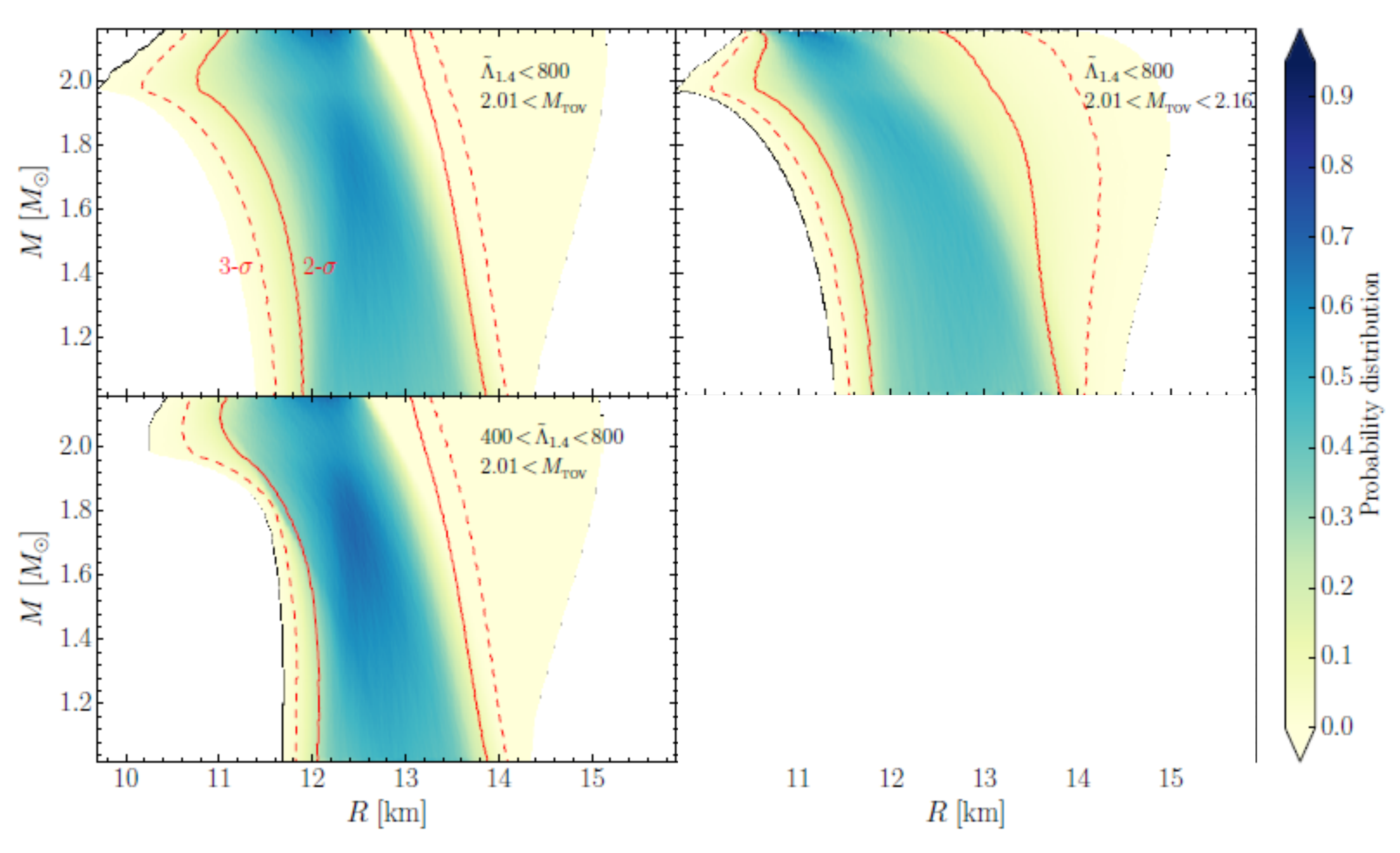
Mass-radius distribution



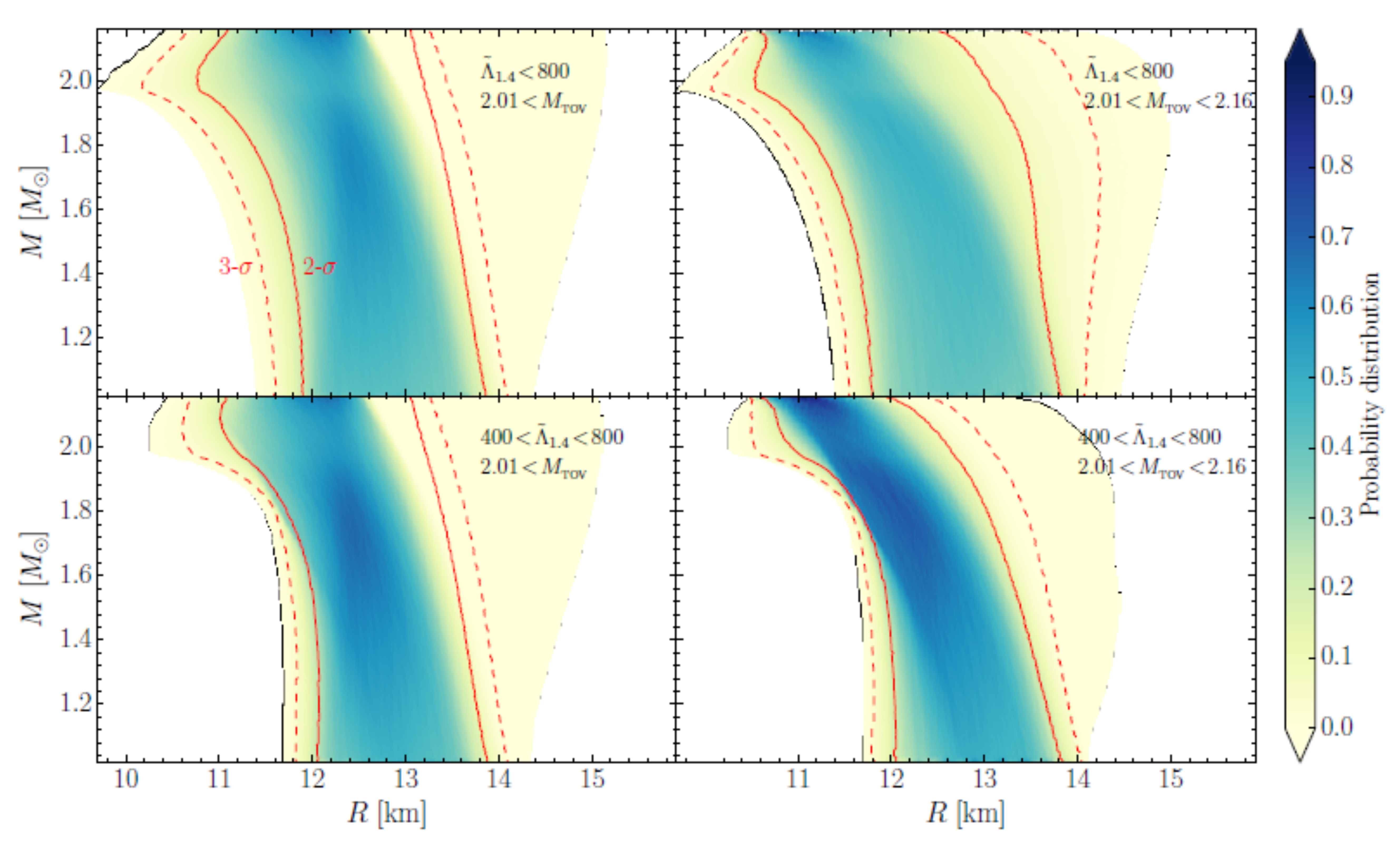
Mass-radius distribution



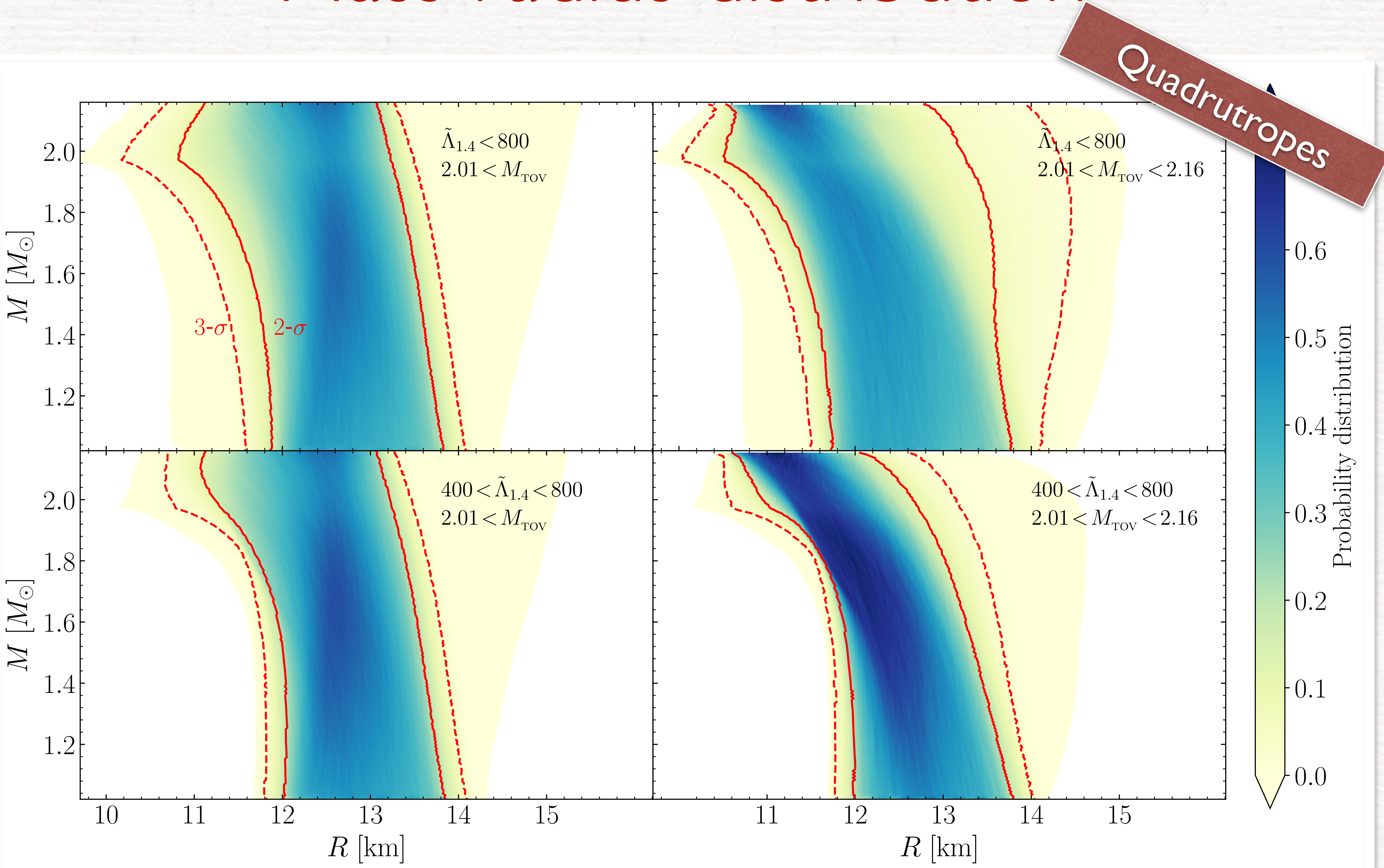
Mass-radius distribution



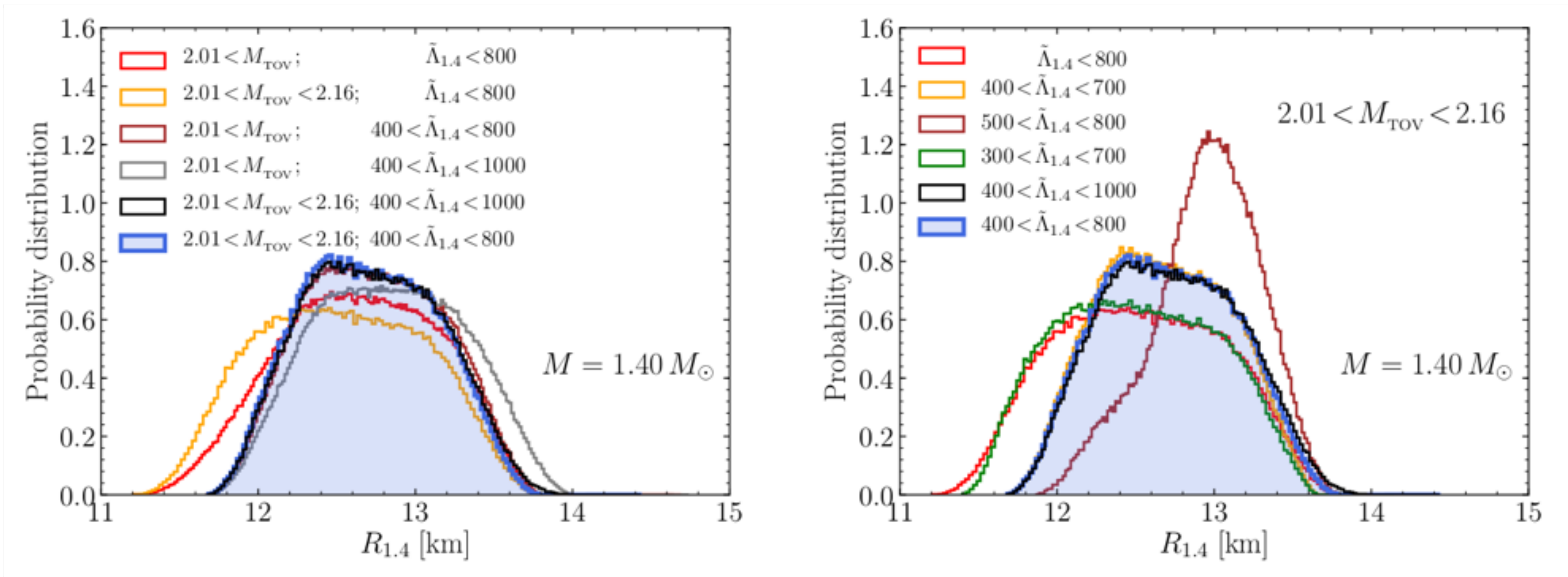
Mass-radius distribution



Mass-radius distribution



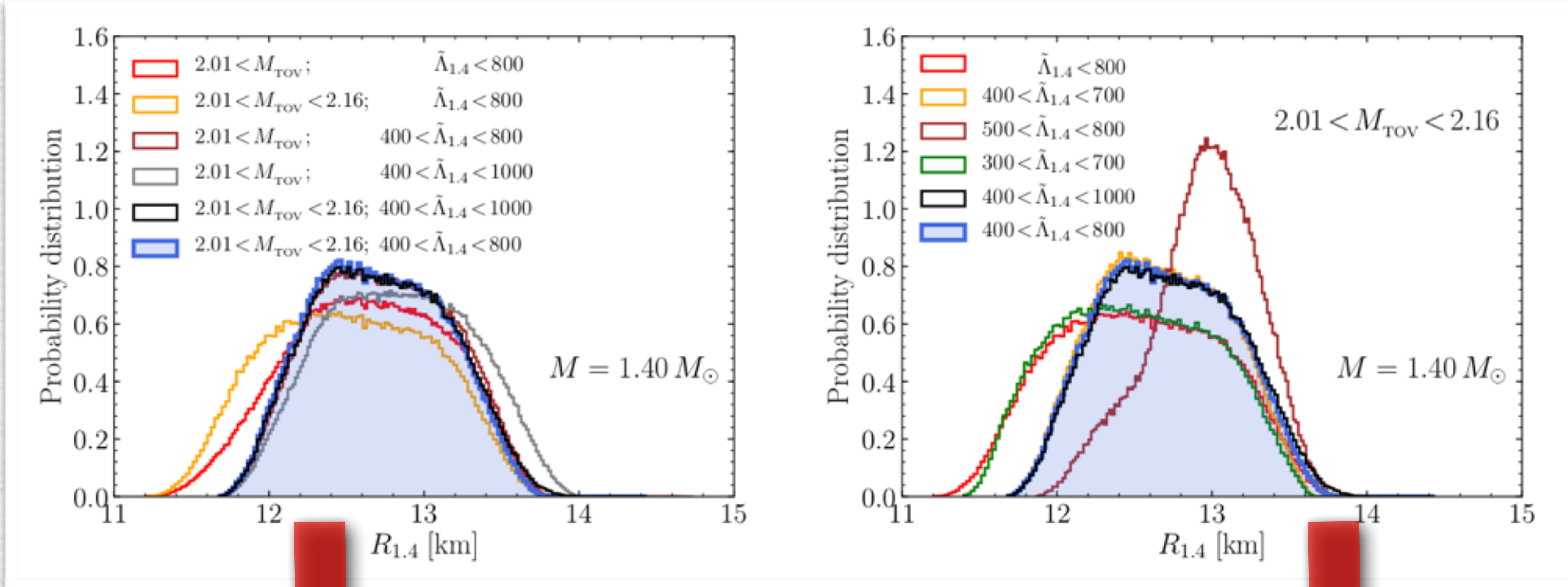
1D cuts



Applying all constraints from GW170817:

$12.0 < R_{1.4} < 13.45$ (at 2σ)

1D cuts



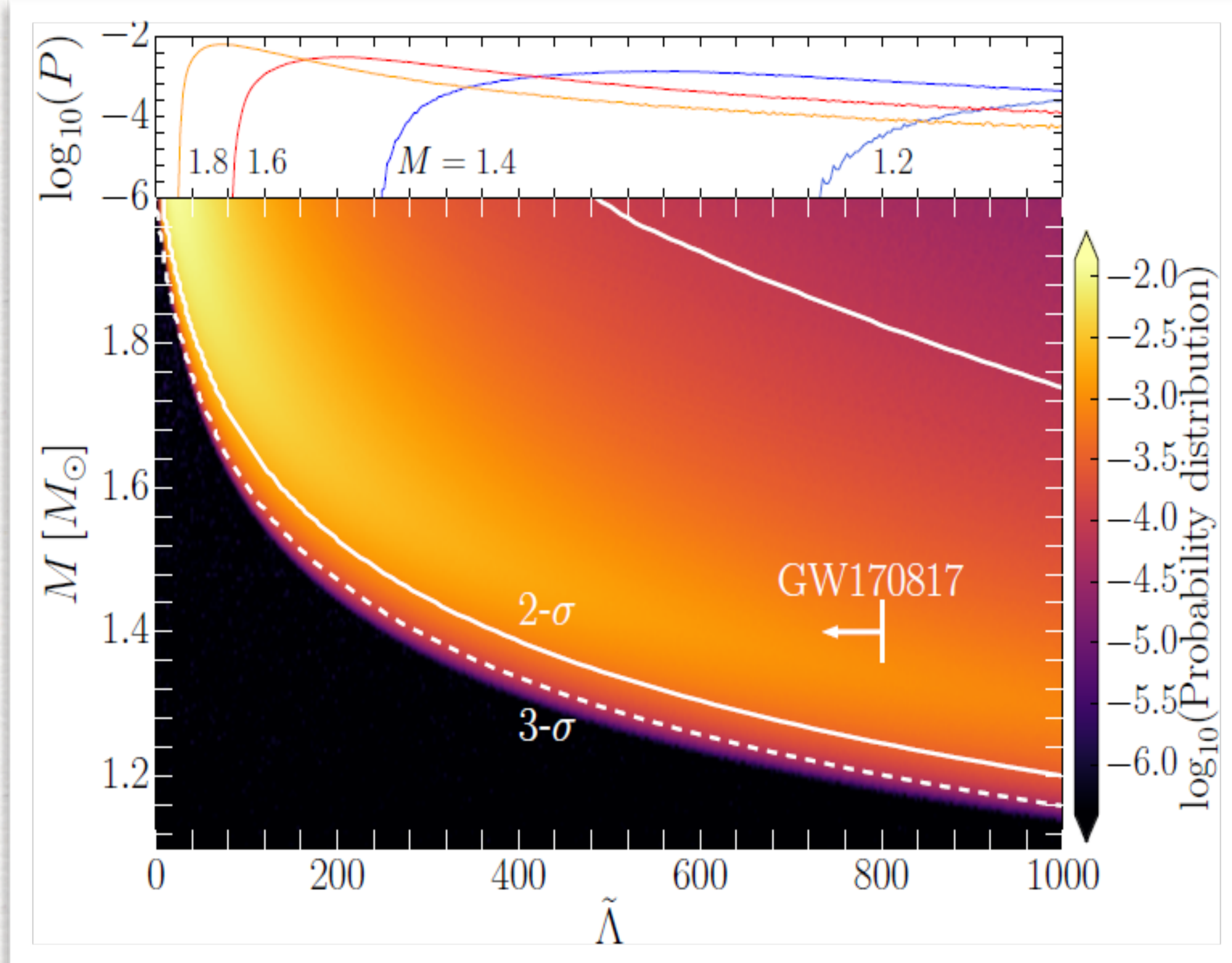
- Distribution insensitive to upper limit of Λ
- Mmax shifts peak to smaller radii

- Very sensitive to lower limit of Λ
- Sharp peak for $\Lambda_{min} \gtrsim 400$

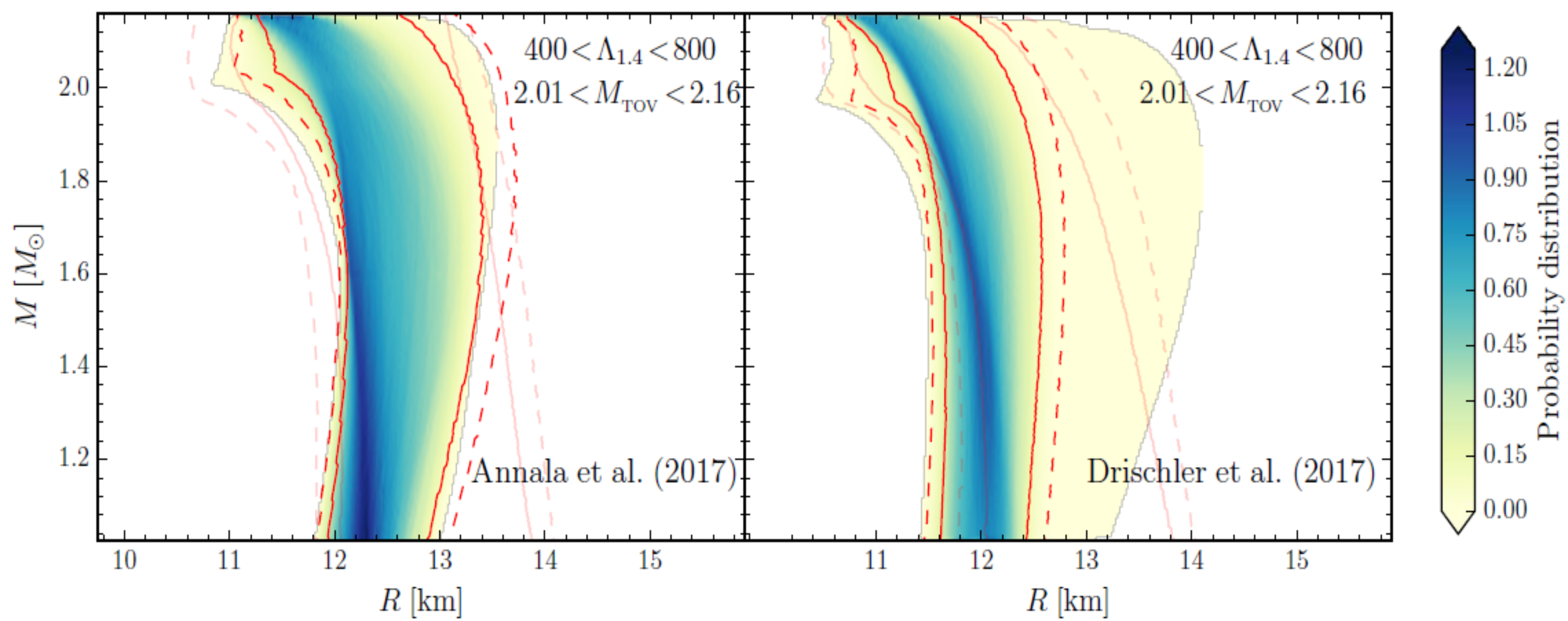
Constraining Λ

All 10^9 models with only $2M_\odot$-constraint:

- Sharp cut-off for lower limit of Λ
- Λ > 375 (at 2$\boldsymbol{\sigma}$)
- Explains why previous distribution insensitive to upper limit of Λ



Other prescriptions for outer-core EOS



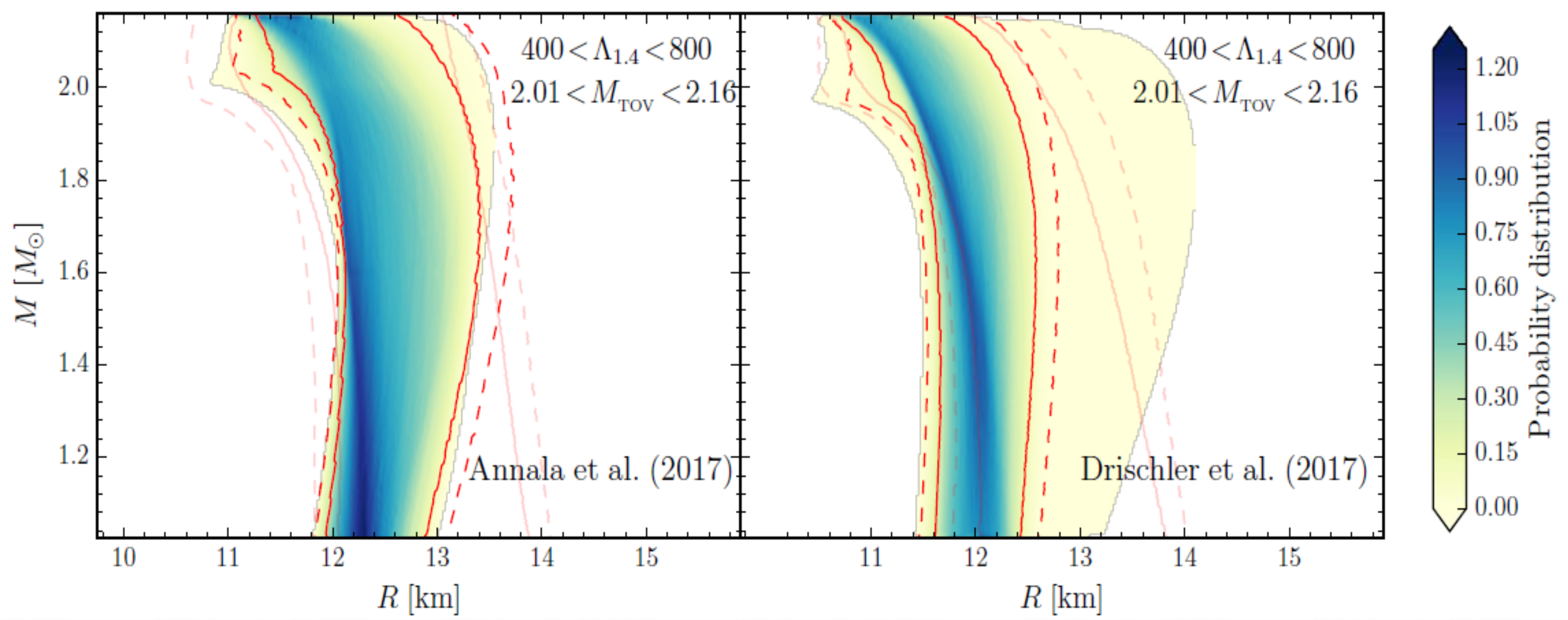
- Annala+ (2017): soft and stiff EOS provided in Hebeler+ (2013)

Softer

- Drischler+ (2017): range over 6 EOSs each based on a different Hamiltonian

Not an actual uncertainty band

Other prescriptions for outer-core EOS



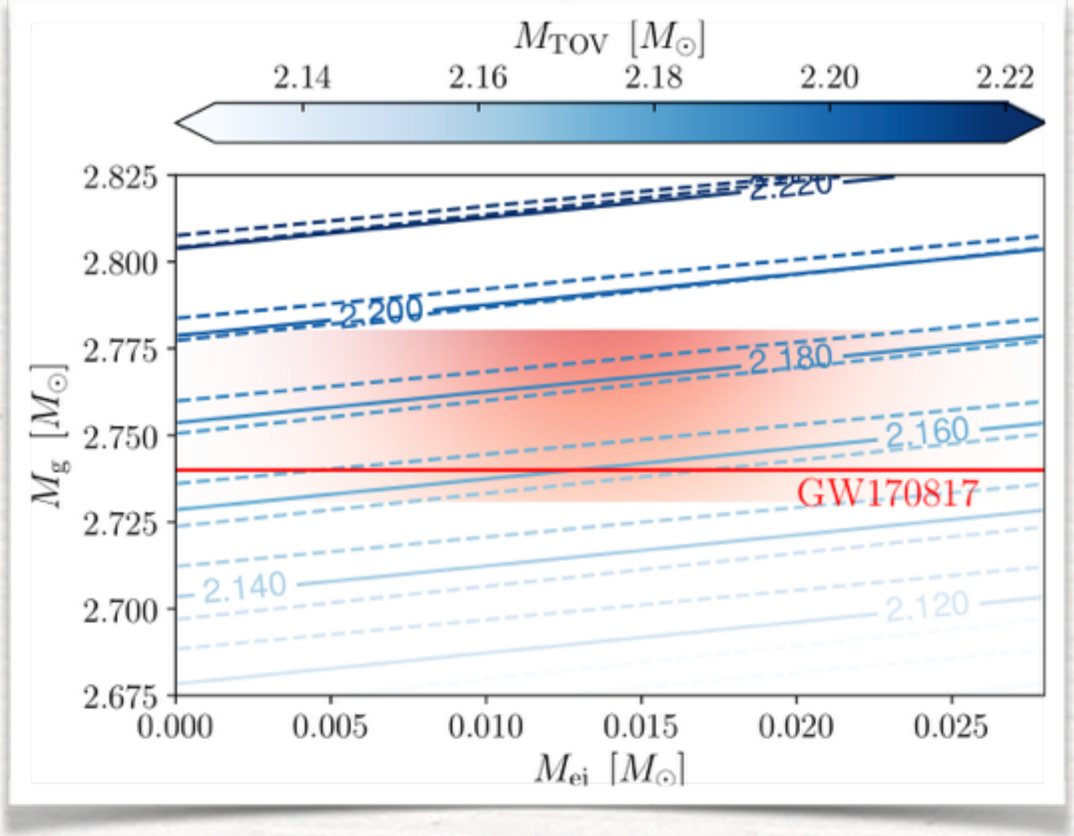
Final radius constraint depends strongly on stiffness and uncertainty of EOS in the region

$0.5n_s < n < 1.3n_s$

Comparison with other works

Authors	$R_{1.4}$ in km	Λ	GW170817 constraints	Methods
Bauswein+	$R_{1.4} \sim R_{1.6} > 10.6$	-	$M_{tot} = 2.74$	Comparison with threshold mass from numerical simulations
Most+	[12.0, 13.5] <R> = 12.45 (using 3-tropes)	$\Lambda_{1.4} > 375$ (2σ)	$M_{max} < 2.16$ $400 < \Lambda < 800$	Statistical analysis of 1.5×10^6 generic EOSs
Annala+	[11.1, 13.4] (3-tropes) [9.9, 13.6] (4-tropes)	$120 < \Lambda_{1.4} < 1504$	$M_{max} < 2.16$ $\Lambda < 800$	Most extreme configurations from $0.9/1.7 \times 10^5$ generic EOSs
Lim+	[11.6, 12.8] <R> = 12.3	$350 < \Lambda_{1.4} < 540$	None. Results largely consistent with above constraints	Statistical analysis of 7.2×10^4 EOSs
Raithel+	< 13.0 (1σ) <R> = 11.7	-	$M_{max} < 2.30$ $\Lambda = 400$ (Gaussian)	Statistical analysis of 10^6 EOSs

Summary



- GW170817 has helped to improve our knowledge of **maximum masses** and **radii** of neutron stars

- Future **multi-messenger observations** will help to even more narrow down uncertainties of neutron star properties and will help to unravel the **EOS**