Holographic model of dense matter in neutron stars

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Fire and Ice: Hot QCD meets cold and dense matter
Saariselkä, Finland
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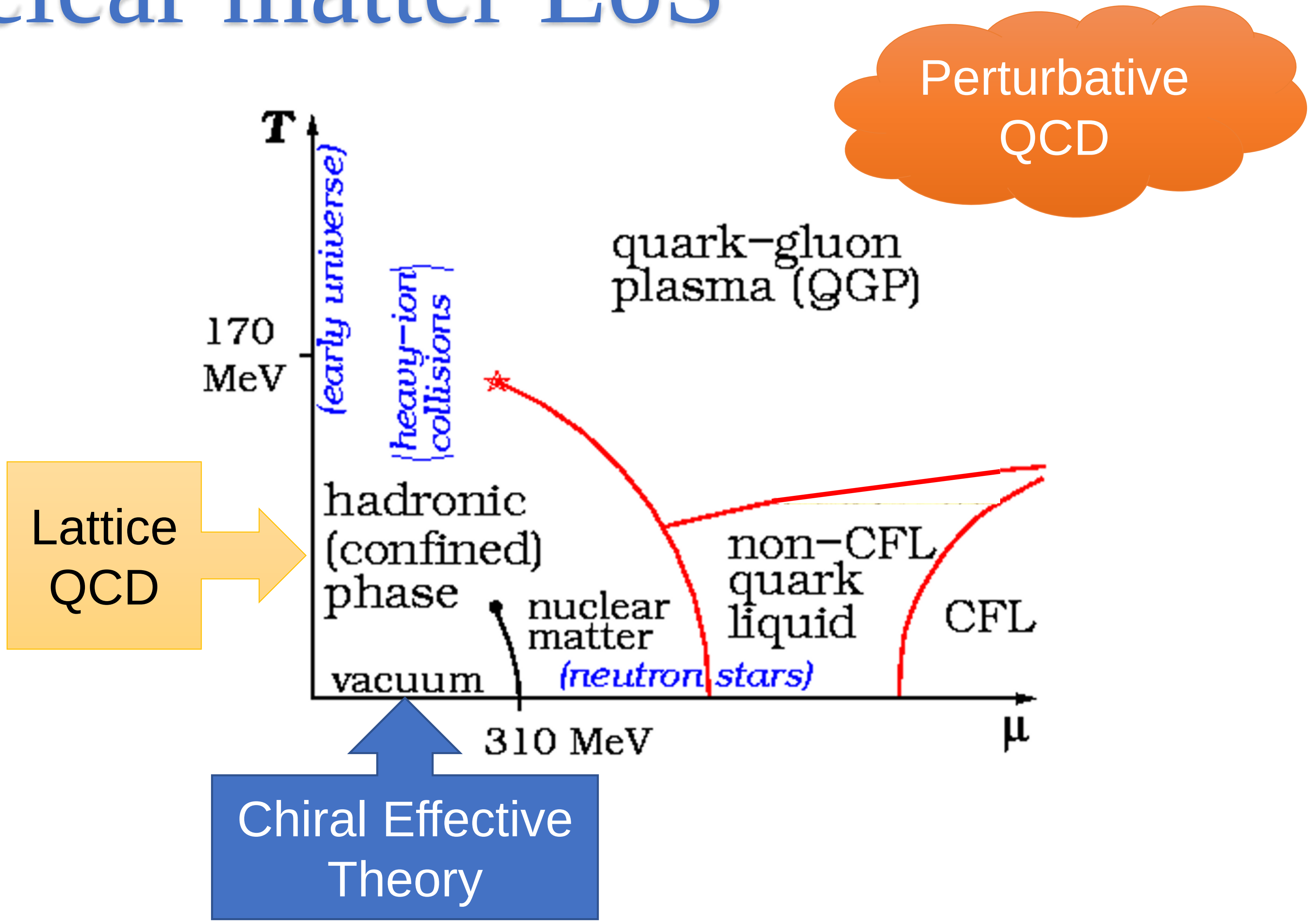
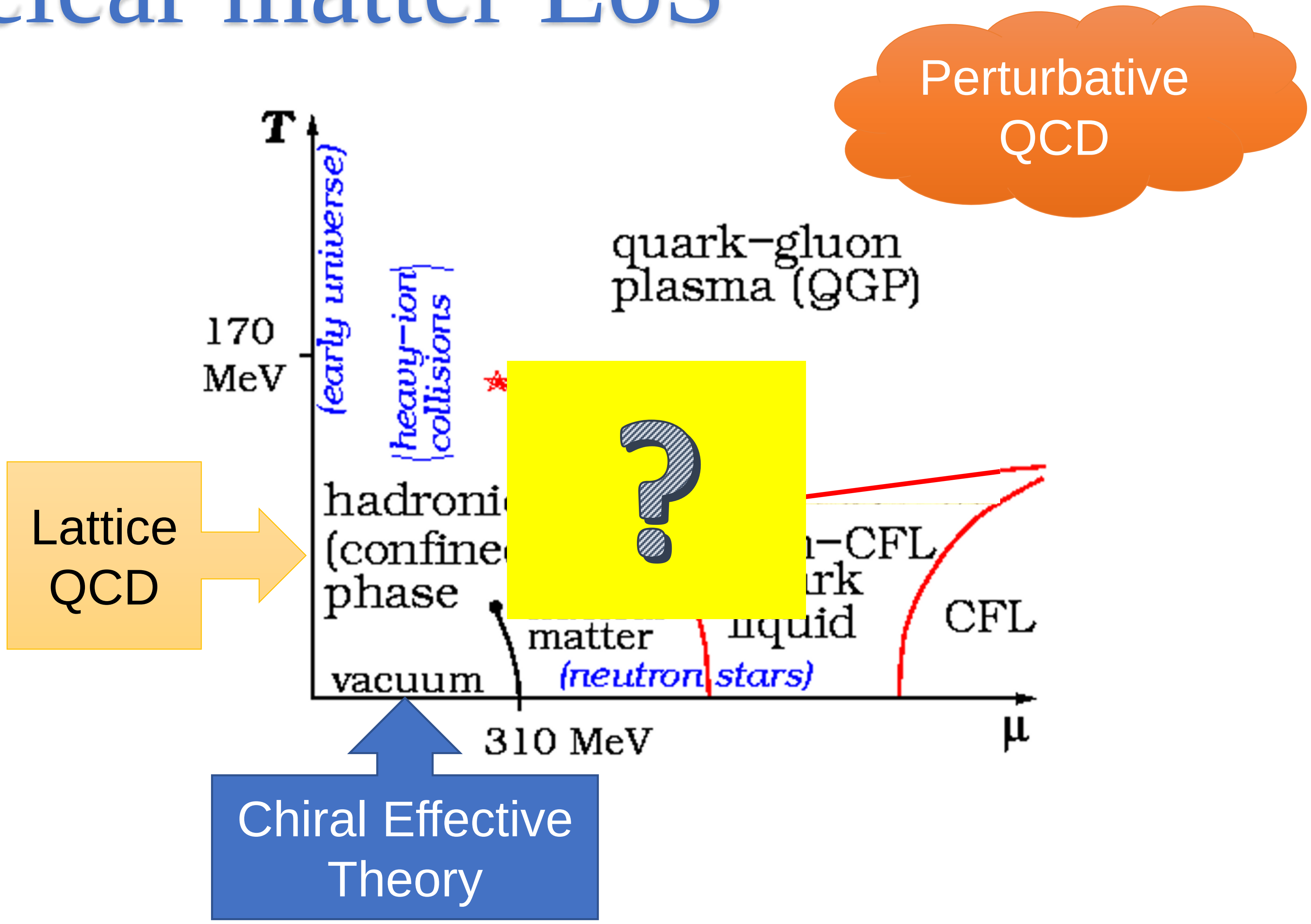
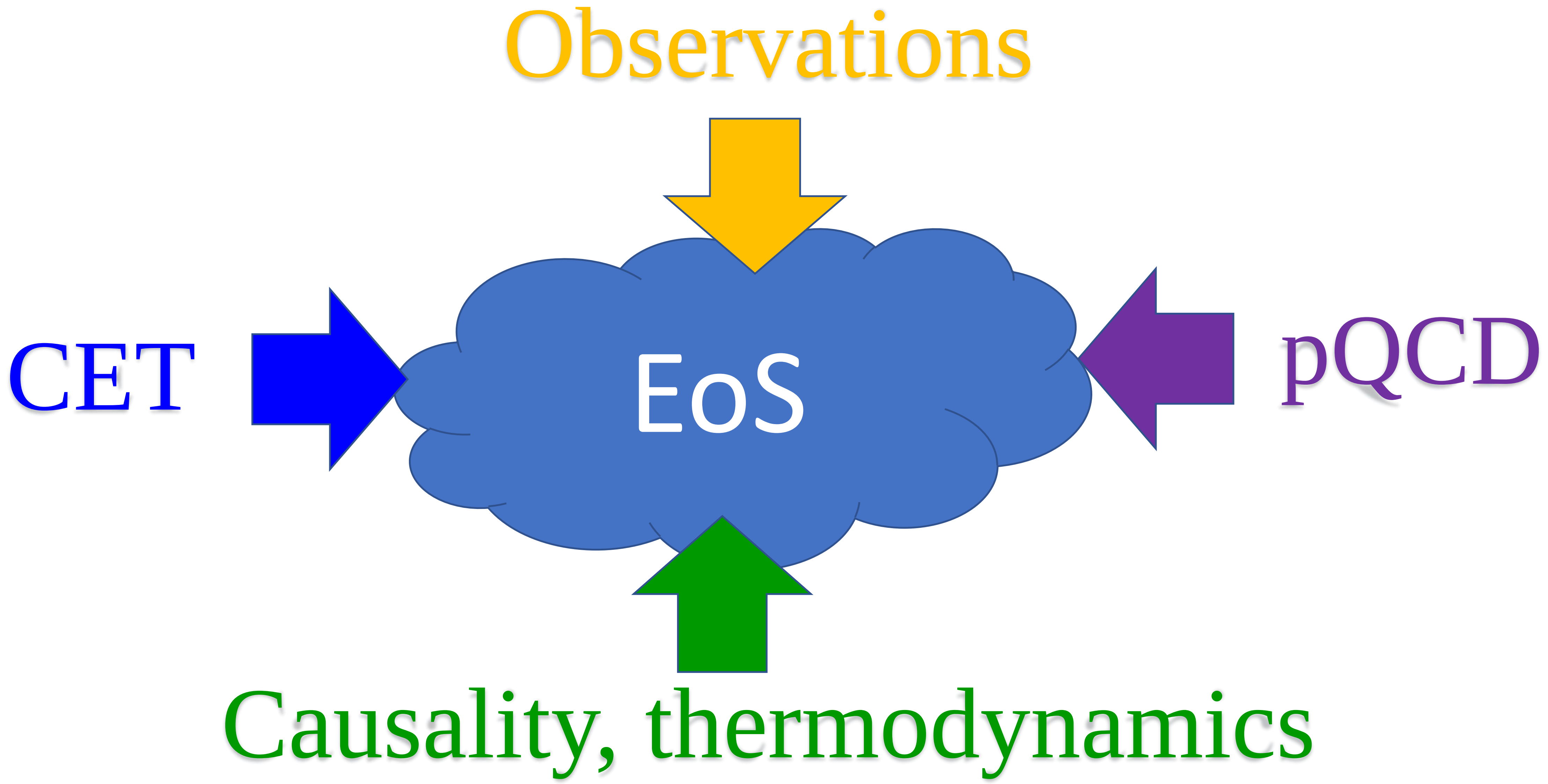
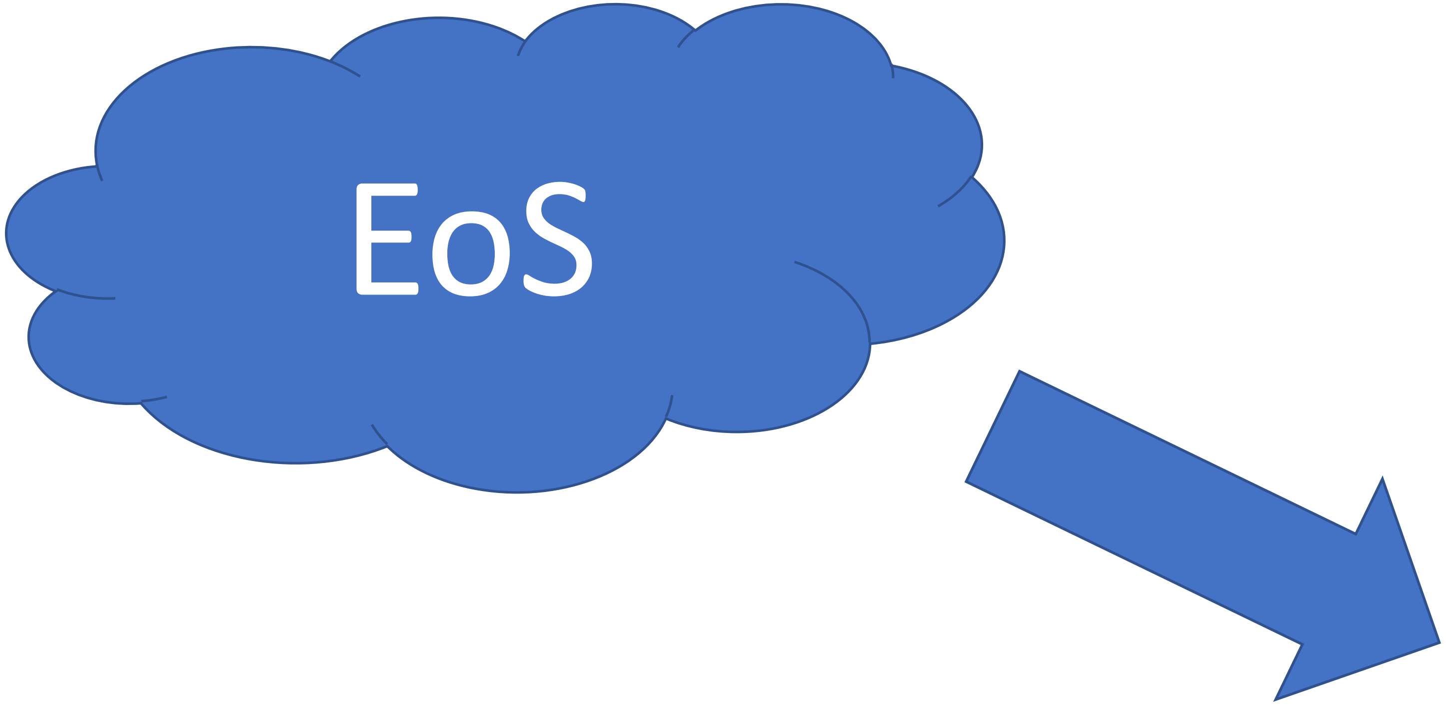
Nuclear matter EoS



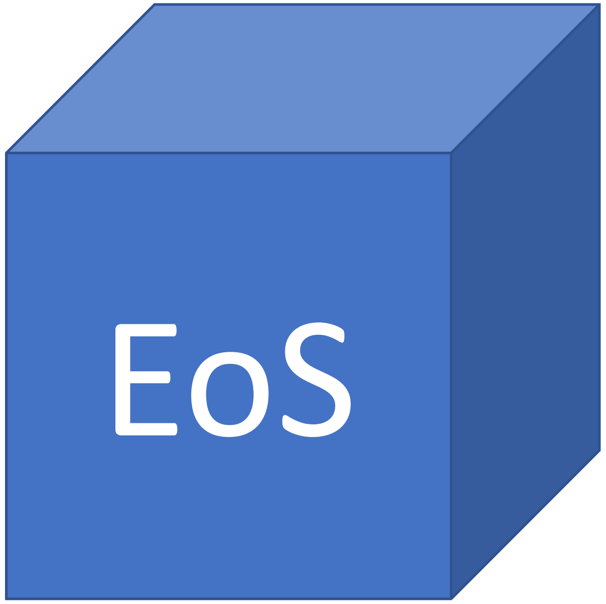
Nuclear matter EoS




Observations
CET
EoS
pQCD
Causality, thermodynamics



Can we restrict further the EoS?
(and gain some understanding?)



“Bottom-up” phenomenology

- Construct a model (capturing right degrees of freedom)
- Fit parameters to experiments/observations
- Extrapolate to regime of interest

“Top-down” phenomenology

- Find a solvable theory (as similar as possible)
- Extrapolate to QCD
- Compare with experiments/observations

“Bottom-up” phenomenology

- … edom)

Goal: accurate description

- Extrapolate to regime of interest

“Top-down” phenomenology

Goal: qualitative properties

- Compare with experiments/observations

Top-down models

They should:

- Have gluons + quarks
- Be at strong coupling (beyond pQCD)
- Be at finite baryon density (no sign problem or similar)

It would be nice if one can also study:

- Non-zero temperature
- Transport properties
- Far from equilibrium properties

Gauge/gravity duality

Pros (within phenomenological limitations):

- Checks on all the points of previous slide
- First principles
- Only gauge-invariant results
- Very simple: solve classical field equations!

Cons:

- Baryonic matter “harder” than quark matter**

** with some exceptions

Hopefully more constrained EoS?

Gauge/gravity models

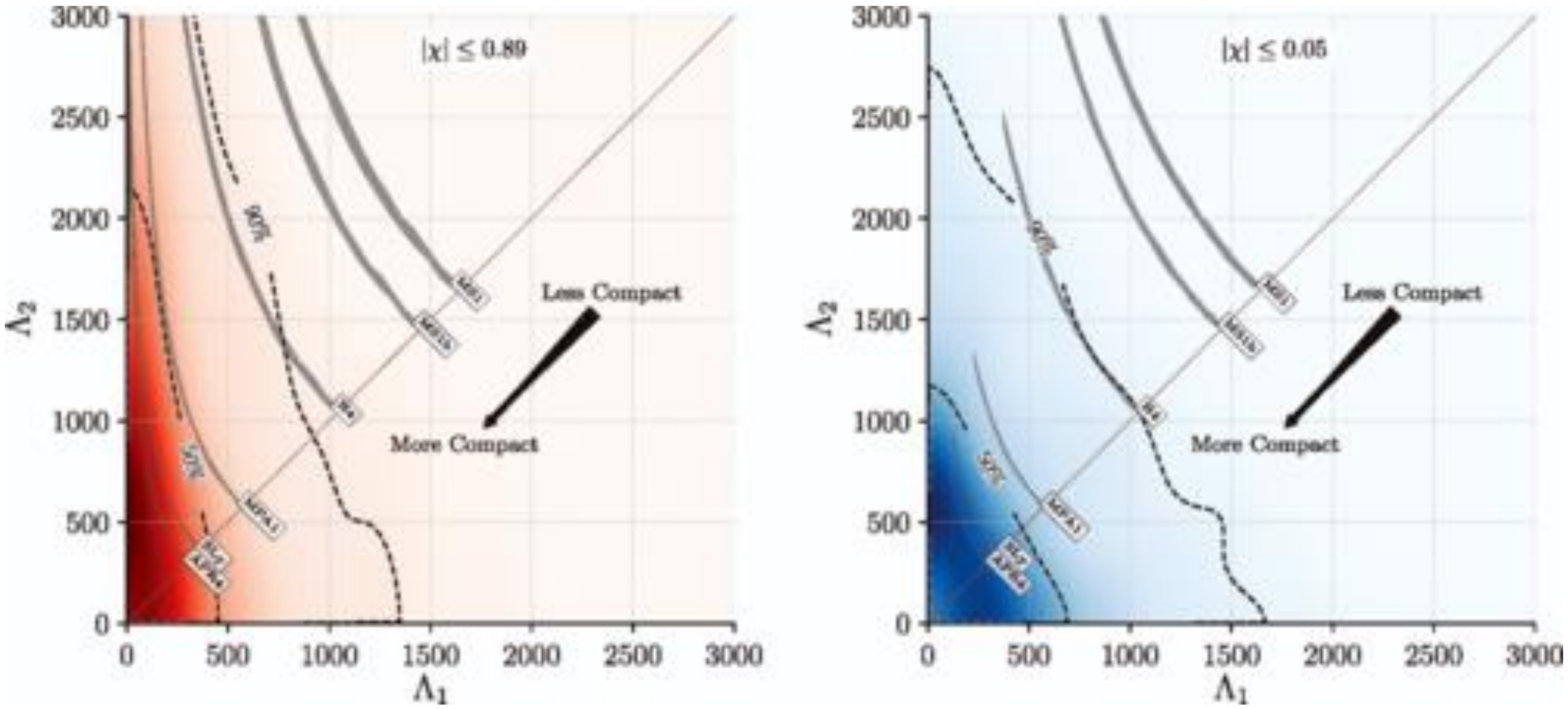
QCD

?

Observations:

Neutron stars up to 2 solar masses

Low tidal deformabilities



Abbot et al. DOI:https://doi.org/10.1103/PhysRevLett.119.161101

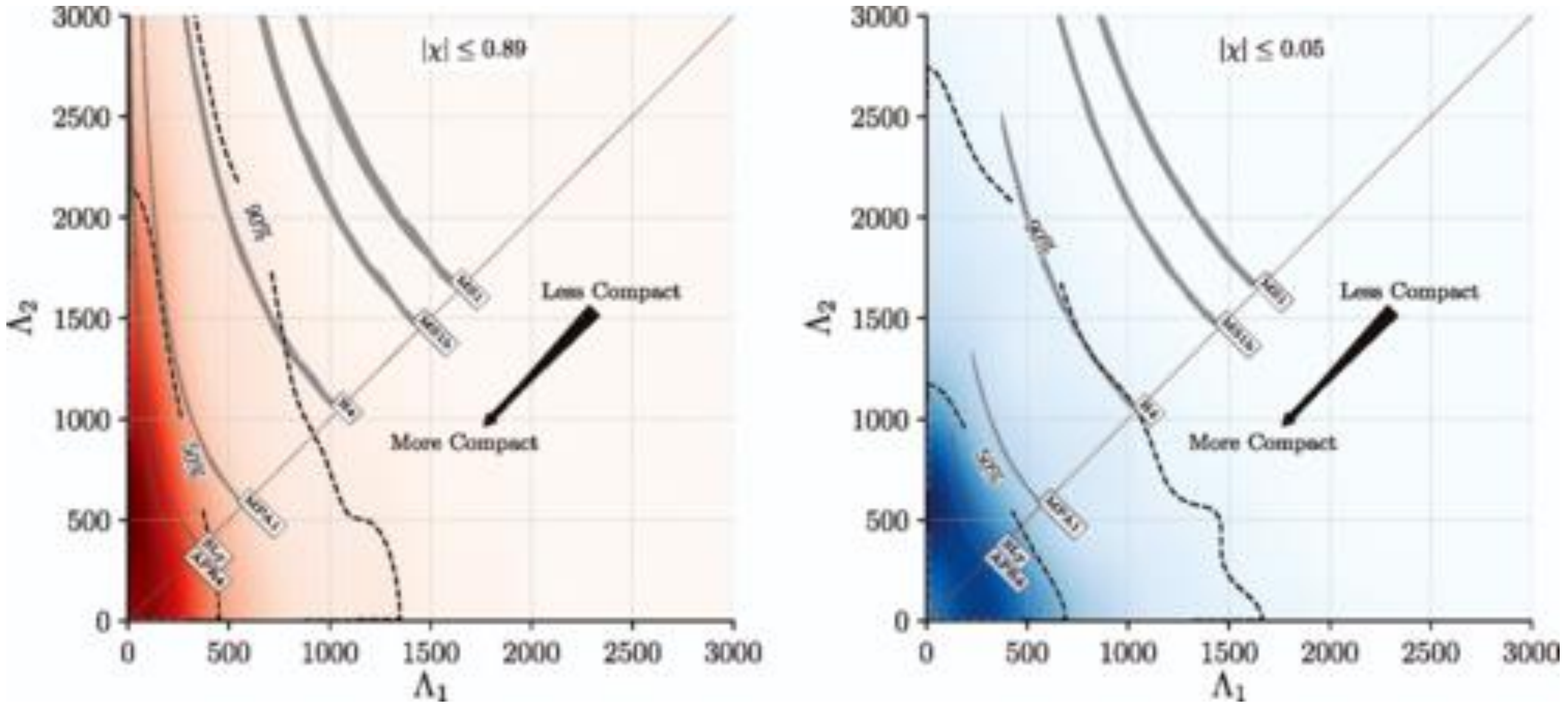
Observations:

stiff EoS

Neutron stars up to 2 solar masses

Holography?
See talk of David Rodriguez

Low tidal deformabilities



Abbot et al. DOI:https://doi.org/10.1103/PhysRevLett.119.161101

Some of the matter in the neutron star could be soft

Two phases:

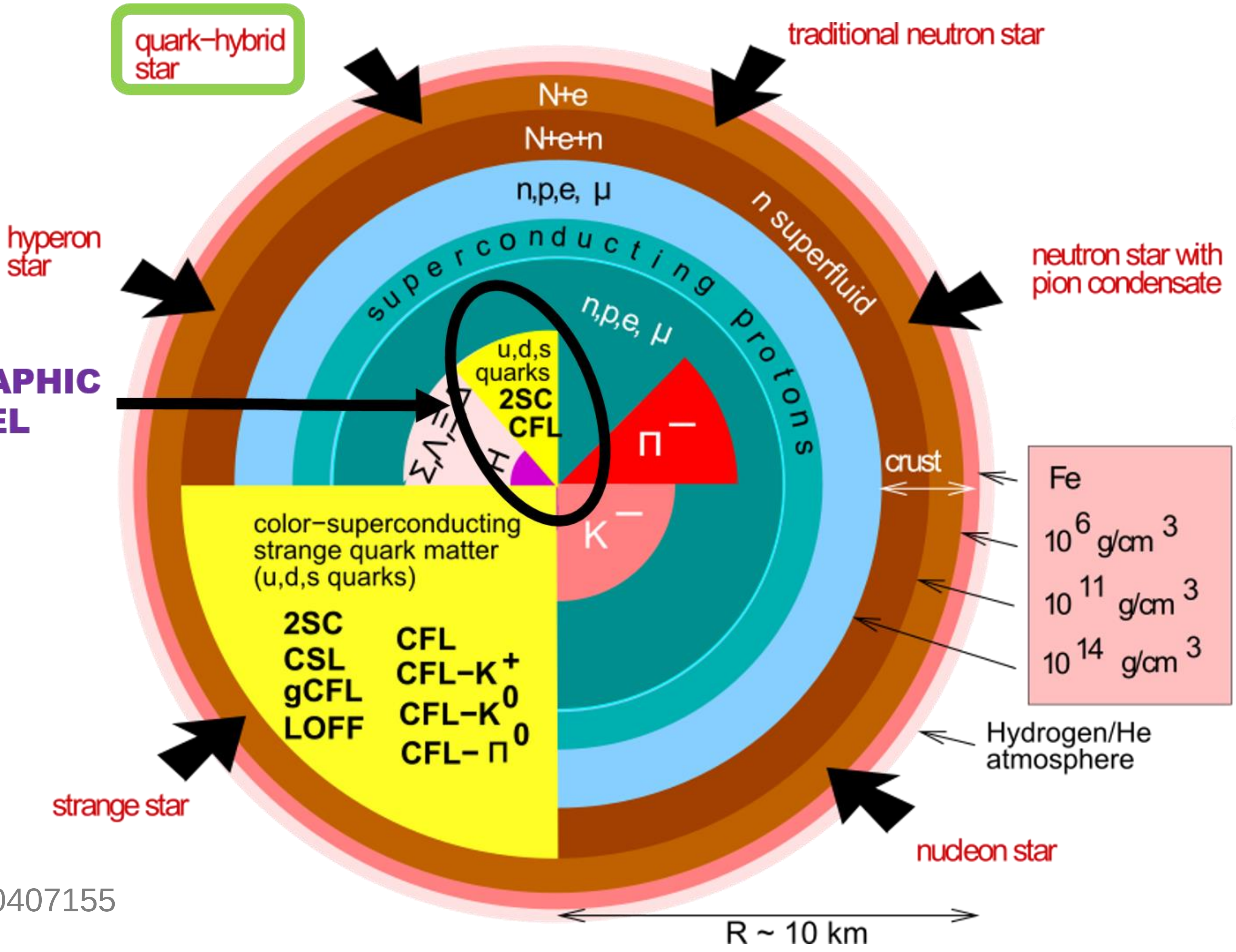
- Baryonic matter, stiff → "hard"
- Quark matter, soft → "easy"

Simplest realistic model:

- Baryonic matter: nuclear matter models
- Quark matter: gauge/gravity duality

Hebeler, Lattimer, Pethick, Schwenk ´13

HOLOGRAPHIC MODEL



Weber astro-ph/0407155

D3/D7 model

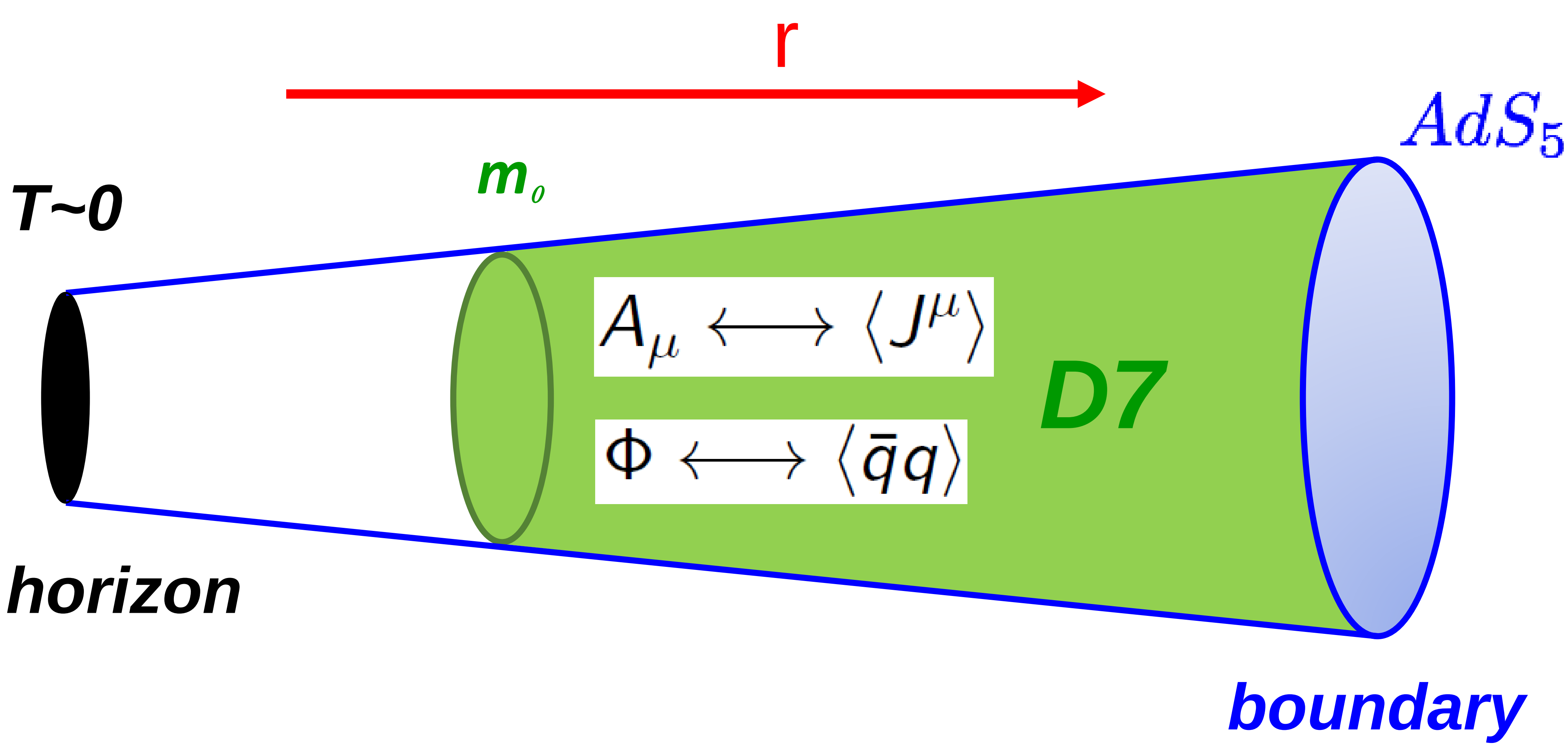
Karch, Katz ‘02

Supersymmetric theory with SU(Nc) gauge group:

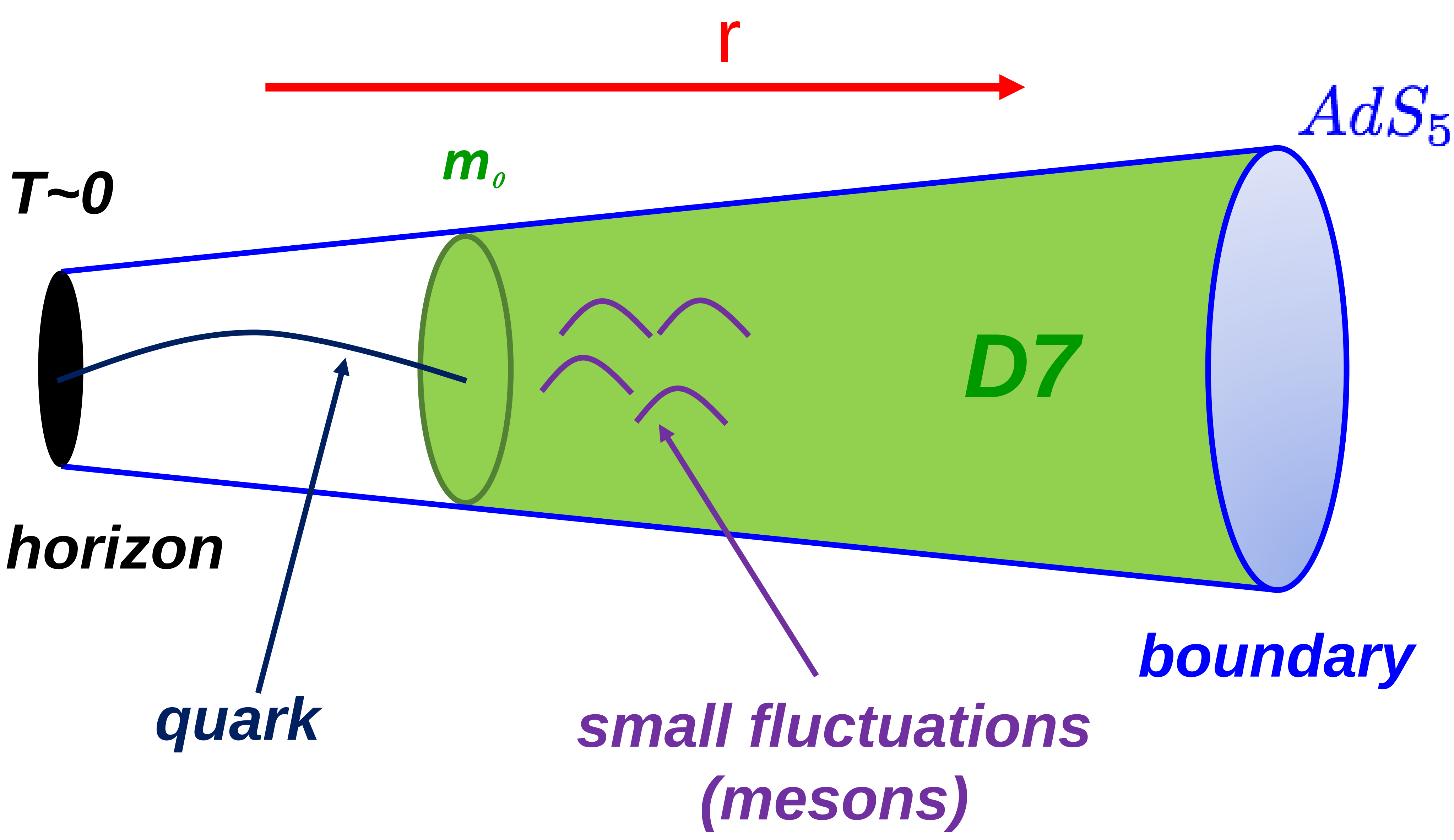
- N=4 sector (adjoint) gluons+4 fermions+6 scalars
- Flavor sector (fundamental) Nf quarks+squarks

Gravity dual:

- Classical gravity solution (AdS_5 dual to D3-brane)
- Extended (codimension 2) object (D7-brane)



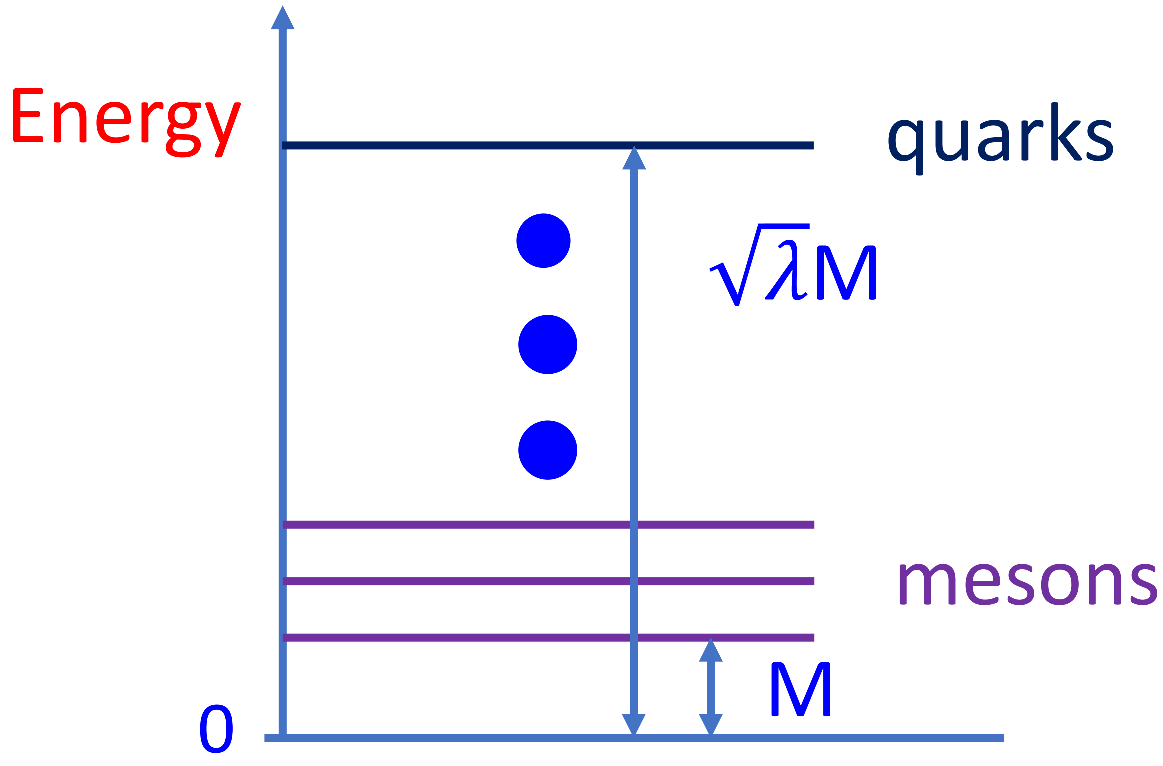
$\Phi(r)$ Chiral symmetry breaking: mass and condensate



r
AdS_5
m_0
T~0
D7
horizon
boundary
quark
small fluctuations
(mesons)

“Confined”:

- Mass gap
- Discrete spectrum



Finite chemical potential and charge

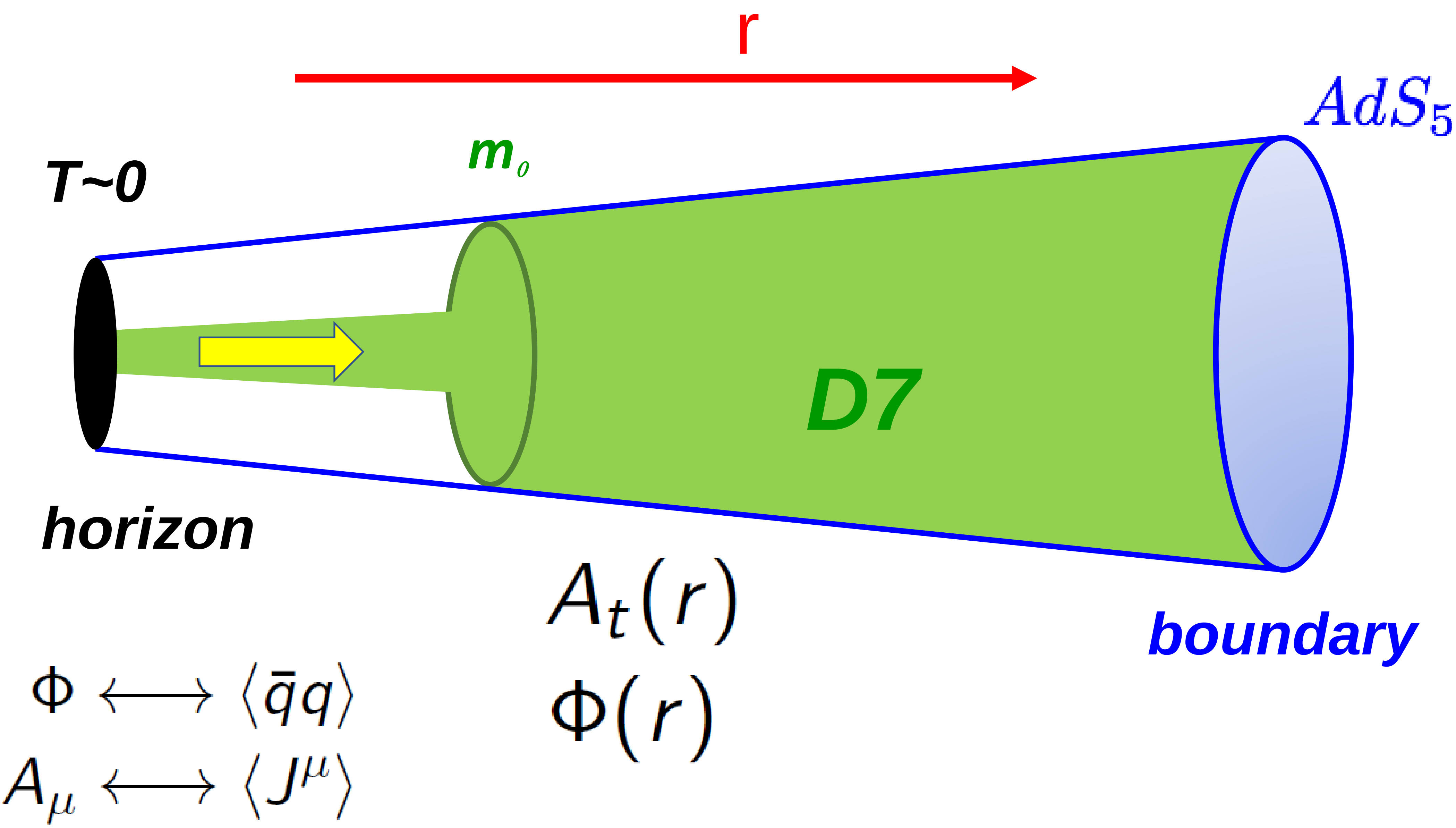
$$A_\mu \longleftrightarrow \langle J^\mu \rangle$$

$$A_t = \mu$$ chemical potential = boundary condition

$$A_t(r)$$ charge density = electric flux

Phase diagram first studied

Kobayashi, Mateos, Matsuura, Myers, Thomson '06
Mateos, Matsuura, Myers, Thomson '07



r
AdS_5
m_0
T~0
D7
horizon
$A_t(r)$
$\Phi(r)$
boundary
$\Phi \longleftrightarrow \langle \bar{q}q \rangle$
$A_\mu \longleftrightarrow \langle J^\mu \rangle$

“Deconfined” phase:

- No gap
- Continuous meson spectrum

Second order phase transition between two phases

- Only involves the flavor sector
- Free energy O(Nf Nc) ~ quarkyonic phase

Assumption:
confined D3/D7 ↔ confined QCD

"Deconfined" phase:

- No gap
- Continuous meson spectrum

Second order phase transition between two phases

- Only involves the flavor sector
- Free energy O(Nf Nc) ~ quarkyonic phase

Confined and deconfined phases
actually same vacuum

Equation of state at low temperatures

$$p = f_0(\mu^2 - m_0^2)^2 + O(\mu^3 T, T^4)$$ Karch, O'Bannon '07

$$\rho = \frac{\partial p}{\partial \mu} \qquad \varepsilon = \mu\rho - p = 3p + 4m_0^2\sqrt{f_0 p}$$

$$f_0 = cN_c N_f \lambda_{YM}^{-1}$$

Extrapolation to QCD

QCD: Nc=3 , Nf=3

Asymptotic value of pressure: $\mu \to \infty$

$$p \longrightarrow \frac{N_c N_f}{12\pi^2}\mu^4$$

$$\lambda_{YM} \simeq 10.74$$

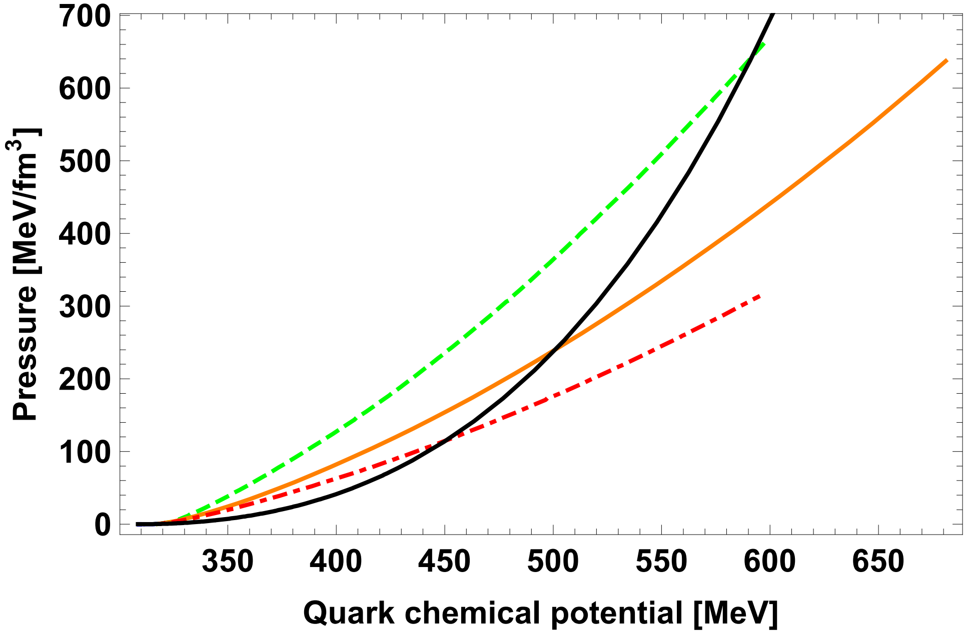
Point of zero pressure $p = 0$: $m_0 = \mu_N \approx 310\ MeV$

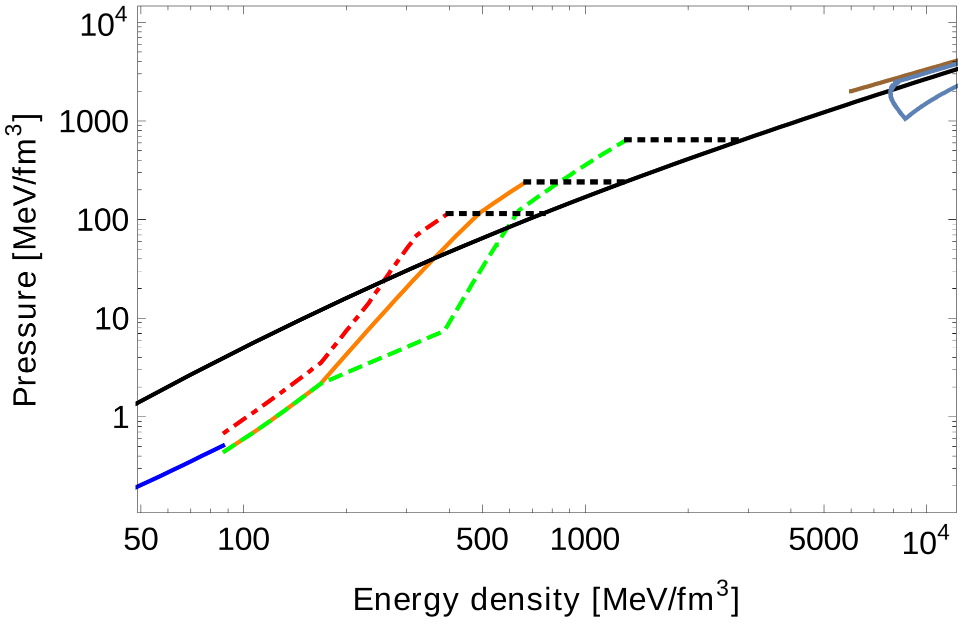
Same chemical potential for all flavors

$$\mu_e = 0$$

$$\mu_u = \mu_d = \mu_s = \mu$$

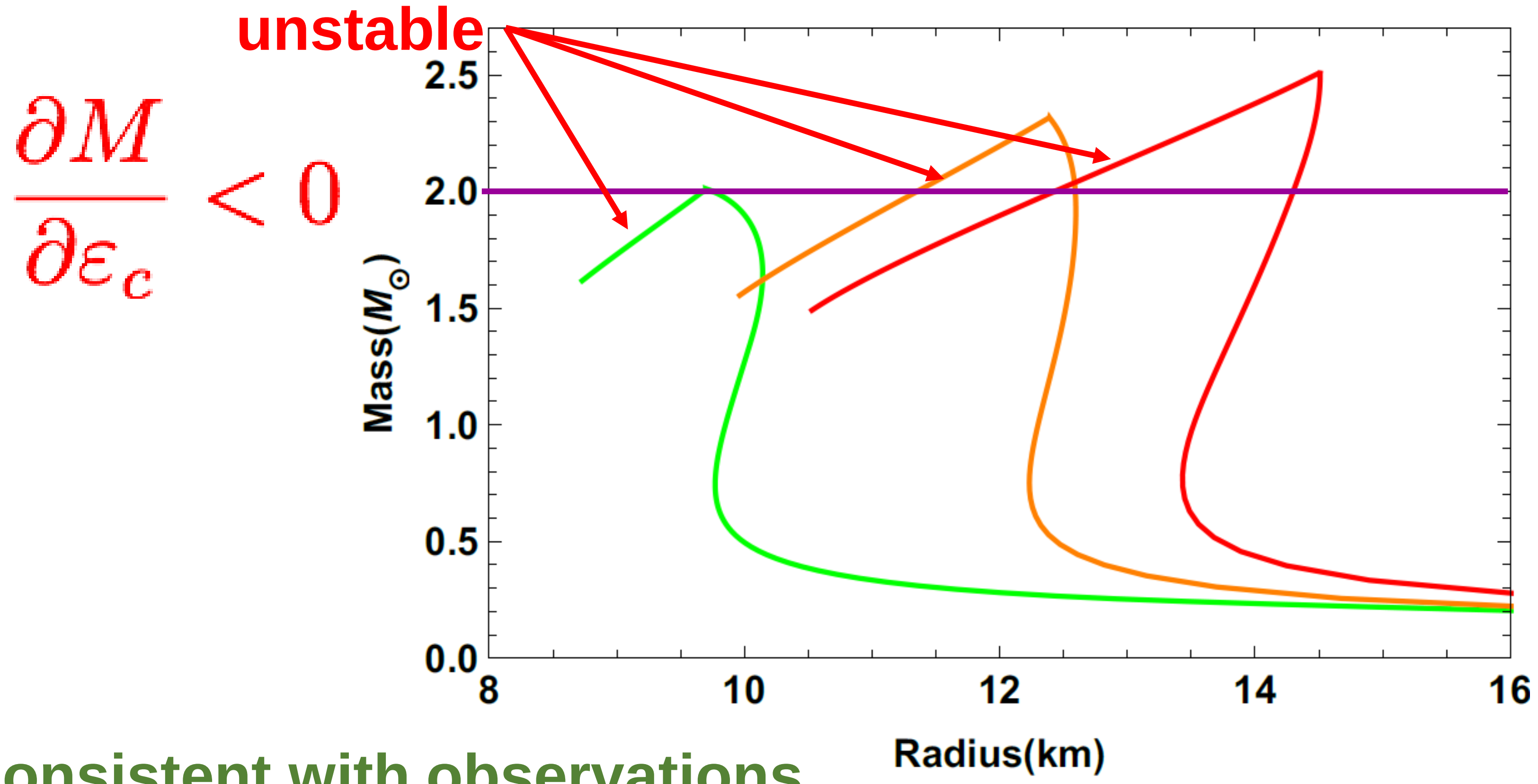
Equations of state





First order phase transition at large densities

Mass versus radius curves



Consistent with observations

No deconfined matter at the core

C.H., Jokela, Rodriguez-Fernandez, Vuorinen '16

Extrapolation to QCD: quark matter stability

Annala, Ecker, C.H., Jokela, Rodriguez-Fernandez, Vuorinen '17

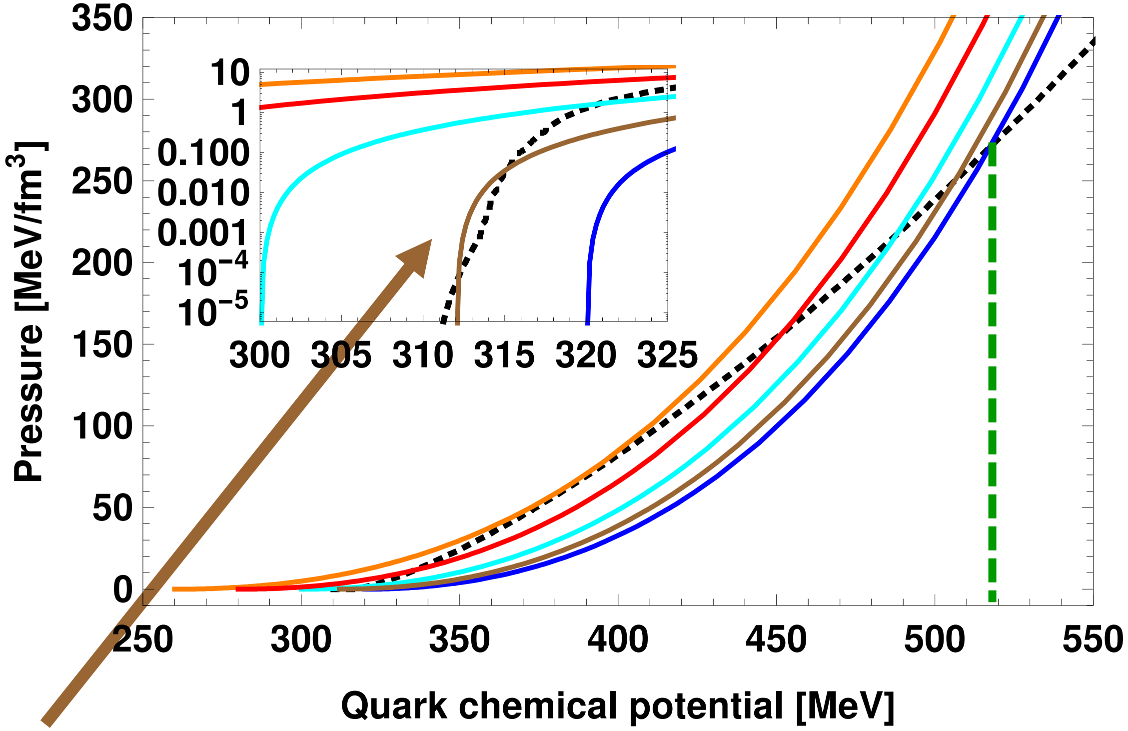
Strange matter hypothesis: 3-flavor quark matter absolutely stable

Bodmer '71, Witten '84

Point of zero pressure $p = 0$: m_0 free parameter

All other parameters fixed as before

Equations of state II



Two crossings

$m_0 < \mu_N$ quark matter

$m_0 \lesssim \mu_N$

$m_0 \lesssim \mu_N$

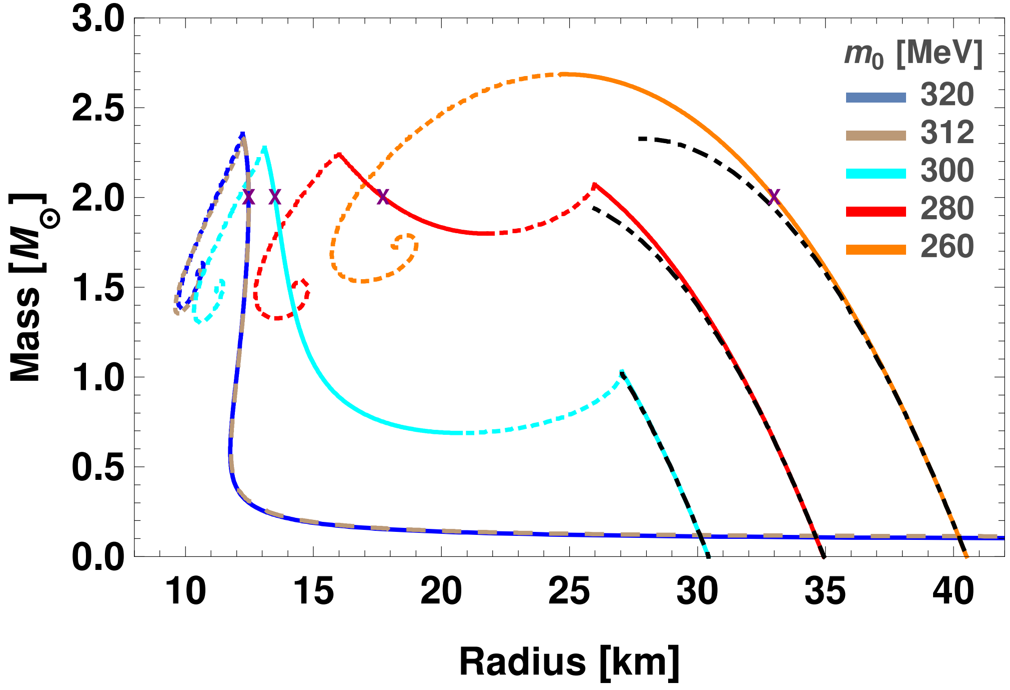
$m_0 \gtrsim \mu_N$

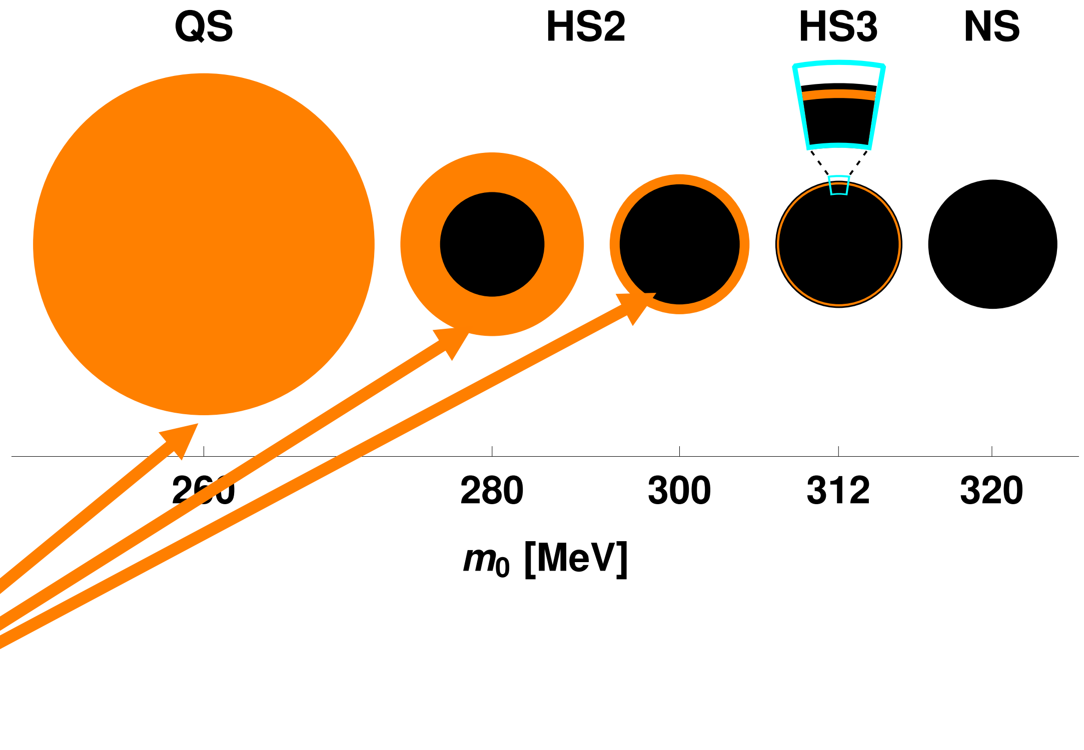
both phases

$m_0 > \mu_N$ nuclear matter

First order phase transitions at low and large densities

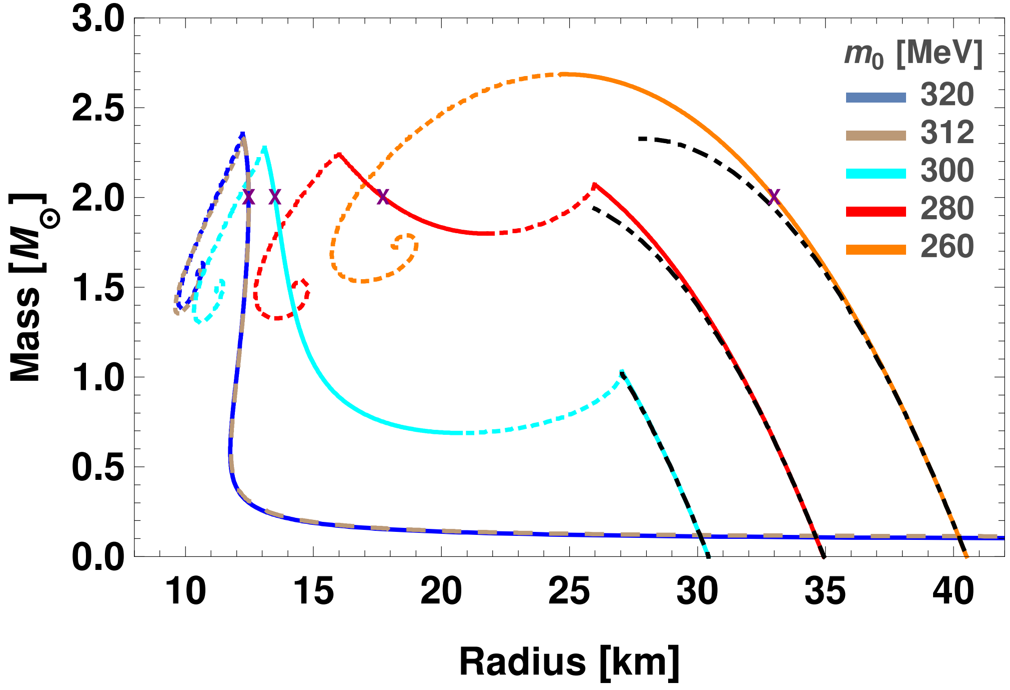
Hybrid stars with outer or inner crust made of quark matter

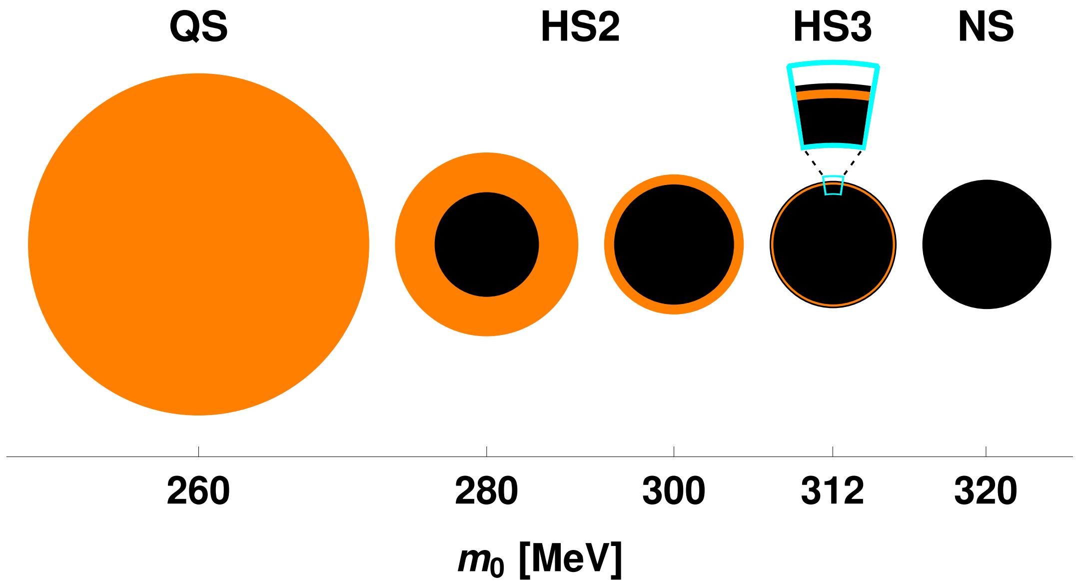




3-flavor quark matter absolutely stable

Hybrid stars with outer or inner crust made of quark matter

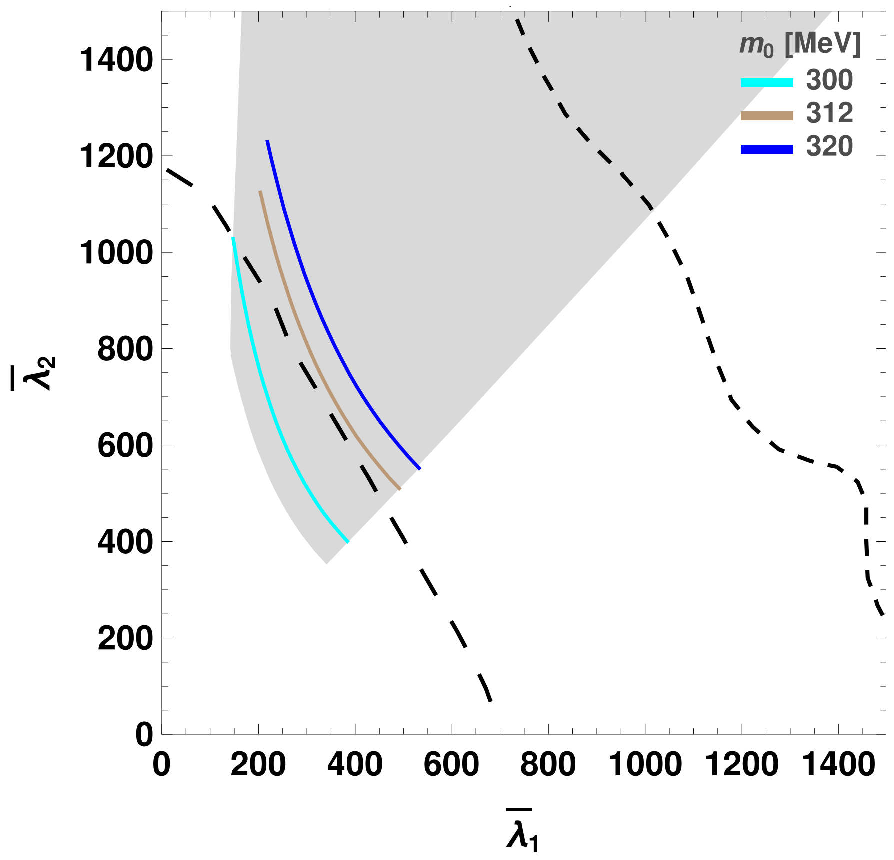


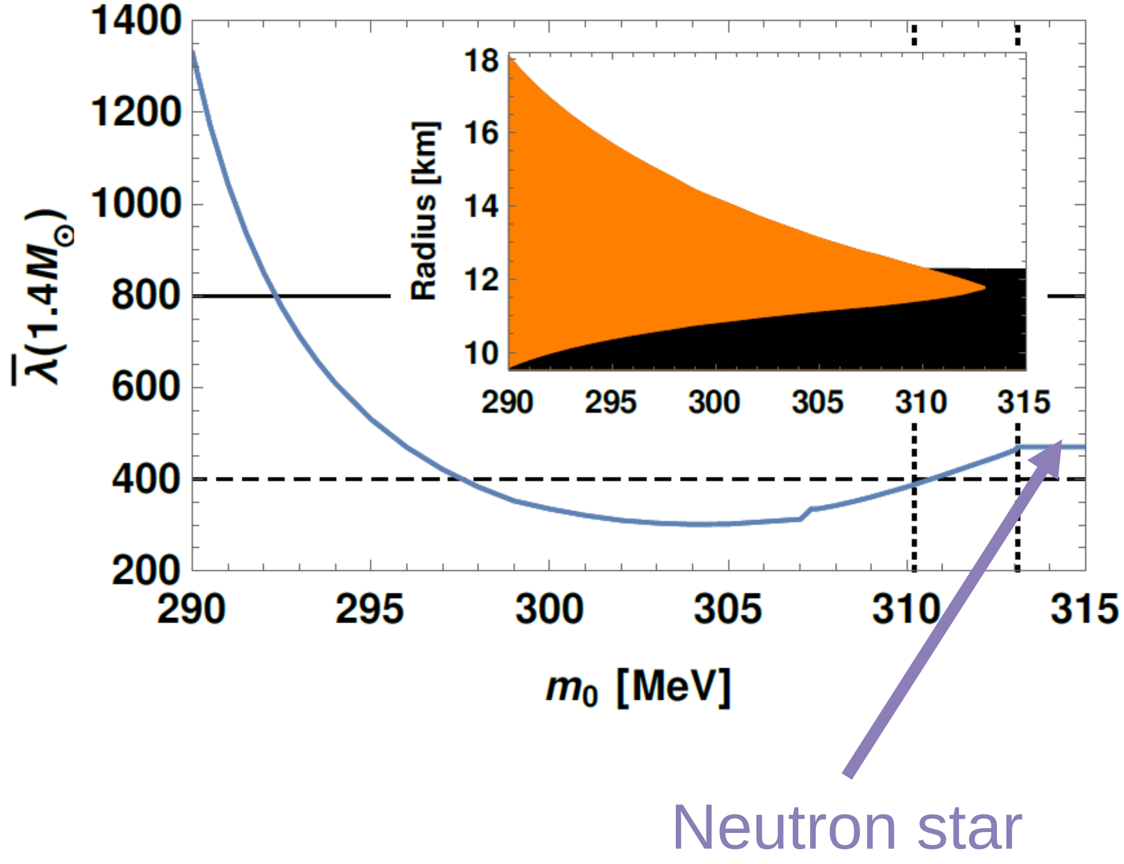


HS2 y HS3 also found in some other phenomenological models

Alford, Braby, Paris, Reddy ‘04

Tidal deformabilities of hybrid stars fit GW observation





Conclusions

First calculations in simplest gauge/gravity dual look promising

Left out: Significant deviations from universal I-Love-Q relations in HS

Pending task #1: stiff EoS for dense quark/baryon matter

Pending task #2: unified description of quark and baryon matter

Other aspects where the duality could be useful:

- Transport, emissivities
- Out-of-equilibrium properties