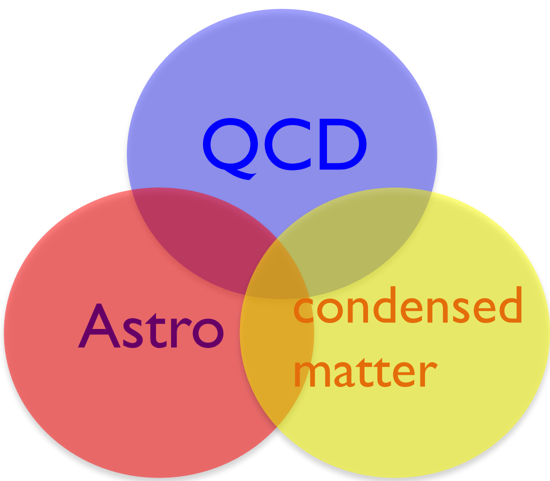
Delineating the properties of matter in cold, dense QCD



Toru Kojo (CCNU)

based on works in collaborations with

G. Baym, K. Fukushima, S. Furusawa, T. Hatsuda, P. Powell, Y. Song, H. Togashi, T. Takatsuka

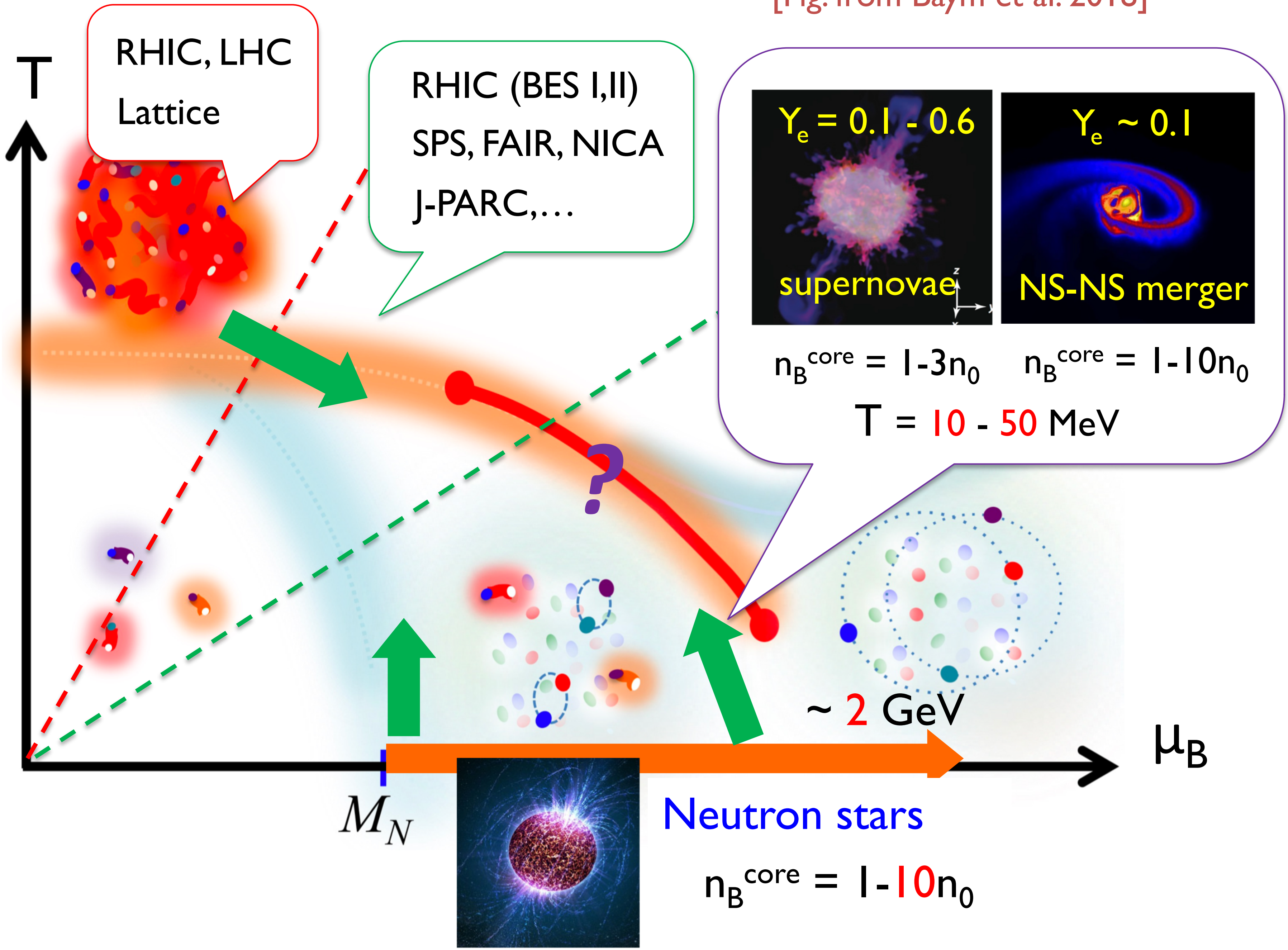
- Review) Rept. Prog. Phys. 81 (2018) no.5, 056902

1, Theoretical orientation from QCD

2, Quick review of constraints from NSs

3, Microphysics based on quark descriptions

[Fig. from Baym et al. 2018]



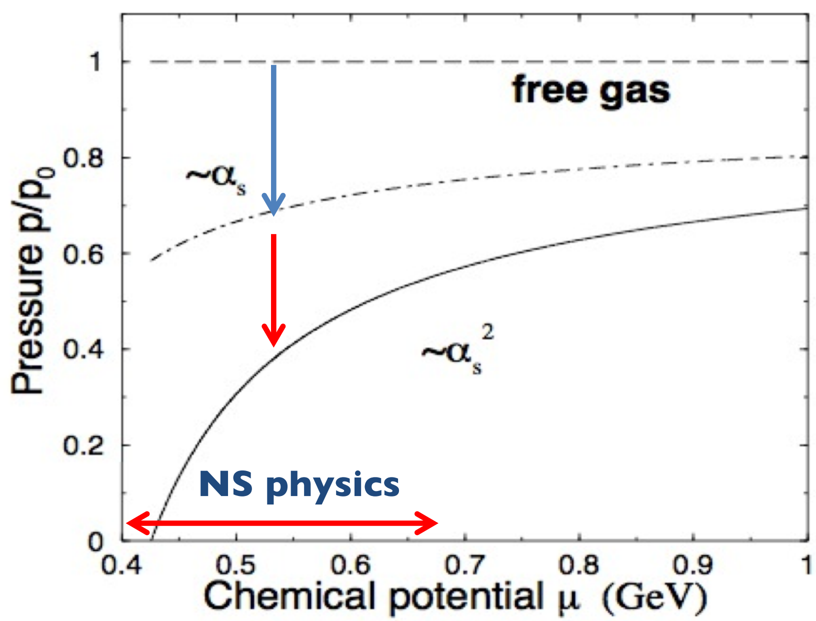
Cold, dense EoS : High density

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

[some **4-loop** contributions: E. Sappi et al.]

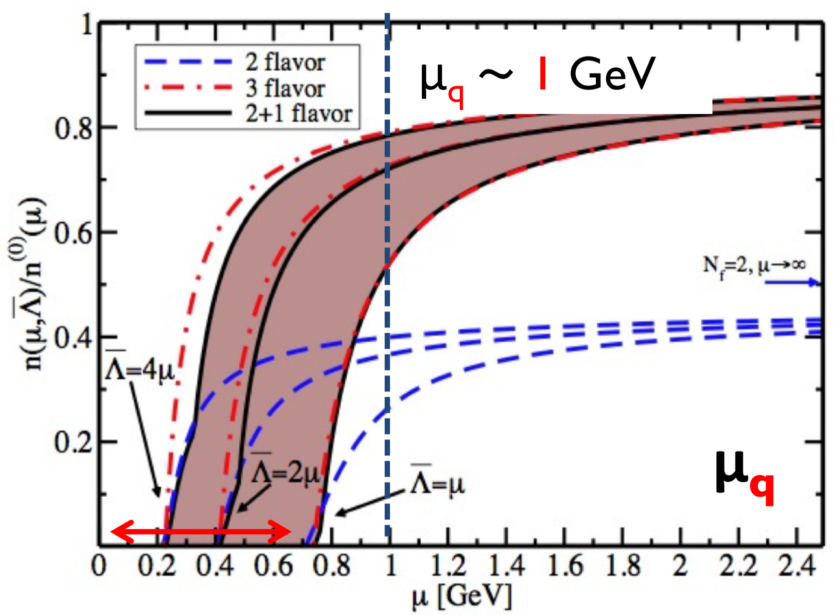
check of convergence

(Fraga-Pisarski-Schaffner-Bielich 01)



check of renorm. scale dep.

(Kurkela-Romatschke-Vuorinen 09)



- Interactions crucial already at $\mu_q \sim$ **1** GeV or $n_B \sim$ **100** n_0

Cold, dense EoS : Low density

For NS applications (n_B=2-10n_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. $\langle v^{\pi}_{ij} \rangle$	2 –body int. $\langle v^{R}_{ij} \rangle$	3 –body int. $\langle V^{2\pi}_{ijk} \rangle$	3 –body int. $\langle V^{R}_{ijk} \rangle$
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

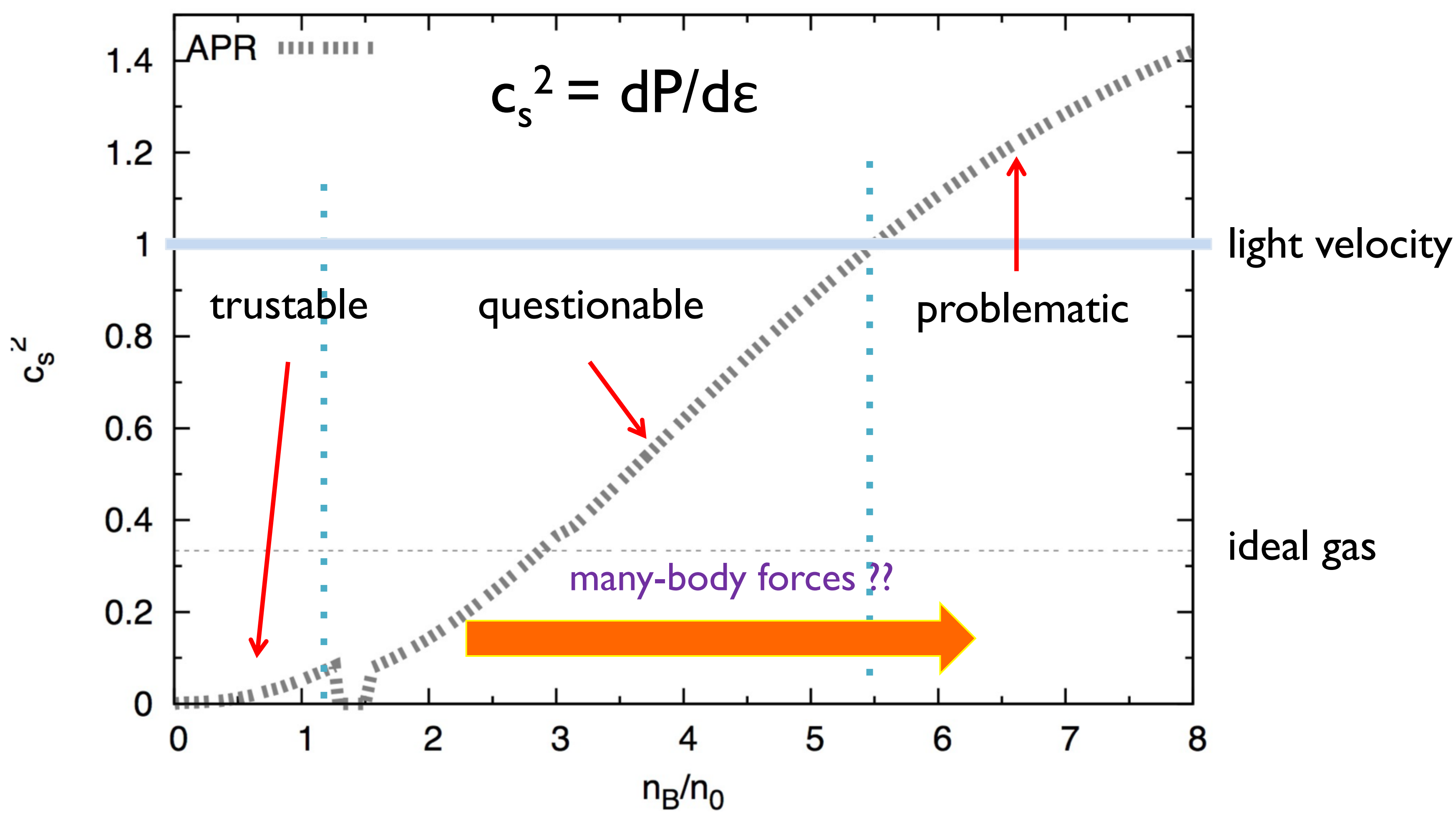
grow rapidly!

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

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

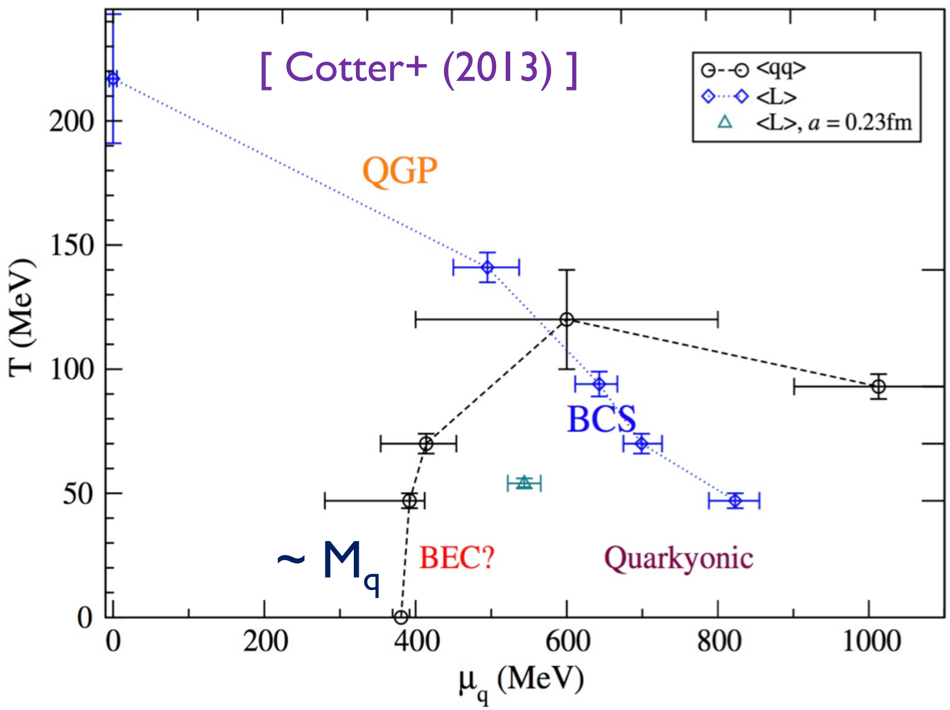
Cold, dense EoS : Low density

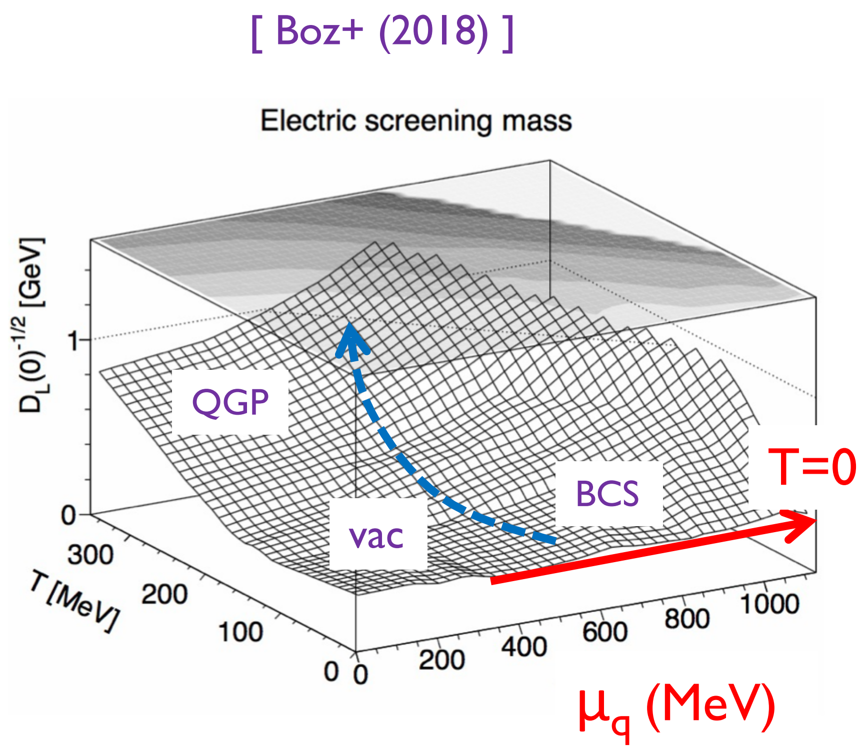
Akmal-Pandharipande-Ravenhall EoS (**APR 98**)



QCD with 2-colors (m_{pi} ~ 700 MeV ~ $2M_q$)

lattice QCD simulations doable

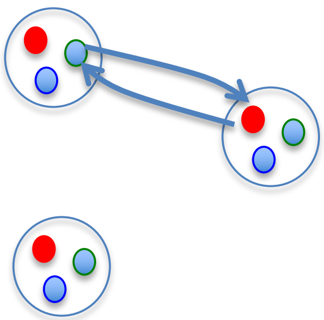




- T_c^{BCS} ~ 100 -120 MeV → **Δ** ~ 1.75 T_c ~ **175 - 210** MeV
- Gluons are **insensitive** to medium effects for μ_q < 1GeV

Overall picture based on QCD

- few meson exchange
- nucleons only

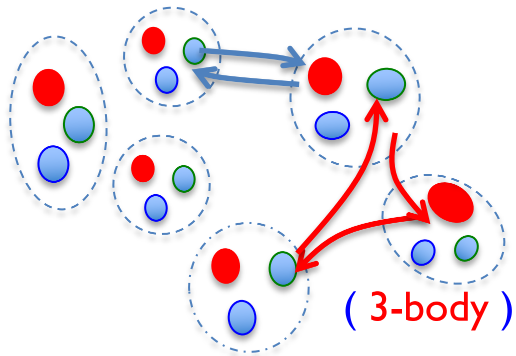


ab-initio nuclear cal.

e.g.) ChEFT, variational

steady progress

- many-quark exchange
- structural change
- hyperons, Δ, ...



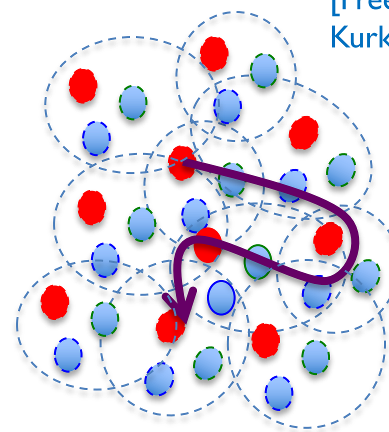
most difficult

(d.o.f ??)

Hints from NSs

- Baryons overlap
- Quark Fermi sea

[Freedman-McLerran 1976, Kurkela et al 2009]



strongly correlated

(d.o.f : quasi-particles??)

not explored well

(pQCD)

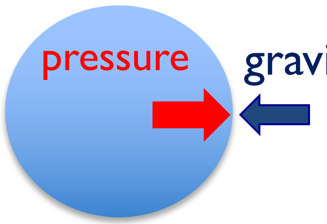
n_B

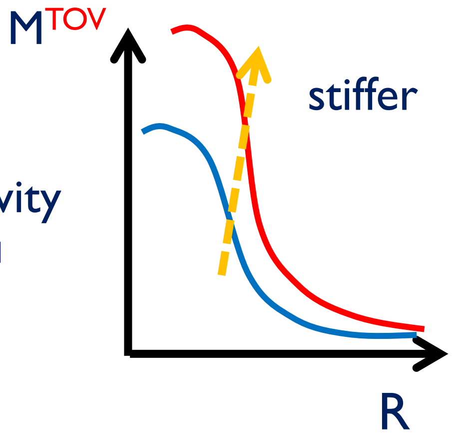
$\sim 2n_0$ $\sim 5n_0$ ($p_F \sim$ 400 MeV) $\sim 100n_0$

Terminology (in this talk)

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

(not necessarily large $c_s^2 = dP/d\varepsilon$)





2) Stiffness strongly depends on density; define, e.g.,

Soft-**Stiff** EoS : **Soft** at $n_B < \mathbf{2} n_0$ & **Stiff** at $n_B > \mathbf{5} n_0$

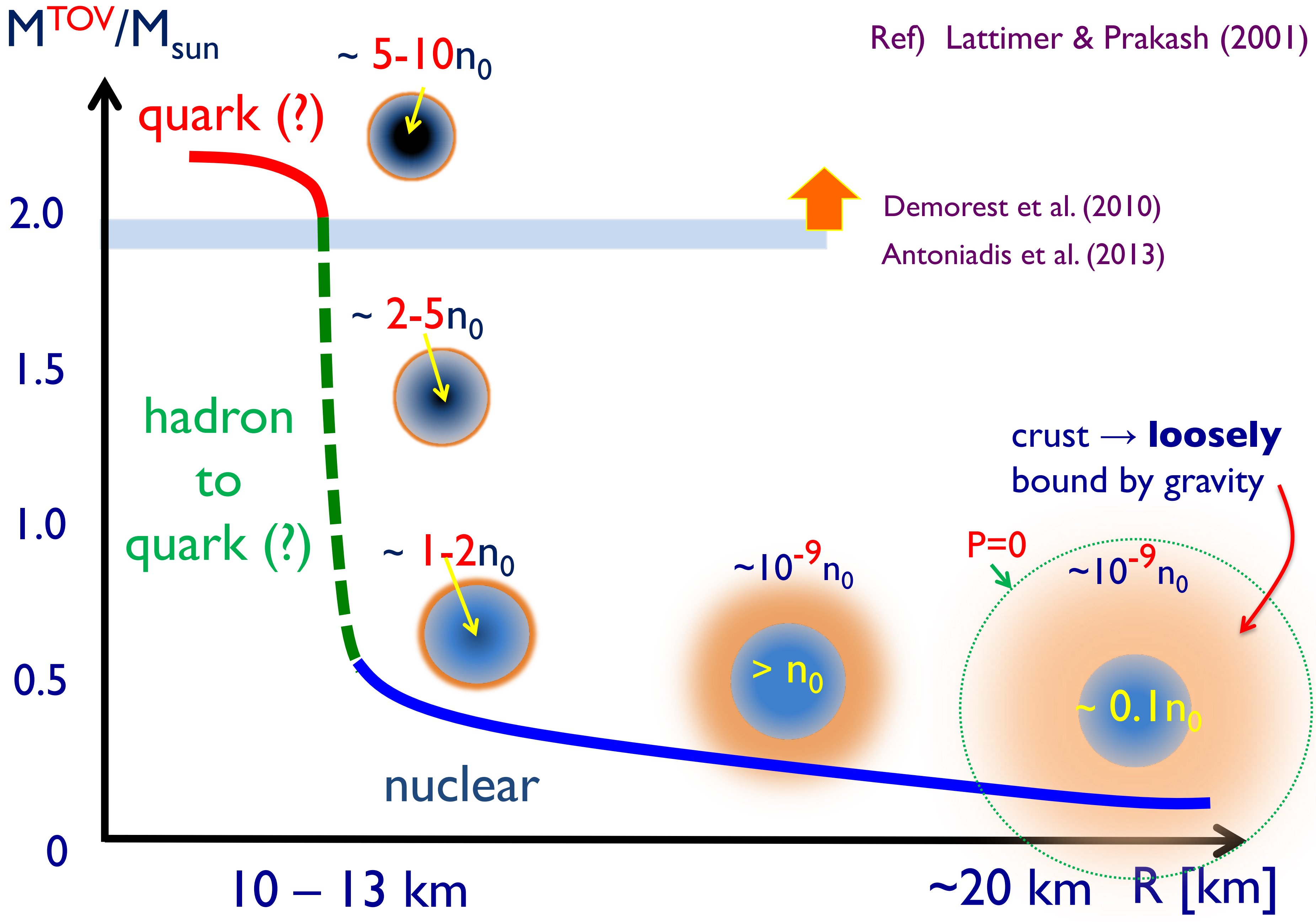
more specifically,

$R_{1.4} < \sim 13$ km $M > \sim 2\, M_{sun}$

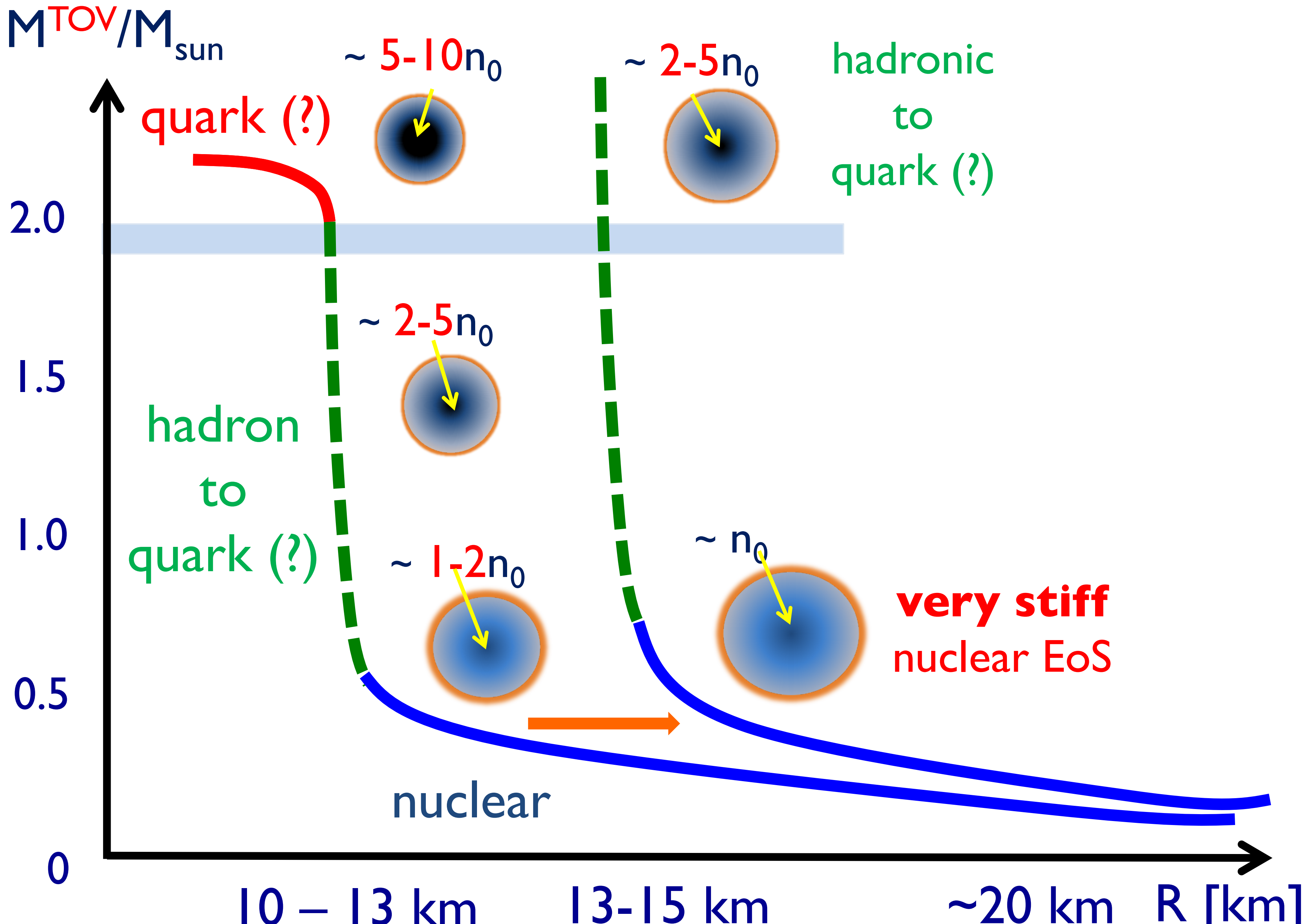
We also use terminology such as stiff-stiff EoS, etc.

Soft-Stiff vs Stiff-Stiff EoS

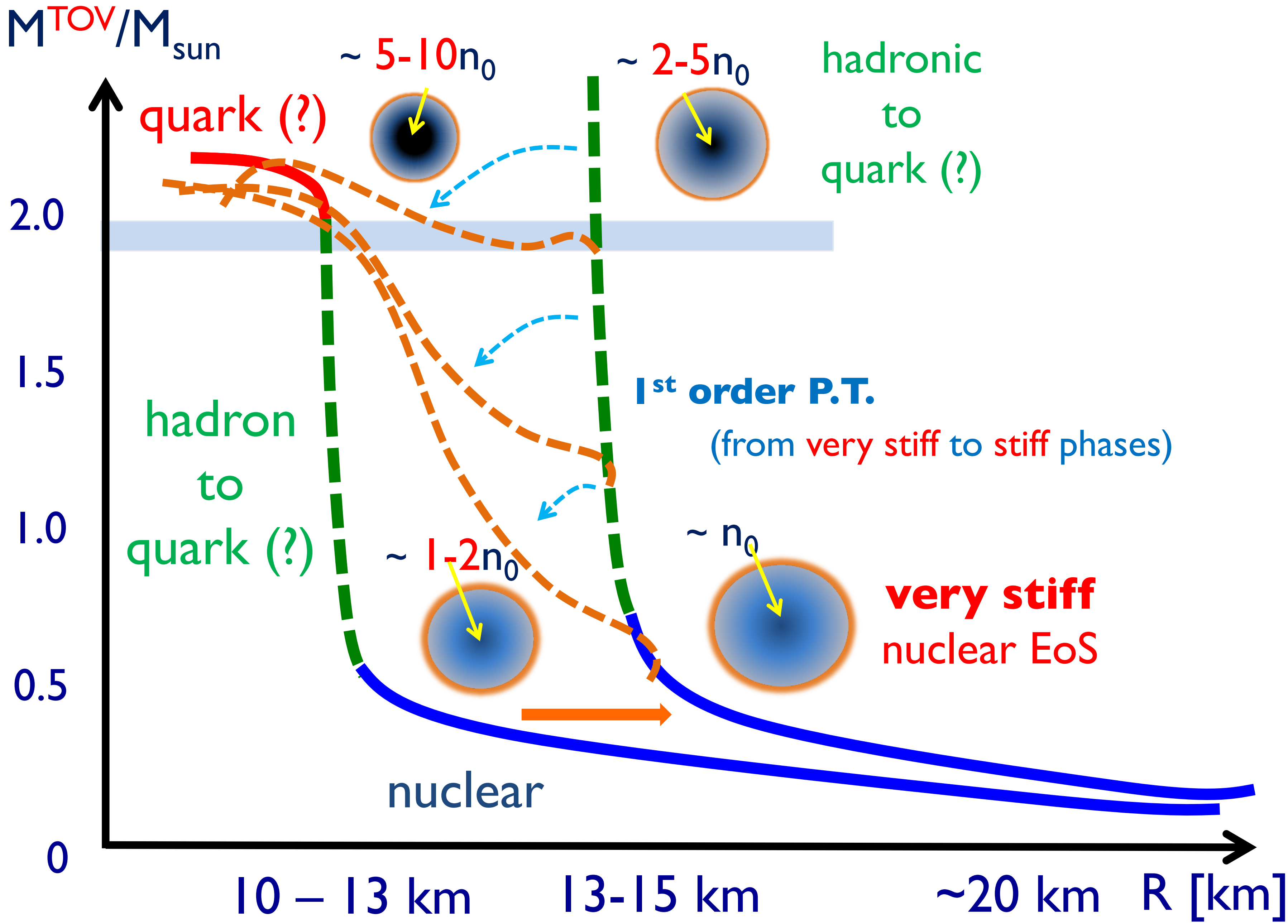
Ref) Lattimer & Prakash (2001)



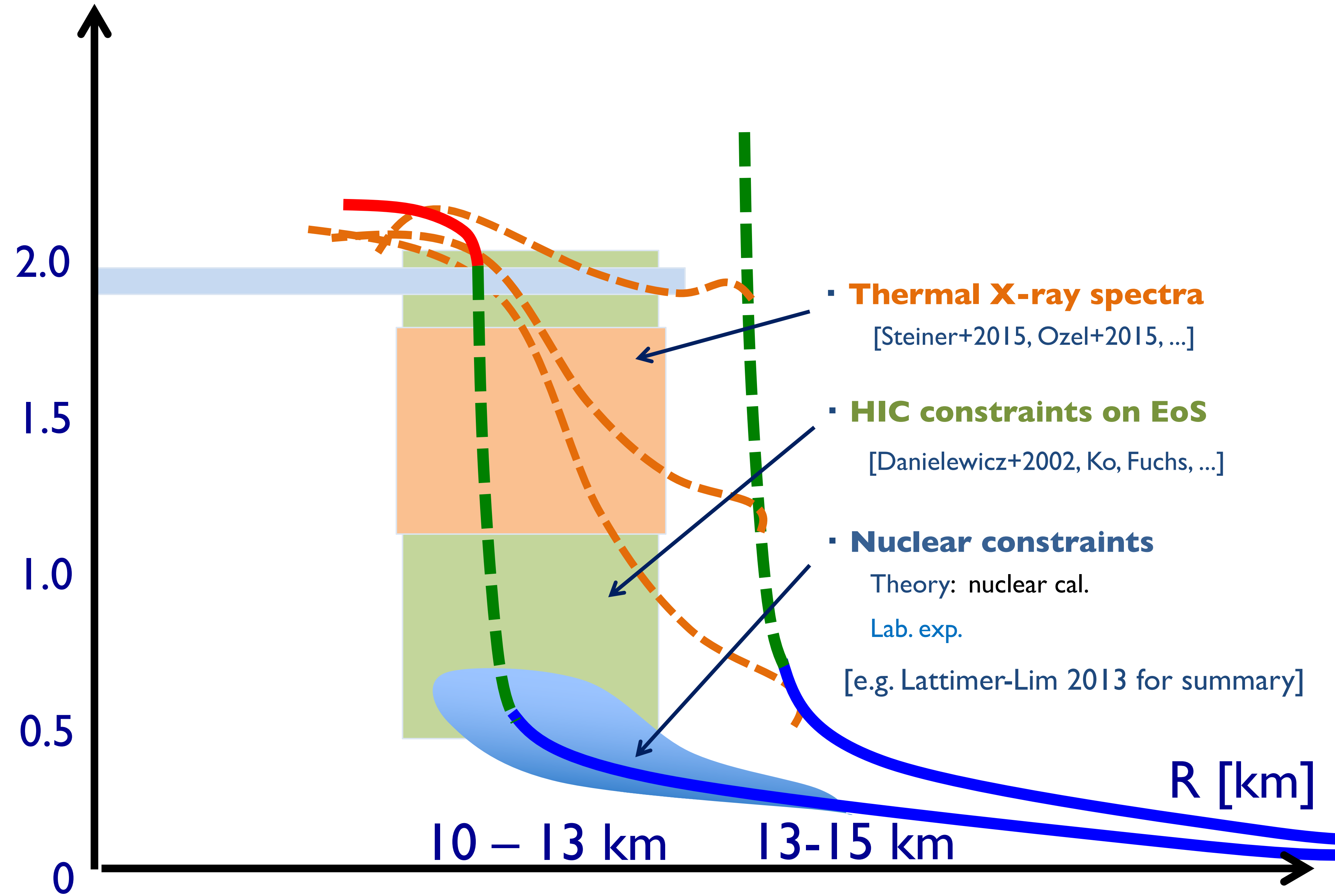
Soft-Stiff vs Stiff-Stiff EoS



Soft-Stiff vs Stiff-Stiff EoS

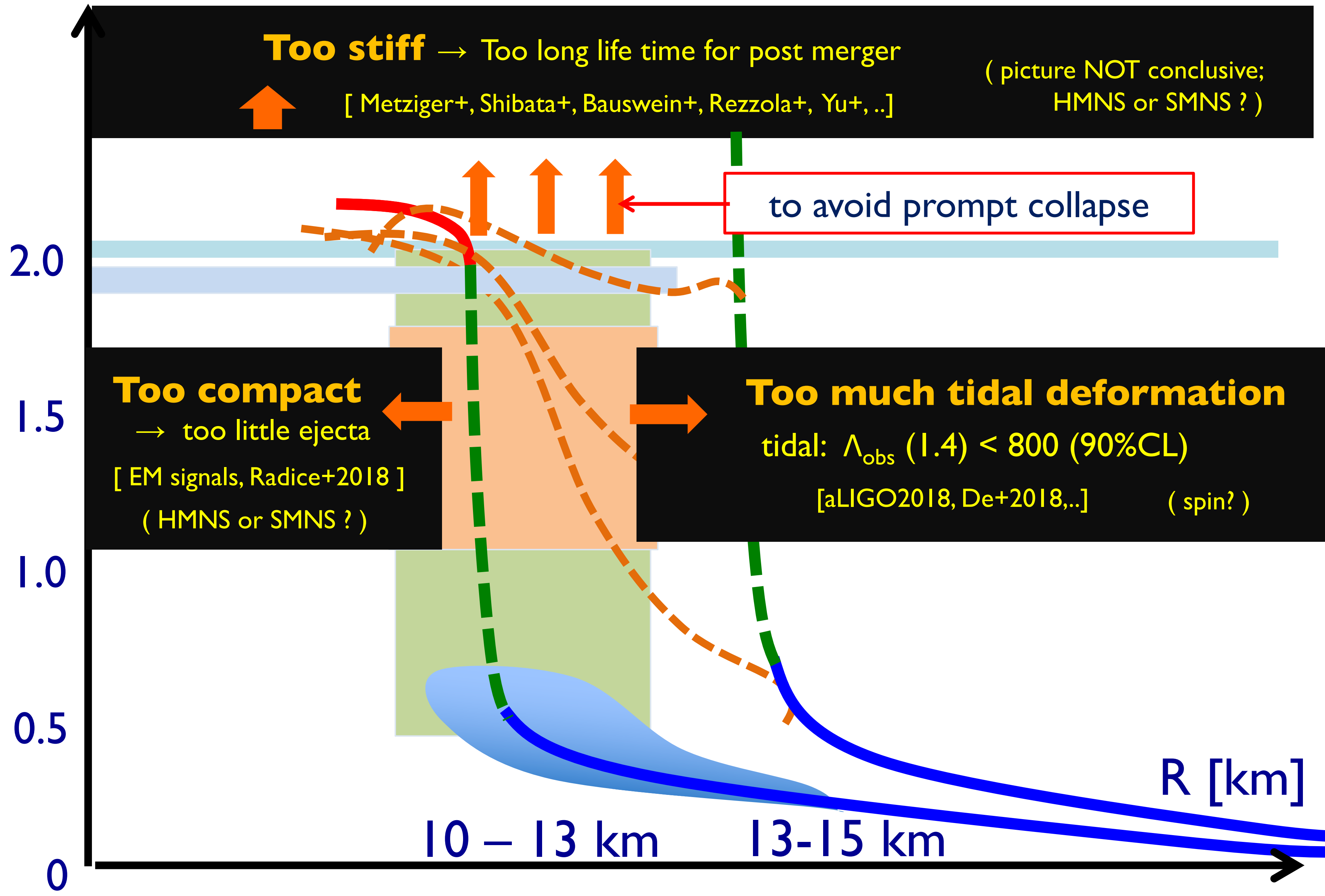


Constraints (before GW170817)

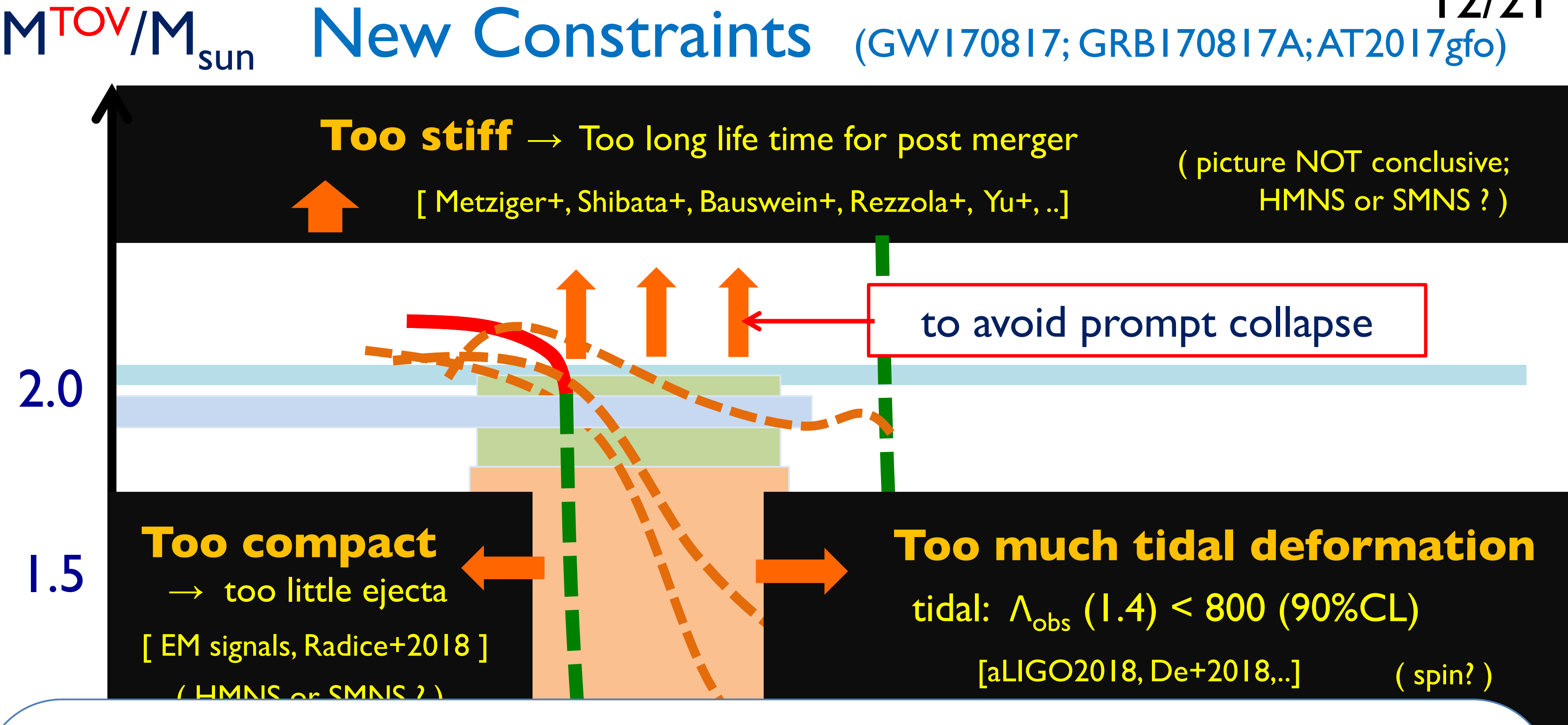


New Constraints (GW170817; GRB170817A; AT2017gfo)

M^{TOV}/M_{sun}



New Constraints (GW170817; GRB170817A; AT2017gfo)

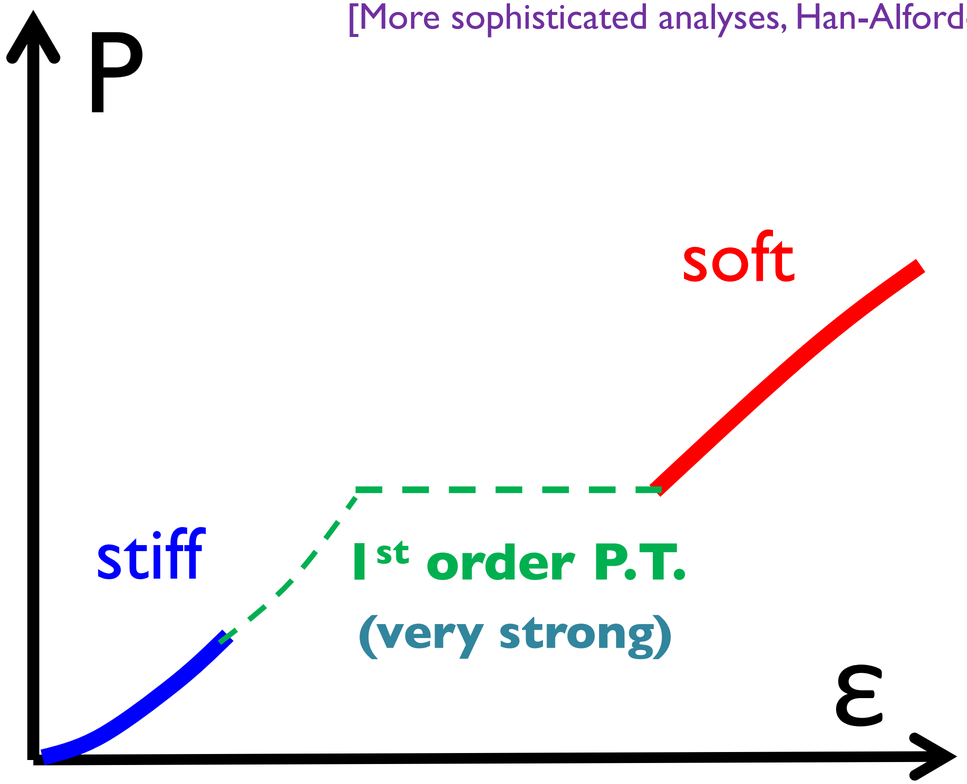


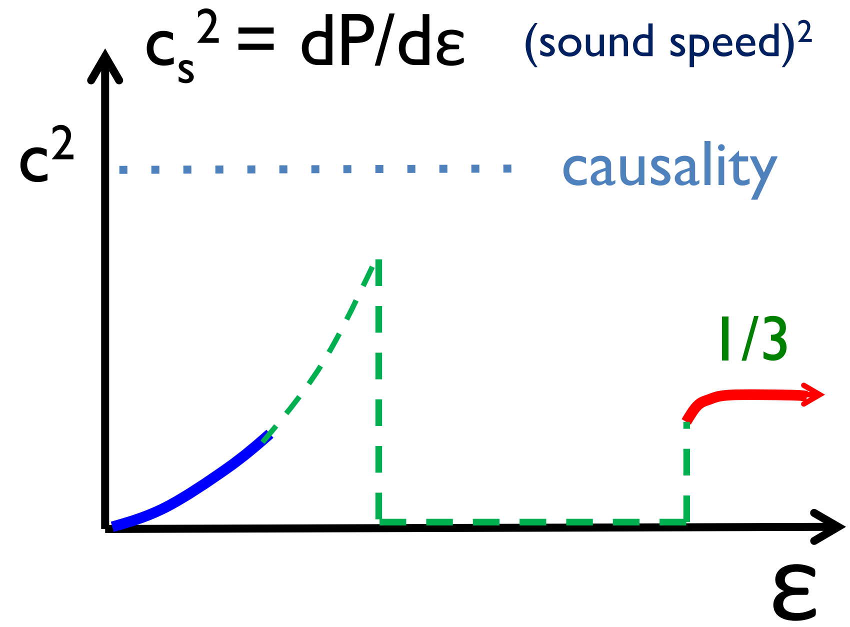
Hints for soft-stiff EoS

$R(1.4)$ [km]		M^{TOV}_{max}/M_{sun}	
11.2 - 13.4	[Radice+2018]	< 2.17	[Metziger+2018]
9.0 - 13.6	[Tews+2018]	2.15 – 2.25	[Shibata+2018]
8.9 - 13.2	[De+2018]	1.97 – 2.33	[Rezzola+2018]
11.1 - 13.4	[Annala+2018]	> 2.25	[Yu+2018]

stiff-soft vs stiff-stiff vs soft-stiff

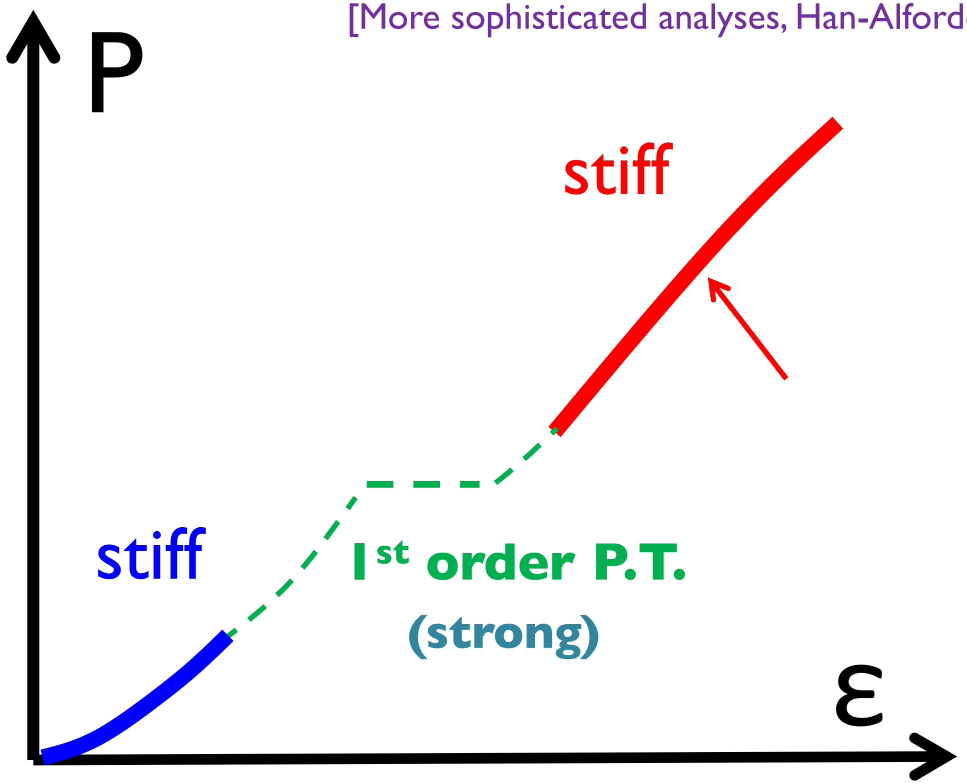
[More sophisticated analyses, Han-Alford-Prakash 2013, Bedaque-Steiner 2015]



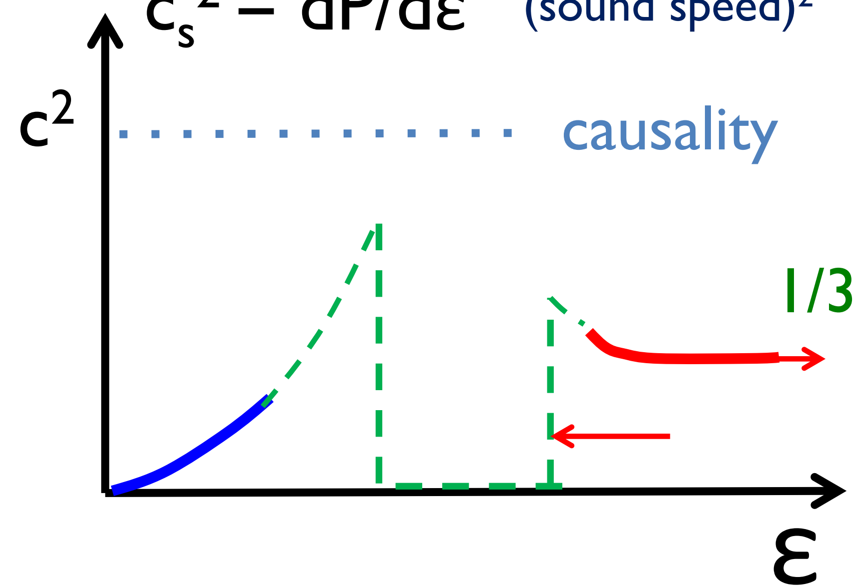


stiff-soft vs stiff-stiff vs soft-stiff

[More sophisticated analyses, Han-Alford-Prakash 2013, Bedaque-Steiner 2015]

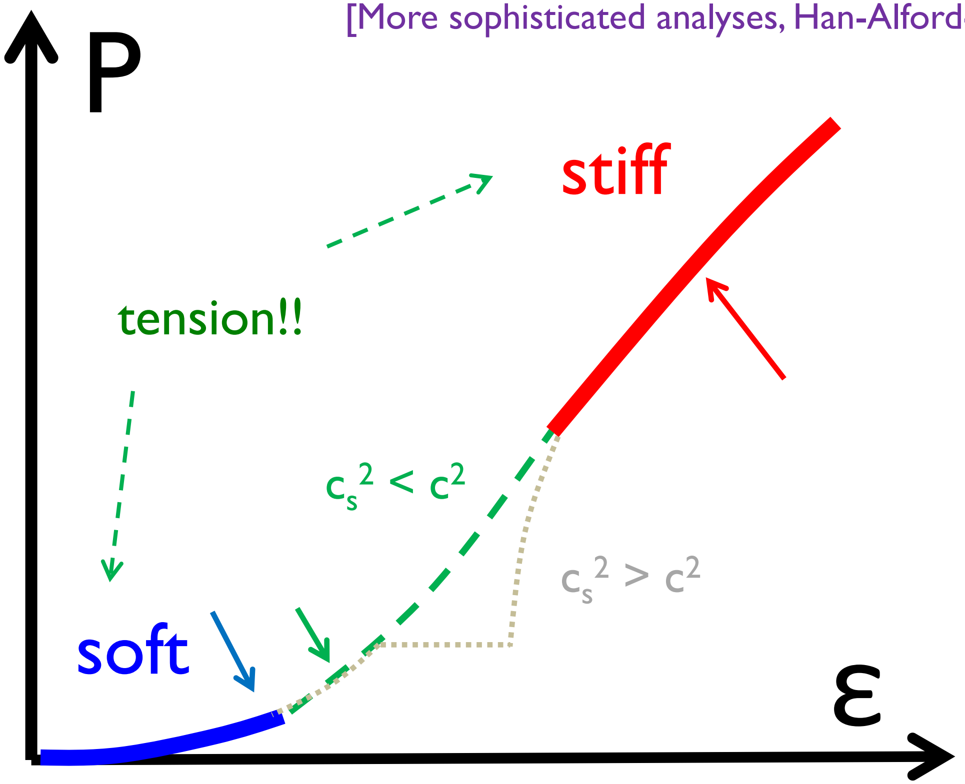


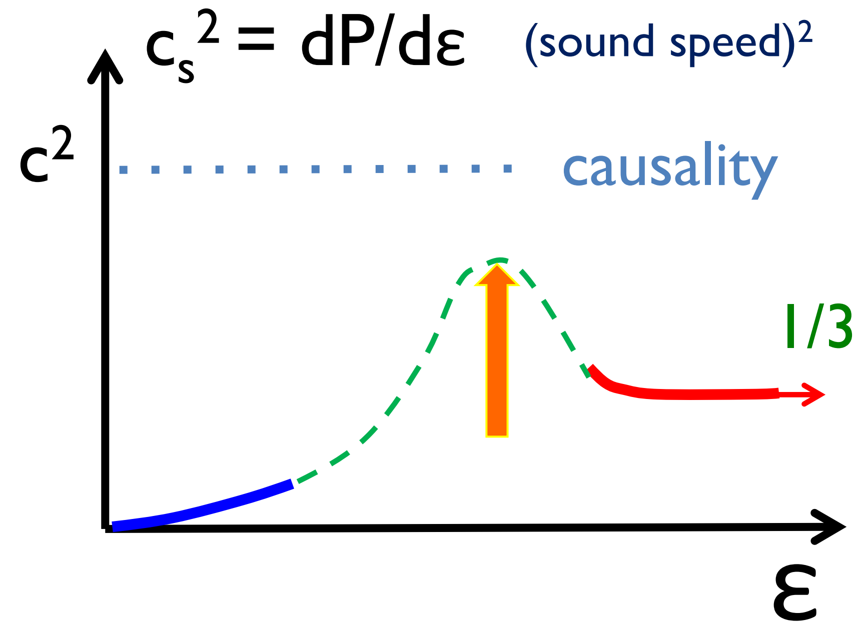
$c_s^2 = dP/d\varepsilon$ (sound speed)^2



stiff-soft vs stiff-stiff vs soft-stiff

[More sophisticated analyses, Han-Alford-Prakash 2013, Bedaque-Steiner 2015]





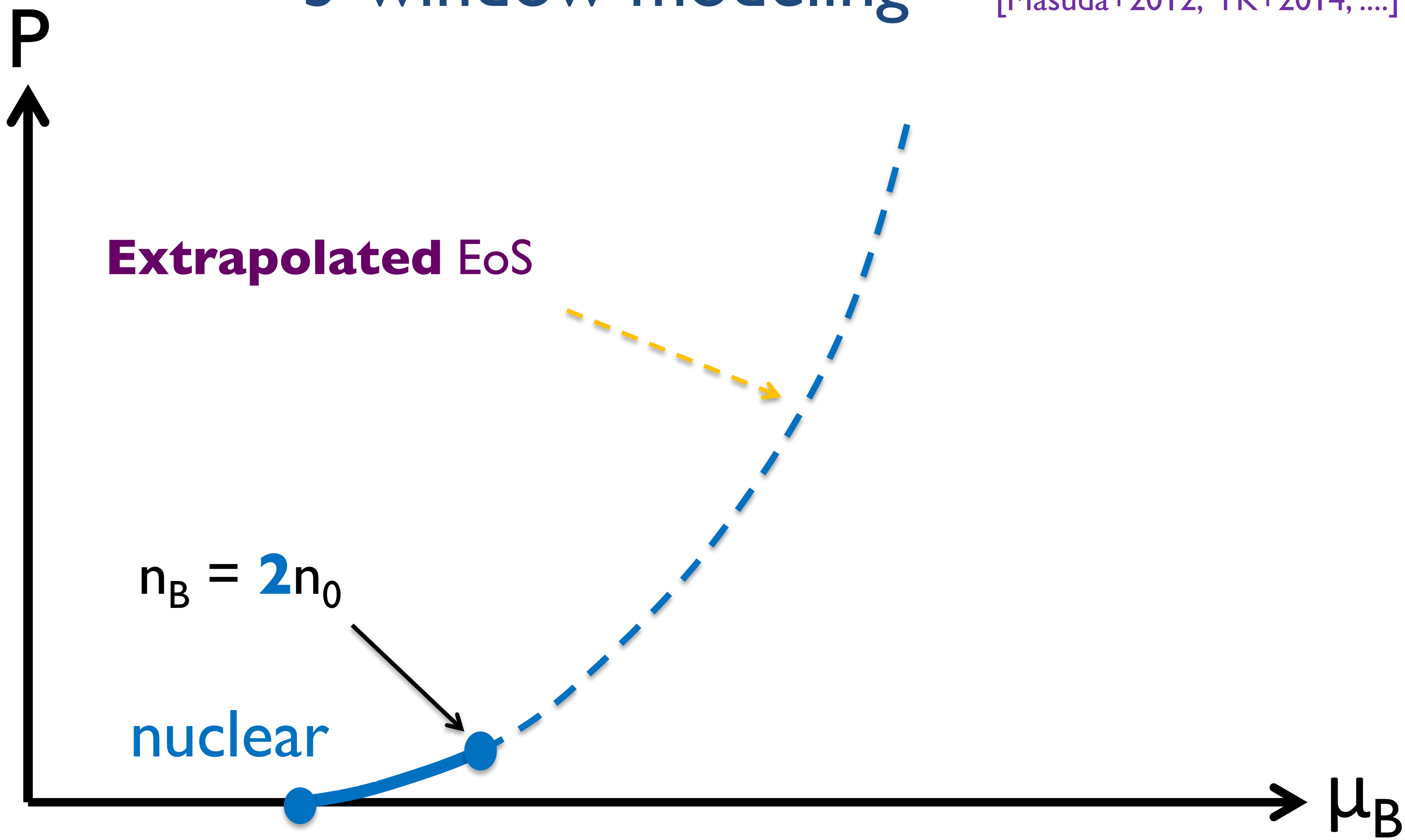
soft-stiff EoS → **crossover** or **weak 1st order** **for 2-5n_0**

"Hadron-quark continuity" (a **new baseline ?**)

[Schafer-Wilczek 1998, Hatsuda+ 2006, ...; cf) quarkyonic; McLerran-Pisarski 2007]

3-window modeling

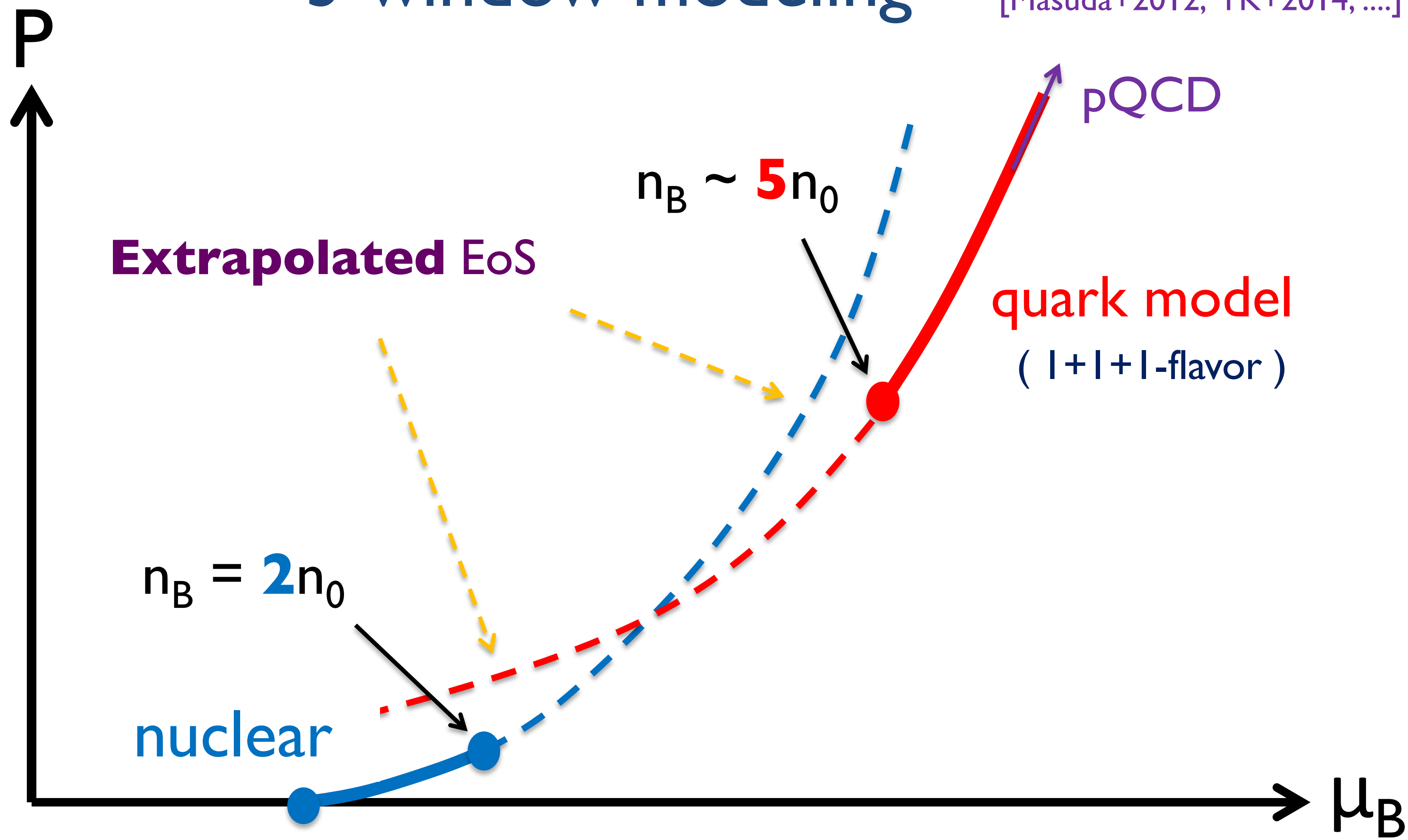
[Masuda+2012, TK+2014, ...]



[Akmal+1998, Togashi+2017,
Hebeler+2017, Gandolfi+, ...]

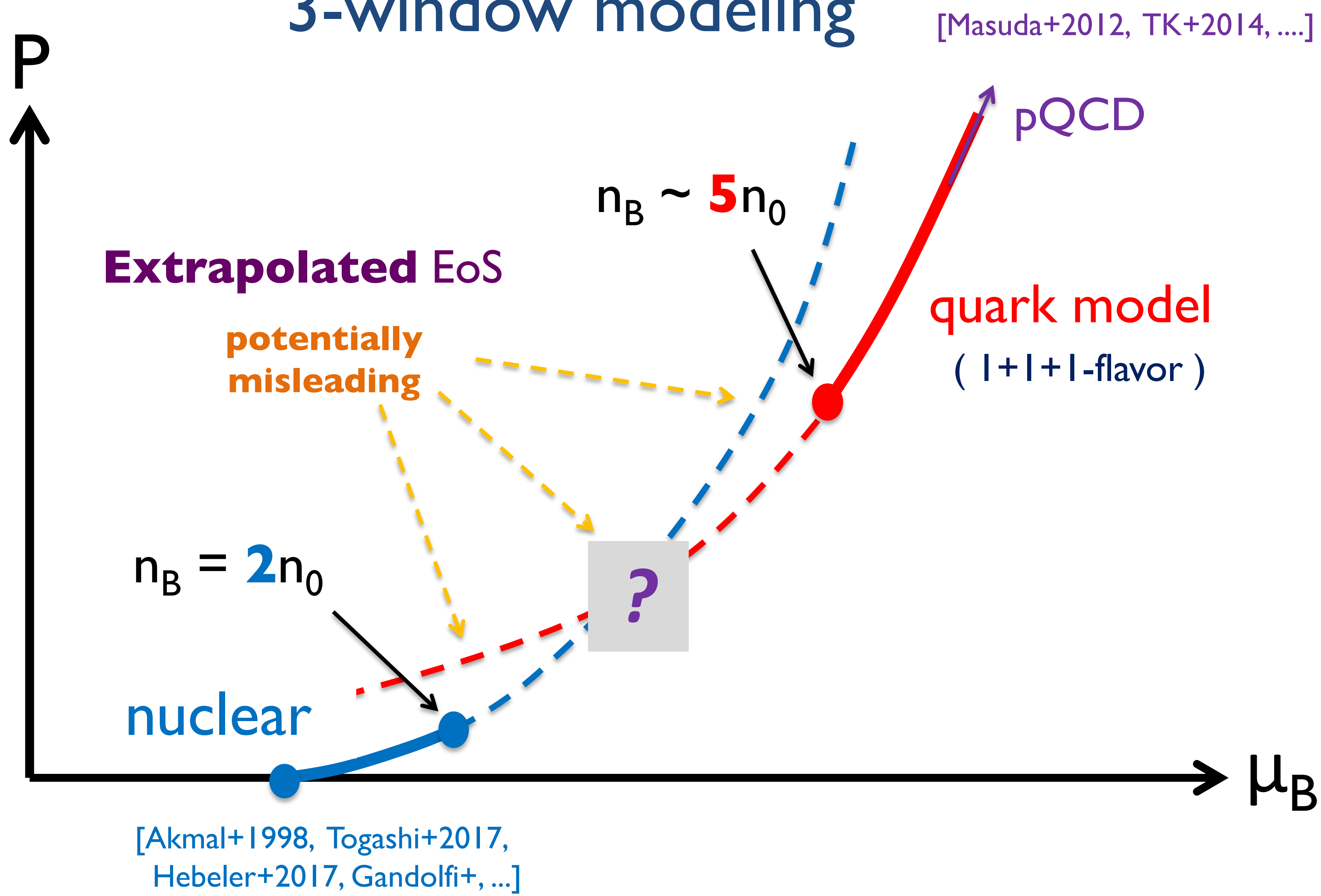
3-window modeling

[Masuda+2012, TK+2014, ...]

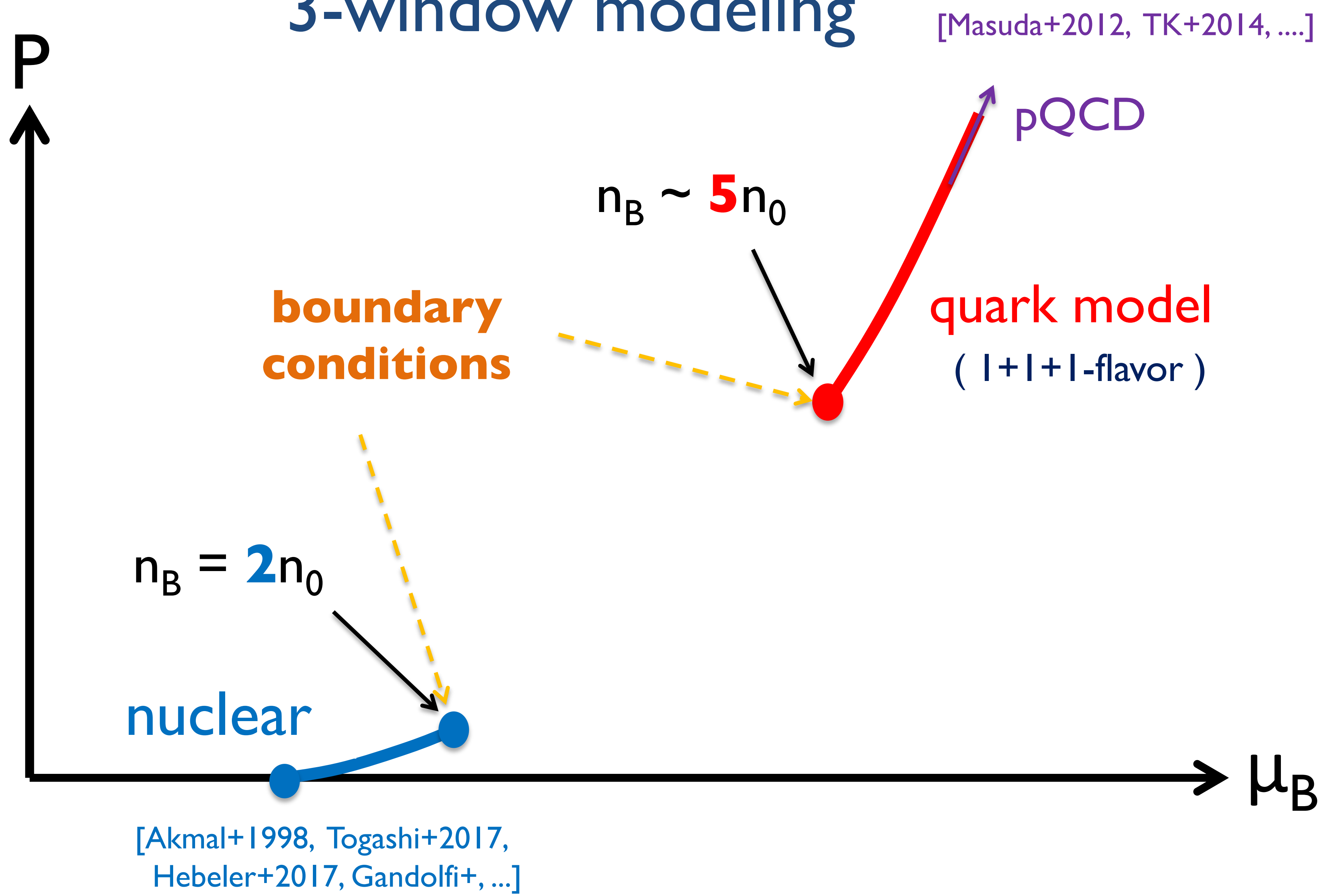


[Akmal+1998, Togashi+2017, Hebeler+2017, Gandolfi+, ...]

3-window modeling

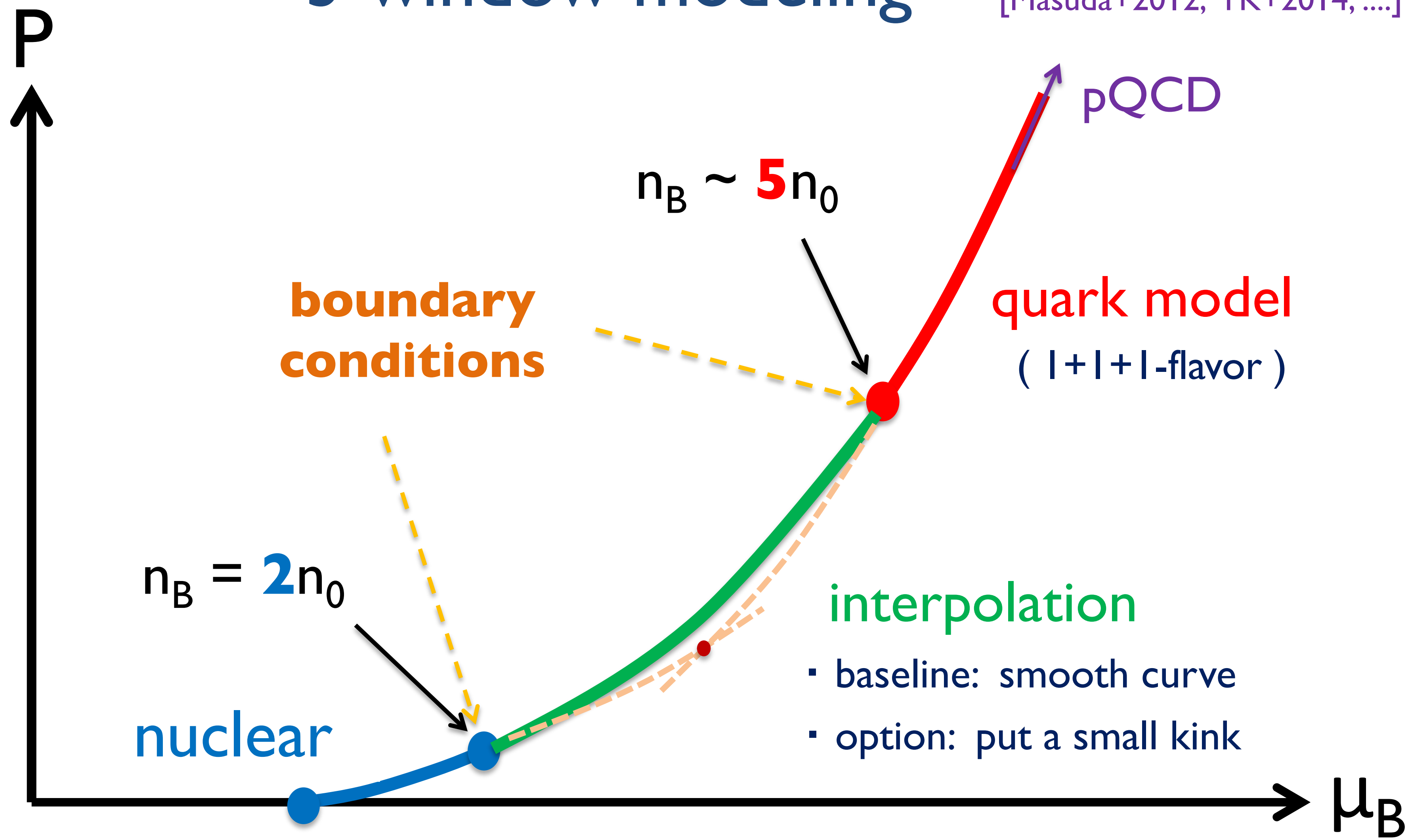


3-window modeling



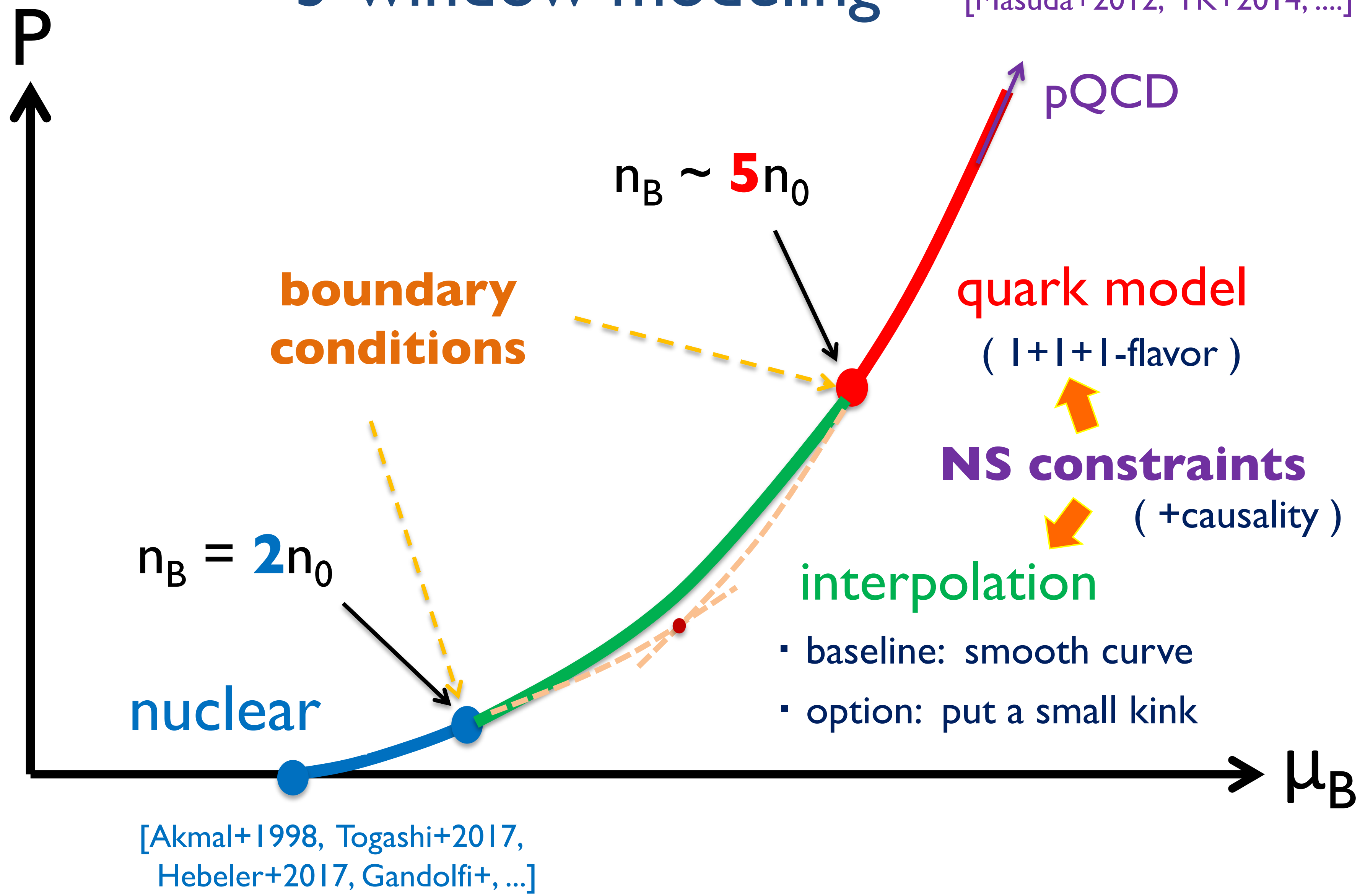
3-window modeling

[Masuda+2012, TK+2014, ...]



[Akmal+1998, Togashi+2017, Hebeler+2017, Gandolfi+, ...]

3-window modeling



A quark model for $n_B > \sim 5 n_0$

H-Q continuity : eff. Hamiltonian continuously evolves from hadron physics

"**3-window**" [Manohar-Georgi 1983, Weinberg 2010,...]

Q < ~0.2 GeV	0.2 GeV < Q < 1-2 GeV	~2 GeV < Q
very long-range (> 1fm)	constituent quarks + OGE (quasi-particles)	short range
confinement	**chiral** SB & color-**mag**. int. & **baryon-baryon**. int.	pQCD

A template) chiral color-mag. nB-nB int.

$$\mathcal{H} = \mathcal{H}_{\rm NJL} - \underline{H} \sum_A (q\Gamma_A q)(\bar{q}\Gamma_A \bar{q}) + \underline{g_V} \left(\bar{q}\gamma_0 q\right)^2$$

[Masuda+2015, TK+2014, Blaschke+....]

(for the moment phenomenological, should be derived from color-mag. int.)

Color-mag. int. : multi-facet aspects

1) **Coupling** $\propto$ **velocity** ~ **p/E**

more important in relativistic regime & high density

2) **Pairing** : smaller color- & flavor- reps are favored

($\rightarrow$ anti-symmetric w.f.) [cf) DeRujula+ (1975), Isgur-Karl (1978), ...]

hadron mass ordering: N-Δ splitting, etc.

source of color-super-conductivity [Alford, Wilczek, Rajagopal, Schafer,... 1998-]

3) **Baryon-Baryon int.** : short-range correlation

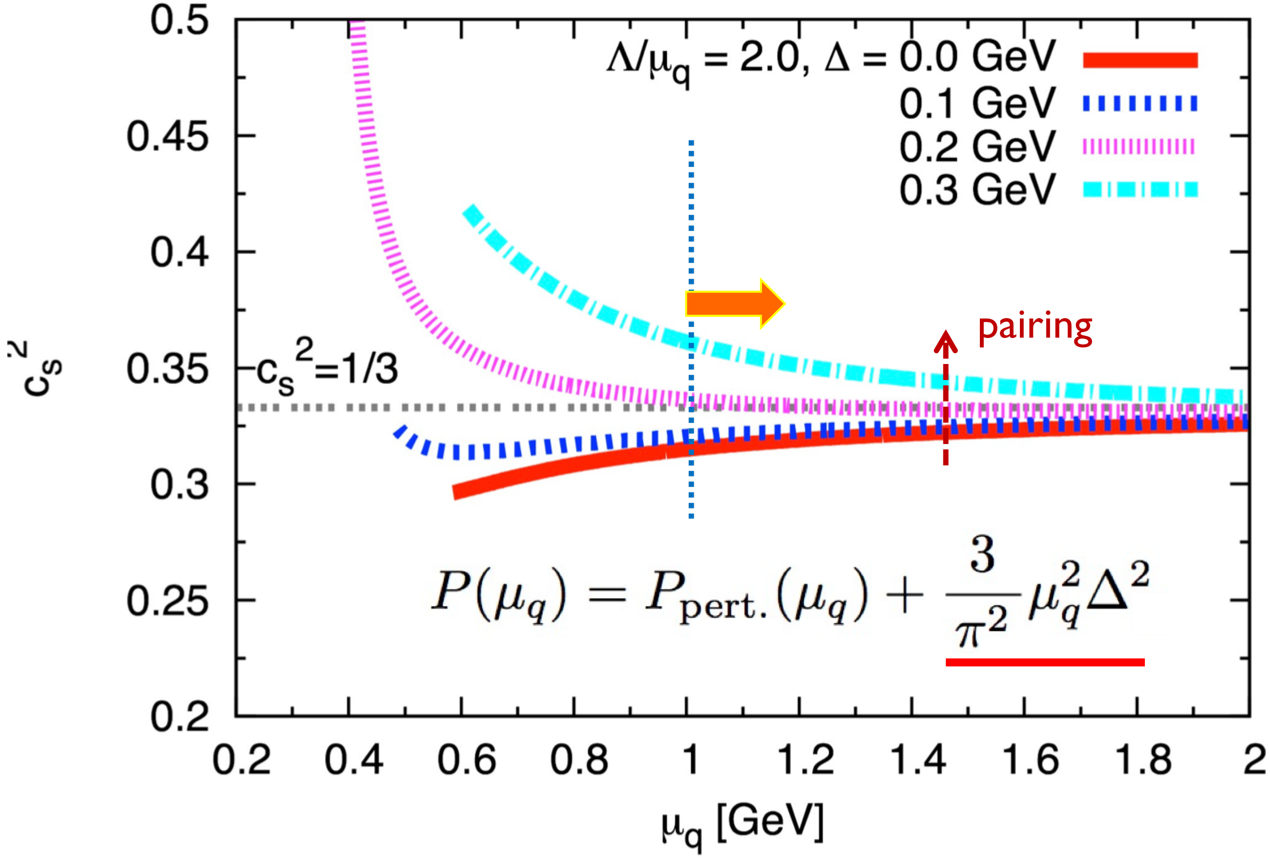
(**Pauli + color-mag**.) [Oka-Yazaki (1980),...]

channel dependence $\rightarrow$ non-universal hard core (some are attractive!)

mass dependence $\rightarrow$ weaker repulsion for strangeness

$\rightarrow$ remarkably **consistent with the lattice QCD** [HAL-collaboration]

Remark) pQCD + pairing vs speed of sound



[pQCD: Kurkela + (2009)]

For Δ > ~ **0.2** GeV

$(\Delta/\mu_q)^2$ ~ **4 %**

nevertheless,

c_s^2 approach 1/3 from **above**

$P \sim \mu^4 \rightarrow c_s^2 = 1/3$

$P \sim \mu^2 \rightarrow c_s^2 = 1$

If μ^2 dominates $\rightarrow c_s^2 > 1/3$

(perhaps Fermi surface effects)

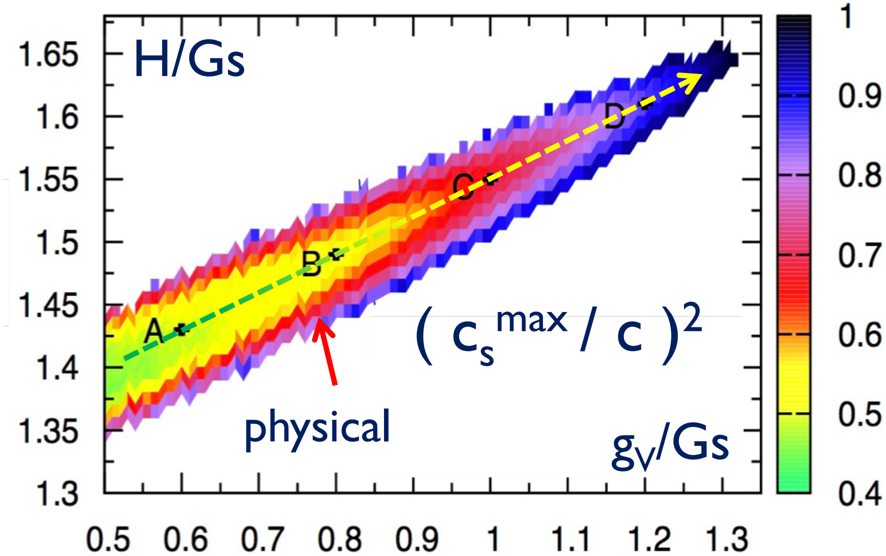
[see also McLerran-Reddy (2018)]

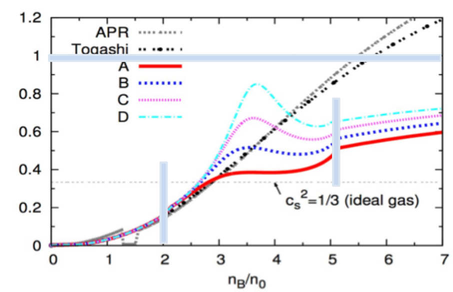
An exercise: survey for $(g_V, H)_{@5n0}$

Step1) Prepare **realistic** nuclear EoS for **0.5-2**n0

[e.g. Akmal+1998, Togashi+2017, ChEFT, ...] ➡ **radius constraint OK**

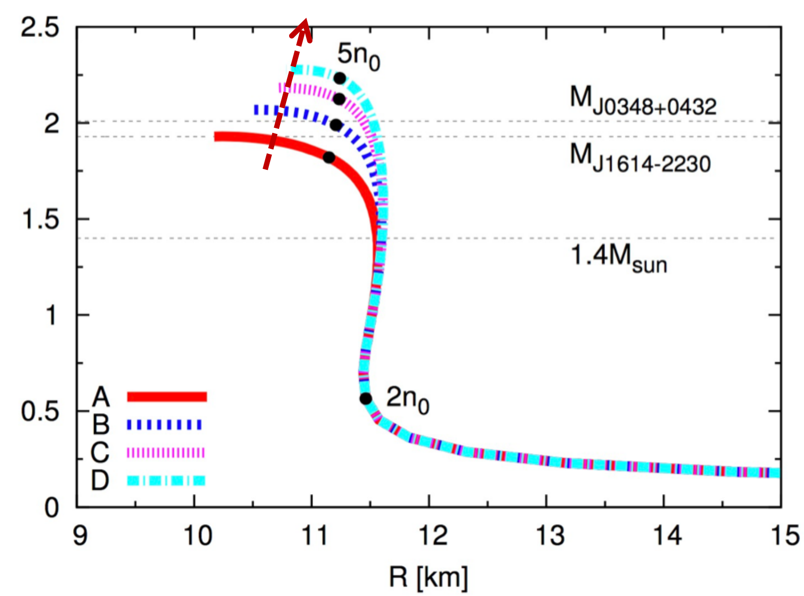
Step2) Survey the range of (g_V, H) compatible with **causality**





Step3) Impose **$2M_{sun}$** constraint

found: $M_{max} <$ **2.35** M_{sun}



Trends found in this exercise

for quark EoS consistent with all constraints

- **Strangeness** seems **unavoidable** for **soft-stiff EoS** :

  $n_s \sim n_u \sim n_d$ for $n_B > 5n_0$ (μ_B > ~1.5 GeV ~ $3M_s$)

- **Pairing**; in MF, color-flavor-locked condensates (color-super)

  stiffening at **high** n_B

- **Repulsive n_B-n_B int.**

  tempers the growth of $n_B \longrightarrow$ smooth chiral restoration

- **not acceptable** for conventional hybrid construction

  in this sense, a **new class** of quark EoS

Summary

Coherent studies essential (Astro-QCD-condensed matter)

- Hints for **soft**-**stiff** EoS & **causality** → H-Q continuity

- Quark descriptions important :

  → **B.C. for EoS** & **BB-int.** & **hyperon problems**

- Pairing important :

  - Hard to prevent theoretically.

  - Temper softening associated with strangeness.

- Quark descriptions at **5 -100** n_0 can & should be improved.

(work in progress)

Back Up

"3-window": constituent quarks for hadrons

cf) Manohar-Georgi (1983), Weinberg (2010)

> 1-2 GeV

(< 0.2 fm)

Perturbative

weakly coupled quarks & gluons

~ 1 GeV

(~ 0.2-1 fm)

$\Lambda_\chi \sim 4\pi f_\pi$

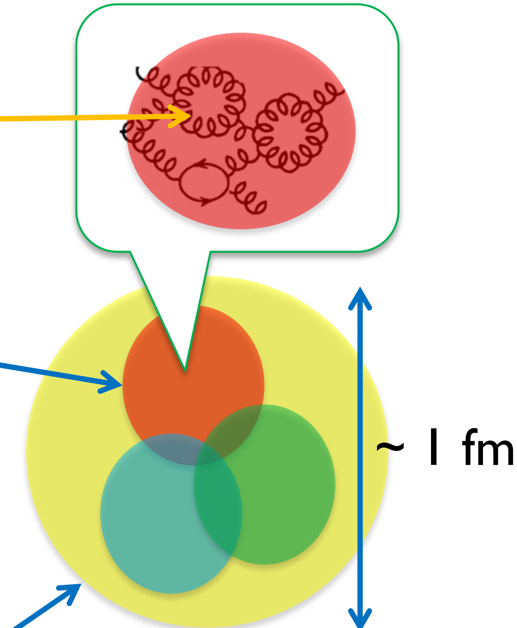
Chiral + OGE

(one-gluon-exchange)

ChSB -> constituent quark mass ~300 MeV

OGE -> int. b.t.w **constituent** quarks

based on **quasi-particle** picture



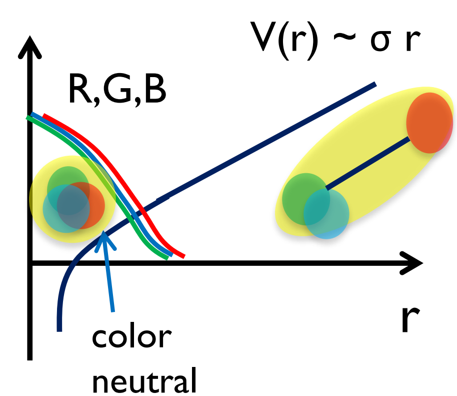
< ~ 0.2 GeV

(> ~ 1 fm)

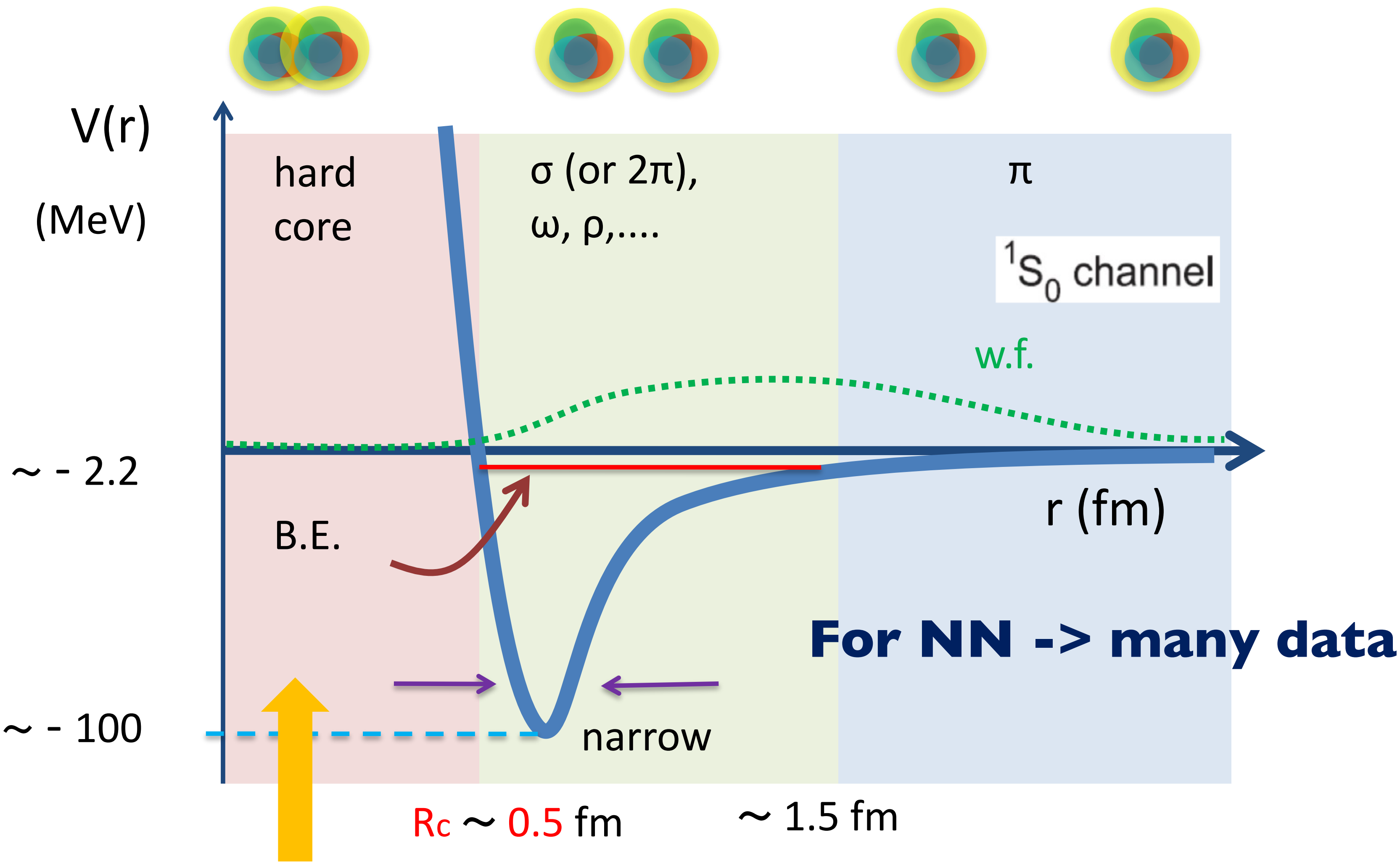
Confinement

trap quarks to keep color white

quasi-particle gluons
→ **unlikely** generate confining forces



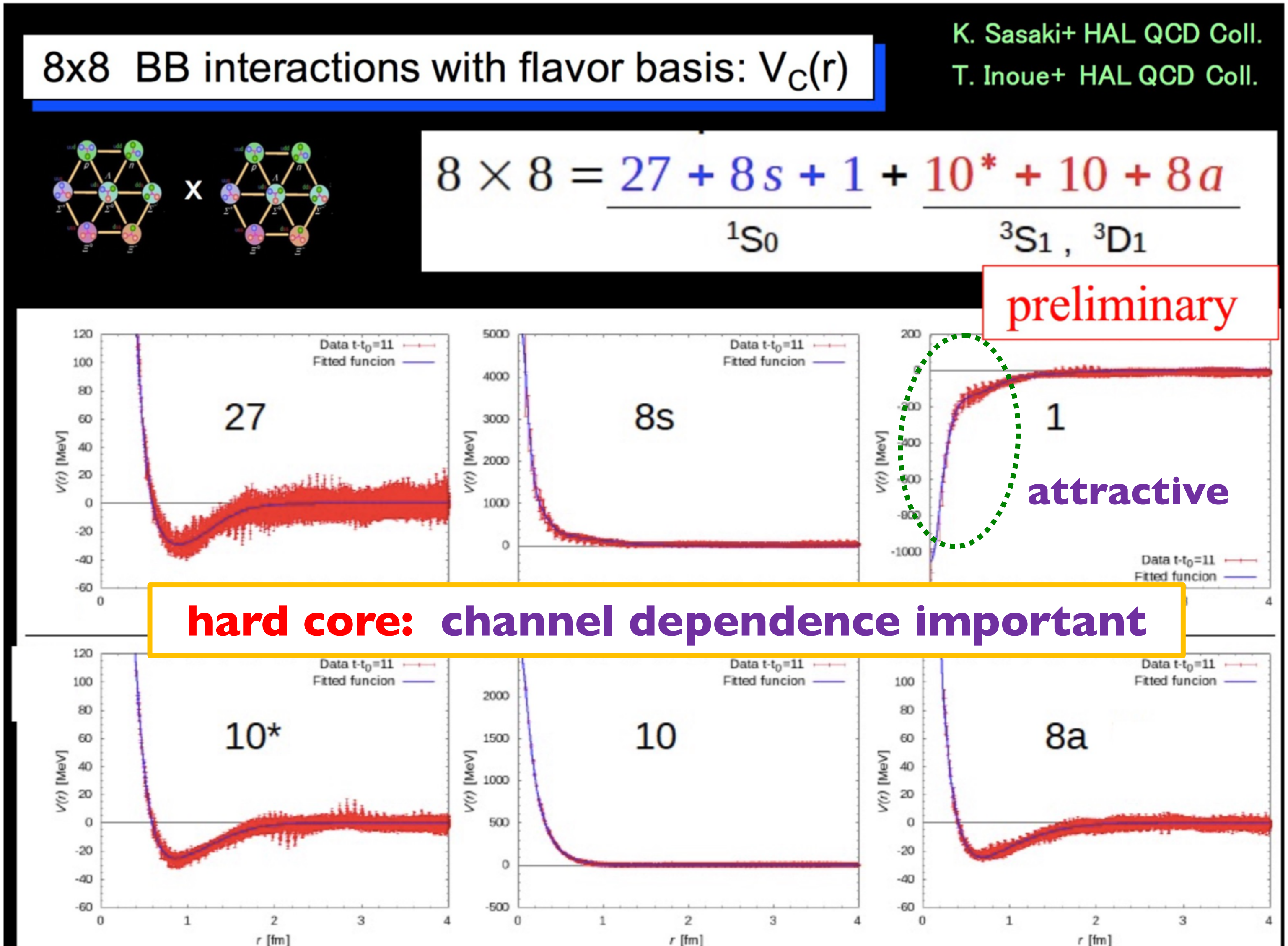
"3-window": N-N interactions



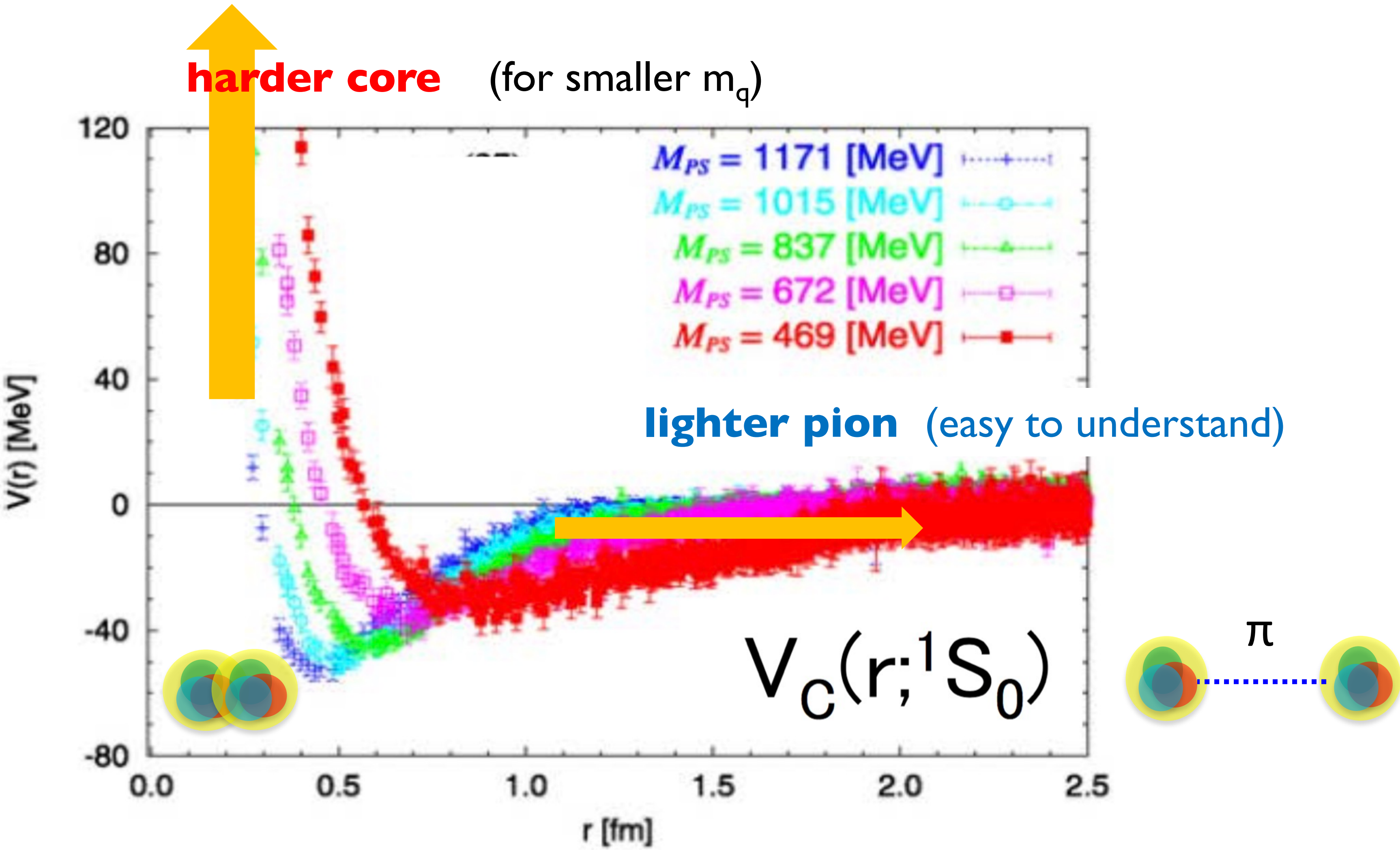
How about other channels, NY, YY, NΔ, ... ??

Baryon-Baryon int. on a lattice (**$SU_f(3)$ limit**)

[Hatsuda's talk at NFQCD2018]



Mass dependence of NN interactions



Hard core → due to some relativistic effects?

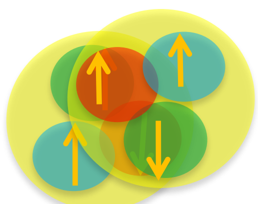
Recent quark model studies for hard cores

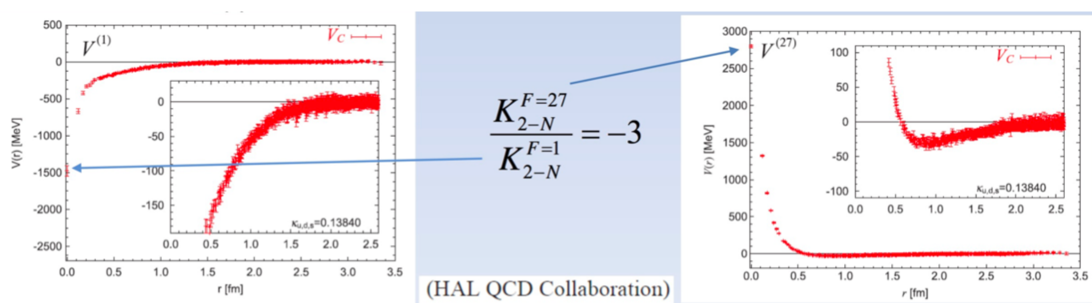
cf) A.Park-W-Park-SuHoungLee (2016),...

evaluate matrix for color-mag. int. for overlapped baryons

→ Channel dep. of the height of the hard core

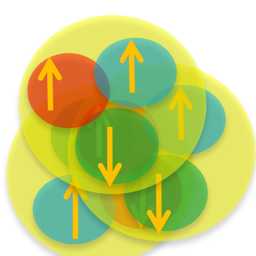
2-body)





→ semi-quantitative agreement with lattice

3-body)

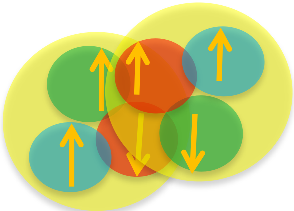


NNN, NNY are partially investigated

→ overall repulsion, though not universal

See, Su Houng Lee's talk in NFQCD2018 (3rd week), Kyoto

Quark descriptions for the hard core



cf) Oka-Yazaki (1980),...

6q problem in constituent quark models

Resonating group method (RGM) [Wheeler 1937, Hill-Wheeler 1953]

$$\int \phi_A^{+}(\xi_A)\phi_B^{+}(\xi_B)(H-E)\,\Psi(\xi_A,\xi_B,\boldsymbol{R}_{AB})\,d\xi_A d\xi_B = 0$$

$$\Psi(\xi_A,\xi_B,\boldsymbol{R}_{AB}) = \mathcal{A}[\phi_A(\xi_A)\phi_B(\xi_B)\chi(\boldsymbol{R}_{AB})]$$

scattering problems $\longrightarrow$ phase shift

Findings

1, Quark Pauli blocking : NOT enough for the hard core

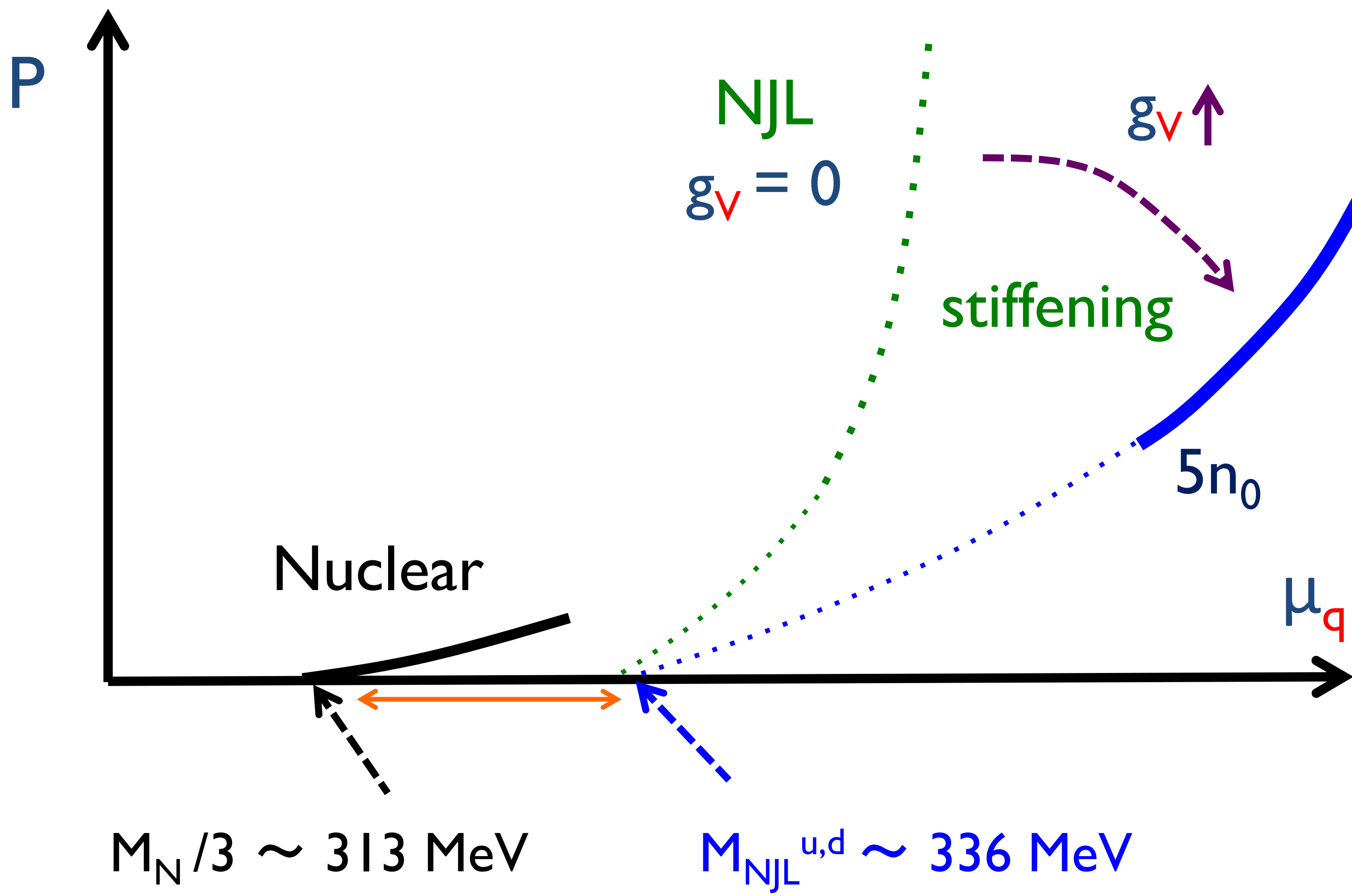
2, Color-magnetic interaction is crucial (enhanced at small mass)

3, Hard cores are not universal: attractive for some channels

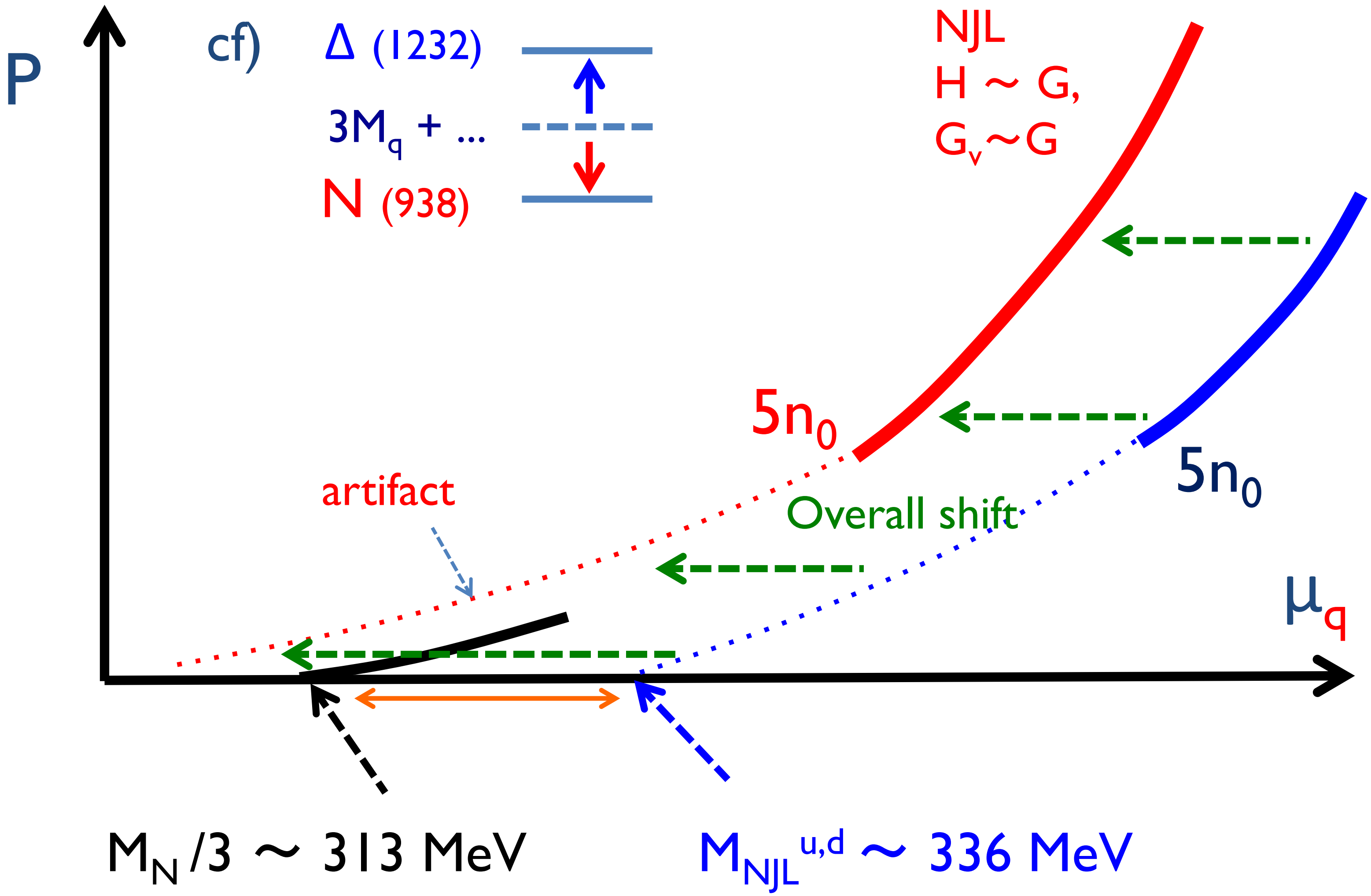
The picture so far is consistent with the lattice's !

see also A.Park-W-Park-SuHoungLee (2016)

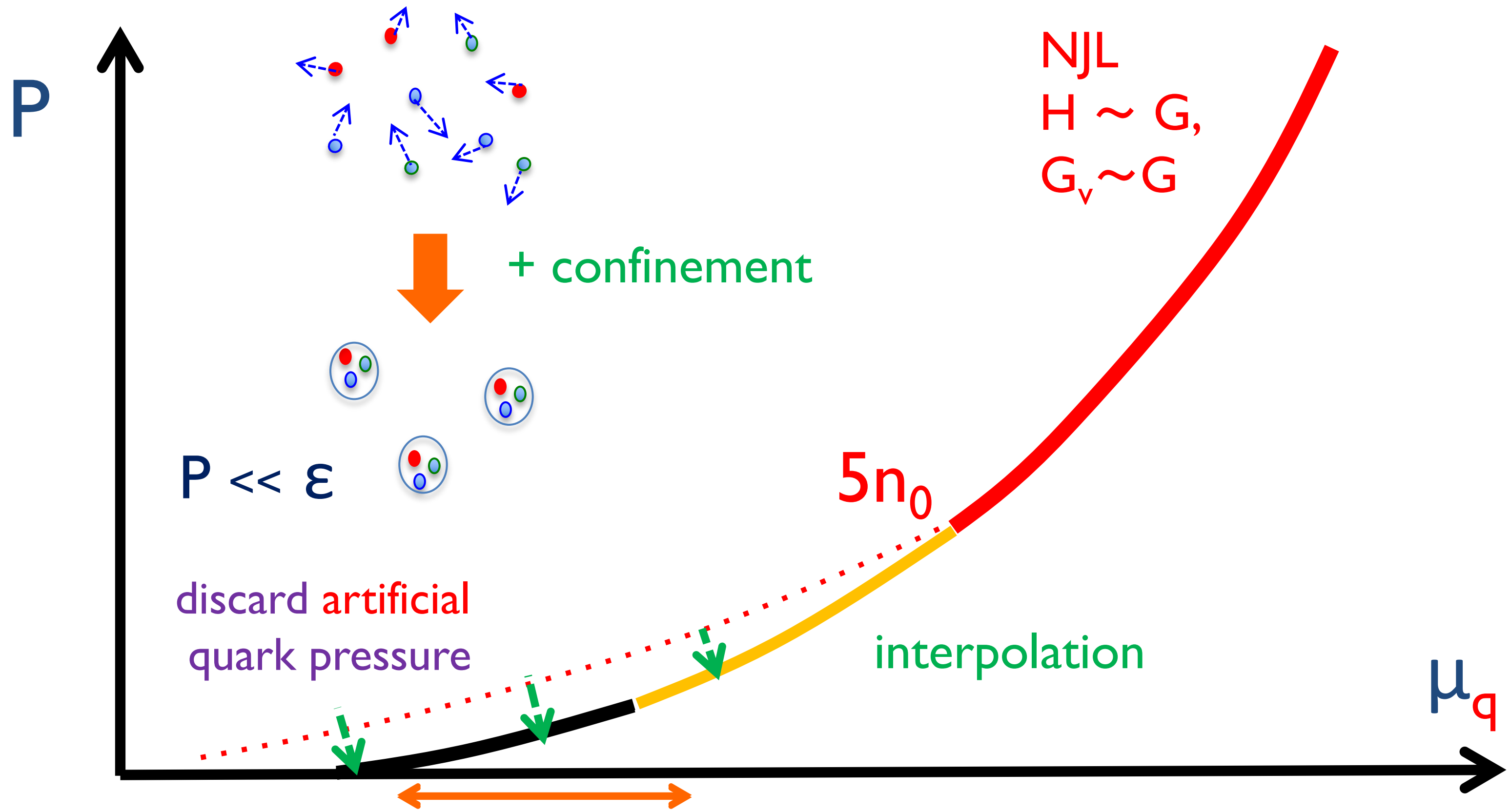
minimal + vector int.



+ attractive color-magnetic int.



+ interpolation



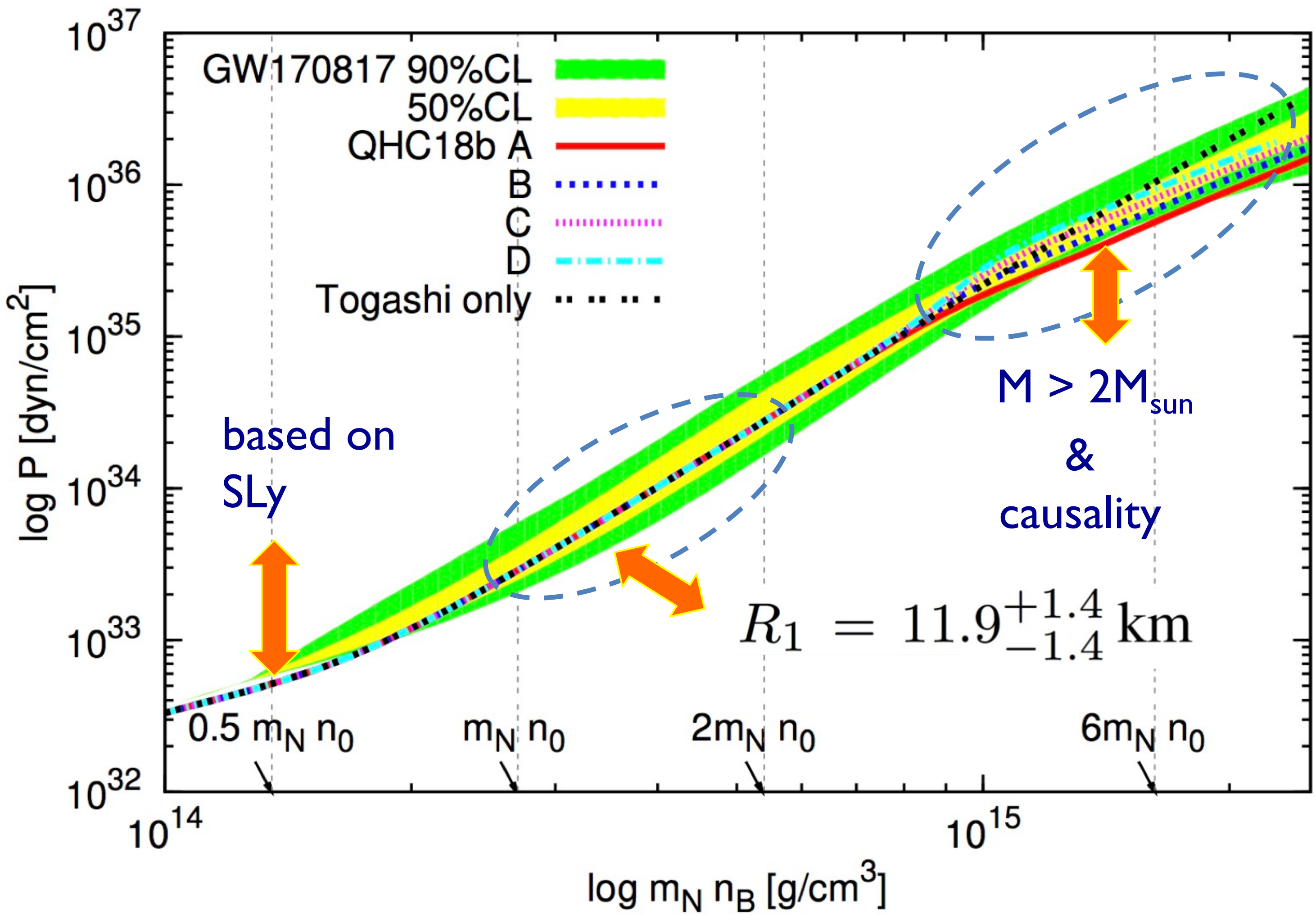
In this picture: **confinement → softening**

or **deconfinement → stiffening**

(opposite to conventional discussions for T=0)

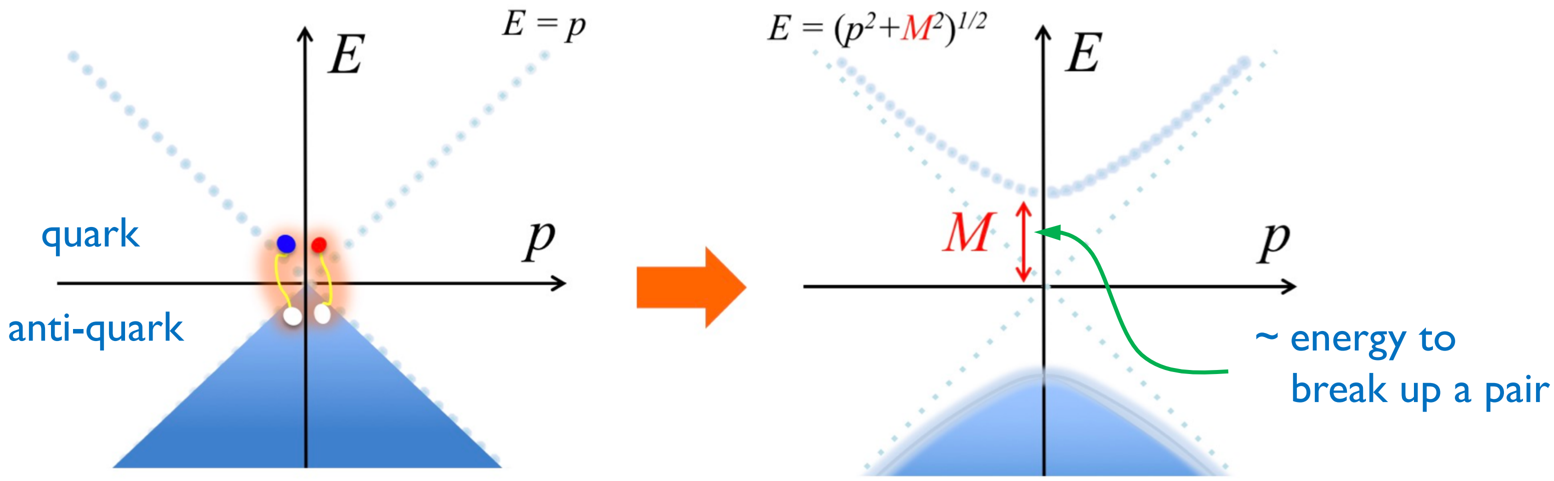
EoS from aLIGO vs QHC18b

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

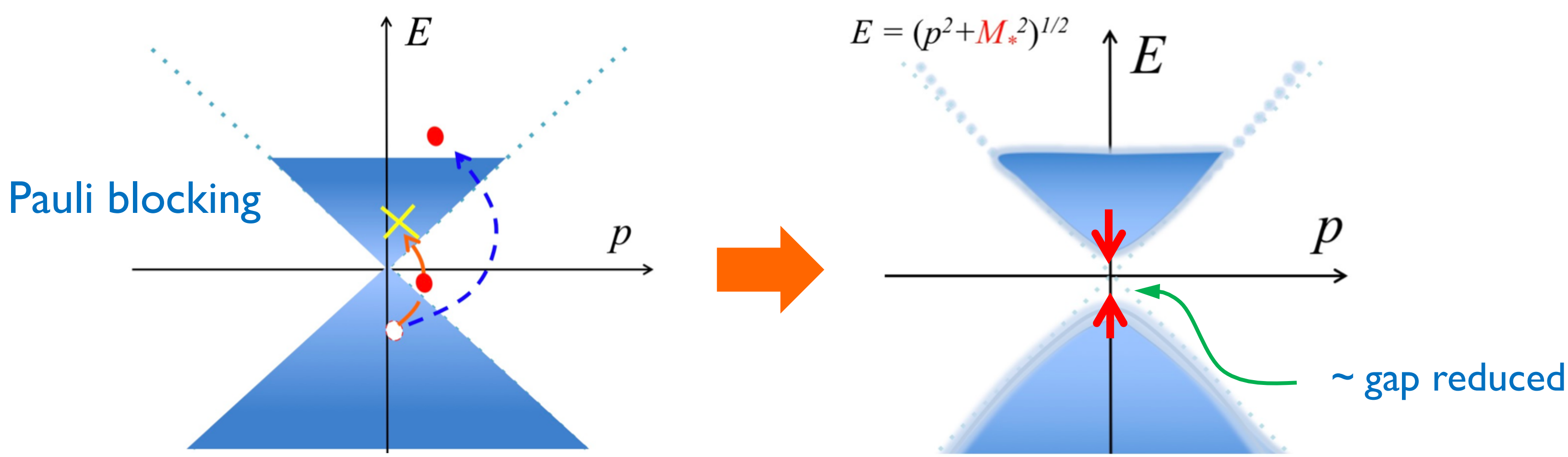


Chiral sym. breaking & restoration

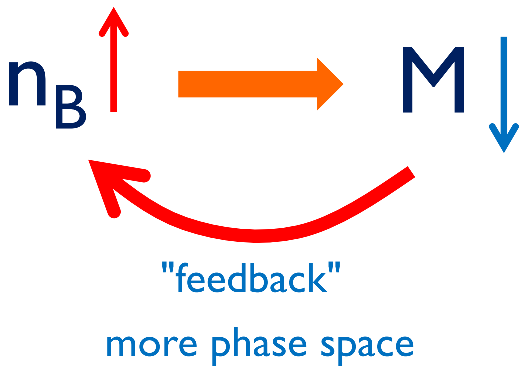
vac



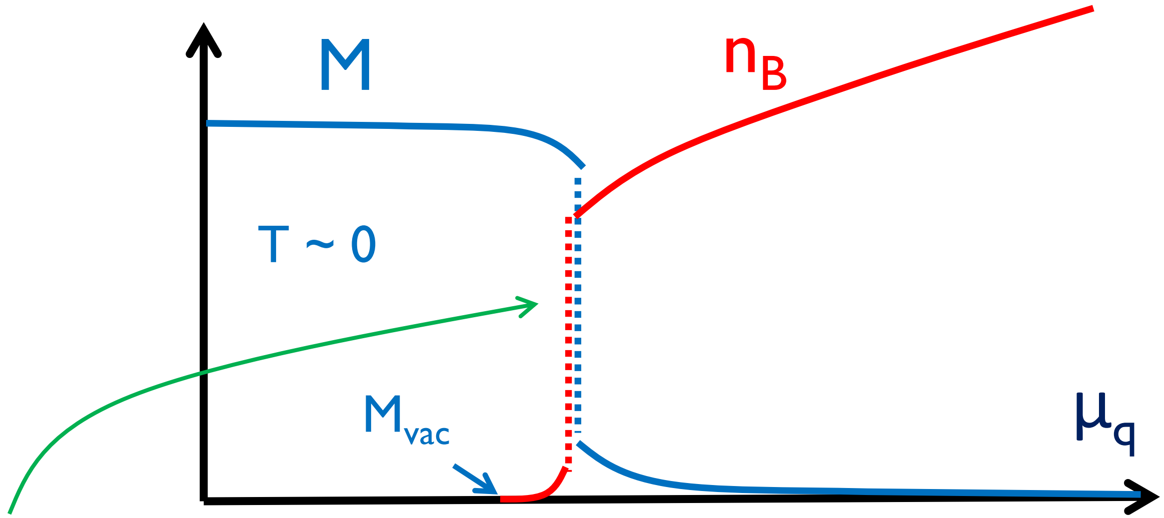
finite density

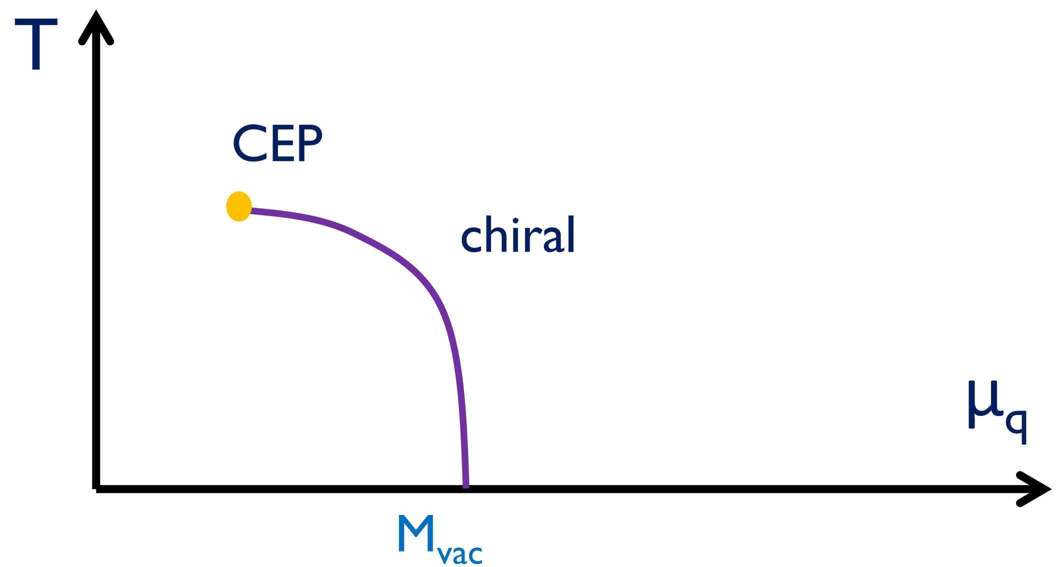


I st order chiral transition (typical quark **models**)



→ radical changes in n_B & M





Braking density evolution: Ist → crossover

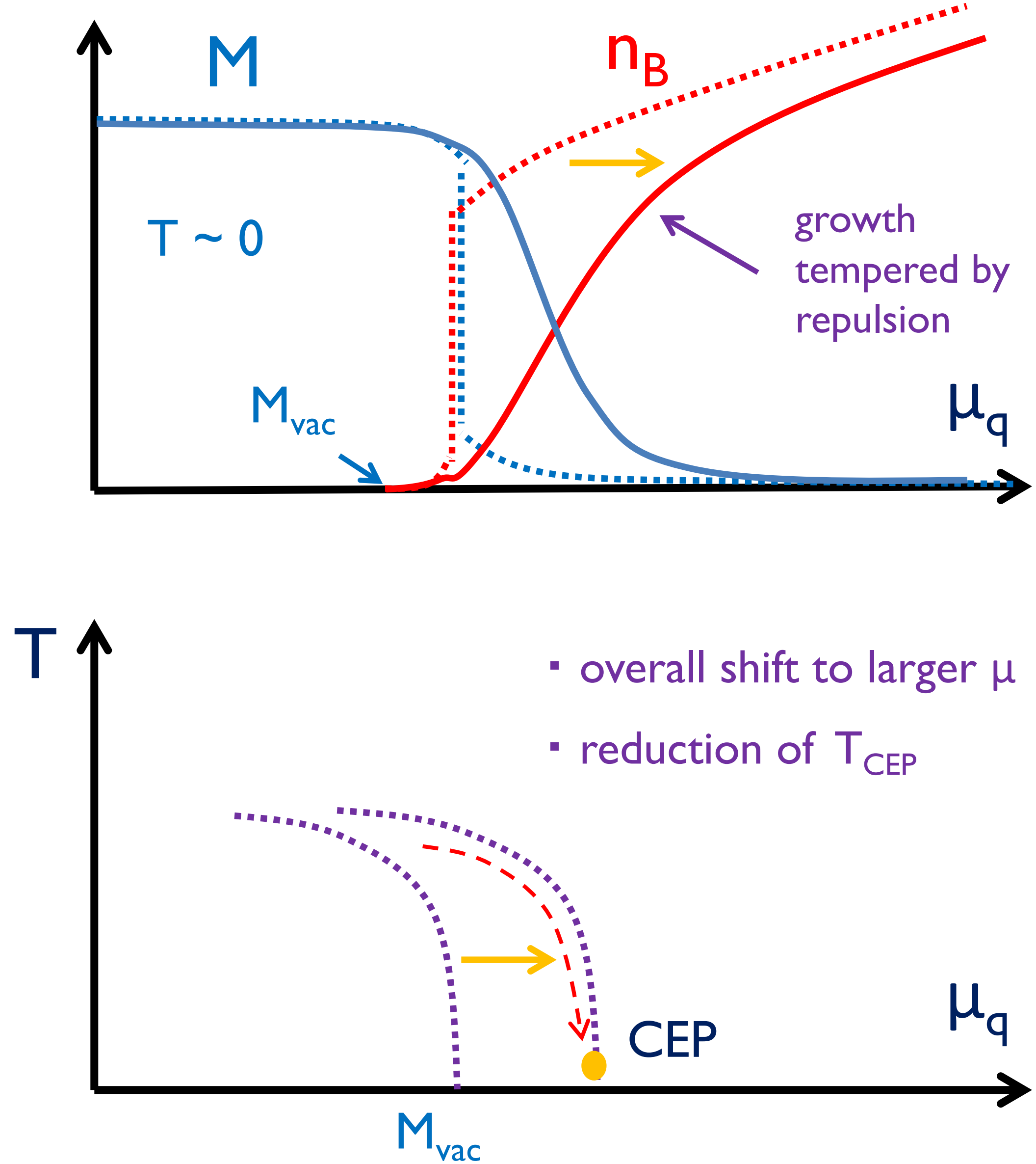
Now add
density-density repulsion

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

braking the evolution of n_B

→ milder changes in M

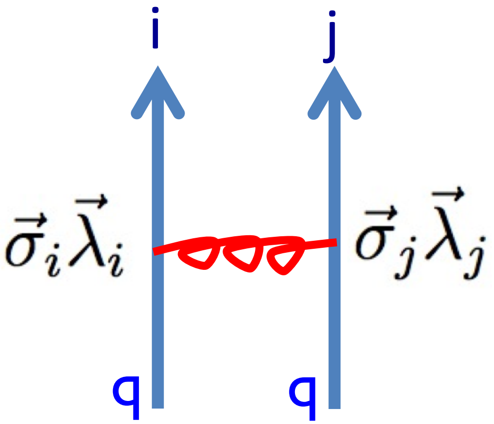
Details of int. are crucial



Constituent quark models for hadrons

cf) DeRujula-Georgi-Glashow (1975), Isgur-Karl (1978), ...

Color-**magnetic** interactions : responsible for **level splitting**



non-rela.

color-color **spin-spin**

$$\alpha_s \lambda_i \frac{\vec{\sigma}_i \cdot \vec{q}}{m_i} \frac{1}{q^2} \lambda_j \frac{\vec{\sigma}_j \cdot \vec{q}}{m_j} \simeq \frac{\alpha_s}{m_i m_j} (\lambda_i \cdot \lambda_j)(\vec{\sigma}_i \cdot \vec{\sigma}_j) \delta(\vec{r}_{ij})$$

channel dependence

& Fermi statistics → **flavor-flavor correlation**

mag. int. is **enhanced** in **relativistic** regimes

coupling ∝ **velocity** ~ **p/E** non-rela. (→ **p/M** << 1.)

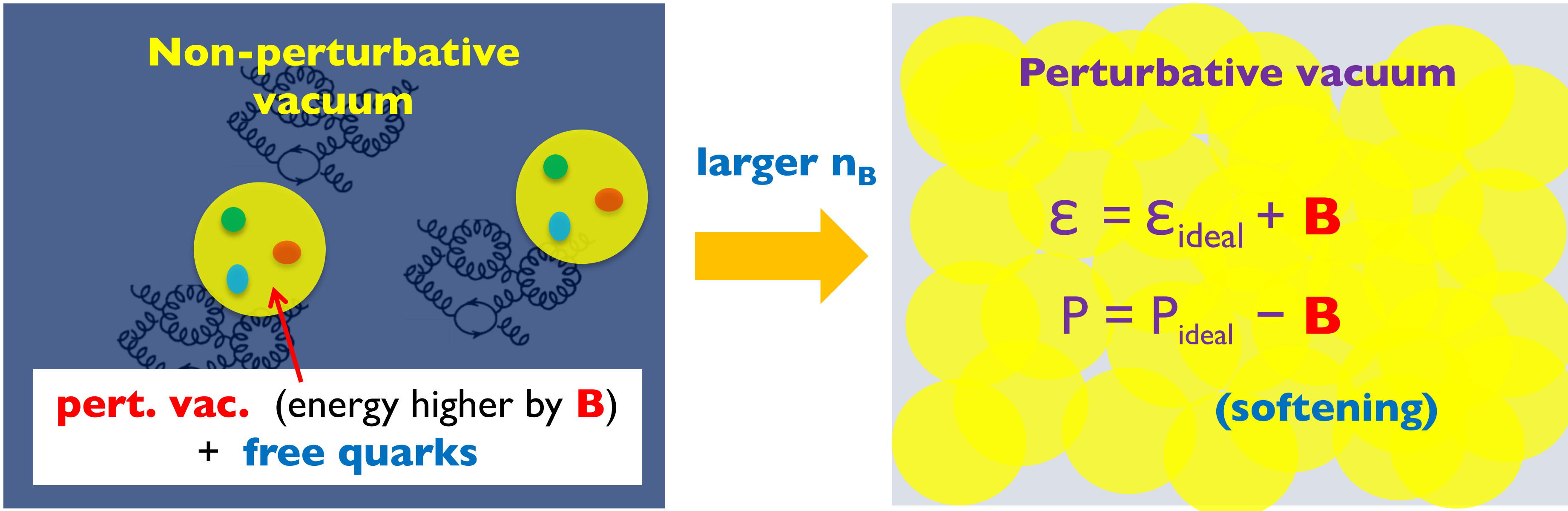
(sensitive to the quark mass)

Capture the gross properties of (S-wave) baryons

(~10% accuracy)

A quark model traditionally used in astro-EoS

cf) Chodos et al (1974), MIT bag model



Over-simplifications

1, Inside of hadrons is NOT like free media: **ChSB** & constituent quark mass

2, Even in the quark matter regime, interactions are **critically important**

($n_B \sim 100\, n_0$ is not enough for free gas picture)

Implications for dense matter

If one accepts the quark description for hard cores, it follows

1, Hard core repulsions are weaker for YN & YY than for NN

color-mag. ~ $1/M_i M_j$ $M_{u,d}/M_s \sim 3/5$

2, Short-range int. can be attractive (though relatively rare)

e.g.) H-dibaryon (uds-uds); double Ω (sss-sss),....

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

3, $M_{u,d,s}$ reduction -> overall enhancement of hard core repulsion

chiral restoration is delayed by the repulsion?

These features are hard to infer from purely hadronic models...

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

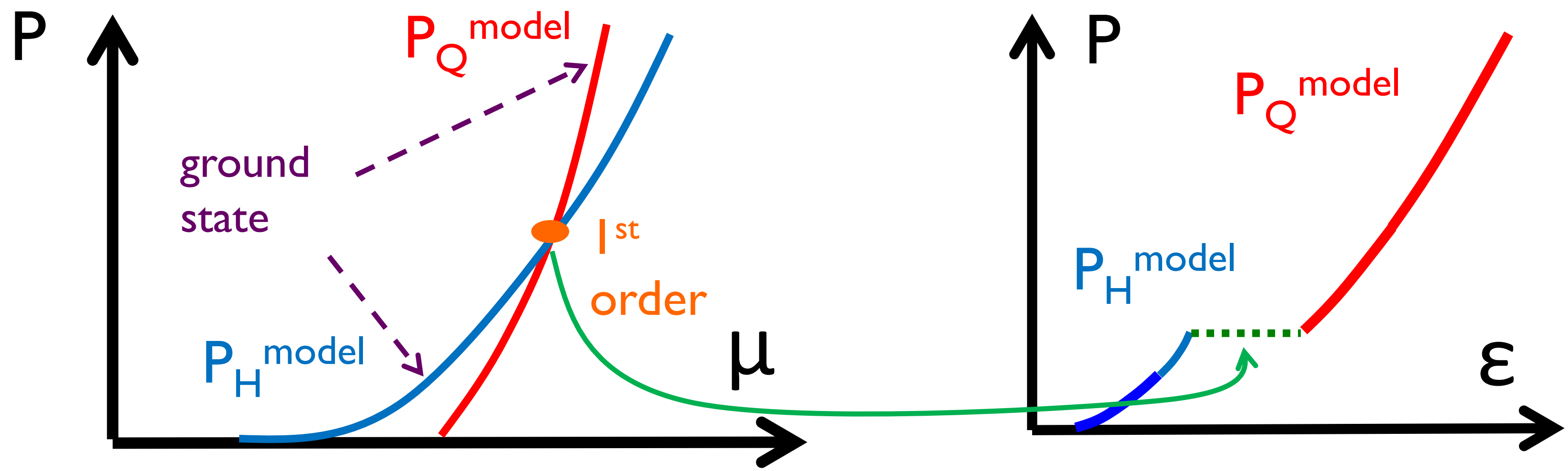
dynamics: the interplay between chiral & diquark

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)

Constituent quark models for hadrons I

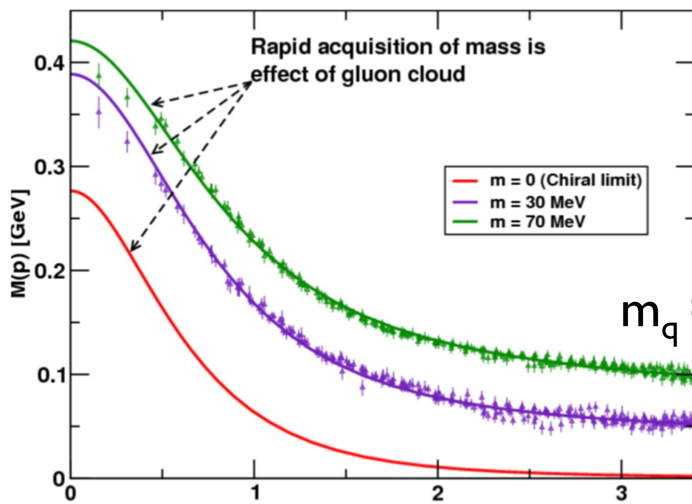
cf) DeRujula-Georgi-Glashow (1975), Isgur-Karl (1978), ...

1, Confining potential put by hand

Even now, no satisfactory analytic derivation... Main info from lattice

2, Constituent quarks assumed: M_u~ 350 MeV, M_s ~ 540 MeV

In modern language, produced by dynamical chiral sym. breaking



M(p)

p [GeV]

lattice & Dyson-Schwinger

m_q = 70 MeV

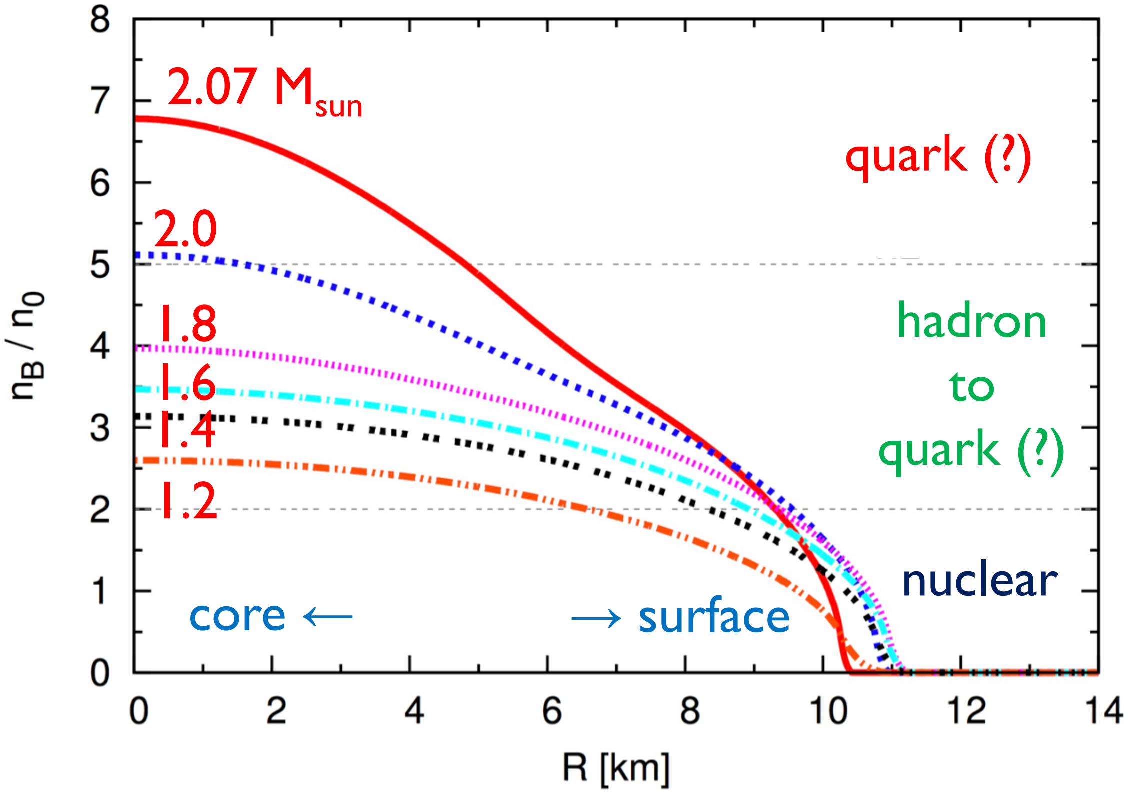
30 MeV

0 MeV

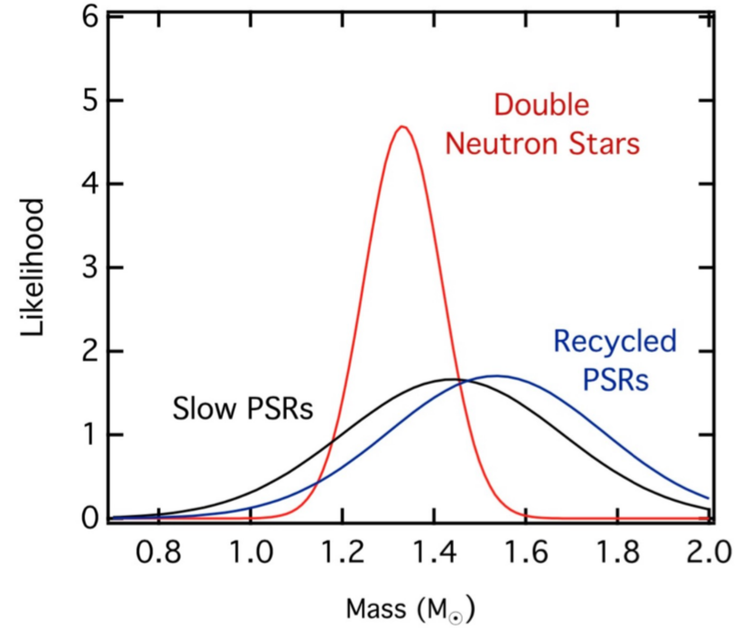
3, OGE -> **semi-short** range color-**electric** & **magnetic** int.

Baryon density in a neutron star (our EoS)

Distribution of n_B for various NSs



Distribution of NSs



based on observations

For typically observed NSs ($M > 1.2M_{sun}$) :

large fraction (> 50%) of matter has $n_B > 2n_0$

→ beyond the nuclear regime is crucial for most of NSs