Using universal relations to test low mass neutron star formation scenarios

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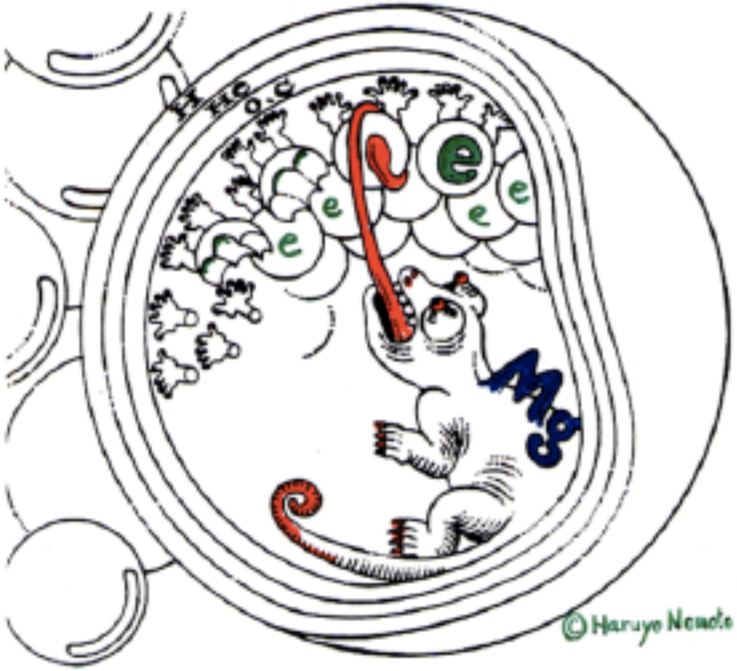

TEXAS A&M
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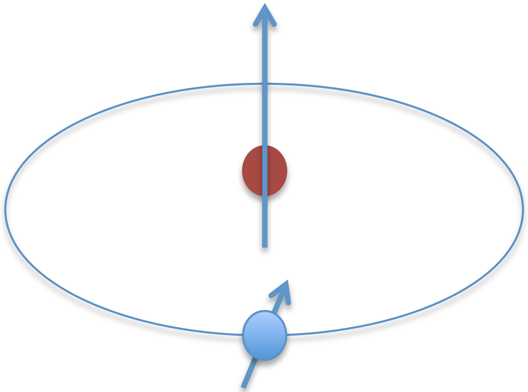
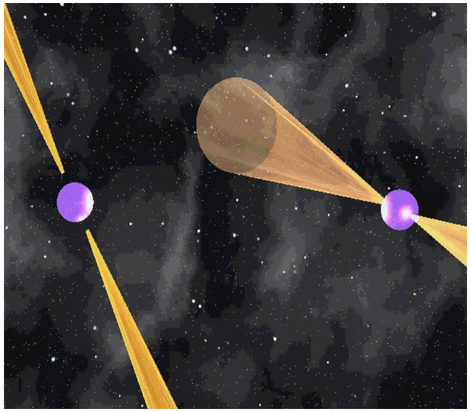
INT-JINA Symposium on
First multi-messenger observations of a neutron star merger and its implications for nuclear physics
March 12-14, 2018

Properties of certain double neutron star systems suggest secondary neutron star was born in a symmetric, possible sub-energetic supernova

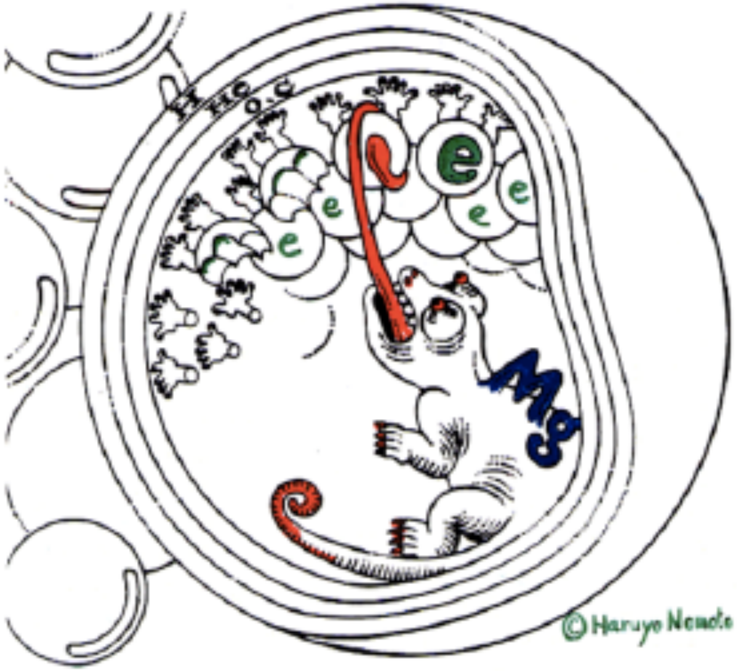
	J0737-3039A/B	J1756-2251
M_G ($M_\odot$)	1.25 (B)	1.23 +/- 0.007 (Companion)
Orbital eccentricity	0.088	0.18
Spin-orbit alignment	≈3° (A)	< 34°
Transverse velocity	~10 km/s	~10 km/s
Galactic scale height	small	small
Pulse profile:	stable (A)	stable





Kramer+, arXiv:astro-ph/0609417
Ferdman+, arxiv:1406.5507
Stairs+, arxiv:astro-ph/0609416
Piran+, arXiv:astro-ph/0409651
Ferdman+,arxiv:1302.2914
Iacolina+, arxiv:1512.03241
Andrews+, arxiv:1410.6797

Electron-Capture Supernova (ECSN) Hypothesis



≈1.37-1.38 M_{SUN} ONeMg Core becomes Unstable to e-capture onto ^{20}Ne,^{24}Mg (Miyaji+, PASJ, 32, 303;1980,Nomoto, ApJ, 322,206; 1987)

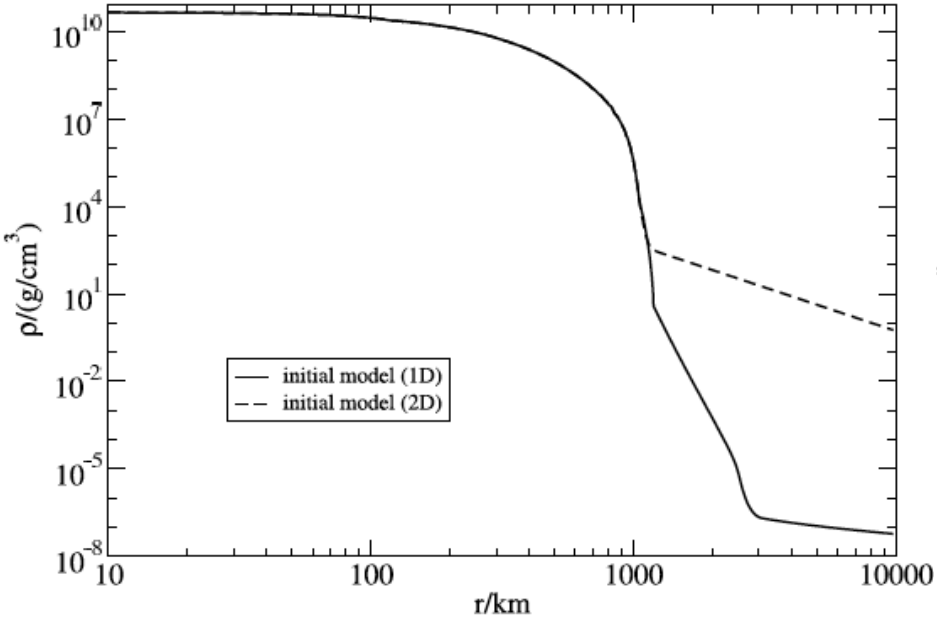
$\tau_{captures} > \tau_{growth}$, freezing ONeMg core mass

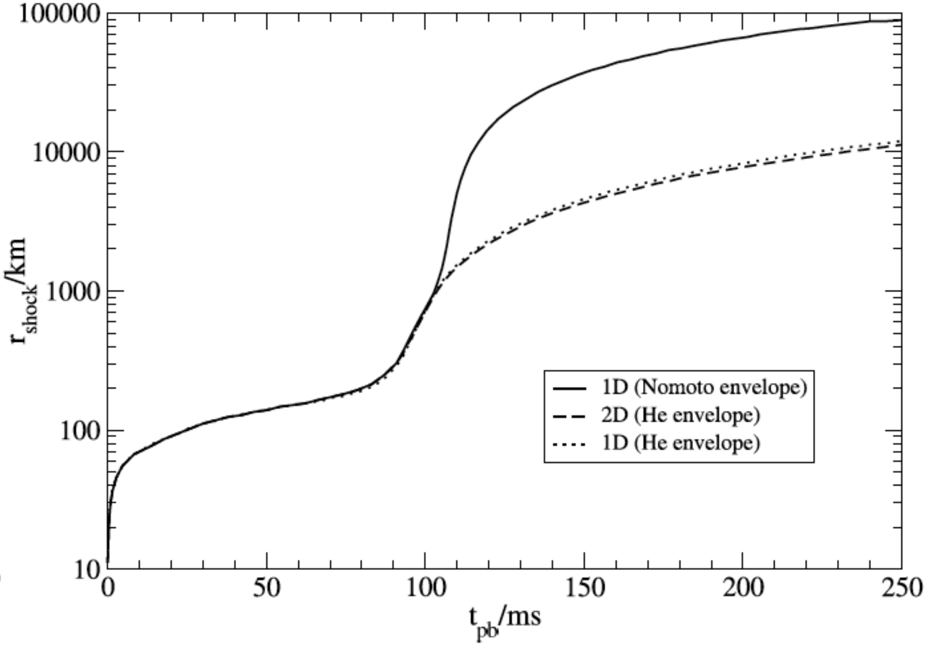
Contraction, heating triggers O+Ne burning, material processed to NSE as a deflagration front moves out

Continuing e-capture onto Fe group accelerates collapse

Electron-Capture Supernovae (ECSN) Hypothesis

Janka+,arxiv:0712.4237





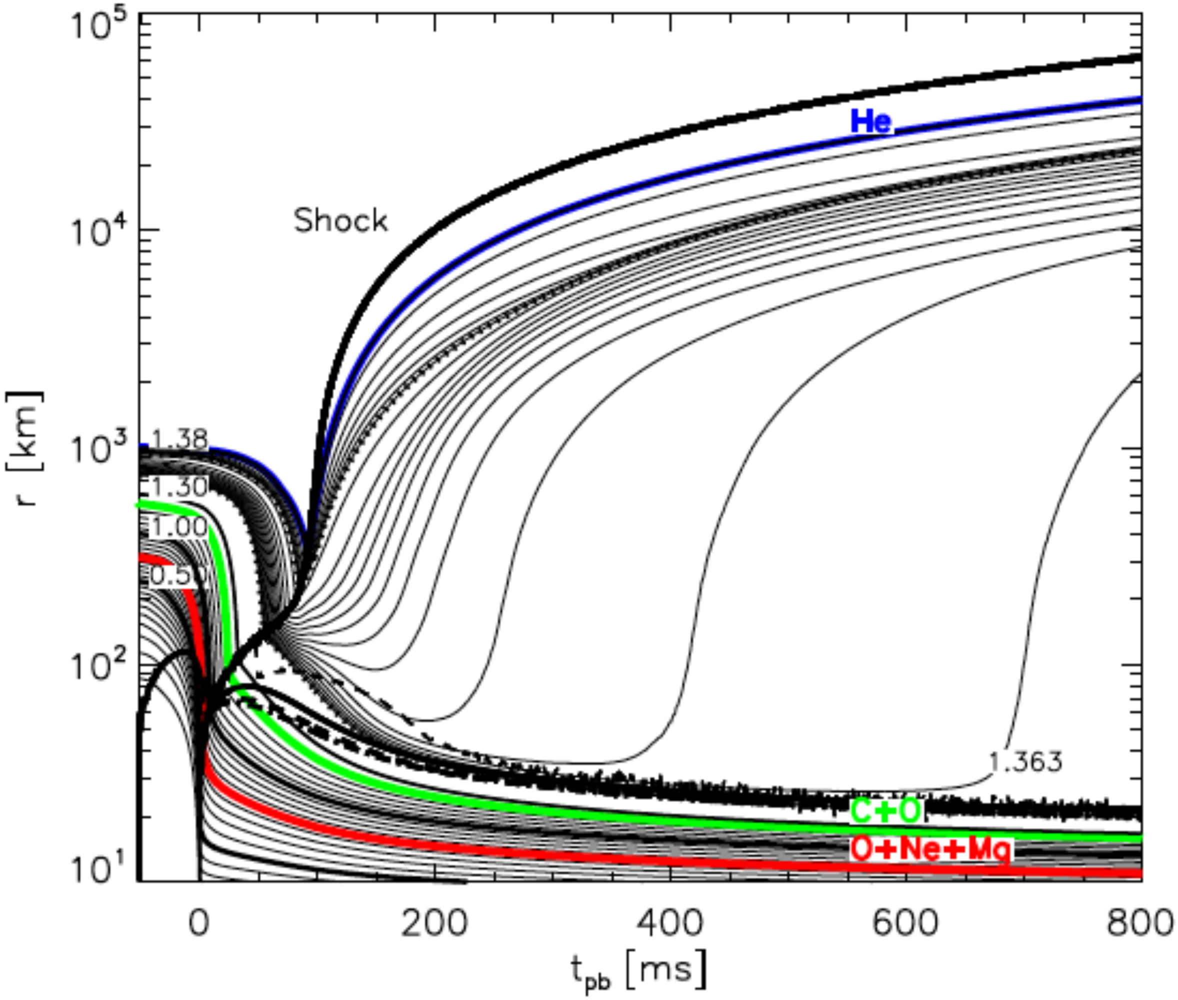
Steep density gradient at core boundary leads to delayed explosion on short timescales, (no time for instability growth), clean mass cut (v. small mass loss from core)

Mayle,Wilson, ApJ 334,909; 1988
Kitaura+, arXiv:astro-ph/0512065
Wanajo+,arxiv:1009.1000
Takahashi+, arxiv:1302.6402

In 2D: Shock has escaped before convection gets going in PNS

> Small disturbance to binary

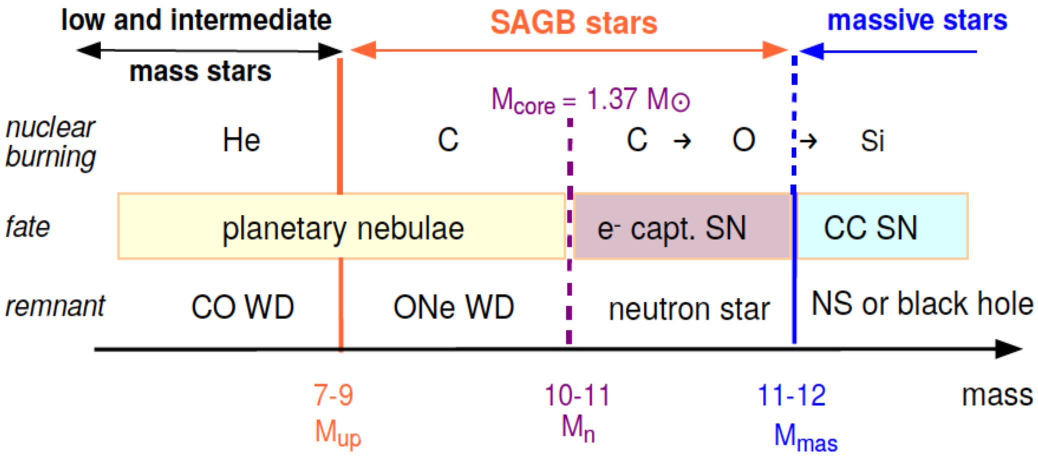
Electron-Capture Supernovae (ECSN) Hypothesis



Kitaura+, arxiv:astro-ph/0512065, Janka+, arxiv:0712.4237

Star explodes with v. little mass loss from core: ~ 10^{-2} M_{sun}

A small fraction (<5% of all CCSN) of single super-AGB stars may go ECSN



low and intermediate mass stars | **SAGB stars** | **massive stars**

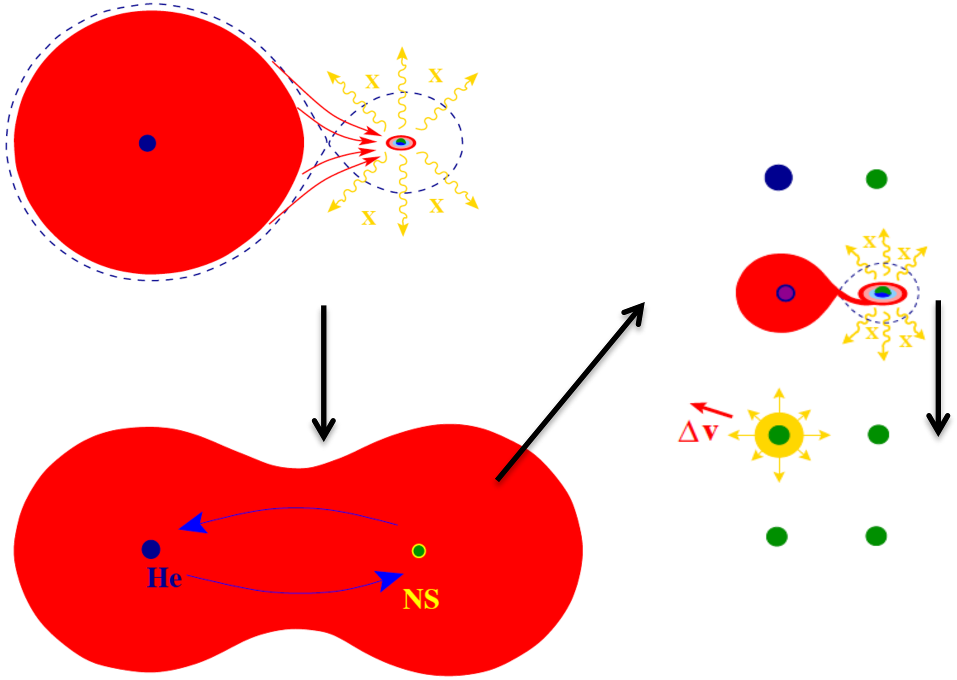
$M_{core} = 1.37 M_{\odot}$

nuclear burning: He | C | C → O | → Si

fate: planetary nebulae | e^- capt. SN | CC SN

remnant: CO WD | ONe WD | neutron star | NS or black hole

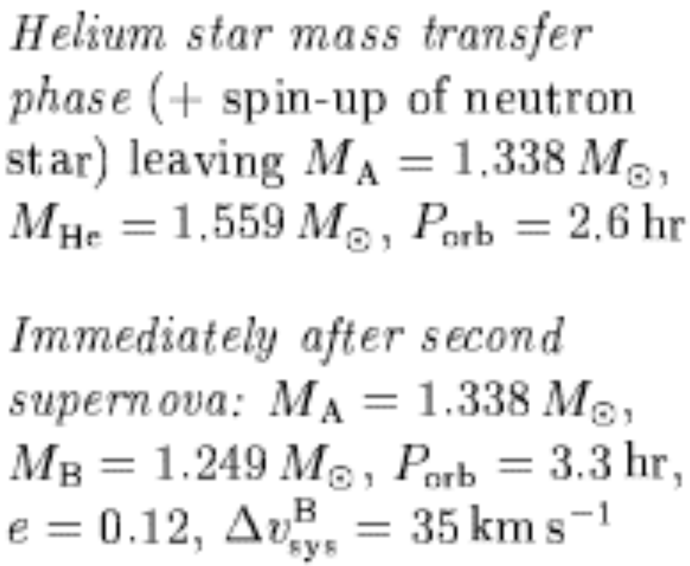
7-9 M_{up} | 10-11 M_n | 11-12 M_{mas} | mass



Binary interactions enhance ECSN rate (**up to 30% of all CC SNe**) and lead to DNS systems

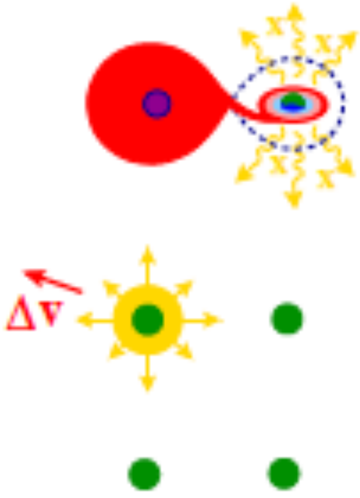
Top right picture: Lionel Seiss
Doherty+, arxiv 1410.5431
Takahashi+, arxiv:1302.6402
Podsiadlowski + arXiv:astro-ph/0506566

Double NS via ECSN: final stage:



Helium star mass transfer phase (+ spin-up of neutron star) leaving $M_{\rm A} = 1.338\,M_\odot$, $M_{\rm He} = 1.559\,M_\odot$, $P_{\rm orb} = 2.6$ hr

Immediately after second supernova: $M_{\rm A} = 1.338\,M_\odot$, $M_{\rm B} = 1.249\,M_\odot$, $P_{\rm orb} = 3.3$ hr, $e = 0.12$, $\Delta v^{\rm B}_{\rm sys} = 35\,{\rm km\,s^{-1}}$



Ph. Podsiadlowski et al MNRAS 361, 1243 (2005)

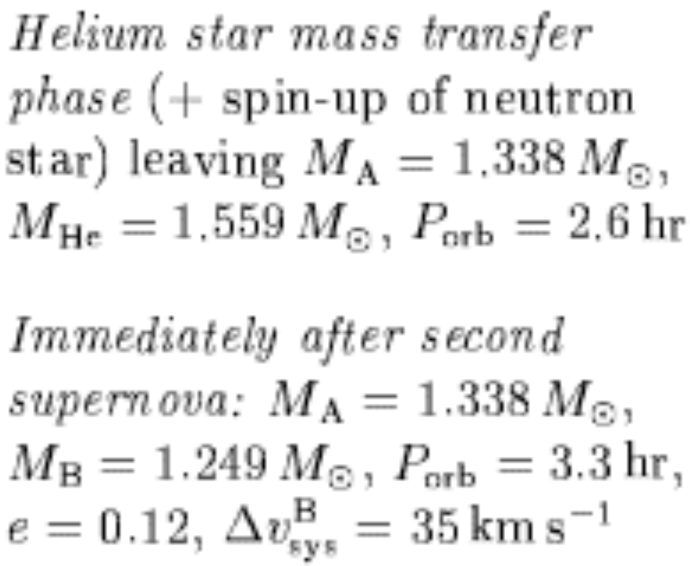
Account for some type Ib/c Supernova?

Bimodal mass distribution of neutron star masses: low mass component enhanced by ECSN? (Schwab+, arXiv:1006.4584)

Population synthesis models suggest J0737-3039B and J1756-2251 formed in ECSN (Andrews+, arxiv:1410.6797)

Be/X-ray binary population is bimodal in orbital and NS spin period – short periods indicate ECSN origin (Knigge+, arXiv:1111.2051)

Double NS via ECSN: final stage:



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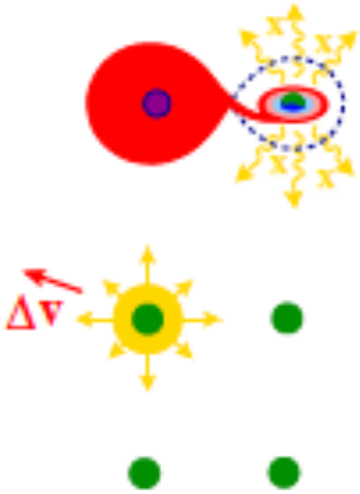


Ph. Podsiadlowski et al MNRAS 361, 1243 (2005)

Why is this important?

Population synthesis models, progenitors of SNe, rates of production of low mass neutron stars and neutron star binaries, GW searches

Constraining the evolutionary history of specific systems and SNe (e.g. double pulsar, Crab)

Constraining the Neutron Star EOS from Binding Energy Estimates

- Astrophysical modelling: ONeMg core collapses at, e.g.

$1.366 < M_0 < 1.375\ M_{SUN}$, Podsiadlowski et al MNRAS 361, 1243 (2005)
$1.358 < M_0 < 1.362\ M_{SUN}$ F.S. Kitaura, H.-Th. Janka, W. Hillebrandt, A&A 450, 345 (2006)
$1.357 < M_0 < 1.377\ M_{SUN}$ Takahashi, 2013

- Very little mass lost during pulsar formation – so the above masses are estimates of the *baryon* mass of the pulsar

- We measure, for example, the *gravitational* mass of pulsar B

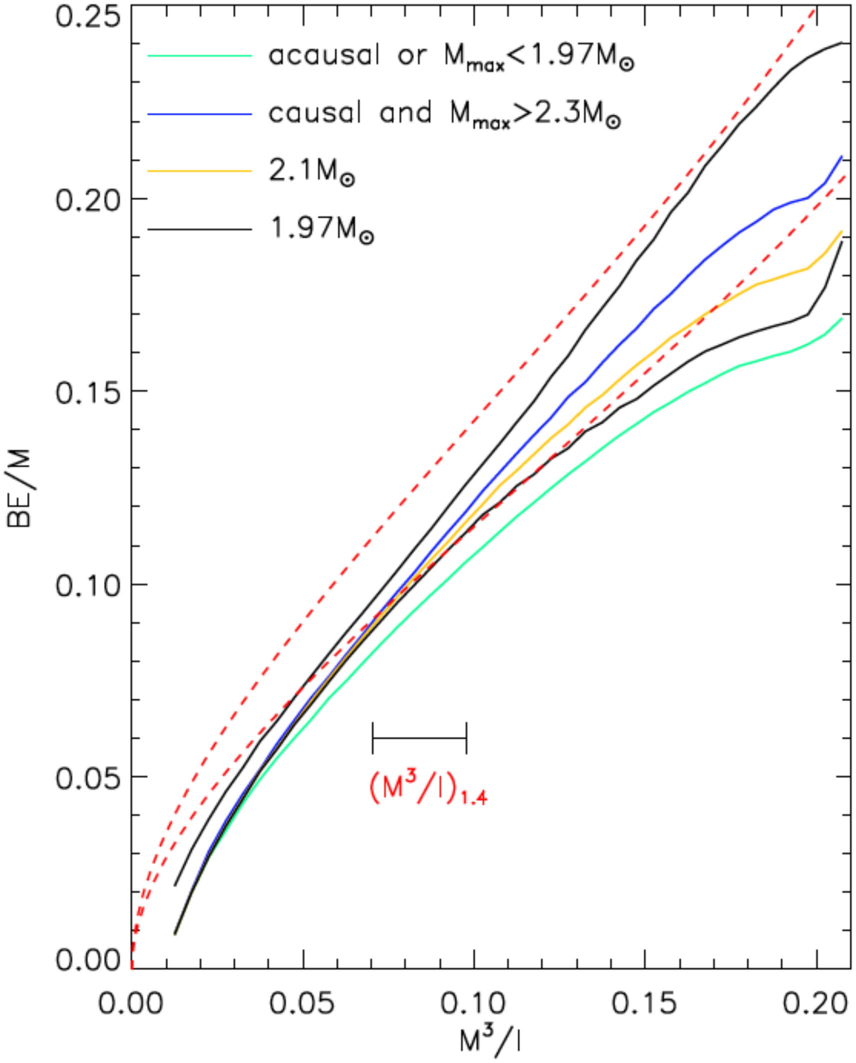
$$M_G = 1.2489 \pm 0.0007\ M_{SUN}$$

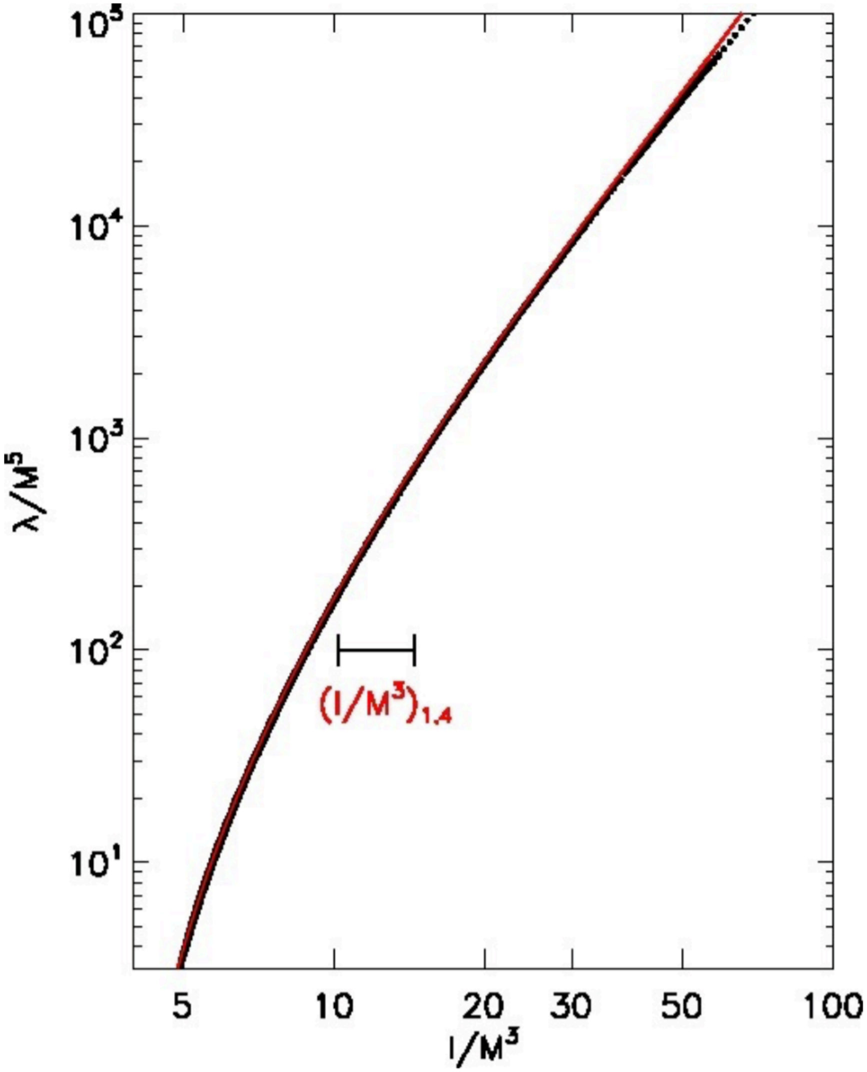
- The difference is the gravitational binding energy *BE* of the star

$$M_B = M_G + BE$$

- ..which correlates with the compactness *M/R* and the EOS
- Independent estimates of the binding energy can constrain the formation scenario

Universal Relations: I-Love-Q (Yagi,Yunes)

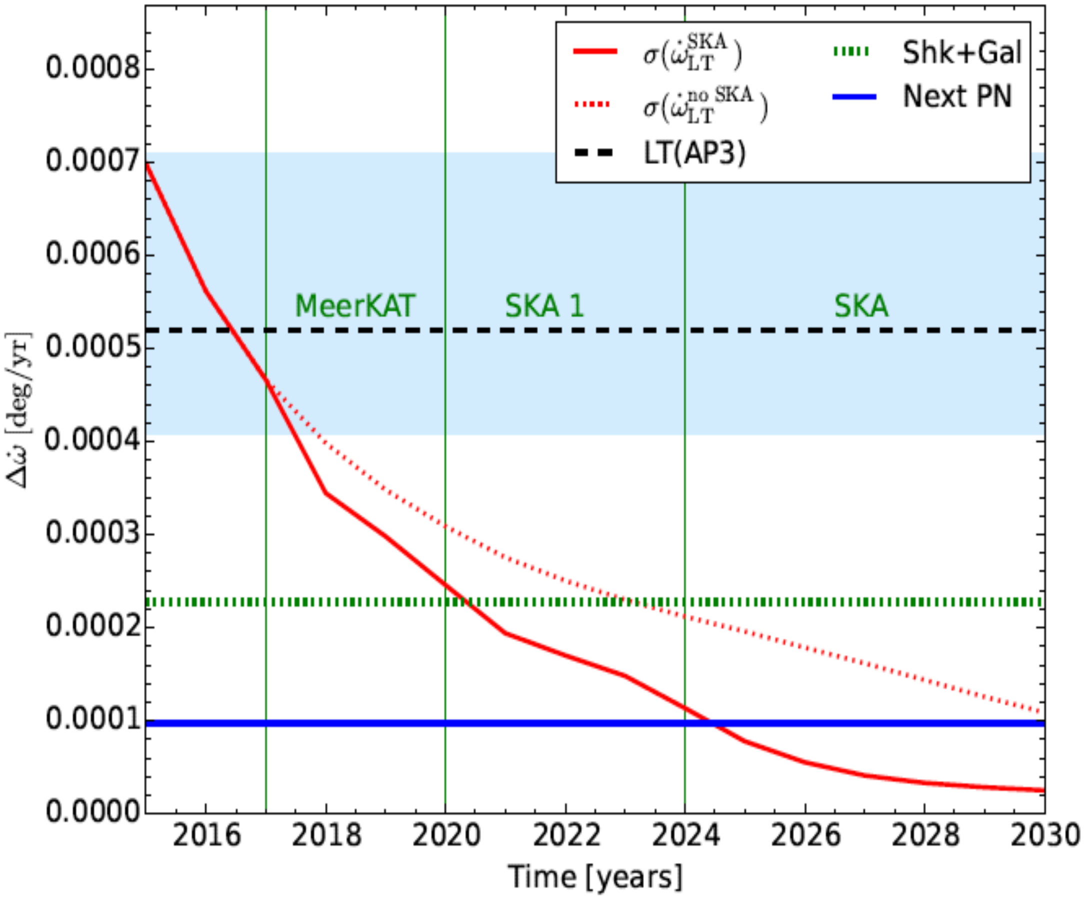




...+BE

Steiner, Lattimer, Brown, arxiv:1510:07515

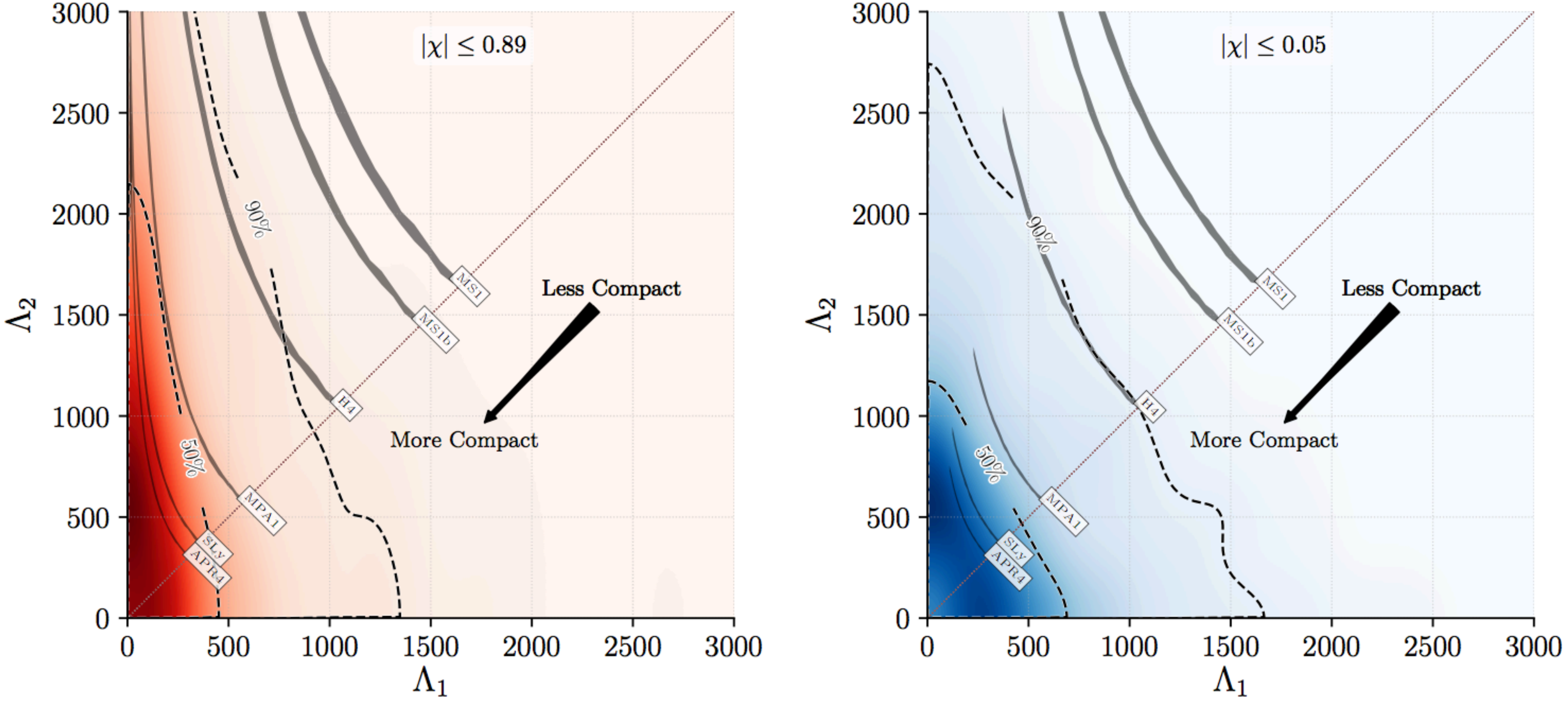
Pulsar A’s moment of inertia should be measurable to within 10% in the next decade from pulsar timing



From contribution to periastron advance (Lense-Thirring precession) (Lattimer&Schutz, arxiv:astro-ph/0411470; Kehl+, arxiv: 1605.00408)

…and a 10% measurement of the Love number of a neutron star from a merger GW signal by advanced LIGO is possible

Already started constraining tidal polarizability!



LSC/LIGO

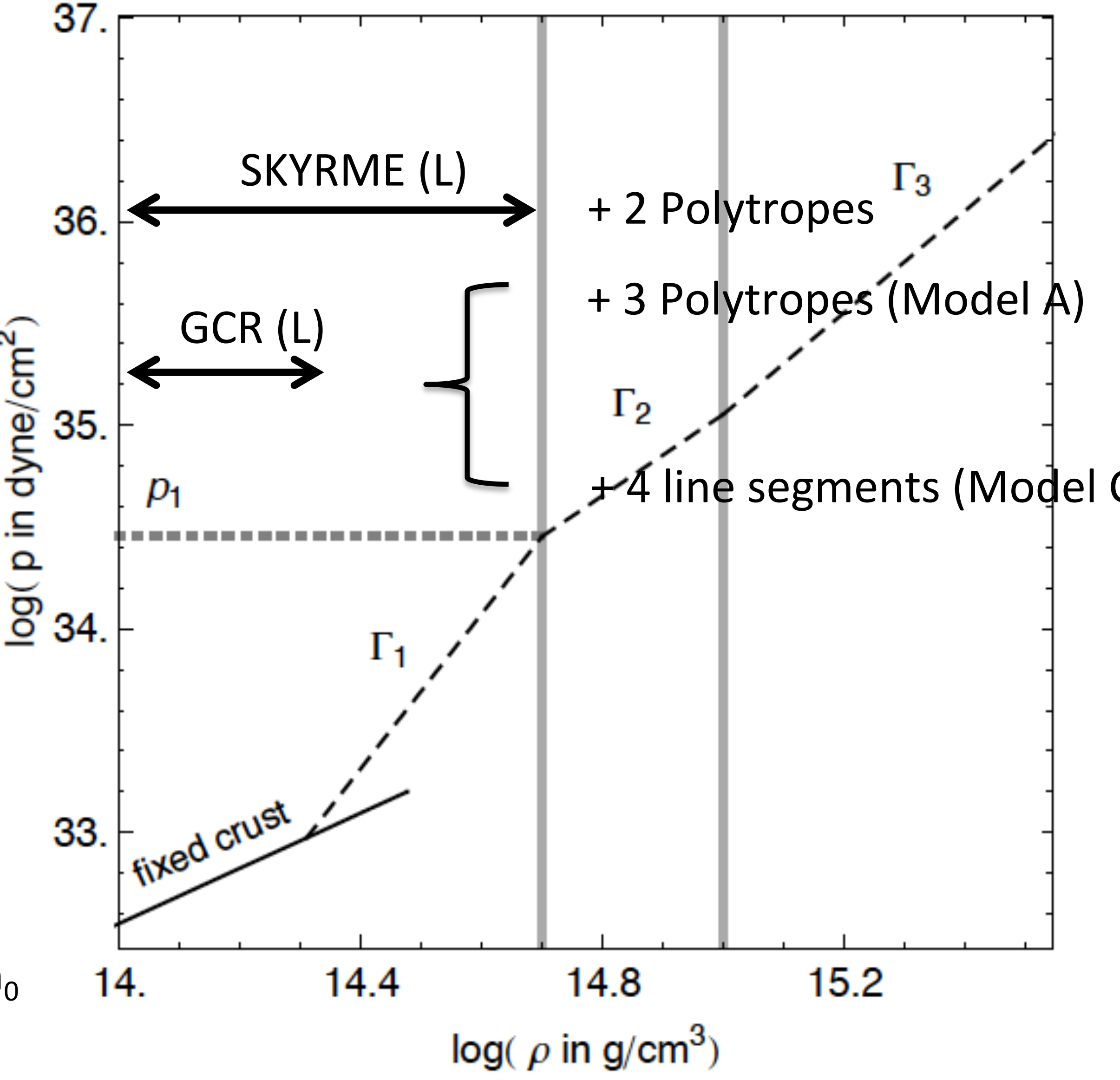
EOS Modeling

Fattoyev+ PRC86, 025804 (2012)
Brown, Schwenk,
PRC89, 011307 (2014)

Steiner+ ApJL 778 L23 (2013)
Steiner+ PRC91, 015804 (2015)

GCR: parameterization of PNM EOS; L = 30-70MeV
(Gandolfi+, PRC85, 032801, 2012)
Polytropes attached at n_0

Skyrme: Fit to PNM EOS;
L=20-80 MeV
(+ L=120MeV)
Polytropes attached at $1.5n_0$ and n_0



SKYRME (L)

GCR (L)

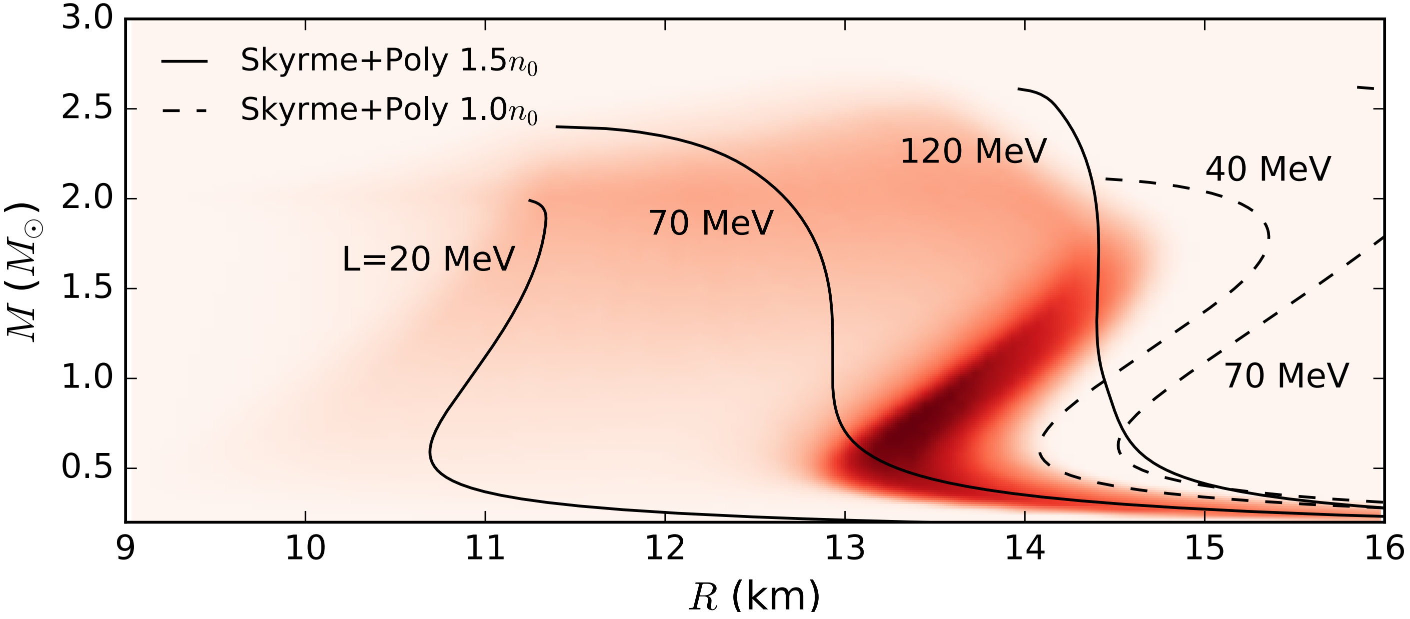
+ 2 Polytropes

+ 3 Polytropes (Model A)

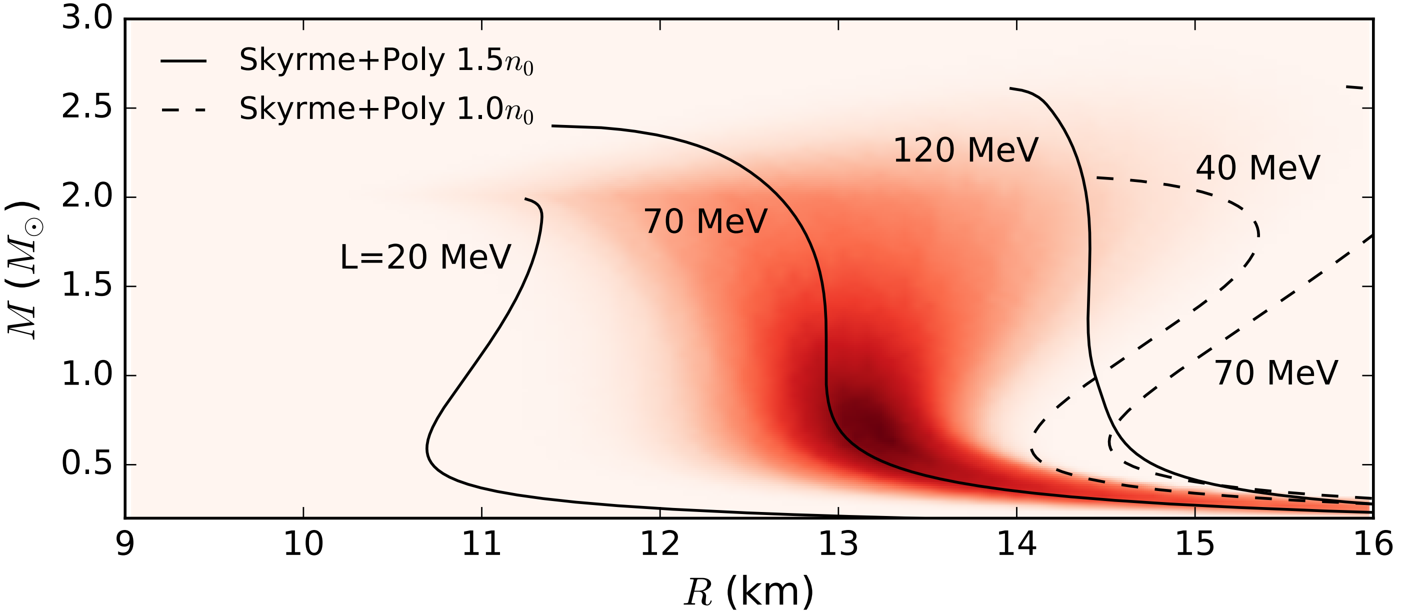
+ 4 line segments (Model

Read+, arxiv:0812.2163

EOS Modeling



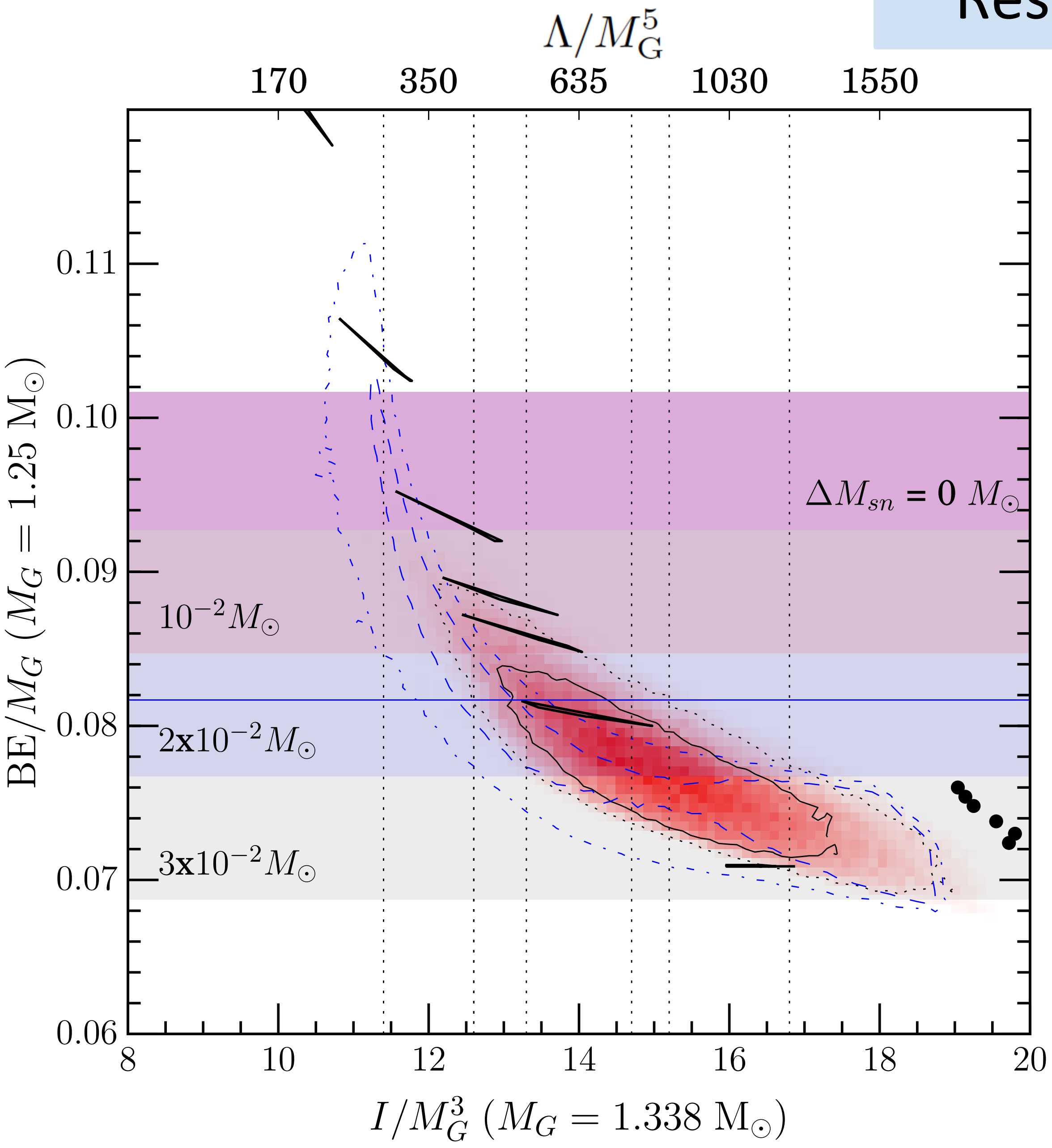
GCR MODEL A



GCR MODEL C

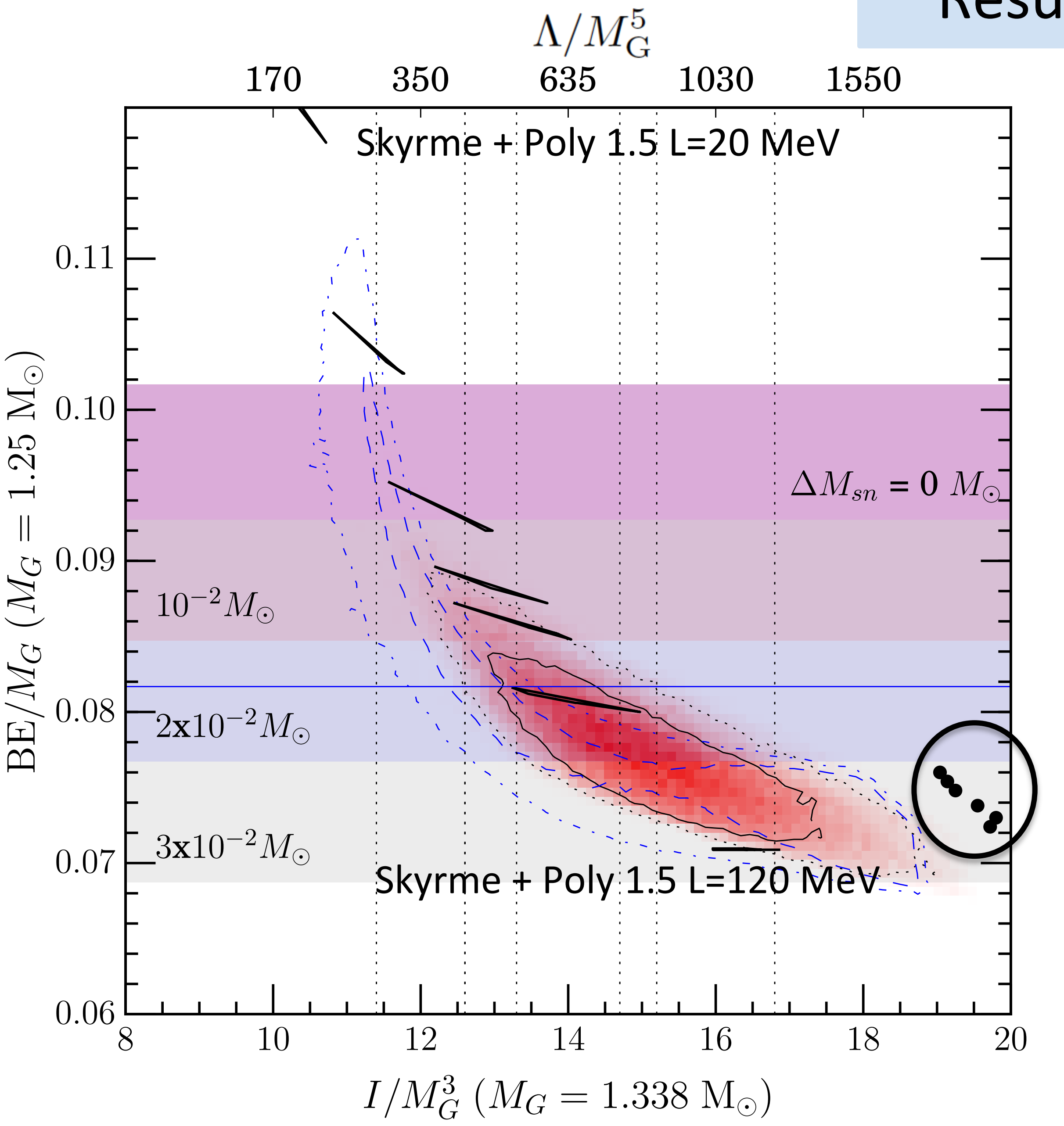
Newton, Steiner, Yagi; ApJ (in production) arxiv: 1611.09399

Results: J0737-3039B



Newton, Steiner, Yagi; ApJ (in production) arxiv: 1611.09399

Results: J0737-3039B



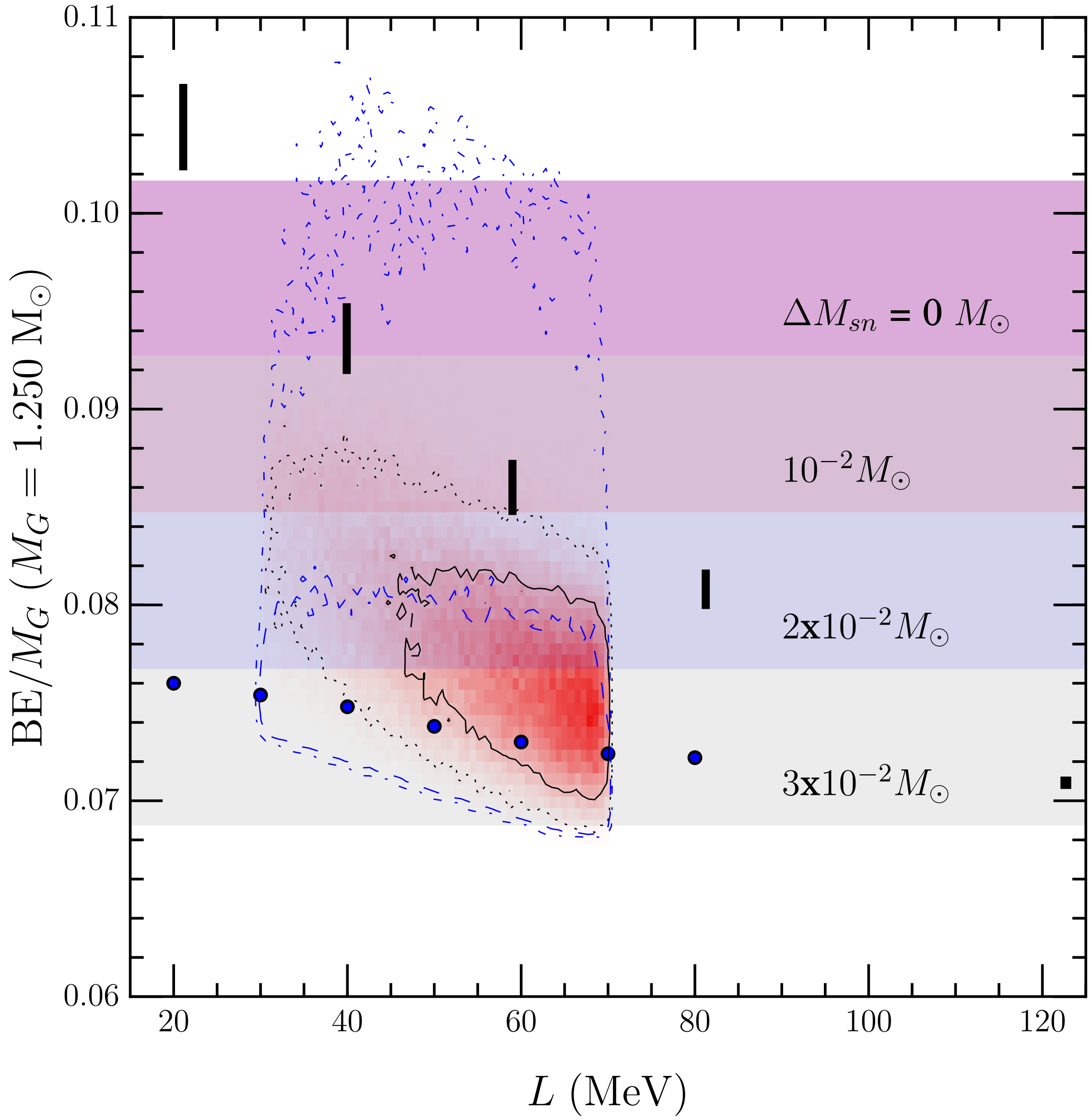
Skyrme + Poly 1.5 L=20 MeV

Skyrme + Poly 1.5 L=120 MeV

Skyrme + Poly 1.0
20-120 MeV

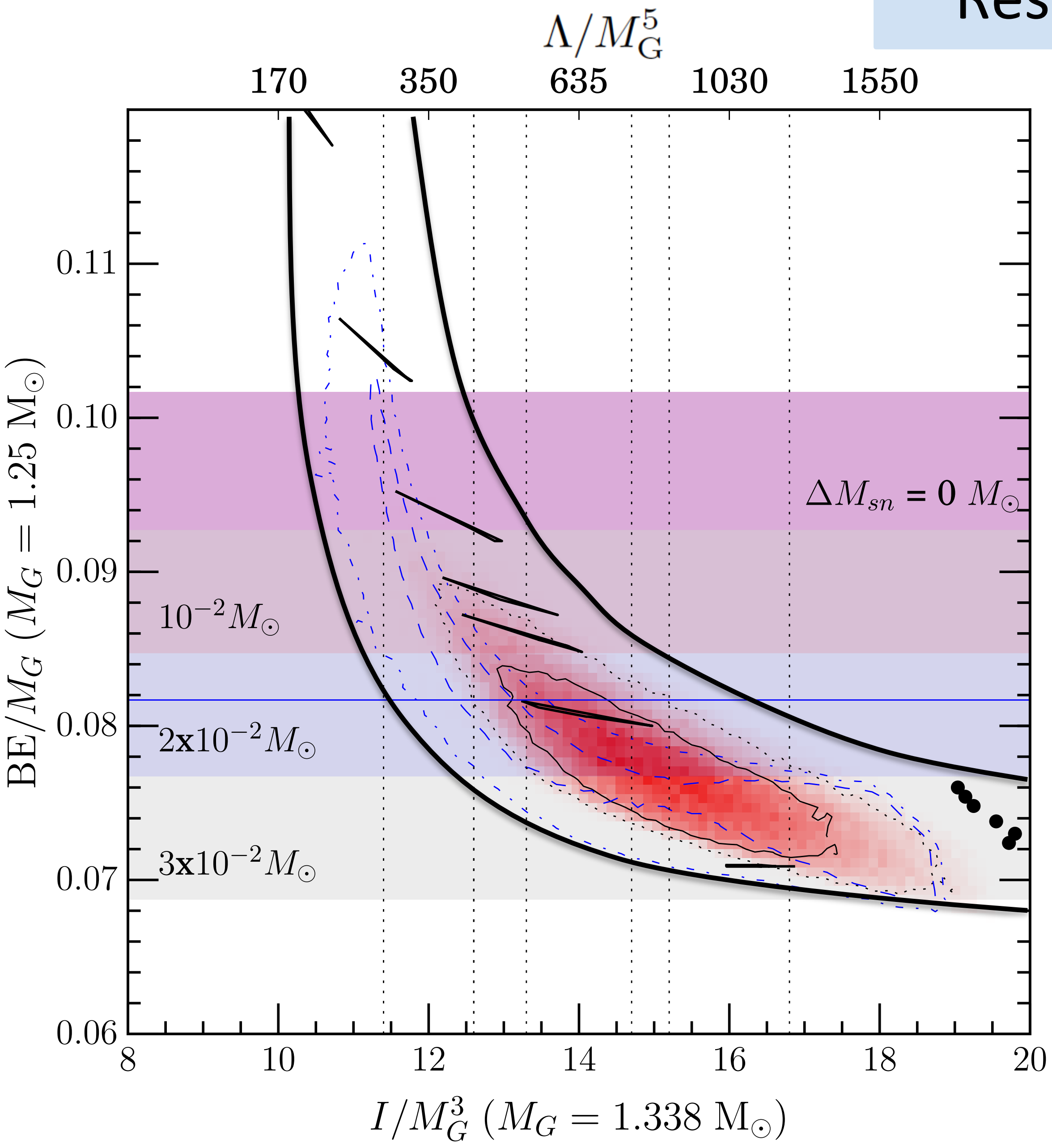
Newton, Steiner, Yagi; ApJ (in production) arxiv: 1611.09399

Results: J0737-3039B



Newton, Steiner, Yagi; ApJ (in production) arxiv: 1611.09399

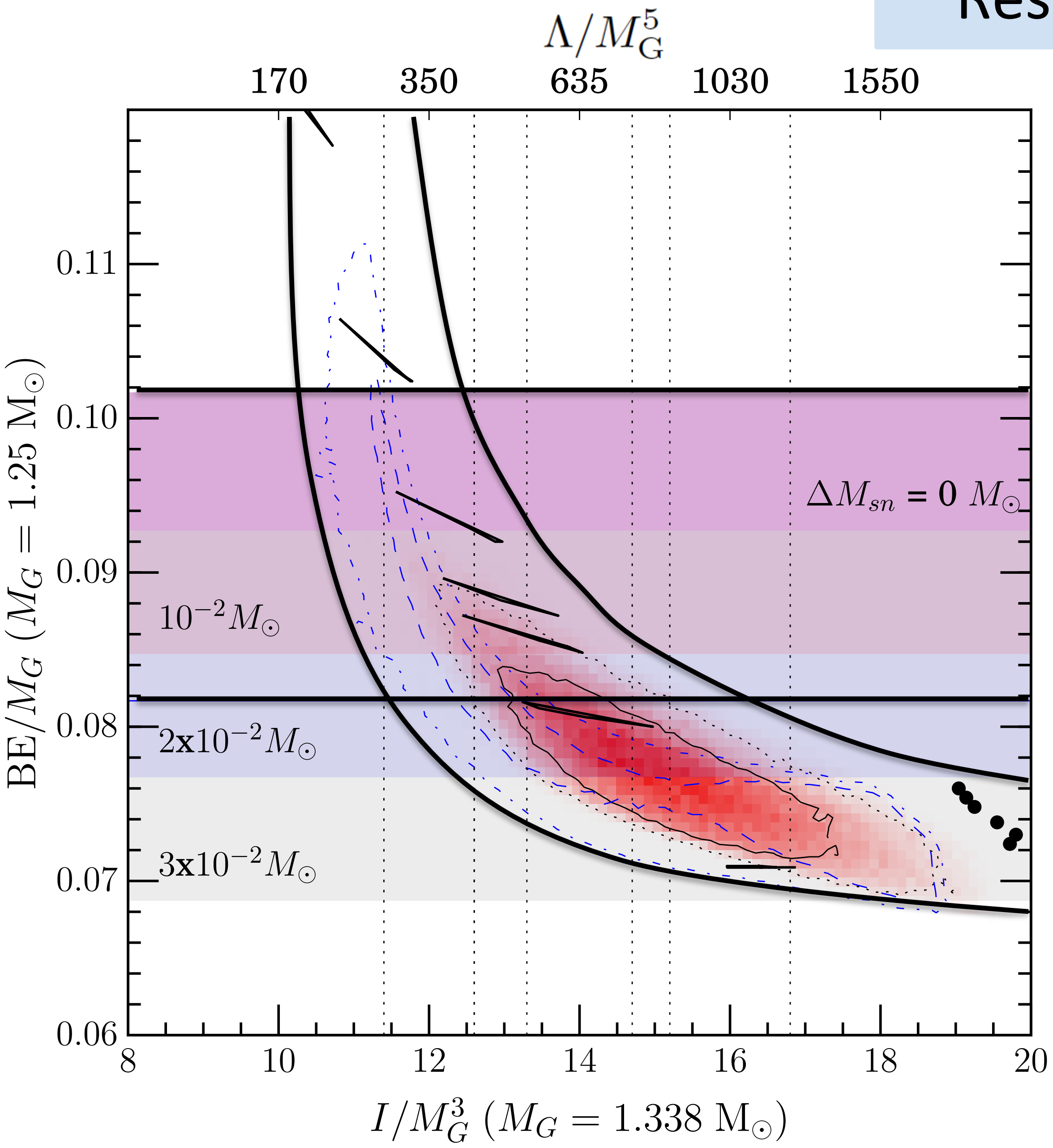
Results: J0737-3039B



Range of *I-BE* relation from EOS modeling

Newton, Steiner, Yagi; ApJ (in production) arxiv: 1611.09399

Results: J0737-3039B

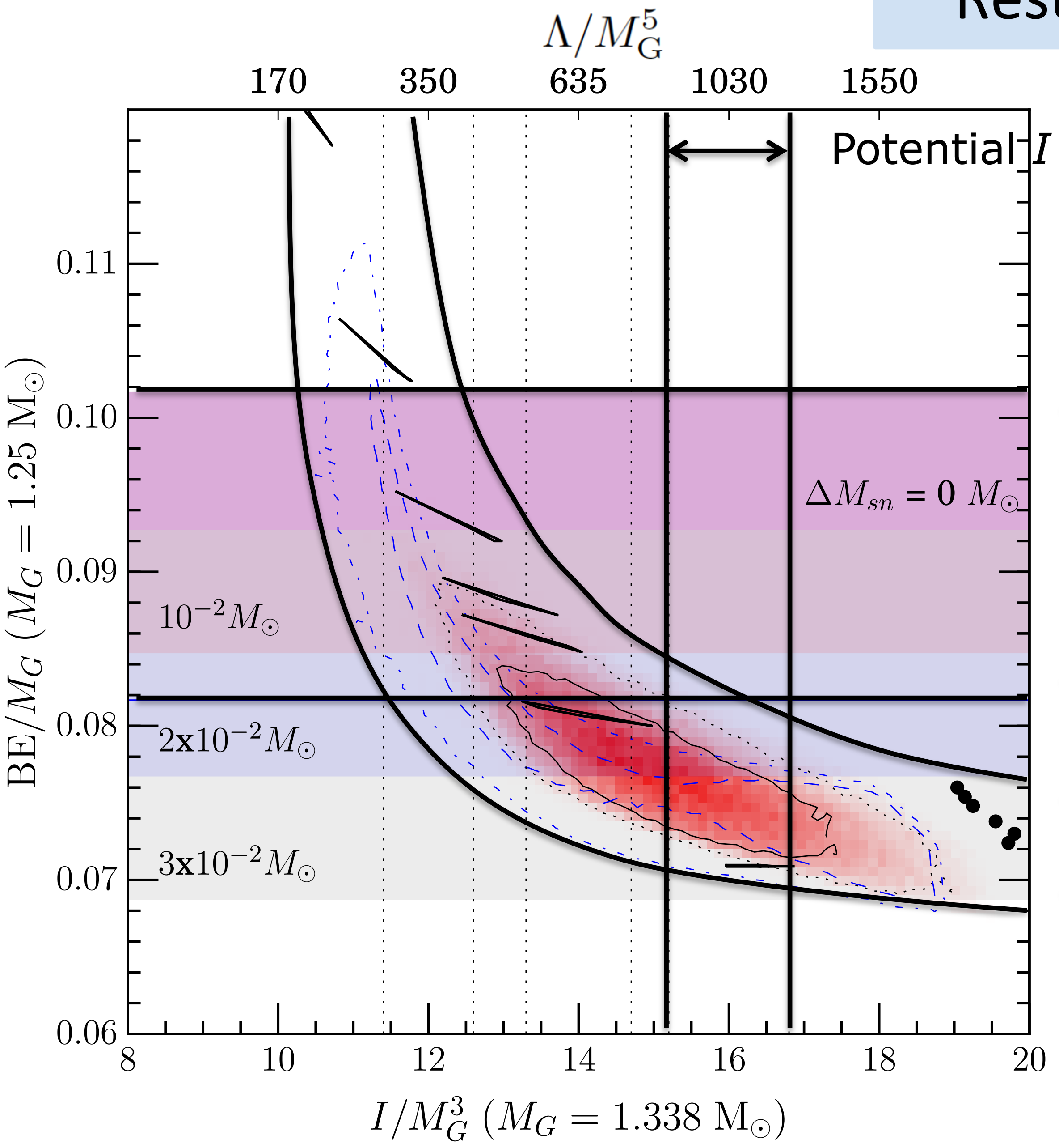


Predicted range from progenitor SN modeling: (1.366 - 1.377 M$_{\mathrm{sun}}$ + mass loss)

Range of *I-BE* relation from EOS modeling

Newton, Steiner, Yagi; ApJ (in production) arxiv: 1611.09399

Results: J0737-3039B



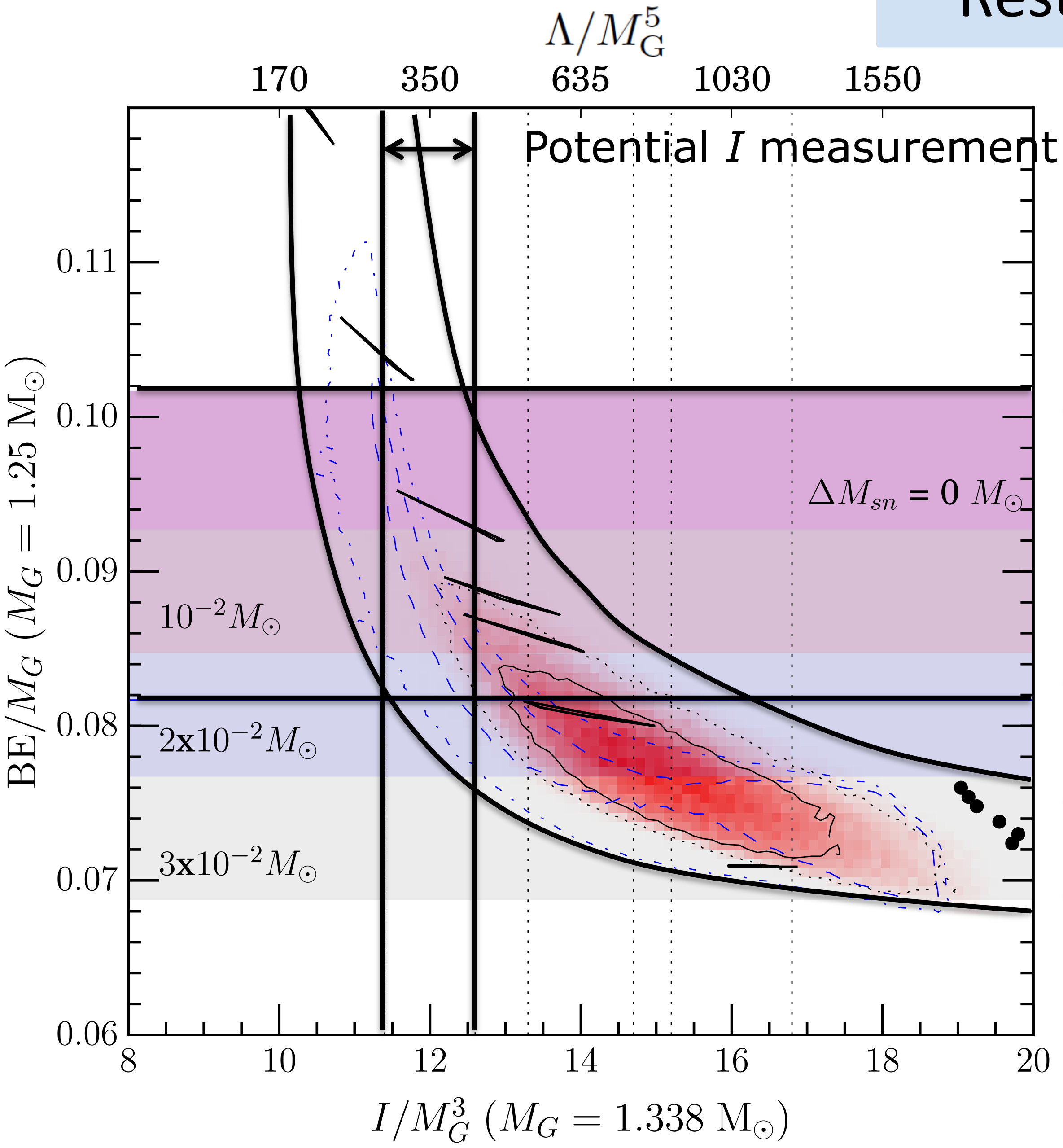
Potential I measurement

Predicted range from progenitor SN modeling: (1.366 - 1.377 M$_{\mathrm{sun}}$ + mass loss)

Range of *I-BE* relation from EOS modeling

Newton, Steiner, Yagi; ApJ (in production) arxiv: 1611.09399

Results: J0737-3039B



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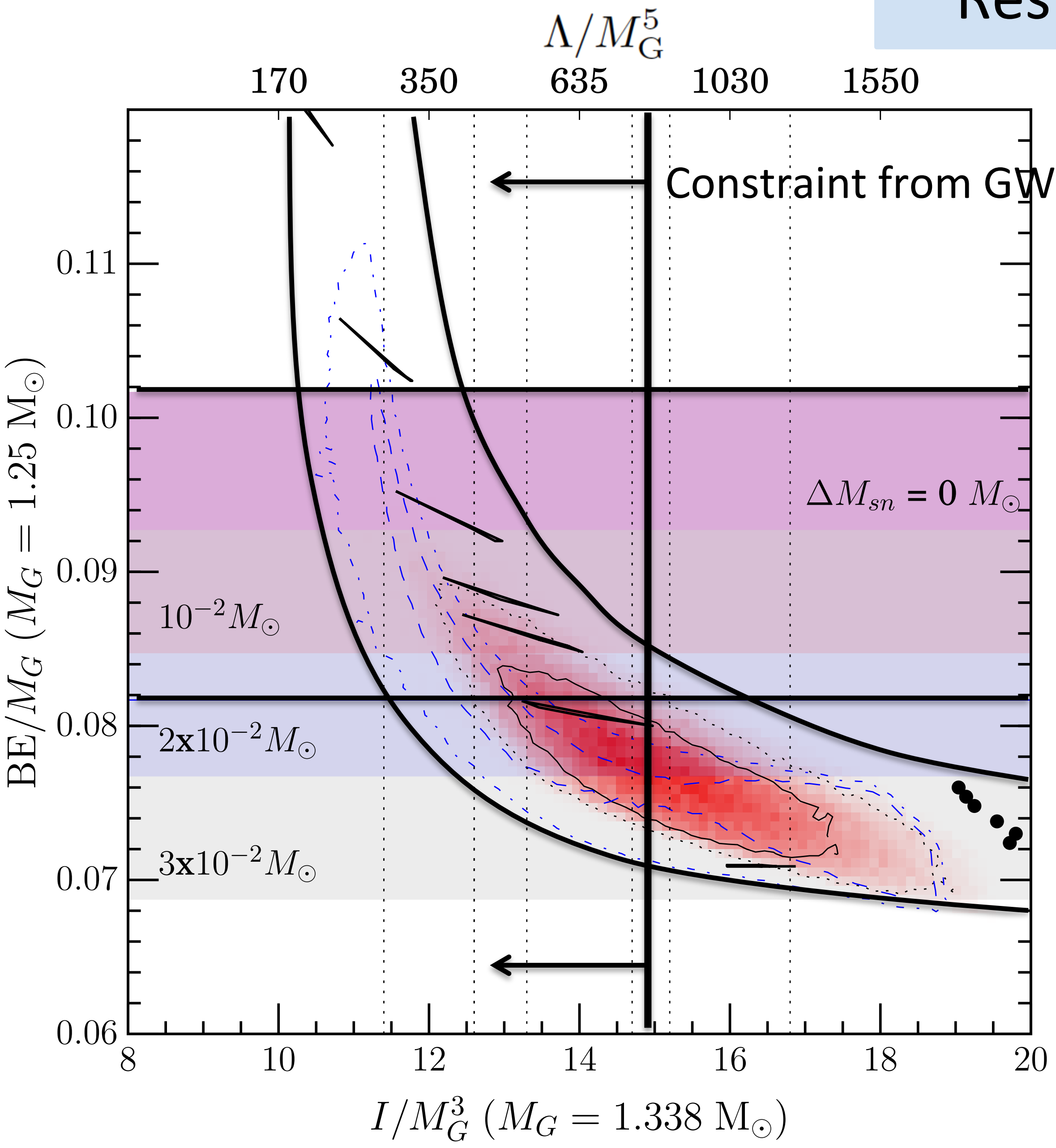


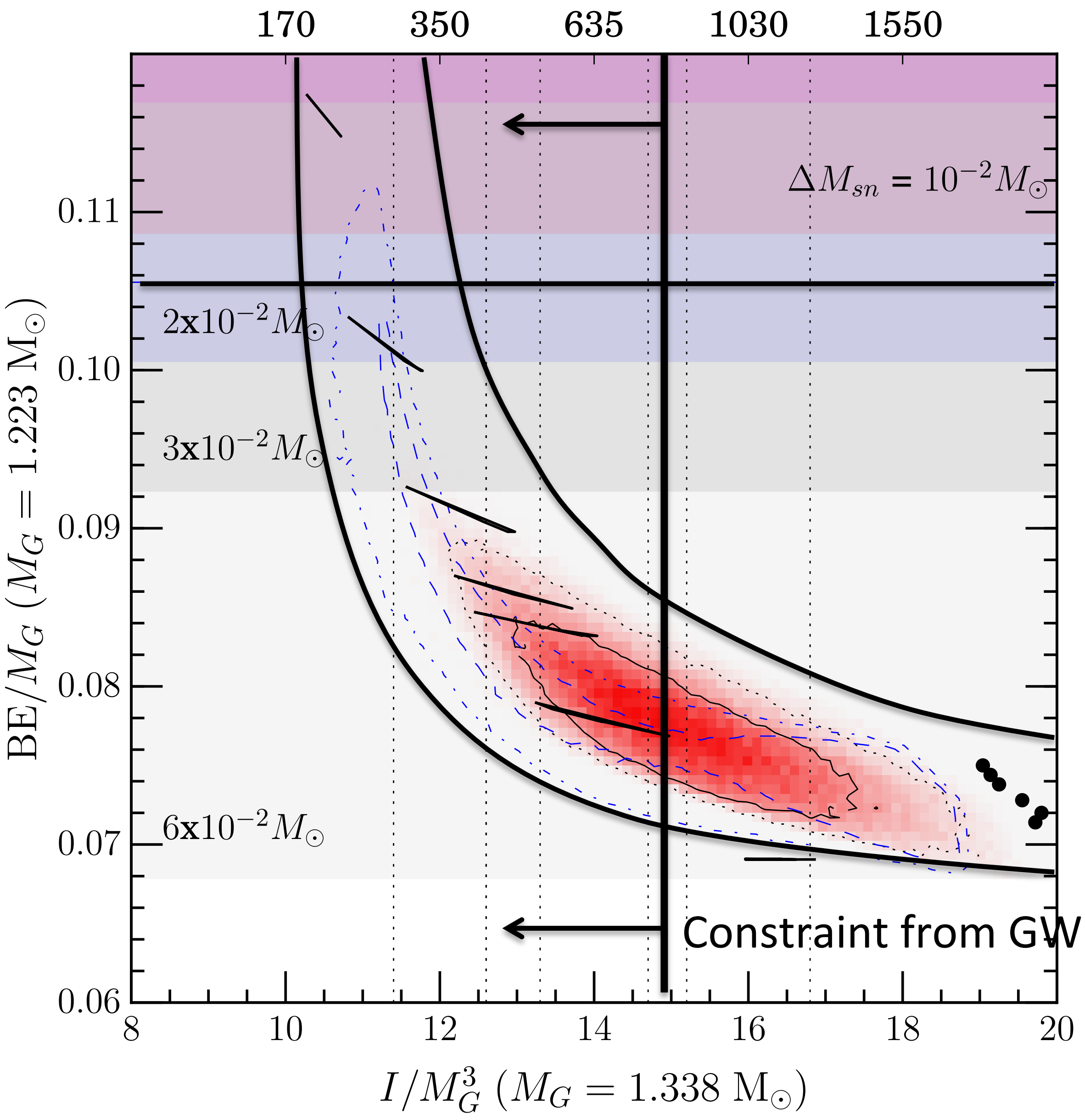
Constraint from GW170817

Predicted range from progenitor SN modeling: (1.366 - 1.377 M_{sun} + mass loss)

Range of *I-BE* relation from EOS modeling

Newton, Steiner, Yagi; ApJ (in production) arxiv: 1611.09399

Results: J1756-2251



Constraint from GW170817

Predicted range from progenitor SN modeling: (1.366 - 1.377 M_{sun} + mass loss)

Newton, Steiner, Yagi; ApJ (in production) arxiv: 1611.09399

Conclusions

Viability and extent of ECSN very important for understanding stellar populations, especially the population of DNS binaries

Current progenitor models and supernova core collapse predict ONeMg cores become unstable in range ≈1.357 – 1.377 M_{sun} and collapse with only ~0.01 M_{sun} escaping

EOS modeling suggests that J0737-3039 and J1756-2251 compatible with ECSN hypothesis if EOS is moderately soft/contains strong phase transition *or* greater mass loss than predicted

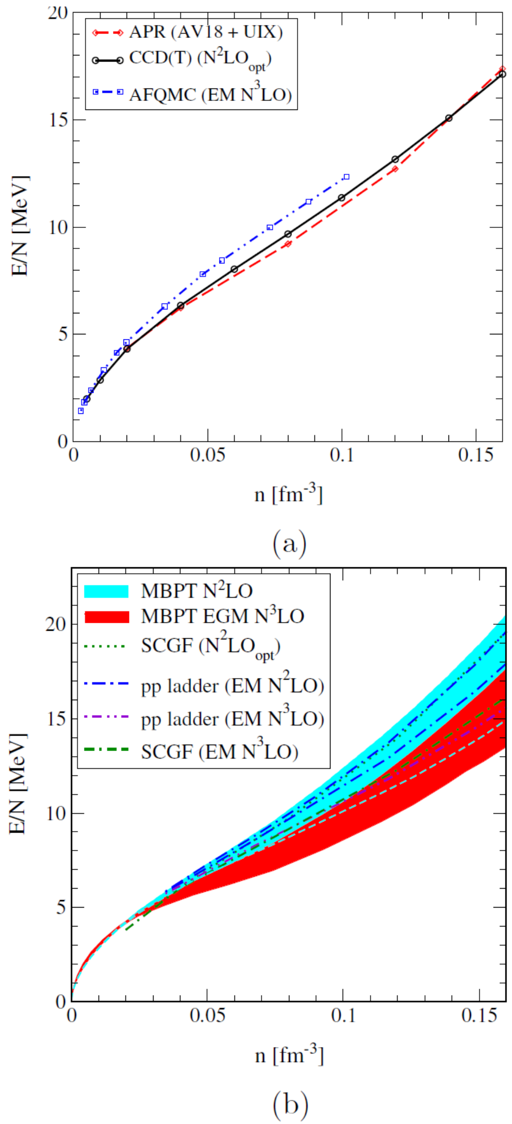
Measurements of Moment of Inertia to within 10% can constrain binding energy to similar precision and the mass loss to within ~0.01 M_{sun} assuming the creation scenario

GW170817 constraints on tidal polarizability consistent with ECSN scenario

Need more simulations of ONeMg core collapse! (2D,3D) and USFeCC

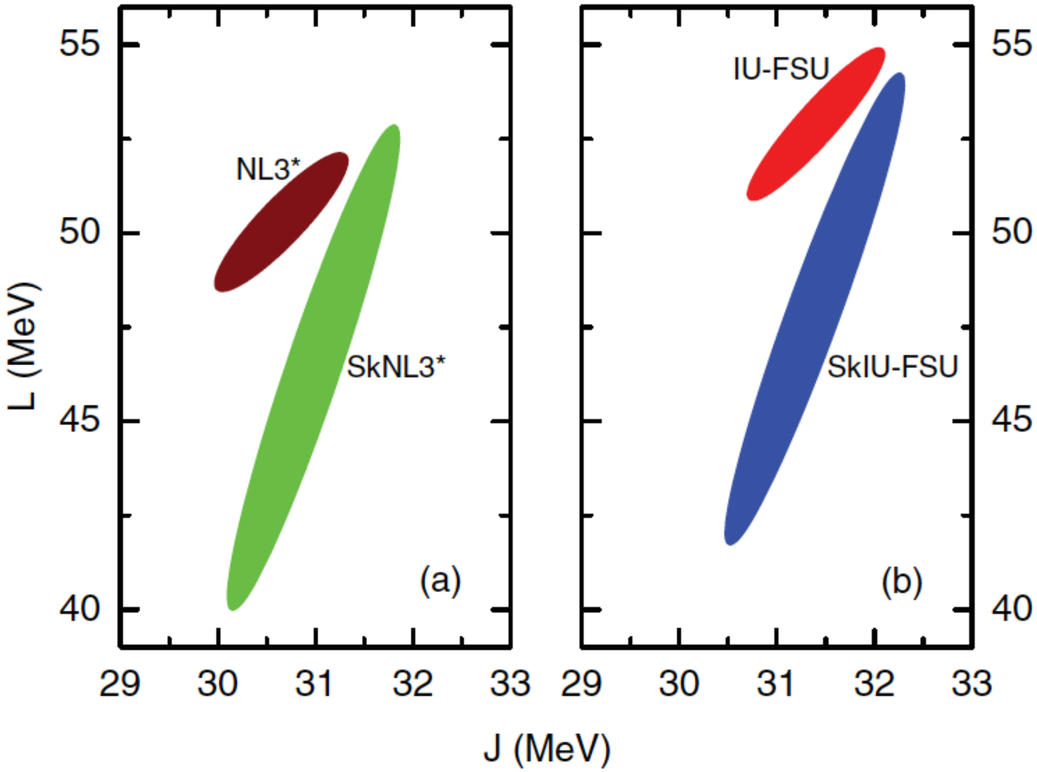
- Are instabilities really insignificant?
- What's the most mass that can be ejected from the core? How does it depend on EOS?
- Does it actually collapse? What factors affect it? (Jones+, arxiv:1602.05771 – for ignition densities below 10^{10} g/cc, deflagration destroys star)

Systematic EOS modeling



Use our best calculations of PNM properties to constrain our EOS models.

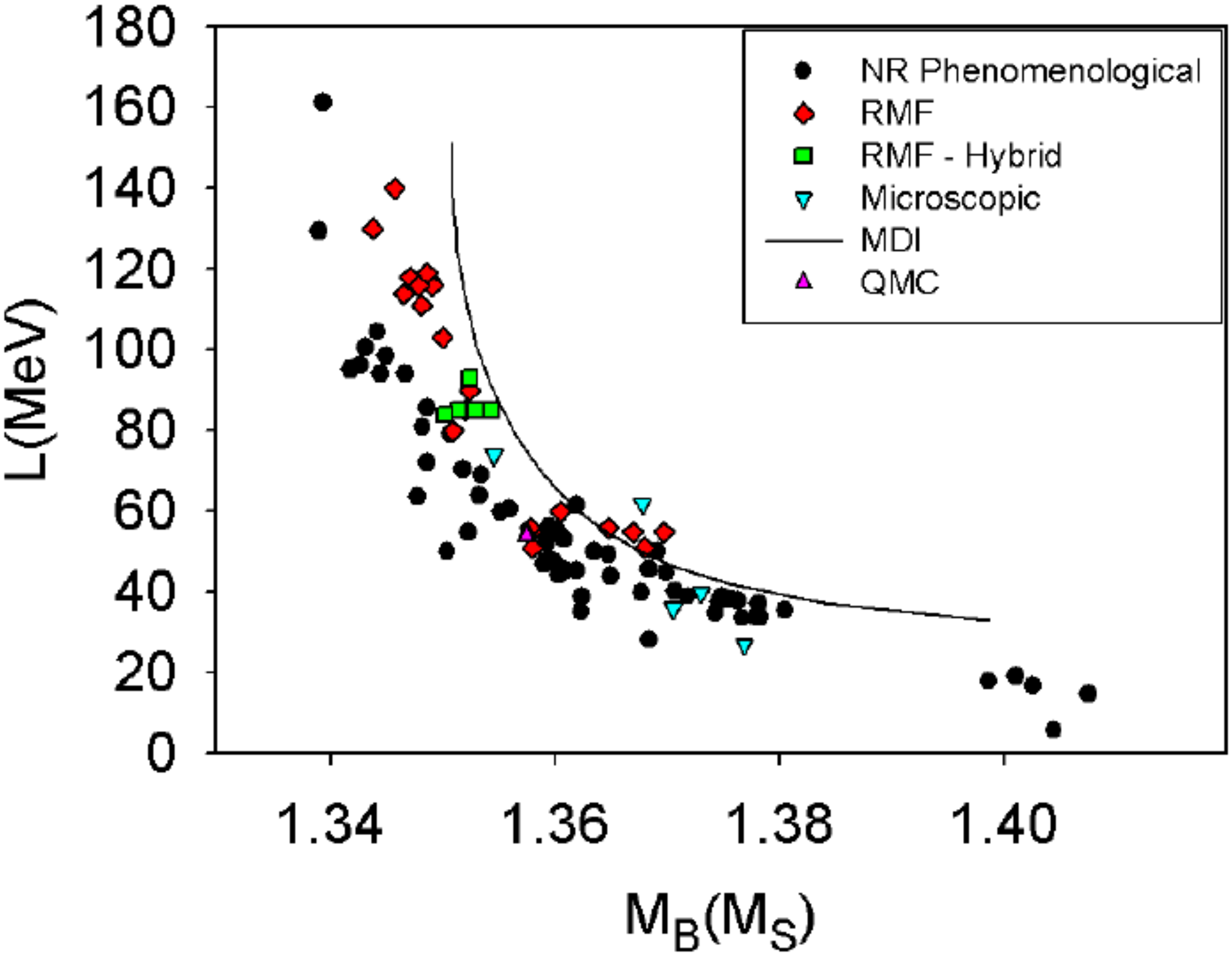
2 purely isovector parameters in Skyrme and RMF energy density functionals – allows us to take a baseline model and refit those two parameters to PNM “data”



Gandolfi, Gezerlis, Carlson, ARNPS 65 (2015)

Fattoyev, Newton, Xu, Li, PRC86, 025804 (2012)
Brown, Schwenk, PRC89, 011307 (2014)

Dependence of L on Baryon Mass of J0737-3039B

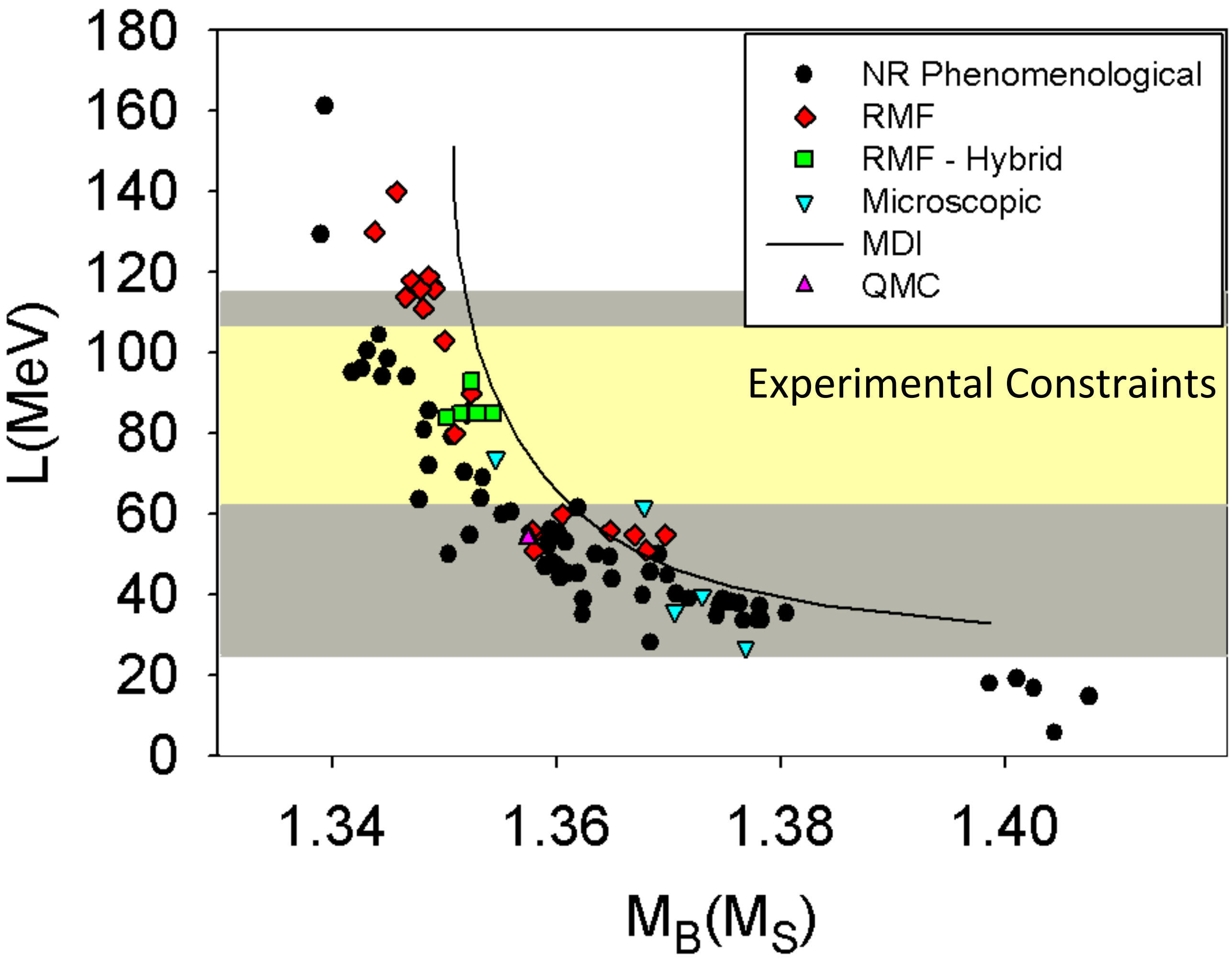


$M_G = 1.249\ M_{SUN}$

$M_0 = M_G + BE$

Newton, Li PRC 80, 065809 (2009)

Dependence of L on Baryon Mass of J0737-3039B



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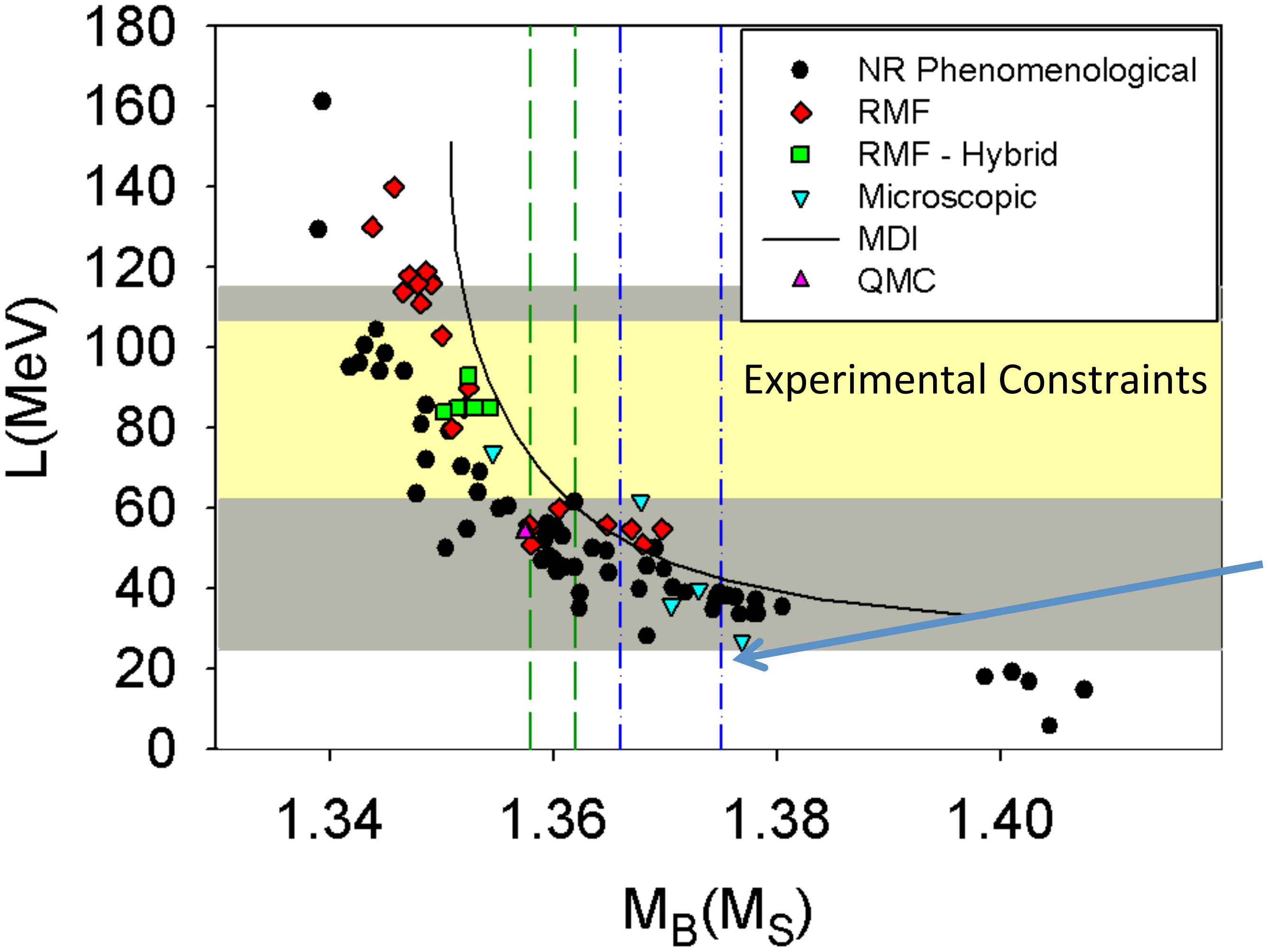

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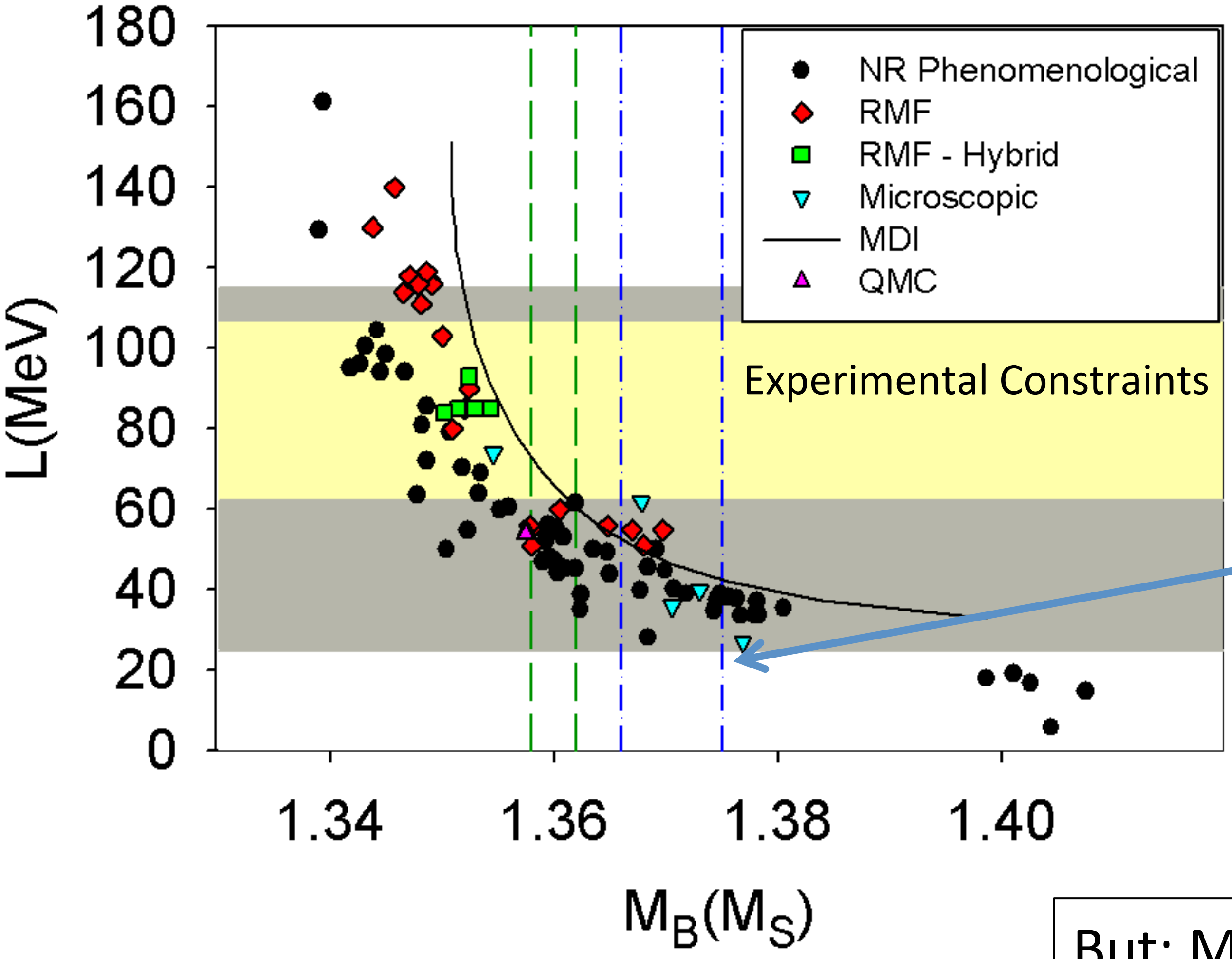
ECSN modeling constraints

Newton, Li PRC 80, 065809 (2009)

Dependence of L on Baryon Mass of J0737-3039B



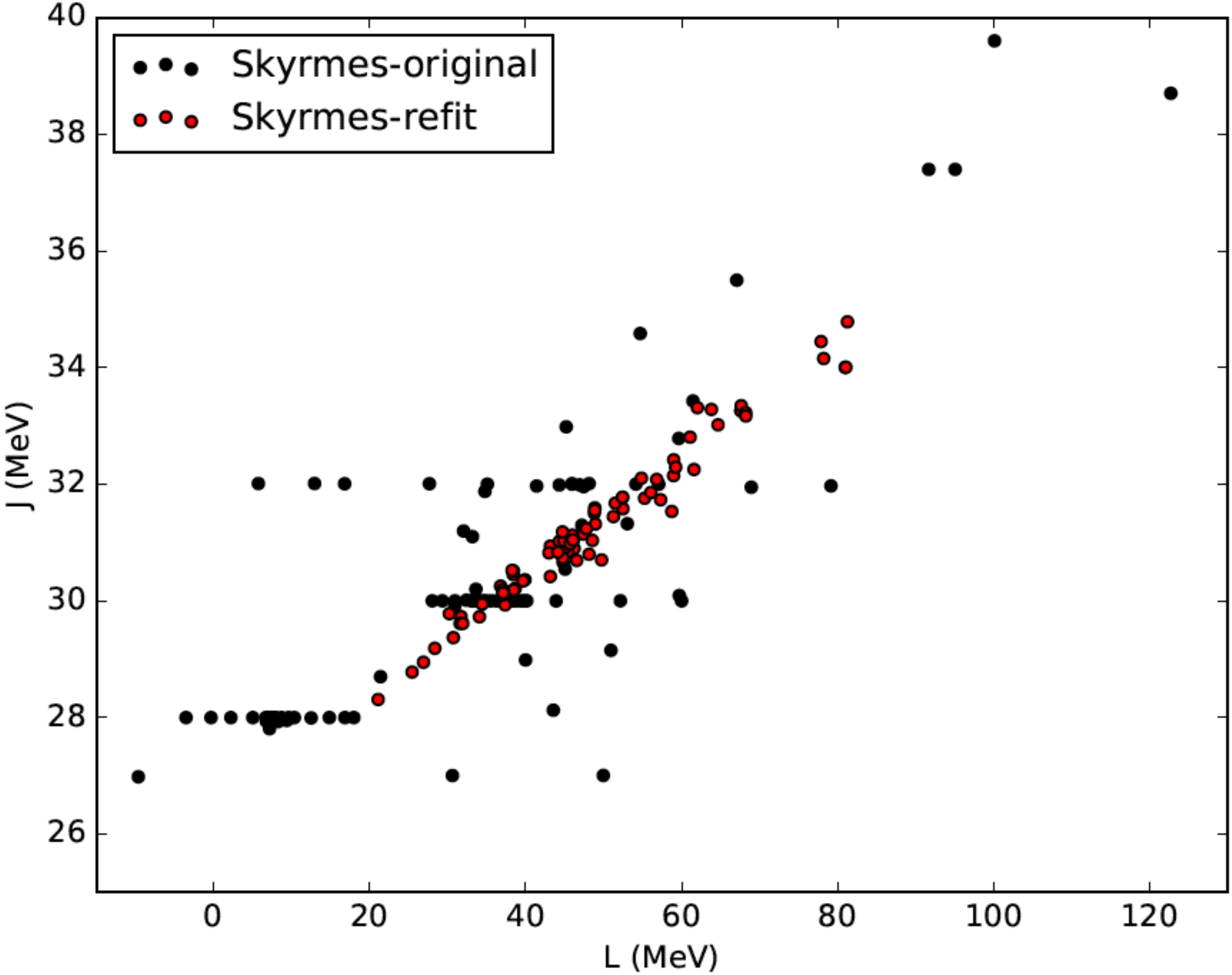
$M_G = 1.249\ M_{SUN}$

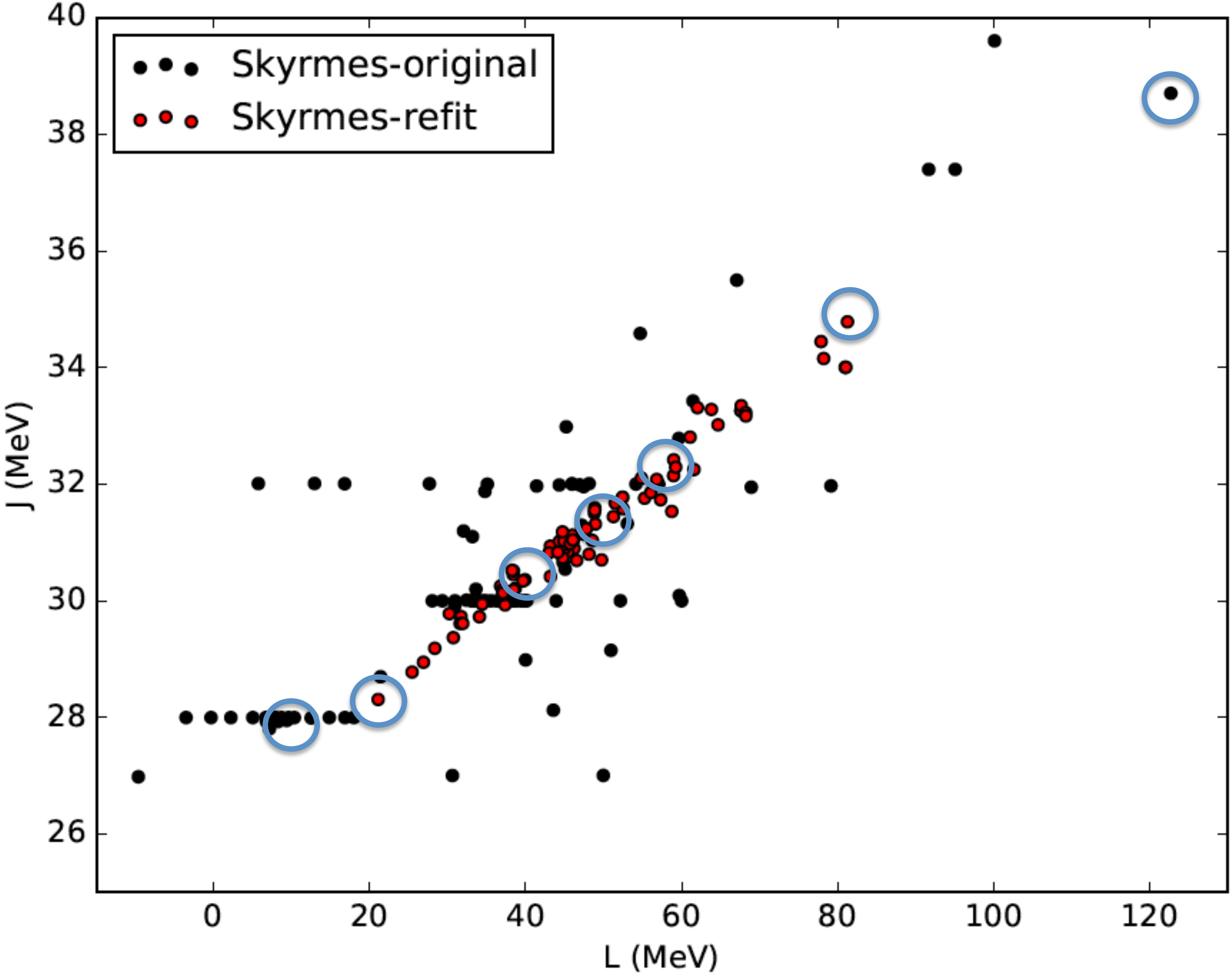
$M_0 = M_G + BE$

ECSN modeling constraints

Newton, Li PRC 80, 065809 (2009)

But: Max mass assumed was $1.44M_{sun}$


Skyrmes-original
Skyrmes-refit
J (MeV)
L (MeV)
40
38
36
34
32
30
28
26
0
20
40
60
80
100
120


Skyrmes-original
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J (MeV)
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40
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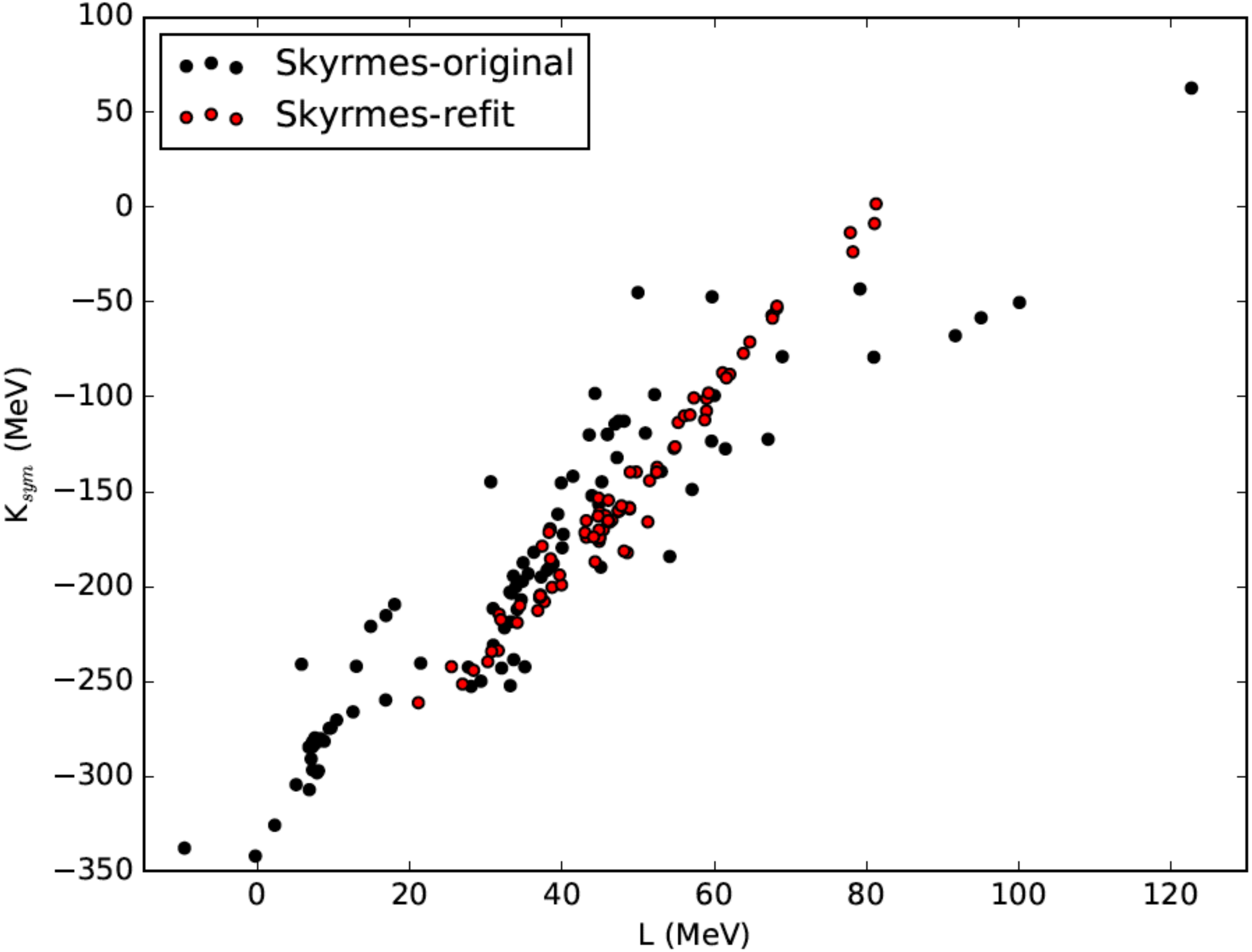
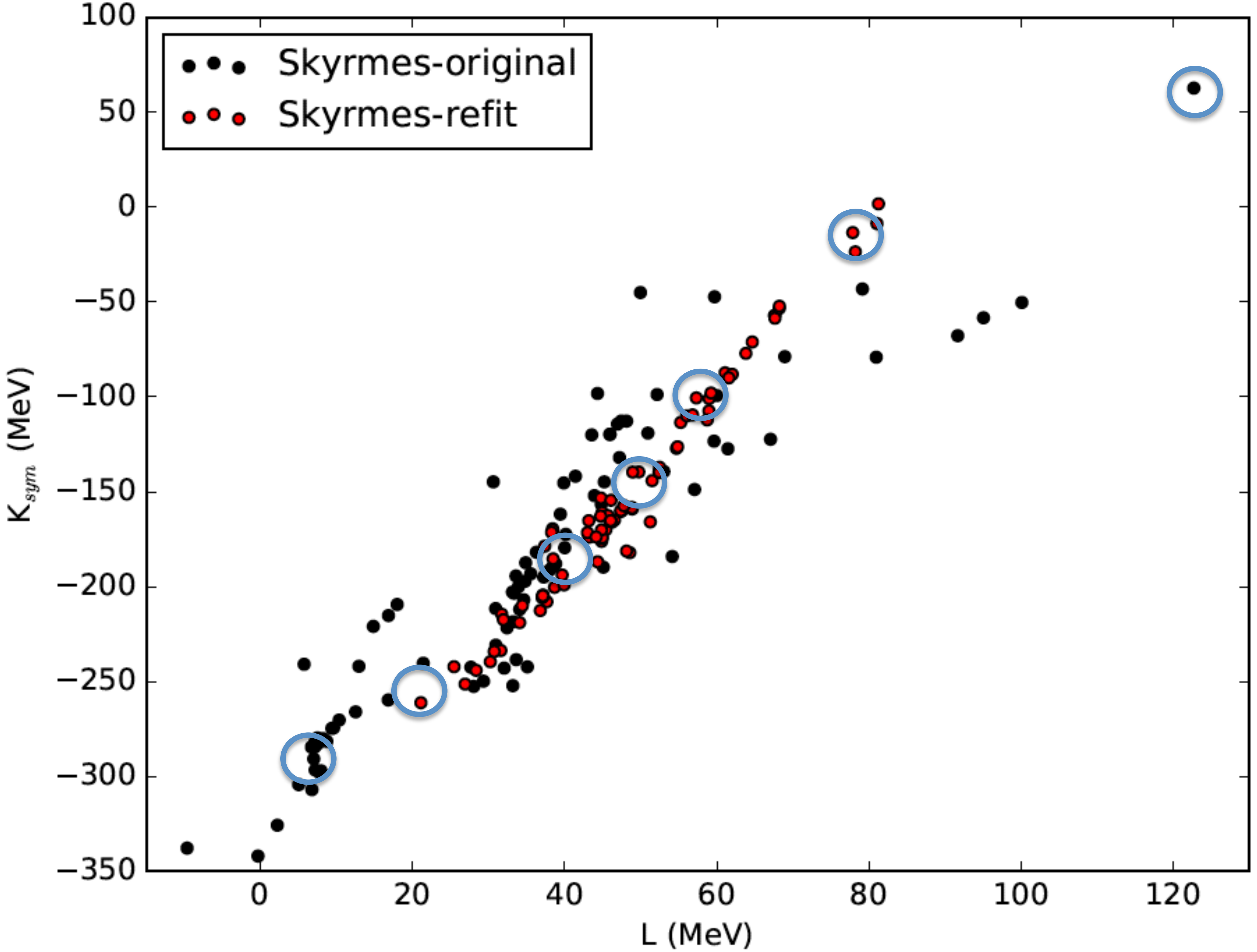
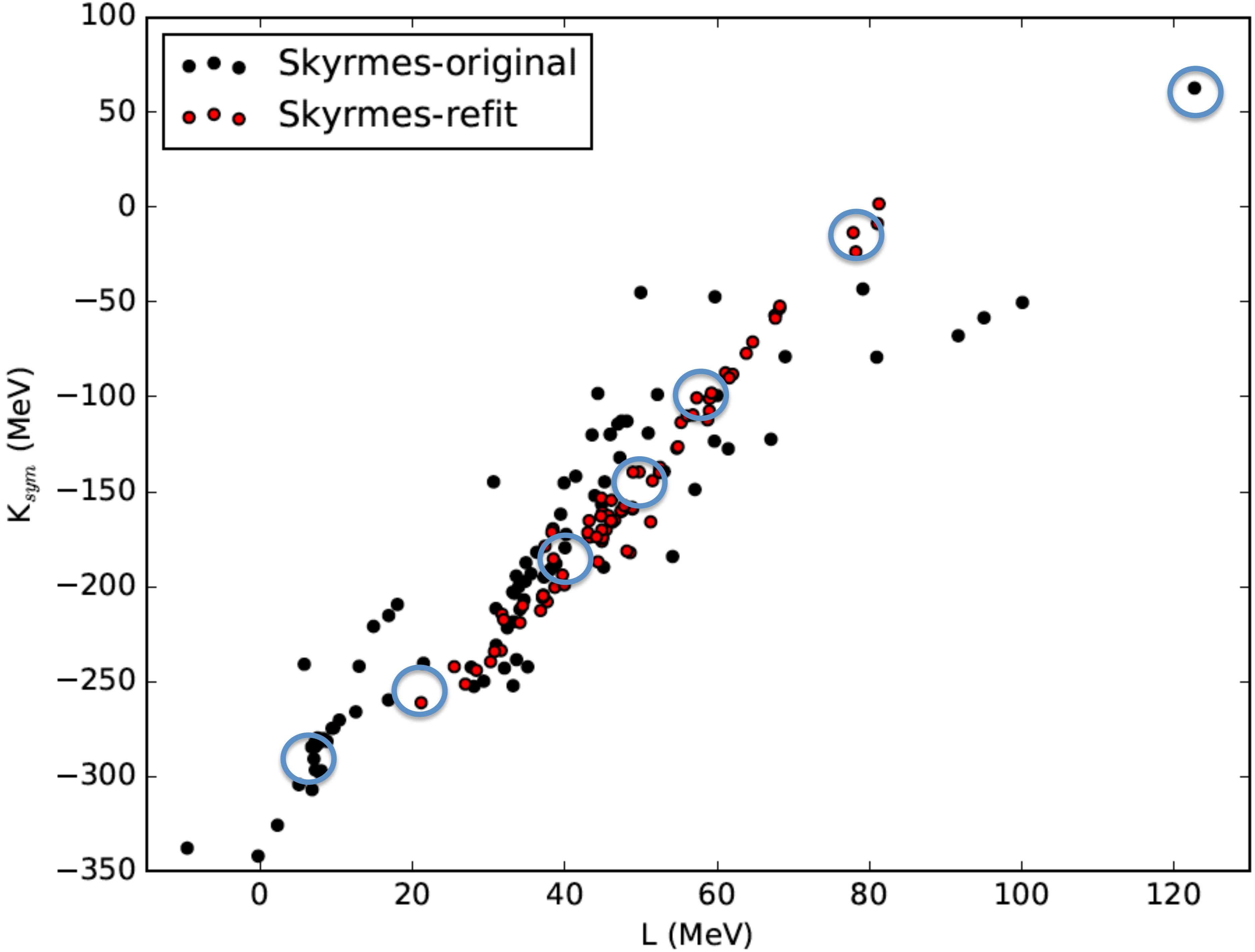
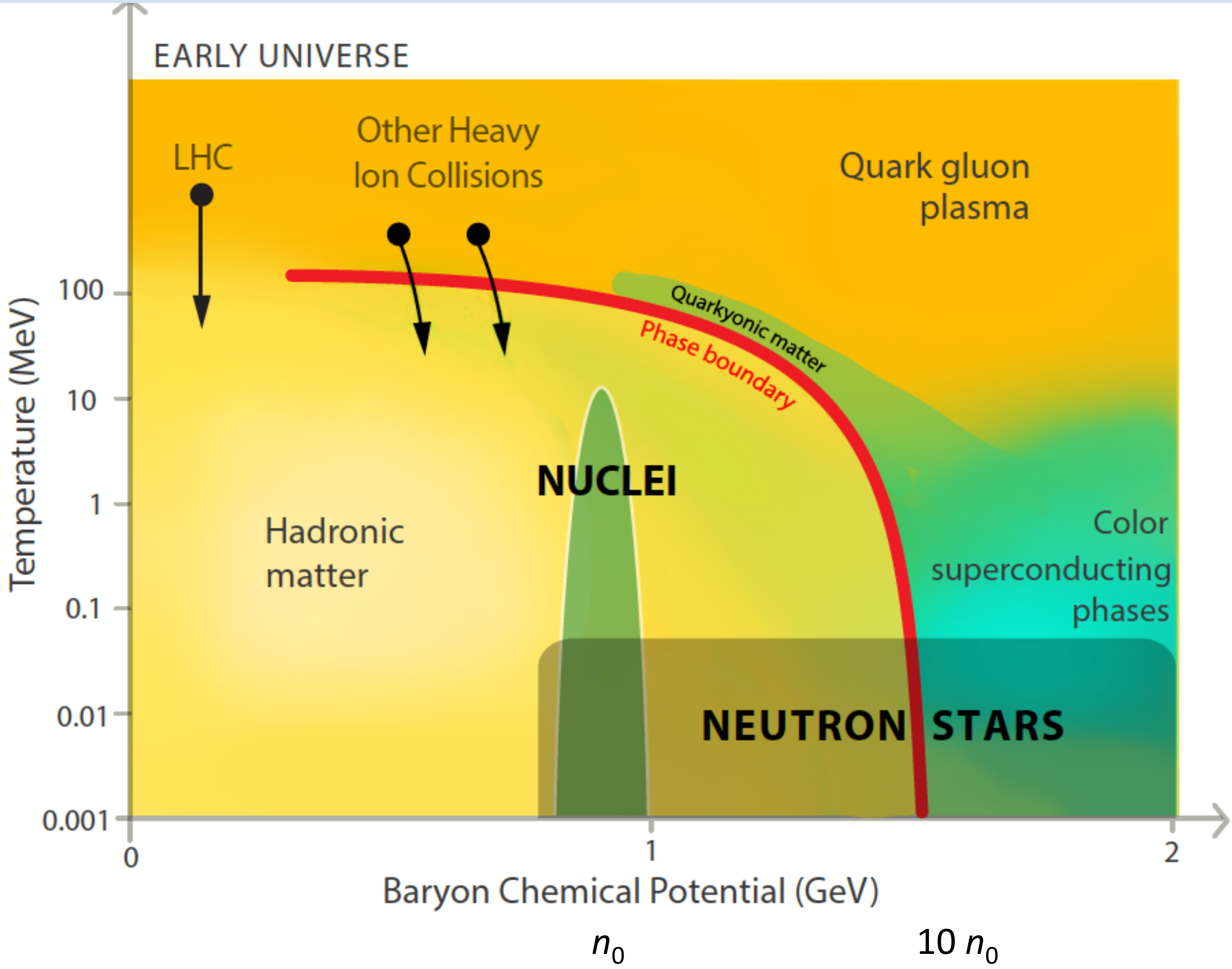

Skyrmes-original
Skyrmes-refit
K_{sym} (MeV)
L (MeV)
100
50
0
−50
−100
−150
−200
−250
−300
−350
0
20
40
60
80
100
120



Skyrmes-original
Skyrmes-refit
K_{sym} (MeV)
L (MeV)
100
50
0
−50
−100
−150
−200
−250
−300
−350
0
20
40
60
80
100
120


Skyrmes-original
Skyrmes-refit
K_{sym} (MeV)
L (MeV)
100
50
0
−50
−100
−150
−200
−250
−300
−350
0
20
40
60
80
100
120

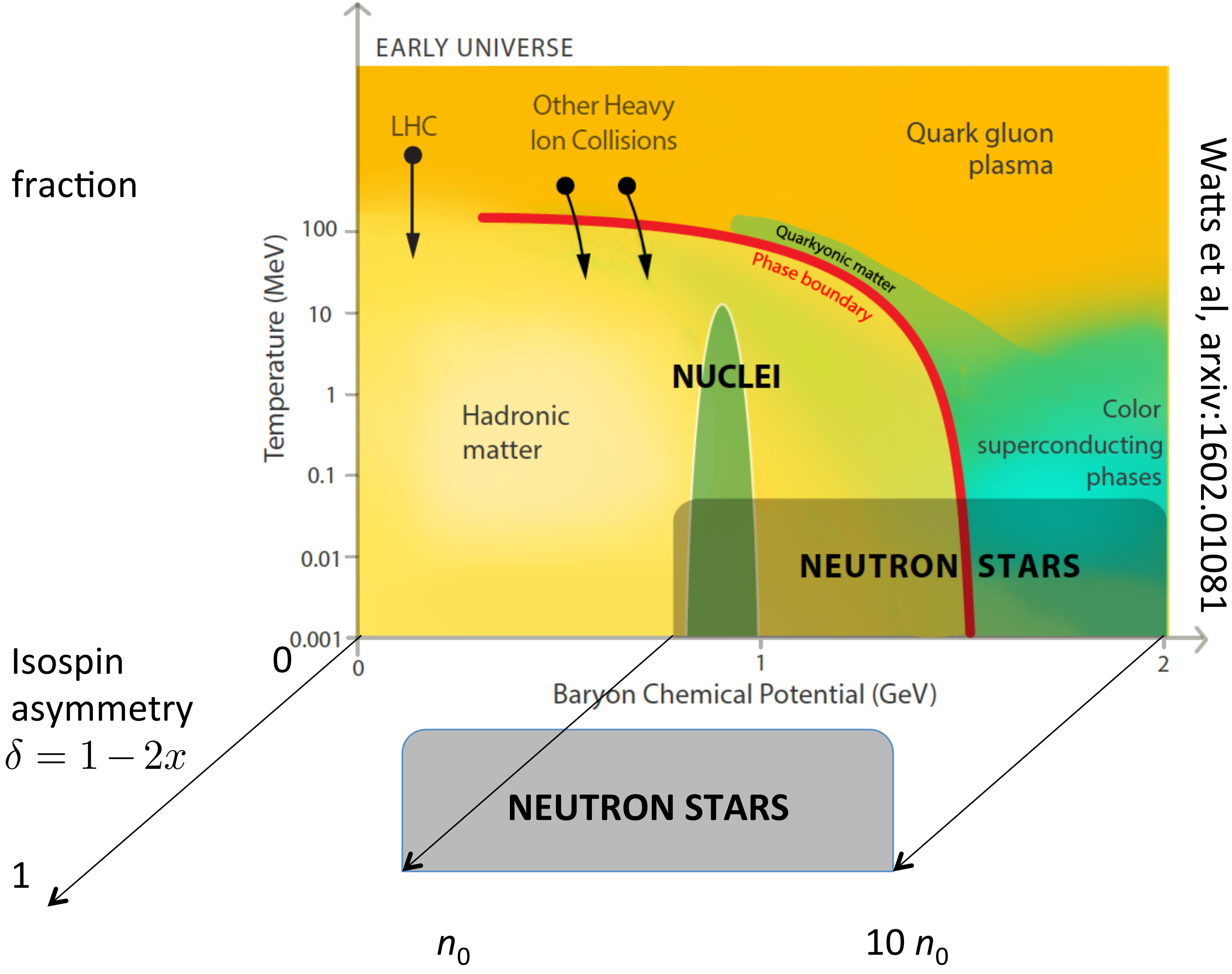
Symmetry energy



Watts et al, arxiv:1602.01081

Symmetry energy

x = proton fraction



Isospin asymmetry $\delta = 1 - 2x$

0

1

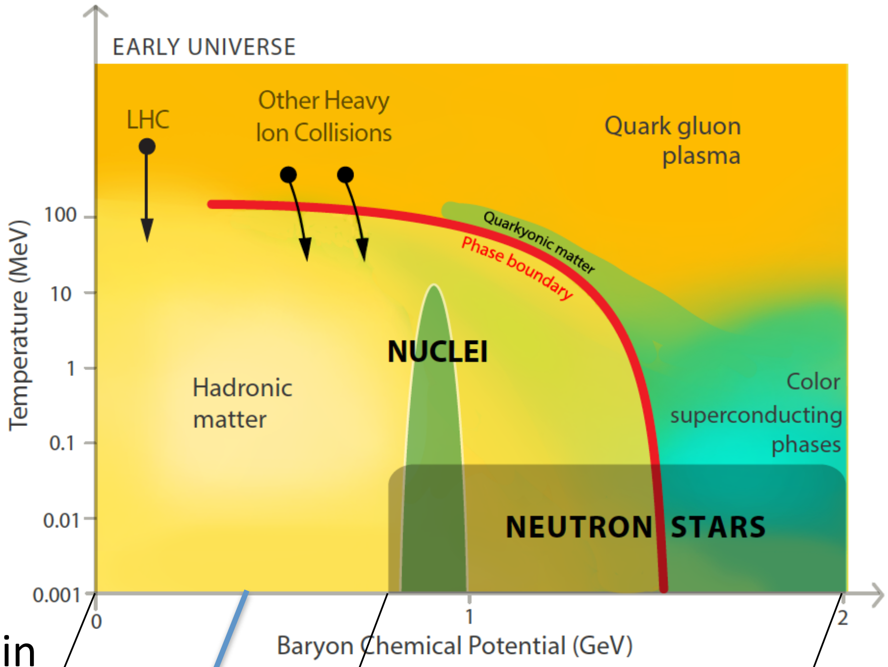
NEUTRON STARS

n_0

10 n_0

Watts et al, arxiv:1602.01081

Symmetry energy



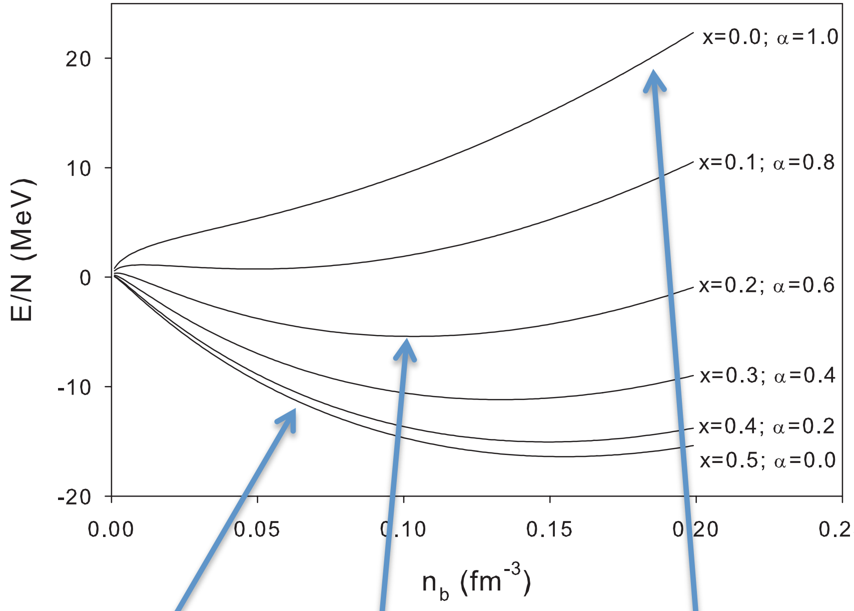
Isospin asymmetry

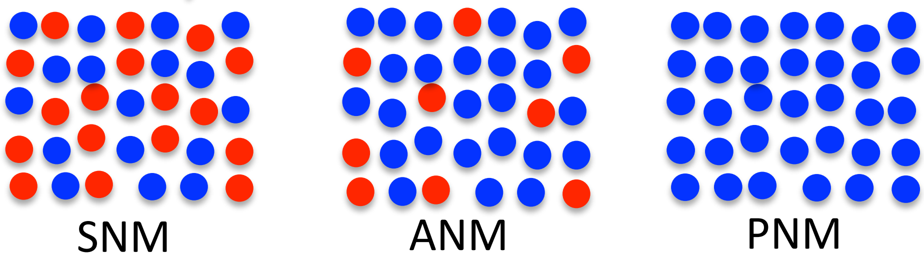
1

Symmetry Energy S(n)

NEUTRON STARS

n_0 $10\,n_0$

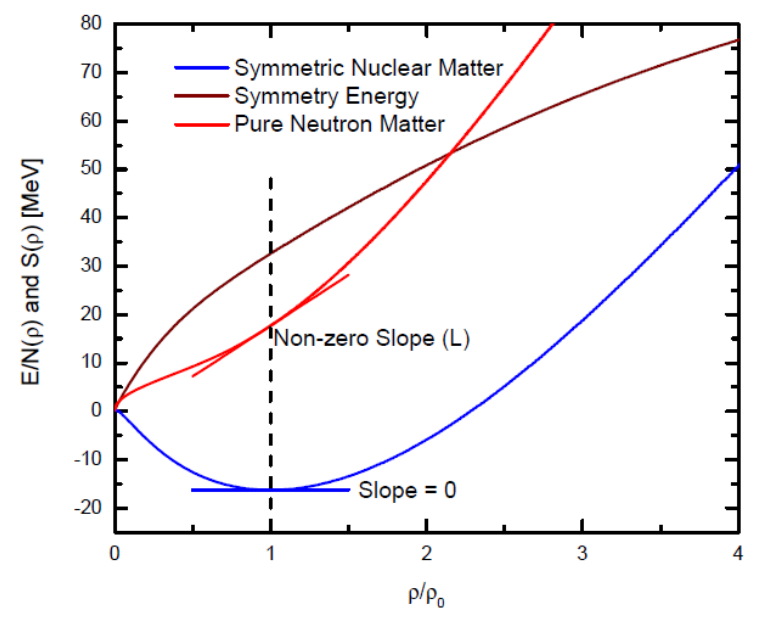


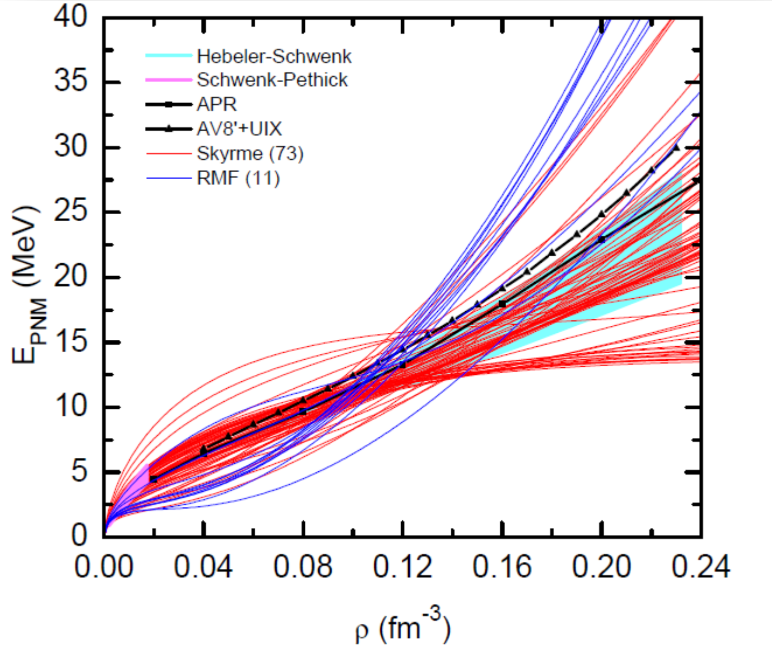


$$E(n,\delta) = E_0(n) + S(n)\delta^2 + \ldots$$

$$\delta = 1 - 2x$$

Symmetry energy





Farrukh Fattoyev, 2013

$$E(n,\delta) = E_0(n) + S(n)\delta^2 + \ldots \qquad \delta = 1-2x$$

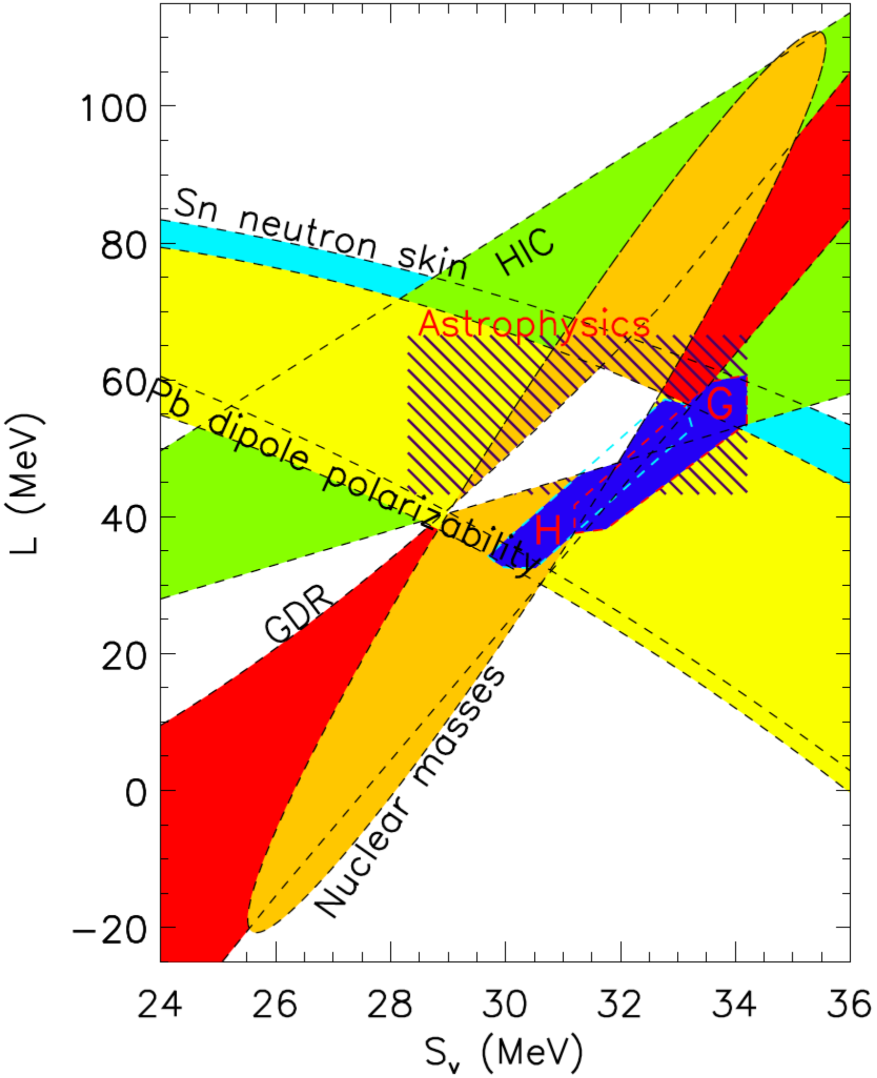
$$S(n) = J + L\chi + \frac{K_{\rm sym}}{2}\chi^2 + \ldots \qquad \chi = \frac{n-n_0}{3n_0}$$

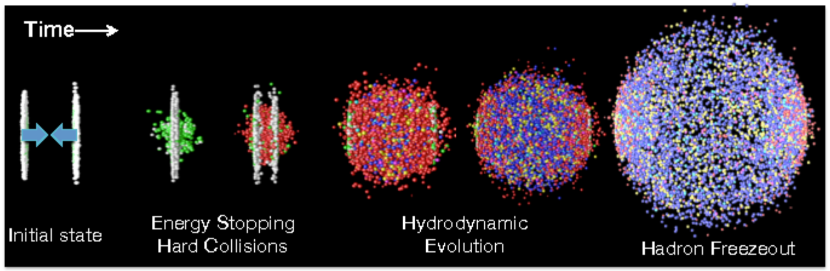
Combined with Coulomb and beta-equilibrium conditions, obtain NS core EoS.

$$P_{\rm NS}(n_0) \approx \frac{n_0}{3}L + 0.048 n_0 \left(\frac{J}{30}\right)^3 \left(J - \frac{4}{3}L\right)$$

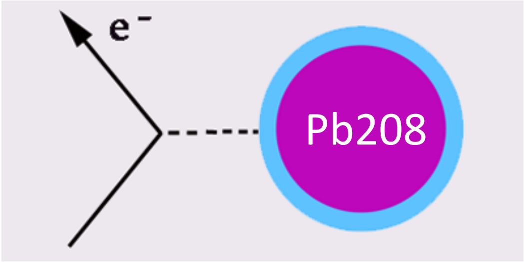
Symmetry energy constraints

Lattimer, Lim ApJ771 (2013)
Lattimer, Steiner EPJA50 (2013)

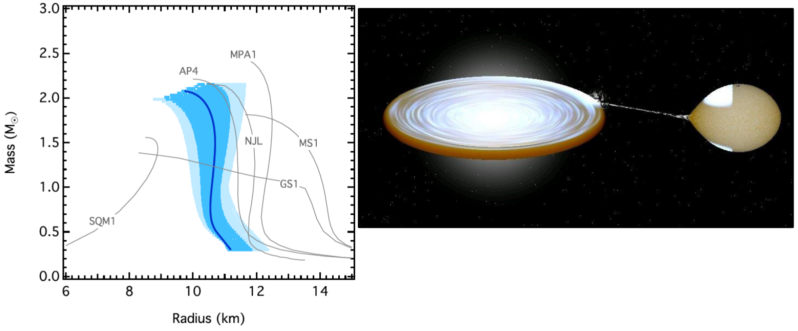




T.K.Nayak, axiv:1201.4264

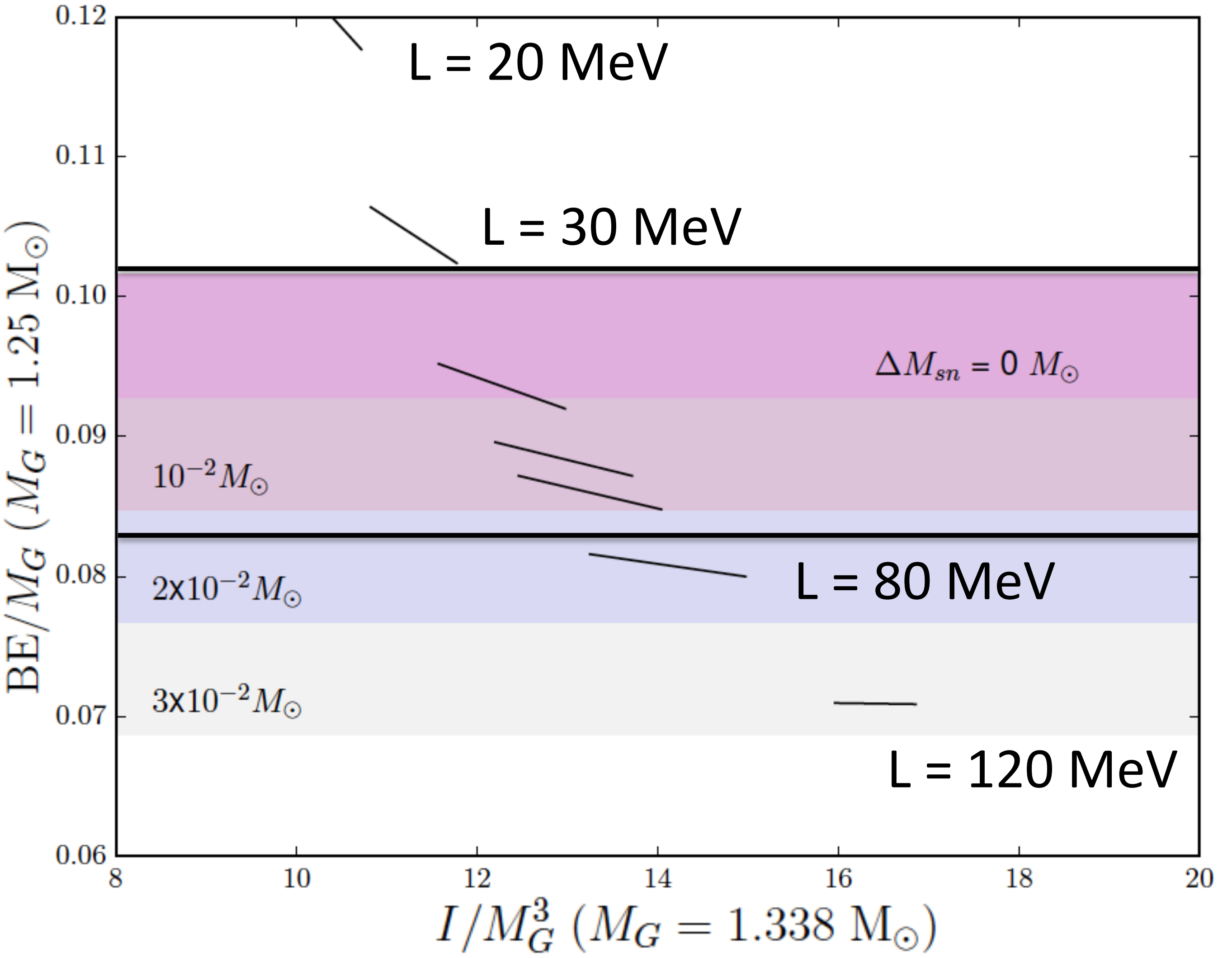


Abrahamyan+, PRL 108, 112592 (2012)



Ozel +, ApJ 820, 2016

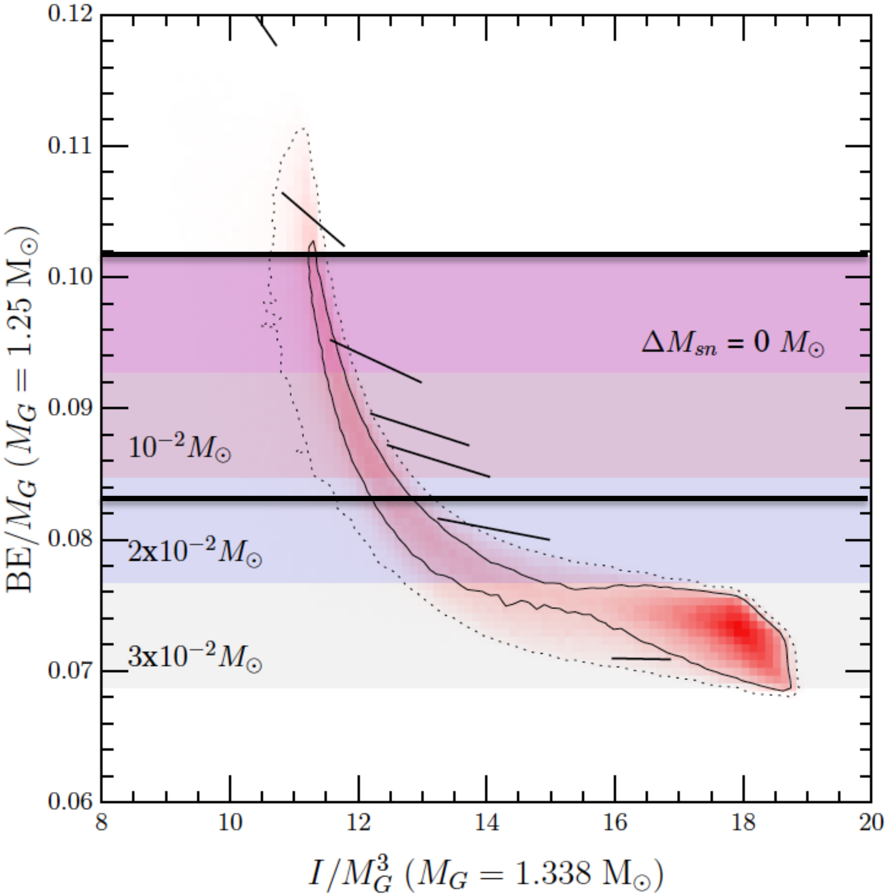
Results: J0737-3039B



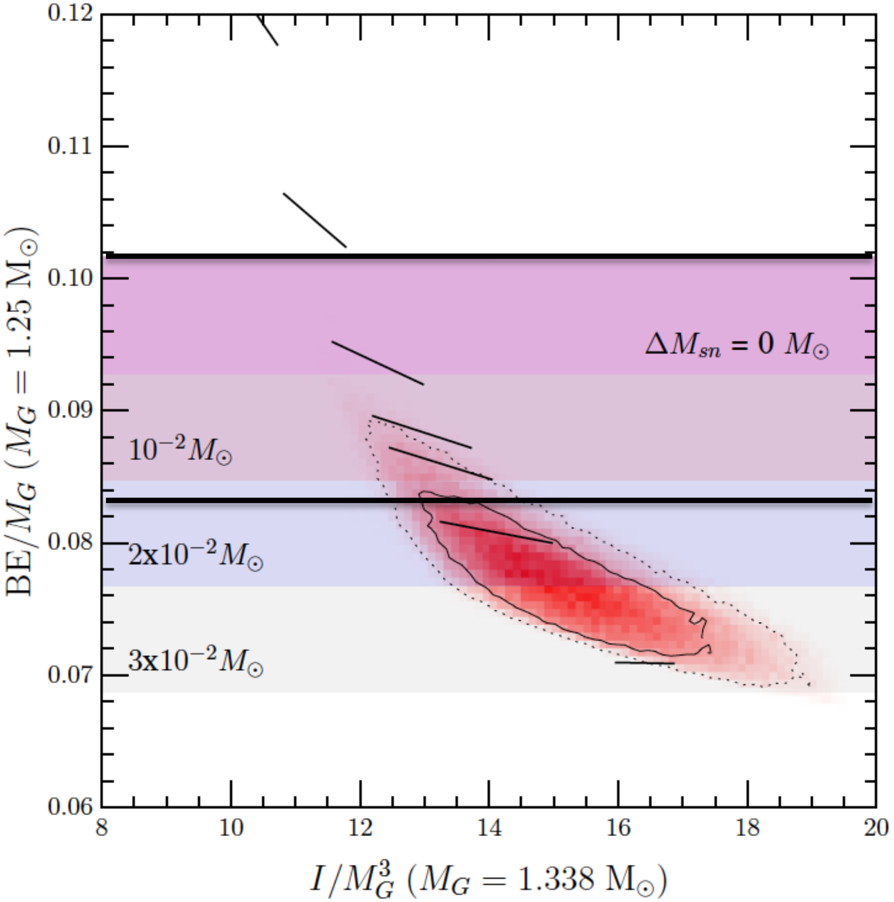
Limits from
progenitor/
SN modeling

Results: J0737-3039B

Strong phase transitions (model C)

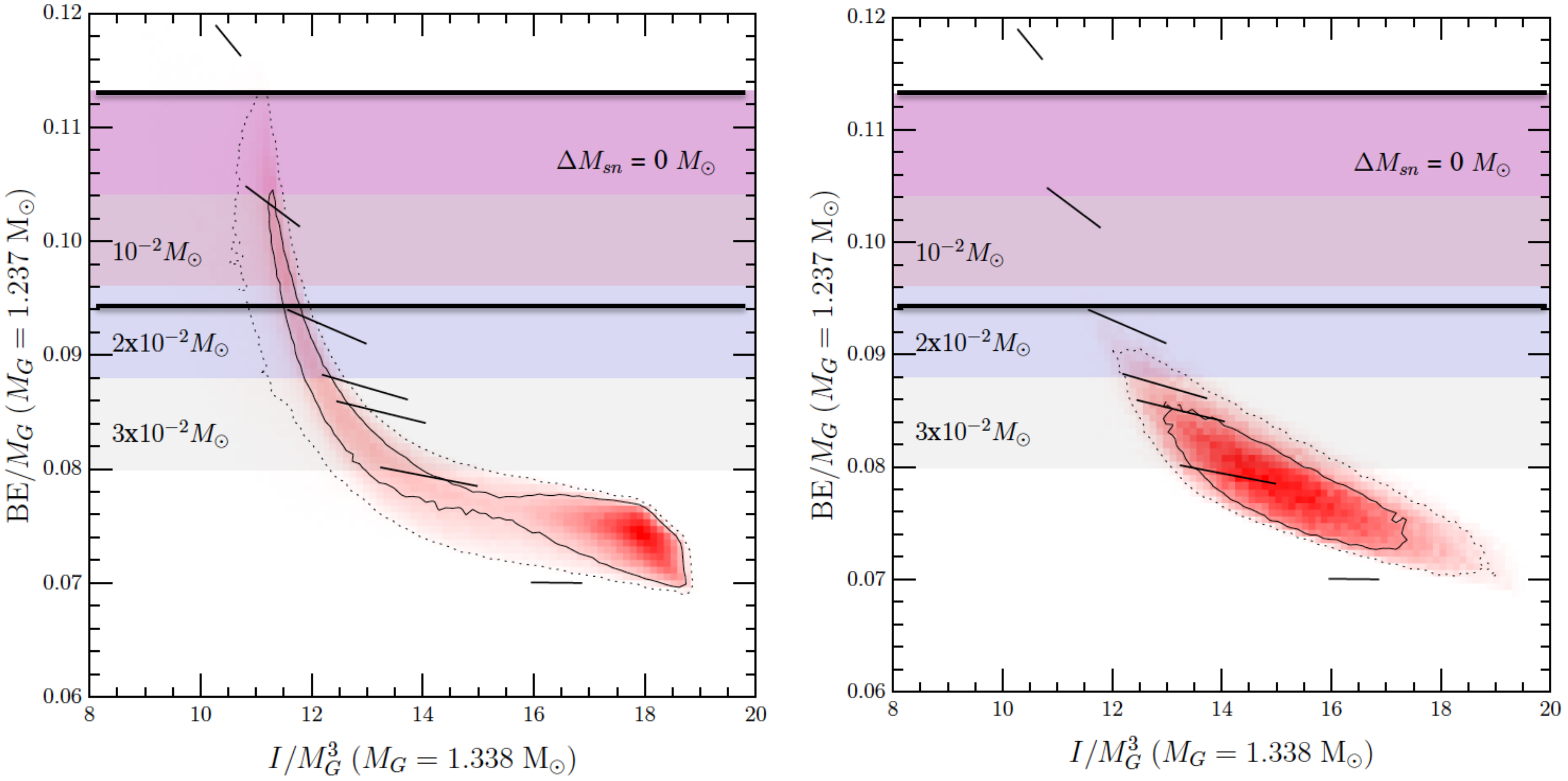


Piecewise polytrope (model A)



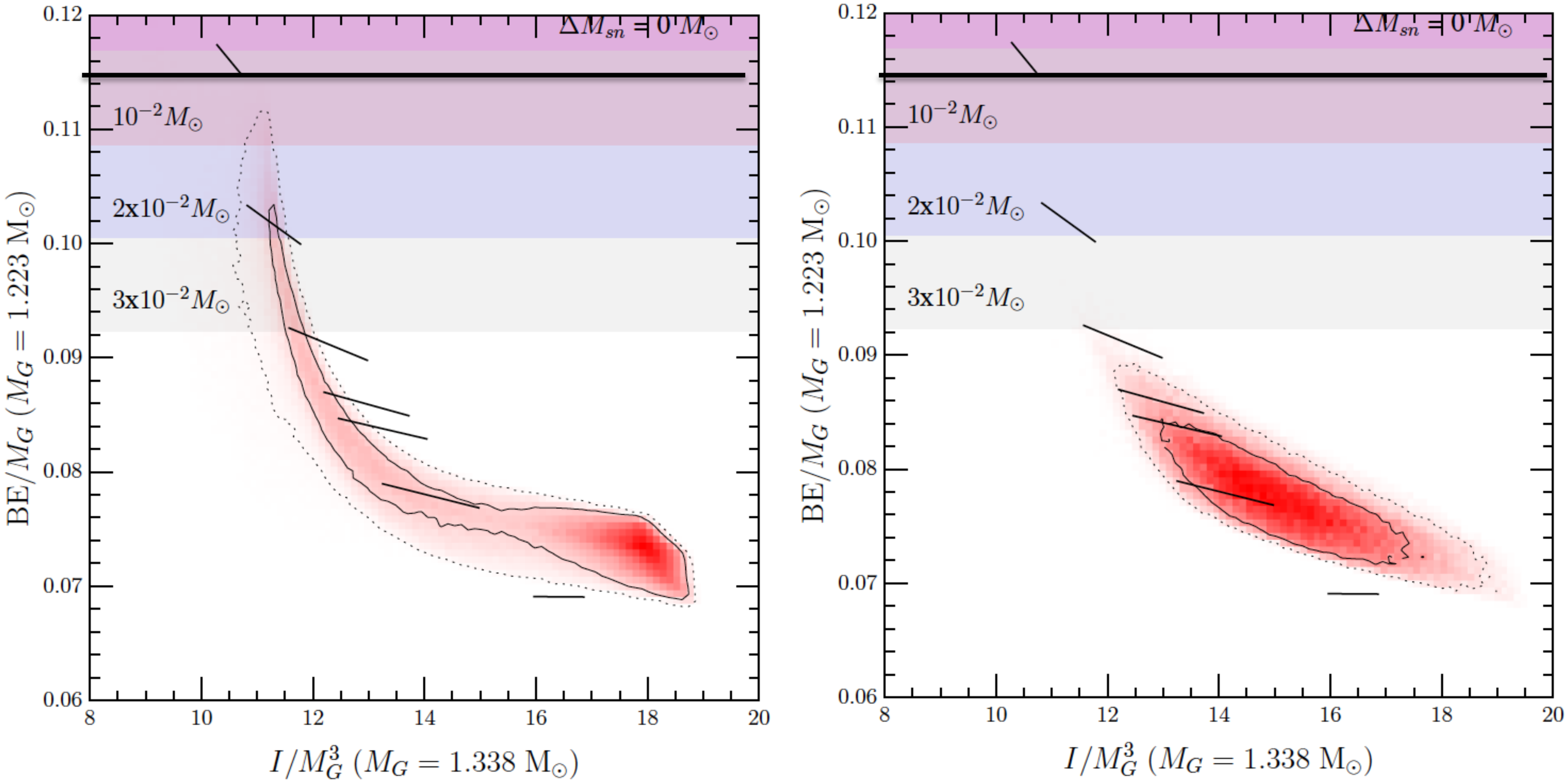
Requires soft EoS/strong phase transitions *or* greater mass loss

Results: J1756-2251 upper mass limit



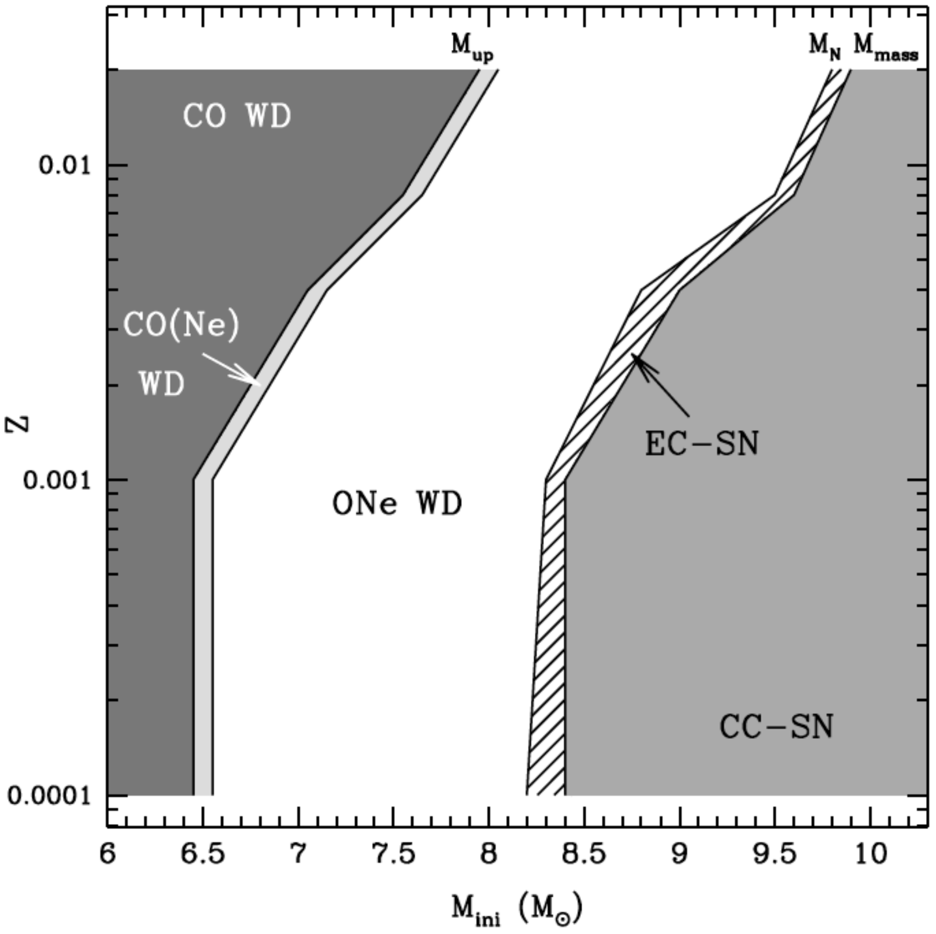
Requires soft EoS/strong phase transitions

Results: J1756-2251 lower mass limit



Requires soft EoS/strong phase transitions, greater mass loss than simulations provide

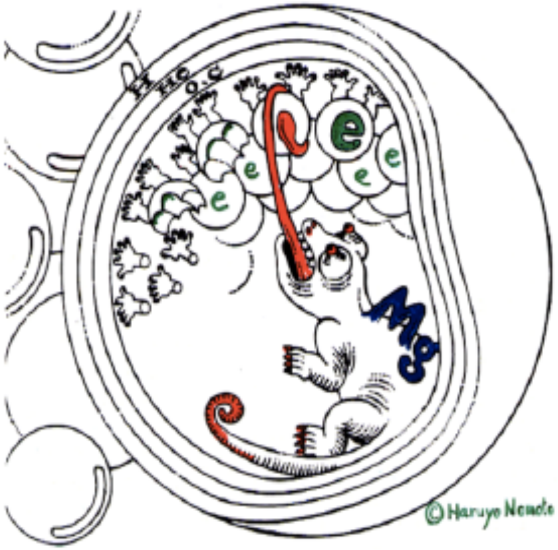
Systems that undergo ECSN

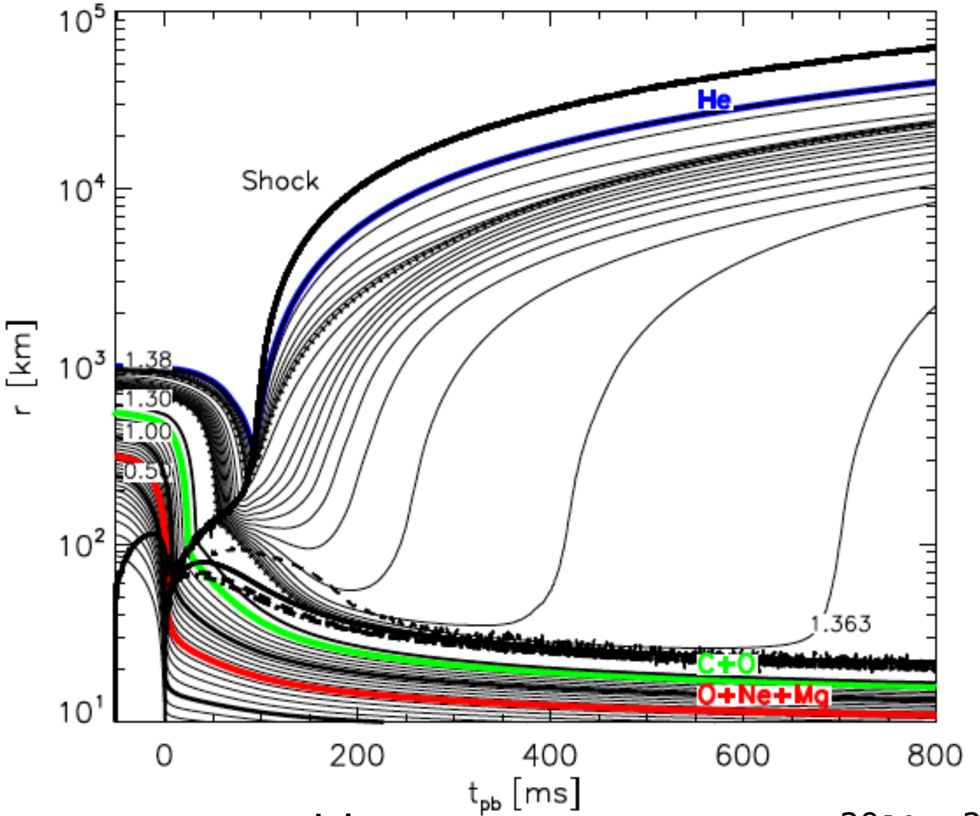


Doherty+, arxiv 1410.5431
Takahashi+, arxiv:1302.6402

Small fraction of single super-AGB stars (estimated <5% of all CCSN)
Rate of ECSN could go up when taking into account binary evolution

One possible channel leads to core collapse at the ONeMg stage. *This happens at a precise core mass* and results in an Electron-Capture Supernovae(ECSN)



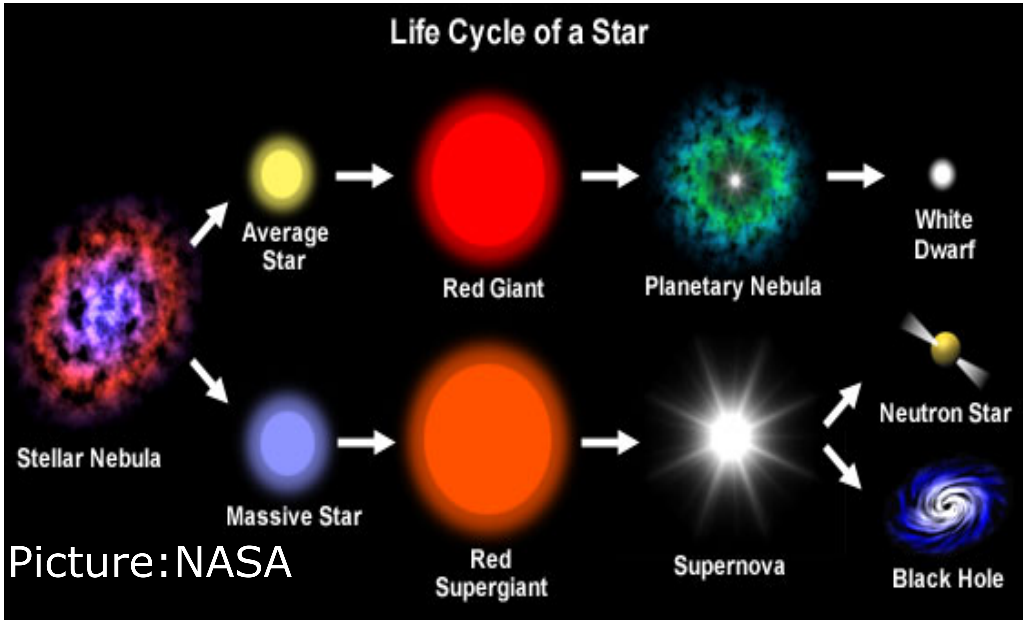


≈1.37-1.38 $M_\odot$ ONeMg Core becomes unstable to e-capture onto ^{20}Ne,^{24}Mg (Miyaji+, PASJ,32,303;1980, Nomoto, ApJ, 322,206; 1987) , collapses

Supernova modeling predicts mass loss from collapsing core **~ 10^{-2} $M_\odot$** (Kitaura+, arxiv:astro-ph/0512065, Janka+, arxiv:0712.4237) and low kicks

Prediction: baryon mass *M_B* of resulting neutron star is≈1.35-1.38 $M_\odot$

The stellar evolutionary channels involving the lowest mass core-collapse supernova progenitors are not well accounted for



$M \lesssim 6\ M_{\odot}$

$11\ M_{\odot} \lesssim M$

Williams, Bolte, Koester, ApJ 693, 2009
Timmes, Woosley, Weaver, ApJ457, 1996

Why is this important?

Population synthesis models, progenitors of SNe, rates of production of low mass neutron stars and neutron star binaries, GW searches

Constraining the evolutionary history of specific systems and SNe (e.g. double pulsar, Crab)