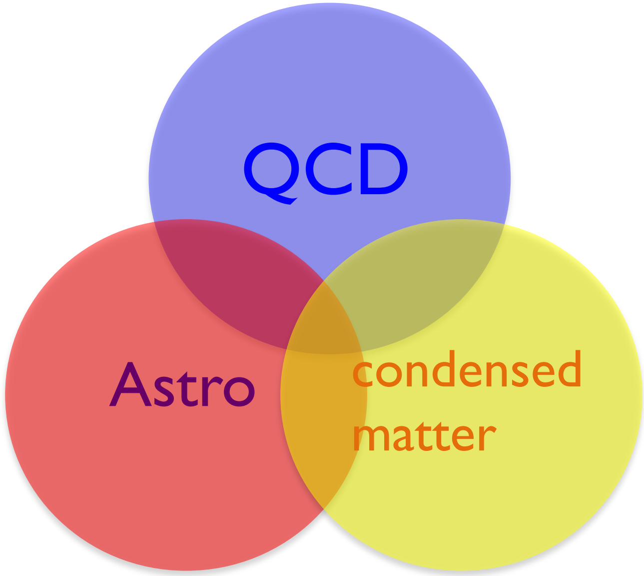
Phenomenological QCD equations of state for Neutron Stars

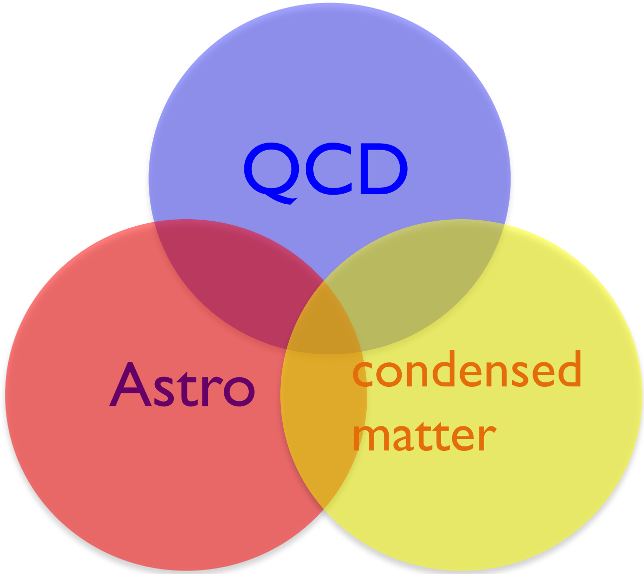


Toru Kojo (CCNU)

- Review) Baym-Hatsuda-TK-Powell-Song-Takatsuka
  Rept. Prog. Phys. 81 (2018) no.5, 056902
  (arXiv: 1707.04966 [astro-ph])

including EoS: Quark-Hadron-Crossover (QHC18)

Neutron Star equations of state for QCD perspectives



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Lattice + HIC + HIC + Astro

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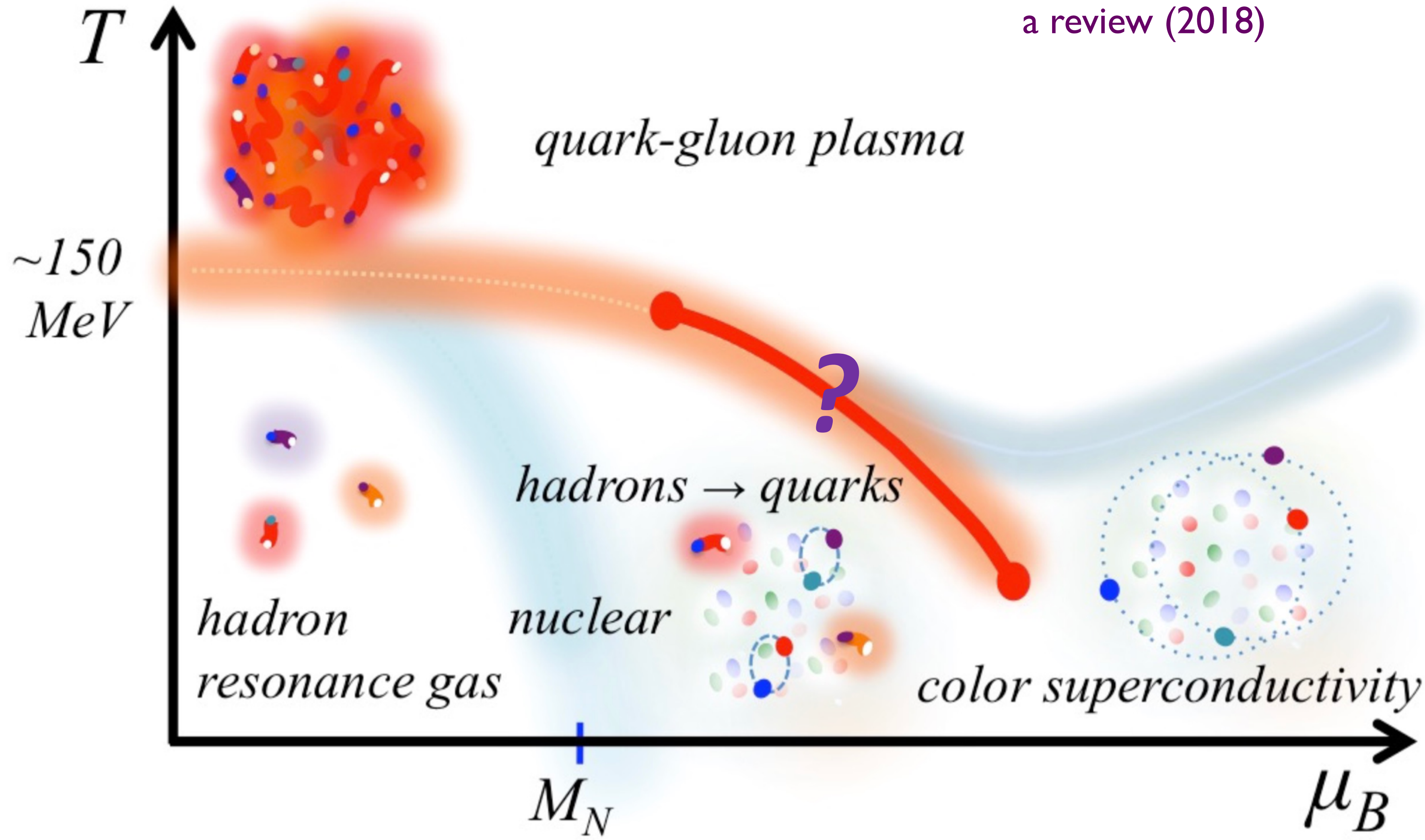

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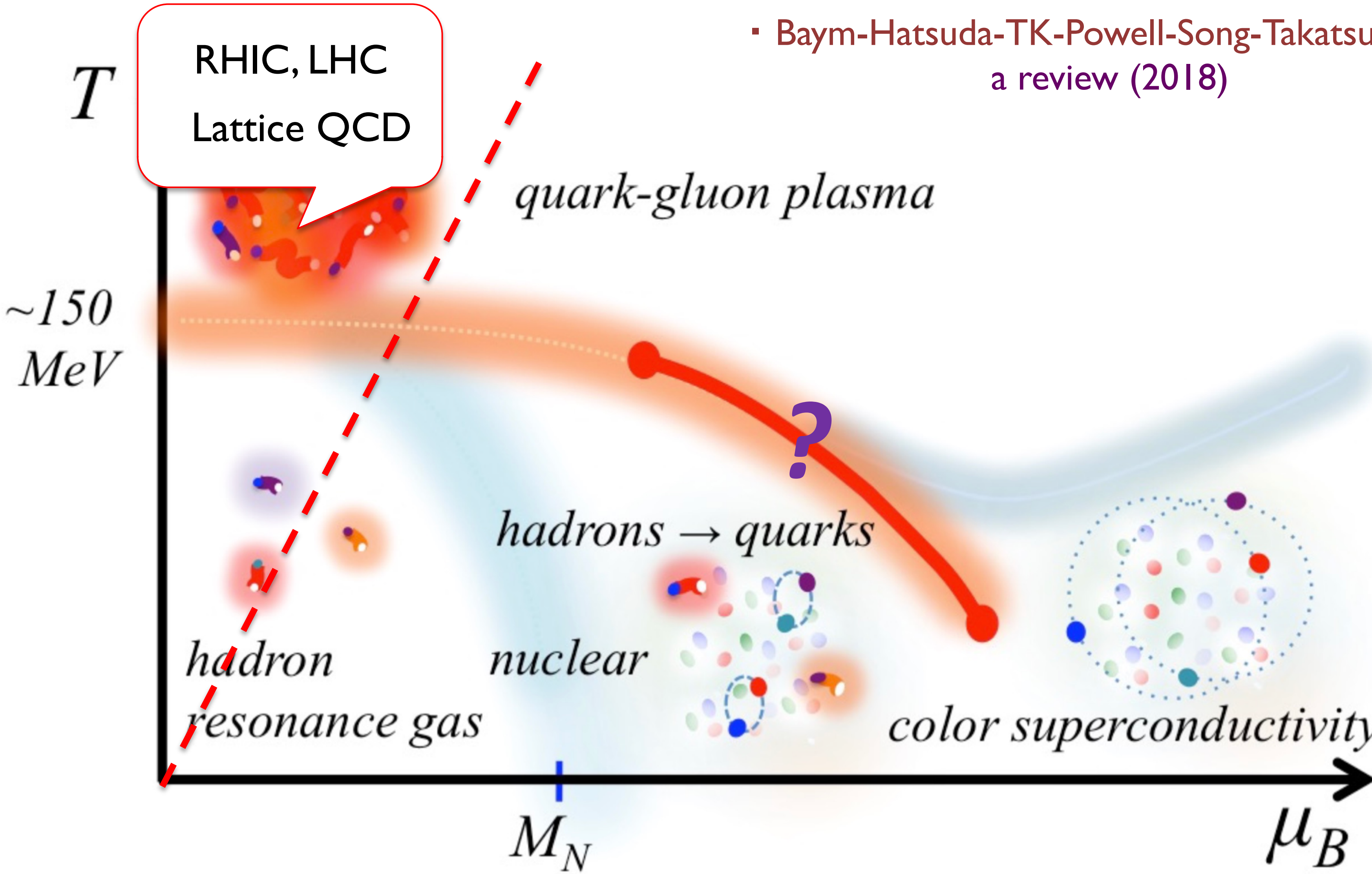

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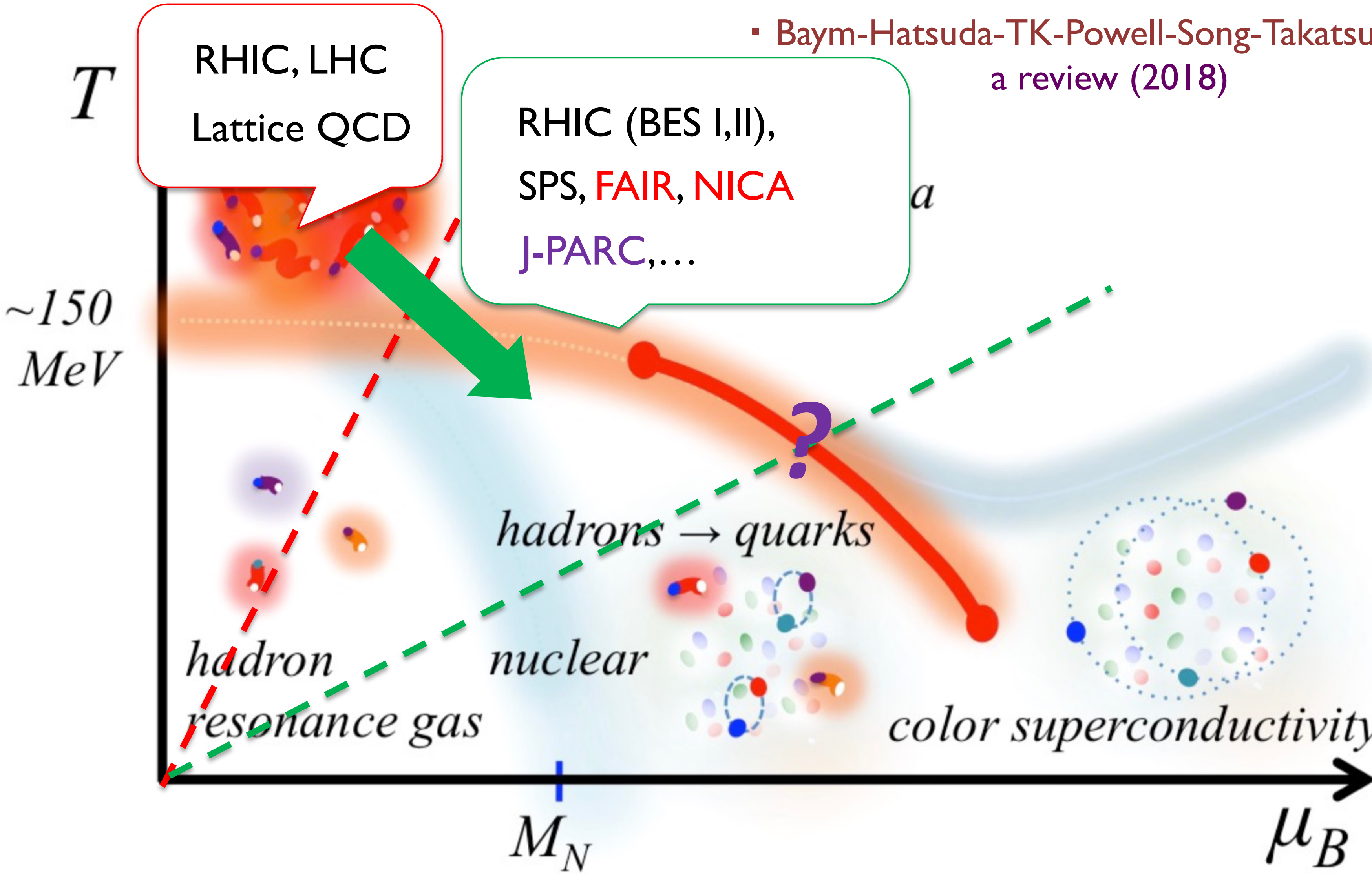
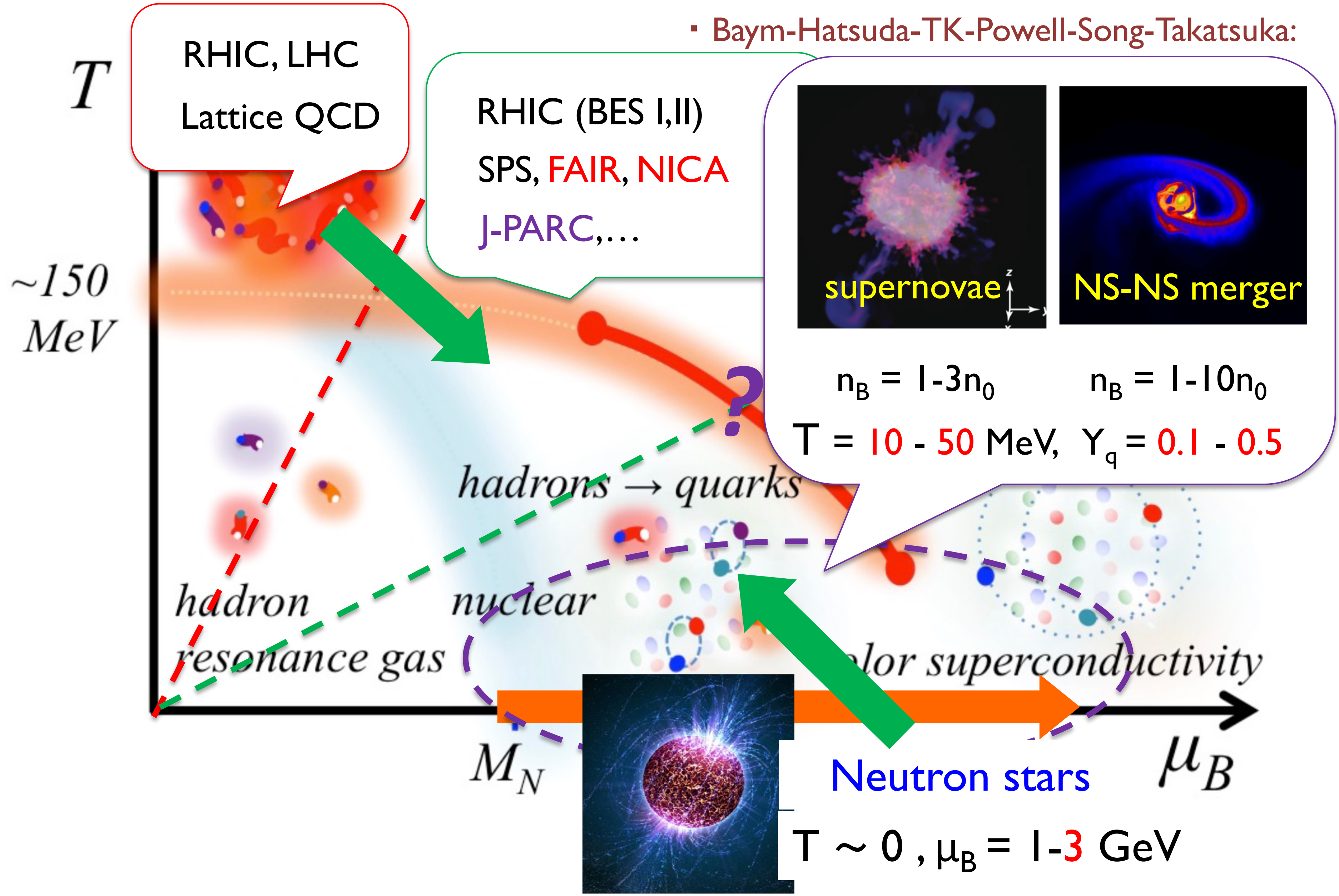


Lattice + HIC + HIC + Astro

▪ Baym-Hatsuda-TK-Powell-Song-Takatsuka:



Contents

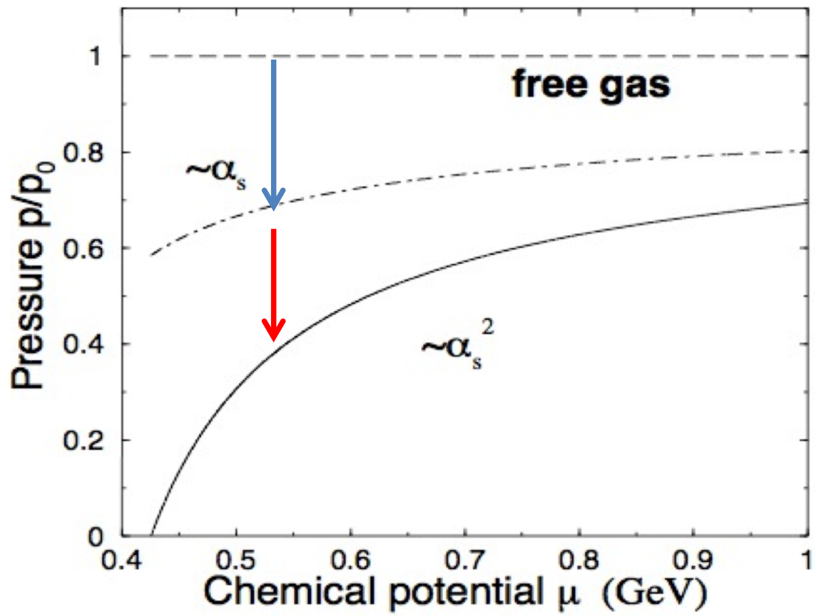
Cold, dense EoS : High density

3-loop pQCD : Freedman-McLerran 78; Baluni 78; Kurkela-Romatschke-Vuorinen 09

[some **4-loop** contributions: E. Sappi, a talk given in the 2nd week]

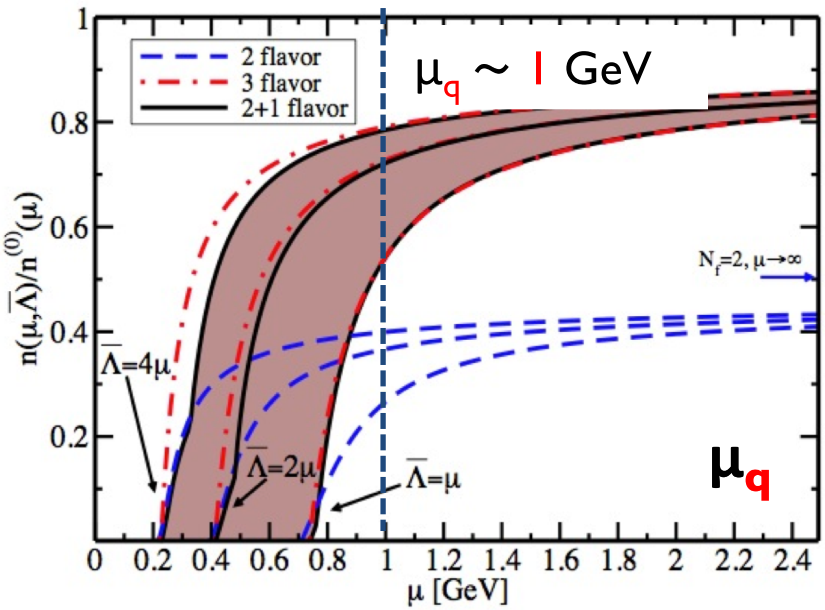
check of convergence

(Fraga-Pisarski-Schaffner-Bielich 01)



check of renorm. scale dep.

(Kurkela-Romatschke-Vuorinen 09)



- Interactions crucial for $\mu_q < \sim$ **1** GeV or $n_B < \sim$ **50**n_0
- Hints for effective **repulsion** (more μ needed to reach n_{ideal})

Cold, dense EoS : Low density

calculations based on microscopic interactions

NN + 3N forces + ...

a) Fit to data
- to E ~ 350 MeV for NN (well constrained)
- fit to nuclei for NNN (uncertain)

Illinois, Argonne, Bonn, ...

b) ChEFT (N^3LO)
- systematics
- symmetry of QCD

Epelbaum, Heberer, Kaiser, Schwenk, ...

c) Lattice QCD
- NN & YN, YY pot.

HAL collaboration, ...

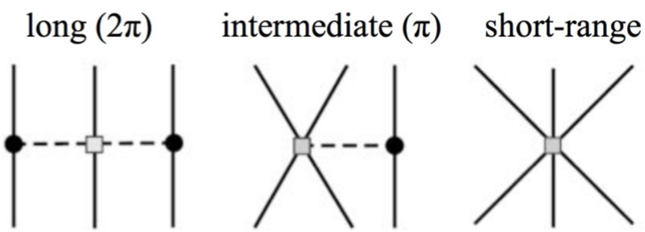
Many-body calculations (non-perturbative for soft nucleons)

- Hartree-Fock, BHF, ...
- Quantum Monte-Carlo — Carlson. Gandolfi, ...
- Variational — Pandharipande, Takano, Togashi, ...

EoS

Cold, dense EoS : Low density

- short range part of 3N forces is uncertain

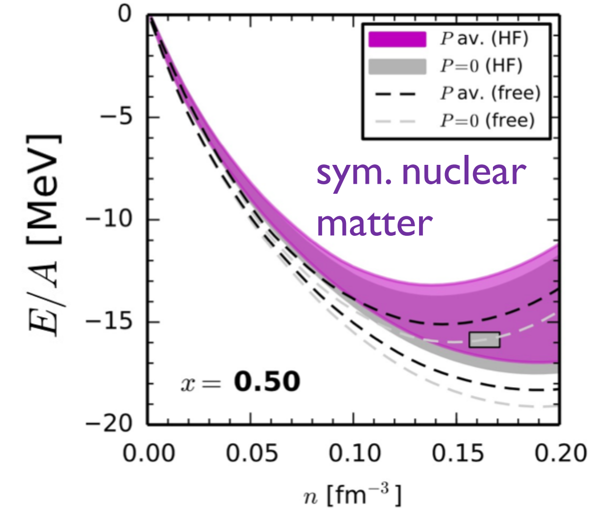


known

uncertain

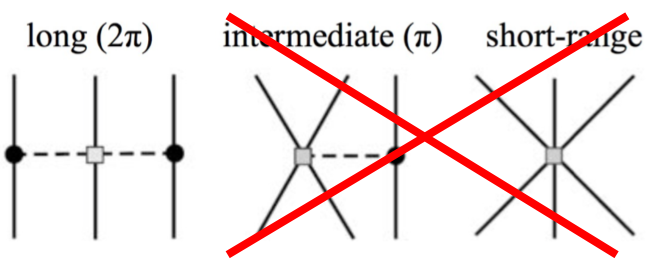
many-body cal.

Drischler-Hebeler-Schwenk, 2016



- pure neutron matter is less uncertain:

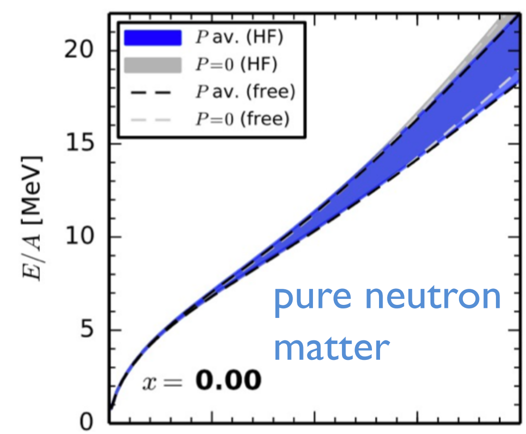
(Good for NS community)



known

forbidden

many-body cal.



microscopic calculations at n_B = 1-2 n_0 : consistent with empirical facts

Cold, dense EoS : Low density

For NS applications (n_B=1-10n_0), the fundamental question is:

convergence of **many-body forces**

e.g.1) parameterized **pure neutron** matter EoS [Gandolfi+, 2009]

~kin. + 2-body ~3-body

$$\varepsilon = n_0 \left[(12 \pm 1\,\mathrm{MeV}) \left(\frac{n_B}{n_0} \right)^{1.45 \pm 0.05} + (4 \pm 2\,\mathrm{MeV}) \left(\frac{n_B}{n_0} \right)^{3.3 \pm 0.3} \right]$$

e.g.2) Akmal-Pandharipande-Ravenhall EoS (**APR 98**) [Table V of APR paper]

pure neutron matter

n_B	2 –body int. $\langle v^{\pi}_{ij} \rangle$	$\langle v^{R}_{ij} \rangle$	3 –body int. $\langle V^{2\pi}_{ijk} \rangle$	$\langle V^{R}_{ijk} \rangle$
n_0	−4.1	−29.9	1.2	4.5
2 n_0	−25.1	−36.4	−17.4	30.6
3 n_0	−35.7	−44.7	−34.1	78.0
4 n_0	−52.2	−41.1	−76.9	160.3

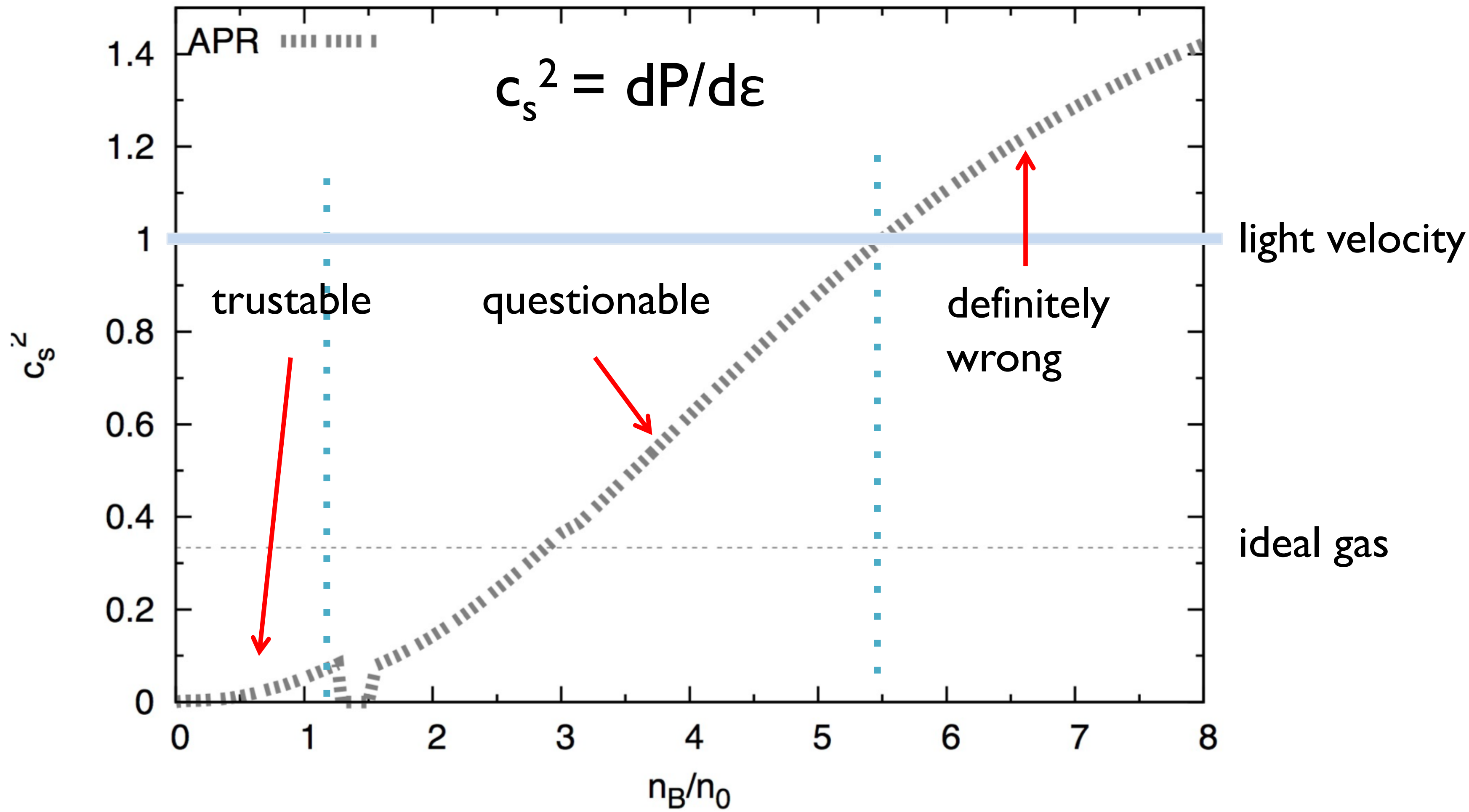
grow rapidly!

4-, 5- or more-body forces should be important as well beyond ~ **$2n_0$**

$$\langle V_{N\text{-body}} \rangle \sim (n_B/n_0)^N$$

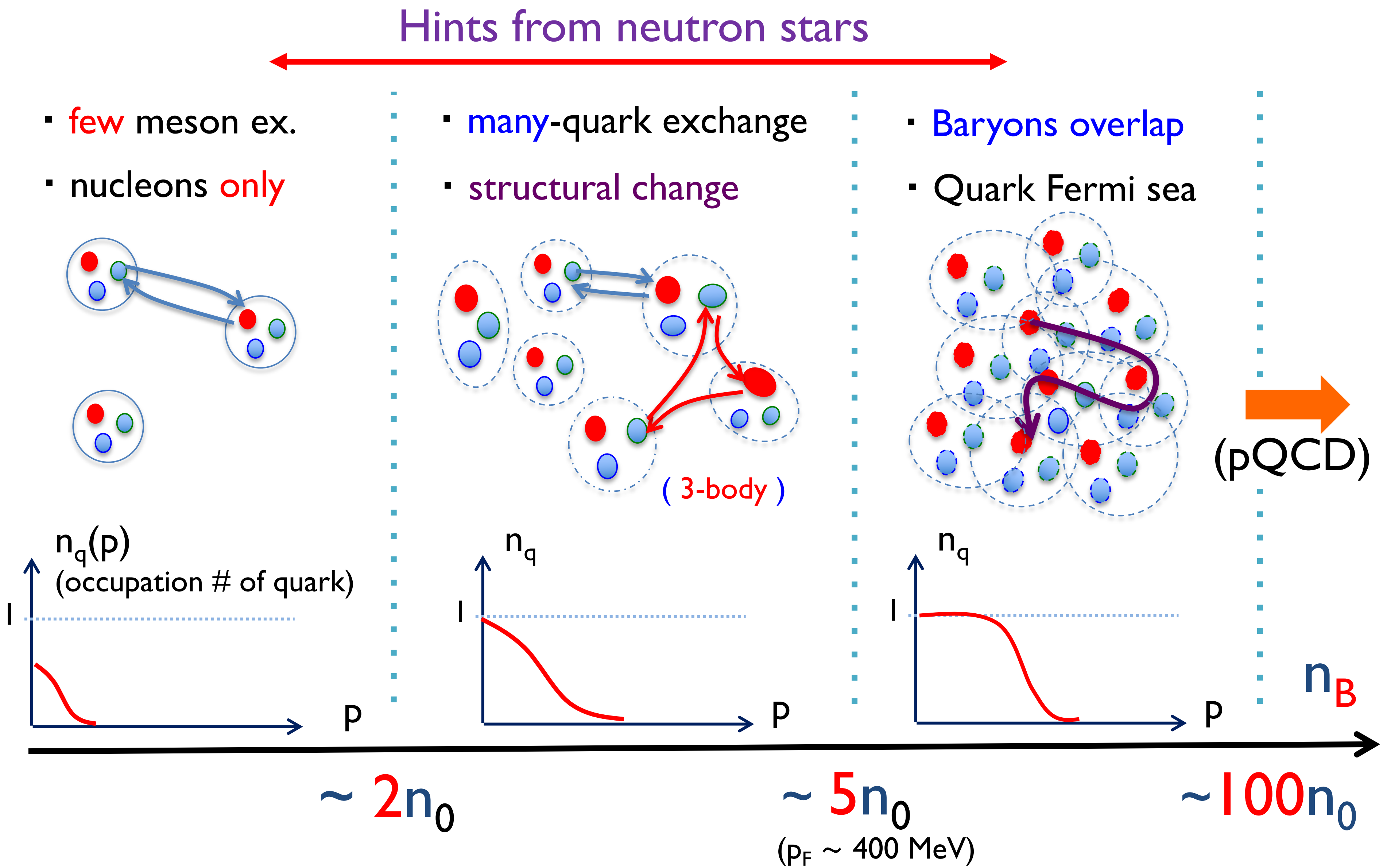
Cold, dense EoS : Low density

Akmal-Pandharipande-Ravenhall EoS (**APR 98**)



Picture to be developed

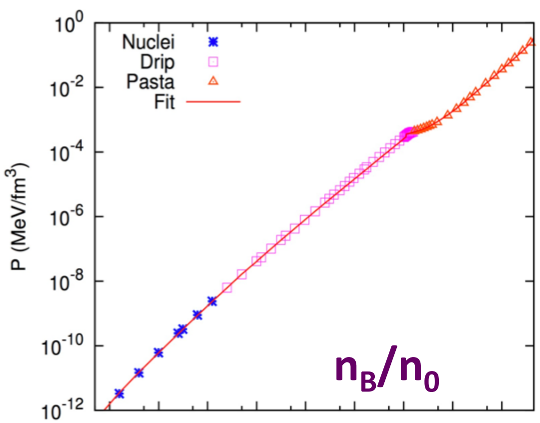
Masuda-Hatsuda-Takatsuka 2012
TK-Powell-Song-Baym 2014



Contents

EoS & M-R relation

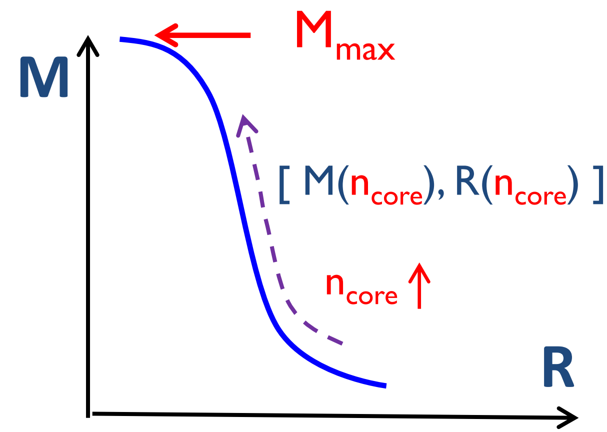
Einstein eq. : $$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$ QCD EoS



[for spherical NS → TOV eq.]

1-to-1 correspondence

Lindblom (1992)



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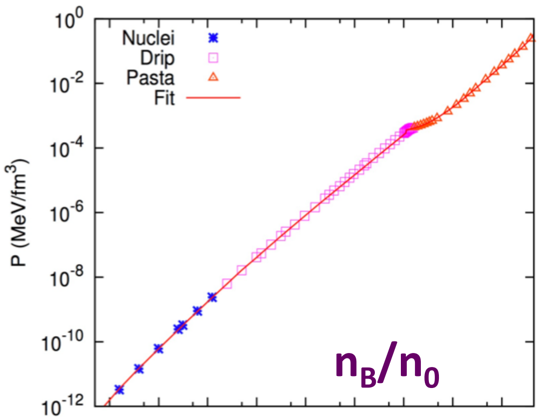

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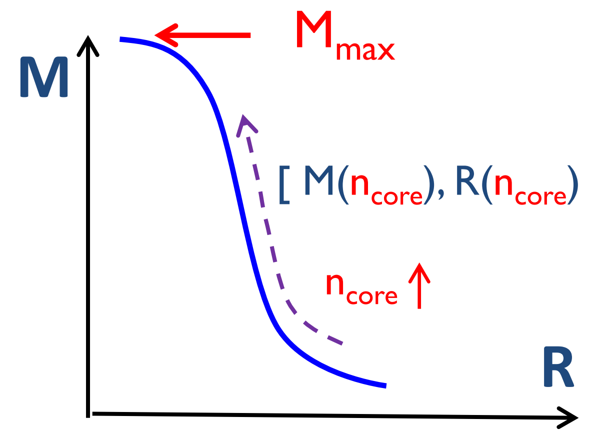
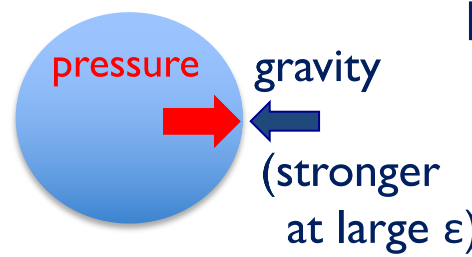
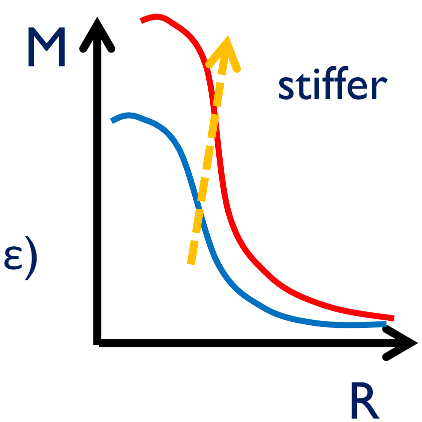


Terminology (my convention)

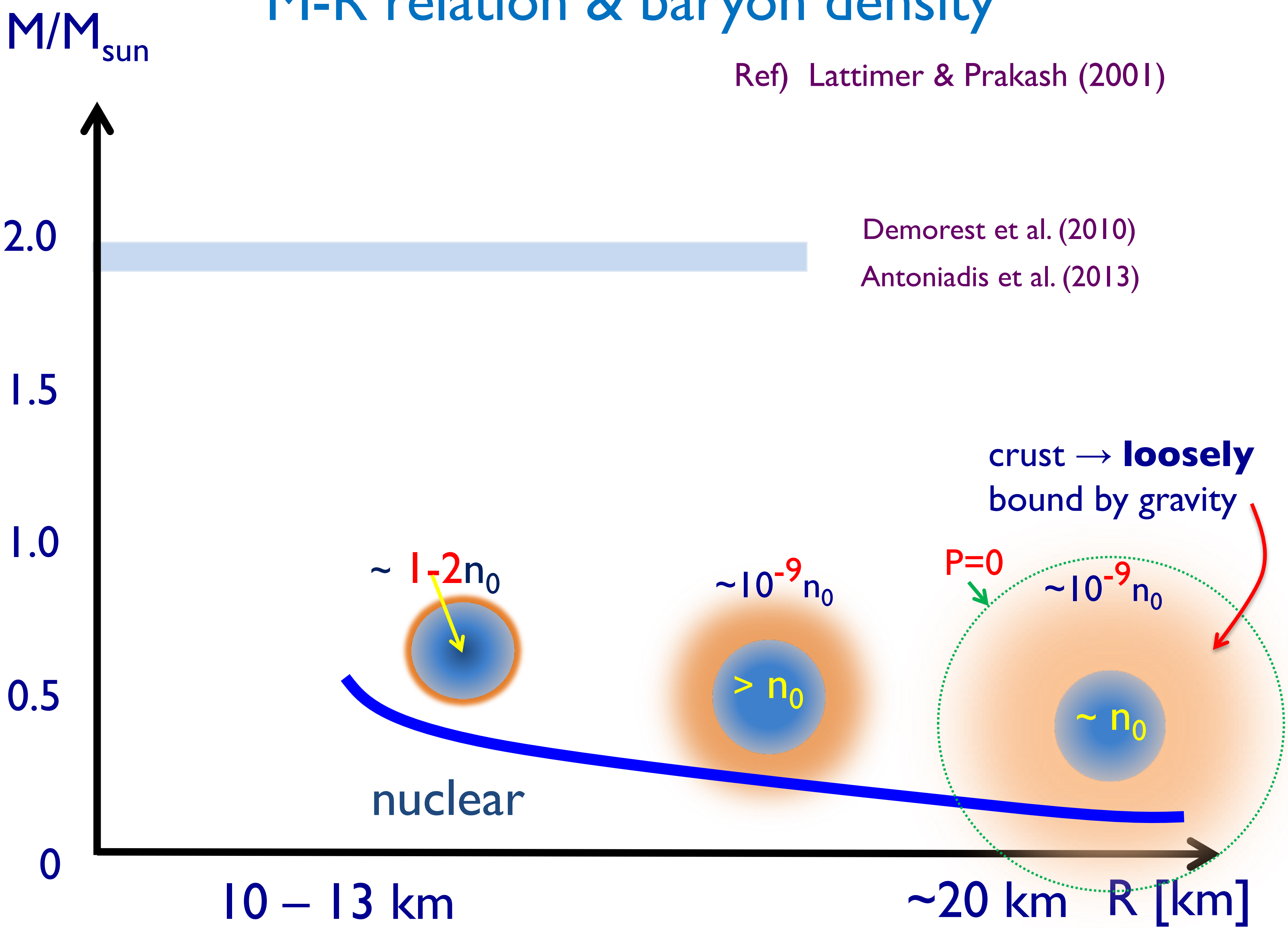




1) **Stiff** EoS : P is large at given ε

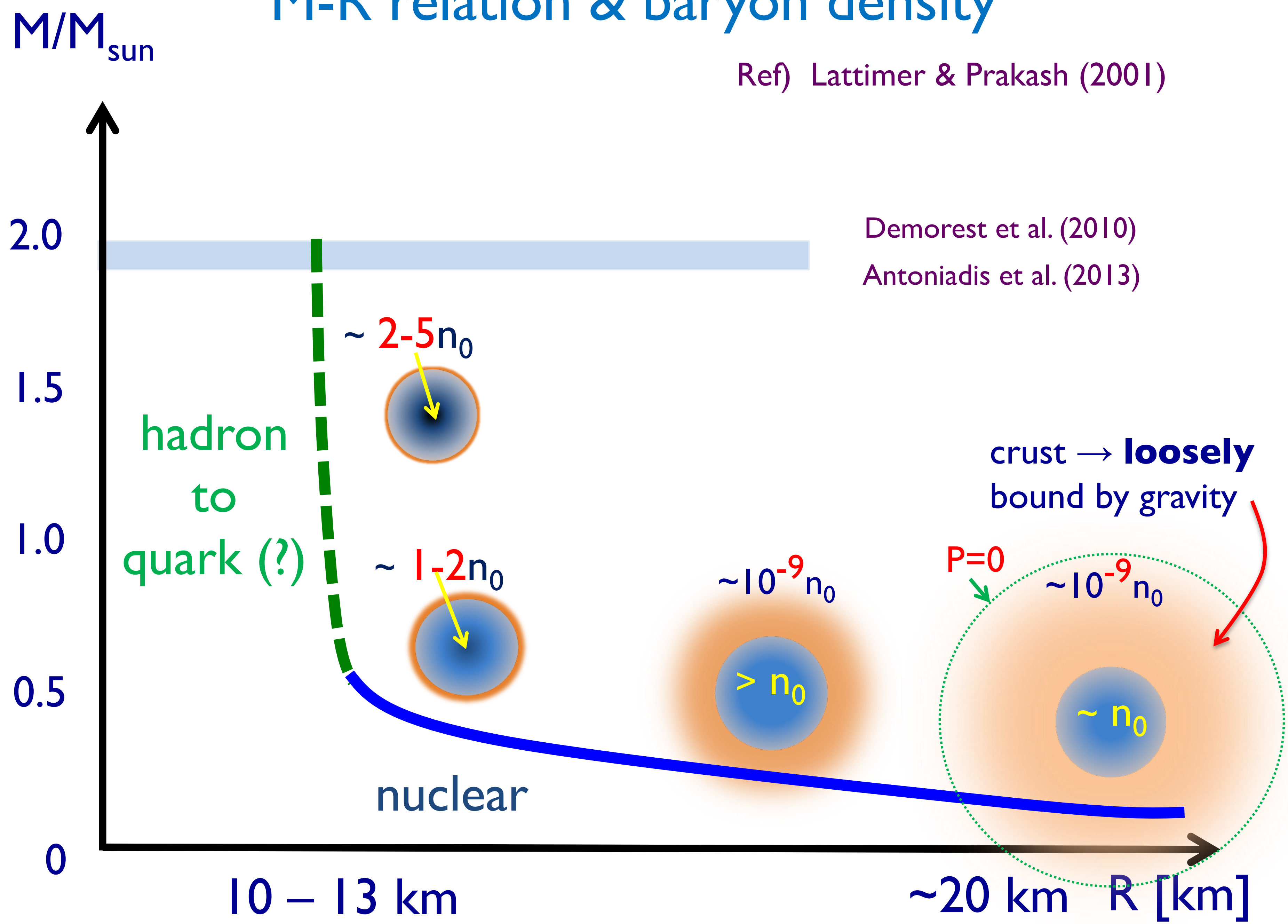
2) **Soft-Stiff** EoS : Soft at $n_B < 2n_0$ & Stiff at $n_B > 5n_0$

M-R relation & baryon density



M-R relation & baryon density

Ref) Lattimer & Prakash (2001)



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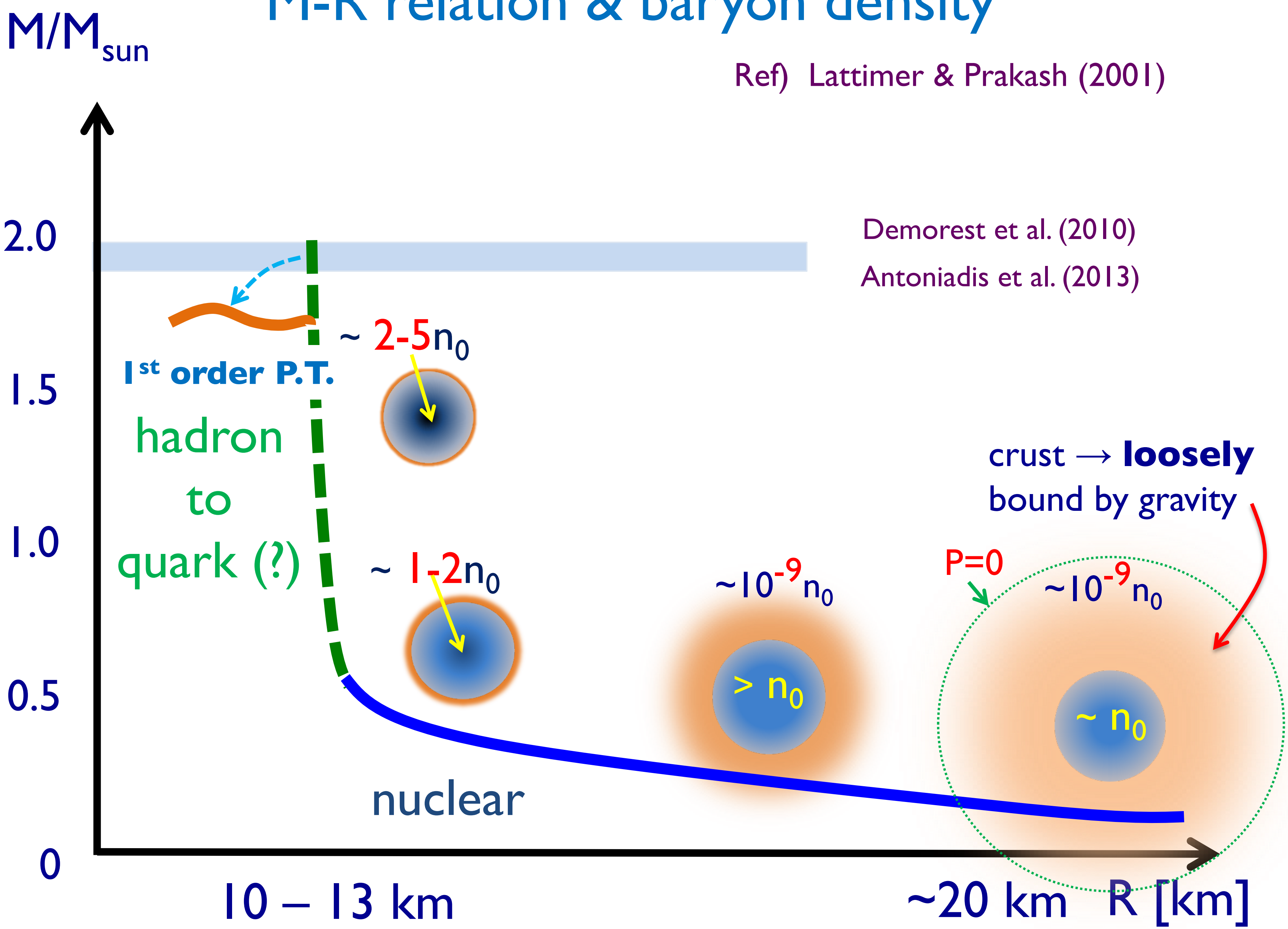

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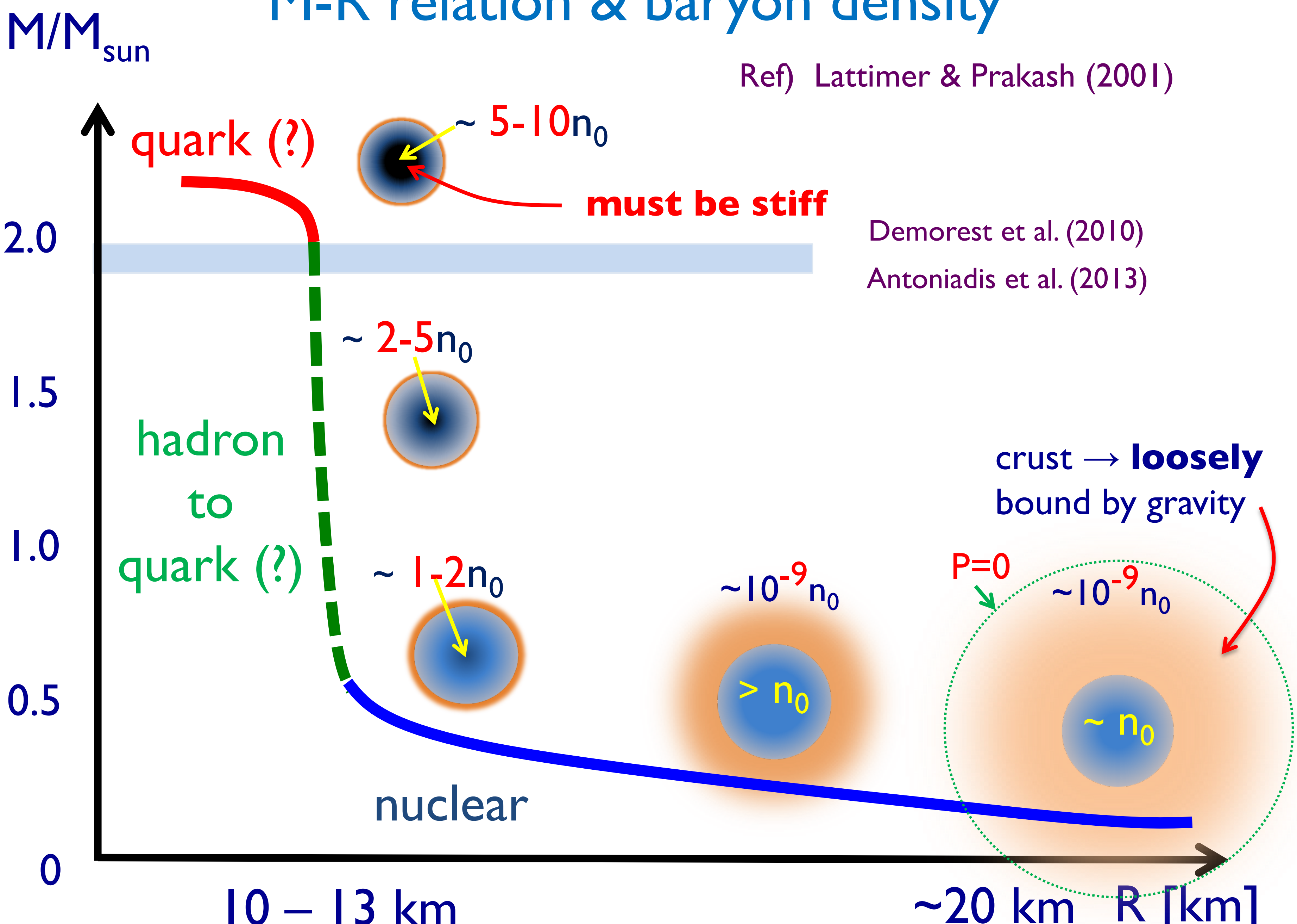

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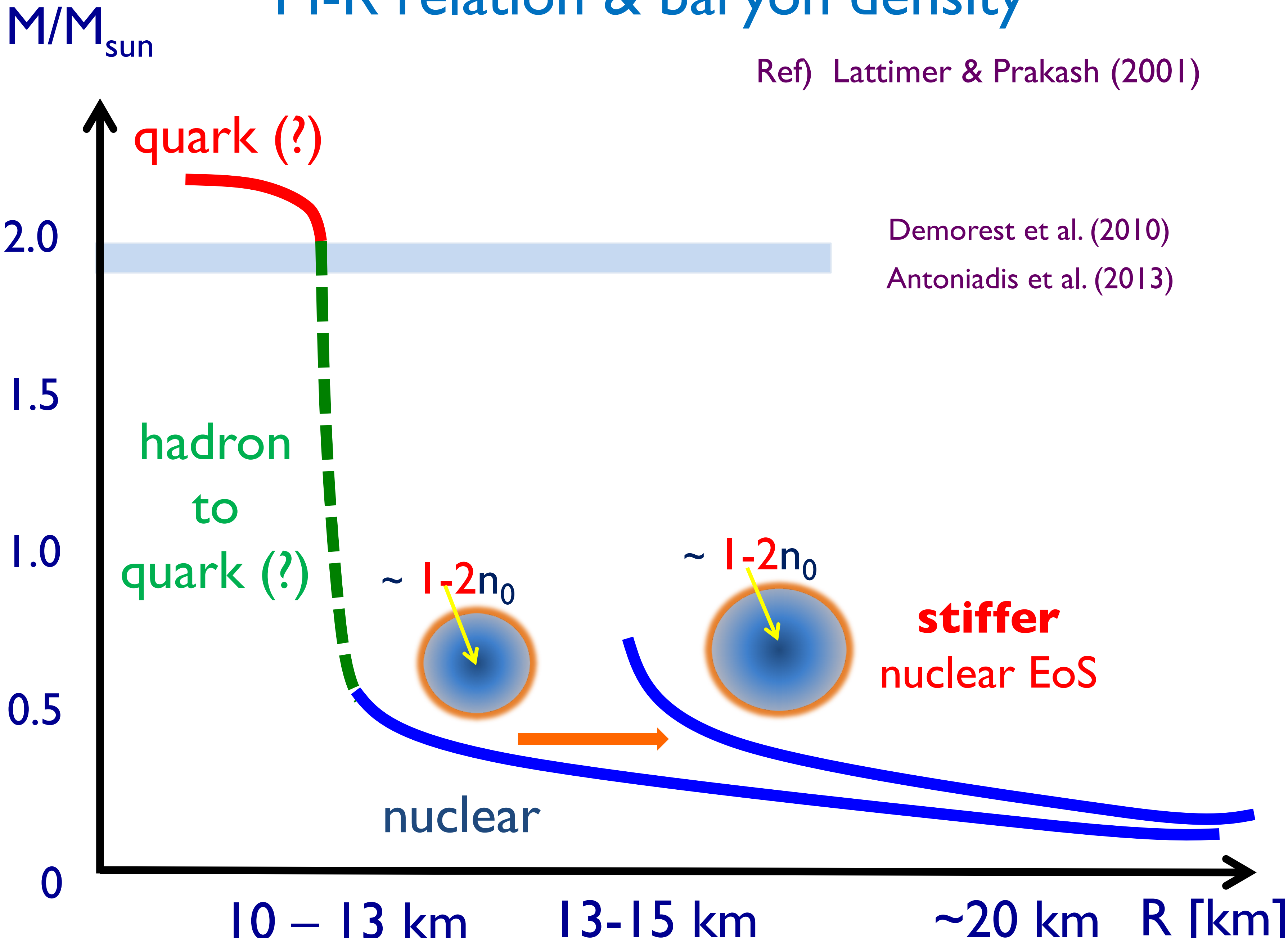

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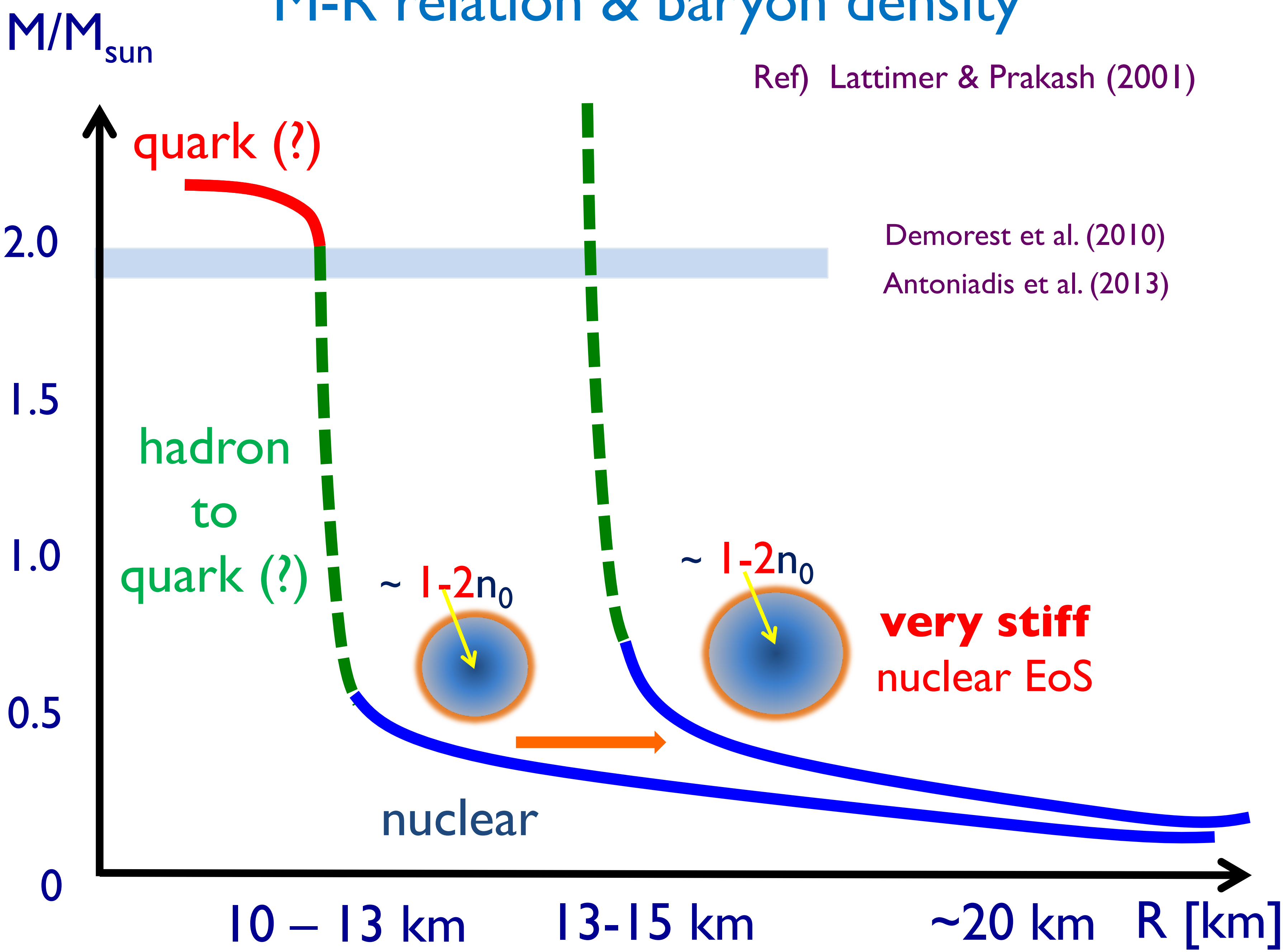

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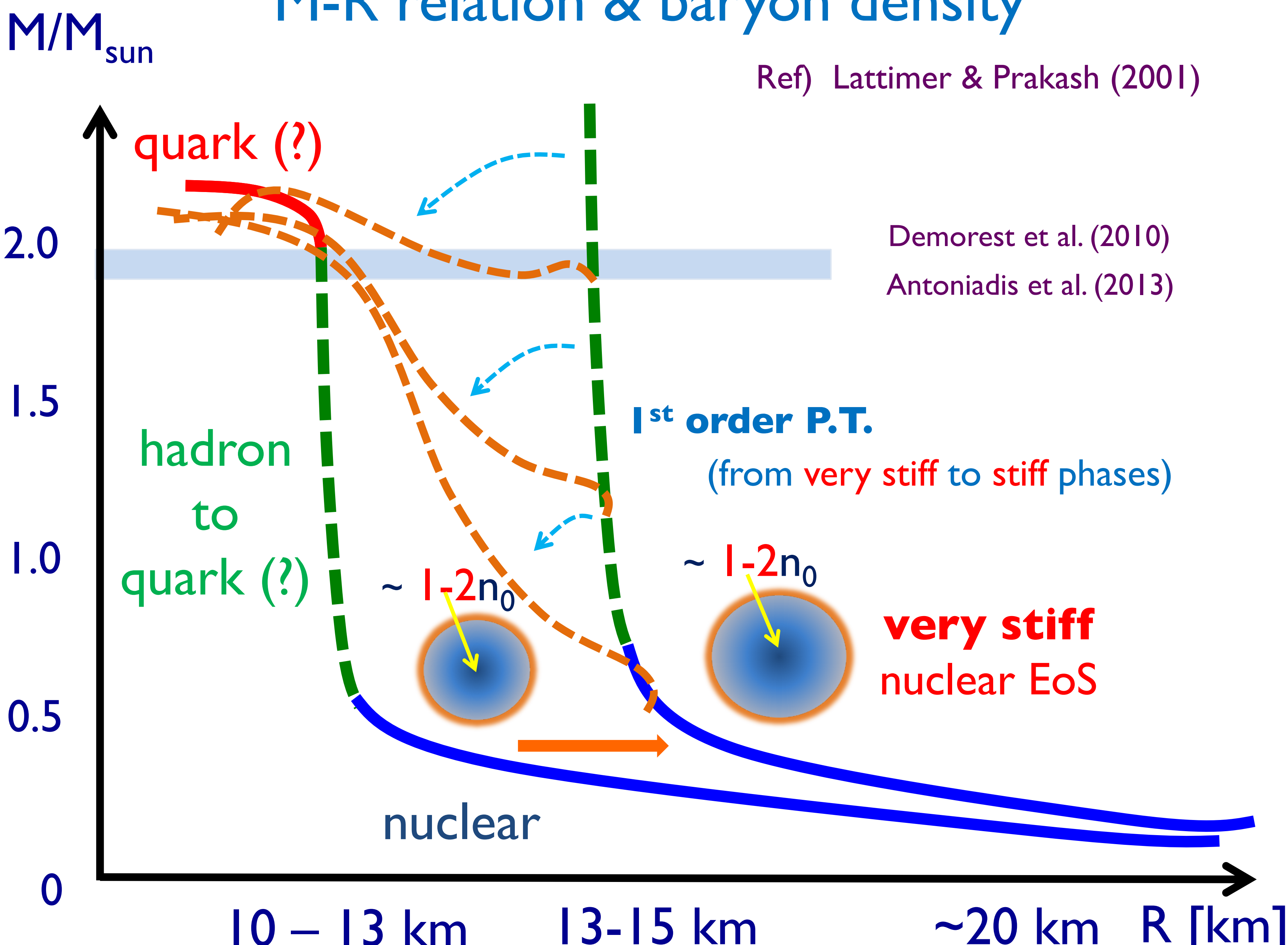


M-R re

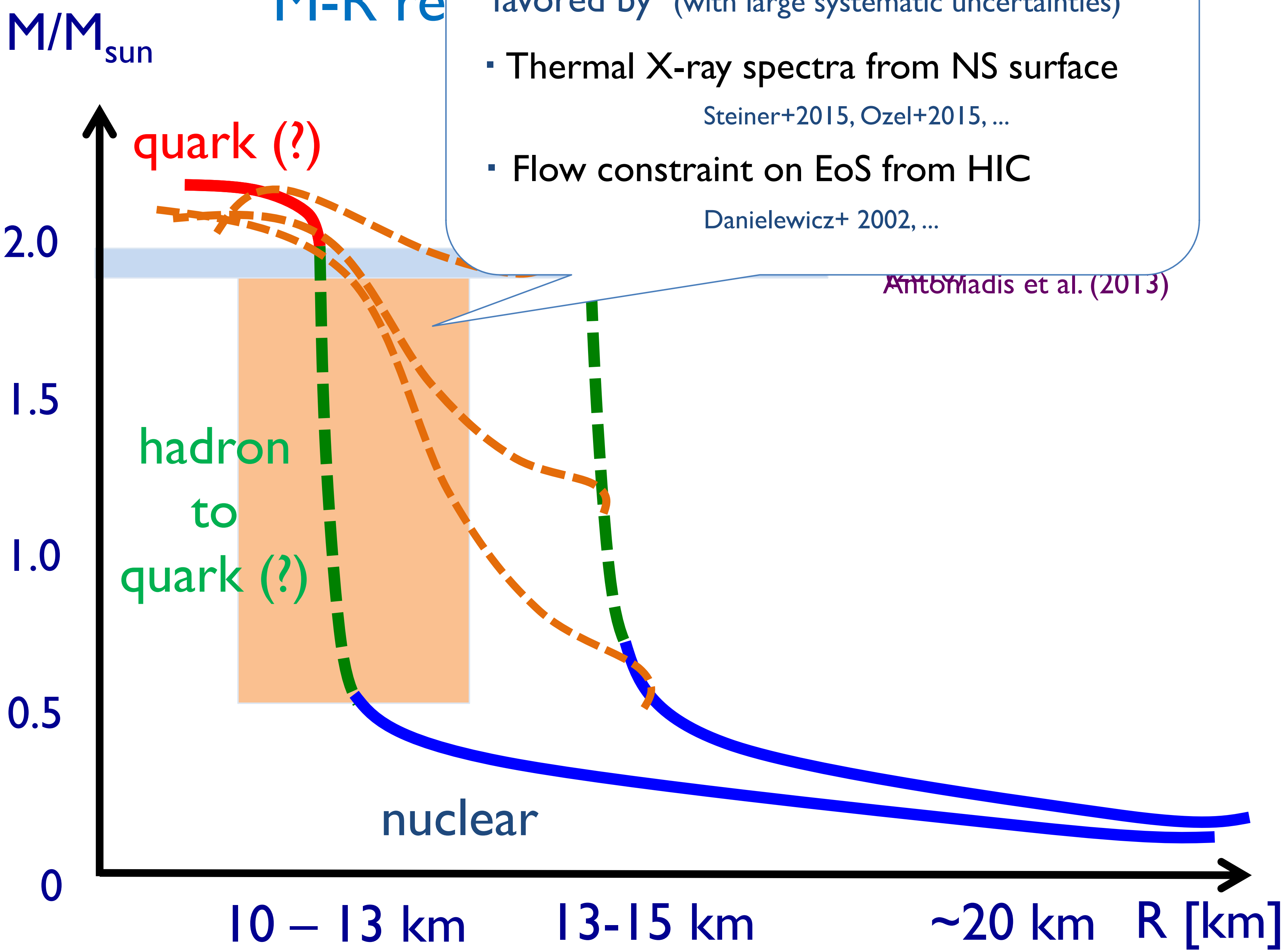
favored by (with large systematic uncertainties)

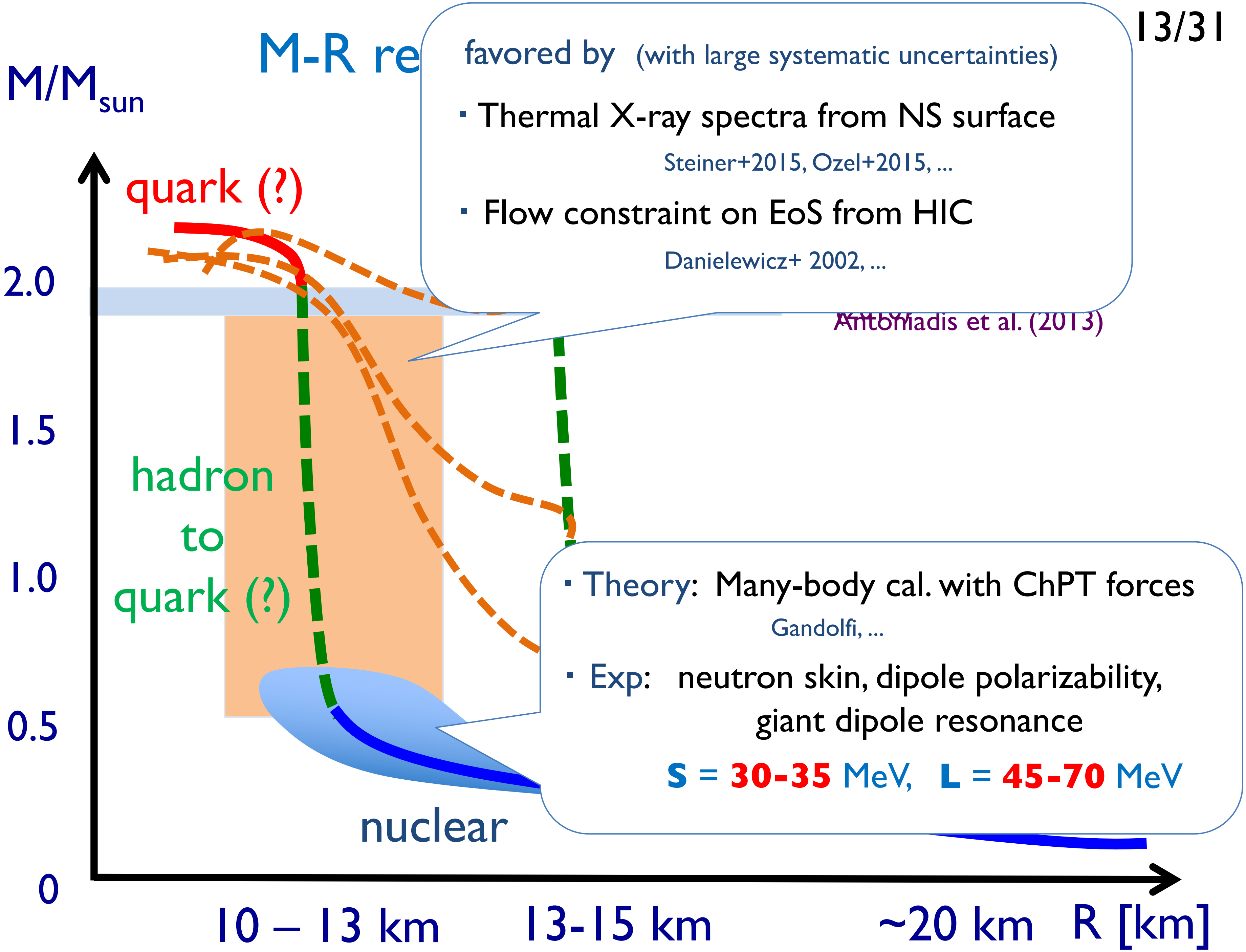
- Thermal X-ray spectra from NS surface

  Steiner+2015, Ozel+2015, ...

- Flow constraint on EoS from HIC

  Danielewicz+ 2002, ...





M-R re
M/M_sun
quark (?)
2.0
1.5
1.0
0.5
0
hadron
to
quark (?)
nuclear
Antoniadis et al. (2013)
10 – 13 km
13-15 km
~20 km
R [km]
favored by (with large systematic uncertainties)
· Thermal X-ray spectra from NS surface
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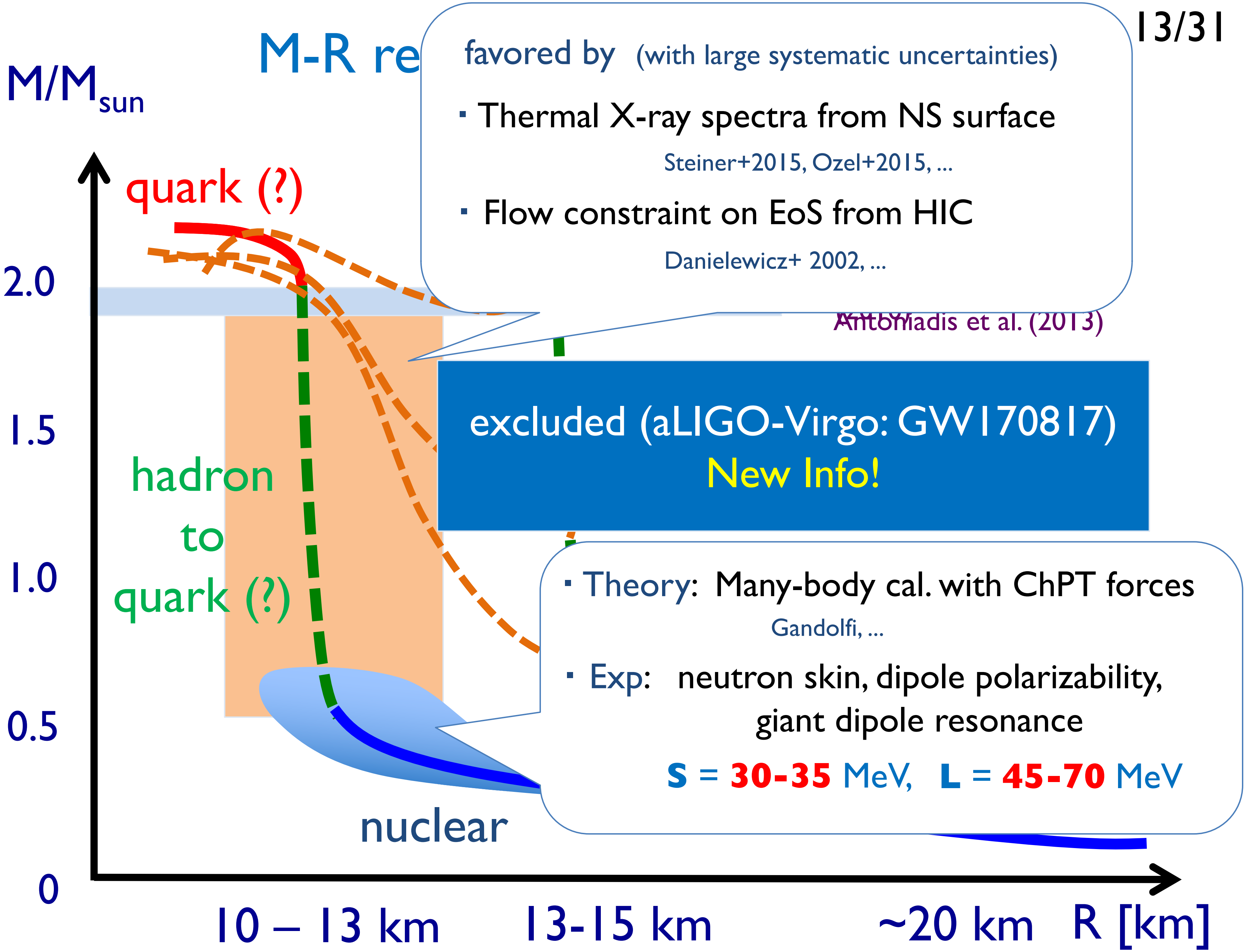
· Theory: Many-body cal. with ChPT forces
Gandolfi, ...
· Exp: neutron skin, dipole polarizability,
giant dipole resonance
S = 30-35 MeV, L = 45-70 MeV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excluded (aLIGO-Virgo: GW170817)
New Info!
· Theory: Many-body cal. with ChPT forces
Gandolfi, ...
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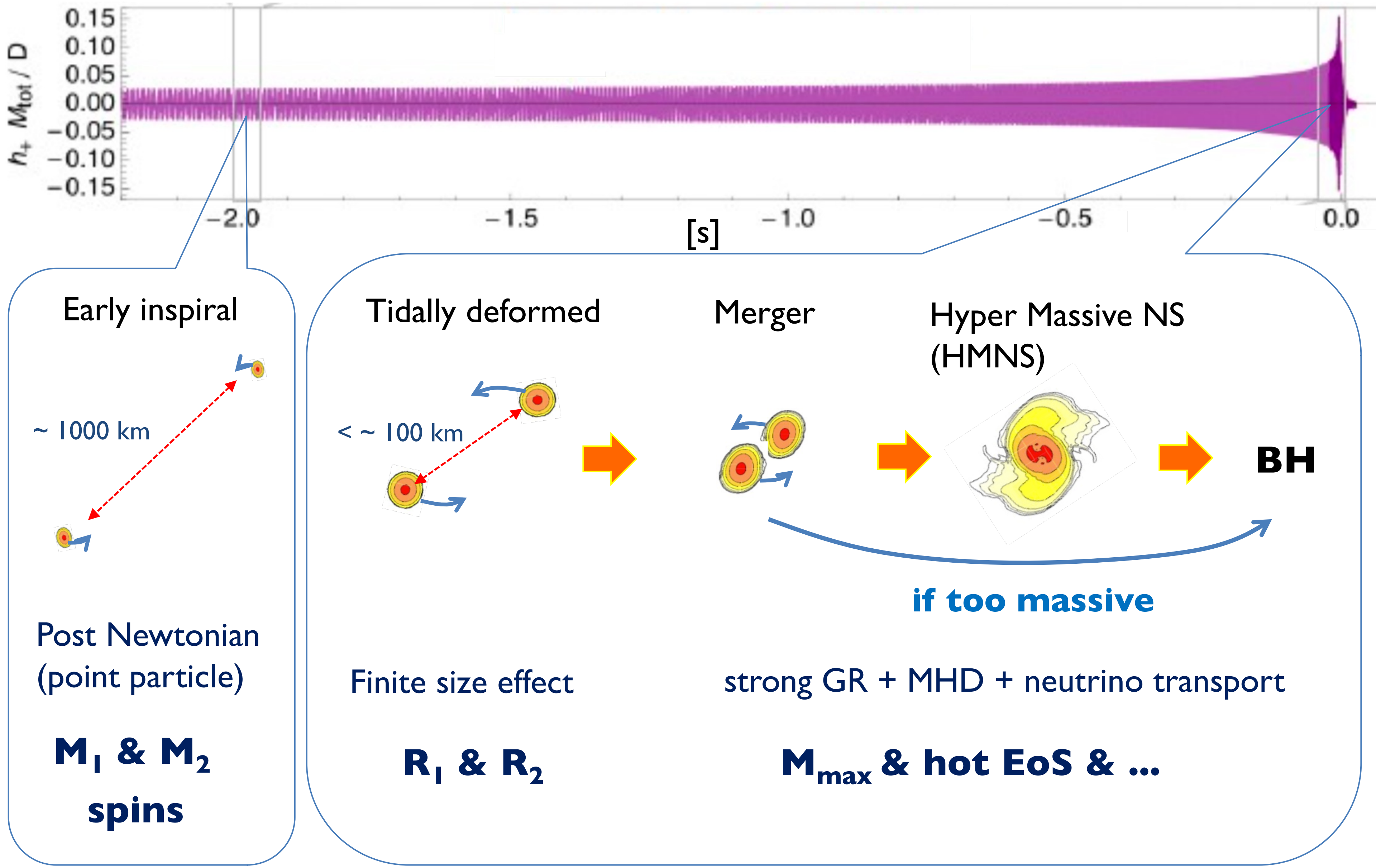
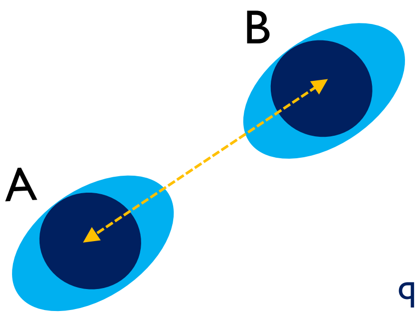
GWs from NS-NS mergers



Tidal deformation → accelerated phase evolution

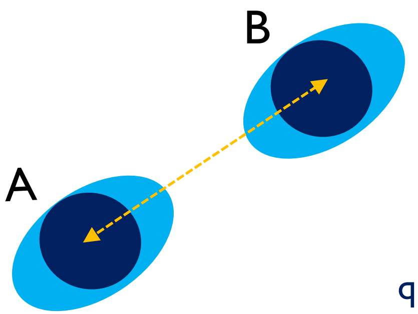


1) grav. fields from star B → the deformation of star A
2) deformed energy density → quadrupole grav. fields

polarizability

quadrupole moment $Q_{ij} = -\lambda(M) E_{ij}$ external field $E_{ij} = -\frac{\partial^2 V}{\partial x_i \partial x_j}$

Tidal deformation → accelerated phase evolution



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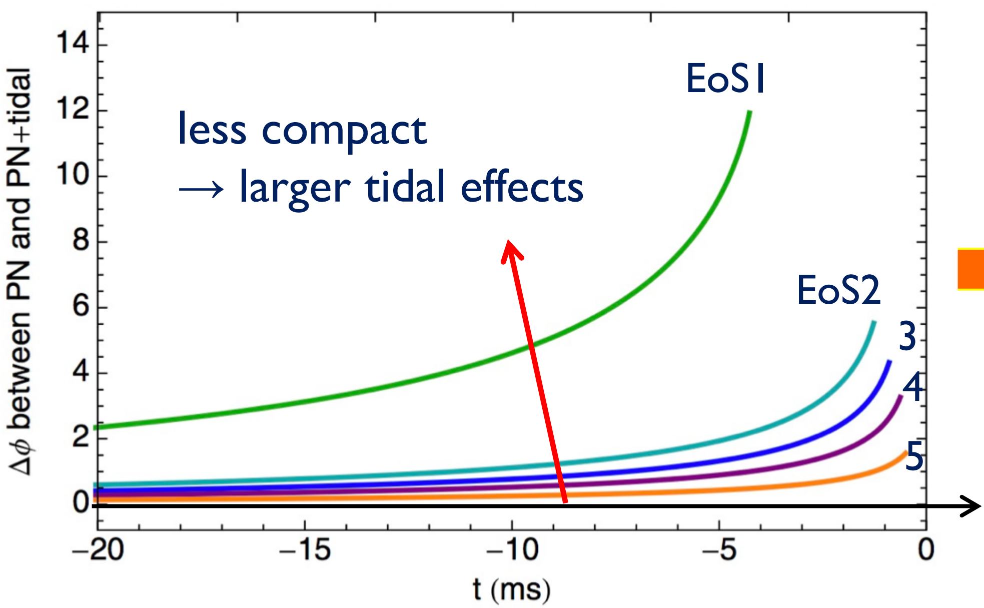
gravitational pot. from the star A

$$V_A(r) \simeq -\frac{GM_A}{r} - \frac{GQ_{AB}}{r^3} \simeq -\frac{GM_A}{r} - \frac{G}{r^3}\left(\frac{\lambda G M_B}{r^3}\right)$$

attractive
→ acceleration

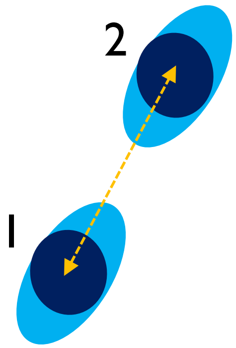


Read+ 2012

upperbound on **λ** & **R**

point particle

Dimensionless tidal deformability → R_{NS}



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

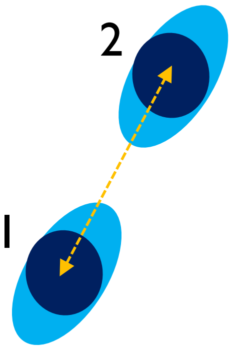
What GW analyses measure: combination of Λ for star 1 & 2 :

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

(measured)

2-parameters: M_1 & M_2

Dimensionless tidal deformability → R_{NS}



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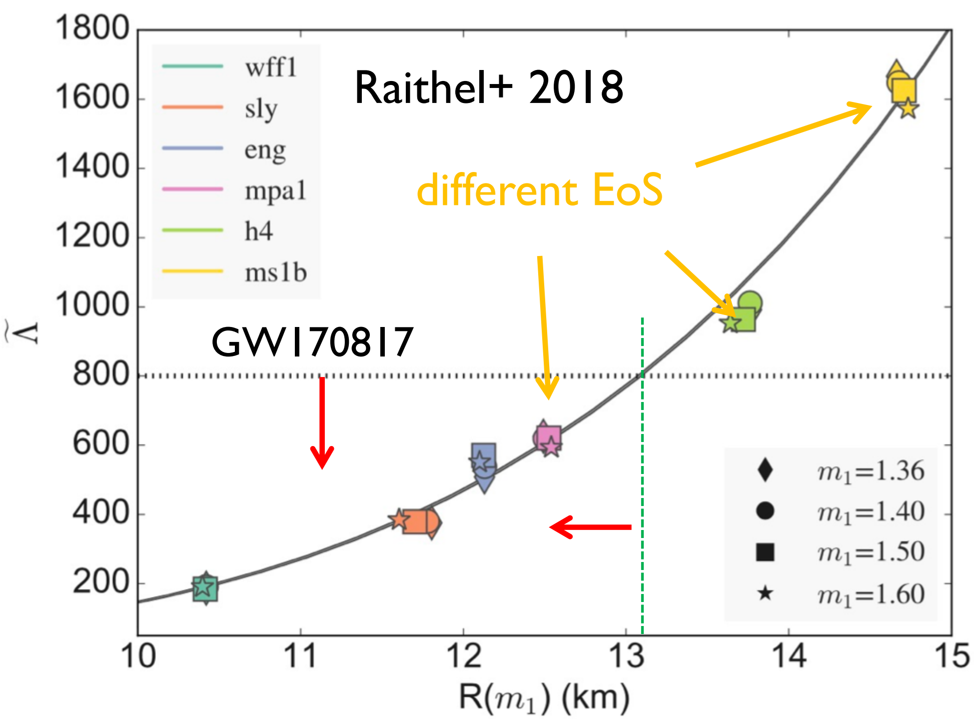


For **GW170817** :

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

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

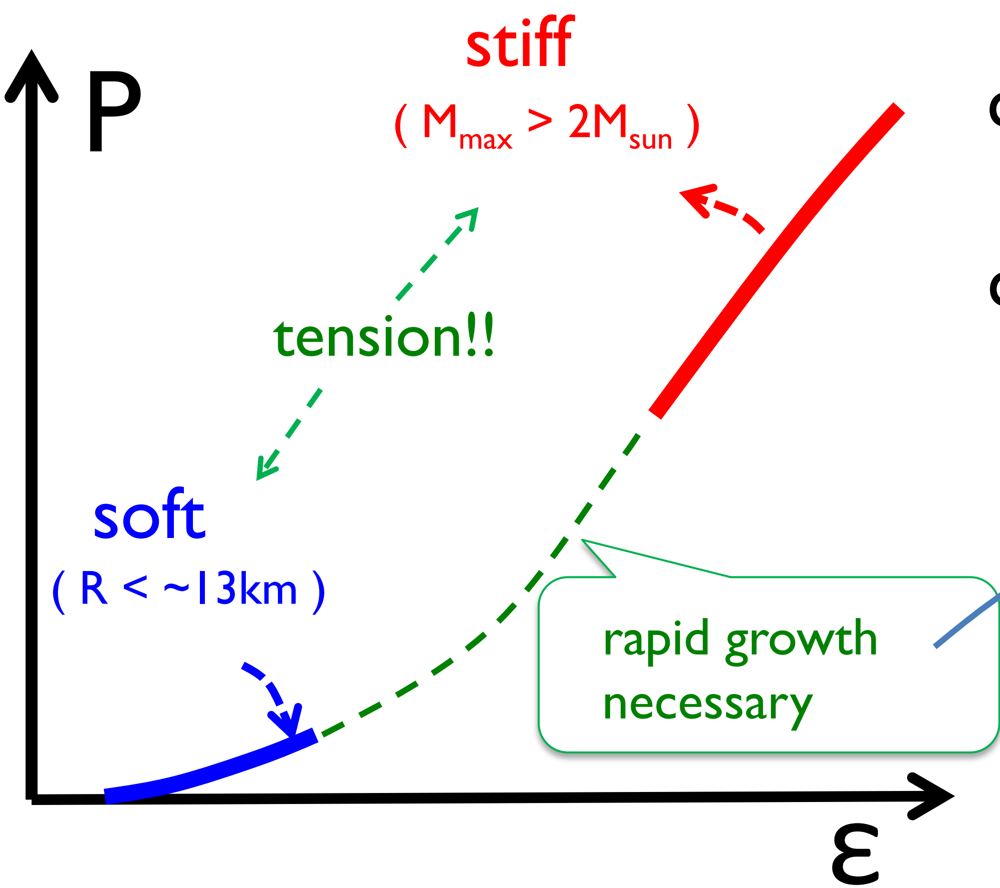
mass ratio

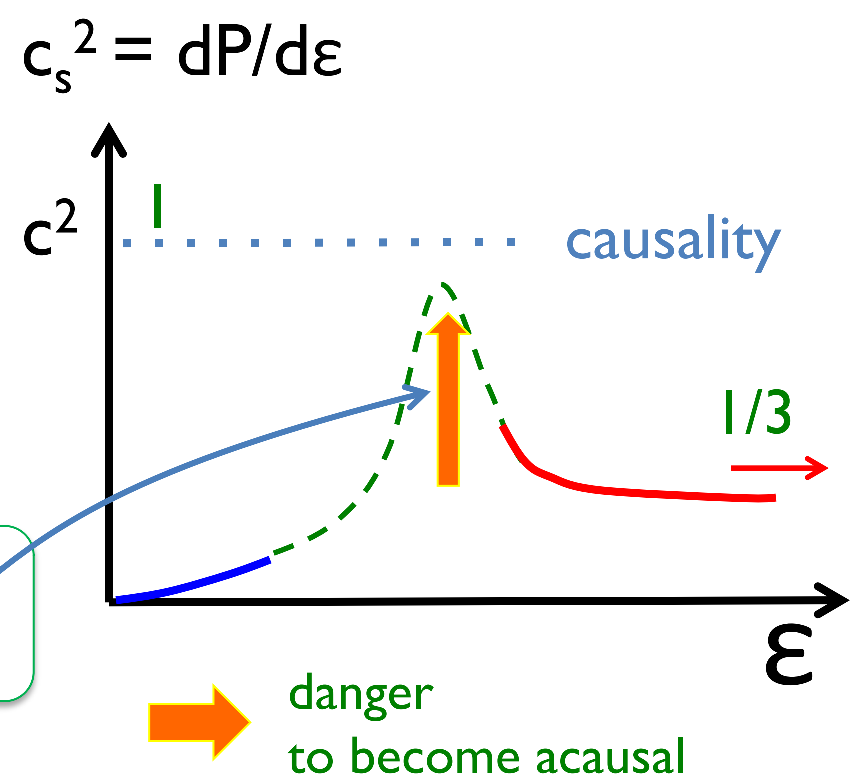
$q = M_2/M_1$ (undetermined)

- different q degenerate !
- R < ~ 13 km

Causality constraint on $2n_0$-$5n_0$ region

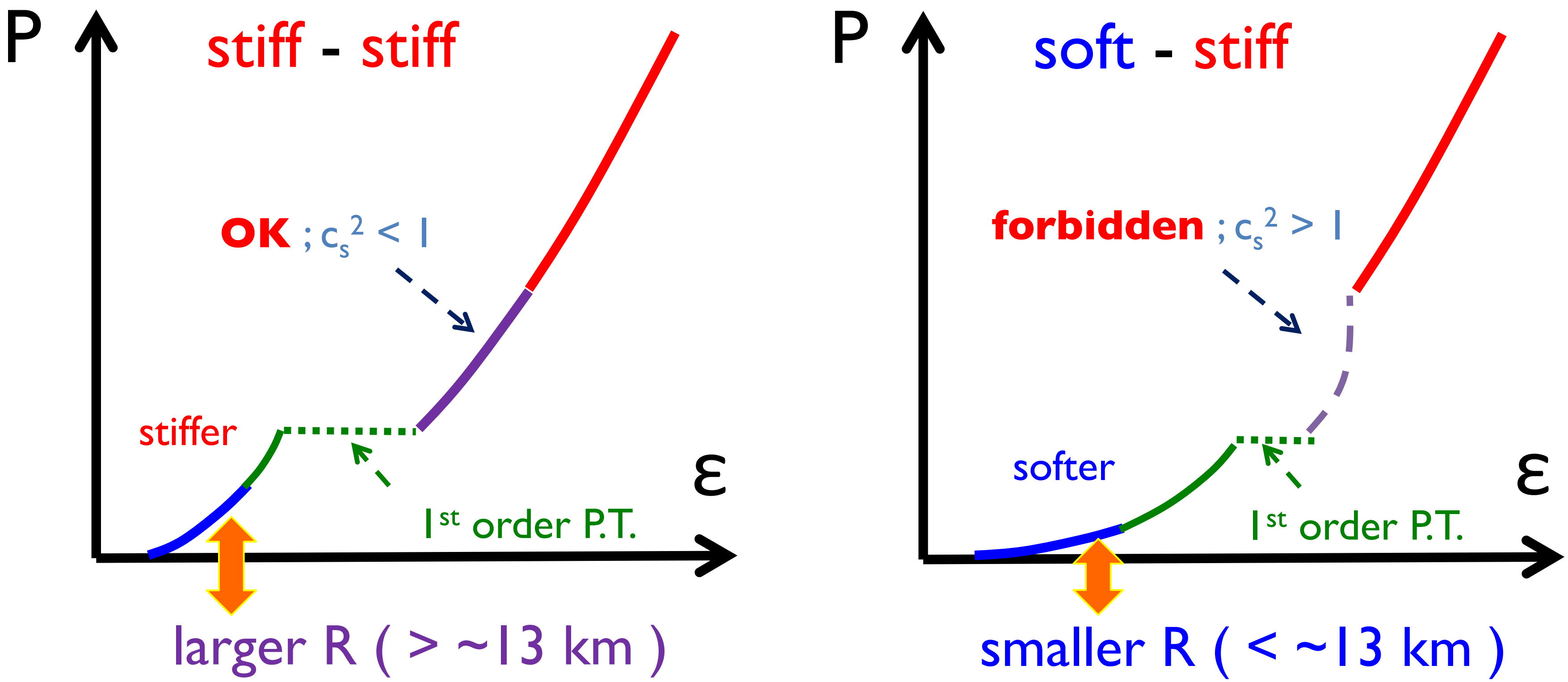
assume: $R < 13$km & $M_{max} > 2M_{sun}$





Stiff-Stiff v.s. Soft-Stiff EoS

[more quantative analyses → Han-Alford-Prakash 13]



→ we consider a **soft-stiff** EoS with **crossover** (or weak 1st order)

Contents

Quark-Hadron continuity (some history)

- 1, Percolation picture   Baym-Chin 1978; Satz-Karsch 1979,...

- 2, In the context of color-superconductivity (CSC)   Schafer-Wilczek 1998

symmetry: hadron super fluidity ~ color-flavor-locked (CFL) phases

same order parameters : $\langle BB \rangle \sim \langle (qqq)^2 \rangle$

color singlet, but break $U(1)_B$; chiral sym. is also broken

confinement-Higgs complementarity   Fradkin-Shenkar 1979

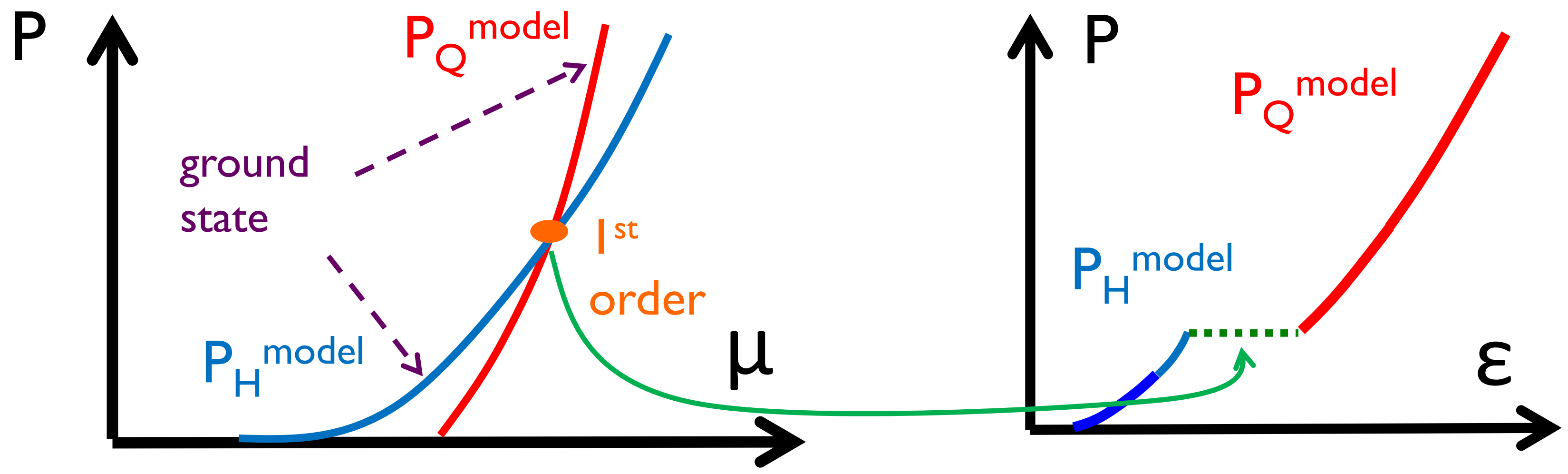
dynamics: the interplay between chiral & diquark

proposal of double CEP   Kitazawa+ 2002; Hatsuda+2006; Zhang+ 2009, ...

- 3, Inferred from the NS constraints (for $2n_0 - 5n_0$)   Masuda+2012, Kojo+2014, ...

soft-stiff EoS & causality $\longrightarrow$ **crossover** or **weak** 1st order

Traditional hybrid construction



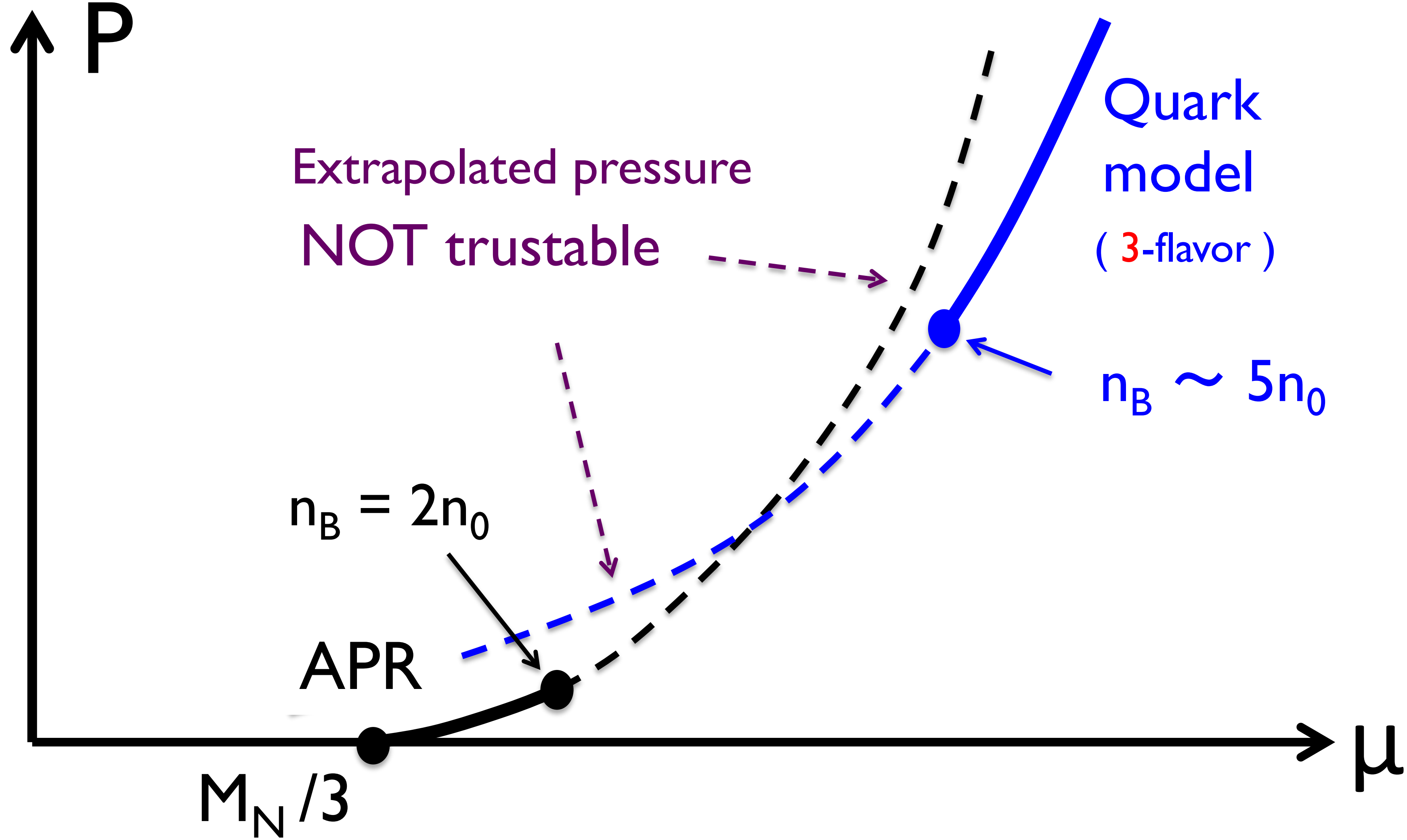
- Key (implicit) **assumptions** :
  - 1) Hadronic & quark phases are distinct (e.g. by order parameters)
  - 2) Both P_H and P_Q are reliable in the overlap region

→ by construction, Q-EoS must be much softer than H-EoS

(unless fine tuning worked out)

3-window modeling : P vs μ

Masuda+2012, Kojo+2014, ...



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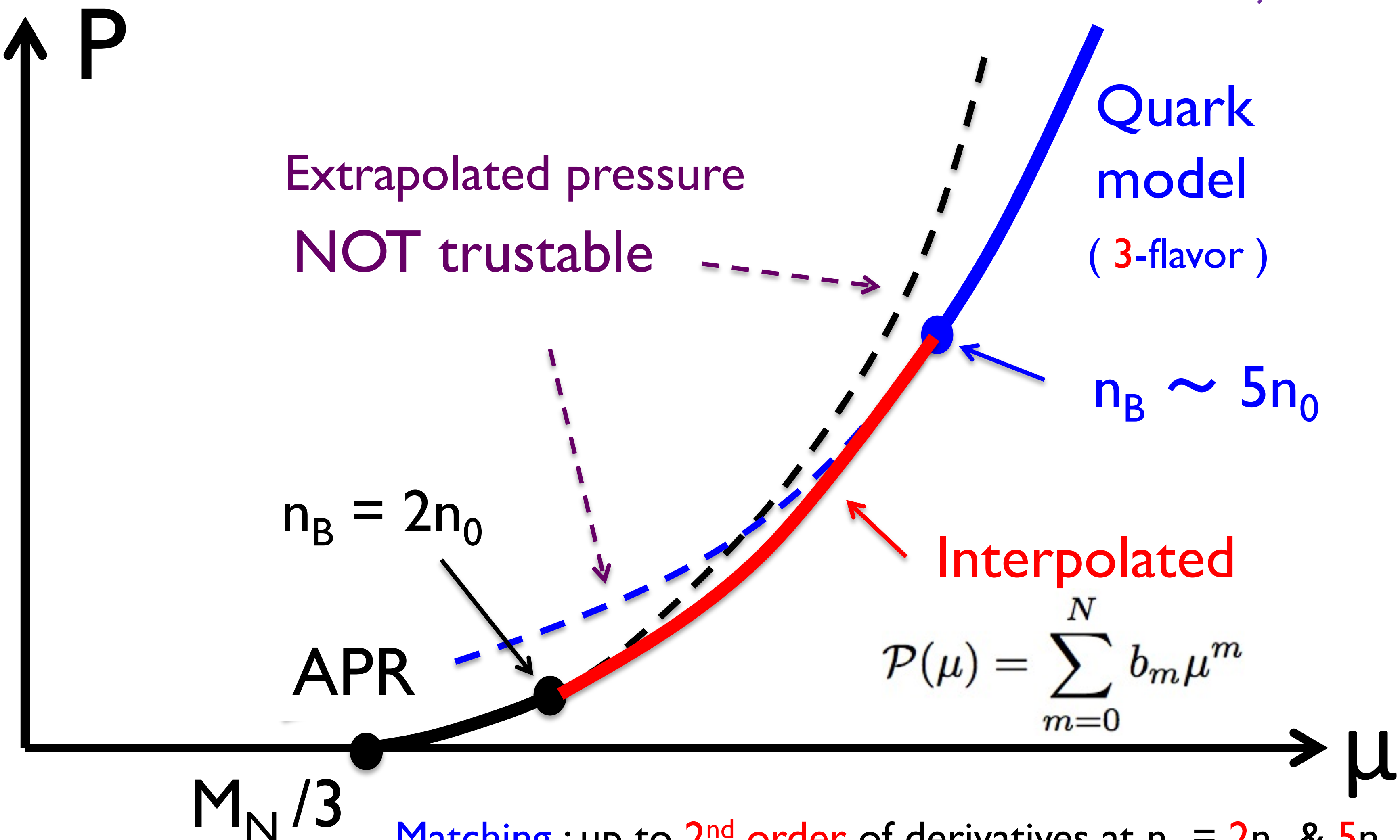


Matching : up to 2nd order of derivatives at $n_B = 2n_0$ & $5n_0$

(if you wish, put a small kink for weak 1st order P.T.)

3-flavor quark MF model : template

Kojo+2014

$$\mathcal{H}_{\rm eff} \sim \bar{\psi}\left[-i\vec{\alpha}\cdot\vec{\partial}+m\right]\psi + \mathcal{H}_{\rm NJL}^{\rm 4Fermi+KMT}$$

→ change in Dirac sea, beyond no-sea approximation

$+ \mathcal{H}_{\rm conf}^{3q\to B}$ ➡ will be ignored at $n_B > \sim 5n_0$

mag. part

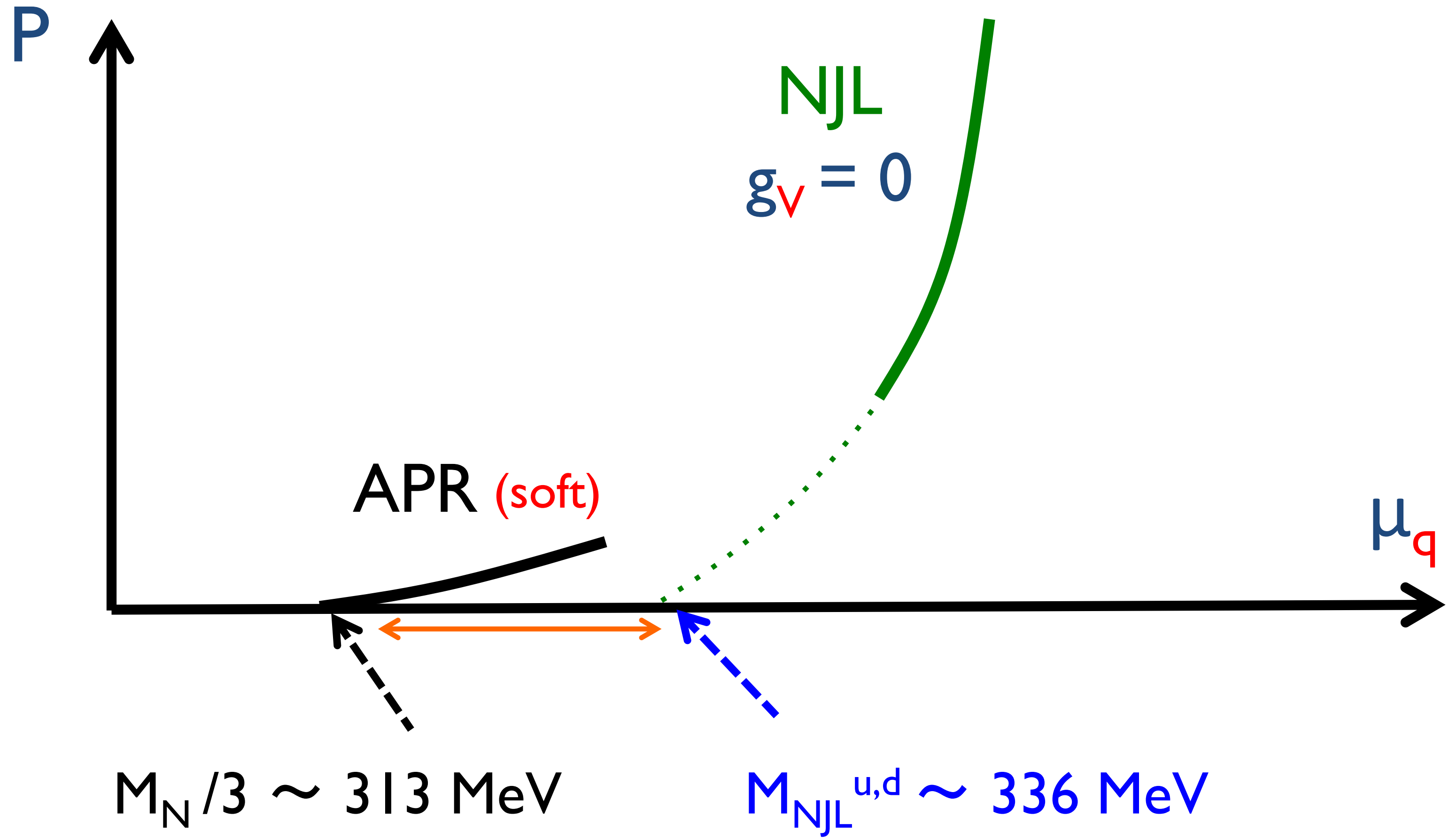
$+ \mathcal{H}_{\rm OGE}$ ➡ $- H \sum_{A,A'=2,5,7} \left(\bar{\psi} i\gamma_5 \lambda_A \tau_{A'} \psi_c\right)^2$ (cf: N-Δ splitting)

$+ \mathcal{H}_{\rm nucl}$ ➡ $+ g_V (\bar{\psi}\gamma_0\psi)^2$ ~ ω-exchange (repulsive)

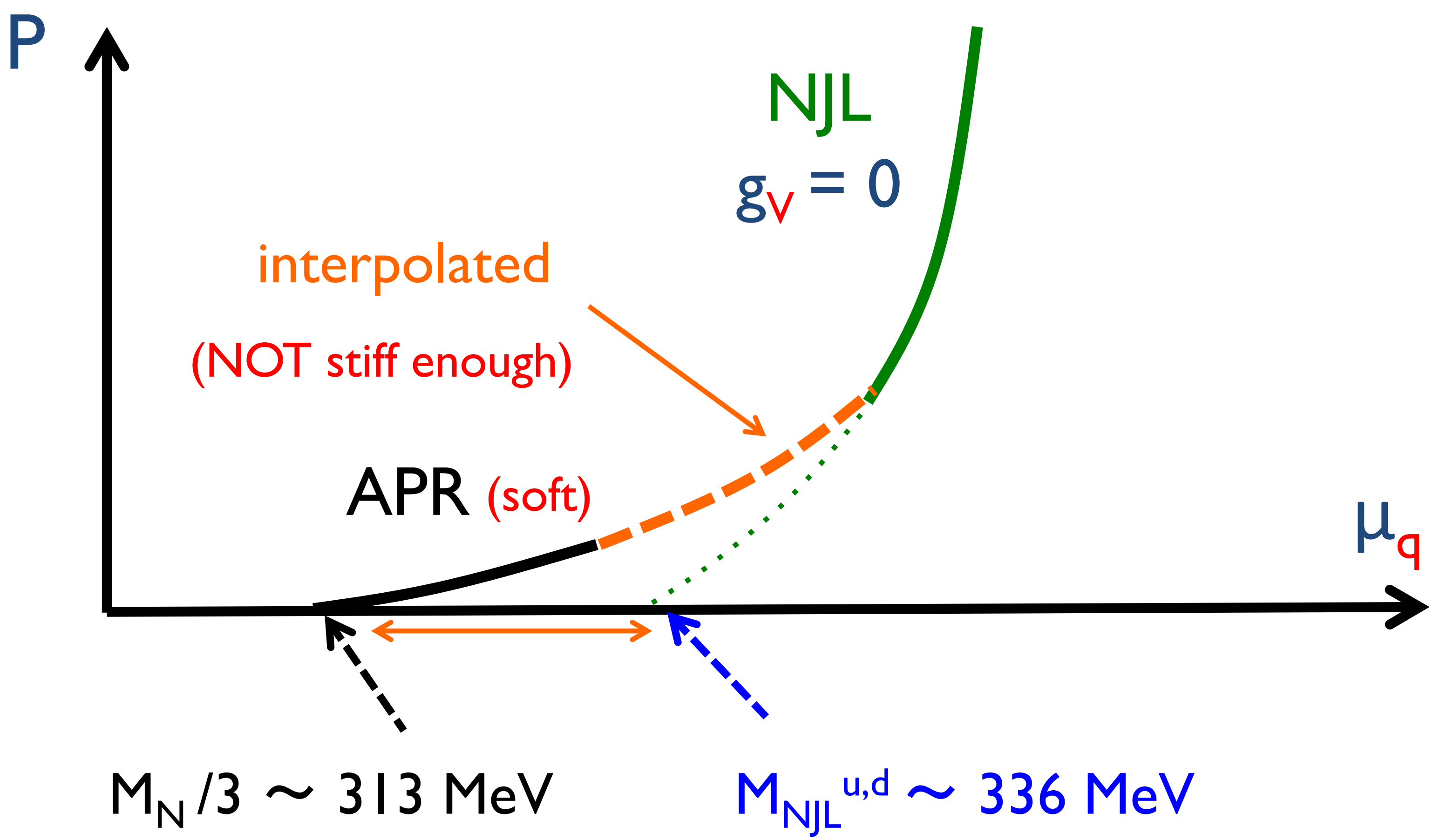
+ **important** constraints (charge neutrality & β- equilibrium & color-neutrality)

Goal: **Delineate** the properties of matter through (G_s, H, g_V)$_{@5\text{-}10n0}$

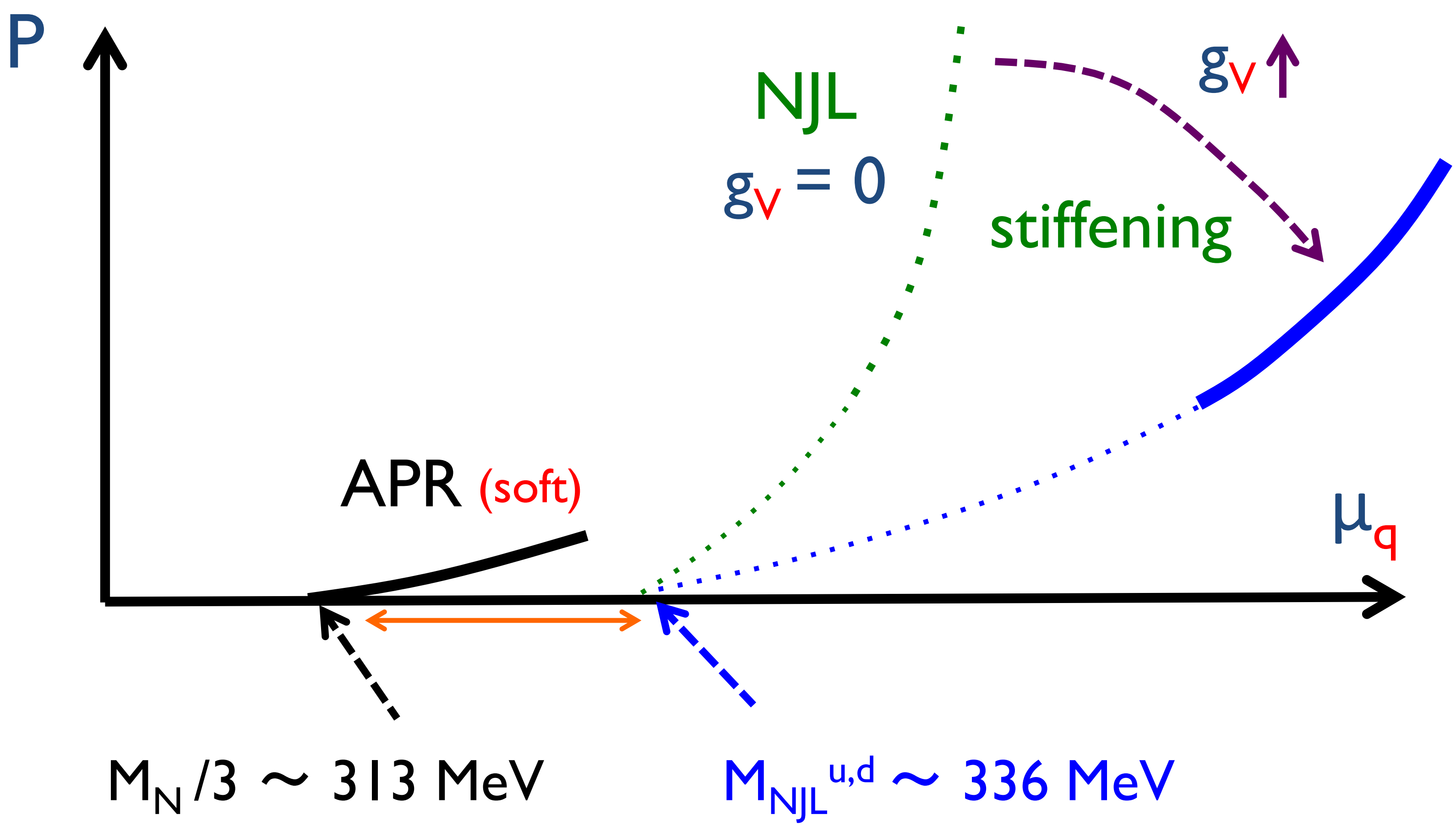
minimal



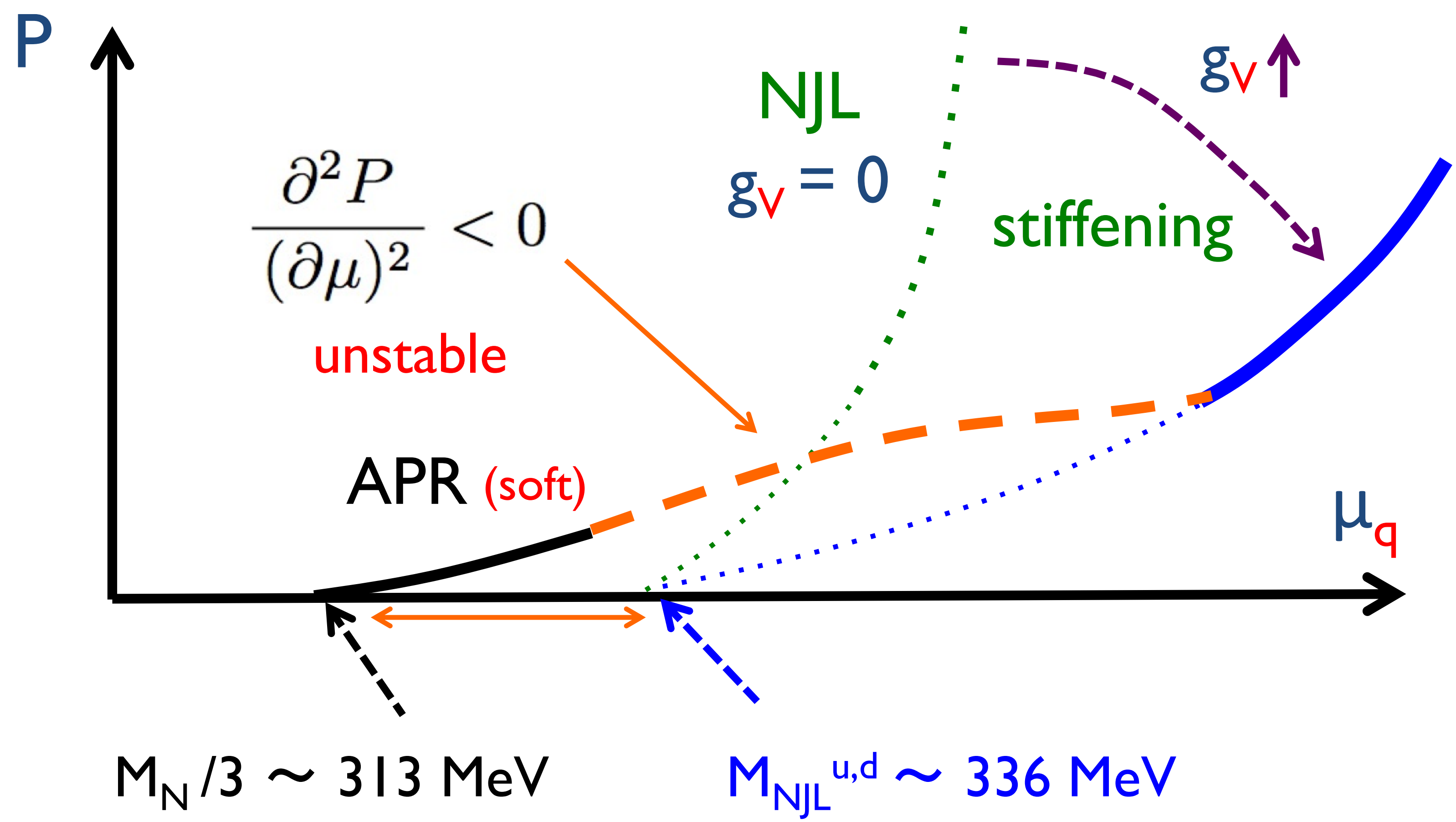
minimal


P
NJL
$g_V = 0$
interpolated
(NOT stiff enough)
APR (soft)
μ_q
$M_N/3 \sim 313$ MeV
$M_{NJL}^{u,d} \sim 336$ MeV

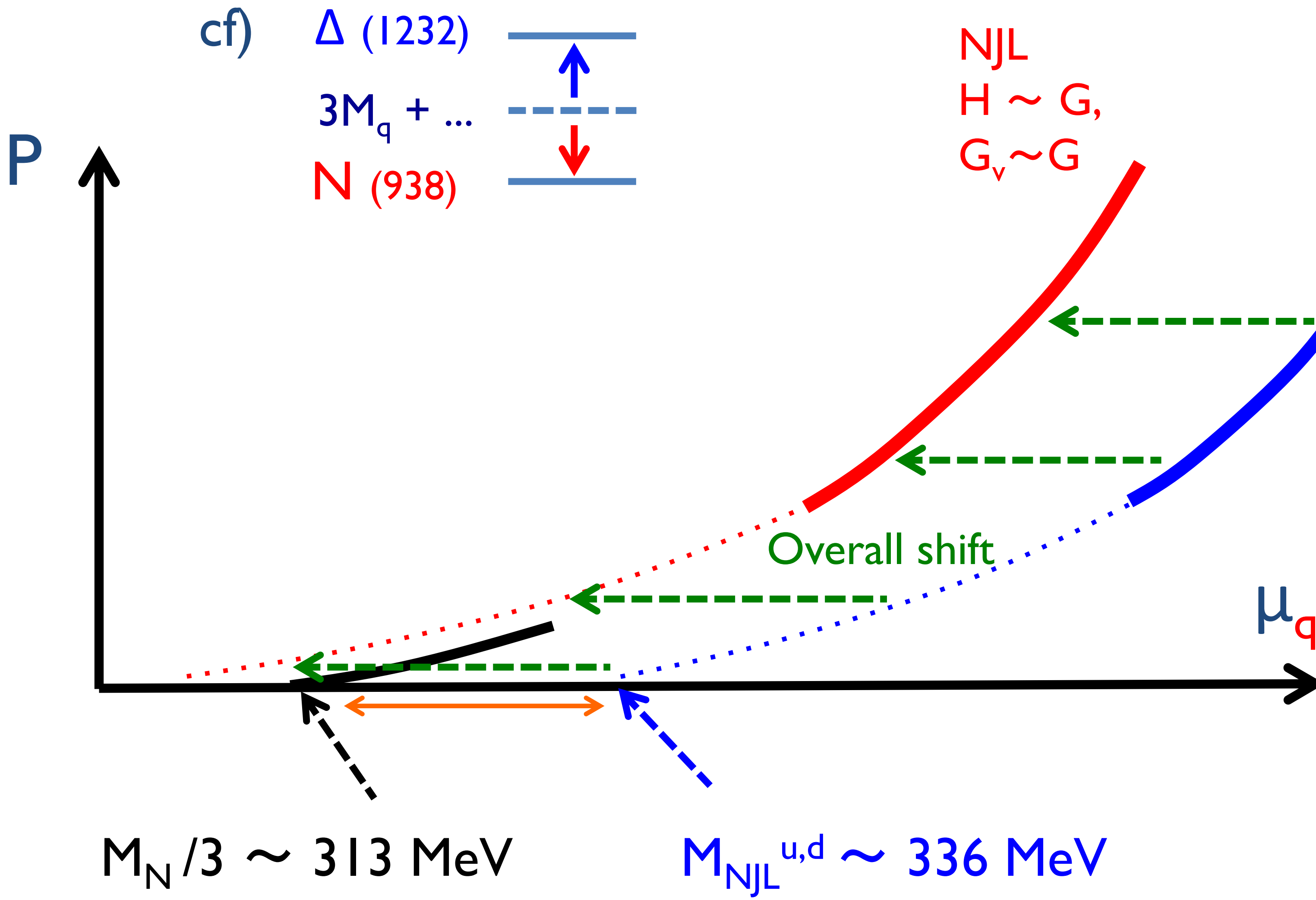
minimal + vector int.



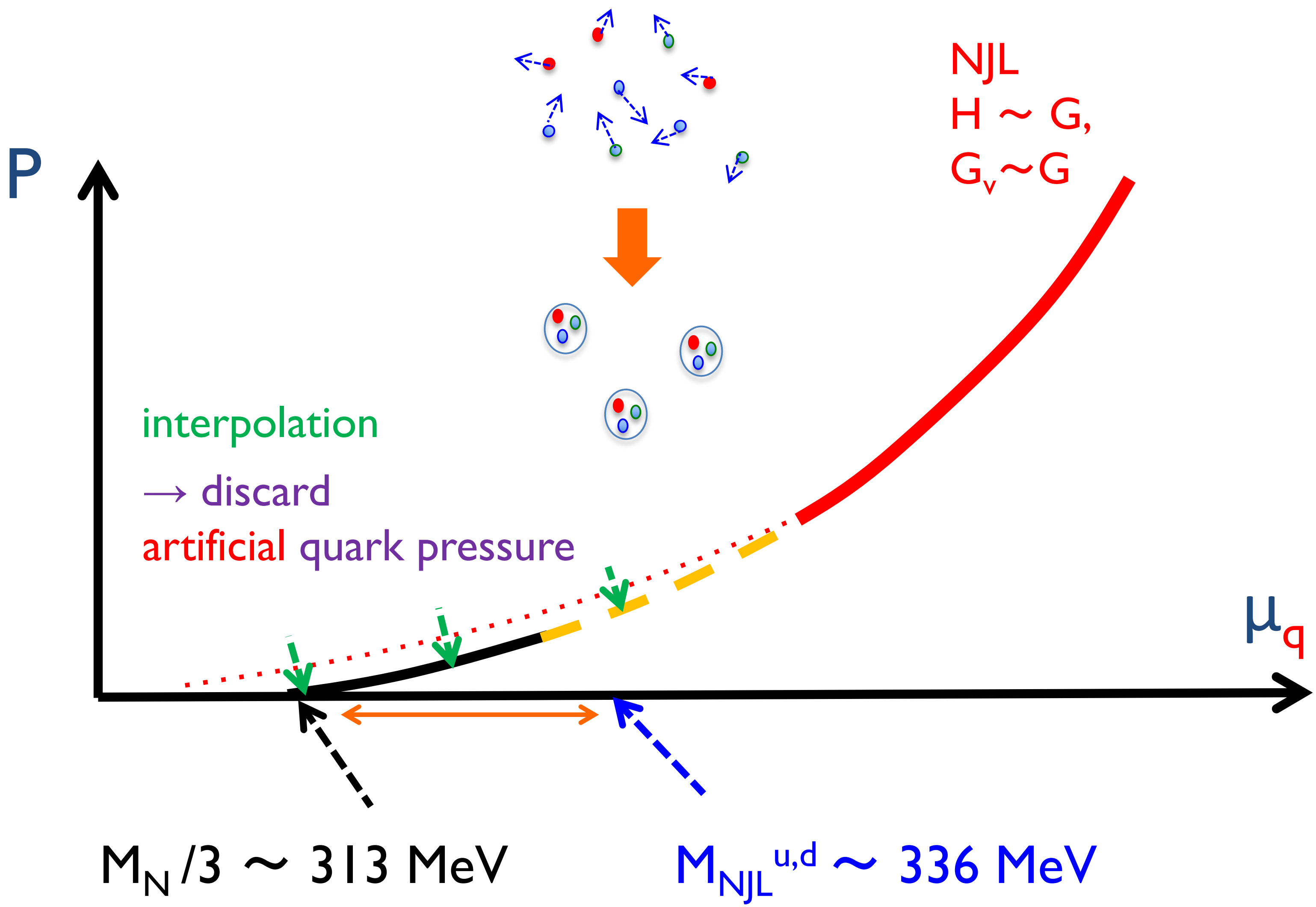
minimal + vector int.



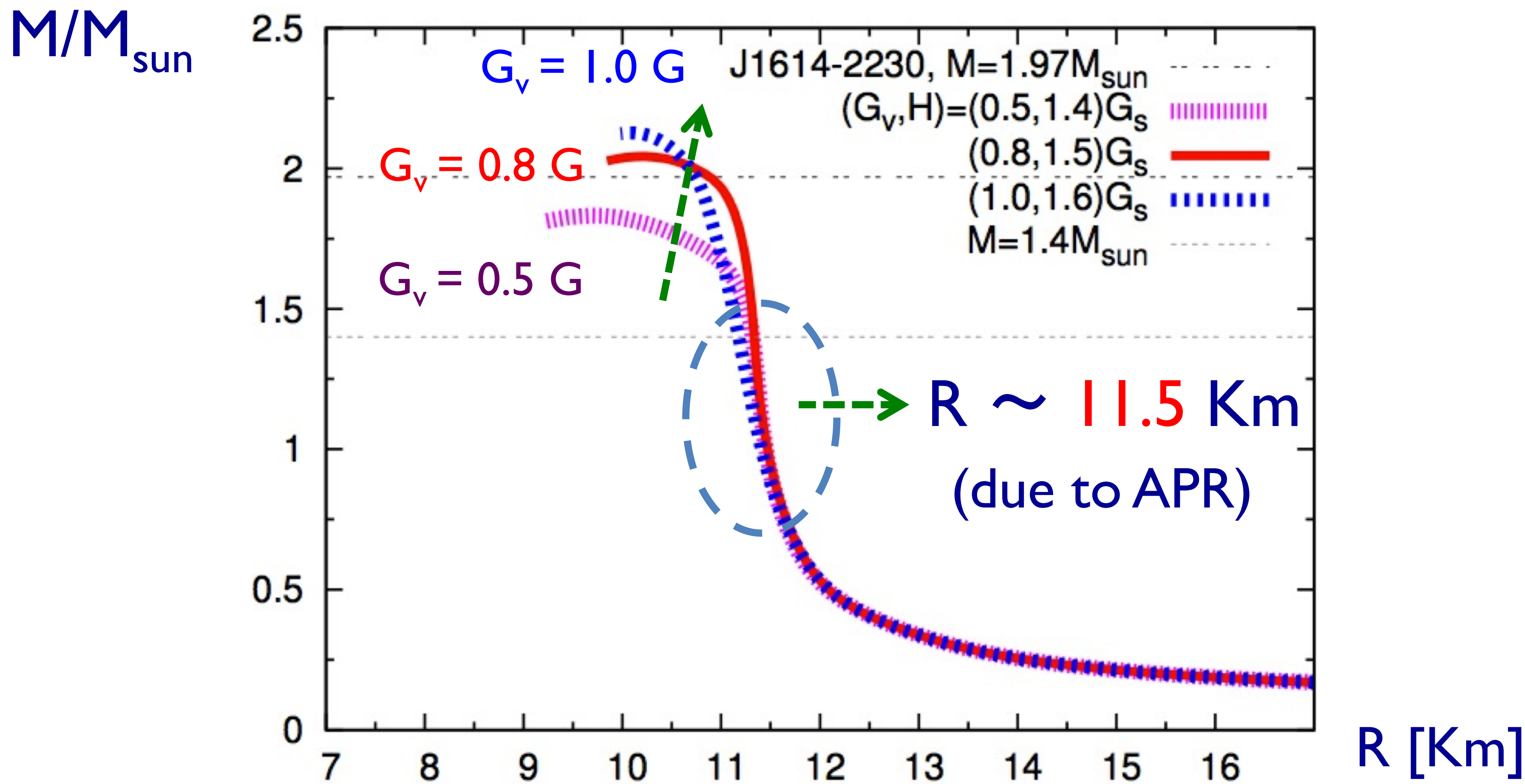
+ attractive color-magnetic int.



+ confinement in dilute matter



M-R curves for QHC18

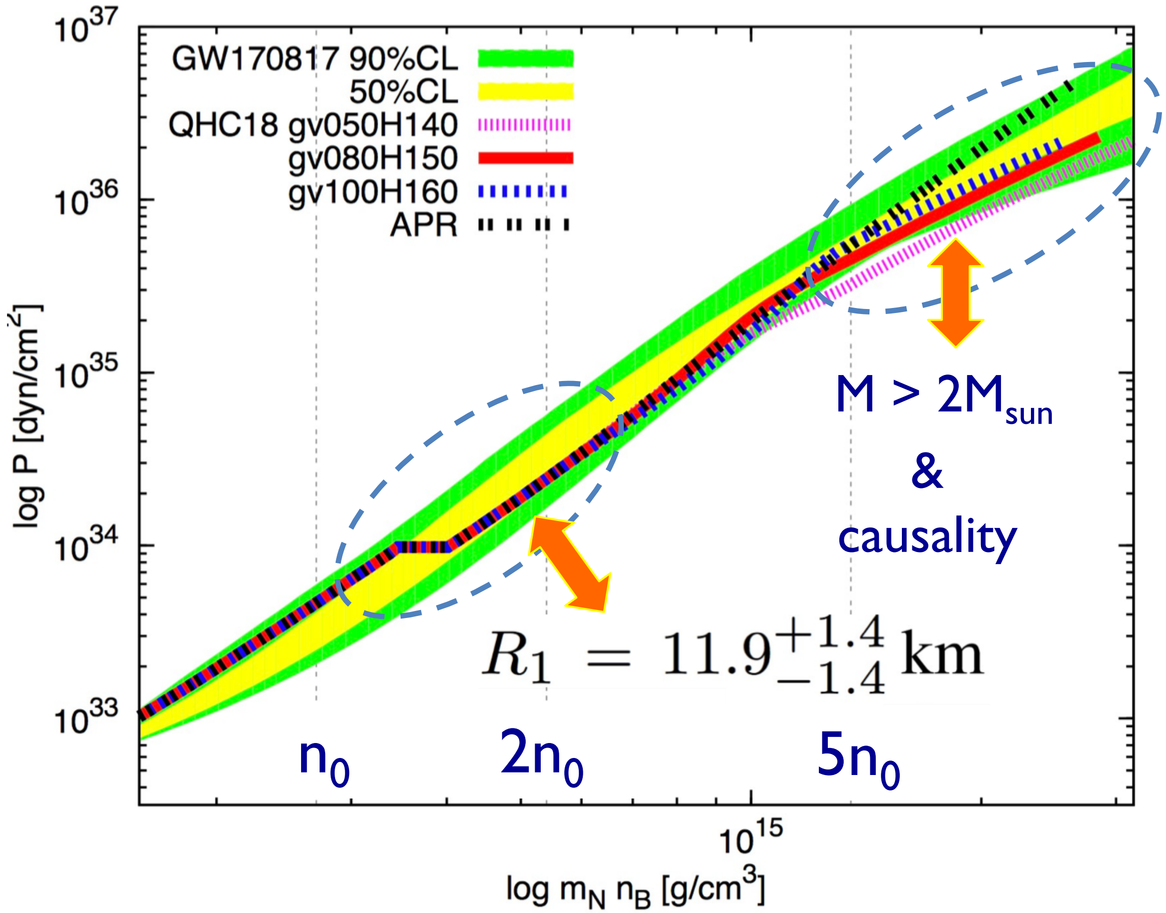


we need :

$$G_s \sim G_v \sim H \ \ @ \ \ n_B = 5\text{-}10\ n_0 \quad \rightarrow \quad O(G_s^{vac})$$

EoS from aLIGO vs QHC18

aLIGO & Virgo new analyses for GW170817 arXiv: 1805.11581 [gr-qc]



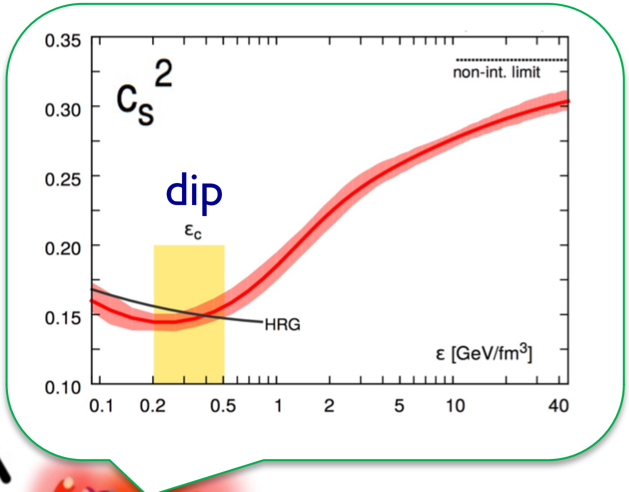
EoS constraints with

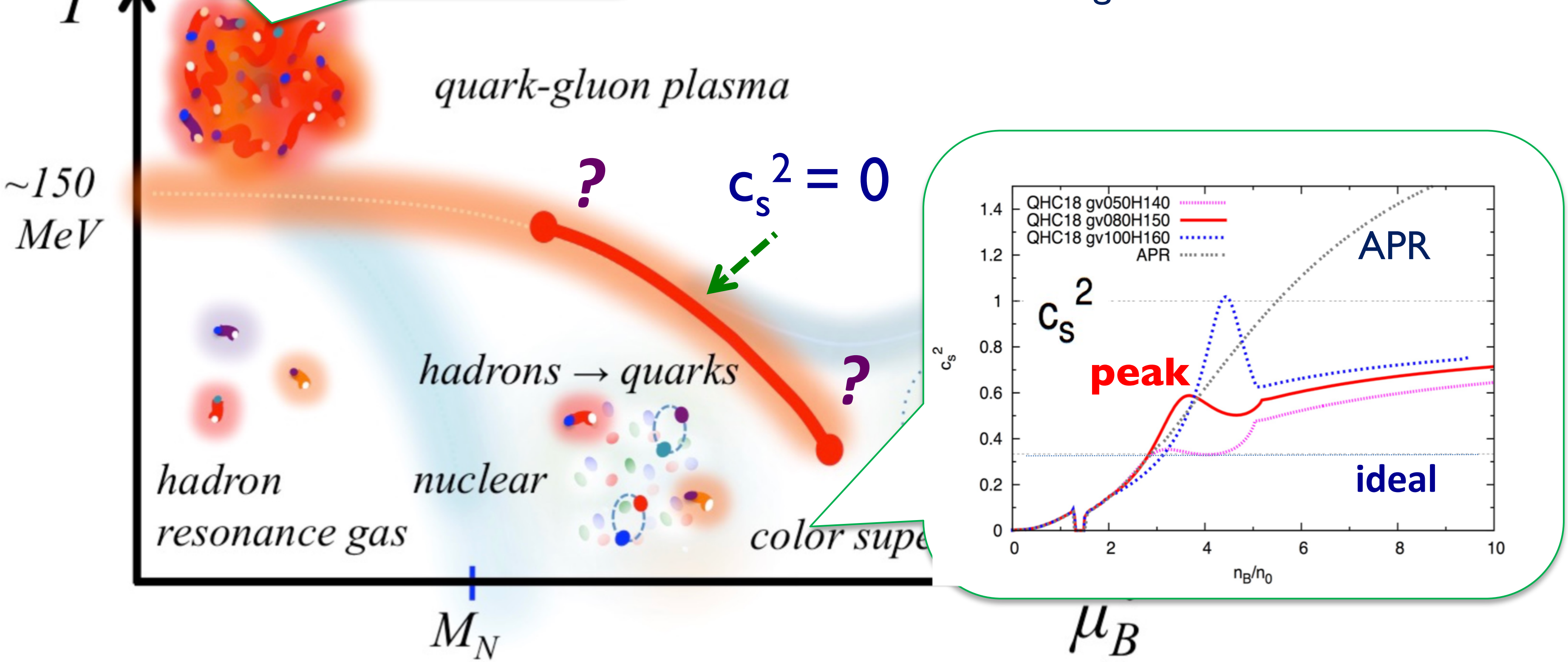
- $M > 2M_{sun}$
- tidal deformability
- causality

Finite T vs low T crossover

Their characters are **different** :

- speed of sound
- thermal vs quantum P.T.
- entropy
- the nature of gluons





Summary

1, Neutron star M-R relations → Direct Info of QCD EoS

2, Hints for **Soft**-**Stiff** EoS

→ crossover or weak 1st order P.T. for 2-5n_0

3, Quark matter EoS can be stiff;

the impression of soft quark EoS was largely biased

by traditional hybrid construction...

4, $(Gs, G, H)_{@5\text{-}10n0} \sim Gs^{vac}$ → Hints for non-pert. gluons

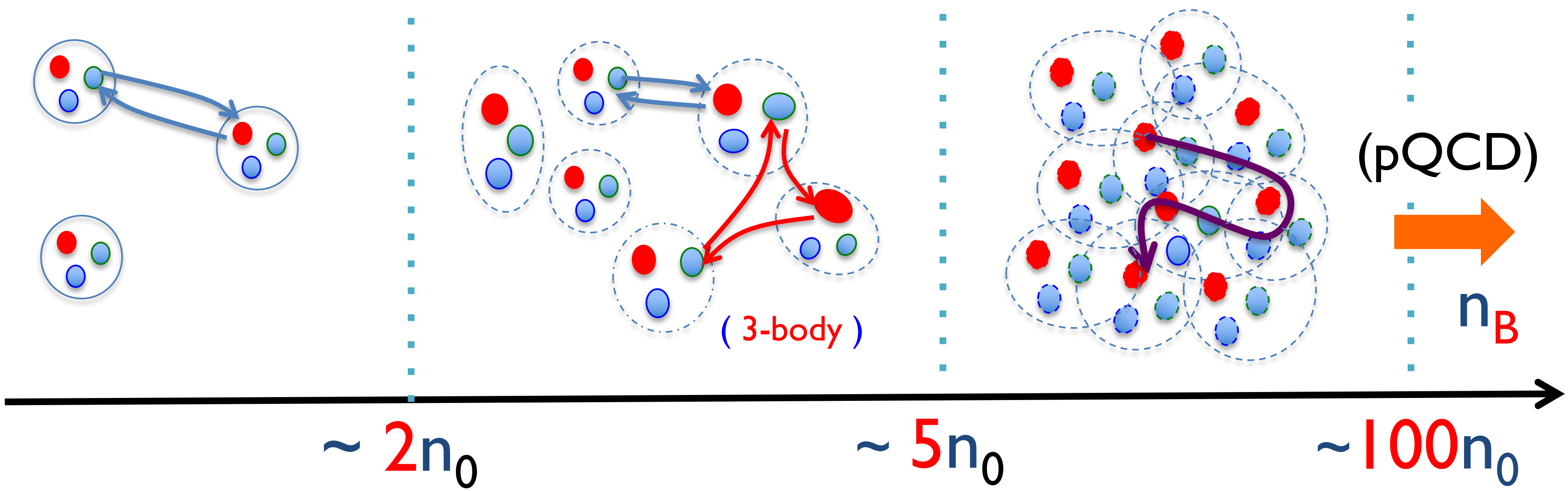
To Do (work in progress...)

Nuclear matter
+ quark substructure corrections

Hardest part

modeling?

Quark matter
+ hadronic correlations

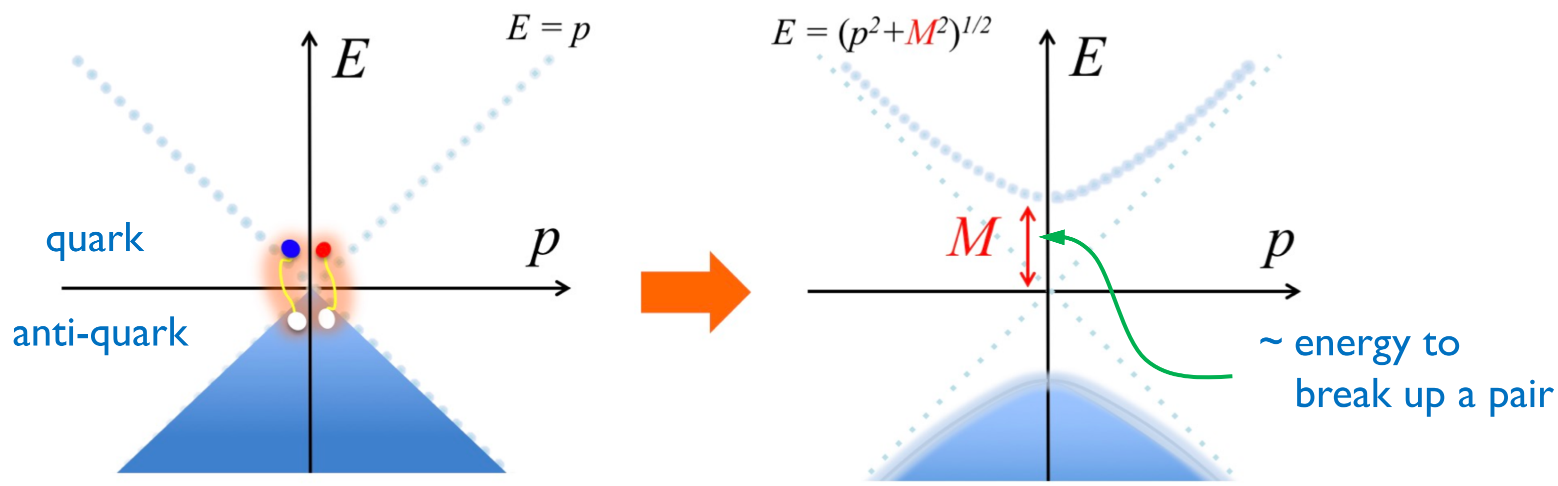


Then the matter should be heated up → predictions for HMNS

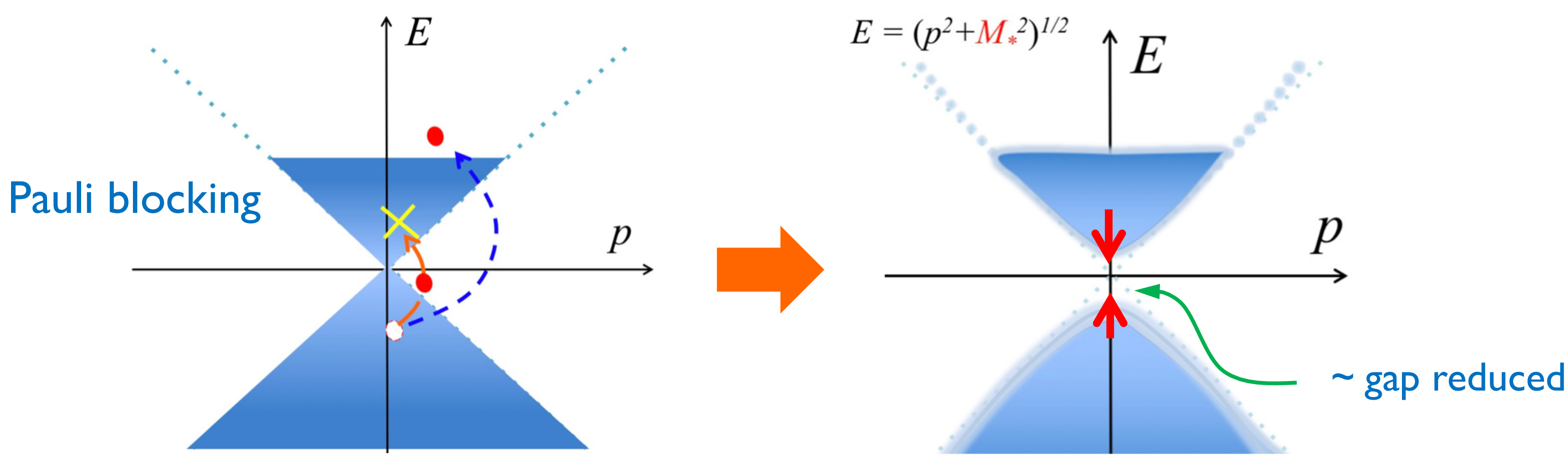
excitation modes ⟺ **the phase structure**

Chiral sym. breaking & restoration

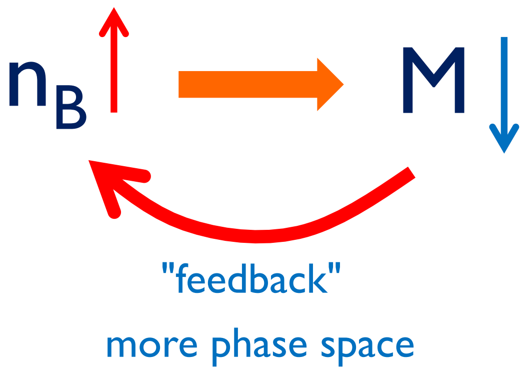
vac



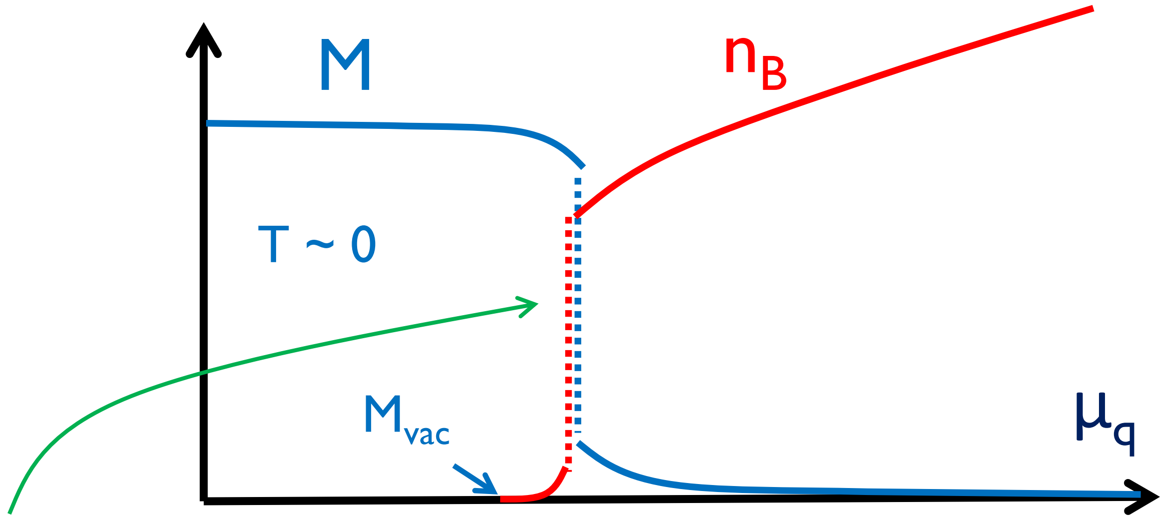
finite density

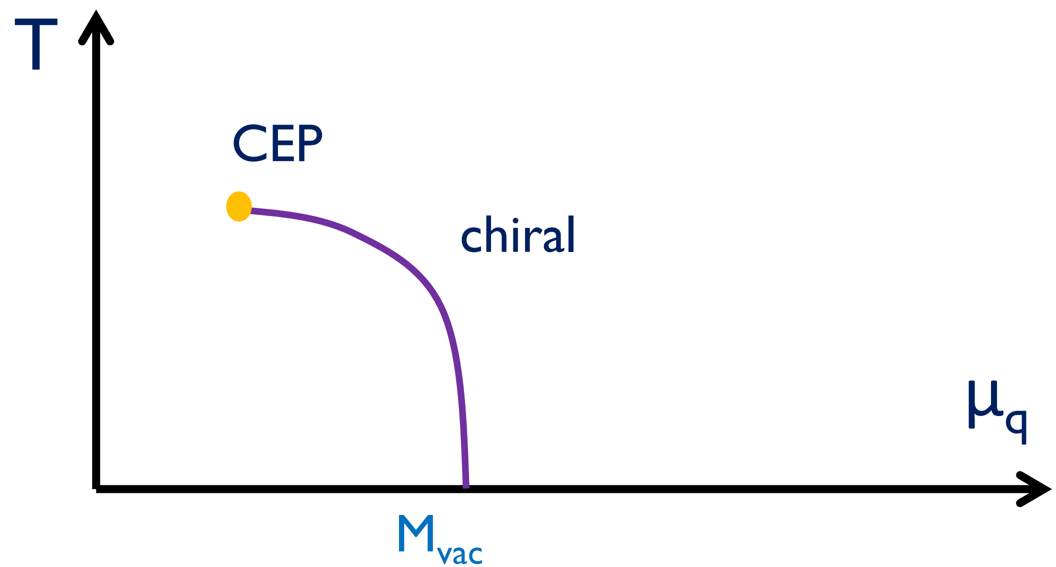


1st order chiral transition (typical quark **models**)



→ radical changes in n_B & M





Braking density evolution: 1st → crossover

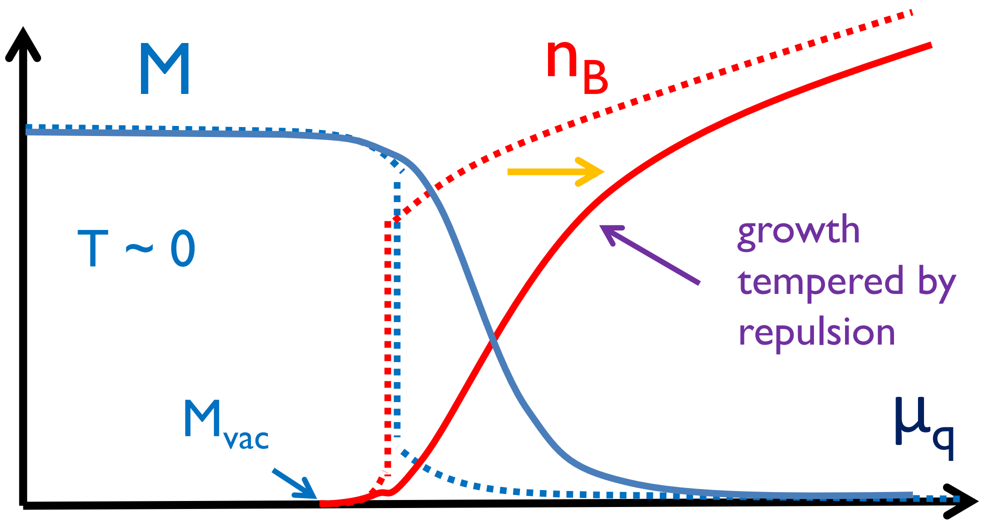
Now add
density-density repulsion

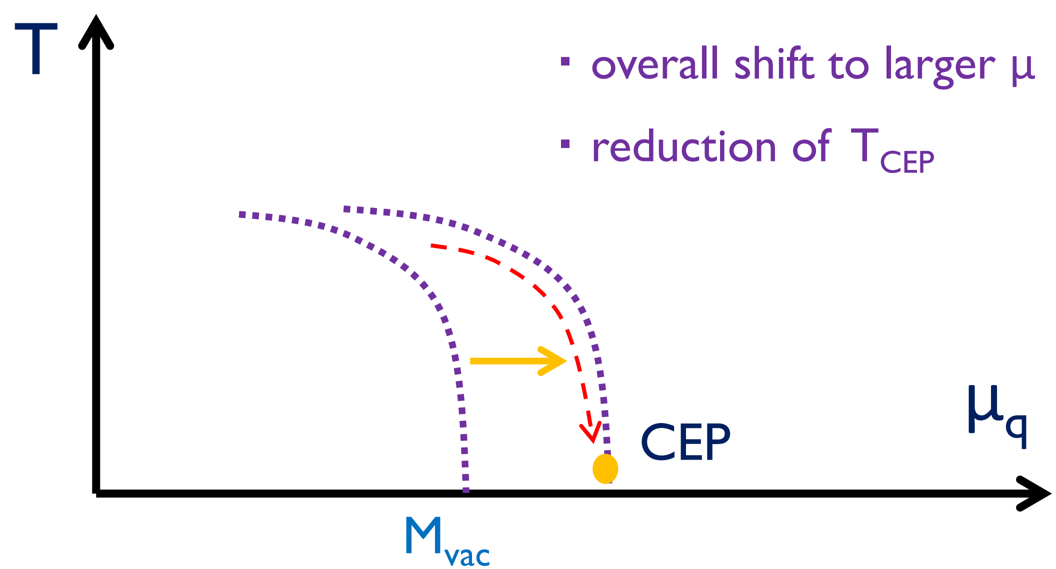
$$\Delta H \sim g_V \, (n_B)^2$$

braking the evolution of n_B

→ milder changes in M

Details of int. are crucial



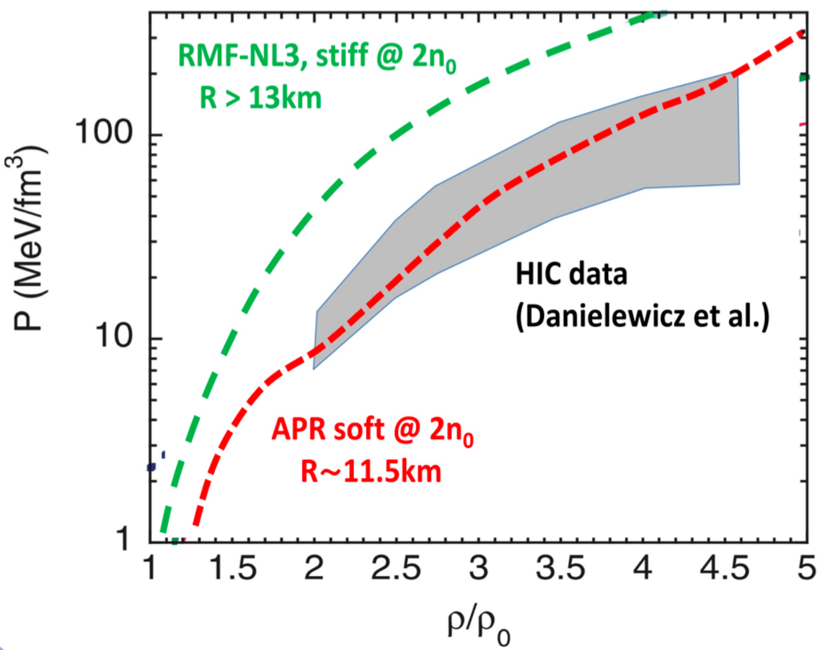


Small $R_{1.4}$ & soft EoS @ 1-2 n_0 ?

- ***Thermal X-rays analyses for NS radii :***
  - **Suleimanov et al (2011) : > 13.9 km**
  - **Guillot et al. (2011) : $9.1^{+1.3}_{-1.5}$ km**
  - **Ozel & Freire (2015) : 10.6 ± 0.6 km**
  - **Steiner et al (2015) : 12.0 ± 1.0 km**

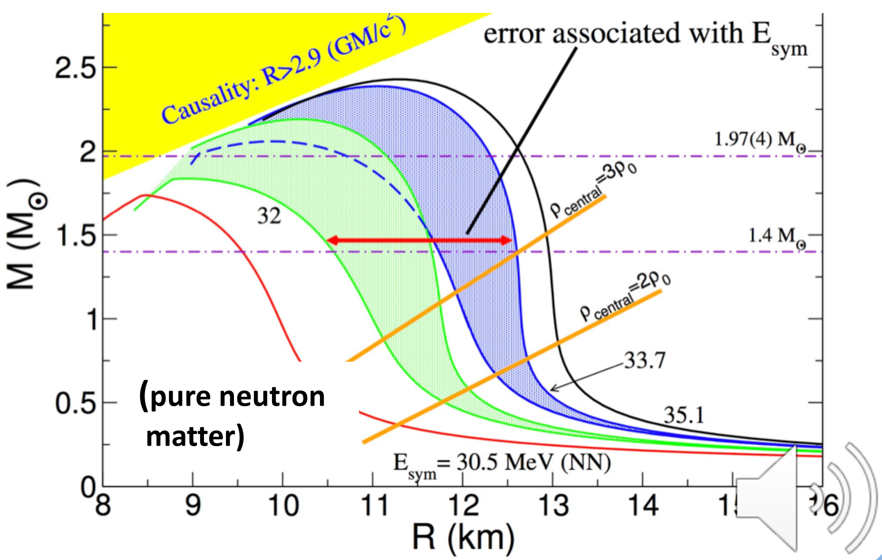
systematic uncertainties : distance to NS, atmosphere of NS, uniform T distributions,…

- ***HIC :*** **(Danielewicz et al. 2002)**

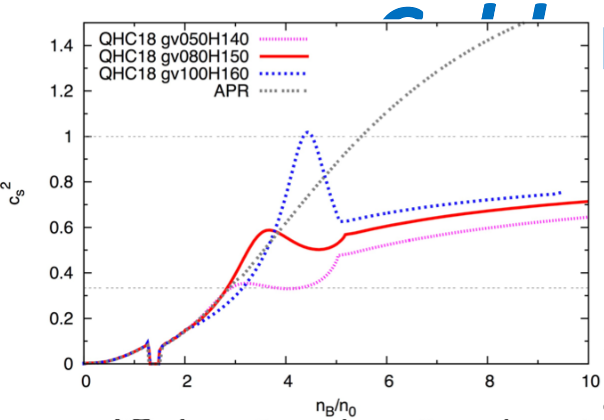


- ***nuclear EoS extrapolation :*** **(Gandolfi et al. 2015)**

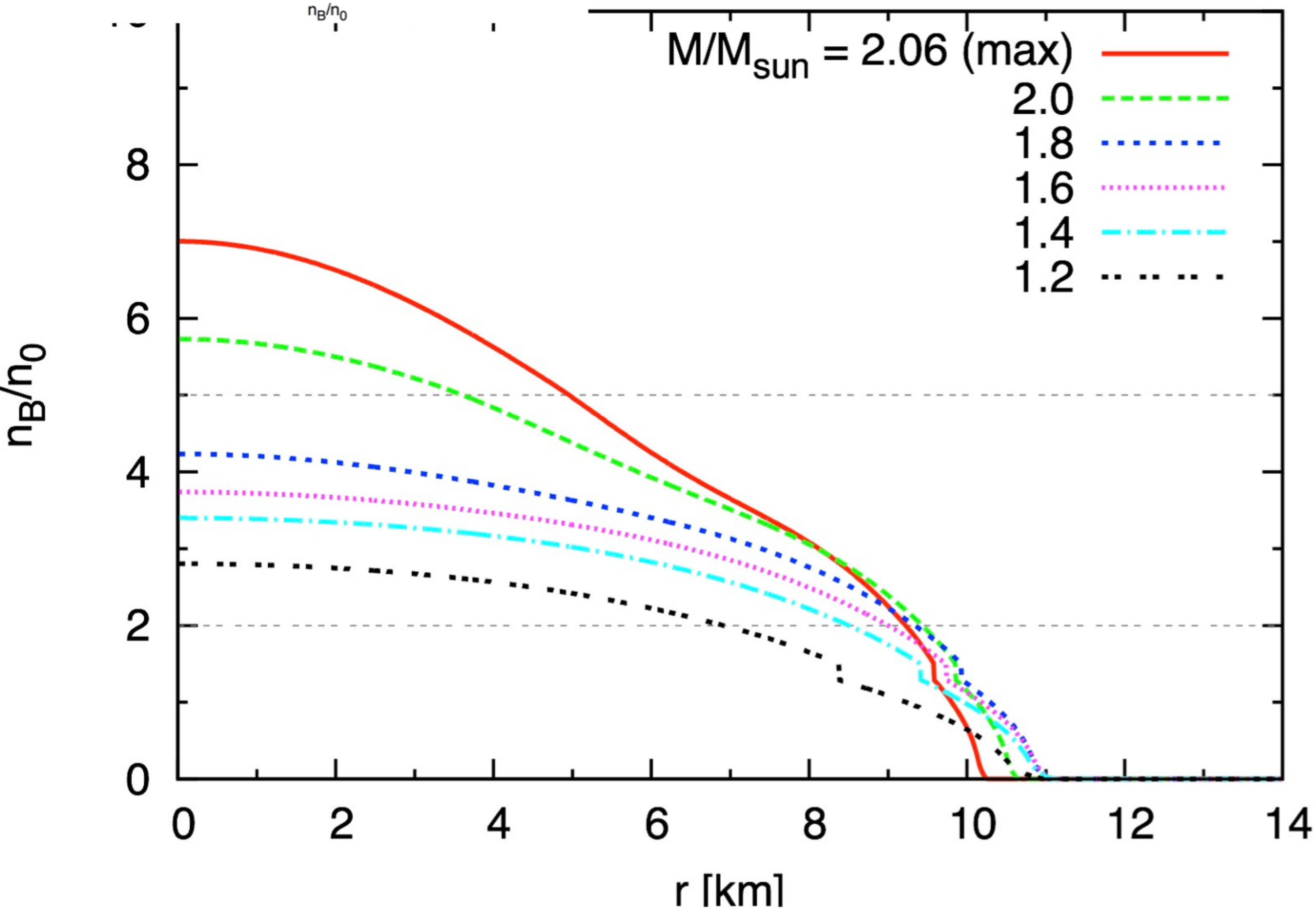
(*sophisticated* potentials & Monte-Carlo)



dense EoS : Low density



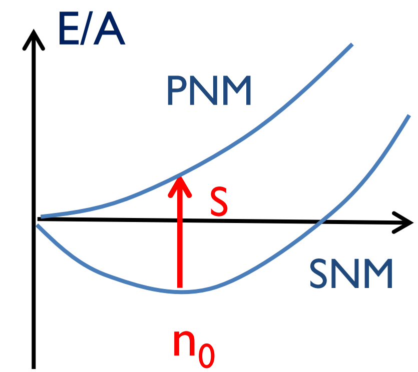
$$R_1 = 11.9^{+1.4}_{-1.4}\ \mathrm{km}$$

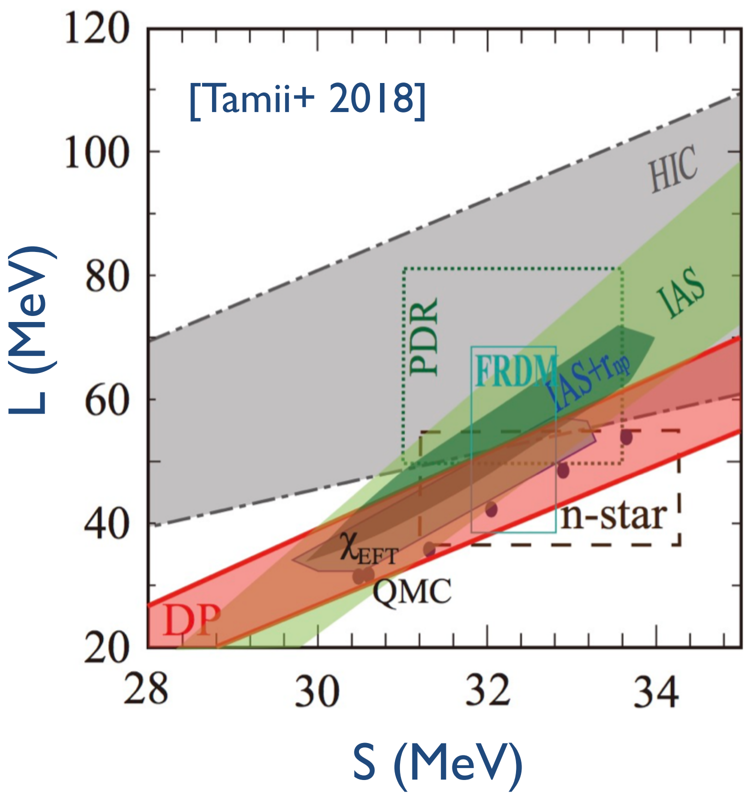


Hints for **soft** EoS at $n_B < 2n_0$

$$\frac{E}{A} = -16\,\mathrm{MeV} + S + \frac{L}{3}\frac{n-n_0}{n_0} + \cdots$$

pure neutron matter EoS — sym. energy — density dep.





Theory · Many-body cal. with ChPT forces

Exp.
- Neutron skin
- Dipole polarizability
- Giant dipole resonance

T ~ 0 MeV

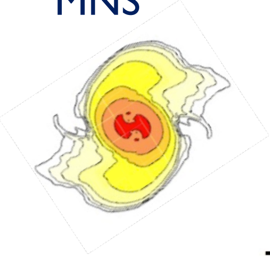
- Heavy ion (E_{lab}/A ~ 200 MeV)

S = **30-35** MeV, **L** = **45-70** MeV

Then, EoS extrapolated to $2n_0$ leads to

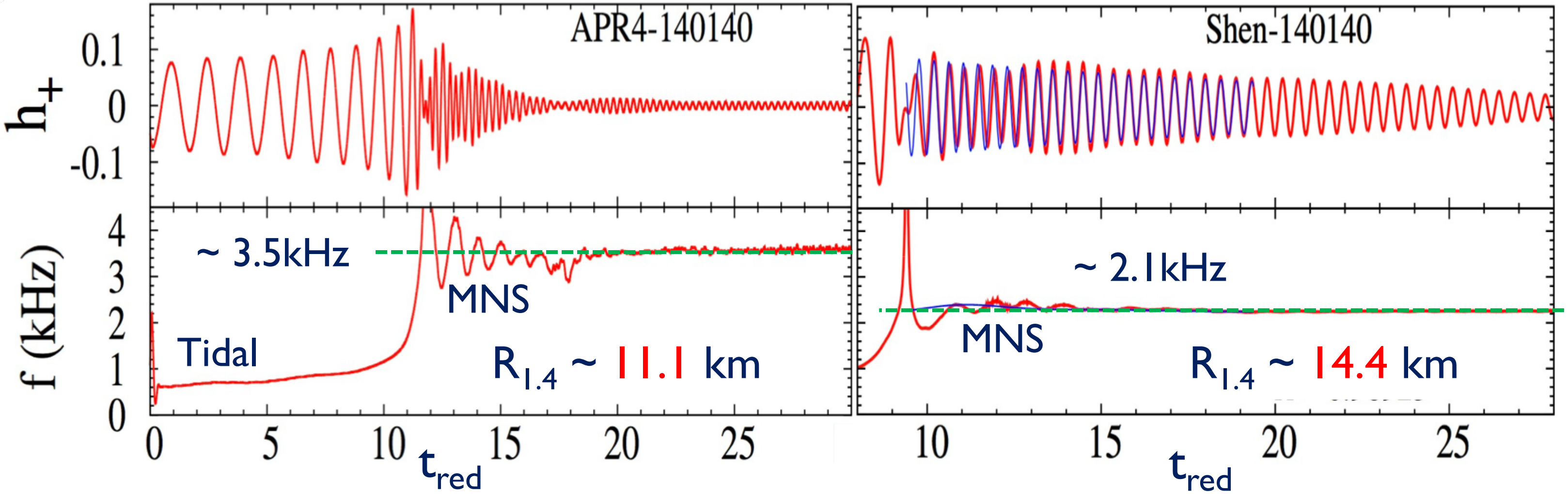
$R_{1.4}$ = 11-13 km

MNS



Merger & HMNS: $f_{GW} \rightarrow R_{NS}$

Figs from Hotokezaka+ 2013



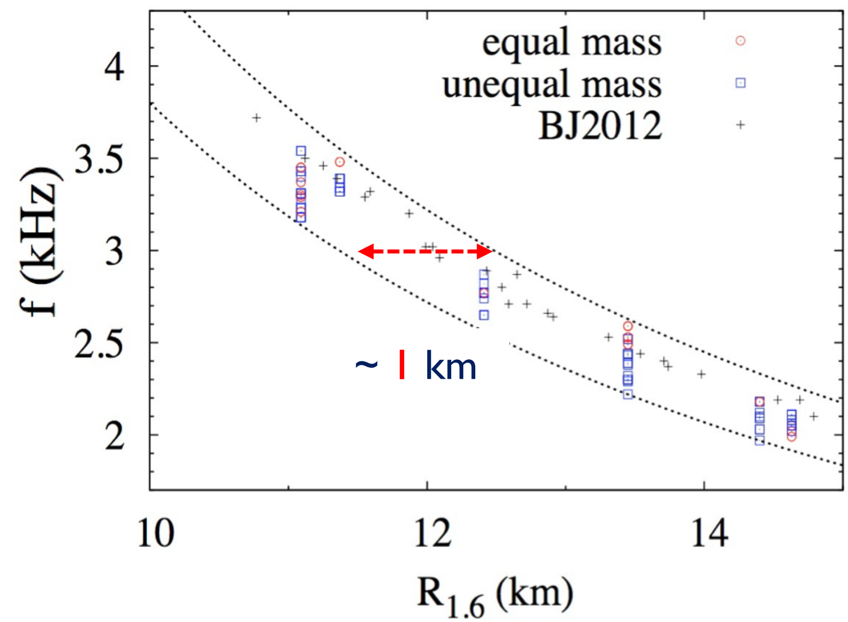
compact stars → high frequency GW

smaller R_{NS} → larger f_{GW}

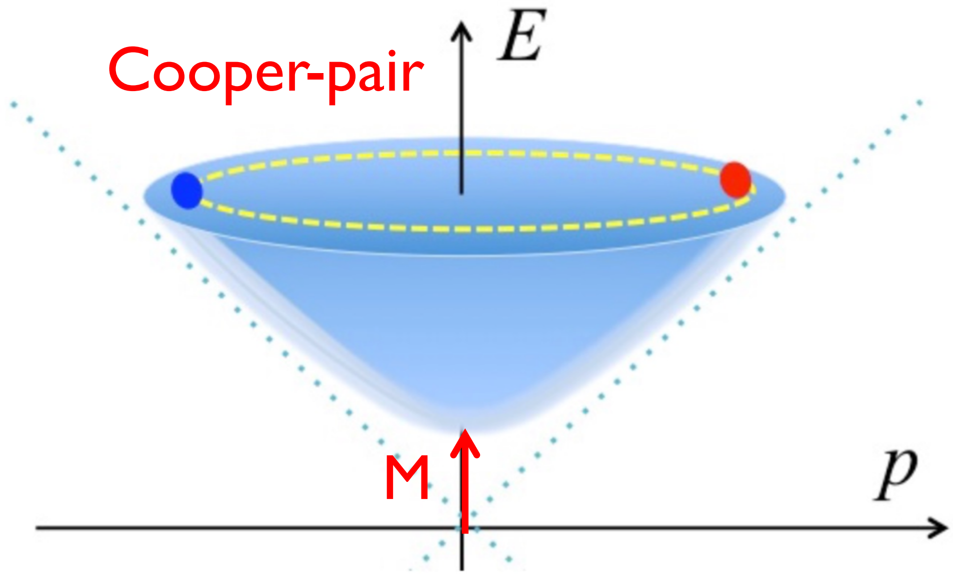
(Bauswein and Janka 2012)

For **GW170817** :

f_{GW} is **NOT measured yet**;
high frequency region → smaller S/N



Di-fermion pairing



Either

di-baryon pairing

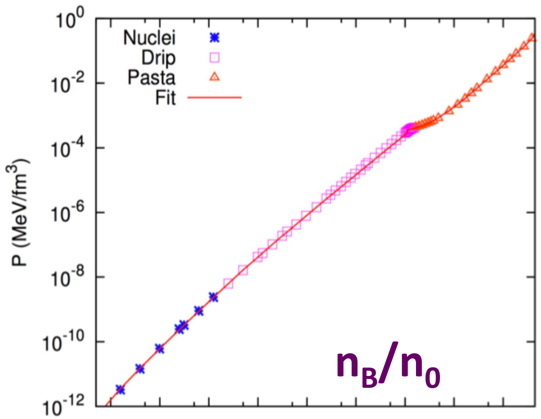
or

di-quark pairing

- Fermi surface effects larger phase space for low E excitations
- Can happen in the presence of chiral condensate (coexistence)
- Chiral sym. can remain broken from hadron to CSC phases

EoS & M-R relation

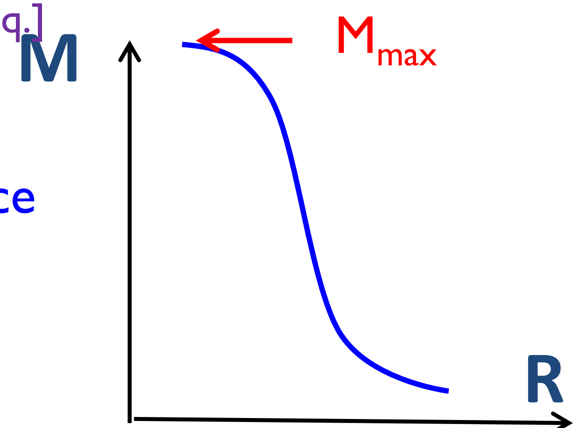
Einstein eq. : $$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$ QCD EoS



[for spherical NS : TOV eq.]

1-to-1 correspondence

Lindblom (1992)



1) non-rotating, spherical NS : TOV equation $M_{TOV} > 2M_{sun}$

2) uniformly rotating NS : e.g. Hartle-Thorne $M_{uni} \sim 1.2\ M_{TOV}$

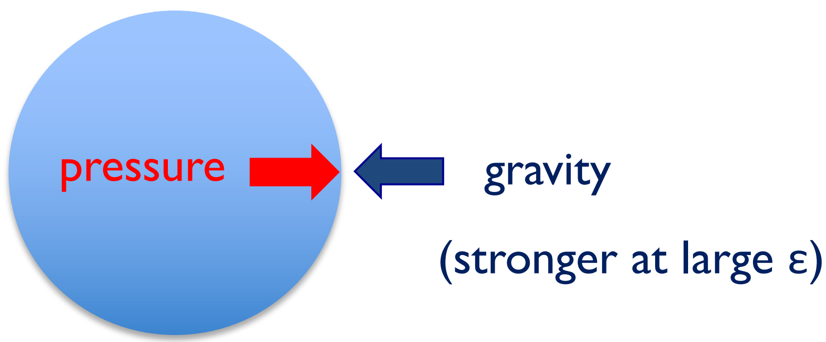
(stable if rotation is slow enough)

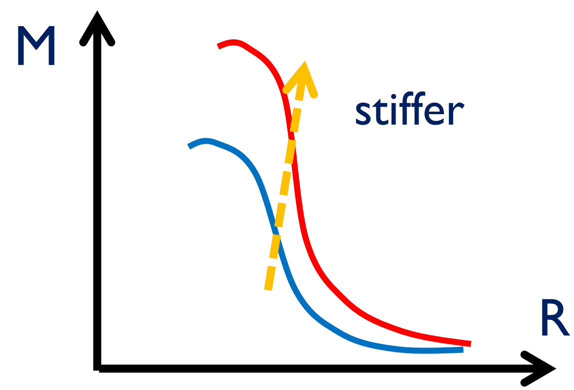
3) differentially rotating NS : Numerical GR $M_{diff} \sim 1.5\ M_{TOV}$

(short-live; dissipation and magnetic braking → collapse)

Definition of terminology in this talk

1, **Stiff** EoS ↔ **P** is large at given **ε**

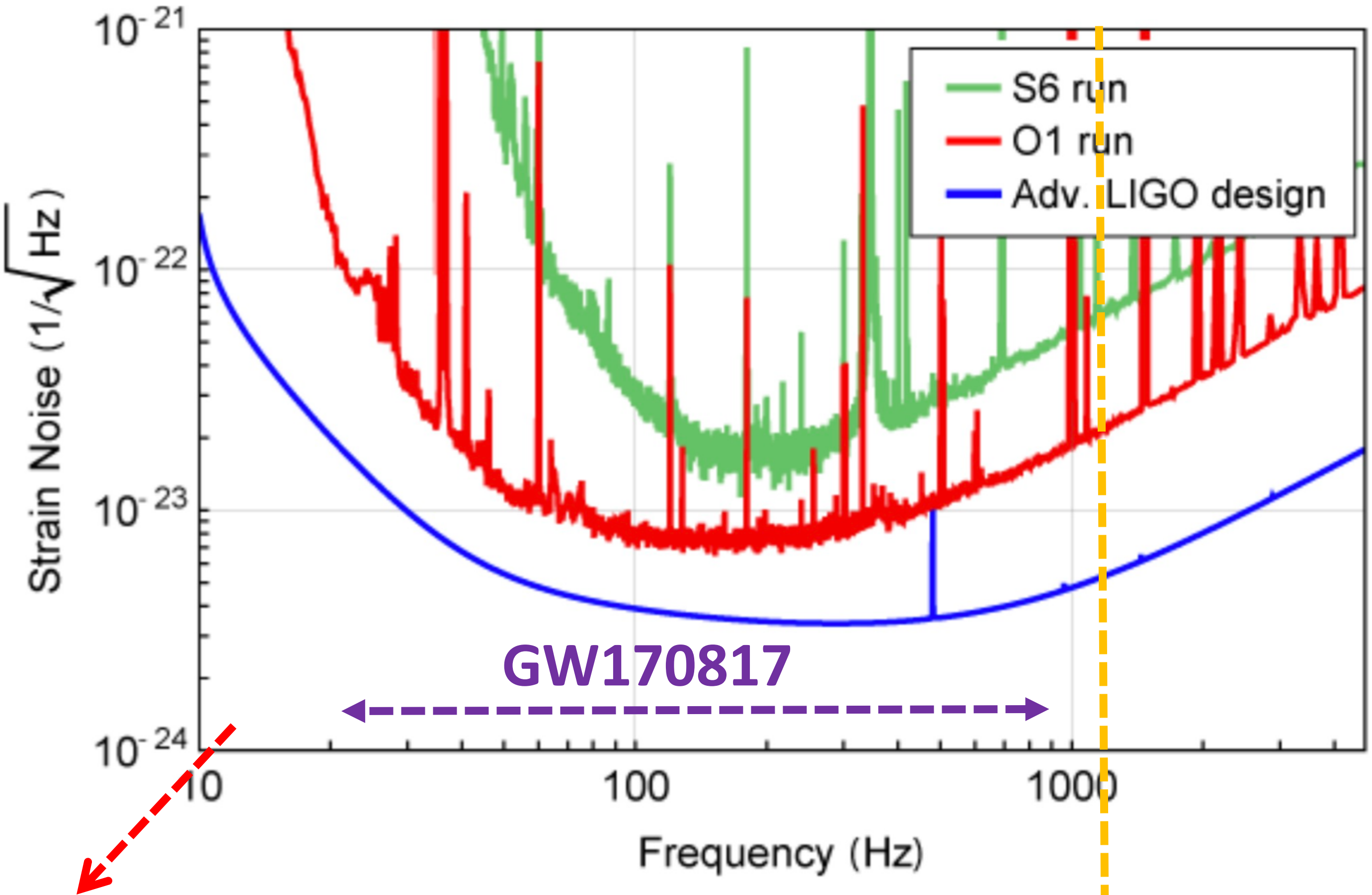




2, soft-stiff EoS

soft at low n_B (< $2n_0$) & stiff at high n_B (> $5n_0$)

Design sensitivity



inspiral

(noise: seismology)

tidally deformed phase

(noise: mirror)

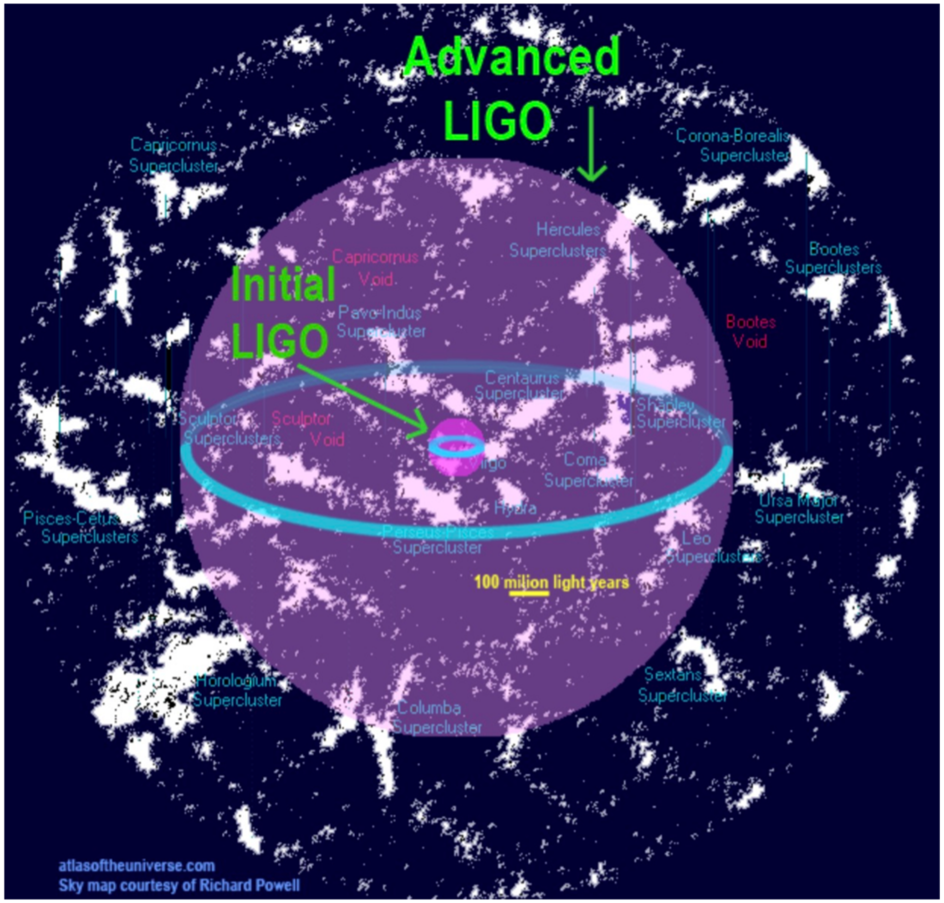
~ post-merger

HMNS or BH

(quantum noise: laser)

To detect rare events

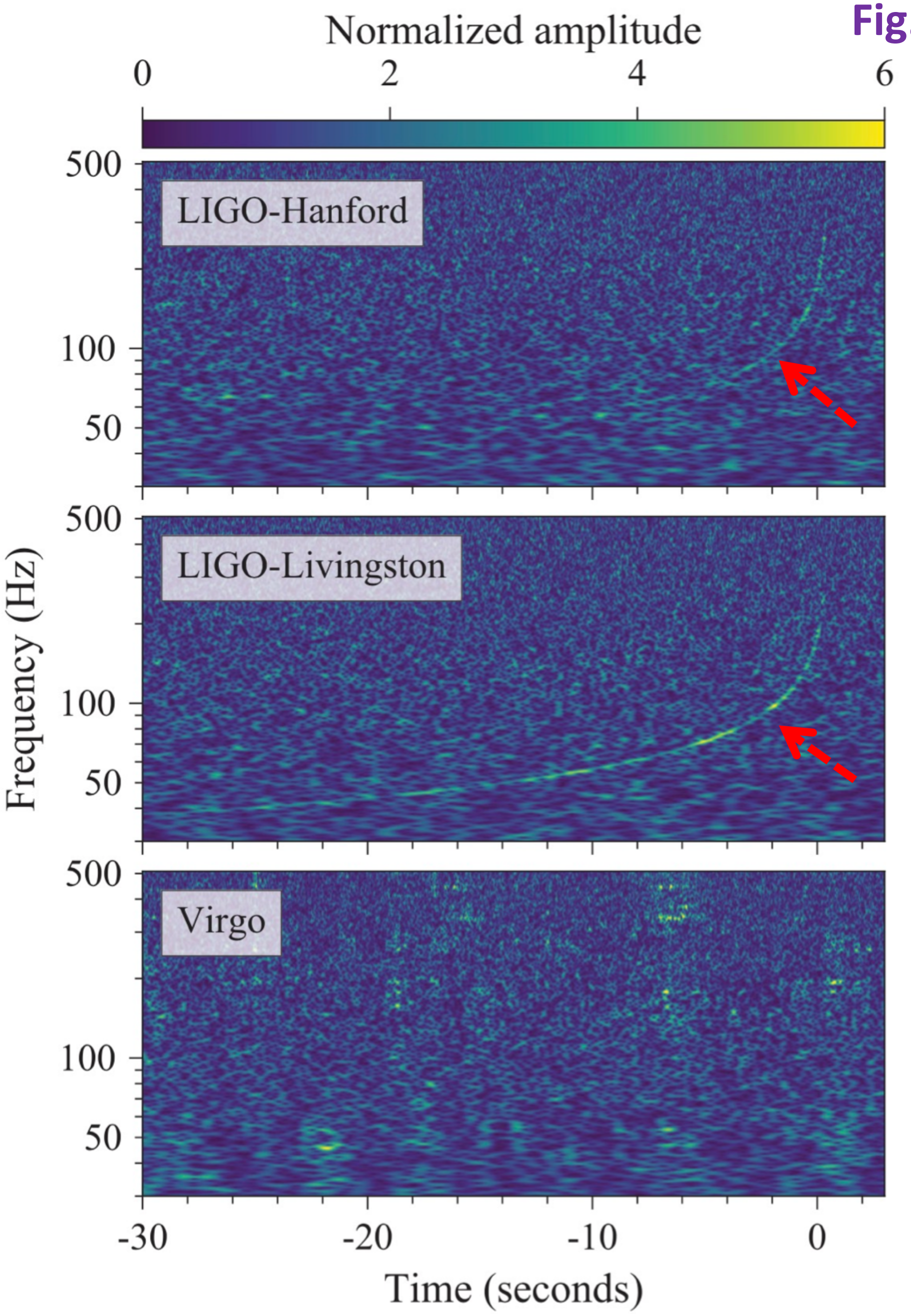
1pc = 3.26 lyr



- our galaxy (milky-way) ~ 31-55 kpc
- to the edge of universe ~ 14 Gpc
- *detector horizon*
  - aLIGO
    Livingston ~ 218 Mpc
    Hanford ~ 107 Mpc
  - Virgo ~ 58 Mpc
- *expected detection rate*
  0.1 – 100 events/year

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

Fig. from PRL 119, 161101 (2017)

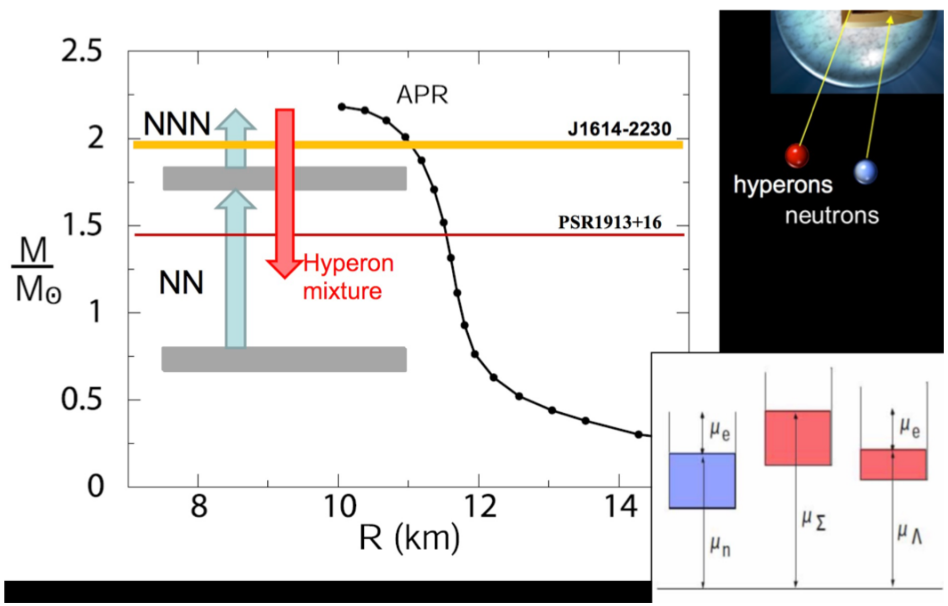


- aLIGO: signal-to-noise = 32.4 !
  - (largest GW signal ever)
- Virgo did not find it
  - GWs from the blind spot of Virgo
  - → strongly constrain the location
  - → trigger follow-up EM studies
- clear signal 20 Hz - 1kHz
  - *inspiral* – *tidal deformed* phases
  - *BH ring-down* not measured
  - (larger noise at higher frequency)
- EM signals from objects just after merger

So we need dynamical arguments

- ***Troubles of purely hadronic EoS at n_B > ~ 2n_0***
  - ***Convergence: 2-body forces ~ 3-body forces***
  - ***Hyperon problems (softening)***

Most typical attempts



Put by hand

Exclusion volume effect for baryons

or

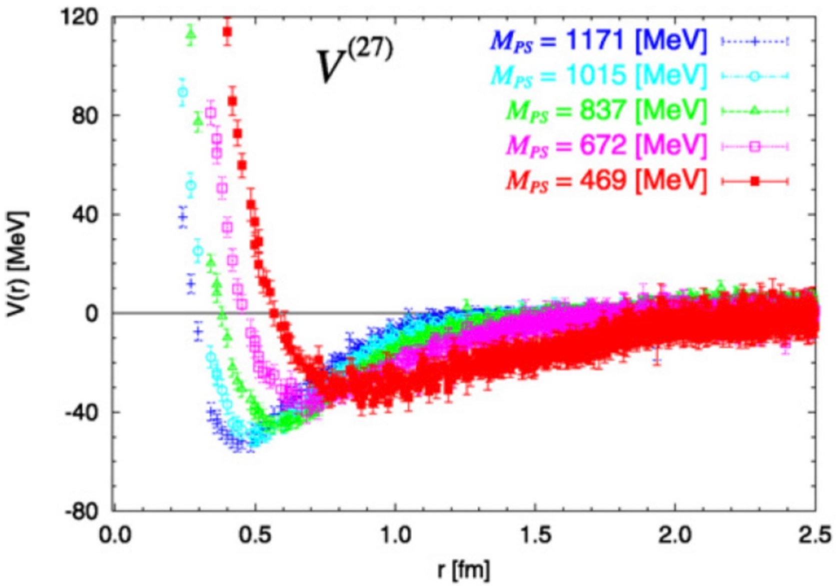
repulsive forces universal for all flavors

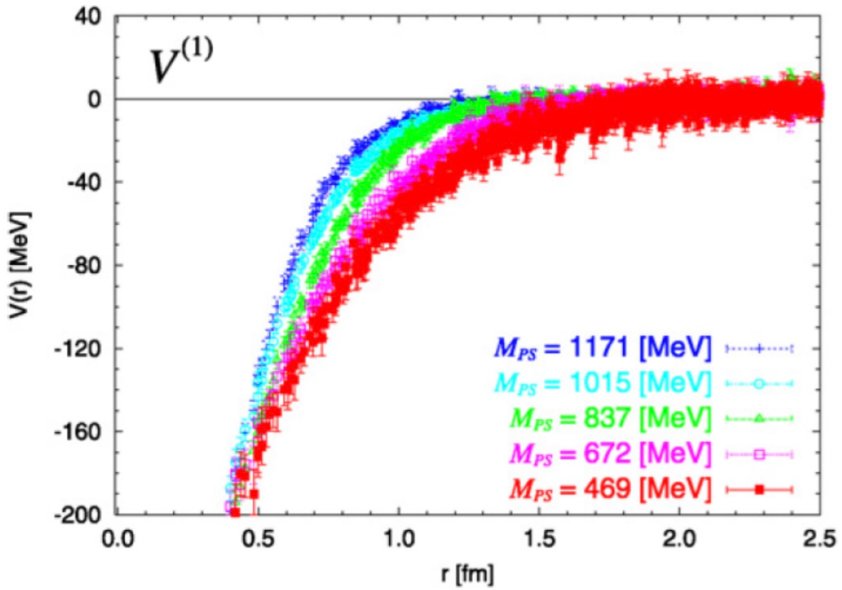
Hard core is not universal

consistent with 6q calculations in constituent quark models;

Pauli-blocking x color magnetic interactions **(Oka-Yazaki)**

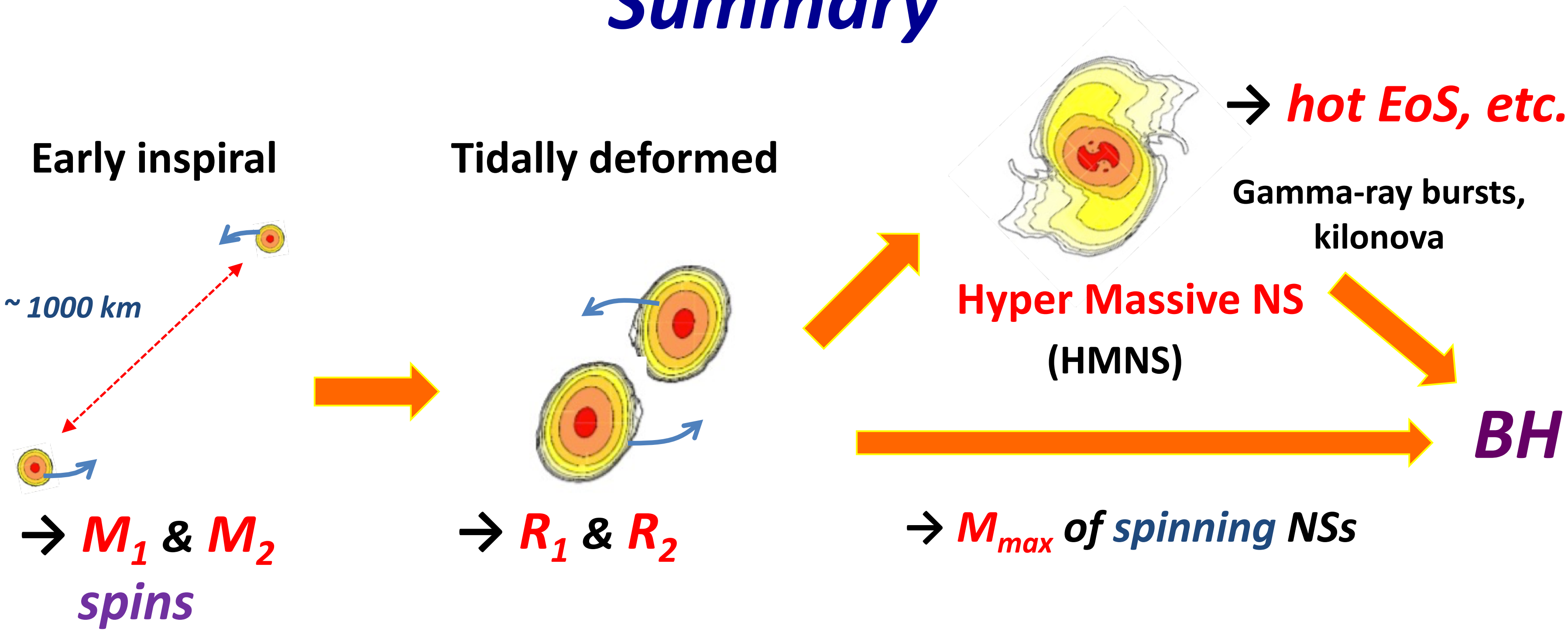
uud-uud Figs. from HAL QCD 2011 **uds-uds**



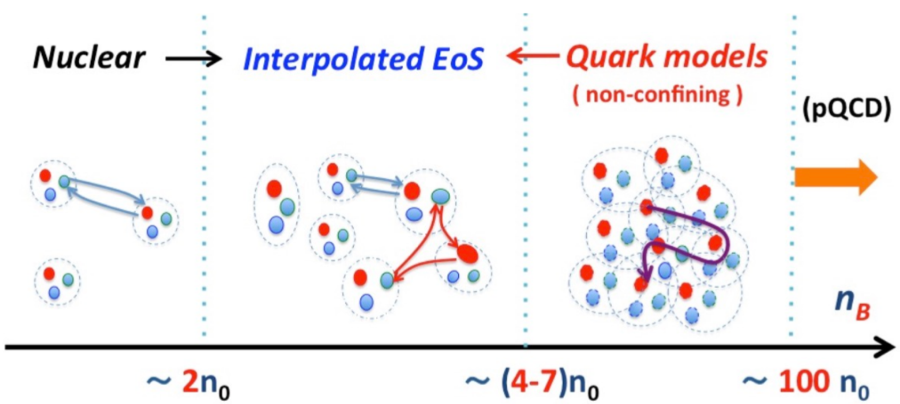


Can we block the appearance of the strangeness to $n_B \sim 5n_0$??

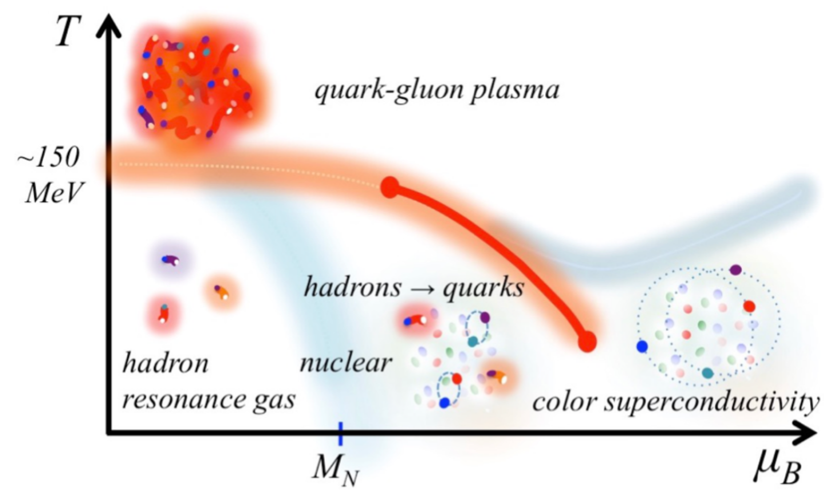
Summary



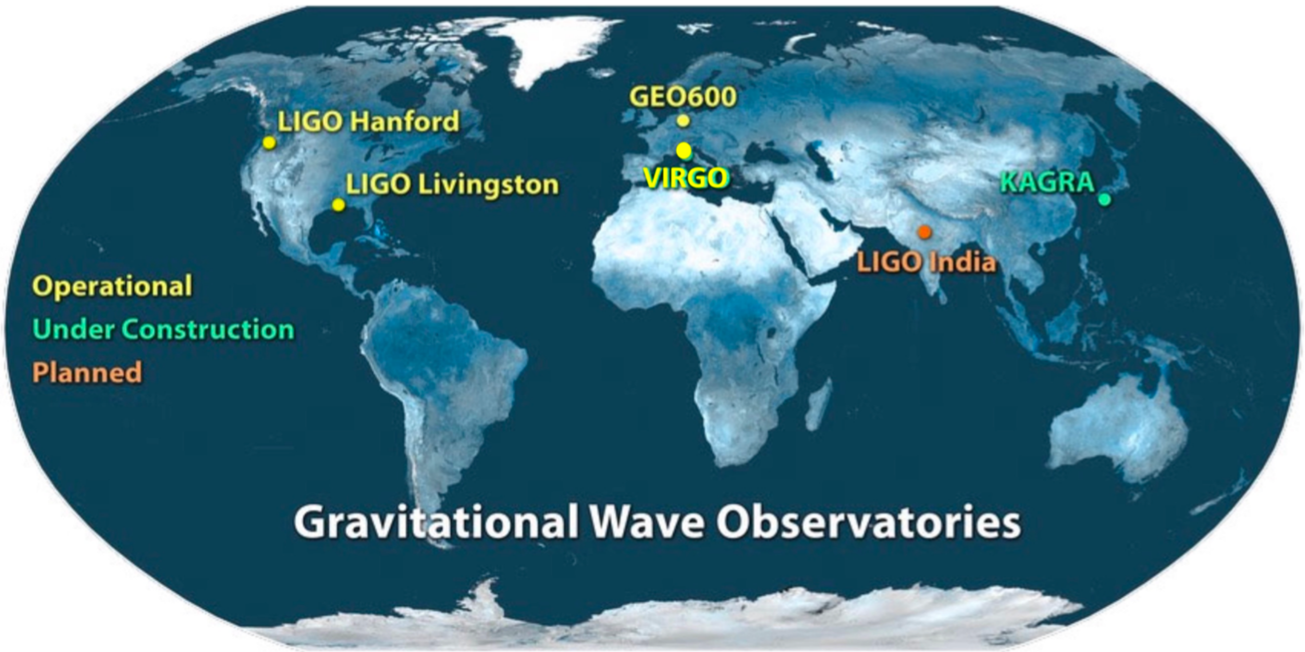
Early inspiral
~ 1000 km
→ M_1 & M_2
spins
Tidally deformed
→ R_1 & R_2
→ hot EoS, etc.
Gamma-ray bursts, kilonova
Hyper Massive NS
(HMNS)
BH
→ M_{max} of spinning NSs



Nuclear
Interpolated EoS
Quark models
(non-confining)
(pQCD)
n_B
~ $2n_0$
~ $(4\text{-}7)n_0$
~ 100 n_0



T
quark-gluon plasma
~150 MeV
hadrons → quarks
hadron resonance gas
nuclear
color superconductivity
M_N
μ_B



- **GW detectors :**

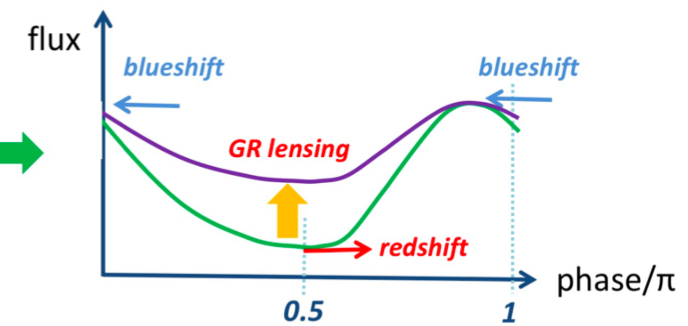
  aLIGO (O3)
  VIRGO
  KAGRA
  LIGO India, …

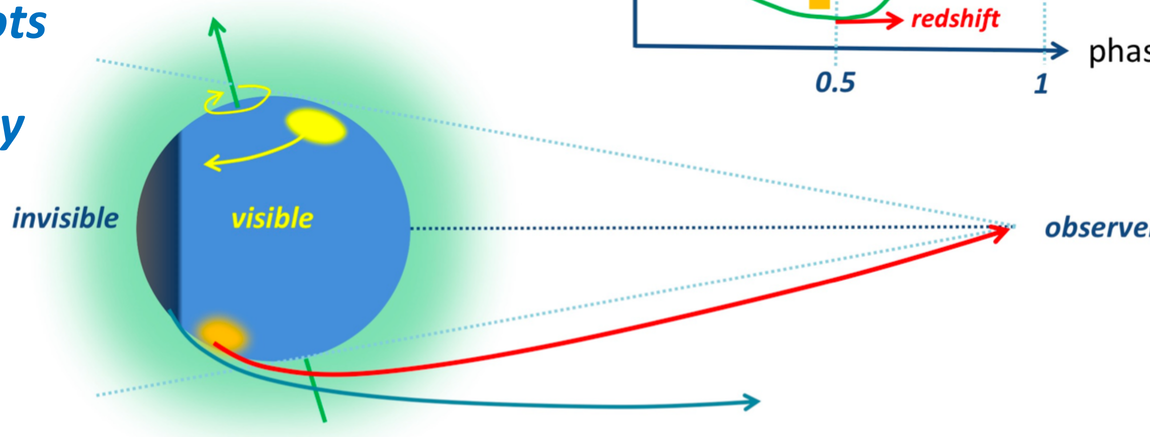
- **NICER (2017~) :**

  timing analyses of hot spots

  R & M/R → 5-10 % accuracy

Modeling ⟷



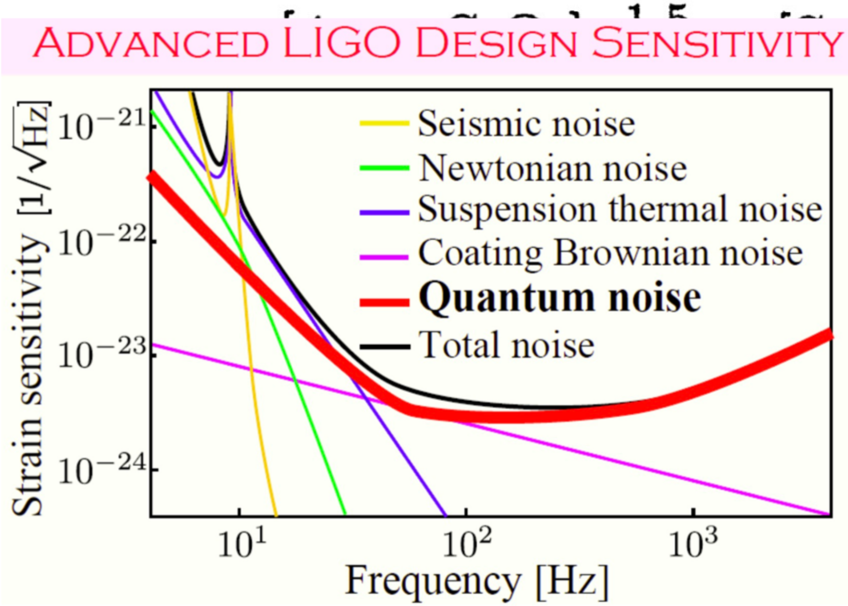


Template 1: post-Newtonian for f < ~1kHz

Cutler et al., PRL70, 2984 (1993)

$$\frac{d\mathcal{N}_{\rm cyc}}{d\ln f} = \frac{5}{96\pi}\frac{1}{\mu M^{2/3}(\pi f)^{5/3}}\left\{1+\left(\frac{743}{336}+\frac{11}{4}\frac{\mu}{M}\right)x\right.$$

$$\left. \ldots \mathrm{S.}]x^2 + O(x^{2.5})\right\}.$$



Delayed vs prompt collapse → $(M^{TOV})_{max}$

Lattimer, talk at INT, 2018

M_{rem}

BH — prompt collapse (life << 1s)

~ 1.5 $(M^{TOV})_{max}$

Hyper Massive — differential rotation (short life ~ **1s**; viscous & mag. braking)

~ 1.2 $(M^{TOV})_{max}$

Supra Massive — uniform rotation (long life >> 1s)

$(M^{TOV})_{max}$ > ~ 2M_{sun}

Non-rotating — (stable)

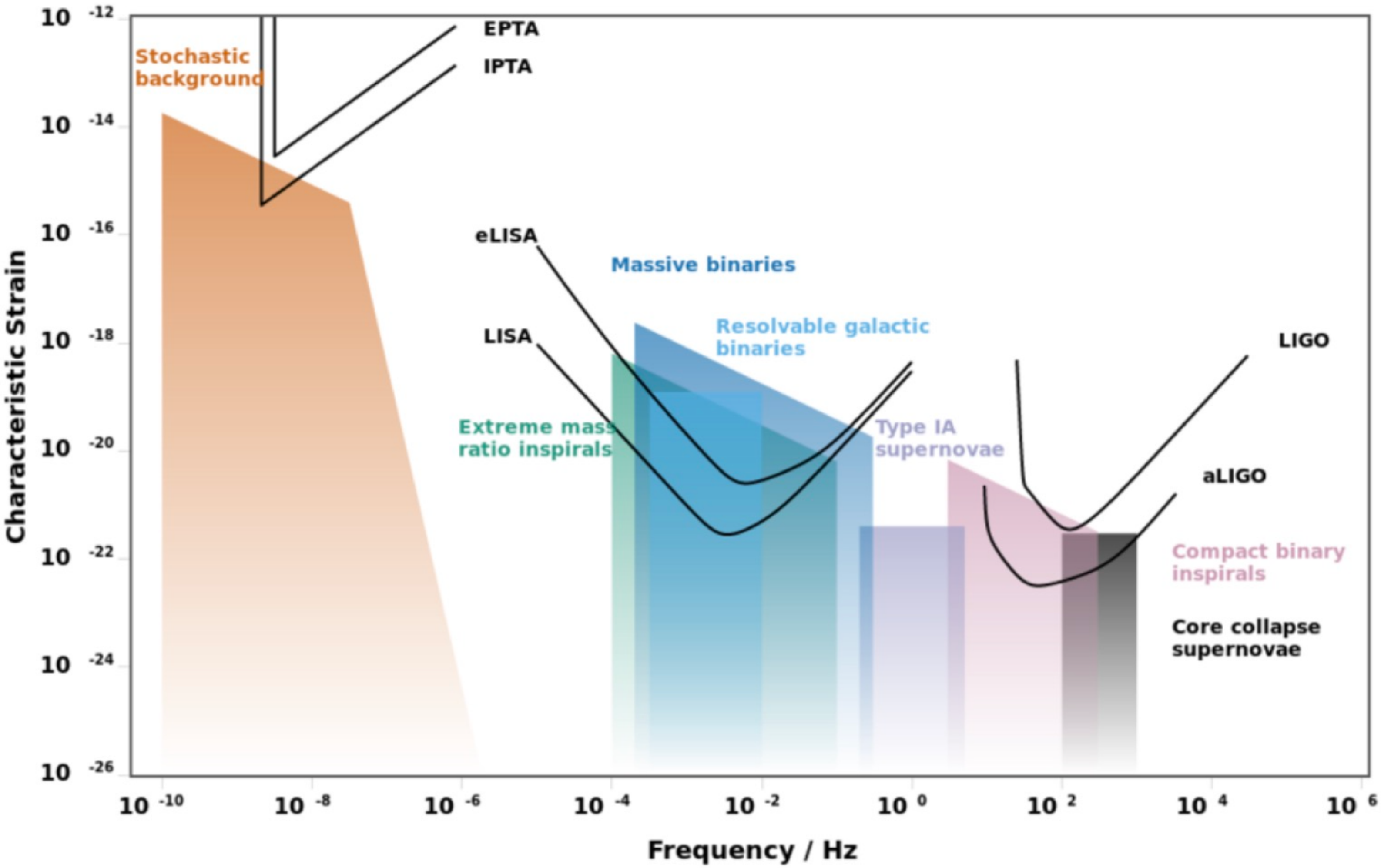
For **GW170817** :

- collapse to BH after ~ **1s**
- ~2.28 < M_{rem}/M_{sun} < ~2.53 (estimated)

1.2 $(M^{TOV})_{max}$ < 2.53 M_{sun}

➡ $(M^{TOV})_{max}$ < 2.11 M_{sun}

- If thermal effects are included, the constraint may be even stronger


EPTA
IPTA
Stochastic background
eLISA
LISA
Massive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
Type IA supernovae
LIGO
aLIGO
Compact binary inspirals
Core collapse supernovae
Characteristic Strain
Frequency / Hz
10 -12
10 -14
10 -16
10 -18
10 -20
10 -22
10 -24
10 -26
10 -10
10 -8
10 -6
10 -4
10 -2
10 0
10 2
10 4
10 6

APR~11.1km, H4~13.6km, MS1~14.5km

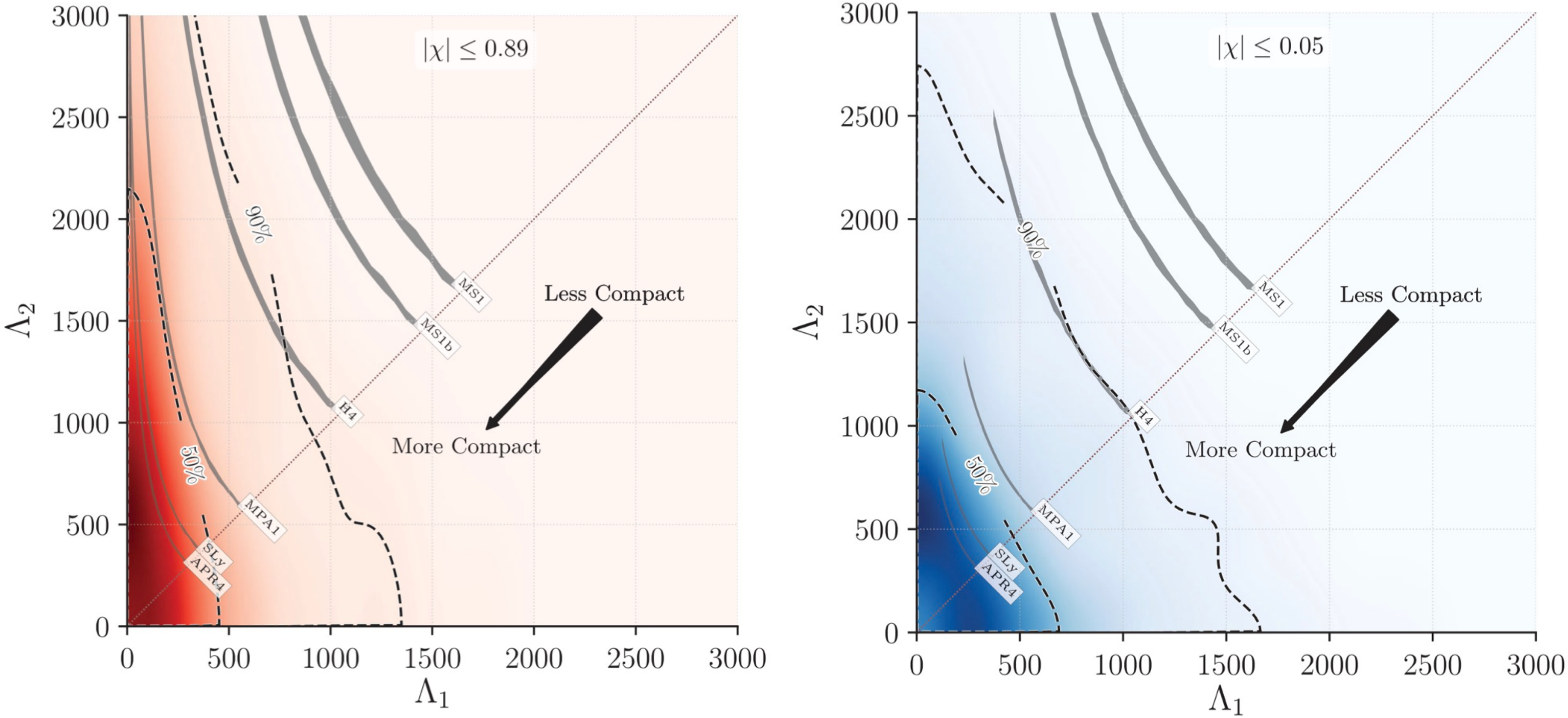


Table 1: Key Properties of GW170817

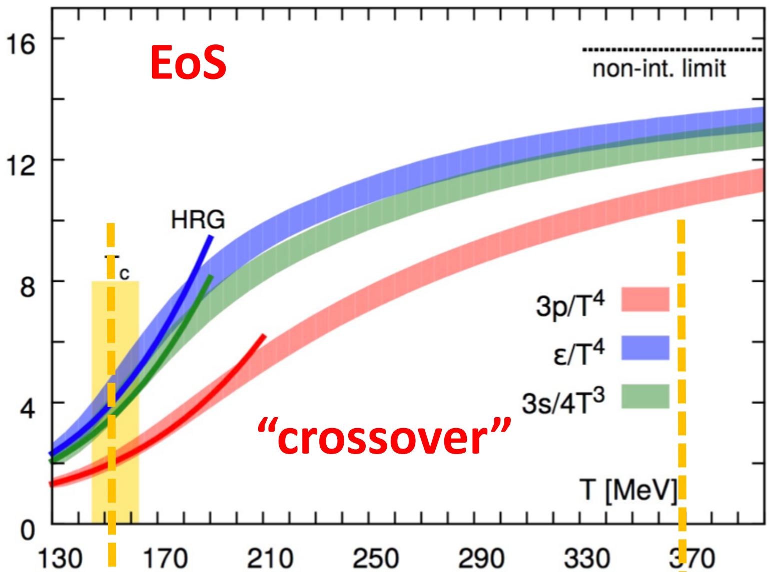
Property	Value	Reference
Chirp mass, $\mathcal{M}$ (rest frame)	$1.188^{+0.004}_{-0.002} M_\odot$	1
First NS mass, M_1	$1.36 - 1.60 M_\odot$ (90%, low spin prior)	1
Second NS mass, M_2	$1.17 - 1.36 M_\odot$ (90%, low spin prior)	1
Total binary mass, $M_{\rm tot} = M_1 + M_2$	$\approx 2.74^{0.04}_{-0.01} M_\odot$	1
Observer angle relative to binary axis, $\theta_{\rm obs}$	$11 - 33^\circ$ (68.3%)	2
Blue KN ejecta ($A_{\rm max} \lesssim 140$)	$\approx 0.01 - 0.02 M_\odot$	e.g., 3,4,5
Red KN ejecta ($A_{\rm max} \gtrsim 140$)	$\approx 0.04 M_\odot$	e.g., 3,5,6
Light r-process yield ($A \lesssim 140$)	$\approx 0.05 - 0.06 M_\odot$	
Heavy r-process yield ($A \gtrsim 140$)	$\approx 0.01 M_\odot$	
Gold yield	$\sim 100 - 200 M_\oplus$	8
Uranium yield	$\sim 30 - 60 M_\oplus$	8
Kinetic energy of off-axis GRB jet	$10^{49} - 10^{50}$ erg	e.g., 9, 10, 11, 12
ISM density	$10^{-4} - 10^{-2}$ cm^{-3}	e.g., 9, 10, 11, 12

(1) LIGO Scientific Collaboration et al. 2017c; (2) depends on Hubble Constant, LIGO Scientific Collaboration et al. 2017d; (3) Cowperthwaite et al. 2017; (4) Nicholl et al. 2017; (5) Kasen et al. 2017; (6) Chornock et al. 2017; (8) assuming heavy r-process ($A > 140$) yields distributed as solar abundances (Arnould et al., 2007); (9)Margutti et al. 2017; (10) Troja et al. 2017; (11) Fong et al. 2017; (12) Hallinan et al. 2017

Delineating QCD matter from HOT EoS

lattice calculations

(Ding-Karsch-Makherjee, review 2015)

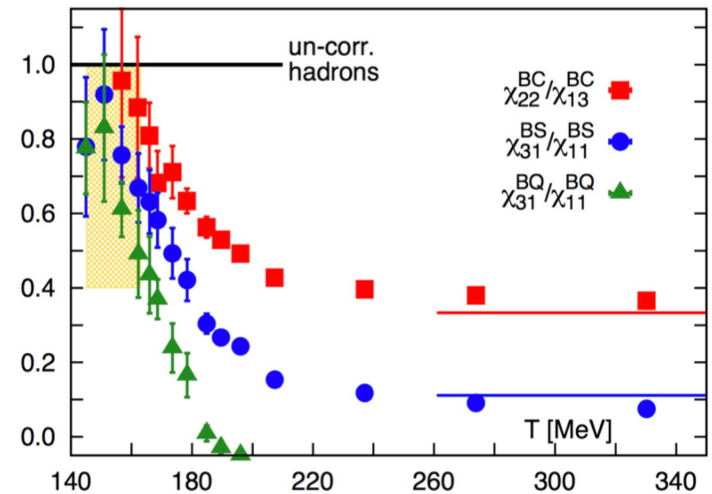


Hadron resonance gas

semi-QGP

pQGP

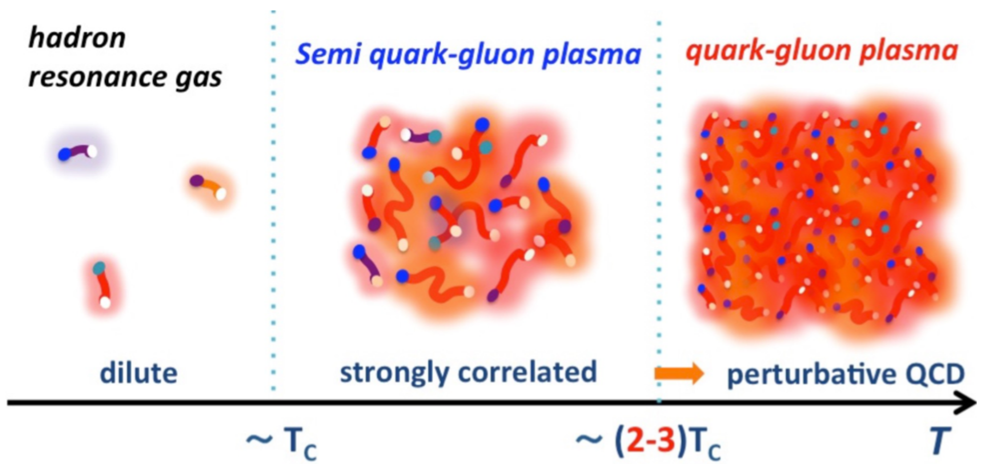
derivatives of EoS



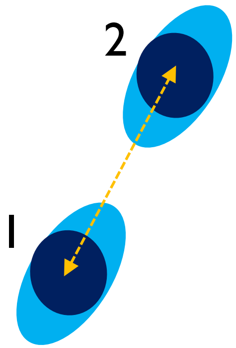
→ T_c: **universal for different flavors**

➡ plausible picture

Fig. from Baym et al. 2018



Dimensionless tidal deformability $\longrightarrow R_{NS}$



more common to use

$$\Lambda(M) = 32\frac{\lambda G}{R^5} = \frac{2}{3}k_2\left(\frac{R}{GM}\right)^5$$

(k_2 : Love number)

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

$$\Lambda(M) = 32\frac{\lambda G}{R^5}$$