STAG RESEARCH CENTRE

University of Southampton

Nuclear Chiral Density Wave

Field Theory, Neutron Stars and Holography

PRD 111, 034010 (2025) with Andreas Schmitt

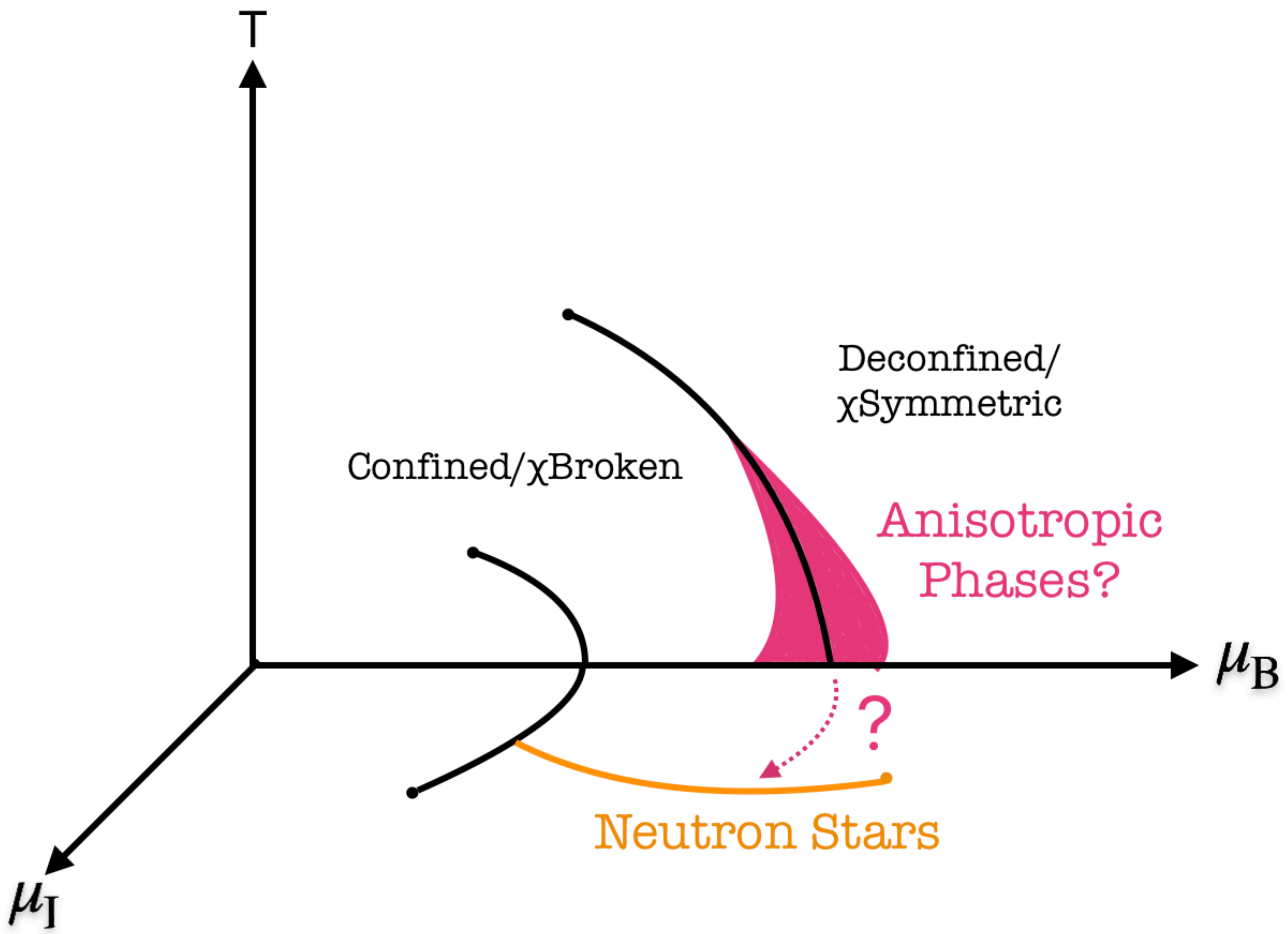
and soon to appear with Nicolas Kovensky and Andreas Schmitt

Orestis Papadopoulos, 18/08/2026

17–21 Aug 2026
Helsinki, Finland

Strong and Electro-Weak Matter 2026

QCD Phase Diagram
Motivation



- Anisotropic phases around deconfinement/chiral phase transition [Buballa, Carignano '14 / Demircik, Jokela, Jarvinen, Piispa '24]

↓

Present in neutron stars?

- Simplest construction: anisotropic chiral condensate = Chiral Density Wave (CDW)

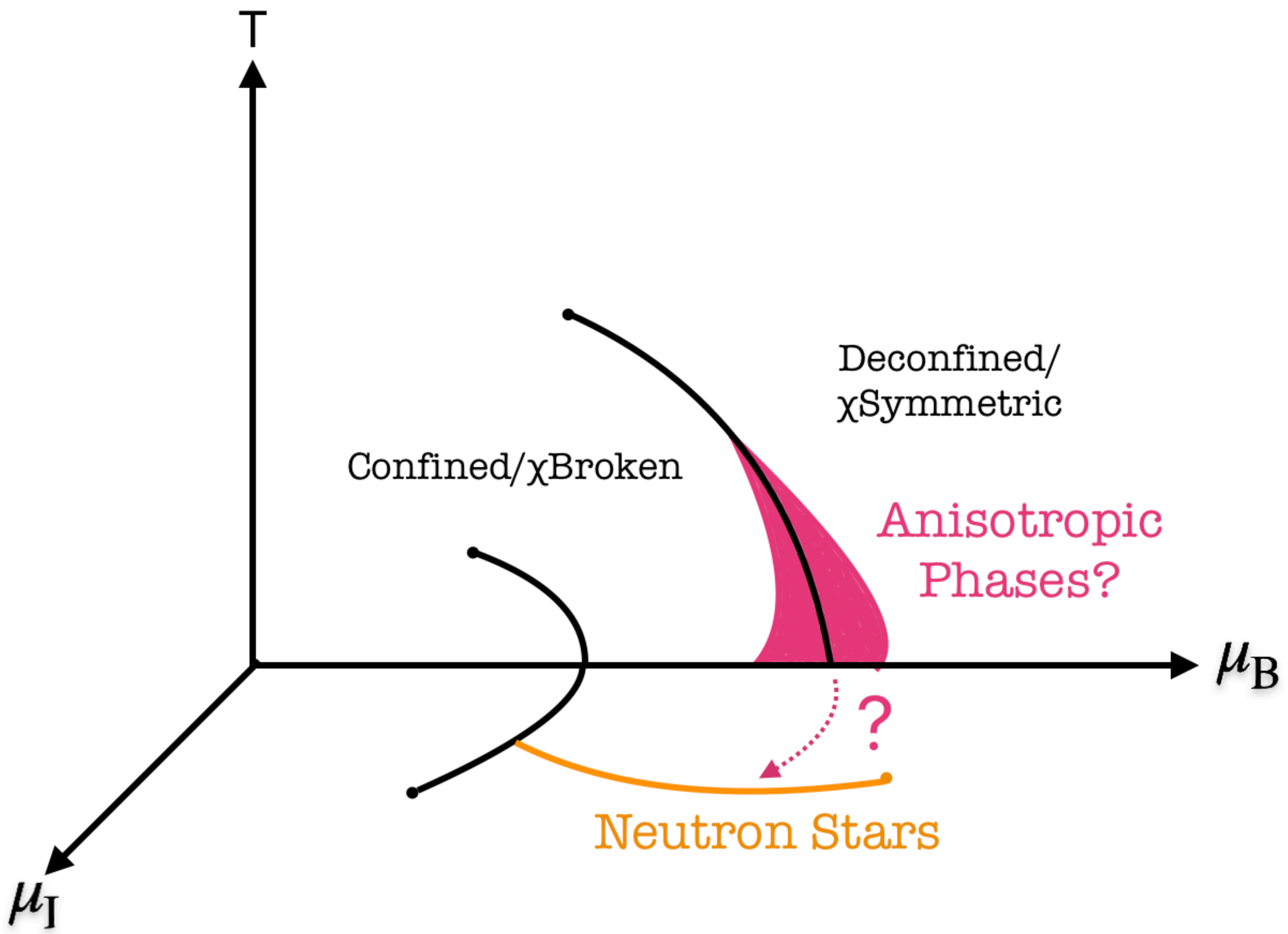
$$\boxed{\langle\bar{\psi}\psi\rangle \equiv \phi\cos(2\vec{q}\cdot\vec{x}),\ \ \langle\bar{\psi}\gamma^5\tau_3\psi\rangle \equiv \phi\sin(2\vec{q}\cdot\vec{x})}$$

[Dautry, Nyman '79 / Nickel '09]

- Present in strongly coupled regime → first principles calculations not feasible
- Two methods:

1. field theory
2. holography

QCD Phase Diagram
Motivation



- Anisotropic phases around deconfinement/chiral phase transition [Buballa, Carignano '14 / Demircik, Jokela, Jarvinen, Piispa '24]

↓

Present in neutron stars?

- Simplest construction: anisotropic chiral condensate = Chiral Density Wave (CDW)

$$\boxed{\langle\overline{\psi}\psi\rangle \equiv \phi\cos(2\vec{q}\cdot\vec{x}), \quad \langle\overline{\psi}\gamma^5\tau_3\psi\rangle \equiv \phi\sin(2\vec{q}\cdot\vec{x})}$$

[Dautry, Nyman '79 / Nickel '09]

- Present in strongly coupled regime → first principles calculations not feasible
- Two methods:

1. field theory
2. holography

I: Nucleon-Meson Model

Q: Can the nuclear CDW be present in the core of neutron stars?

Nucleon-Meson Model

[Drews, Weise '15 / Fraga, Mata, Pitsinigkos, Schmitt '22]

$$\mathscr{L} = \mathscr{L}_{\rm nuc} + \mathscr{L}_{\rm mes} + \mathscr{L}_{\rm int}$$

CDW ansatz:

$$\langle \sigma \rangle = \phi \cos(2\vec{q} \cdot \vec{x}), \quad \langle \pi^0 \rangle = \phi \sin(2\vec{q} \cdot \vec{x})$$

- Neglect mesonic but keep nucleonic vacuum fluctuations: renormalise the pressure
  [Pitsinigkos, Schmitt '23]
- Electric charge neutrality, β-equilibrium → neutron star matter

---

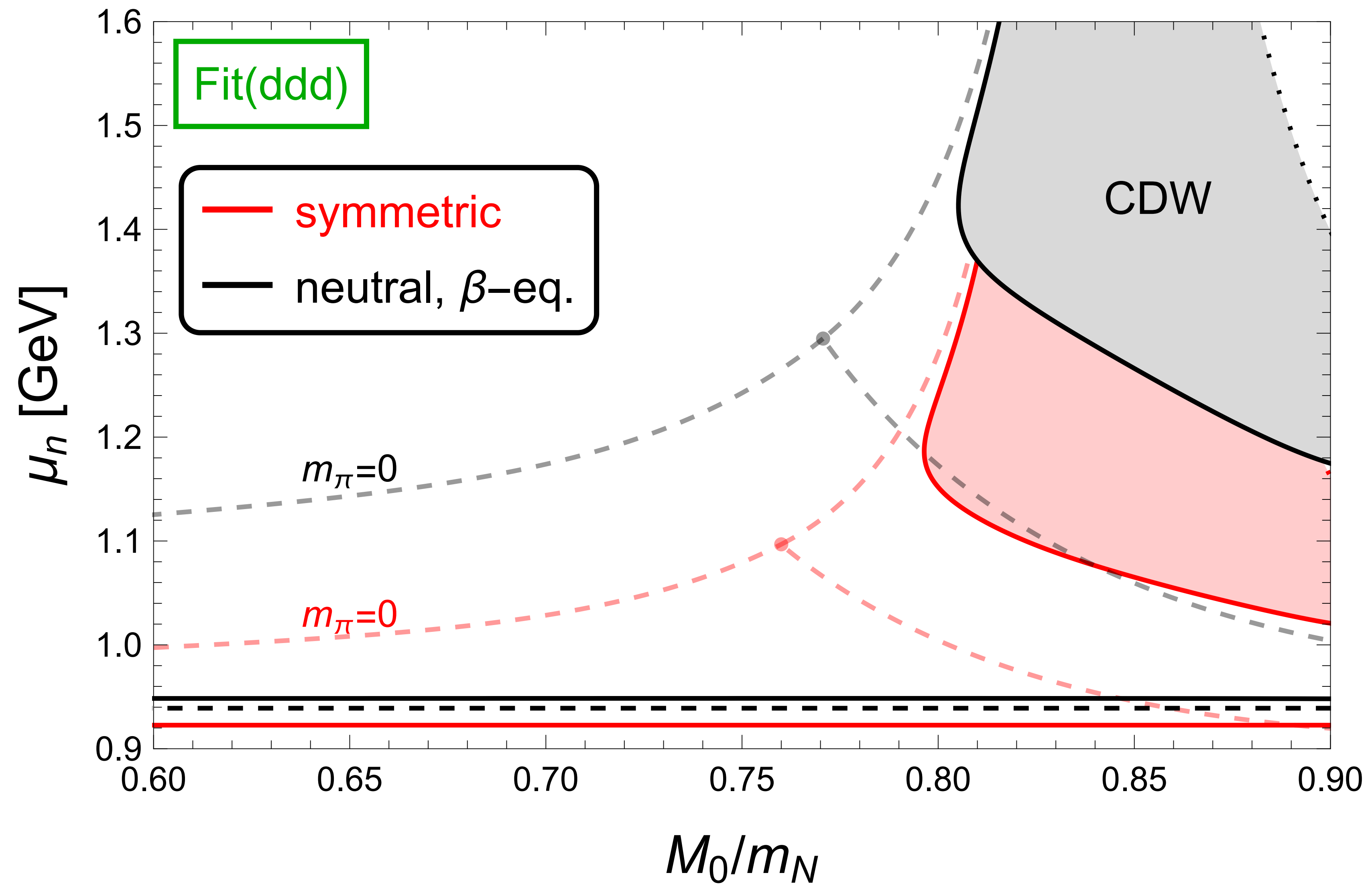
- Fit parameters to properties of:

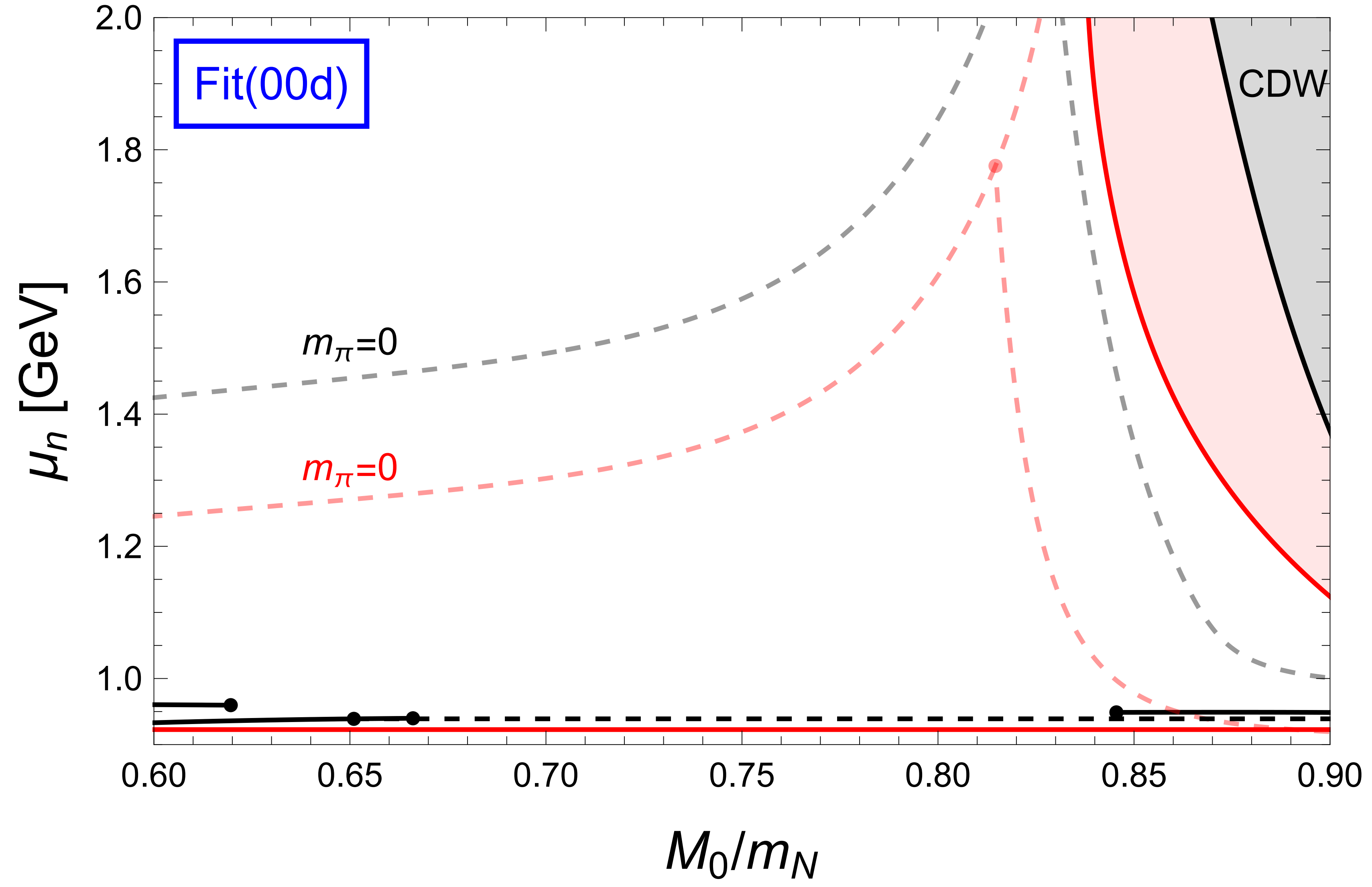
1. Vacuum
2. Saturation (isospin-symmetric)
3. Pure neutron matter

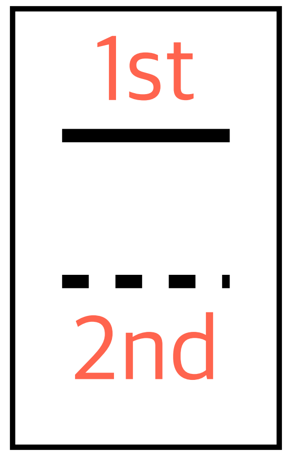
→ Two fits: Fit(00d) and Fit(ddd)

[Tews, Carlson, Gandolfi, Reddy '18 / Alford, Brodie, Haber, Tews '22]

Effect of Neutron Star Conditions







- Plots in terms of nucleon mass at saturation M_0
- For both fits:

Chiral phase transition with nucleonic vacuum fluctuations: 1st order → crossover

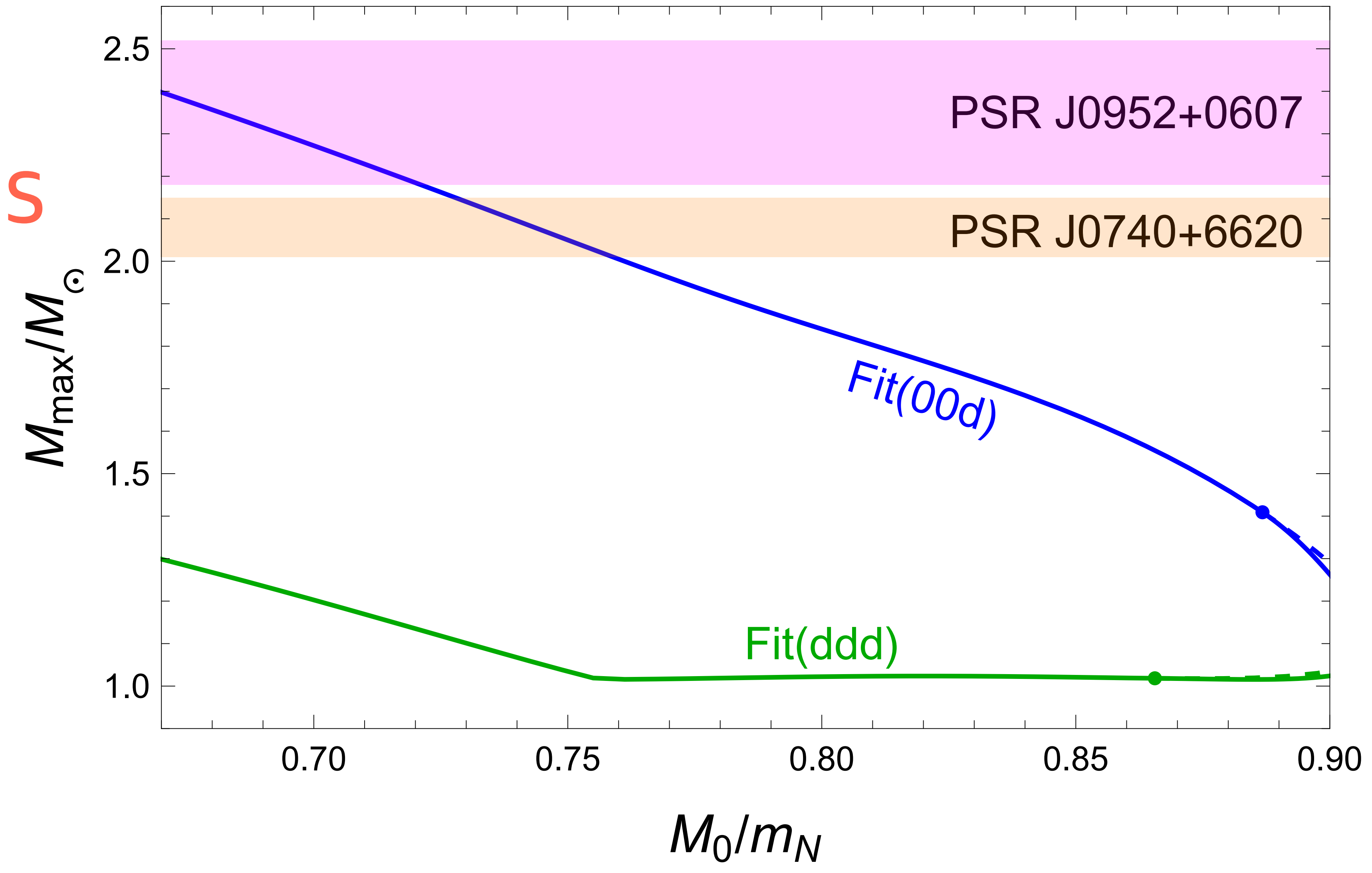
Neutron star conditions → CDW less favoured

Combine with gravity → TOV equations → neutron stars

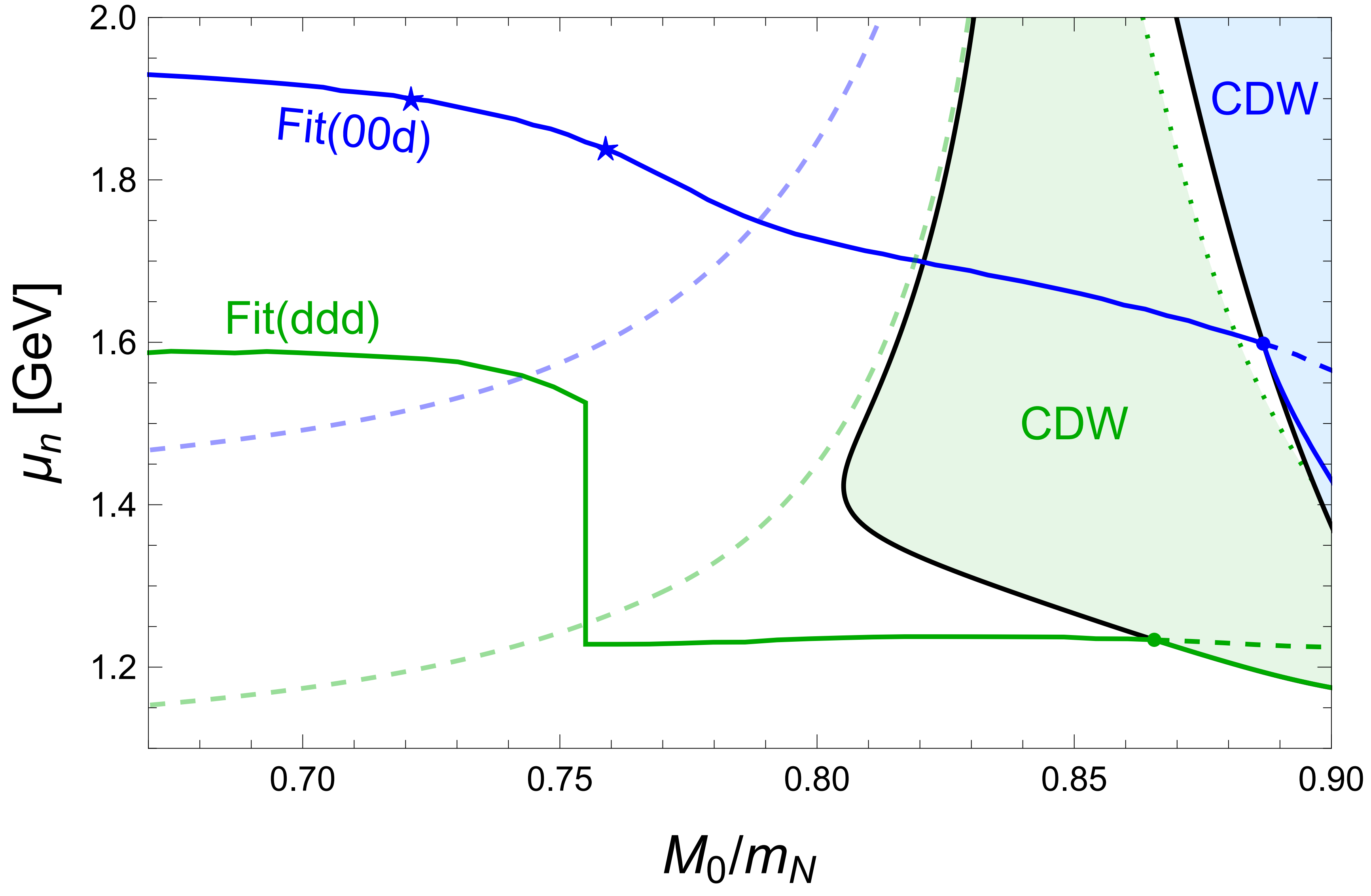
CDW in Neutron Stars?

observations

mass of the heaviest star

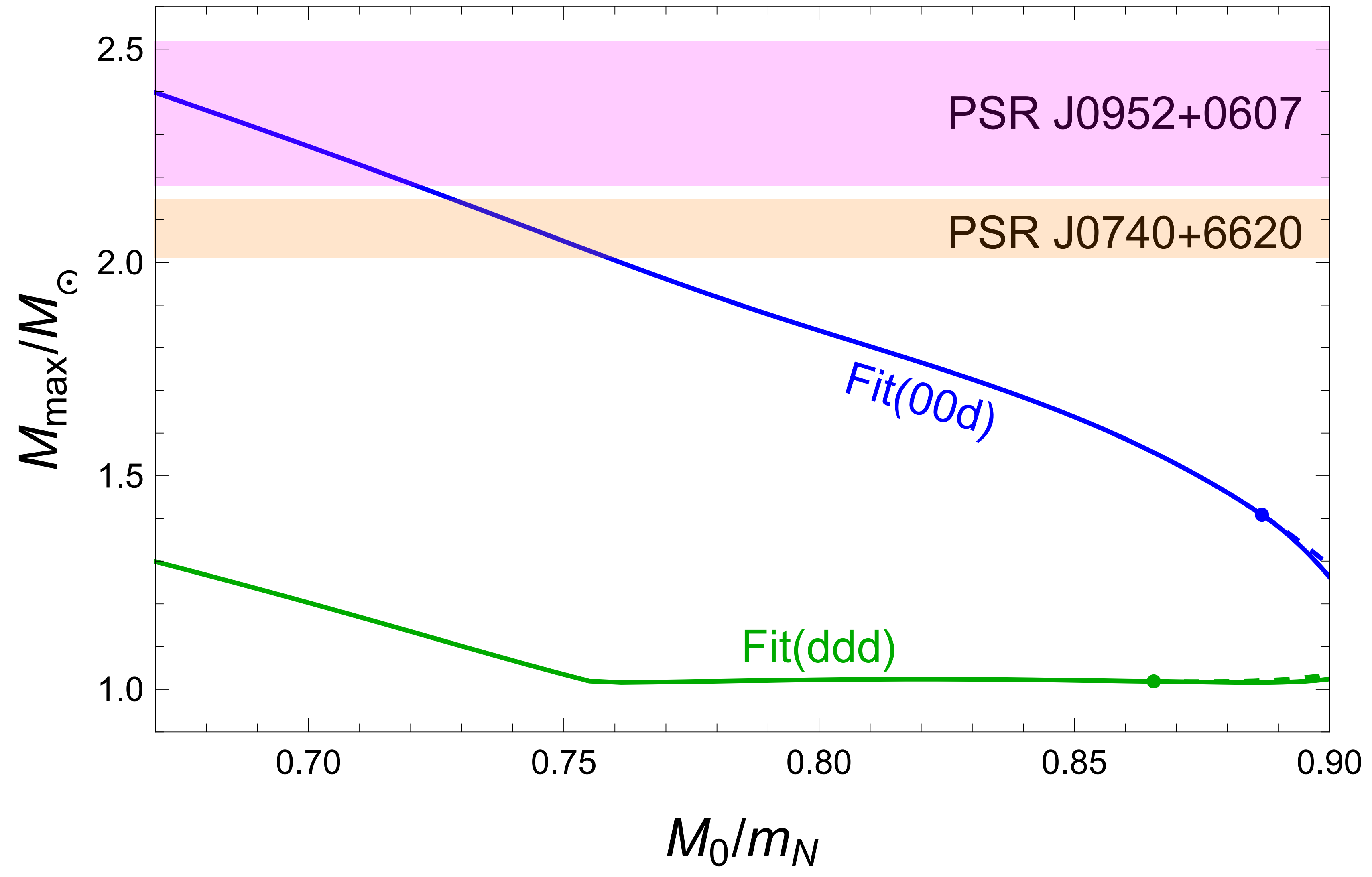


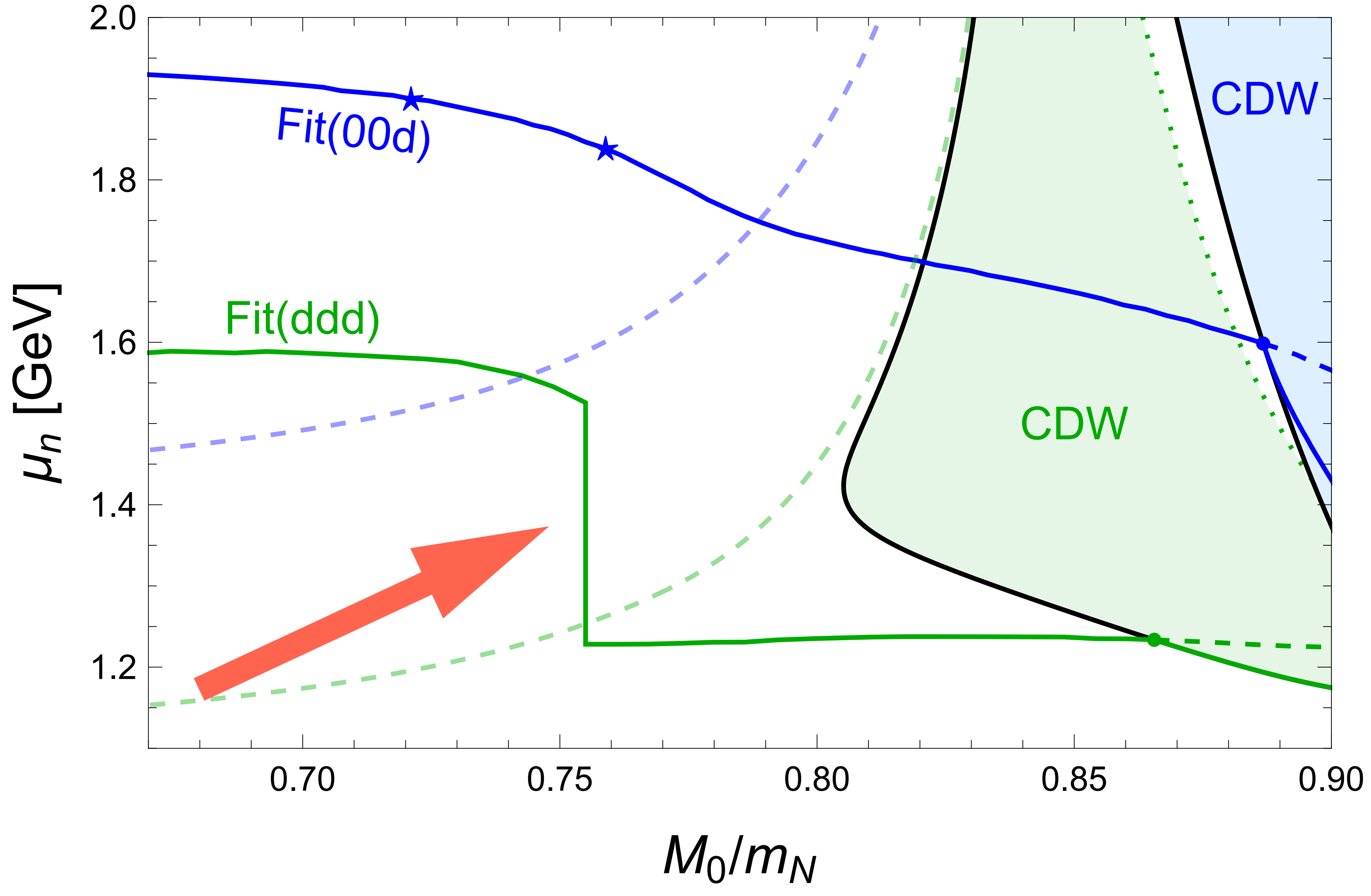
μ_n at centre of the heaviest star



CDW in Neutron Stars?

- Fit (ddd) features twin stars

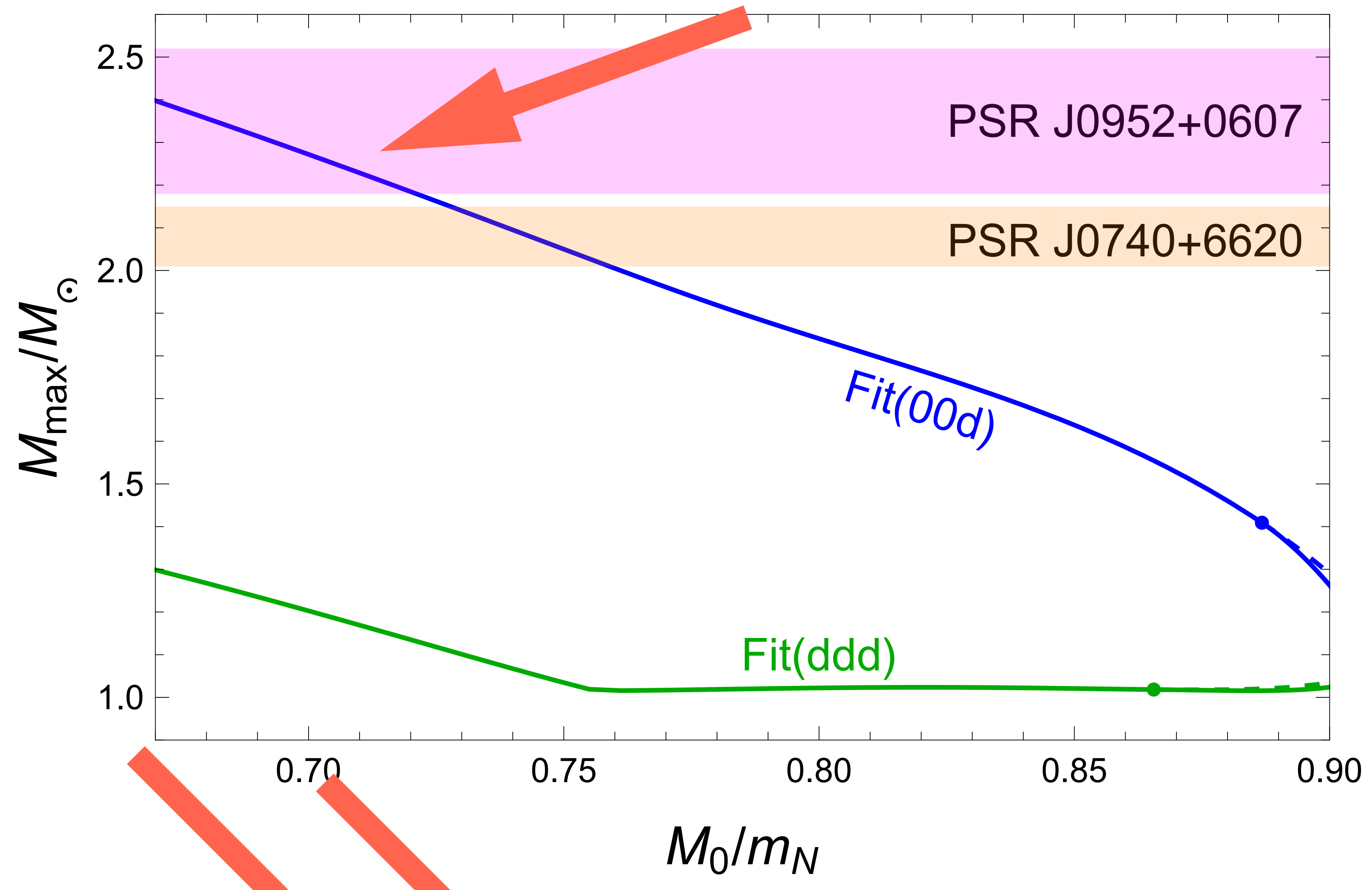


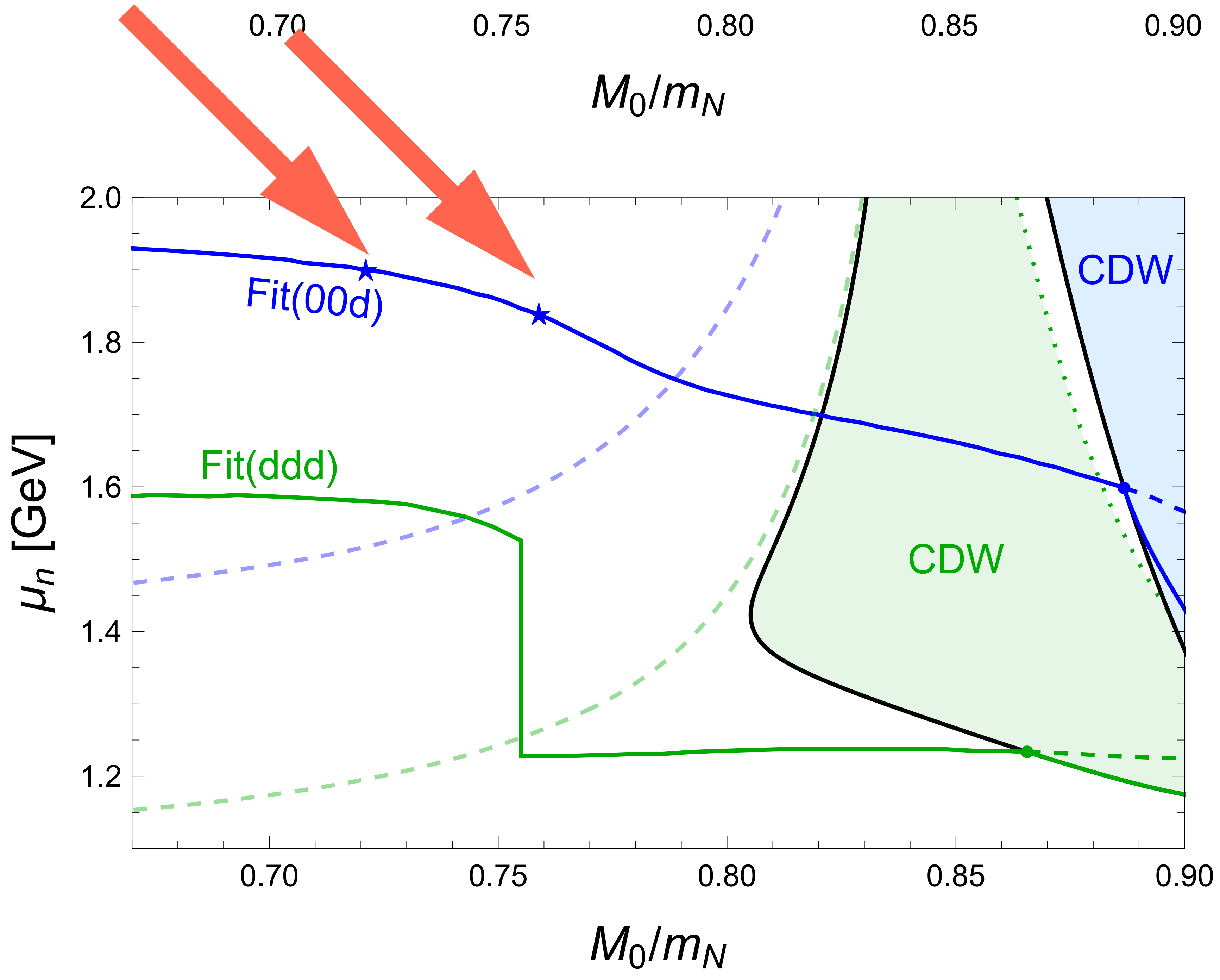


CDW in Neutron Stars?

- Fit (ddd) features twin stars

- Fit(00d) can create stars that agree with measurements

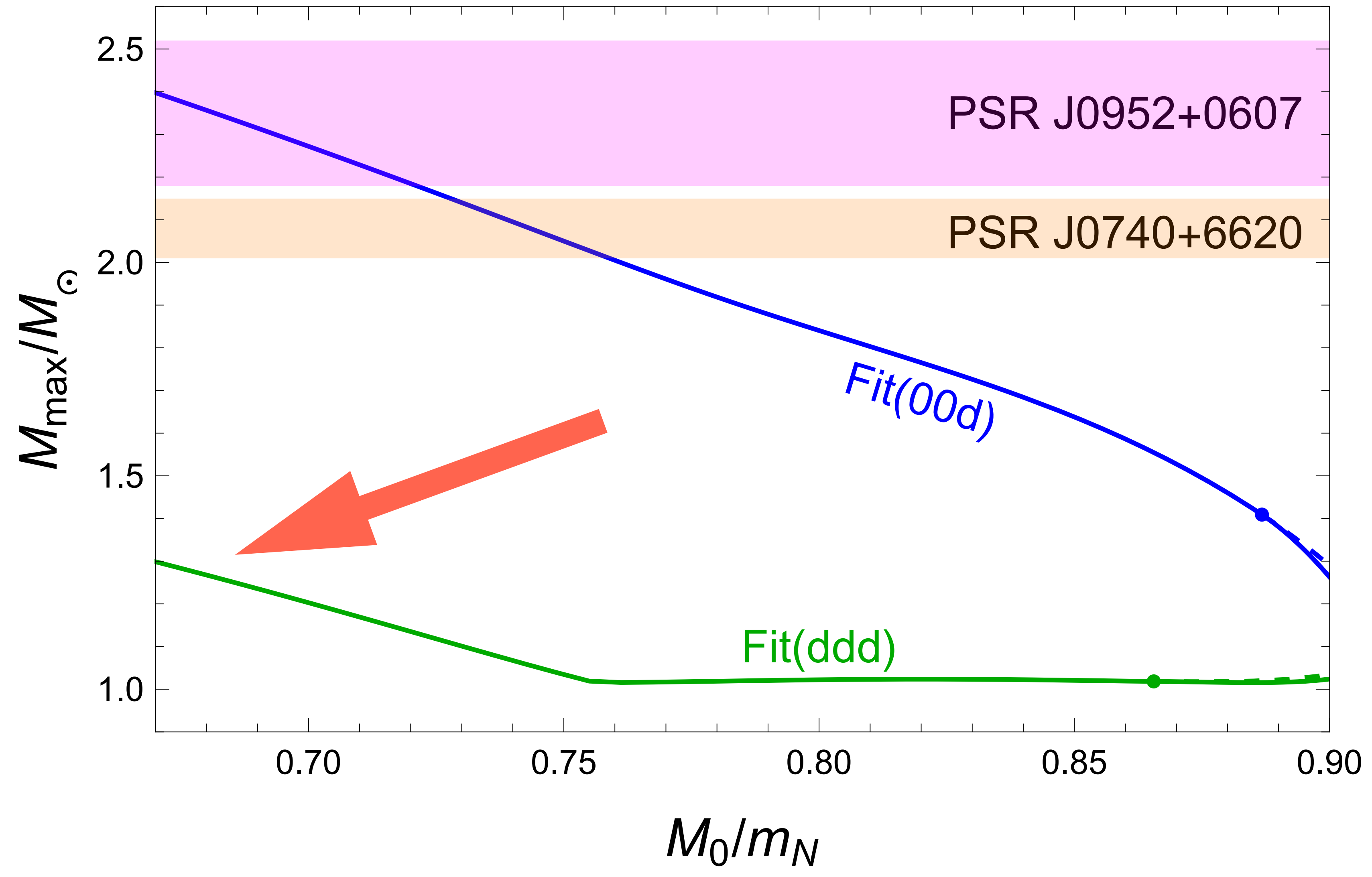


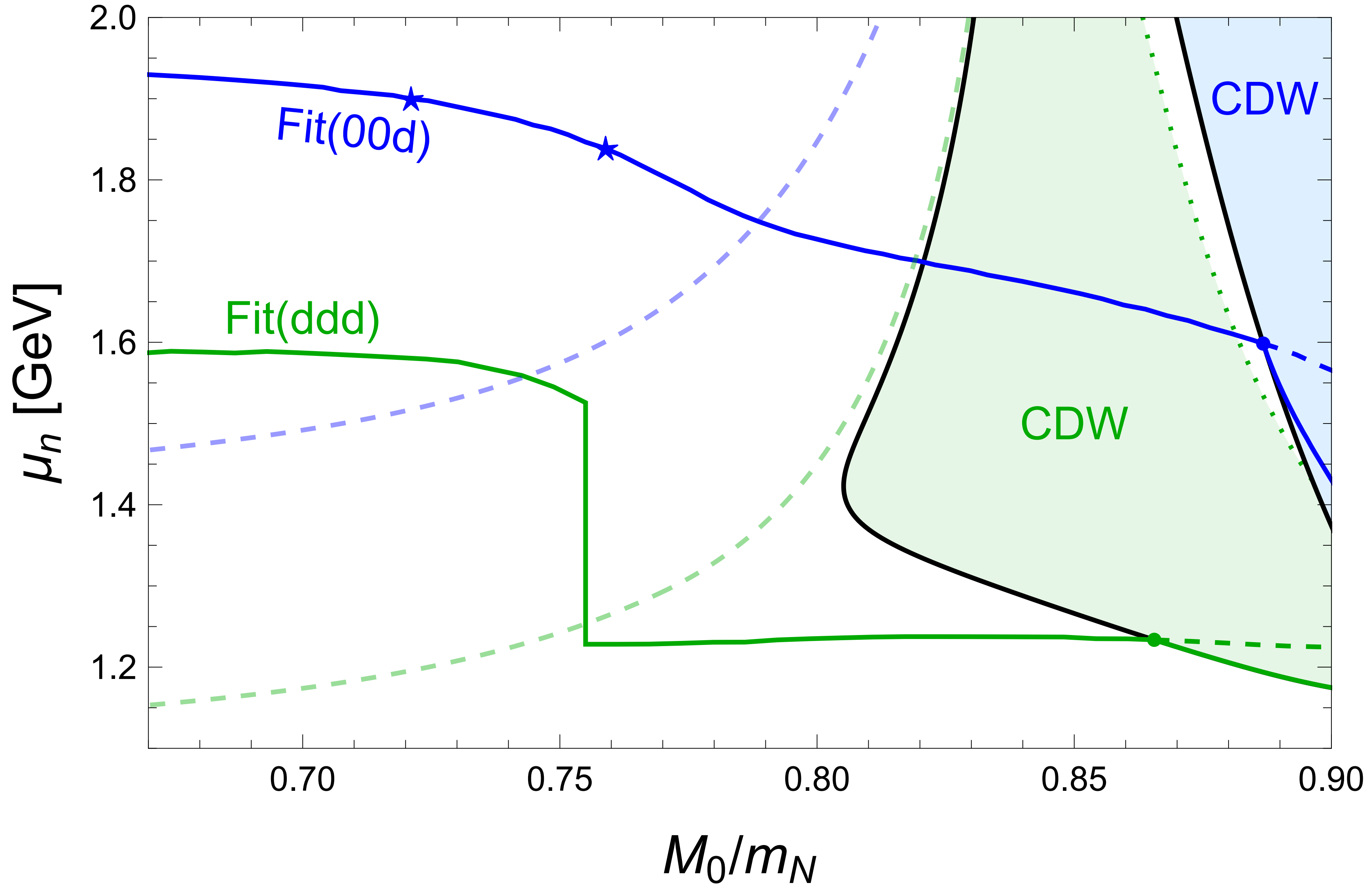


CDW in Neutron Stars?

- Fit (ddd) features twin stars

- Fit(00d) can create stars that agree with measurements
- Fit(ddd) cannot

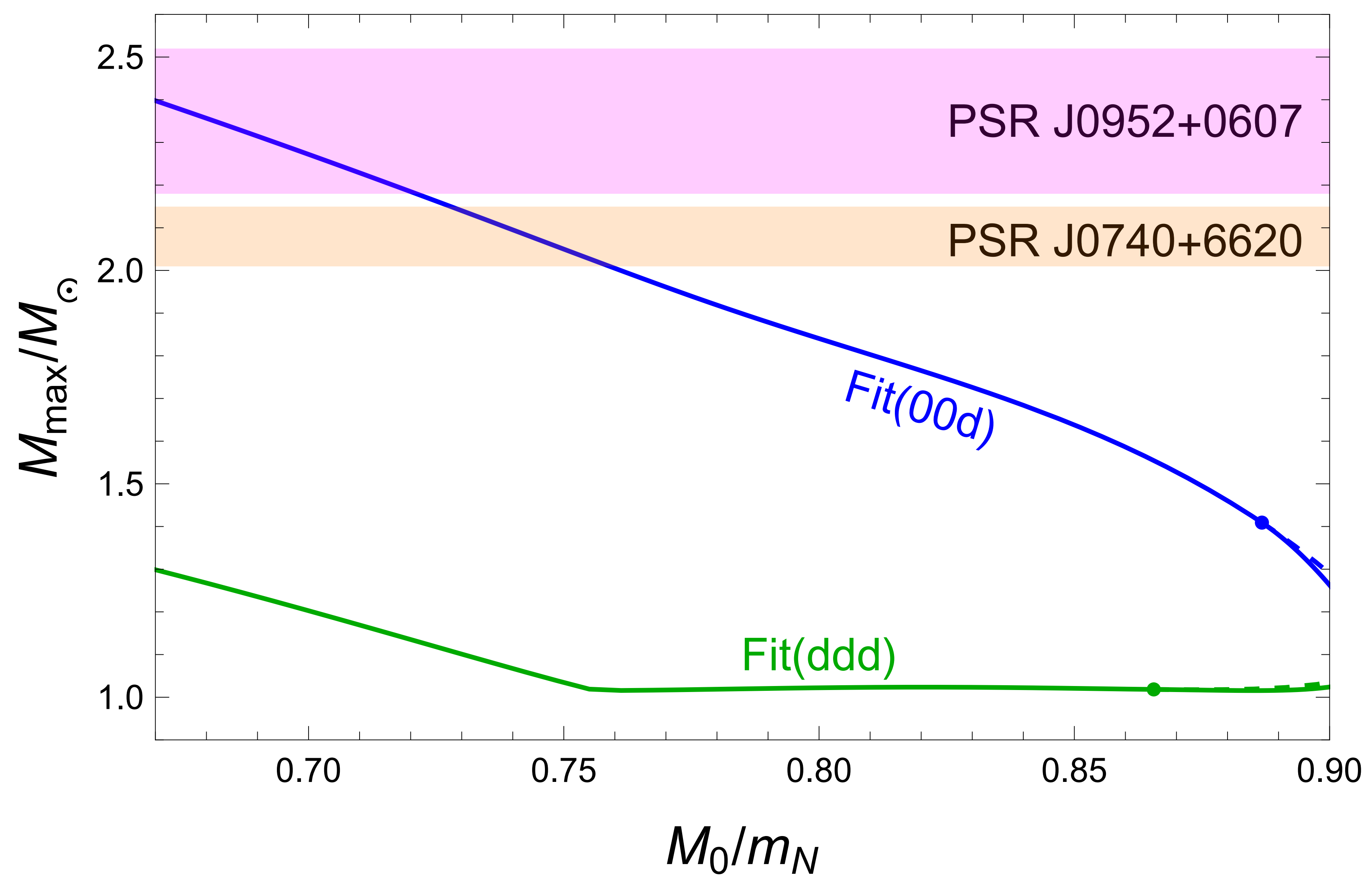


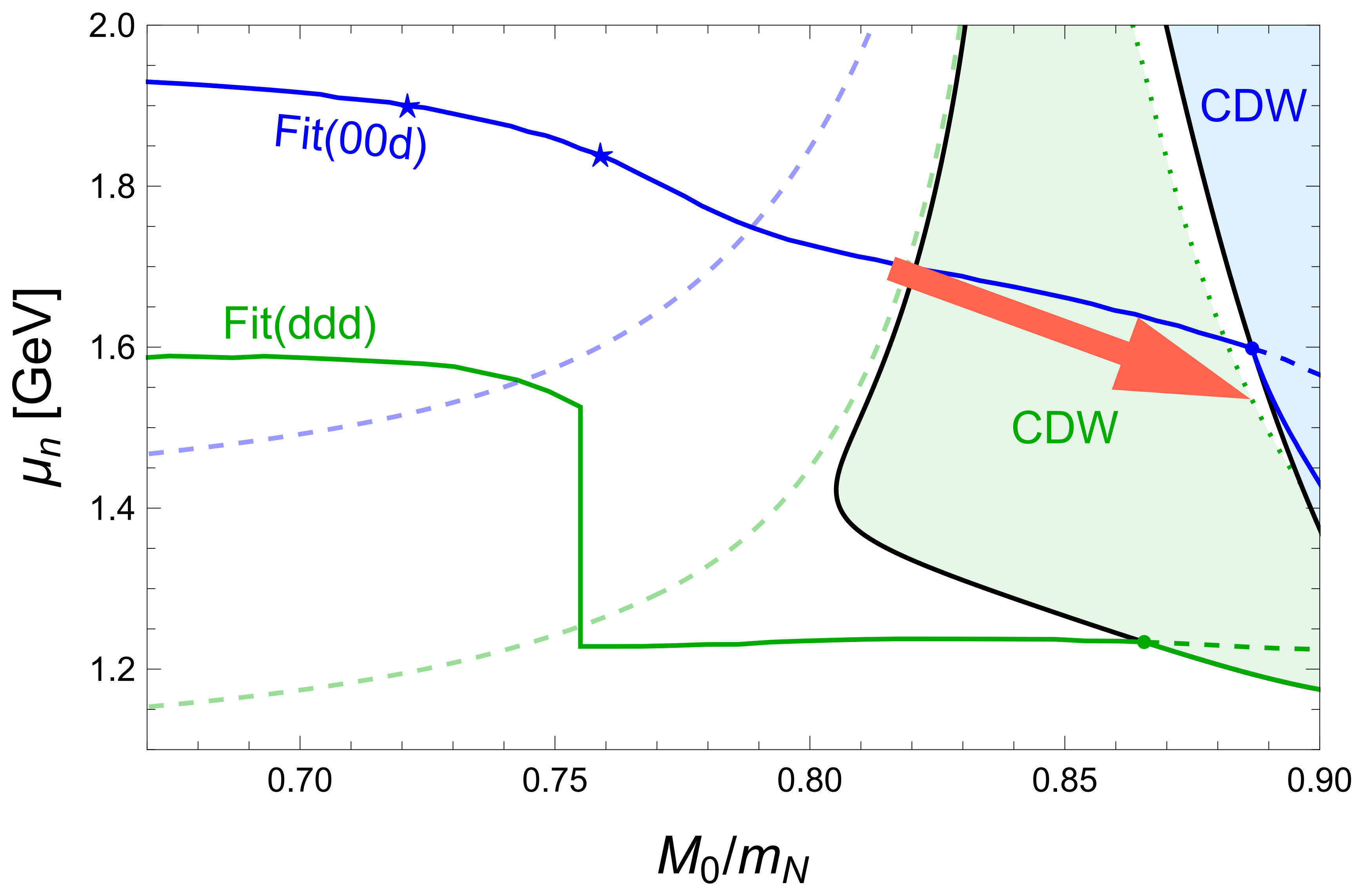


CDW in Neutron Stars?

- Fit (ddd) features twin stars

- Fit(00d) can create stars that agree with measurements
- Fit(ddd) cannot
- Fit(00d) can create stars with stable CDW cores

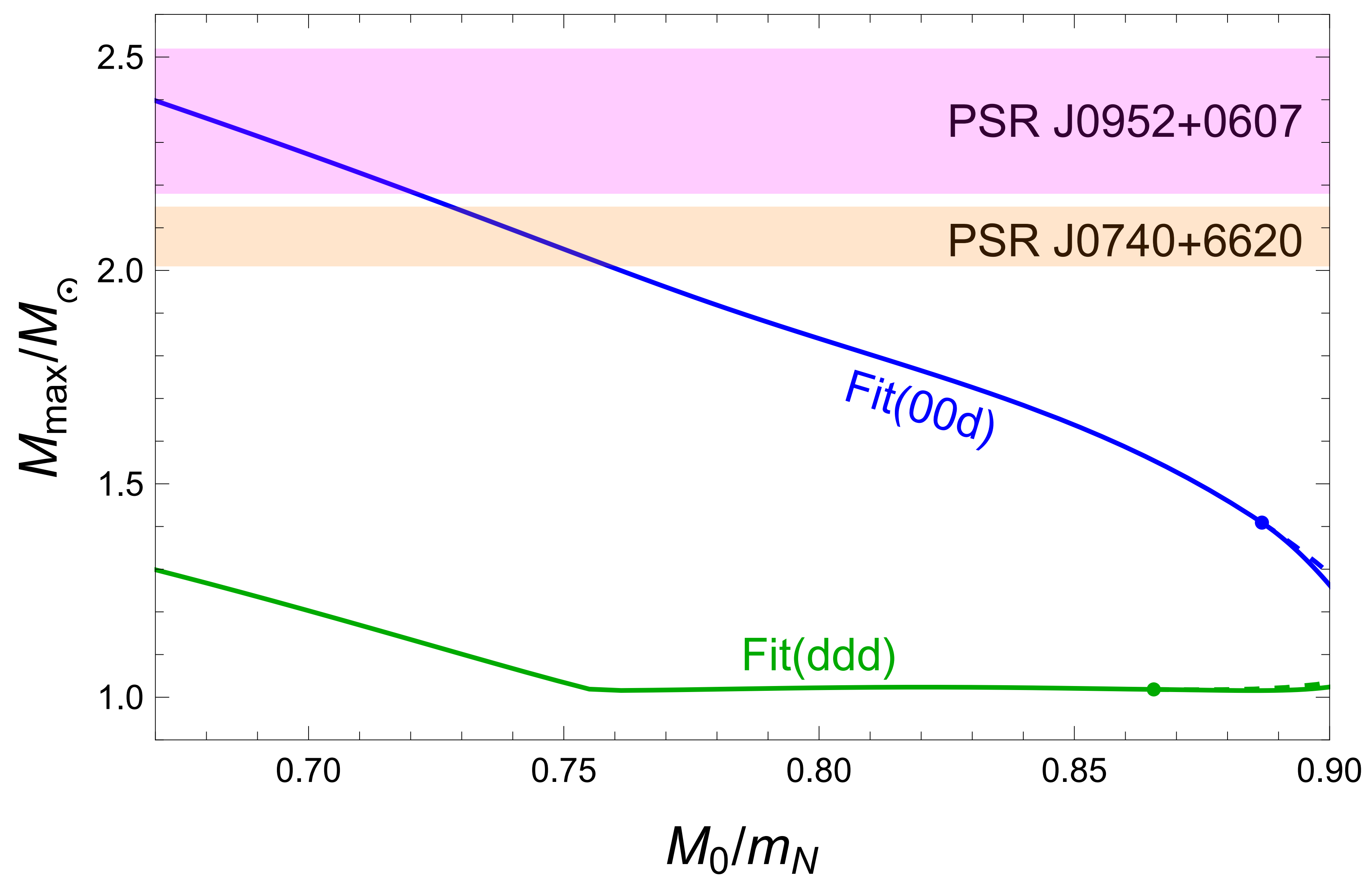


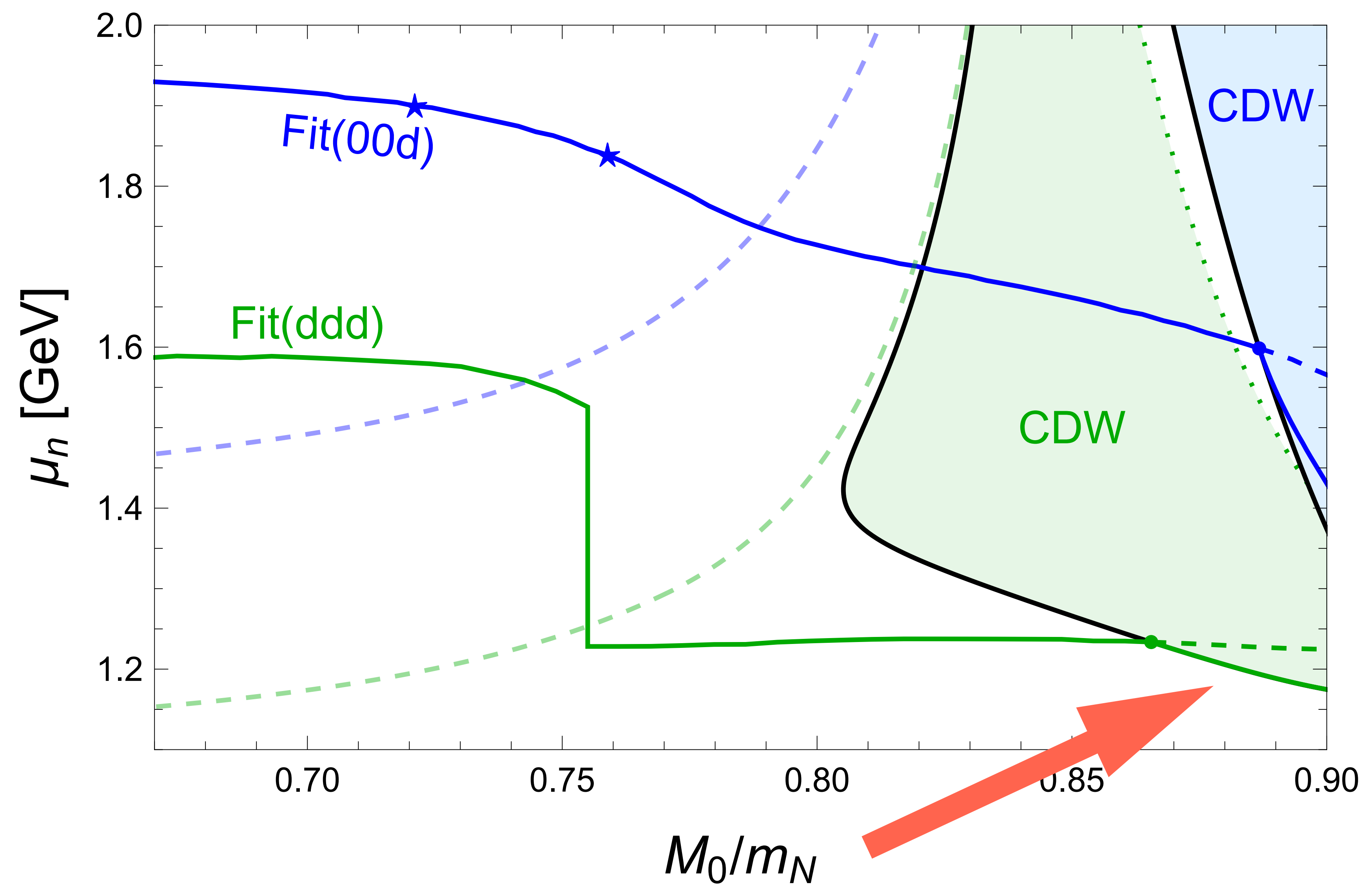


CDW in Neutron Stars?

- Fit (ddd) features twin stars

- Fit(00d) can create stars that agree with measurements
- Fit(ddd) cannot
- Fit(00d) can create stars with stable CDW cores
- Fit(ddd) cannot



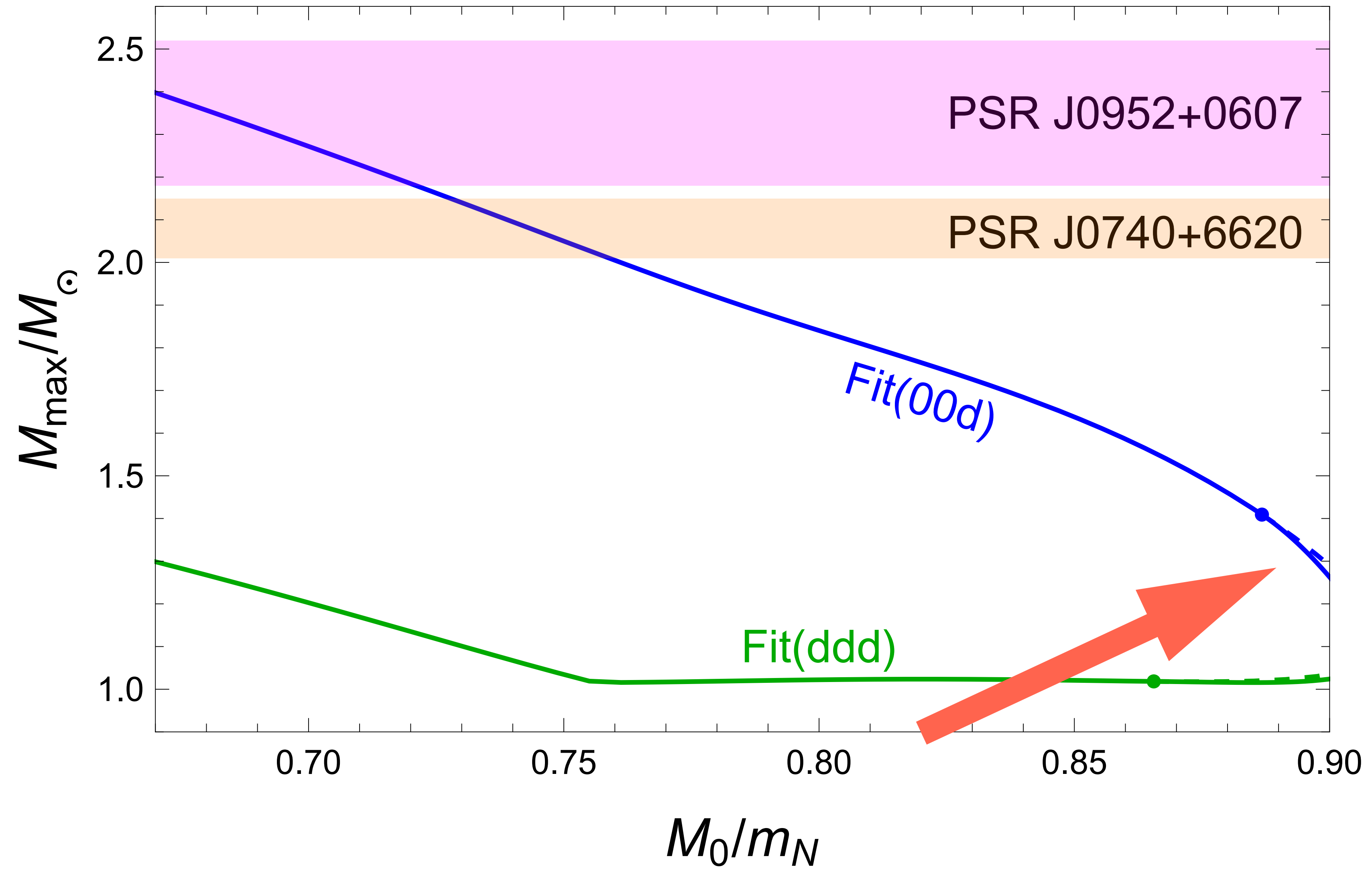


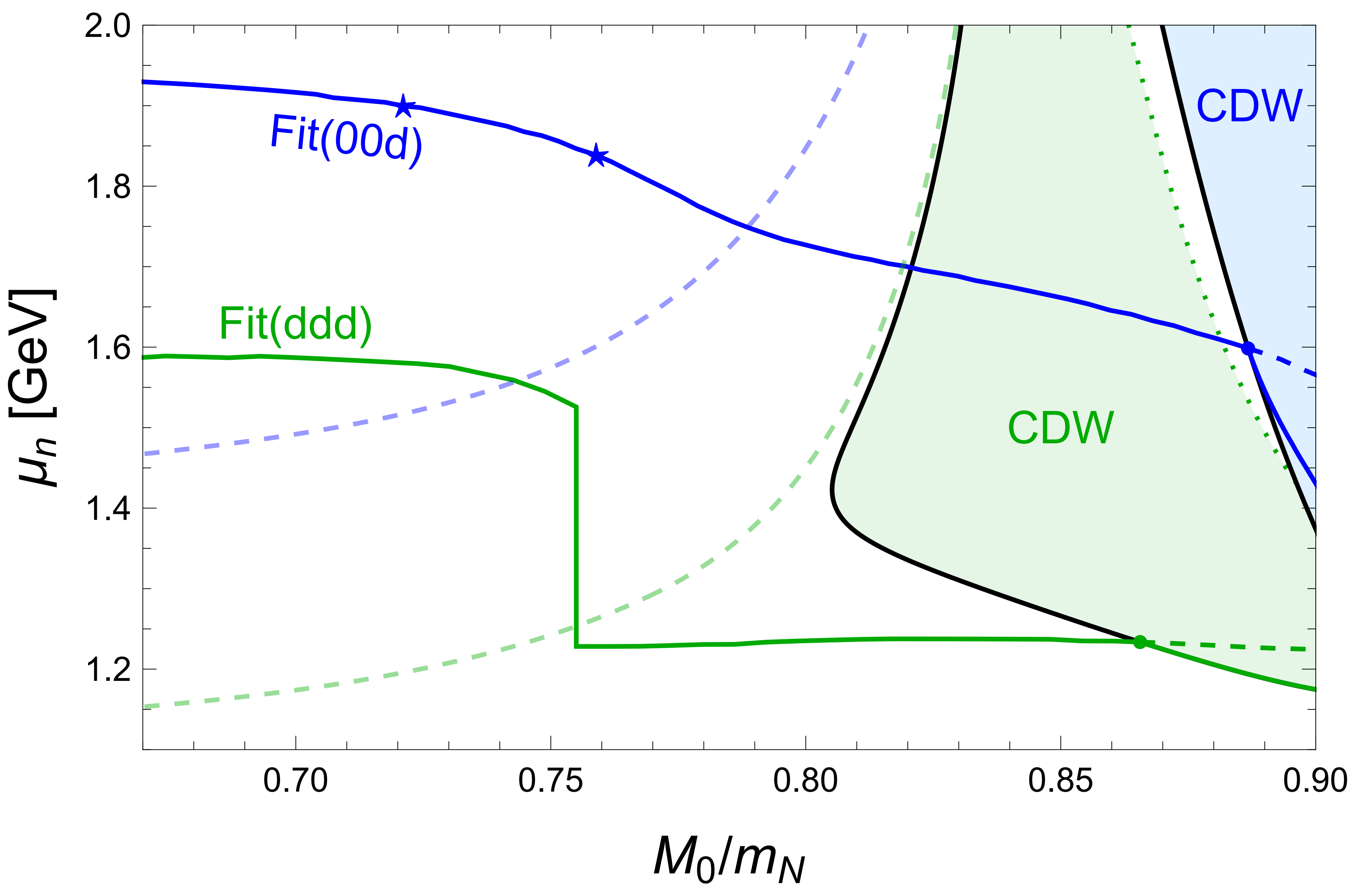
CDW in Neutron Stars?

- Fit (ddd) features twin stars

- Fit(00d) can create stars that agree with measurements
- Fit(ddd) cannot
- Fit(00d) can create stars with stable CDW cores
- Fit(ddd) cannot

<u>But</u> stars with stable CDW cores are not heavy enough!





I: Nucleon-Meson Model

Q: Can the nuclear CDW be present in the core of neutron stars?

I: Nucleon-Meson Model

Q: Can the nuclear CDW be present in the core of neutron stars?

A: No, although realistic isotropic stars can be created

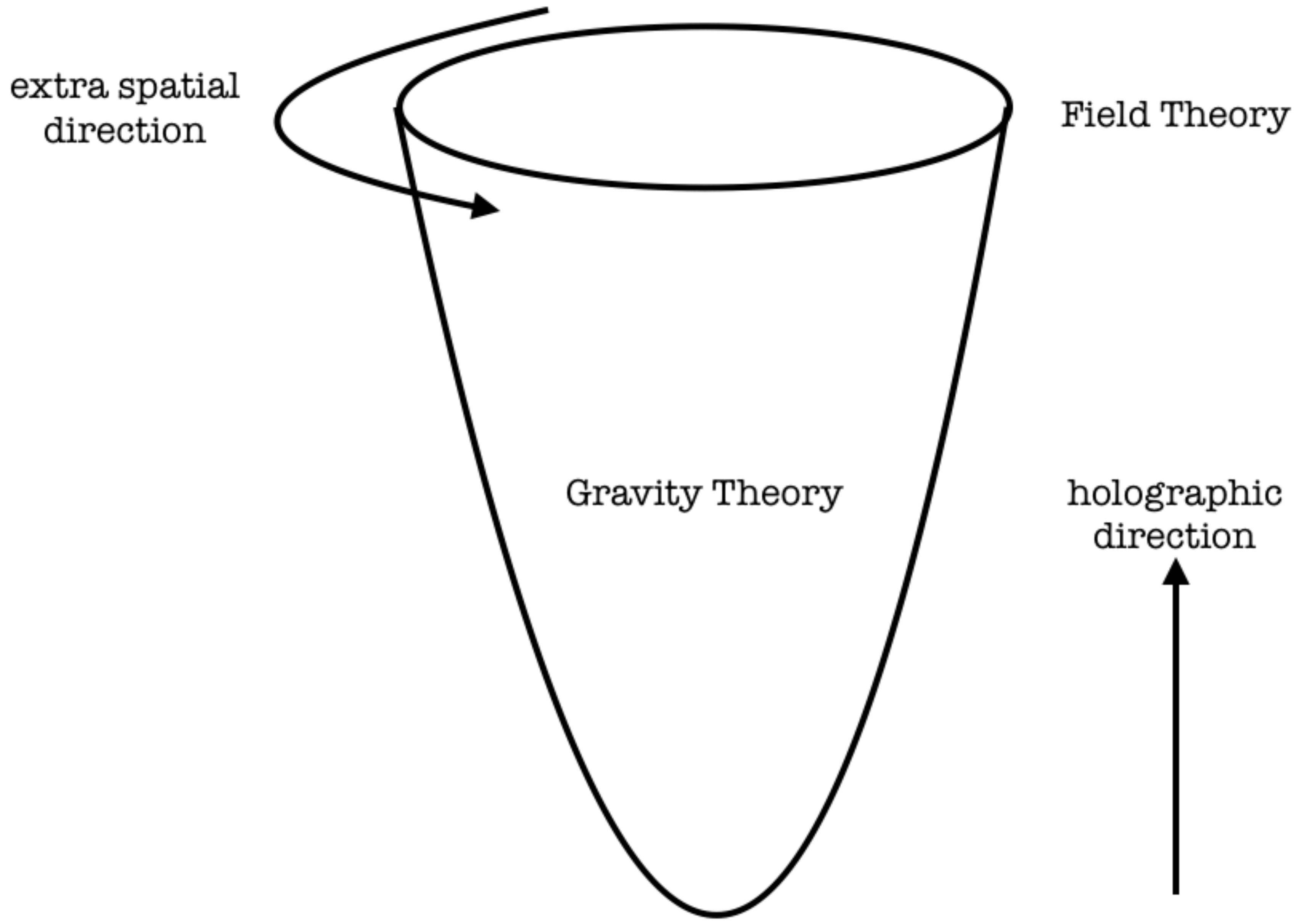
II: Holography

Q: Can we construct the CDW in nuclear matter using AdS/CFT?

Witten-Sakai-Sugimoto (WSS) model

[Witten '98 / Sakai, Sugimoto '04]

- Holography: strongly coupled field theory in 4D = gravity theory in 10D [Maldacena '97]
- <u>Witten-Sakai-Sugimoto model</u>: colour and flavour branes, <u>confined</u> and deconfined geometry



In WSS. . .

Global flavour symmetry of QCD $\to$ $U(2)$ gauge symmetry (gauge fields) in the bulk

Chiral Density Wave

Recall CDW:

$$\langle\overline{\psi}\psi\rangle \equiv \phi\cos(2\vec{q}\cdot\vec{x}), \quad \langle\overline{\psi}\gamma^5\tau_3\psi\rangle \equiv \phi\sin(2\vec{q}\cdot\vec{x})$$

CDW ansatz: boundary condition for non-abelian component

$$A_3^3(\pm\infty) = q$$

Baryonic matter

- Baryons = instantonic solutions for the non-abelian gauge fields
  [Hashimoto, Sakai, Sugimoto '08]
- Depend on space and the holographic direction, numerical computations difficult
- Large densities $\to$ homogeneous ansatz (no spatial dependence)
- Use preferred isotropic phase
  [Ecker, Kovensky, Papadopoulos, Schmitt '25]

In WSS. . .

Global flavour symmetry of QCD → $U(2)$ gauge symmetry (gauge fields) in the bulk

Chiral Density Wave

Recall CDW:

$$\langle\bar{\psi}\psi\rangle \equiv \phi\cos(2\vec{q}\cdot\vec{x}), \quad \langle\bar{\psi}\gamma^5\tau_3\psi\rangle \equiv \phi\sin(2\vec{q}\cdot\vec{x})$$

CDW ansatz: boundary condition for non-abelian component

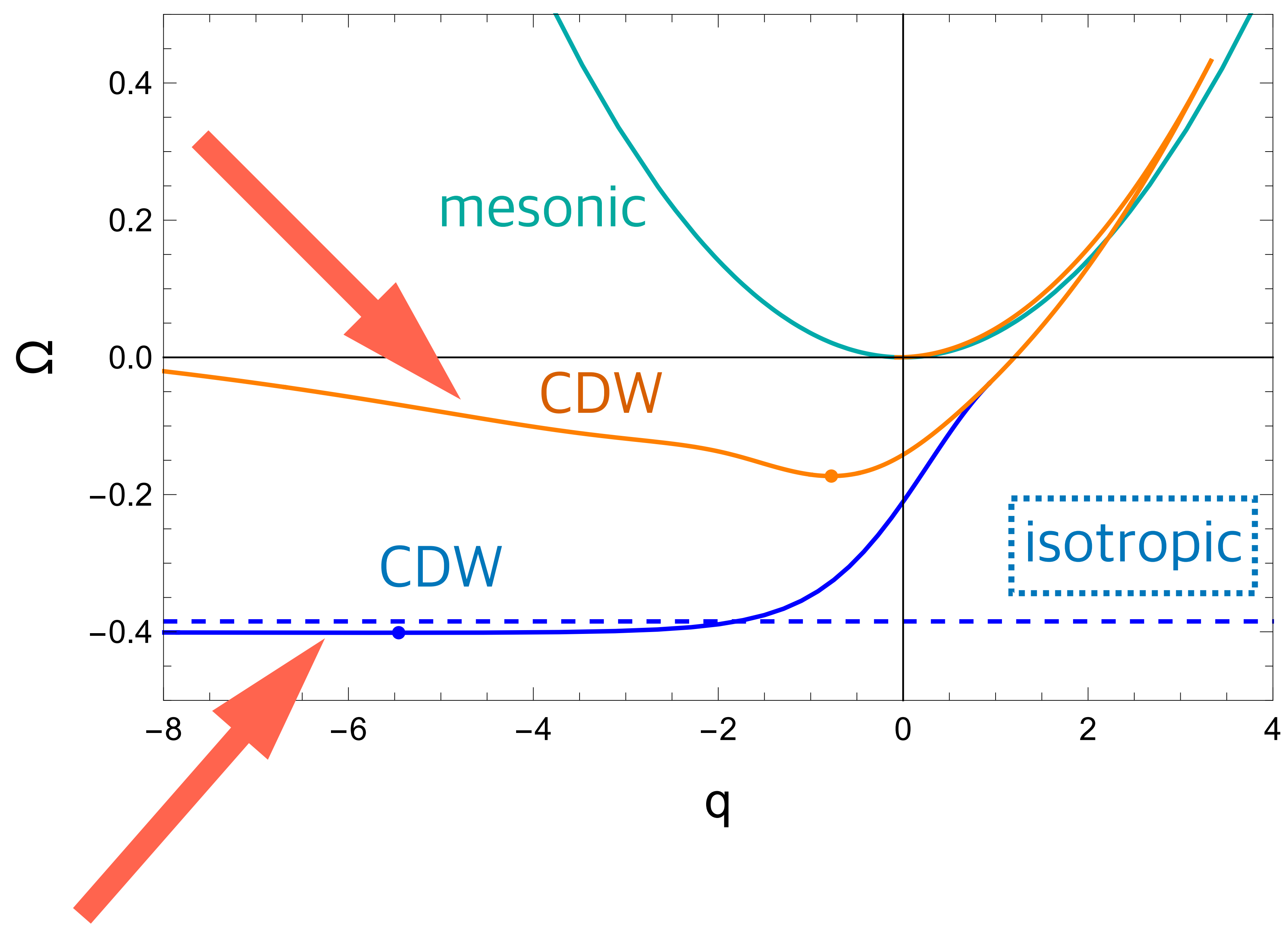
$$A_3^3(\pm\infty) = q$$

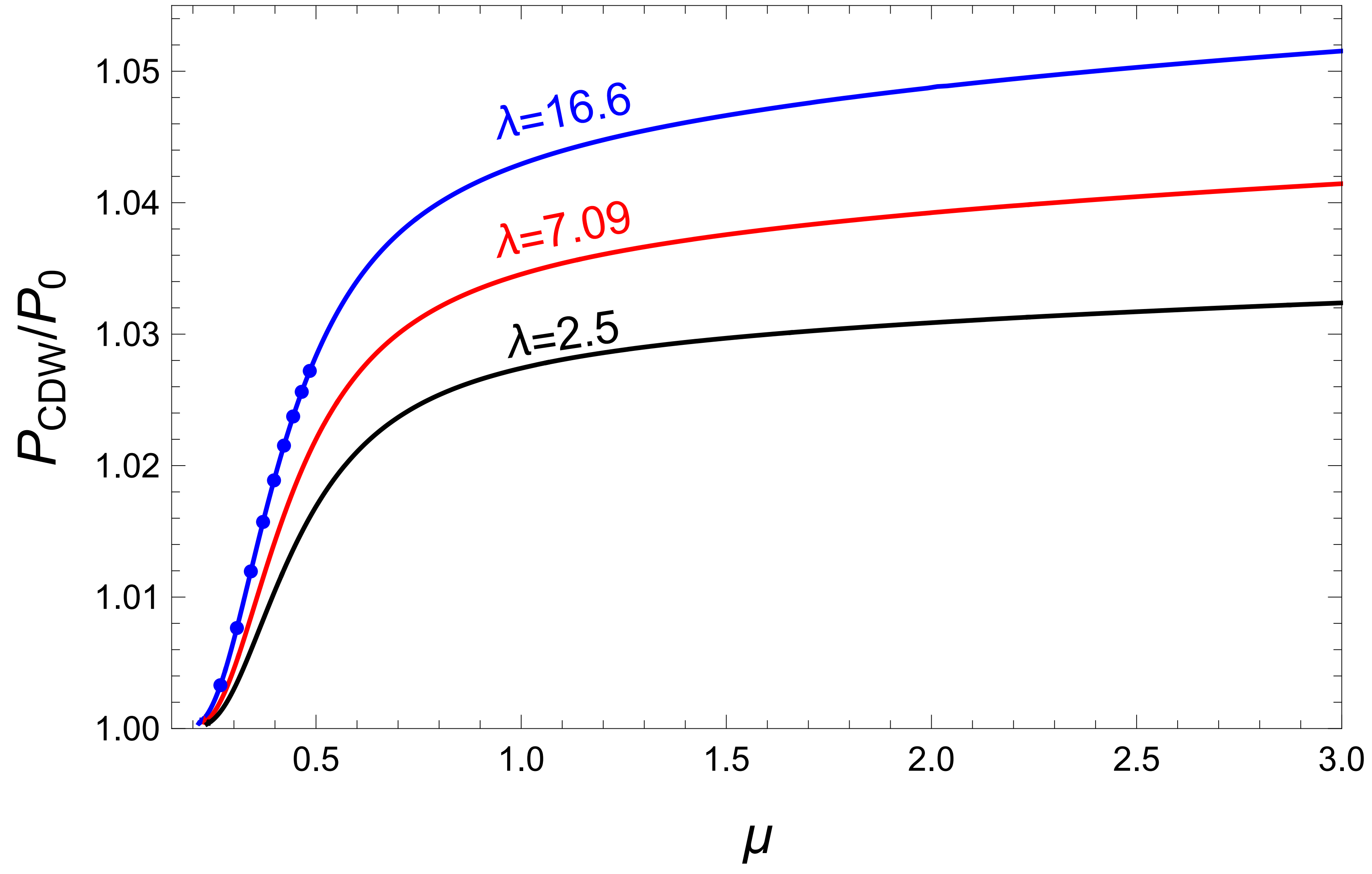
Baryonic matter

- Baryons = instantonic solutions for the non-abelian gauge fields
  [Hashimoto, Sakai, Sugimoto '08]
- Depend on space and the holographic direction, numerical computations difficult
- Large densities → homogeneous ansatz (no spatial dependence)
- Use preferred isotropic phase
  [Ecker, Kovensky, Papadopoulos, Schmitt '25]

CDW Solution

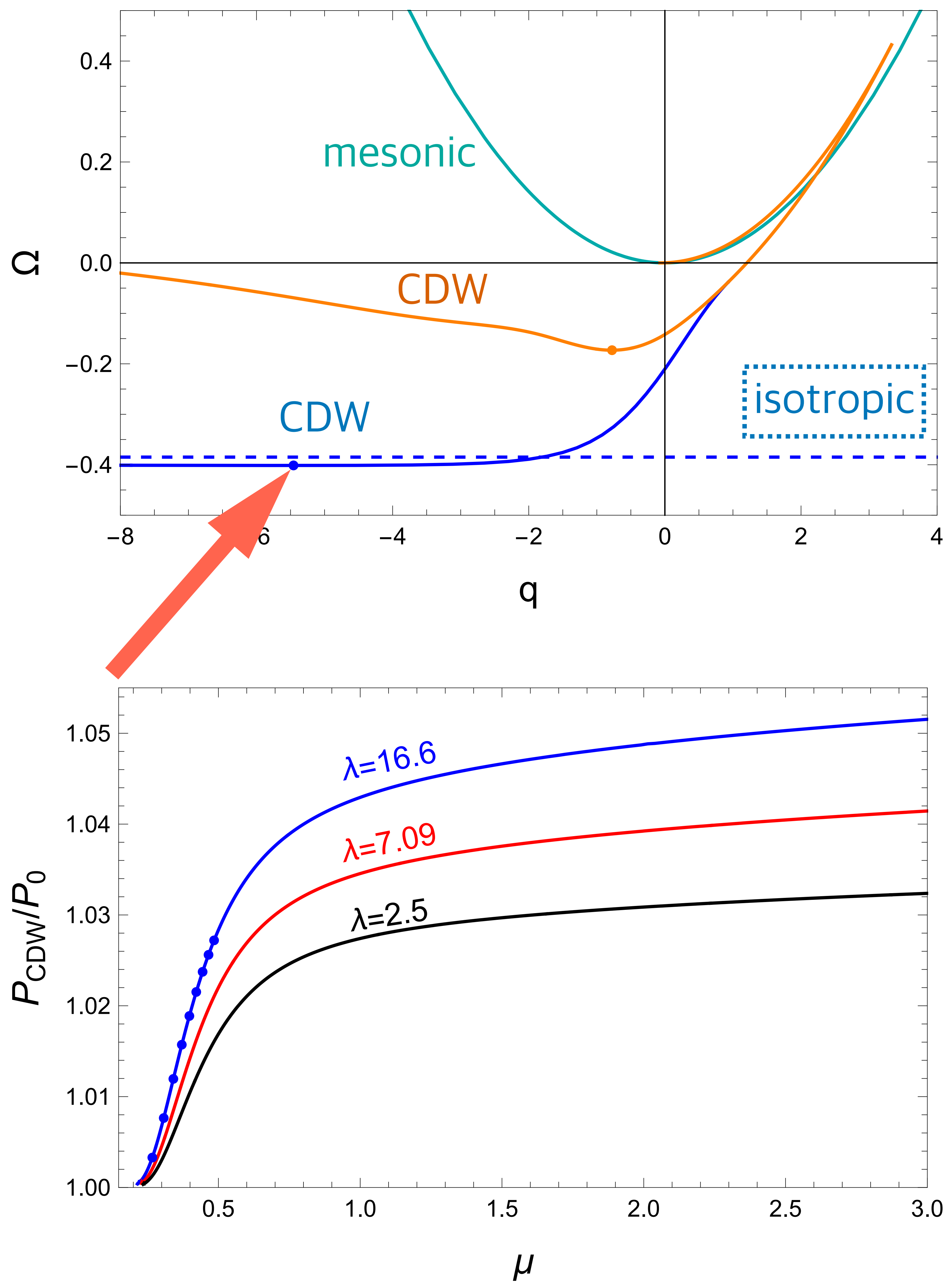
- Two CDW branches





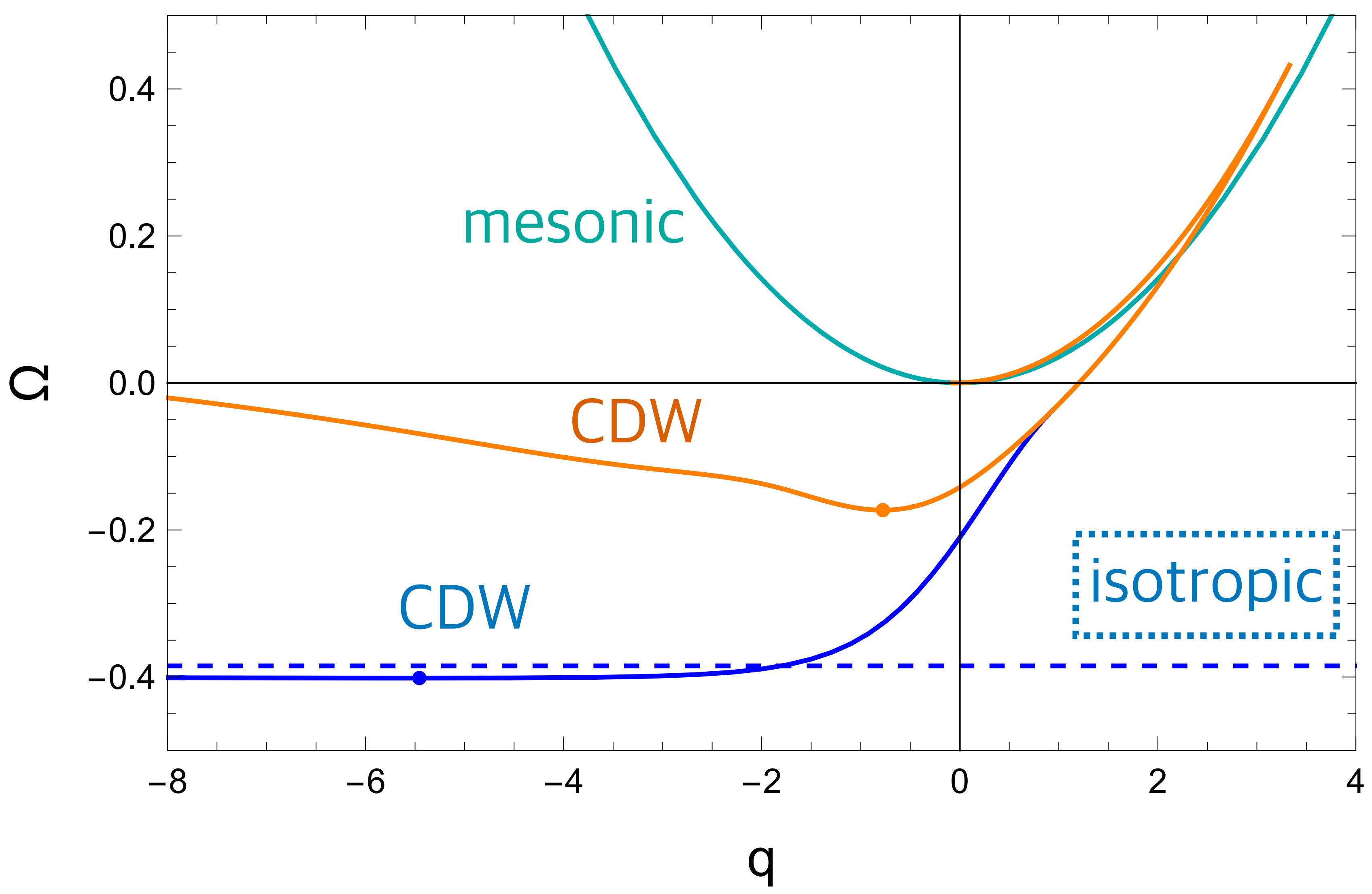
CDW Solution

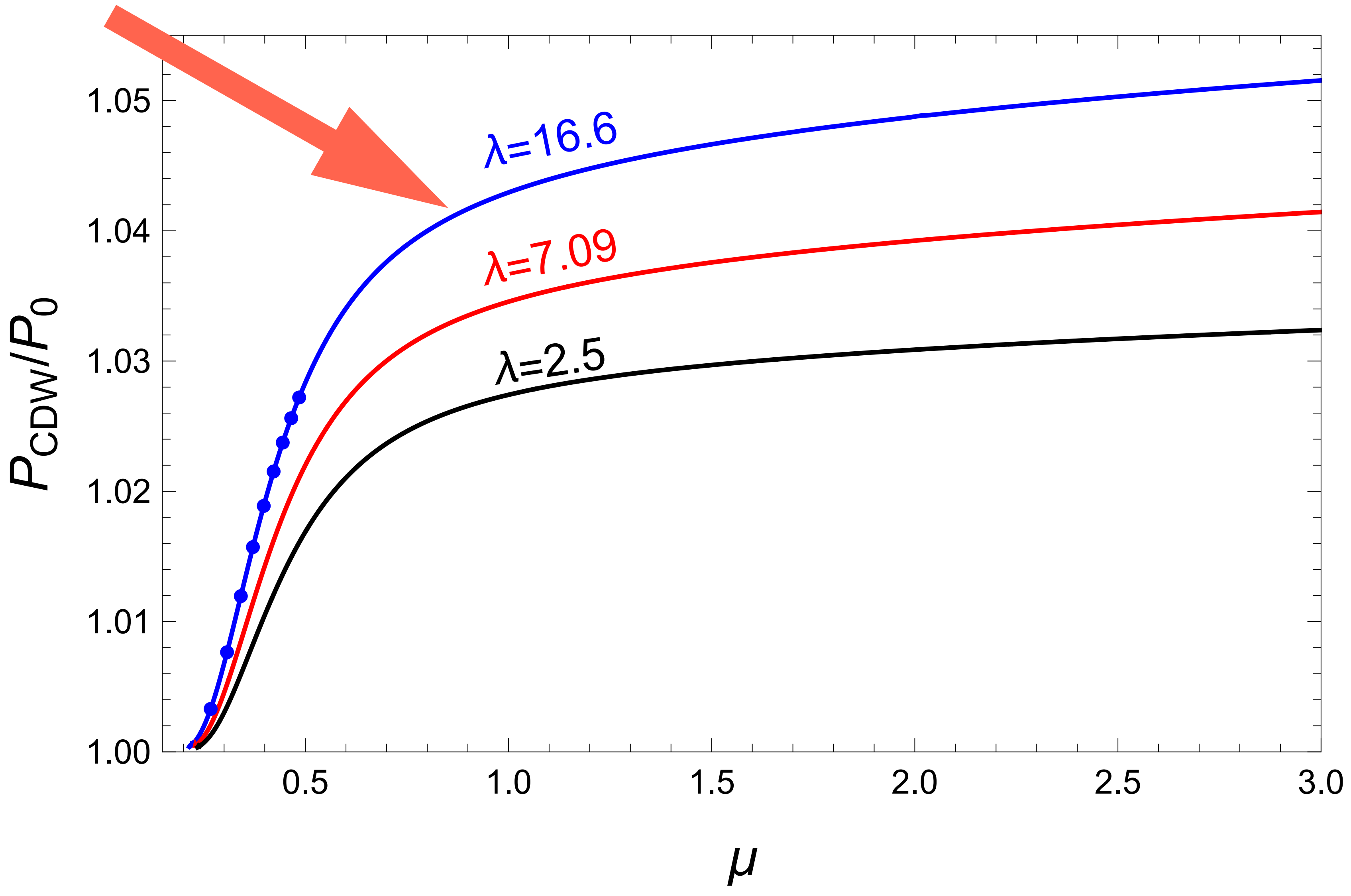
- Two CDW branches
- Dot = minimum of free energy → CDW phase preferred over isotropic



CDW Solution

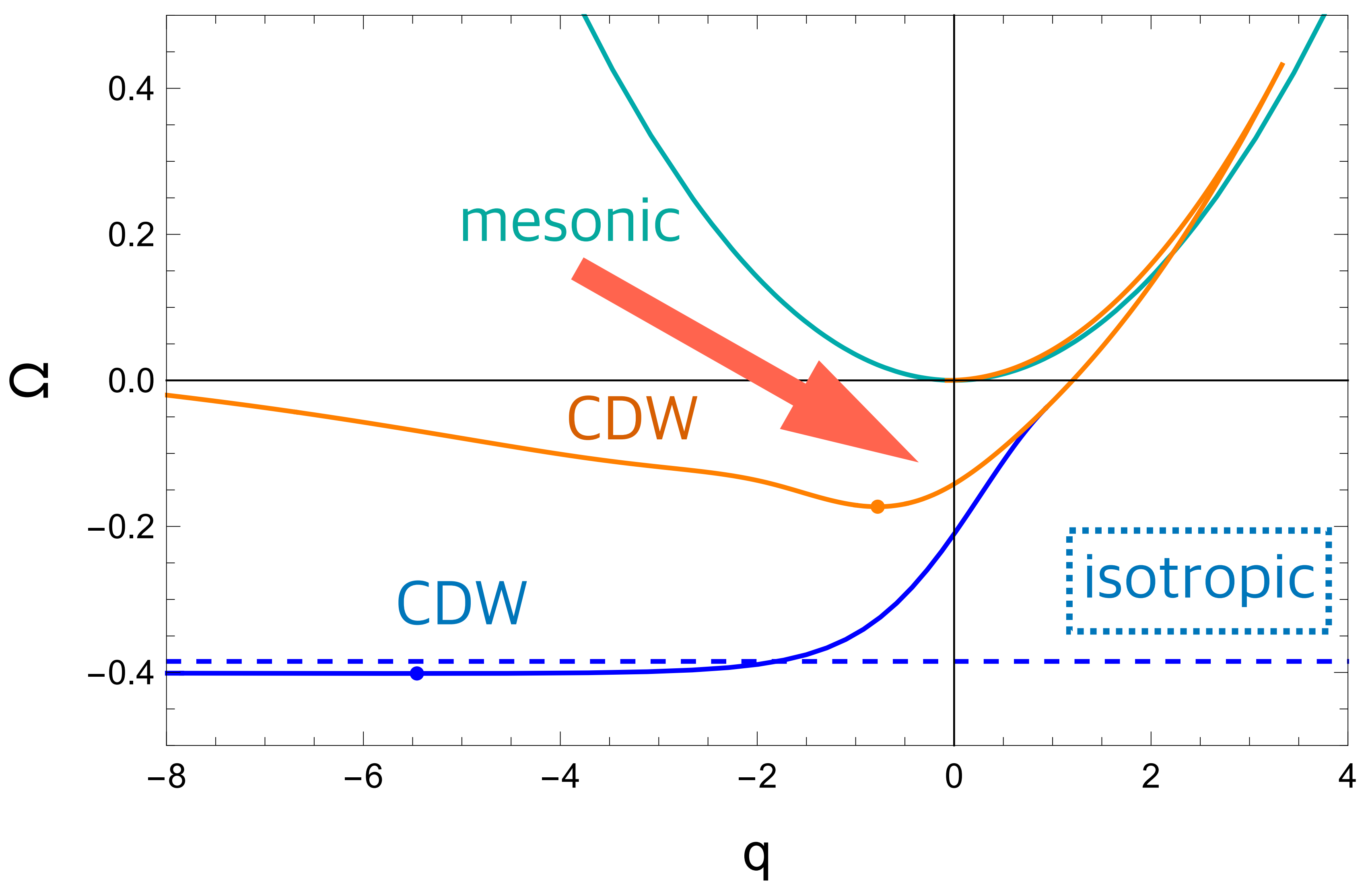
- Two CDW branches
- Dot = minimum of free energy → CDW phase preferred over isotropic
- CDW preferred over the whole μ range

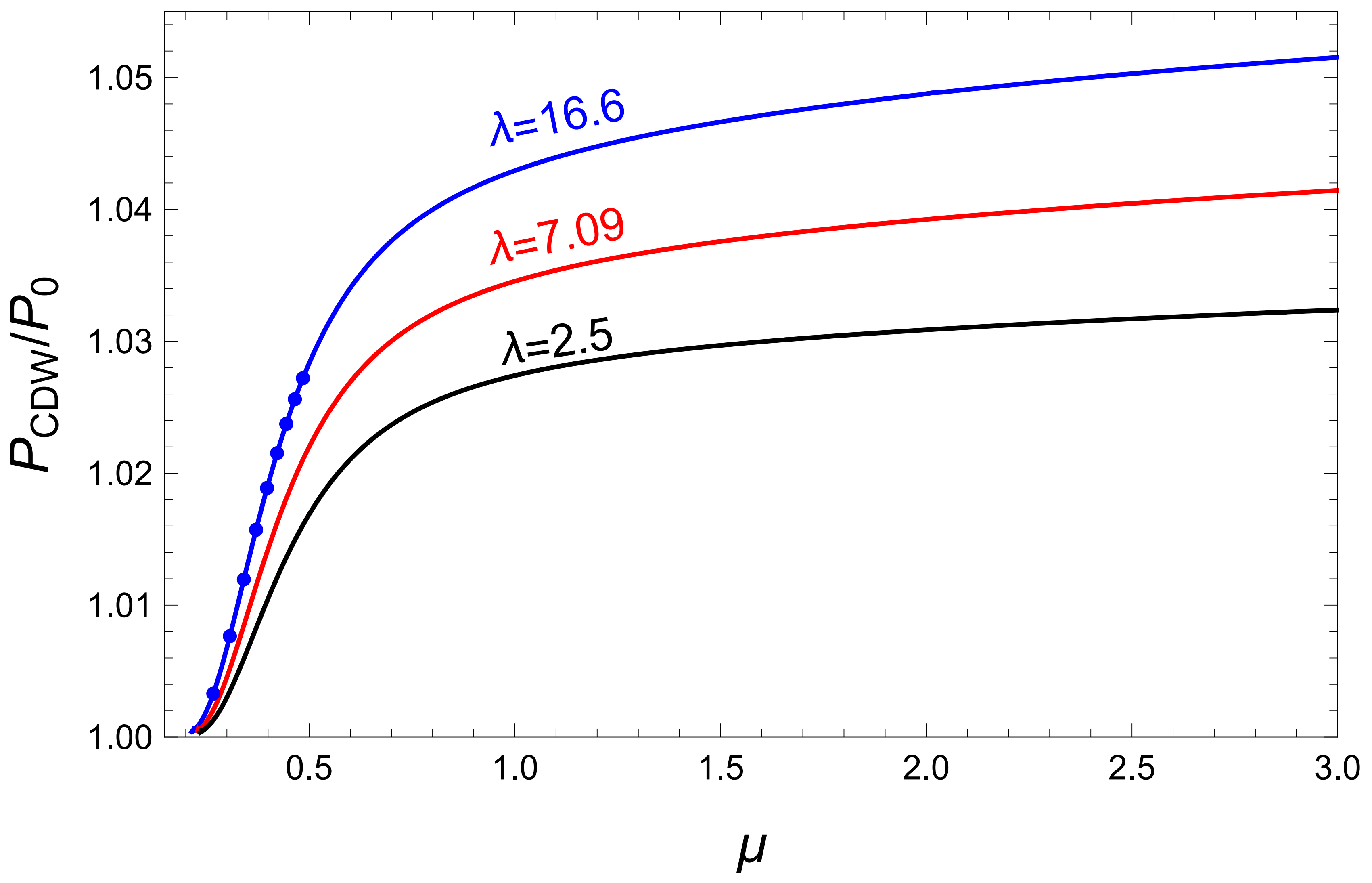




CDW Solution

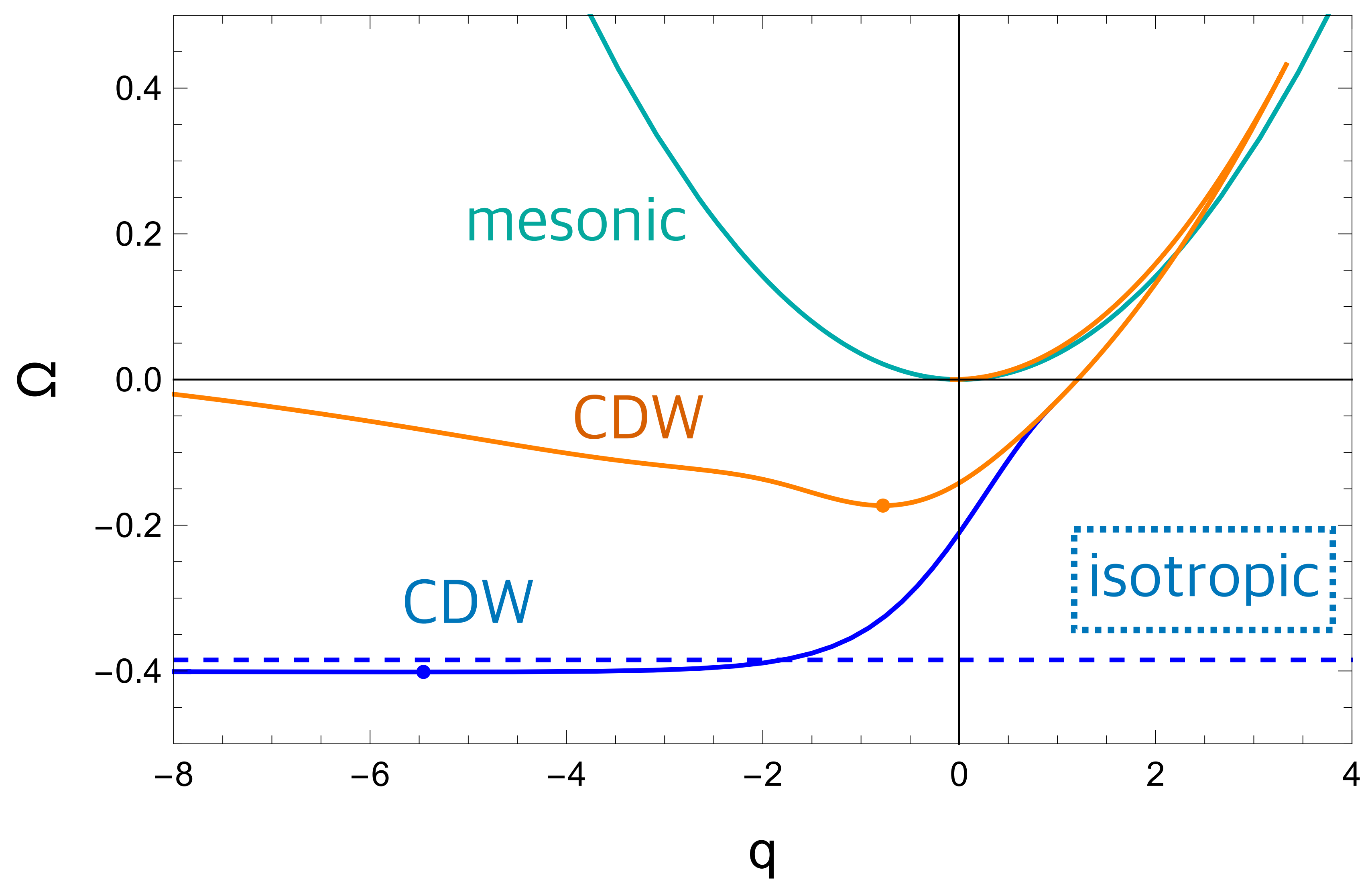
- Two CDW branches
- Dot = minimum of free energy → CDW phase preferred over isotropic
- CDW preferred over the whole μ range
- Free energy is not even in q. Why?

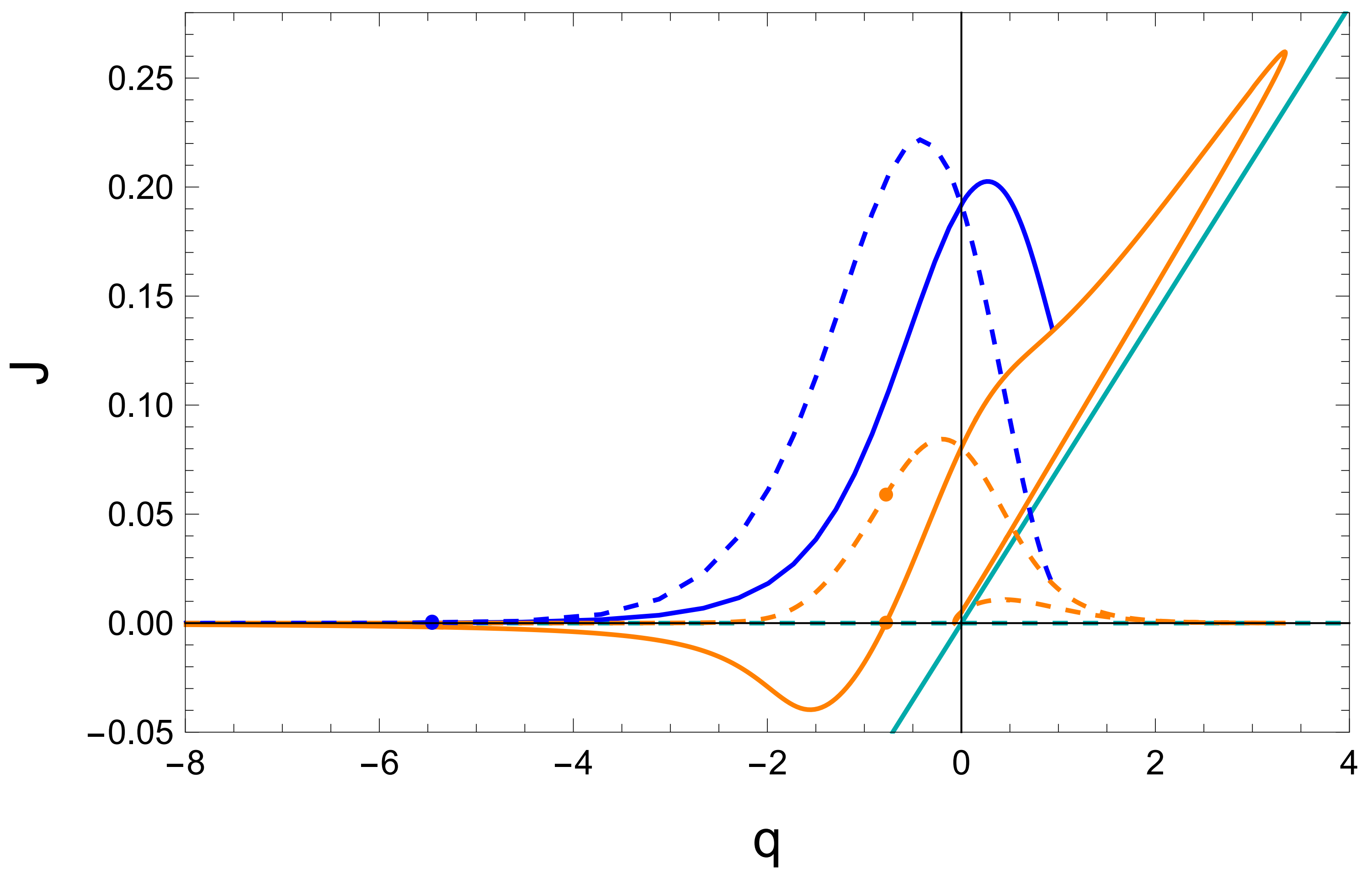




CDW Solution

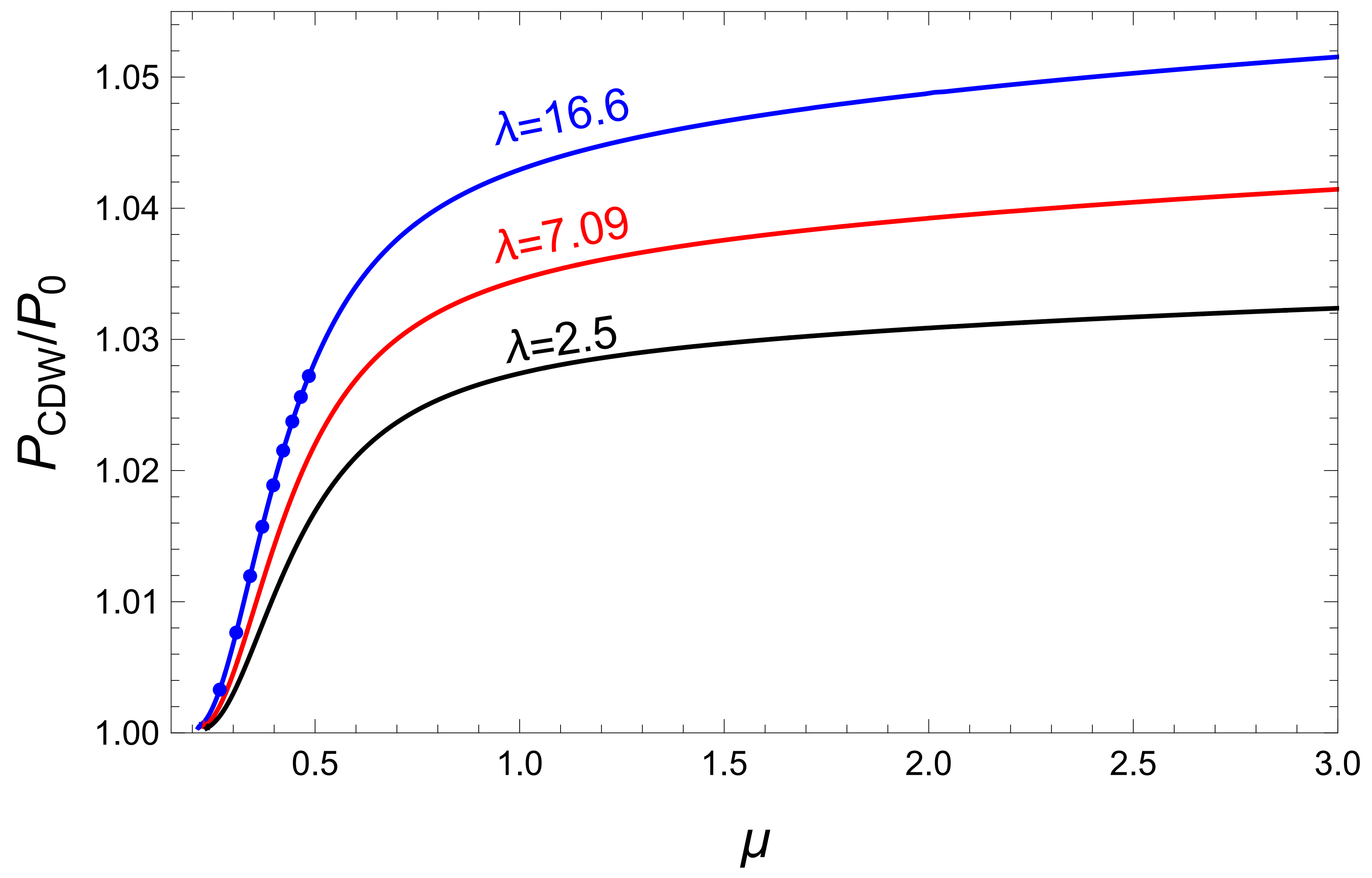
- Two CDW branches
- Dot = minimum of free energy → CDW phase preferred over isotropic
- CDW preferred over the whole μ range
- Free energy is not even in q. Why?





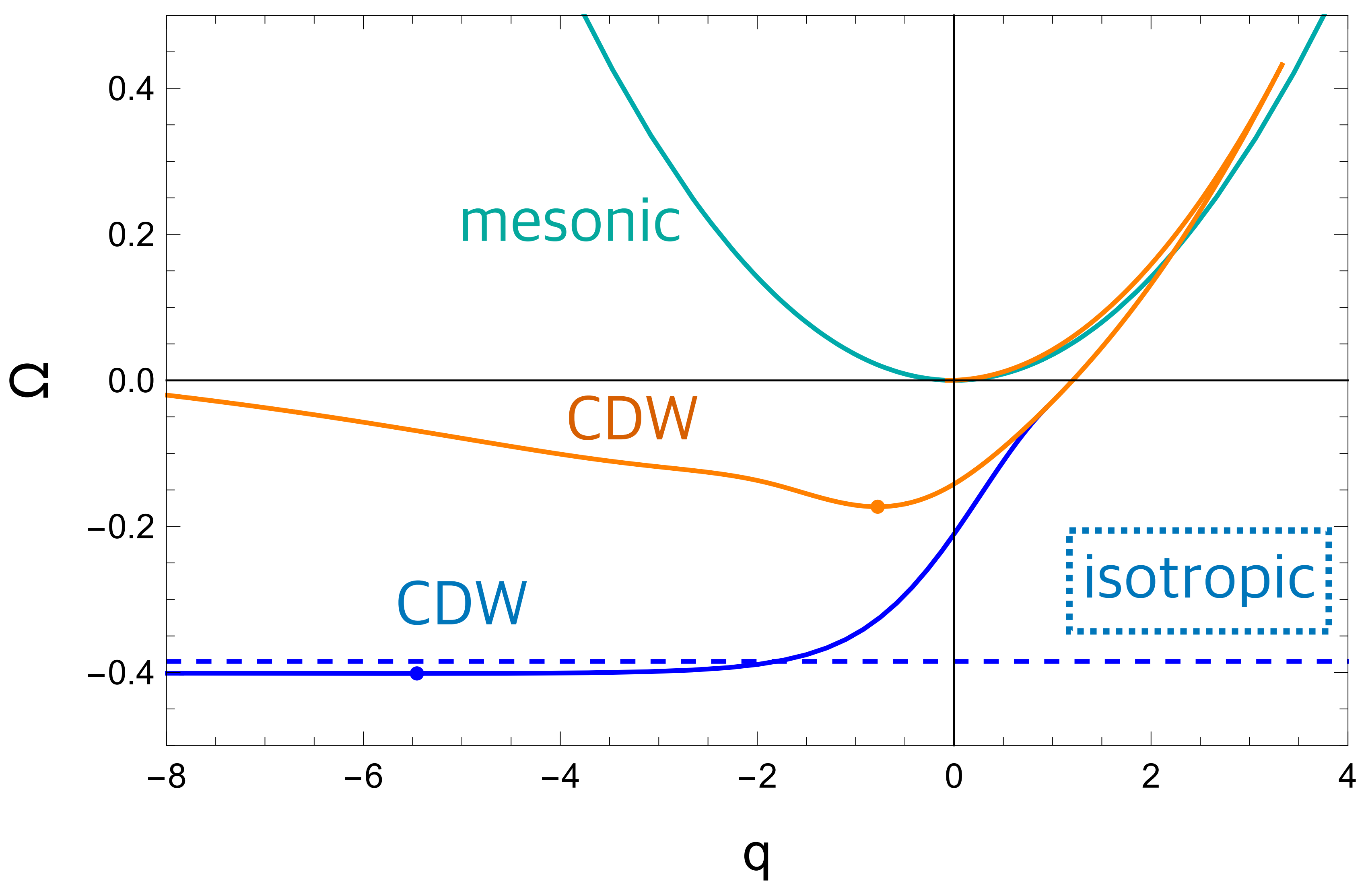
Unphysical axial currents

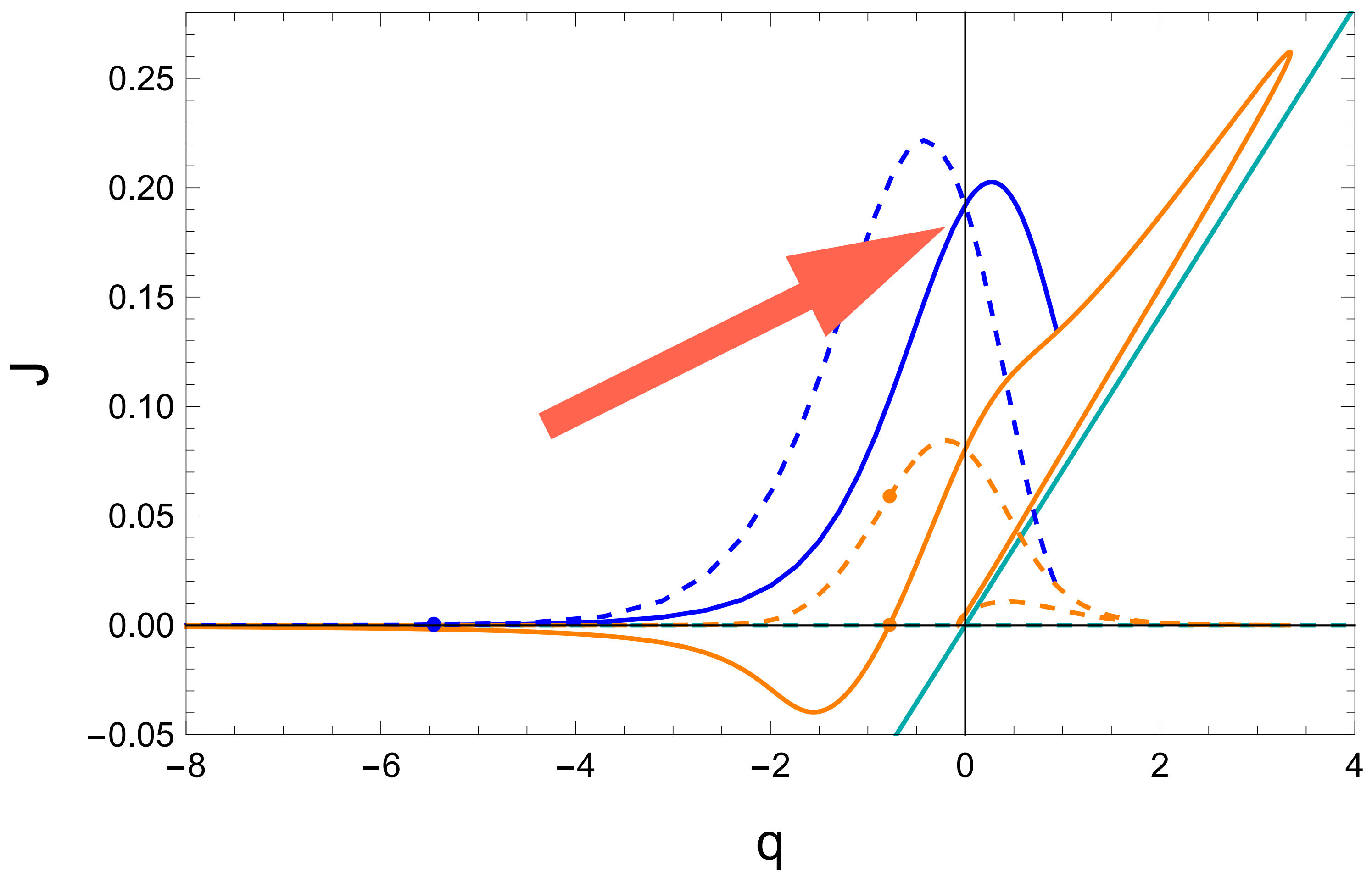
Solid (dashed) lines = J_3^3 (J_1^1, J_2^2)



CDW Solution

- Two CDW branches
- Dot = minimum of free energy → CDW phase preferred over isotropic
- CDW preferred over the whole μ range
- Free energy is not even in q. Why?

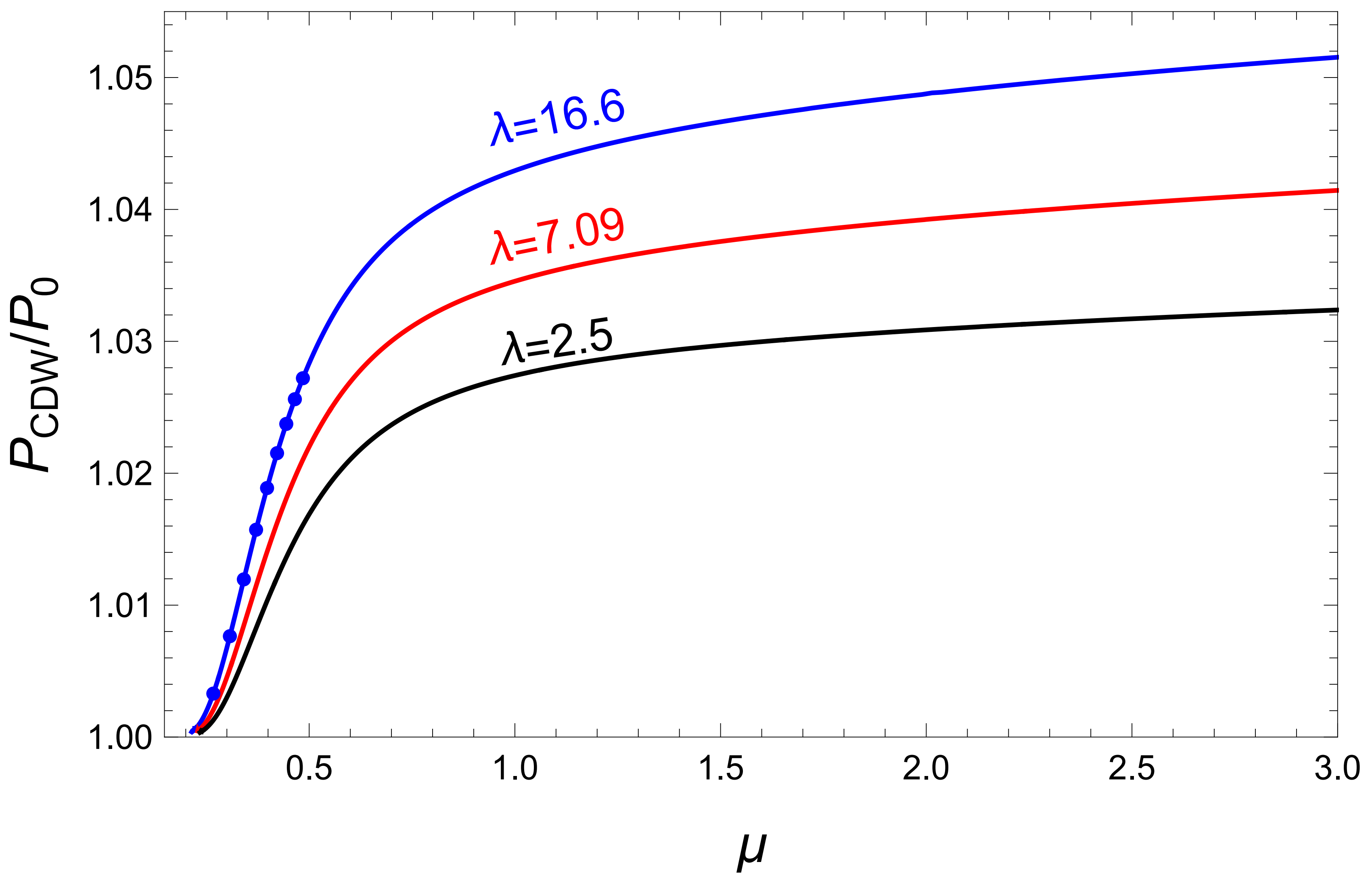




Unphysical axial currents

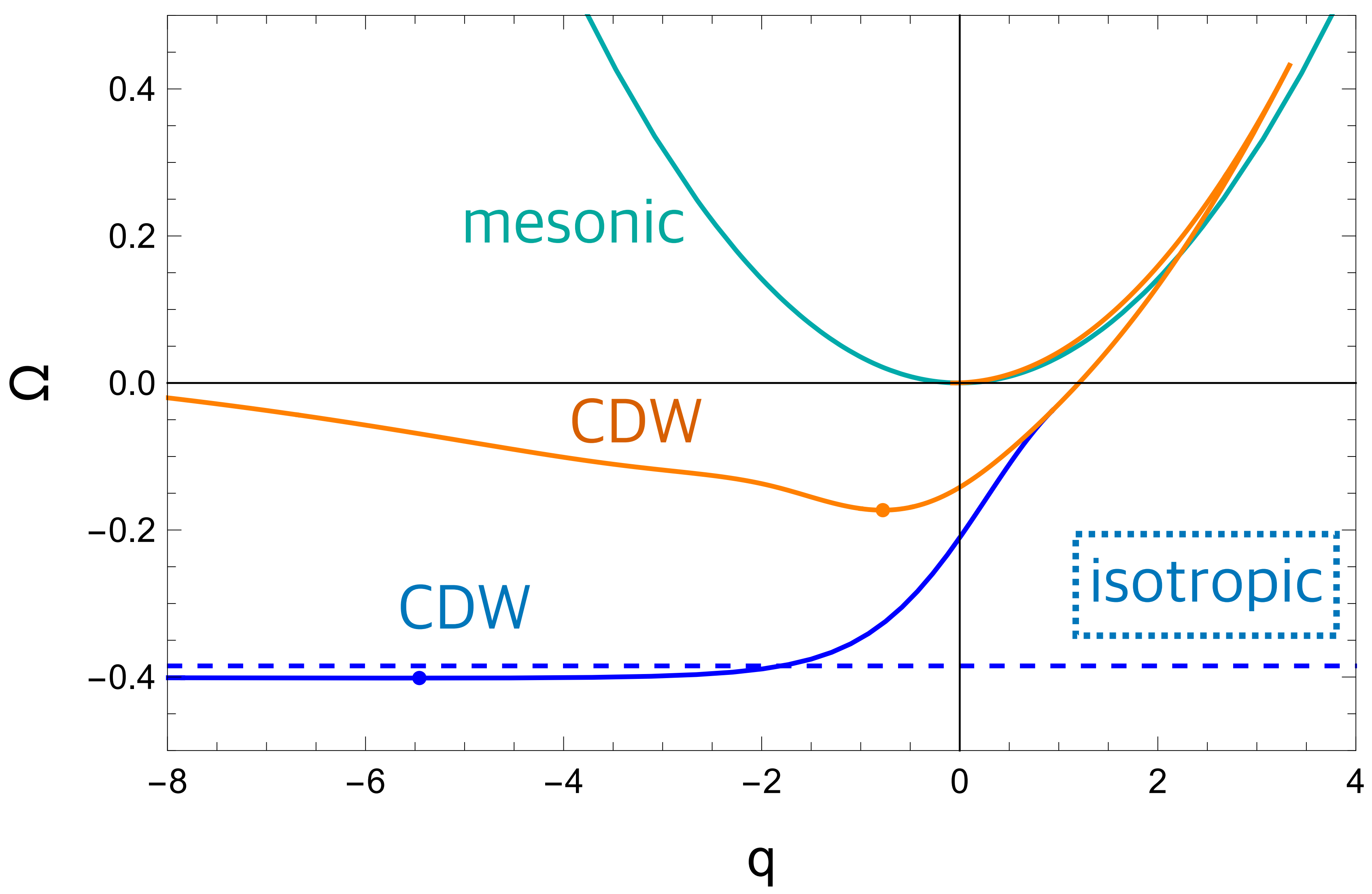
Solid (dashed) lines = $J_3^3\ (J_1^1, J_2^2)$

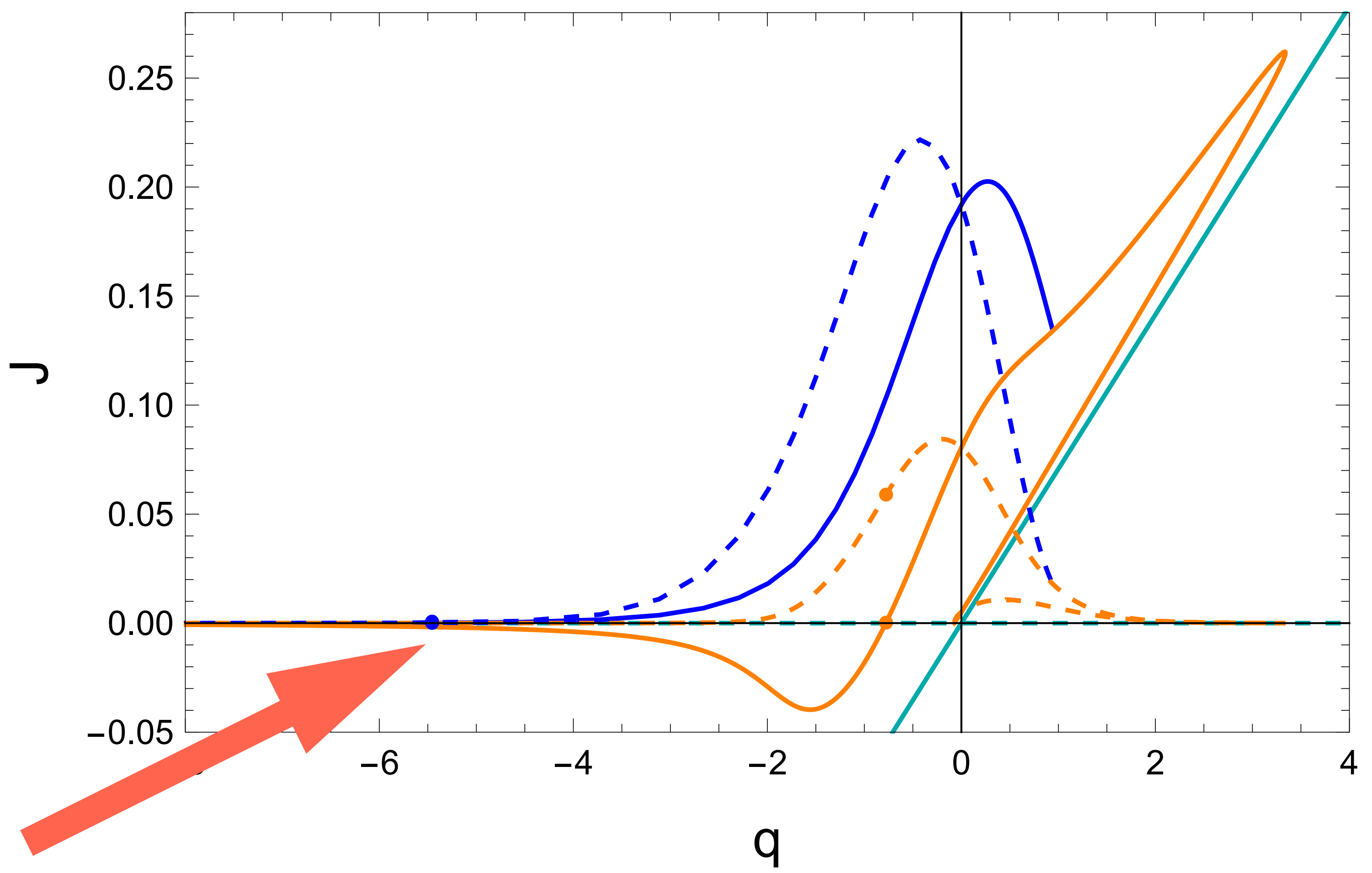
At $q = 0$: give nonzero slope to Ω



CDW Solution

- Two CDW branches
- Dot = minimum of free energy → CDW phase preferred over isotropic
- CDW preferred over the whole μ range
- Free energy is not even in q. Why?



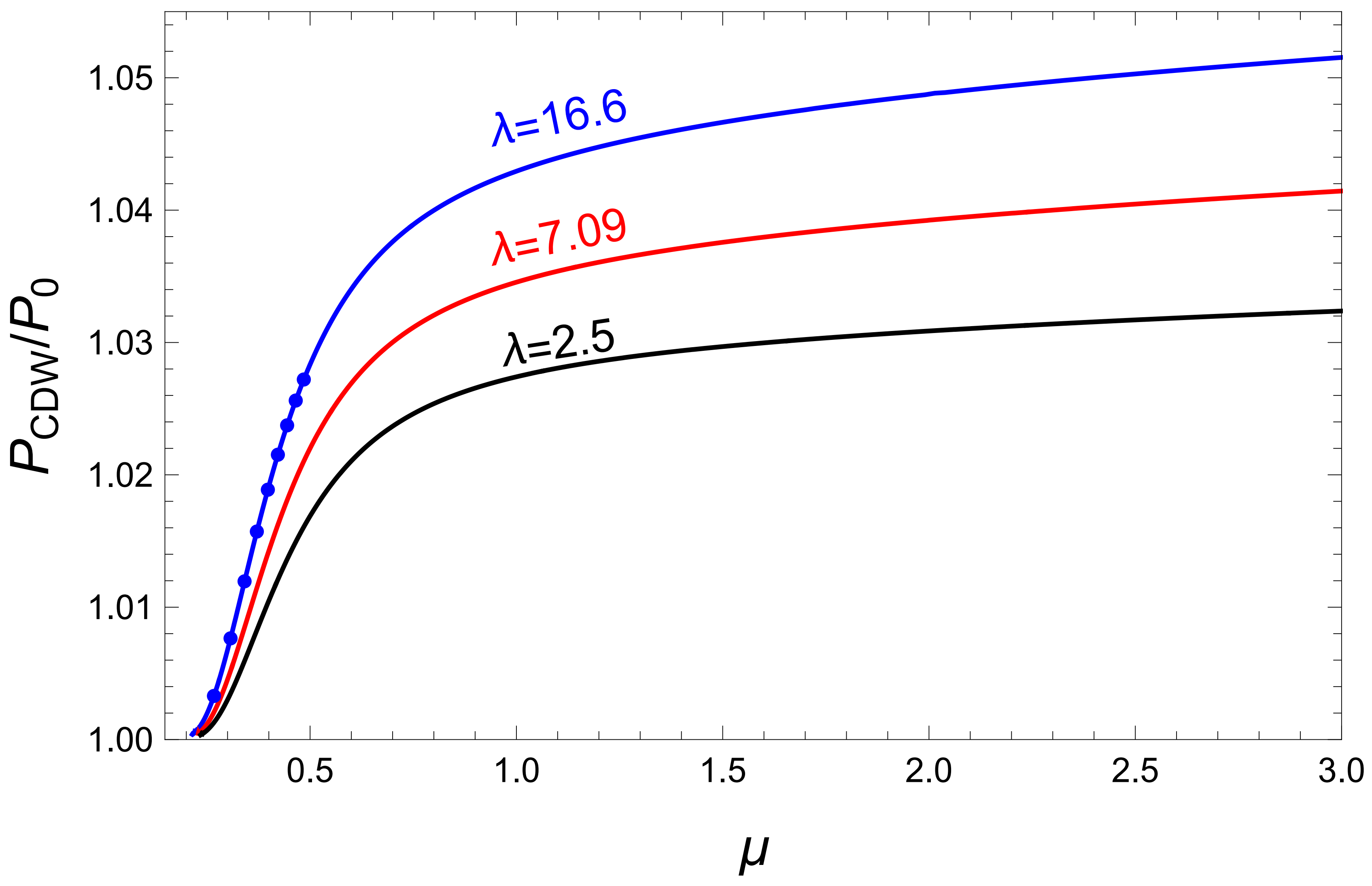


Unphysical axial currents

Solid (dashed) lines = J_3^3 (J_1^1, J_2^2)

At $q = 0$: give nonzero slope to Ω

But at minimum: $J_3^3 = 0,\ \ J_1^1, J_2^2$ small



II: Holography

Q: Can we construct the CDW in nuclear matter using AdS/CFT?

II: Holography

Q: Can we construct the CDW in nuclear matter using AdS/CFT?

A: Yes, and it is preferred over isotropic nuclear matter (despite artificial currents)

Summary: Studied the CDW in

Field theory →

- Applied neutron star conditions → CDW disfavoured
- Built neutron stars with CDW cores → not massive enough

Holography →

- Constructed the first nuclear CDW solution using AdS/CFT
- Preferred over isotropic nuclear matter

Future Directions

- Add magnetic field (both in field theory and holography) [Carignano, Ferrer, de la Incera, Paulucci '15]
- More complicated anisotropic phases (shifted CDW, 2D phases)
- Interplay with Cooper pairing [Mu, Gholami, Buballa '26]
- Improve holographic approach (combine approximations, isospin)
- Construct holographic neutron stars with CDW phase [Kovensky, Poole, Schmitt '21]

Thank you very much!

Paljon kiitoksia!

Any questions?

17–21 Aug 2026
Helsinki, Finland

Strong and Electro-Weak Matter 2026