Neutron star kicks at birth – QCD in strong B-field?

David Blaschke
University of Wroclaw, Poland &
HZDR/CASUS Görlitz, Germany

Astronomers observed a ghostly pulsar, a superdense, rapidly spinning neutron star exploded from a supernova 10,000 years ago, racing through space at nearly 2.5 million miles an hour - so fast it could travel the distance between Earth and the Moon in just 6 minutes. The discovery was made using NASA’s Fermi Gamma-ray Space Telescope and the National Science Foundation’s Karl G. Jansky Very Large Array (VLA).

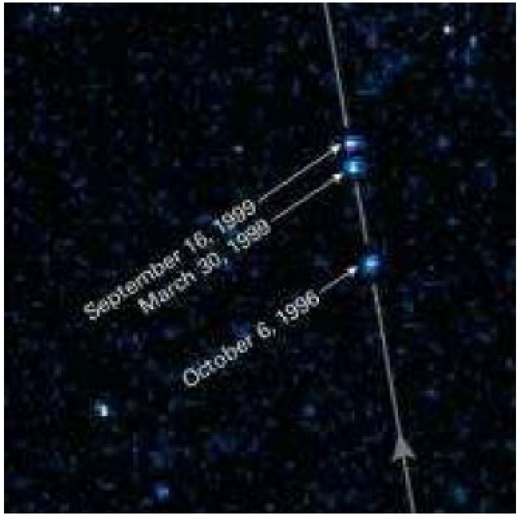
F.K. Schinzel et al., arxiv:1904.07993

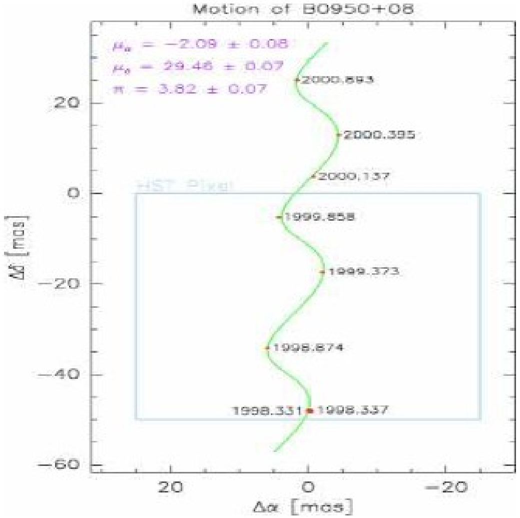
PSR J0002+6216

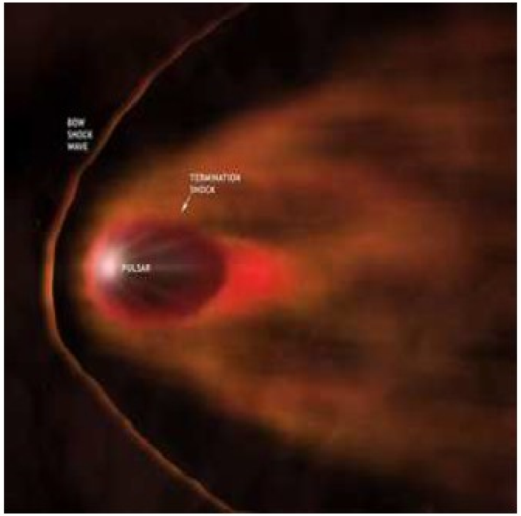
Observations of pulsar kicks

Optical: Hubble Space Telescope

- Lonely neutron star RX J1856.5-3754
- Motion of binary system B 0950+08
- Bow shock

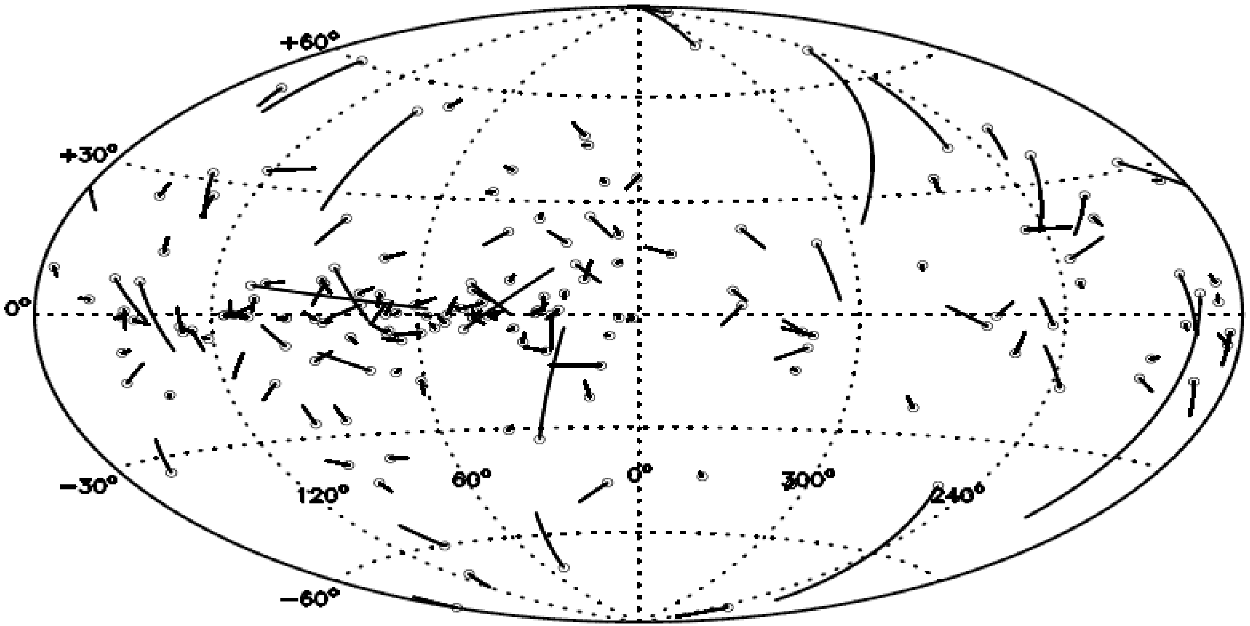






Observations - Map

- small fraction of 10^9 NS/galaxy visible
- proper motion (pulsar timing 58%,interferometer 41%,optical 1%)
- 50% of pulsars in solar neighborhood will escape the galaxy
- 10% of pulsars ¡ 20 kyr outside their host remnants



Observations - N(v)

- velocity distribution
  - bimodal

$$v_d \simeq 100\ \mathrm{km/s}\ \ 20\%$$
$$v_u \simeq 500\ \mathrm{km/s}\ \ 80\%$$

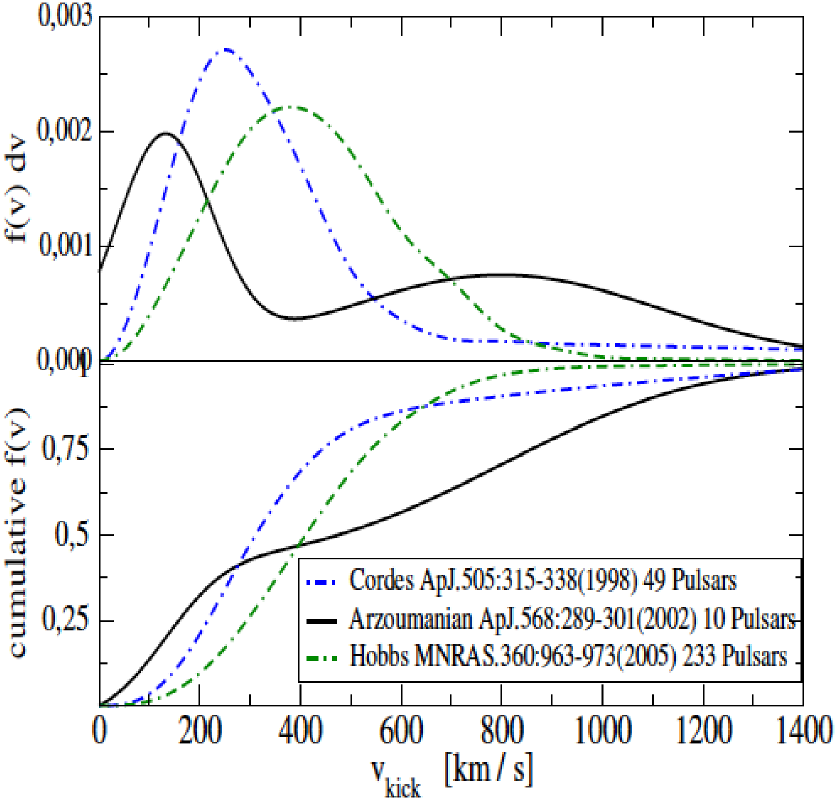
  - gaussian

$$\bar{v} \simeq 400\ \mathrm{km/s}$$

- high velocity tail

$$v \geq 1000\ \mathrm{km/s}\ \ 15\%$$

- B - v correlation
  (Spruit et al astro-ph/9803201)



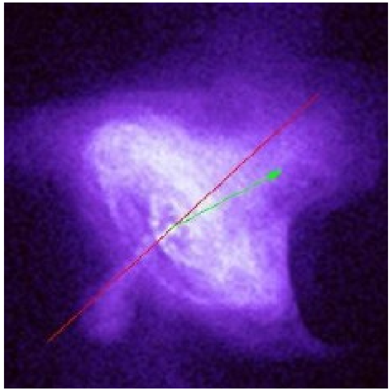
Observation of spin - kick connection

- Suggested by Sprout & Phinney (1998)
- Theory by Lai et al. (2001)
  kicks last few seconds, neutrino-mediated kicks tenable, anisotropy from B-fields (10^{15} G)
- For $\tau_{\text{kick}} \ll P_0$, transverse component rotationally erased

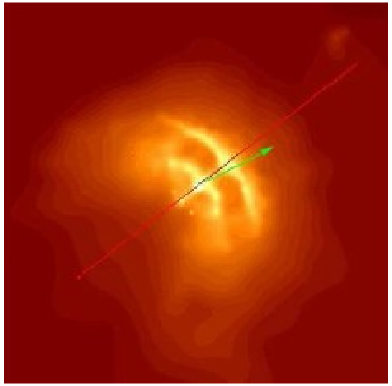
Chandra X-ray PWNe and best-fit torus models for Crab and Vela;

Romani, (2004)

Spin-kick correlation: PSR B 1706-44



Crab nebula
& pulsar

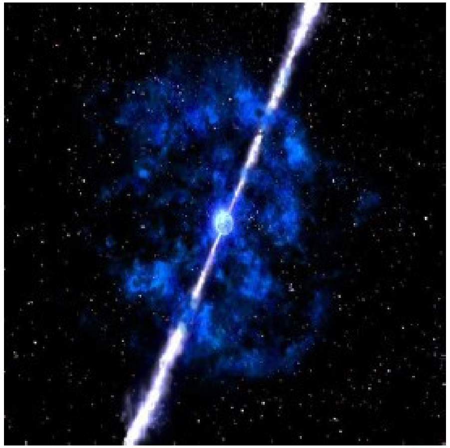


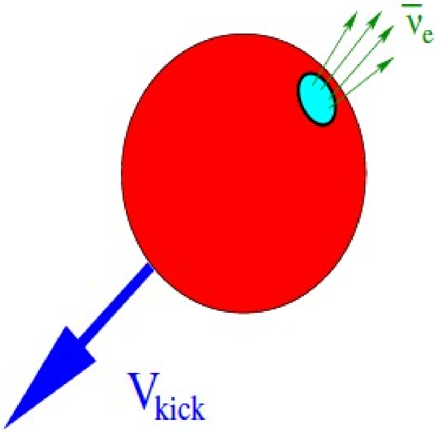
Vela nebula
& pulsar

Spin & kick velocity almost aligned, Examples: Crab and Vela pulsars

Models for pulsar kicks

- small supernova asymmetries
  - from numerical SN calc. $v \leq 200$ km/s
    C. Fryer et al, ApJ 601, L175 (2004)
- break up of binary systems
- neutrino driven mechanisms due to
  - neutrino oscillations & sterile neutrino
    A.Kusenko, G. Segre, PLB 396, 197 (1997)
  - emission of Majorons
    Y. Farzan et al, hep-ph/0502150
  - parity symmetry violation
    C. Horowitz, J. Piekarewicz, NPA 640, 281 (1998)
    D. Lai et al., ApJ 549, 1111 (2001)
  - beamed GRBs from PNS
    J. Berderman, D.B., D. Voskresensky (2005)
- “no go theorem” A. Vilenkin, ApJ 451, 700 (1995)





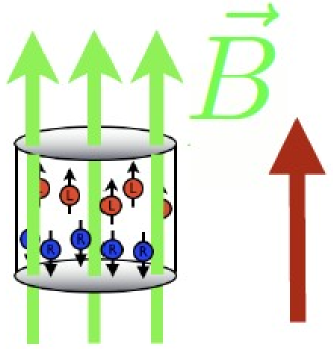
Models - Summary

Mechanism	Time scale	$V_{\max}$, km s^{-1}	Alignment (spin and V)	Main recent refs.
Hydrodynamical	0.1 s	$\sim (100 - 200)$	random	Lai et al. (2001)
ν-driven	$\sim$ few s	$\sim 50\ B_{15}$	parallel	Lai et al. (2001)
Electromagnetic rocket	long	$1400\ R_{10}^2\ P_{\rm ms}^{-2}$	parallel	Lai et al. (2001), Huang et al. (2003)
Binary disruption (without add. kick)	$<< P_{\rm orb}$	~ 1000	perpendicular	Iben & Tutukov (1996)
NS instability	few ms	~ 1000	perpendicular	Colpi & Wassermann (2003), Imshennik & Ryazhskaya (2004)
Magnetorotational	0.2 s – minutes	~ 300 (up to 1000)	quasirandom	Moiseenko et al: (2003), Ardeljan et al. (2004)

From: Bombaci and Popov, A& A (2004), astro-ph/0405250

Chiral hydrodynamics kicks neutron stars (Matthias Kaminski, slide 23)

[Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; Phys.Lett.B (2016)]

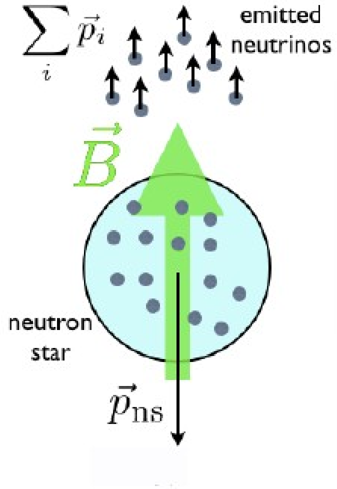


$$J^\mu = \xi_B B^\mu$$

hydrodynamics: fluids with left-handed and right-handed particles produce a **current** along magnetic field

e.g. right/left-handed electrons, neutrinos, ...

Idea:



Chiral hydrodynamics leads to neutron star kicks

Engine for pulsar propulsion? Neutrinos!

- momentum of kicked pulsar

$$p_{\mathrm{kick}} = 8.4 \times 10^{51} (M/1.4M_\odot)(v_{\mathrm{kick}}/1000\mathrm{km\ s}^{1})\mathrm{erg}/c$$

- neutrino gas

$$E_\nu \ \simeq\ 8.3 \times 10^{-17}\, T_9^4\, N_q\, n^{-1}\ \mathrm{erg} = 1.2 \times 10^{52}\ \mathrm{erg}$$

- quark matter

$$E_q \ \simeq\ 4.8 \times 10^{-15}\, g\, \mu_q^2\, T_9^2\, N_q\, n^{-1}\ \mathrm{erg} = 3.2 \times 10^{54}\ \mathrm{erg}$$

- Goldstone bosons (CFL-phase)

$$E_G \simeq 7.2 \times 10^{-17}\, N_G\, T_9^4\, N_q\, n^{-1}\ \mathrm{erg} = 1.0 \times 10^{52}\ \mathrm{erg}$$

- specific heat (quark matter)

$$C_V^q = 9.7 \times 10^{-24}\, g\, \mu_q^2\, T_9\, N_q\, n^{-1}\, \zeta_{\mathrm{Cv}}\ \mathrm{erg\ K}^{-1}$$

- suppression factor (Δ - diquark gap in CFL phase)

$$\zeta_{\mathrm{Cv}} = 3.1\ (T_c/T)^{5/2}\ \exp(-\Delta/T)$$

T=40 MeV

$T_9 = (T/10^9\ \mathrm{K}),\ T_9 = 11.6\ T_{\mathrm{MeV}},\ n = (n_B/n_0),\ n_0 = 0.16\ \mathrm{fm}^{-3},\ \mu_q = 330\ \mathrm{MeV},\ N_q = 5 \times 10^{57},\ g = 9$

Quark matter, color superconducting

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

Inverse propagator of Nambu-Gorkov spinors

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

with diquark gaps ($\Delta_{ur} = \Delta_{ds}, \ldots$)

$$
\Delta_{k\gamma} = 2G_D\langle \bar{q}_{i\alpha} i\gamma_5 \epsilon_{\alpha\beta\gamma}\epsilon_{ijk} q^C_{j\beta}\rangle .
$$

as elements of the gap matrix

$$
\widehat{\Delta} \;=\; i\gamma_5\epsilon_{\alpha\beta\gamma}\epsilon_{ijk}\Delta_{k\gamma} .
$$

Fermion determinant (Tr ln D = ln det D)

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

Result for thermodynamic potential

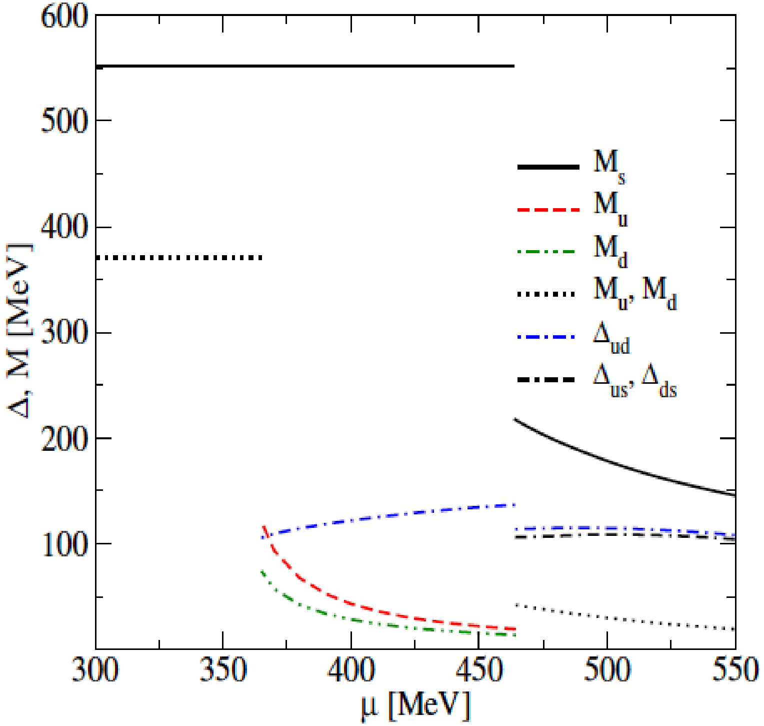
$$
\begin{aligned}
\Omega(T,\mu) \;=\; & \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S}+\frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D} \\
- \; & \int \frac{d^3p}{(2\pi)^3}\sum_{a=1}^{18}\left(\lambda_a + 2T\ln\left(1+e^{-\lambda_a/T}\right)\right) \\
+ \; & \Omega_e - \Omega_0 .
\end{aligned}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

Neutrality conditions: $n_Q = n_8 = n_3 = 0$,

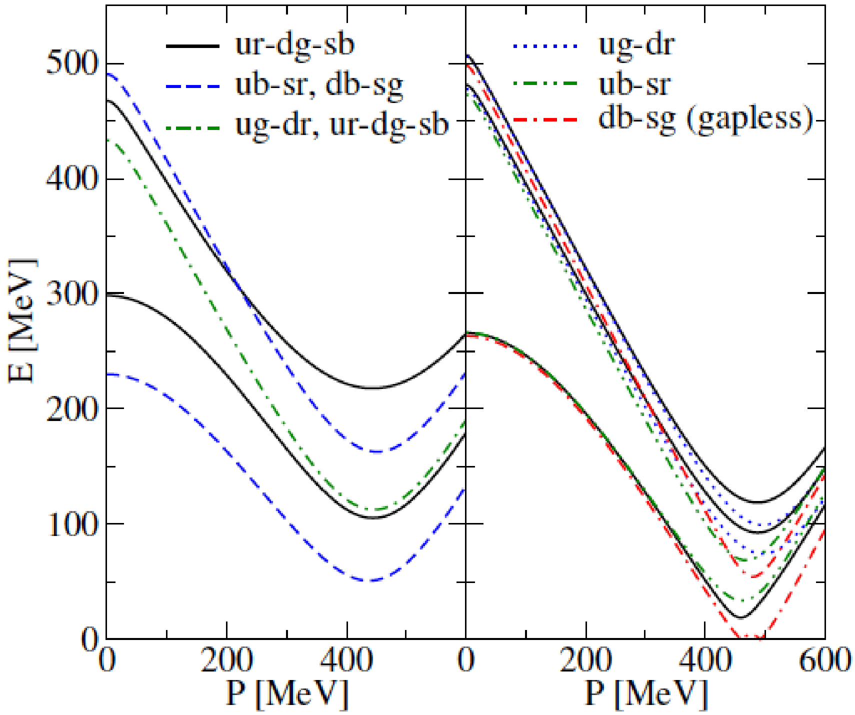
$$
n_i \;=\; -\frac{\partial\Omega}{\partial\mu_i} = 0,
$$

Equation of state: $P = -\Omega$, etc.

Quark Masses, Diquark Gaps, Gapless Modes

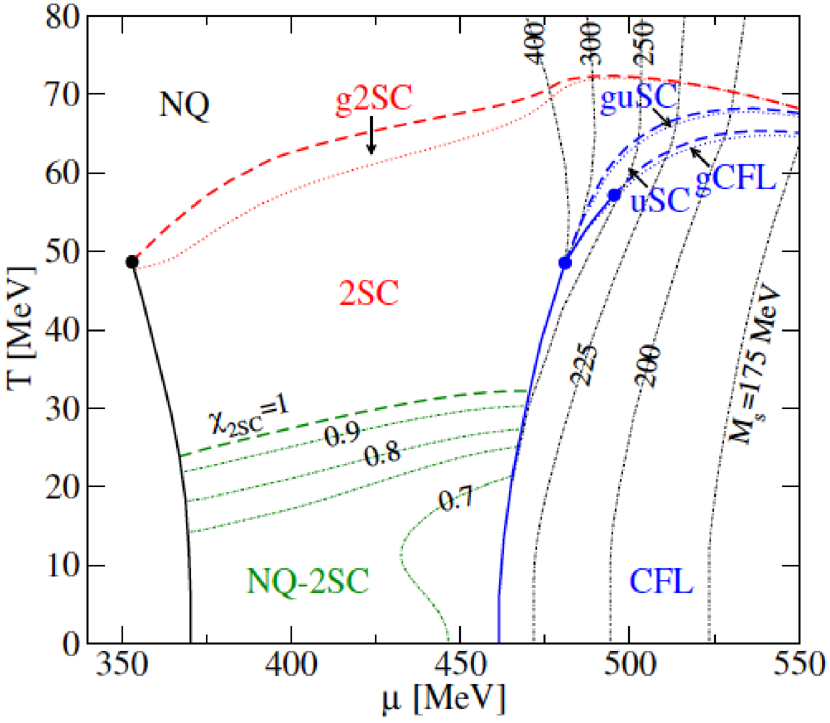


Dynamical quark masses and diquark gaps at $T = 0$ for intermediate diquark coupling $G_D = 0.75\ G_S$



Dispersion relations for $G_D = 0.75\ G_S$, $T = 0$, $\mu = 465$ MeV (left), $G_D = 1.0\ G_S$, $T = 59$ MeV, $\mu = 500$ MeV (right)

Three-flavor Quark Matter Phase Diagram



Rüster et al: hep-ph/0503184
Blaschke et al: hep-ph/0503194

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.

Superconductivity and magnetic vortices

- coherence length ξ, penetration depth λ for CFL matter
  K.Iida and G.Baym Phys.Rev. **D66**:014015 (2002)

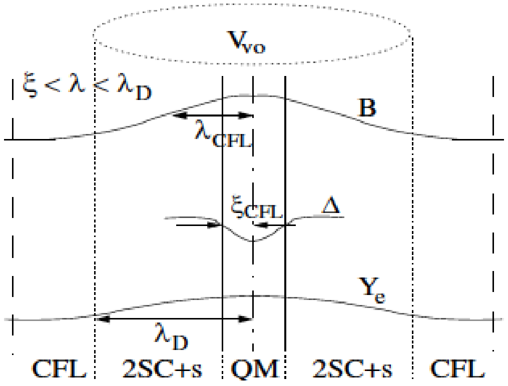
$$\begin{aligned}\xi_{\mathrm{CFL}} &\simeq 0.26\left(\frac{100\ \mathrm{MeV}}{T_c}\right)\left(1-\frac{T}{T_c}\right)^{-1/2}\ \mathrm{fm}\\ \lambda_{\mathrm{CFL}} &\simeq 2.1\left(\frac{3\sqrt{2}}{\sqrt{3g^2}}\right)\left(\frac{300\ \mathrm{MeV}}{\mu_q}\right)\left(1-\frac{T}{T_c}\right)^{-1/2}\ \mathrm{fm}\end{aligned}$$

- critical Ginzburg-Landau parameter $\kappa_{GL}^c = (\lambda/\xi) \simeq (1/\sqrt{2}) \Rightarrow T_c^{I-II} \sim 20$ MeV
- QM: $T_c \simeq 0.57\,\Delta$ with $\Delta_{\mathrm{CFL}} >\ 40$ MeV $\Rightarrow T_c \geq T_c^{I-II}$ and hence $\kappa_{GL} > \kappa_{GL}^c \Rightarrow$ Type II
- (HM: $\Delta \leq 1.3 \pm 0.3$ MeV and $T_c \leq 0.7$ MeV $\Rightarrow$ Type I)

- surface $B_s \sim 10^{12} - 10^{15}$ G
- inner surface $B_{in,s} \sim 10^{15} - 10^{17}$ G

$$B_{in,s} = B_s(n_{in}/n_s)^{2/3}$$

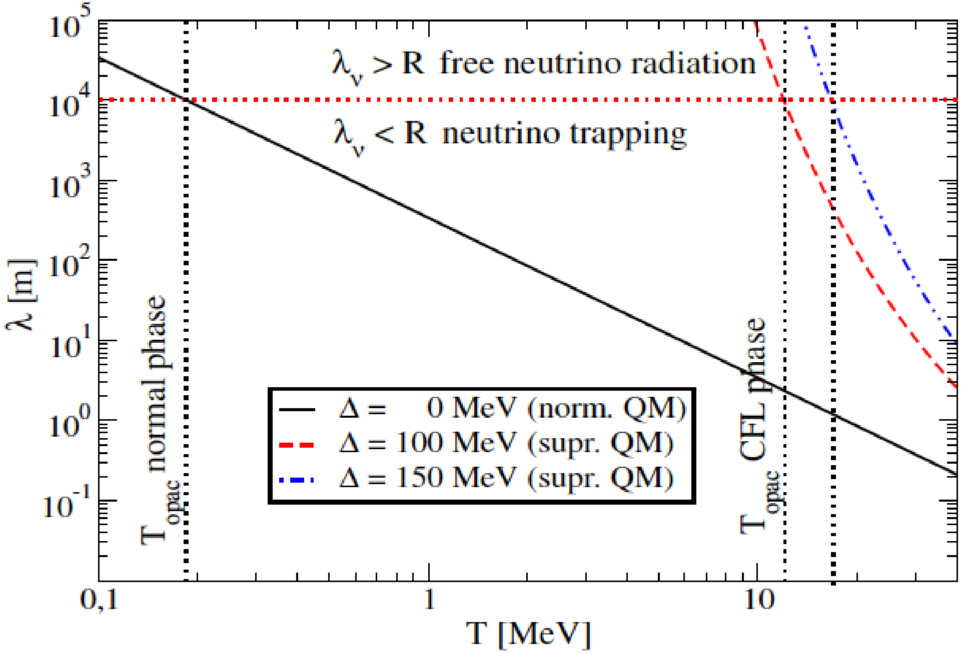
- creation of vortices
  D.Blaschke et al A& A**350**:L47 (1999)
  D.M.Sedrakian et al Astrofiz.**44**:443-454 (2001)
- inside vortices $B_{vo}^{qm} \sim 10^{17} - 10^{18}$ G



Neutrino transport in warm, dense quark matter

Neutrino mean free path[a]

$$\lambda_\nu = 6.3 \times 10^3 \, \alpha_c^{-1} \, n^{-1} \, Y_e^{-1/3} \, T_9^{-2} \text{ m}$$



---

[a] N.Iwamoto Ann.Phys. **141**:1-49 (1982)

Magnetic vortex structure

- vortex number

$$N_{vo}\Phi_q = \pi B_{in} R^2$$

$$\Phi_q \simeq 6\Phi_0,\ \Phi_0 = 2 \times 10^{-7}\text{G cm}^2$$

- vortex distance

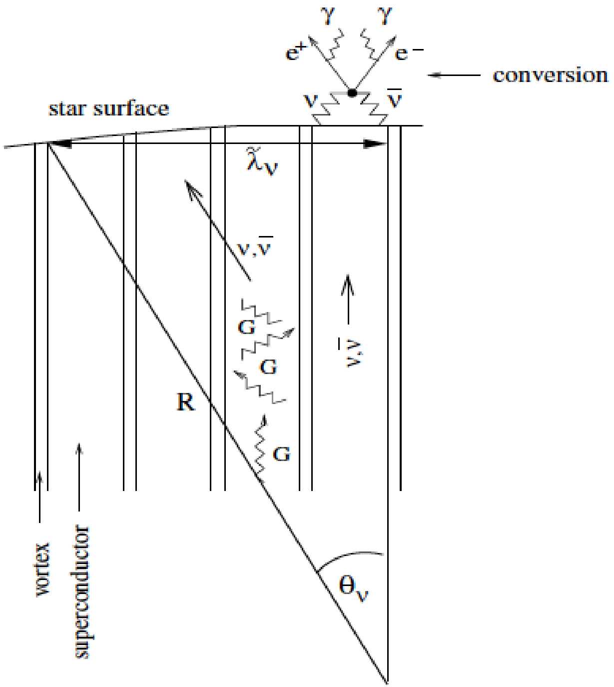
$$d \sim \left(\frac{\Phi_q}{B_{in}}\right)^{1/2}$$

- vortex volume

$$V_{vo} \sim 2\pi R(\nu \cdot \lambda_{CFL})^2 \simeq 10^{20}\ \text{fm}^3$$

- total vortex volume

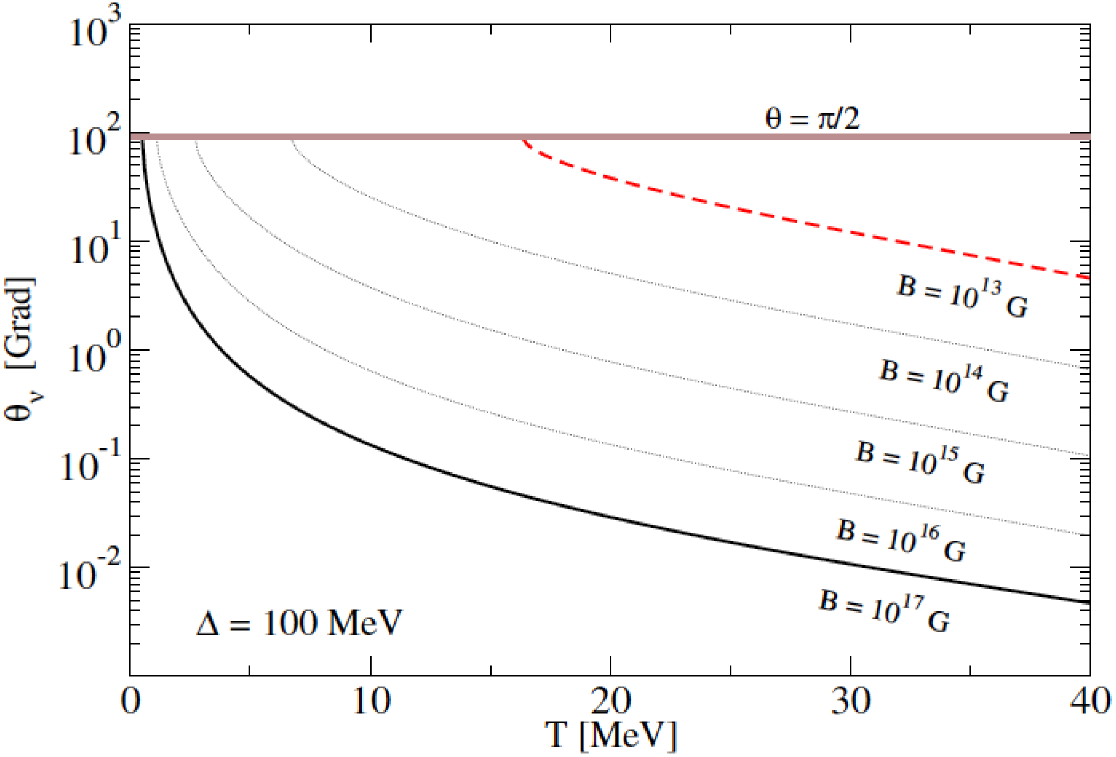
$$N_{vo}V_{vo} \simeq 10^{51-55}\ \text{fm}^3$$



$\mathbf{B_{in}}$ [G]	N_{Vo}	d [fm]	$N_{vo}V_{vo}/V$
$\mathbf{1.0 \times 10^{13}}$	2.6×10^{31}	3464.1	4.0×10^{-7}
$\mathbf{1.0 \times 10^{14}}$	2.6×10^{32}	1095.4	4.0×10^{-6}
$\mathbf{1.0 \times 10^{15}}$	2.6×10^{33}	346.4	4.0×10^{-5}
$\mathbf{1.0 \times 10^{16}}$	2.6×10^{34}	109.5	4.0×10^{-4}
$\mathbf{1.0 \times 10^{17}}$	2.6×10^{35}	34.6	4.0×10^{-3}

Beaming angle evolution

$$\theta_\nu \simeq \arcsin[\tilde{\lambda}_\nu / R], \quad \tilde{\lambda}_\nu = \lambda_\nu (V / N_{vo} V_{vo})$$



Anisotropic neutrino cooling

- cooling equation

$$\Delta t = -\int_{T_i}^{T_f} \frac{C_v(T)\,\mathrm{d}T}{L(T)}$$

- emissivity u,d,s quark matter[a]

$$\epsilon_\nu^{QDU} \simeq 1.6 \times 10^{24}\, \mu_s\, p_{F,u}\, p_{F,e}\, T_9^6 \;\mathrm{erg\ m^{-3}\ s^{-1}}$$

- total star luminosity

$$L_0 = \left(\frac{N_{vo}V_{vo}}{V}\right) \int \mathrm{d}V \epsilon_\nu^{QDU} + \left(1 - \left(\frac{N_{vo}V_{vo}}{V}\right)\right) \int \mathrm{d}V \epsilon_\nu^{QDU} \mathrm{e}^{(-\frac{\Delta}{T})}$$

- neutrinos conversion $\bar{\nu} + \nu \leftrightarrow e^+e^-$ rate[b]

$$\dot{E}_{e^+e^-} \sim 5 \times 10^{32}\, T_{s,9}^9\, R_{10}\, t \;\mathrm{erg\ s^{-1}}$$

- $e^- + e^+ \leftrightarrow \gamma$ $(\sim 100\%)$ enforced due to beaming

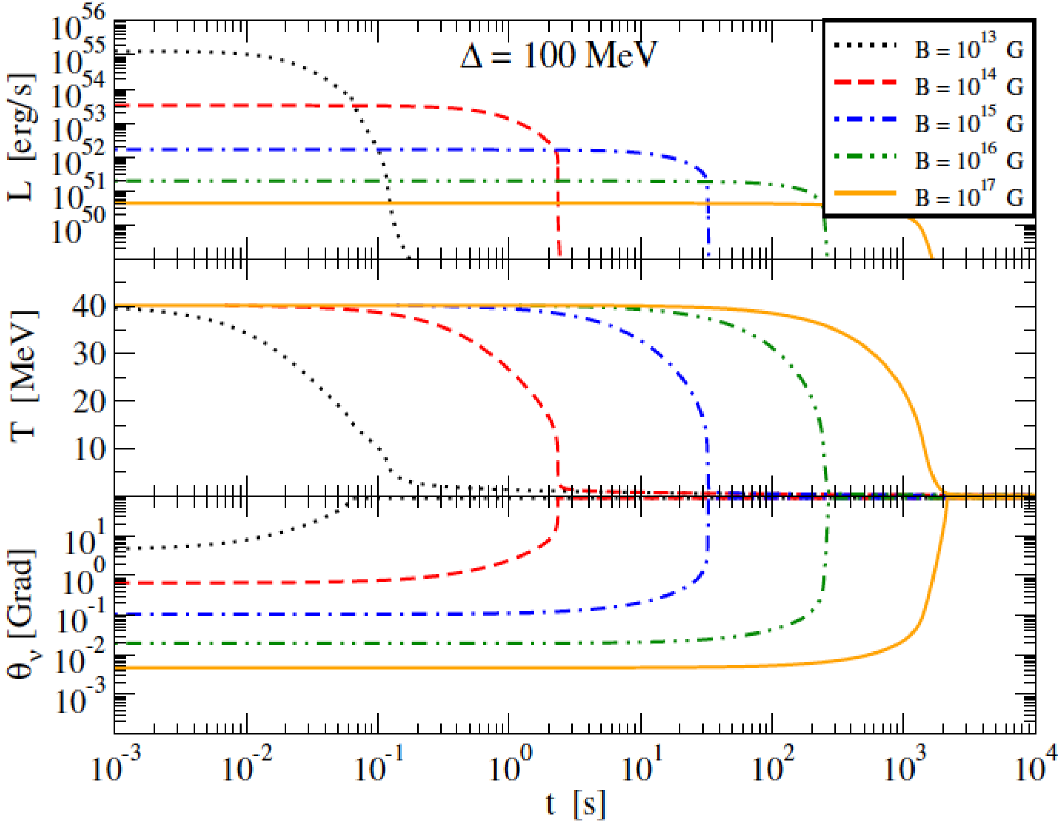
---

[a] N.Iwamoto Ann.Phys. **141**:1-49 (1982)

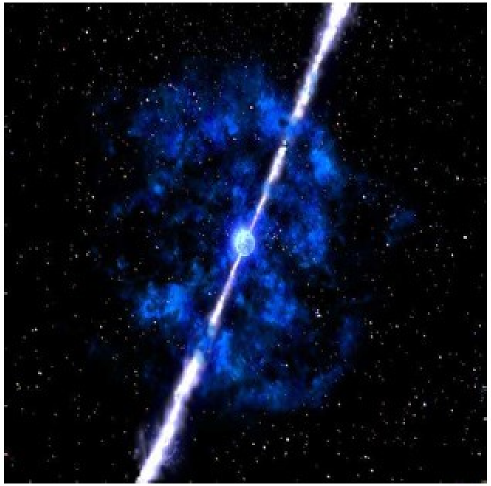
[b] P.Haensel et al ApJ**375**:209 (1991)

Evolution of temperature and luminosity

$$L(T,\theta_\nu) = (1-\cos\theta_\nu)L_0(T)$$



Pulsar kick model



- general equation

$$v_{Kick} = F_{as}\, a\, \Delta t = F_{as}\, \frac{F}{M}\, \Delta t = F_{as} \frac{p\, A}{M} \Delta t$$

- neutrino asymmetry factor

  Horowitz et al. Nucl. Phys. **A640**:281 (1998)

$$F_{as} = \frac{eB}{E_\nu^2} \approx 0.6 \times 10^{-2} B_{14}$$

- pressure of neutrinos (id. Fermi gas)

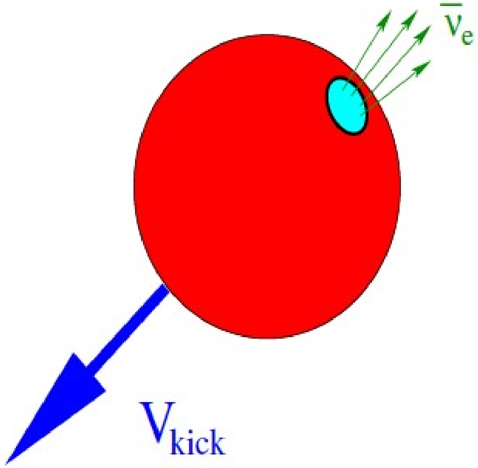
$$p \;=\; g \frac{4\pi}{(2\pi\hbar)^3} \frac{1}{3} \int_0^\infty p^3 dp \frac{dE(p)}{dp} n(p, T, \mu)$$

- escape surface

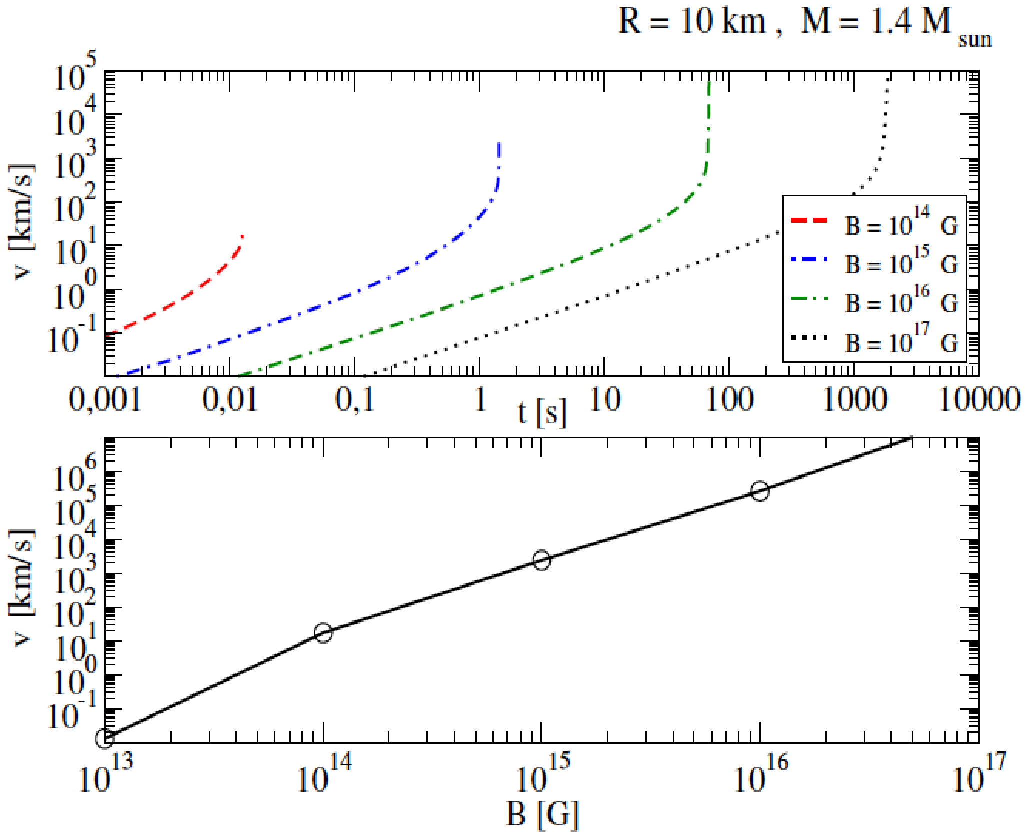
$$A = 2\pi R^2 (1 - \cos\theta_\nu)$$

---

star mass M and radius R (TOV equation)



Result: B-field dependence of v_{kick}



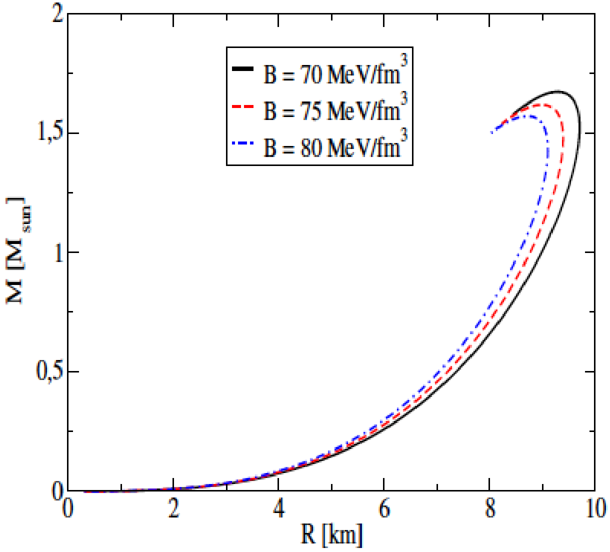
Bimodal neutron star mass distribution

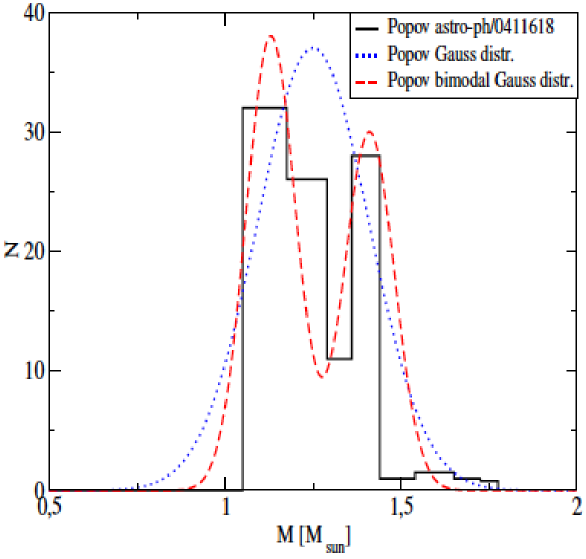
1. Stability

$$\frac{dP(r)}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2}\left(1+\frac{P(r)}{\varepsilon(r)}\right)\left(1+\frac{4\pi r^3 P(r)}{m(r)}\right)\left(1-\frac{2Gm(r)}{r}\right)^{-1}$$

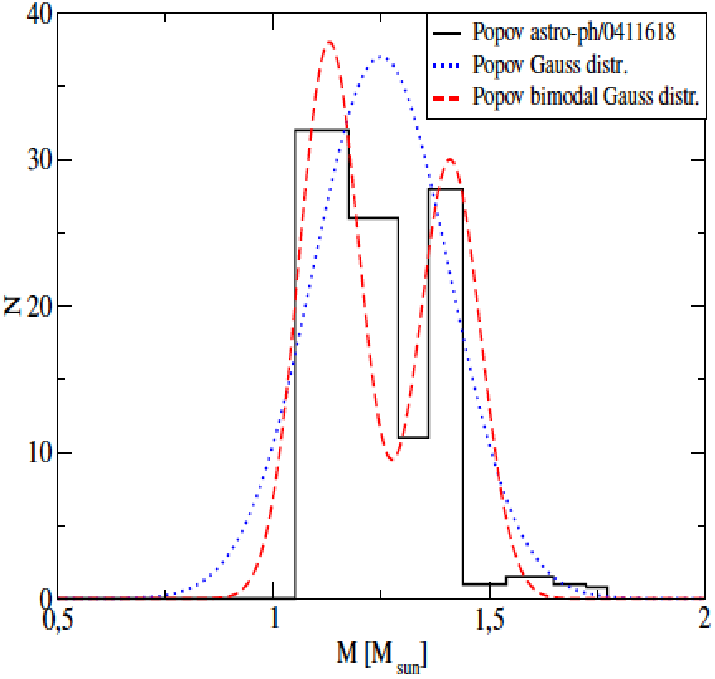
2. Mass distribution

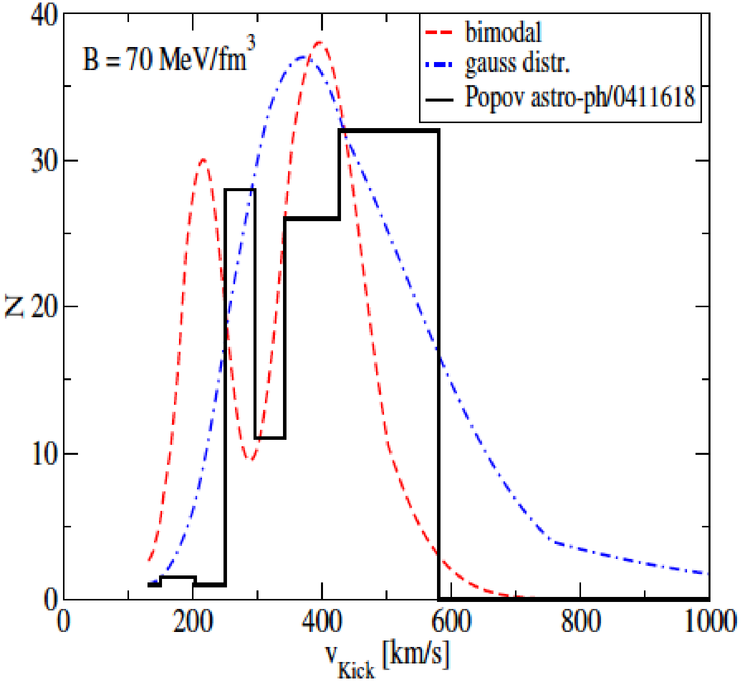
$$m(R) = \int_0^R \varepsilon(r)\, 4\pi\, r^2\, dr$$





Result: Bimodal N(v) from bimodal N(M)





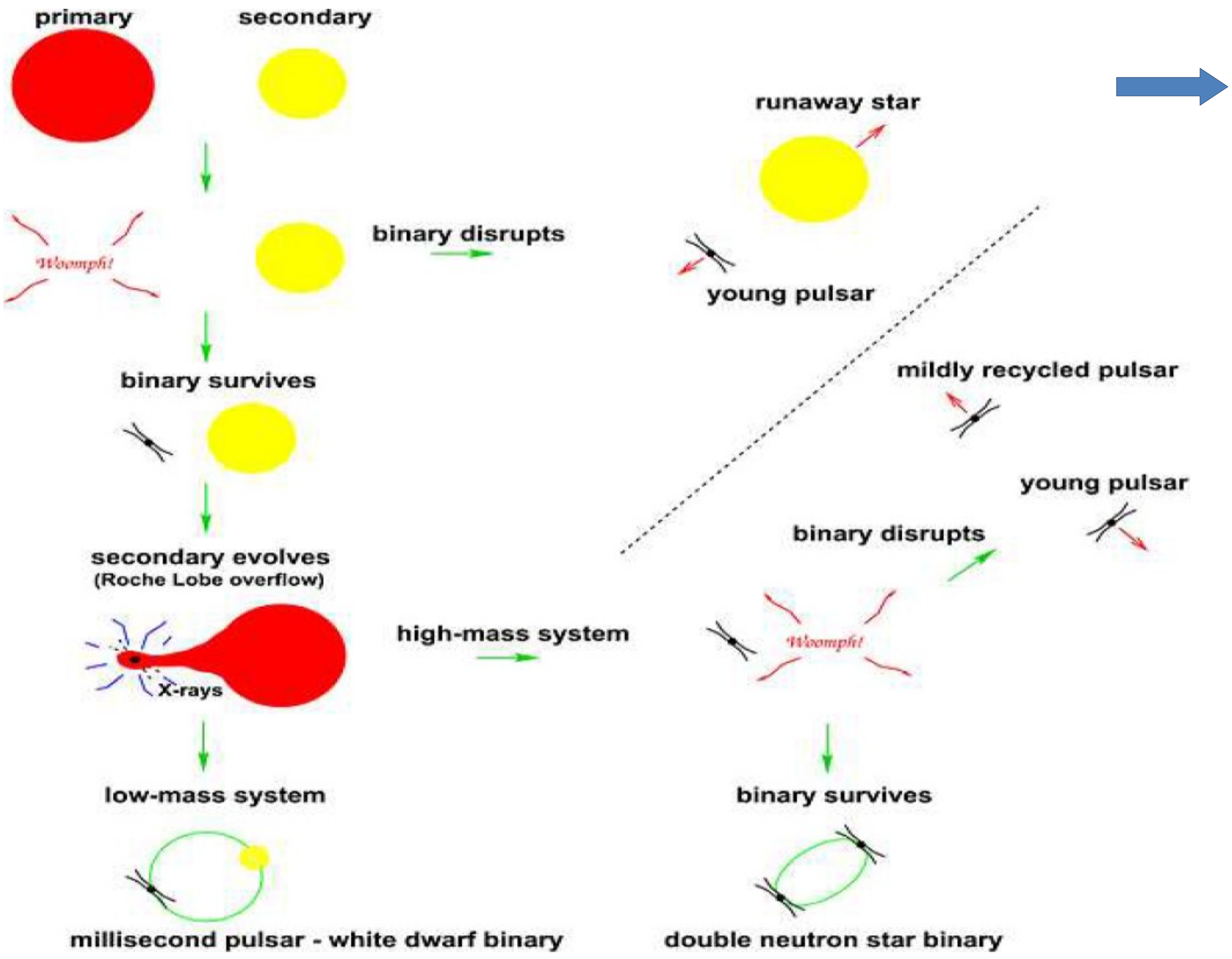
Summary

- Great variety of pulsar kick models
- Bimodality of kick distribution ↔ mass distribution
- Neutrino driven kicks - only PNS/ need asymmetry
- B - v correlation in our model, observational hints?
- Reproduce recent velocity distribution

Outlook

- Discussion of neutrino oscillations in hot, dense matter
- Comparison with observations (e.g magnetic field/pulsar number/mass and velocity distributions)
- Inversion: determine mass distribution from recent pulsar kick statistics by use of an EOS ⇒ EOS-Test
- Relation to Gamma-ray bursts

Another kick explanation: Strong QCD phase transition in NS evolution!

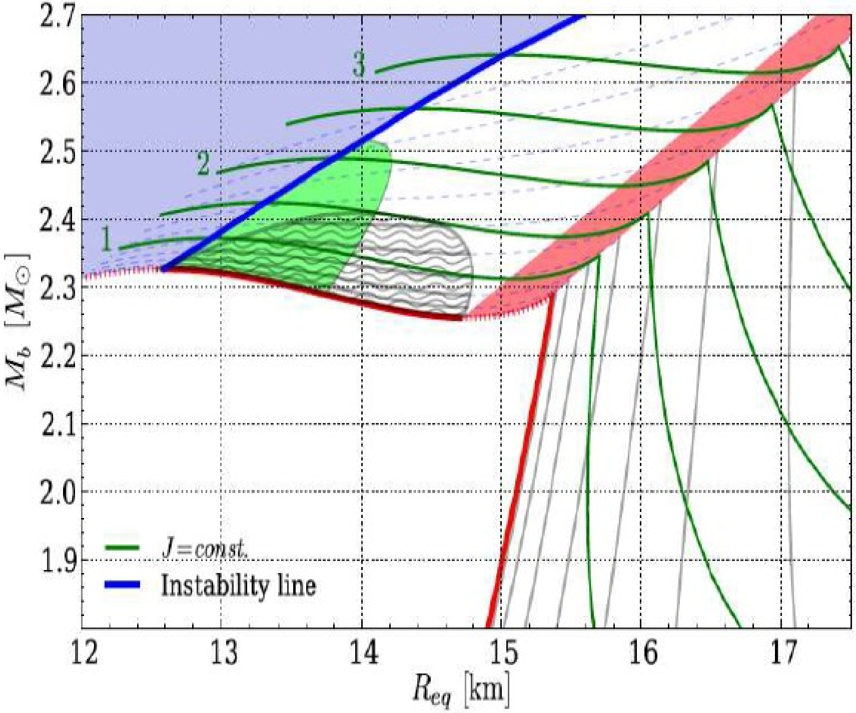


→ Disruption or anomalous eccentricity of a binary system due to mass defect (grav. binding) in NS catastrophic rearrangement ...

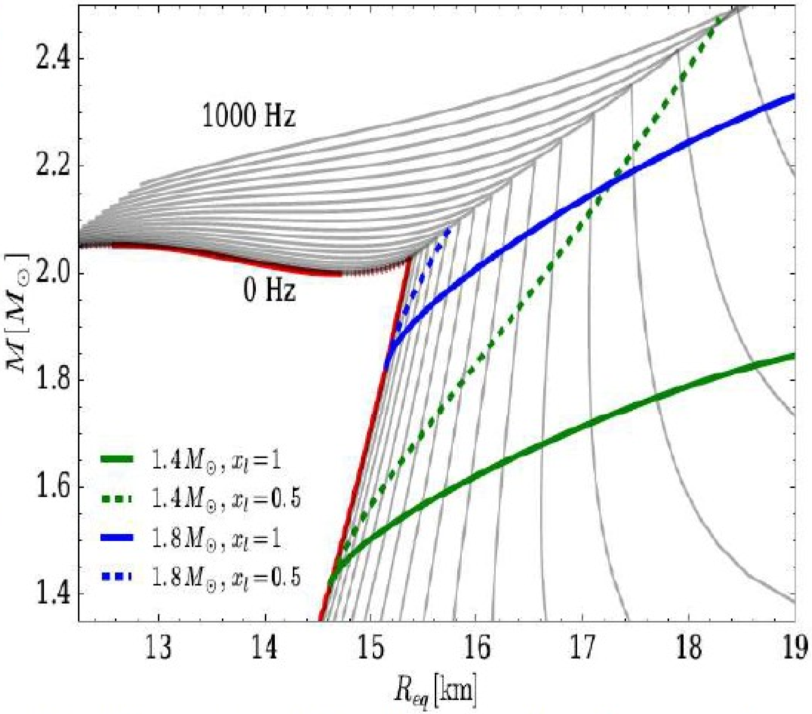
Let us discover the 3rd family of compact stars!

Observation:

With a strong PT (mass twins), a sudden transition NS → HS is possible, Triggered by accretion, under simultaneous conservation of Mb and J



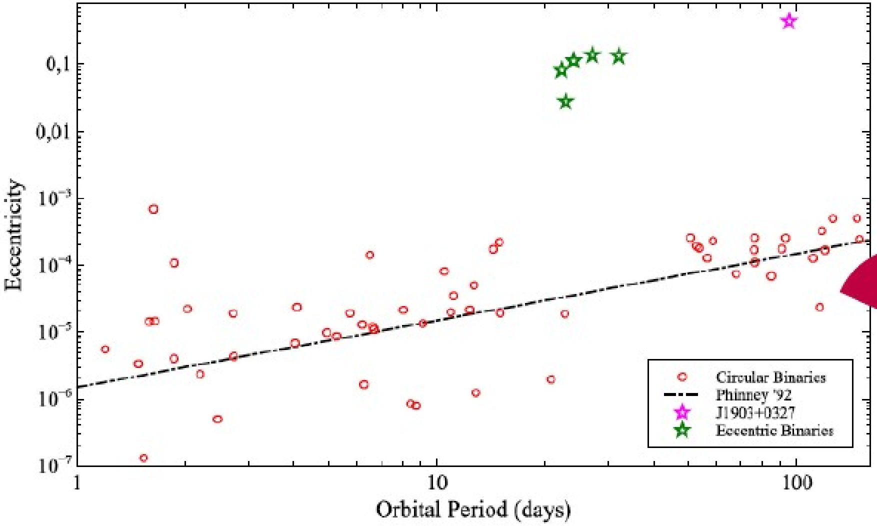
M. Bejger, D.B., et al., A&A 600 (2017) A39



Evolutionary tracks for disc accretion of mass with efficiency xl=1(0.5) of angular momentum transfer

Let us discover the 3rd family of compact stars!

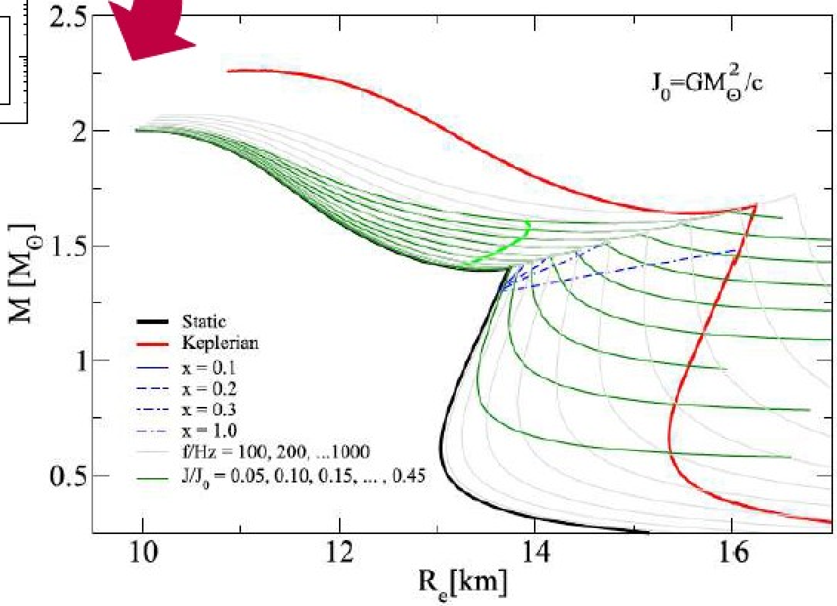
Antoniadis-puzzle



J. Antoniadis, ApJ Lett. 797, L24 (2014)

K. Stovall, P.C.C. Freire, J. Antoniadis,
ApJ 870(2), 74 (2019)

How to relate this ?

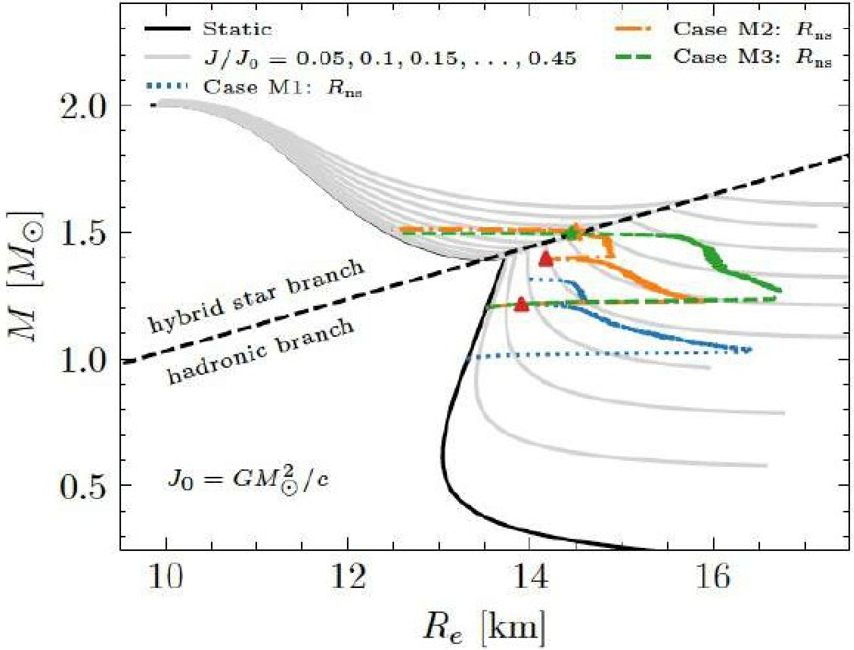


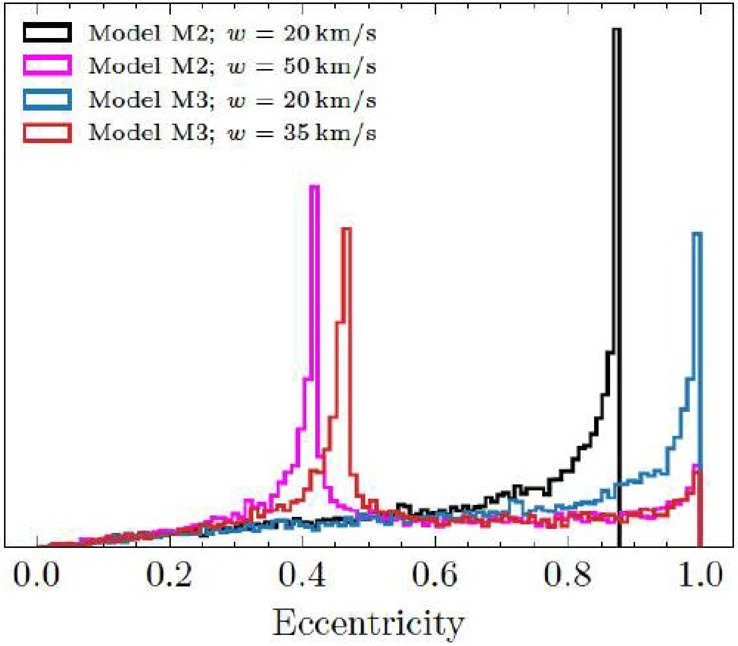
D.E. Alvarez.Castillo, J. Antoniadis, A. Ayriyan,
D. Blaschke, V. Danchev, H. Grigorian, N. Khosravi
Largani, F. Weber,
Accretion-induced collapse to third family compact stars as trigger for eccentric orbits of Millisecond pulsars in binaries,
Astron. Nachr. 340 (2019) 878;
arXiv:1912.08782 [astro-ph.HE]

Let us discover the 3rd family of compact stars!

Work in preparation ...

S. Chanlaridis, D. Ohse, A. Aspradakis, J. Antoniadis, D. Blaschke, D.E. Alvarez-Castillo,
V. Danchev and N. Langer





Prescription for transition-triggered kicks adapted from supernova case following:
J.G. Hills, ApJ 267, 322 (1983) and T.M. Tauris et al., ApJ 846, 170 (2017)