Institute of High Energy Physics
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New possibilities for quark matter and compact stars

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Quarks and Compact Stars @YZU, 2023

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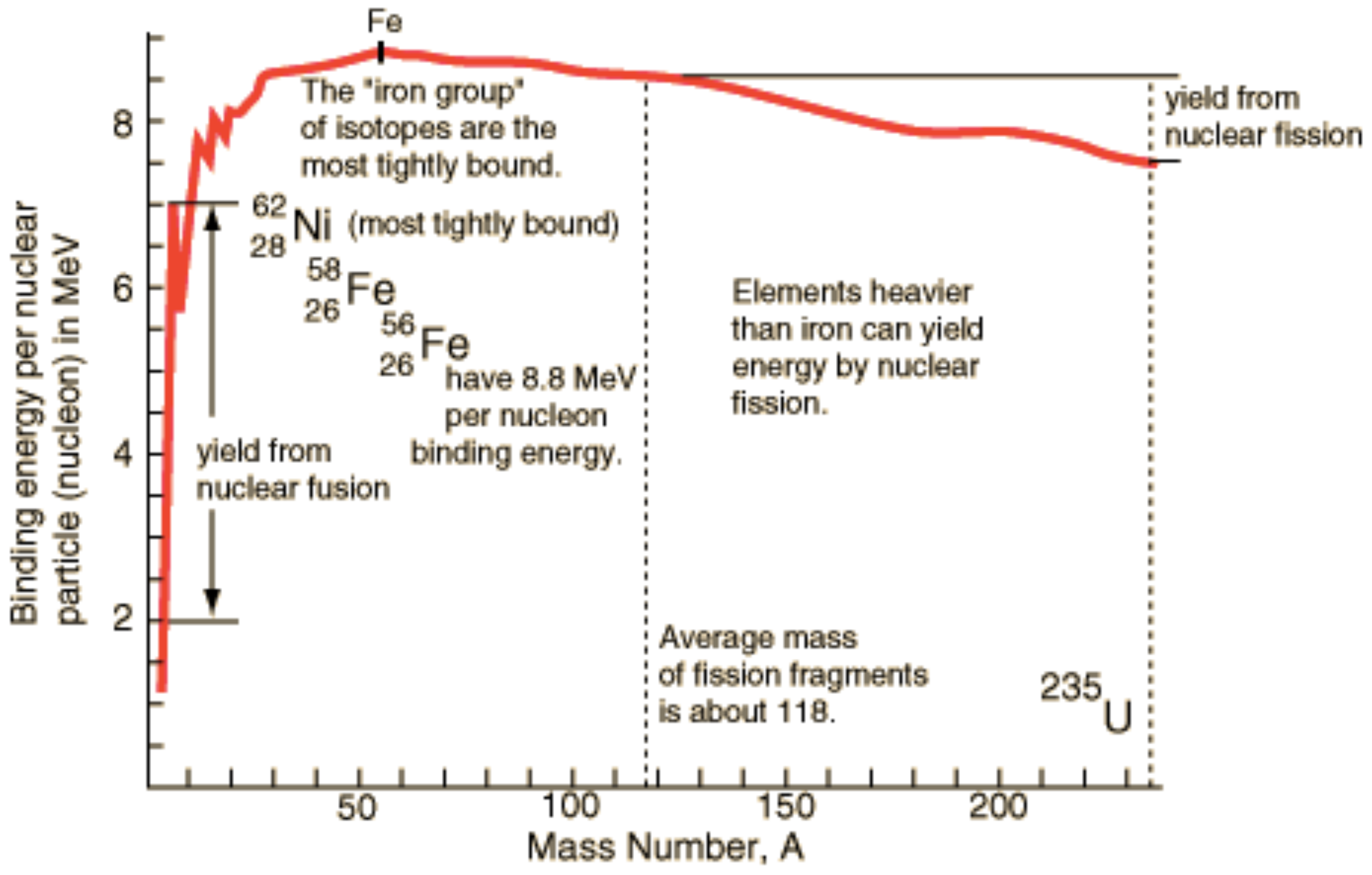
Based on collaboration with Bob Holdom and Chen Zhang

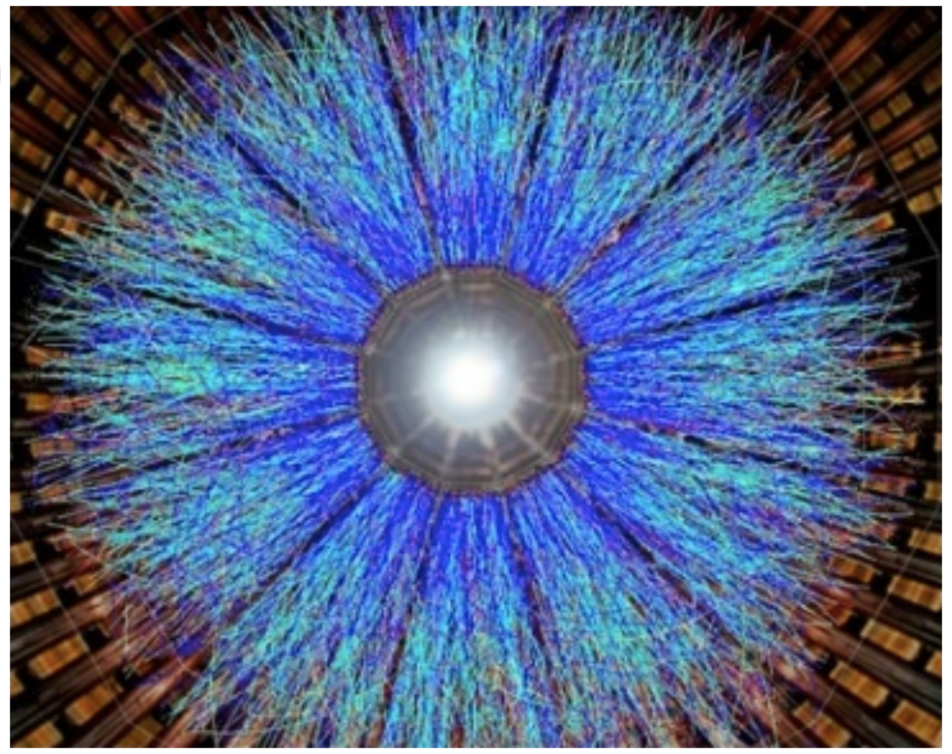
Content

Quark matter in general

✦ **Common sense**

- Hadronic matter (HM) is the ground state of baryonic matter at zero *T* and *P*
- Quark matter (QM) becomes energetically favorable only in an environment like a heavy ion collider *(high T)* or deep inside a neutron star *(high P)*





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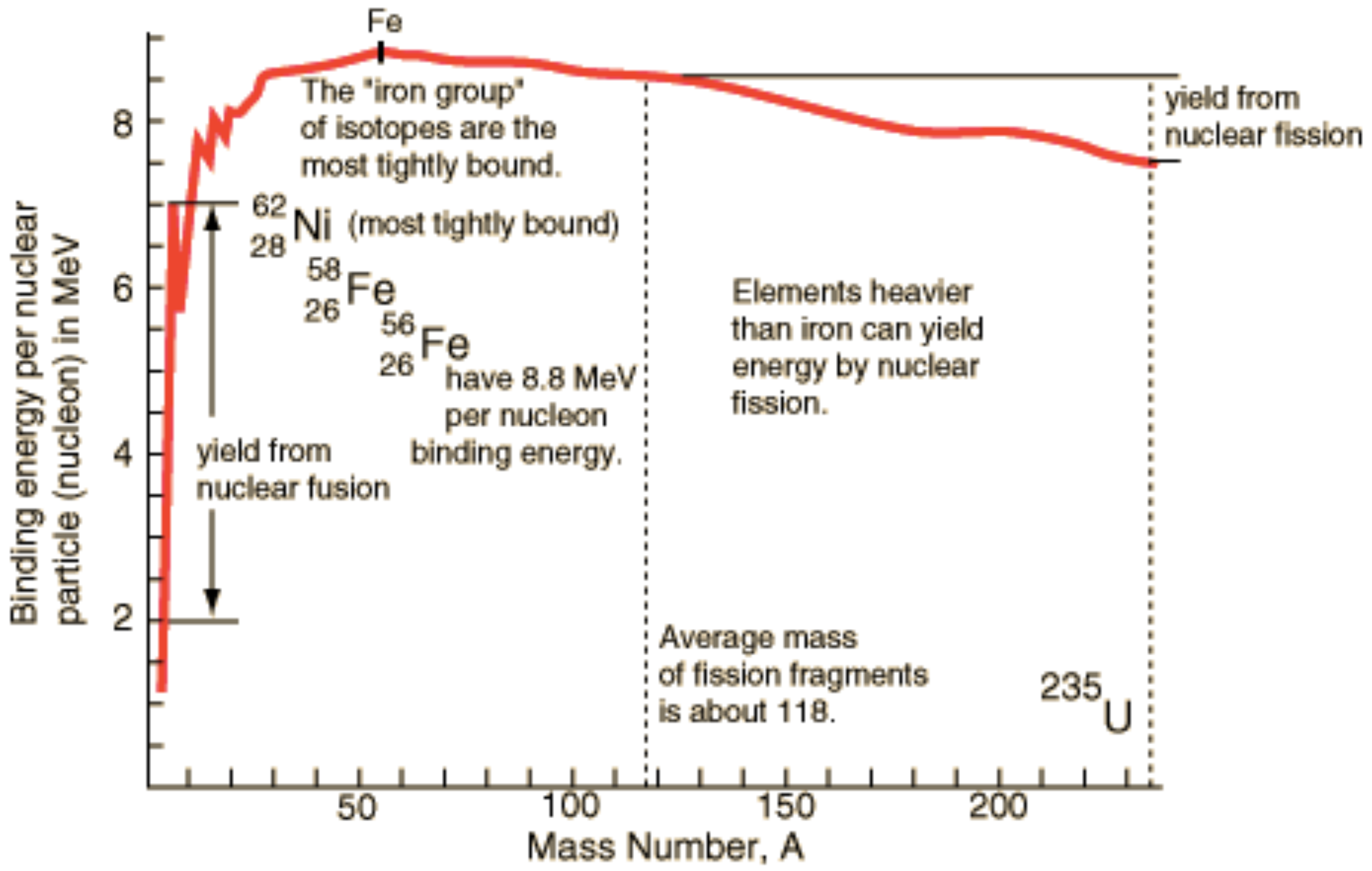
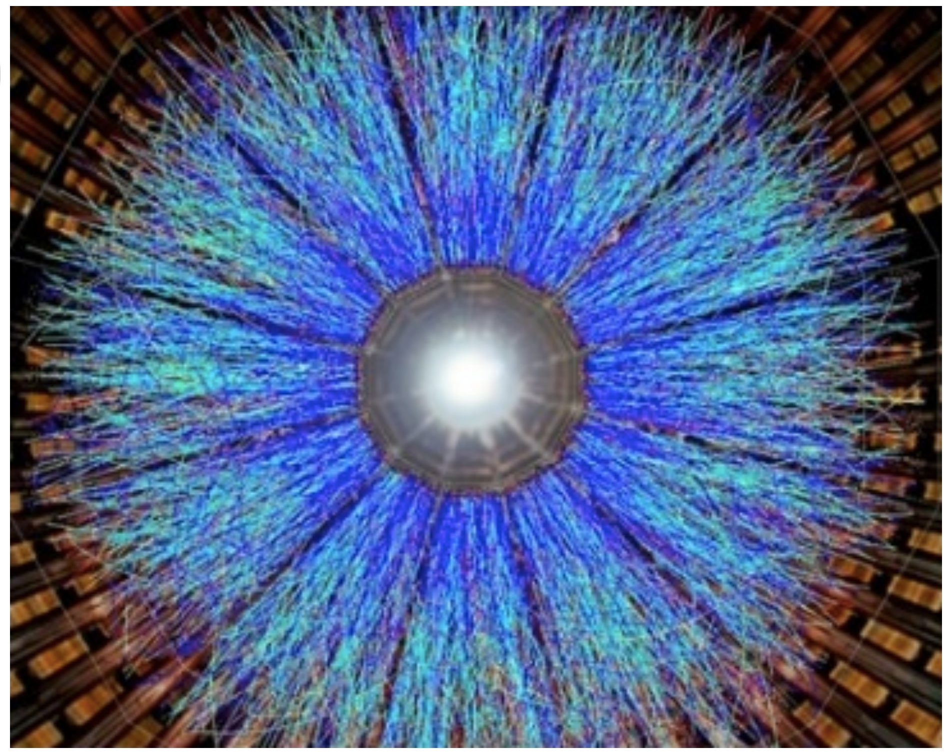
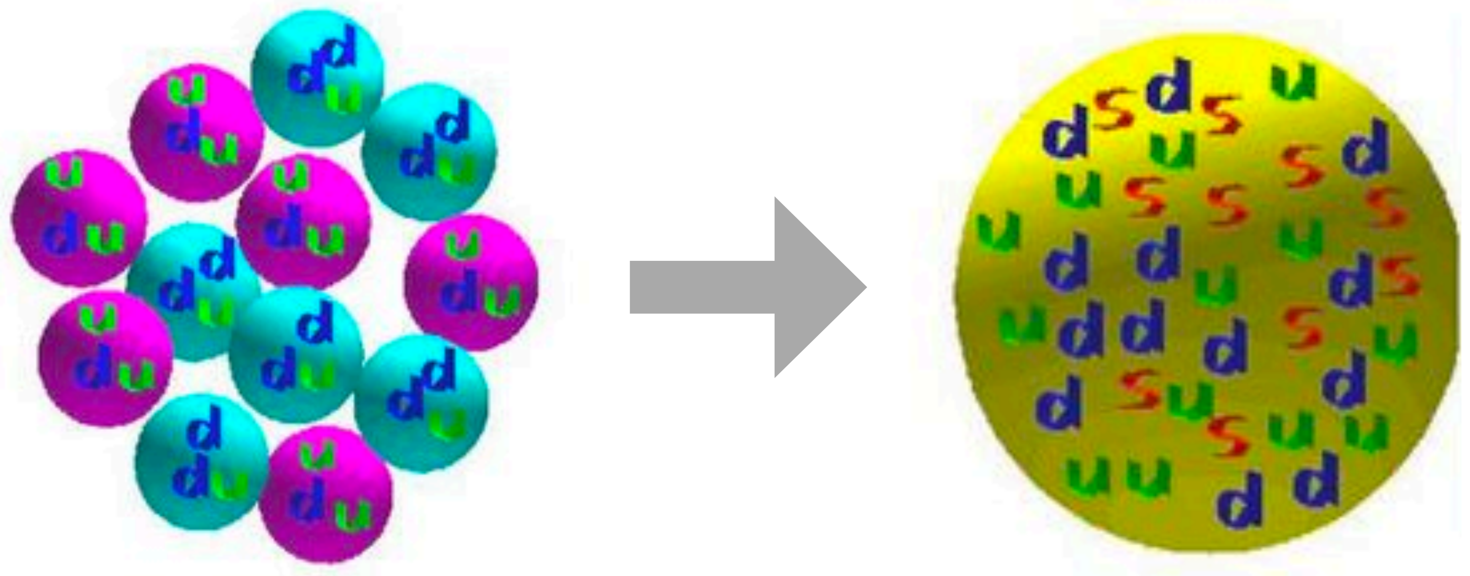




✦ Quark matter hypothesis

- Quark matter (QM) *could be* the ground state of baryonic matter at zero *T* and *P*
- Specifically, the *strange quark matter (SQM) hypothesis* has been proposed back in1970s

[Bodmer (1971); Terazawa (1979); Witten (1984)]



SQM with comparable number of u, d, and s has lower E/A even than the most stable ^{56}Fe

Why is “QM hypothesis” interesting?

Existence of a new ground state of baryonic matter implies …

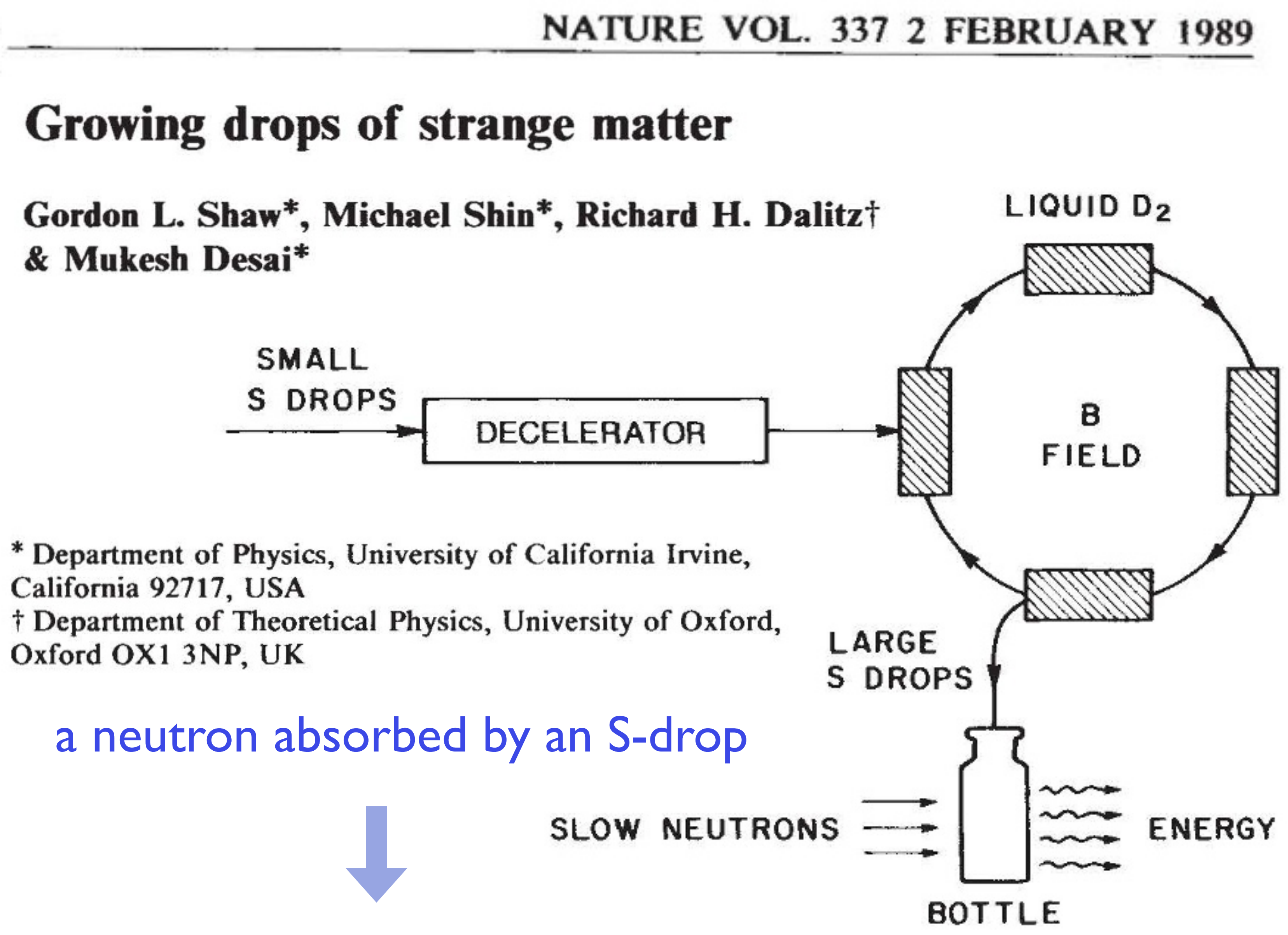
New type of energy source

The New York Times

'Strange Matter' May One Day Fuel Reactors

By Walter Sullivan

March 7, 1989



NATURE VOL. 337 2 FEBRUARY 1989

Growing drops of strange matter

Gordon L. Shaw*, Michael Shin*, Richard H. Dalitz†
& Mukesh Desai*

* Department of Physics, University of California Irvine, California 92717, USA
† Department of Theoretical Physics, University of Oxford, Oxford OX1 3NP, UK

a neutron absorbed by an S-drop

↓

energy ~(938-E_0) MeV released in γ-rays

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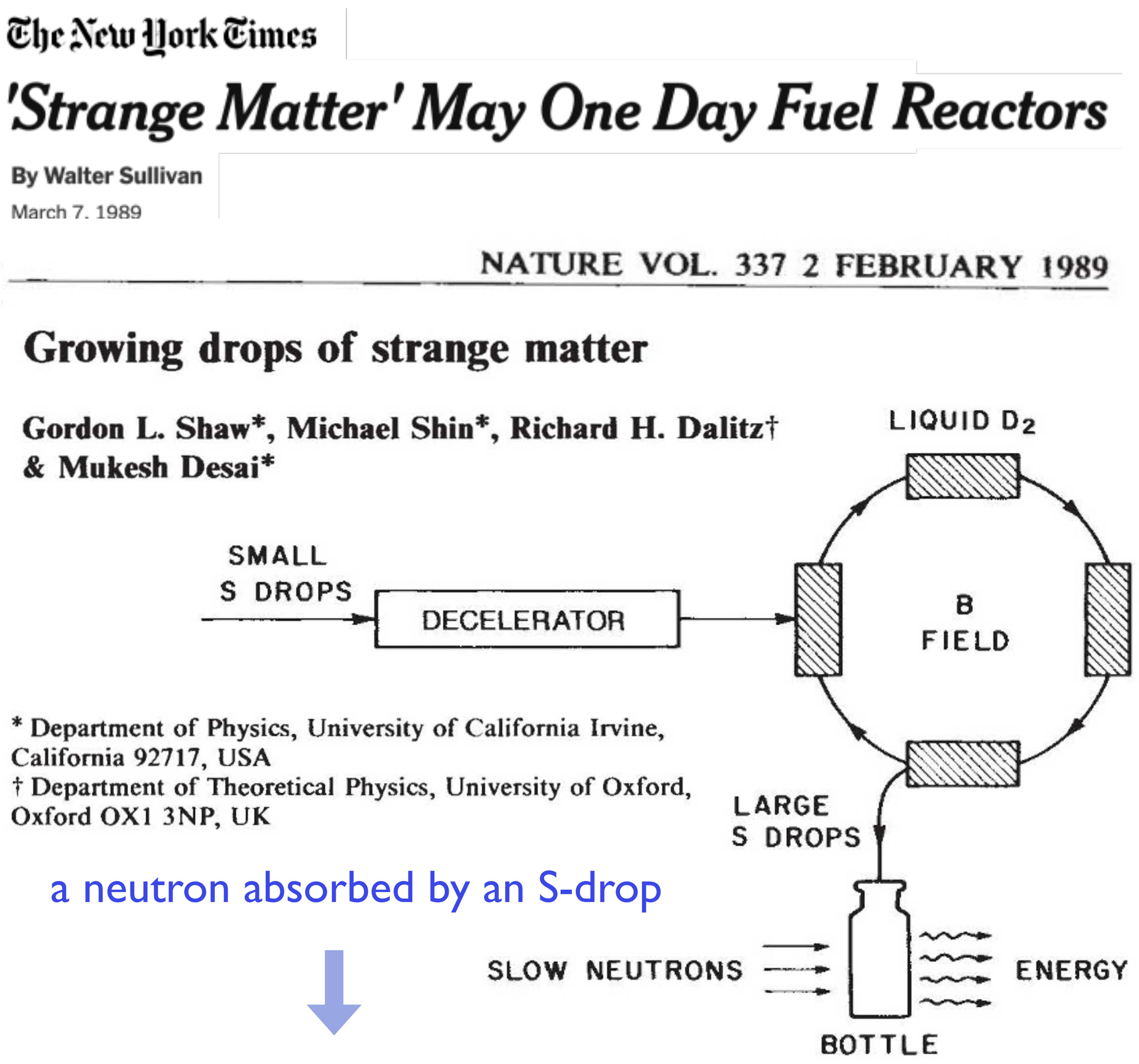

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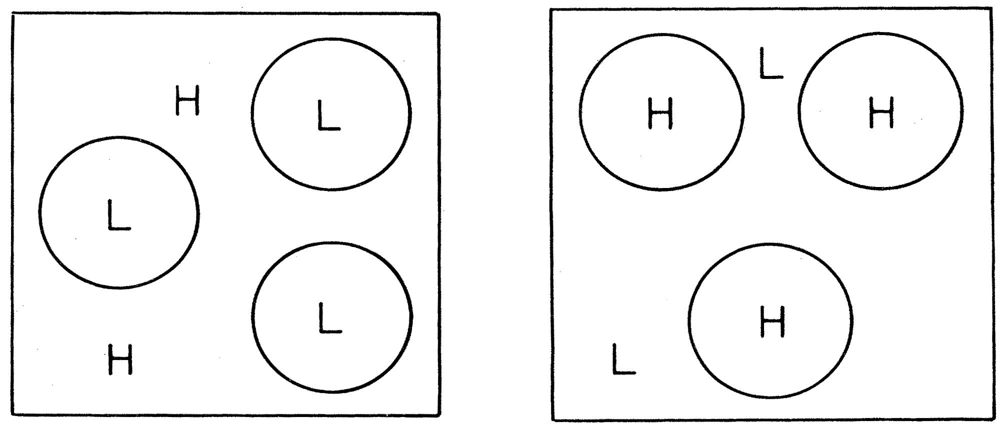
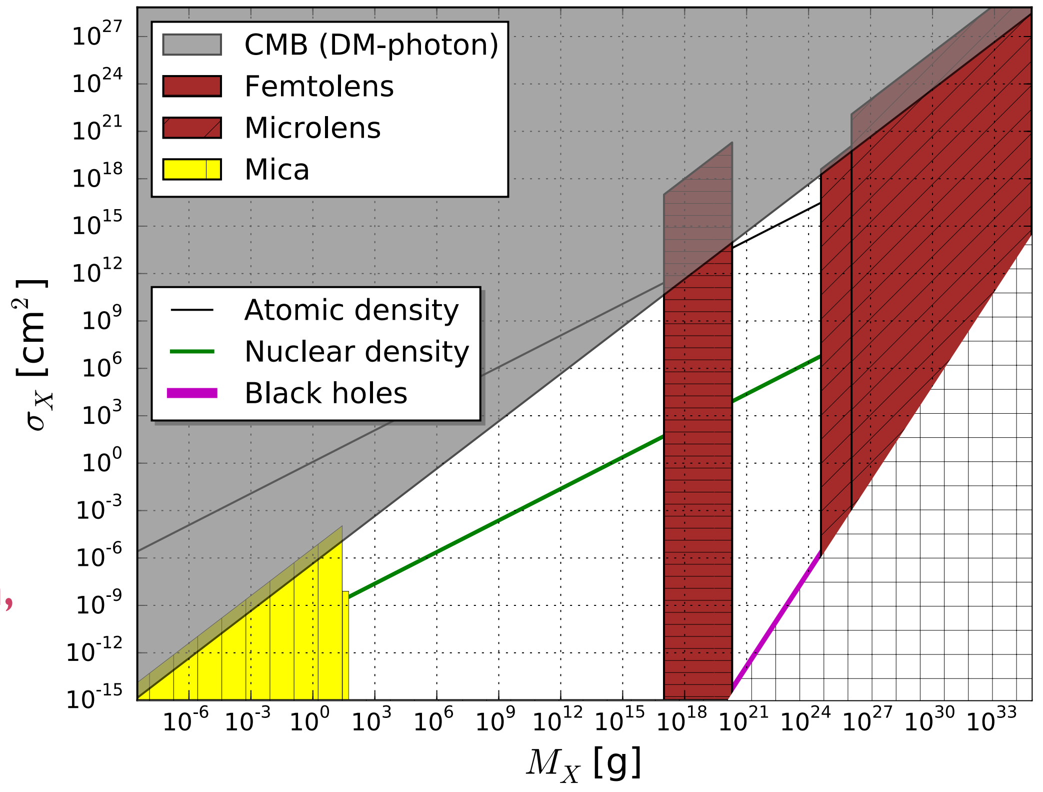
Cold dark matter candidate

QCD phase transition, if first-order, can generate quark nuggets with large mass, providing a DM candidate without BSM [Witten PRD 30 (1984)]



Constraints on Macro Dark Matter

a large range of parameter space remains valid for quark nuggets



[Jacobs, Starkman, Lynn, MNRAS 450(2014)]

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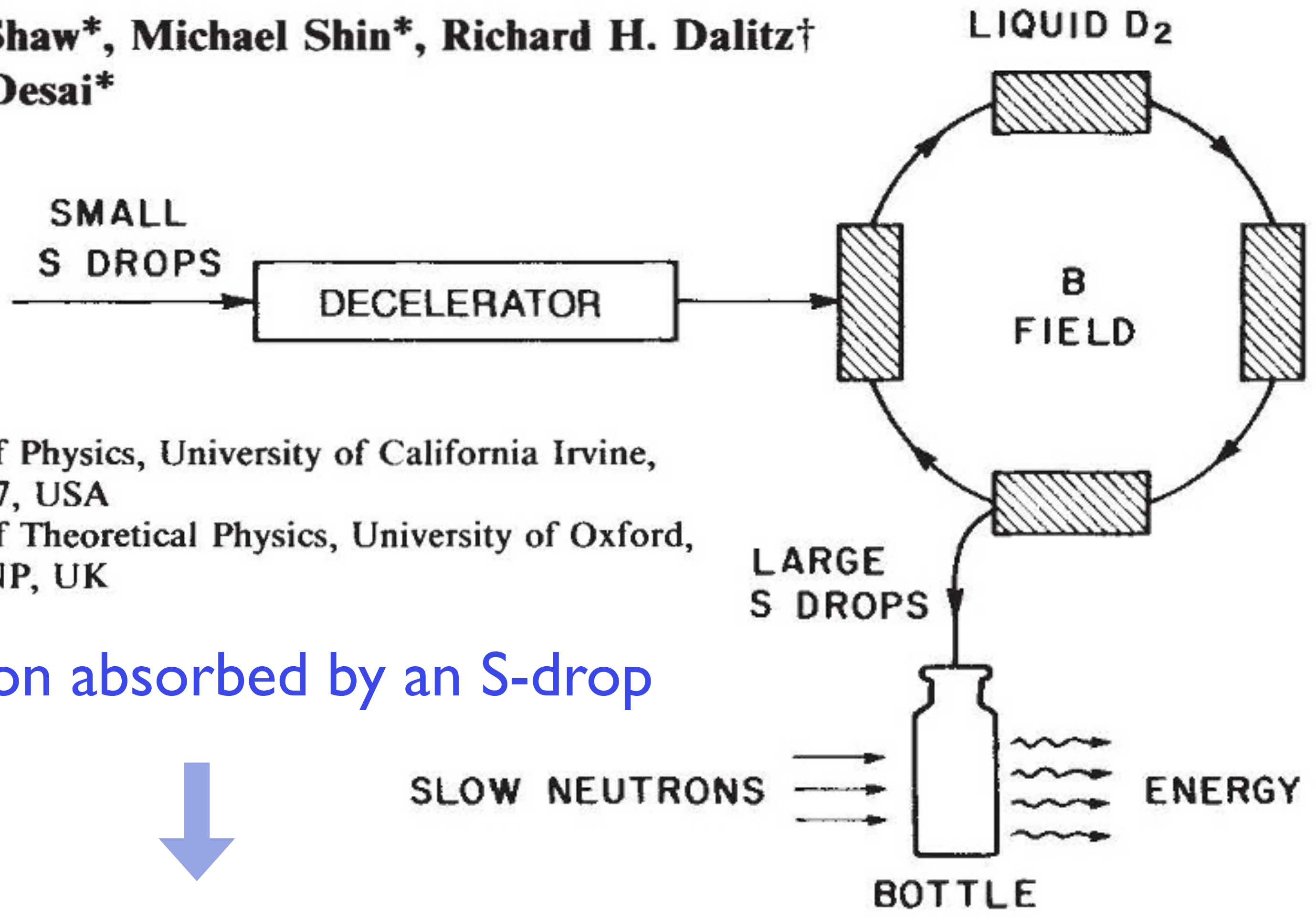

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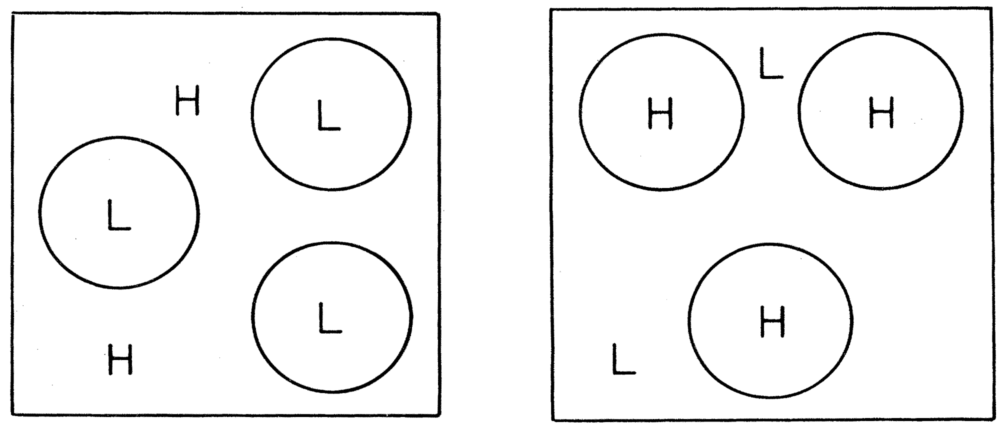

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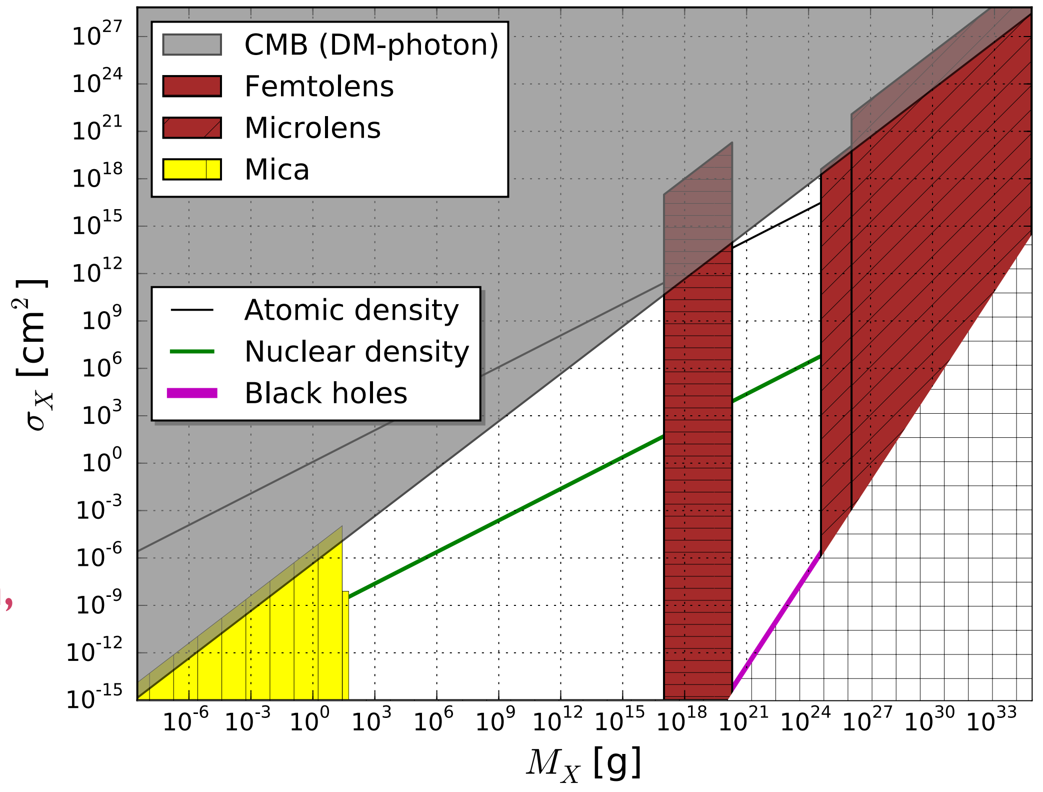
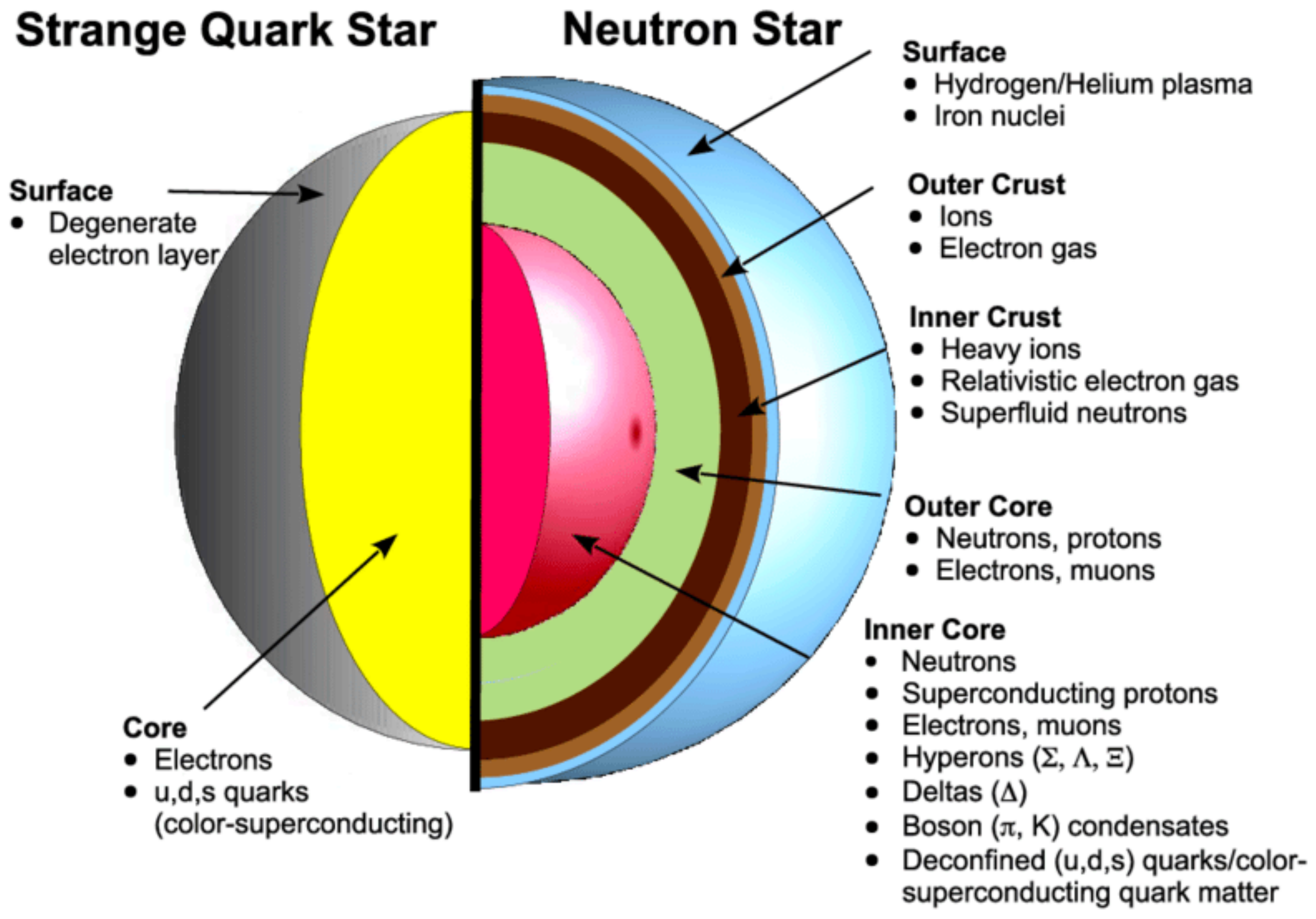


New type of compact stars

Strange quark star

[Haensel, *et al.* AA 160 (1986); Alcock, *et al.* ApJ 310 (1986)]



Strangeon stars: quark cluster

[Xu, ApJL 596 (2003)]

Quark matter may not be strange

Strange quark matter hypothesis

Strange quark matter might be the ***ground state*** of baryonic matter at zero *T* and *P*, which doesn't ruin the stability (or extremely long lifetime) of ordinary nuclei. [Bodmer (1971);Witten (1984)]

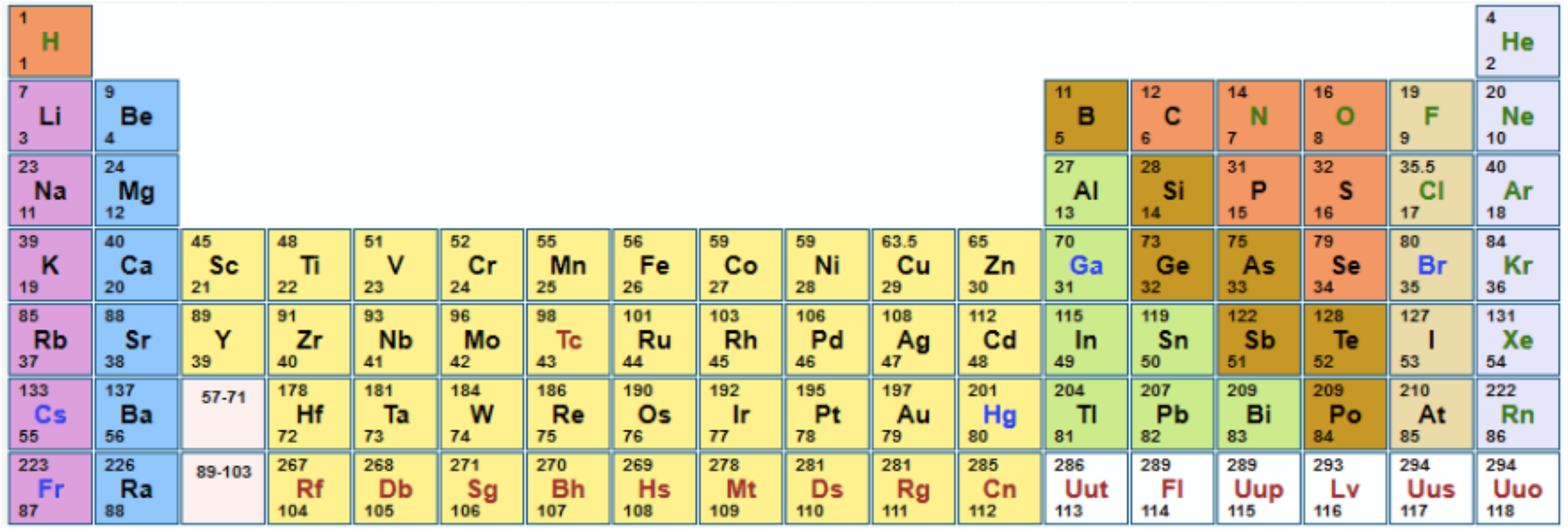
Why strange quark matter *(SQM)* rather than ud quark matter *(udQM)?*

- Ordinary heavy nuclei will convert to udQM with the same *A* catastrophically fast
- Forming SQM needs simultaneous conversion of a sufficiently large number of down quark to strange quark via the weak interaction, so the probability is negligibly small
- In the context of MIT bag model, SQM has lower energy than udQM

Loopholes for SQM hypothesis

- **Empirical evidence?**

As the periodic table of elements ends for $A>300$, udQM could be the ground state and the catastrophic decay of ordinary nuclei would not happen as long as the minimal $A_{min}>300$ for udQM



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39 K 19	40 Ca 20	45 Sc 21	48 Ti 22	51 V 23	52 Cr 24	55 Mn 25	56 Fe 26	59 Co 27	59 Ni 28	63.5 Cu 29	65 Zn 30	70 Ga 31	73 Ge 32	75 As 33	79 Se 34	80 Br 35	84 Kr 36
85 Rb 37	88 Sr 38	89 Y 39	91 Zr 40	93 Nb 41	96 Mo 42	98 Tc 43	101 Ru 44	103 Rh 45	106 Pd 46	108 Ag 47	112 Cd 48	115 In 49	119 Sn 50	122 Sb 51	128 Te 52	127 I 53	131 Xe 54
133 Cs 55	137 Ba 56	57-71	178 Hf 72	181 Ta 73	184 W 74	186 Re 75	190 Os 76	192 Ir 77	195 Pt 78	197 Au 79	201 Hg 80	204 Tl 81	207 Pb 82	209 Bi 83	209 Po 84	210 At 85	222 Rn 86
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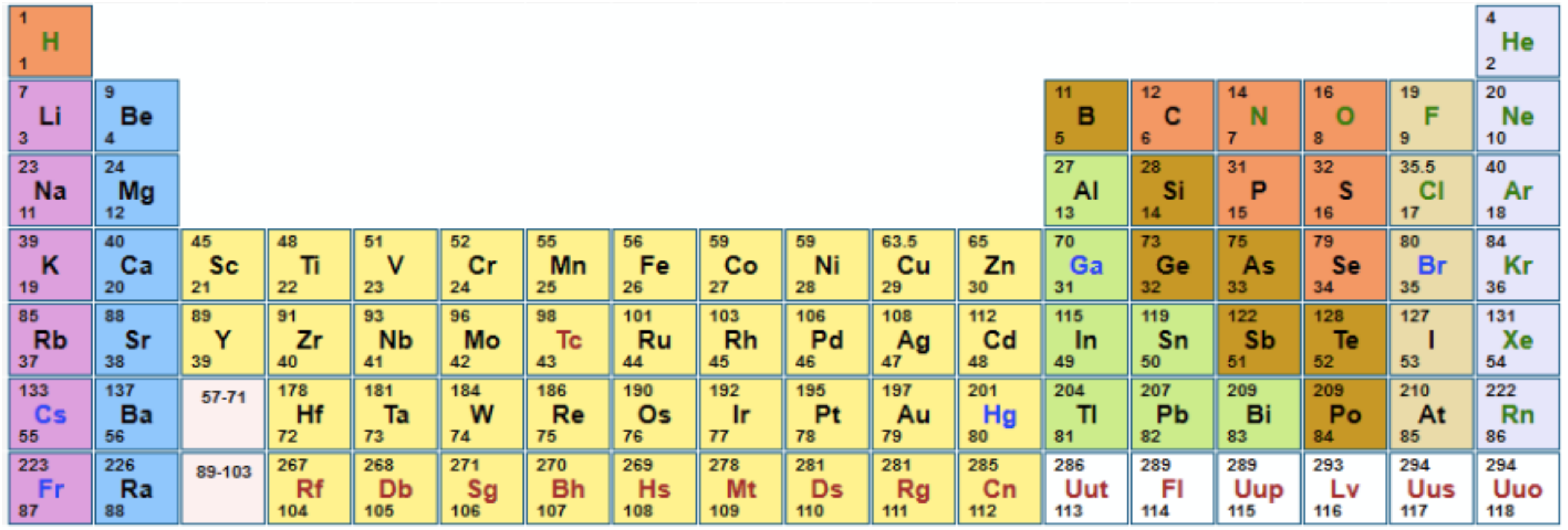

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- **Theoretical prediction?**

The MIT bag model may not adequately model the feedback of a dense quark gas on the QCD vacuum. Particularly, the badly broken flavor symmetry of u, d, s ***not*** reflected in the response of constituent quark masses to the gas.

$$\rho = \underline{\frac{N_C}{4\pi^2}\left(\sum_i \overset{\text{quark fraction}}{f_i^{4/3}}\right)p_F^4 + \frac{N_C}{2\pi^2} f_s^{2/3} p_F^2 m_s^2} + \boxed{B}$$

SQM with comparable u, d, s attains the lowest kinetic energy with m_s~100MeV

BUT the bag constant might not be flavor independent

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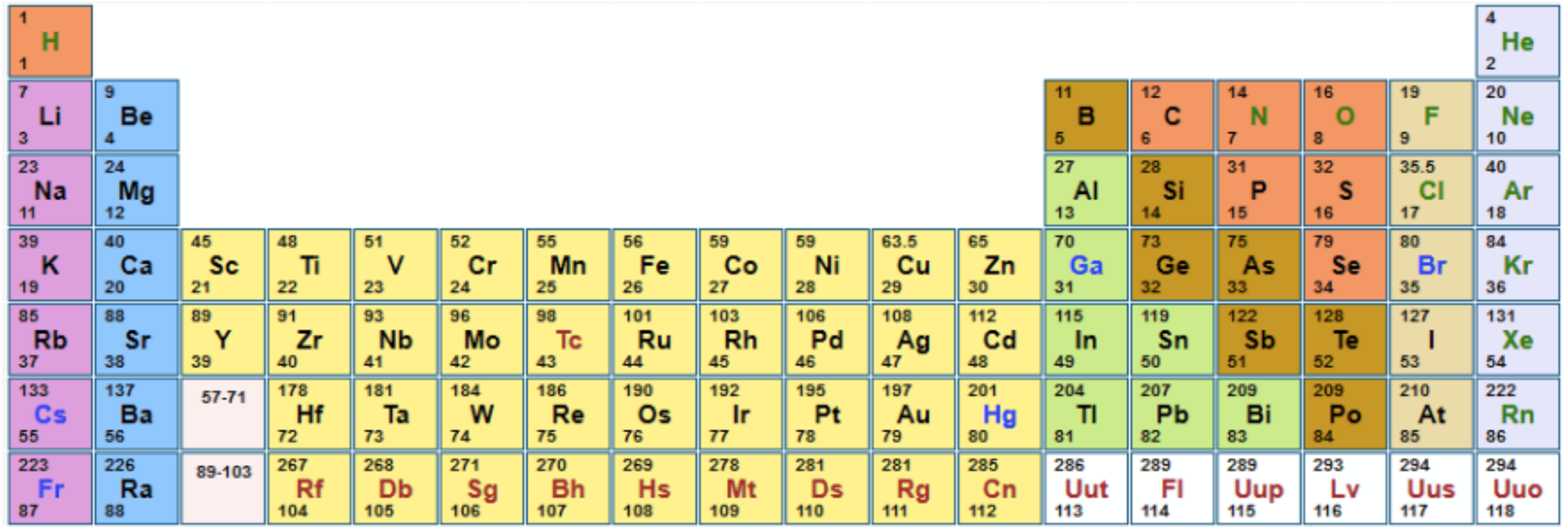

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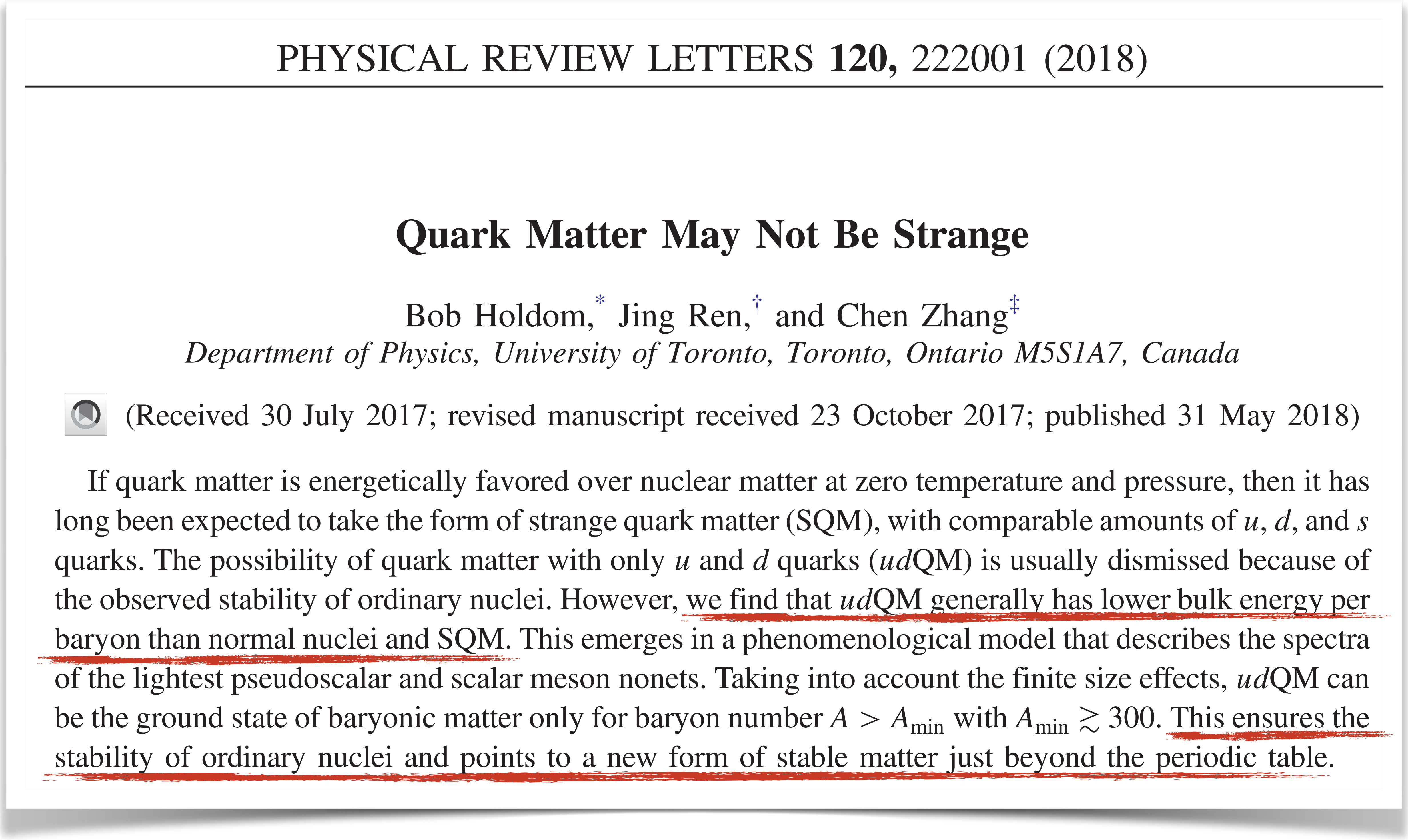

PHYSICAL REVIEW LETTERS **120,** 222001 (2018)

Quark Matter May Not Be Strange

Bob Holdom,[*] Jing Ren,[†] and Chen Zhang[‡]
Department of Physics, University of Toronto, Toronto, Ontario M5S1A7, Canada

(Received 30 July 2017; revised manuscript received 23 October 2017; published 31 May 2018)

If quark matter is energetically favored over nuclear matter at zero temperature and pressure, then it has long been expected to take the form of strange quark matter (SQM), with comparable amounts of u, d, and s quarks. The possibility of quark matter with only u and d quarks (udQM) is usually dismissed because of the observed stability of ordinary nuclei. However, we find that udQM generally has lower bulk energy per baryon than normal nuclei and SQM. This emerges in a phenomenological model that describes the spectra of the lightest pseudoscalar and scalar meson nonets. Taking into account the finite size effects, udQM can be the ground state of baryonic matter only for baryon number $A > A_{\text{min}}$ with $A_{\text{min}} \gtrsim 300$. This ensures the stability of ordinary nuclei and points to a new form of stable matter just beyond the periodic table.

Effective theory for quark matter

Yukawa term + meson potential: $\mathcal{L}_m = \mathrm{Tr}\left(\partial_\mu \Phi^\dagger \partial^\mu \Phi\right) - V, \quad \mathcal{L}_y = -2g\bar{\psi}\Phi\psi$

- An effective theory describing the sub-GeV mesons: assuming other QCD degrees of freedom integrated out and encoded in the parameters of meson potential *V*
- Residual QCD effects subdominant on the energy similar to constituent quark model for QCD spectrum

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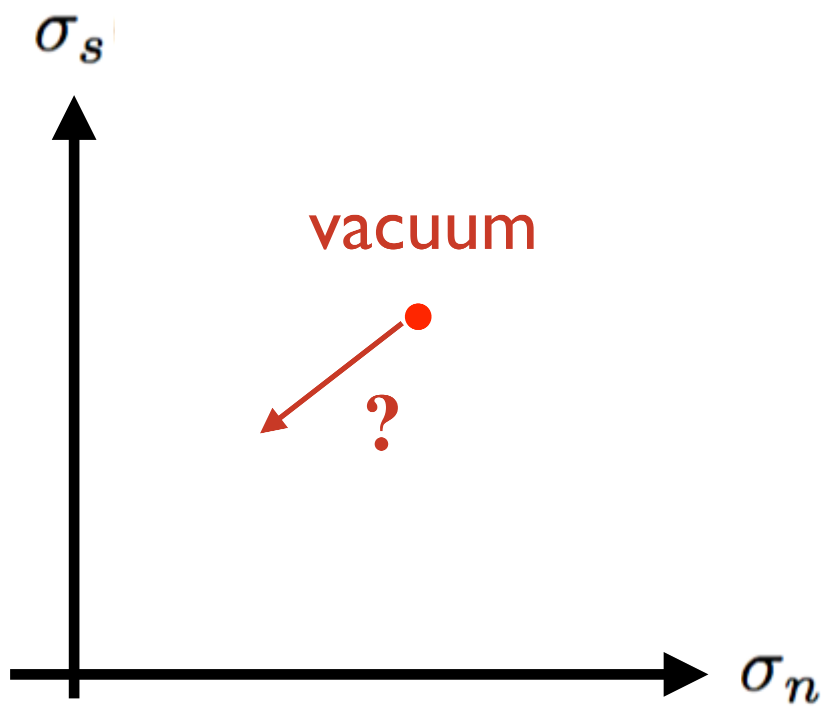
$$\nabla^2 \sigma_n(r) = \frac{\partial V}{\partial \sigma_n} + g \sum_{i=u,d} \langle \bar{\psi}_i \psi_i \rangle,$$

$$\nabla^2 \sigma_s(r) = \frac{\partial V}{\partial \sigma_s} + \sqrt{2} g \langle \bar{\psi}_s \psi_s \rangle.$$

Quark gas densities: depend on $p_{Fi} = p_F f_i$, quark masses inside

$m_{u,d}(r) = g\sigma_n(r) + m_{ud0}$

$m_s(r) = \sqrt{2} g\sigma_s(r) + m_{s0}$



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- Varying constituent quark masses and additional flavor symmetry breaking

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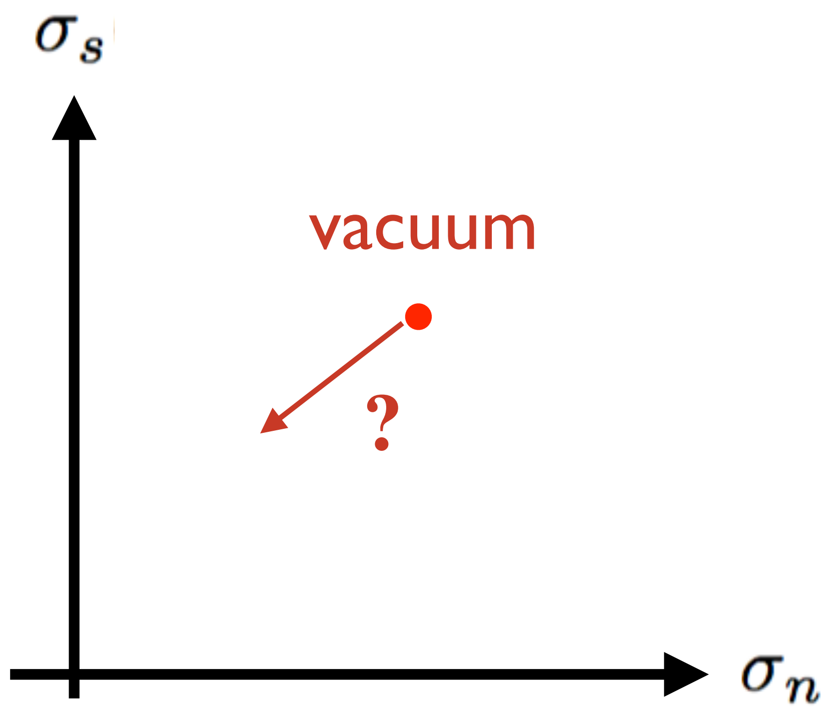
Energy budget

$$E = \int_0^R d^3r(\rho_\psi + \rho_\phi + \rho_Z)$$

Quark energy (kinetic)

Scalar energy (kinetic + potential)

Coulomb energy



- Quark densities drive meson fields away from the vacuum
- Varying constituent quark masses and additional flavor symmetry breaking

- Mass reduction (chiral symmetry restoration) makes quark matter energetically favorable
- (f_i, R) found by minimizing *E*/*A*

A minimal model for sub-GeV mesons

$V = V_{\text{inv}} + V_b.$ $\boxed{\Phi = T_a(\sigma_a + i\pi_a)}$ pseudoscalar
scalar nonets

$$V_{\text{inv}} = \lambda_1 \left(\text{Tr}\,\Phi^\dagger\Phi\right)^2 + \lambda_2\,\text{Tr}\left((\Phi^\dagger\Phi)^2\right) + m^2\,\text{Tr}\left(\Phi^\dagger\Phi\right) - c\left(\det\Phi + h.c.\right).$$

Explicit *SU(3)* flavor symmetry breaking incorporated in current quark masses: $\mathcal{M} = \text{diag}(m_{u0}, m_{d0}, m_{s0})$

$$\begin{aligned}
V_{b1} &= b_1\,\text{Tr}\left(\Phi^\dagger\mathcal{M} + h.c.\right),\\
V_{b2} &= b_2\epsilon_{ijk}\epsilon_{mnl}\mathcal{M}_{im}\Phi_{jn}\Phi_{kl} + h.c.\,,\\
V_{b3} &= b_3\,\text{Tr}\left(\Phi^\dagger\Phi\Phi^\dagger\mathcal{M}\right) + h.c.\,,\\
V_{b4} &= b_4\,\text{Tr}\left(\Phi^\dagger\Phi\right)\text{Tr}\left(\Phi^\dagger\mathcal{M}\right) + h.c.\,,\\
V_{b5} &= b_5\,\text{Tr}\left(\Phi^\dagger\mathcal{M}\Phi^\dagger\mathcal{M}\right) + h.c.\,,\\
V_{b6} &= b_6\,\text{Tr}\left(\Phi\Phi^\dagger\mathcal{M}\mathcal{M}^\dagger + \Phi^\dagger\Phi\mathcal{M}^\dagger\mathcal{M}\right),\\
V_{b7} &= b_7\left(\text{Tr}\,\Phi^\dagger\mathcal{M} + h.c.\right)^2,\\
V_{b8} &= b_8\left(\text{Tr}\,\Phi^\dagger\mathcal{M} - h.c.\right)^2.
\end{aligned}$$

12 free parameters (with isospin symmetry)

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$$V_{b3} = b_3\,\mathrm{Tr}\left(\Phi^\dagger\Phi\Phi^\dagger\mathcal{M}\right) + h.c.\,,$$
$$V_{b4} = b_4\,\mathrm{Tr}\left(\Phi^\dagger\Phi\right)\mathrm{Tr}\left(\Phi^\dagger\mathcal{M}\right) + h.c.\,,$$
$$V_{b5} = b_5\,\mathrm{Tr}\left(\Phi^\dagger\mathcal{M}\Phi^\dagger\mathcal{M}\right) + h.c.\,,$$
$$V_{b6} = b_6\,\mathrm{Tr}\left(\Phi\Phi^\dagger\mathcal{M}\mathcal{M}^\dagger + \Phi^\dagger\Phi\mathcal{M}^\dagger\mathcal{M}\right),$$
$$V_{b7} = b_7\left(\mathrm{Tr}\,\Phi^\dagger\mathcal{M} + h.c.\right)^2,$$
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12 free parameters (with isospin symmetry)

- **Dynamical ChSB:** $\langle\Phi\rangle = T_0 v_0 + T_8 v_8 = \frac{1}{2}\mathrm{diag}(v_n, v_n, \sqrt{2}v_s)$

  $v_n = f_\pi = 92$ MeV, $v_s = \sqrt{2}f_K - f_\pi/\sqrt{2} =$ 90.5 MeV
- **Mass spectrum:** $m^2_{a_0} = \mathbb{M}^2_{s,11},\ m^2_\kappa = \mathbb{M}^2_{s,44},\ m^2_\pi = \mathbb{M}^2_{p,11},\ m^2_K = \mathbb{M}^2_{p,44}$

  $m^2_\sigma,\ m^2_{f_0},\ m^2_\eta,\ m^2_{\eta'}$ from diagonalizing (0,8) sector
- **Decay widths:** constrain mixing angles

	m_π	m_K	m_η	m'_η	θ_p
Exp.	138	496	548	958	…
Set 1	138	496	548	958	−15.0°
Set 2	148	454	569	922	−10.8°
	m_{a_0}	m_κ	m_σ	m_{f_0}	θ_s
Exp.	980 ± 20	700–900	400–550	990 ± 20	…
Set 1	980	900	555	990	31.5°
Set 2	887	916	555	955	21.7°
	$\Gamma_{\eta\to\gamma\gamma}$	$\Gamma_{\eta'\to\gamma\gamma}$	$\Gamma_{\sigma\to\pi\pi}$	$\Gamma_{\kappa\to K\pi}$	
Exp.	0.52–0.54	4.2–4.5	400–700	~500	
Set 1	0.59	4.90	442	451	
Set 2	0.54	4.87	422	537	
	$\Gamma_{f_0\to\pi\pi}$	R_{f_0}	$\Gamma_{a_0\to\eta\pi}$	R_{a_0}	
Exp.	10–100	3.8–4.7	50-100	1.2–1.6	
Set 1	11	4.3	37.4	2.4	
Set 2	20	4.0	52.0	1.2	

[Holdom, JR and Zhang, PRL 120 (2018)]

Find two benchmarks:

- a good fit to observables with less free parameters
- reasonable choose of parameters

θ_p : related to diphoton radiative decay of η, η', and strong decay of a_0, κ

θ_s : fit small and large $\pi\pi$ widths of f_0 and σ

Quark matter in the bulk limit

Large *A* limit: meson fields and fermion densities are roughly spatially constant, and quark fractions are driven to approach charge neutral

- "Force balancing" between scalar potential v.s. fermion density determines meson fields values
- Bulk properties $(\bar{p}_F, \bar{f}_i)$ determined by minimizing the energy per baryon $\mathcal{E}$

  [Holdom, JR and Zhang, PRL 120 (2018)]

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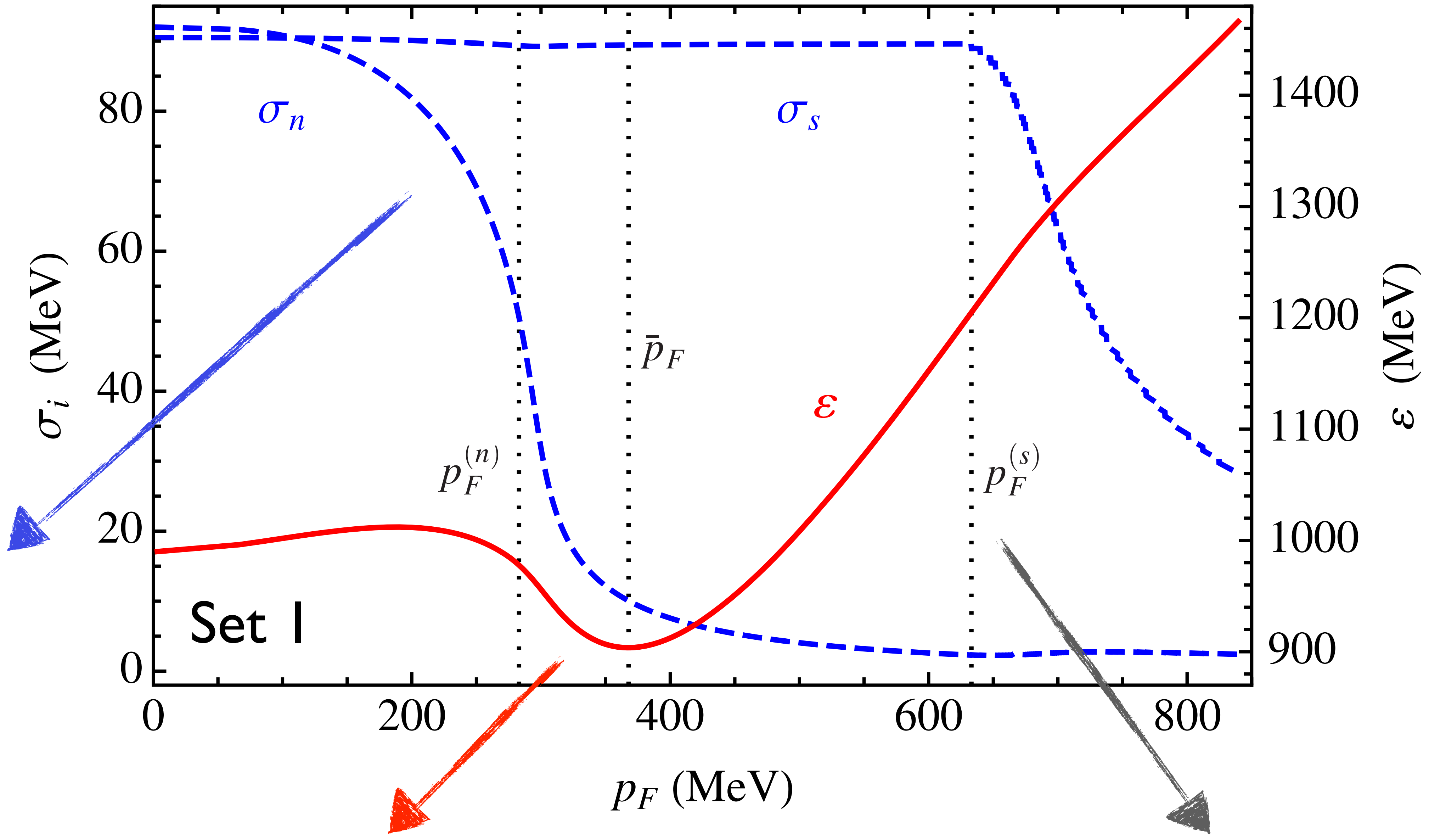
- Bulk properties $(\bar{p}_F, \bar{f}_i)$ determined by minimizing the energy per baryon ε

[Holdom, JR and Zhang, PRL 120 (2018)]



ud quarks becomes light first

Minimum achieved (only ud quark)

$$\bar{\varepsilon} \approx N_C \bar{\chi} \bar{p}_F, \quad \bar{p}_F^4 \approx 12\pi^2 \Delta V_n / (N_C \bar{\chi})$$

strange fraction turns on

Quark matter in the bulk limit

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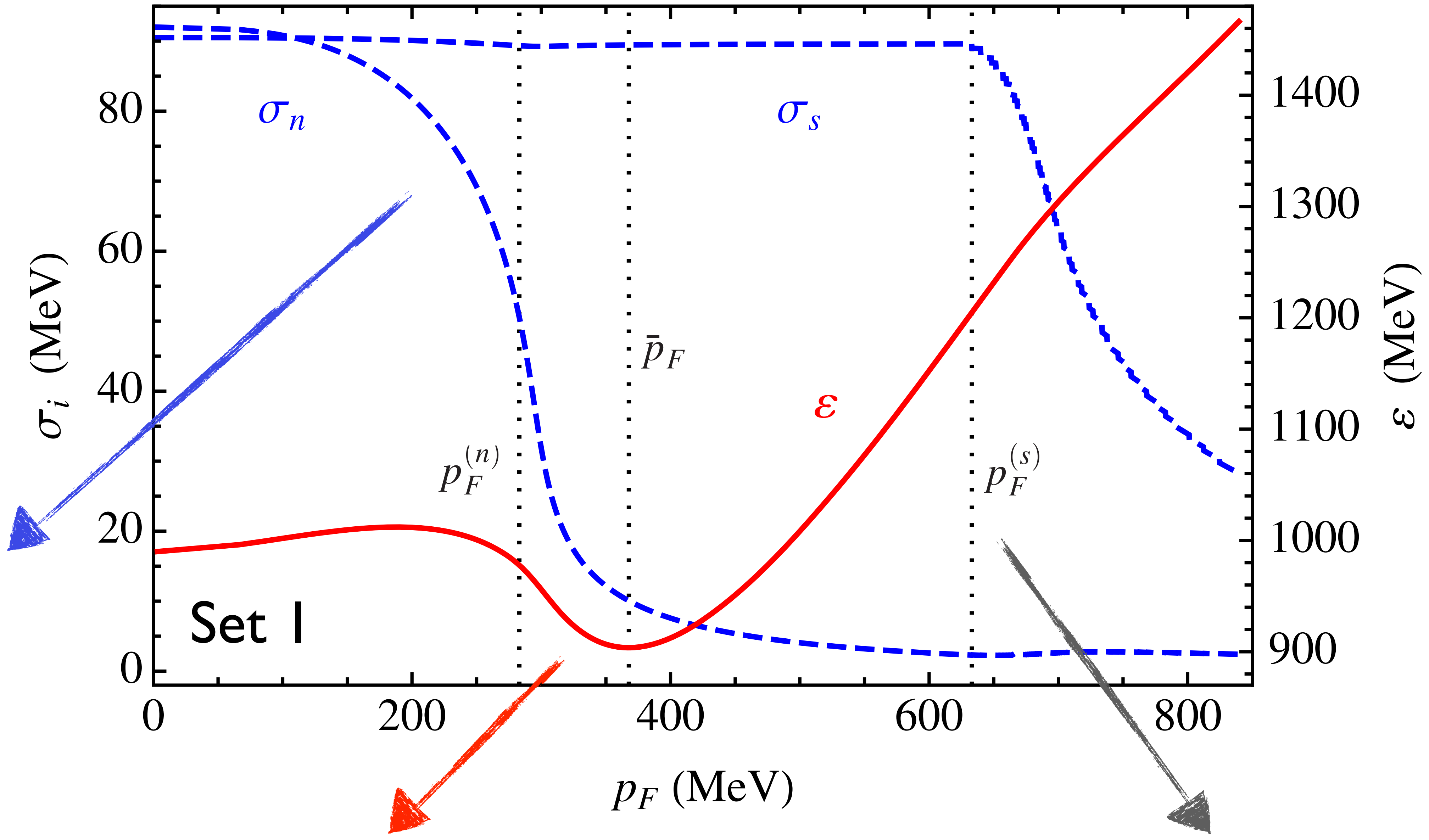

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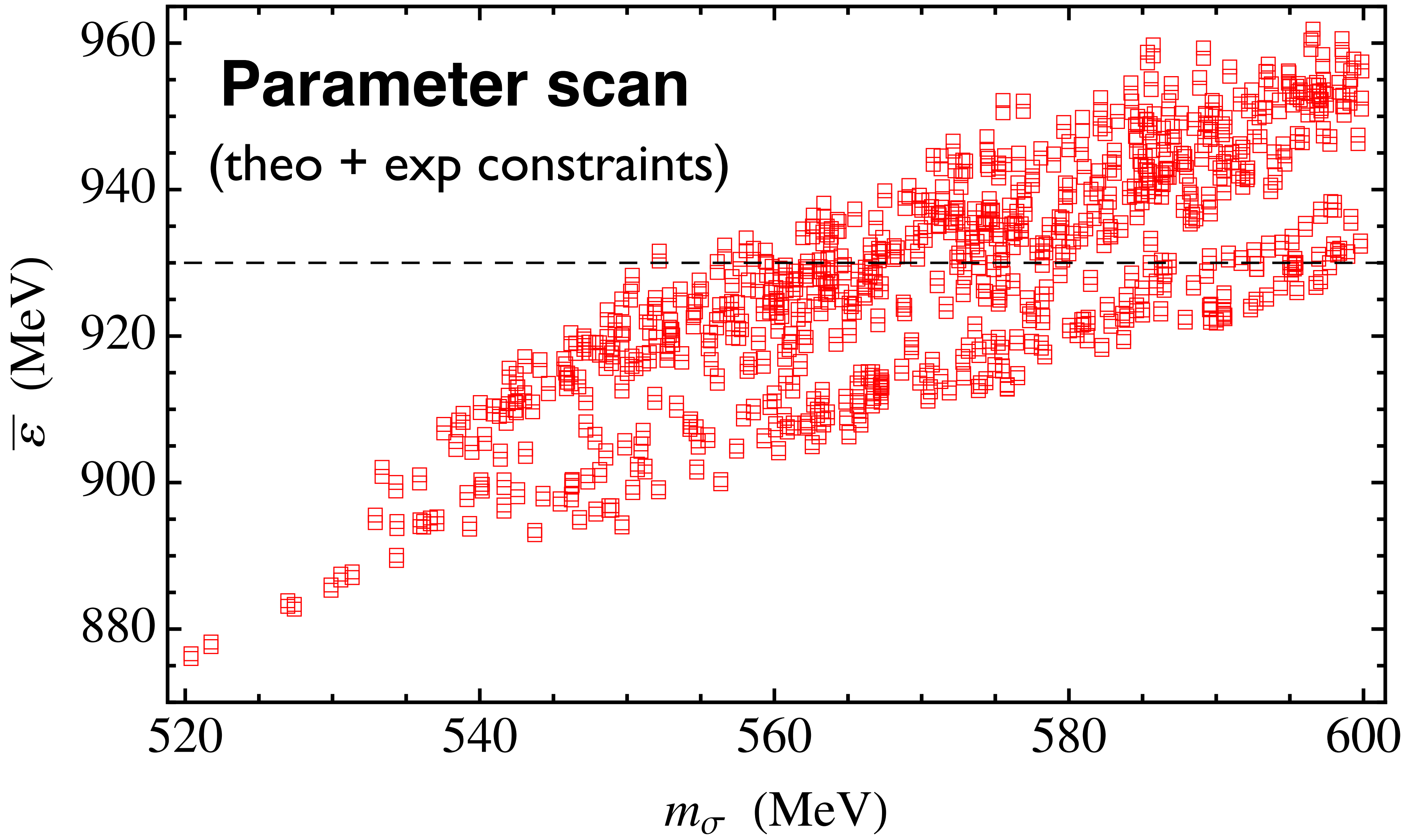


For a wide range of parameter, **udQM is more stable then SQM and is the ground state of baryonic matter**

udQM away from the bulk limit

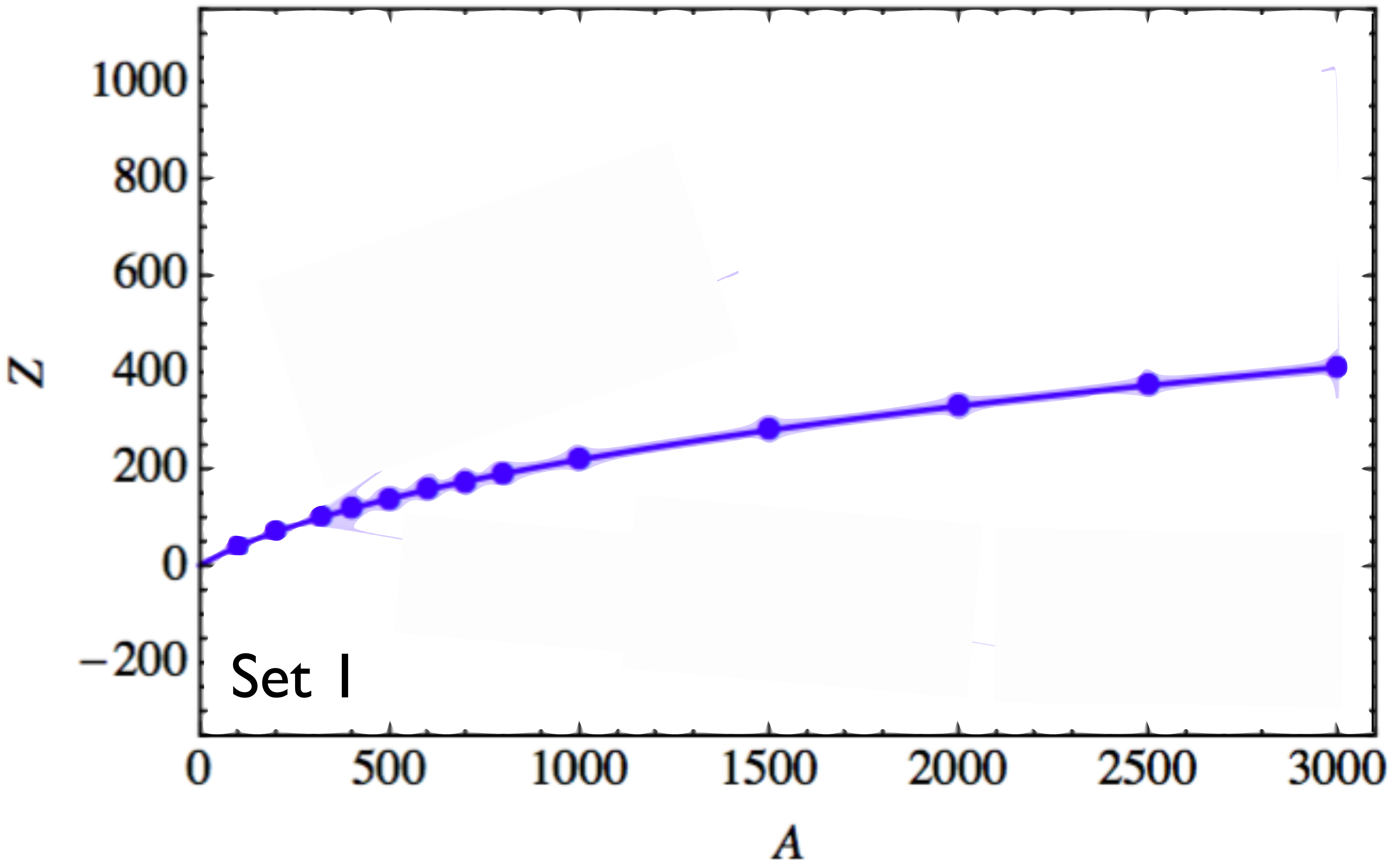
Small *A* limit: need to include the Coulomb energy contribution and the finite size effects

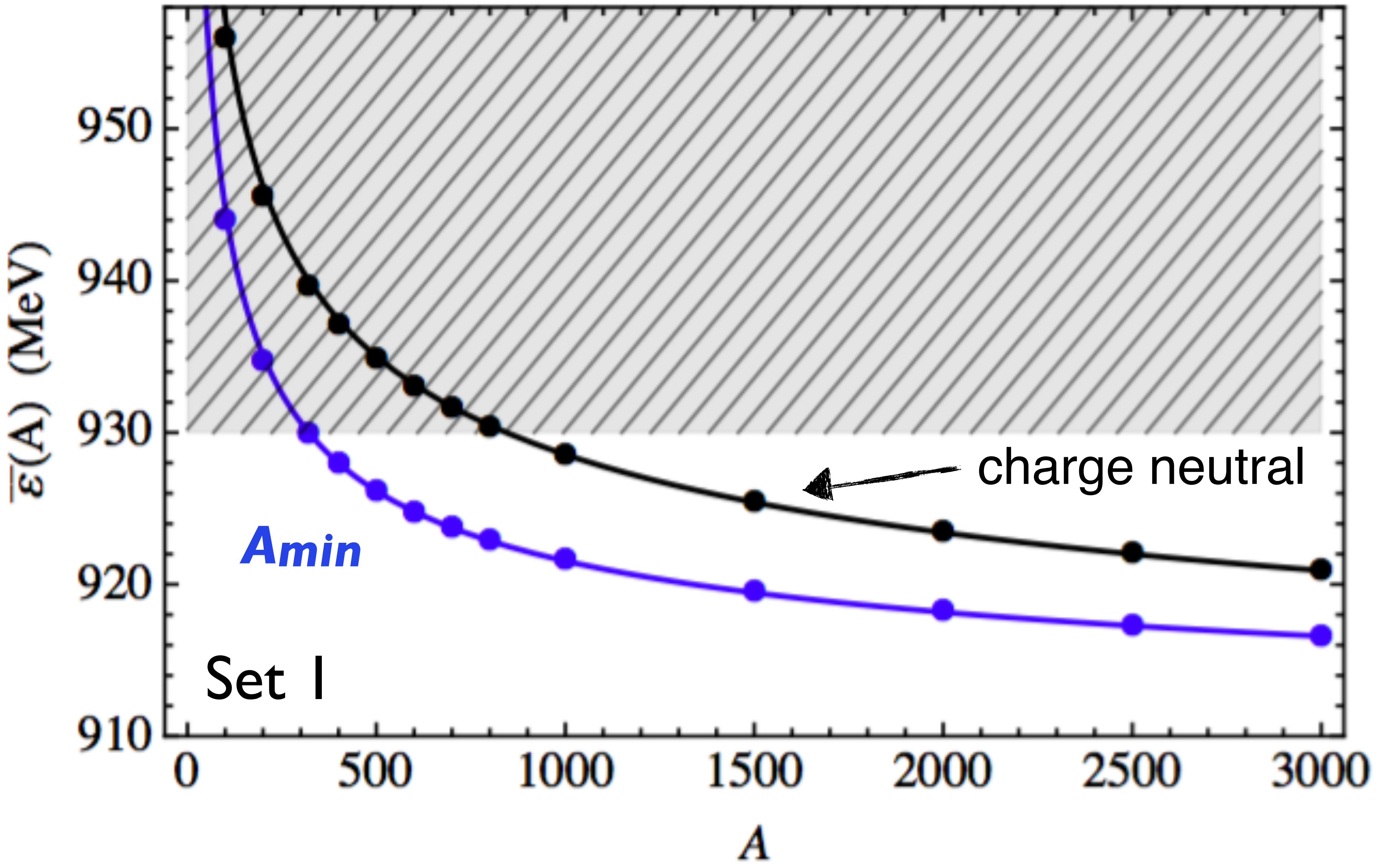
$$E = \int_0^R d^3r(\rho_\psi + \rho_\phi + \rho_Z) \qquad\qquad Z = N_C A(\bar{f}_u(A) - 1/3)$$

$$\bar{\varepsilon}(A) \approx \bar{\varepsilon} + \underline{46\,\Sigma/(\bar{p}_F^2 A^{1/3})} + \underline{0.31\,\alpha\, Z^2 \bar{p}_F / A^{4/3}}$$

mainly surface effects

minimizing the kinetic and Coulomb energies of u,d gas





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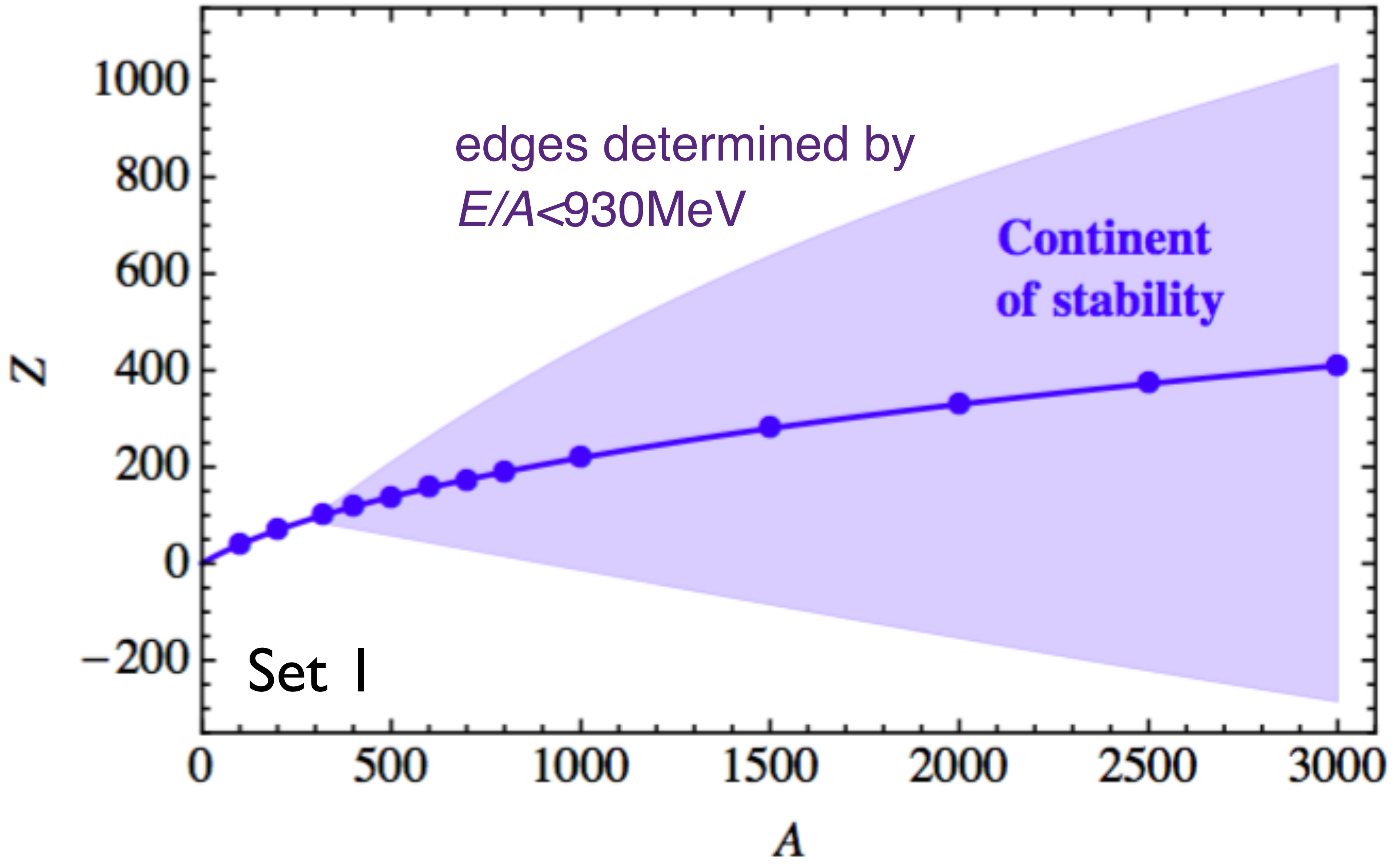


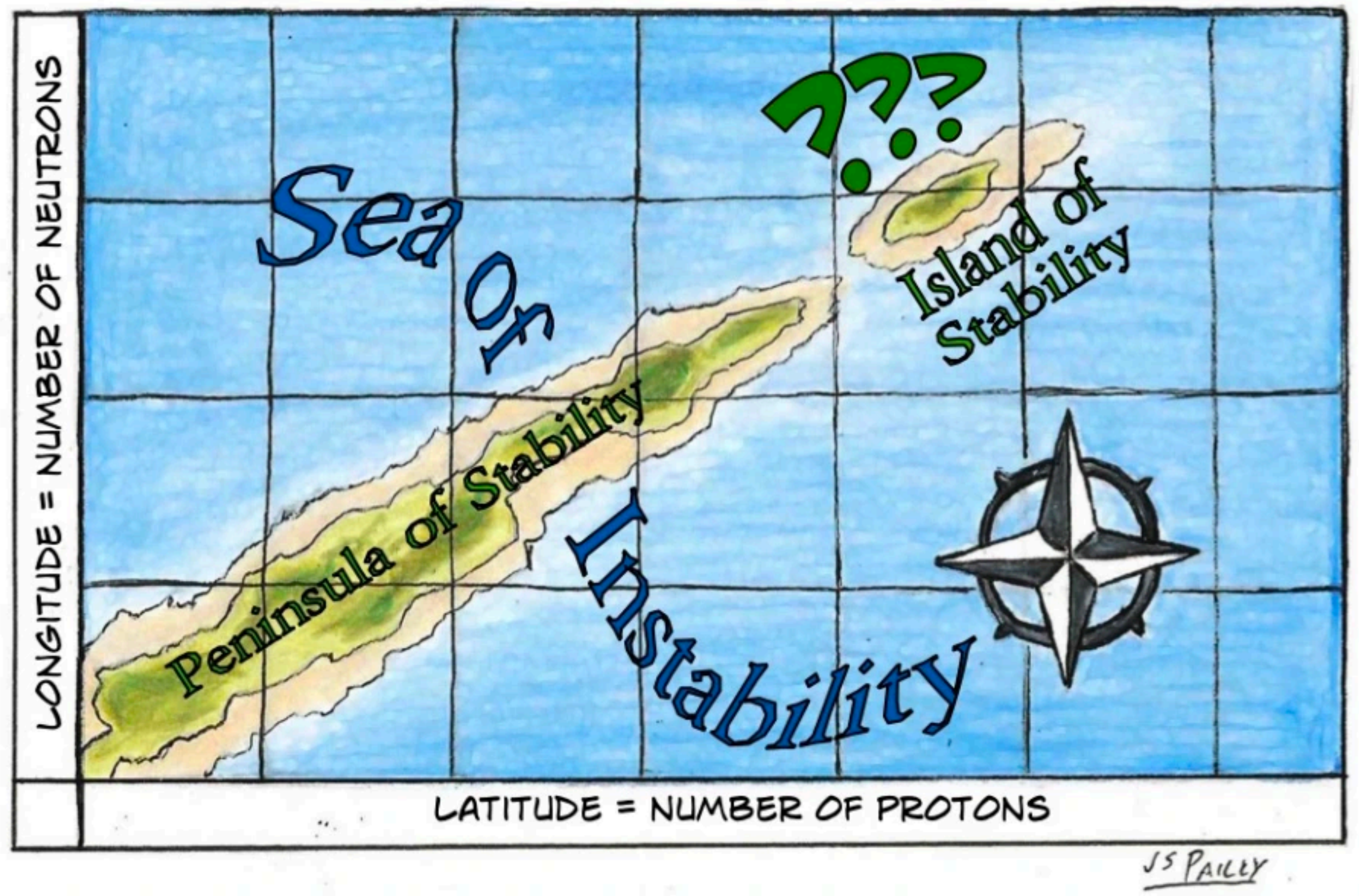
[Holdom, JR and Zhang, PRL 120 (2018)]

Continent of Stability

v.s.

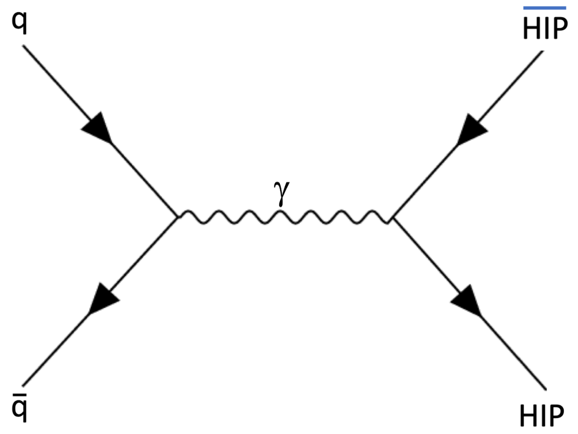
Island of Stability

If A_{min}~300, maybe udQM with large *Z/A* could be produced by fusion of heavy elements within “continent of stability”?

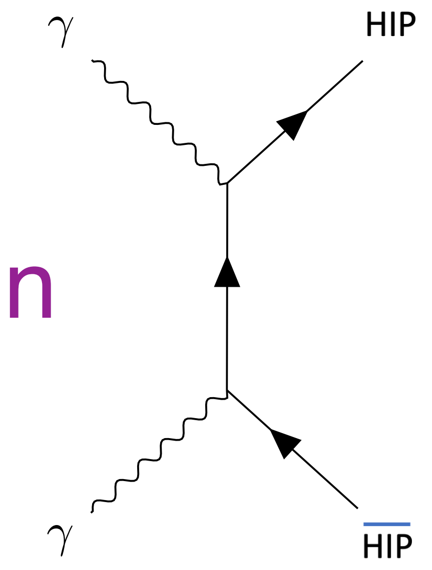


Collider searches of highly ionizing particles

LHC search for highly-ionizing particles (HIP): Drell-Yan



+ photon-fusion

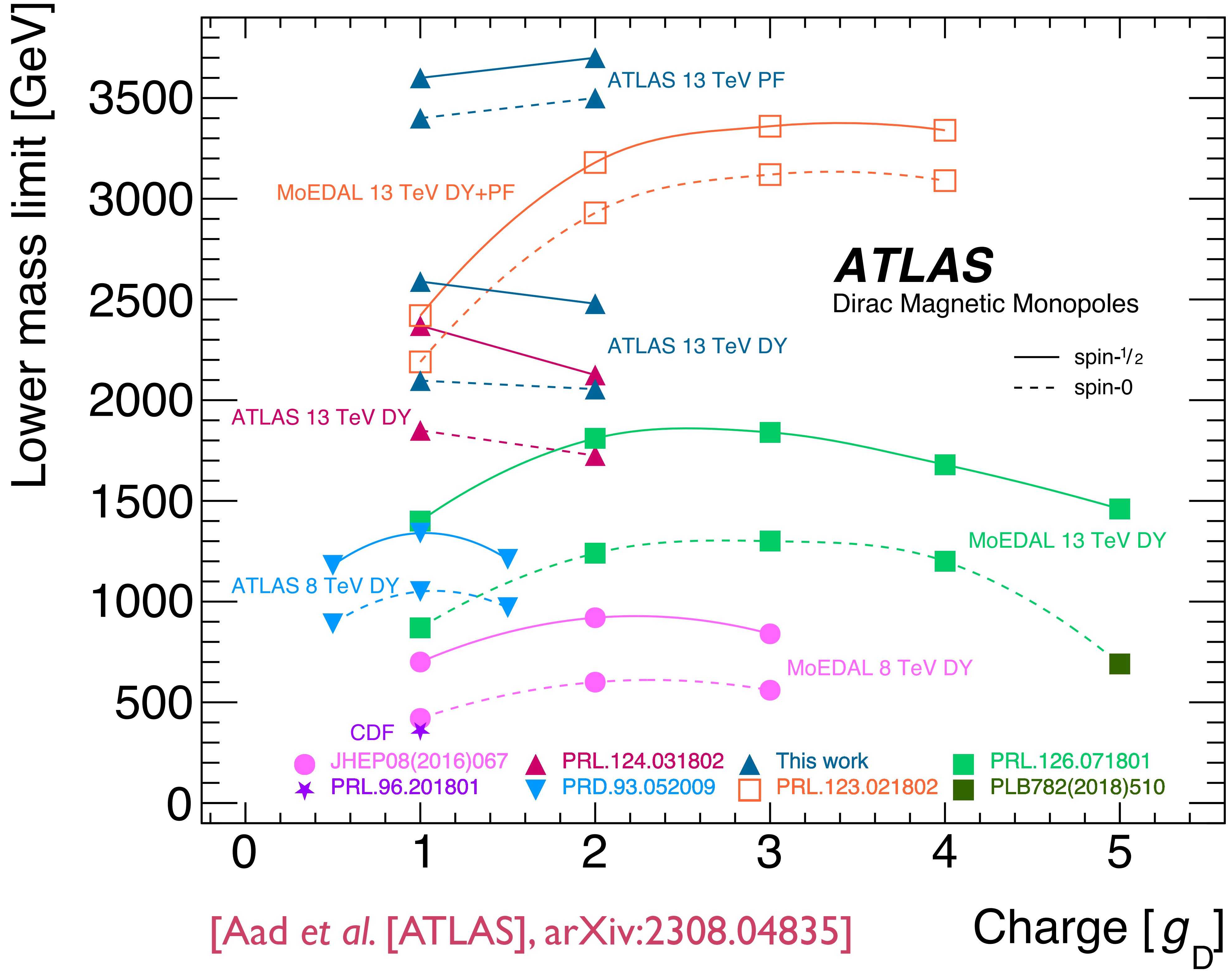


- **ATLAS:** general purpose detector by utilizing highly ionizing signature, better limits [Aad *et al.* [ATLAS], arXiv:2308.04835]

	95% CL lower limits on the mass of HIPs [TeV]						
	$\lvert g\rvert = 1g_D$	$\lvert g\rvert = 2g_D$	$\lvert z\rvert = 20$	$\lvert z\rvert = 40$	$\lvert z\rvert = 60$	$\lvert z\rvert = 80$	$\lvert z\rvert = 100$
DY spin-0	2.1	2.1	1.4	1.8	1.9	1.8	1.7
DY spin-½	2.6	2.5	1.8	2.2	2.2	2.1	1.9
PF spin-0	3.4	3.5	2.1	2.8	2.9	2.8	2.5
PF spin-½	3.6	3.7	2.5	3.1	3.1	3.0	2.5

- **MoEDAL:** passive detection methodologies tuned for HIPs, good for higher charge [Acharya *et al.* [MoEDAL], EPJC 82 (2022)]

	Electric charge (e)											
	15	20	25	50	75	100	125	130	140	145	150	175
Spin	95% CL mass limits [GeV/c^2]											
0	70	120	190	560	580	550	500	490	470	470	460	400
1/2 (γ-exchange)	180	280	440	780	780	730	660	640	580	520	500	-
1/2 (γ/Z^*-exchange)	170	310	440	780	780	710	640	620	620	510	580	-
1	280	430	590	1000	1020	1000	960	950	930	920	900	870



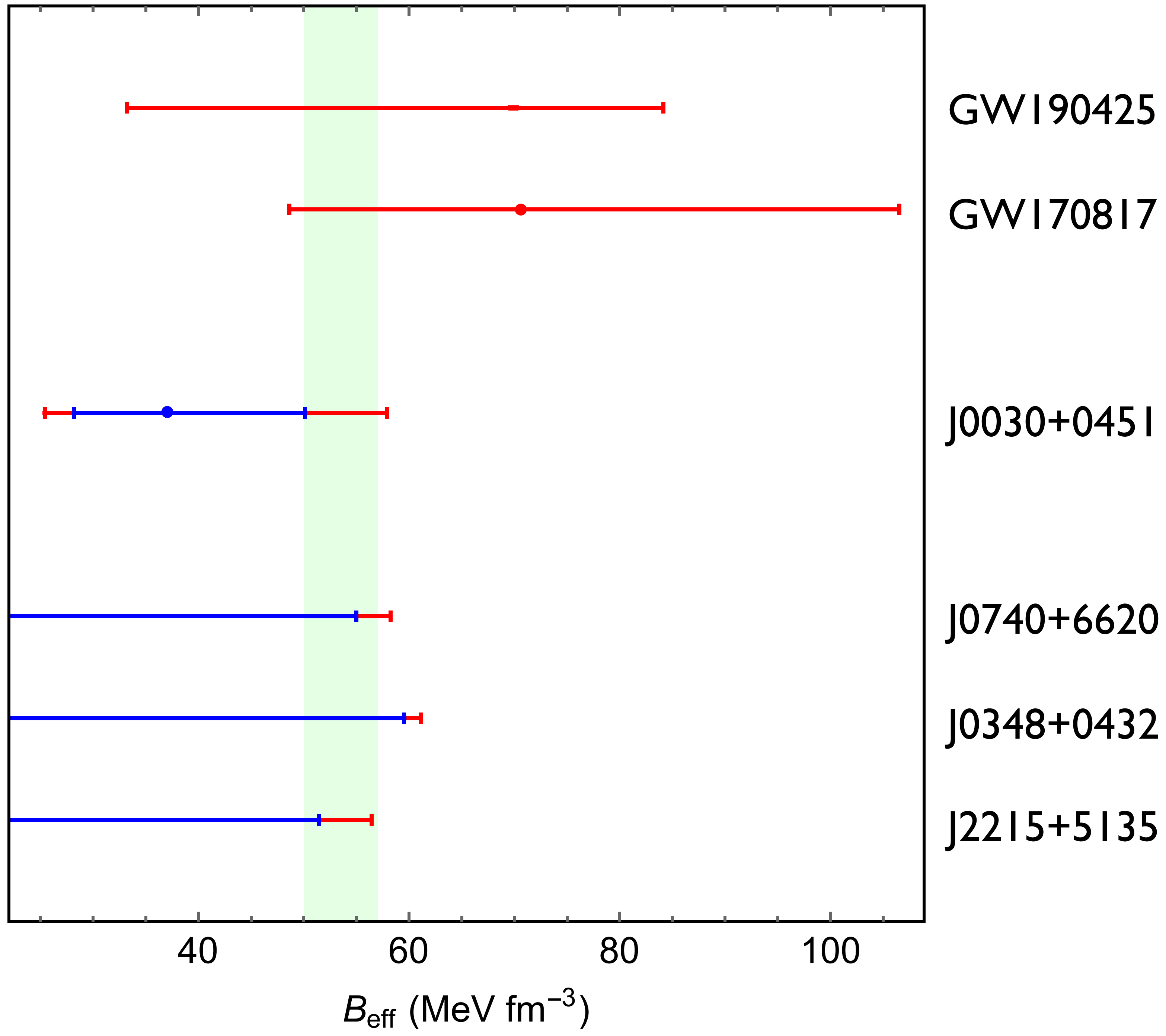
[Aad *et al.* [ATLAS], arXiv:2308.04835]

Astrophysical implications: ud quark stars (udQSs)

udQM nucleates inside hadronic stars through quantum tunneling, forming pure ud quark stars (udQSs)

[JR and Zhang, PRD 102 (2020)]

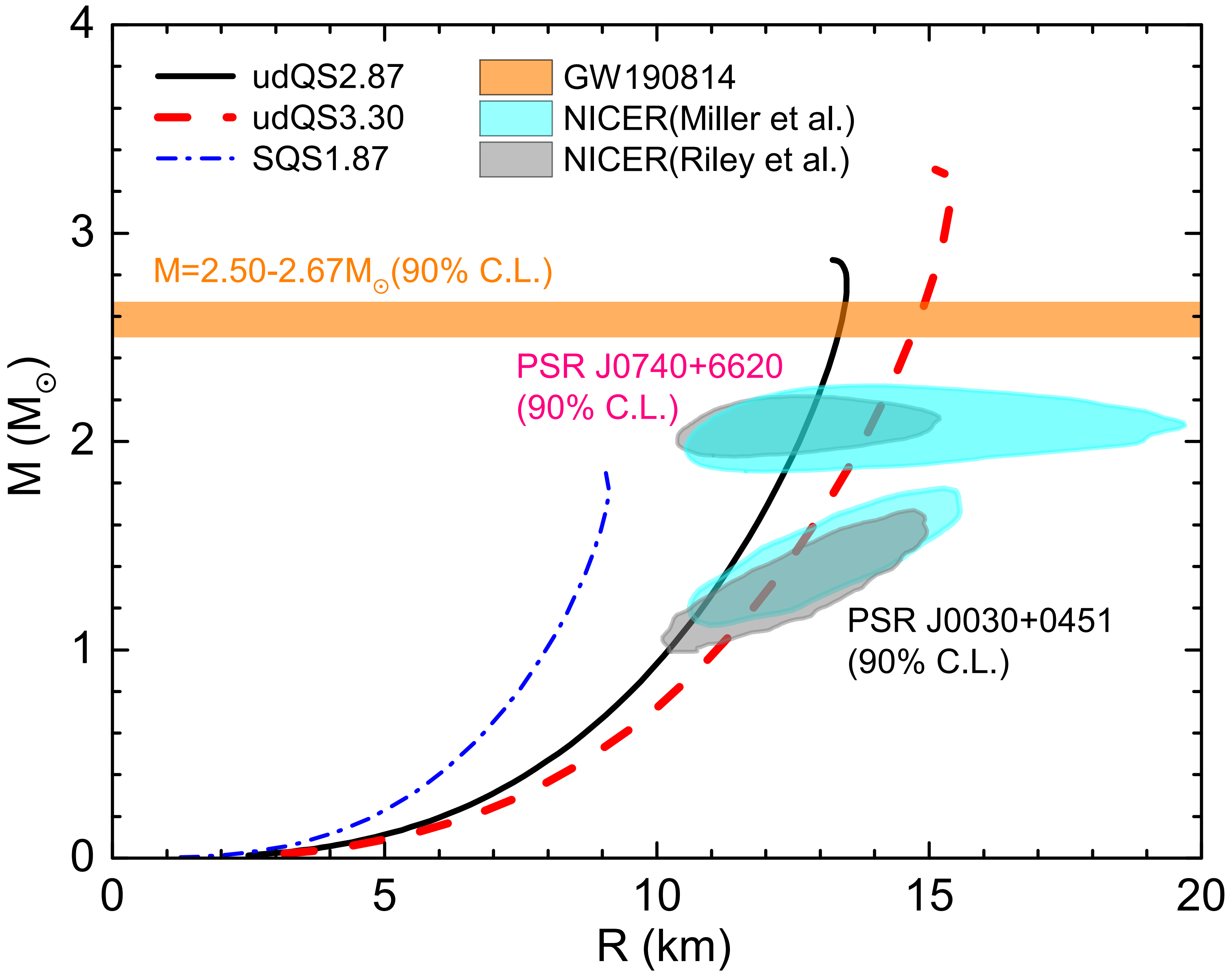
- **“All compact stars being udQSs”:** instantaneous transition typically predicted; consistent with observations



[Zhao, *et al.* PRD 100 (2019), Ren and Zhang, PRD 102 (2020)]

- **“Two family scenario”:** high-mass stars are udQSs and low-mass ones are hadronic stars

GW190814 as udQS (confining quark matter)



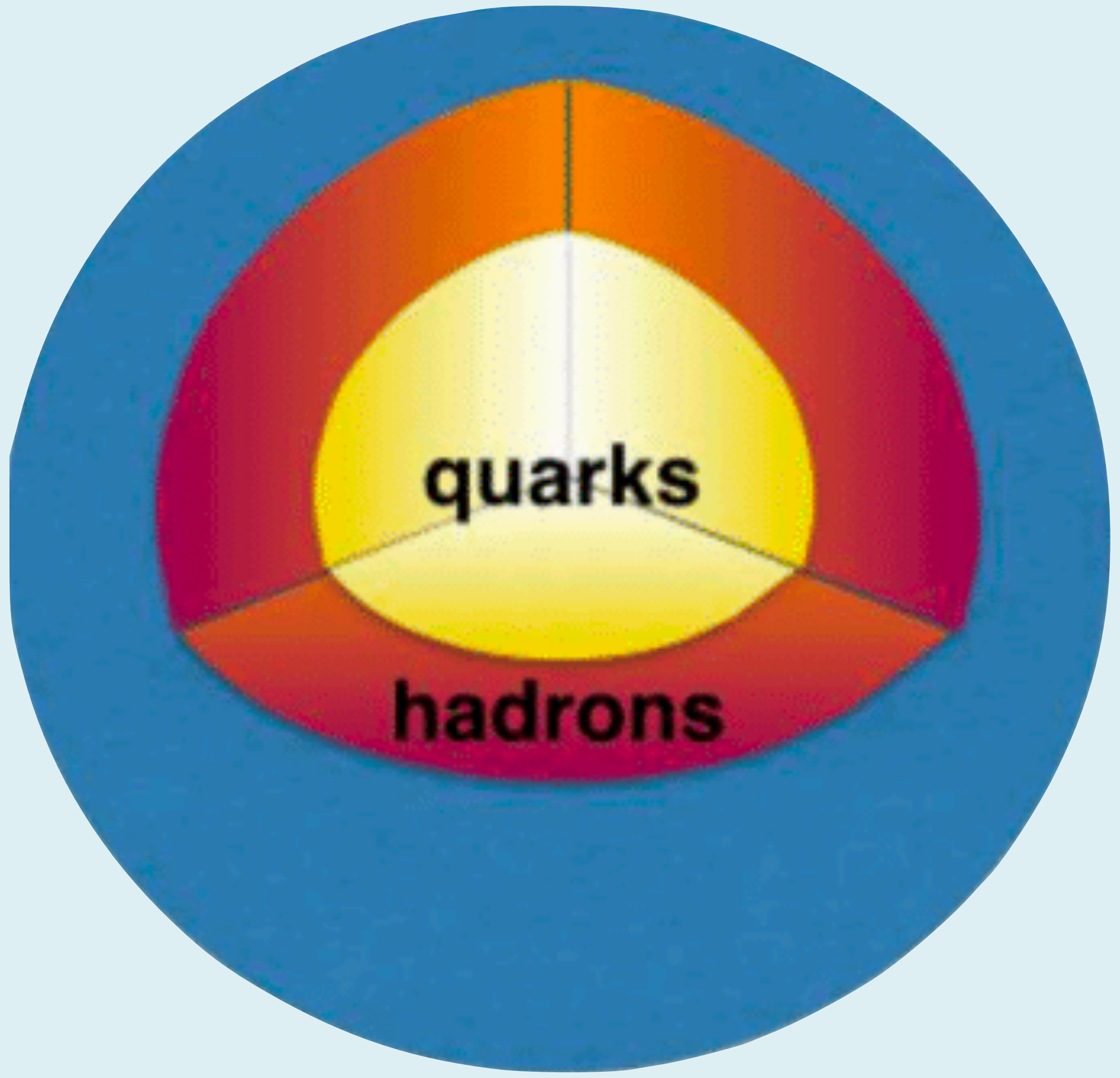
[Cao, Chen, Chu and Zhou, PRD 106 (2022)]

Hybrid stars may have an inverted structure

Hybrid stars: maybe an inverted structure?

Conventional picture

Hadronic matter → Deconfined quark matter



As density increases, nucleons may get decomposed into deconfined strange quark matter, forming hybrid stars

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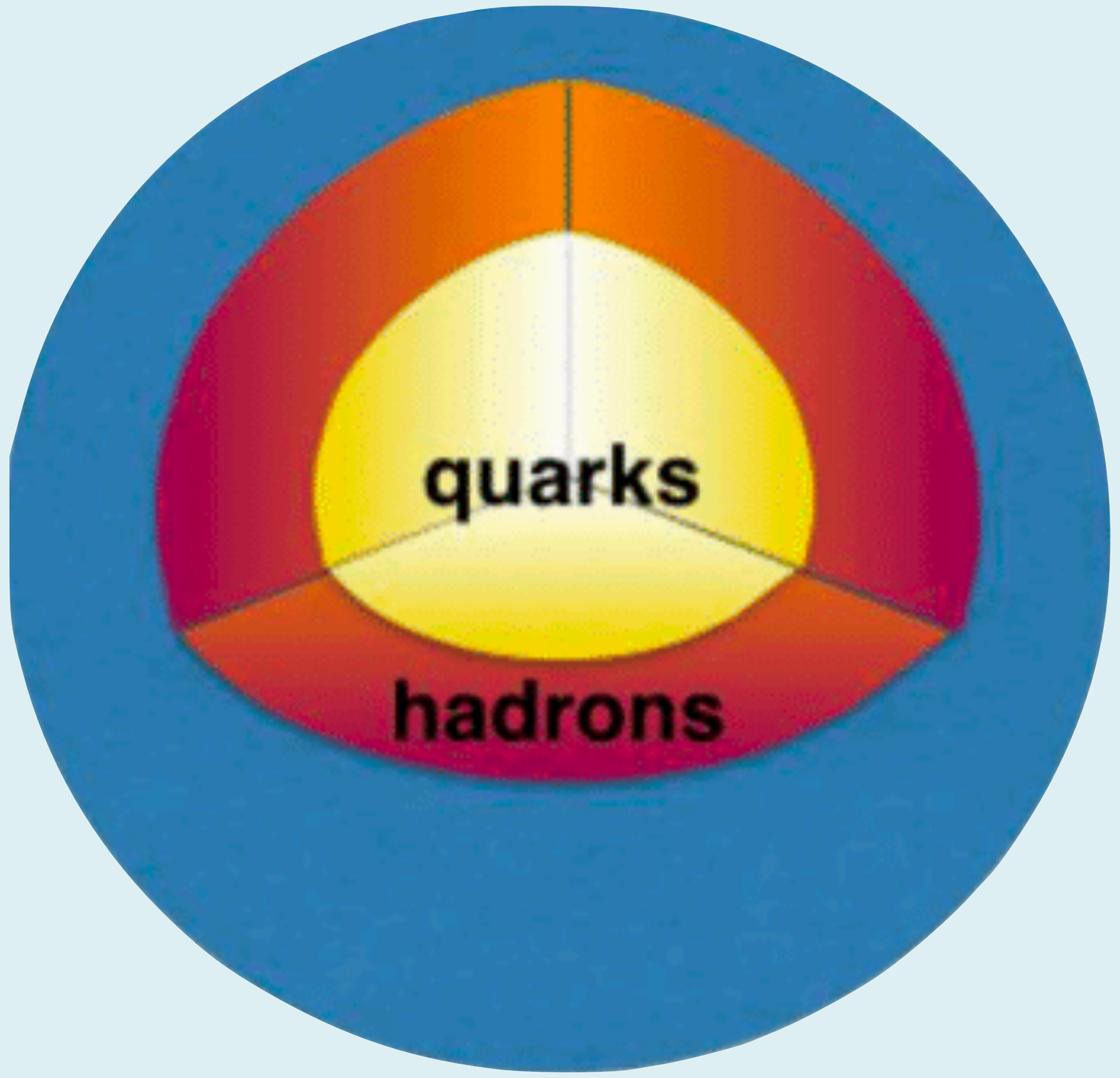

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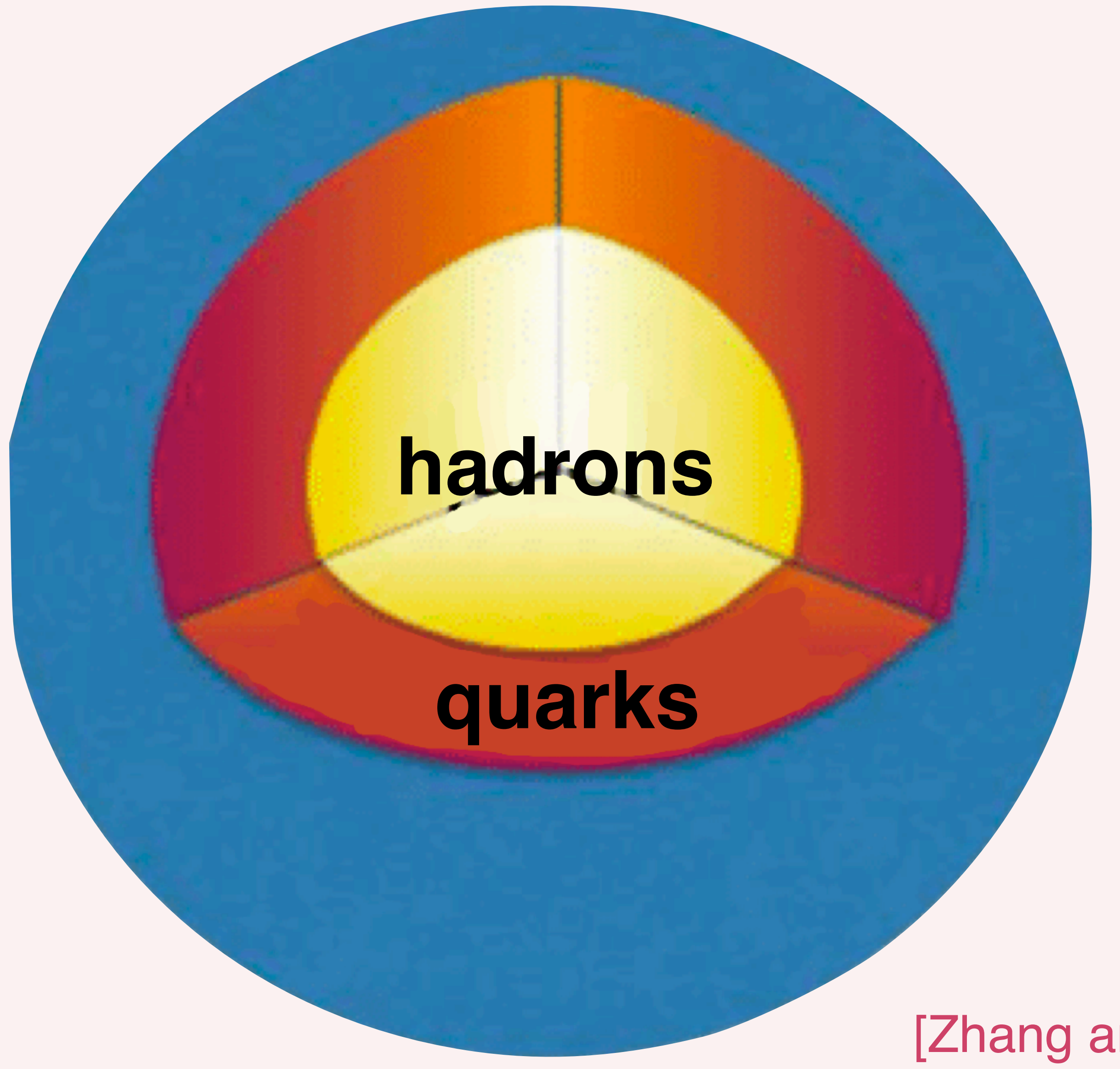
QM hypothesis

Quark matter → Hadronic matter → Deconfined quark matter



[Zhang and JR, PRD 108 (2023)]

If HM is more stable than QM at intermediate density, inverted structure can be formed by NSs hit by QM or quantum nucleation of QM (HM) inside NSs (QSs)

Crossing from QM to HM

Considering a sharp phase transition (Maxwell construction), QM to HM transition occurs when $\mu_{\rm Q}$ and $\mu_{\rm H}$ cross, i.e. a softer HM EOS and stiffer QM EOS at low densities, given $\mu(P) \approx \mu(0) + \int_0^P dP' \frac{1}{n(P')}$ [Zhang and JR, PRD 108 (2023)]

QM EOS

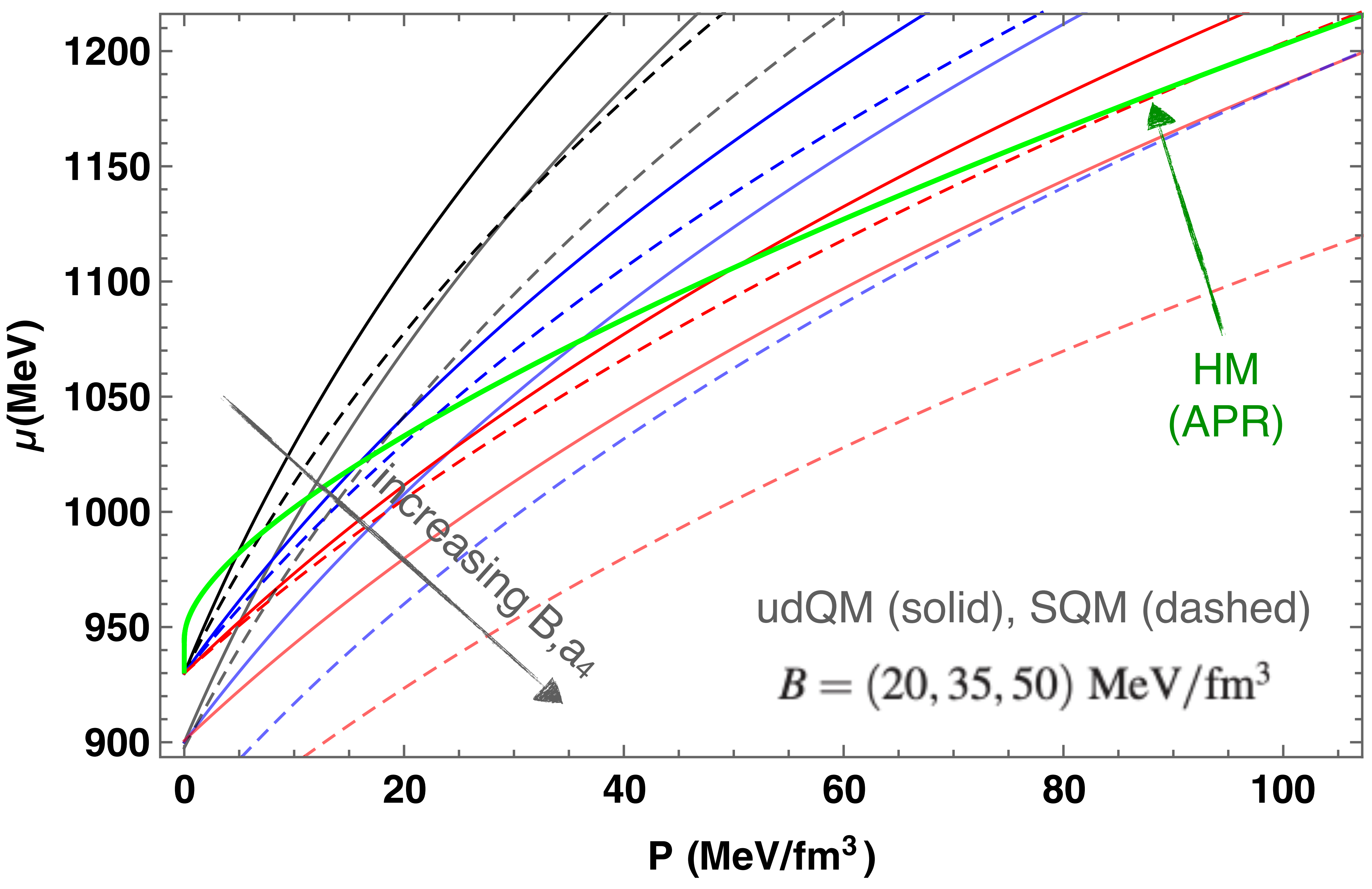
QCD corrections

bare mass or pairing

flavor dependent bag constant

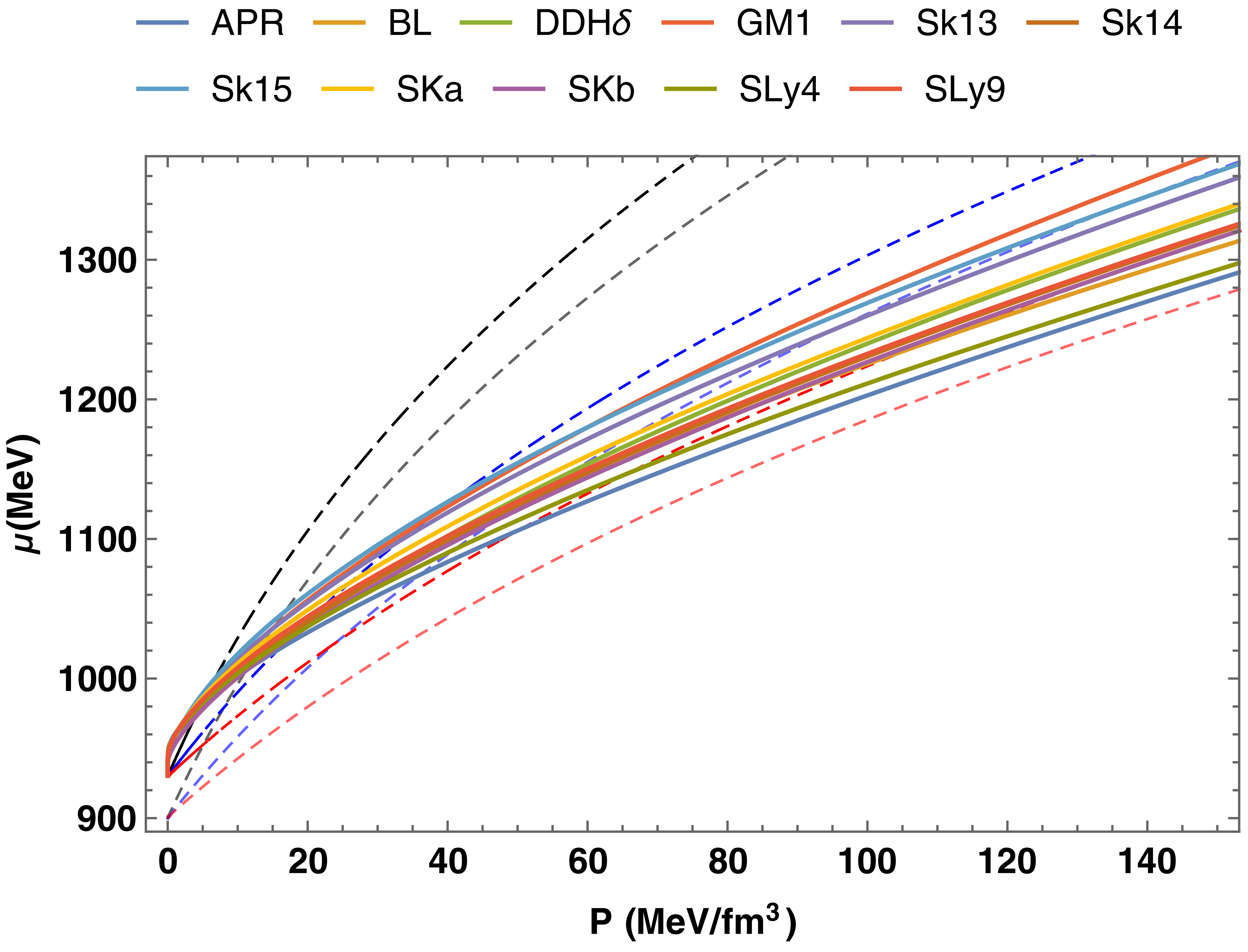
General grand potential: $\Omega = -\frac{\xi_4 a_4}{4\pi^2}\mu^4 - \frac{a_2}{\pi^2}\mu^2 + B$

$$\longrightarrow \mu_{\rm Q} = \frac{3\sqrt{2}}{(a_4\xi_4)^{1/4}}\sqrt{[(P+B)\pi^2+\lambda^2]^{1/2}-\lambda}. \quad \lambda = a_2/\sqrt{\xi_4 a_4}$$



HM EOS

Considering representative models from CompOSE:



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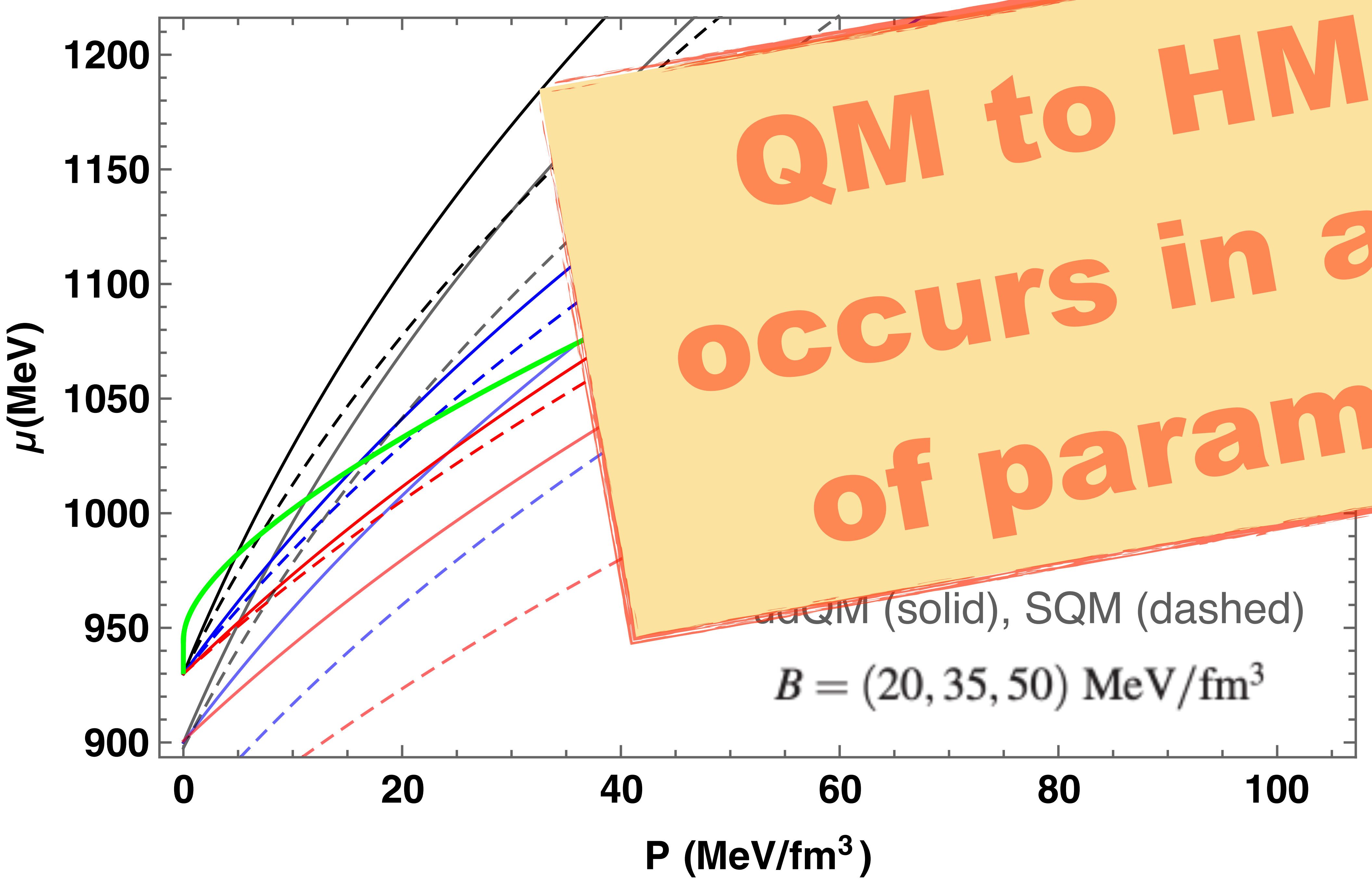

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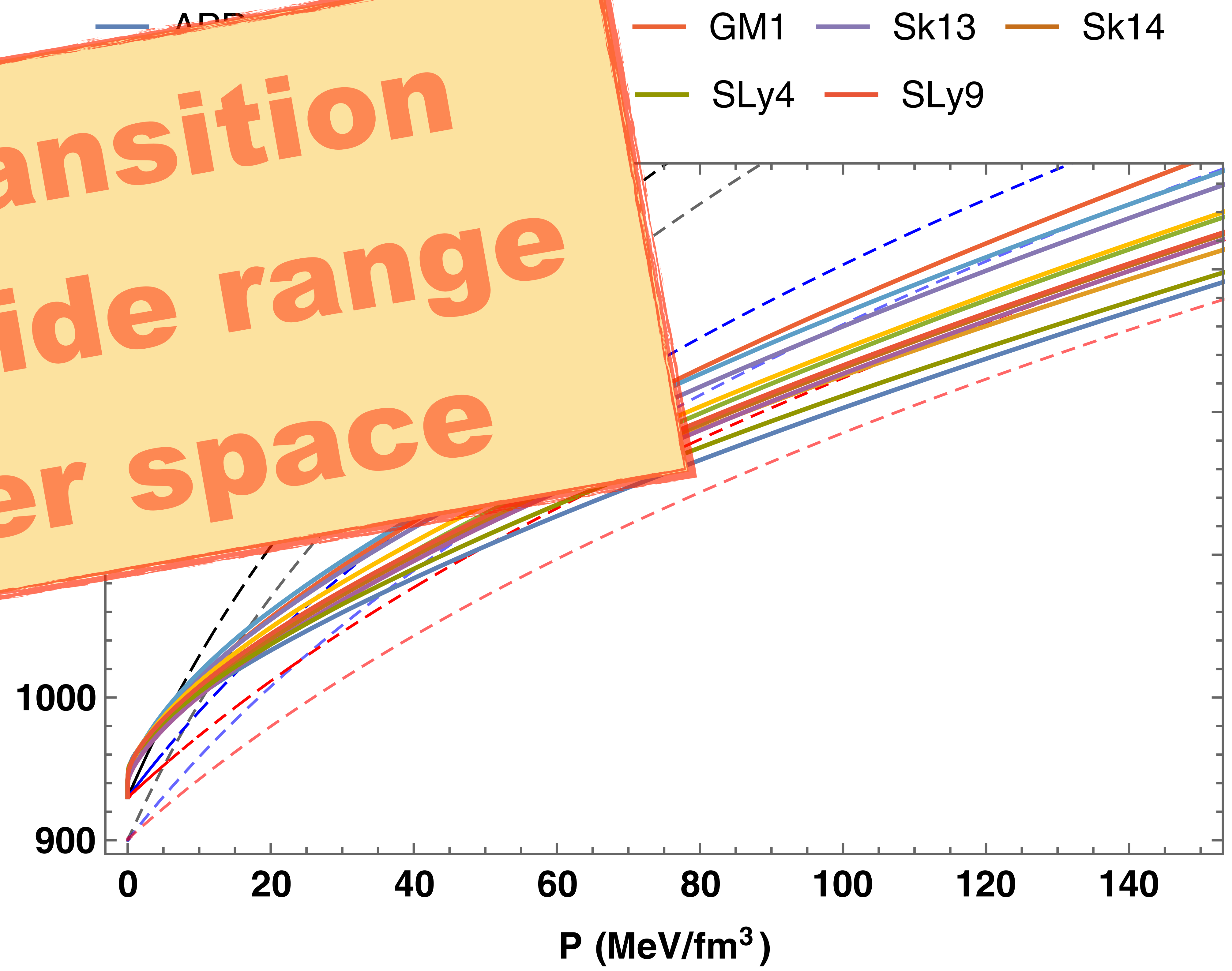


QM to HM transition occurs in a wide range of parameter space

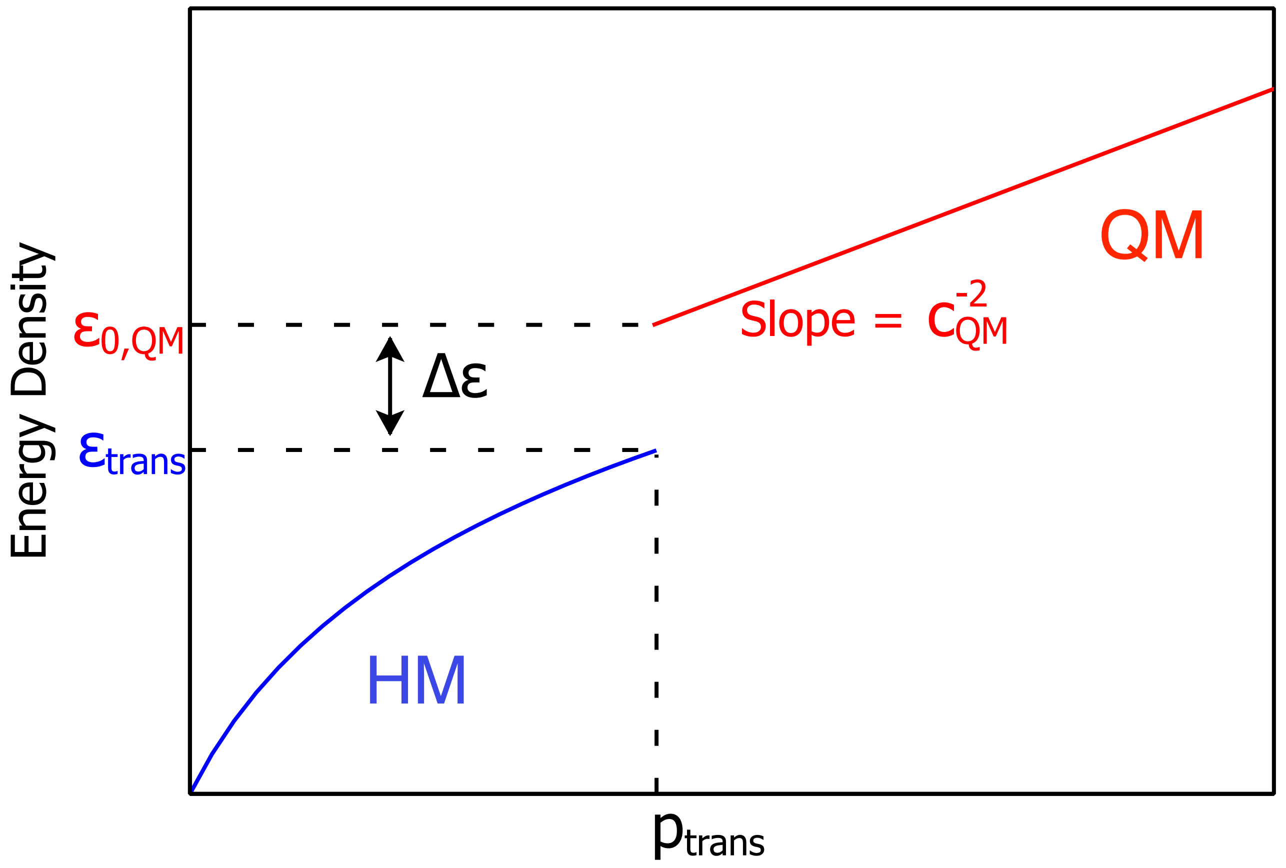
Comparison to conventional hybrid stars

- **Conventional hybrid stars**

Constant-sound-speed (CSS) parametrizations

[Alford, Han and Prakash, PRD 88 (2013)]

$$\rho(P)=\begin{cases}\rho_{\mathrm{HM}}(P) & P<P_{\mathrm{trans}}\\ \rho_{\mathrm{trans}}+\Delta\rho+c_s^{-2}(P-P_{\mathrm{trans}}) & P>P_{\mathrm{trans}}\end{cases},$$



a generic QM equation of state allowing for a first order phase transition between HM and QM

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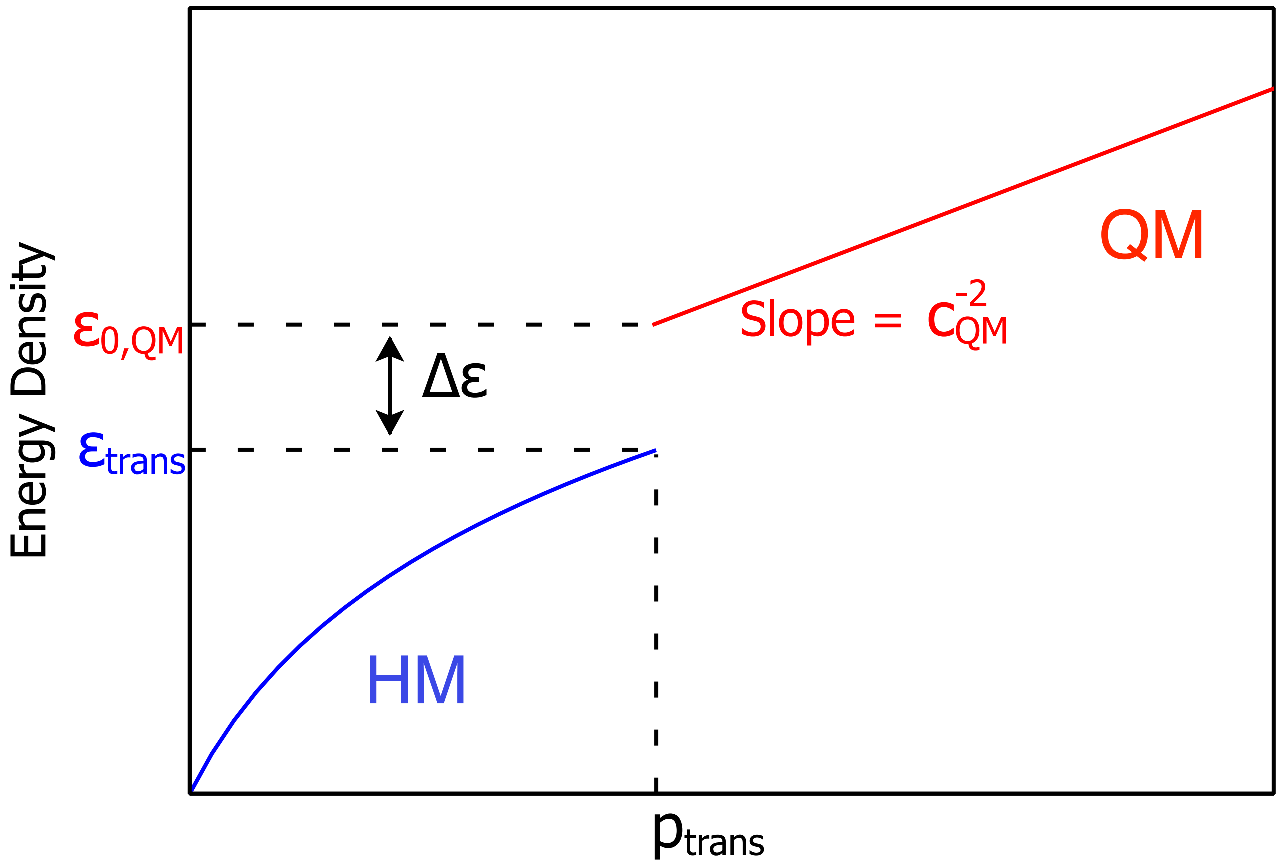


a generic QM equation of state allowing for a first order phase transition between HM and QM

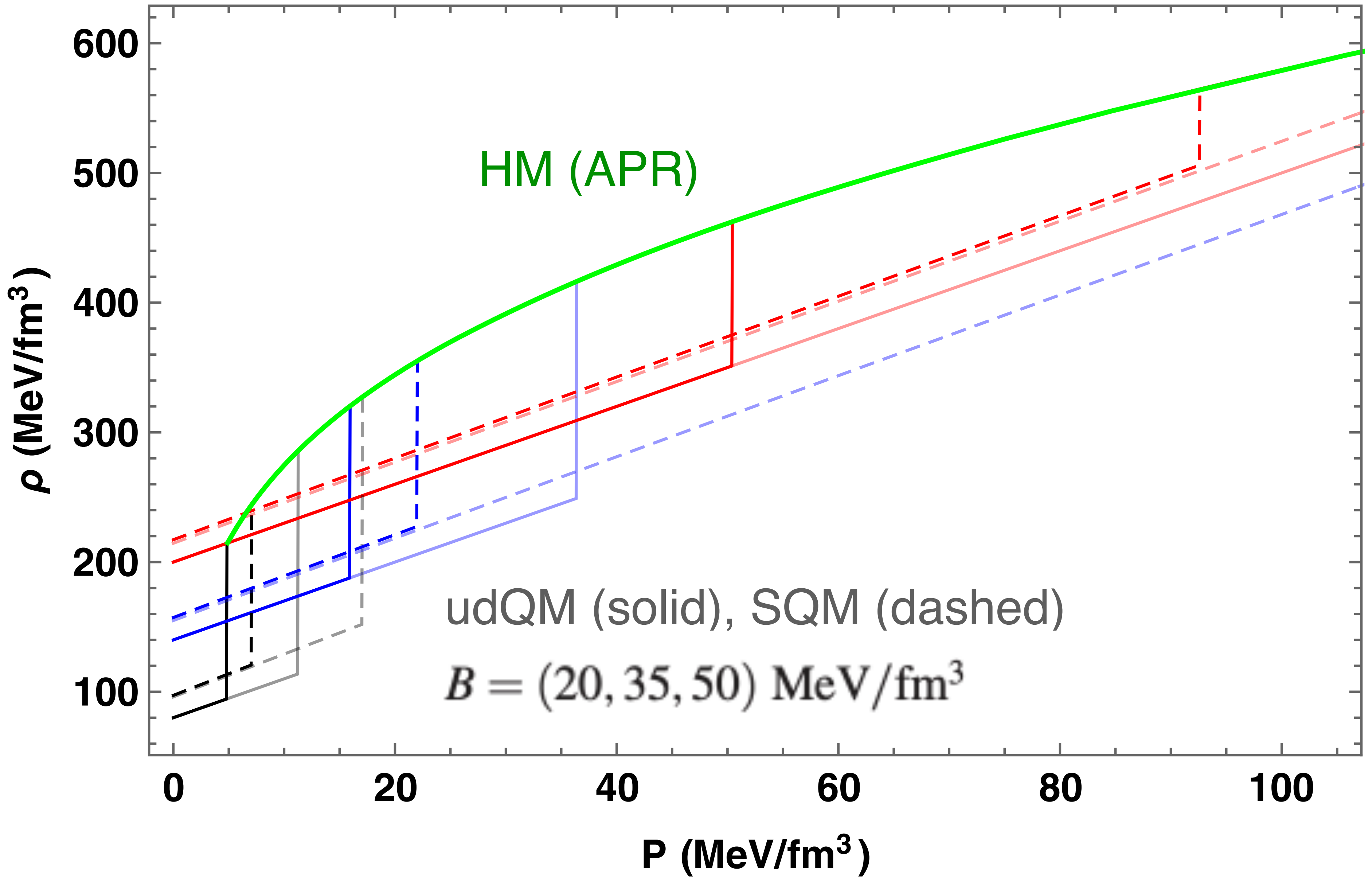
- **Inverted hybrid stars**

$$\rho(P) = \begin{cases} \rho_{\rm QM}(P) & P < P_{\rm trans} \\ \rho_{\rm HM}(P) & P \gtrsim P_{\rm trans} \end{cases},$$

$$\rho_{\rm trans} = \rho_{\rm QM}(P_{\rm trans})$$

$$\Delta\rho = \rho_{\rm HM}(P_{\rm trans}) - \rho_{\rm QM}(P_{\rm trans})$$

[Zhang and JR, PRD 108 (2023)]



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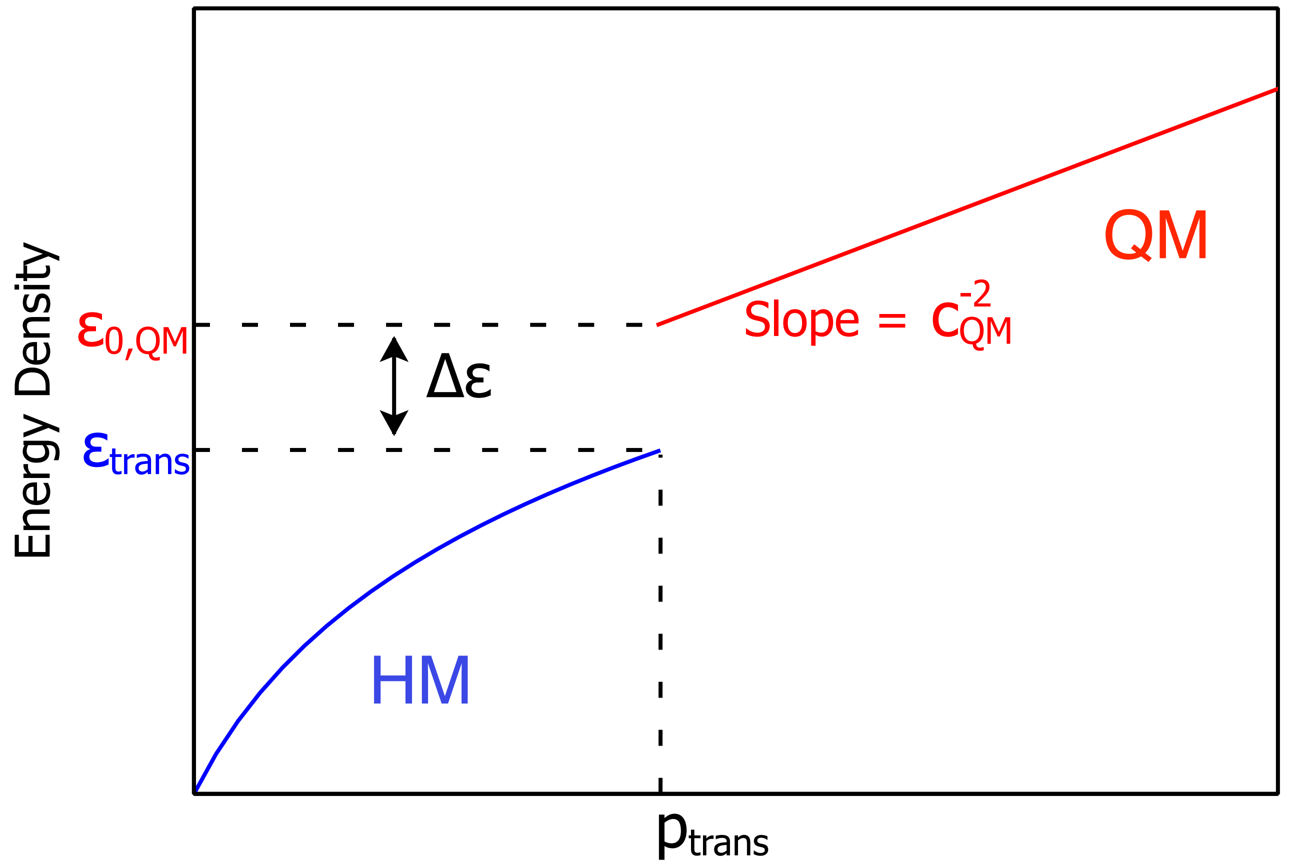

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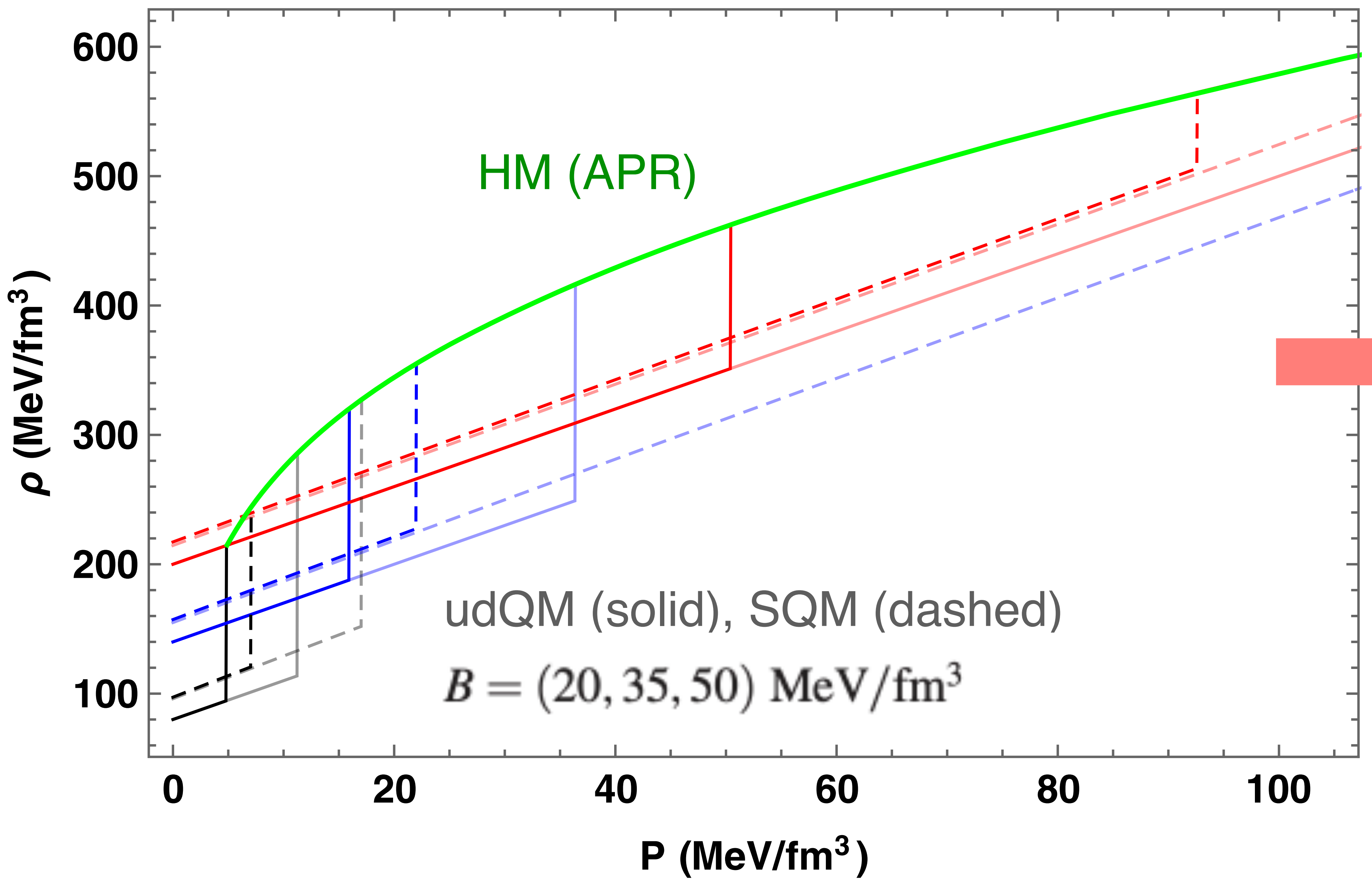


$$P_{\rm trans} = 5 \sim 96(7 \sim 93)\ {\rm MeV/fm^3},$$

$$\rho_{\rm trans} = 94 \sim 489(121 \sim 506)\ {\rm MeV/fm^3},$$

$$\Delta\rho = 83 \sim 111(59 \sim 175)\ {\rm MeV/fm^3},$$

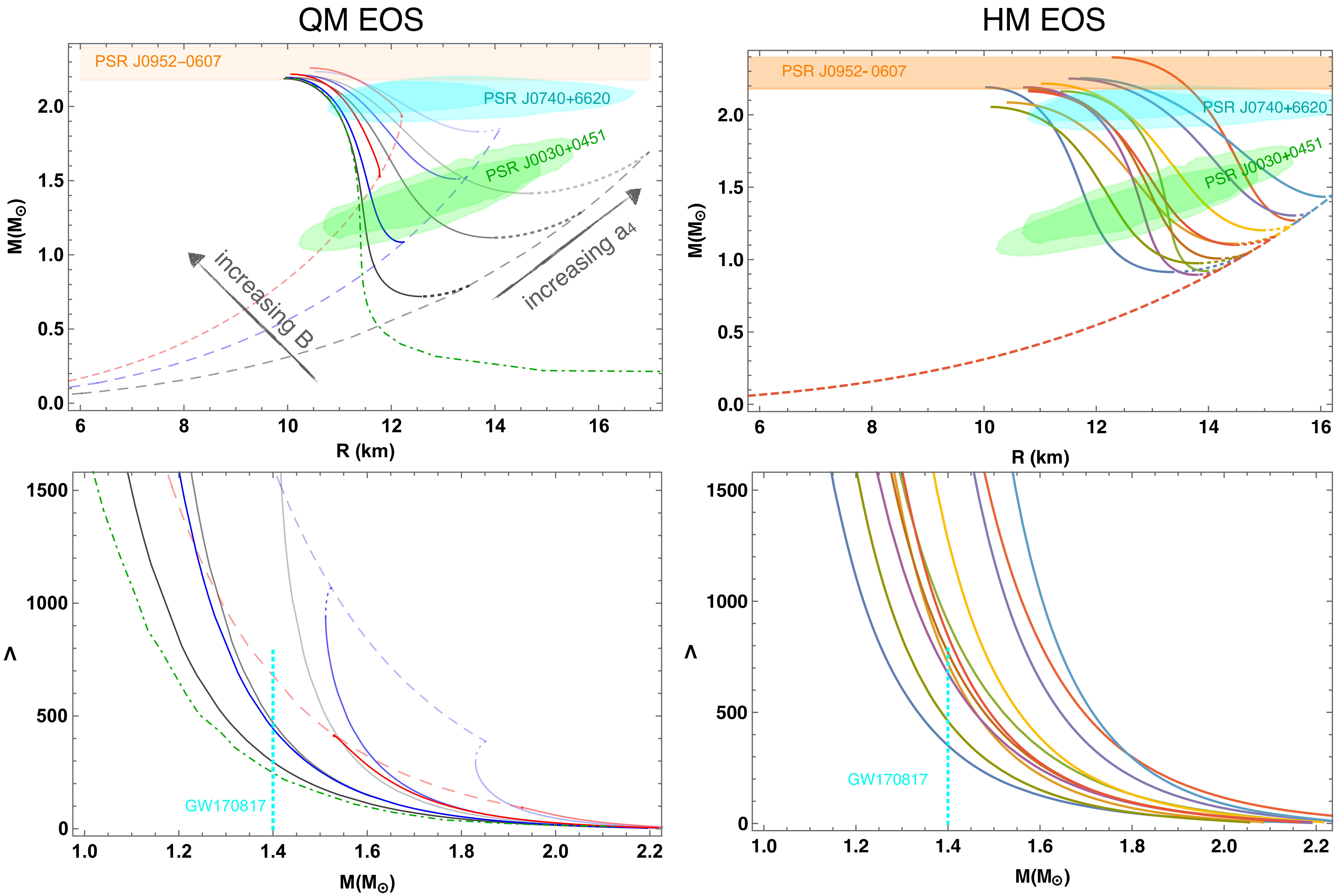
$$\Delta\rho/\rho_{\rm trans} = 0.17 \sim 1.51(0.12 \sim 1.15)$$

cover a large variation of the CSS parameters

Astrophysical implications of inverted hybrid stars

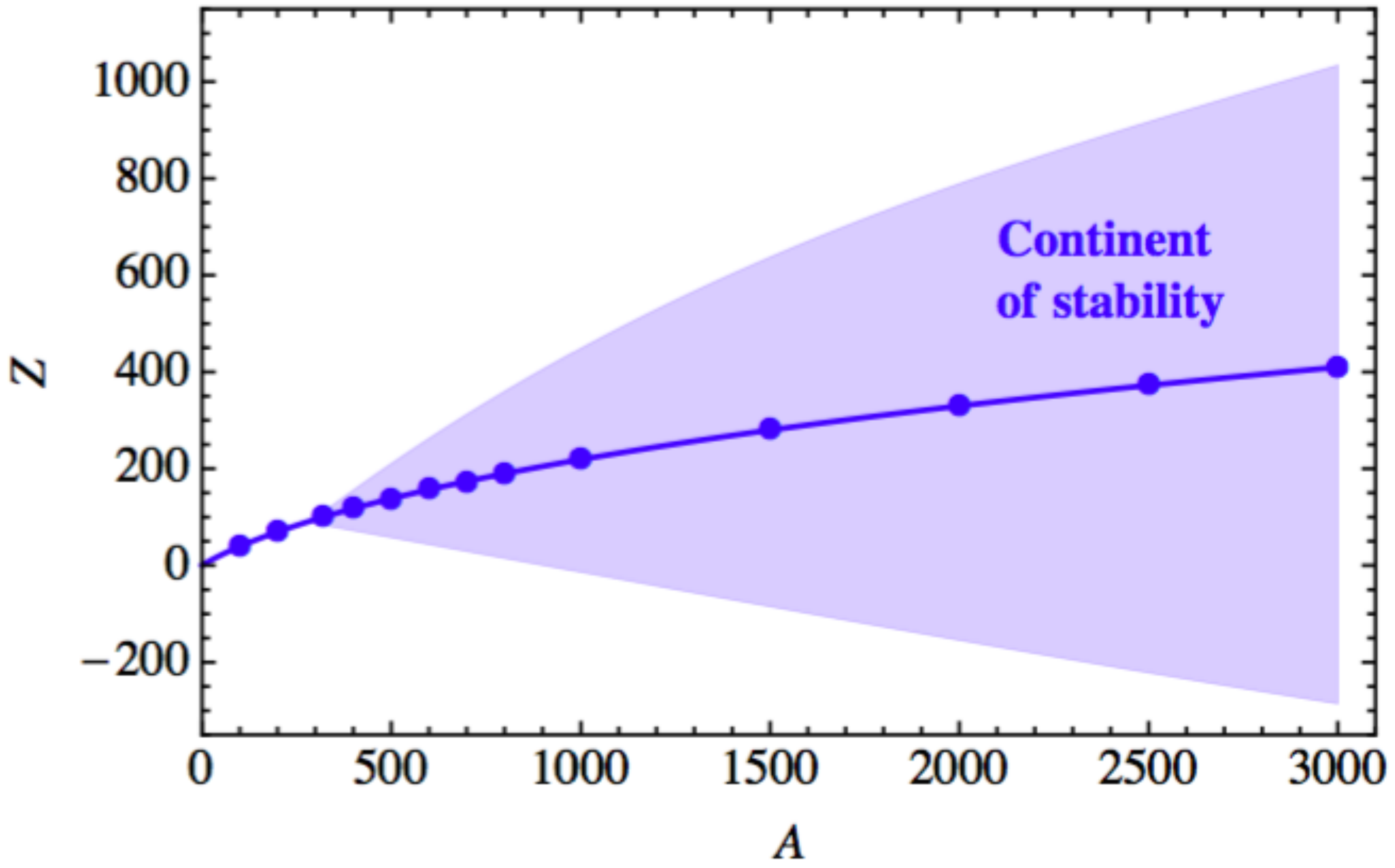
- Its *M* larger than HSs of the same *R*, while (R,Λ) in between those for QSs and HSs of the same *M*
- Interplay between HM and QM helps to reconcile astrophysical constraints at low and high masses
- “Twin star” configurations (identical *M* but very different *R*) exist in cases of small B and large a_4
- The new stellar structure leaves more space open for EOS of both HM and QM

[Zhang and JR, PRD 108 (2023)]

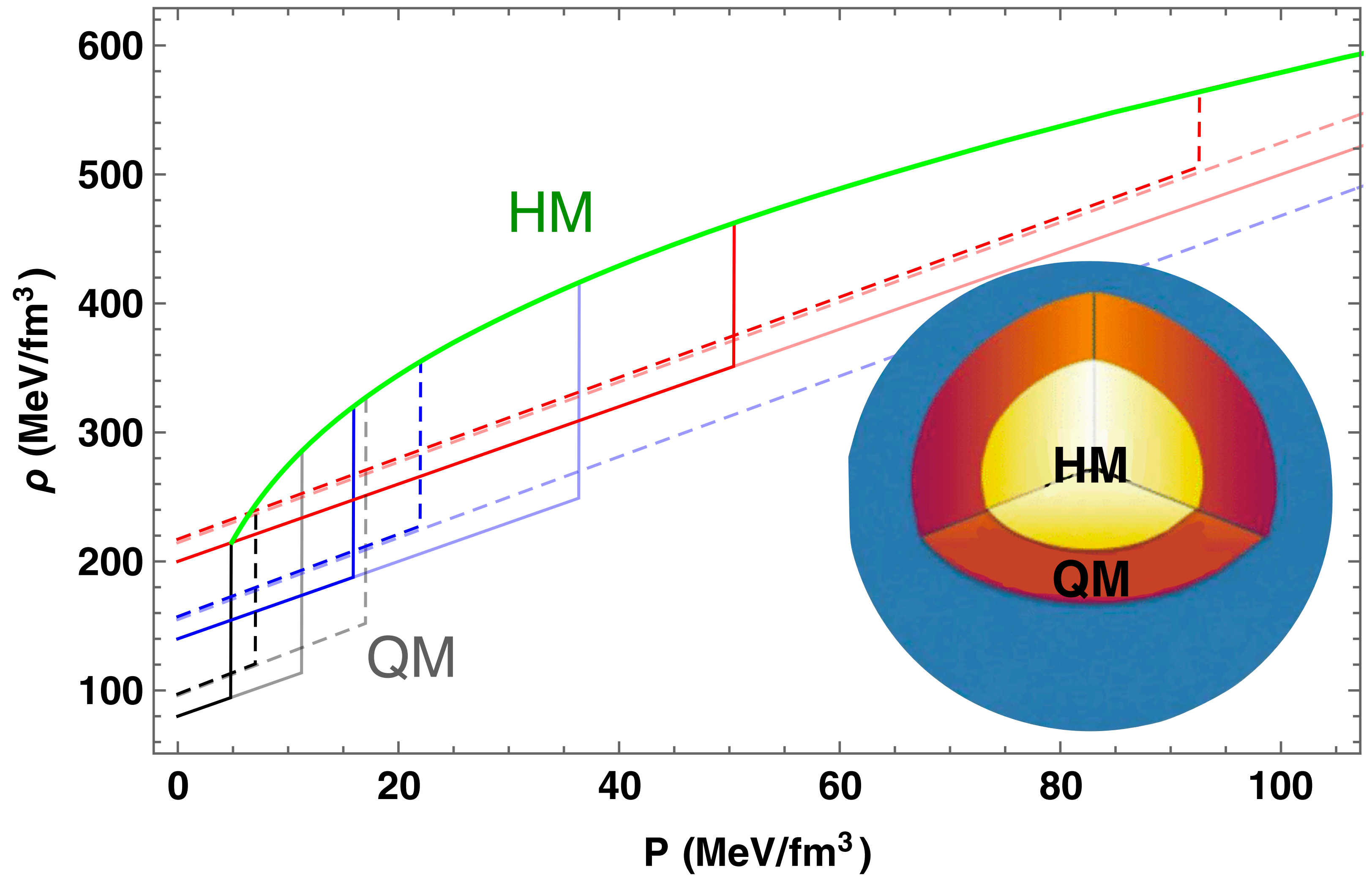


Summary

- ## Quark matter may not be strange
  - udQM generally has lower bulk E/A than normal nuclei and SQM; serve as ground stater at zero *T* and *P* for *A*>300; ensure stability of ordinary nuclei
  - Production of udQM by the fusion of heavy elements within the new “continent of stability”…



- ## Hybrid stars may have an inverted structure
  - Under the QM hypothesis, inverted hybrid stars naturally arise (no need to fine-tune) when the HM becomes more stable in the intermediate density
  - Astrophysical implications of inverted hybrid stars deserve further study…



See Yudong Luo’s talk for GW asteroseismology of inverted hybrid stars

Thank you!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Institute of High Energy Physics Chinese Academy of Sciences

Comparing udQM and SQM hypothesis

- Transition usually takes place at a higher pressure for SQM compared to udQM, and thus less parameter space exists to realize stable inverted hybrid stars in the SQM hypothesis
- The parameter space for inverted hybrid stars with a SQM crust is more constrained by the astrophysical observations, especially for hadronic EOSs that are relatively stiffer than APR at low pressure like SLy4