

Constraints on dense nuclear matter from the strong interaction

Jens Braun
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KHuK Meeting 2020

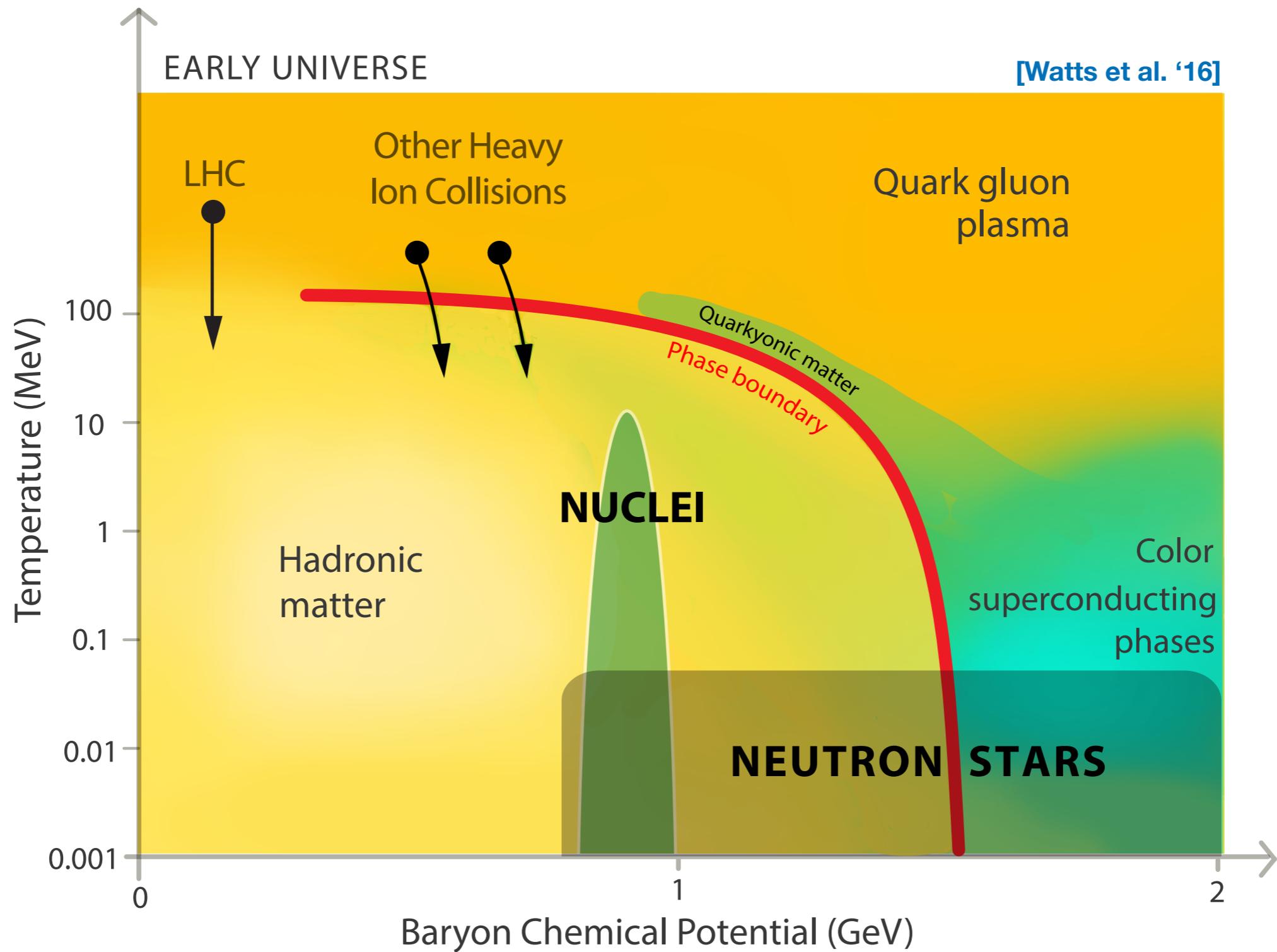


The talk between you
and your weekend
(my apologies 😬)

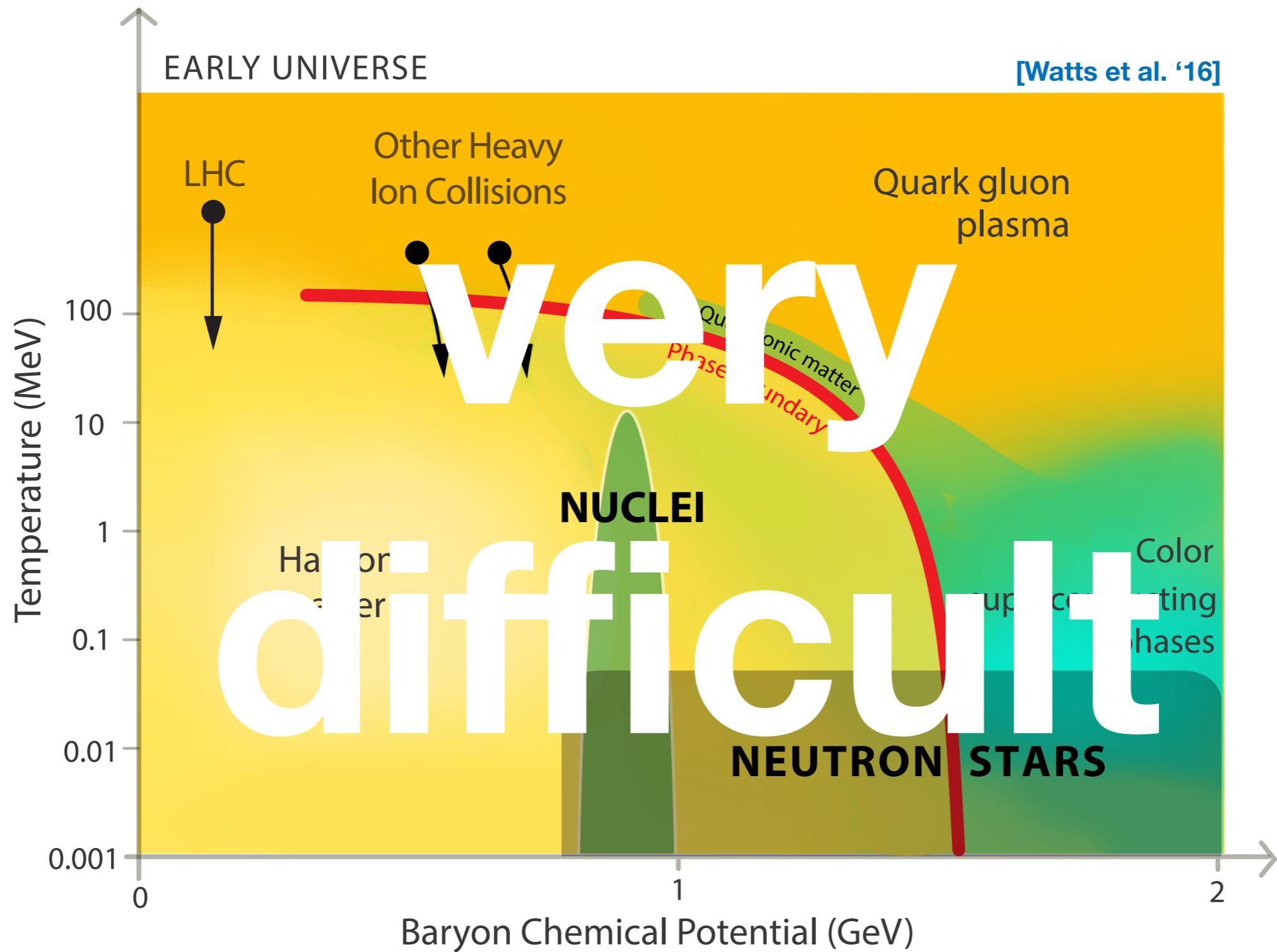
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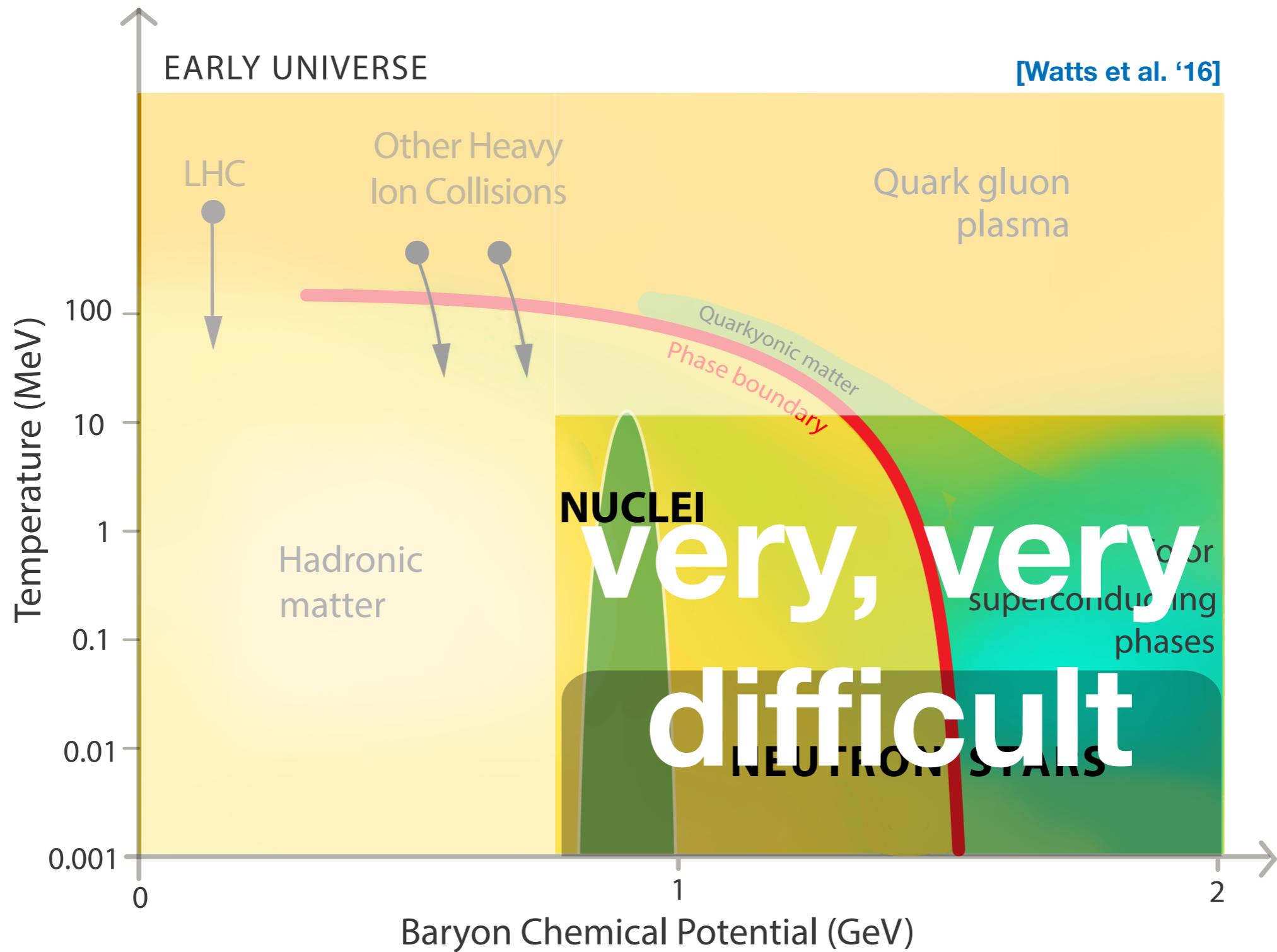
Phases of strong-interaction matter



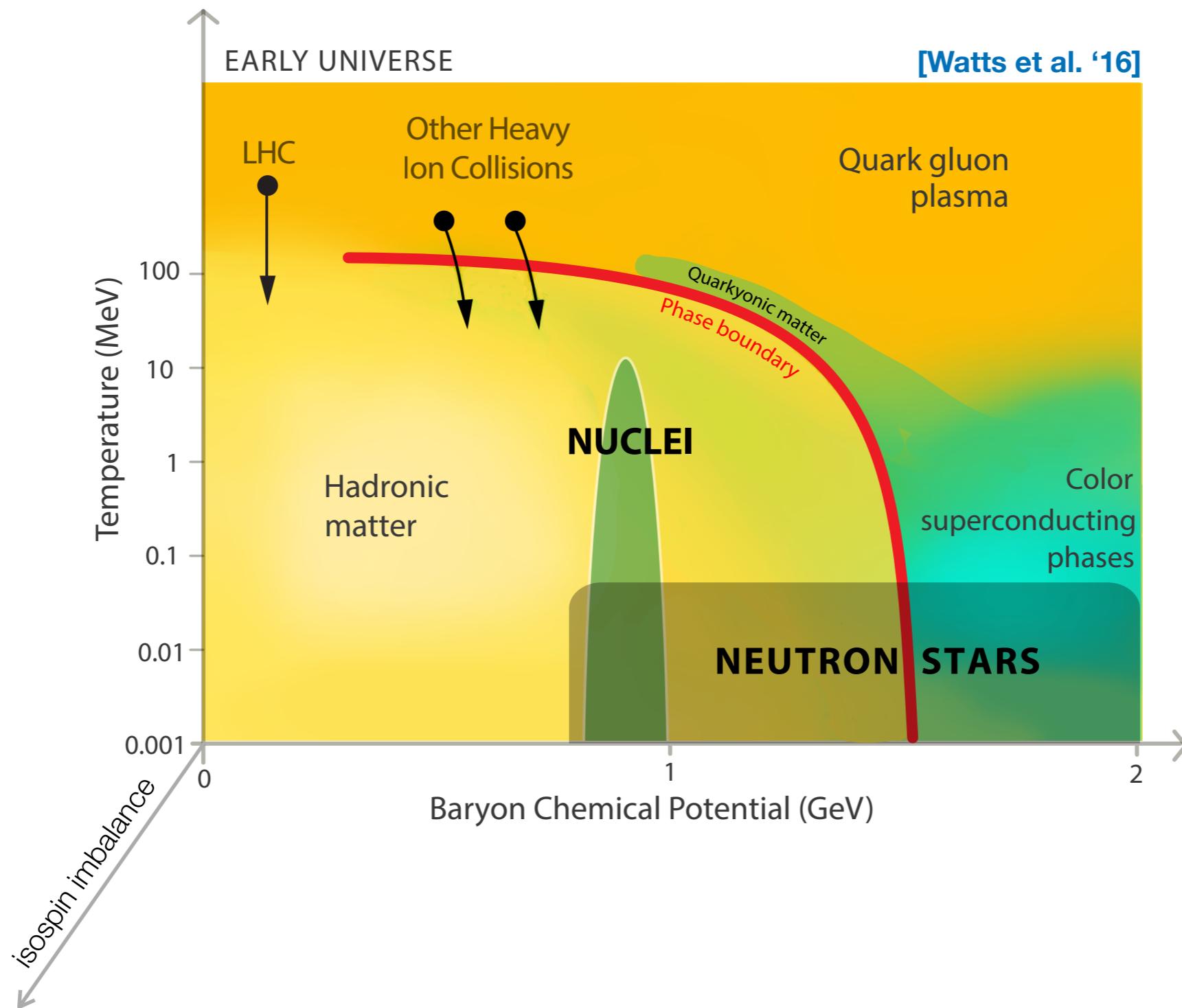
Phases of strong-interaction matter



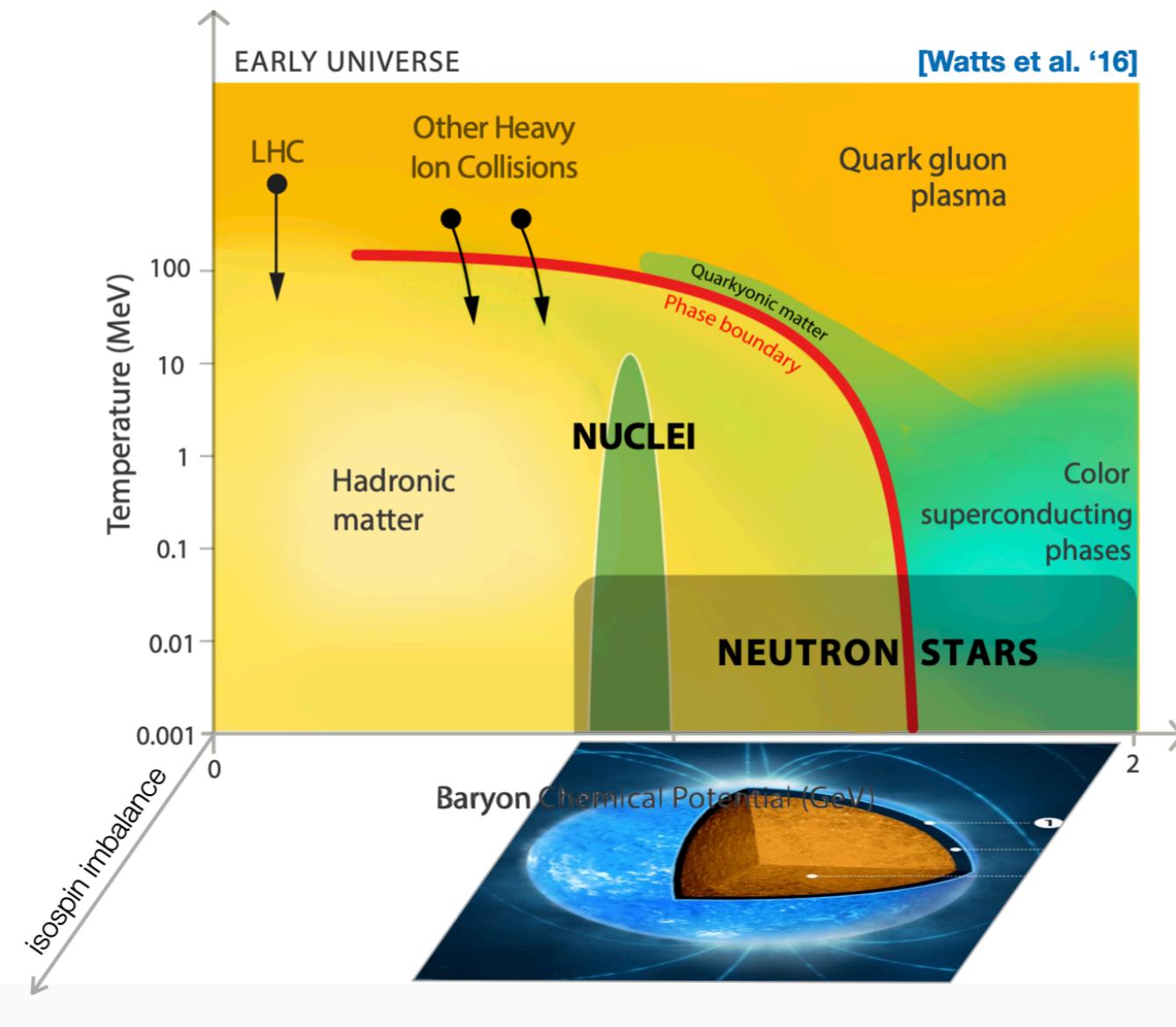
Phases of strong-interaction matter



Making things more difficult ...

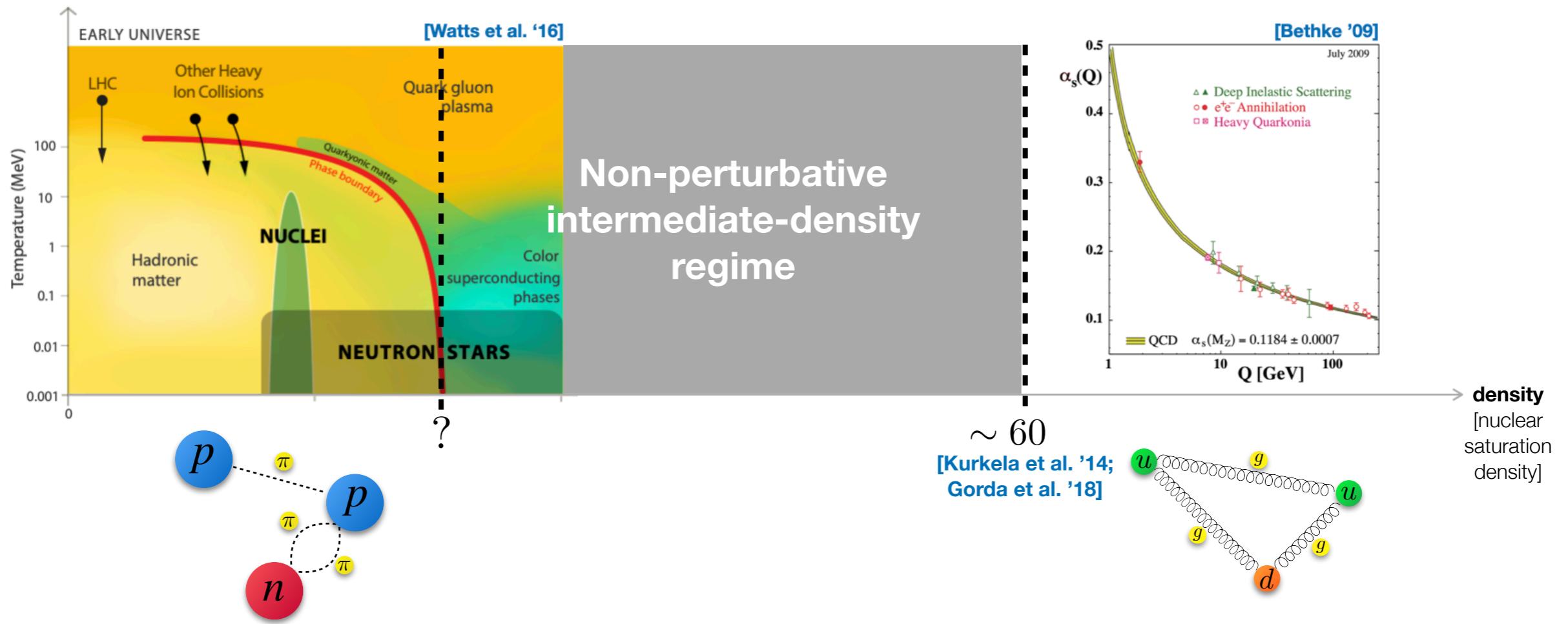


Astrophysical applications: equation of state (EOS)



Astrophysical applications require the EOS as input over a **wide range of densities** (beyond 2-3 saturation density), proton fractions, and also temperatures ...

Dense QCD matter: effective degrees of freedom



- Spontaneous chiral symmetry breaking
- Protons & neutrons
- Systematic studies via chiral EFT

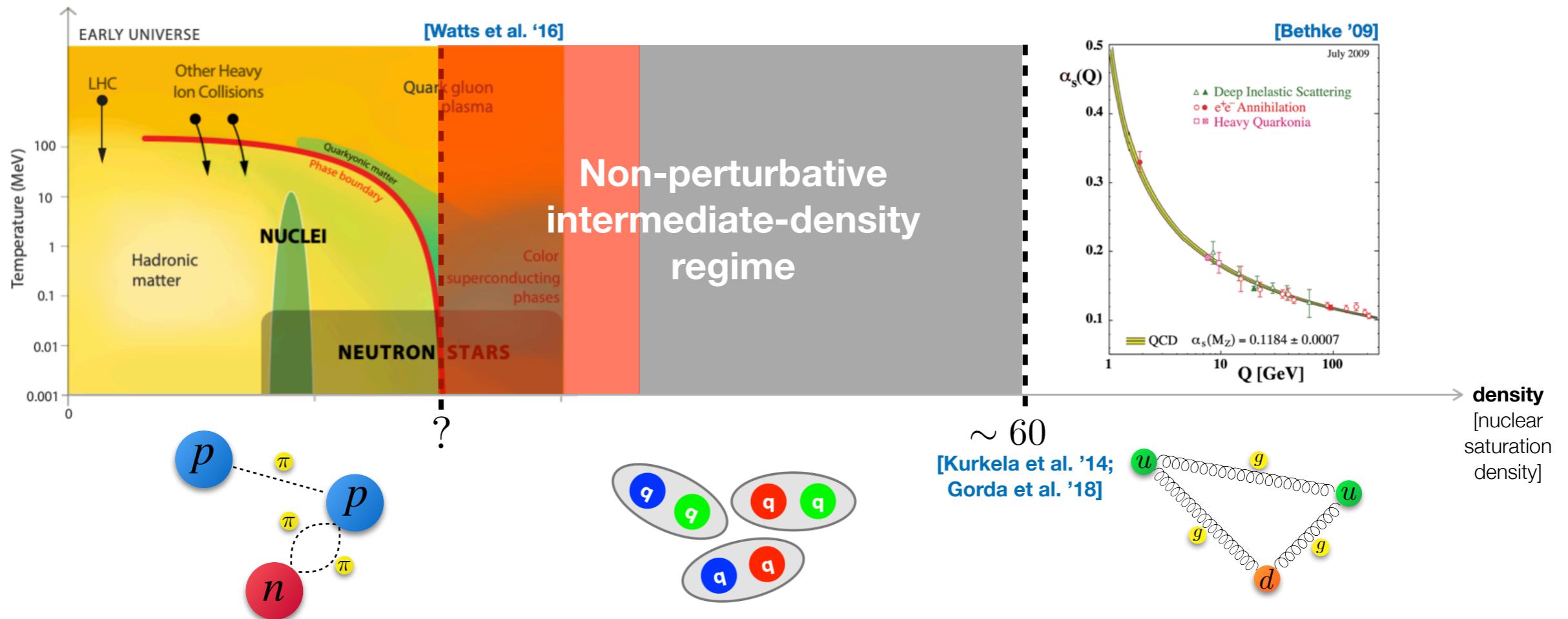
[Review:
Epelbaum, Hammer, Meissner '09]

~ 60

[Kurkela et al. '14;
Gorda et al. '18]

- Assumption: no symmetry breaking
- Quarks & gluons
- Weak-coupling expansion

Dense QCD matter: effective degrees of freedom

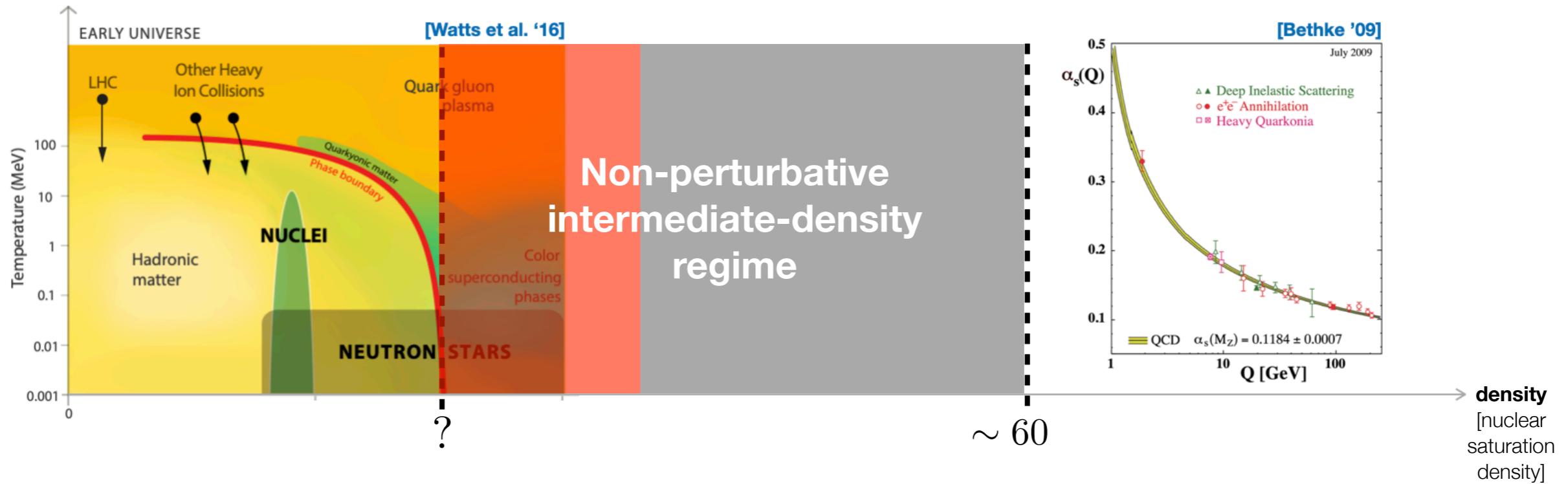


- Spontaneous chiral symmetry breaking
- Protons & neutrons
- Systematic studies via chiral EFT [Review: Epelbaum, Hammer, Meissner '09]

- Many competing interaction channels
 - Diquark condensation, Color superconductor
- [Alford, Rajagopal, Wilczek '98; Rapp et al. '98; Schäfer, Wilczek '99; Berges, Rajagopal '99; Son '99; Pisarski, Rischke '00; ...; Reviews, e.g.: Buballa '04; Alford, Rajagopal, Schäfer, Schmitt '08]

- Assumption: no symmetry breaking
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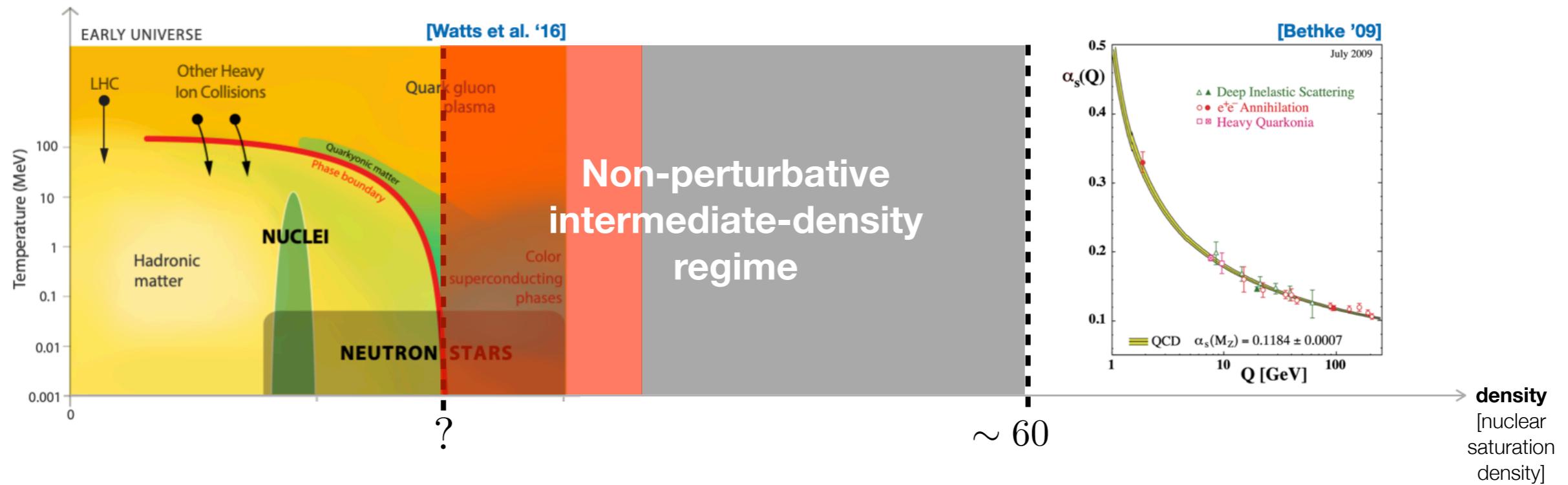
To avoid disappointments before the weekend ...



What this talk is about ...

... on the **equation of state (EOS)** of dense **isospin-symmetric QCD** with **two massless quark flavors**
... “report” on first steps on a longer trip

To avoid disappointments before the weekend ...

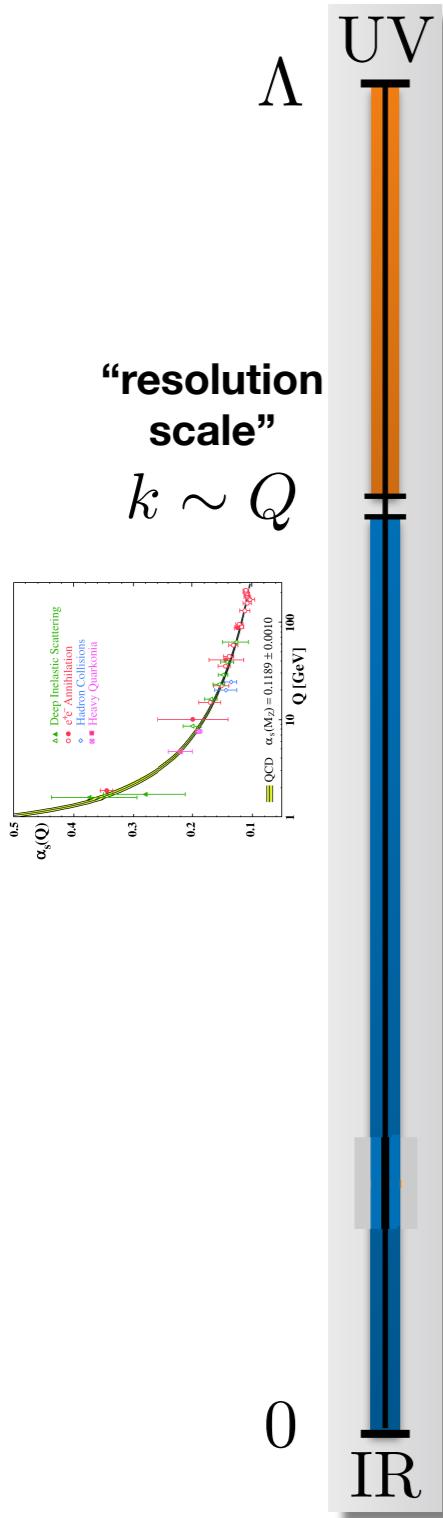


What this talk is **NOT(!)** about ...

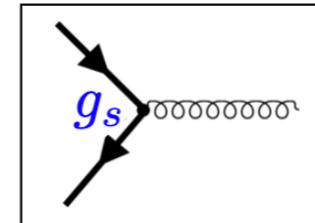
... technical details (because it's late by now ...)

What we do: Renormalization group (RG)

[Functional RG (FRG): Wetterich '92]

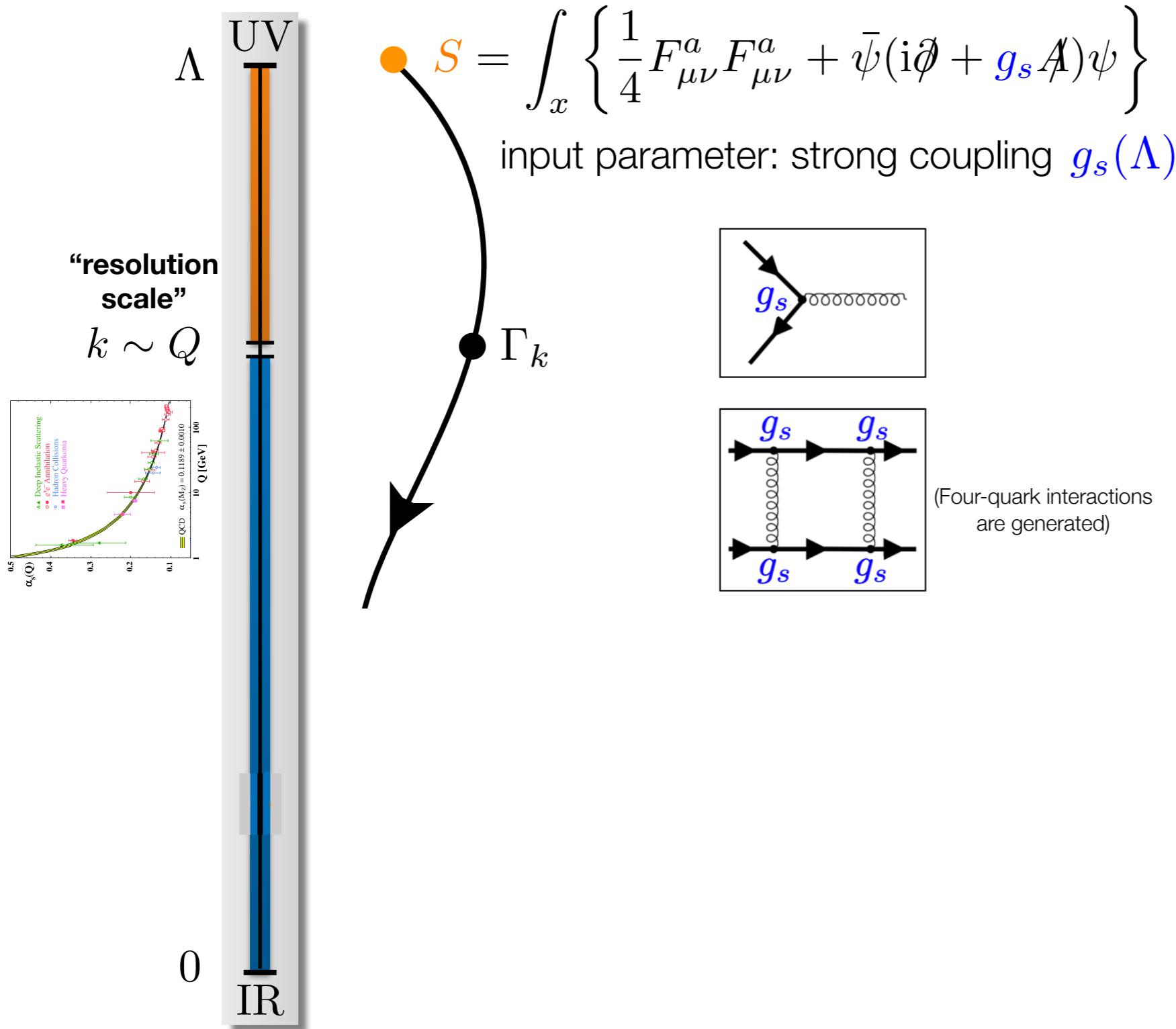


● $S = \int_x \left\{ \frac{1}{4} F_{\mu\nu}^a F_{\mu\nu}^a + \bar{\psi} (i\partial + g_s A) \psi \right\}$
input parameter: strong coupling $g_s(\Lambda)$



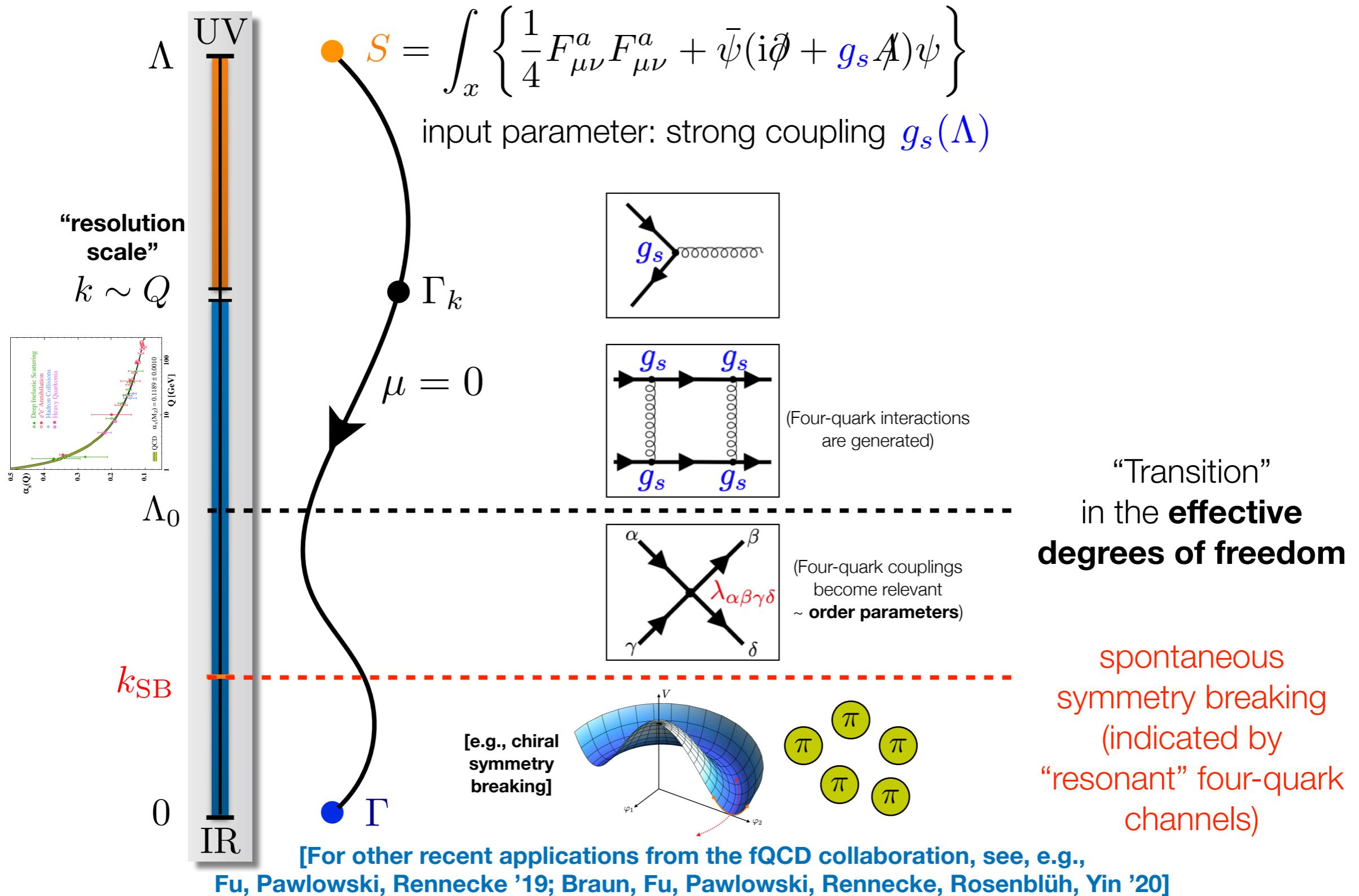
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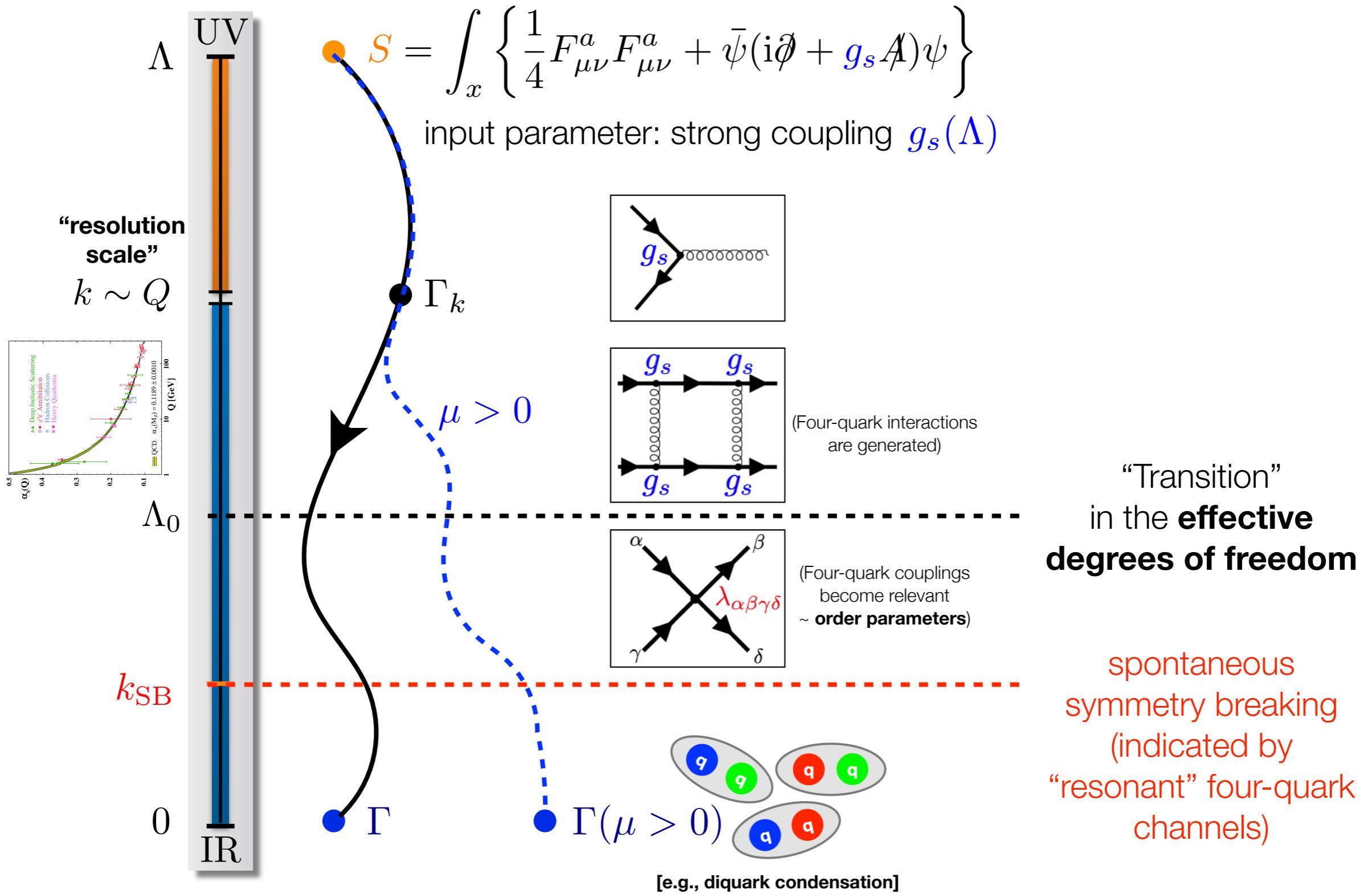
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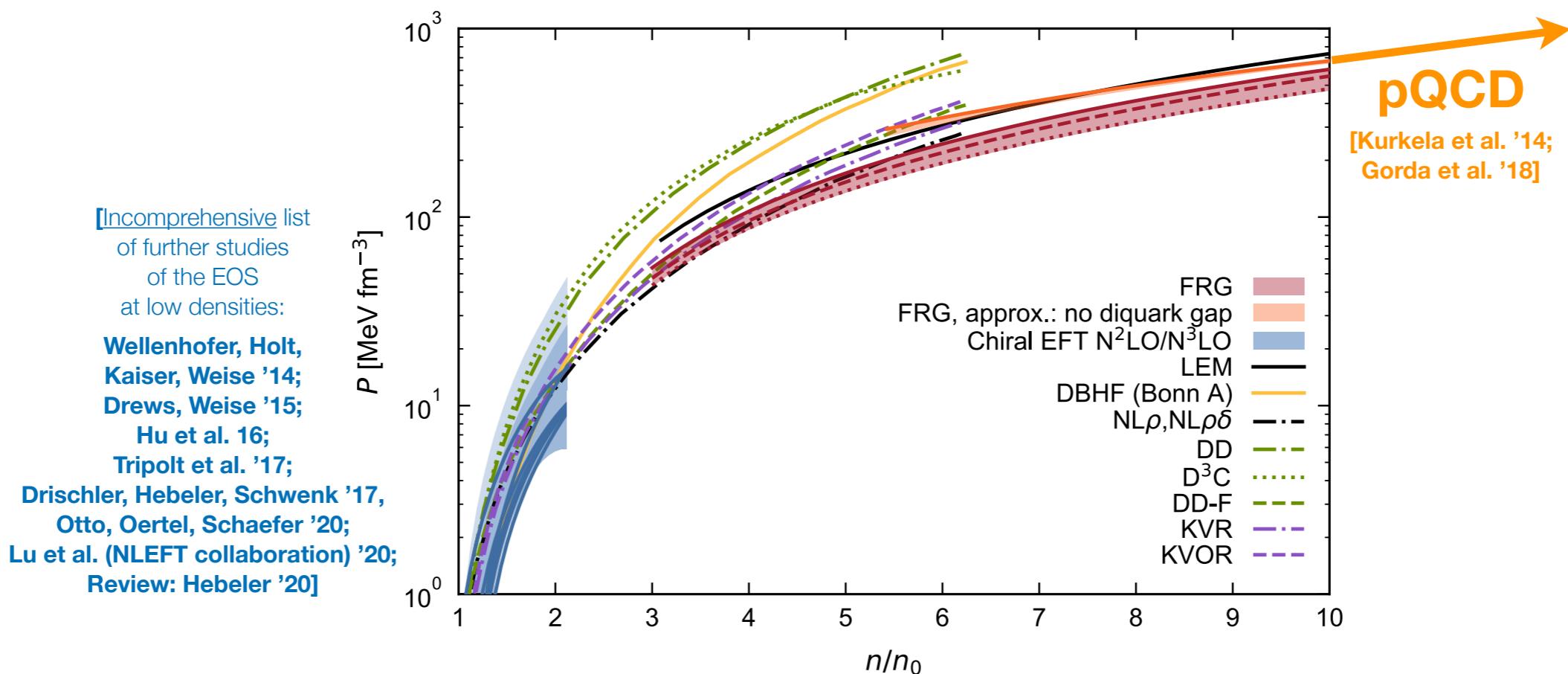
What we do: Renormalization group (RG)

[JB, Leonhardt, Pospiech '19]



Equation of state of dense matter

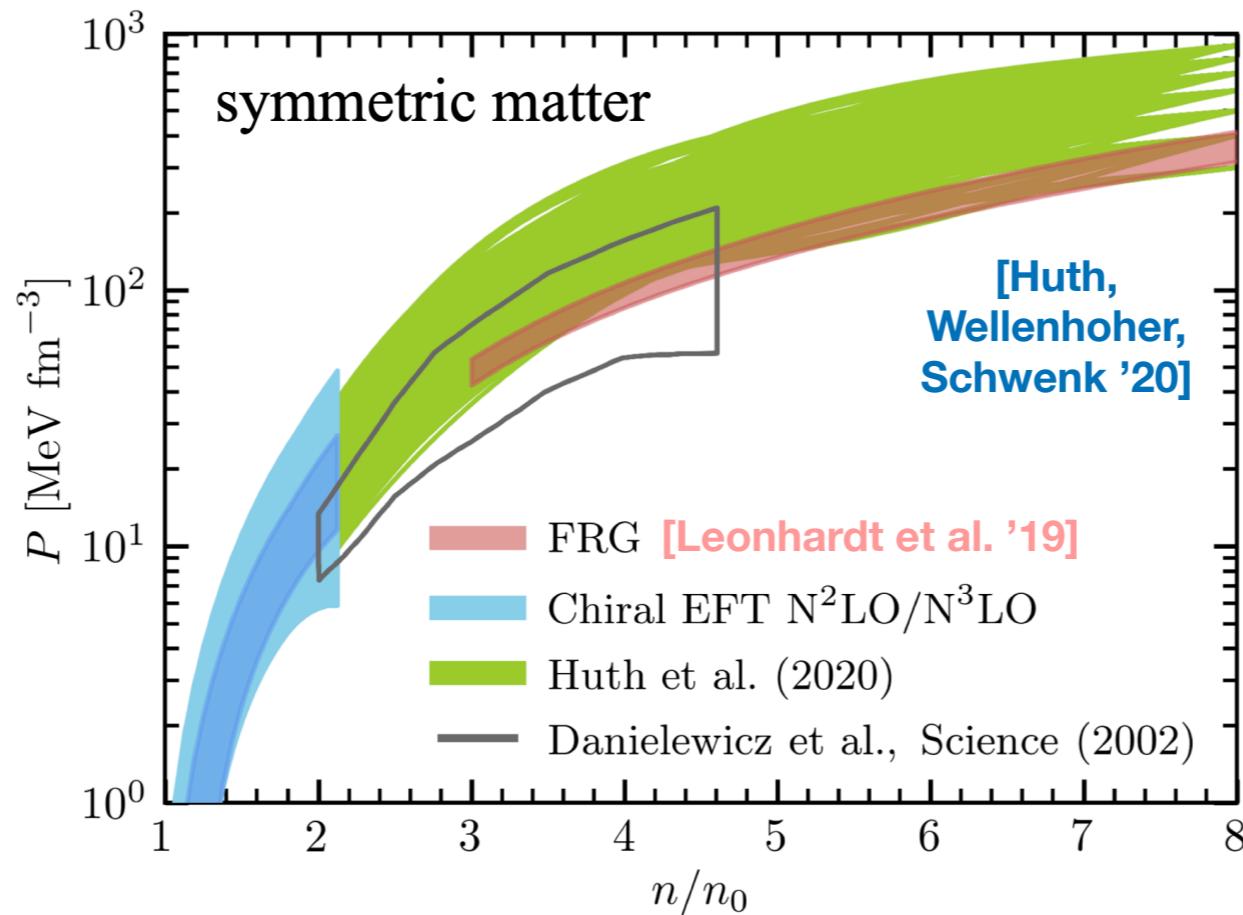
[Leonhardt, Pospiech, Schallmo, JB, Drischler, Hebeler, Schwenk '19]



- Consistent with **pQCD studies** at high densities
- Consistent with studies based on **chiral EFT**
- Inclusion of **diquark condensation** appears crucial to connect the low- and high-density regime

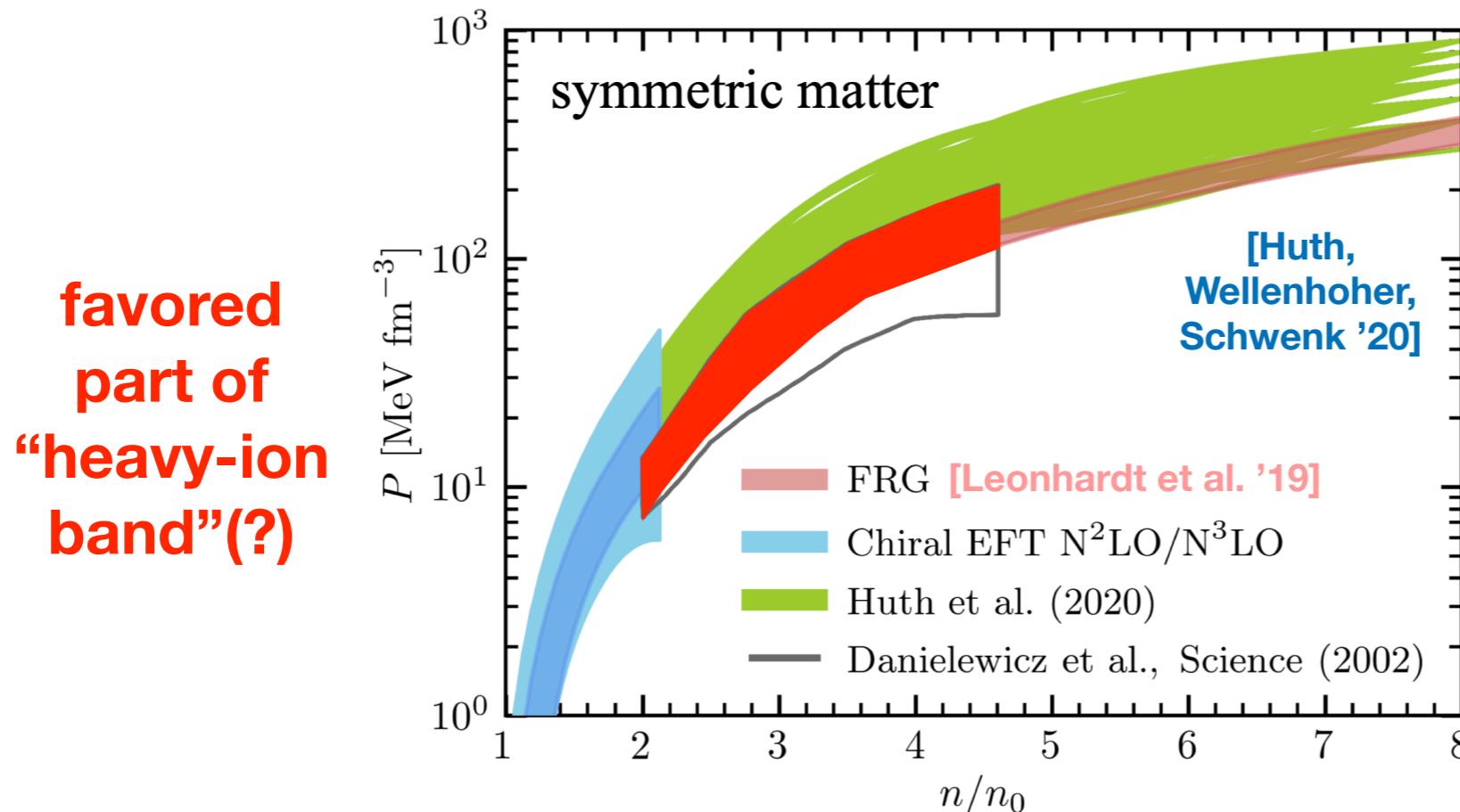
From the equation of state to astrophysics?

Constraints on the EOS of dense matter



- FRG results can be used to constrain **new density functionals** together with constraints coming from neutron-star observations & chiral EFT [Huth, Wellenhofer, Schwenk '20]
- Consistent with constraints from **heavy-ion collision experiments**

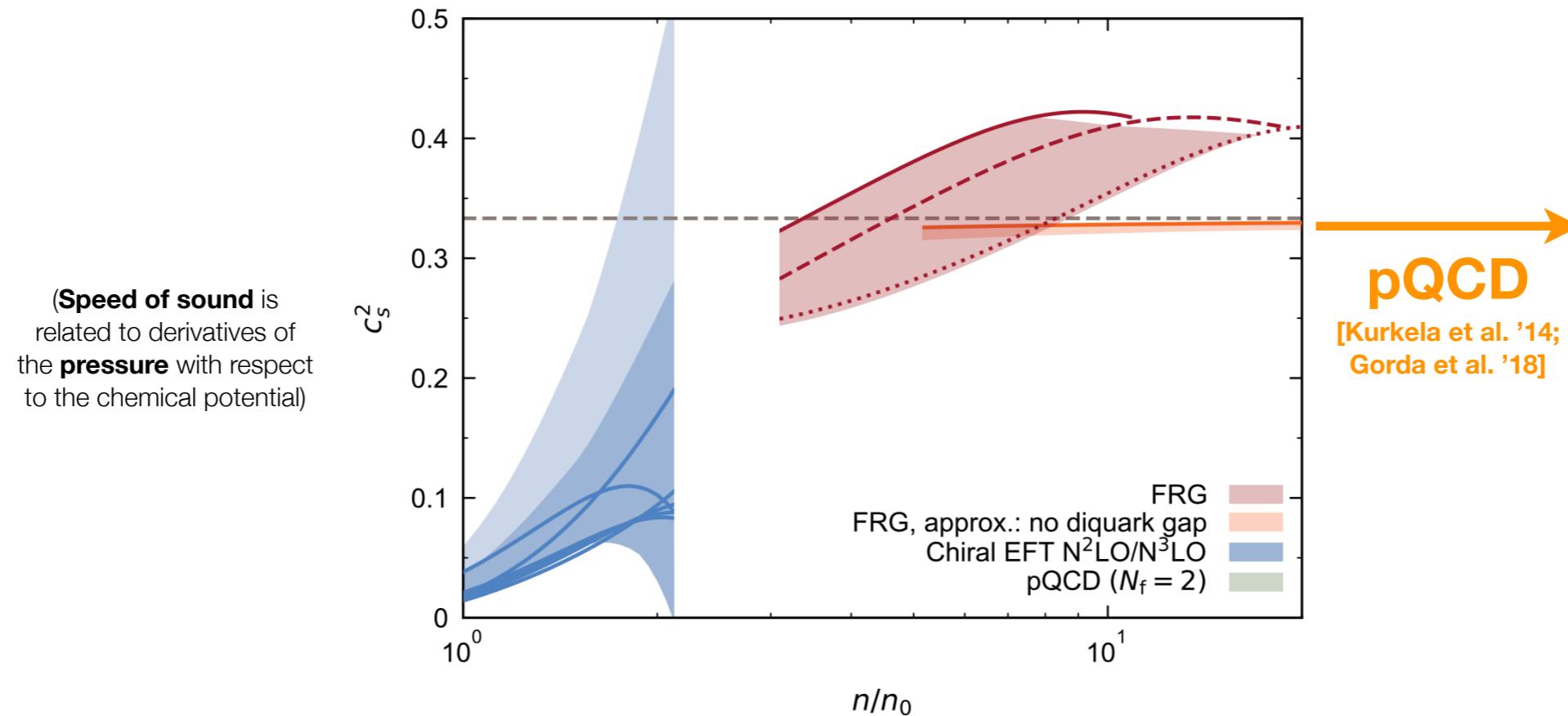
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Speed of sound of symmetric nuclear matter

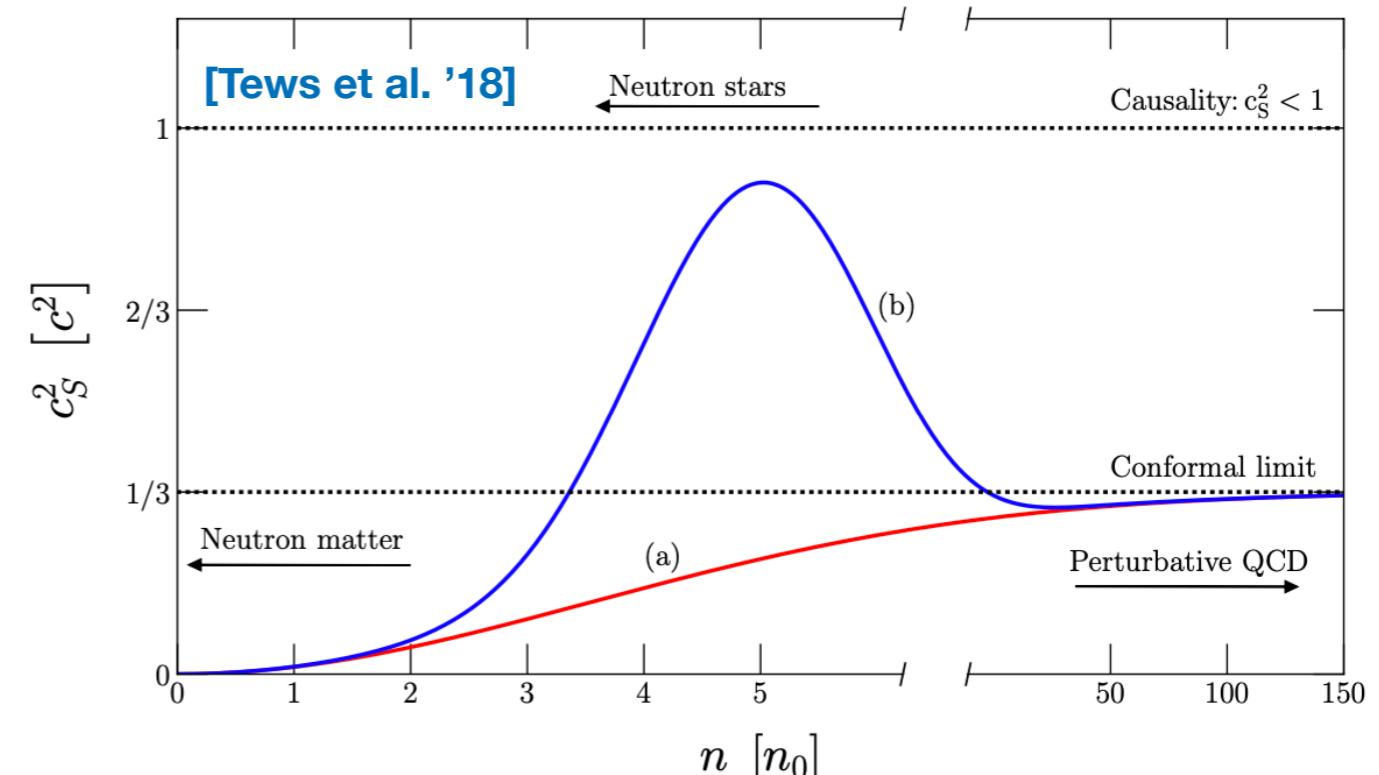
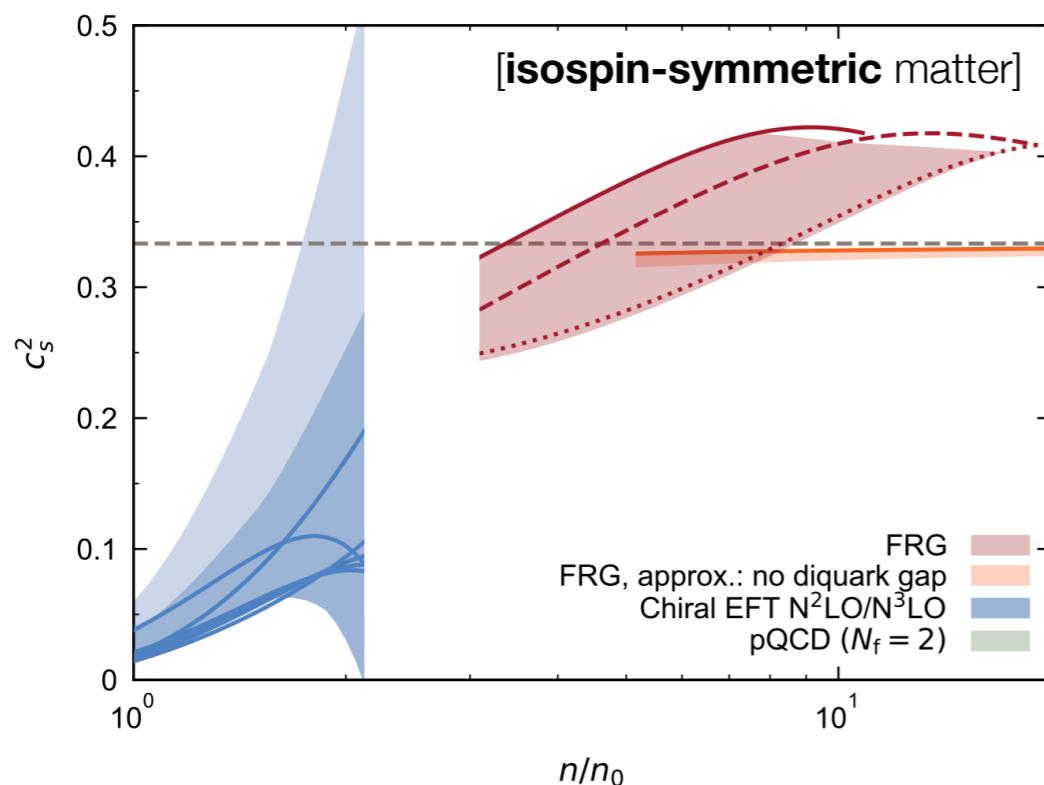
[Leonhardt, Pospiech, Schallmo, JB, Drischler, Hebeler, Schwenk '19]



- Consistent with studies based on **chiral EFT**
- Emergence of a peak/maximum is tightly connected to the formation of **diquark gap**

Cautious comparison to astrophysical constraints

[Leonhardt, Pospiech, Schallmo, JB, Drischler, Hebeler, Schwenk '19]



- Constraints from neutron-star observations combined with theoretical results at low and high densities suggest a global **maximum of the speed of sound**

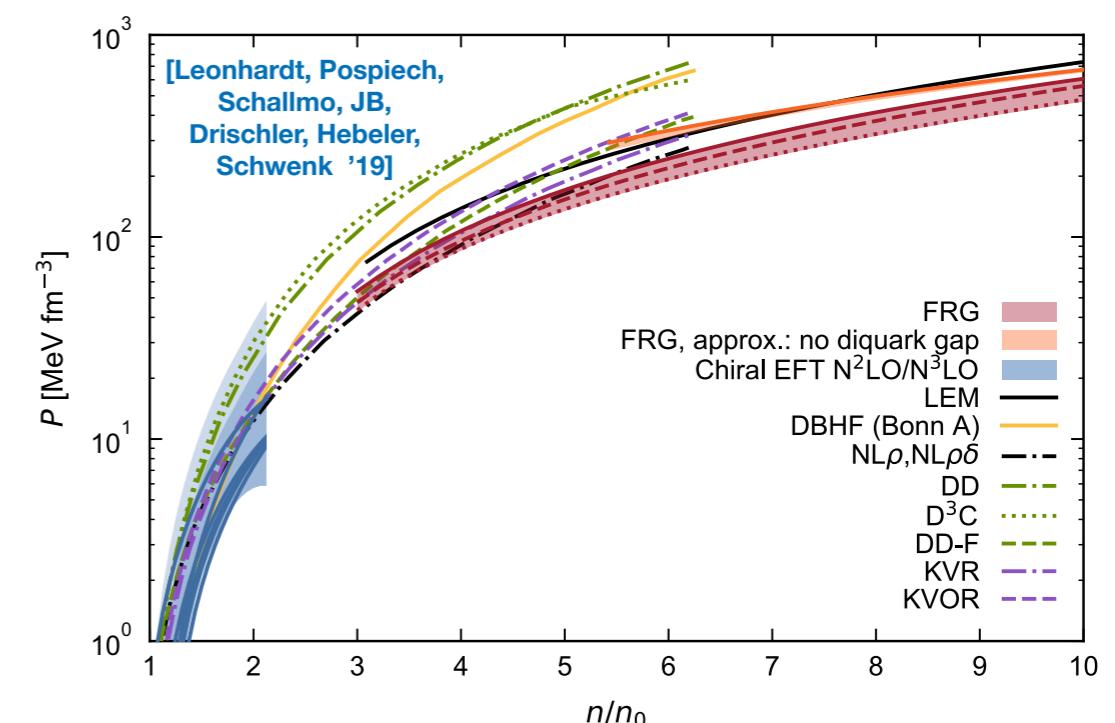
[Bedaque, Steiner '15; Tews et al. '18; Greif et al. '18; Raaijmaakers '19; Annala et al. '19; Huth, Wellenhofer, Schwenk '20]

- Mild “overshooting” of the speed of sound supports the existence of quark cores in heavy neutron stars [Annala et al. '19]

Conclusions & outlook



- **Combination of studies based on chiral EFT** at low densities and **RG studies** at intermediate/high densities yields a **consistent description of the EOS of dense matter** over a wide range of densities
- Consistent with constraints from heavy-ion collisions and neutron-star observations
- **Things to do from here on:**
 - Narrow down theoretical uncertainties [JB, Schallmo, in prep.]
 - Isospin asymmetry [JB, Geissel, Schallmo, in prep.]
 - temperature, 2+1 flavors



Conclusions & outlook



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Thank you very much

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