# Implications from GW170817 and I-Love-Q relations for relativistic hybrid stars

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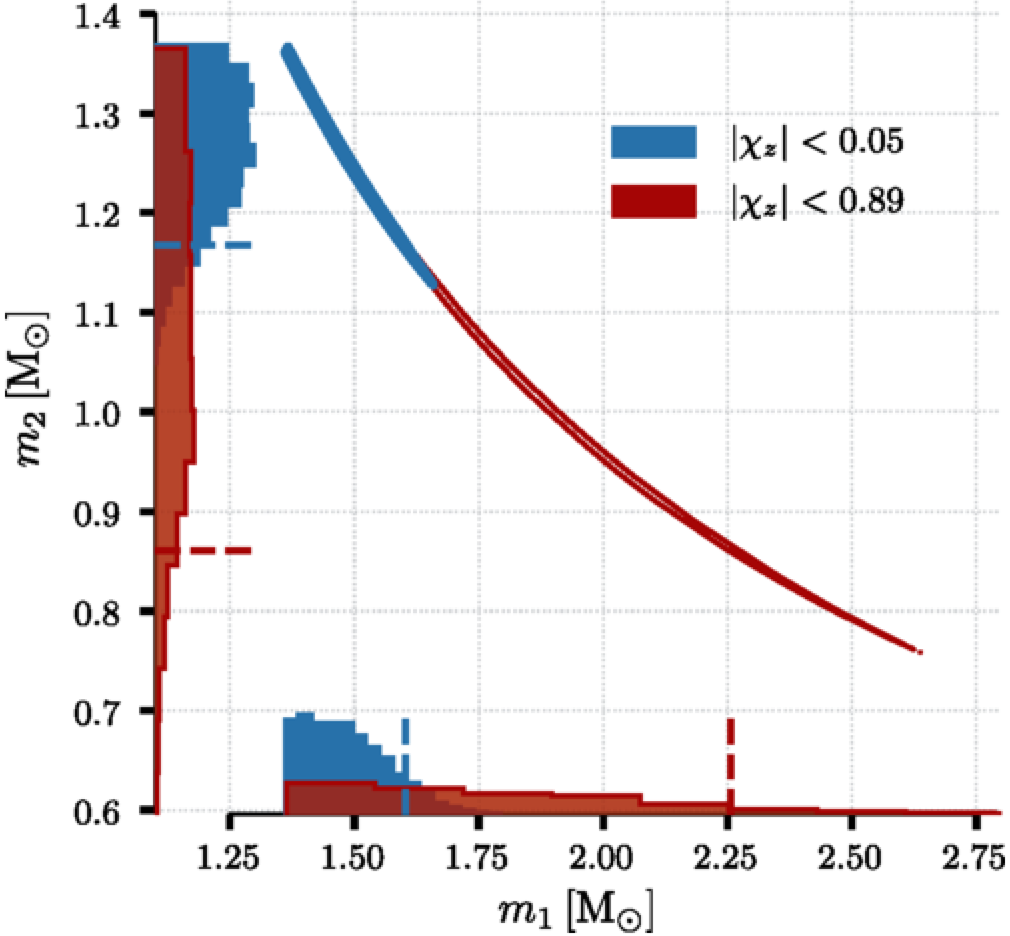
# GW170817 nature of the progenitor: binary neutron star?

- Mass – mass plane

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

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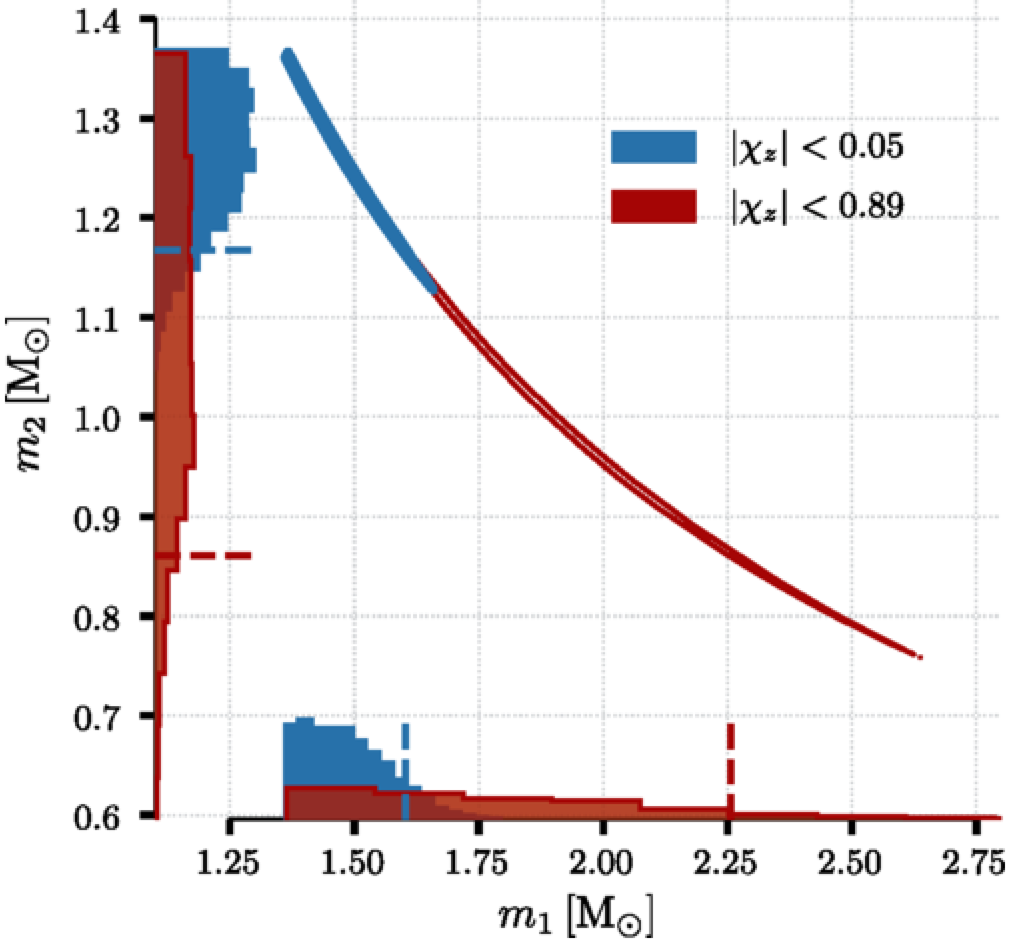


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GW data do not rule out black hole – neutron star or other exotic compact objects

# LIGO/Virgo GW detection of GW170817

- Waveform model
  - Point mass (black hole binary) – Post-Newtonian (PN) that include spin-spin effects
  - Finite size effects post-1PN $[O(\frac{v}{c})^2]$ parametrized through the tidal deformabilities $\Lambda_i = \left(\frac{2}{3}\right) k_{2,i} \left[\left(\frac{c^2}{G}\right)\left(\frac{R_i}{m_i}\right)\right]^5$, $k_{2,i}$= tidal Love numbers

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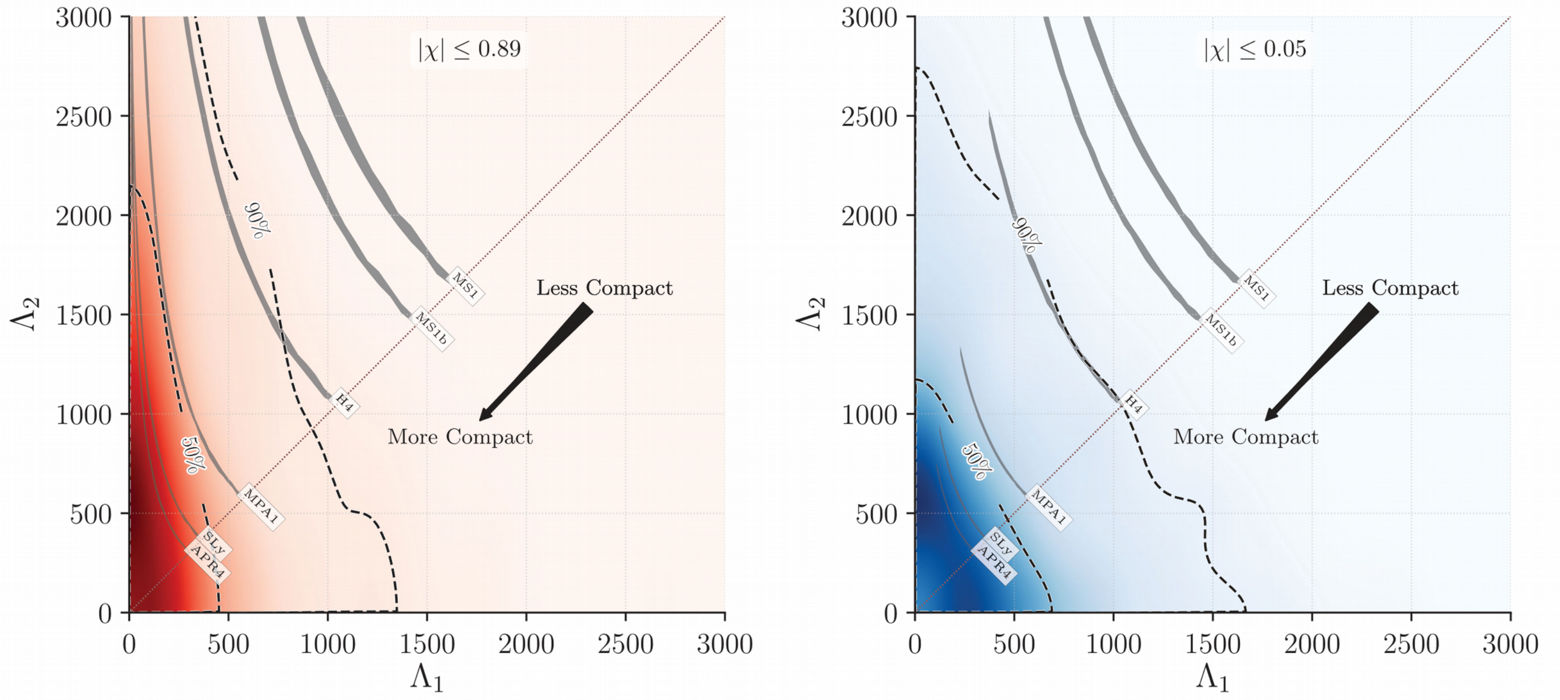
  - For an external gravitational potential (tidal field) $\mathcal{E}_{ij} = \frac{\partial^2 \Phi_{ext}}{\partial x^i \partial x^j}$, there is a quadrupole moment indunced on a star $Q_{ij} = \int d^3x\, \delta\rho(x) \left(x_i x_j - \frac{1}{3} r^2 \delta_{ij}\right)$ with $Q_{ij} = -\frac{2R^5}{3G} k_2 \mathcal{E}_{ij}$
  - For neutron stars: $k_2 \sim 0.05 - 0.15, \Lambda \sim 150 - 2000$;
    For black holes: $k_2 = 0, \Lambda = 0$

# GW170817: implications for nuclear physics

- Tidal deformability: assuming a single EOS describes both neutron stars

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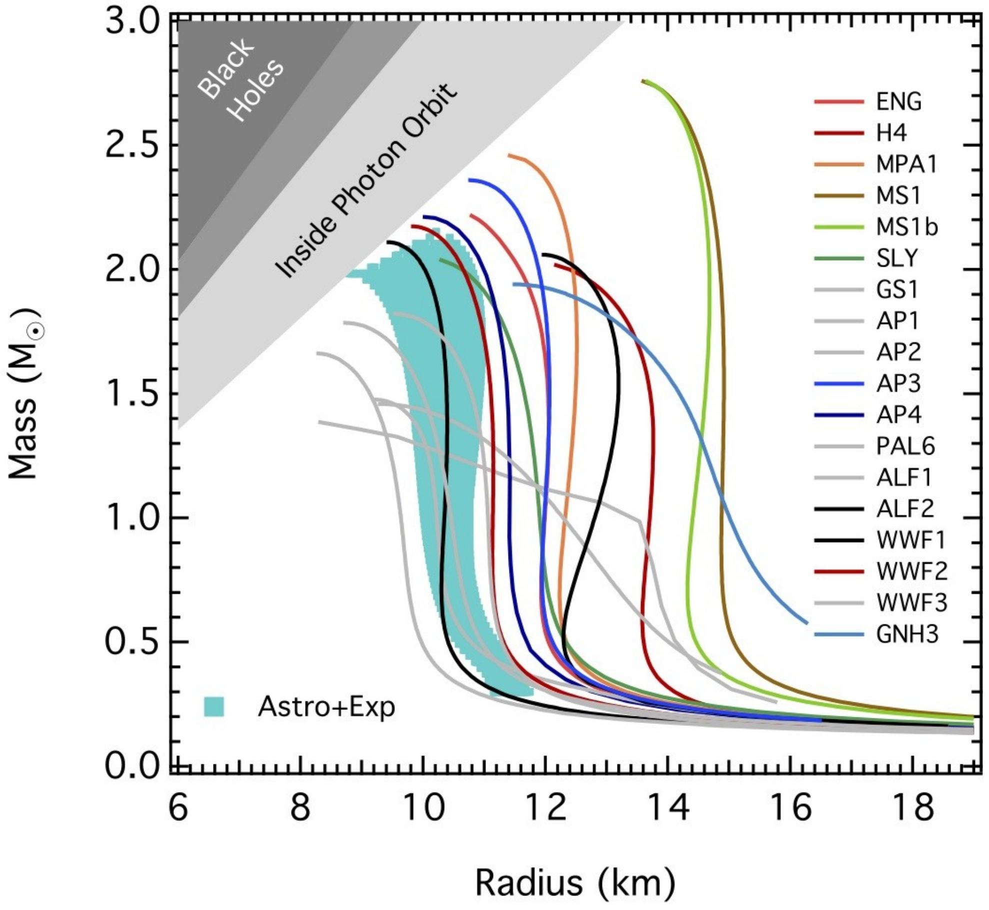


- Data favor more compact stars

# Hybrid compact stars

- For sufficiently high densities quark deconfinement can take place
- In 1968 Ulrich Gerlach considered equations of state which allow a first-order transition between the hadronic phase and quark matter phase.
- For a sufficiently large “jump” in energy density over which the pressure remains constant at the phase transition a third family of compact objects can emerge
- Stars with a quark core surrounded by a hadronic shell with a first-order phase transition in between are called hybrid compact stars

# Hybrid compact stars

There exist two prescriptions for matching the low-density nucleonic EoS to the quark matter EoS; which one is realized in nature depends on the surface tension between nuclear and quark matter (e.g. Glendenning 1997)

If the tension between these phases is low, a mixed phase of quark and nucleonic matter is formed in-between purely nuclear and quark matter phases.

If the tension is high, a sharp transition boundary is energetically favorable → third family of compact object (usually referred to as the “third family”)

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# Consider two sets of EOSs

**Low-density regime**

Set I: density functional theory with density-dependent couplings applied to hadronic matter Colucci and Sedrakian 2013

Set II: either stiffest EOS of Hebeler, Lattimer, Pethick, and Schwenk (2013) or the density-dependent relativistic meanfield EoS DD2-p30 Alvarez-Castillo, Ayriyan, Benic, Blaschke, Grigorian, and Typel (2016)

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**High-density regime**

Set I:  Constant sound speed parametrization Alford, Han, and Prakash 2013

Set II: Piecewise polytropic representation (Read et al. 2009, Hebeler et al. 2013 etc.)

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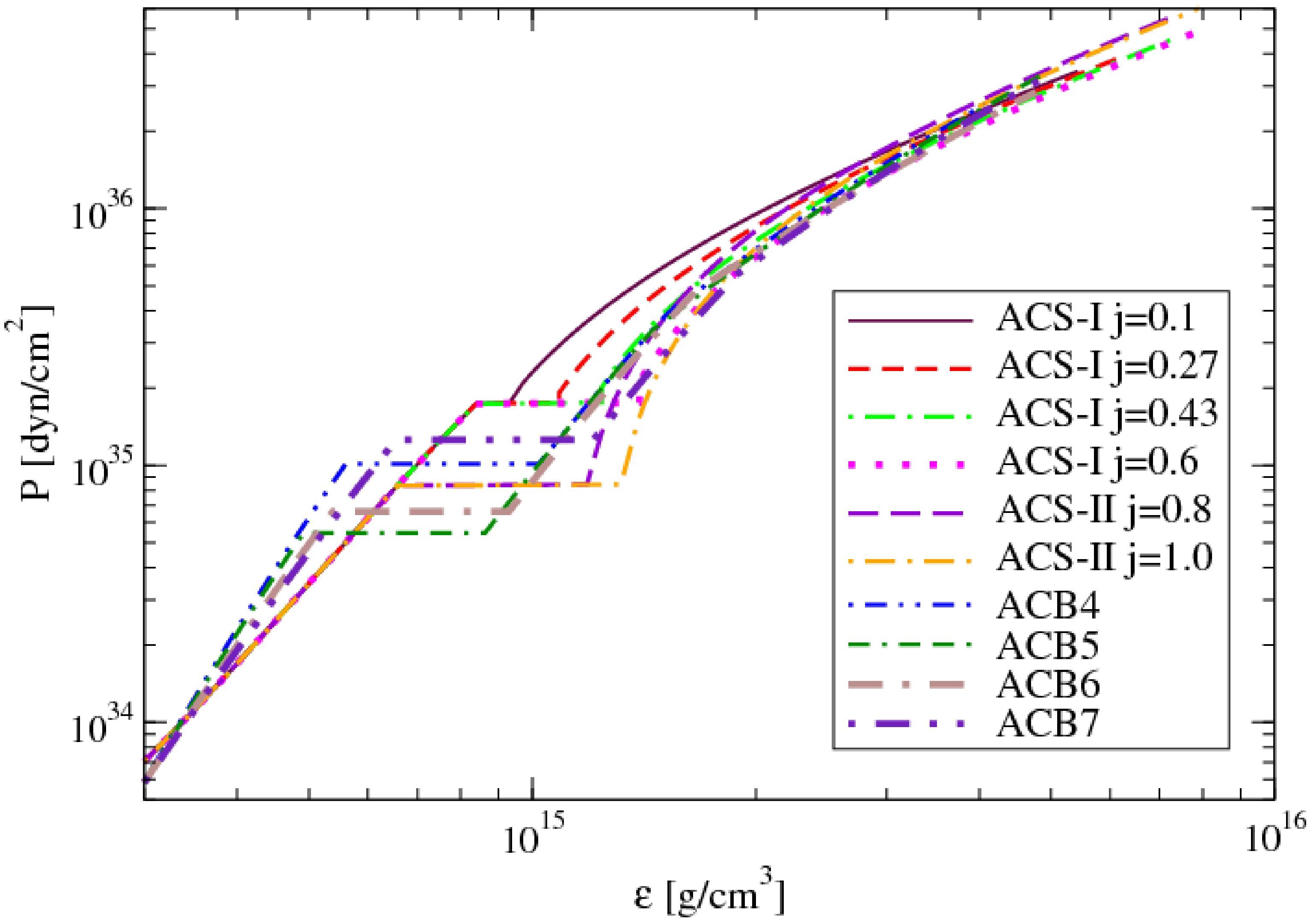
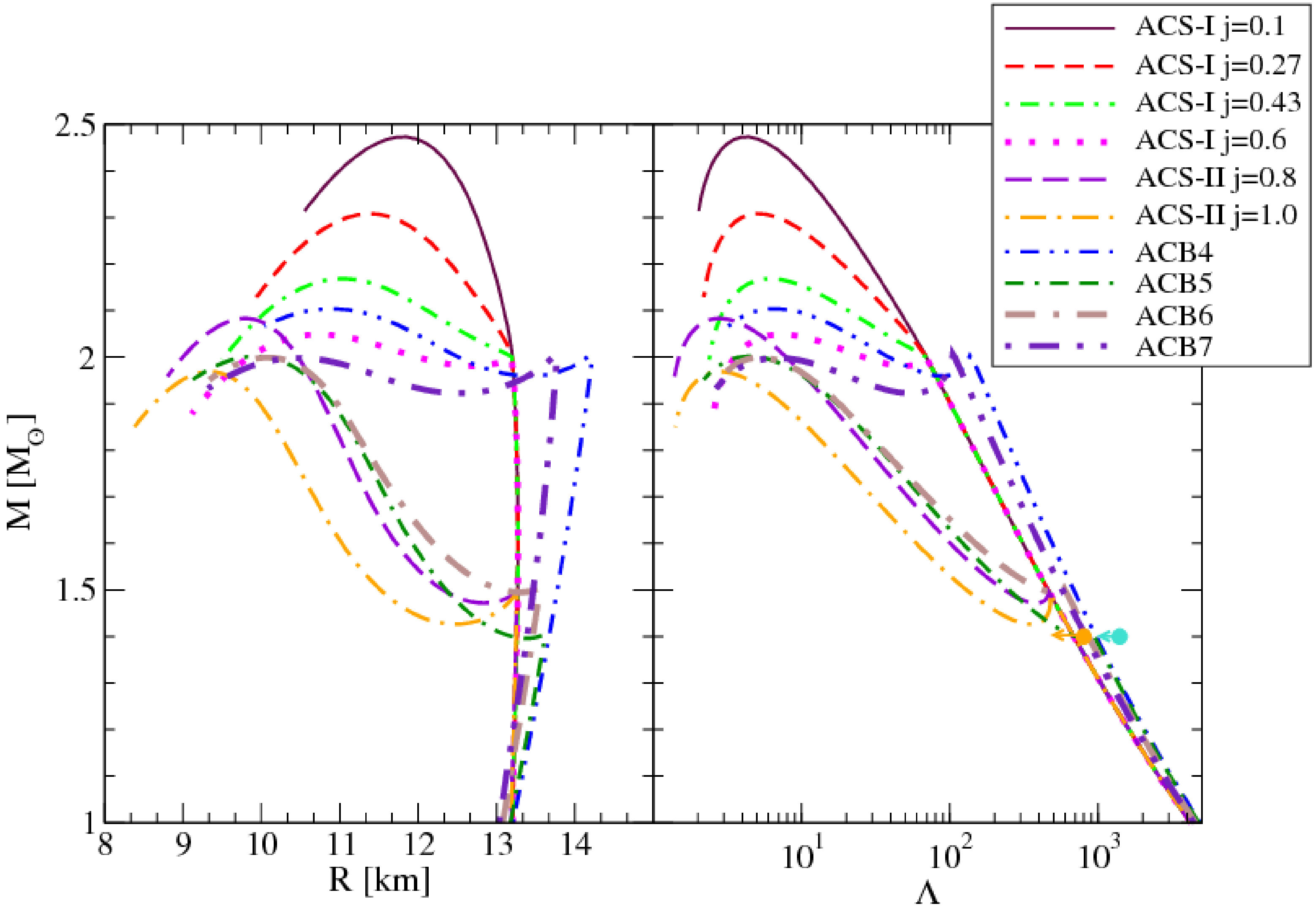
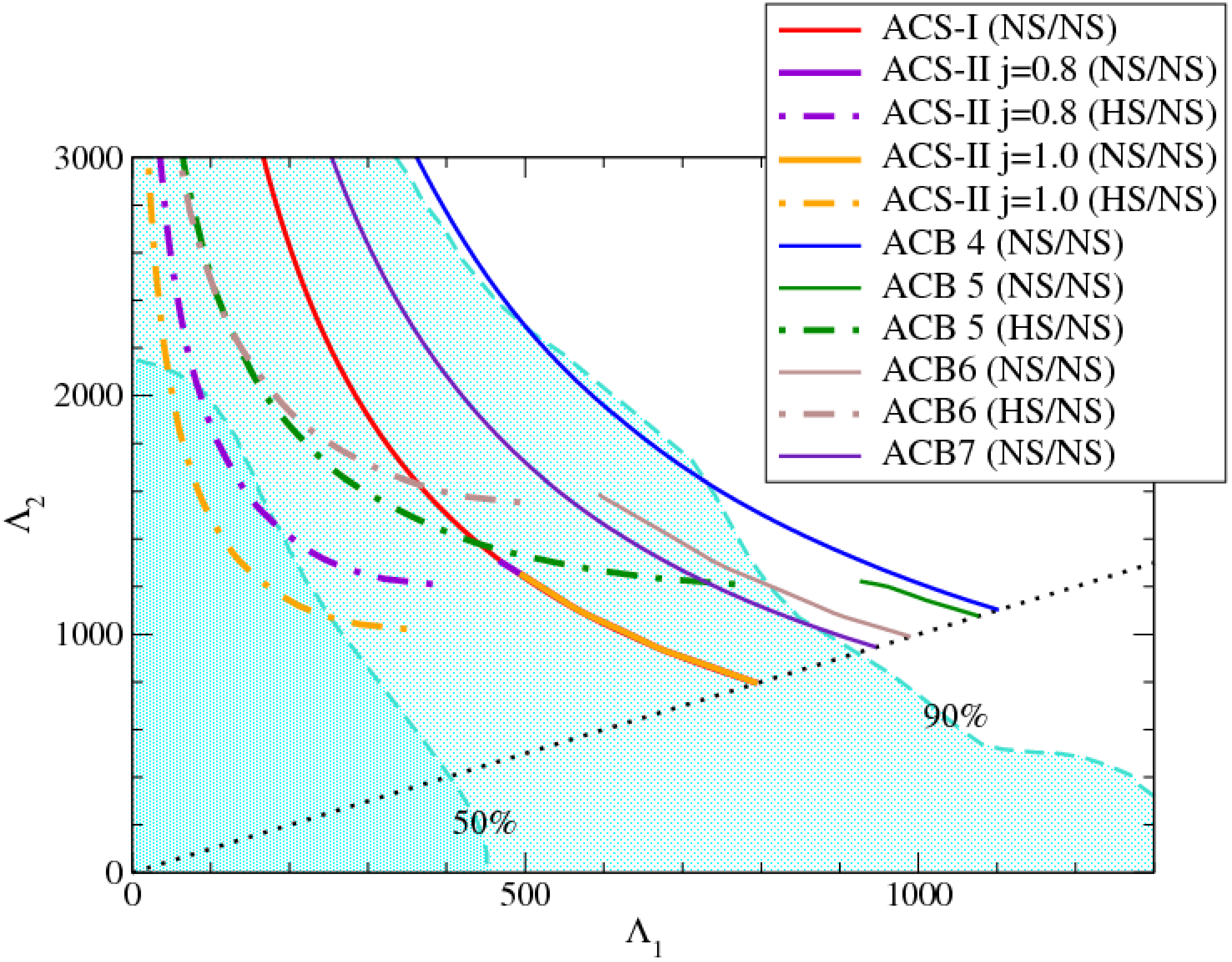
# Pressure vs density



# Mass – Radius & Mass – Λ

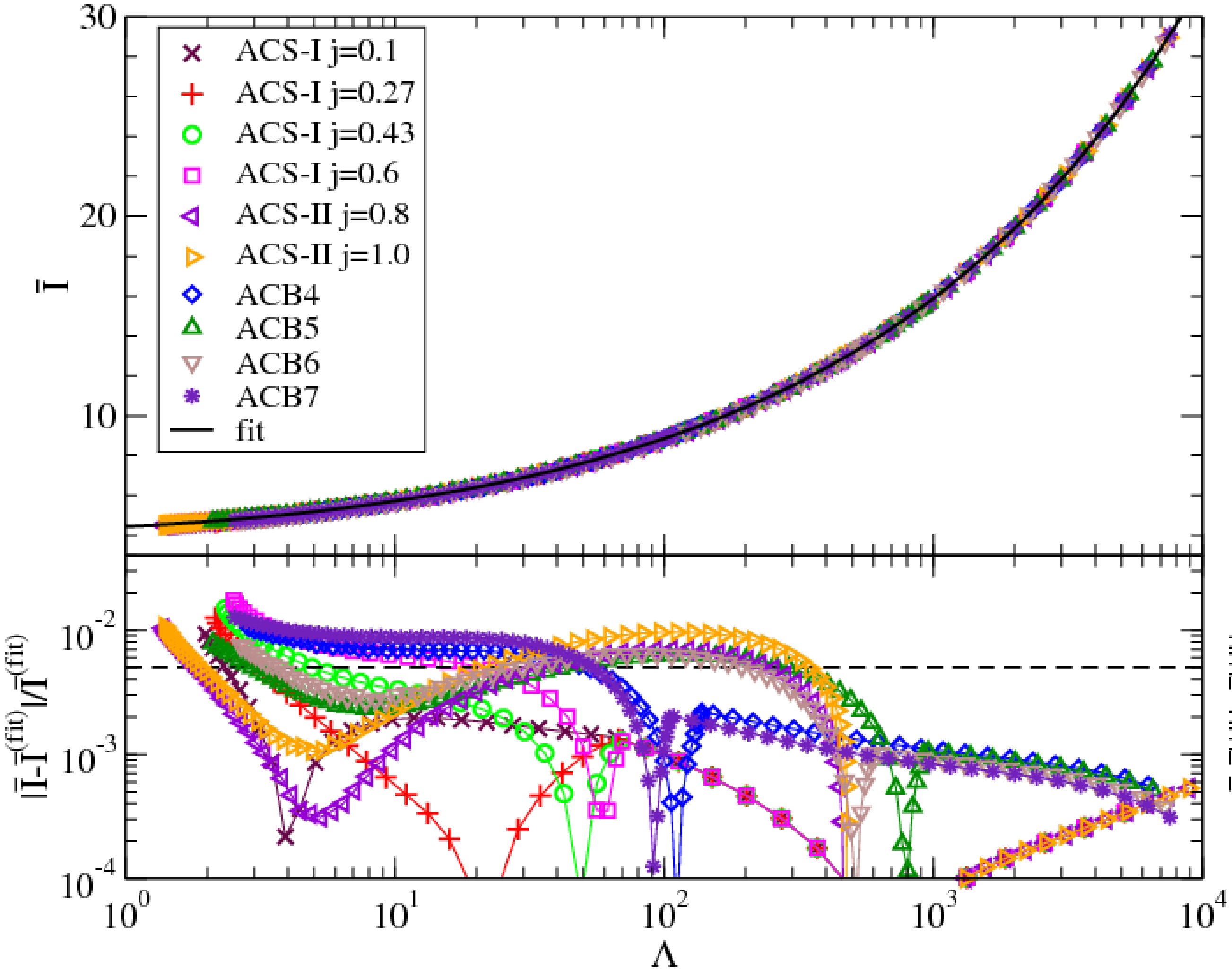


# Λ1 vs Λ2

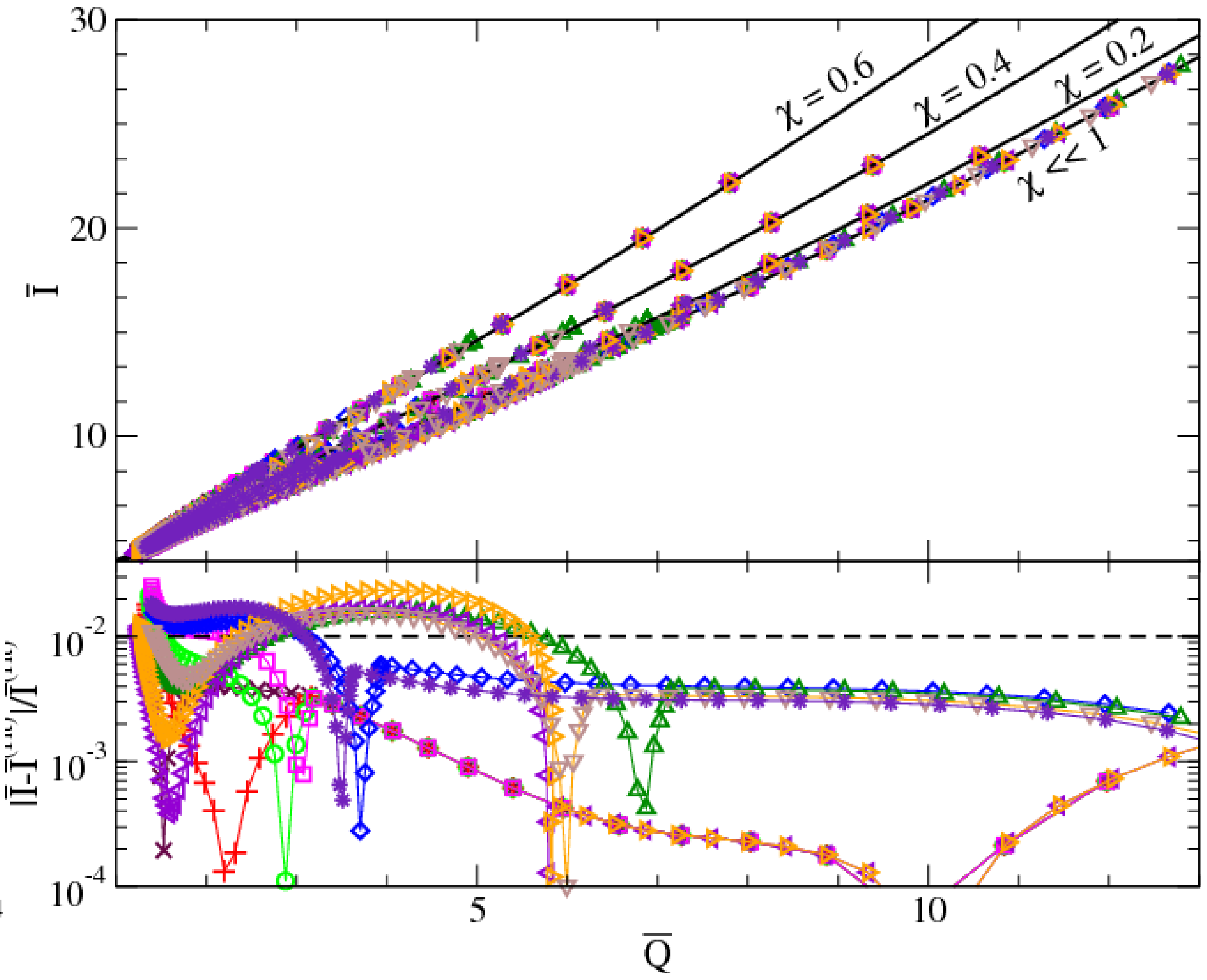


ACS-I (NS/NS)
ACS-II j=0.8 (NS/NS)
ACS-II j=0.8 (HS/NS)
ACS-II j=1.0 (NS/NS)
ACS-II j=1.0 (HS/NS)
ACB 4 (NS/NS)
ACB 5 (NS/NS)
ACB 5 (HS/NS)
ACB6 (NS/NS)
ACB6 (HS/NS)
ACB7 (NS/NS)
3000
2000
1000
0
500
1000
90%
50%
Λ2
Λ1

# I-Love and I-Q



ACS-I j=0.1
ACS-I j=0.27
ACS-I j=0.43
ACS-I j=0.6
ACS-II j=0.8
ACS-II j=1.0
ACB4
ACB5
ACB6
ACB7
fit
$\bar{I}$
$|\bar{I}-\bar{I}^{(fit)}|/\bar{I}^{(fit)}$
$\Lambda$

$\chi=0.6$
$\chi=0.4$
$\chi=0.2$
$\chi<<1$
$\bar{I}$
$\bar{Q}$

# GW170817 and GRB 170817A implications for fundamental physics: nuclear physics

- What could the merger remnant and hence the sGRB engine be?
  - NSNS merges -> Remnant collapse to BH -> BH + disk -> jet
  - NSNS merges -> Remnant is a massive, ms mangetar + disk -> jet
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- Observations cannot cleanly distinguish these scenarios, but constraints on the nuclear equation of state (EOS) can be placed from either scenario
- NS matter cannot support an arbitrary amount of baryonic mass
- For any given EOS there is a maximum baryonic mass $M_{B,max}$ that can be supported
- If $m_{1B} + m_{2B} - m_{\infty} > M_{B,max}$, the remnant will ultimately collapse and form a BH
- If $m_{1B} + m_{2B} - m_{\infty} < M_{B,max}$, the remnant will not collapse