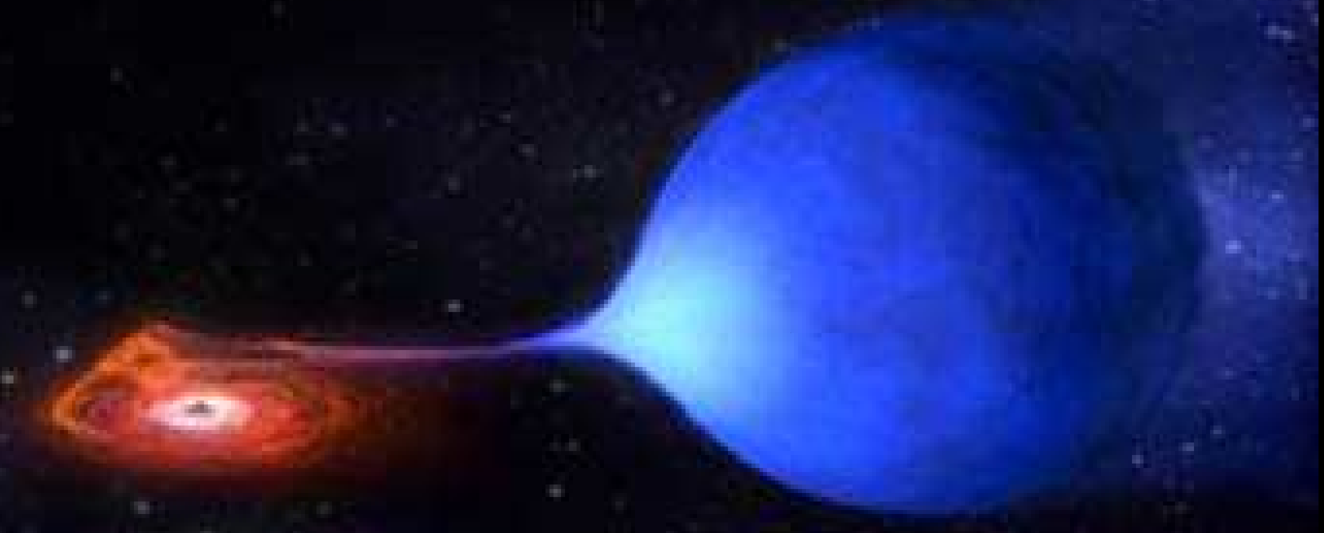
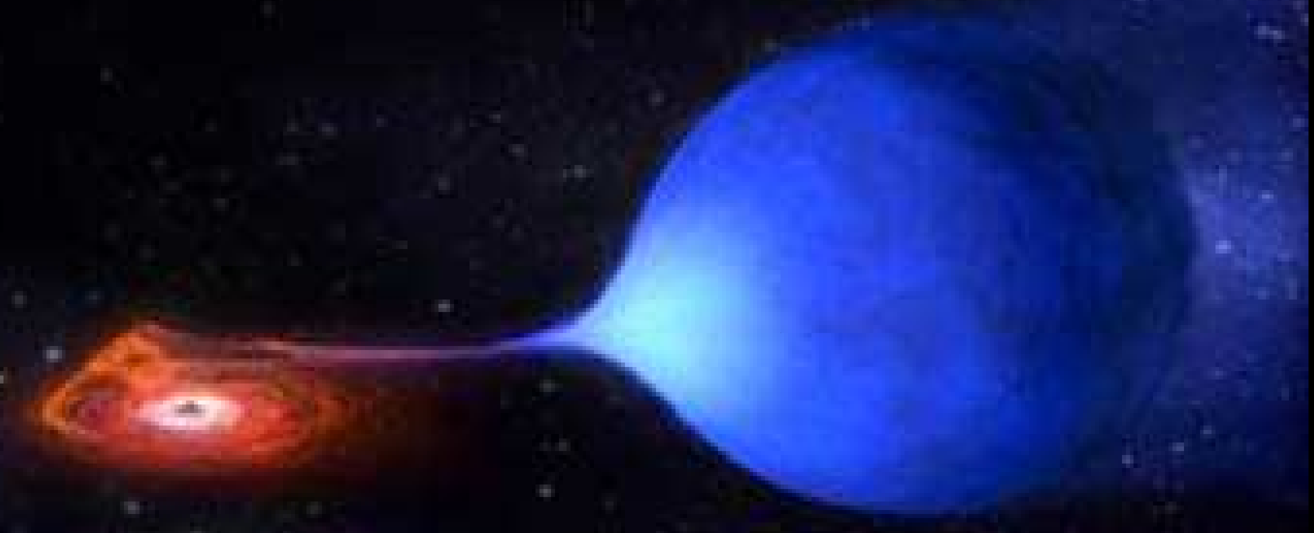
Color Superconductivity in Compact Stars (prel.)

David Blaschke
Univ. Wroclaw & JINR Dubna



Color Superconductivity in Compact Stars (prel.)

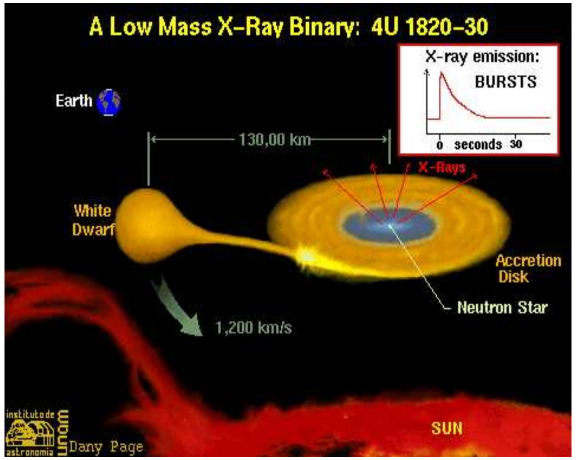
David Blaschke
Univ. Wroclaw & JINR Dubna



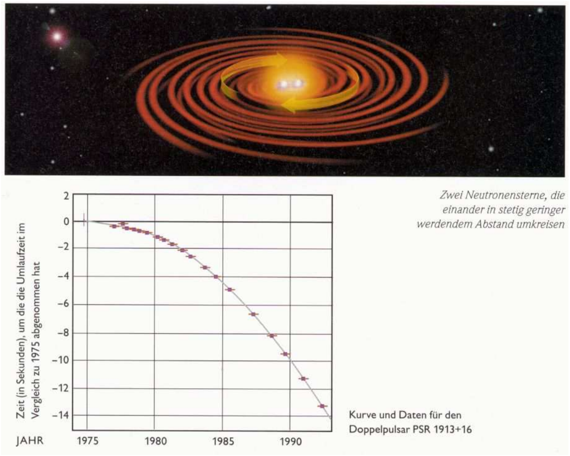
- Mass and Flow constraint on high-density EoS
- Local charge neutrality
  $\longrightarrow$ 2SC + DBHF hybrid stars
- Global charge neutrality
  $\longrightarrow$ d-CSL + DBHF hybrid stars

Masses of binaries

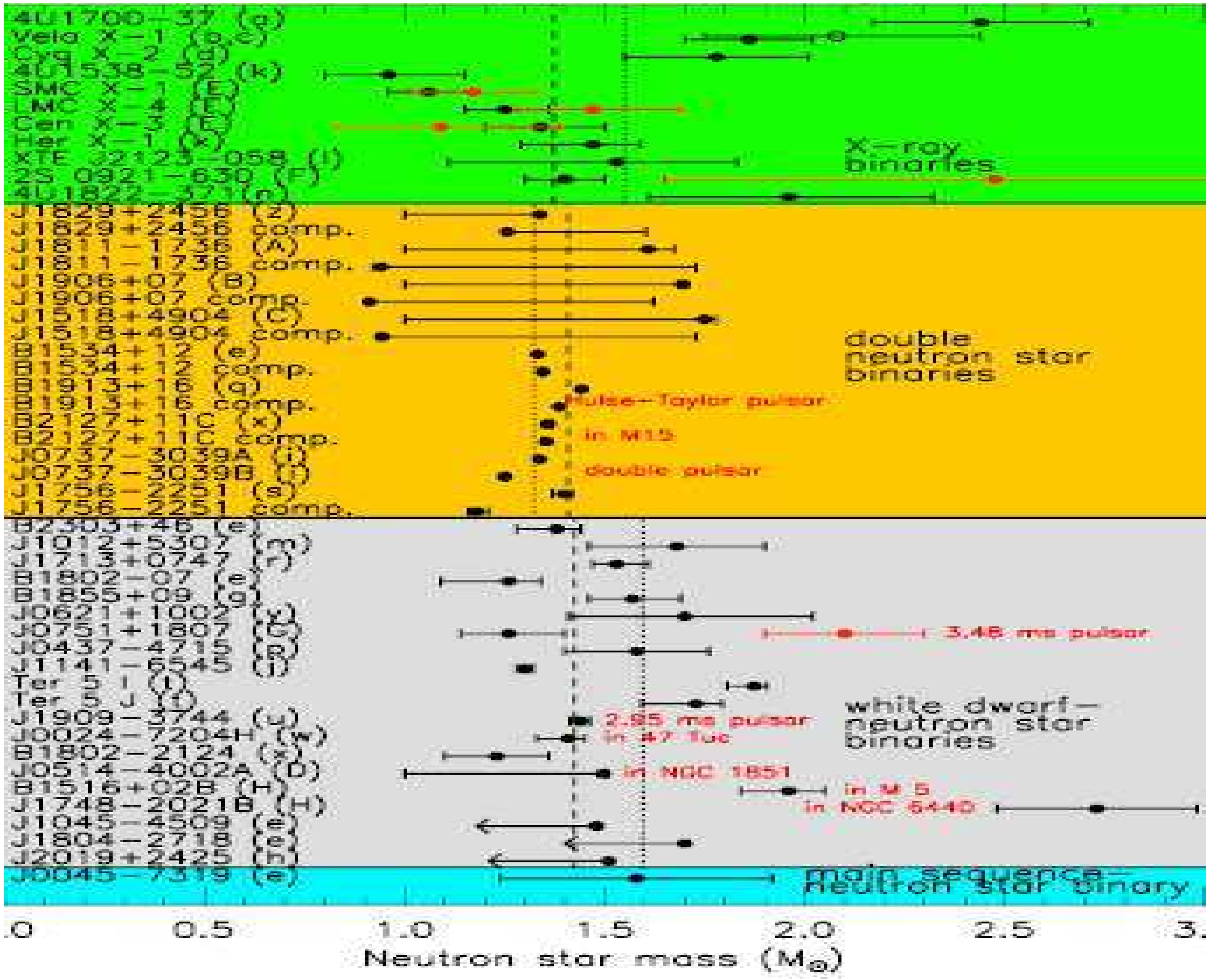
’Young’ binary system:



’Old’ binary system



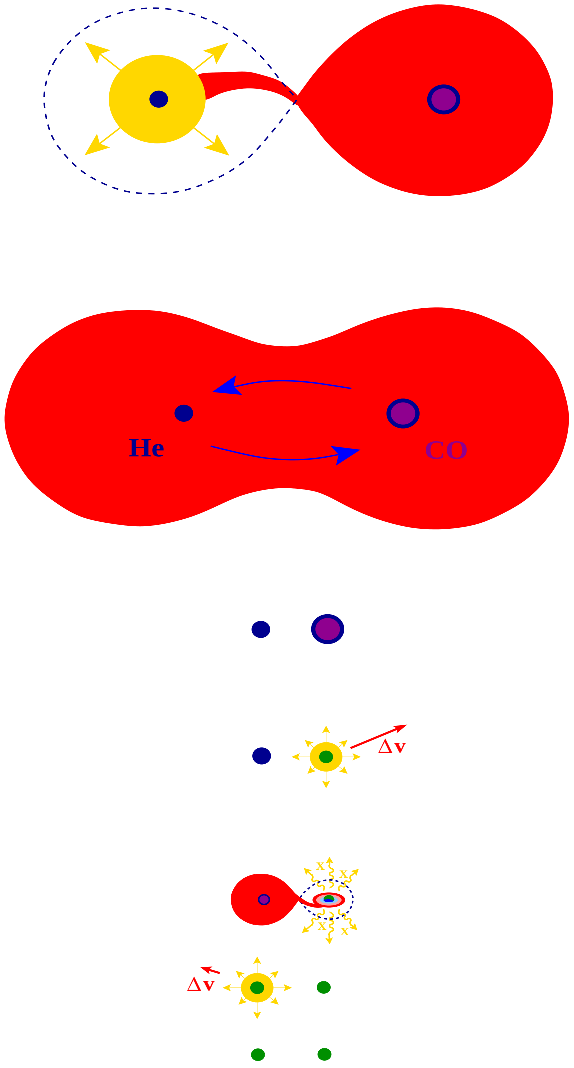
Masses of Neutron Stars in binaries - clustering vs. maximum



Lattimer, Prakash, PRL 94 (2005) 111101 + updates

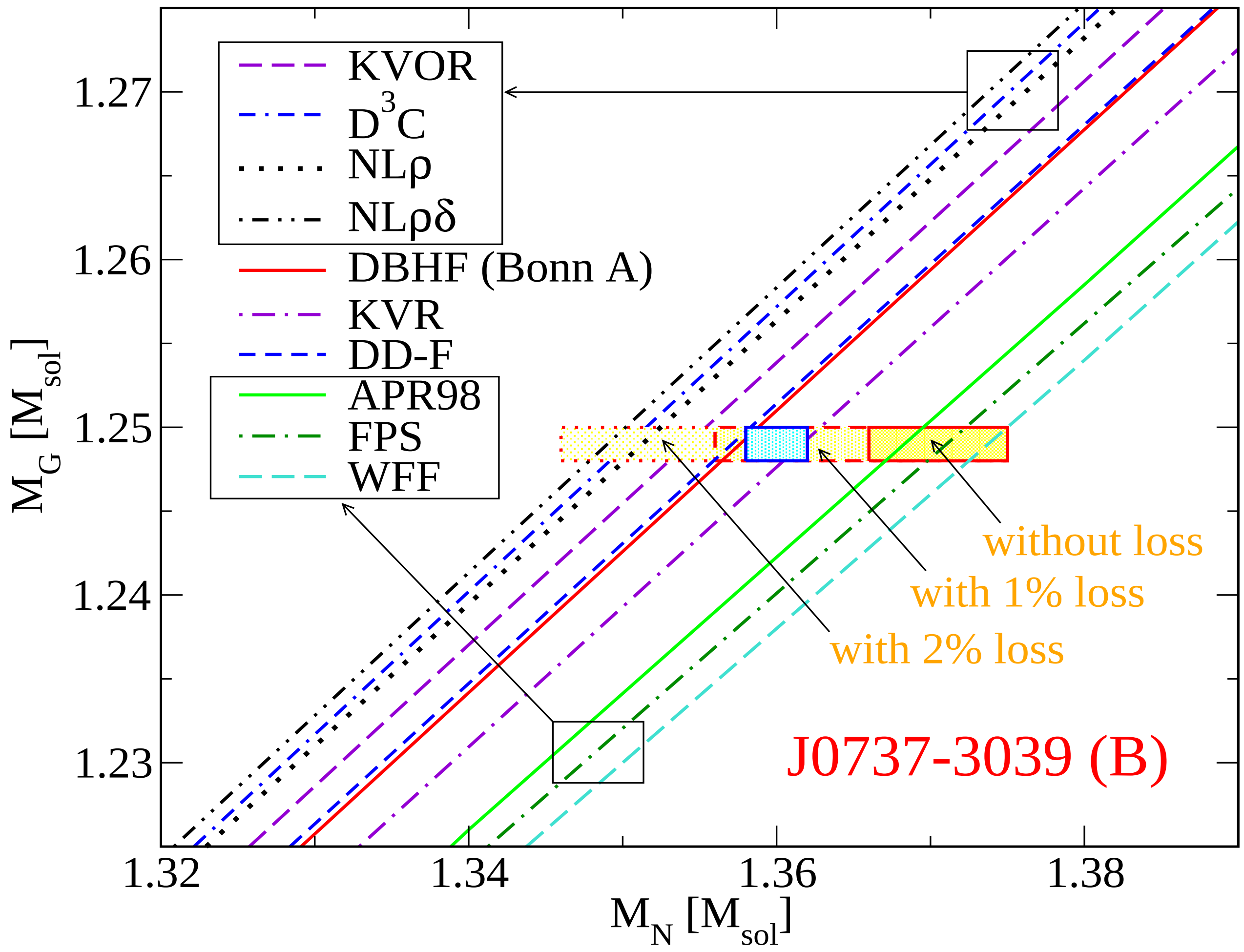
EoS constraint from double pulsar J0737-3039?

Double core scenario:



Dewi et al., MNRAS (2006)

Baryon mass vs. gravitational mass - constraint or consistency check?



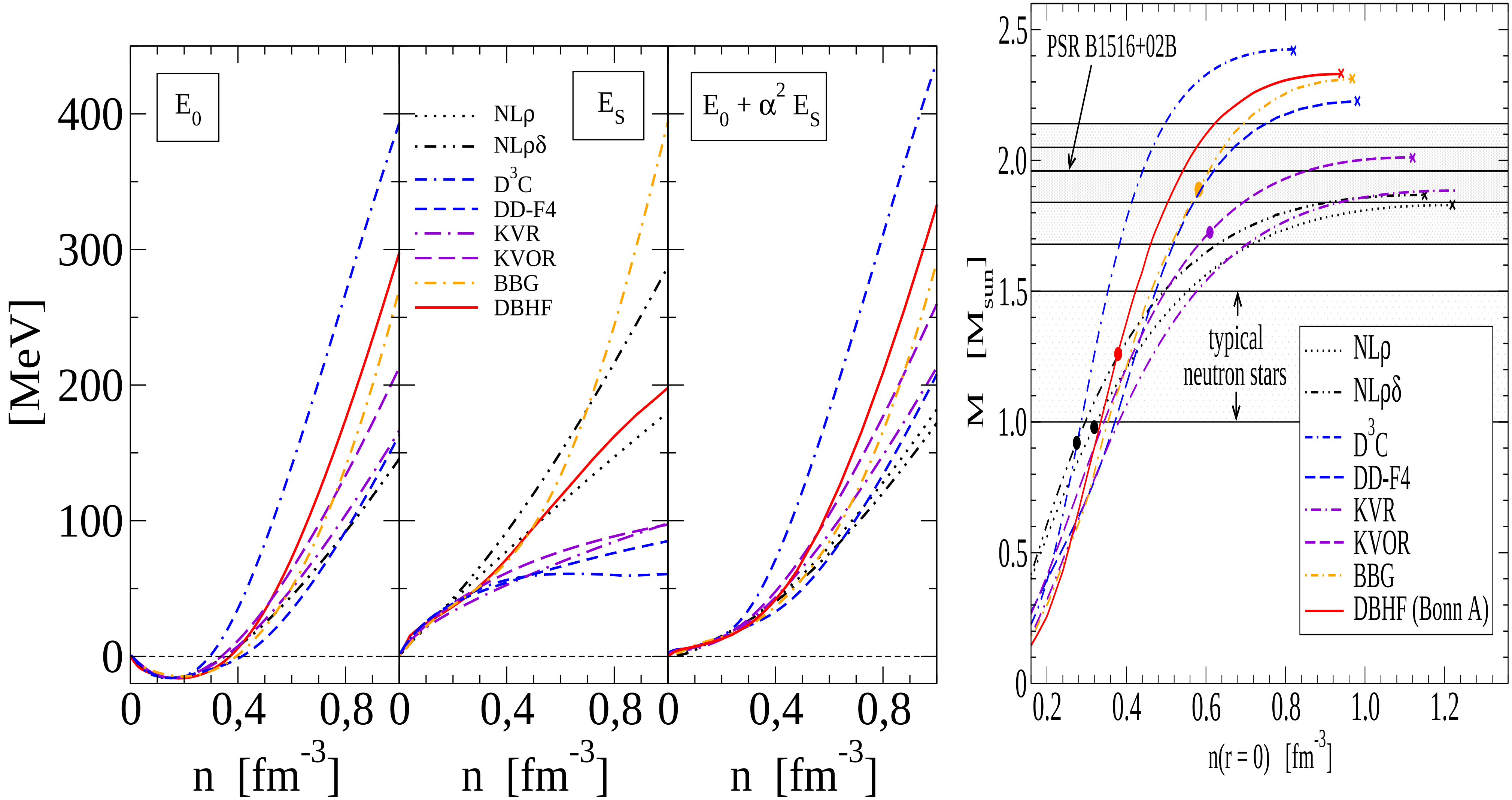
Podsiadlowski et al., MNRAS 361 (2005) 1243

Kitaura, Janka, Hillebrandt, A& A (2006); [astro-ph/0512065]

D.B., T. Klähn, F. Weber, CBM Physics Book (2008)

EoS and masses - DU constraint

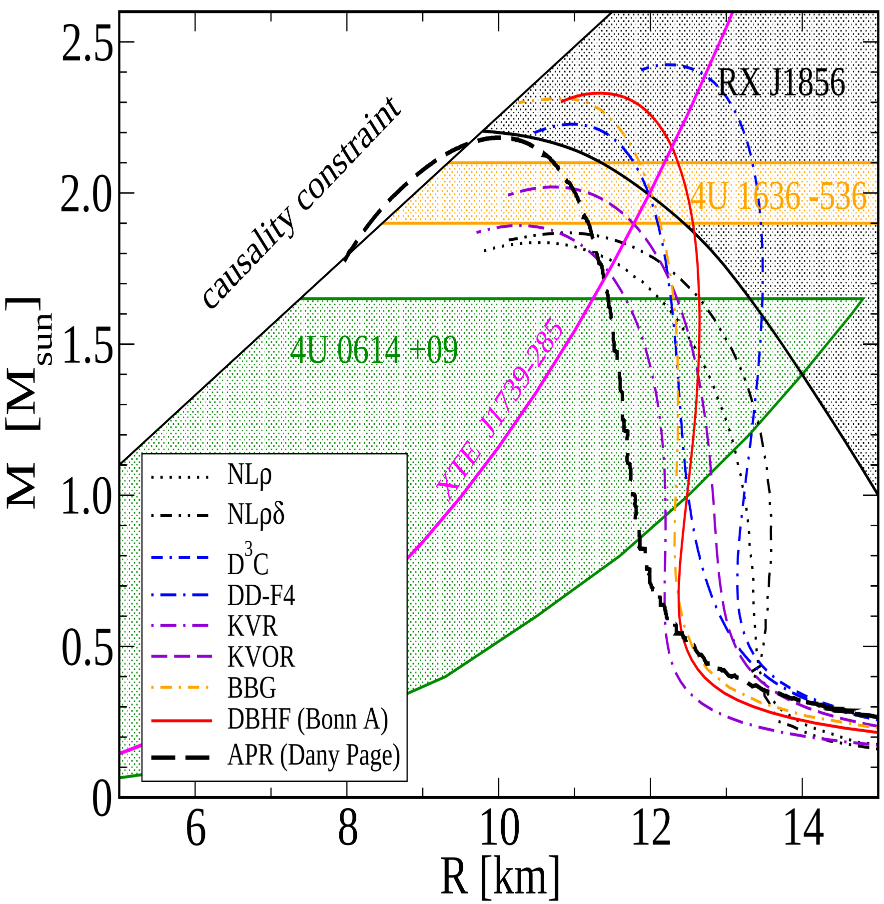
1. Mass and flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusions

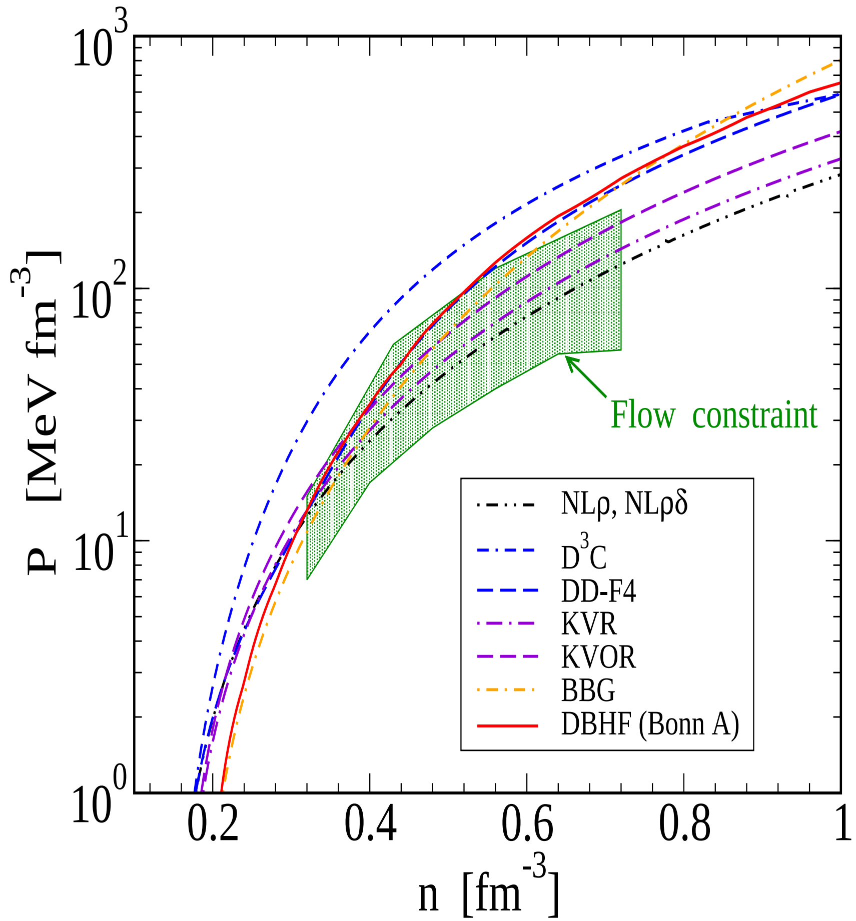


DU threshold for most hadronic EoS active in neutron stars with typical masses !

Klähn, et al., PRC 74, 035802 (2006); [nucl-th/0602038]

Mass-Radius constraint and Flow constraint

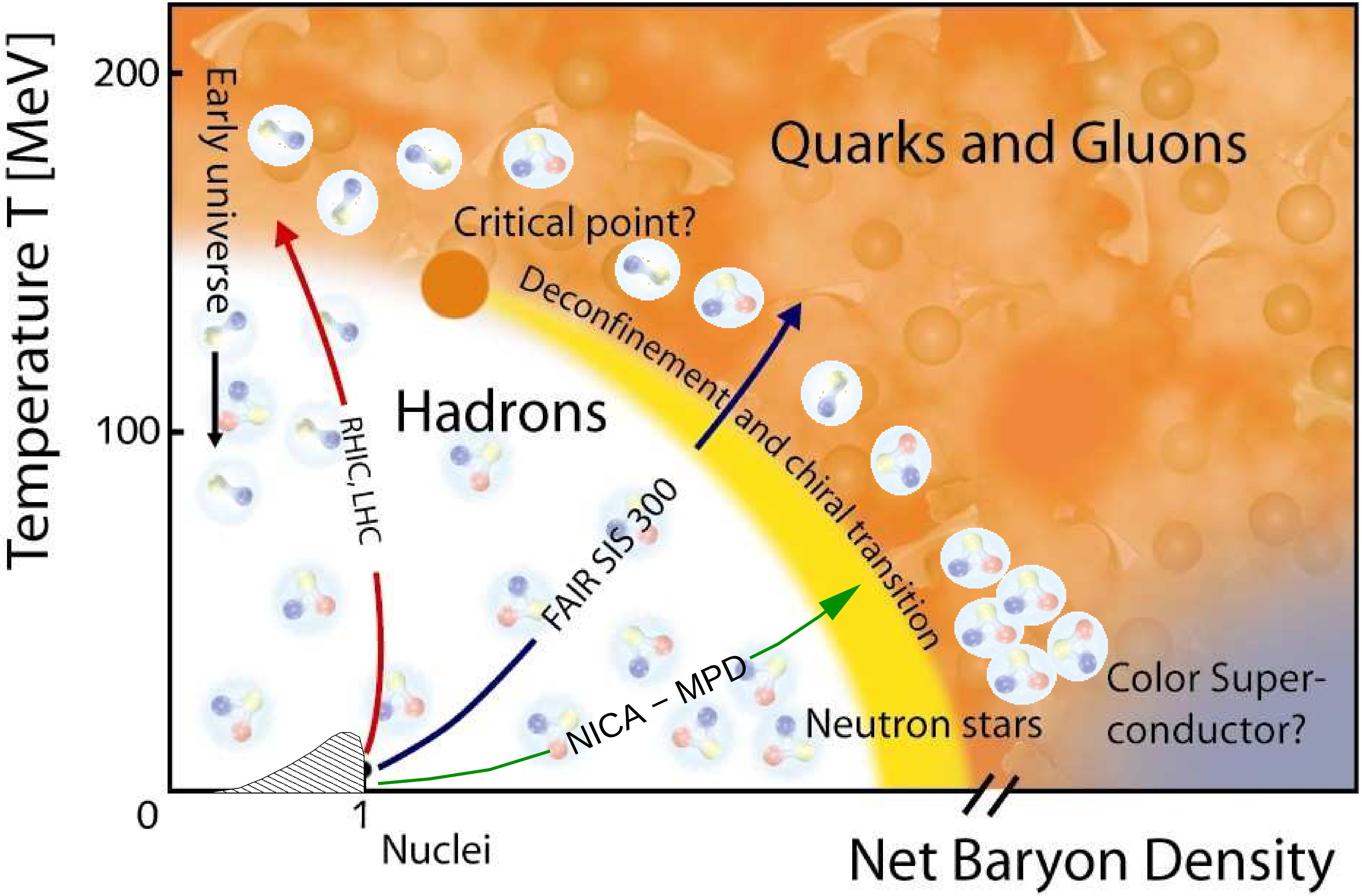




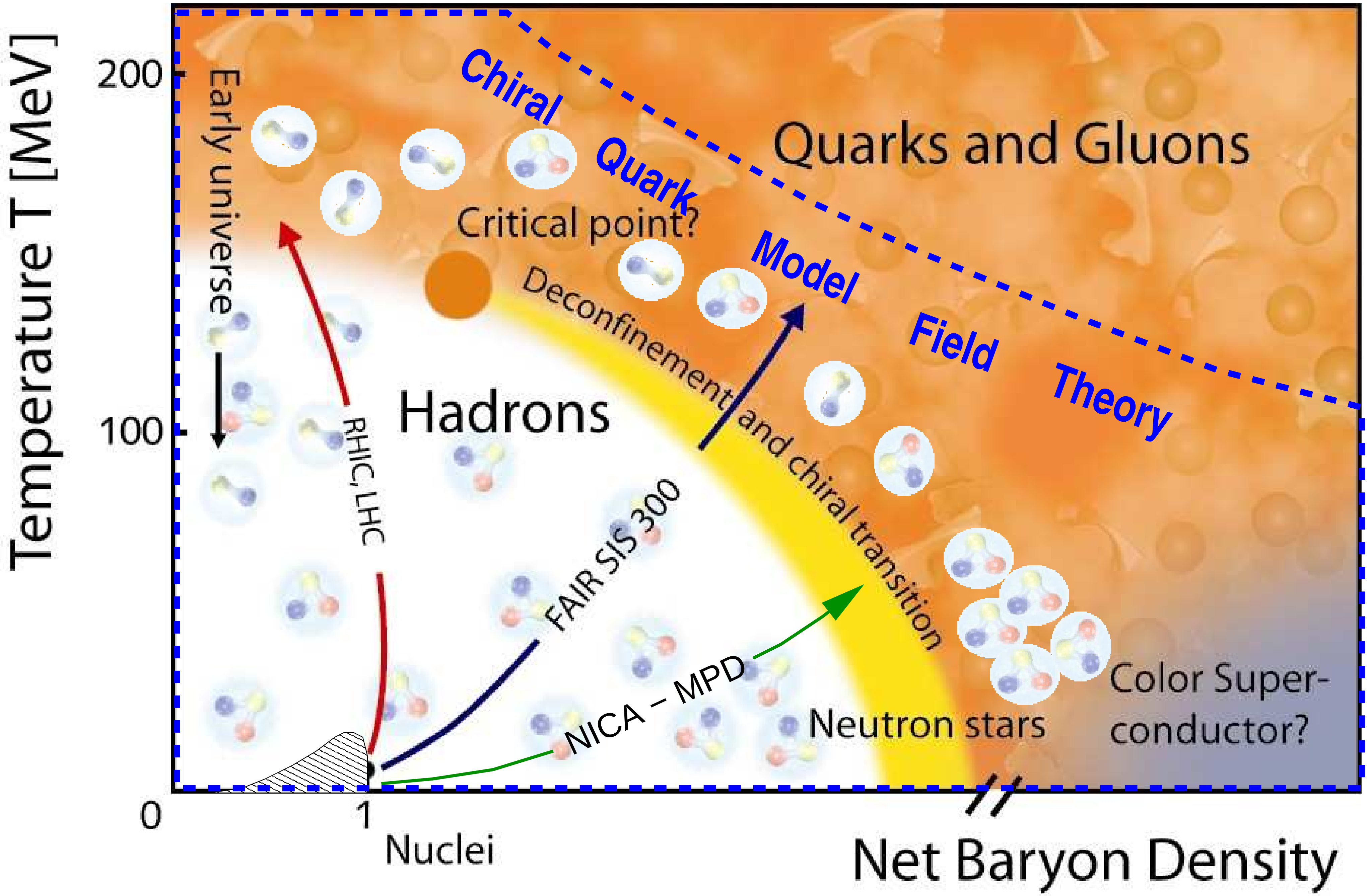
- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff EoS;
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS !

Klähn, D.B., Typel, Fuchs, Faessler, Grigorian, Miller, Röpke, Trümper, et al: PRC 74, 035802 (2006)

Quark Substructure and Phase Diagram



Phase diagram of QCD: Chiral quark models



Quantum Field Theory for chiral Quark Matter

- Partition function for chiral Quark Field theory

$$Z[T,V,\mu] = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi \exp\left\{ -\int^{\beta} d\tau \int_V d^3x [\bar{\psi}(i\gamma^\mu\partial_\mu - m - \gamma^0\mu)\psi - \mathcal{L}_{\rm int}] \right\}$$

- Current-current coupling (4-fermion interaction)

$$\mathcal{L}_{\rm int} = \sum_{M=\pi,\sigma,\ldots} G_M(\bar{\psi}\Gamma_M\psi)^2 + \sum_D G_D(\bar{\psi}^C\Gamma_D\psi)^2$$

- Bosonisation (Hubbard-Stratonovich Transformation)

$$Z[T,V,\mu] = \int \mathcal{D}\phi_M \mathcal{D}\Delta_D^\dagger \mathcal{D}\Delta_D \exp\left\{ -\sum_M \frac{\phi_M^2}{4G_M} - \sum_D \frac{|\Delta_D|^2}{4G_D} + \frac{1}{2}\mathrm{Tr}\ \ln S^{-1}[\{M_M\},\{\Delta_D\}] \right\}$$

- Collective (stochastic) Fields: Mesons (ϕ_M) and Diquarks (Δ_D)
- Systematic Evaluation: Mean field + Fluctuations
  - Mean-field Approximation: Order parameter for Phase transitions (Gap equations)
  - Fluctuations (2. Order): Hadronic Correlations (Bound- & Scattering states)
  - Fluctuations of higher Order: Hadron-Hadron Interaction

Phase diagram for 3-Flavor Quark Matter

Thermodynamic Potential $\Omega(T,\mu) = -T \ln Z[T,\mu]$

$$\Omega(T,\mu) = \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D} - T\sum_n \int \frac{d^3p}{(2\pi)^3}\frac{1}{2}\mathrm{Tr}\ln\left(\frac{1}{T}S^{-1}(i\omega_n,\vec{p})\right) + \Omega_e - \Omega_0.$$

$$\mathrm{InverseNambu-GorkovPropagator} \quad S^{-1}(i\omega_n,\vec{p}) = \begin{bmatrix} \gamma_\mu p^\mu - M(\vec{p}) + \mu\gamma^0 & \widehat{\Delta}(\vec{p}) \\ \widehat{\Delta}^\dagger(\vec{p}) & \gamma_\mu p^\mu - M(\vec{p}) - \mu\gamma^0 \end{bmatrix},$$

$$\Delta_{k\gamma} = 2G_D\langle \bar{q}_{i\alpha} i\gamma_5 \epsilon_{\alpha\beta\gamma}\epsilon_{ijk} g(\vec{q}) q^C_{j\beta}\rangle. \quad \widehat{\Delta}(\vec{p}) = i\gamma_5\epsilon_{\alpha\beta\gamma}\epsilon_{ijk}\Delta_{k\gamma} g(\vec{p}).$$

Fermion Determinant (Tr ln D = ln det D)

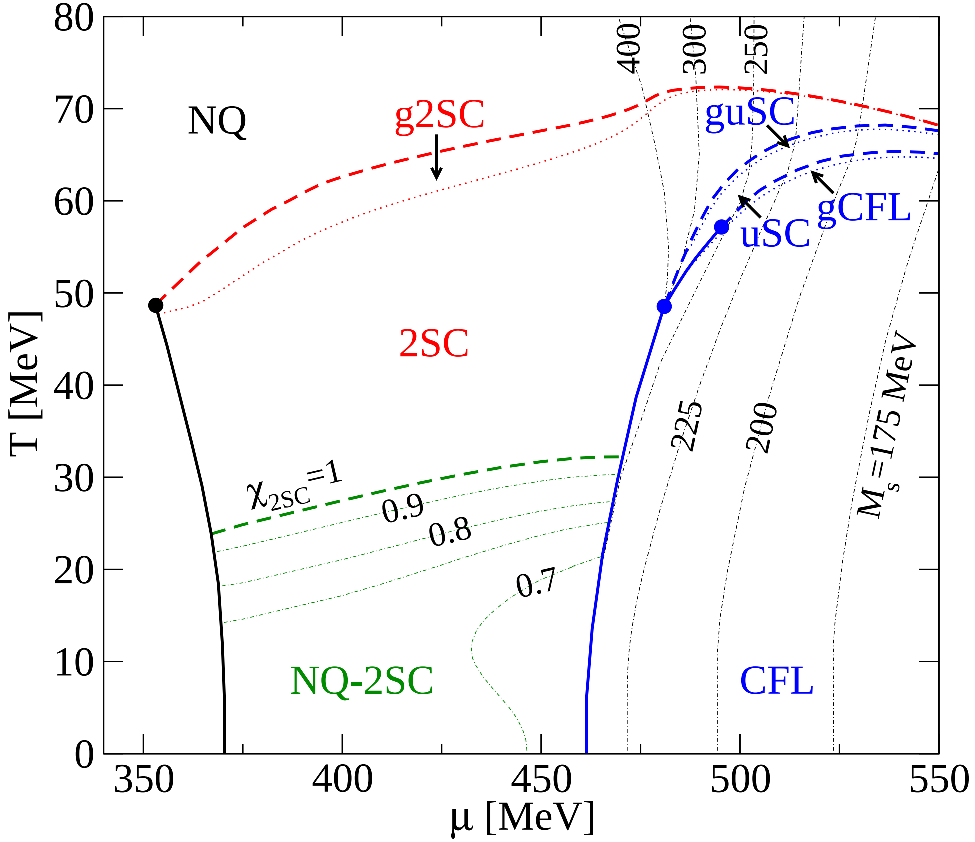
$$\mathrm{lndet}\left(\frac{1}{T}S^{-1}(i\omega_n,\vec{p})\right) = 2\sum_{a=1}^{18}\ln\left(\frac{\omega_n^2+\lambda_a(\vec{p})^2}{T^2}\right).$$

Result for the thermodynamic Potential (Meanfi eld approximation)

$$\Omega(T,\mu) = \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D} - \int \frac{d^3p}{(2\pi)^3}\sum_{a=1}^{18}\left[\lambda_a + 2T\ln\left(1+e^{-\lambda_a/T}\right)\right] + \Omega_e - \Omega_0.$$

Neutrality constraints: $n_Q = n_8 = n_3 = 0$, $n_i = -\partial\Omega/\partial\mu_i = 0$,
Equations of state: $P = -\Omega$, etc.

Three-flavor Quark Matter Phase Diagram



Rüster et al, PRD 72 (2005) 034004;
Blaschke et al, PRD 72 (2005) 065020;
Abuki, Kunihiro, NPA768 (2006) 118;
Warringa et al, PRD 72 (2005) 014015

The phases are:

- NQ: $\Delta_{ud} = \Delta_{us} = \Delta_{ds} = 0$;
- NQ-2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$, $0 \leq \chi_{2SC} \leq 1$;
- 2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$;
- uSC: $\Delta_{ud} \neq 0$, $\Delta_{us} \neq 0$, $\Delta_{ds} = 0$;
- CFL: $\Delta_{ud} \neq 0$, $\Delta_{ds} \neq 0$, $\Delta_{us} \neq 0$;

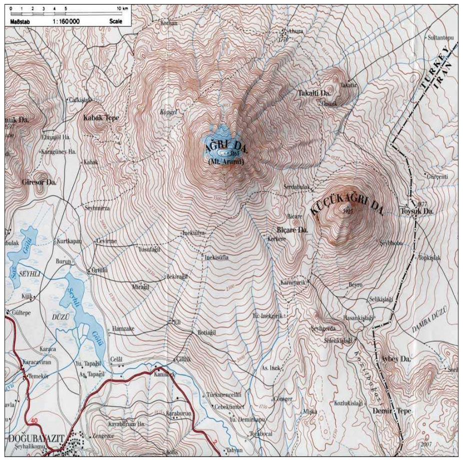
Result:

- Gapless phases only at high T,
- CFL only at high chemical potential,
- At T $\leq$25-30 MeV: mixed NQ-2SC phase,
- Critical point (T_c,μ_c)=(48 MeV, 353 MeV),
- Strong coupling, $G_D = G_S$, similar,
  no NQ-2SC mixed phase.

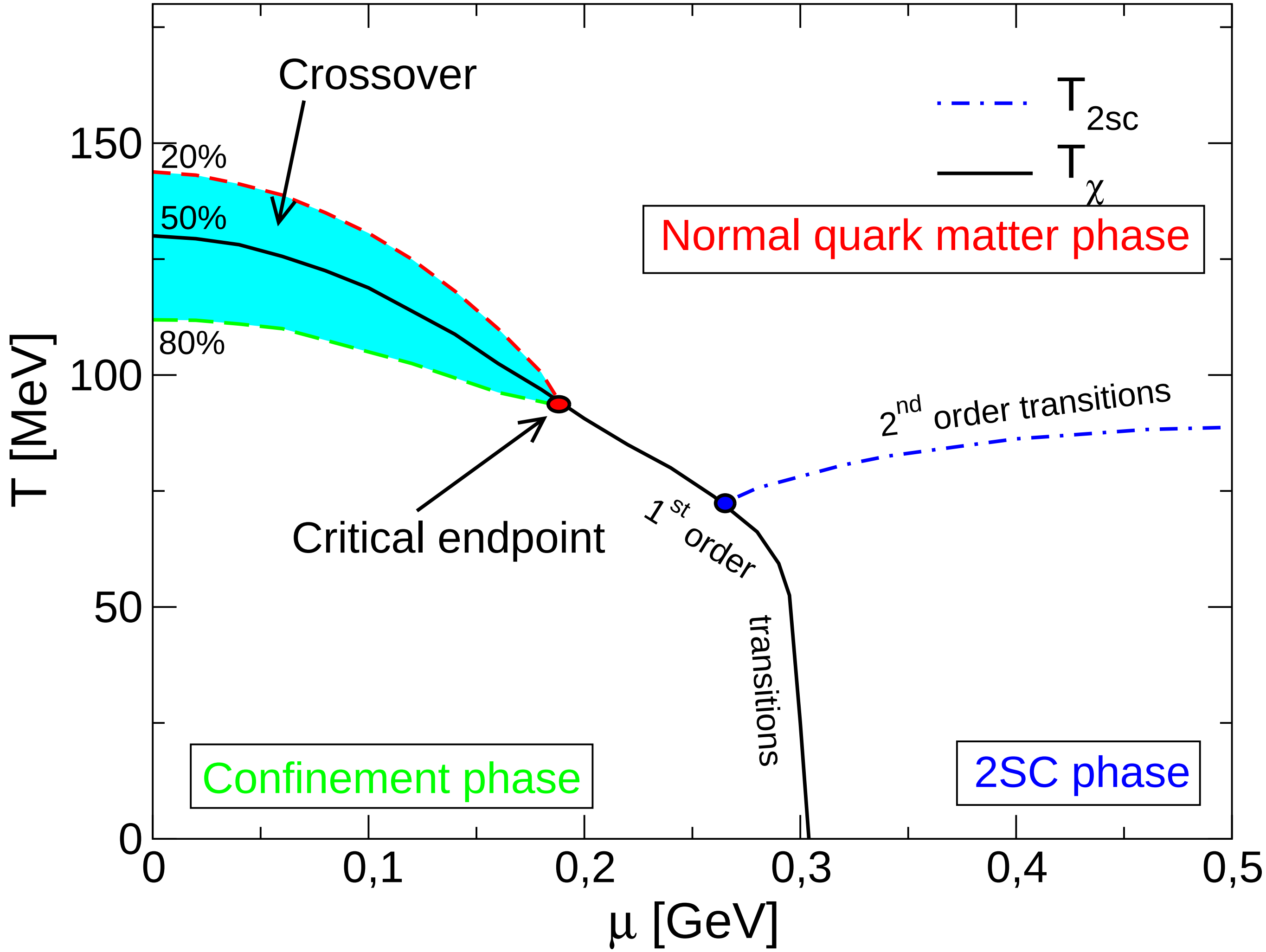
The T-mu plane: Introduction to the map

Armenia in Europe:

Ararat



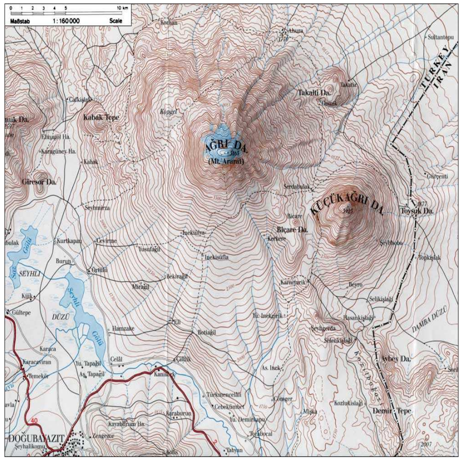
Three phases of quark matter: confi ned, deconfi ned, superconducting



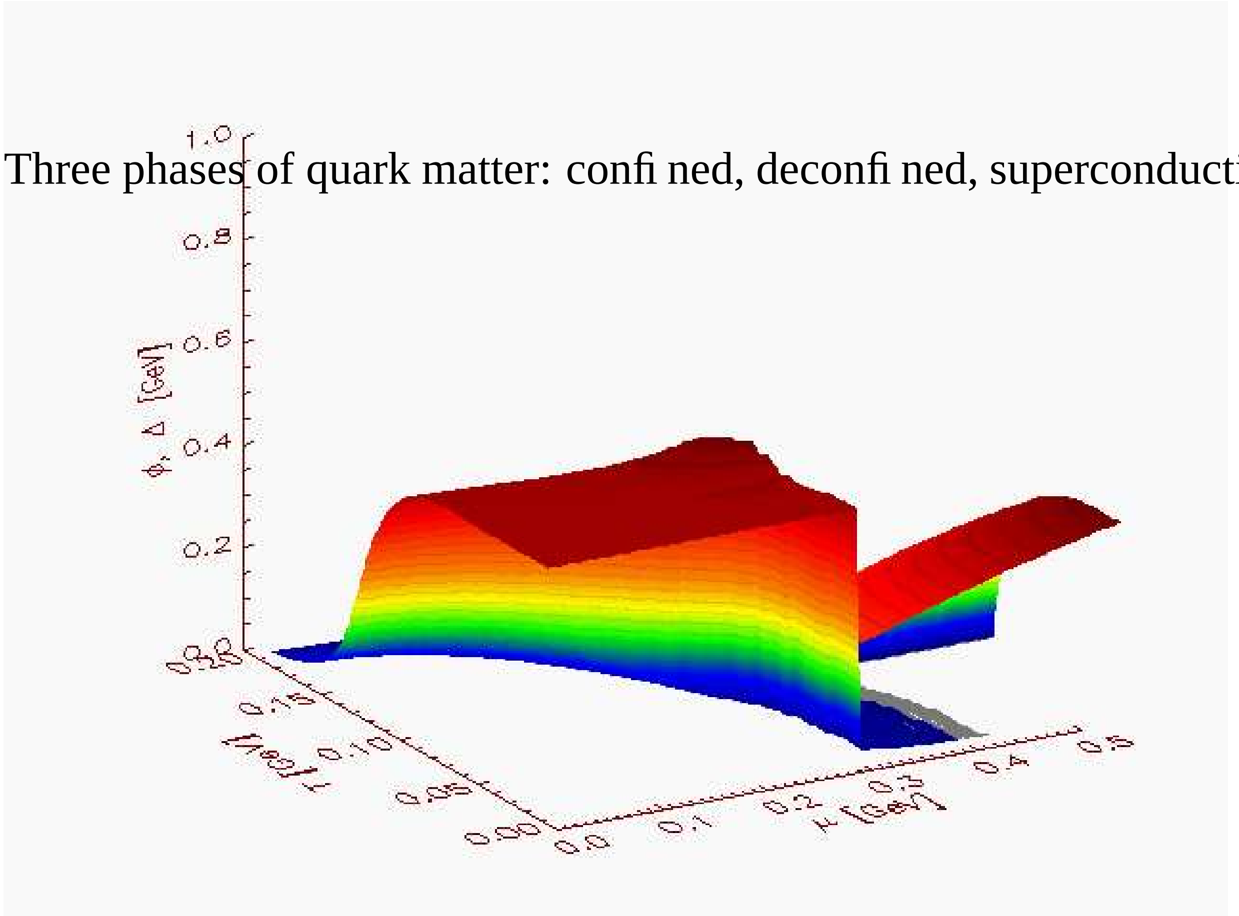
The T-mu plane: Landscape

Map of Armenia:

Ararat



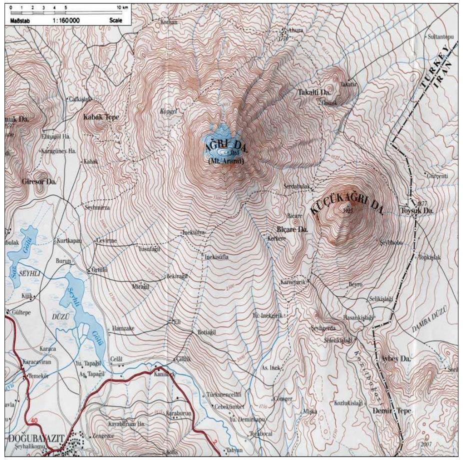
Three phases of quark matter: confined, deconfined, superconducting



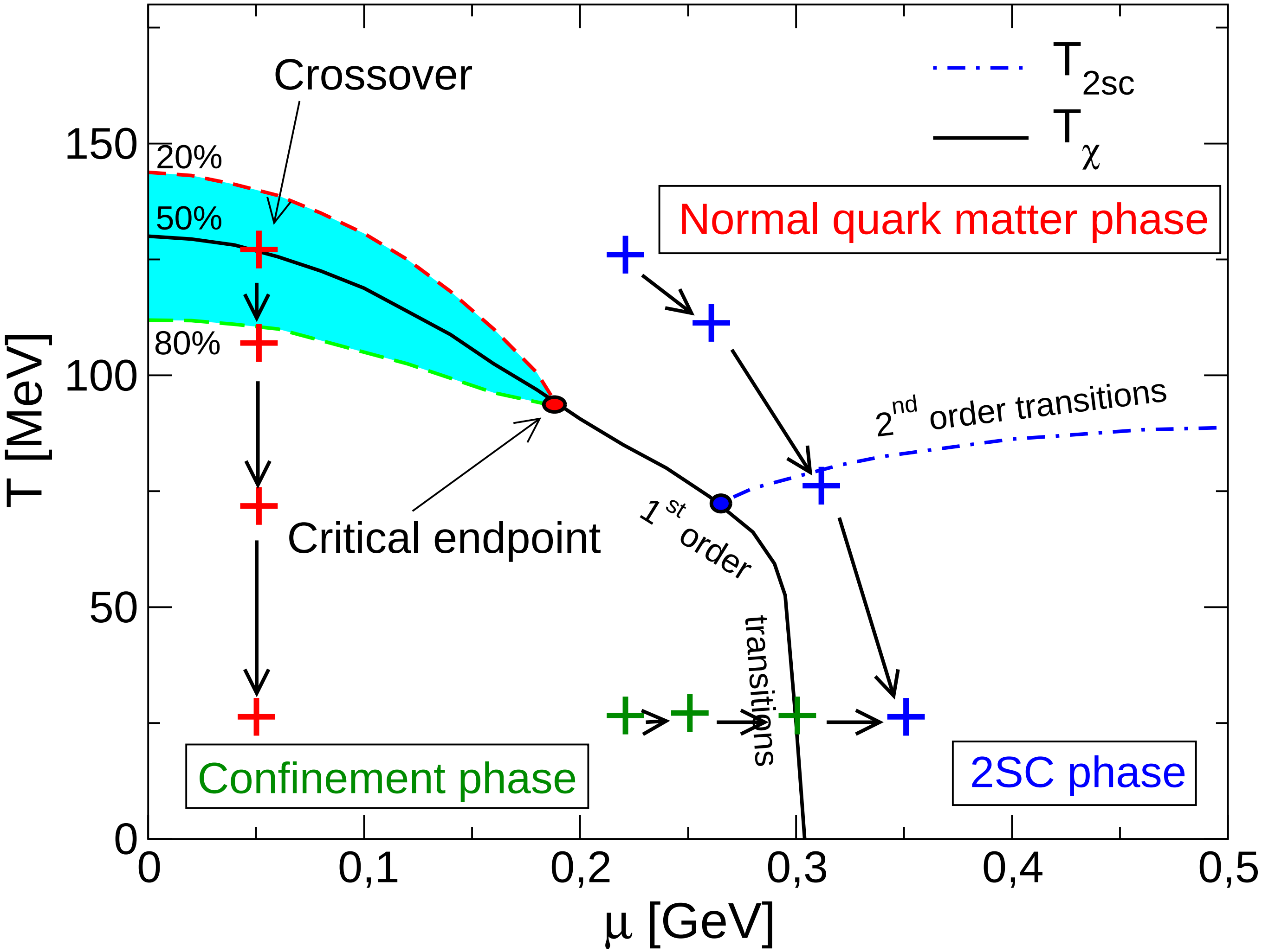
The T-mu plane: walking on the map

Armenia in Europe:

Ararat

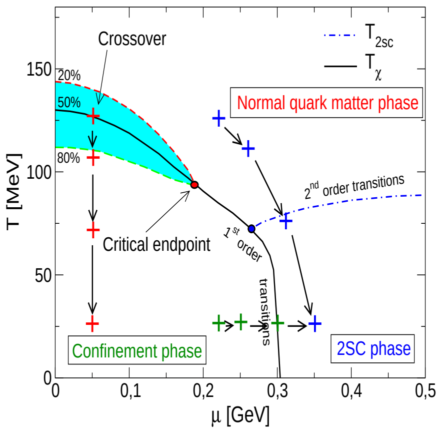


Three phases of quark matter: confi ned, deconfi ned, superconducting

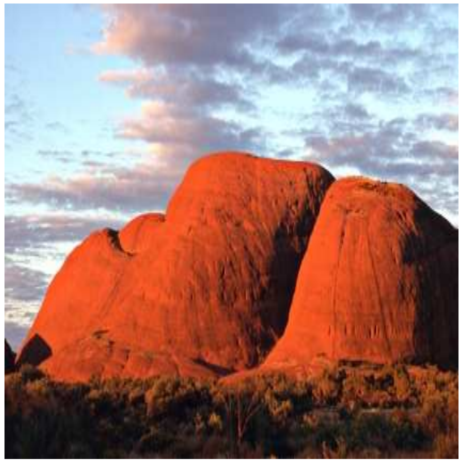


The T-mu plane: walking the routes (I)

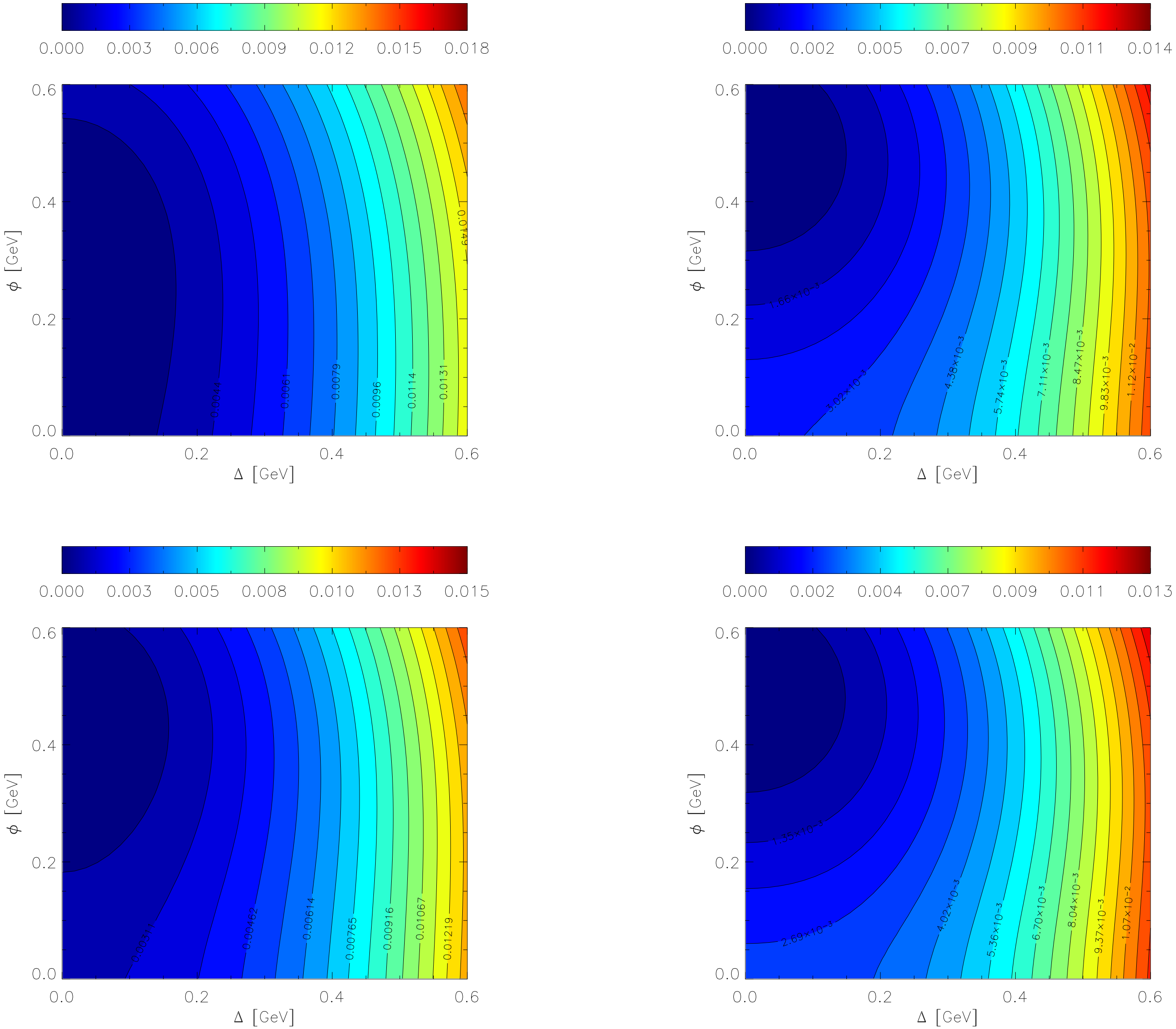
Map of routes:



The Olgas



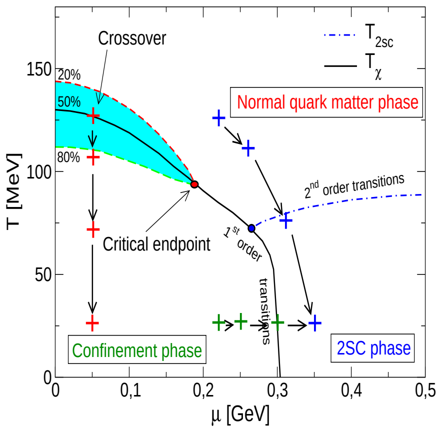
Route 1: deconfined $\longrightarrow$ confined



The T-mu plane: walking the routes (II)

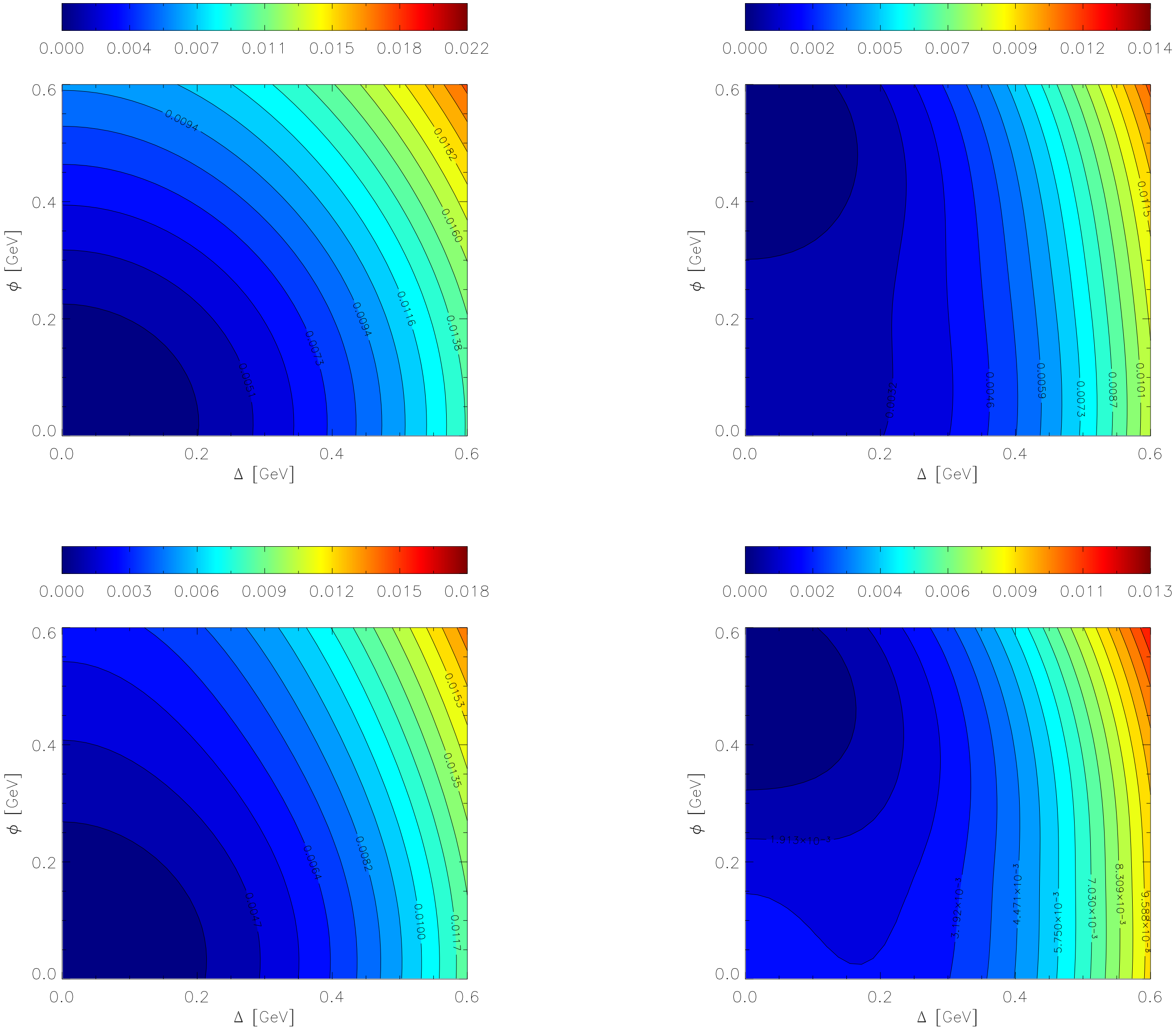
1. Introduction
2. Hadronic Cooling
3. Quark Substructure and Phases
4. Hybrid Star Cooling
5. Conclusions

Map of routes:



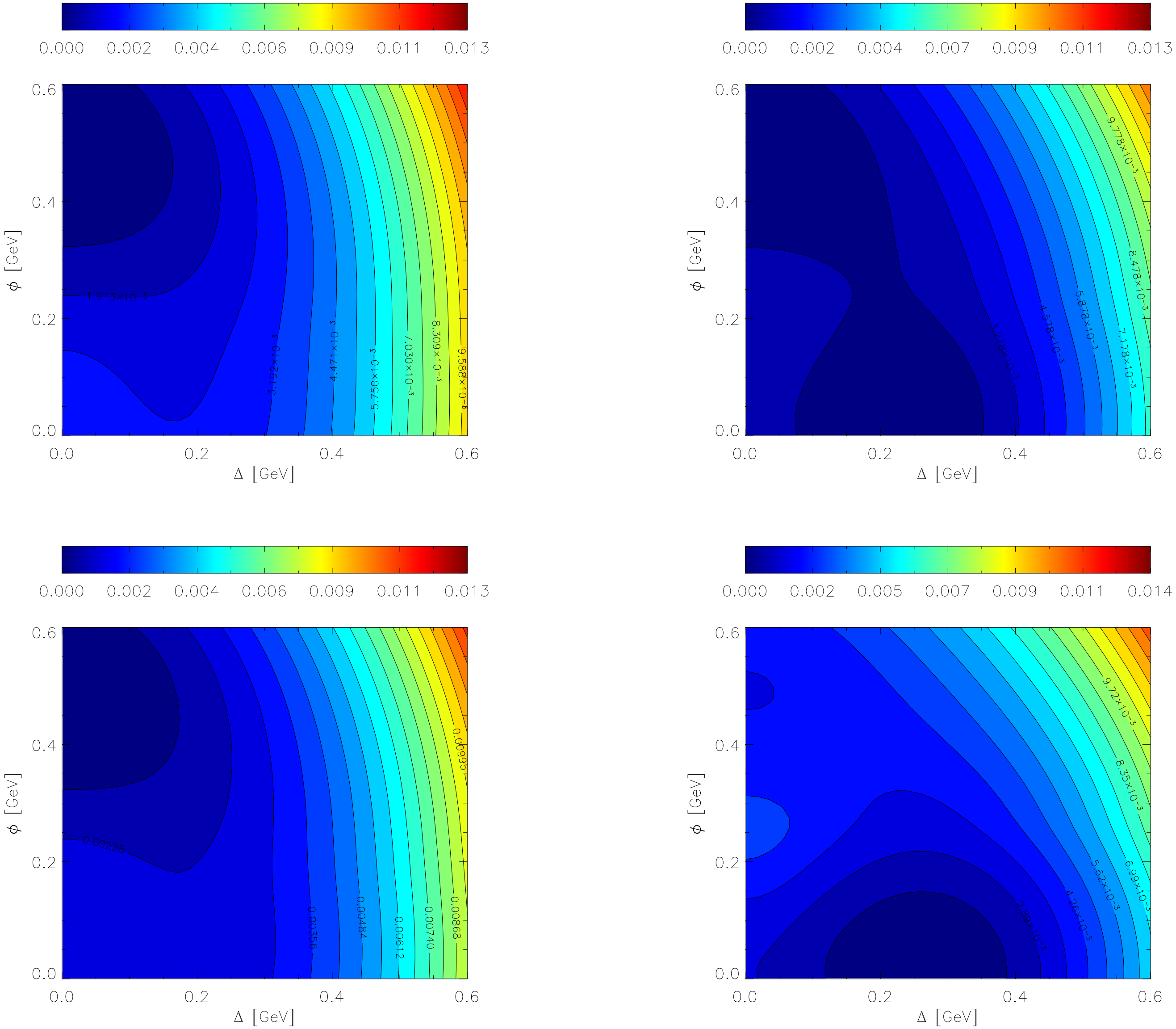
Mount Rainier

Route 1’: deconfi ned ⟶ confi ned

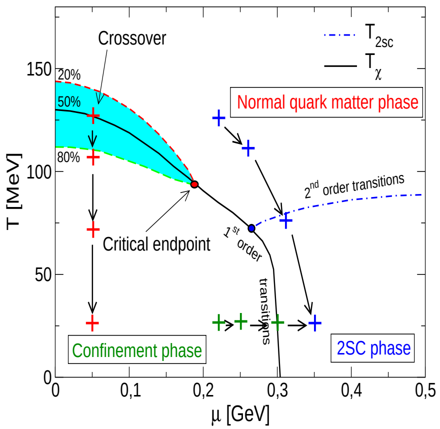


The T-mu plane: walking the routes (III)

Route 2: confined ⟶ superconducting



Map of routes:

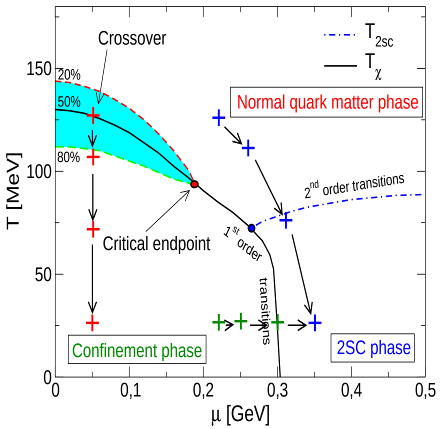


Schneekoppe

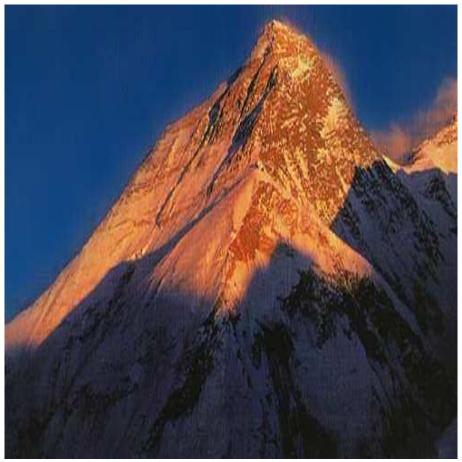
The T-mu plane: walking the routes (IV)

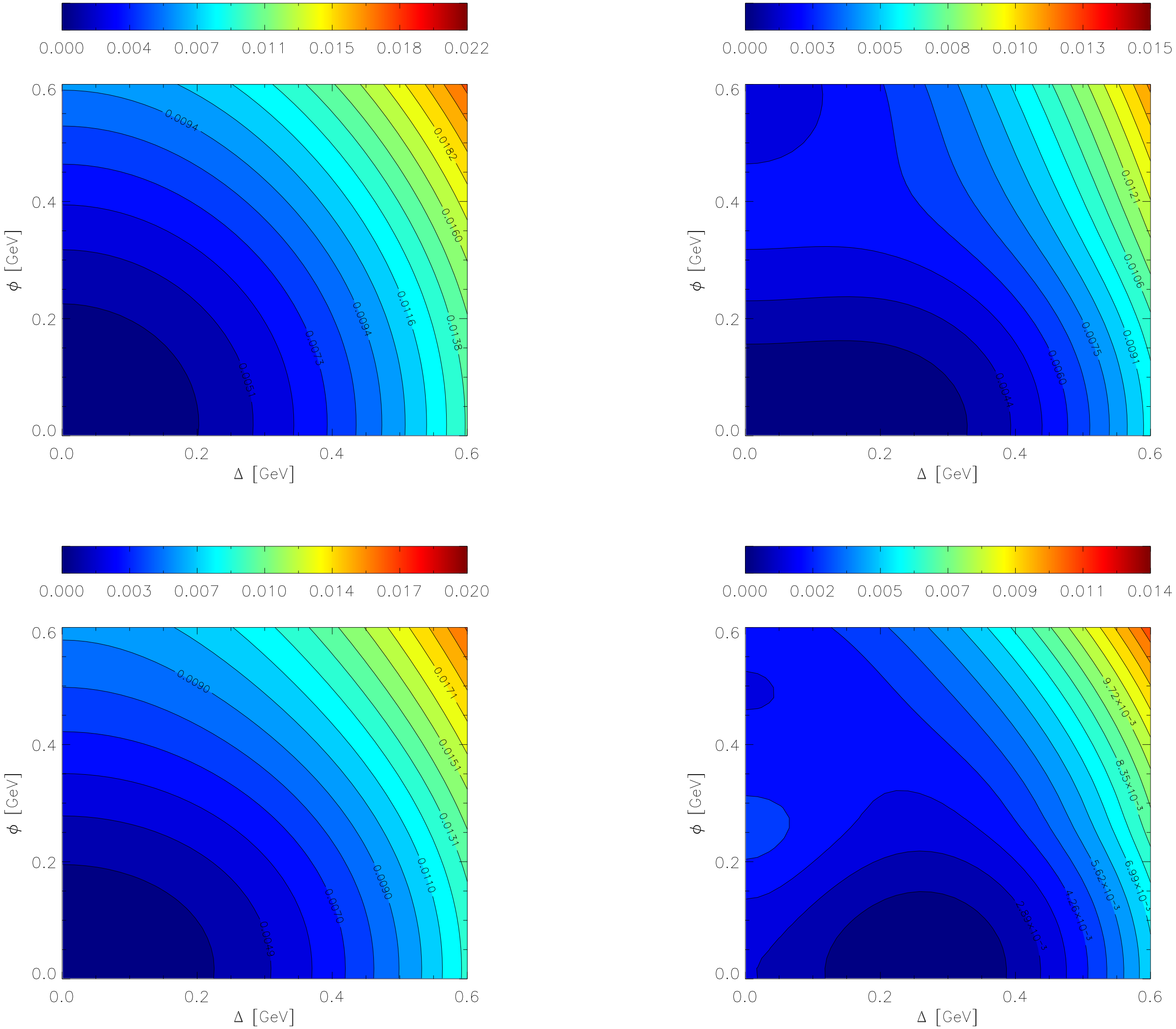
Route 3: deconfined $\longrightarrow$ superconducting

Map of routes:

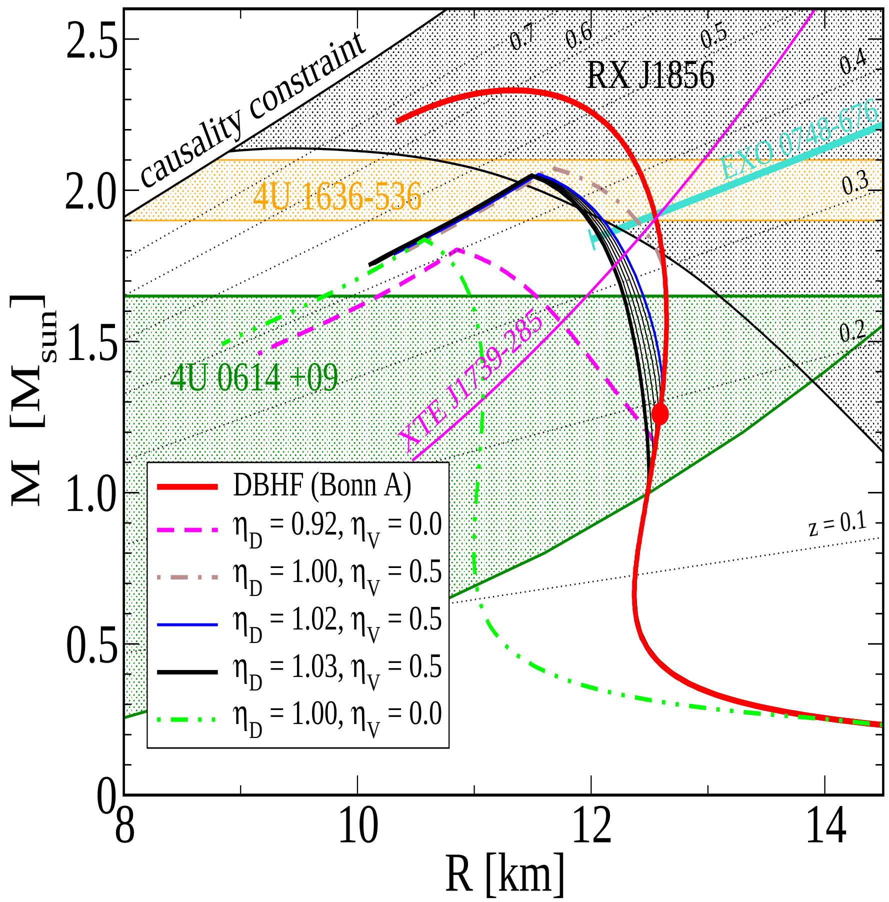


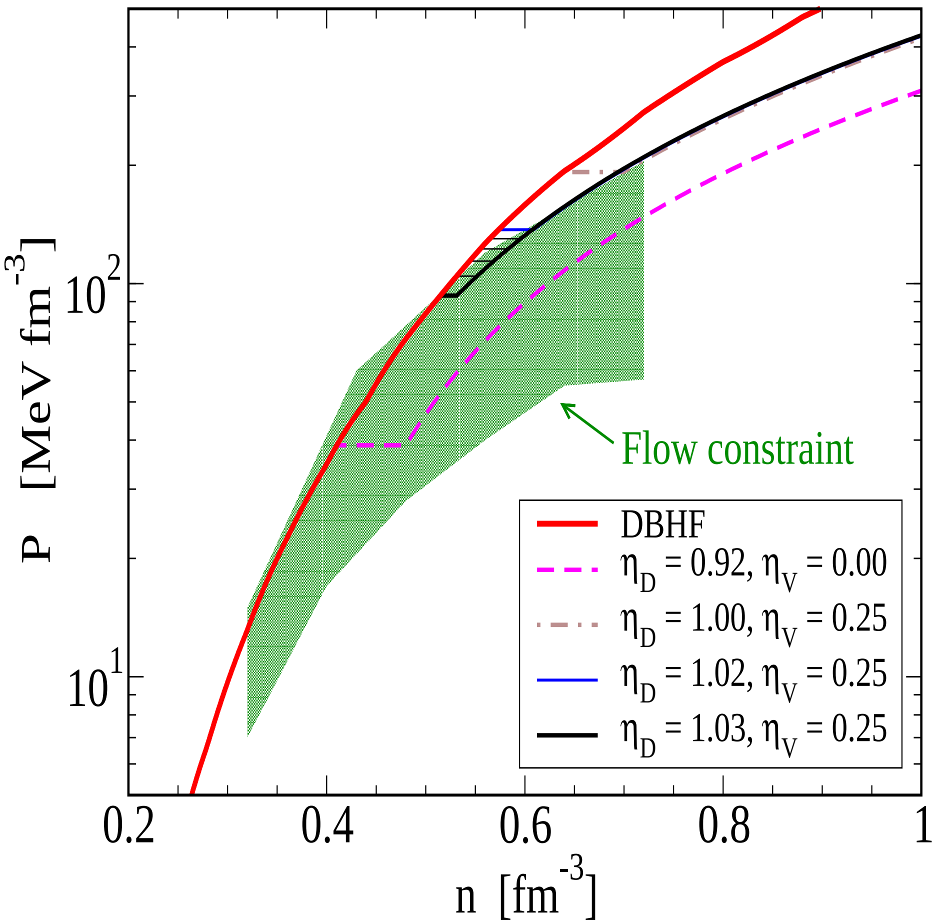
Mount Everest





Mass-Radius constraint and Flow constraint (II)

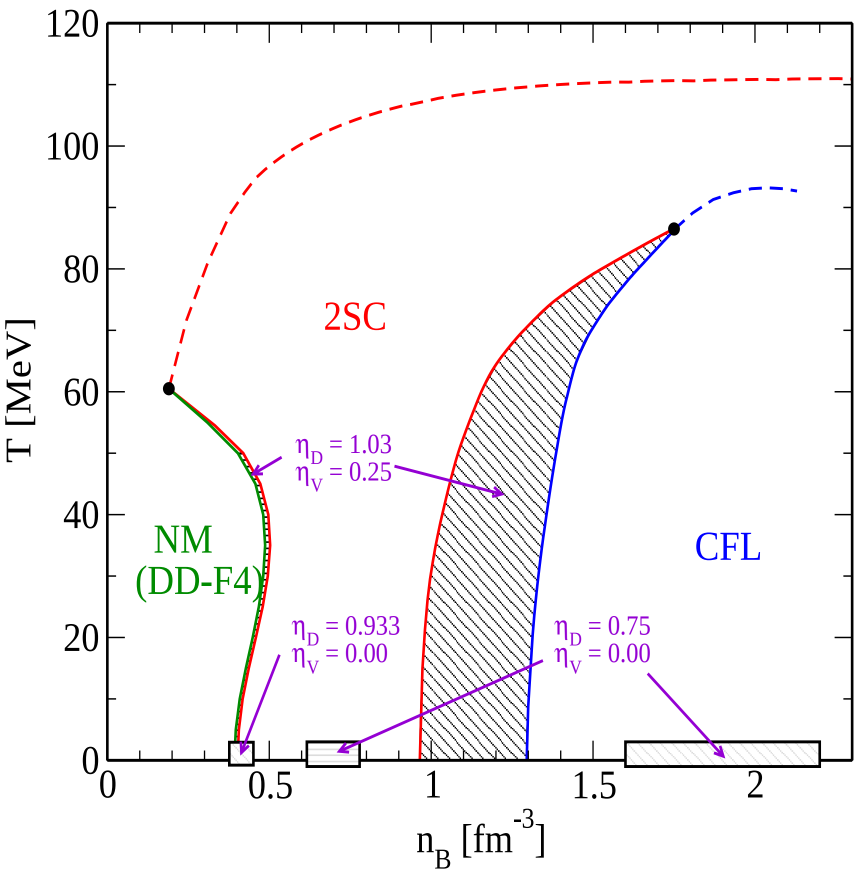


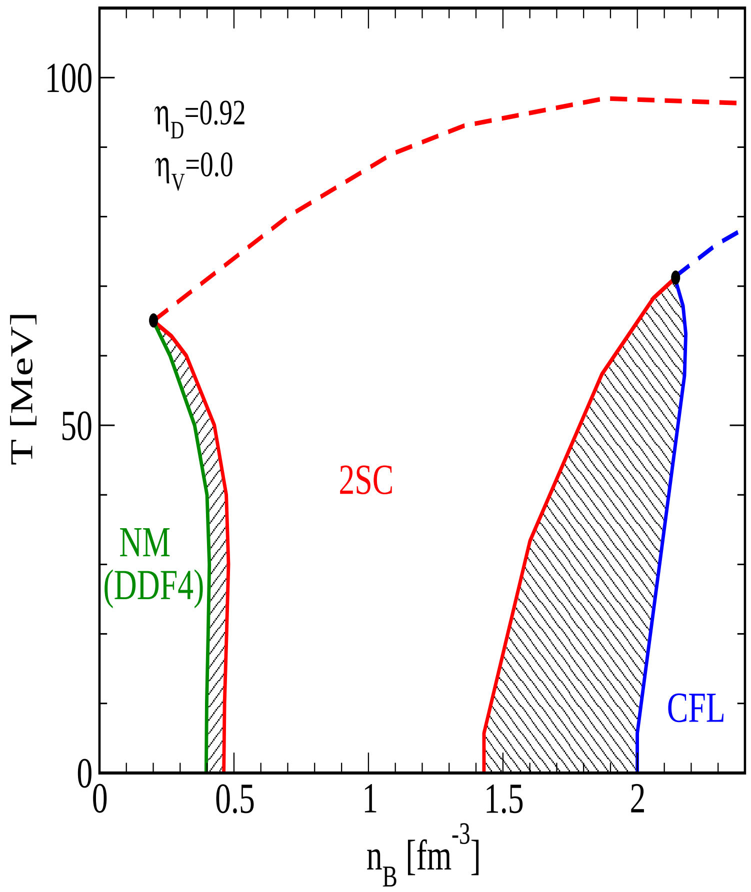


- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff quark matter EoS;
  Note: DU problem of DBHF removed by deconfinement! and: CFL core Hybrids unstable!
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS !
  Note: Quark matter removes violation by DBHF at high densities

Klähn, D.B., Sandin, Fuchs, Faessler, Grigorian, Röpke, Trümper: Phys. Lett. B567, 160 (2007)

Phase diagrams for the CBM experiment

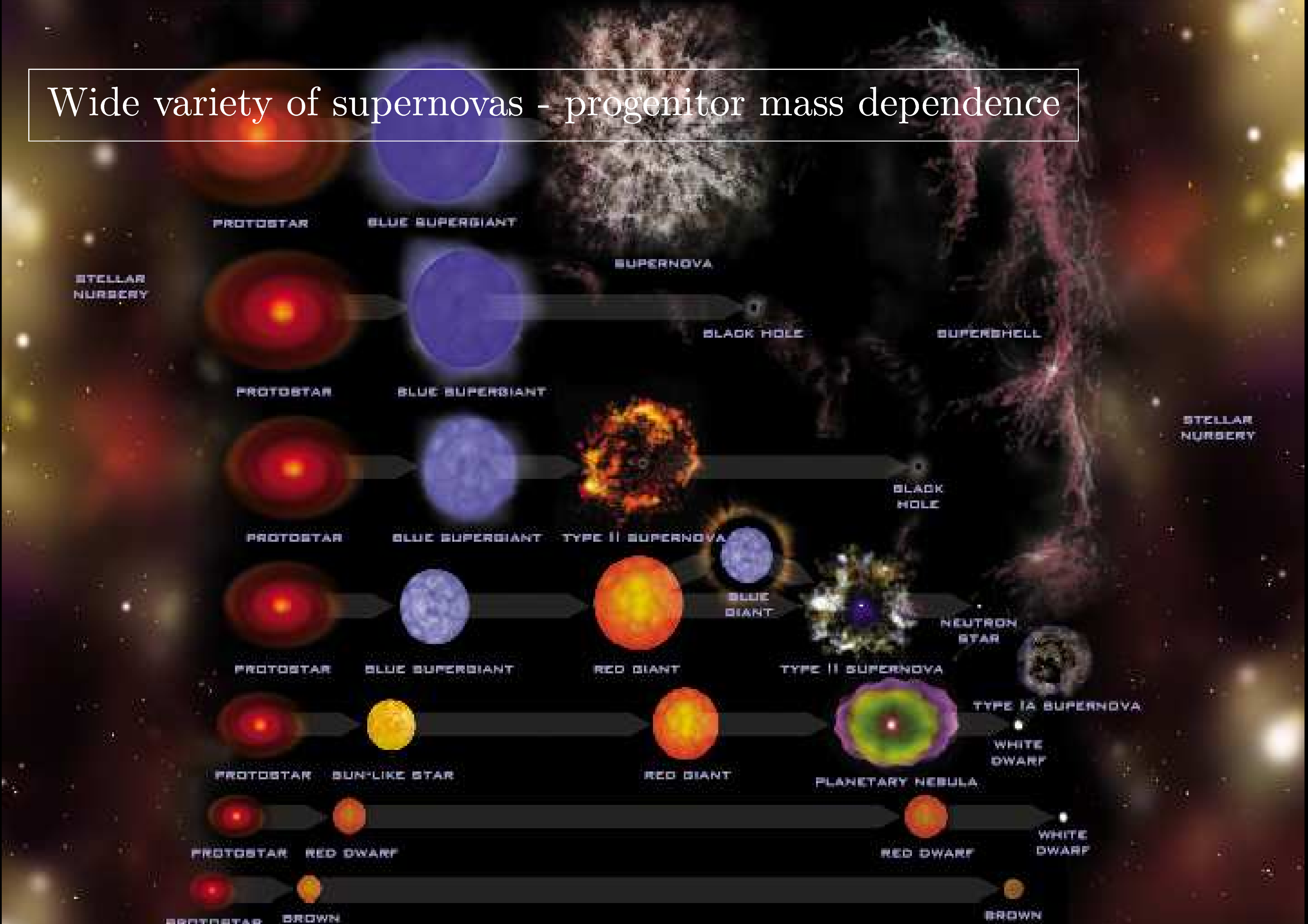




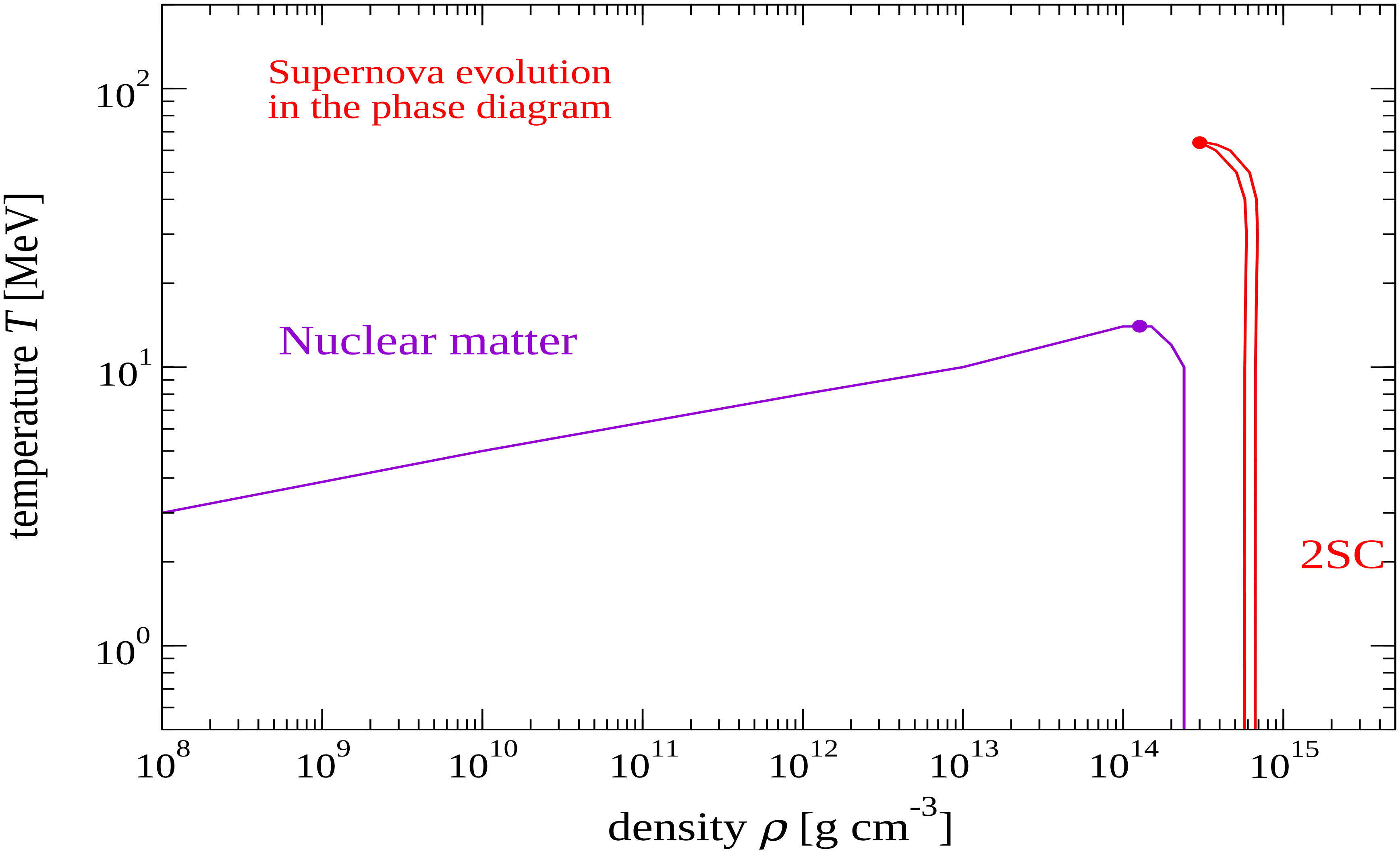
Phase diagrams for isospin-symmetric matter, for hybrid star maximum mass $M_{max} = 2.1\ M_\odot$ (left-hand side) and $M_{max} = 1.7\ M_\odot$ (right-hand side).

D. B., F. Sandin, S. Typel, in preparation.

Wide variety of supernovas - progenitor mass dependence

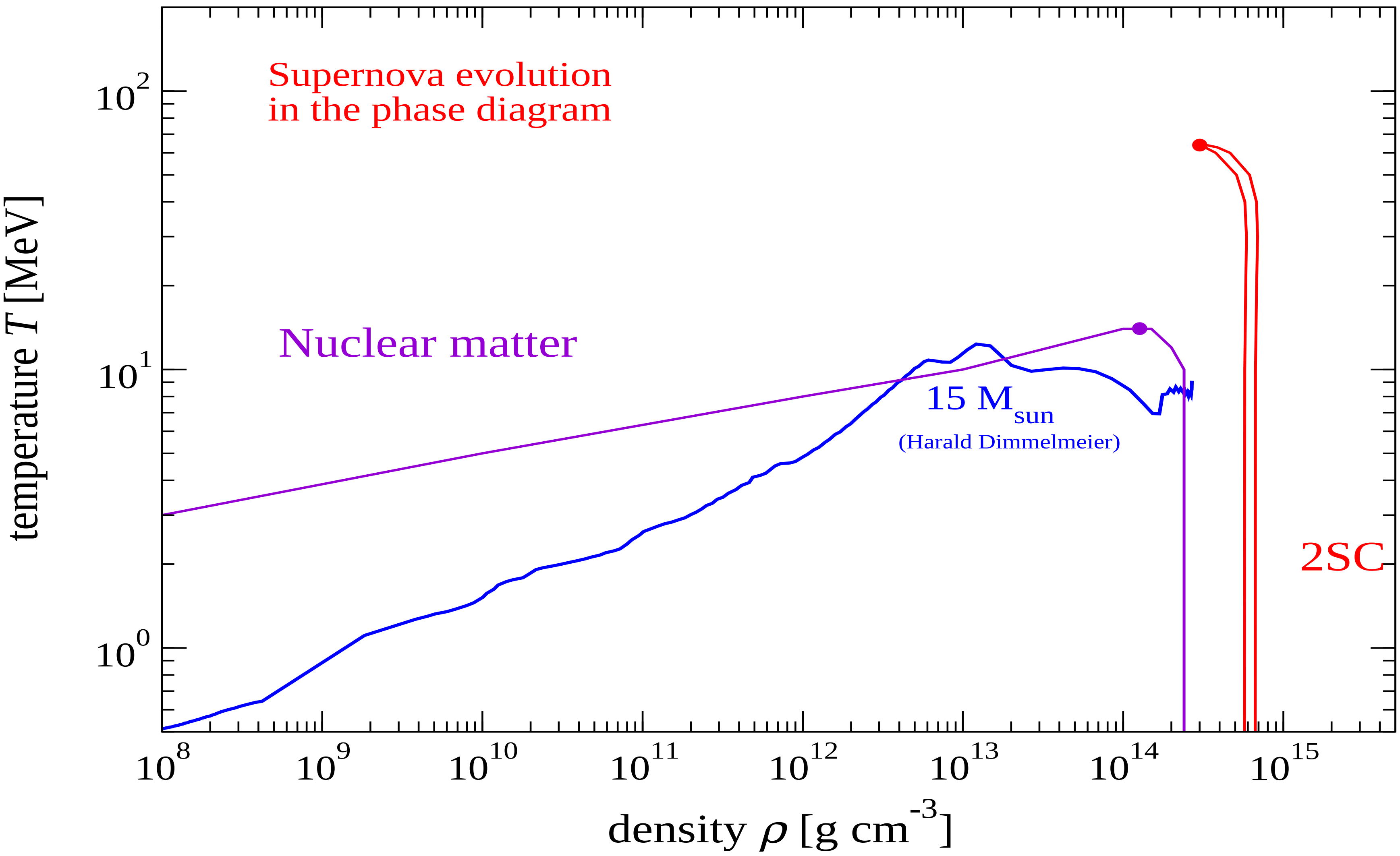


Supernova Collapse in the Phase Diagram

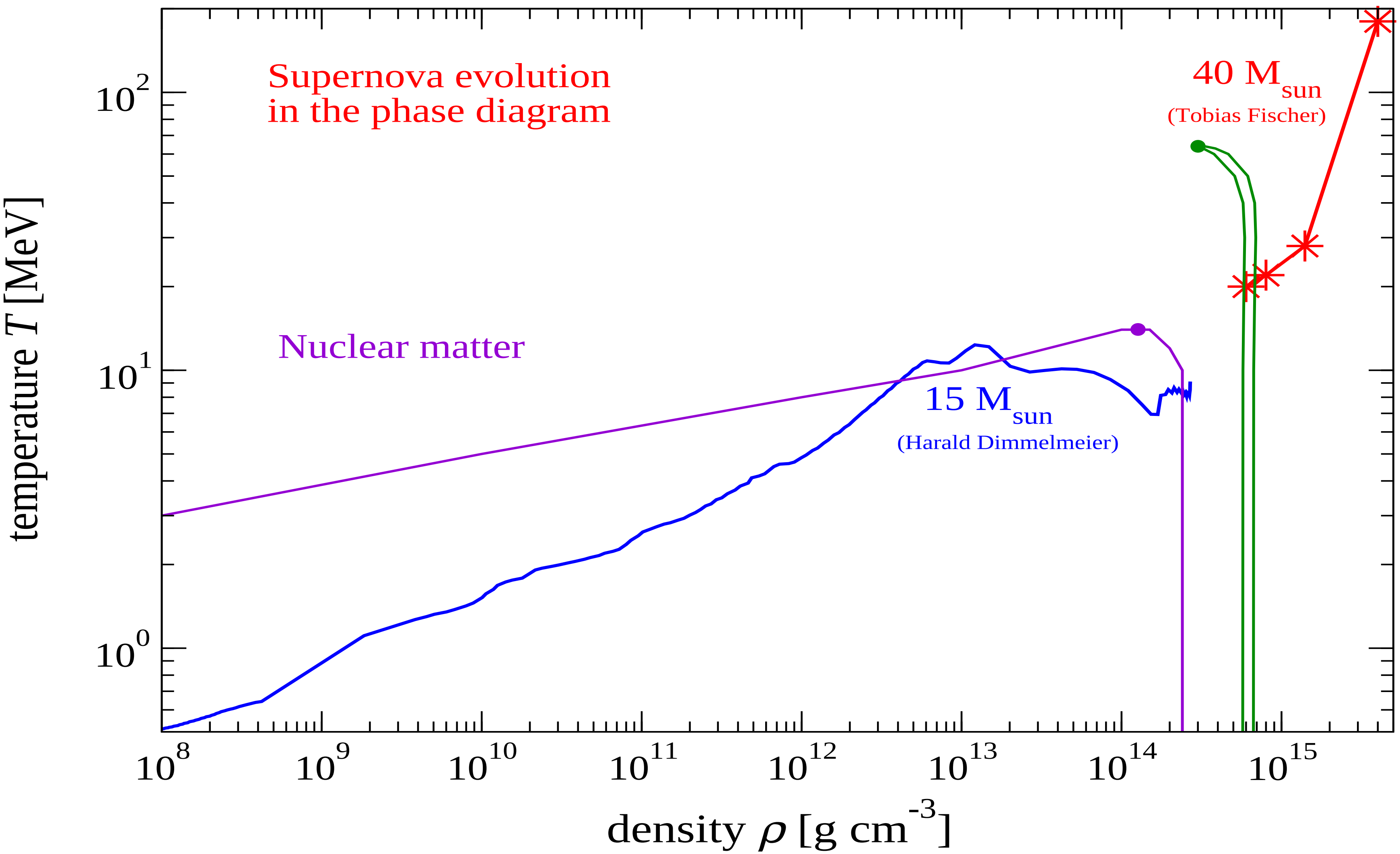


Supernova Collapse in the Phase Diagram (II)

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

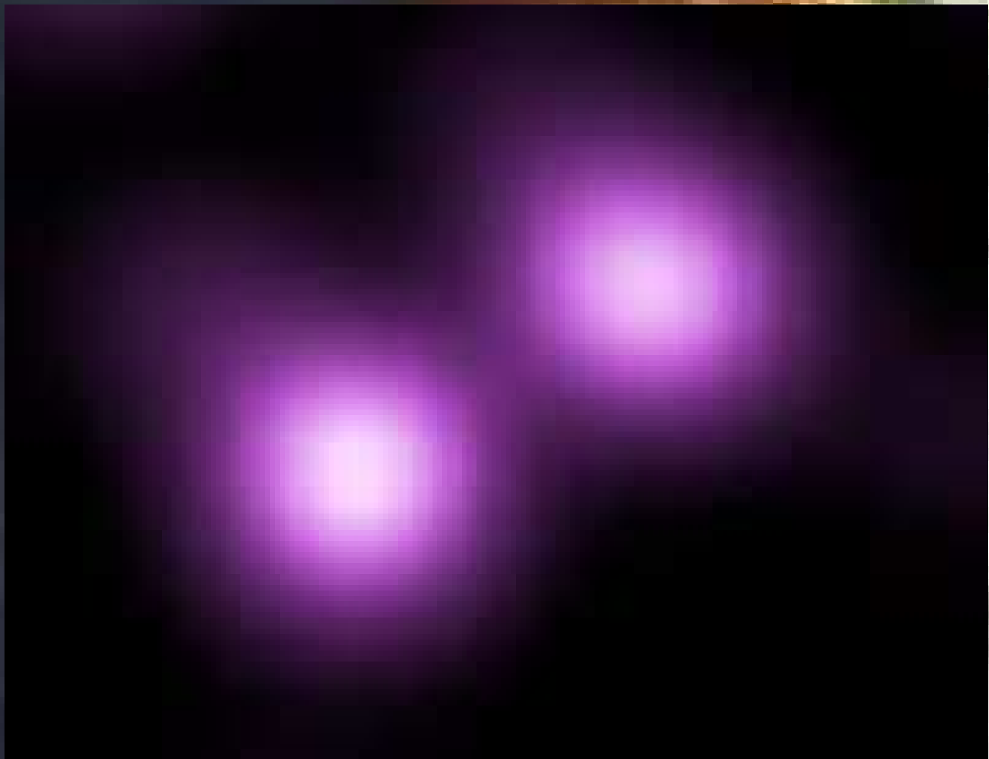


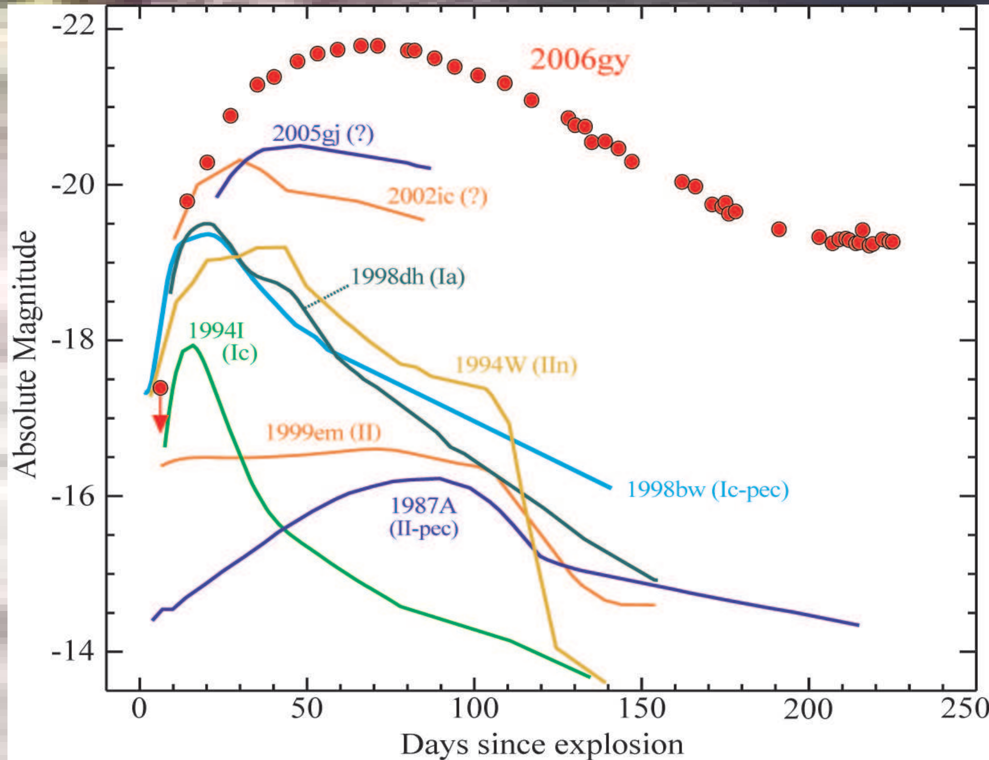
Supernova Collapse in the Phase Diagram



The case of SN2006gy

The case of SN2006gy - a Quarknova ?

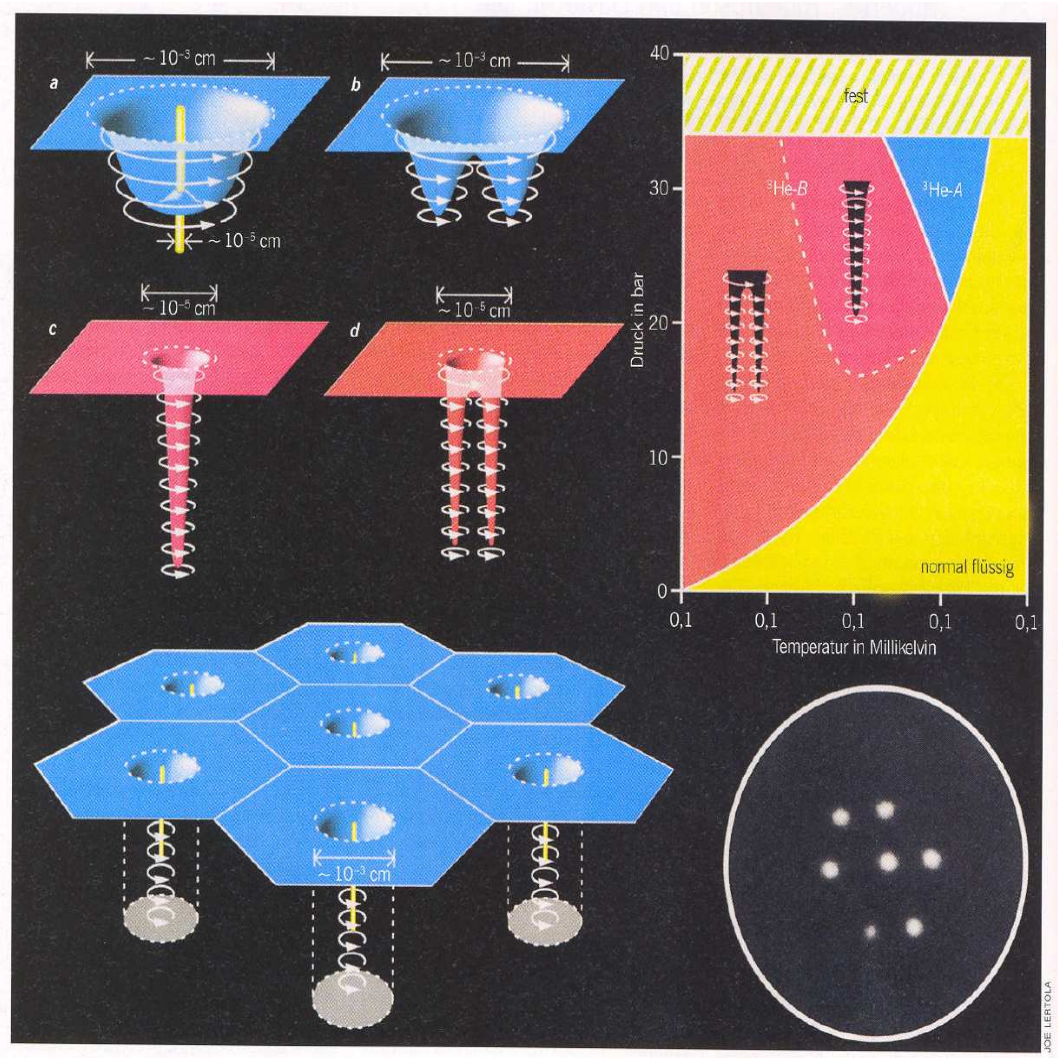




Discovery: Sept. 18, 2006
in NGC 1260 (Perseus)
Distance: 72 Mpc=238 Mill. Ly
(Smith et al.: astro-ph/0612617)

Light curve: 70 days rise time
Energy release: 10^{52} erg= 10 bethe
Progenitor star: $\approx 150\ M_\odot$?
Engine: Quark-star formation?
(Leahy & Ouyed: 0708.1787 [astro-ph])

Single flavor (d-CSL) Phase in Compact Stars

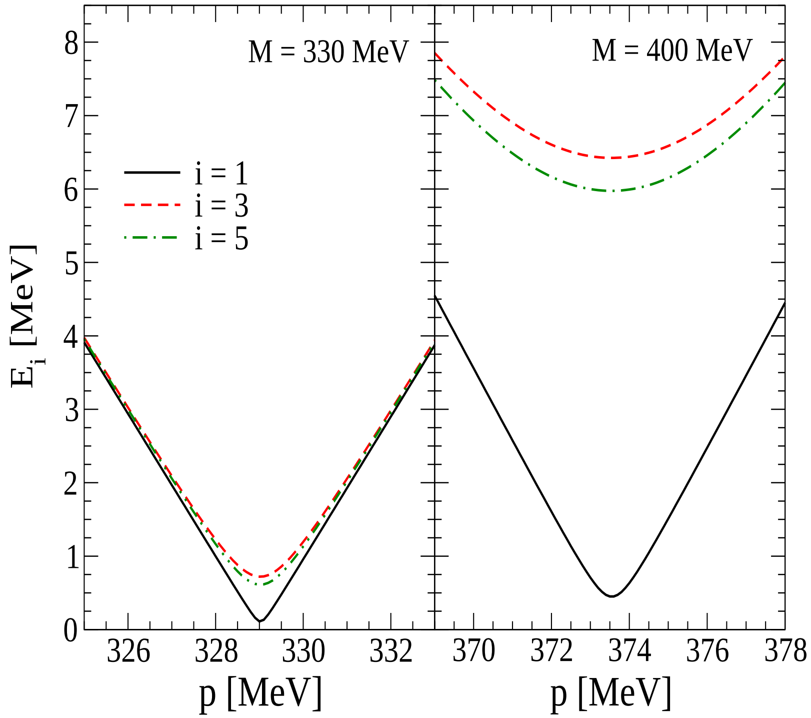


Phases of superfluid ^{3}He

Ansatz Color-spin-locking (CSL) gap:

$\hat{\Delta} = \Delta(\gamma^3\lambda_2 + \gamma^1\lambda_7 + \gamma^2\lambda_5)$

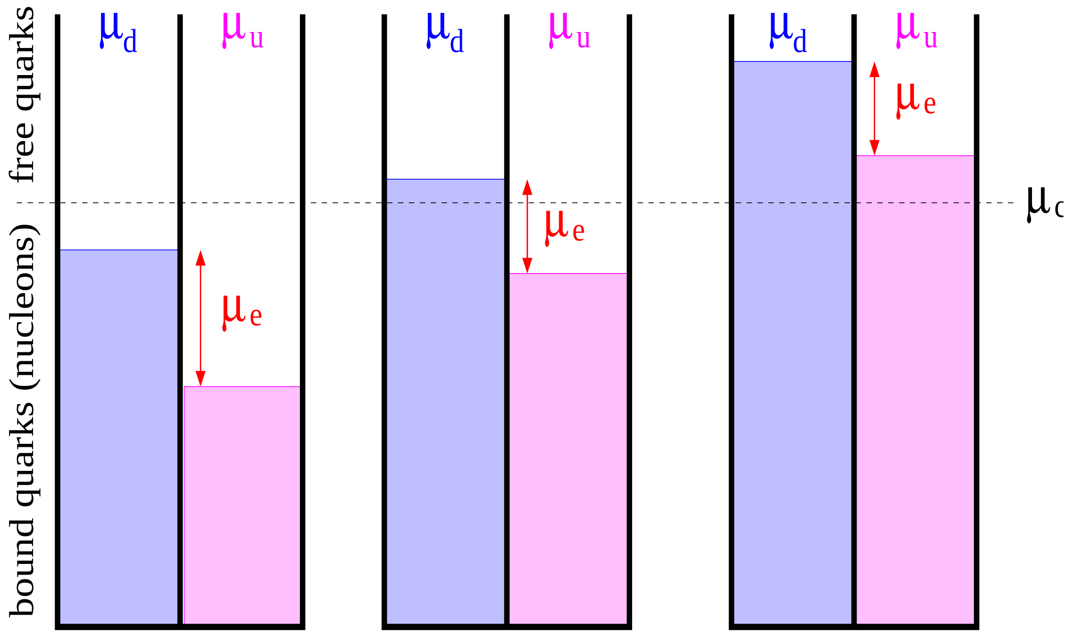
Aguilera et al., PRD 72 (2005) 034008;
PRD 74 (2006) 114005



d-quark 'dripline' and single-flavor (d-CSL) phase

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

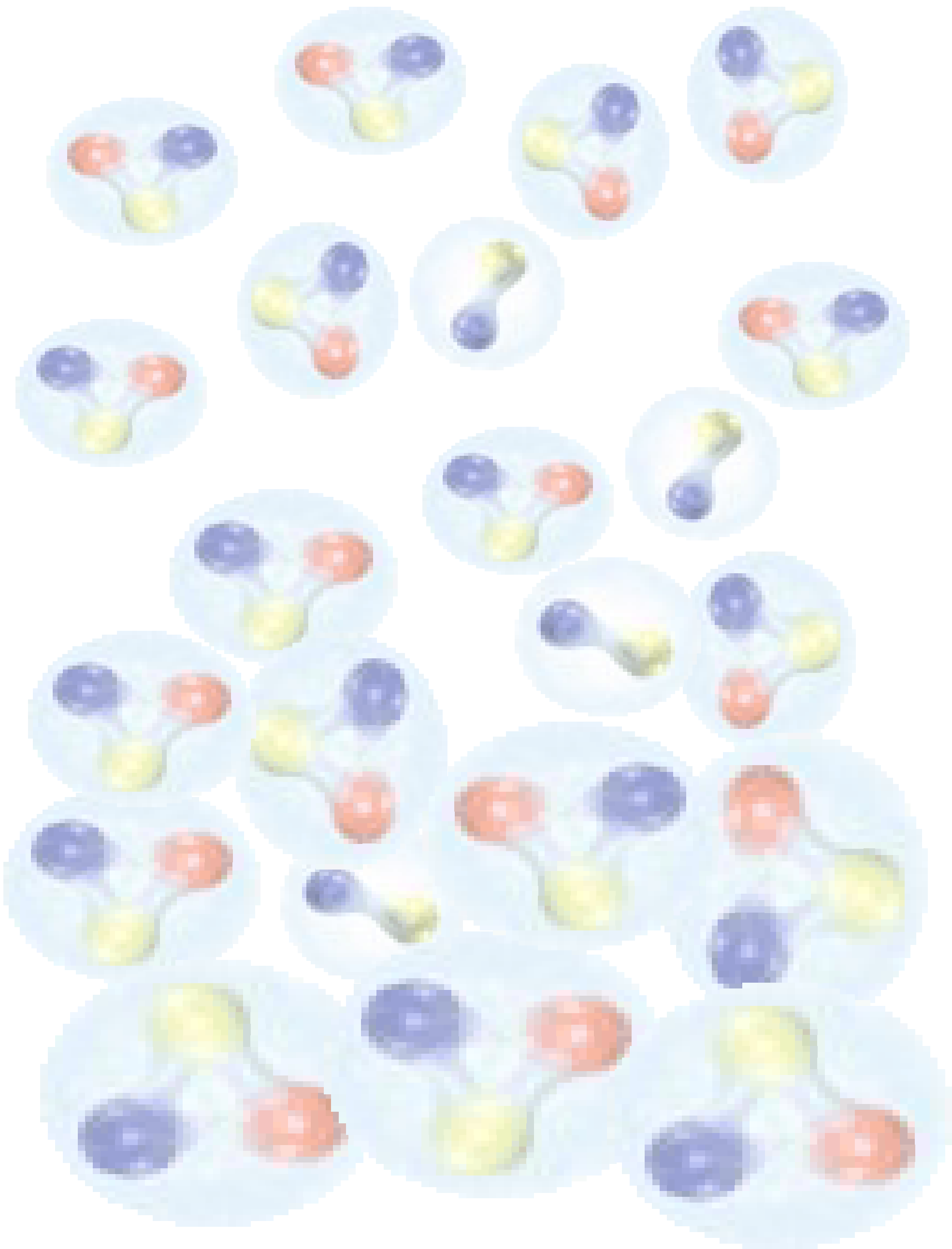
Sequential 'deconfinement' of quark flavors



pure nuclear matter (NM)

d−quark drip (NM + d−CSL phase)

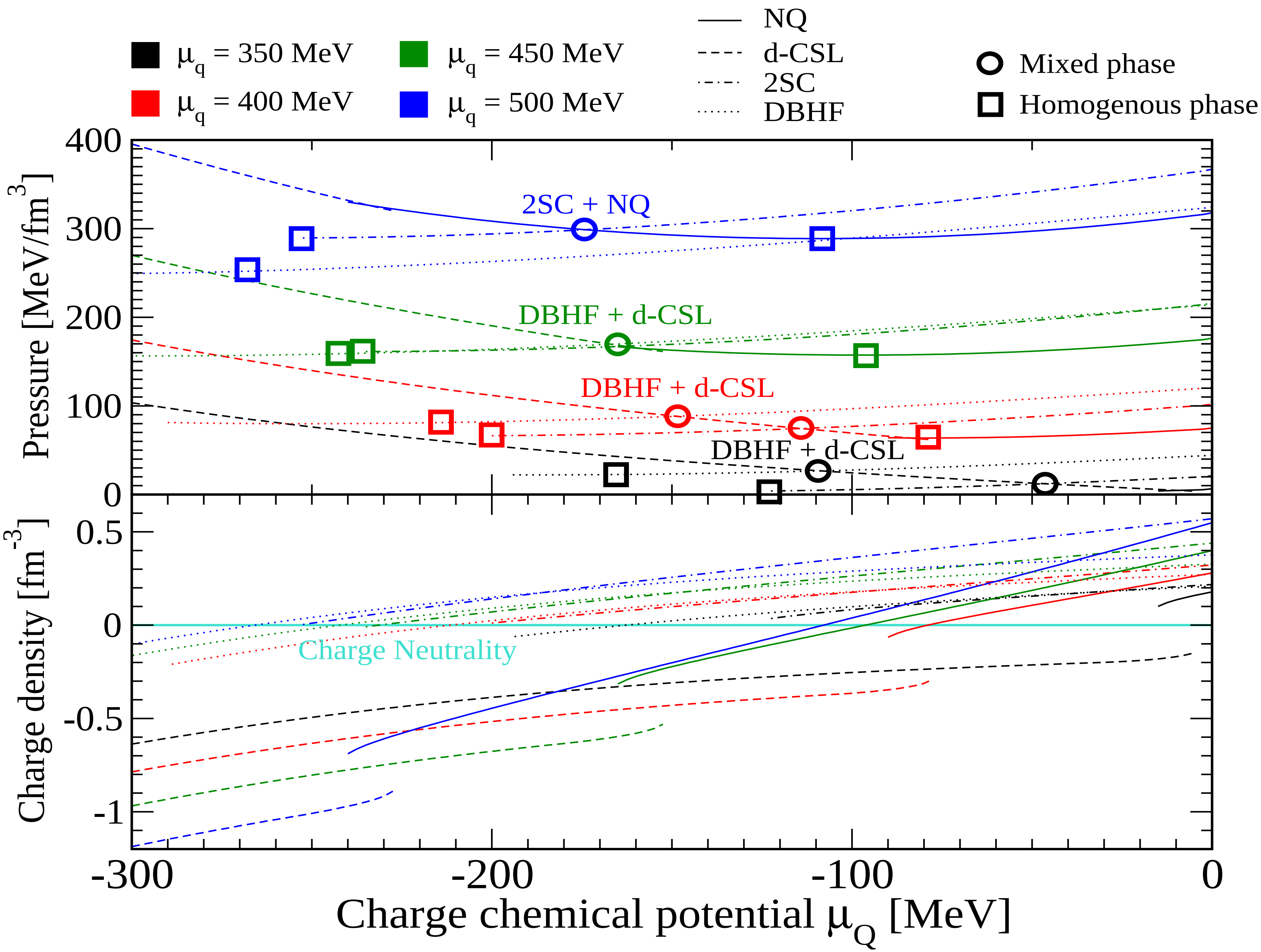
2−flavor quark matter (2SC phase)



D.B., F. Sandin, T. Klähn, J. Berdermann,
arXiv:0807.0414 [nucl-th]; arXiv:0808.1369 [astro-ph]
arXiv:0808.0181 [nucl-th], J. Phys. G, in press

Global charge neutrality: quark-nuclear hybrid

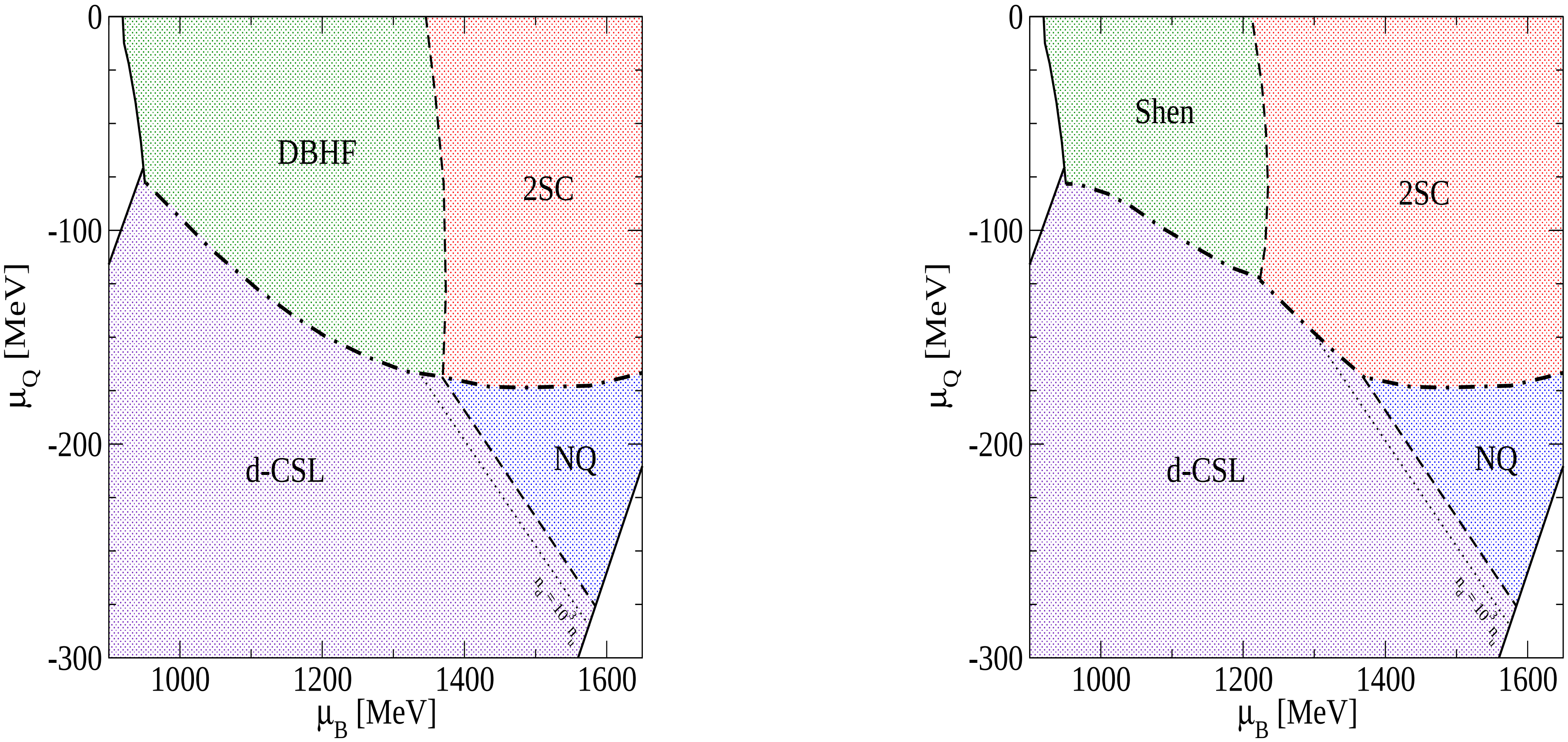
1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion



d-CSL: single-flavor phase in competition

Dash-dotted lines: border between oppositely charged phases

⟹ single-flavor phase only in isospin-asymmetric matter!

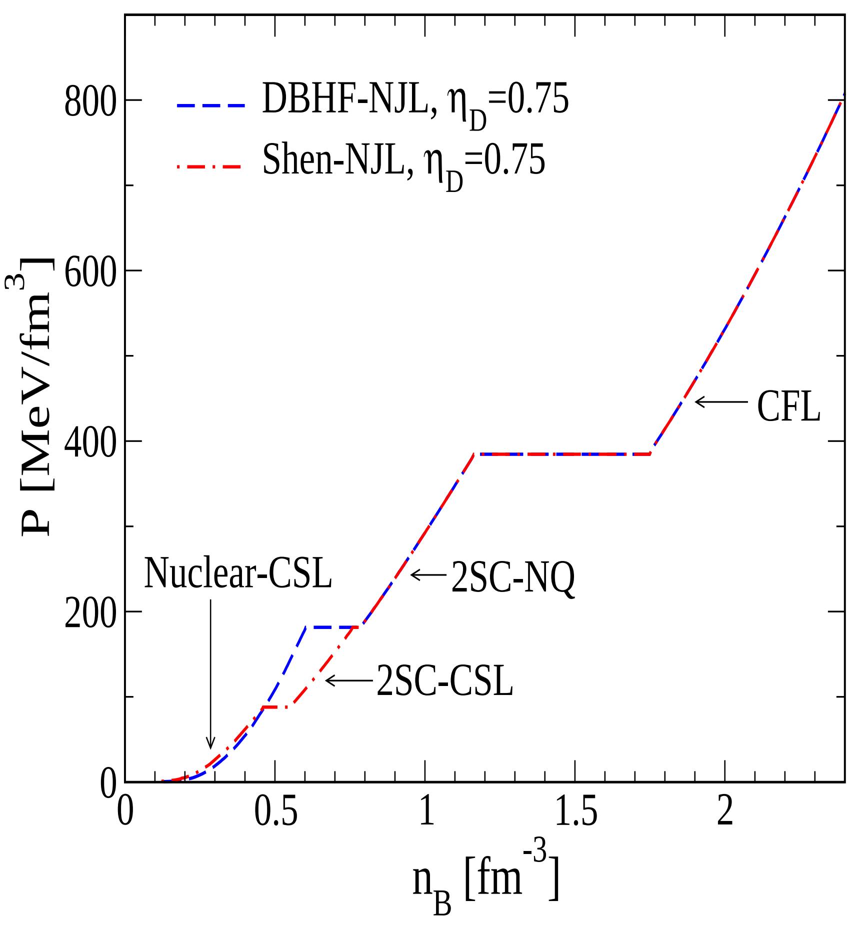


D.B., F. Sandin, T. Klähn, J. Berdermann, arXiv:0807.0414 [nucl-th]; arXiv:0808.1369 [astro-ph]

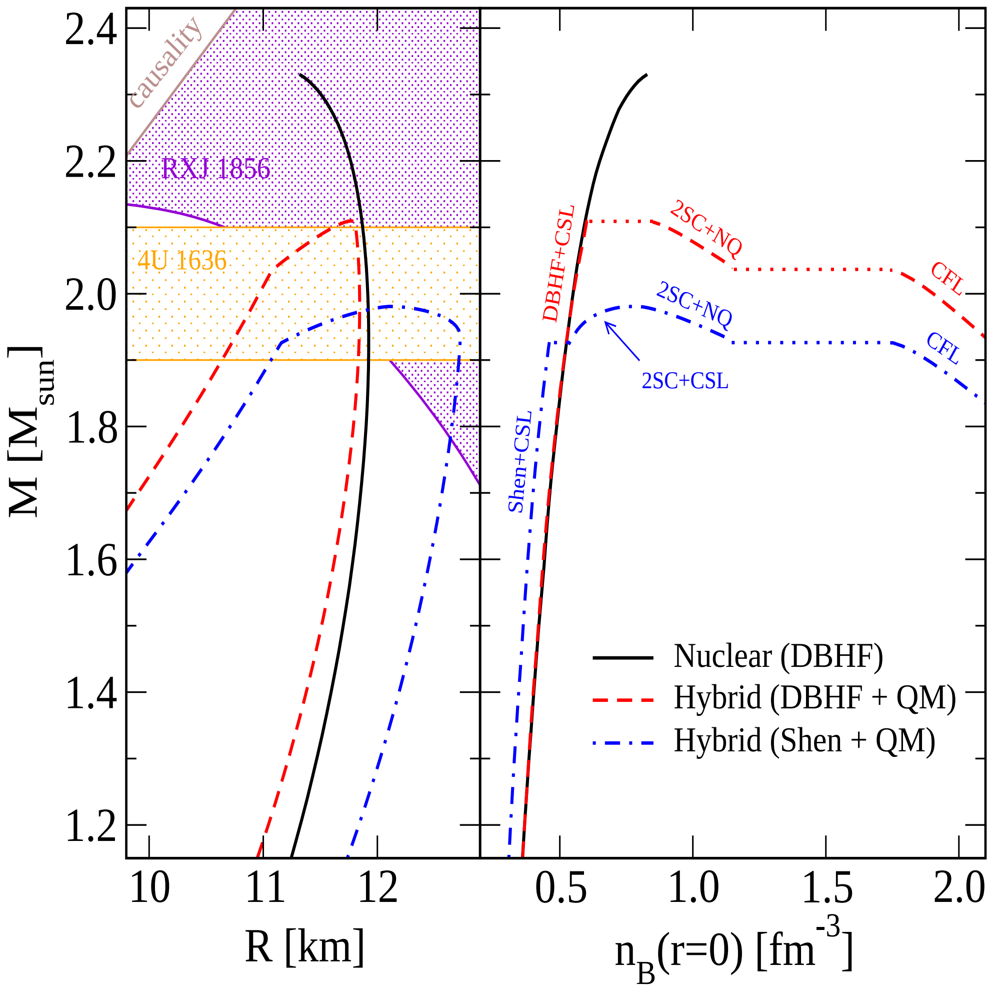
d-CSL: single-flavor phase in neutron stars

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

Equation of state



Configuration Sequences

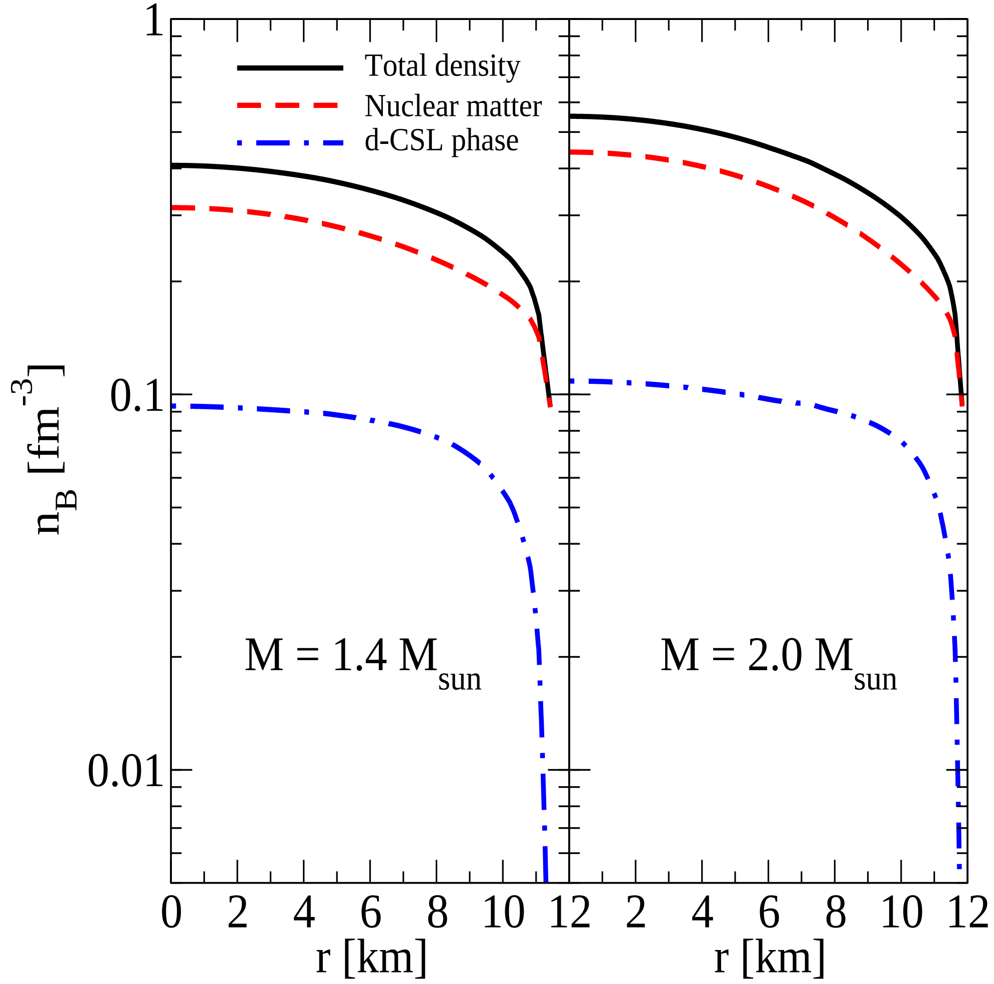


D. B., F. Sandin, T. Klähn, J. Berdermann, arXiv:0807.0414 [nucl-th]; arXiv:0808.1369 [astro-ph]; arXiv:0808.0181 [nucl-th], J. Phys. G, in press (2008).

d-CSL: single-flavor phase in neutron stars (II)

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

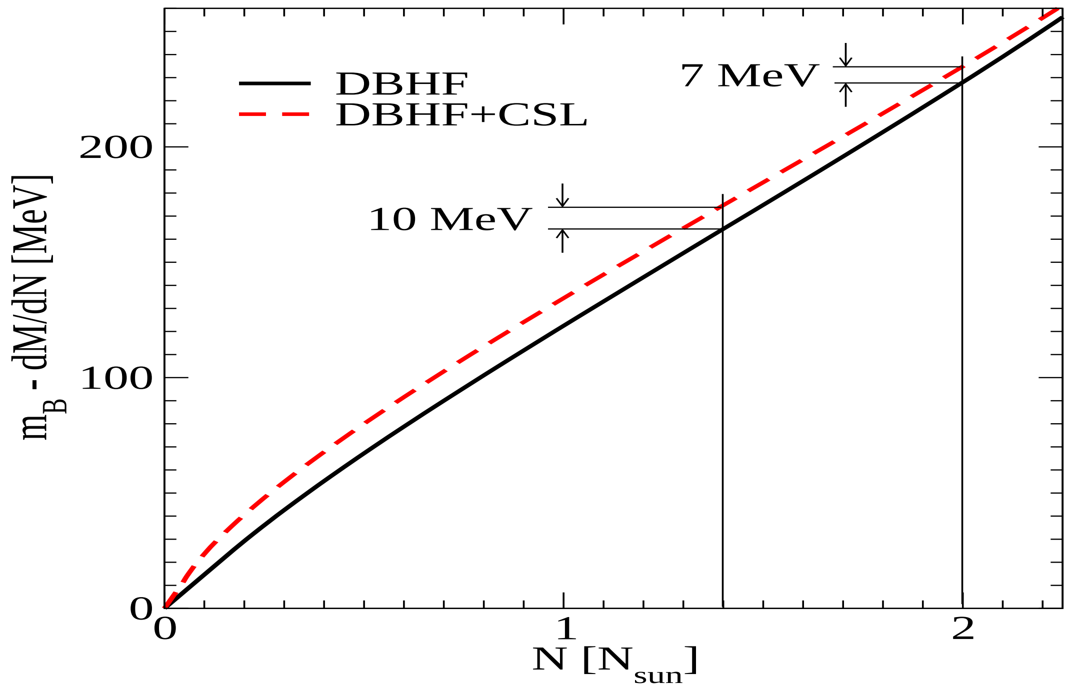
d-quark drip at crust-core boundary: Candidate for "deep crustal heating" (DCH) process?



Haensel and Zdunik,A& A **227**, 431 (1990)
Ushomirsky and Rutledge, MNRAS **325**, 1157 (2001)

Page and Cumming,ApJ **635**, L157 (2005): Superbursts & Strange Stars
Stejner and Madsen,A& A **458**, 523 (2006): SS + Transient Cooling

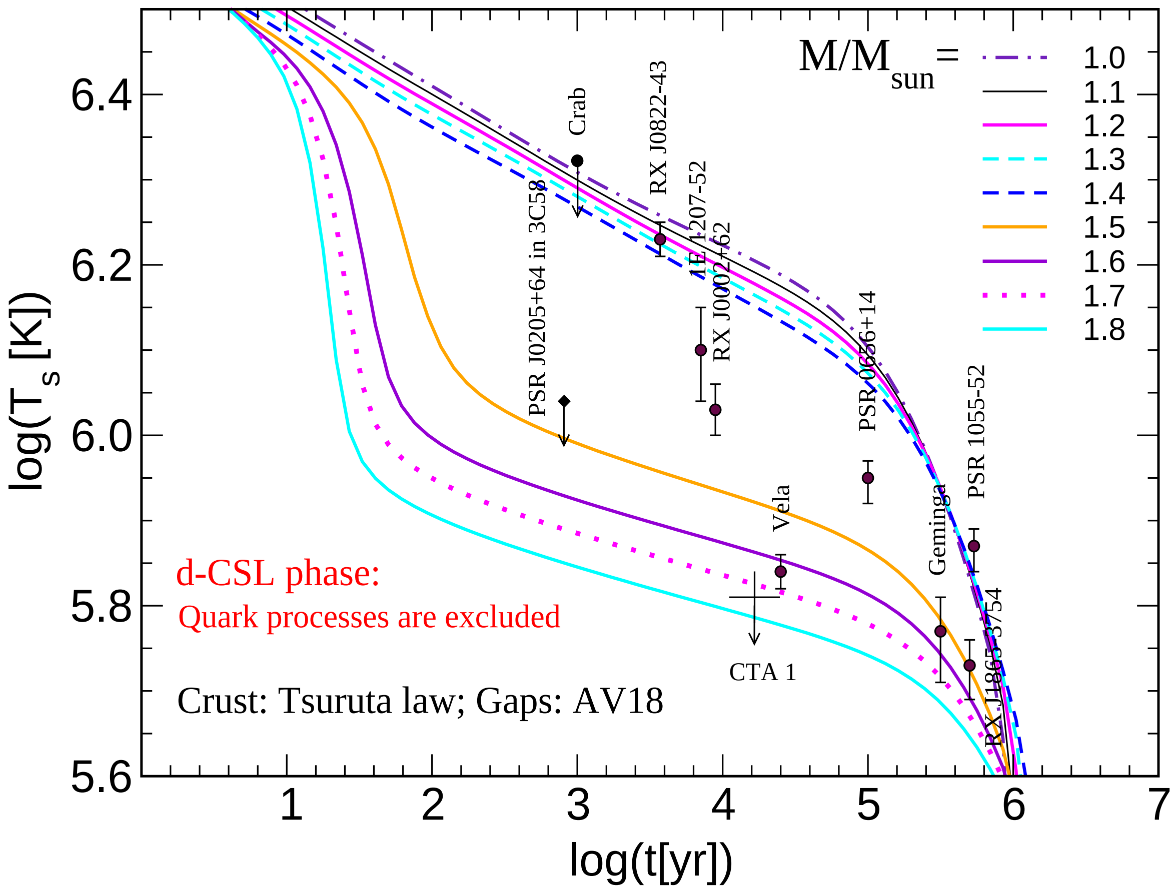
Shternin, Yakovlev, Haensel and Potekhin, MNRAS **382**, L43 (2007): KS1731



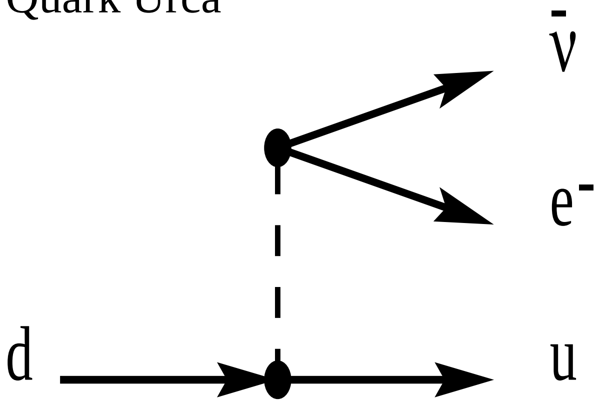
D. B., F. Sandin, T. Klähn, J. Berdermann, arXiv:0807.0414 [nucl-th]

d-CSL: single-flavor phase in neutron stars

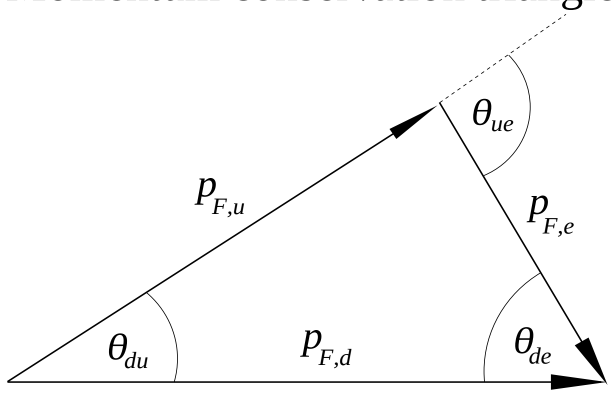
Cooling: processes in single-flavor quark matter are blocked!



Quark Urca



Momentum conservation triangle



not operative since u-quark Fermi sea not populated ($p_{F,u} = 0$)

D. B., F. Sandin, H. Grigorian, in preparation.

Conclusions

Constraints on the high-density EoS

- Compact star masses $\sim 2\ M_\odot$ require stiff EoS
- Flow data provide upper limits on the stiffness

Local charge neutrality: 2SC + DBHF hybrid

- diquark coupling lowers phase transition density
- vector meanfield stiffens quark matter EoS

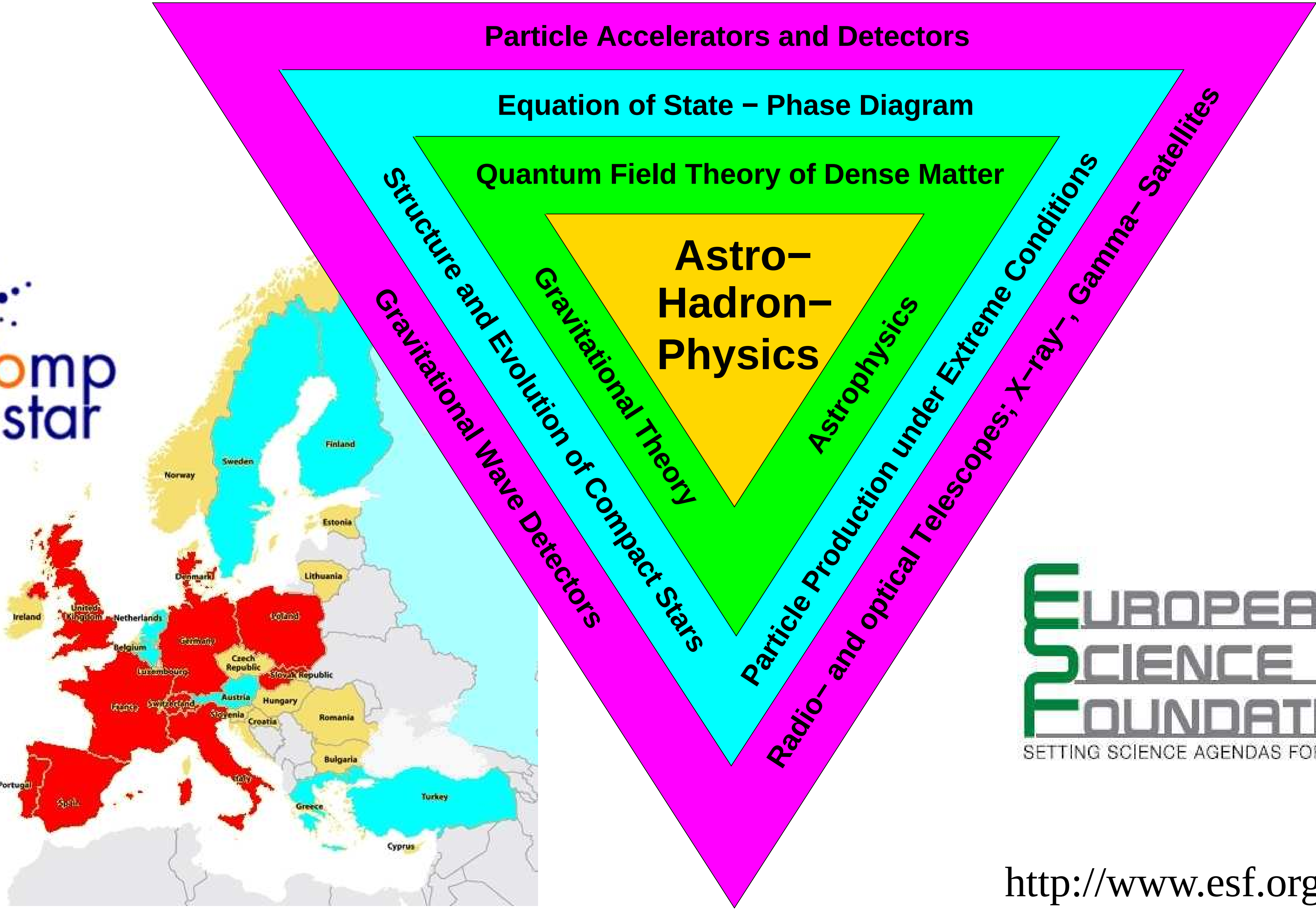
Global charge neutrality: d-CSL + DBHF hybrid

- single flavor phase (d-CSL) as consequence of dynamical χSR
- no d-CSL in symmetric matter: $x_{p,crit} < 0.2$
- no Urca cooling processes $\longrightarrow$ no neutrino trapping?

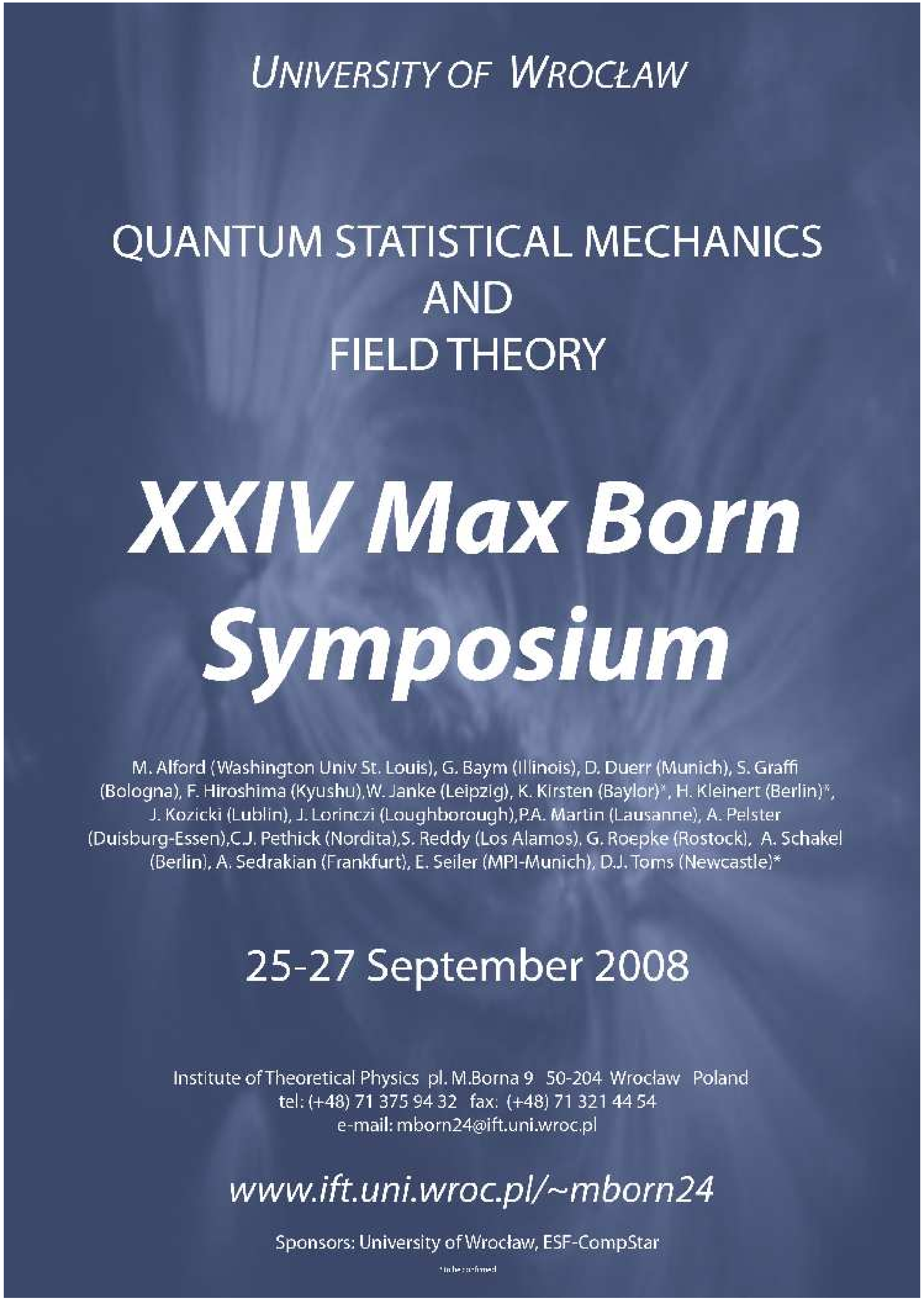
Next steps

- apply to superbursts, X-ray transients, high-mass supernovae
- extend to inhomogeneous phases: surface tension and Coulomb effects

New ways to understand Dense Matter



http://www.esf.org/compstar



Invitations

Helmholtz International Summer Schools
Dubna, Russia, 2007 - 2009 - ??
http://theor.jinr.ru/meetings

XXIV. Max Born Symposium
"Quantum Statistics and Field Theory"
Wroclaw, Poland, September 25-27, 2008
http://www.ift.uni.wroc.pl/∼mborn24

ESF Research Networking Programme
"CompStar" (2008-2013)
http://www.esf.org/compstar

THANKS FOR YOUR ATTENTION!