DARK MATTER SEEDING IN NEUTRON STARS

M Ángeles Pérez-García

Fundamental Physics Department & IUFFyM,
University of Salamanca
Salamanca, Spain

mperezga@usal.es

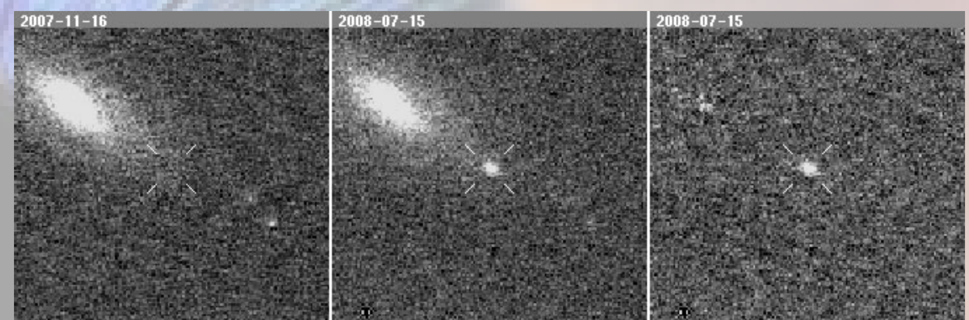
NSs from SN event

- NS appears in the aftermath of a SN explosion event

- Remains: Nebula+pulsar

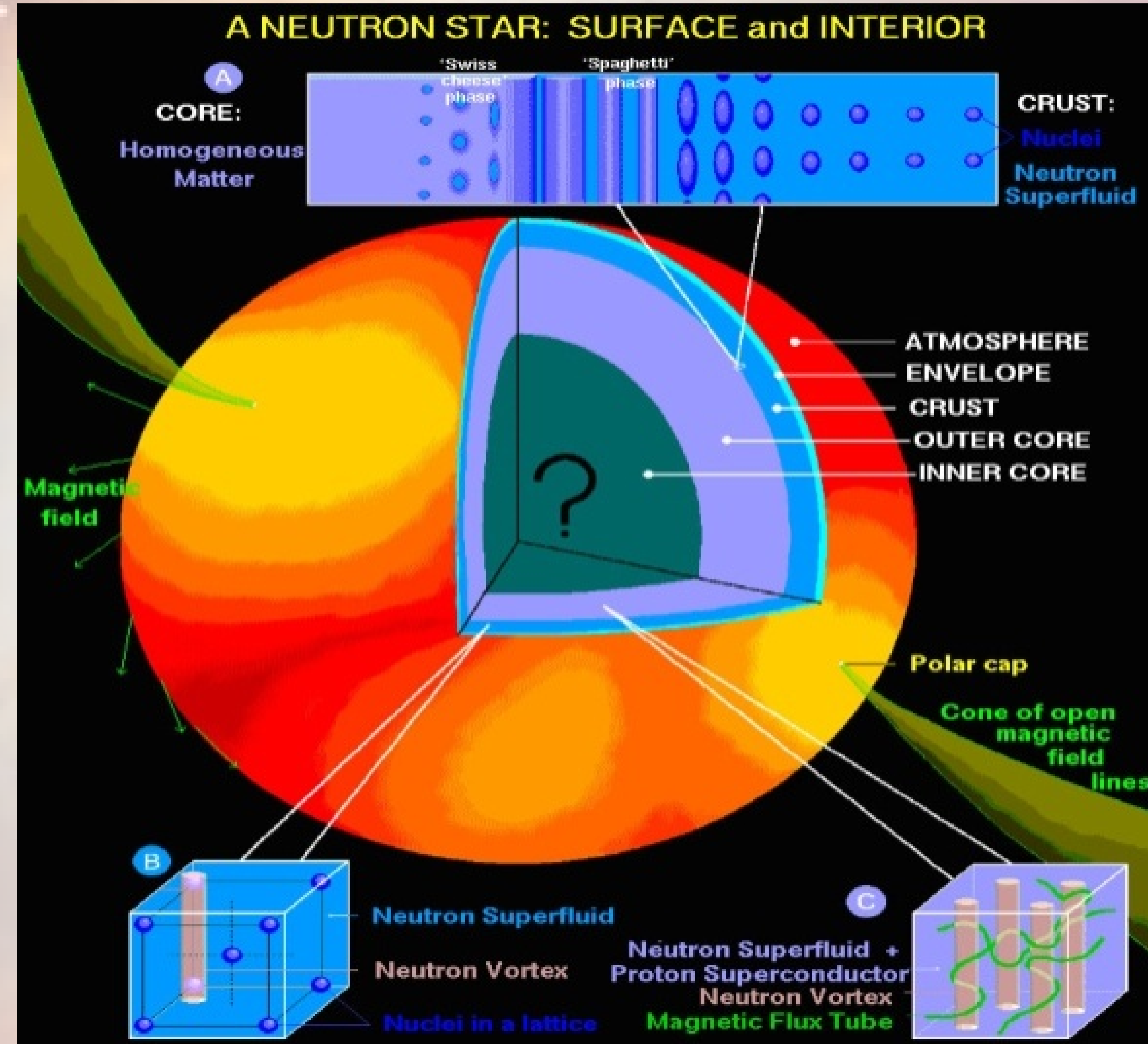
- Its typical numbers:

  - 1.5 solar masses
  - 12 km radius
  - Central densities $n \approx 10^{14}$ g/cc in the center
  - $T/E_F \approx 0$, $T \approx$ 1-10 keV.



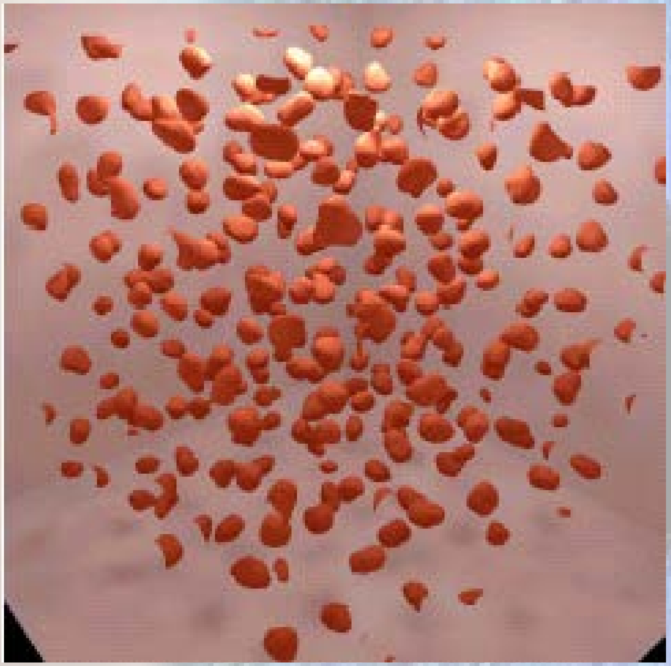
Supernova 2008ed
in UGC 2740
by CHASE
collaboration

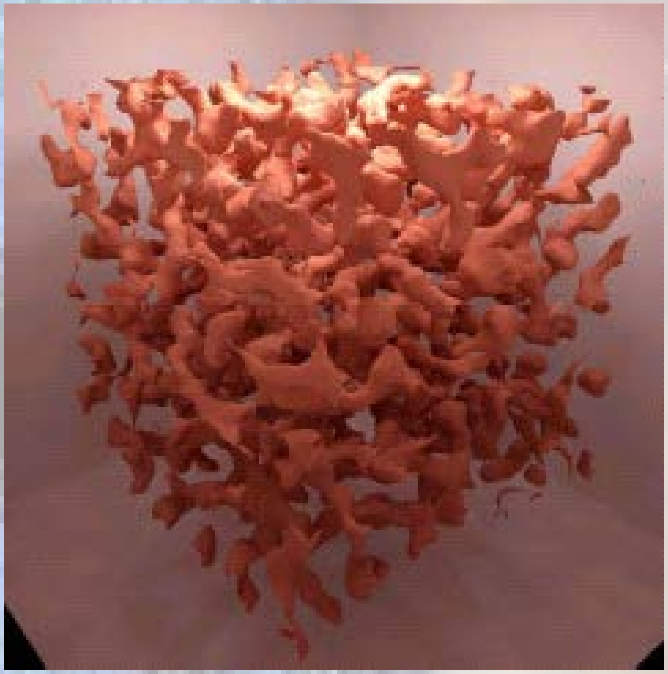
R.A. = 3h26m 43s.62
Decl. = +7º42‘ 34".9


A NEUTRON STAR: SURFACE and INTERIOR
A
CORE:
Homogeneous
Matter
'Swiss cheese' phase
'Spaghetti' phase
CRUST:
Nuclei
Neutron
Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic
field
Polar cap
Cone of open
magnetic
field
lines
B
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
C
Neutron Superfluid +
Proton Superconductor
Neutron Vortex
Magnetic Flux Tube

NSs from SN event

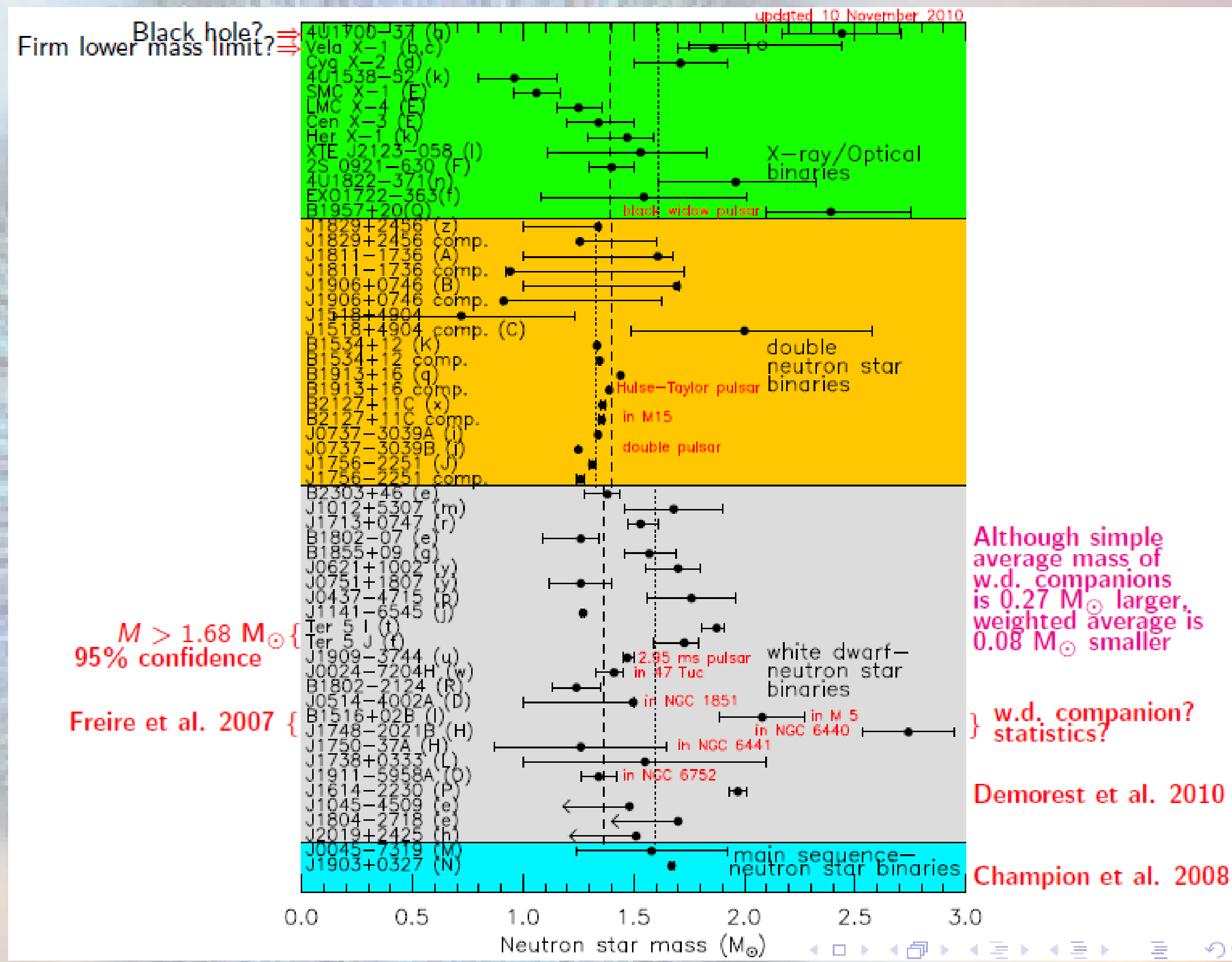
- In outer crust-core matter goes non-uniform phase called PASTA PHASE





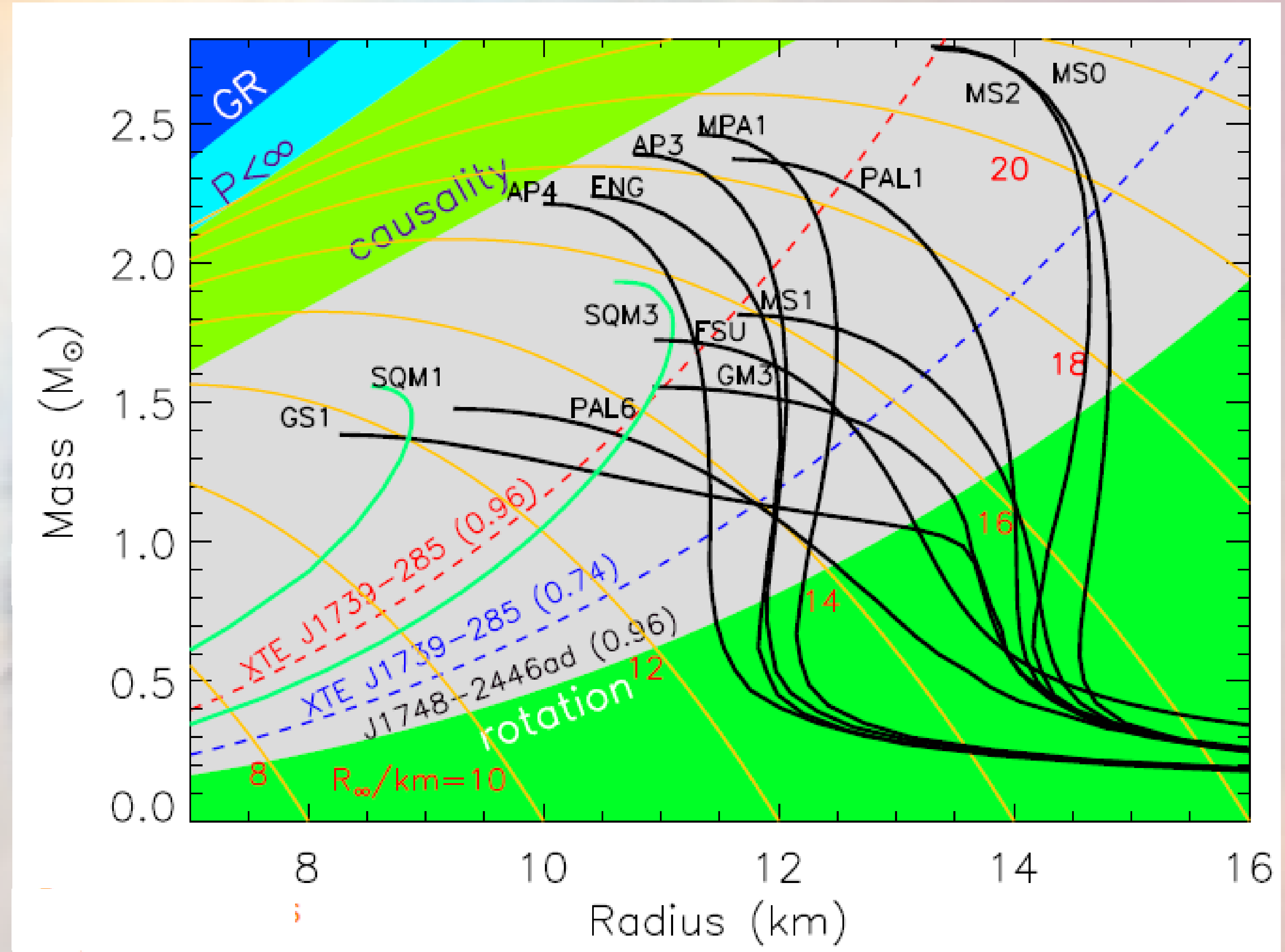
CJ. Horowitz, M.A. Pérez García, J.Piekarewiz
Phys. Rev. C, 70, 048555,2004

NS masses

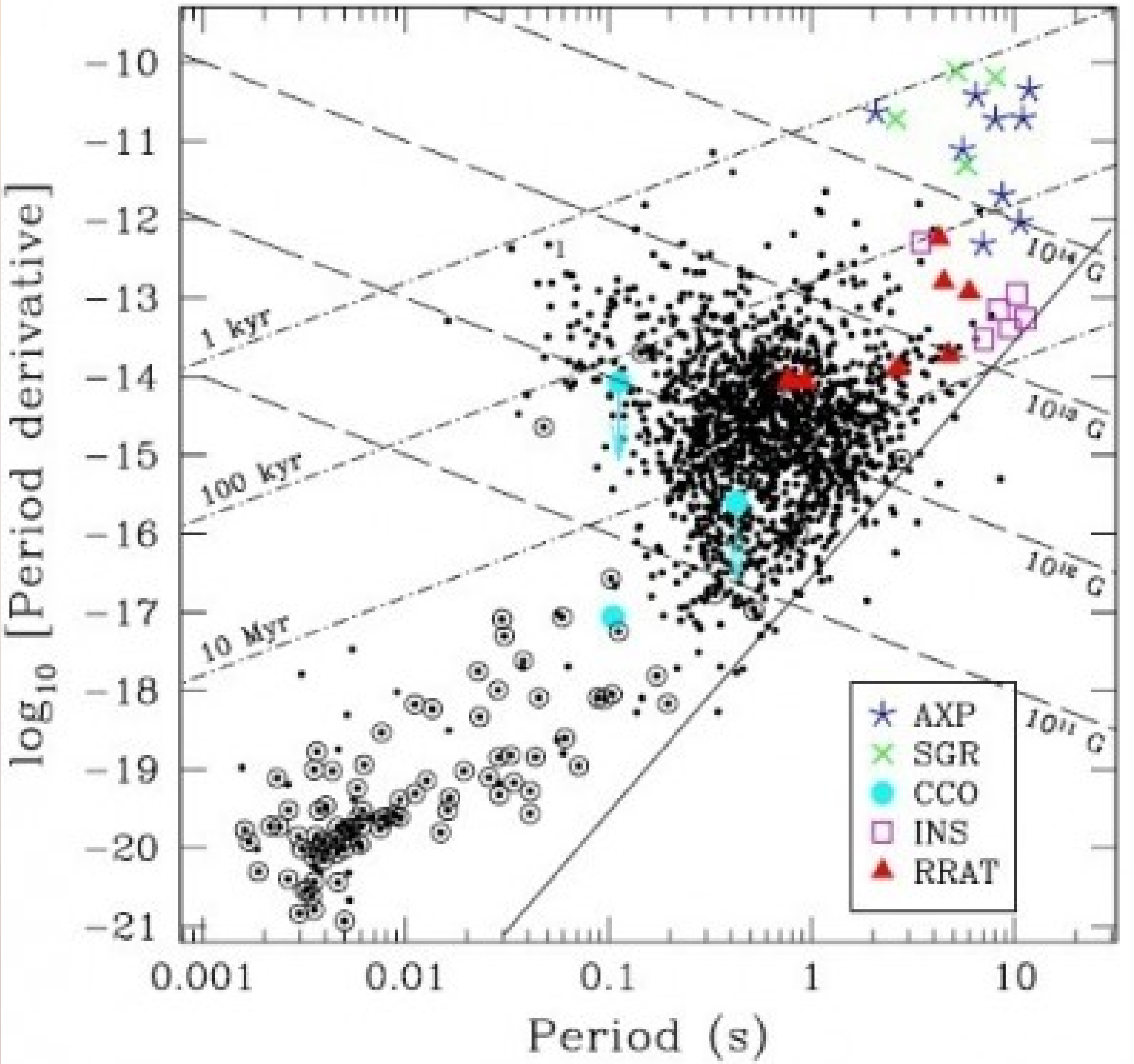


updated 10 November 2010
Black hole?
Firm lower mass limit?
4U1700−37 (a)
Vela X−1 (b,c)
Cyg X−2 (d)
4U1538−52 (k)
SMC X−1 (E)
LMC X−4 (E)
Cen X−3 (E)
Her X−1 (k)
XTE J2123−058 (l)
2S 0921−630 (F)
4U1822−371(n)
EXO1722−363(f)
B1957+20(Q)
black widow pulsar
X−ray/Optical binaries
J1829+2456 (z)
J1829+2456 comp.
J1811−1736 (A)
J1811−1736 comp.
J1906+0746 (B)
J1906+0746 comp.
J1518+4904
J1518+4904 comp. (C)
B1534+12 (k)
B1534+12 comp.
B1913+16 (q)
B1913+16 comp.
Hulse−Taylor pulsar
B2127+11C (x)
B2127+11C comp.
in M15
J0737−3039A (i)
J0737−3039B (i)
double pulsar
J1756−2251 (J)
J1756−2251 comp.
double neutron star binaries
B2303+46 (e)
J1012+5307 (m)
J1713+0747 (r)
B1802−07 (e)
B1855+09 (g)
J0621+1002 (y)
J0751+1807 (y)
J0437−4715 (R)
J1141−6545 (J)
Ter 5 I (f)
Ter 5 J (f)
J1909−3744 (u)
2.15 ms pulsar
J0024−7204H (w)
in 47 Tuc
B1802−2124 (R)
J0514−4002A (D)
in NGC 1851
B1516+02B (l)
in M 5
J1748−2021B (H)
in NGC 6440
J1750−37A (H)
in NGC 6441
J1738+0333 (L)
J1911−5958A (O)
in NGC 6752
J1614−2230 (P)
J1045−4509 (e)
J1804−2718 (e)
J2019+2425 (h)
white dwarf−neutron star binaries
J0045−7319 (M)
J1903+0327 (N)
main sequence−neutron star binaries
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)
$M > 1.68\ M_\odot$
95% confidence
Freire et al. 2007
Although simple average mass of w.d. companions is 0.27 $M_\odot$ larger, weighted average is 0.08 $M_\odot$ smaller
w.d. companion? statistics?
Demorest et al. 2010
Champion et al. 2008

NS structure: Mass & Radius



Pulsars vs NSs

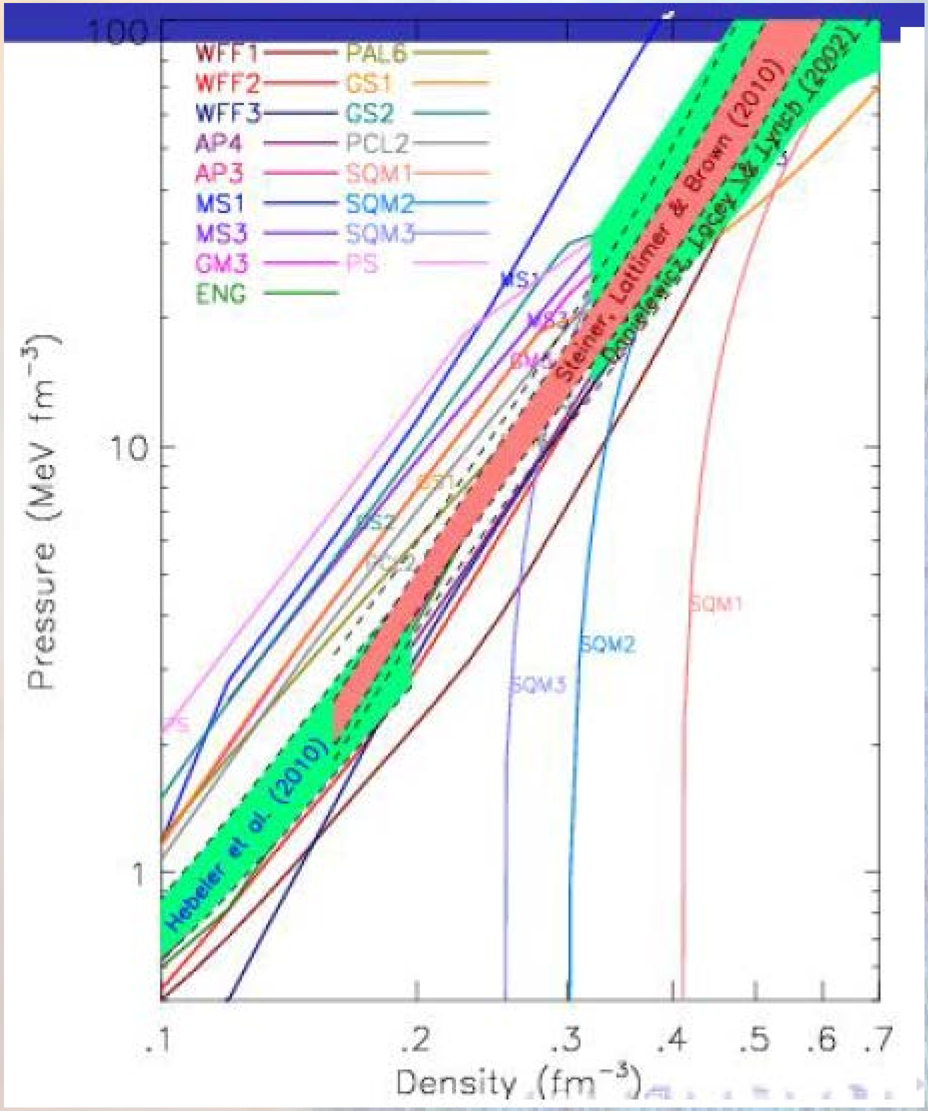


A selection of neutron star varieties including RPPs (small black dots), magnetars; and CCOs (cyan circles), The solid line is the *death line* (see text). Note magnetars have some of the lowest spins, despite being the most luminous.

For smaller neutron stars, a spin rate that slow would have already put them over the death line (where a neutron star no longer pulses and may only be faintly luminous).

Credit: Kaspi, 2010.

Interior: experimental constraints:



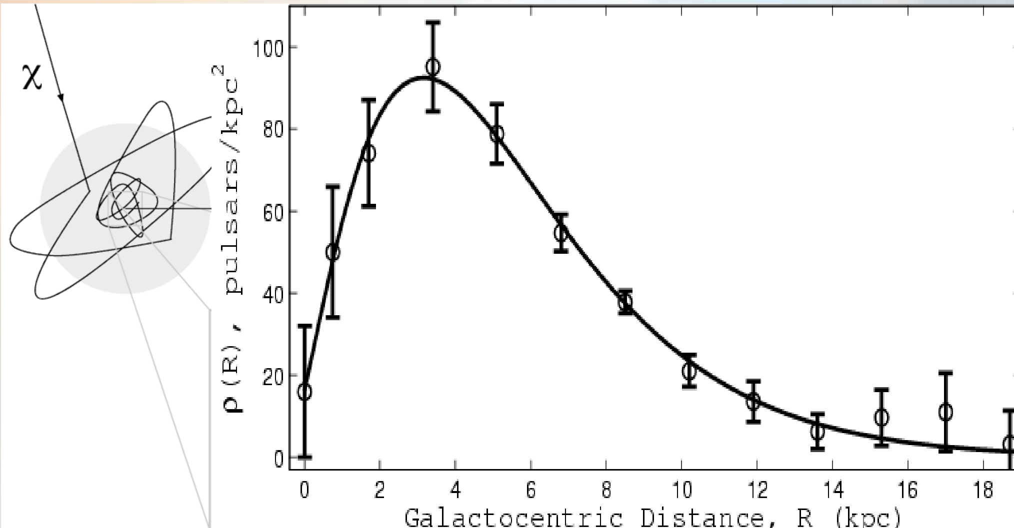
•EOS constraint from:

• Mass-radius relationships [Steiner et al 2010]

•Heavy Ion collision measurements [Danielewicz et al, Scien ce, 2002)

•Neutron matter studies [Hebeler et al 2010]

NS as accretors of DM



$$\dot{N}(t) = F - \Gamma_{annih} - \Gamma_{evap} - \Gamma_{decay}$$

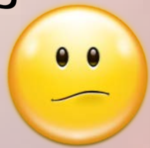
$$\Gamma_{annih} = C_A N^2(t)$$

$$\Gamma_{evap} \approx e^{-GMm_X/RT}$$

$$F(x) = \frac{3.042\ 10^{25}}{m_X(GeV)} \rho_{DM} / \rho_{DM,0}\ (s^{-1})$$

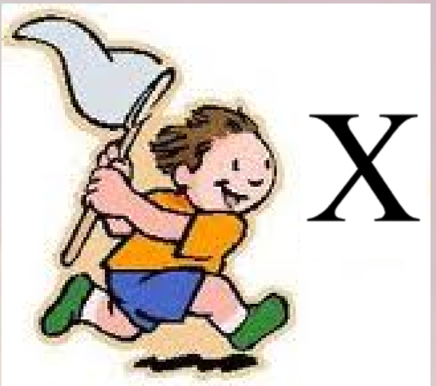
$$\Gamma_{decay} = C_D N(t)$$

- Pulsar profile peaks at closer distances 3 kpc.
- WIMP DM particle candidate of Majorana type
- Capture rate vs. processes removing DM: annihilation, evaporation, decay..
- DDExp as DAMA and COGENT experiments seem to fit a 4-12 GeV/c² mass particle ….
- …but surface event rejection may come into play..

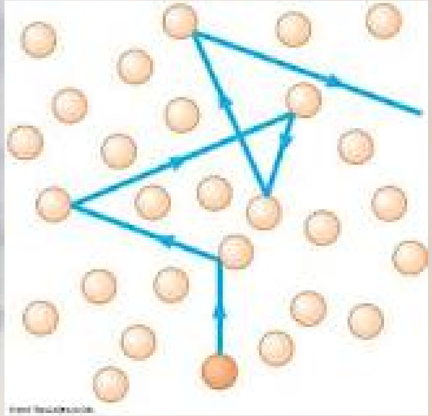


DM in dense matter: MFP

The efficiency of NS to capture DM is much larger than for the sun since:



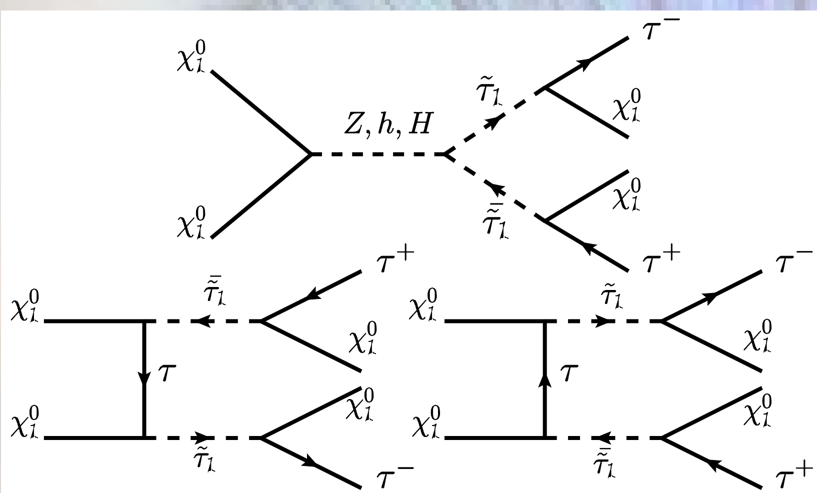
Magnitude	Sun	Neutron star
Central mass density [g/cc]	10^{2}	10^{14}
Mean free path [1/σn] cm	10^{14}	100
Capture rate [s^{-1}]	10^{23}	10^{25}

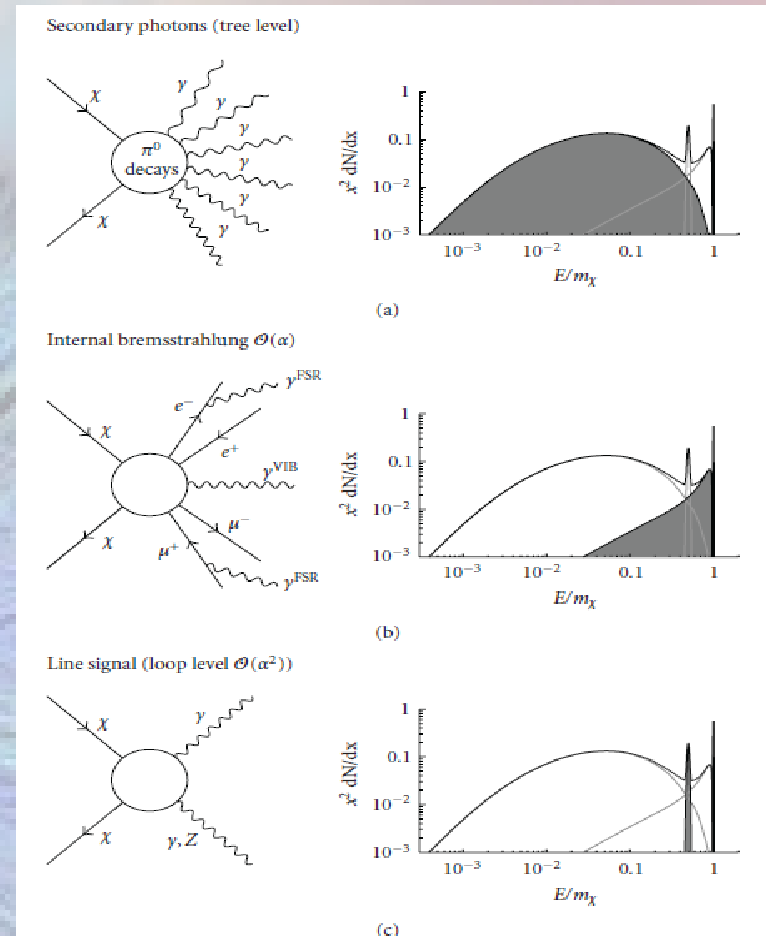


- DM can be accreted from galactic profile by many massive astrophysical objects[Goldam, Nussinov, Press, Spergel, Kouvaris, Lavallaz, Fairbairn, Silk, Stone, PG,..]

DM annihilation

The energy deposition and spectrum will depend on the astrophysical situation and allowed channels : Standard Model…….





…..or additional particle creation in more exotic NLSPs in SUSY models

Cannoni, Gómez, Perez-García, Vergados (2012) in prep

Kuhlen, Adv in Astronomy, 2010

DM energy release in NSs

$$N(t) = F\tau \tanh\left(\frac{t}{\tau}\right)$$

$$t \to \infty \quad N(t) \to F\tau$$

$$\dot{E} = f\,F\tau m_X c^2$$

$$f \approx 0.01-1$$

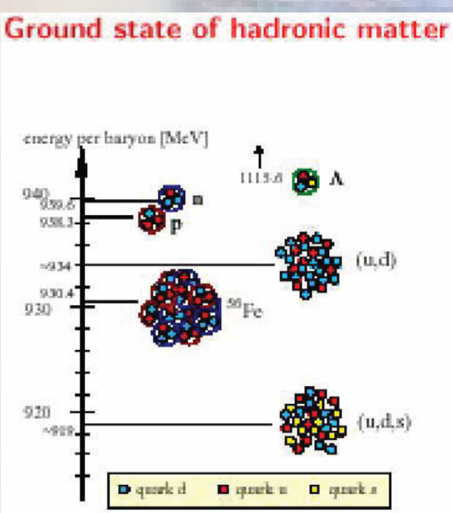
W. Press et al, ApJ 296 679 (1985)

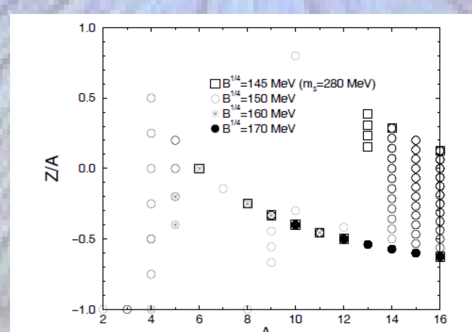
Annihilation can stimulate ud quark droplets and uds bubble formation: strangelets.

The u-d-s phase is the most stable matter (E. Witten'84) and is formed by weak decay

Strangelet (clusters with s) stability depends on : charge, size and s-fraction

DM annihilation may cause steady engine low T, hard to see [Kouvaris,2008]





J. Madsen PRD 47 1993, PRD 50 1994

DM Seeding mechanism: Trojan horse

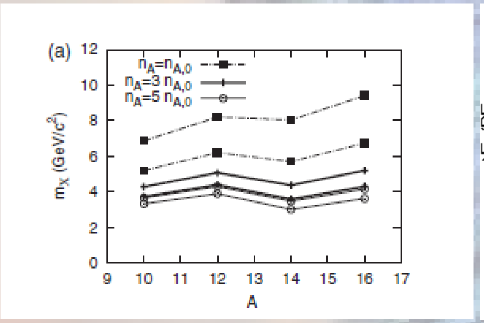
$$\dot{N}_{slet} = \frac{\dot{E}_{annih}}{E_{slet}} \approx 10^{23} \quad s^{-1}$$

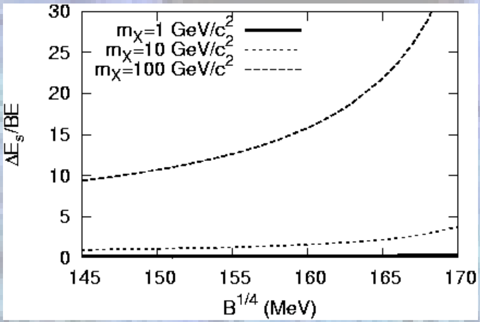
$$m_X = 1 \quad GeV/c^2 \quad n_A = 0.17\, fm^{-3} \quad f = 0.9$$

$$\dot{E} = f F \tau m_X c^2$$

$$f \approx 0.01 - 1$$

$$m_X \geq \frac{E_{slet}(\mu_i, m_i, A, B)}{2f}$$

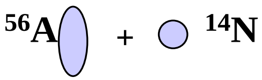




- Minimum value of A strangelet=10-100 model, A=10 for a light X yields estimation of huge amounts of droplets.
- Smaller droplets will decay, may percolate though, but larger will be stable over t≈100 days.
- Formation of stable bubbles may be triggered with this mechanism.

Perez-Garcia, Silk, Stone
PRL 105, 141101 (2010)

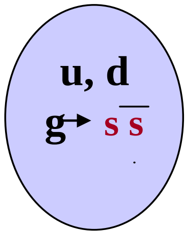
CENTAURO FIREBALL EVOLUTION



CENTRAL COLLISION

at the top of the atmosphere

$E_p \sim 1740$ TeV

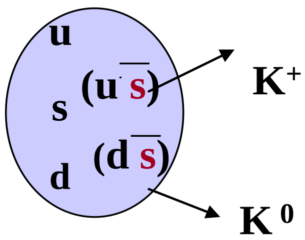


QUARK MATTER FIREBALL

in the baryon-rich fragmentation region

High μ_q suppresses production

of (u ū) , (d d̄), favoring g → s s̄

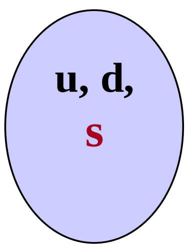


(pre-equilibrium)

KAON EMISSION

K^+, K^0 carry out:

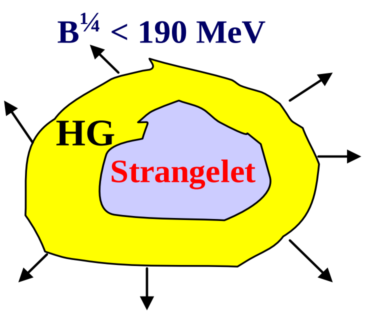
anti-strangeness, positive charge, entropy

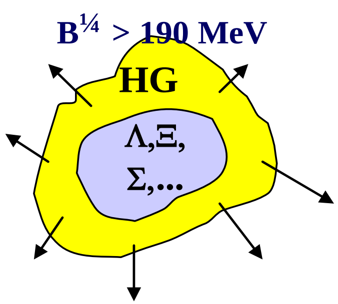


SQM FIREBALL

Stabilizing effects of s quarks

→ long lived state





EXPLOSION

~75 non strange baryons + strangelet

(A ~ 10 -15)

Strangeness distillation mechanism.

Estimates for Centauro at LHC

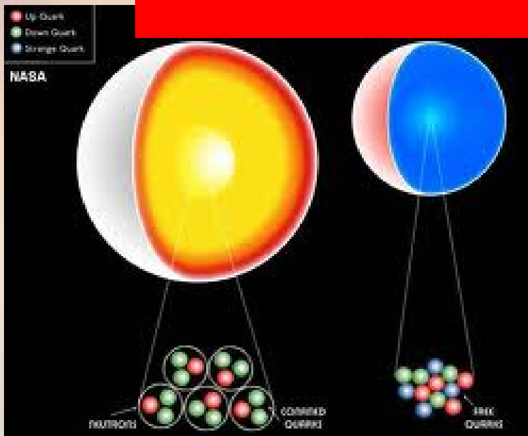
- Energy density
  $\varepsilon \sim 3$ - 25 GeV/fm^3,
- Temperature
  T ~ 130 - 300 MeV
- Baryo-chemical potential
  $\mu_b \sim 0.9$ - 1.8 GeV/fm^3

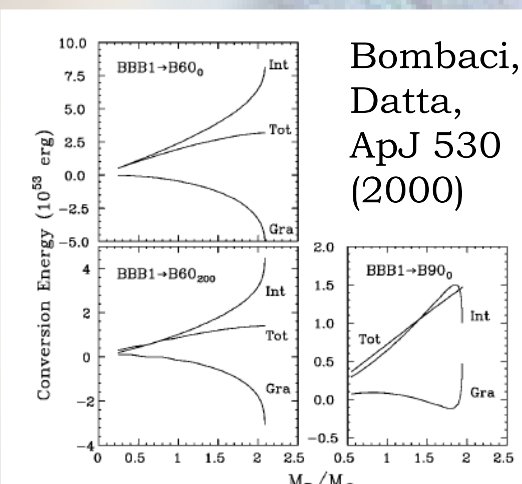
Centauro & Strangelet Generator

(from A. Panagiotou)

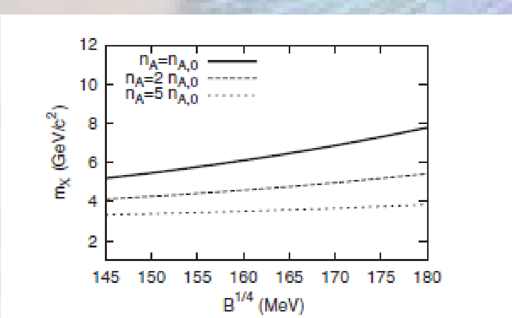
Phys. Rev. D45(1992)3134
Astroparticle Phys. 2(1994)167
Astroparticle Phys. 13(2000)173
Phys. Atom. Nucl. 67(2004)396

NS conversion





Bombaci, Datta, ApJ 530 (2000)



- Transition from nucleon to quark phase may happen -> constraints to DM particle candidate.

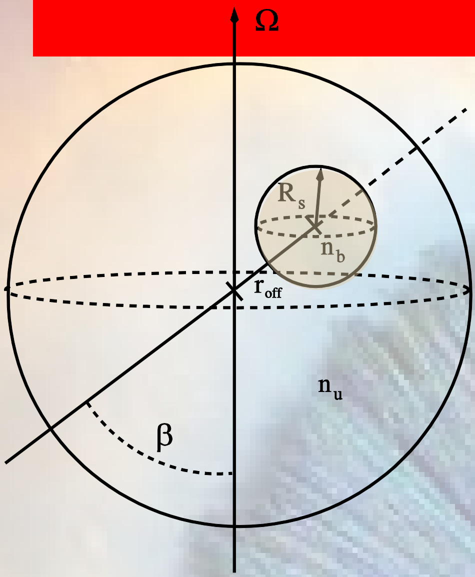
- This effect may convert NS into strange quark matter (SQM) stars.

- A gamma ray burst GRB would be emitted from the conversion assuming all gravitational energy is converted into photons.

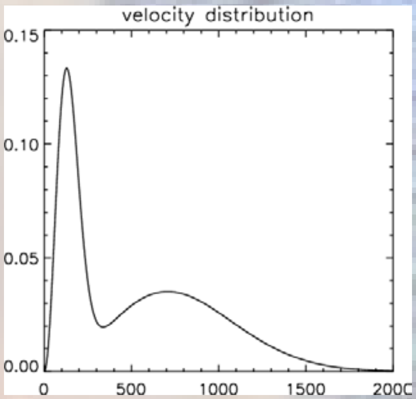
$$\Delta E \approx 10^{53} \frac{\Delta R}{R} \quad erg$$

- If conversion takes place in SN event, likely off center->asymmetric explosion.

Kinematic effects

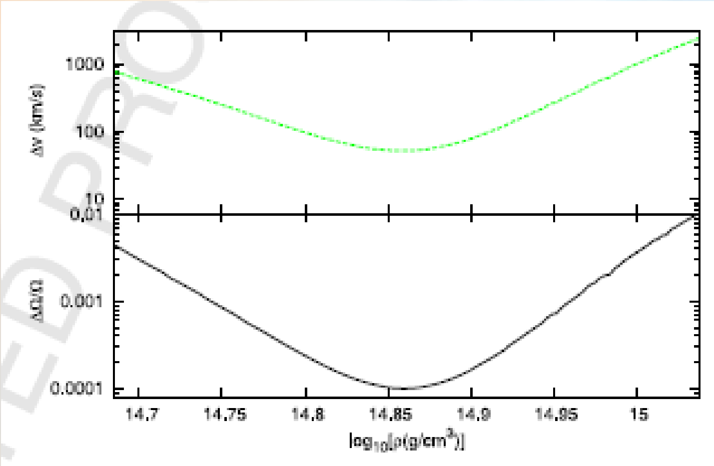


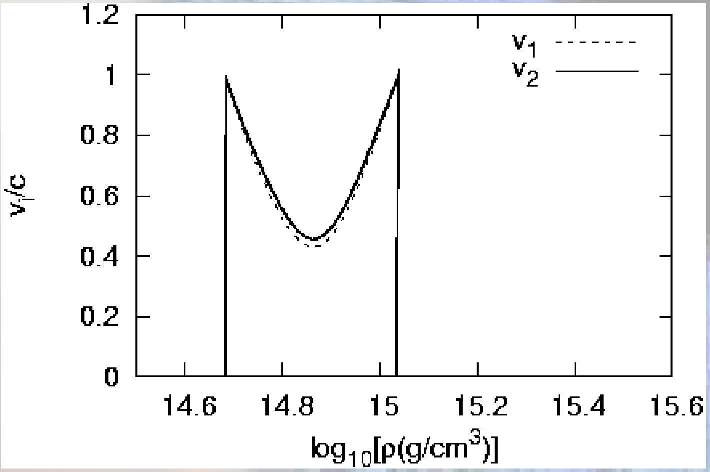
M A Perez-Garcia, J Silk, arXiv:1111.2275, Phys. Lett. B 711, 6 (2012)



- Multispot or bubble coalescence is energetically allowed and may cause burning front.
- Typically this is off-center mechanism with asymmetry parameter $\alpha = \frac{r_{off}}{R} \approx 10^{-2}$
- The front releases energy, neutrinos, building an excess of momentum, "neutrino rockets" are not strong enough though..
- Recoils are measured, indicating a bimodal distribution, hint for NS-> QS conversion? [Bombaci, Popov A&A2004]

Kinematic effects





M A Perez-Garcia, J Silk, arXiv:1111.2275, PLB 711, 6 (2012)

- If the seeding allows a burning front then there is a velocity kick and angular velocity change

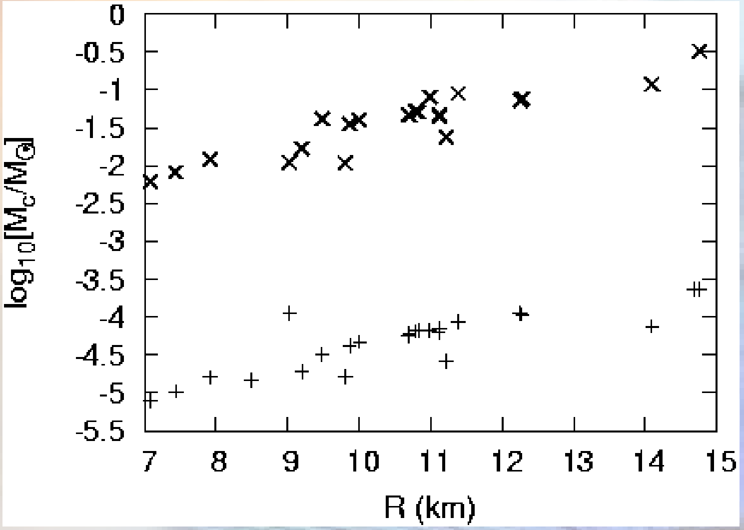
$$\frac{\Delta\Omega}{\Omega} \approx 10^{-4} - 10^{-2}, \Delta v \approx 10^{2} - 10^{3}\ km/s$$

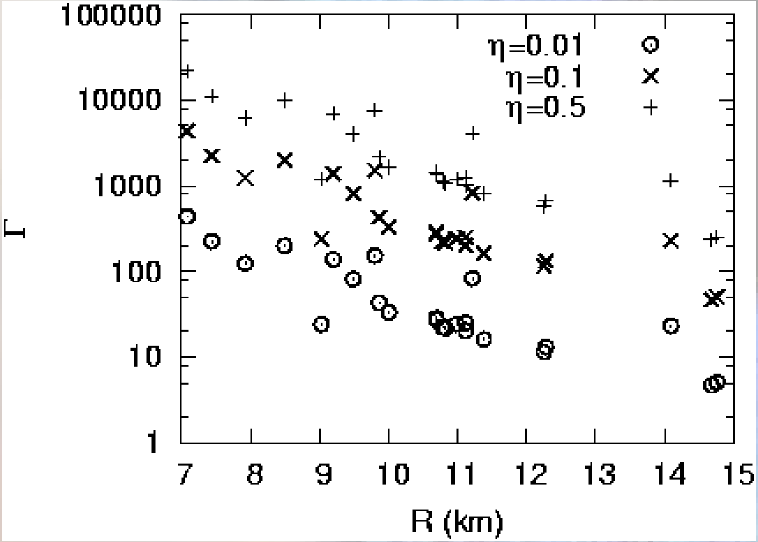
- It is consistent with estimations from X-ray bursts [Heyl ApJ 542 (2000)]

- The front releases energy, neutrinos, building an excess of momentum

- There is a correlation of kick and rotation pattern change.

GRBs: crust ejection mechanism





F. Daigne, M A Perez-Garcia, J Silk, 2012, in prep

- In NS the EOS governs the crust. Typically the "neutron drip" sets the external crust.
- In the fireball model burning front may eject part of the crust, especially above neutron drip.
- In this model DM annihilation may be considered the internal engine.
- Lorentz factors in the range

$$\Gamma \approx 10 - 10^4$$

are allowed.

Conclusions

•Dark matter seeding in NSs constitute a very powerful test-bench as another indirect DM search tool.

•If DM is Majorana self-annihilation may release enough energy to deconfine quark content in hadrons at large central densities.

•This could drive conversion NS → SQM star, hypotesized by Bodmer in 70's, Witten , de Rújula & Glashow in 80's.

•Deep NS to QS conversion may have correlated kinematic effects in kick velocities and rotation consistent with observed changes.

•DM seeding may then constitute a physical mechanism.

• Additional GRB emission effects may constitute an internal engine and an observable indirect DM signature.