Short and long GRBs in the proto-magnetar model with quark deconfinement

Alessandro Drago - Ferrara

- A.D., A.Lavagno, G.Pagliara, Phys.Rev. D89 (2014) 043014

  Two-families scenario

- A.D., A.Lavagno, G.Pagliara, D.Pigato, Phys.Rev. C90 (2014) 065809

  Delta resonances and «delta-puzzle»

- A.D., G.Pagliara, Phys. Rev. C 92 (2015) 045801

  Combustion of hadronic stars into quark stars: the turbulent and the diffusive regime

- A.D., A.Lavagno, G.Pagliara, D.Pigato, Eur.Phys.J. A52 (2016) 40

  A.D., G.Pagliara, Eur.Phys.J. A52 (2016) 41

  Review papers on the two-families scenario

- A.D., A.Lavagno, B.Metzger, G.Pagliara, Phys. Rev. D93 (2016) 103001

  Quark deconfinement and duration of short GRBs

- A.G.Pili, N.Bucciantini, A.D., G.Pagliara, L. del Zanna, sent for publication

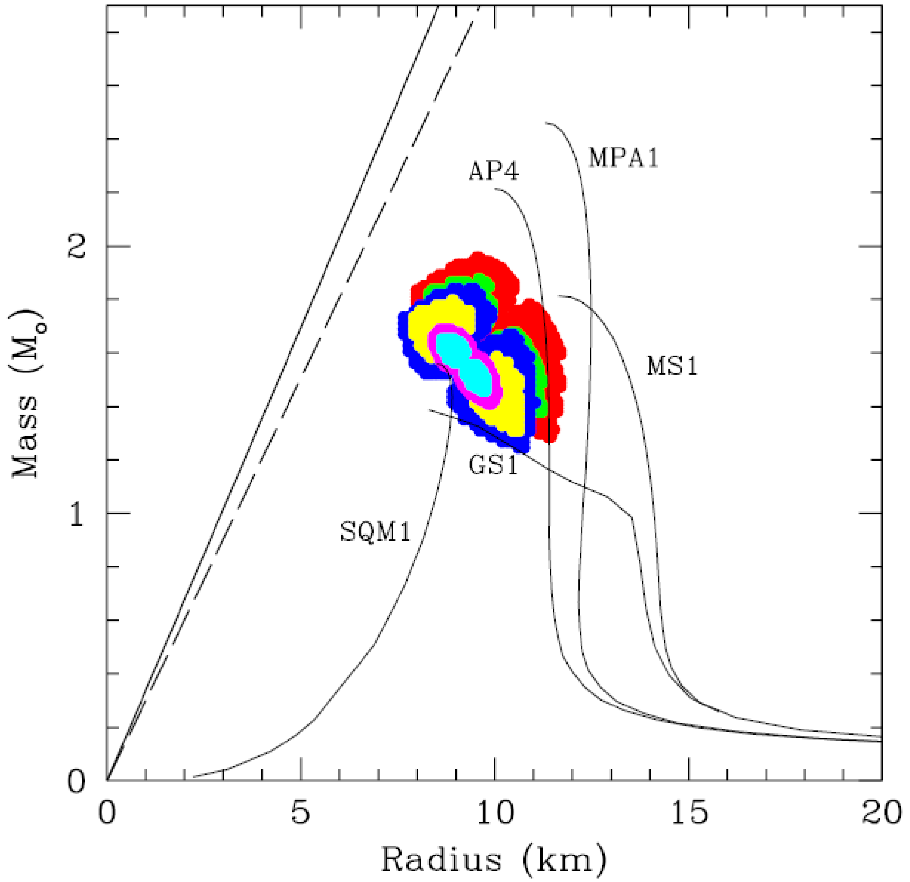
  Quark deconfinement and late-time activity in long GRBs

Why a two-families scenario?

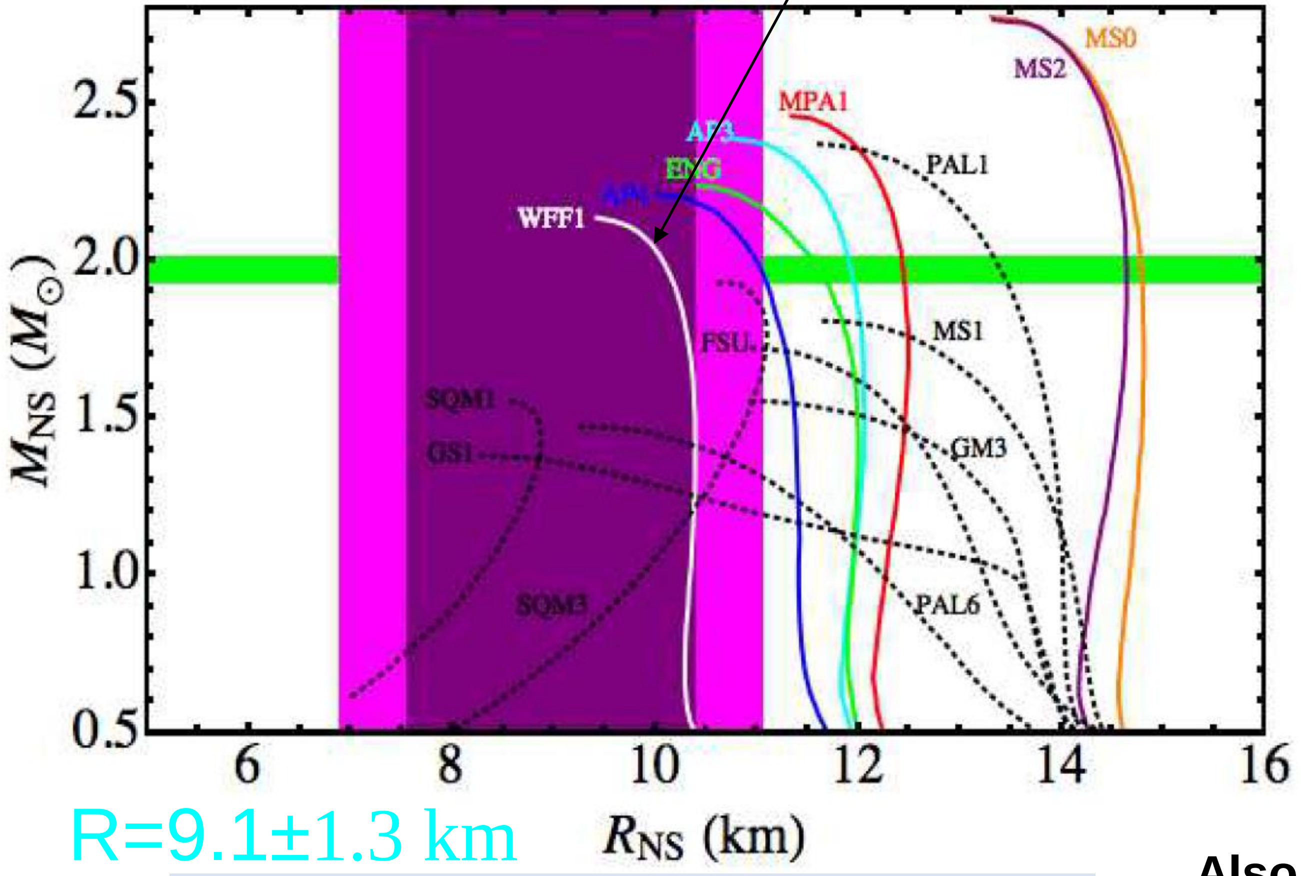
The problem of the radii of compact stars

Indications for SMALL radii:
a VERY controversial result

Oezel, Baym, Guever PRD82 (2010) 101301



Nice, but just nucleons,
And it violates causality!

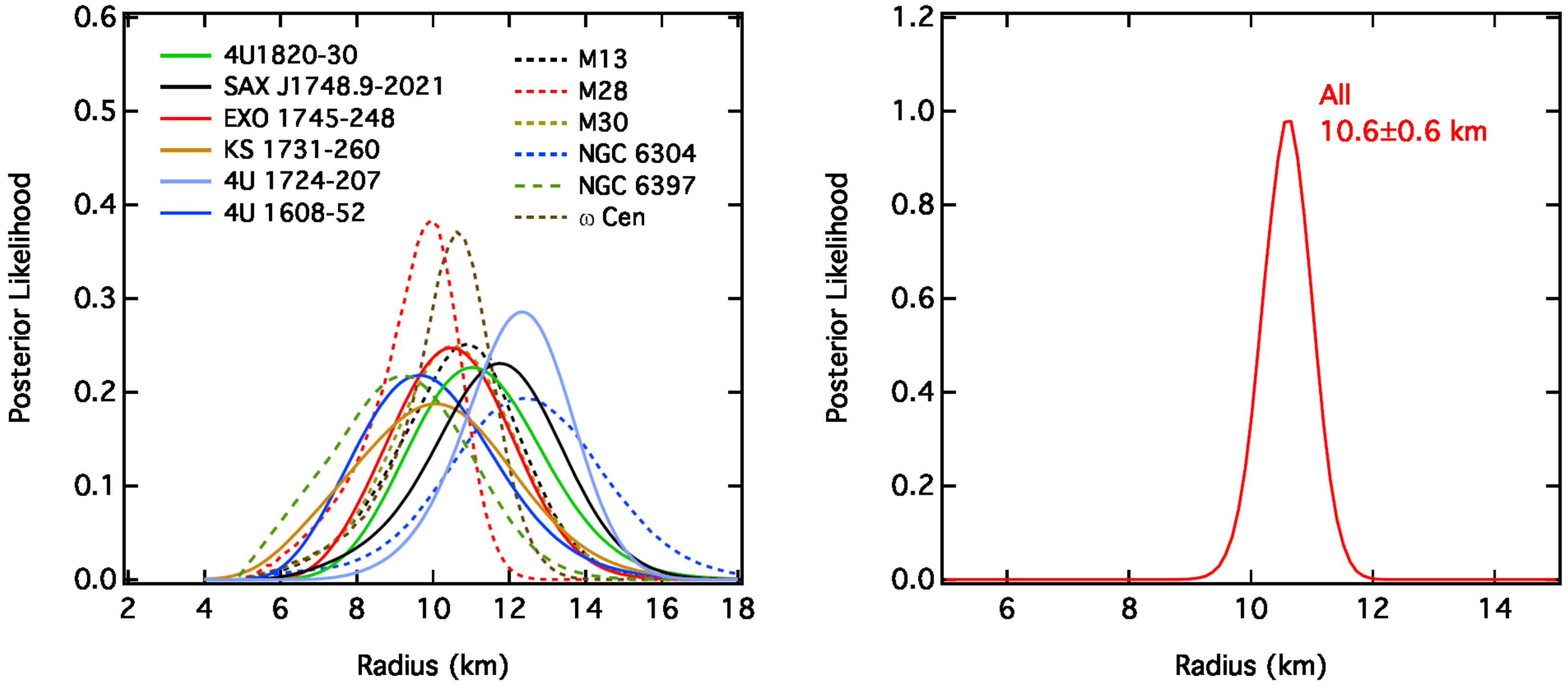


R=9.1±1.3 km

Guillot et al. ApJ772(2013)7
analysis of 5 QLMXBs

Also Guillot and Rutledge 1409.4306
R=(9.4 ± 1.2)km

Oezel, Psaltis, Guever, Baym, Heinke, Guillot, ApJ 820(2016)28



Bogdanov, Heinke, Ozel, Guver, arXiv:1603.01630

R ~ (9.9—11.2) km for a 1.5 M s star

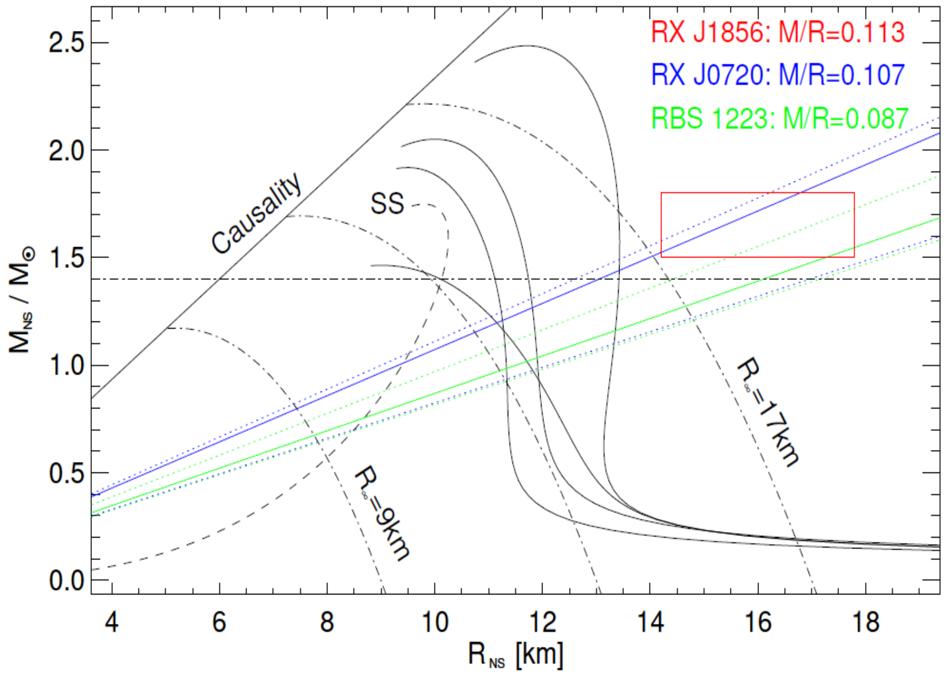
Indications for LARGE radii

Hambaryan et al 2014

RXJ1856.5-3754

Is the nearest INS and the distance (d = 123+11-15 pc) is known with relatively good accuracy.

The X-ray spectrum does not show any signicant absorption feature and the pulsed fraction is quite low (1.5%).

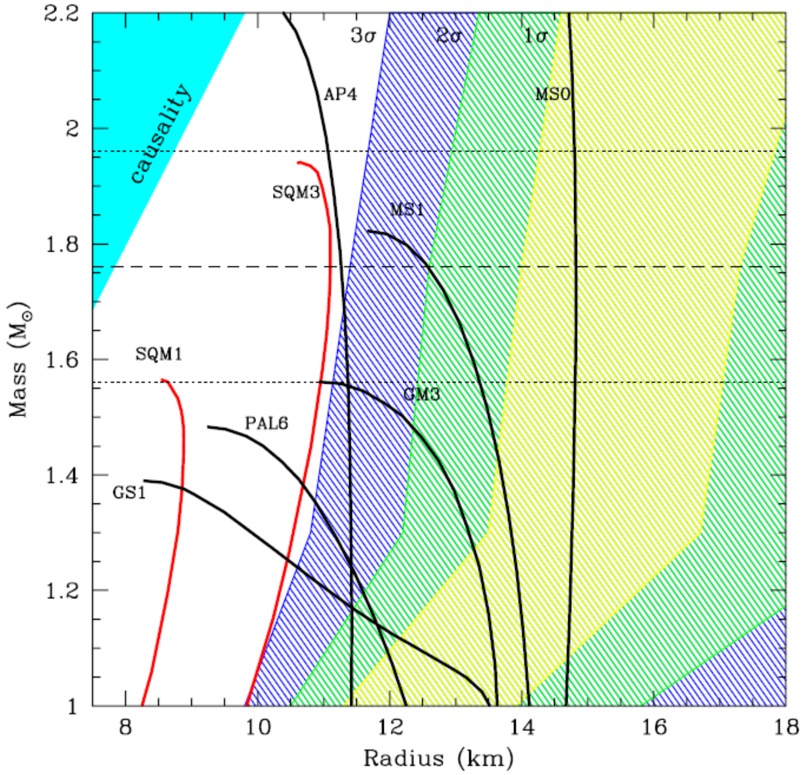


Bogdanov 2013

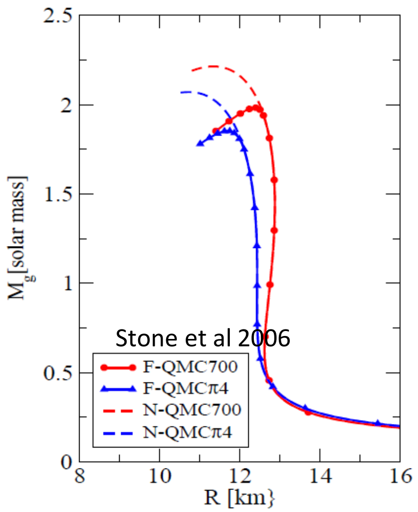
PSR J0437–4715, *XMM-Newton*

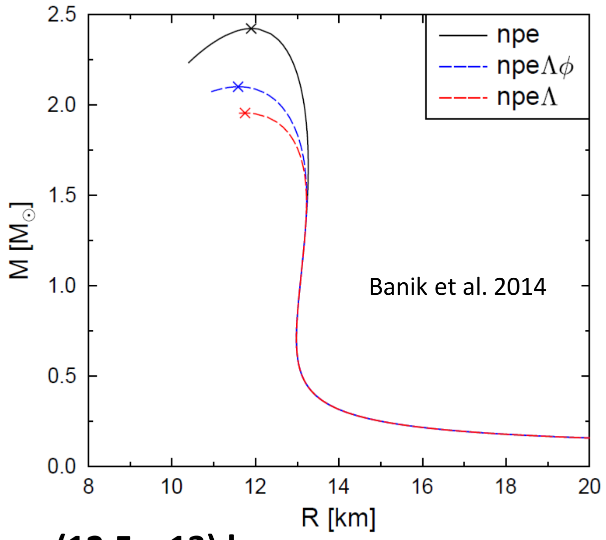
The thermal radiation exhibits at least three components, with the hottest two having total effective areas consistent with the expected polar cap size.

The coolest component, on the other hand, appears to cover a significant portion of the stellar surface

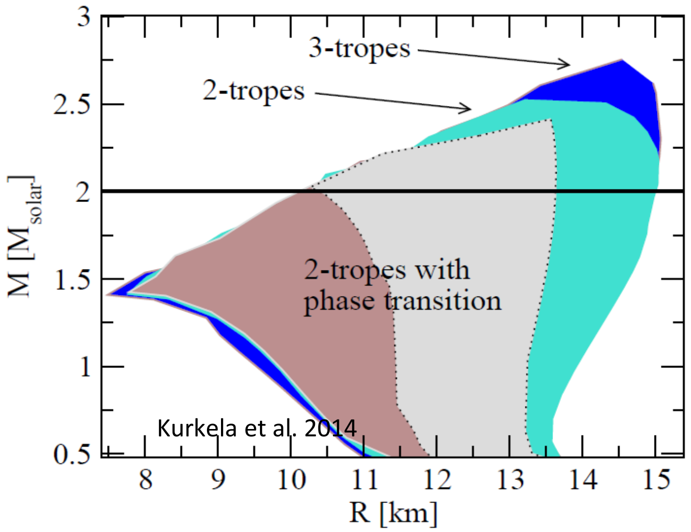


Minimum radius for a 1.4 M_s star

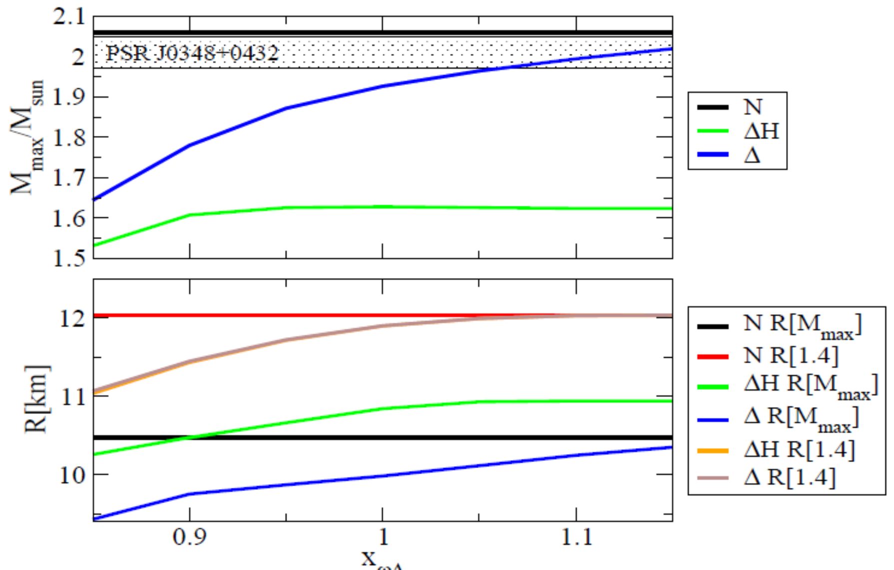




Hyperonic stars $R_{1.4}$ > (12.5 – 13) km



Hybrid stars $R_{1.4}$ > 11.5 km



Delta – resonance stars
$R_{1.4}$ order of (10-11) km,
BUT the maximum mass
is smaller than 2 M_s

Strong softening… is this surprising?

Heavy ions physics:

(Kolb & Heinz 2003)

Also at finite density the quark matter equation of state should be stiffer than the hadronic equation of state in which new particles are produced as the density increases

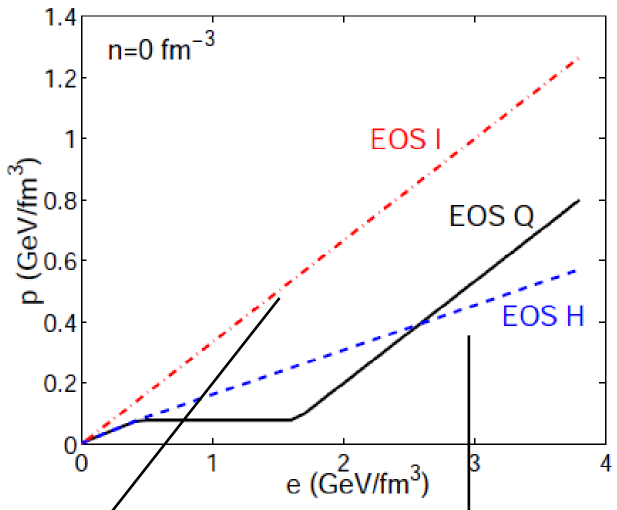
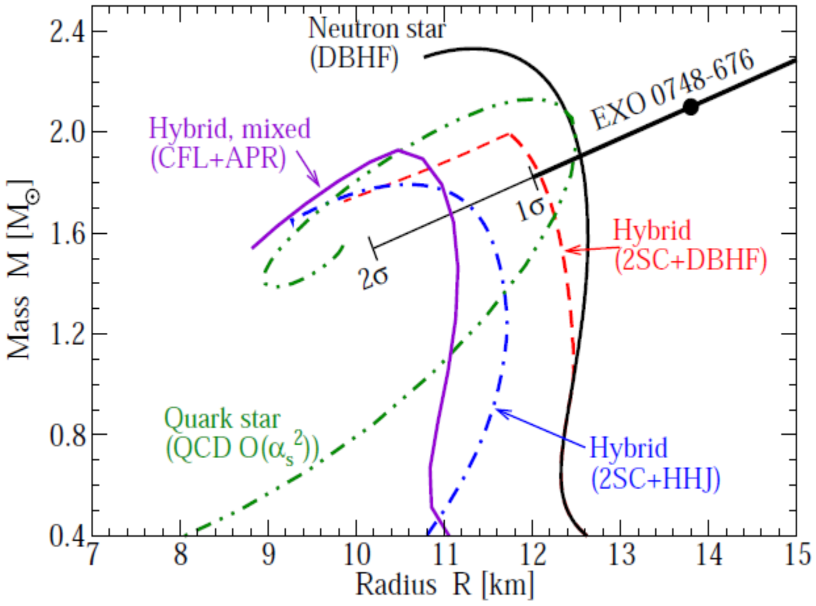


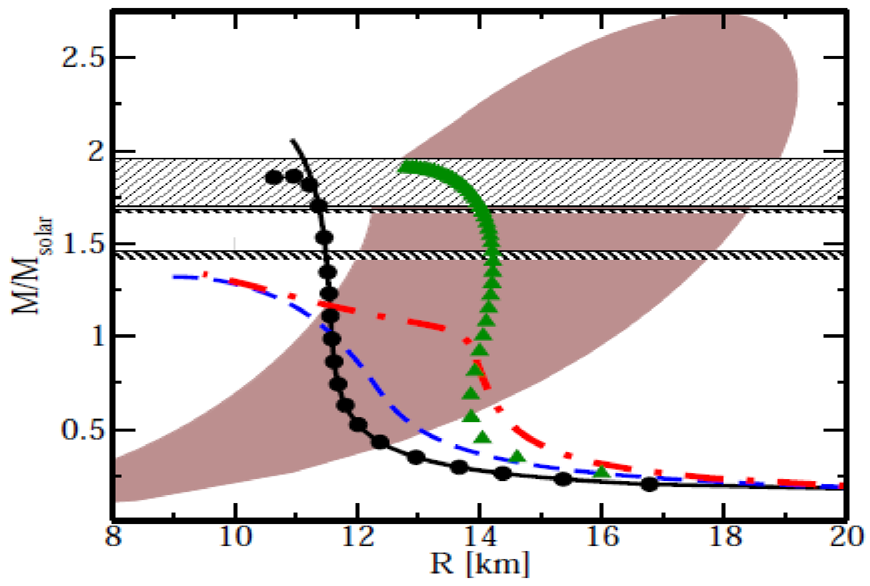
Fig. 1. Equation of state of the Hagedorn resonance gas (EOS H), an ideal gas of massless particles (EOS I) and the Maxwellian connection of those two as discussed in the text (EOS Q). The figure shows the pressure as function or energy density at vanishing net baryon density.

p=e/3 massless quarks **Hadron resonance gas p=e/6**

Hybrid stars or quark stars?



Alford et al Nature 2006



Kurkela et al PRD81(2010)105021

pQCD calculations: " … equations of state including quark matter lead to hybrid star masses up to 2Ms, in agreement with current observations.

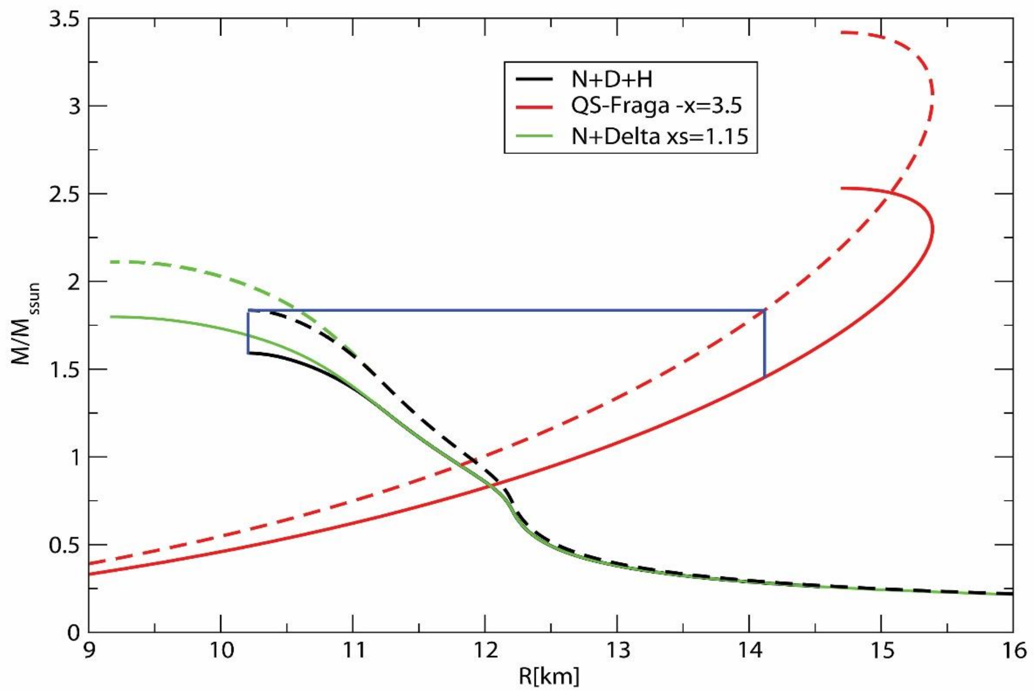
For strange stars, we find maximal masses of 2.75Ms and conclude that confirmed observations of compact stars with $M > 2M_s$ would strongly favor the existence of stable strange quark matter"

Before the discoveries of the $2M_s$ stars!!

Why conversion should then occur?
Quark stars are more bound:
at a fixed total baryon number
they have a smaller gravitational
mass wrt hadronic stars.

The hadronic stars are stable
till when some strangeness
component (e.g. hyperons)
starts appearing in the core.
Only at that point quark matter
nucleation can start.

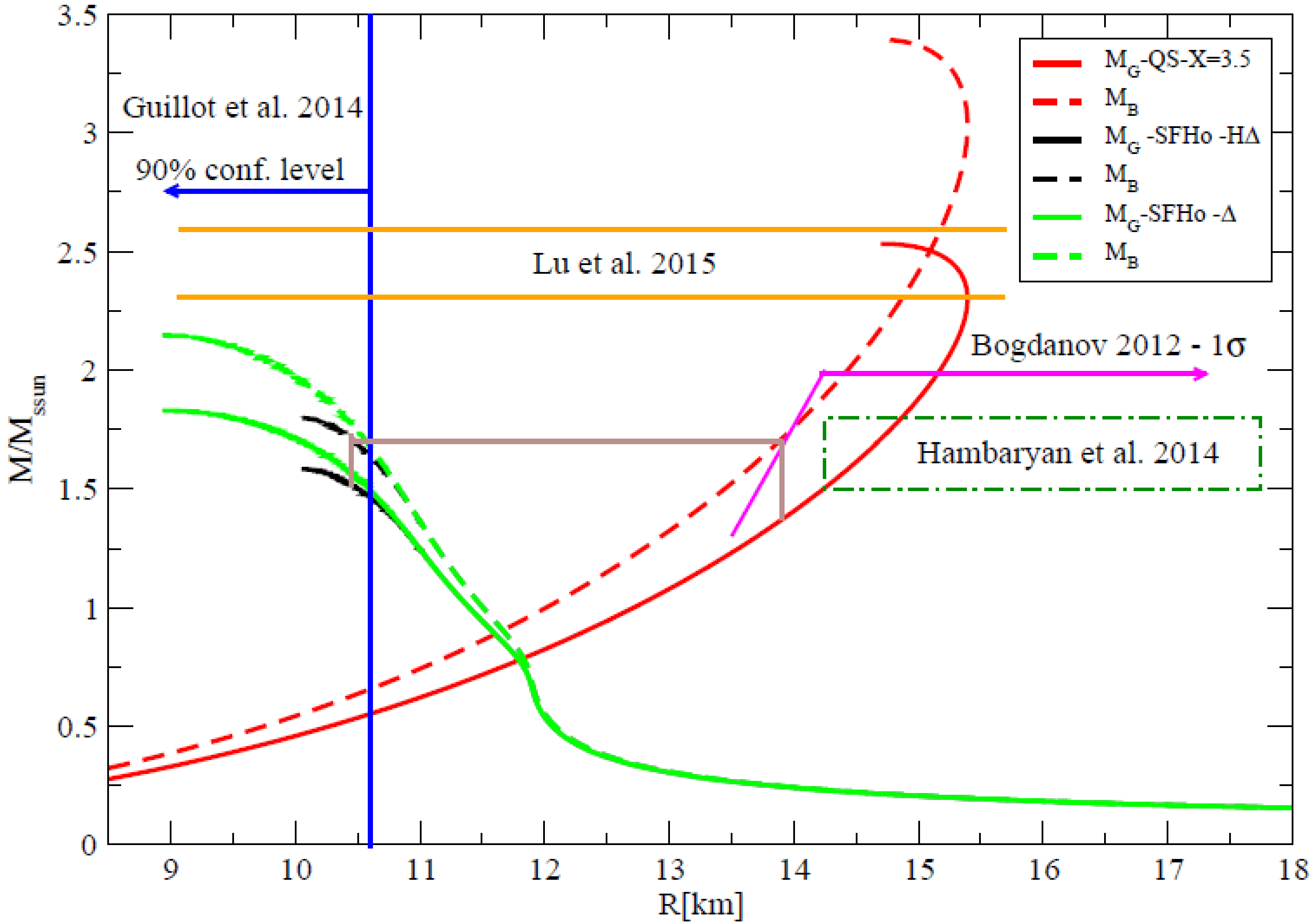
Finite size effects (surface tension)
can further delay the formation
of the first droplet of strange matter



The maximum mass of a quark star can be as large as
2.75 $M_s \geq 2$ x (1.3 ÷ 1.4) M_s .(Dynamically stable up to almost 1.3+1.3)
Therefore it is possible to have a ultra-massive quark star produced
by the merging of two normal-mass neutron stars.
The post-merging e.m. signal of the associated short GRB could show a
quasi-plateau emission, similar to the one observed in many long GRBs.

Previsions and tests of the two-families scenario

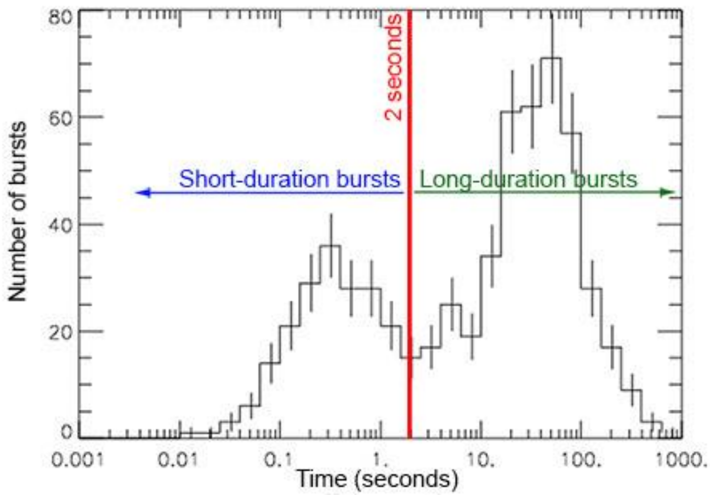
- Radii (NICER, LOFT)
- Anomalous mass function (SKA)
- Moment of inertia (SKA)
- GW signal in NS-NS merger (LIGO & VIRGO)



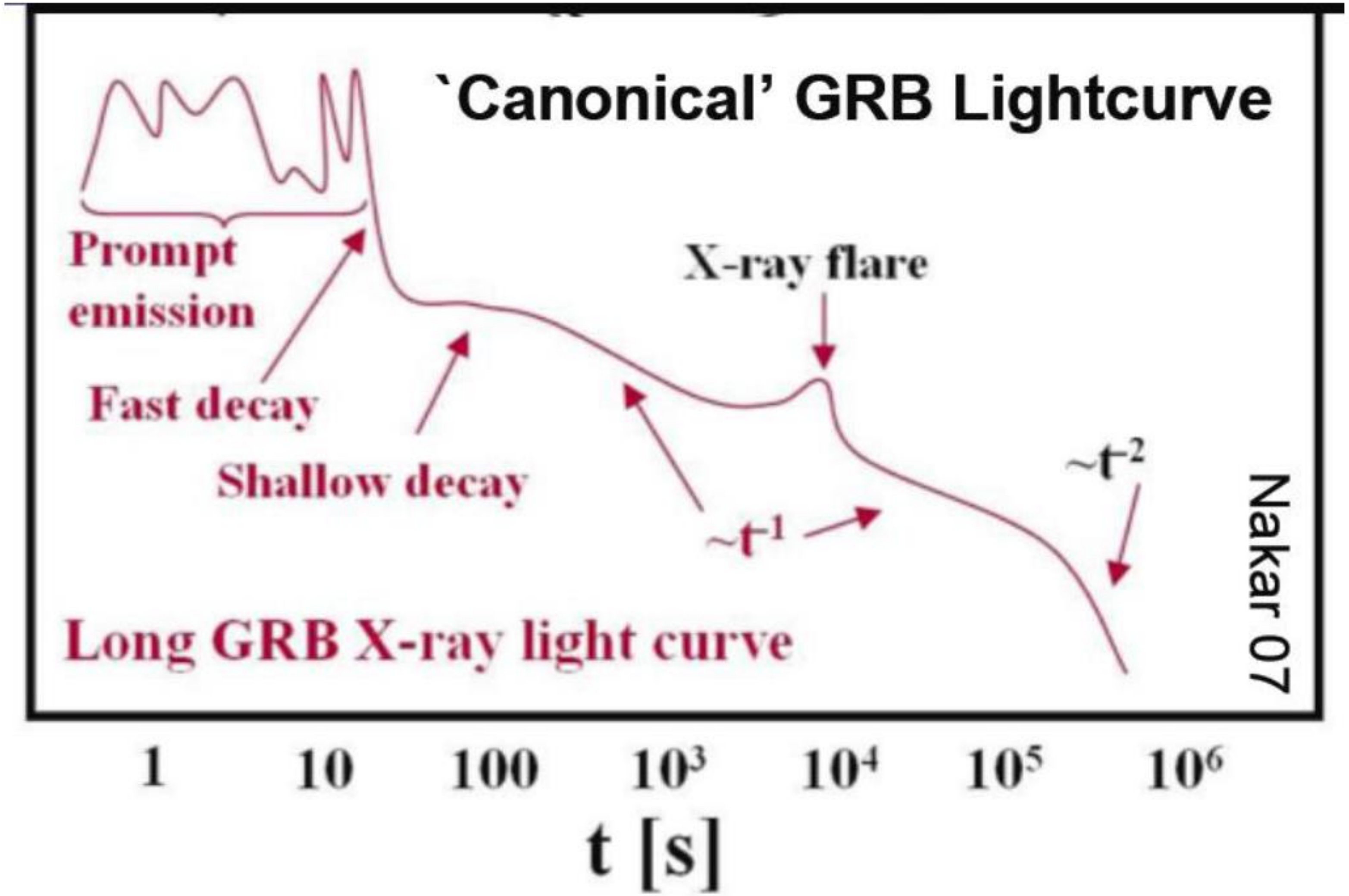
Gamma Ray Bursts

The role of quark deconfinement in GRBs

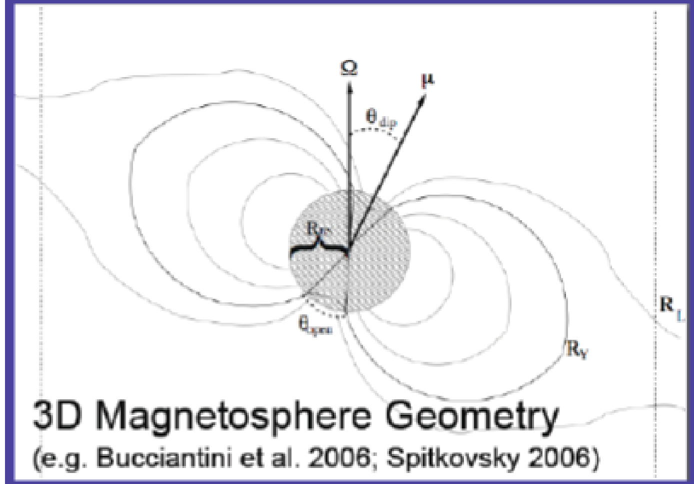
Long and short Gamma Ray Bursts

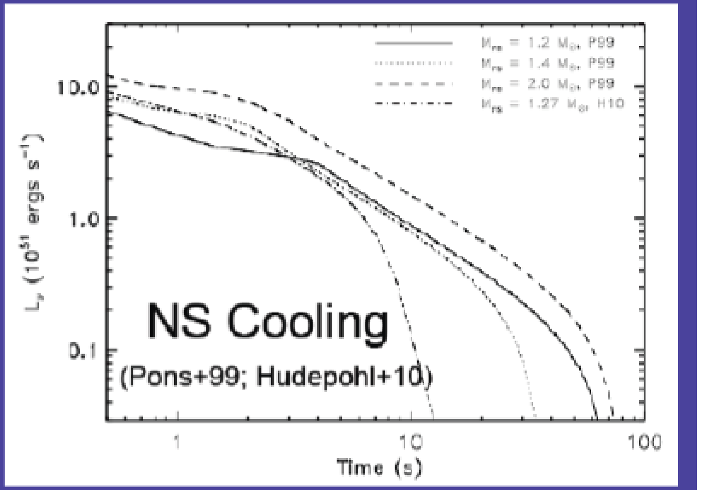


Long GRBs: collapse of a heavy progenitor
Short GRBs: merger of two neutron stars


`Canonical' GRB Lightcurve
Prompt
emission
Fast decay
Shallow decay
X-ray flare
~t-1
~t-2
Nakar 07
Long GRB X-ray light curve
1
10
100
10³
10⁴
10⁵
10⁶
t [s]

Evolutionary wind model





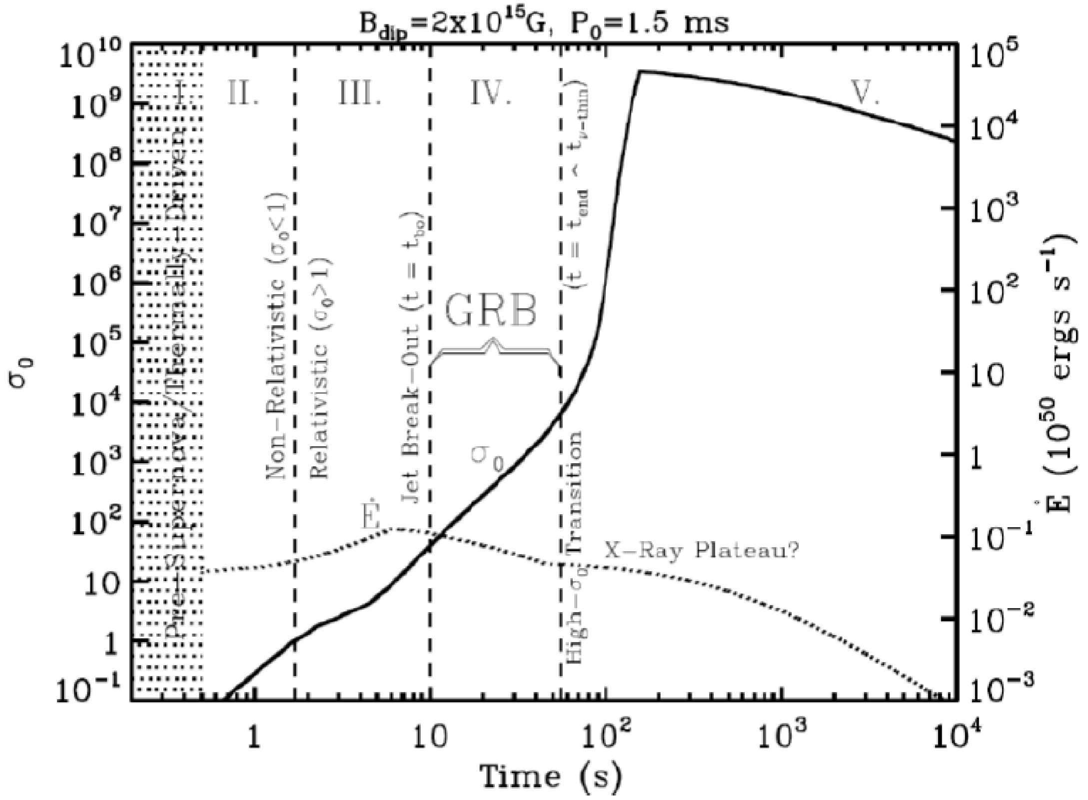
Calculate: Wind Power $\dot{E}(\mathrm{t})$, Mass Loss Rate $\dot{M}(\mathrm{t})$,

$$\Rightarrow \text{'Magnetization'}\ \sigma(\mathrm{t}) \sim \dot{E}/\dot{M}c^2 = \Gamma_{\max}(\mathrm{t})$$

In terms of

Initial Rotation Period P_0 , **Dipole Field Strength** B_{dip} & **Obliquity** θ_{dip}

Magnetar model of GRBs (Metzger et al.)



$$\sigma_0 \equiv \frac{\phi^2 \Omega^2}{\dot{M} c^3} \qquad \phi \equiv B_r r^2$$

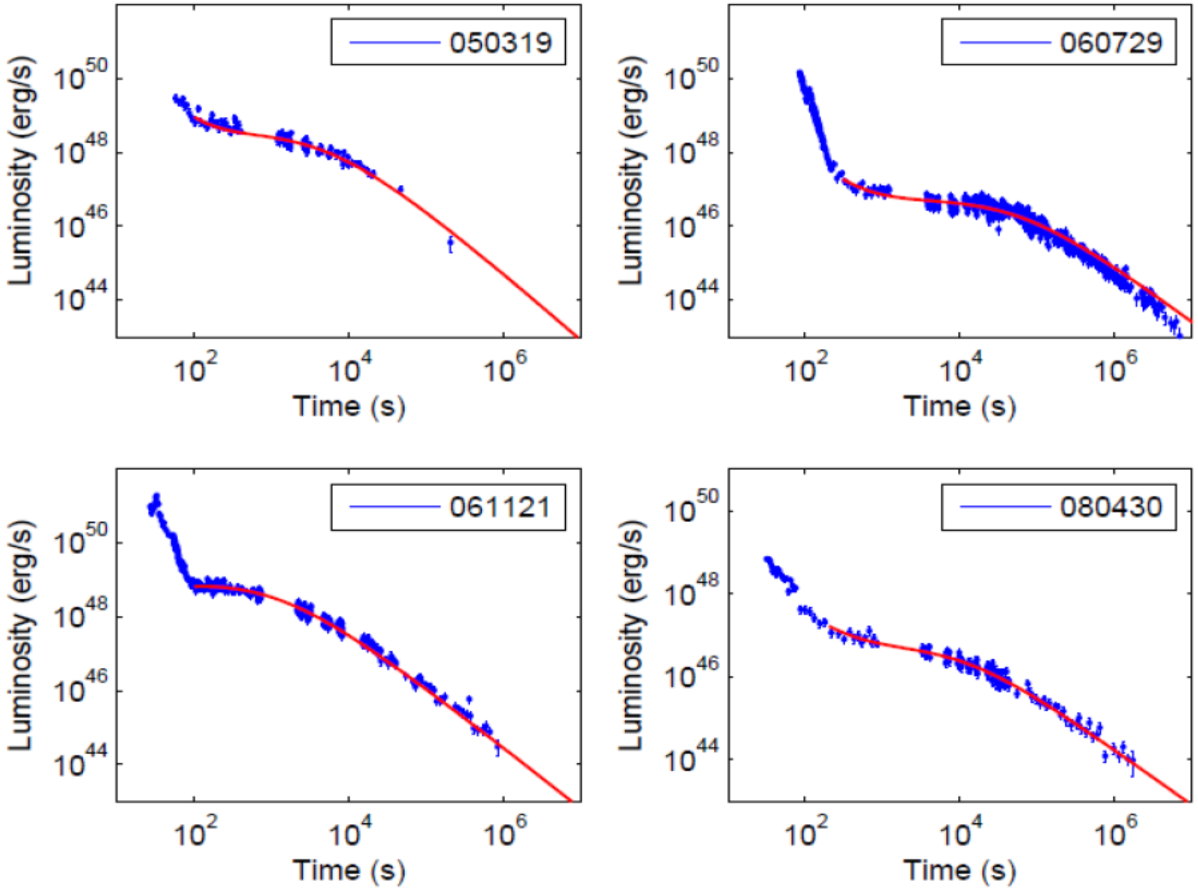
Quark deconfinement would reheat the star and generate a new mass ejection

Modeling the quasi-plateau of **long** GRBs: slow down of the protomagnetar

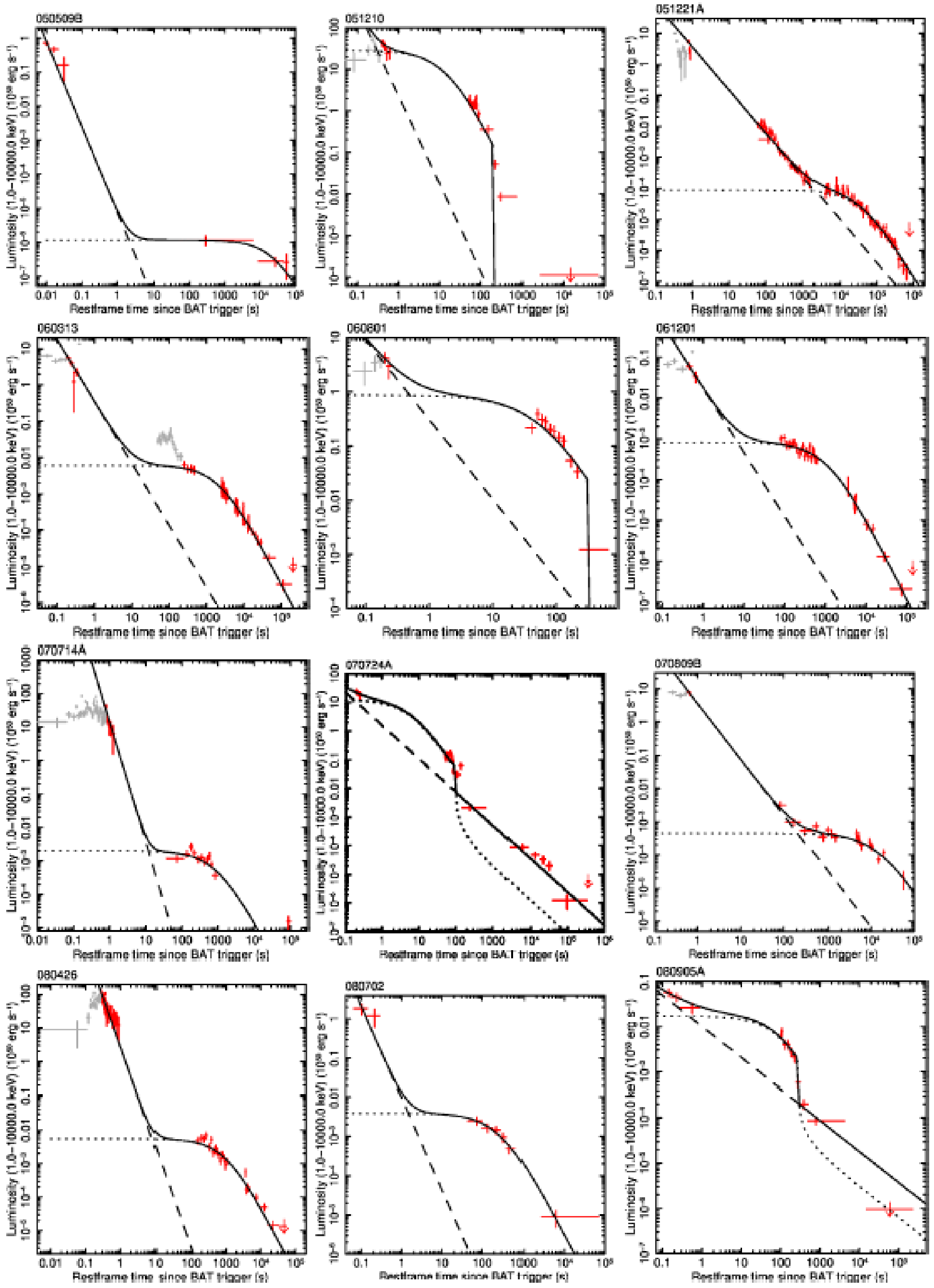
From Dall'Osso et al. 2010,

Quasi-plateau taking into account also the inter-stellar medium

$B = (0.3 - 1)\ 10^{15}$ G, $P = (1 - 3)$ ms



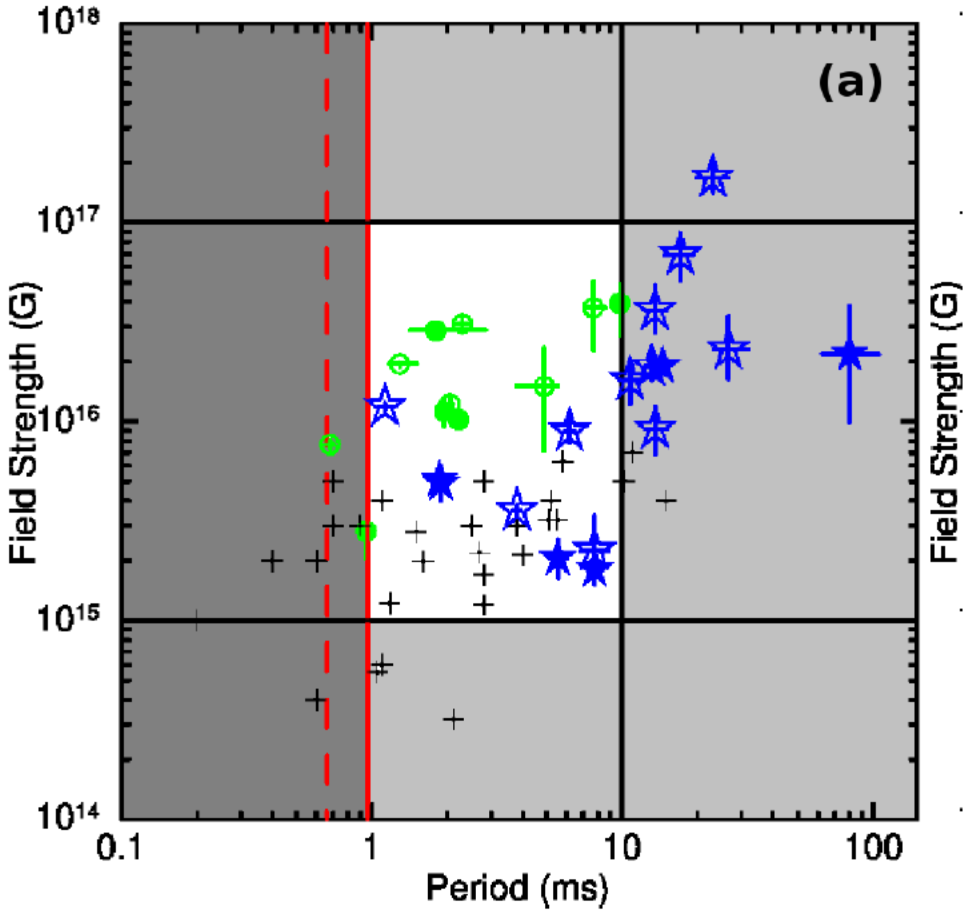
Rowlinson et al. 2013



Interpreting **short** GRBs extended emission in the same way as the quasi-plateau in long GRBs

Rowlinson et al. 2013: similarities between long and short GRBs

Similar values of B and P for long and short GRBs. B for sGRBs is roughly one order of magnitude larger than for lGRBs. Periods for sGRBs are slightly longer.



How to describe the prompt emission of short GRBs?

Long GRBs quasi-plateau **and short** GRBs extended emission are described very well by the spin-down of a rapidly rotating magnetar **with similar values of B and P**.

The promt emission of long GRBs is well described by the wind of a newly formed magnetar having values of B and P compatible with the description of the quasi-plateau. The duration of the prompt emission is of the order of the cooling time of the proto-magnetar, i.e. a few tens seconds.
During that time baryonic matter is ablated from the surface of the star by the neutrinos and accelerated by the radiation pressure.

Question: why the prompt emission of short GRBs lasts only a fraction of a second? What regulates the duration of ablation in that case?
Notice that the temperature in the short GRBs is even larger than in the long GRBs.

Prompt emission of long and short GRBs

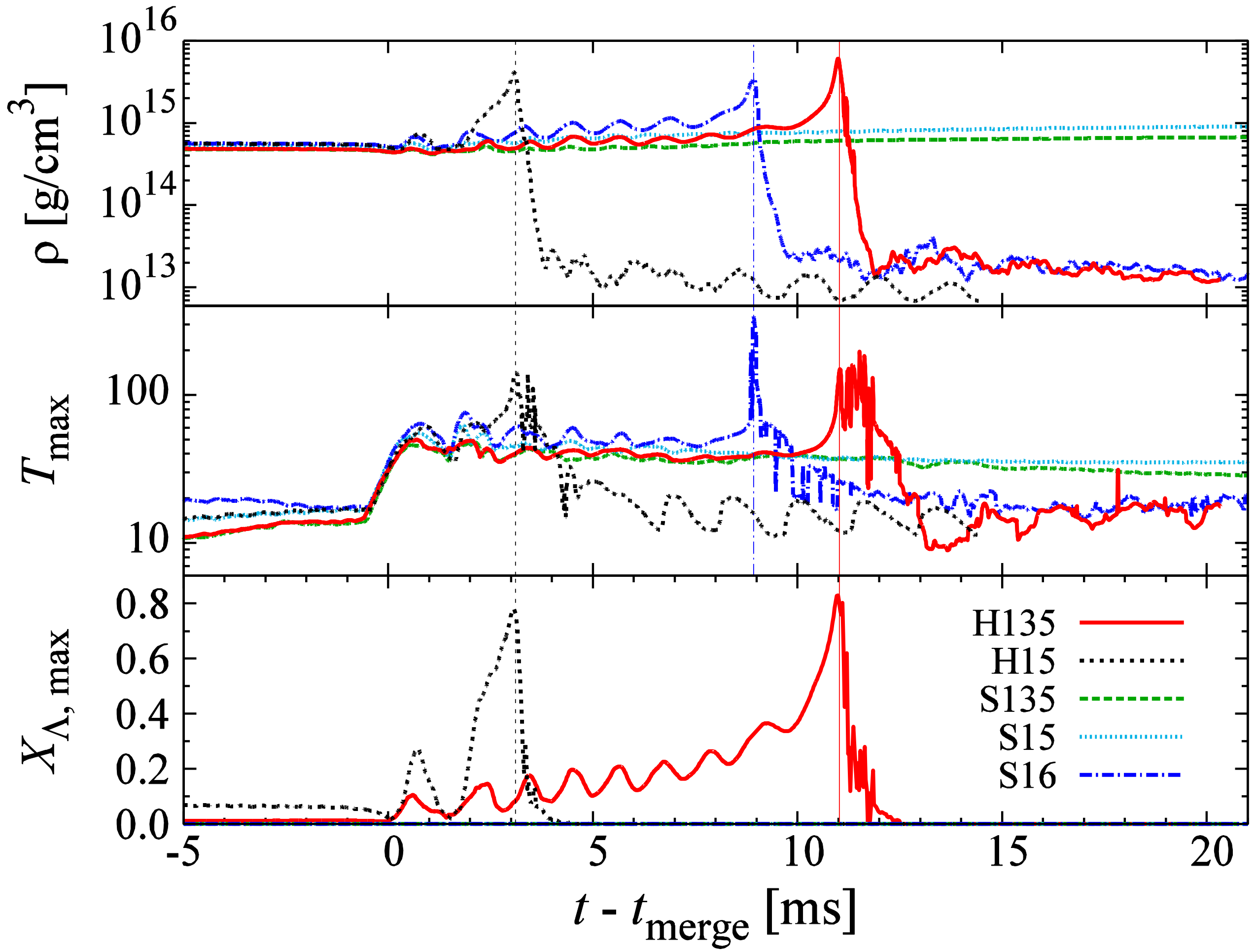
It was generally assumed that the prompt emission of short GRBs is spectrally harder than the one of long GRBs, but the differences are less evident when the sample is restricted to short GRBs with the highest peak fluxes (Kaneko et al. (2006)) or when considering only the first ~ 2 s of long GRBs light curves.

When comparing the prompt emission of short GRBs and the first seconds of long's one finds: (i) the same variability, (ii) the same spectrum, (iii) the same luminosity and (iv) the same $E_{peak} – L_{iso}$ correlation (Ghirlanda et al. 2009).

In other words, **if the central engine of a long GRB would stop after ~ 0.3 (1+z) seconds the resulting event would be indistinguishable from a short GRB** (Calderone et al. 2014).

Effects of hyperons in binary neutron star mergers

Sekiguchi, Kiuchi, Kyutoku and Shibata, Phys. Rev. Lett. **107**, 211101



Hyperons are produced a few milliseconds after the merger.

Rapid conversion of the **core** of a 1.4 Msun star

Rayleigh-Taylor instabilities develop and the conversion of the core occurs on the time scale of ms.

The rapid burning stops before the whole hadronic matter has converted (the process is no more exothermic as a hydrodynamical process, about 0.5 Msun of unburned material)

After the rapid burning the conversion proceeds via strangeness production and diffusion. The burning reaches the surface of the star after about 10-30 s.

Herzog, Roepke 2011, G.P. Herzog, Roepke 2013

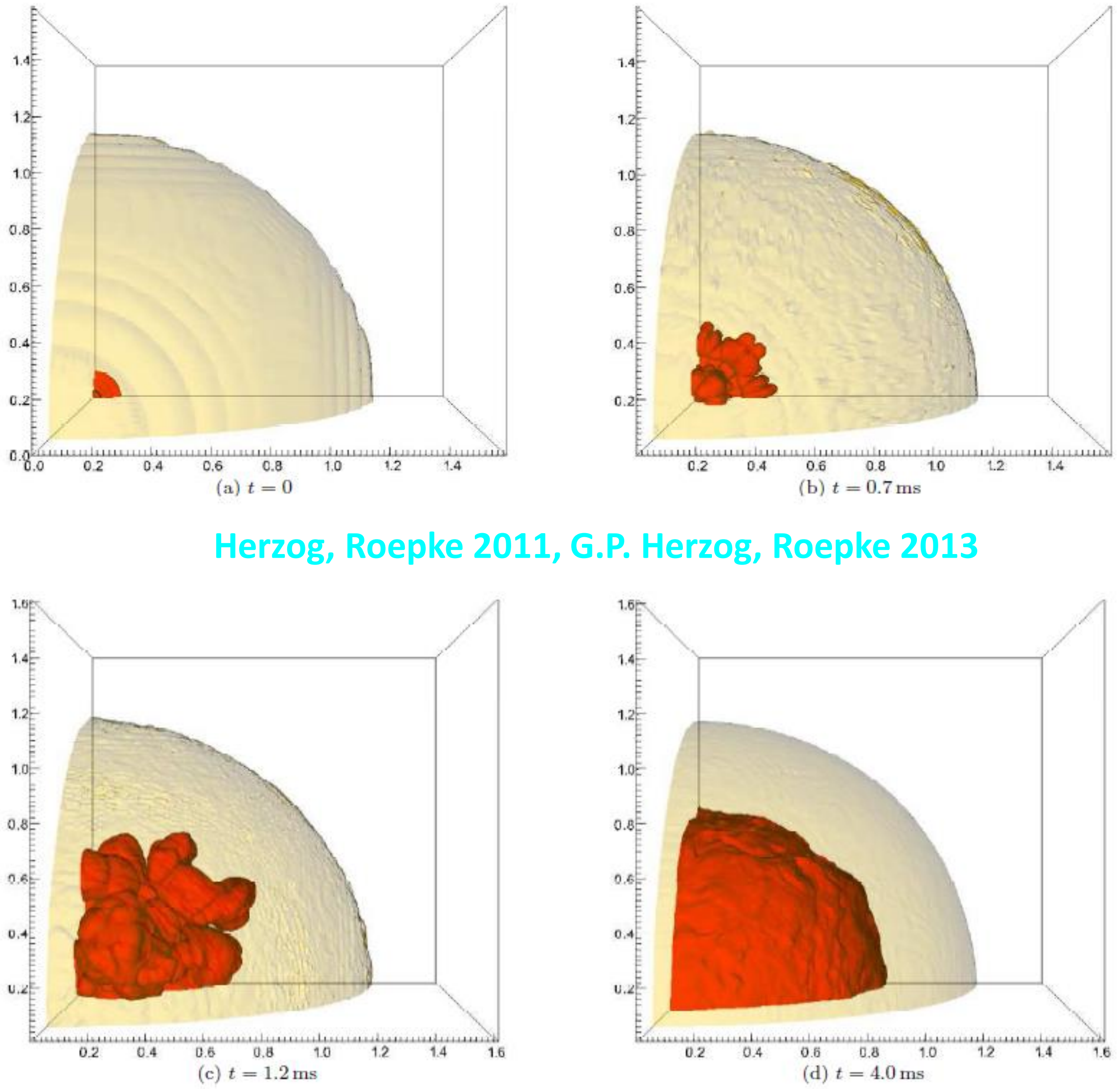
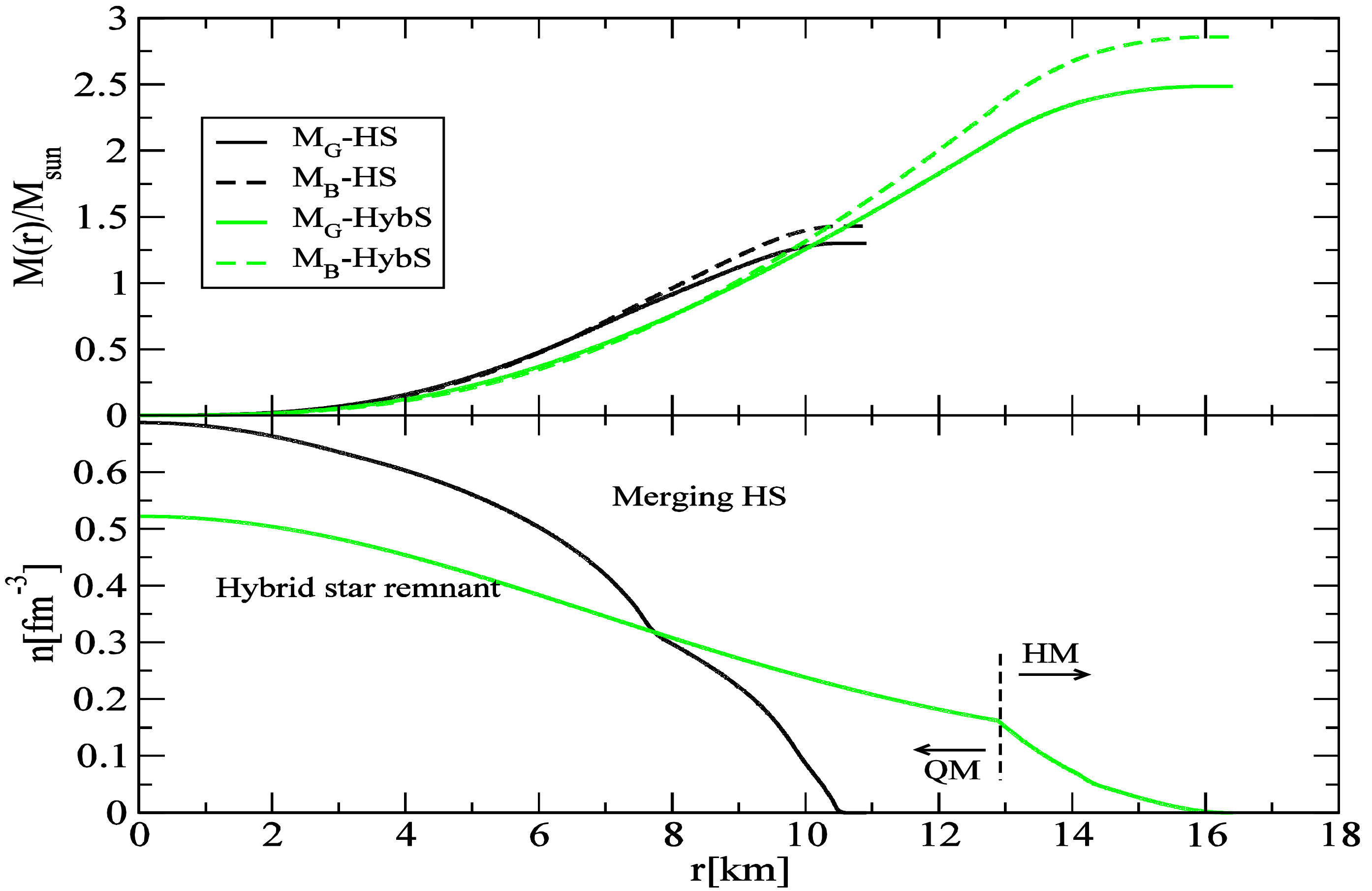


FIG. 1: (color online) Model: Set 1, $M = 1.4 M_\odot$. Conversion front (red) and surface of the neutron star (yellow) at different times t. Spatial units 10^6 cm.

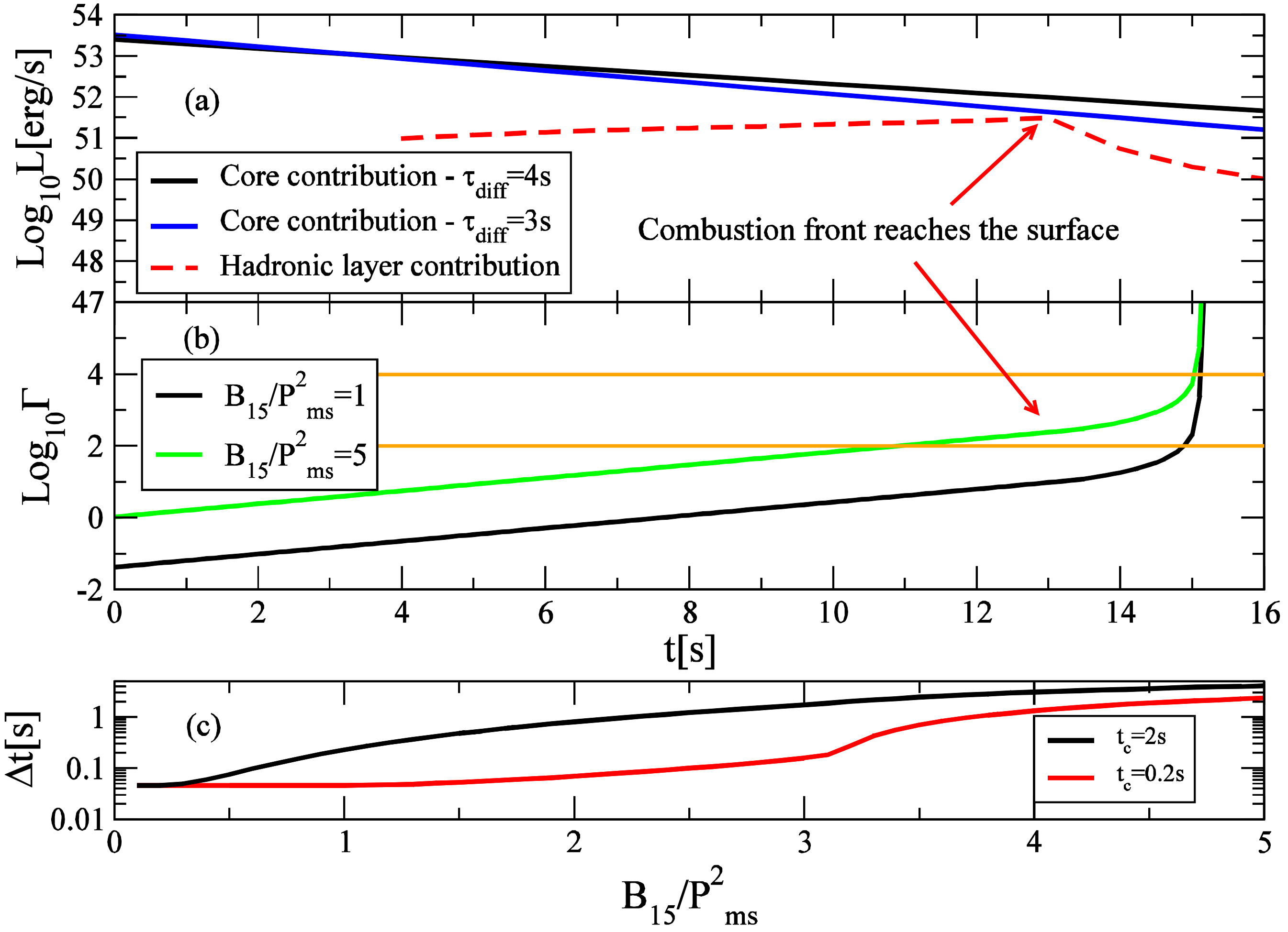
Structure of the stars before the merging and after the merging at the moment the fast burning halts



The configuration obtained after the rapid burning is mechanically stable although not yet in chemical equilibrium

Duration of the sGRB in the two-families scenario

A.D., A.Lavagno, B.Metzger, G.Pagliara paper in preparation



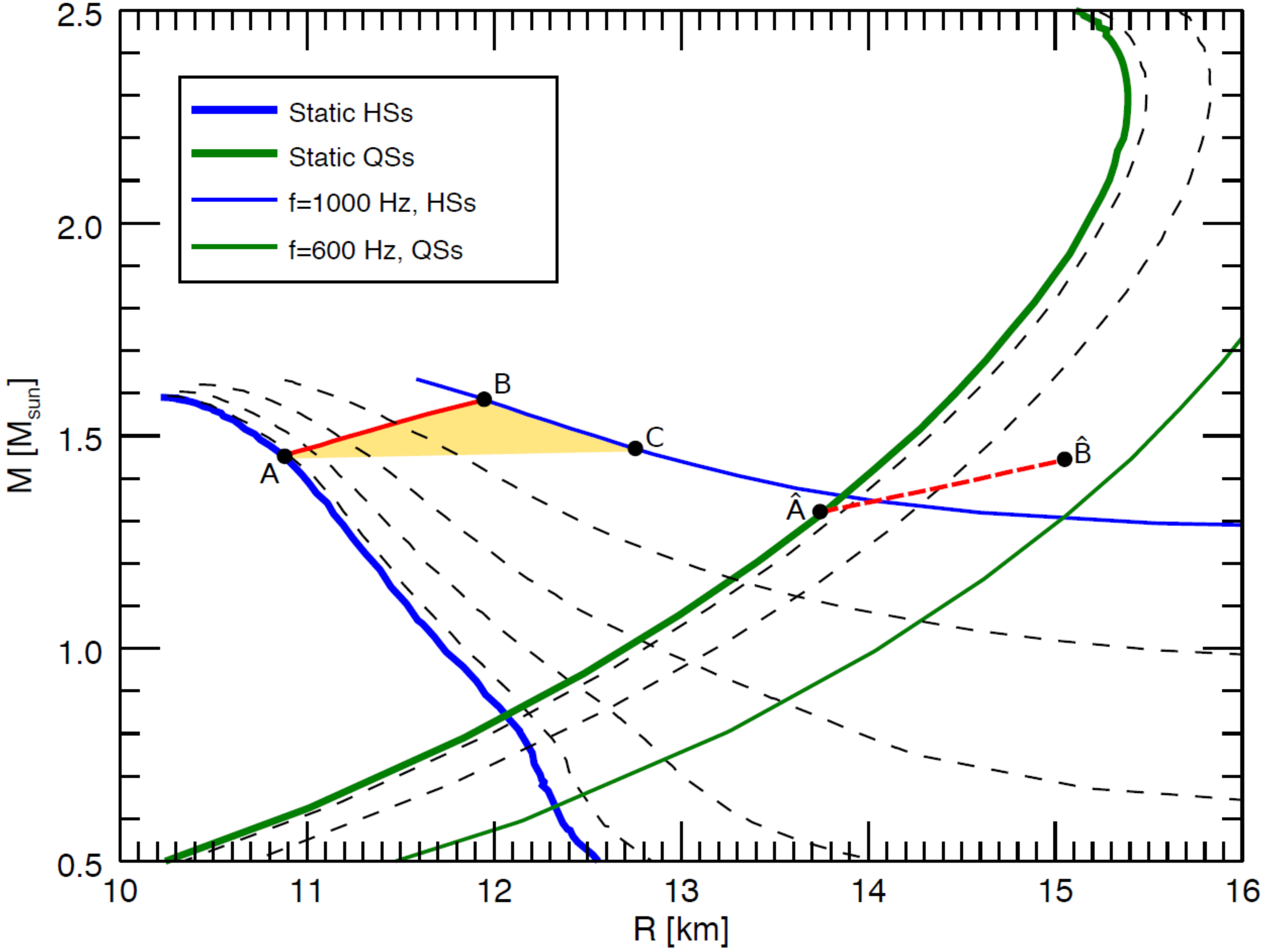
Neutrino luminosity

Magnetization or maximum Lorentz factor

Duration of the burst

Strong correlation between duration and luminosity as seen in the data Shahmoradi, Nemiroff MNRAS 451 (2015) 1

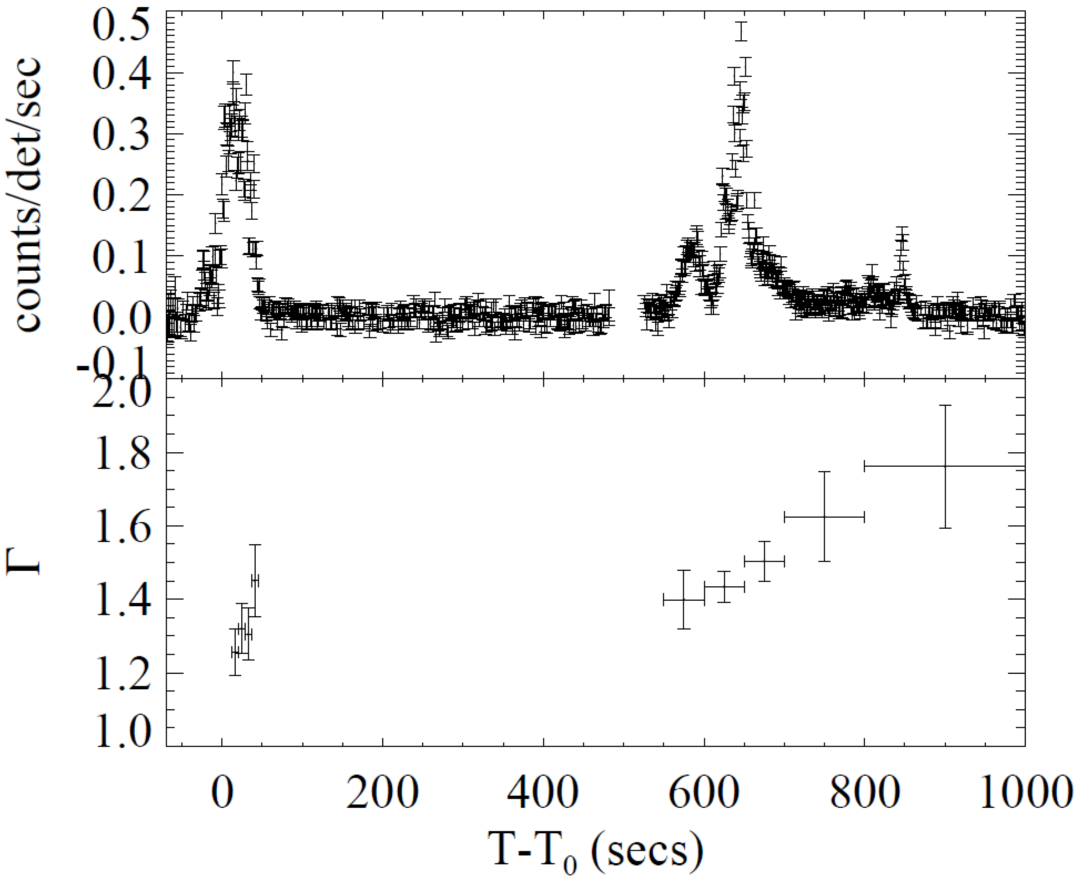
Rapid rotation and the two-families



Late-time emission of lGRBs and quark deconfinement

Table 2. Spin-down timescales to quark deconfinement Δt_{sd} together with the associated variation of the rotational kinetic energy ΔK_{sd} starting from an initial spin period P_i for the equilibrium sequences shown in figure 3. We also report the spin-down timescales Δt_{q} (defined as the time needed to half the rotational frequency of the QS) and the corresponding rotational energy loss ΔK_{q} after quark deconfinement. The initial magnetic field is of 10^{15} G.

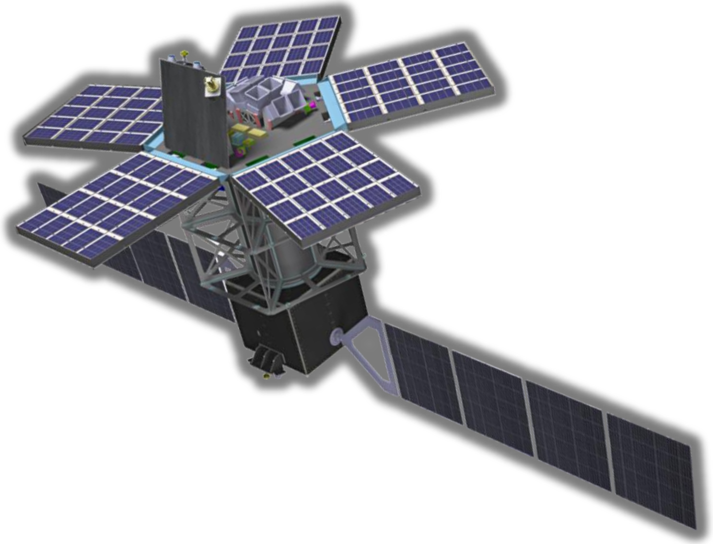
M_0 $[M_\odot]$	$P_i \rightarrow P_{\mathrm{d}}$ [ms]	Δt_{sd}	ΔK_{sd} $[10^{52}$ erg$]$	Δt_{q}	ΔK_{q} $[10^{52}$erg$]$
1.666	$1.0 \rightarrow \infty$	∞	5.91	-	-
1.677	$1.0 \rightarrow 3.3$	2.7 hr	5.48	37 hr	0.19
	$2.0 \rightarrow 3.3$	1.8 hr	0.82		
	$3.0 \rightarrow 3.3$	37 min	0.13		
1.687	$1.0 \rightarrow 2.5$	1.5 hr	5.13	21 hr	0.33
	$2.0 \rightarrow 2.5$	36 min	0.46		
1.698	$1.0 \rightarrow 2.0$	55 min	4.68	14 hr	0.53
1.733	$1.0 \rightarrow 1.4$	23 min	3.37	8.2 hr	1.20
1.785	$1.0 \rightarrow 1.1$	6 min	1.37	5.4 hr	1.95
1.820	$1.0 \rightarrow 1.0$	0	0	4.6 hr	2.41



Conclusions

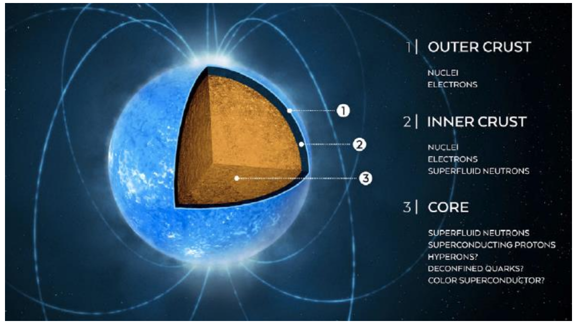
- The two-families scenario is a radical solution to the problem posed by the (possible) existence of stars with very small radii and by star with very large masses
- It provides a large set of previsions (radii, masses, moment of inertia, GW signals) all testable in future observations
- The formation of a quark star after the merger of two neutron stars allows to explain short GRBs within the proto-magnetar model
- The transition between a rapidly rotating proto-neutron star and a quark star can explain the late-time activity in long GRBs
- The model is based on the existence of quark stars and therefore on Witten's hypothesis of the metastability of ordinary matter: the confirmation of this hypothesis would constitute a revolutionary step in the understanding of nature.

X-ray Spectral-Timing: exploit the diagnostics of rapid time and spectral variability in compact sources



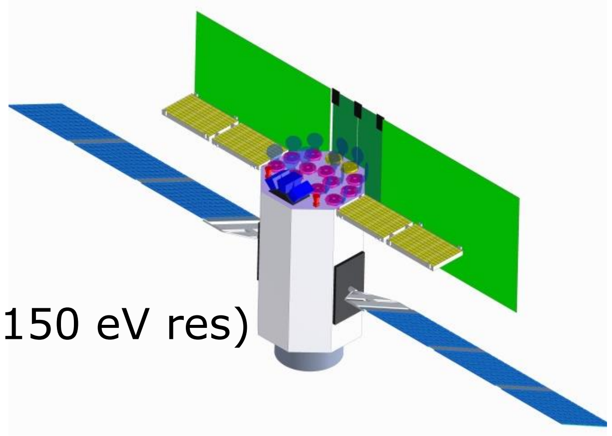
Key Science Drivers:

- Study the state and the nature of matter at extreme densities: determine the equation of state in neutron stars

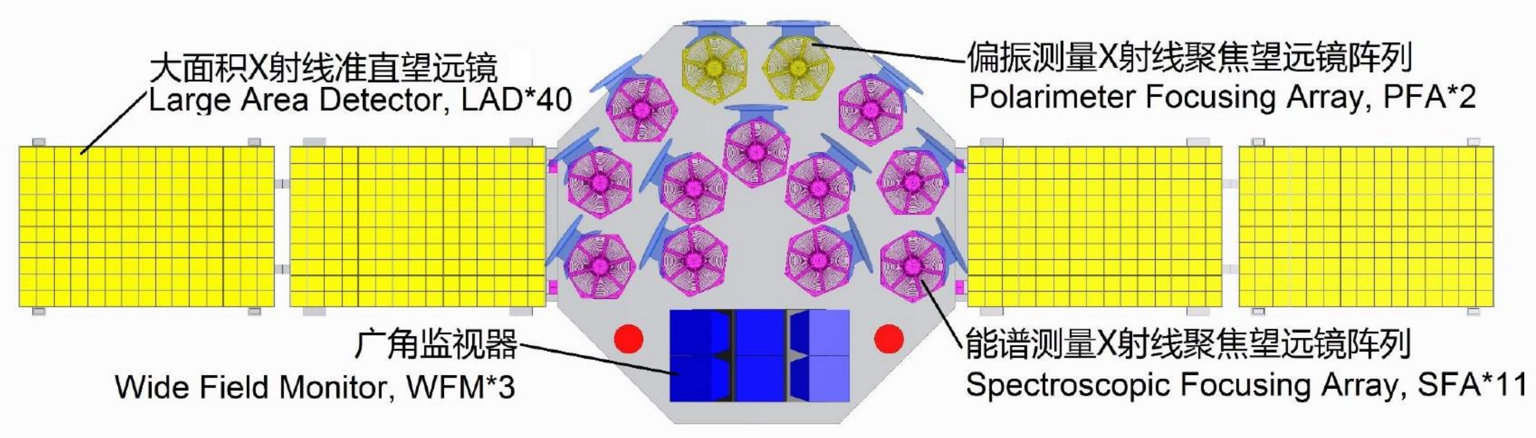


- Study the behaviour of matter under extreme gravity: verify key predictions of General Relativity in the strong-field regime near black holes and neutron stars

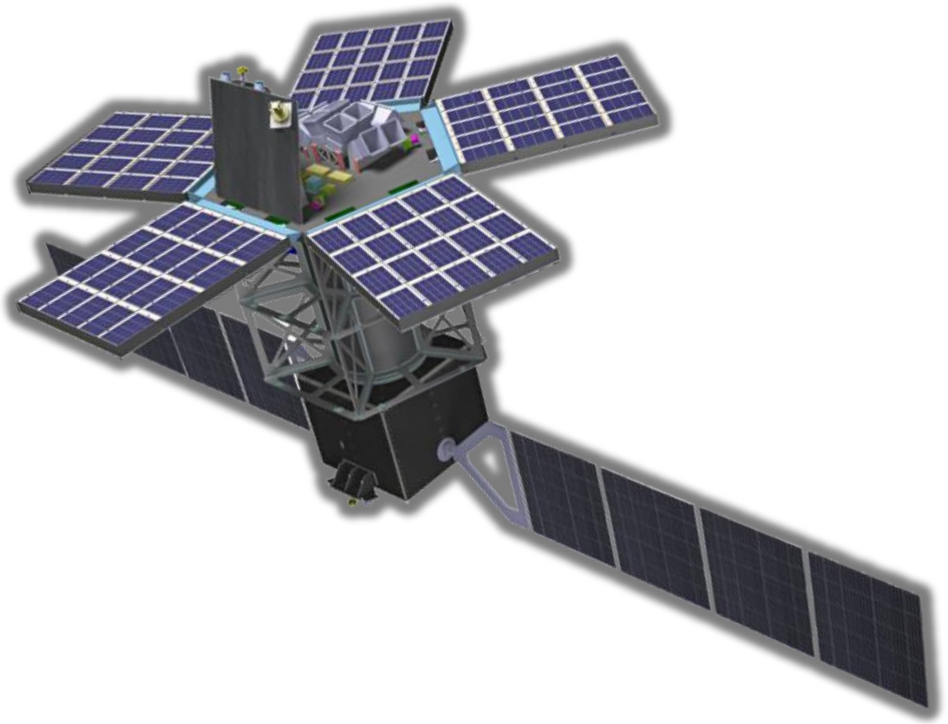
- Mission of the Chinese Academy of Sciences (CAS)
- Selected by CAS as one of 8 «Background Missions»
- Target launch in 2025



- Payload:
  - 3.5-m^2 Collimated area LAD (2-30 keV)
  - 0.9-m^2 (@1 keV) 11 telescopes (0.5-10 keV, low bkg, 150 eV res)
  - 6-camera Wide Field Monitor
  - 2 Polarimeters (2 optics, 250 cm^2 effective area)



- ESA-M5 call out on 29 April 2016
- 5 October: proposals submission deadline
- June 2017: candidate selection
- 2029: launch
- Budget boundary conditions: same as ESA-M3



NASA LOFT-PROBE

- NASA Decadal Survey 2020 process ongoing
- Strong community push for Probe-class, PI missions (<1 B$)
- NASA: task to WGs to set-up a prioritization process, still TBD
- Possible process:
  - ✓ 2-page White papers requested March 2016 (done)
  - ➢ Call for mission concepts end-2016/early-2017
  - ➢ Call for mission: early 2020's. Launch: late 2020's.

- LOFT-P (LOFT-Probe): same concept as LOFT-M3, but US-based
- NASA/MSFC funded a 5-week system study of LOFT-P with its Advanced Concepts Office (ongoing).