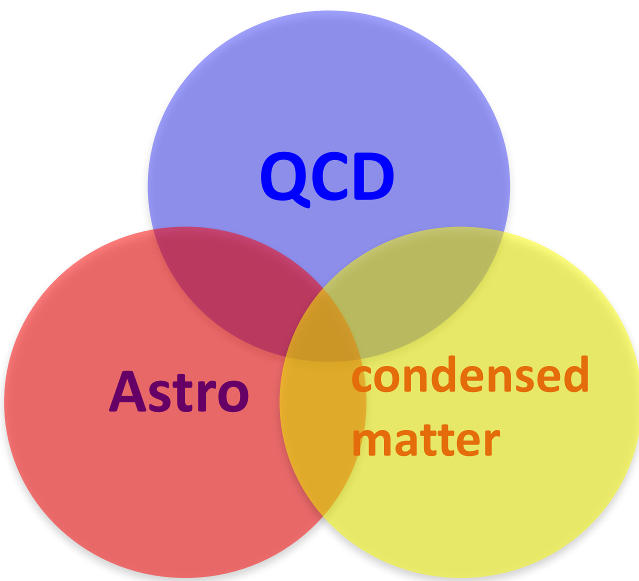
QCD EoS in hadron-quark continuity

Toru Kojo (CCNU)



- TK, P.D. Powell, Y. Song, G. Baym
  1412.1108 [hep-ph] , PRD91, 045043 (2015)
- TK, 1508.1108 [hep-ph], review in EPJA
- K. Fukushima & TK, 1509.1108, APJ817(2016)2
- TK, 1610.05486 [hep-ph], PLB769 (2017) 14
- Baym-Hatsuda-TK-Powell-Song-Takatsuka,
  (review) 1707.04966 [astro-ph]
- H.Zhang-D.Hou-TK-B.Qin, 1709.05654 [hep-th]

Lattice + HIC (> 20 GeV) + HIC (< 20 GeV) + Astro

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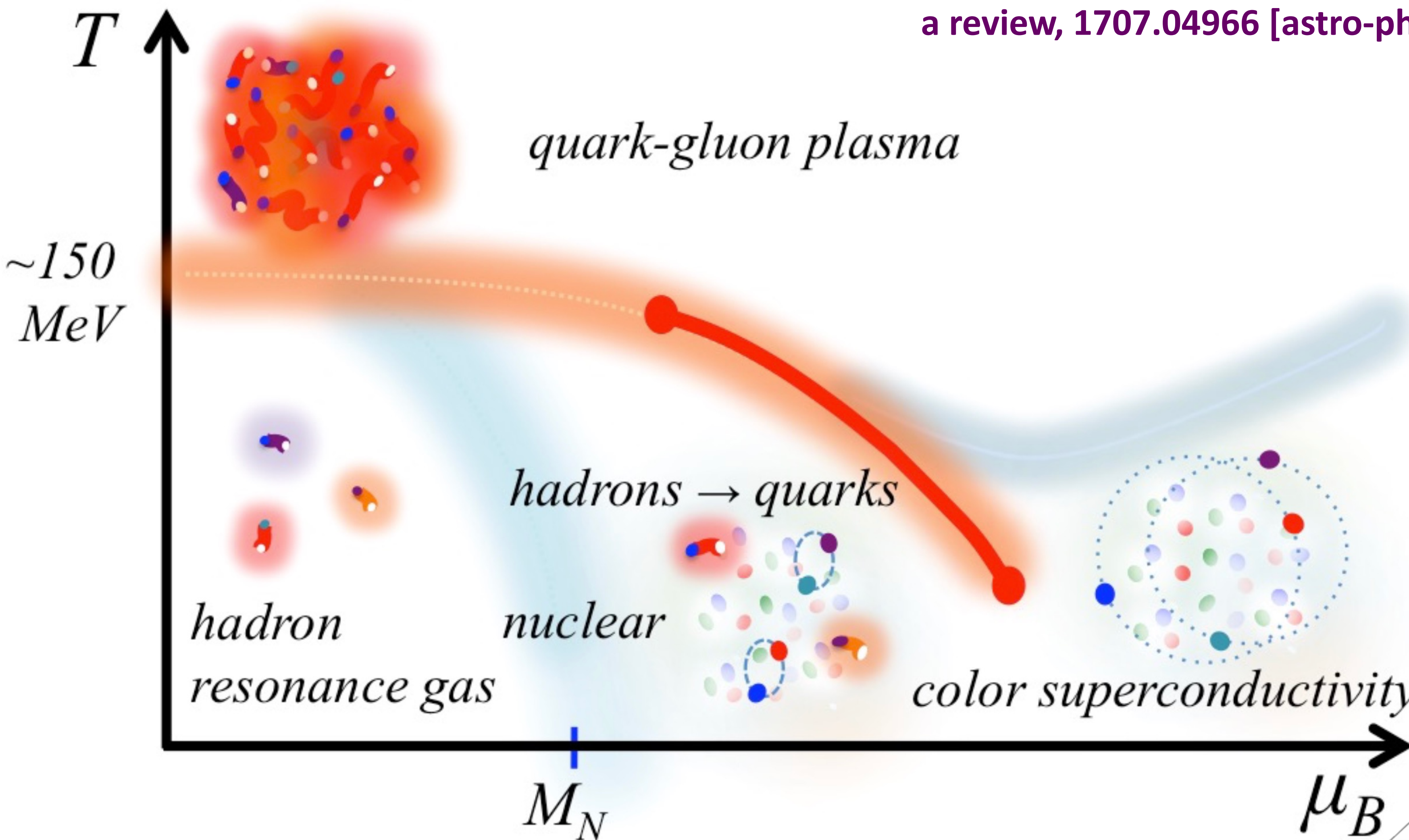

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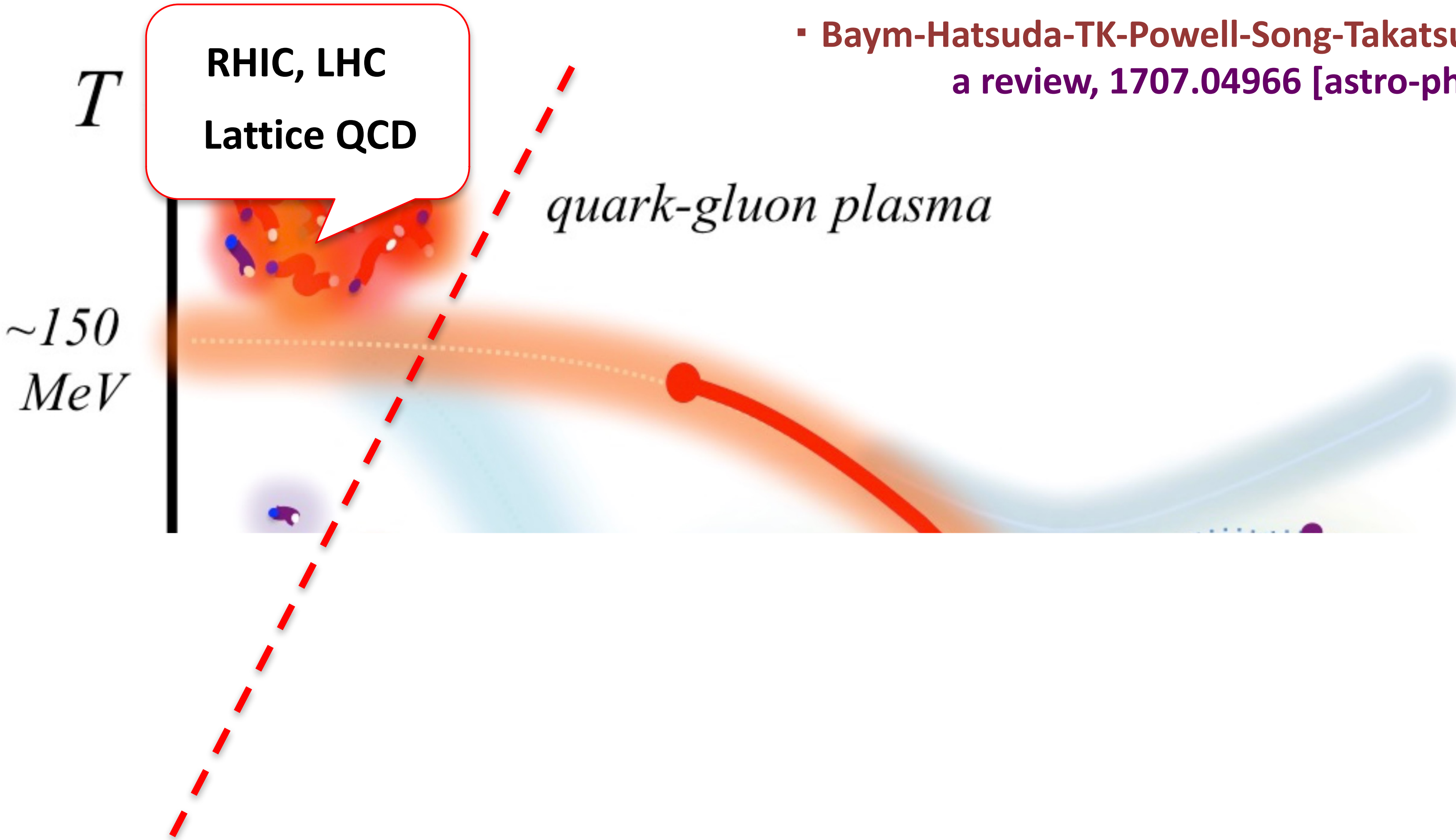

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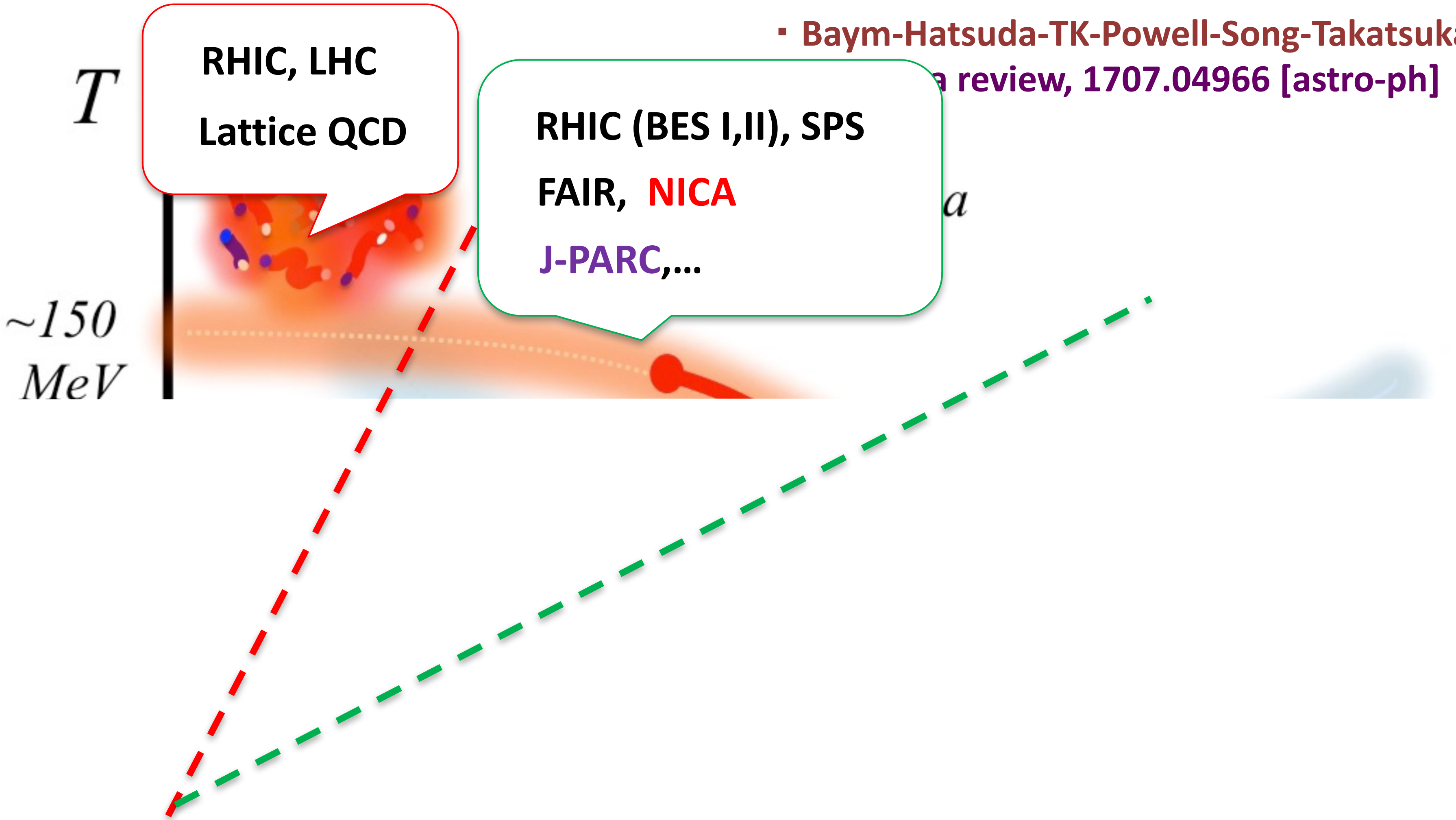

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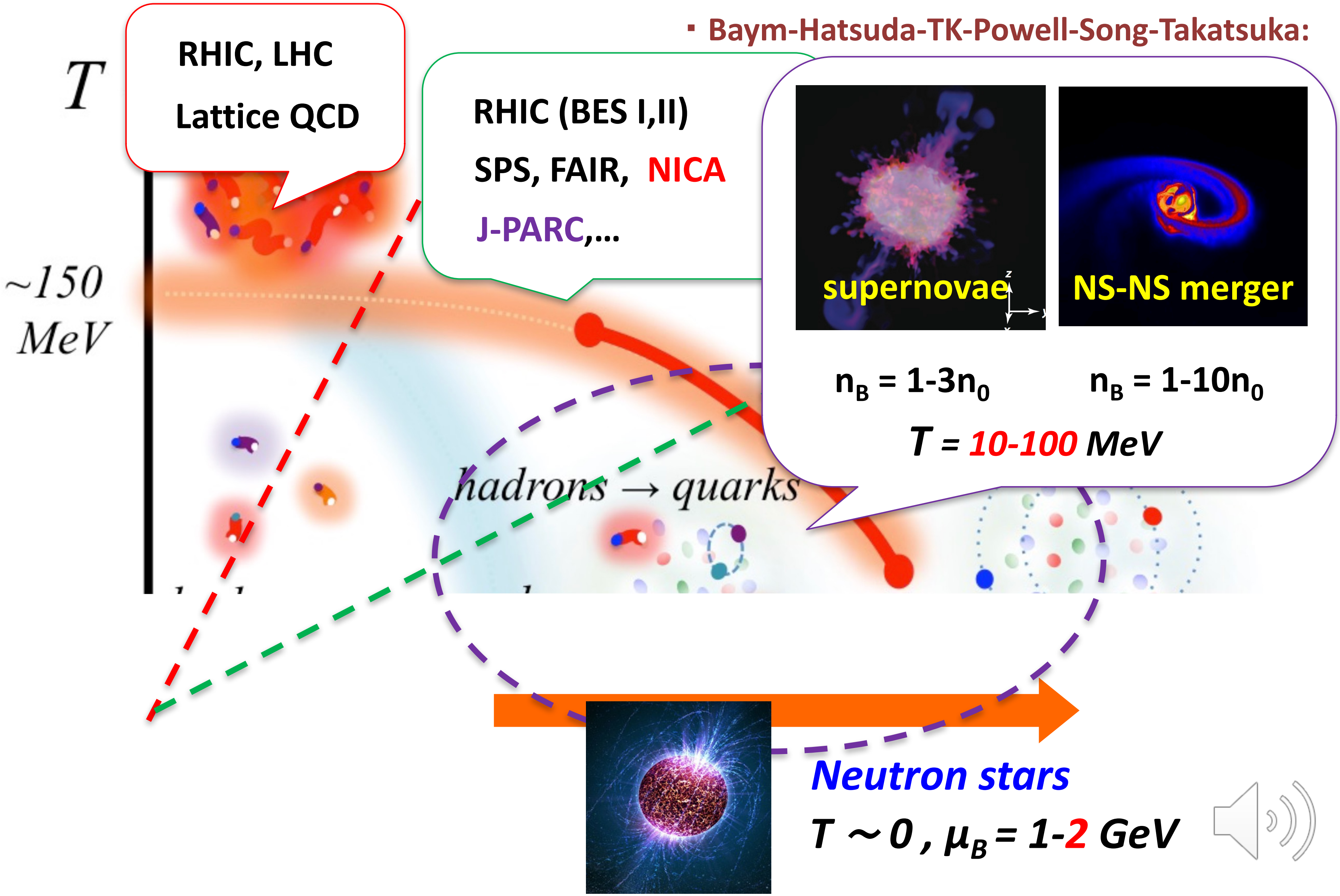


Questions to be addressed

1, Do we need 1st order P.T. to define quark matter?

2, The nature of gluons in quark matter?

3, The role of pairing effects on EoS?

Outline

1, NS and nuclear constraints

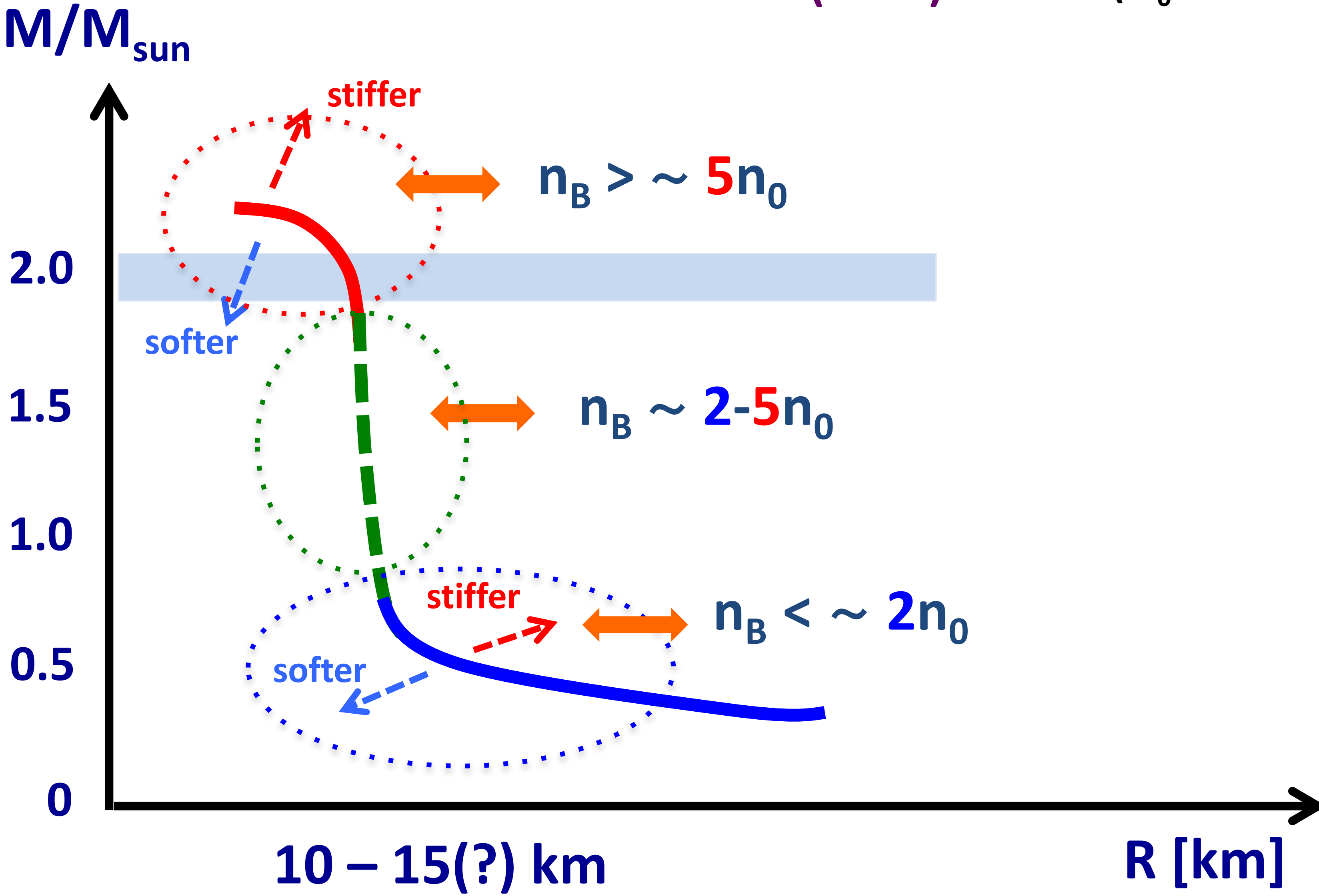
2, 3-window modeling, quark EoS

3, Summary & outlook

M-R relation & EoS

Lattimer & Prakash (2001)

(n_0 = 0.16 fm^{-3})



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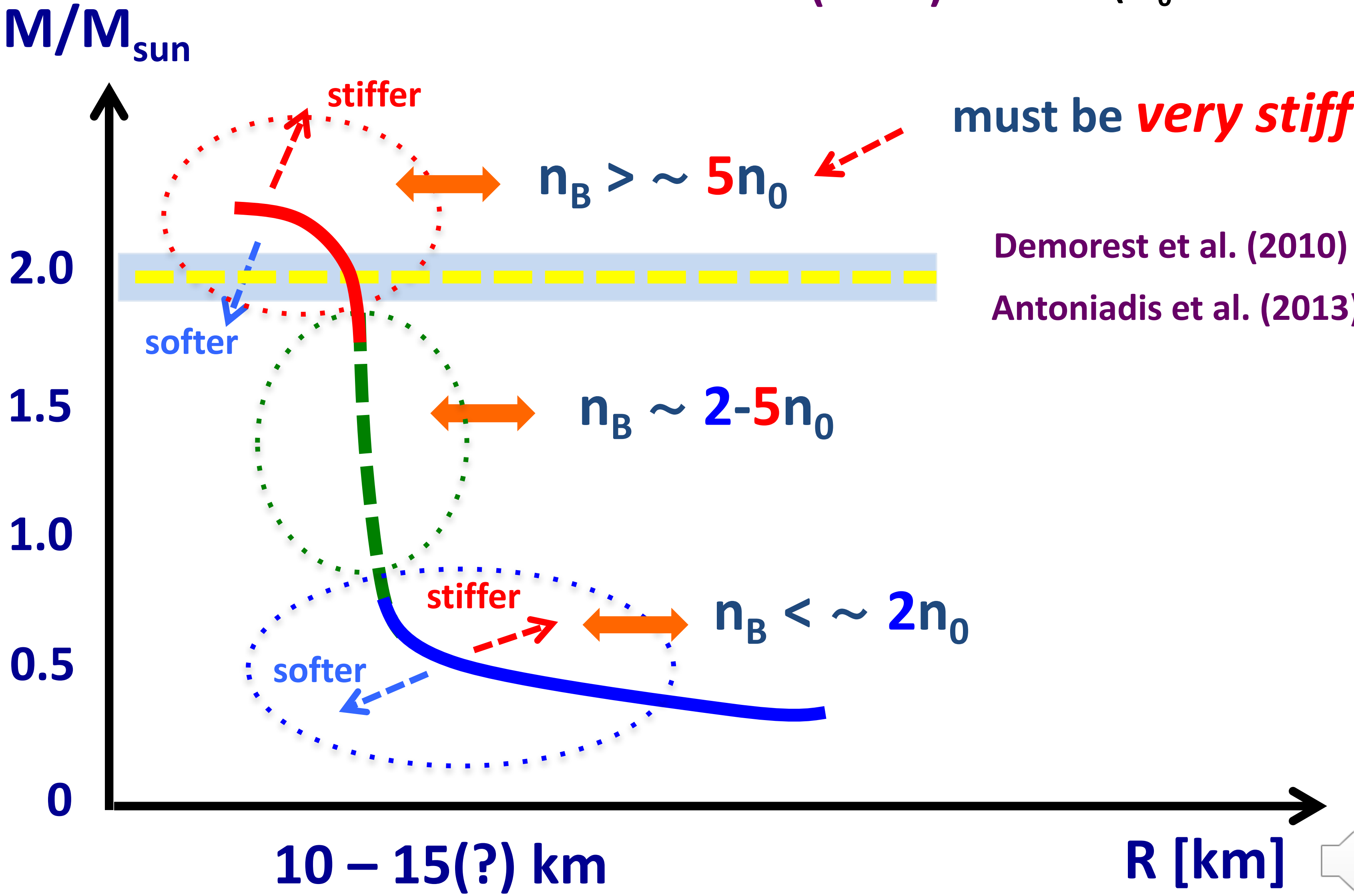

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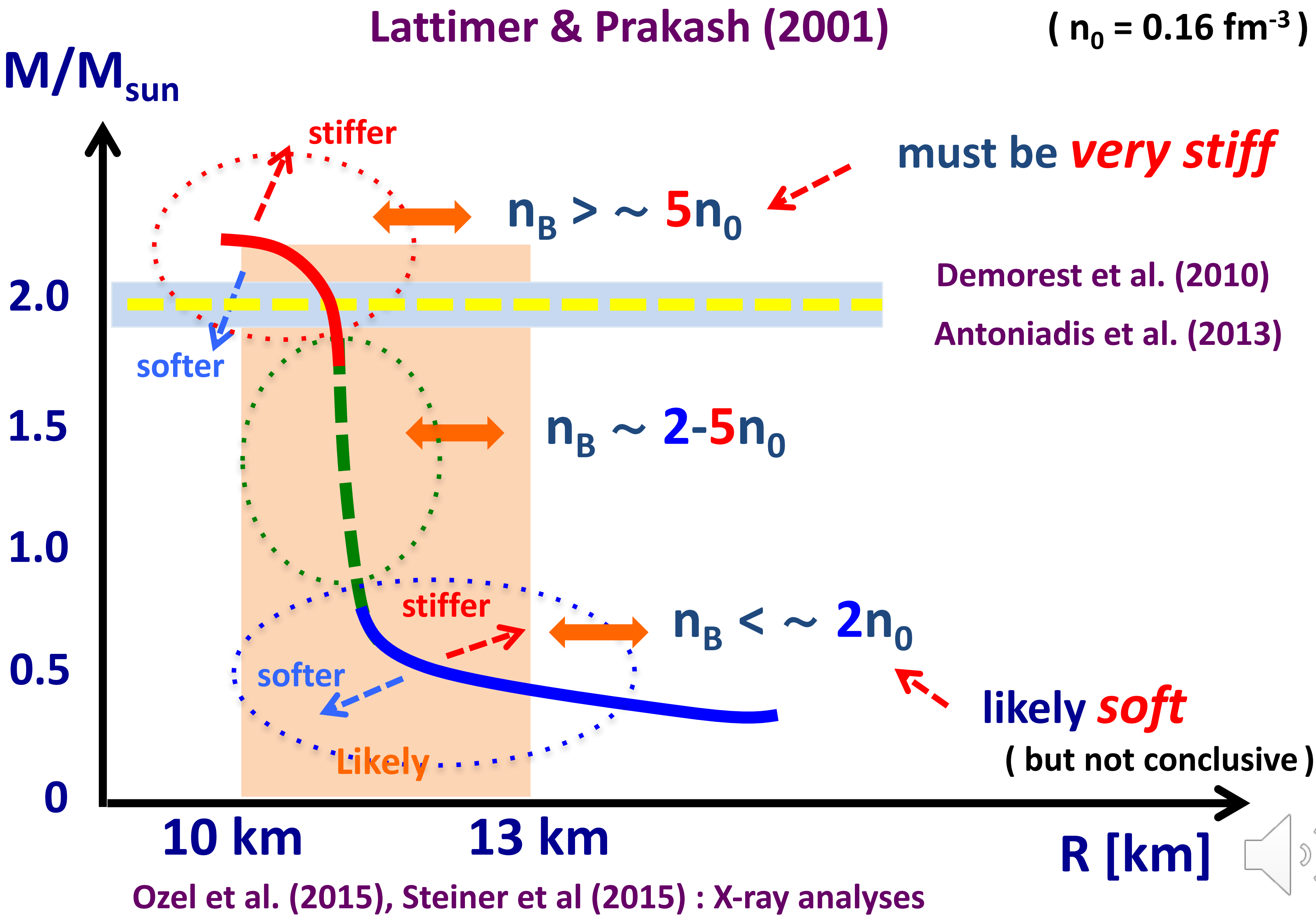
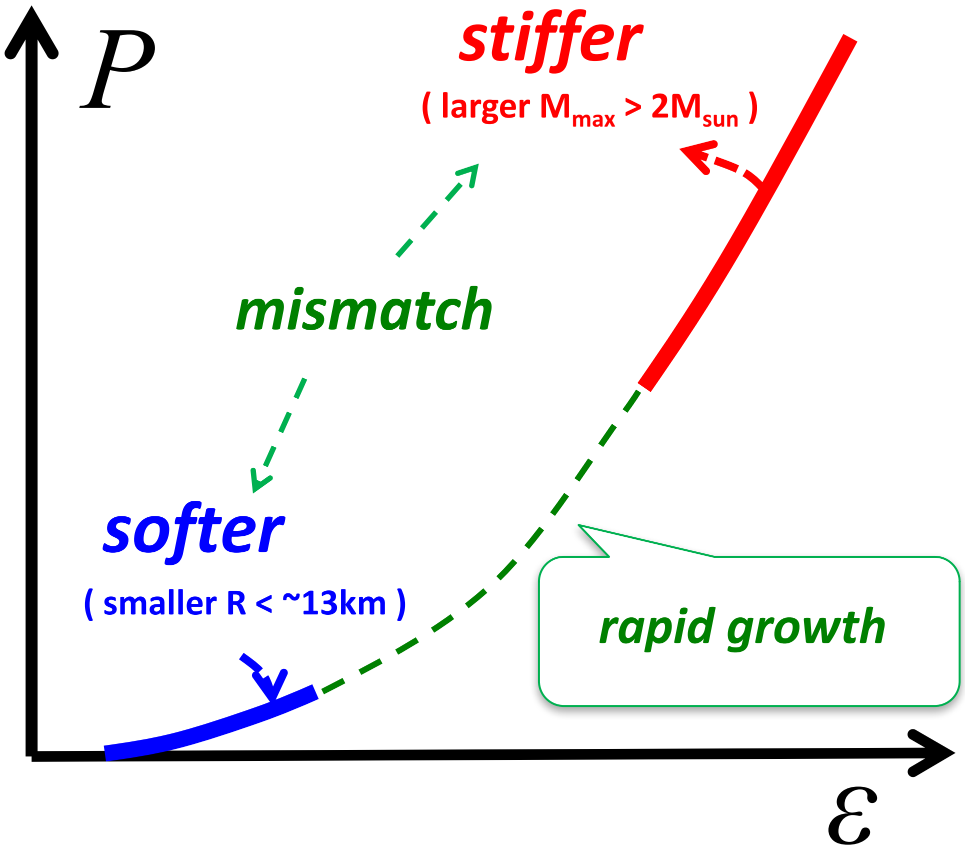


Causality constraint on $2n_0$-$5n_0$ region



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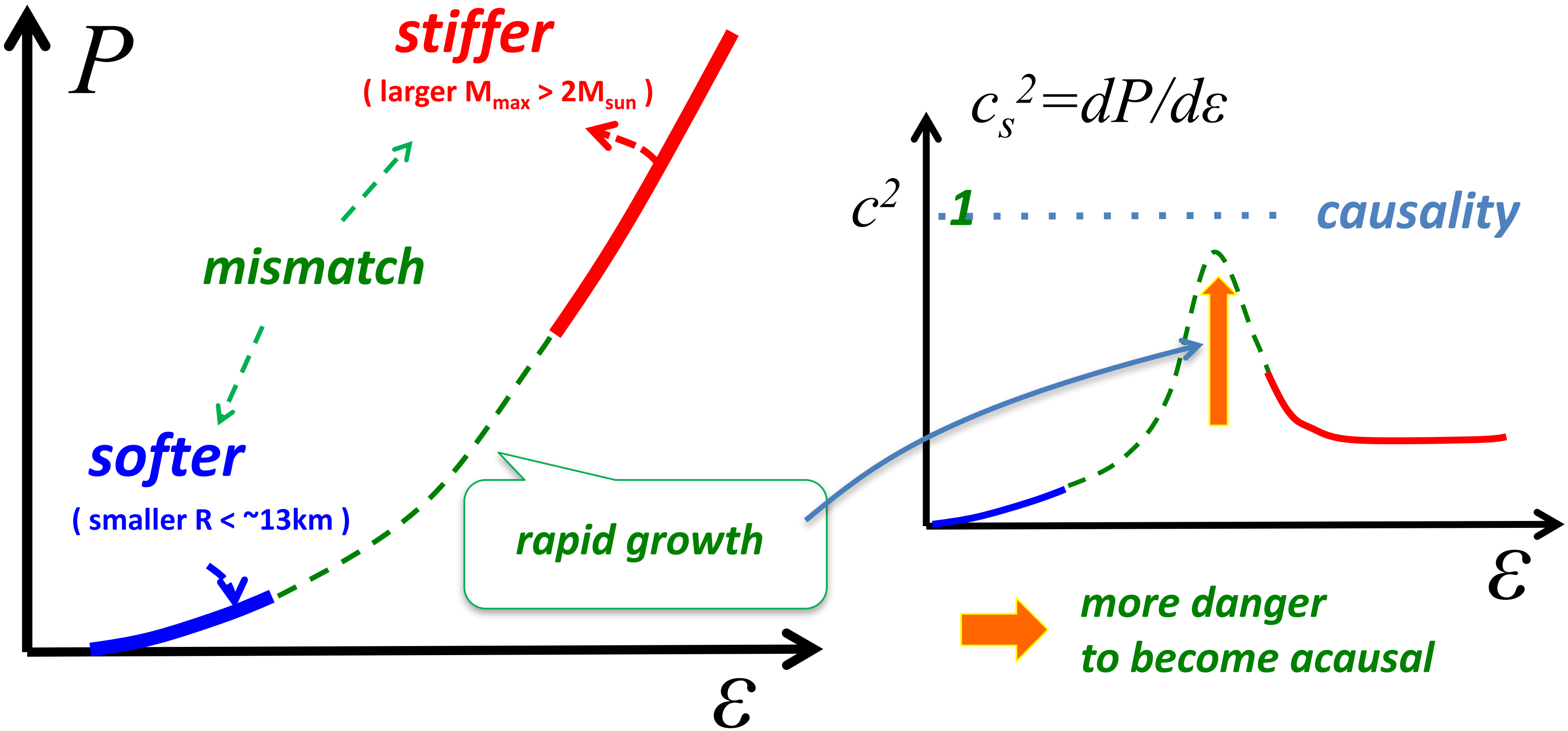
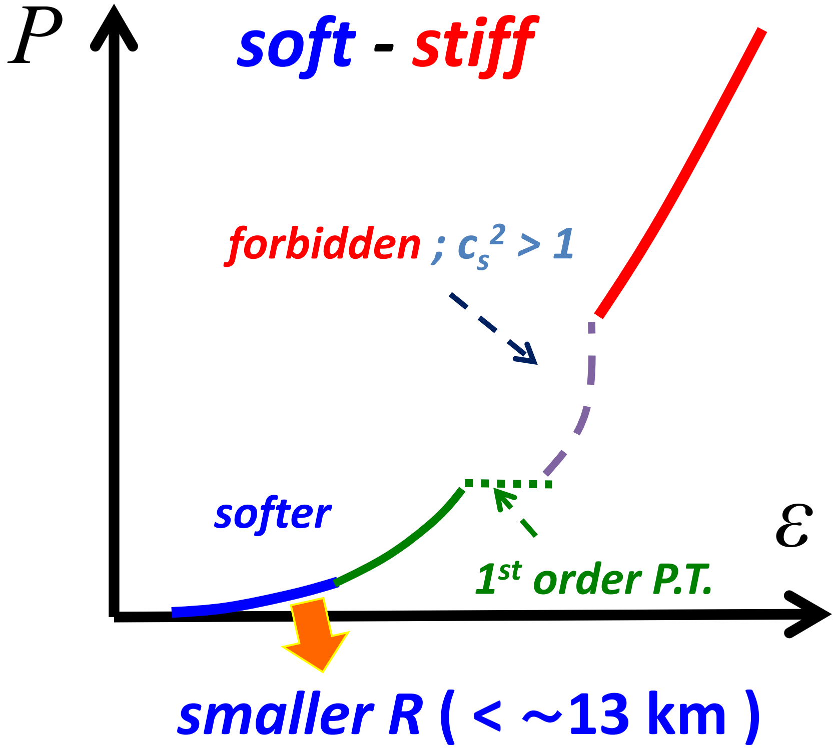


For *softer* - *stiffer EoS* ⇒ *less freedom* for $2n_0$- $5n_0$ region

Soft-Stiff v.s. Stiff-Stiff EoS

[more systematic analyses -> Han-Alford-Prakash 13]



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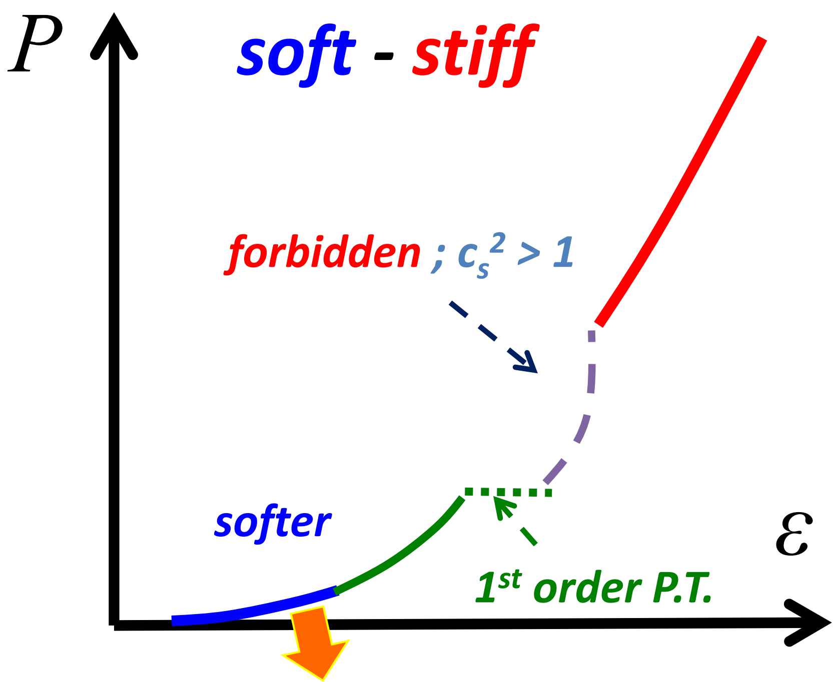
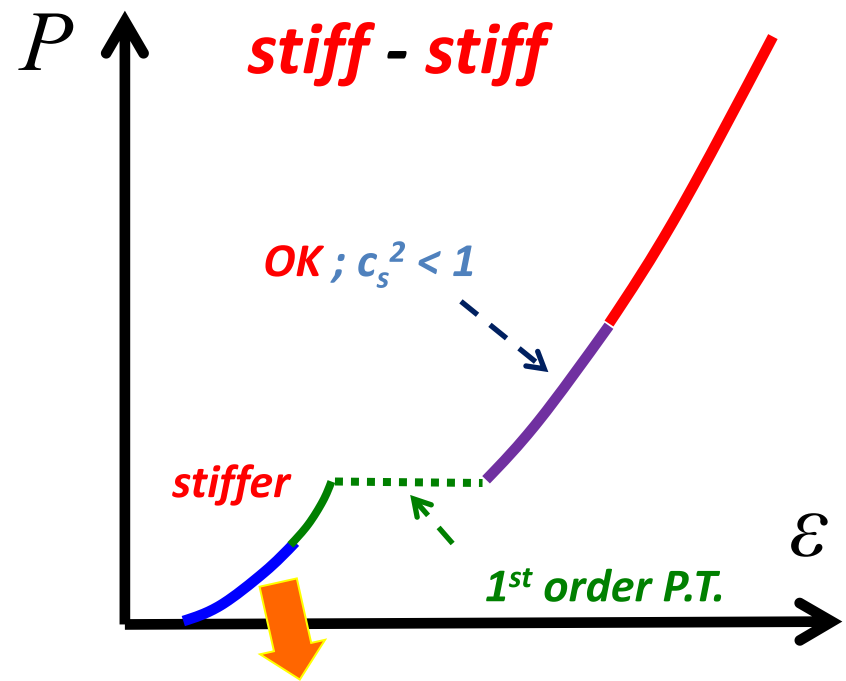


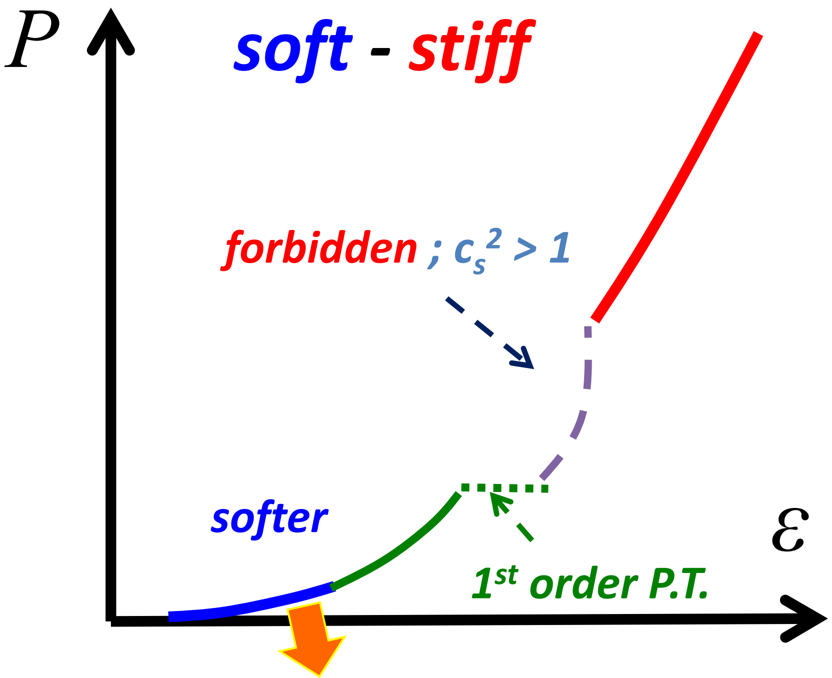
smaller R (< ~13 km)



larger R (> ～13 km)

Soft-Stiff v.s. Stiff-Stiff EoS

[more systematic analyses -> Han-Alford-Prakash 13]



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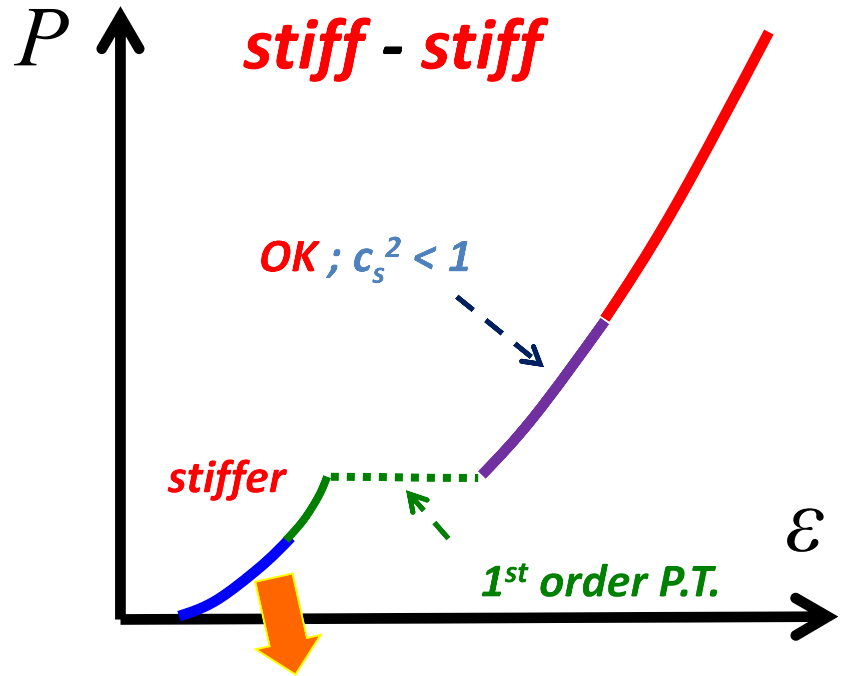

larger R (> ~13 km)

NS Radius ⇒

- ***nuclear EoS at (1.5-2) n_0*** (beyond ChEFT)
- ***strength of 1st P.T.*** (weaker for smaller

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,…

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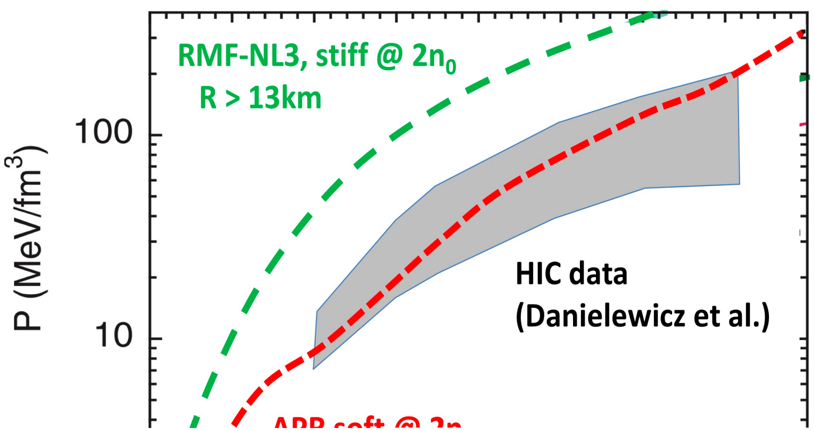
- ***HIC :*** (Danielewicz et al. 2002)



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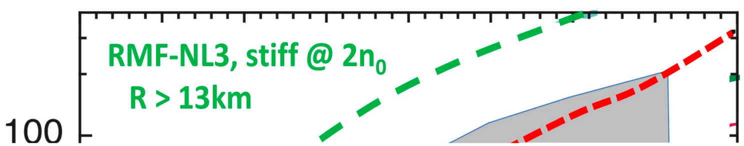
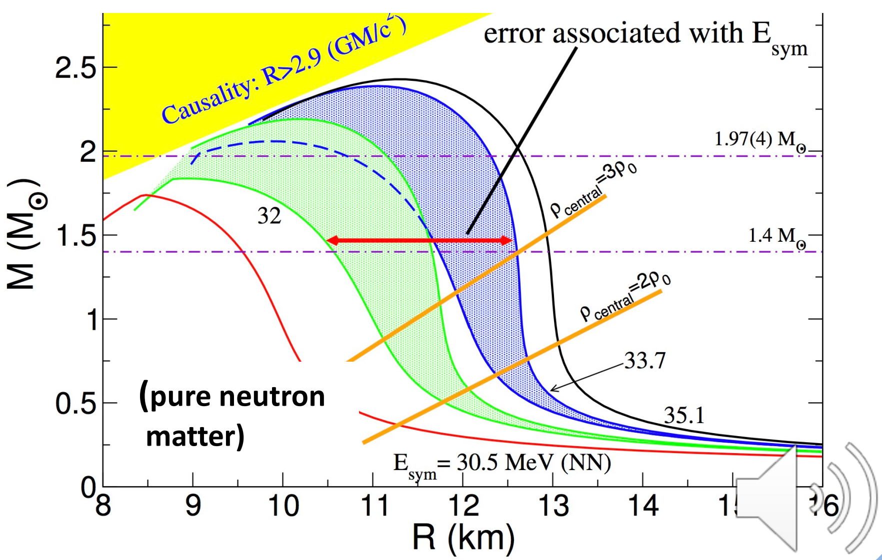


▪ *nuclear EoS extrapolation :*

(Gandolfi et al. 2015)

(*sophisticated* potentials & Monte-Carlo)



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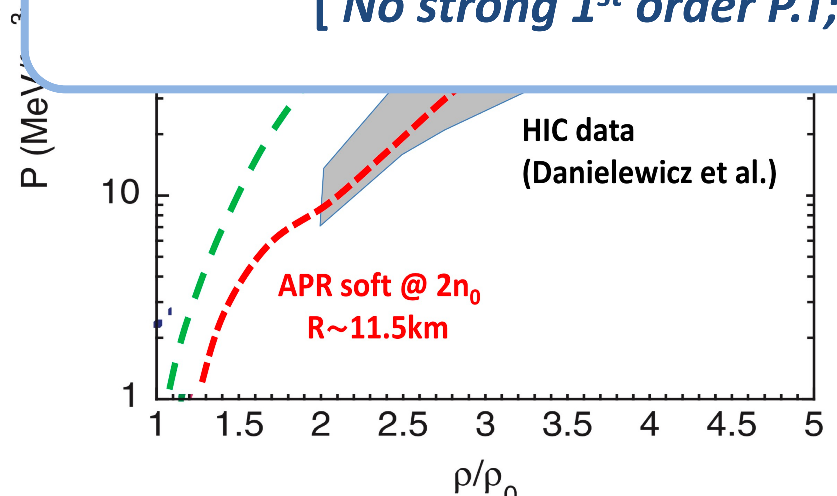
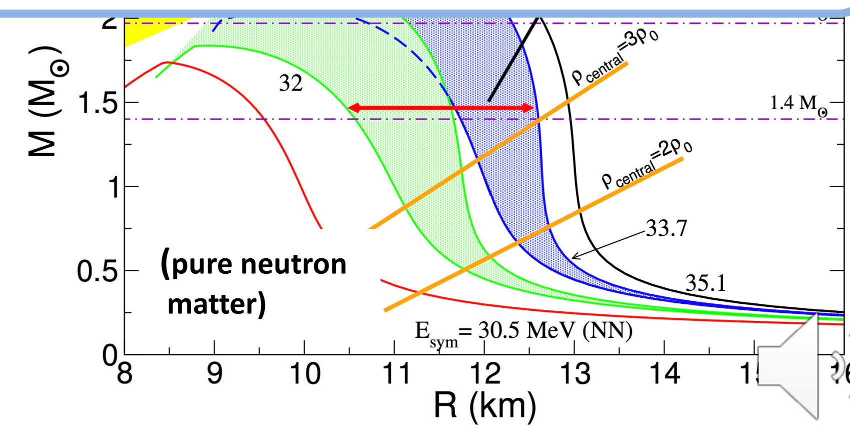
***Recent trends* : R <~13 km, soft EoS @ 1-2n_0**

(although each of them is not free from systematic uncertainties)

Based on this, below we try to construct soft-stiff EoS

[No strong 1st order P.T; either crossover or weak 1st order]





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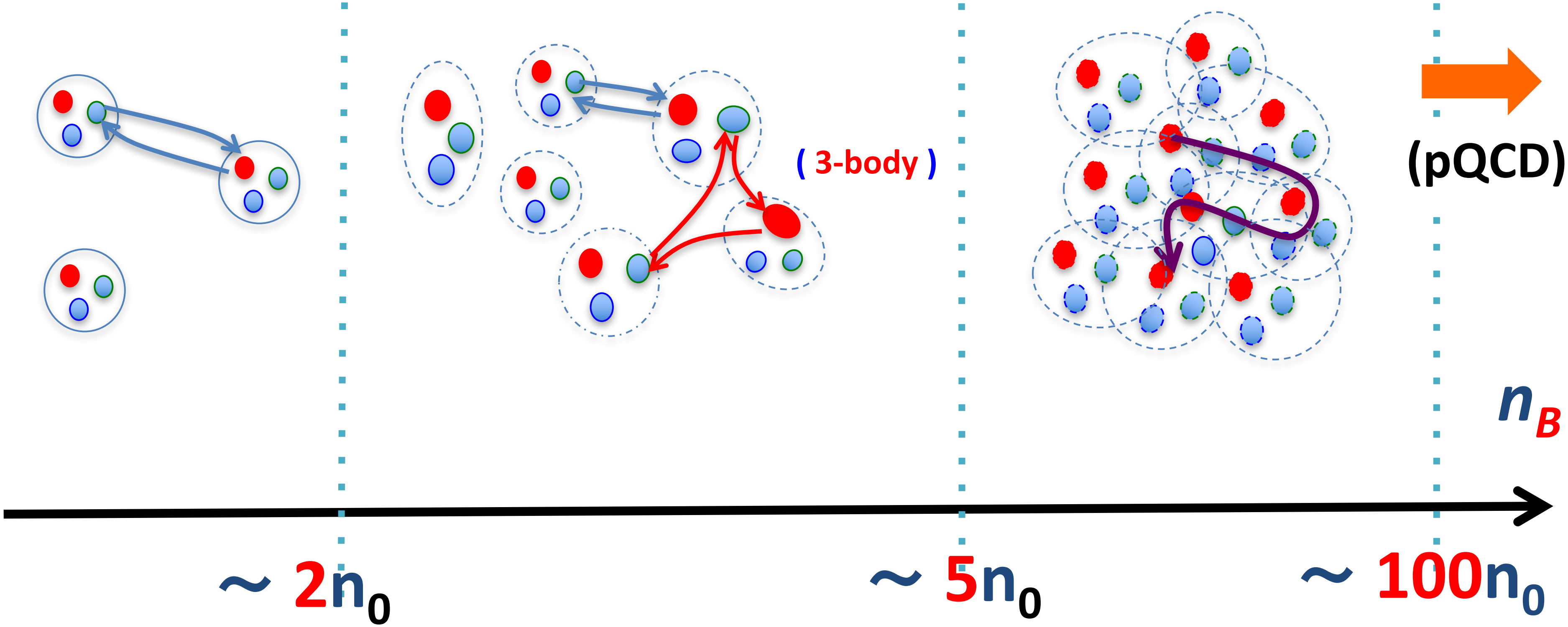
3-window modeling

(Masuda-Hatsuda-Takatsuka 12)

- few meson exchange
- nucleons only

- many-meson exchange
  (mobility --cf: Karsch-Satz '80)
- structural change of hadrons

- Baryons overlap
- Quark Fermi sea
  $p_F \sim 400$ MeV



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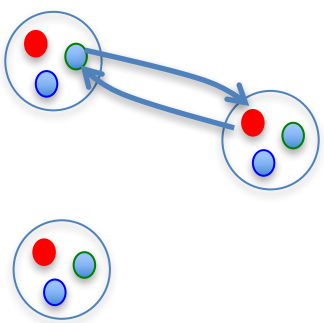

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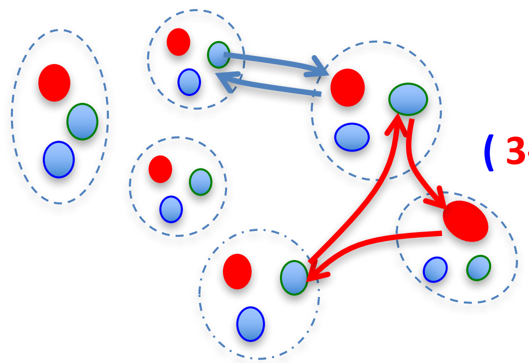
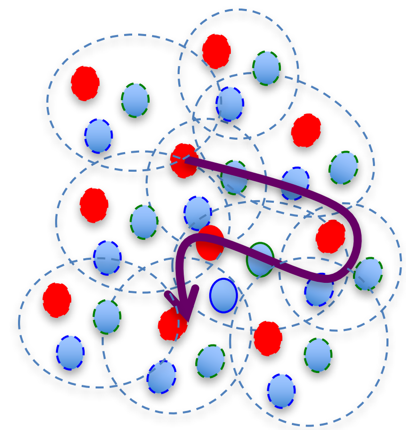


(3-body)

- **Baryons overlap**
- **Quark Fermi sea**
  p_F ~ 400 MeV



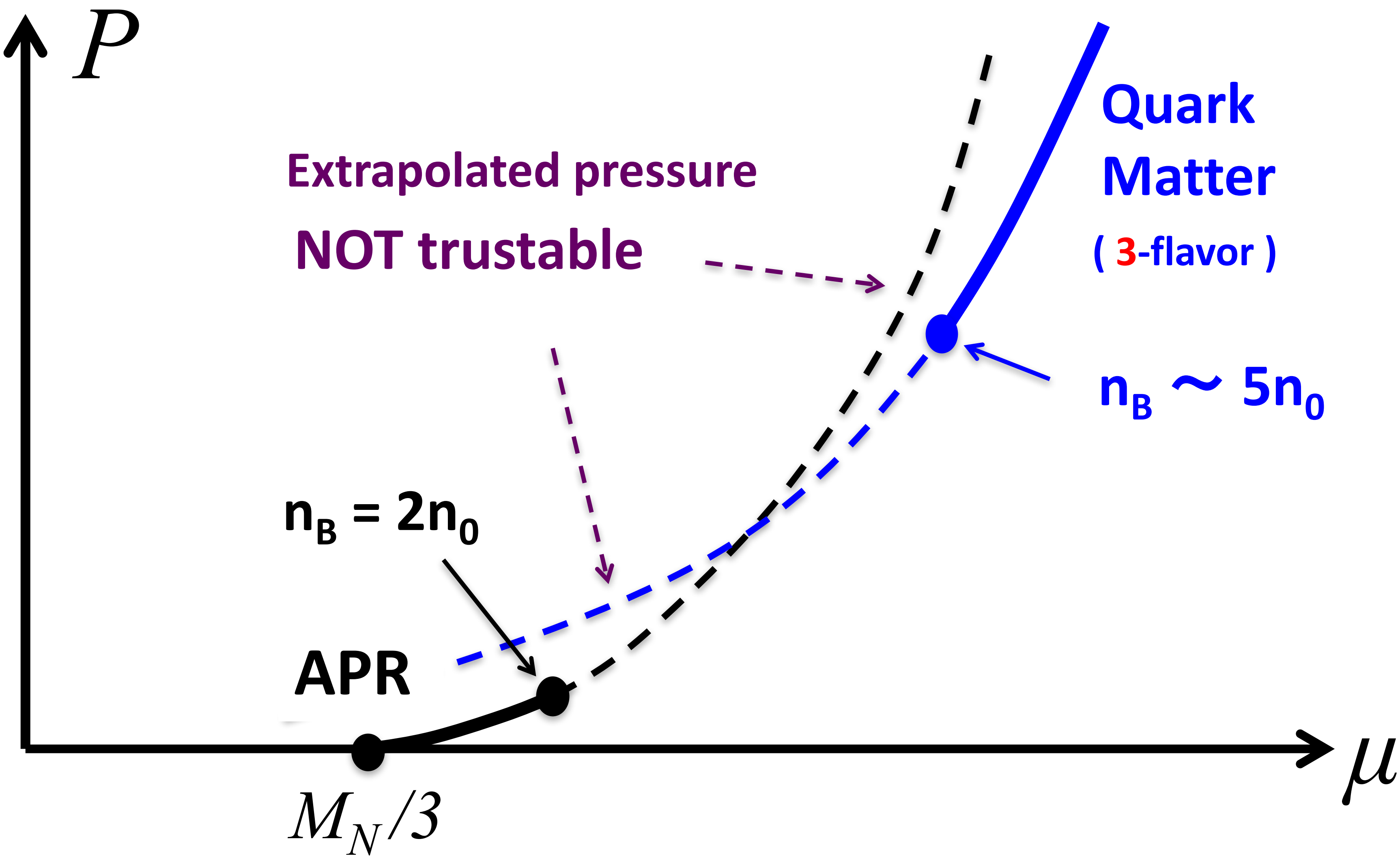
(pQCD)

APR → ***Interpolated EoS*** ← ***Quark models***

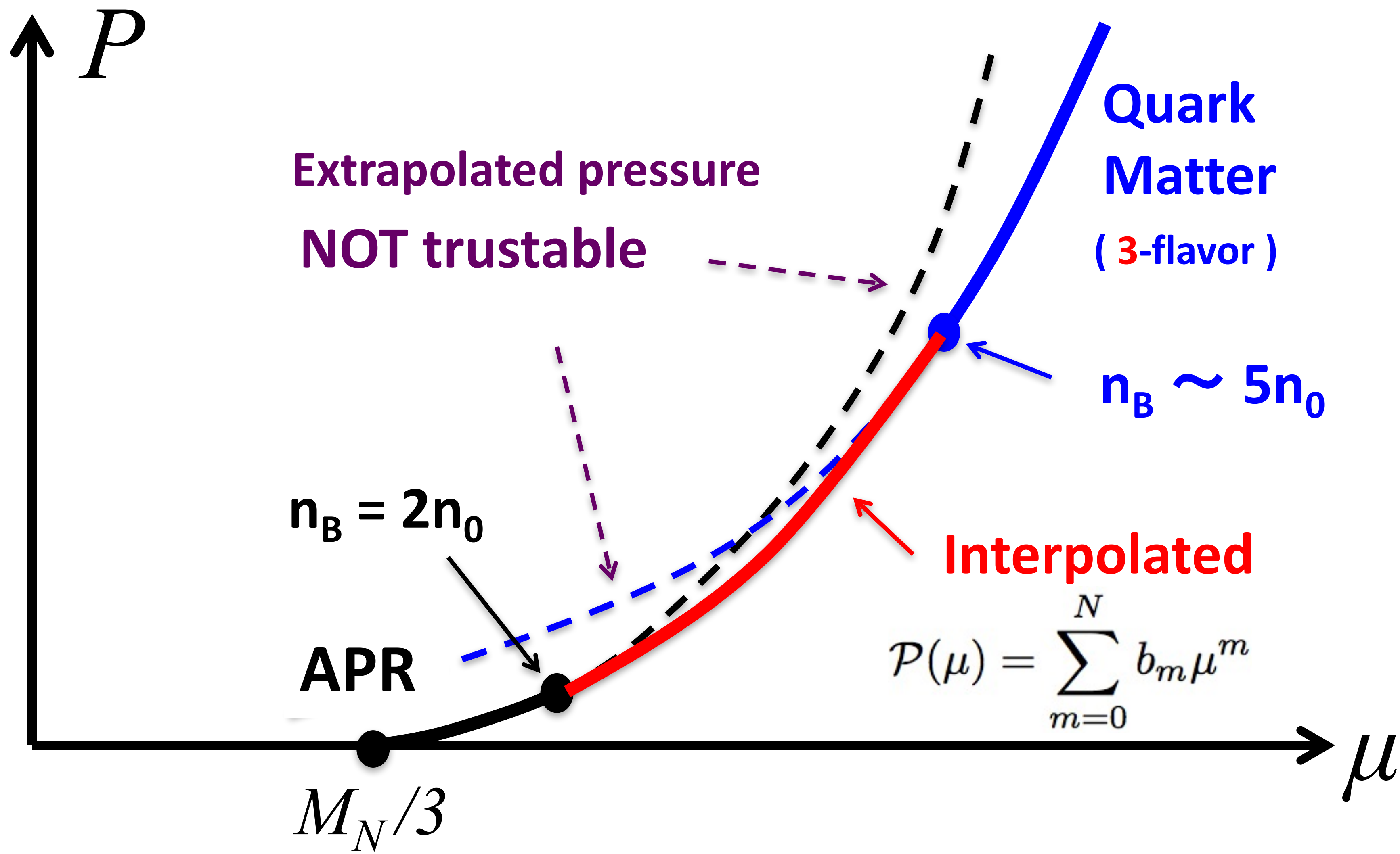
n_B

~ $2n_0$ **~ $5n_0$** **~ $100n_0$**

3-window modeling : P vs μ



3-window modeling : P vs μ



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

3-flavor quark MF model : template

Effective Hamiltonian (inspired by **hadron** & **nuclear** physics):

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

→ change in *Dirac sea*, beyond *no-sea approximation*

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

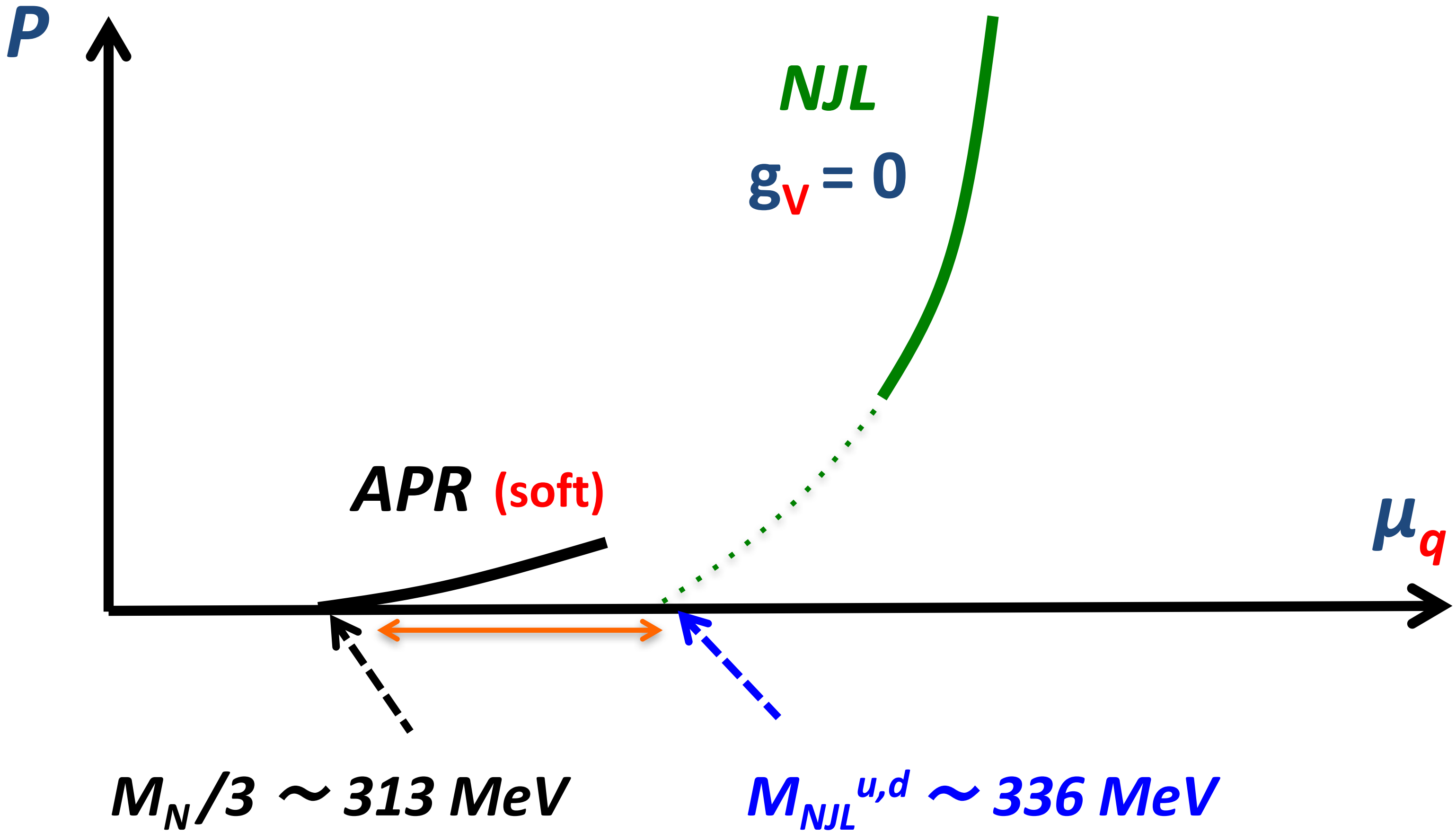
$+ \ \mathcal{H}_{\rm OGE}$ ➡ (mag. part) $- H\sum_{A,A'=2,5,7}\left(\bar{\psi}{\rm i}\gamma_5\lambda_A\tau_{A'}\psi_c\right)^2$ (cf: *N-Δ splitting*)

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

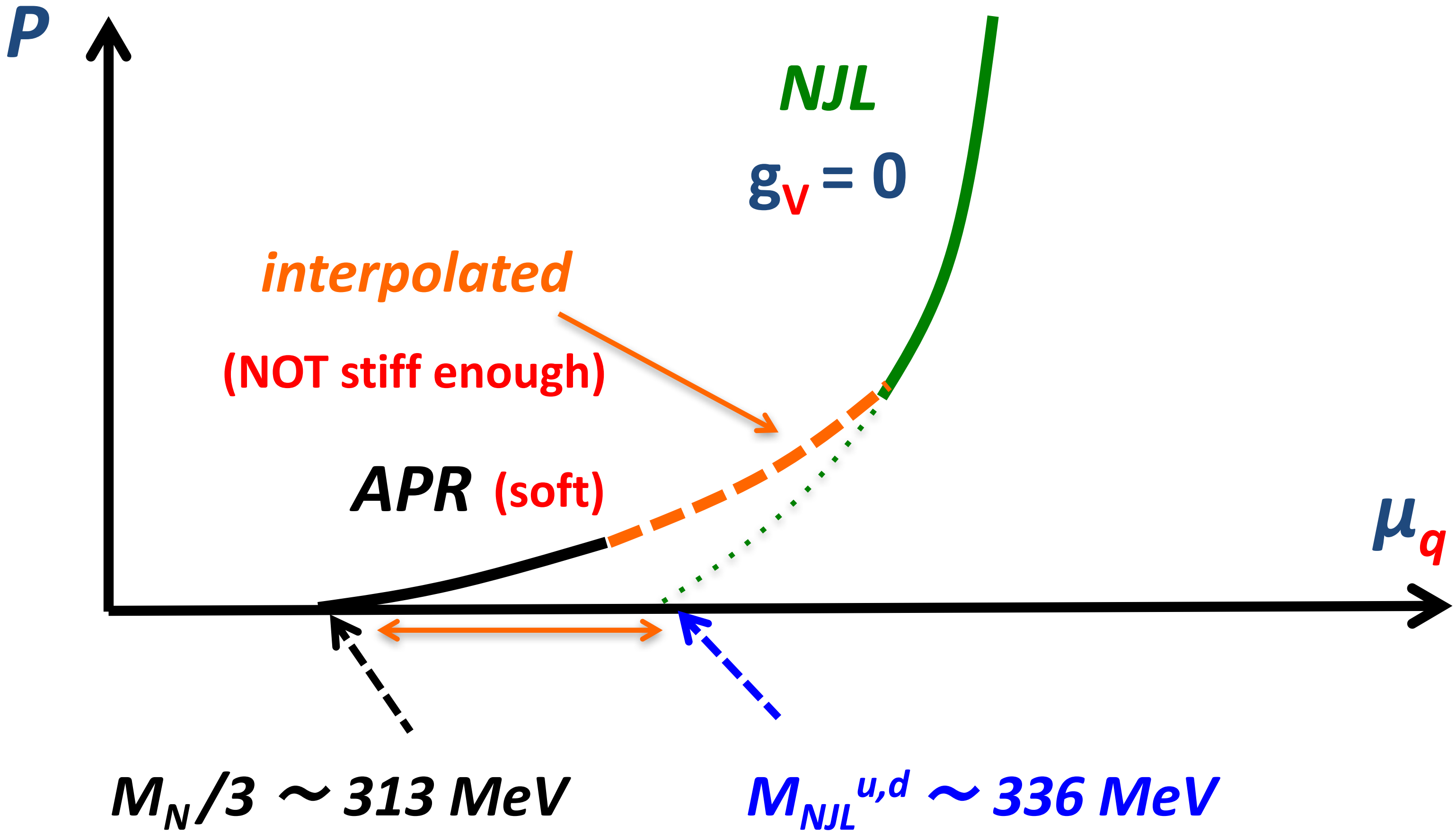
+ constraints (charge neutrality, β- equilibrium, color-neutrality)

Goal: *NS constraints* → $(G_s, H, g_V)_{@5\text{-}10n_0}$

minimal

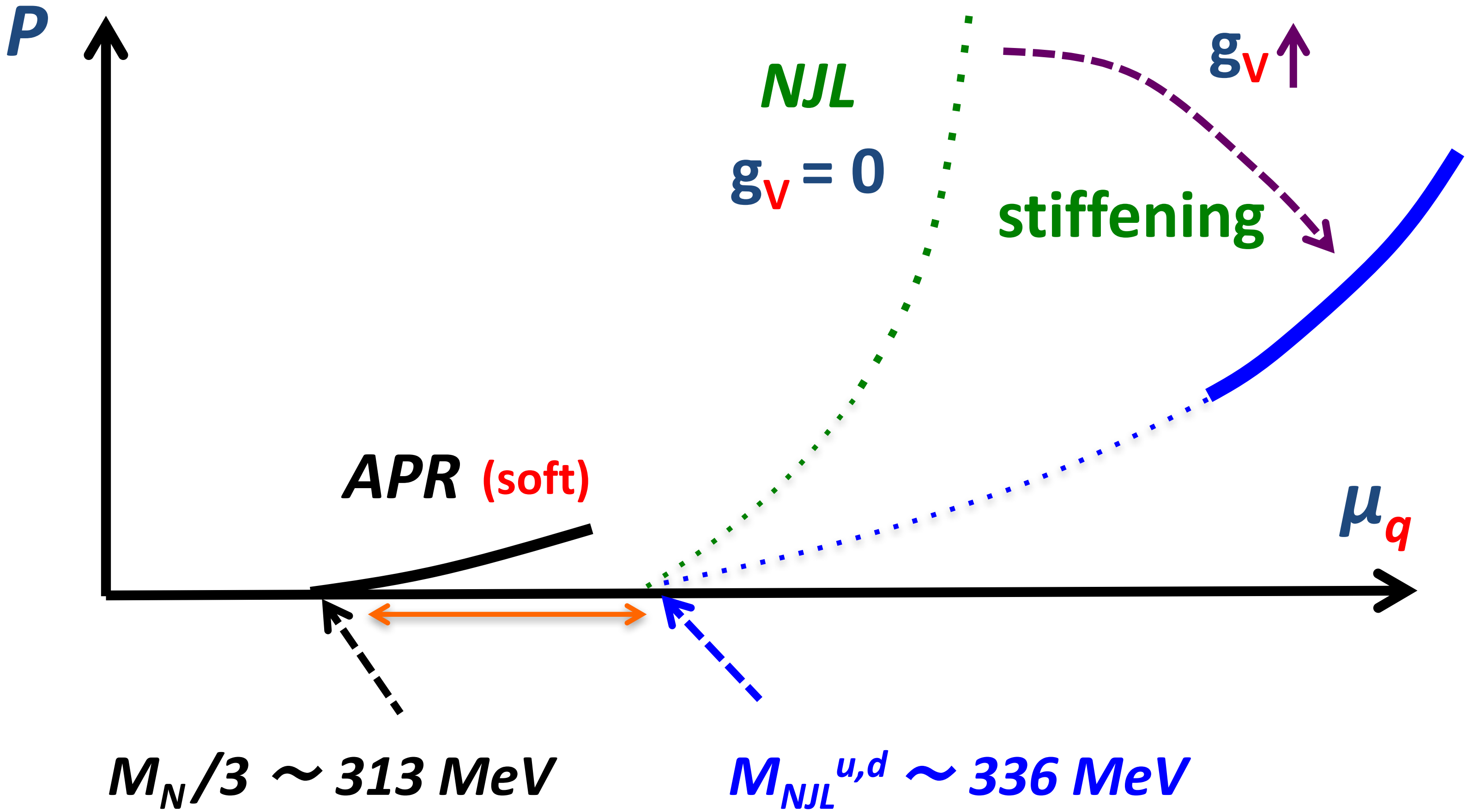


minimal



P
NJL
gV = 0
interpolated
(NOT stiff enough)
APR (soft)
μq
MN/3 ~ 313 MeV
MNJLu,d ~ 336 MeV

minimal + vector int.



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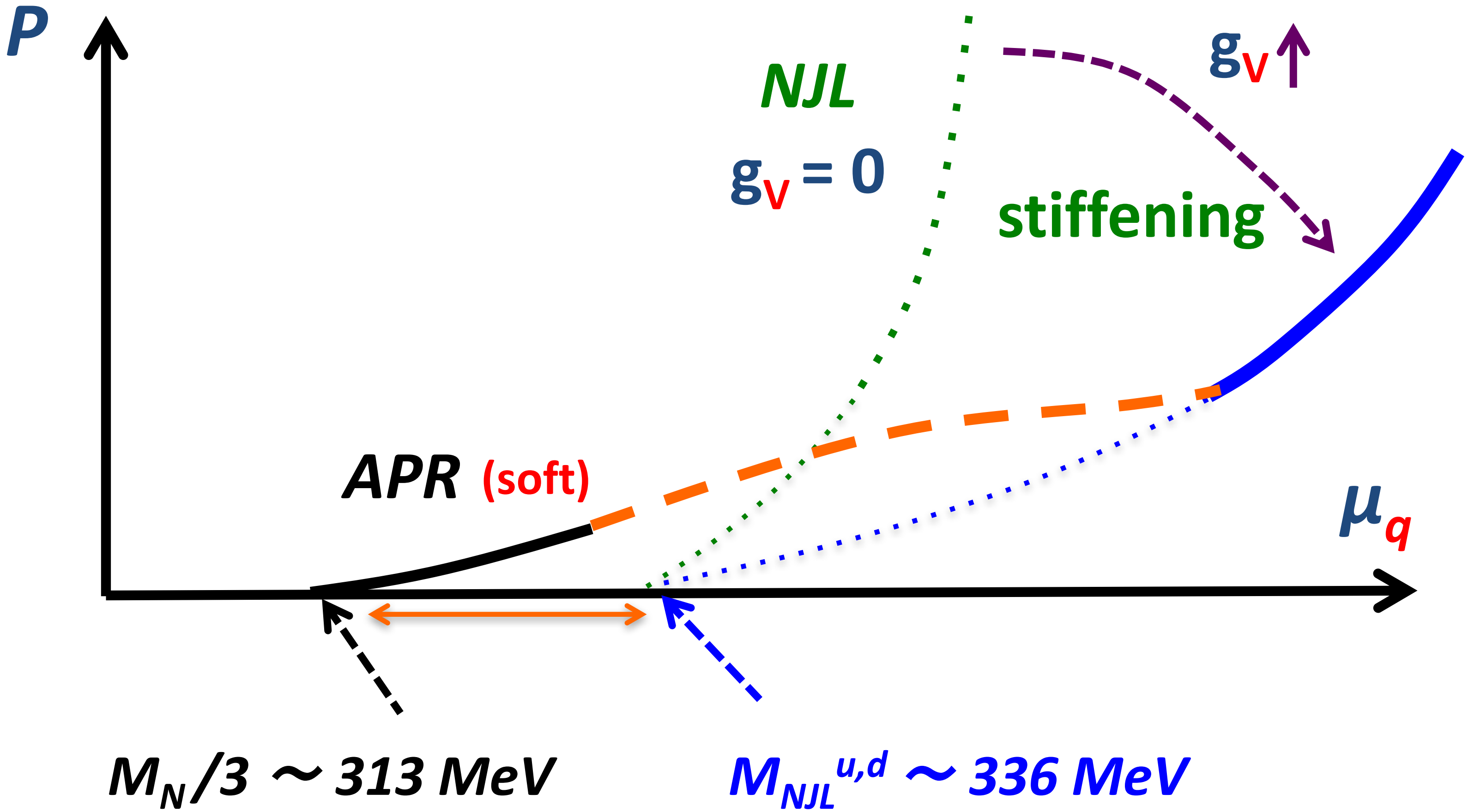

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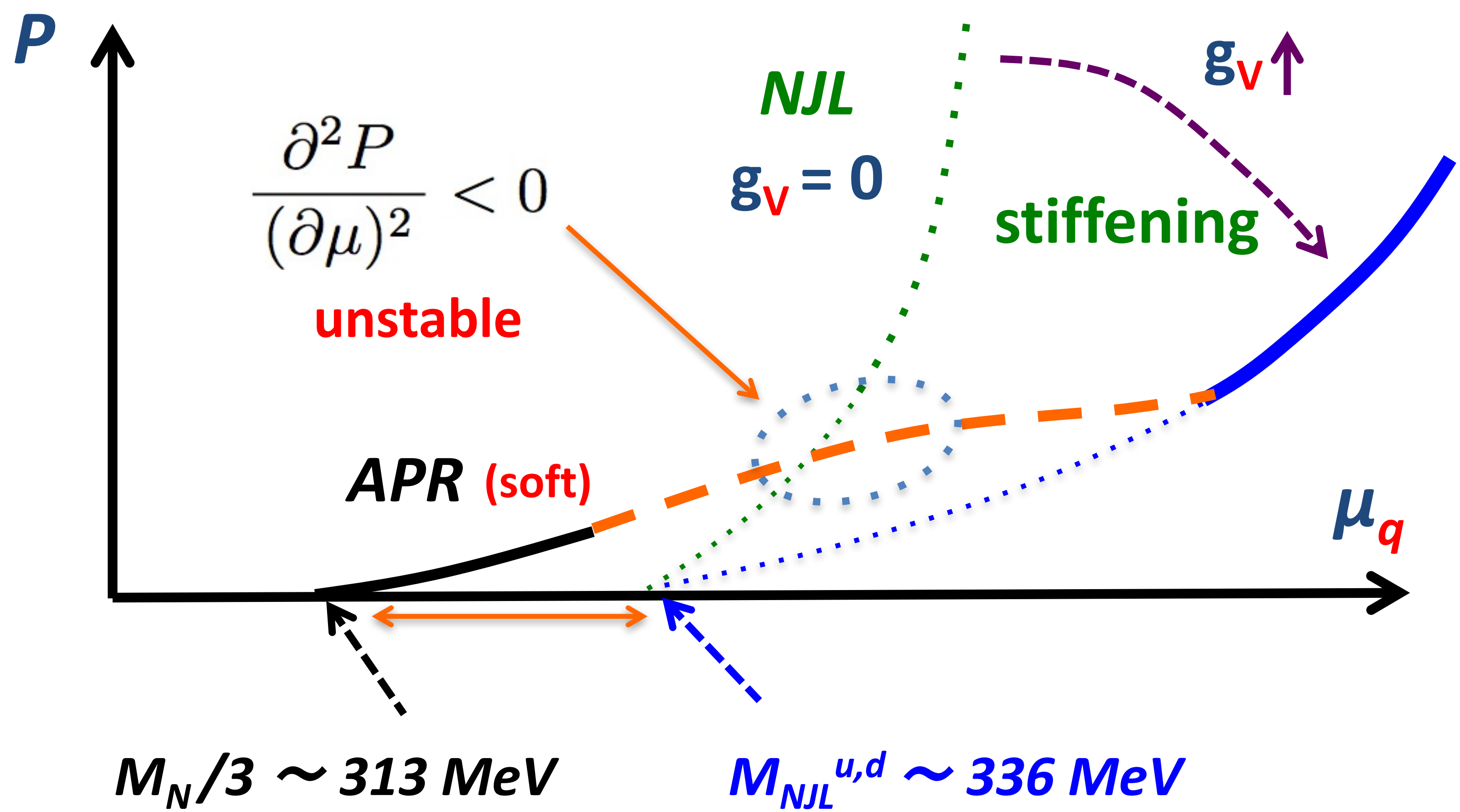
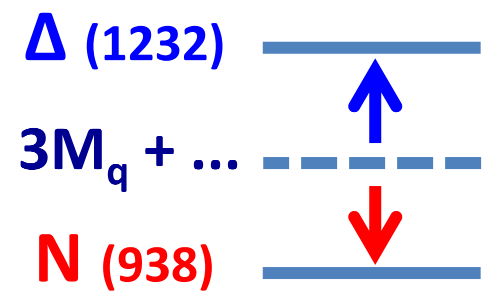


+ color magnetic interaction

(in *MF*, effects appear as diquark condensate)



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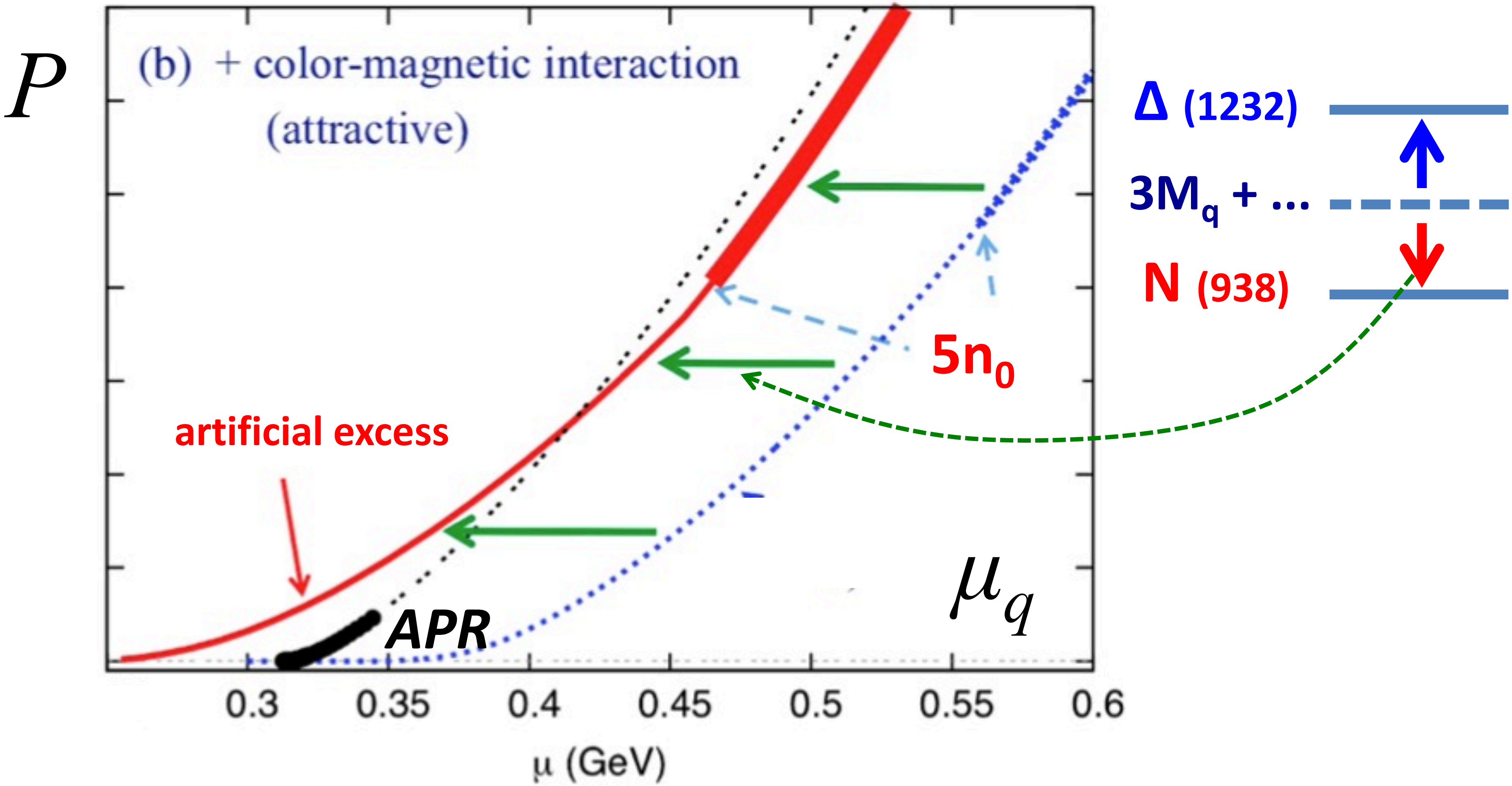
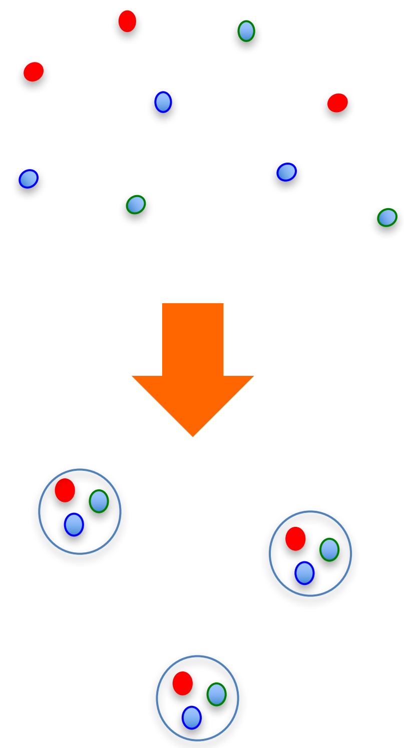


→ overall shift of P(μ) toward lower μ

+ APR constraint at low density

(*mimic* ***confining*** *effects*)



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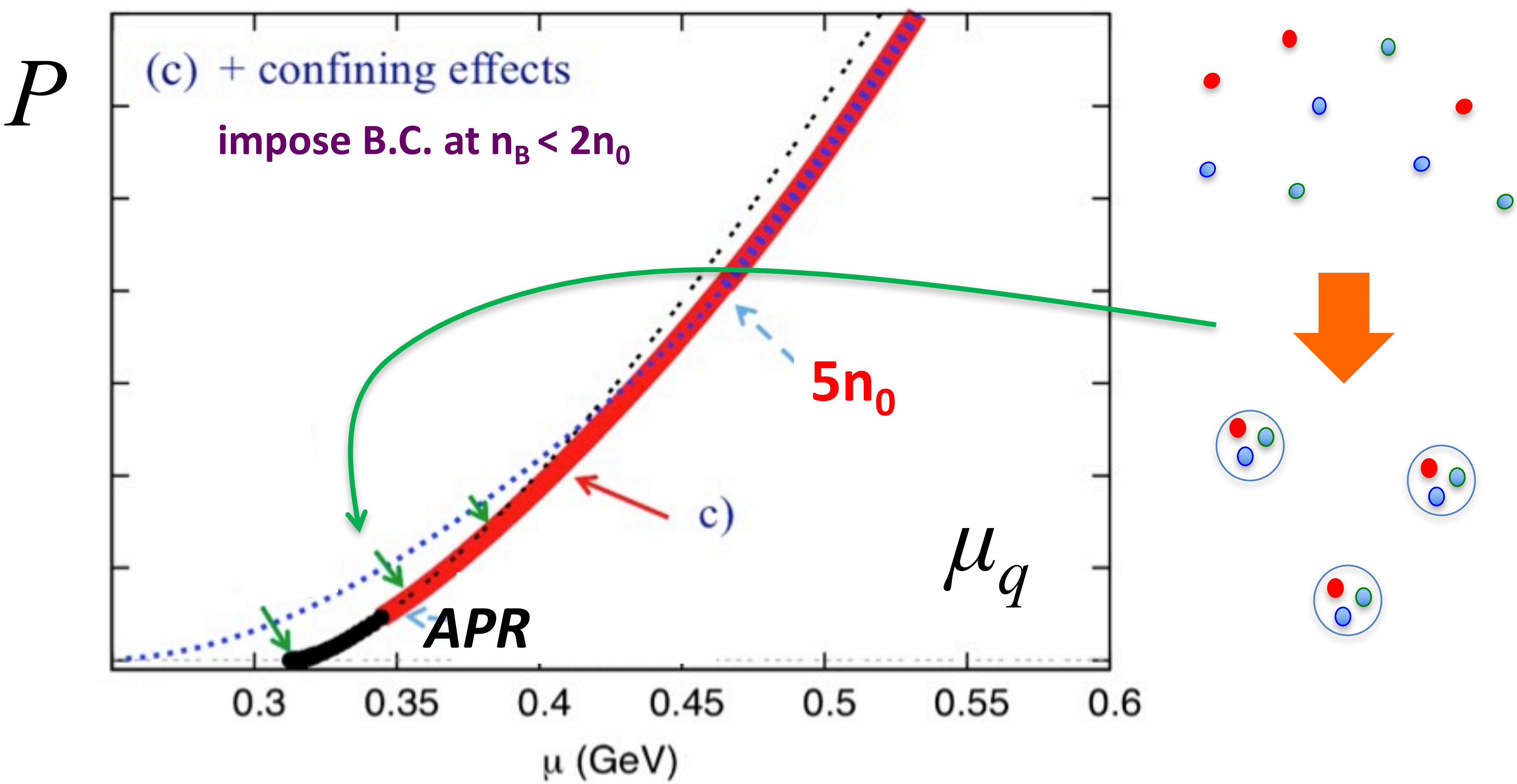
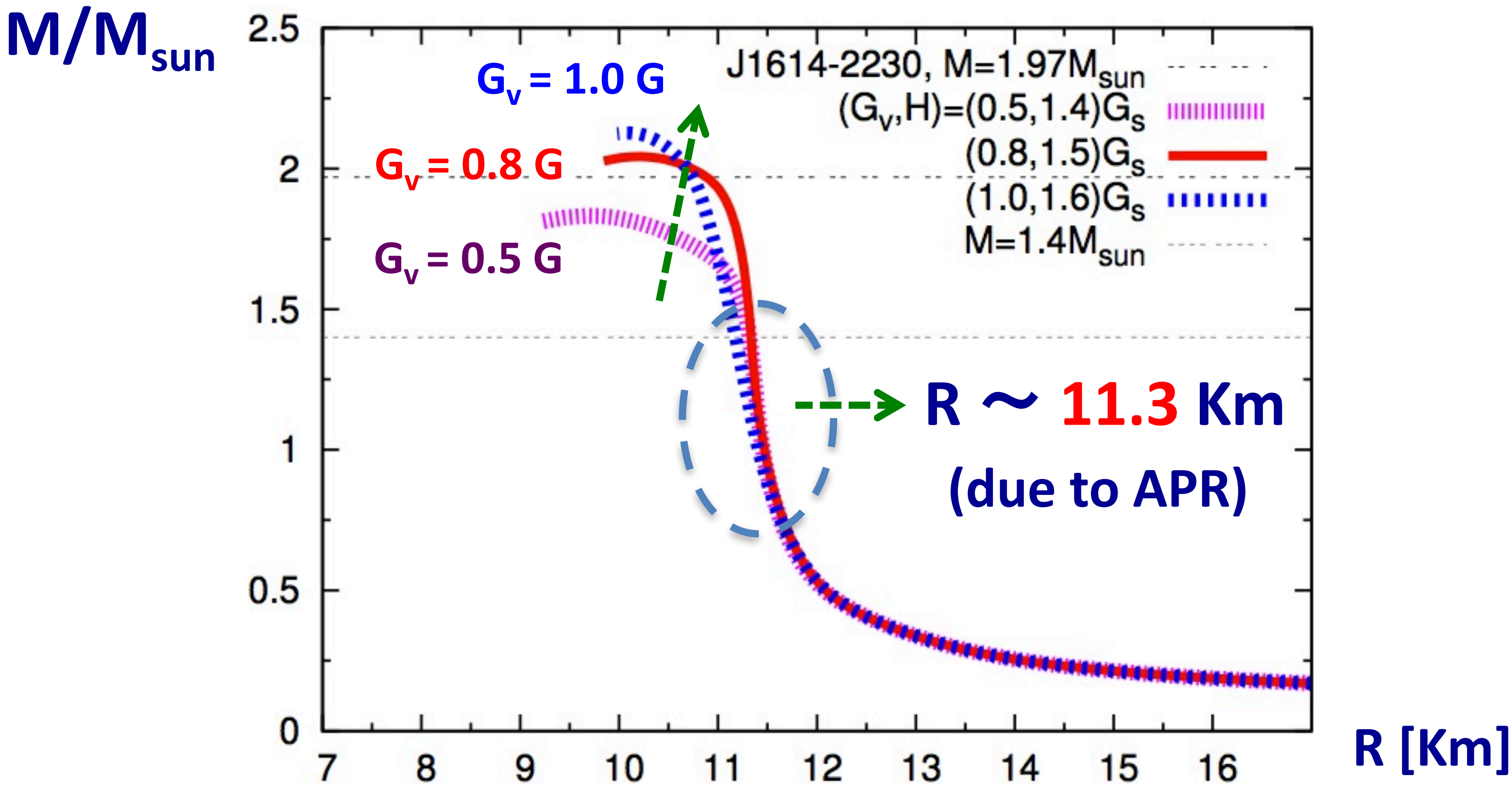


→ discard *artificial* excess of P at $n_B < \sim 5n_0$

(*like Polyakov loop effects in hot QCD*)

M-R curves



we need :

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

Gluons behind models

- ***Statement :***

  To $n_B \sim$ 5 - 10 n_0, gluons should be as non-perturbative as in the vacuum

If NOT

- NJL parameters (at $n_B \sim 5n_0$) : $(G_s, G_v, H) << G_s^{vac}$
- The (gluonic) bag constant of $O(\Lambda_{QCD}^4)$ must be included
- Too much strange quarks; $m_s \sim 100$ MeV

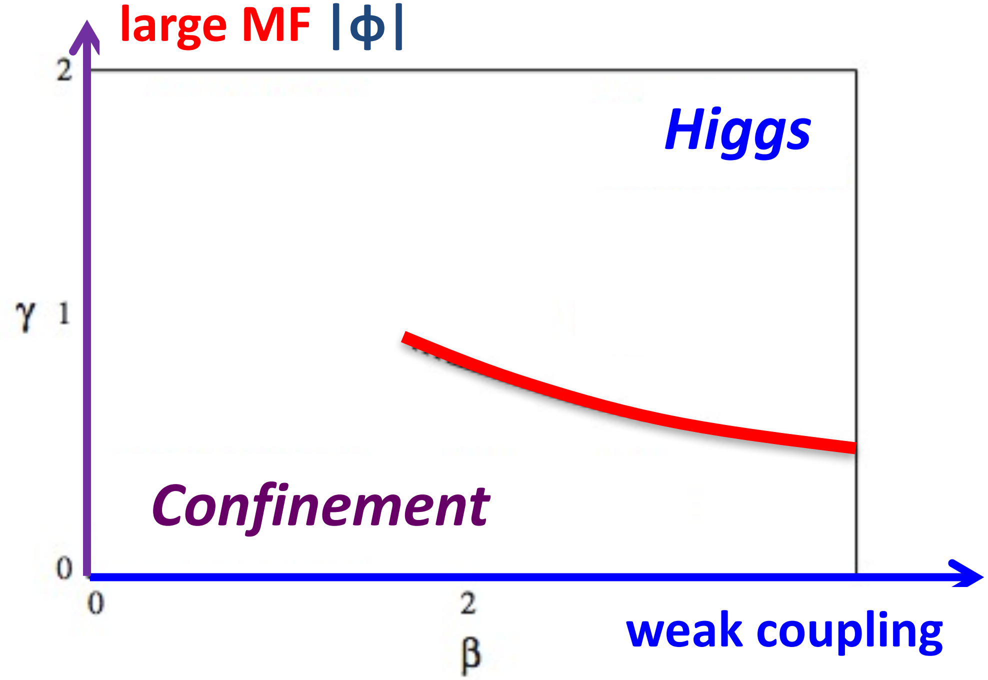
→ Troubles with the $2M_{sun}$ constraint

Crossover : gauge dynamics

e.g.) Higgs model *with const. amplitude* [Fradkin-Shenkar 79]

amp. of Higgs |ϕ| phase of Higgs

$$S = \beta \sum_{\text{plaq}} \frac{1}{2} \mathrm{Tr}[UUU^\dagger U^\dagger] + \gamma \sum_{x,\mu} \frac{1}{2} \mathrm{Tr}[\phi^\dagger(x) U_\mu(x) \phi(x+\hat{\mu})]$$



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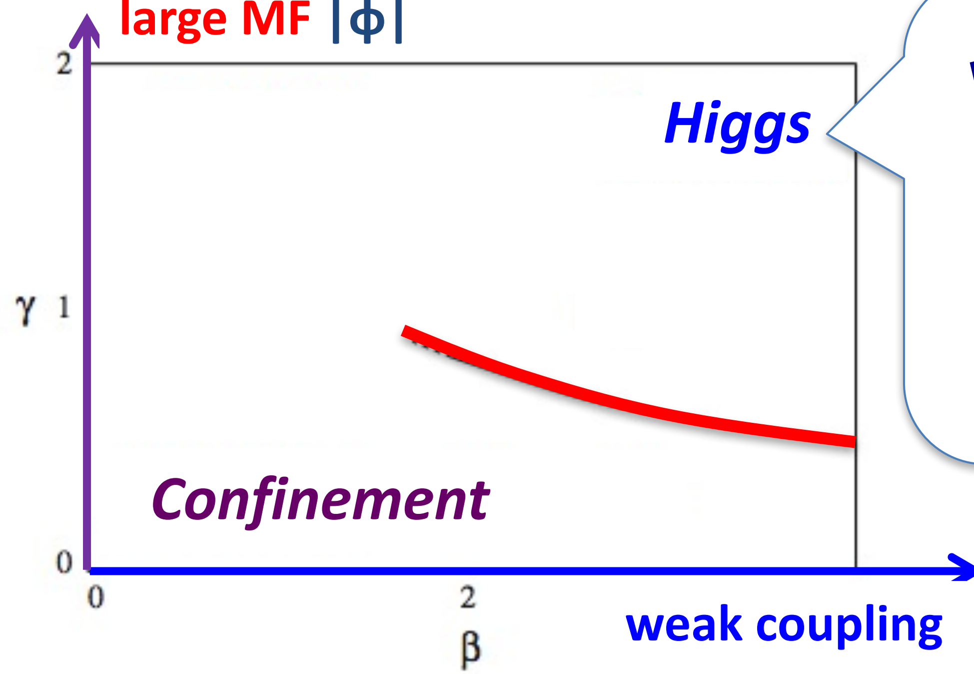

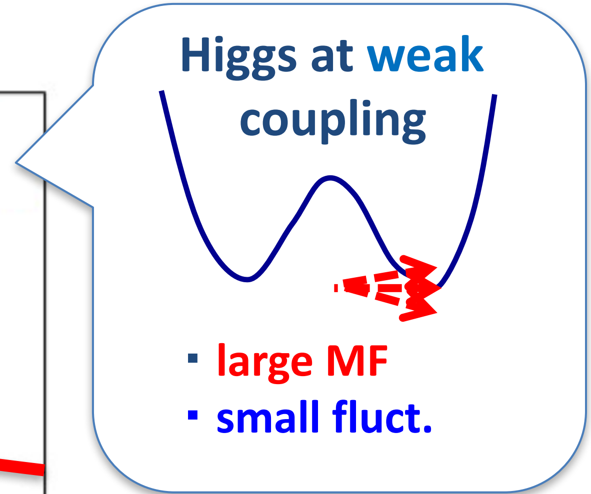

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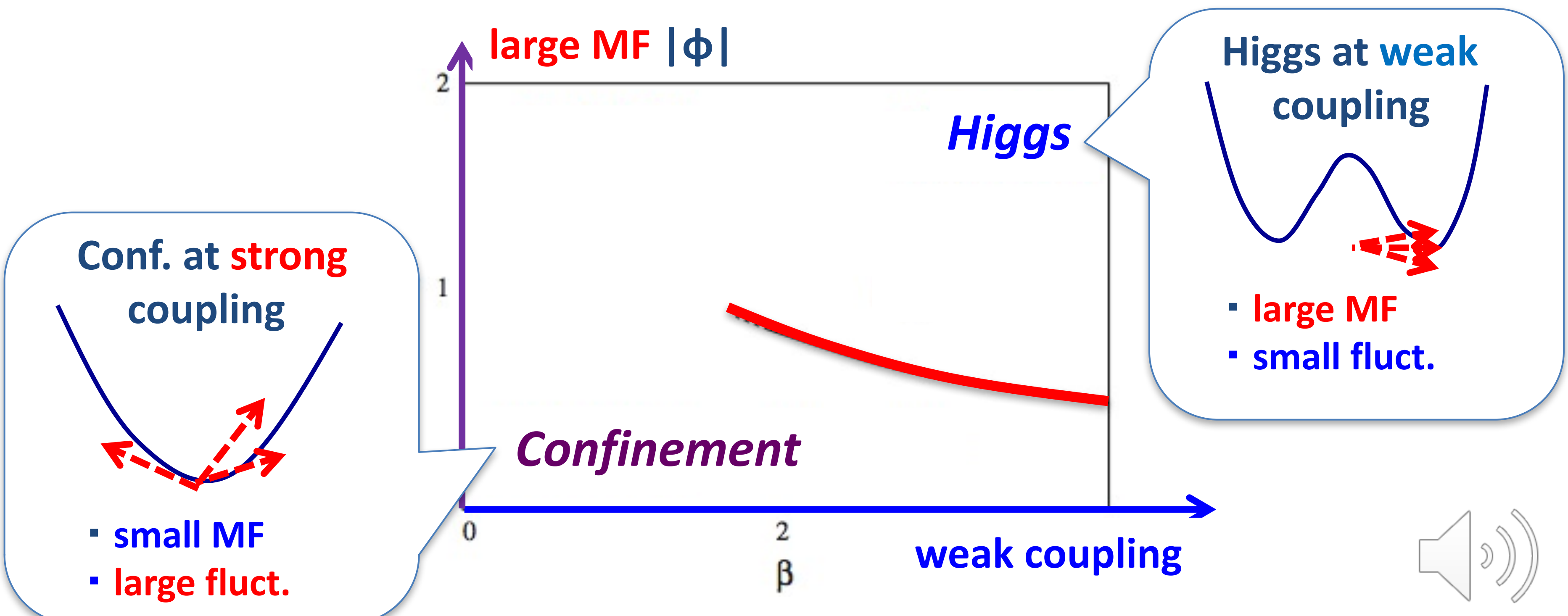

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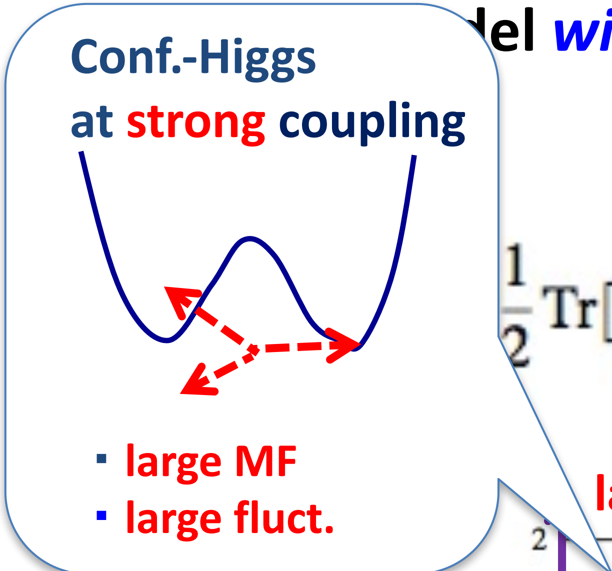
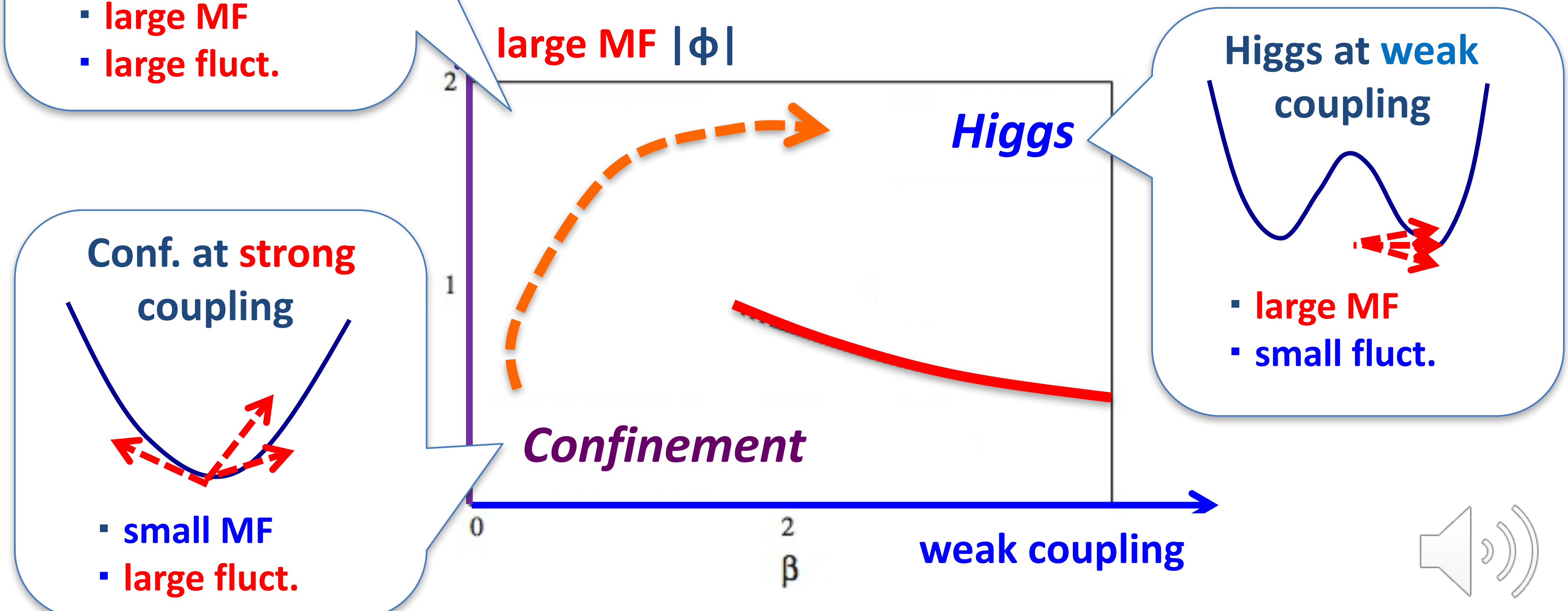
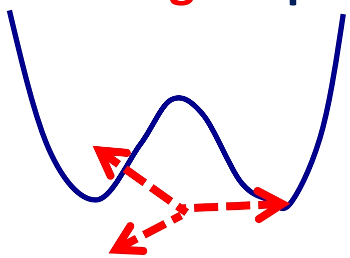




Crossover : gauge dynamics

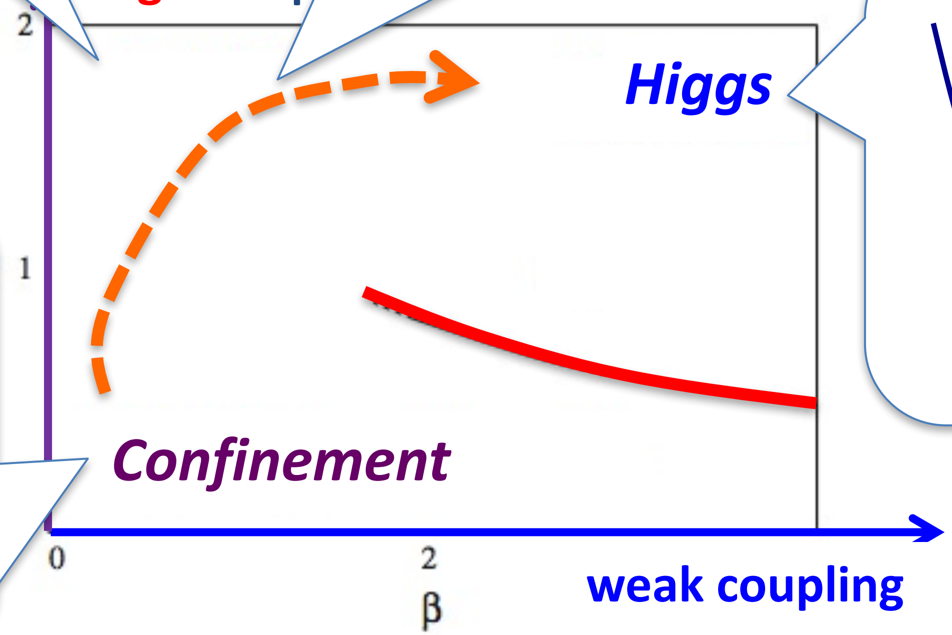
Conf.-Higgs at strong coupling



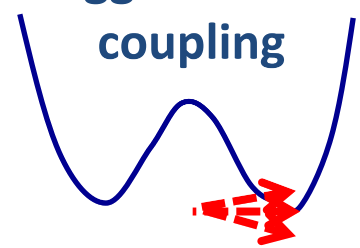
- large MF
- large fluct.

Conjecture:

To complete the hadron-quark continuity picture to the level of gauge dynamics, the strong coupling is necessary to bypass conf-Higgs transition at weak coupling.



Higgs at weak coupling



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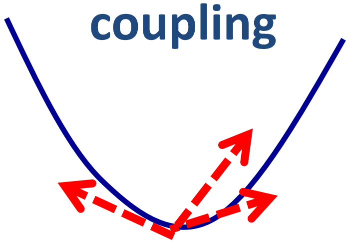
Conf. at strong coupling



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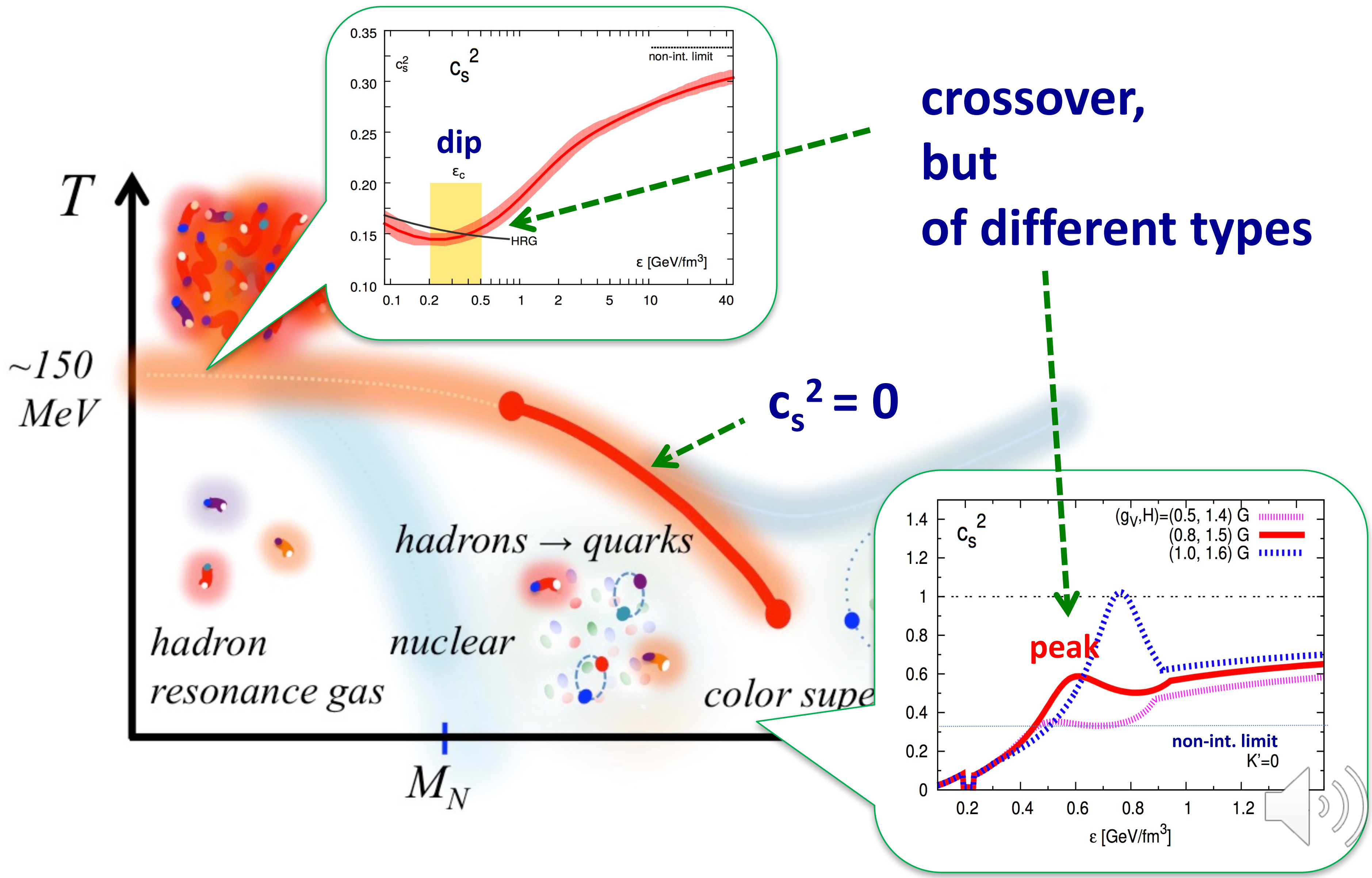
Speed of sound



Summary

- Small NS radii & $M_{max} \sim 2M_{sun}$ & causality

  → crossover or weak 1st order P.T. for hadron-quark transition

- Systematic uncertainties in radii estimates, but in near-future NICER and aLIGO will estimate R to 5-10% accuracy.

- Quark models inside hadrons may be extrapolated to 5-10n_0.

  intermediate-short range correlations (chiral & color-magnetic int.)

- Crossover in hot QCD and dense QCD are likely different:

  hot QCD: smooth, but rapid change from HRG to QGP picture

  dense QCD: smooth, strongly int. hadrons ~ strongly int. quarks

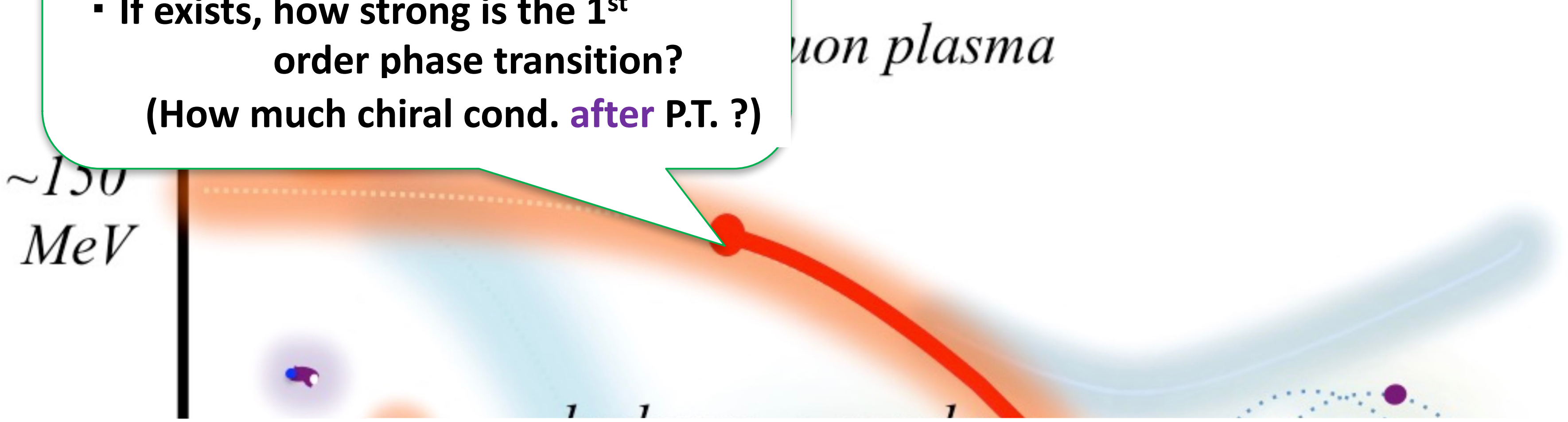
  "quark-hadron duality" or "quarkyonic" (quark matter with non-pert. gluons)

Back up

Questions relevant for continuity picture

RHIC, NICA, FAIR, J-PARC, …

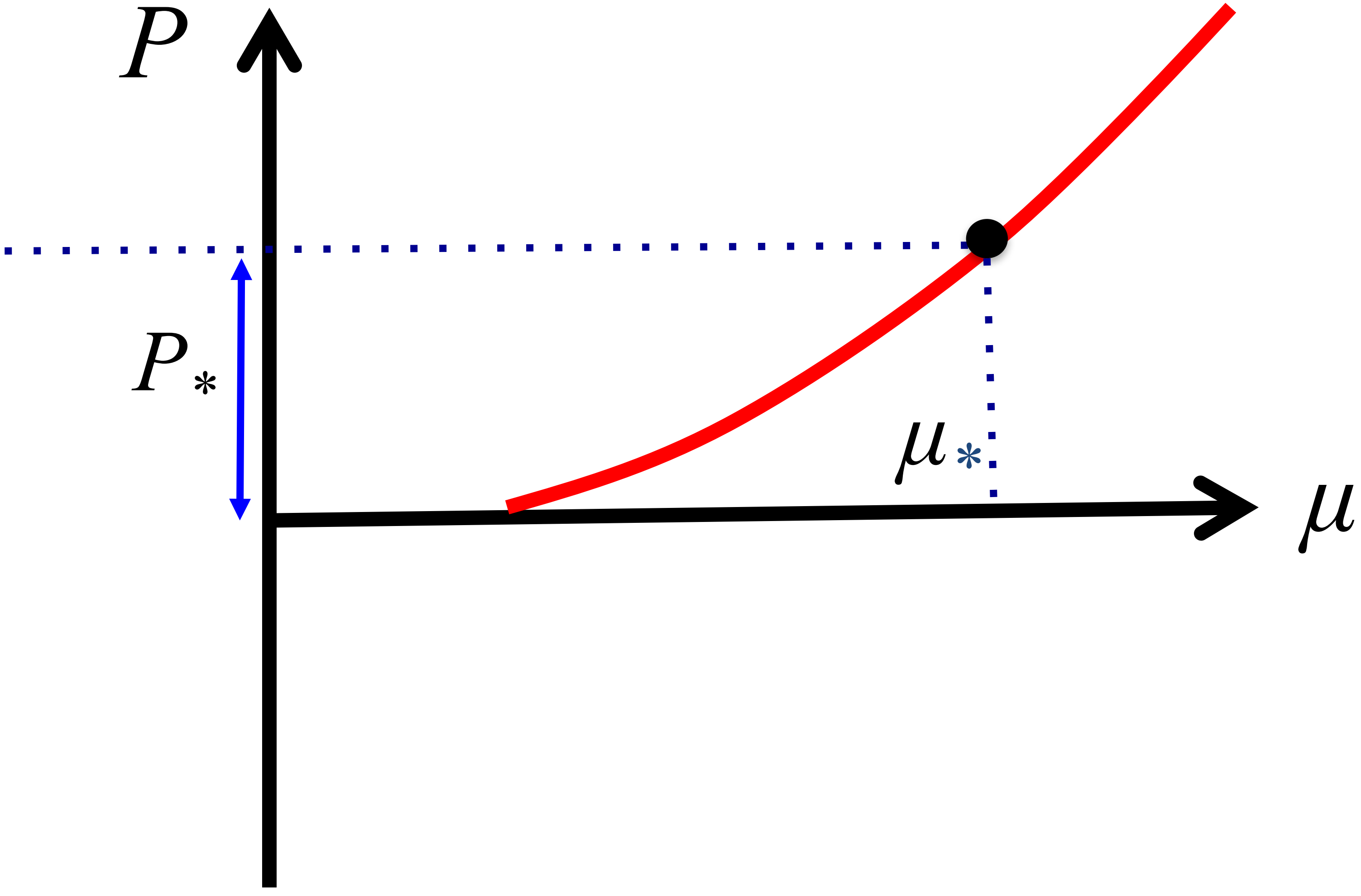
- **CEP exists or not?**
- **If exists, how strong is the 1st order phase transition?**
  (How much chiral cond. after P.T. ?)



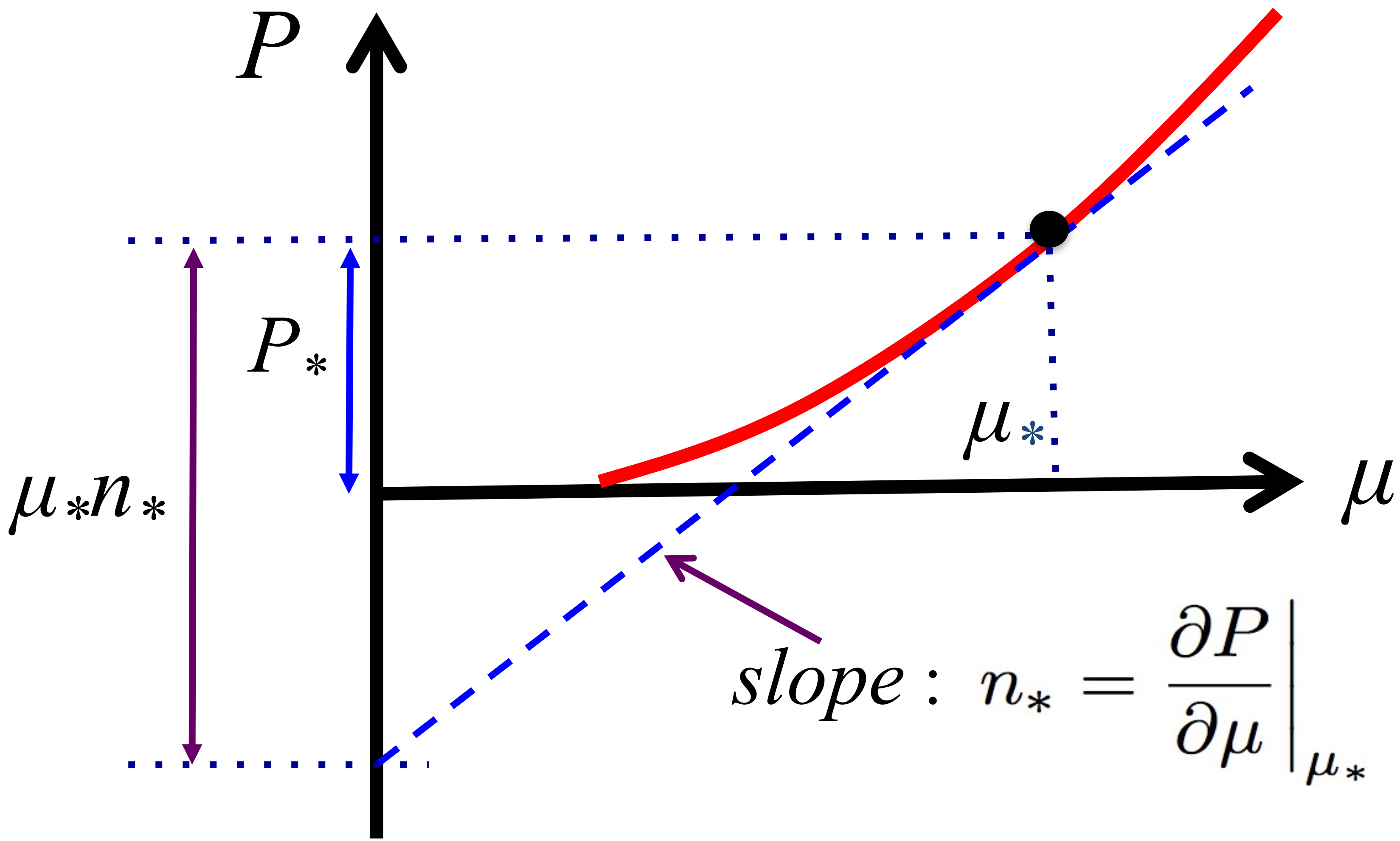
NICER, aLIGO, VIRGO,…

- **How large is NS radius?**

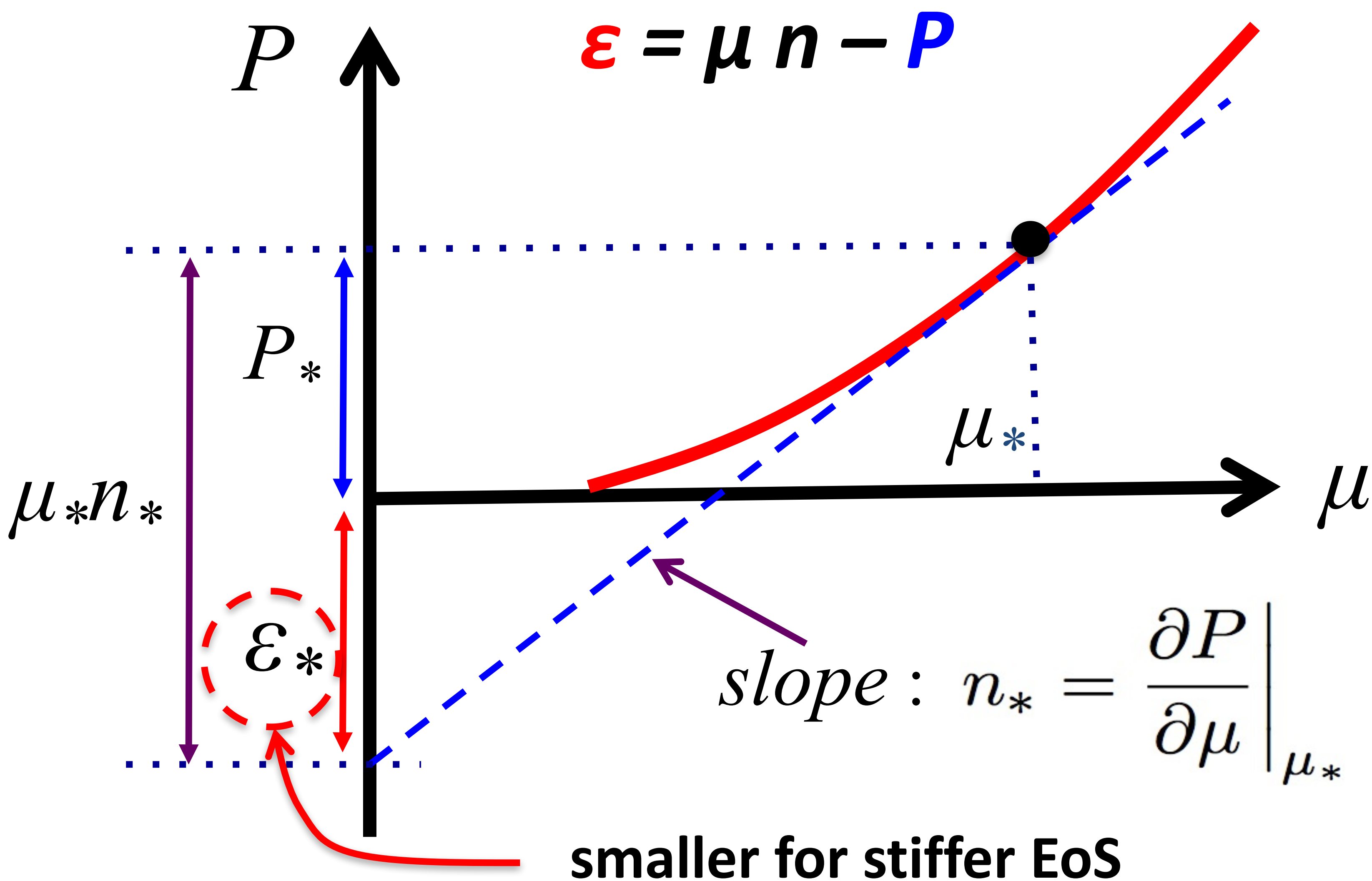
How stiff EoS looks like in P(μ) curves



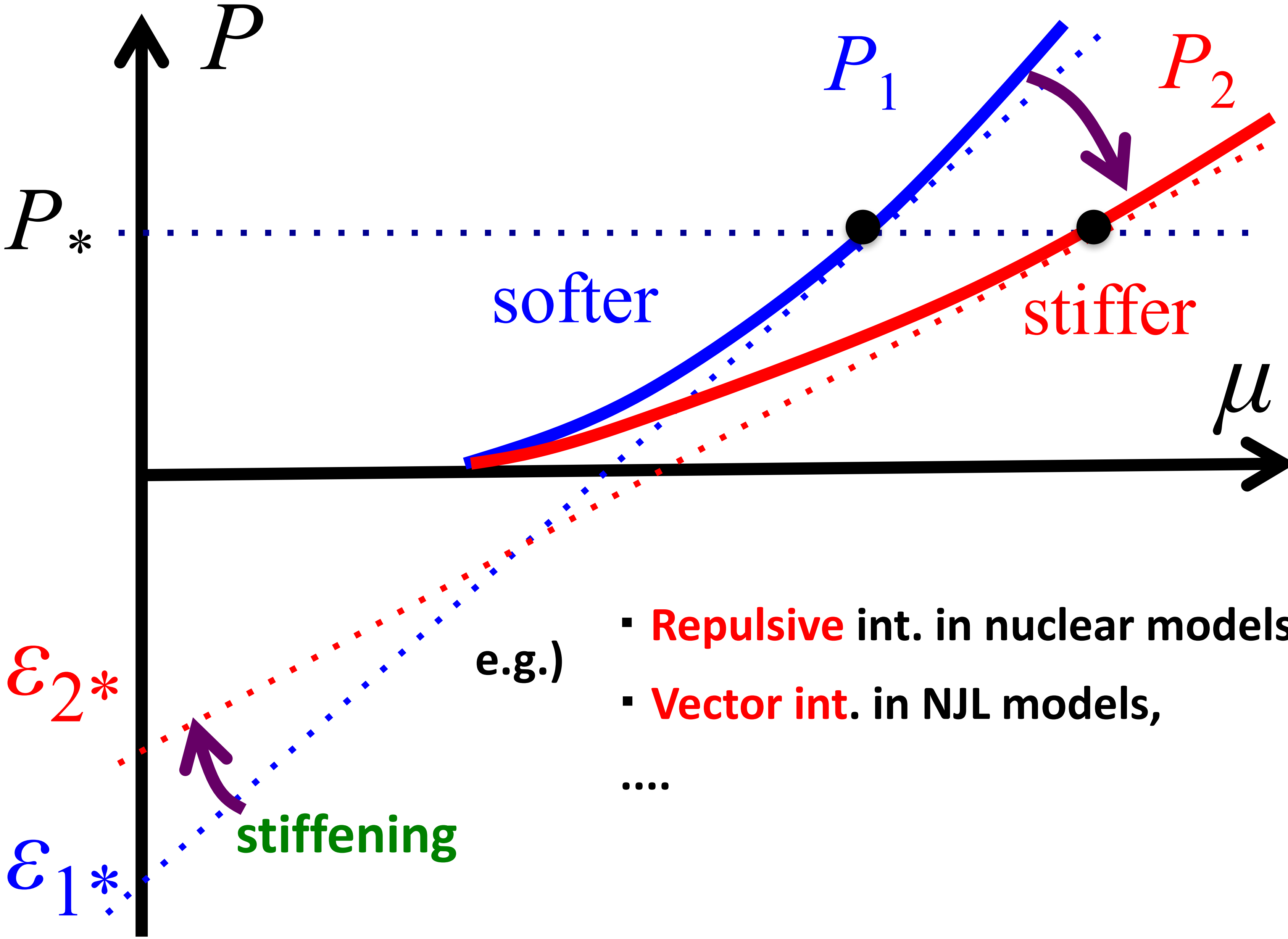
How stiff EoS looks like in P(μ) curves



How stiff EoS looks like in P(μ) curves



Example of stiffening 1

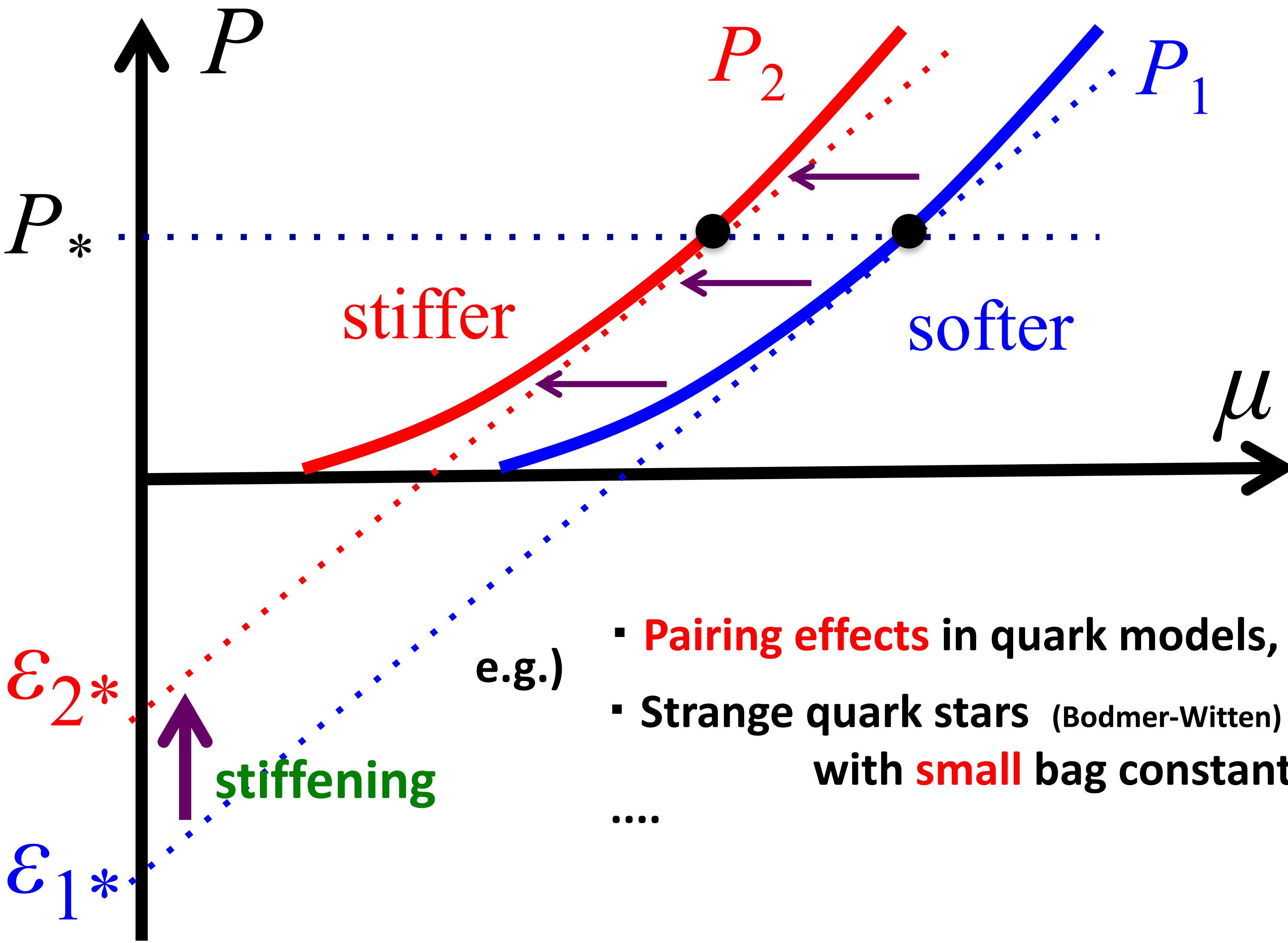


e.g.)

- **Repulsive int. in nuclear models,**
- **Vector int. in NJL models,**

....

Example of stiffening 2



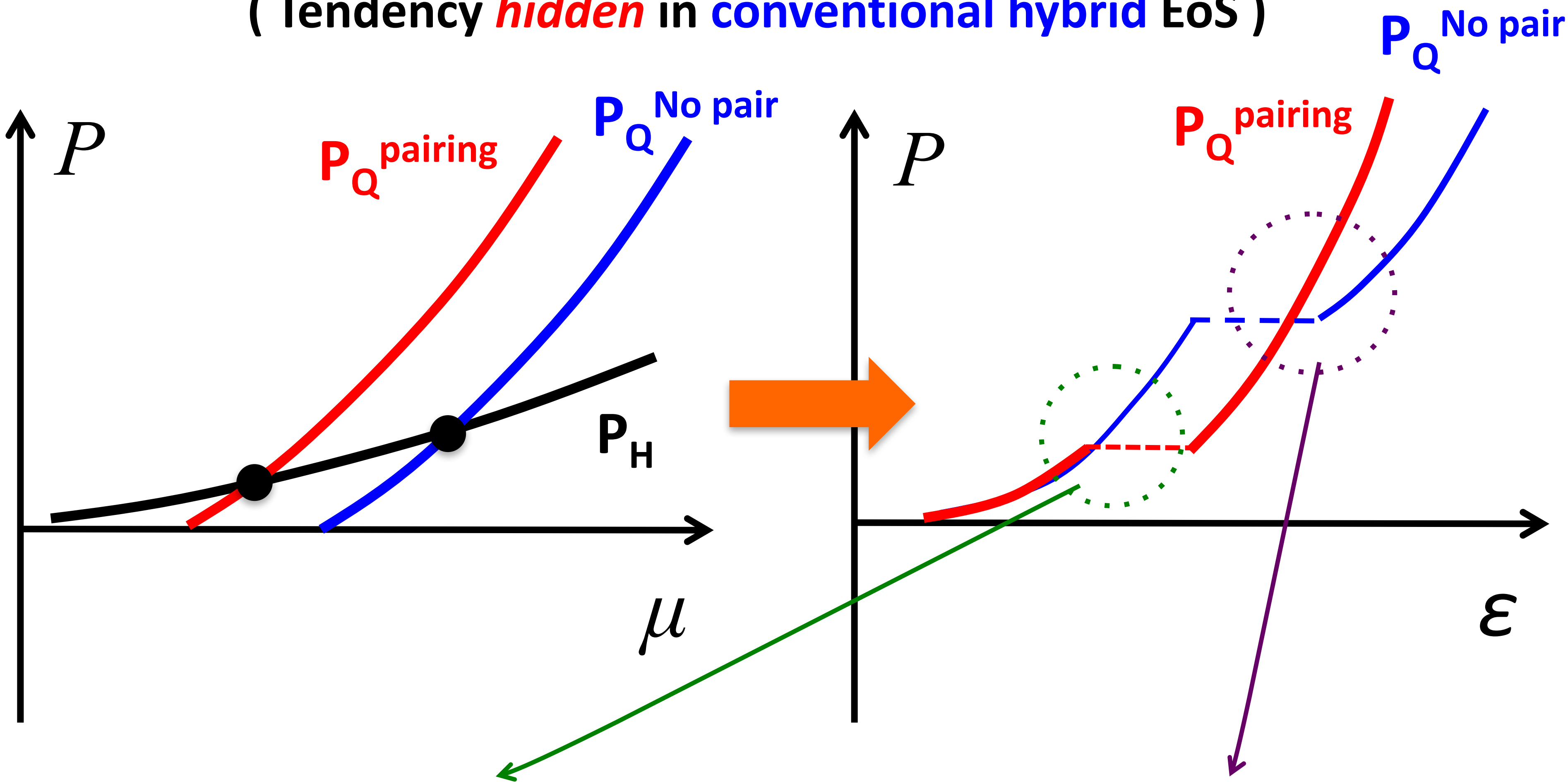
e.g.)

- **Pairing effects in quark models,**
- **Strange quark stars** (Bodmer-Witten) **with small bag constant,**

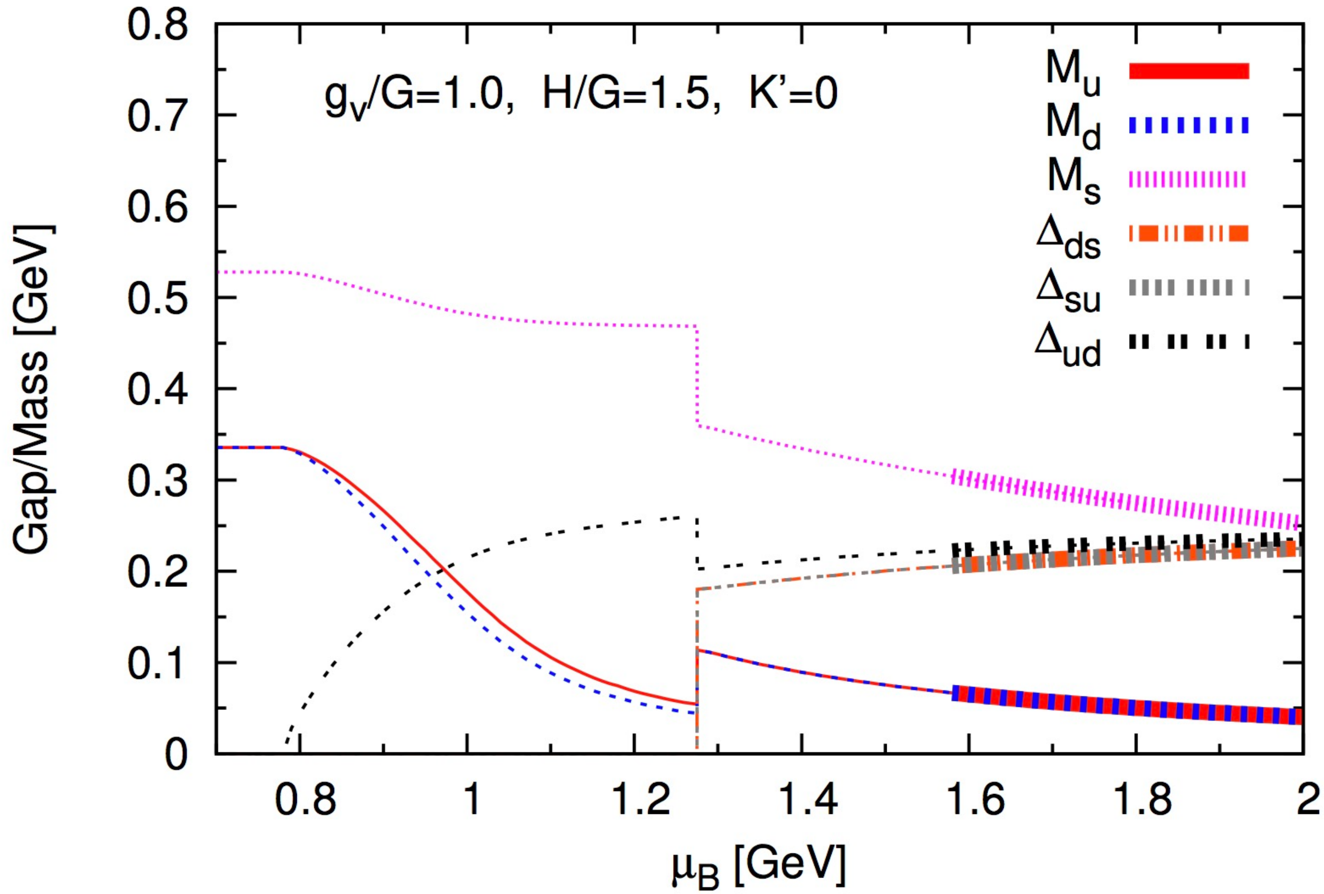
....

"Pairing" can stiffen EoS

(Tendency *hidden* in conventional hybrid EoS)



→ ***Softening*** **at *low* n_B & *stiffening* at *high* n_B**



0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.8
1
1.2
1.4
1.6
1.8
2
Gap/Mass [GeV]
μB [GeV]
gv/G=1.0, H/G=1.5, K'=0
Mu
Md
Ms
Δds
Δsu
Δud

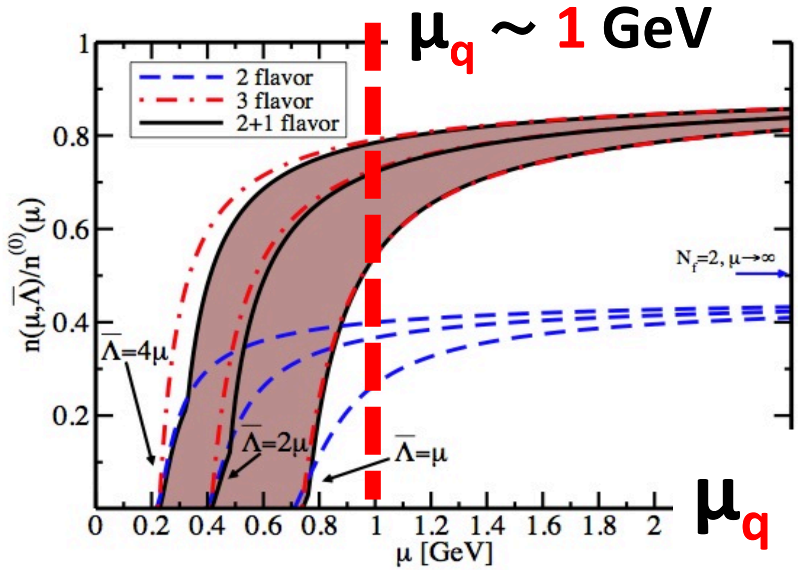
Theoretical guides at N_c=3

- 3-loop *pQCD at large μ_q*

  [Freedman-McLerran 78; Baluni 78
  Kurkela-Romatschke-Vuorinen 09, ...]

  - large α_s corrections at μ_q < 1 GeV

    → soft gluons important at n_B < 100 n_0



- *Nuclear calculations* (ChEFT+many-body) *at small μ_q*

  - reliable at $n_B \sim n_0$ [Akmal et al. (APR) 98; Gandolfi et al. 12, ...]

  - At n_B > 2n_0
    - *convergence* problems : $< V_{2\text{-body}} > \sim < V_{3\text{-body}} > \sim$ ...
    - *hyperon softening*, unless introducing ad hoc repulsion
    - *changes in hadron w.f. & Dirac sea negligible?*

Nuclear EoS : convergence ?

Many-body interaction (APR-A18+UIX case)

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. $\langle V^{R}_{ijk} \rangle$	4 –body int. (our guess)
n_0	−4.1	−29.9	1.2	4.5	small
$2\, n_0$	−25.1	−36.4	−17.4	30.6	marginal
$3\, n_0$	−35.7	−44.7	−34.1	78.0	large
$4\, n_0$	−52.2	−41.1	−76.9	160.3	large

grow rapidly !!

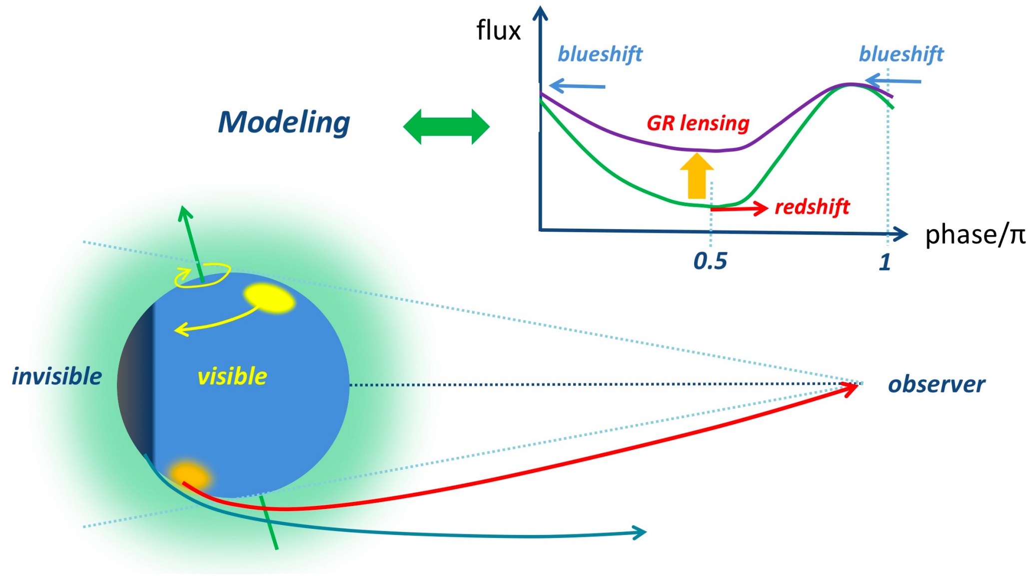
$$\langle V_{N\text{-body}} \rangle \sim c_N \,(n_B / n_0)^N$$

Near future NS radius measurements

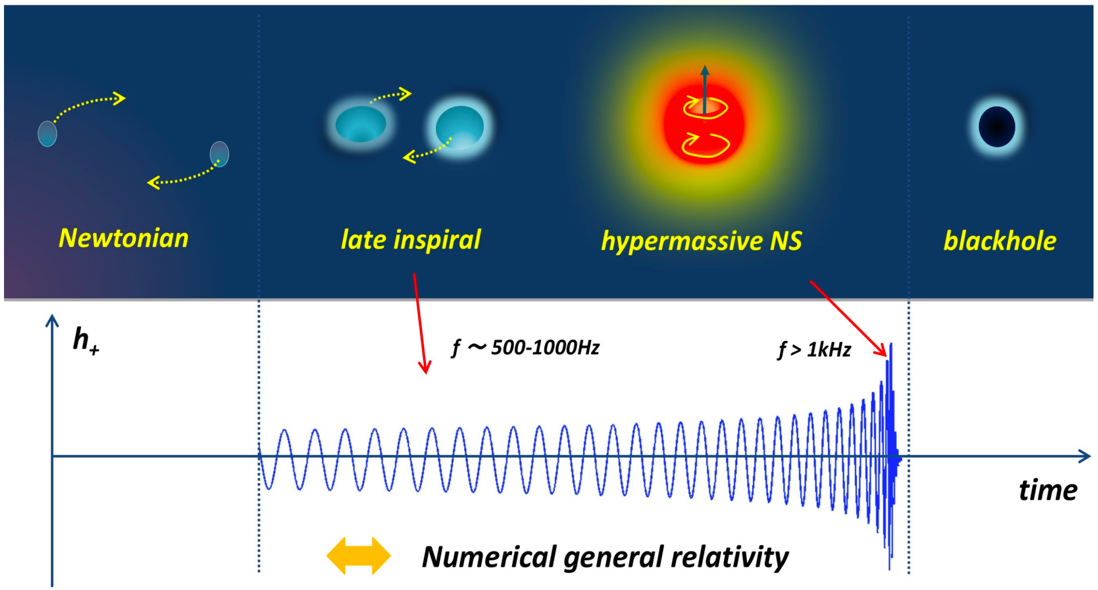
- **NICER (2017~) :**

  timing analyses of hot spots

  R & M/R → 5-10 % accuracy



- **aLIGO (2015~)** : *GWs from NS-NS mergers*



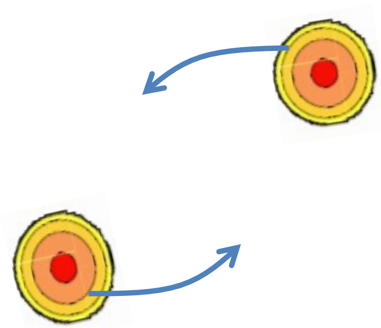
tidal deformation of stars

R & M/R → 5-10 % accuracy

GW from NS-NS mergers

(0.1-10 (?) events / year)

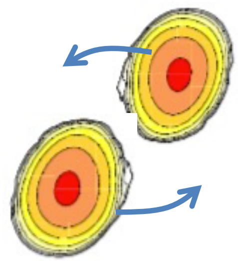
Early inspiral



→ *M_1 & M_2*

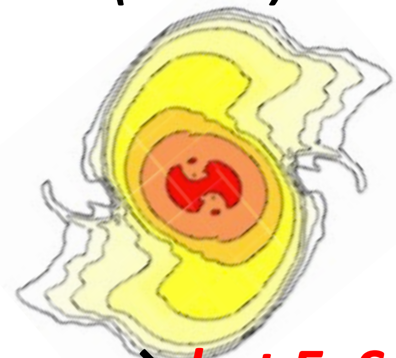
spins

Tidally deformed phase



→ *R* *(deformability & compactness)*

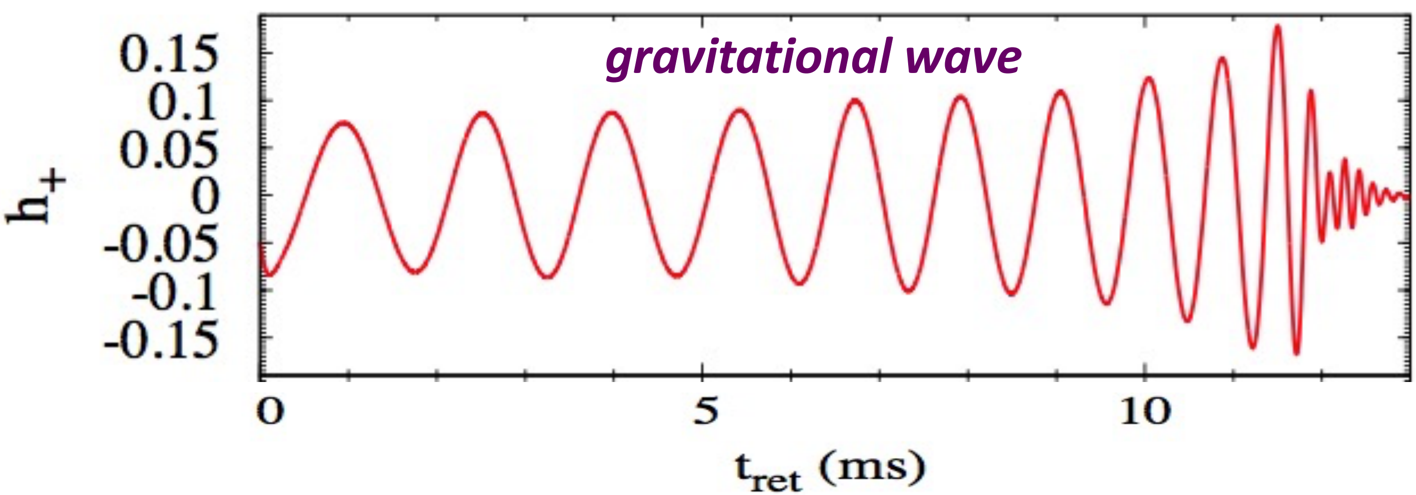
Hyper Massive NS (HMNS)



→ *hot EoS, etc.*

BH

(aLIGO, VIRGO, ...)

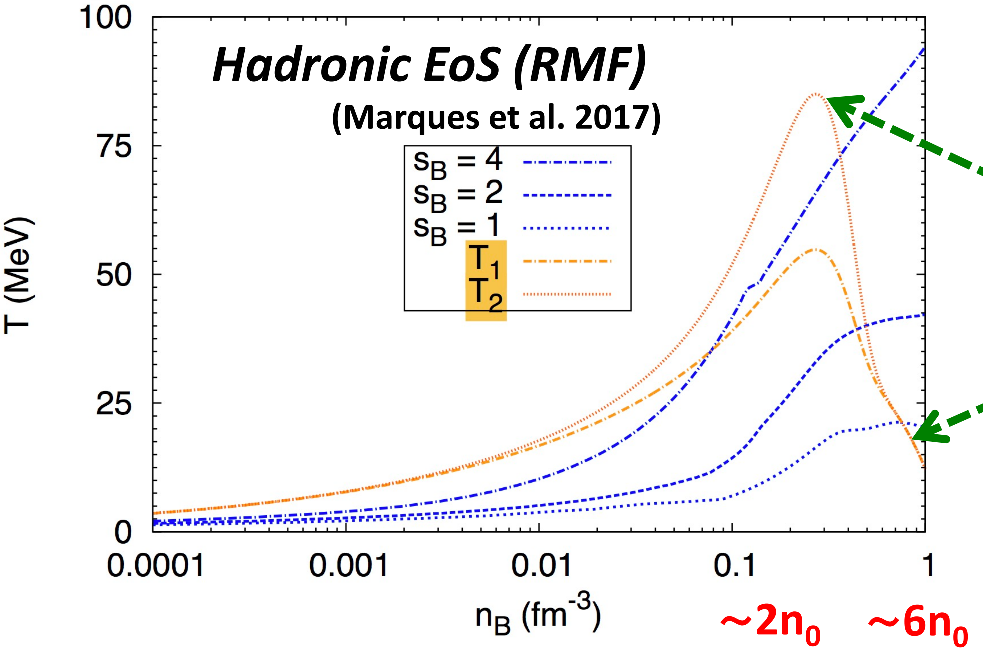


Hyper massive NS (HMNS)

Differential rotation & *thermal pressure*

→ stars of $2\text{-}3M_{sun}$ can survive for ~10ms

Which density region is hot?



For typical hadronic EoS coupled to GR simulations :

T = 30-100 MeV at $n_B \sim 2n_0$

T = 10-20 MeV at $n_B \sim 5n_0$

NOTE: profiles depends on *EoS*

Hot EoS for *post mergers*

- Almost all GR simulations use hot *nuclear* EoS

[Shen-EoS (Shen et al.), SLy EoS (Lattimer-Swetsy), ...]

- *Hot quark* matter EoS (for $n_B > 5n_0$)

Normal **quark matter**

- *pQCD EoS* (gapless quarks & gapped gluons) [Kurkela-Vuorinen '16]
- *3-window EoS* (gapless quarks) [Masuda-Hatsuda-Takatsuka '15]
- *...*

gapless quarks → $\Delta P(T) \sim p_F^2\, T^2$ (>> T^4)

This work → *Gapped* **quark matter,** ***Color-Flavor-Locked*** **(CFL)**

For T < Δ ; $\Delta P(T) \sim T^4 + \ldots$

neutrinos, photons, NG modes

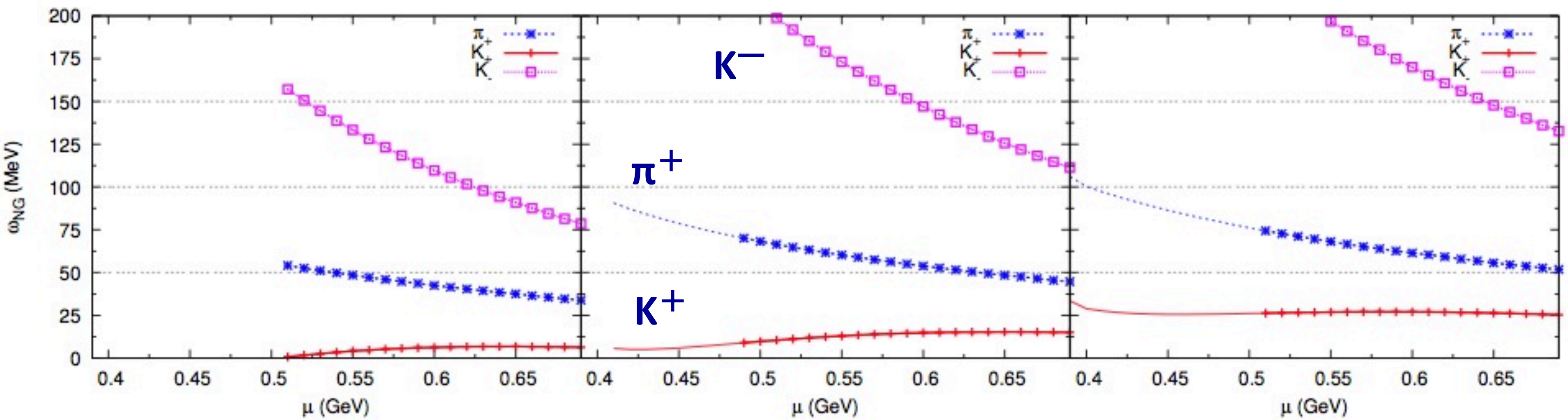
NG mode contributions (CFL color-super phase)

[Son-Stephanov 2000, Bedaque-Schafer 2002, ...]

- **setup consistent with T=0 NS descriptions**
  - explicit sym. breaking, mass & $U_A(1)$
  - neutrality conditions
  - coexistence of chiral and diquark condensates
  - keep "pa", "pp", "aa" contributions to be consistent with gap eq.

- **spectra in RPA (results consistent with EFT)** [Basler-Buballa '10, TK16]

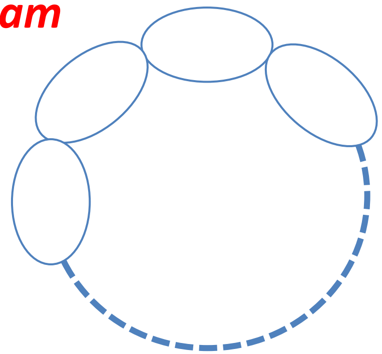
weak coupling ← ***setup for NS constraints*** **→ strong coupling**



most NG modes > 50 MeV; light K; more massive at stronger coupling

Thermodynamics (beyond low T regime)

Ring diagram



connected Green's function

NG bosons (bound states)

pre-formed pairs (p-a, p-p, a-a pairs)

decaying pairs (continuum)

very important to keep (see below)

The phase shift rep. of thermodynamic-potential :

[Beth-Uhlenbeck1939, Dashen-Ma-Bernstein 1969]

$$\Omega_X(T,\mu) = \int \frac{\mathrm{d}\vec{q}}{(2\pi)^3} \int \frac{\mathrm{d}\omega}{2\pi} \left[\omega + T\ln\left(1 - \mathrm{e}^{-\frac{\omega-\mu_X}{T}}\right) + T\ln\left(1 - \mathrm{e}^{-\frac{\omega+\mu_X}{T}}\right)\right] \frac{\partial \delta_X(\omega,\vec{q})}{\partial \omega}$$

$$\mathcal{G}/\mathcal{G}_0 = |\mathcal{G}/\mathcal{G}_0|\, \mathrm{e}^{\mathrm{i}\delta(\omega,\vec{q})}$$

full/free Green's function

phase shift

Constraint: Levinson's theorem

$$\mathcal{G}/\mathcal{G}_0 = |\mathcal{G}/\mathcal{G}_0|\, \mathrm{e}^{\underline{\mathrm{i}\delta(\omega,\vec{q})}}$$

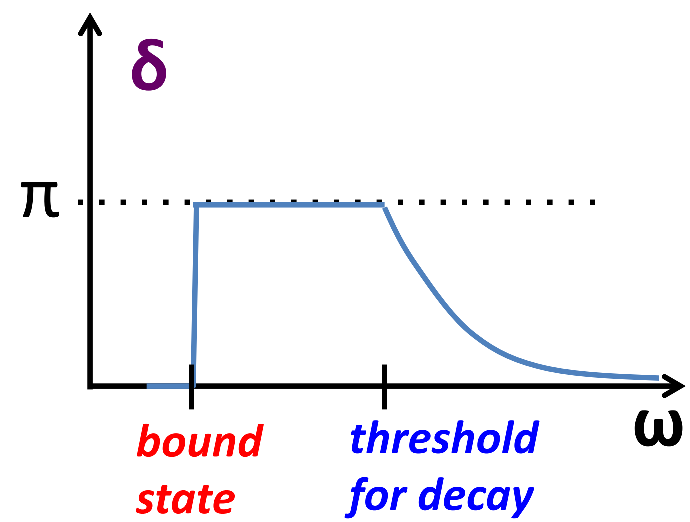
Meaning: Total num. of states does not change by interactions

$$0 = \int_0^\infty \mathrm{d}E\, \mathrm{Tr}\left[\mathrm{Im}\mathcal{G} - \mathrm{Im}\mathcal{G}_0\right]$$

$$= \int_0^\infty \mathrm{d}E\, \partial_E \mathrm{Tr}\left[\mathrm{Im}\ln \mathcal{G}^{-1}/\mathcal{G}_0^{-1}\right]$$

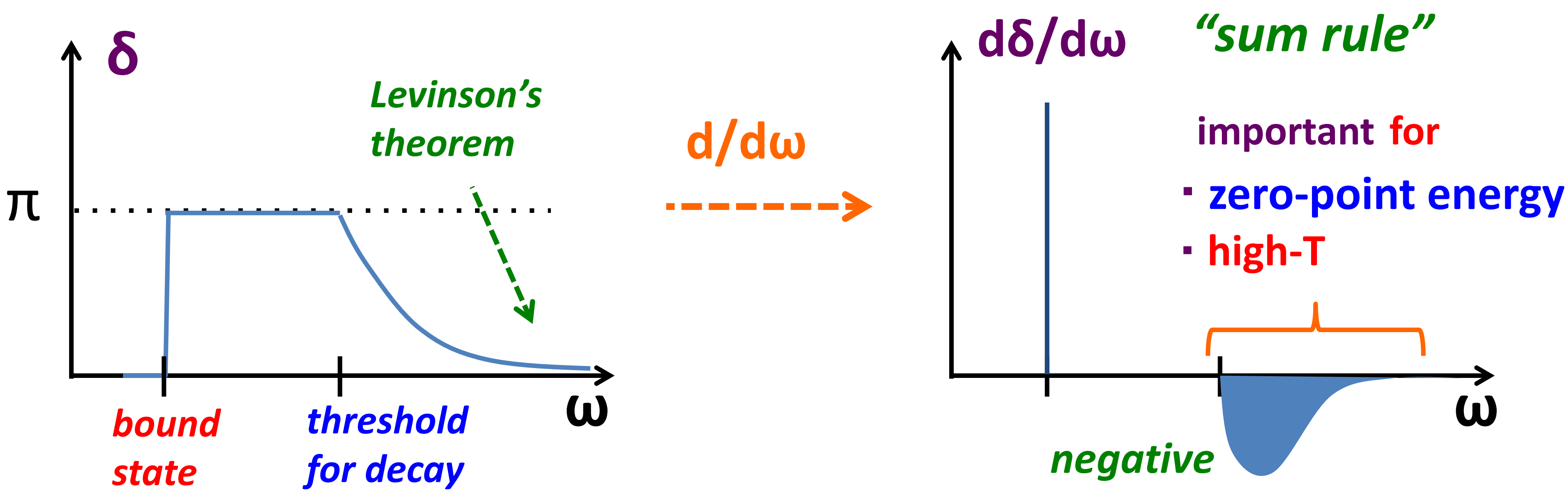
$$= -\mathrm{Tr}\left[\delta(\infty) - \delta(0)\right]$$

invariant



Phase shifts & Levinson's theorem

$$\Omega_X(T,\mu) = \int \frac{d\vec{q}}{(2\pi)^3} \int \frac{d\omega}{2\pi} \left[\omega + T \ln\left(1 - e^{-\frac{\omega-\mu_X}{T}}\right) + T \ln\left(1 - e^{-\frac{\omega+\mu_X}{T}}\right)\right] \frac{\partial \delta_X(\omega,\vec{q})}{\partial \omega}$$

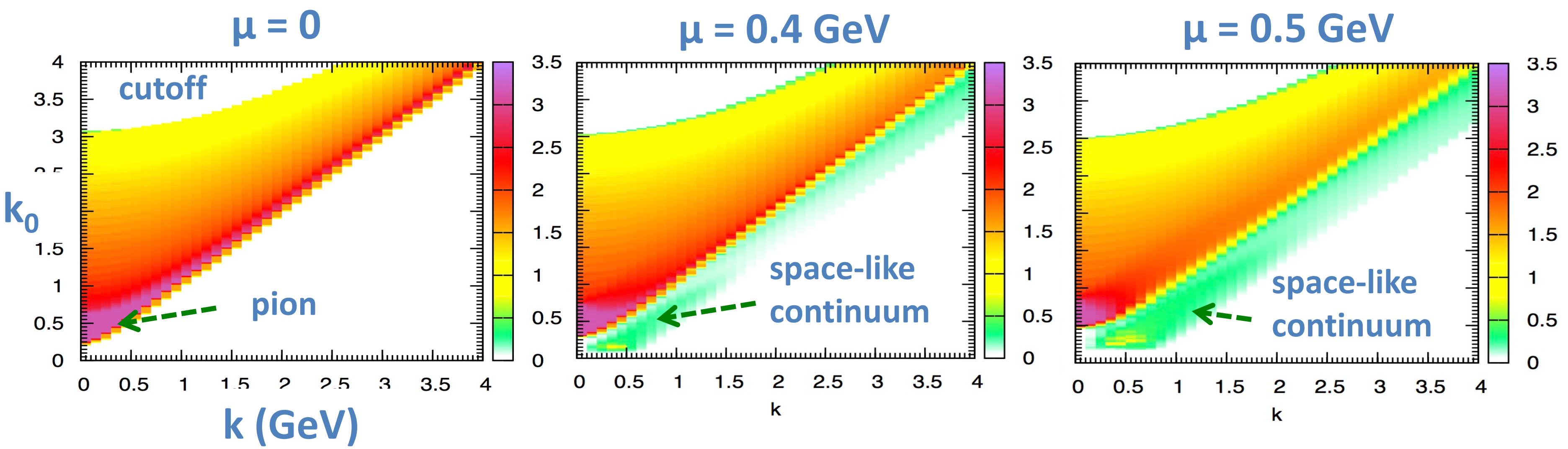


origin: $\mathcal{G}^{\text{conn.}} = \mathcal{G}^{\text{full}} - \mathcal{G}_0$

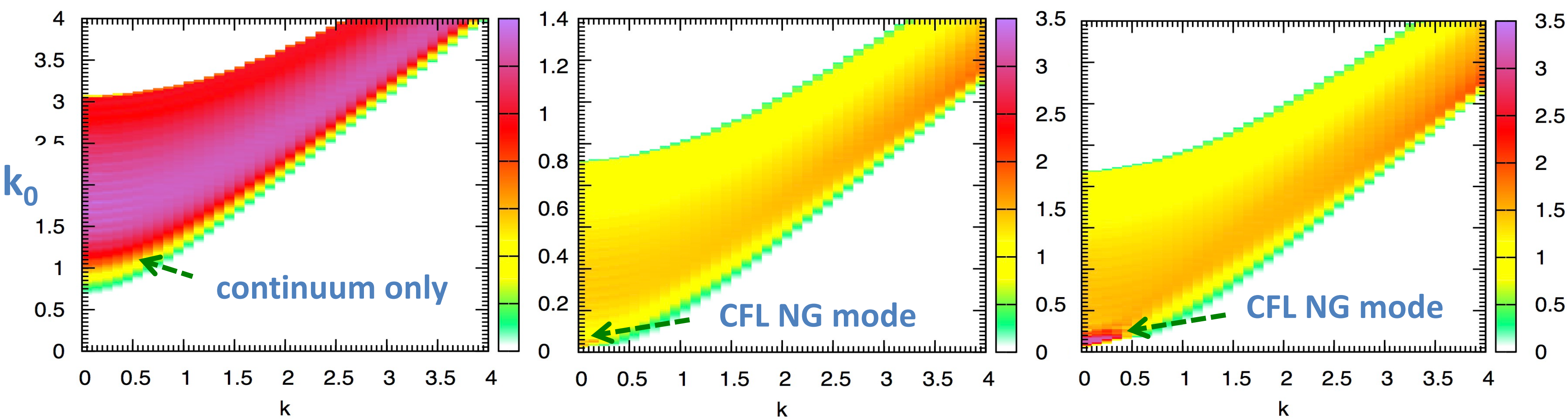
Pressure from low E and high E cancel one another;
taming a meson (diquark) gas at high T

Phase shift $\delta(k_0, k)$: e.g. π-channel

particle-hole, particle-antiparticle

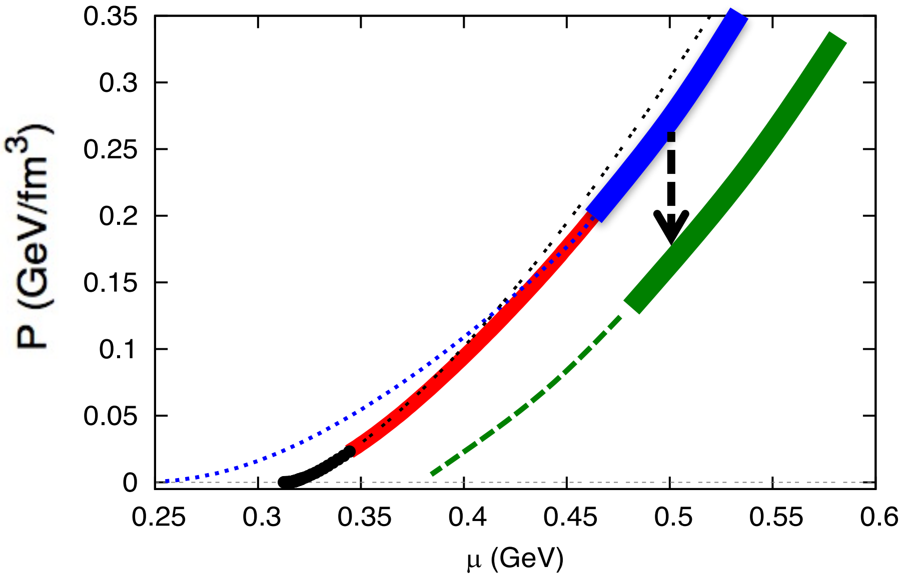


particle-particle, hole-hole



Discussion : Bag constant ?

P_{NJL} @ 5 n_0 → only 200 - 400 MeV fm^{-3}



If $B_g \sim \Lambda_{QCD}{}^4$ *appears @* $5n_0$

EoS → impossible to pass any constraints

Together with $G_V \sim H \sim G_s^{vac}$ **, we claim :**

Gluons *should remain non-perturbative* to $n_B \sim$ 5-10 n_0

Discussion : Bag constant ?

Def: $\mathcal{B} \equiv \epsilon^{vac}_{pert} - \epsilon^{vac}_{full} \sim \Lambda^4_{\rm QCD}$ **> 0**

- **Energy *gain* by *non-pert. effects* ;**

  e.g.) ChSB in Dirac sea, gluon condensation, ...

If μ is large enough :

(softening)

- **Loss of *non-pert. effects* →** $\begin{cases} \epsilon_{\rm matter} \rightarrow \epsilon_{\rm matter} + \mathcal{B} \\ P_{\rm matter} \rightarrow P_{\rm matter} - \mathcal{B} \end{cases}$

- **NJL takes into account the *vac. contributions* *only partially* ;**

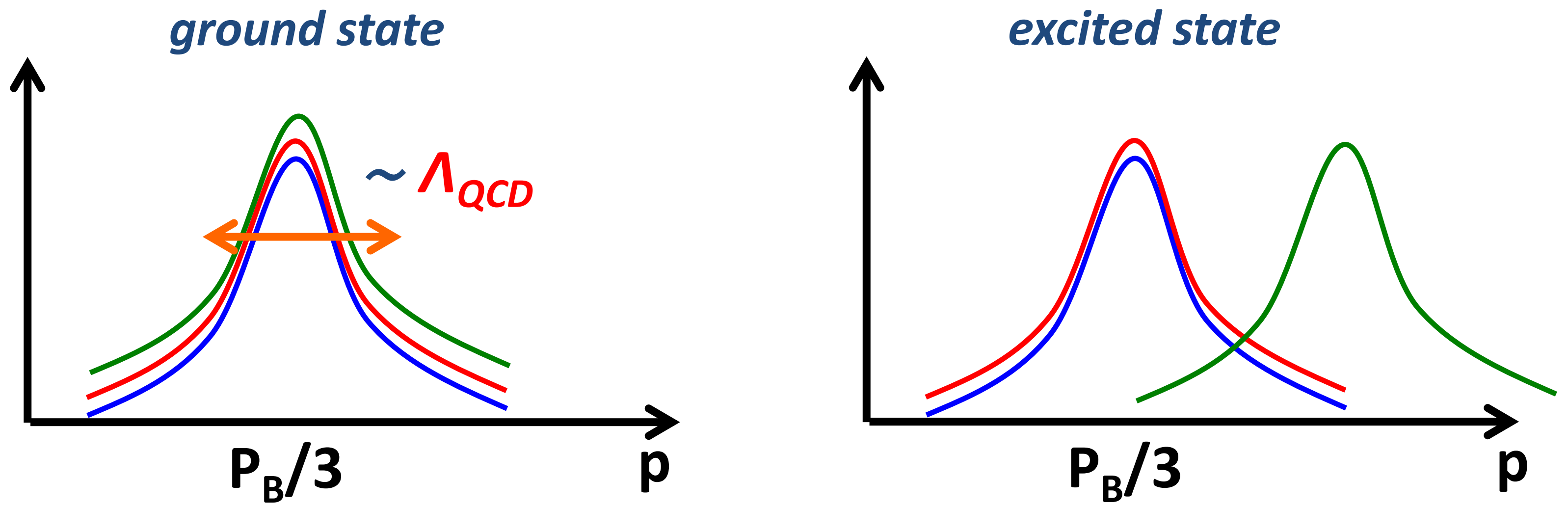
  it *misses* contributions from *gluonic* one, B_g

Discussion 3: Hyperon problems ?

How did we avoid hyperon softening ?

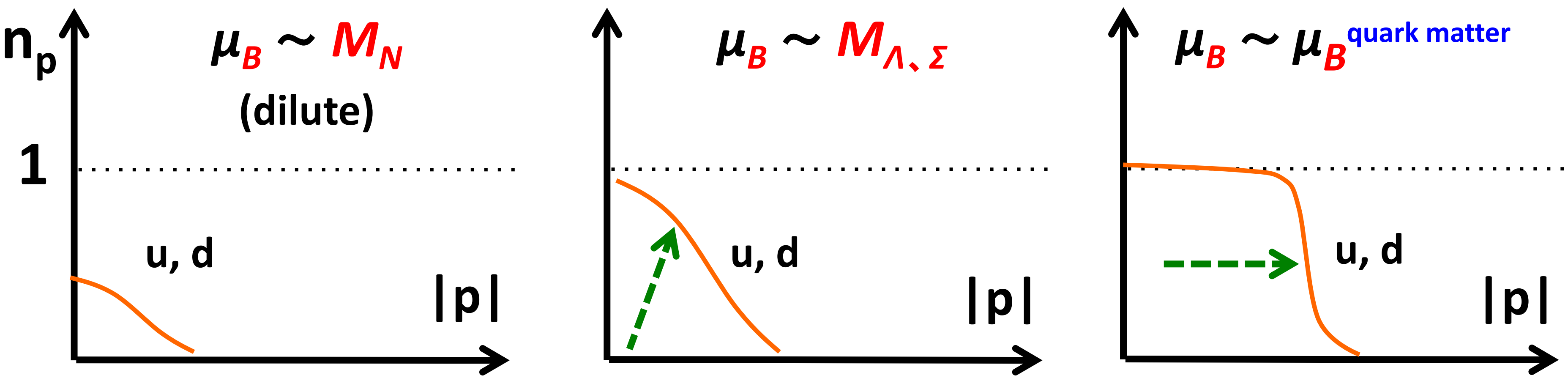
- μ_B^{th} for strangeness :
  - $\mu_B \sim 3M_s \sim$ 1.5 GeV (quark picture)
  - $\mu_B \sim \mu_\Lambda, \mu_\Sigma \sim$ 1.1-1.2 GeV (hadron picture)
    (uds, uus,...)

- *A quark w.f. for a baryon* (e.g. Isgur-Kahl)



Discussion 3: Hyperon problems ?

- Quark descriptions of hadronic matter :



How to put hyperons ??

- $M_{\Lambda、\Sigma}$ at *low P* is *rejected* by quark Pauli blocking on (u,d)
- $M_{\Lambda、\Sigma}$ at *high P* avoid the blocking, but *is energetic*

[Note: this argument becomes *more powerful* at *higher* n_B]

Several ***branches***

- **Confined, *but chiral symmetric* matter** (many papers ...)
  - **have been *challenged* by many model calculations** [Glozman et al. 2007, ...]

- **Confined, *inhomogeneous* chiral *SSB*** (still ongoing ...)

  (*chiral sym. broken only locally*)
  - **Skyrme crystals, ...**
  - **Chiral density wave (1-D periodic structure)** [Carignano-Nickel-Bubbala]
  - **Quarkyonic Chiral Spirals**
  - **Interweaving Chiral Spirals**

  } [TK-Hidaka-Fukushima -McLerran-Pisarski-Tsvelik 09-11]

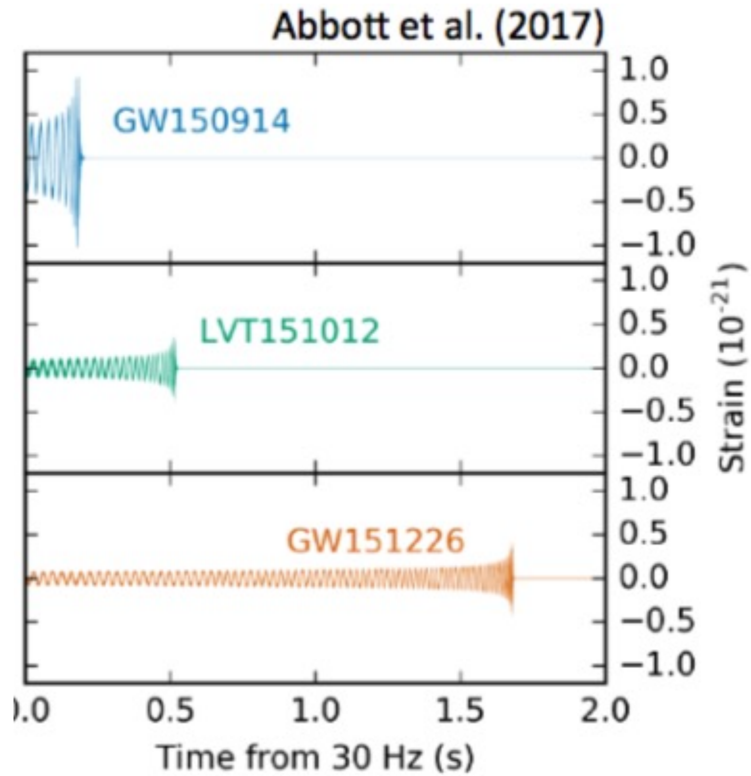
- **Reinterpretation of *Hadron-Quark Continuity***
  - **Original proposal : Schafer-Wilczek**
  - **CSC in quarkyonic matter & NS context** [Fukushima-TK '15]

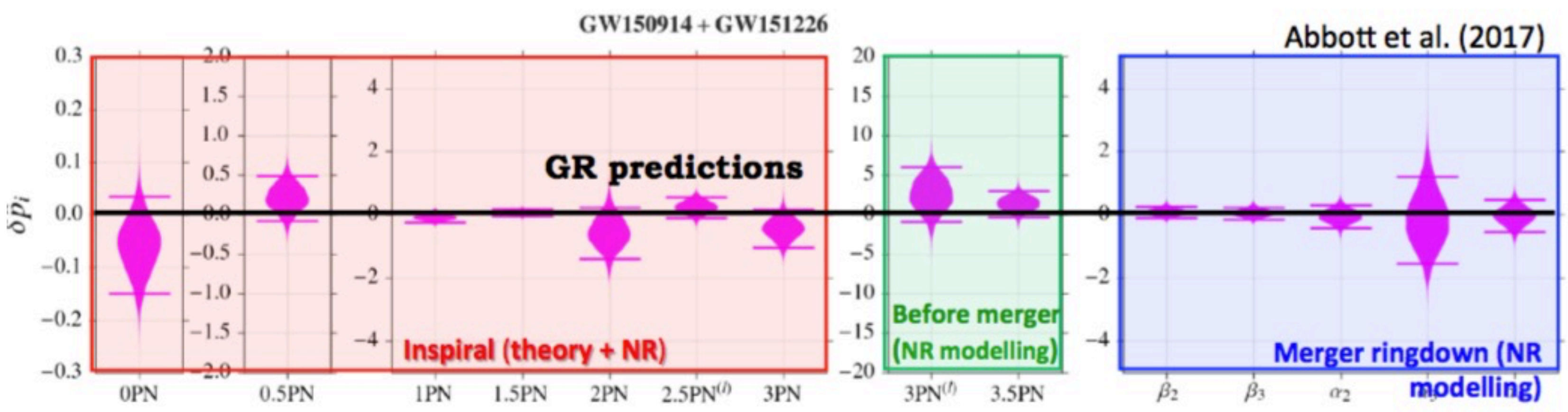
GW159014 : the discovery of GWs

***BH-BH** mergers*

→ larger amplitudes

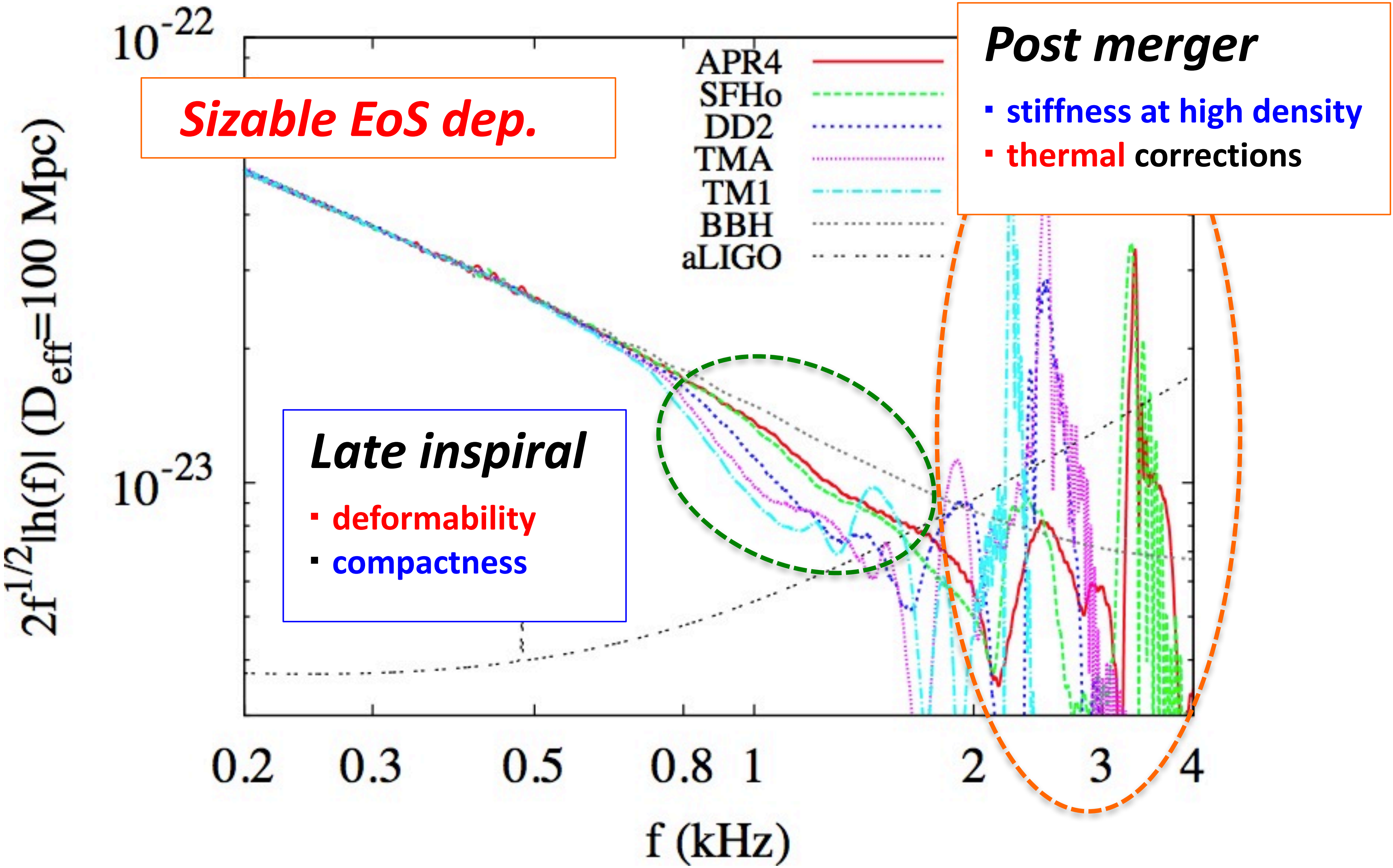
The wave patterns:
consistent with
the general relativity
*in **strong field regimes***

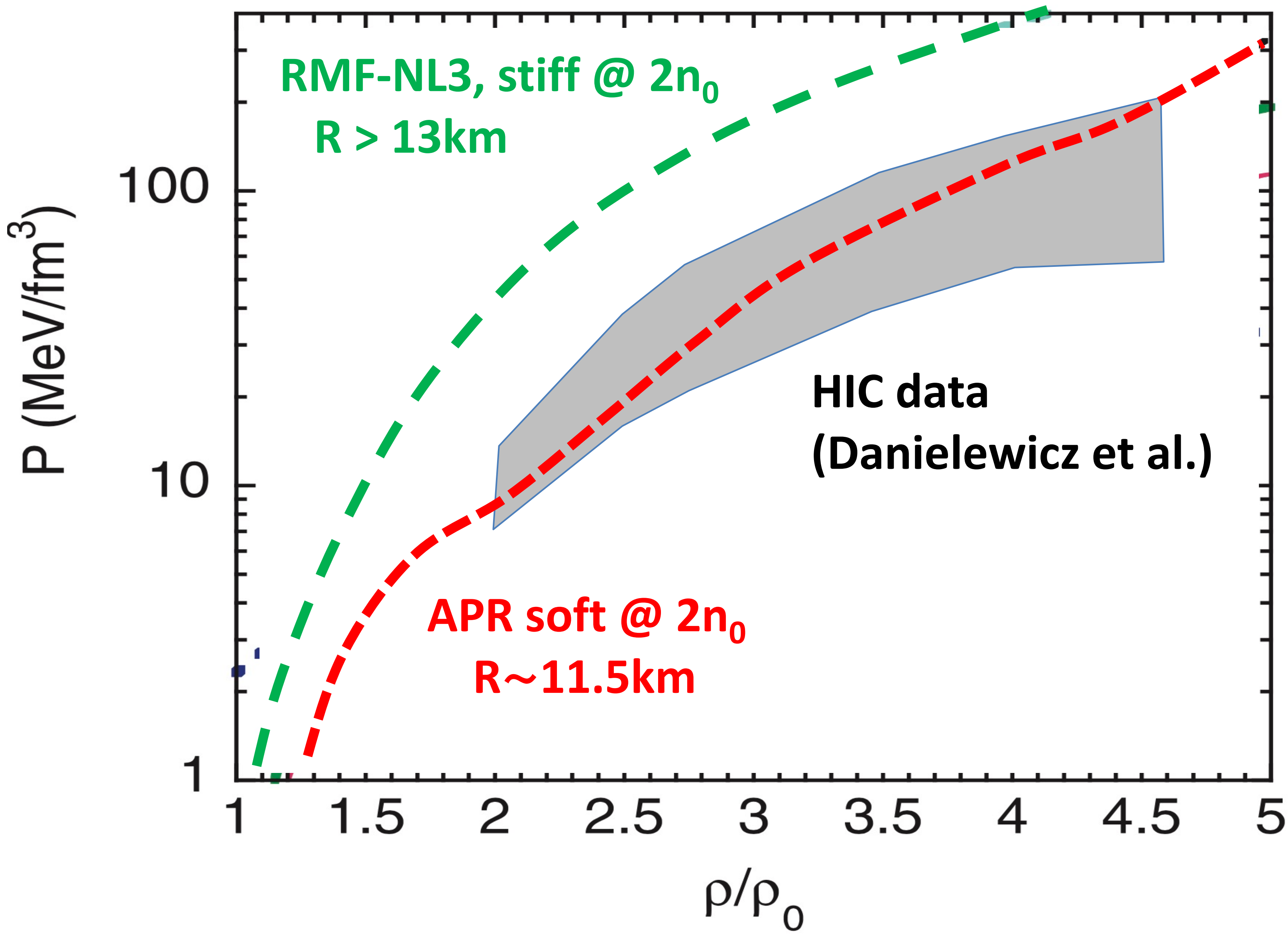




Frequency spectrum

GR simulations, Hotokezaka et al. 2016




RMF-NL3, stiff @ 2n0
R > 13km
HIC data
(Danielewicz et al.)
APR soft @ 2n0
R~11.5km
P (MeV/fm3)
ρ/ρ0
1
10
100
1
1.5
2
2.5
3
3.5
4
4.5
5