Delineating QCD matter in extreme conditions

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Career

- 2008 : Ph.D., Kyoto University (supervisor : Prof. Hideo Suganuma)

(**Hadron physics**; QCD sum rules for multi-quarks; holographic QCD)

2008 - 2011 : Posdoc, RIKEN-BNL research center, USA (host: Larry McLerran)

(**cold, dense QCD** in general; low dimensional condensed matter; baryons in large Nc)

2011 - 2013 : Posdoc, Bielefeld University, Germany (host: Aleksi Vuorinen)

(QCD in strong magnetic fields; ...)

2013 - 2015 : Research Associate, University of Illinois, Urbana-Champaign, USA

(**Neutron Stars**; 2-color QCD; ...) (host: Gordon Baym)

2015 - Now : Associate professor, Central China Normal University

(Delineating neutron star phenomena; functional methods; ...)

Achievements

- 29 (+1) papers & 27 proceedings published (1307 cited in inspires, h-index 18)

  most cited: *From hadrons to quarks in neutron stars: a review* ('18) : 205 times

  Quarkyonic Chiral Spirals ('10) : 189 times

  (will be presented today):

- 57 talks (31 invited) in international conferences
- 44 seminars
- Honors: "*the most valued referee*" : Nucl. Phys. A ('13) & Phys. Lett. B ('14)

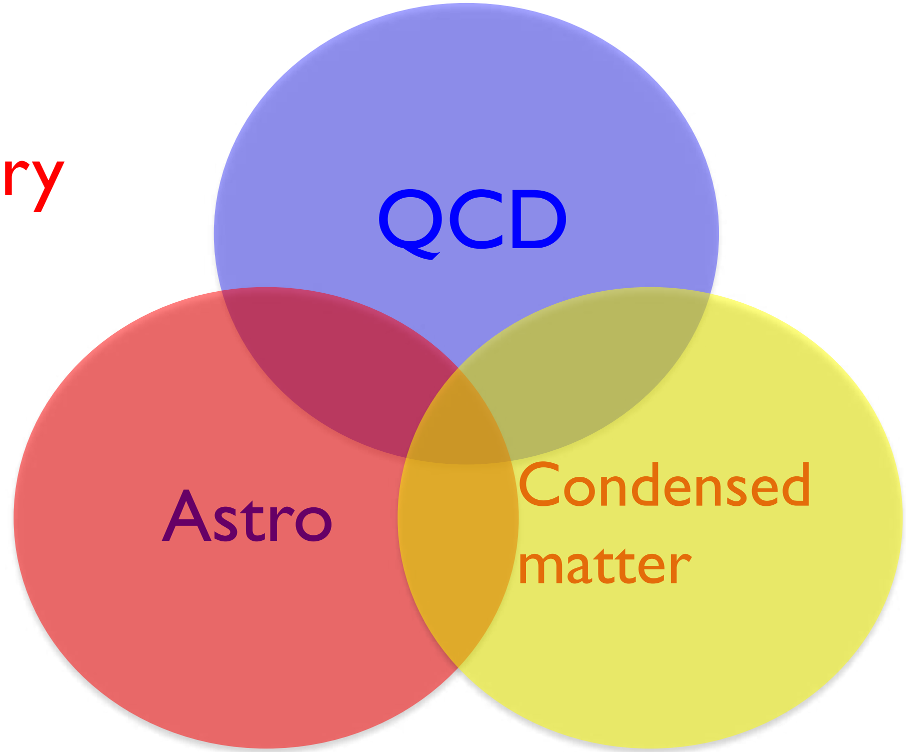
  Special posdoc (RIKEN, $10,000 x 3-years)

  NSFC (2016: ~$20,000, 2018-2021: ~ $100,000)

Research interests

- **Hot & Dense QCD**
- QCD in magnetic fields
- Hadron spectroscopy
- Nuclear forces

Interdisciplinary



- **Neutron stars**
- Supernovae

- **Super-conductivity**
- Topological matter
- Low-dim. physics

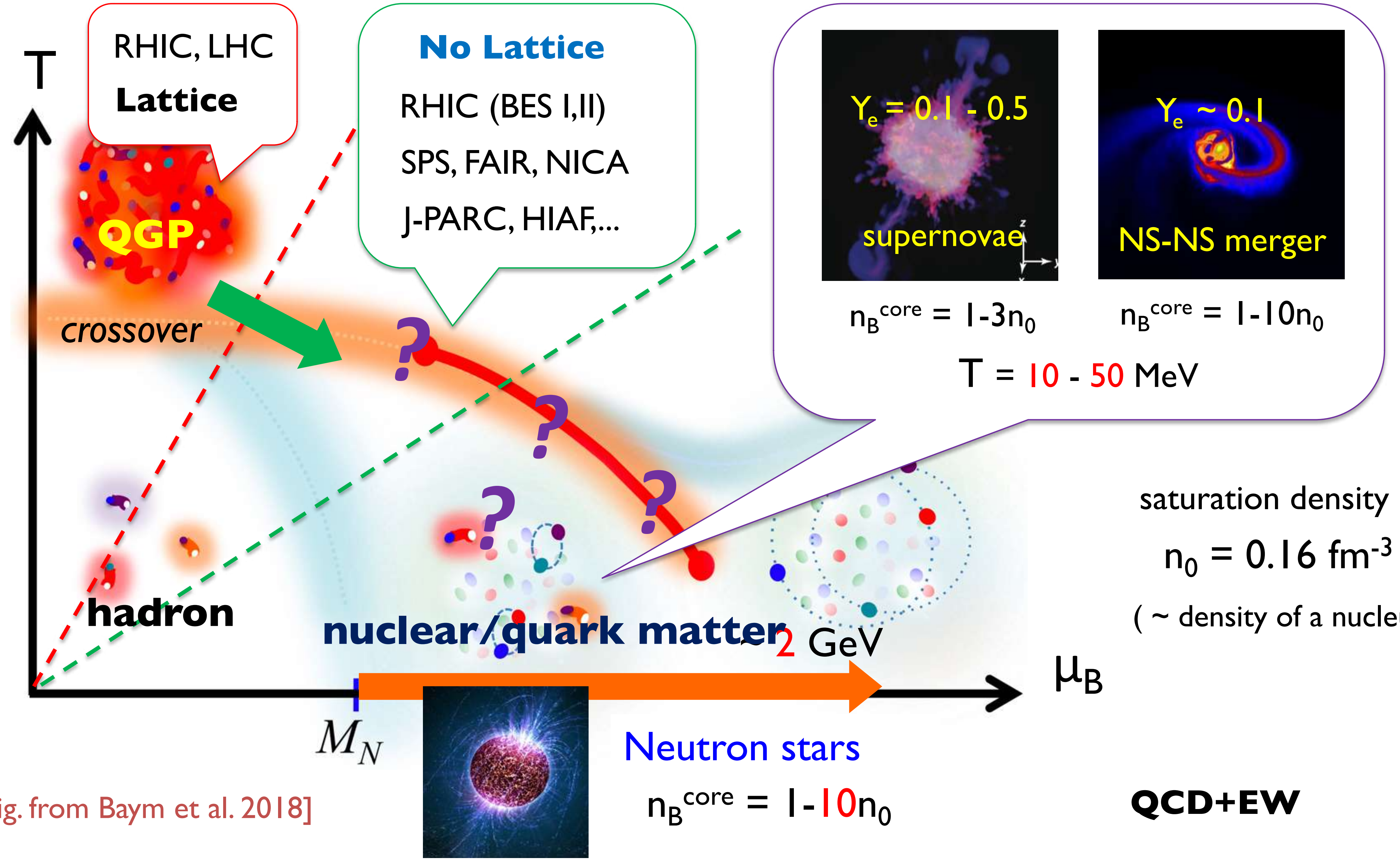
Contents

1, Dense QCD matter – overall sketch

2, 2-topics on dense QCD (achievements)

- *Quarkyonic matter*
- *Neutron star equations of state*

3, On-going works & future prospects



saturation density

$n_0 = 0.16\ \mathrm{fm}^{-3}$

(~ density of a nucleus)

QCD+EW

[Fig. from Baym et al. 2018]

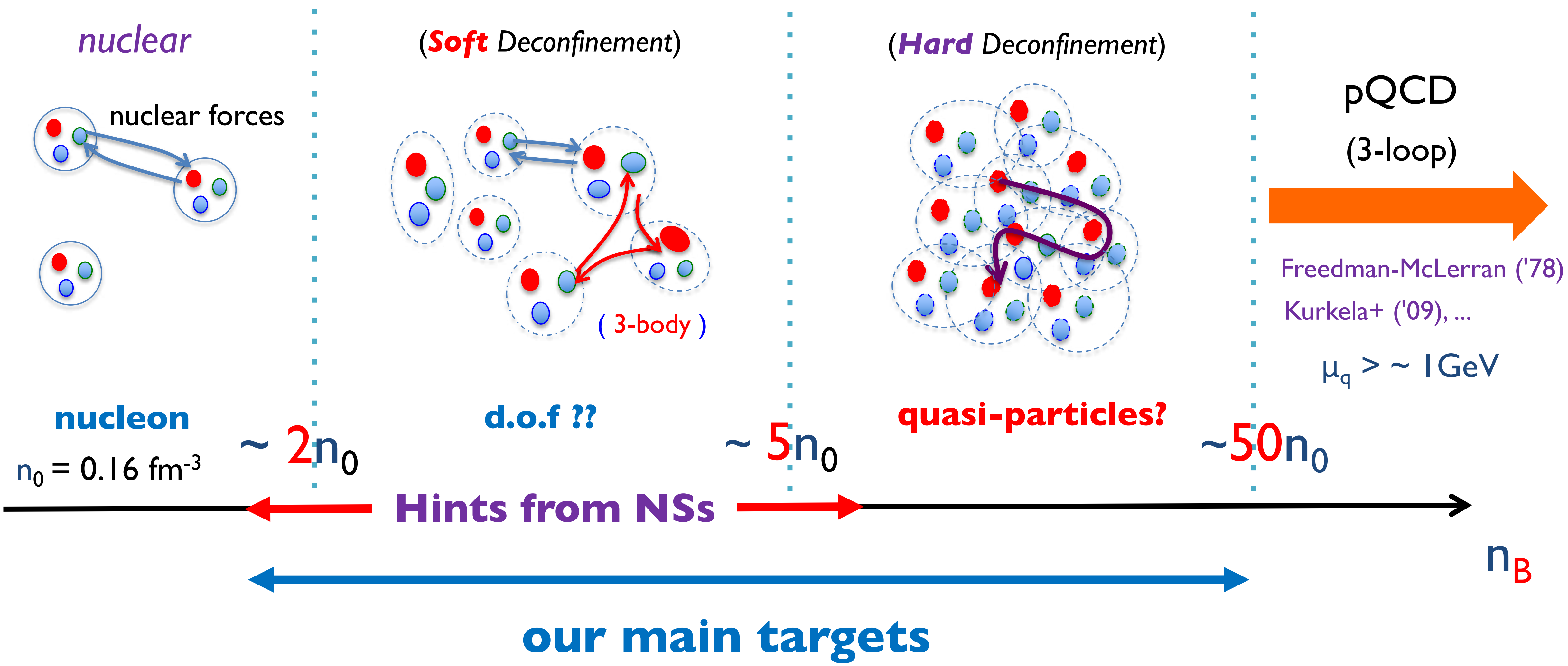
Dense QCD: my motivations

- 1, *Interdisciplinary* subjects : QCD x condensed matter x astrophysics
- 2, There remain *fundamental questions* & *paradoxes*
  - Rooms for new concepts & ideas
- 3, Relevant pieces to *complete* the QCD phase diagram
  - The long-standing problem; a lot of experimental & observational efforts
- 4, Practically important for *astrophysical* phenomena

  e.g.)
  - Neutron star EoS: M-R relations & compositions
  - Hot EoS for supernovae & NS mergers
  - Reducing QCD uncertainties: beneficial for the beyond-SM physics

Sketch of dense QCD matter

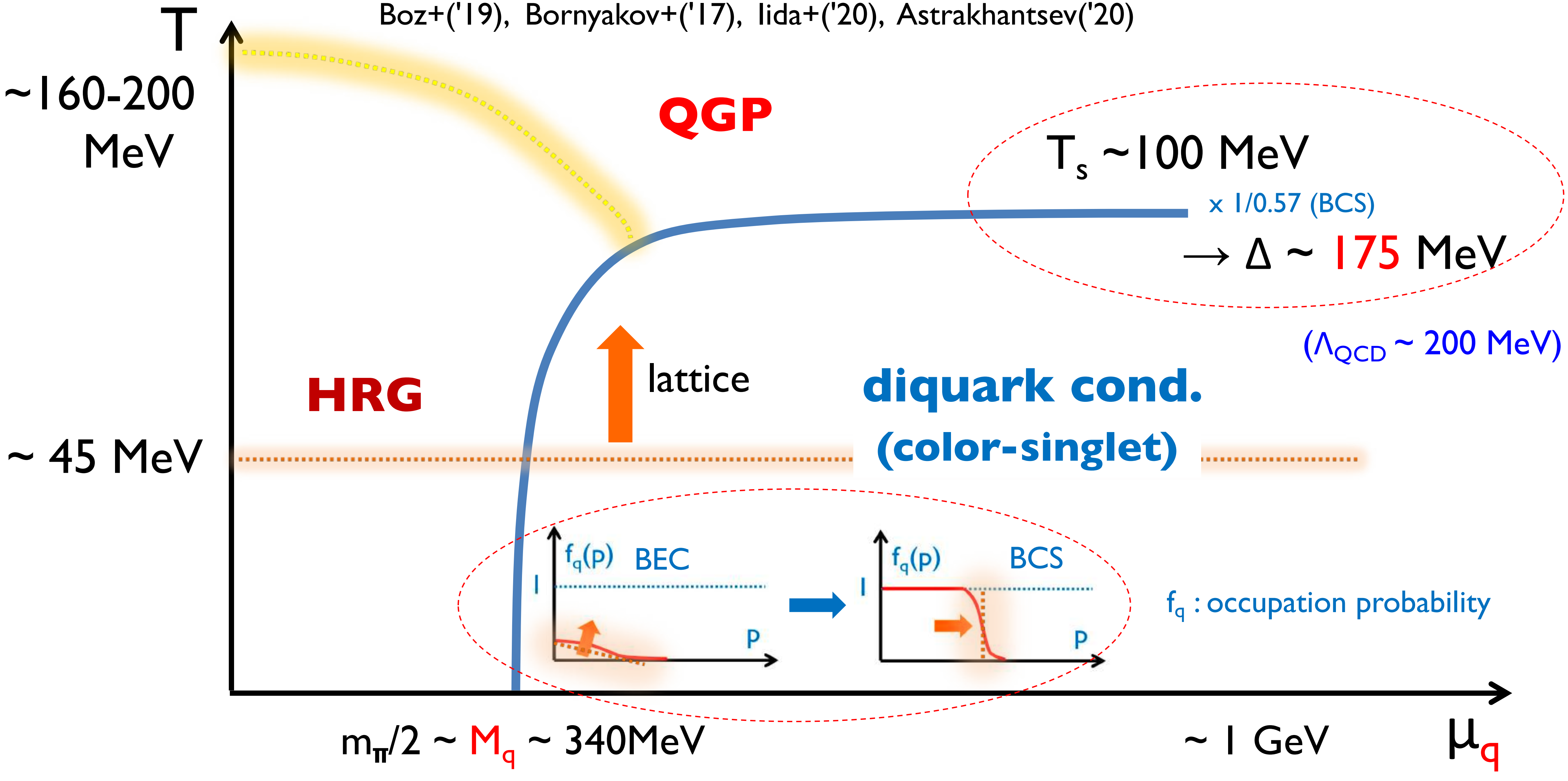
A sketch for Nc = 3: Masuda+('12), TK+('14), Fukushima+('20),...



Hints from 2-color QCD: lattice studies

no sign problem!

Boz+('19), Bornyakov+('17), Iida+('20), Astrakhantsev('20)

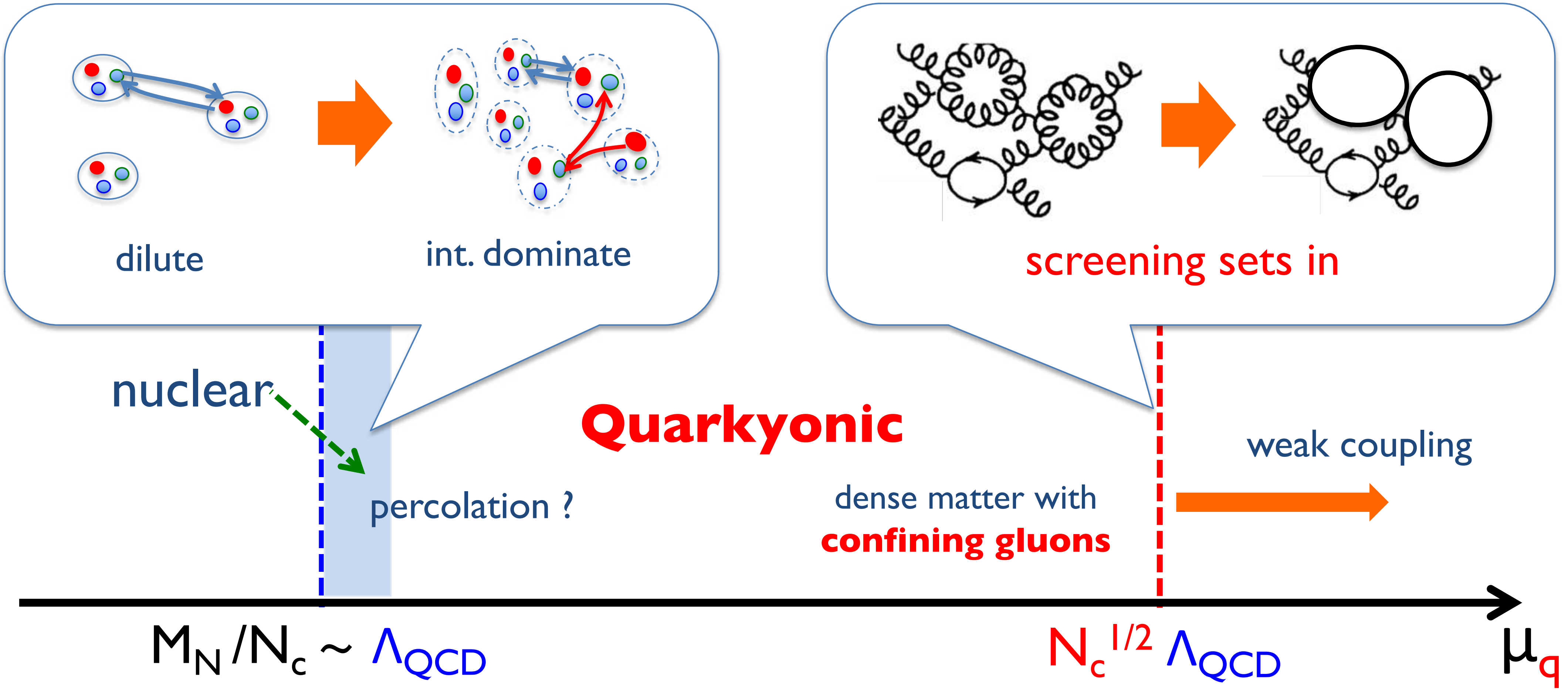


Strong coupling at *high density* ?

The **interplay** between **gluons** & **dense quarks**

e.g.) **large N_c :** [McLerran-Pisarski ’07]

$N_c^2 \Lambda_{QCD}^2 \sim N_c \mu_q^2$

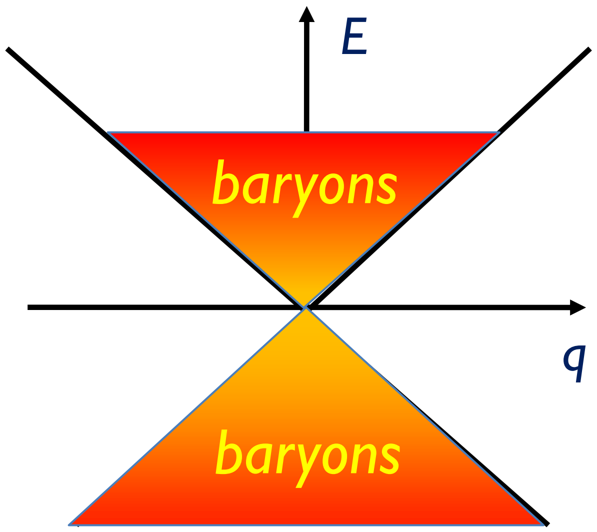


baryon vs quark Fermi sea/surface

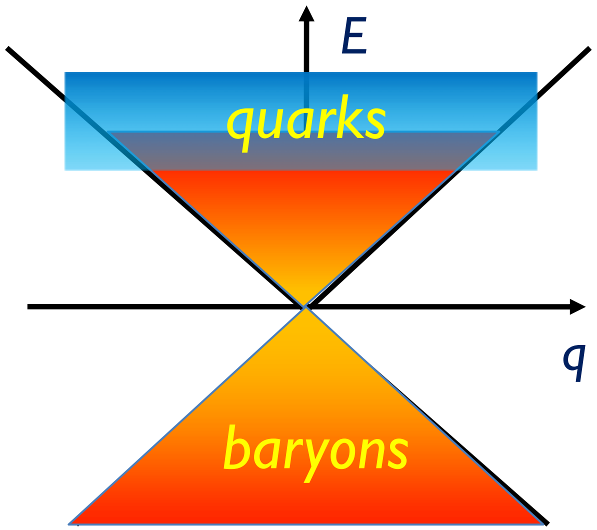
Dense matter with **confining gluons**

effective d.o.f ? (minimizing impacts of int.?)

use only colorless d.o.f.



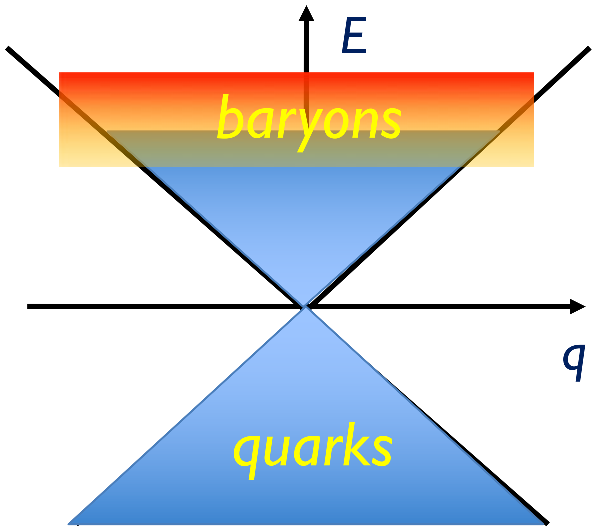
often claimed picture



transports
thermal

bulk: EoS

McLerran-Pisarski ('07)



This question has *direct relevance* to *phenomenology* (e.g. neutron stars)

2-topics for dense matter

- 1, Quarkyonic matter (theoretical topic)

- 2, Neutron star equations of state

A solvable model for quarkyonic matter [TK '12]

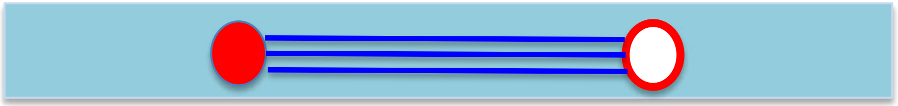
QCD$_2$ (axial gauge)

['t Hooft '74]

$$S^{2D}_{QCD} = \int_x \bar{\psi}(i\partial\!\!\!/ + \mu\gamma_0 + m)\psi + \int_{x,y} J_0^A(x) D_{00}^{AB}(x-y) J_0^B(y)$$

Confining propagator : $D_{00}^{AB}(x-y) = \delta_{AB} \times g_{2D}^2 |\vec{x}-\vec{y}|$

electric flux is squeezed in 1D



- The spectra in large N_c : mesons & baryons (solitons) ['t Hooft '74, Witten '79, ...]
- At **finite density** ?

How does the ***EoS*** *look like?* ***Deconfined colors*** *after baryons overlap?*

A solvable model for quarkyonic matter [TK '12]

- Non-Abelian bosonization: $S^{2D}_{QCD} = \int_x \bar{\psi}(i\partial\!\!\!/ + \mu\gamma_0 + m)\psi + \int_{x,y} J_0^A(x) D_{00}^{AB}(x-y) J_0^B(y)$

  [Novikov '82; Witten '84;...]

baryon num. - color charge separation $h \sim e^{i\pi_A T_A}$

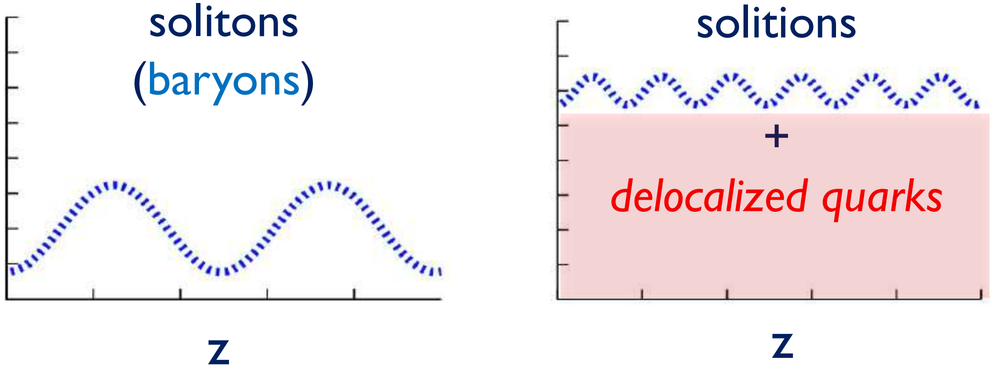
$$S^{2D}_{QCD} = S_{U(1)}[\phi;\mu] + S^{WZW}_{k=1}[h] + S_{int}[h] \quad + \textit{pert. of } O(m)$$

free** theory **with μ *gauge dynamics* (**same as vac. !**)

- **Consequences:**
  - $P(\mu)$ = Free Fermi sea + Vac. int. energy (!)
  - The colored objects remain confined (!)
  - ChSB by *inhomogeneous chiral spirals.*

    [see below]

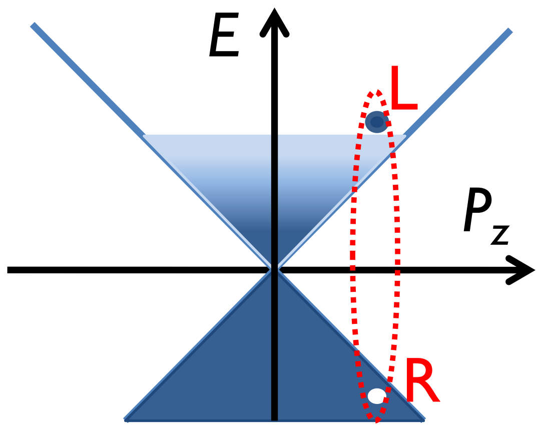
baryon density distribution



Chiral symmetry in dense matter?

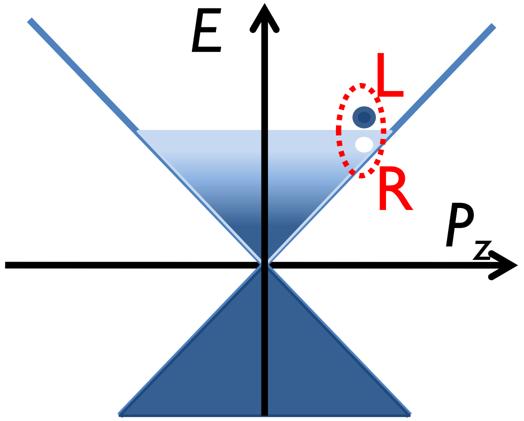
Candidates of chiral pairing (in general dimensions) [TK+ '09]

Dirac Type



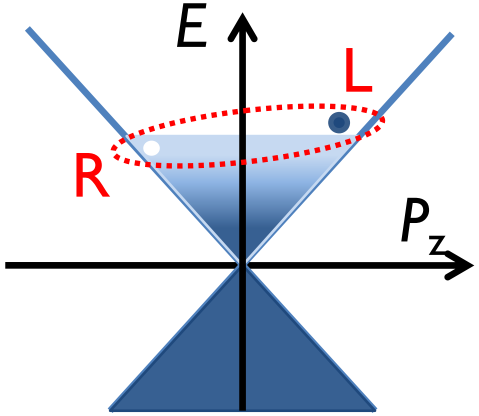
$P_{Tot} = 0$ (uniform)

Exciton Type



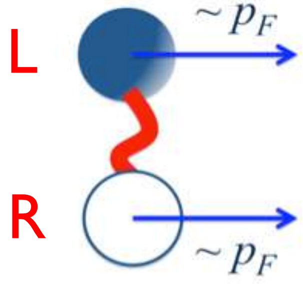
$P_{Tot} = 0$ (uniform)

Density wave



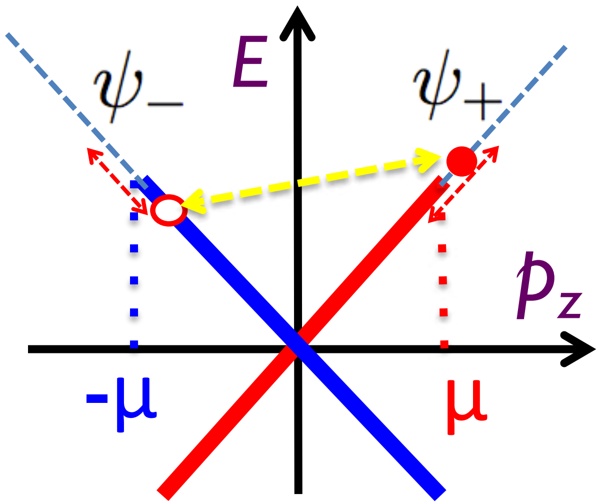
$P_{Tot} = 2\mu$ (non-uniform)

comoving color-singlet pairs of particle-hole



Chiral spirals (2D-case)

[Thies+('00); Basar+('08); TK('11)..]



" **moving directions** (z) "
(in any dim.)

$$\psi_\pm = \frac{1 \pm \gamma_0\gamma_z}{2}\psi \quad (\gamma_5)_{2D}$$

Measure momenta from the **Fermi points** :

$$\psi_- = \mathrm{e}^{-\mathrm{i}\mu z}\psi'_-$$
$$\psi_+ = \mathrm{e}^{\mathrm{i}\mu z}\psi'_+$$

then

$$\bar\psi_\pm(\mathrm{i}\partial\!\!\!/ + \mu\gamma_0)\psi_\pm \Rightarrow \bar\psi'_\pm \mathrm{i}\partial\!\!\!/ \psi'_\pm$$
$$J^A_\mu \Rightarrow J'^A_\mu$$

leading to the same gap equation as in vacuum:

in "*vacuum*"

$$\langle\bar\psi'_+\psi'_-\rangle = \langle\bar\psi'_-\psi'_+\rangle = \Delta \Rightarrow$$

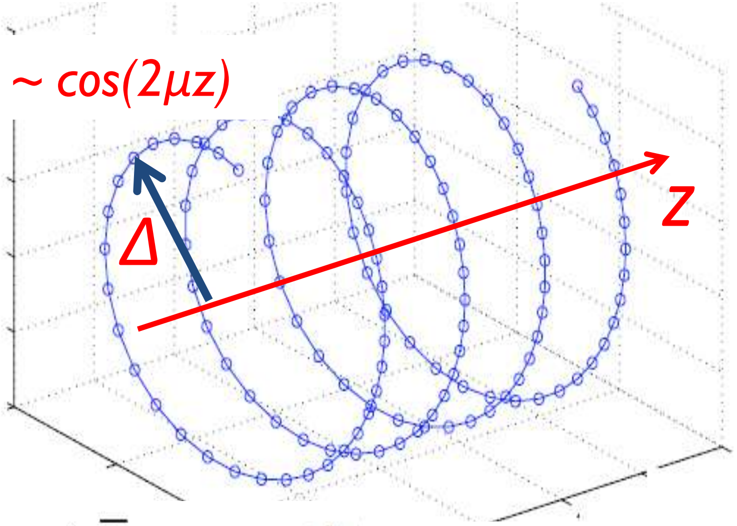
(known)

in *original bases*

$$\langle\bar\psi_-\psi_+\rangle = \Delta\mathrm{e}^{2\mathrm{i}\mu z}$$
$$\langle\bar\psi_+\psi_-\rangle = \Delta\mathrm{e}^{-2\mathrm{i}\mu z}$$

sum → $\langle\bar\psi\psi\rangle$ ~ *cos(2μz)*

difference → $\langle\bar\psi\gamma_0\gamma_z\psi\rangle$ ~ *sin(2μz)*



Chiral spirals: from 2D to 4D?

- A confining propagator for quark-antiquark (quark-hole) :

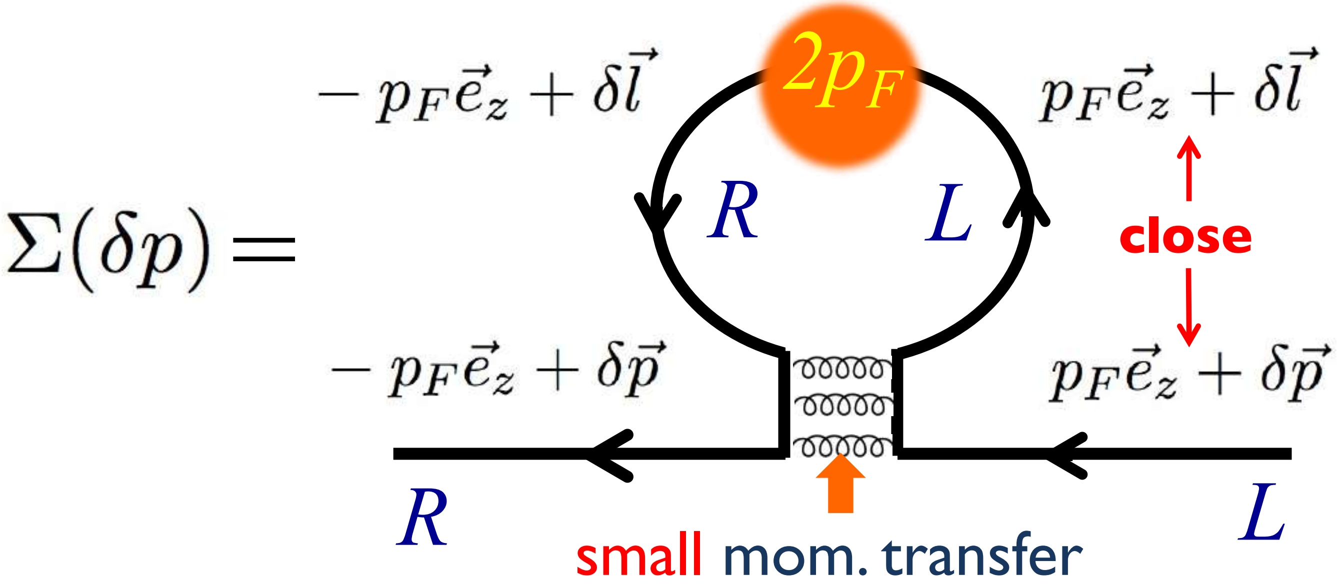
$$D_{\mu\nu} = C_F \times g_{\mu 0} g_{\nu 0} \times \frac{\sigma}{(\vec{p}^2)^2}$$

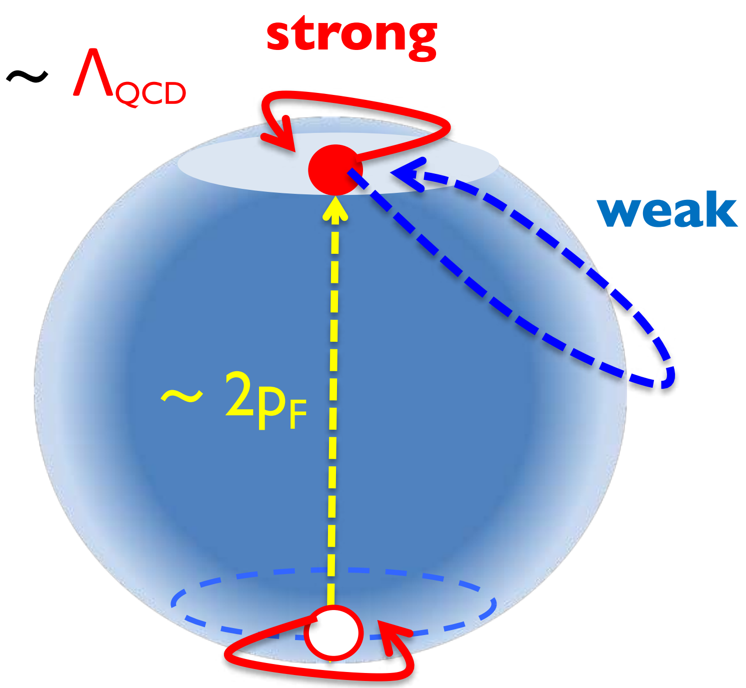
linear rising type, **Coulomb** gauge

(ref: Gribov, Zwanziger)

strong IR enhancement

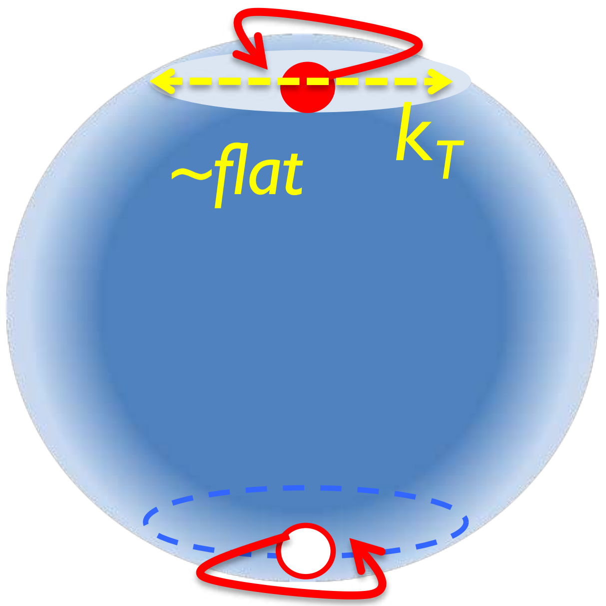
- Schwinger-Dyson eq. for chiral spirals





Dimensional reduction of integral eqs.

[TK-Hidaka-McLerran-Pisarski ('10)]



$$\Sigma(\delta p) = C \int \frac{\mathrm{d}^2 k_L \mathrm{d}^2 \vec{k}_T}{(2\pi)^4} \gamma_0 S(\delta k_L, \underline{\delta k_T}) \gamma_0 \frac{\sigma}{|\delta\vec{p} - \delta\vec{k}|^4}$$

quarks insensitive to k_T → *factorization*

$$\underbrace{\int \frac{\mathrm{d}^2 k_L}{(2\pi)^2} \gamma_0 S(\delta k_L, \underline{\vec{0}_T}) \gamma_0}_{\text{2D propagator}} \otimes \underbrace{\int \frac{\mathrm{d}^2 \vec{k}_T}{2\pi} \frac{\sigma}{|\delta\vec{p} - \delta\vec{k}|^4}}_{\text{2D confining propagator}}$$

Schwinger-Dyson eq.
in **4-D** conf. model

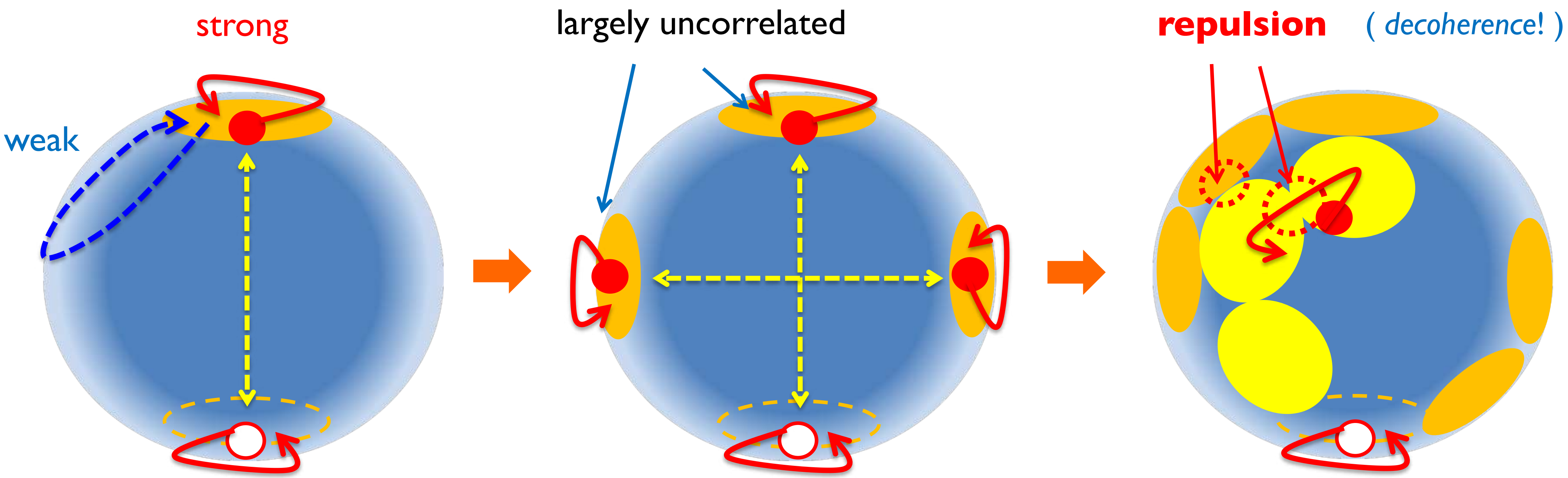
→

Schwinger-Dyson eq.
in **2-D** QCD (axial gauge)

[we know solutions: *chiral spirals*]

Interweaving chiral spirals

[TK-Pisarski-Tsvelik ('10); TK-Fukushima-Hidaka-McLerran-Pisarski ('11)]



chiral spiral cond. → energy **gain**

patch-patch int. → energy **cost**

balance →

a novel structure:

interweaving CSs

(energy gain: **comparable to the Color-super**)

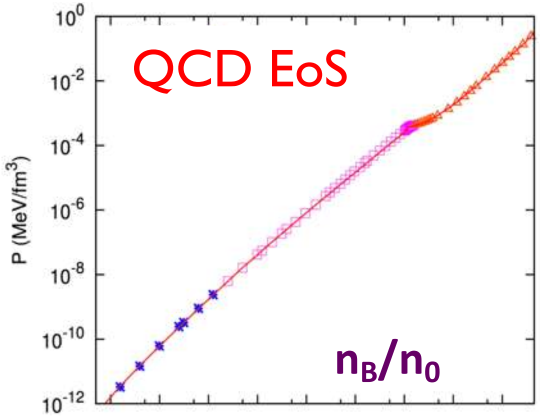
2-topics for dense matter

- 1, Quarkyonic matter (theoretical topic)

- 2, Neutron star equations of state

EoS & M-R relation

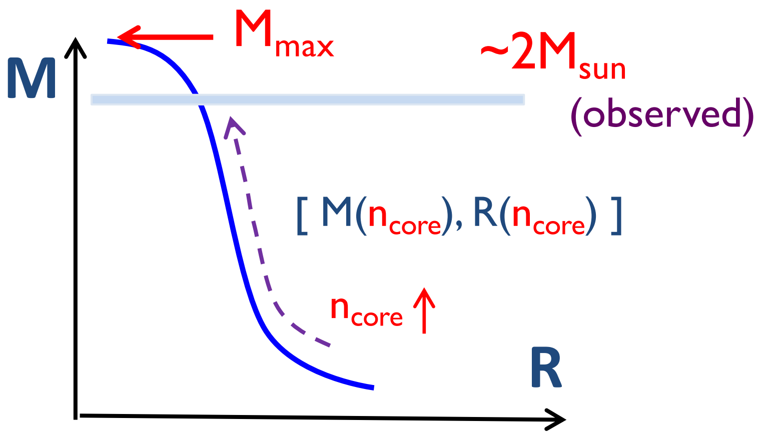
Einstein eq. : $G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$ ······· QCD EoS



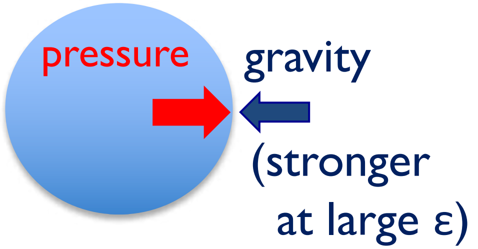
[for spherical NS → TOV eq.]

1-to-1 correspondence

Lindblom (1992)

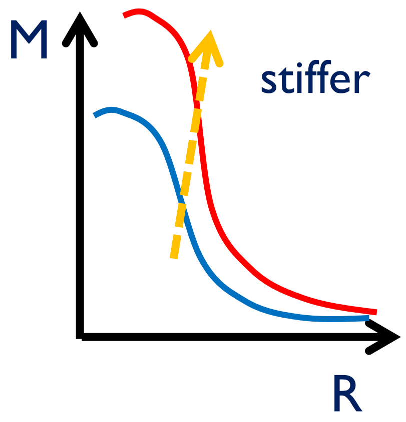


Terminology (my convention)

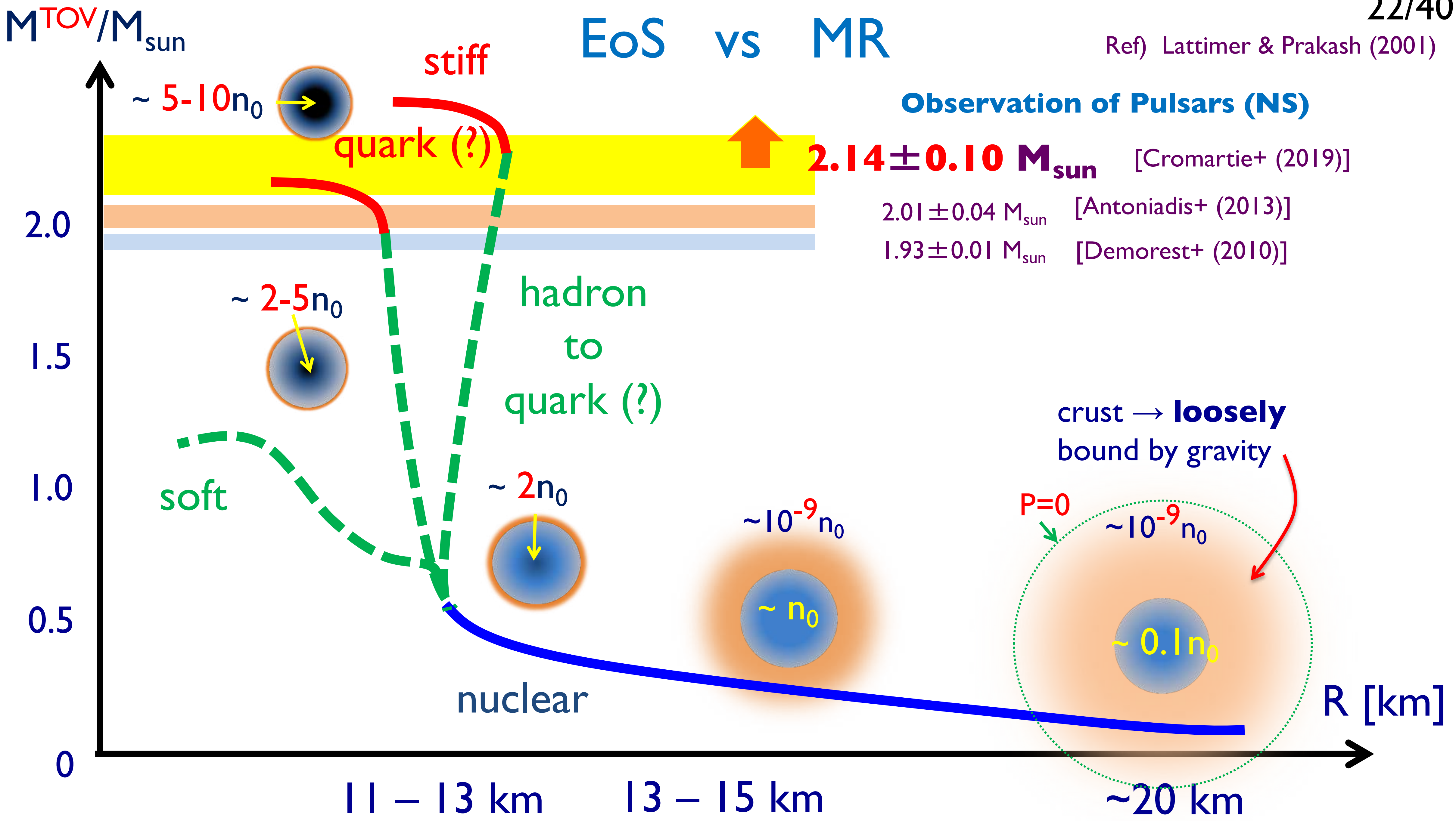


1) **Stiff** EoS : P is large at given ε

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

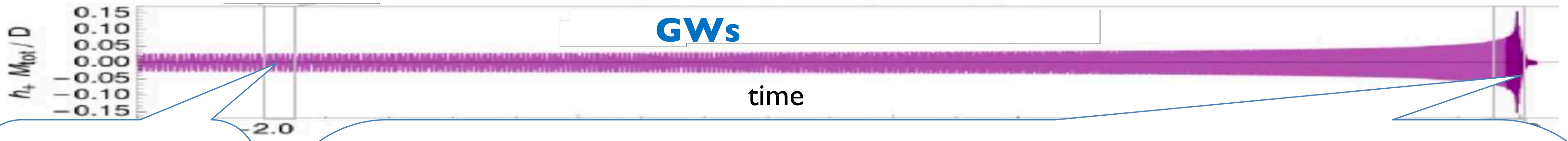


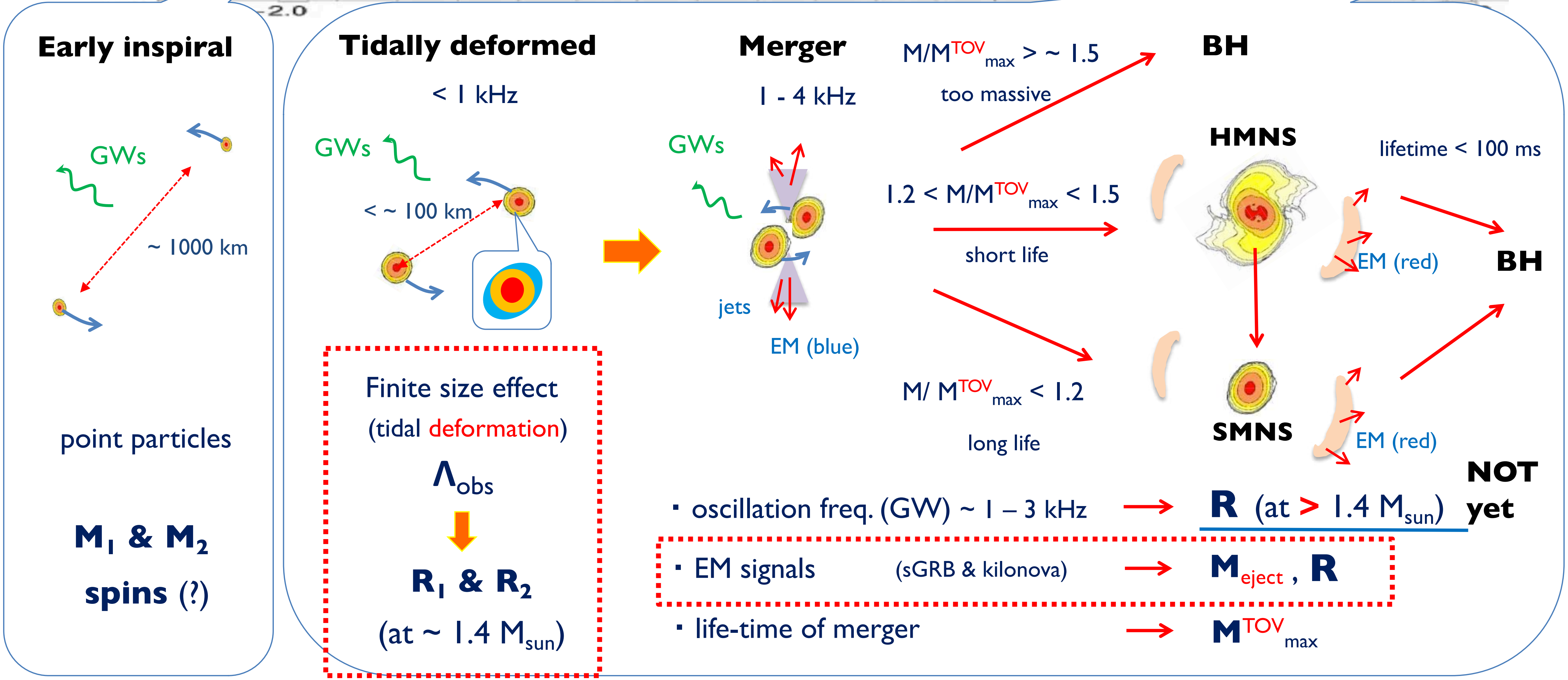
EoS vs MR



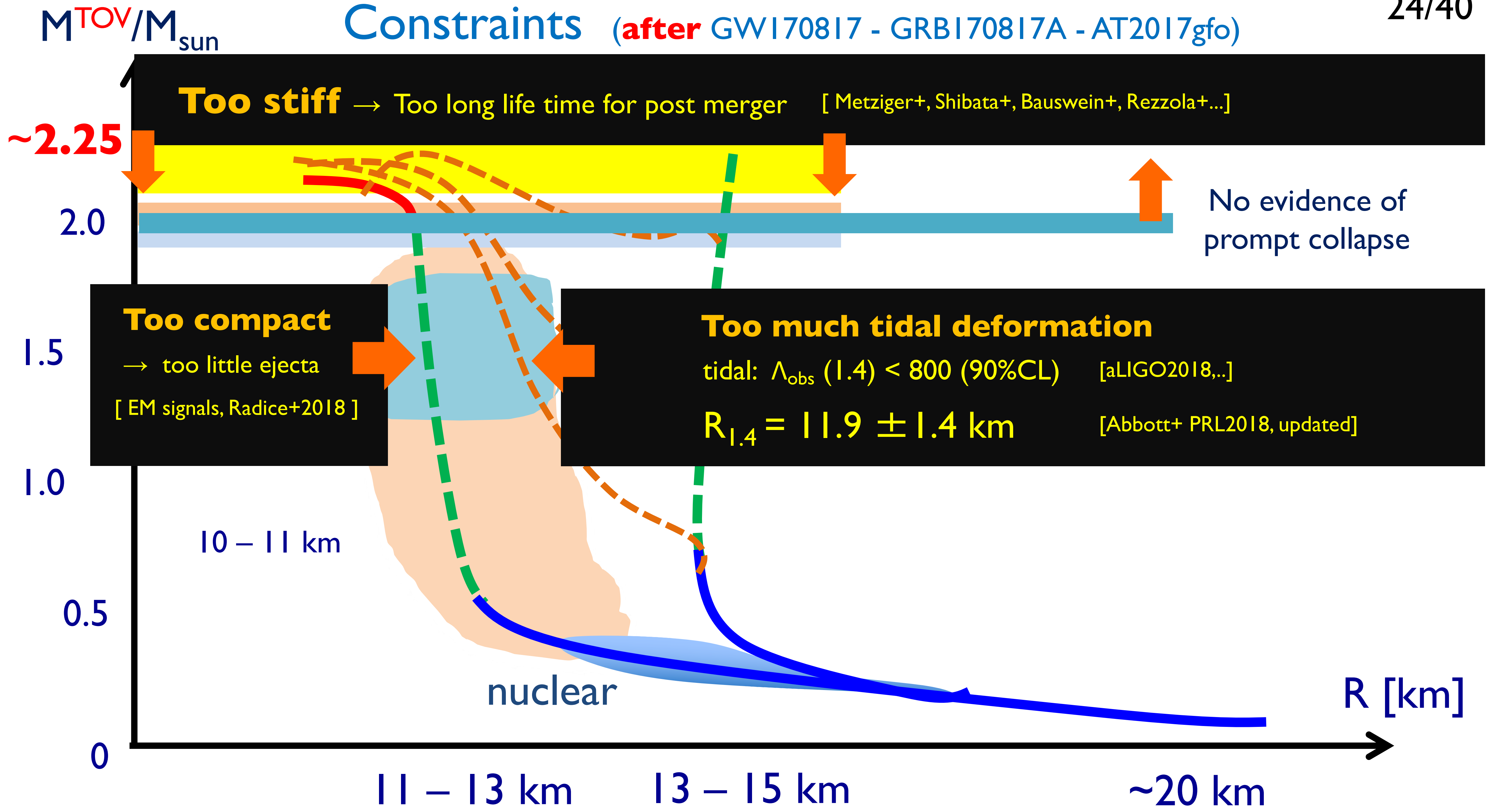
M^{TOV}/M_{sun}
Ref) Lattimer & Prakash (2001)
stiff
~ 5-10n_0
quark (?)
Observation of Pulsars (NS)
2.14±0.10 M_{sun} [Cromartie+ (2019)]
2.01±0.04 M_{sun} [Antoniadis+ (2013)]
1.93±0.01 M_{sun} [Demorest+ (2010)]
2.0
1.5
1.0
0.5
0
~ 2-5n_0
hadron
to
quark (?)
crust → loosely
bound by gravity
soft
~ 2n_0
~$10^{-9}n_0$
P=0
~$10^{-9}n_0$
~ n_0
~ 0.1n_0
nuclear
R [km]
11 – 13 km
13 – 15 km
~20 km

NS-NS mergers [detectability 0.1~100 /year , aLIGO-Virgo-KAGRA]





Constraints (after GW170817 - GRB170817A - AT2017gfo)



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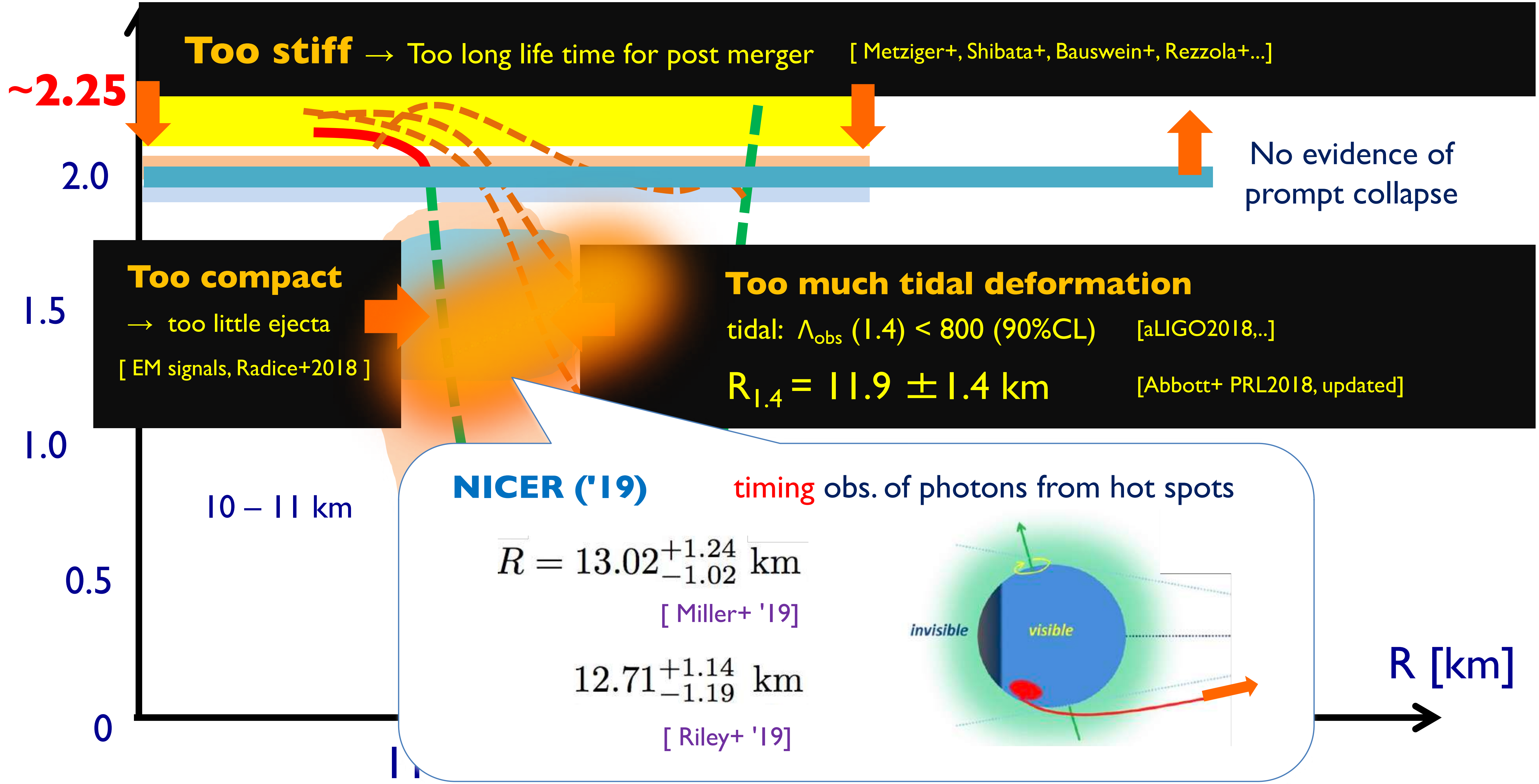
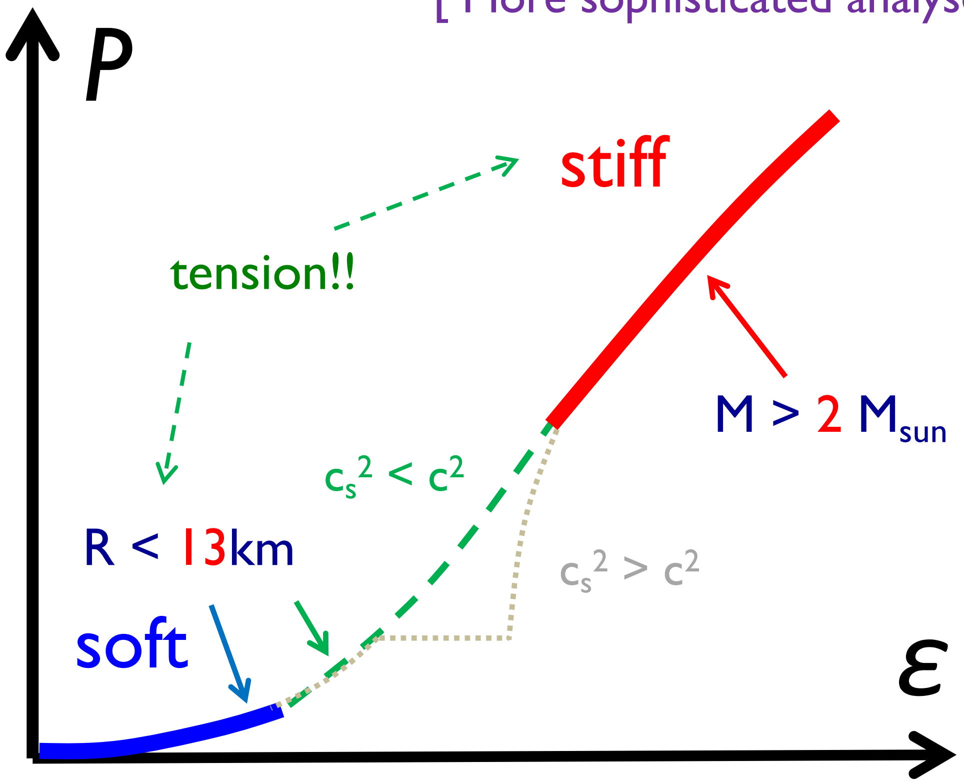
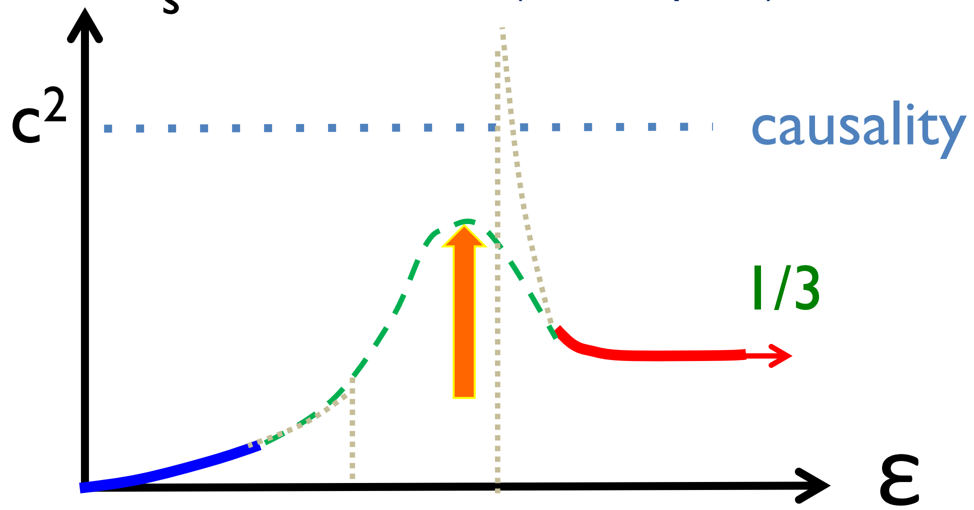


Causality constraint

[More sophisticated analyses: Han-Alford-Prakash '13, Bedaque-Steiner '15]



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

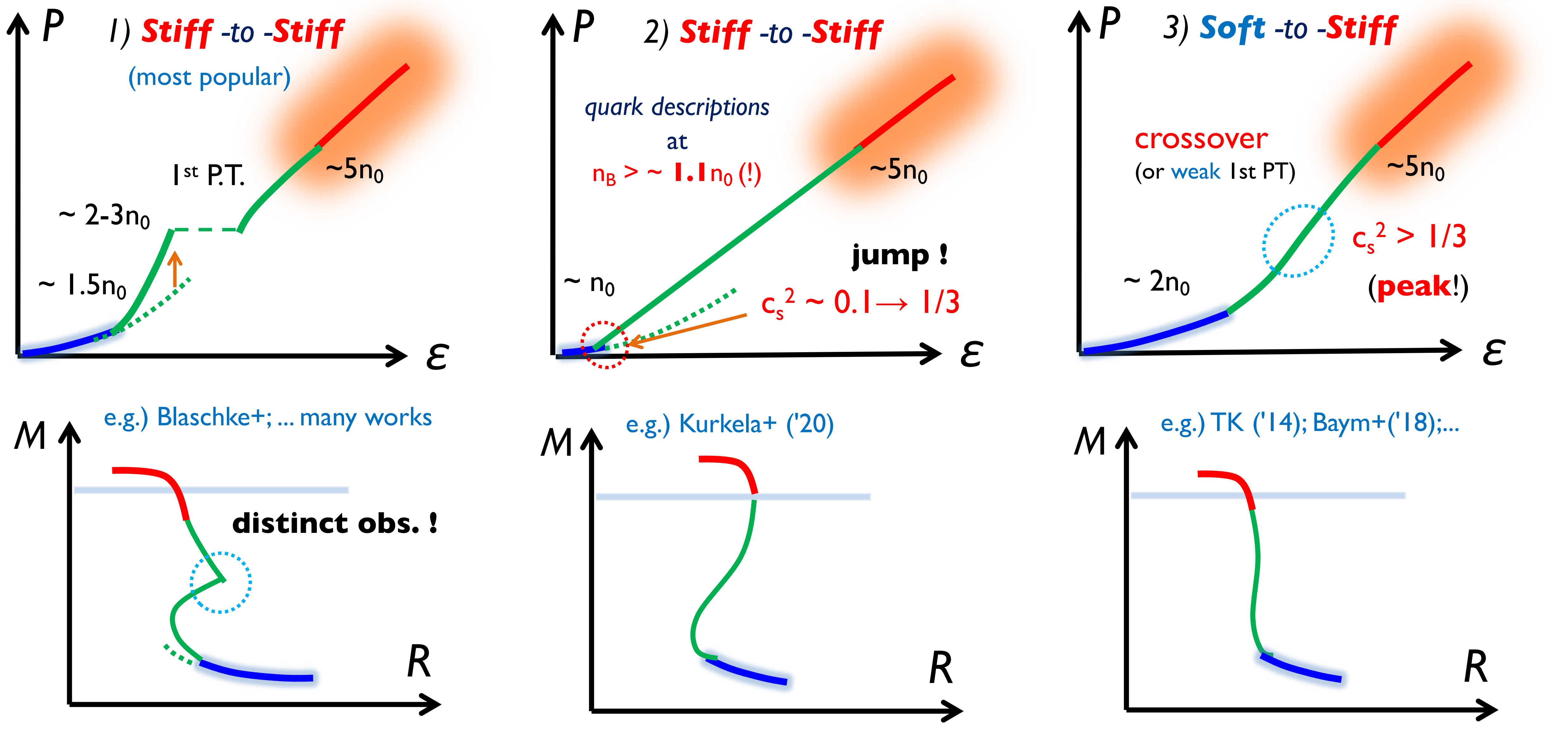


softer at low density & stiffer at high density

severer constraint on **P.T.** from the causality

(too radical 1st order P.T. is disfavored)

Three possibilities in literatures



The reasons we take the continuity as a *baseline*

Q) why not assuming the strong hadron-quark 1st order P.T. ? (as in choice 1)

A) *nuclear forces* ~ *quark exchanges* (from meson exchange to hard core repulsion)

many-quark exchanges important at $n_B > \sim 2n_0$

→ difficult to imagine ***sharp interface*** between quark-hadron matter

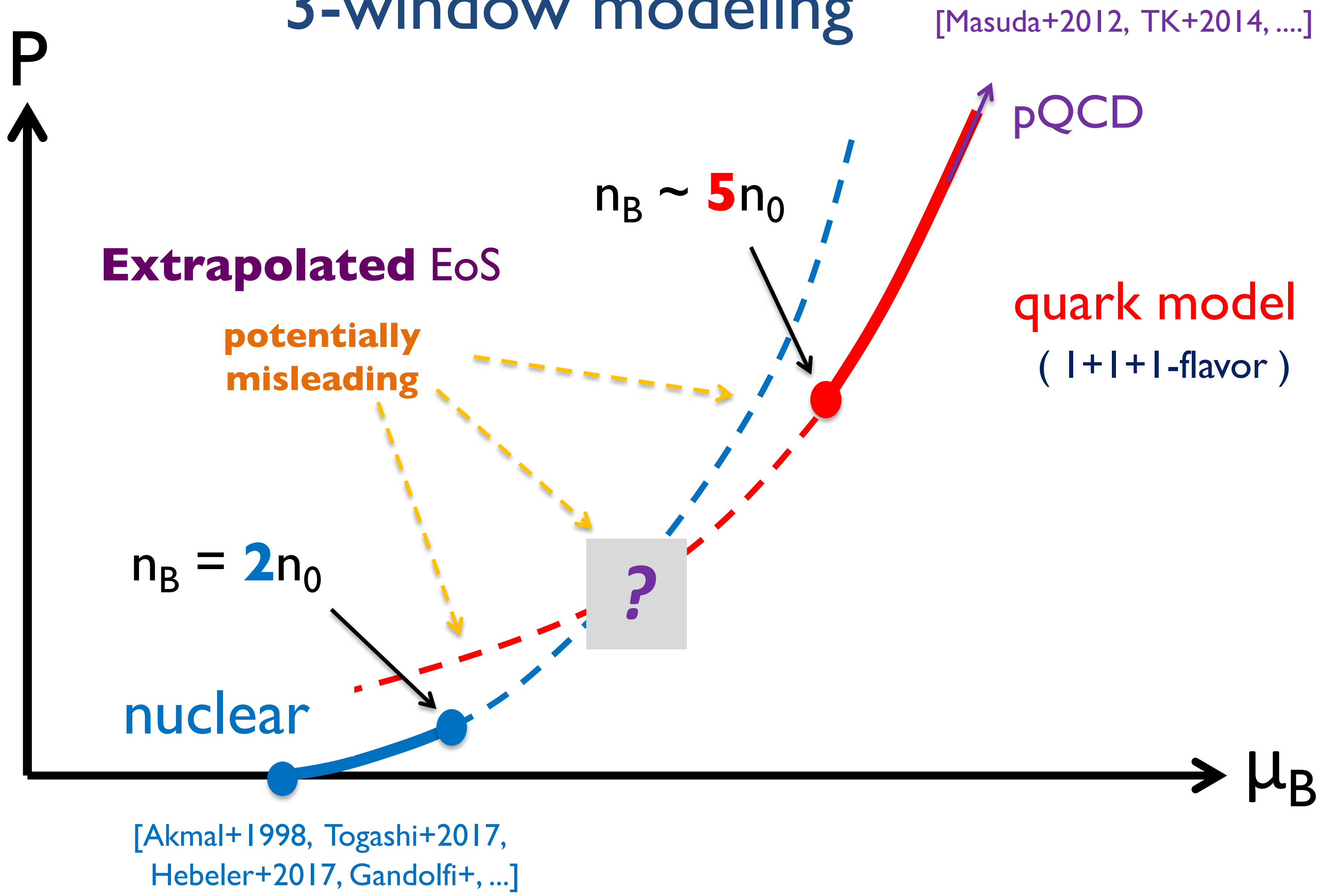
Q) why not switching to (almost free) quark matter at $n_B \sim 1.1n_0$? (as in choice 2)

A) I don't know any models that allow a *positive jump* in c_s^2. (any P.T. doesn't allow either)

Also, nuclear cal. has problems *in precision* at $\sim 1.1n_0$, but not *in systematics*.

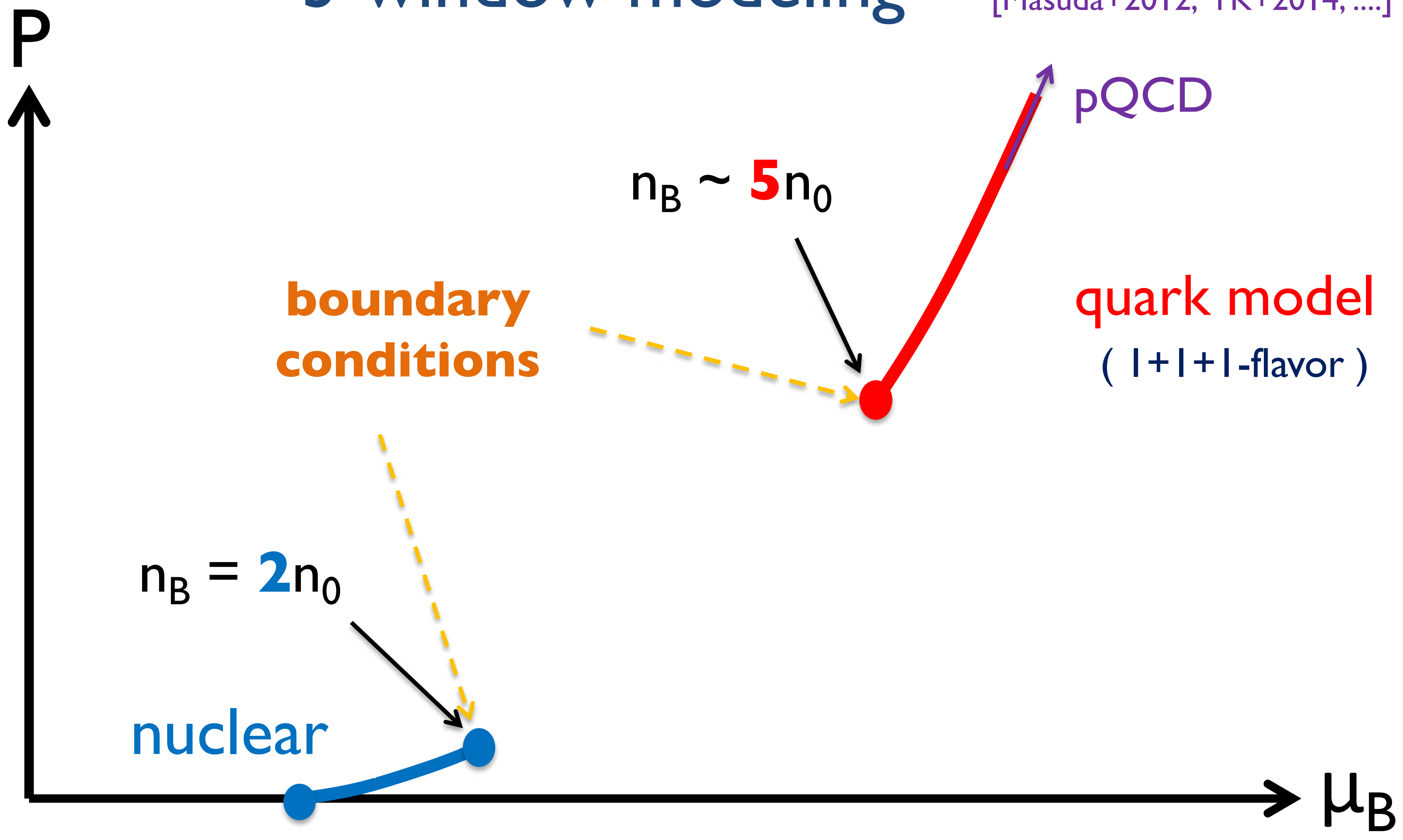
(nuclear cal. should be OK at low density)

3-window modeling



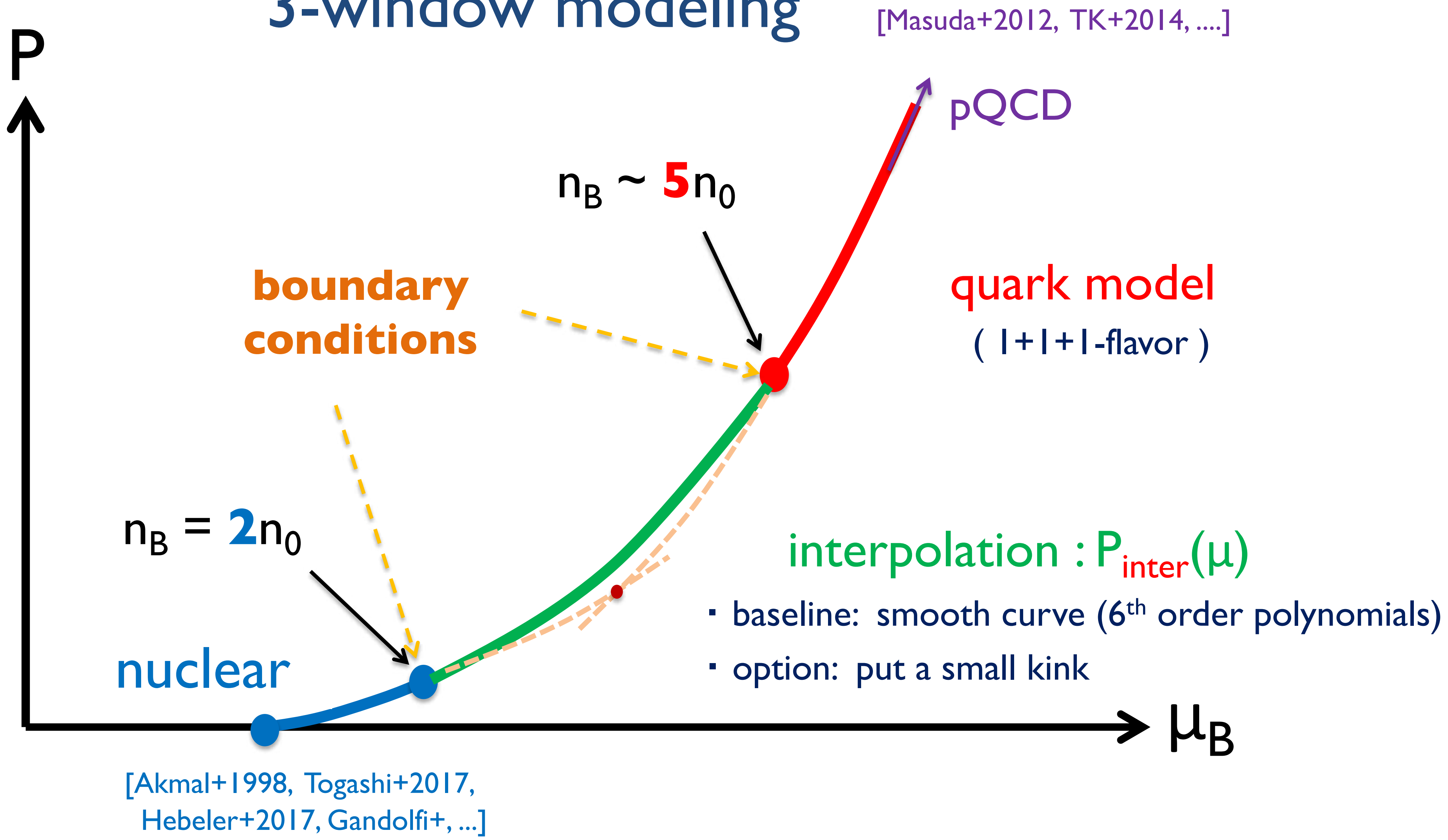
3-window modeling

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



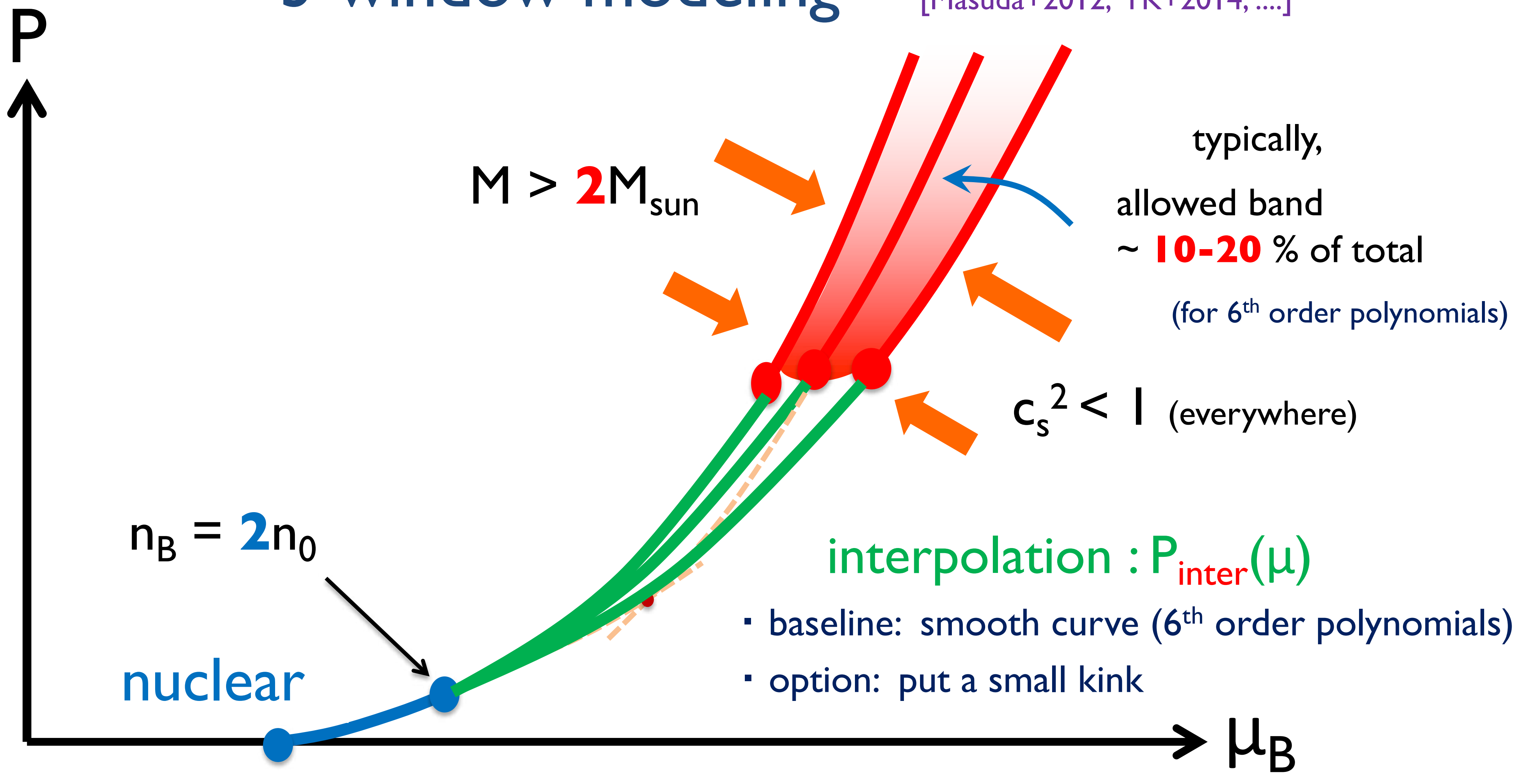
[Akmal+1998, Togashi+2017,
Hebeler+2017, Gandolfi+, ...]

3-window modeling



3-window modeling

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



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

A quark model for n_B > ~ **5**n_0 (~ 1fm^{-3})

A guide : *Hadron-Quark 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.

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

solve within **MF**
+ color- & charge- neutrality
+ β-equilibrium

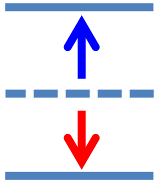
[Masuda+2015, TK+2014, Blaschke+....] ➡ *color-superconductivity* & *smooth chiral restoration*

Color-magnetic interaction play **many** roles

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

become important in relativistic regime & high density

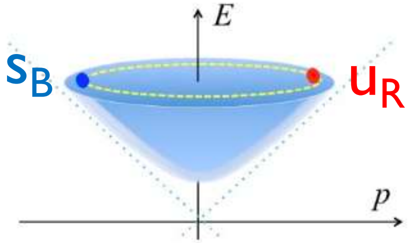
cf) Δ (1232) / $3M_q$ + ... / N (938)



2) **Pairing** : strongly channel dependent

hadron mass ordering: N-Δ, etc. [DeRujula+ (1975), Isgur-Karl (1978), ...]

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



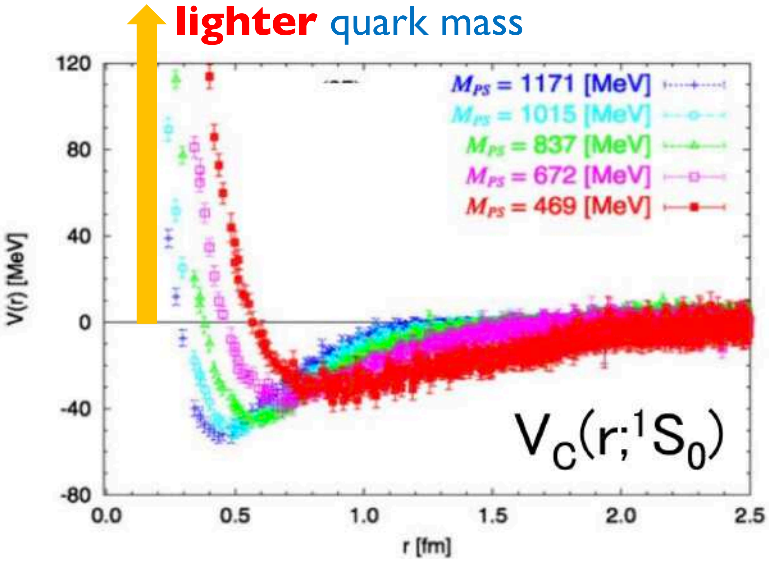
3) **Baryon-Baryon int.** : **short-range** correlation

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

channel dep. → non-universal hard core (some are attractive!)

mass dep. → stronger hard core in relativistic quarks

→ **consistent with the lattice QCD** [HAL-collaboration]

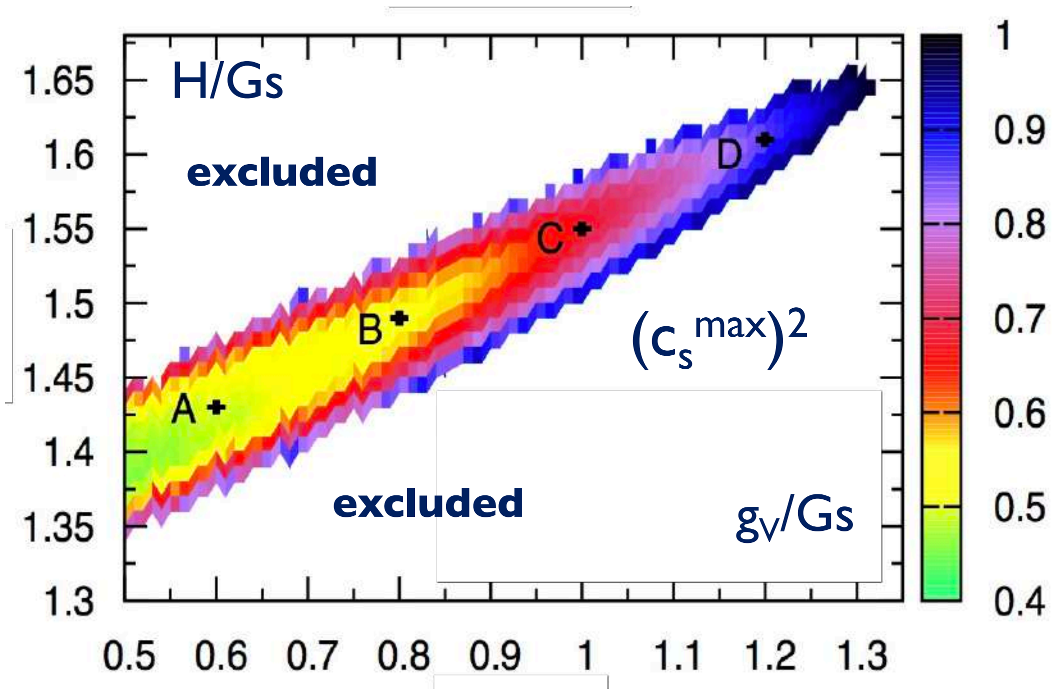


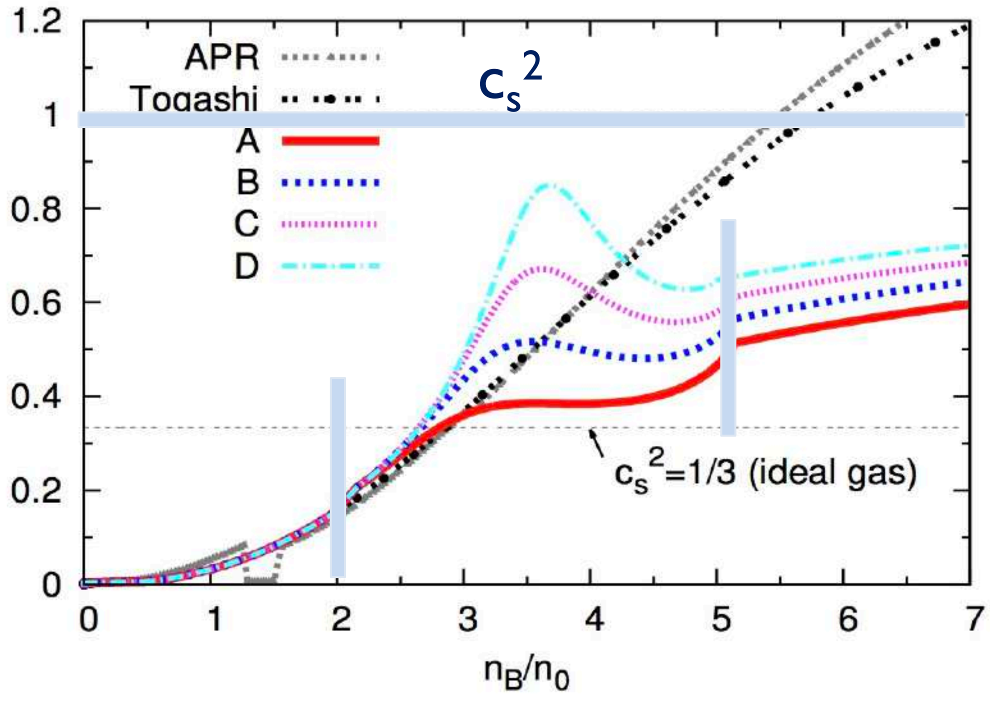
An exercise: survey for $(g_V, H)_{@5n0}$ [Baym+ '19]

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

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

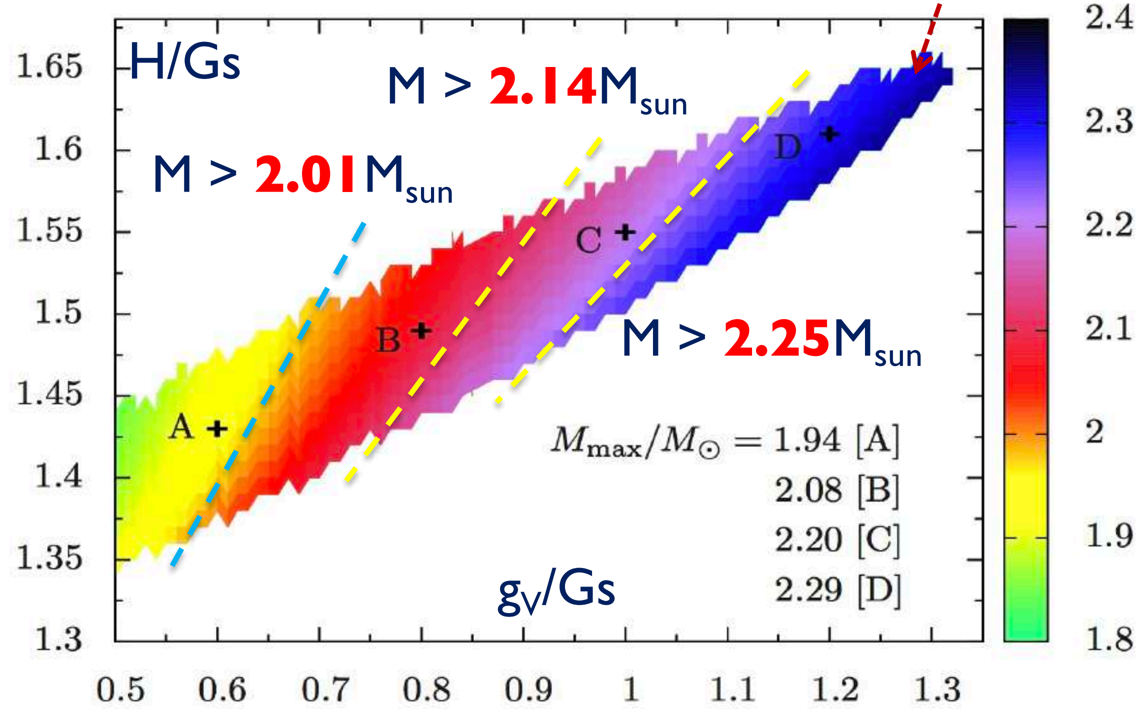
Step2) Survey the range of (g_V, H) compatible with **causality & stability**

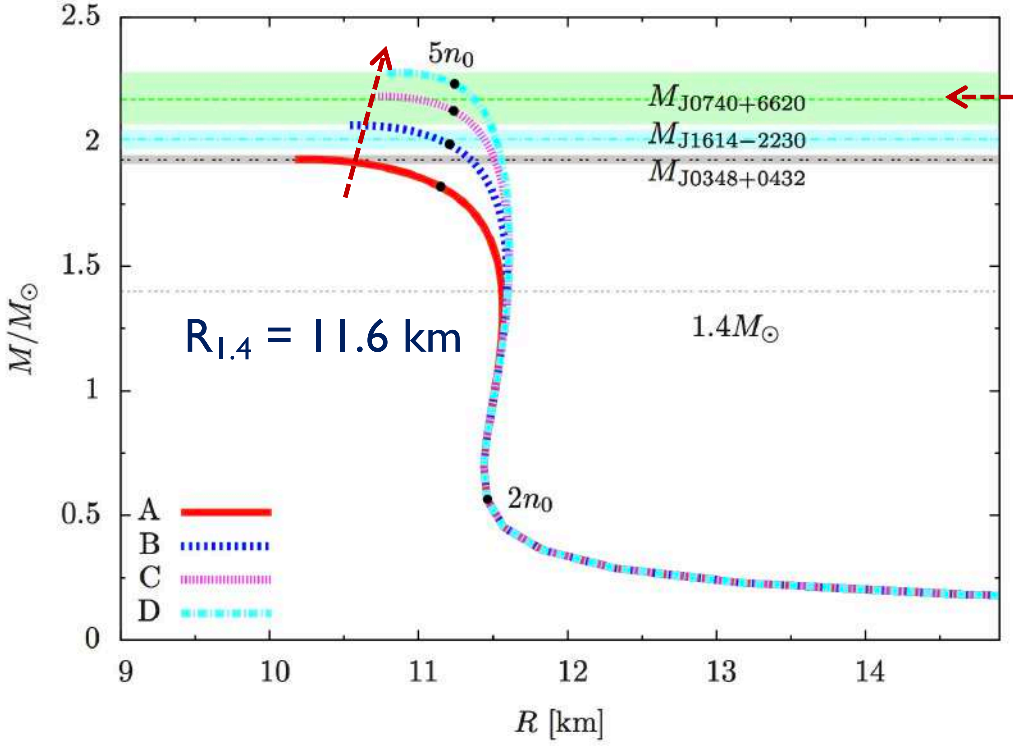




An exercise: survey for $(g_V, H)_{@5n0}$ [Baym+ 2019]

Step3) Impose $M > 2 M_{sun}$





bottom line: $(g_V, H)_{@5n0} \sim (G_s)_{@vac}$

On-going works & future prospects

Next 10 years ? *NS-physics*

More experimental programs to come:

[(2nd) aLIGO-aVirgo (2015-), KAGRA(2019-), IndIGo (2023-); (3rd) Einstein-Telescope (2030s), ...]

- more events (1-100/year) of NS-NS (BH) mergers → statistical analyses

& *if we are lucky:*

- an event happens at not far distance → significant post-merger GWs at **1-4 kHz**
- *asymmetric* binaries → more *head-on* collisions

core heated up; reaching T > 20 MeV at $n_B > 2n_0$ *thermal EoS* ($Y_e \sim 0.1$)

& *if we are very lucky:* *(a few event per century)*

- **galactic** supernovae (like SN1987A): GWs & **neutrinos** *thermal EoS* ($Y_e \sim 0.4$)

(detector has improved by > 10^4 x Kamiokande)

Need: **EoS** catalog & corresponding **GW** templates

EoS projects I

1) General purpose EoS: $P\ (\mu_B, \mu_L, T)$ [with Baym-Furusawa-Hatsuda-Togashi]

with *explicit* descriptions for 2-5n_0, including:

- *matter composition* (strangeness, lepton fractions, ...)
- *thermal excitations* (d.o.f. near the Fermi surface)
- *microphysics* (based on hadron physics & QCD)

Testing several continuity scenarios **one by one**, **systematically** :

1) nuclear-2SC; [TK-Hou-Okafor-Togashi, to appear]
2) hypernuclear-CFL; [work in progress]
3) nuclear-quarkyonic [work in progress]

EoS projects 2

my role: responsible for *EoS tables*; clarification of *microphysics*

2) *NS-merger simulations* (RIKEN-iTHEMS collaboration)

[with Y. Huang, S. Nagataki, L. Biotti, K. Takami, H. Sotani, Hatsuda, Togashi]

3) *Machine learning* for global analyses (Illinois-RIKEN collaboration)

[with N. Yunes, J. Noronha-Hostler, Baym, Hatsuda, Togashi]

4) Construct *cyber-infra structure of EoS* in *full QCD phase diagram*

[with C. Ratti, V. Dexheimer, J. Noronha-Hostler, J. Noronha, and N. Yunes]

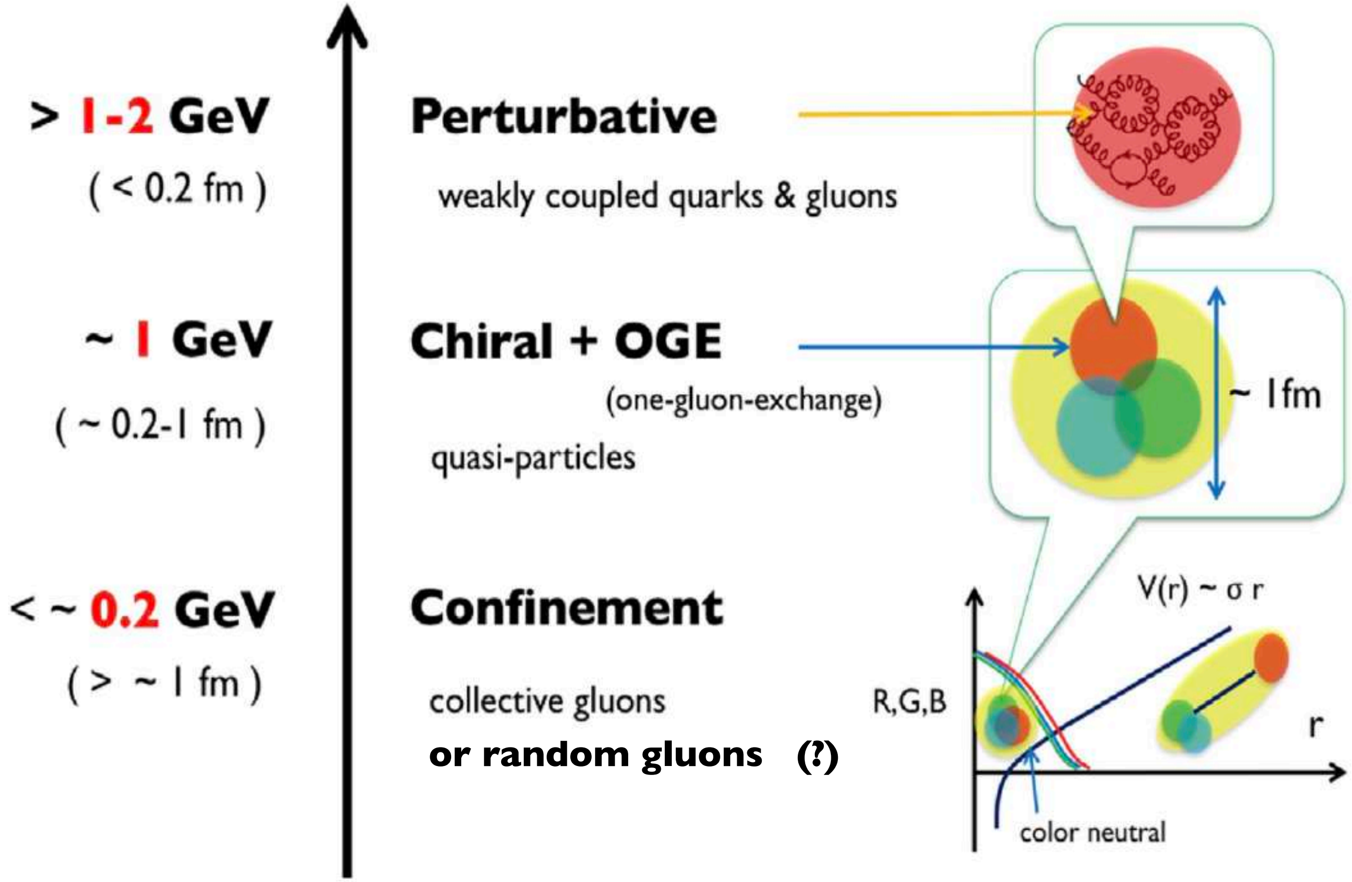
also connections to *low energy heavy-ion experiments*

Next 5 years ? *beyond pQCD*

quasi-particles → the **residual** interactions get **under control**

e.g.) **a** hadron [Manohar-Georgi('83), Weinberg('10)]

[fig. from Suenaga+ ('19)]



EoS

$> \sim$ **50** n_0

$\sim$ **5 -50** n_0

calculations doable with proper bases ?

EFT ? (work in progress)

[with D. Suenaga]

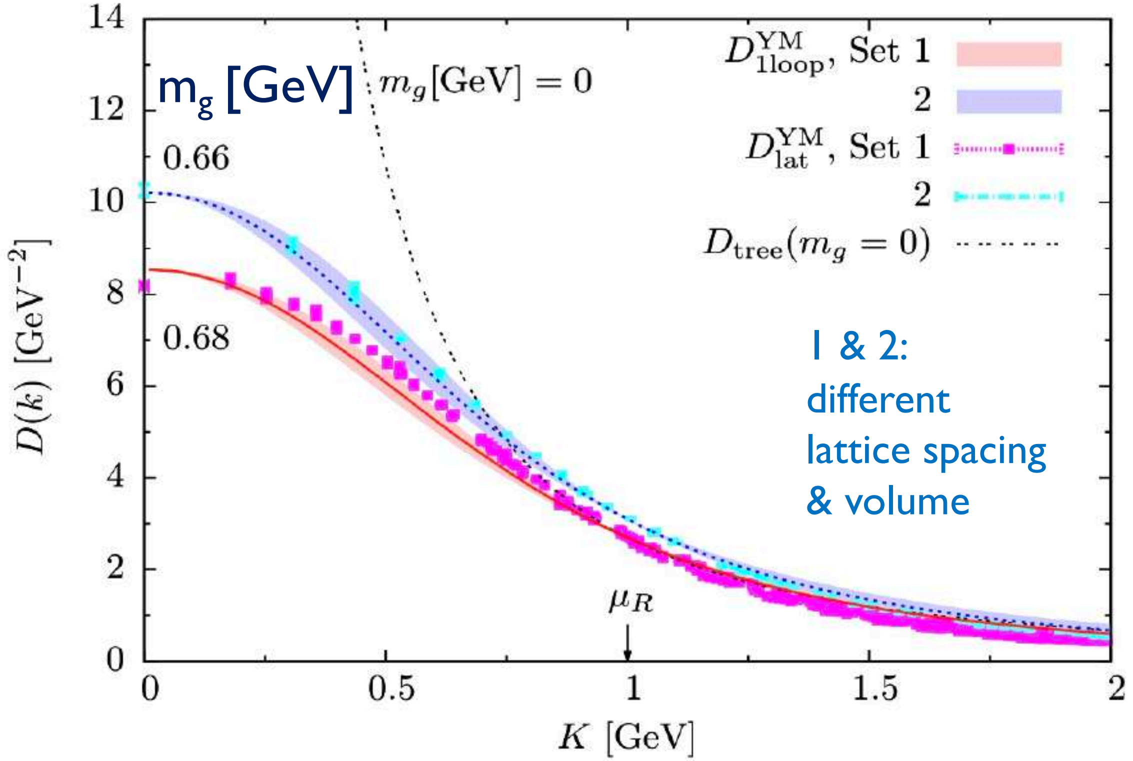
$< \sim$ **5** n_0

quasi- gluons & *perturbative stability* (**Landau** gauge)

Gribov ('78): found gauge copies in QCD → negative FP-det. (!)

suggested a condition to keep FP-det. positive ; effective mass m_g ~ 600 MeV for gluon **excitations**

comparisons with pYM data (Boz+'19)



error bands for theory side

variations: α_s = **1-3** (!) → only **< ~10 %** corrections!

at **small *k***

$$D^{-1}_{\mathrm{tree}}(k) \sim \underline{k^2} \qquad \ll \quad m_g^2$$
$$\Pi(k) \sim \underline{\alpha_s} \times \underline{k^2}$$

better **systematics** in loop corrections

(once m_g is properly chosen)

Next 5 years ? *QCD-like theories*

Numerical simulations of Nc=**3** QCD at finite density remain difficult problems

For *2-color QCD*, *isospin-QCD*, *QCD in magnetic fields:*

lattice simulations are doable; very useful **lab. to test theories** !

On-going work: **2-color** gluon propagators in medium [*quasi-particle domain*]

1-loop: Suenaga-TK ('19); RG-improvement (work in progress)

2nd step: calculations of **2-color** EoS, and compare it with lattice

3rd step: calculations of **3-color** EoS [*quasi-particle domain*]

Summary

The physics of dense QCD is a long-standing topic,
but still there are *revolutionary discoveries* to refresh our understandings.

collaborative works are essential

- The NS physics will not be closed by astrophysics community alone, even if everything could be measured;

- The QCD phase diagram will not be closed by QCD community alone, even if the sign problem on the lattice were solved;

- from hadron spectroscopy to nuclear forces to quark matter:

  unified descriptions are called for. (on the right track)