Compressed baryonic matter of astrophysics

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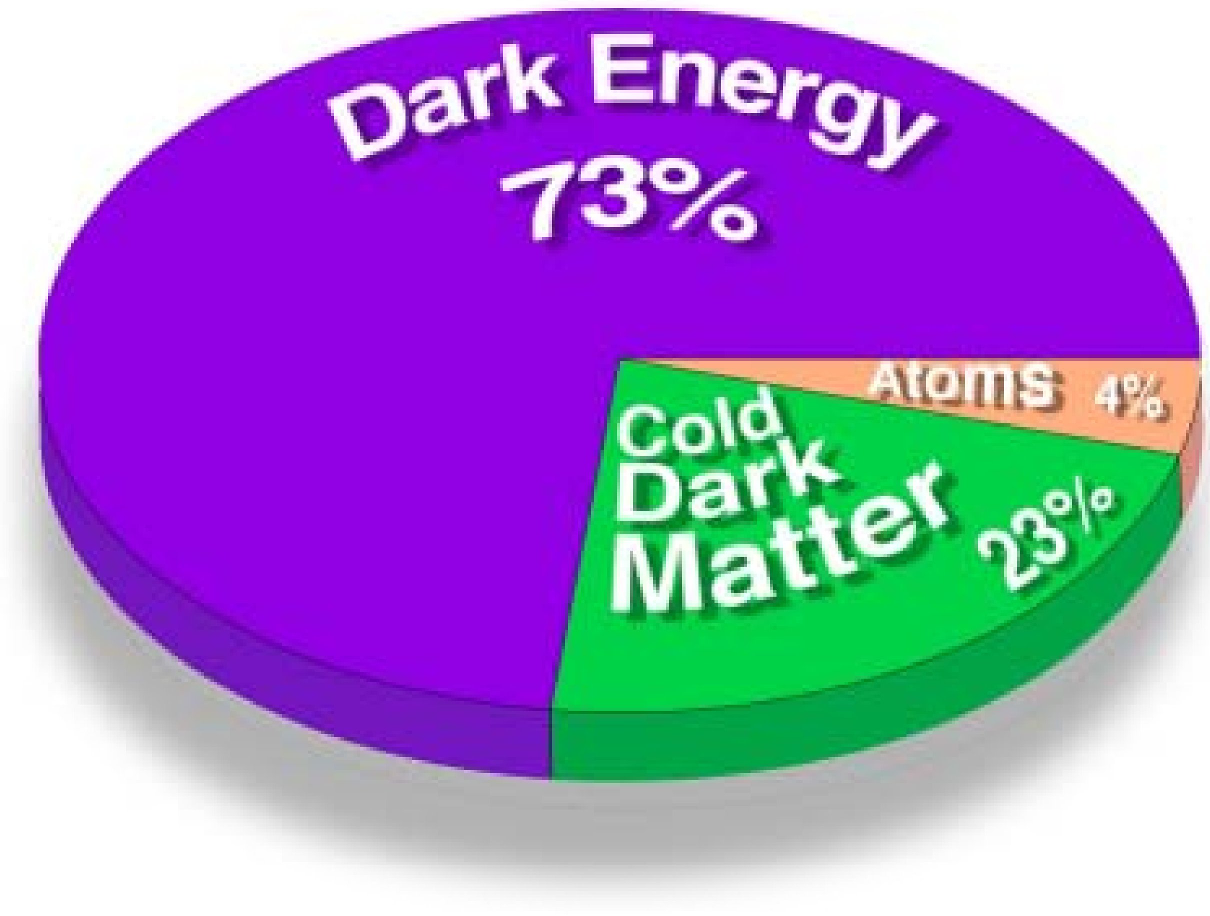
Summary

- Introduction: What's **C**ompressed **BM**?
- What do we ***know*** about CBM?
- What ***don't*** we know about CBM?
- What can ***observations*** teach us?
- Conclusions

Introduction: what's compressed BM?

- What is ***baryon***?



Our Universe is dominated by dark matter and dark energy. Nevertheless, the most familiar composition we know best is the atomic part, the ***baryons*** and ***leptons***!

Introduction: what's compressed BM?

- What is ***baryon***: the standard model of particle physics

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Baryon (a quark) = 1/3

	Leptons		Quarks（mass）	
color number	1	1	3	3
electricity	0	−1	+2/3	-1/3
1st generation	νe	e	u(2-8MeV)	d(5-15MeV)
2nd generation	νμ	μ	c(~1GeV)	s(~200MeV)
3rd generation	ντ	τ	t(~100GeV)	b(~4GeV)

	Strong	electro-magn.	Weak	gravity
Gauge Boson	gluon	photon	W, Z	graviton
Spin	1	1	1	2
number	8	1	3	1

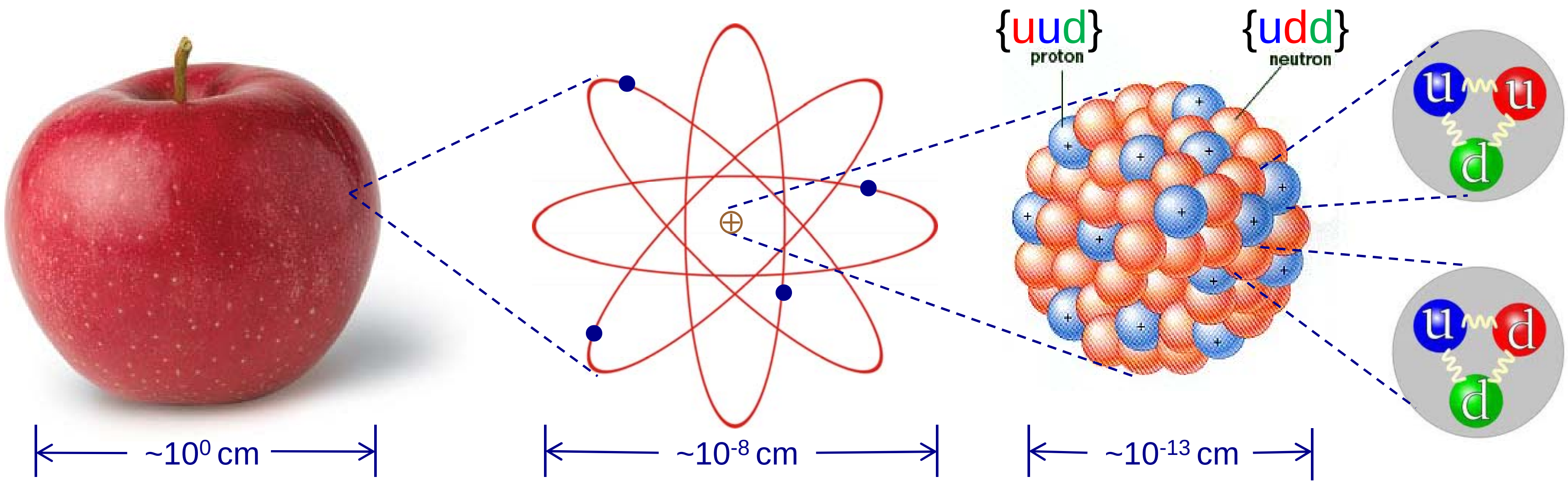
13

Higgs Boson 1

(July 2012, 5σ!)

Totally: 62

Introduction: what's compressed BM?



There is plenty of ***empty space*** between atoms…

- What if the space is squeezed out? —— high density, $> \rho_{nucl}$
- How can one squeeze space out of normal matter? —— gravity!
- Where could CBM be? —— in the heaven!

⇒ *Supernova would make CBM from atoms!*

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What do we know about CBM?

- Baryon number~10^{57}!→*medium effect significant*
- Density > ρ_{nucl} if *considering nuclei as gravity-free*

What do we know about CBM?

- Energy scale $E_{\text{scale}} \sim 400\text{MeV}$ by either Heisenberg's relation or Fermi energy $\Rightarrow$

  - ***Strangeness*** because of $E_{\text{scale}} > m_s \sim 100\text{MeV}$ ~~heavy quarks~~
  - Strong ***NQCD*** effects because of $E_{\text{scale}} < 1\text{GeV}$

- $\sim 10^{57}$ quarks there and, by comparing with other forces, color interaction should play an important role in determining EoS,

but … what's more?

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What don’t we know about CBM?

- Confinement or de-confinement in CBM?

  A challenging problem!

Scenarios suggested?

Hadron star: quarks confined

Quark star: quarks de-confined

Hybrid/mixed star

Quark-cluster star: quarks grouped in clusters

(> **6**, rather than 3, grouped in a cluster of CBM possible?)

Gravity-bound (Hadron star; Hybrid/mixed star)

Self-bound on surface (Quark star; Quark-cluster star)

What don't we know about CBM?

- 3-flavor symmetry in CBM?

{u,d}		{u,d,s}	
nucleus	gigantic one	nucleus	gigantic one
electron outside ⇓ $E_e \ll$ MeV	electron inside ⇓ $E_e \sim 100$ MeV	electron outside ⇓ $E_e \ll$ MeV	electron inside ⇓ $E_e \sim 10$ MeV
stable	$e+p \rightarrow n+\nu_e$ E_e decreases but E_{sym} increases	unstable due to surface energy	stable

⇒ ***CBM: strange quark-cluster matter*?**

What don't we know about CBM?

- What if CBM is made of quark-cluster matter?

Stiff EoS (**NR** clusters, repulsion, 3-body?)

$E = (c^2p^2+m^2c^4)^{1/2} \sim p^2 \rightarrow P \sim \rho^\gamma \; (\gamma > 1!)$

Self-bound by residual interaction between clusters

Global solid if kT < residual interaction energy

→ Free energy elastic and gravitational

and…***How to*** model quark-cluster matter stars?

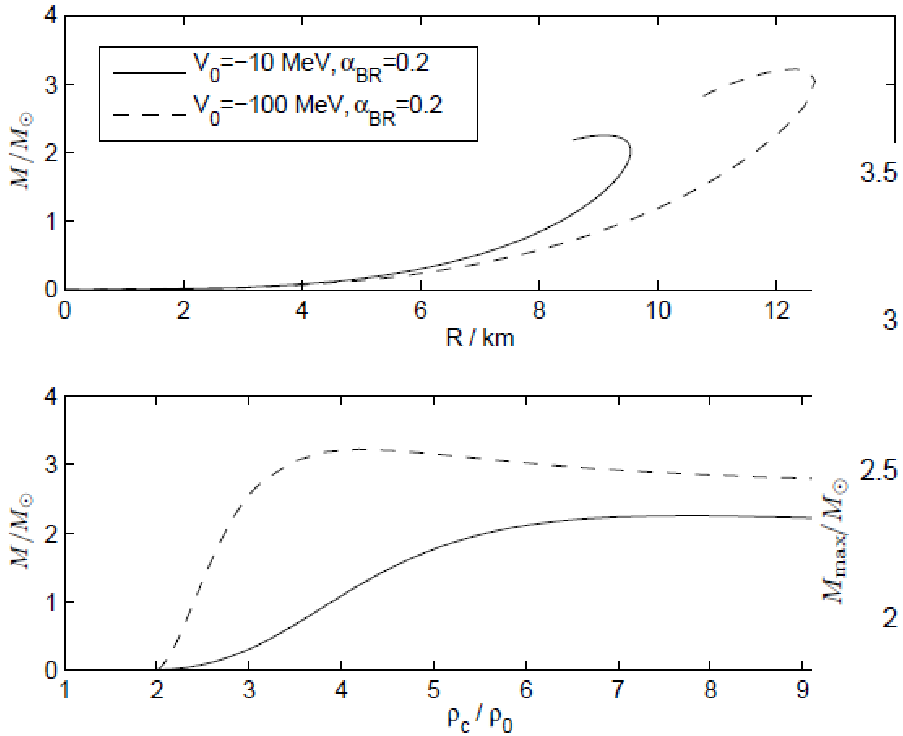
Very difficult from first principles,

but phenomenologically …

What if CBM is made of quark-cluster matter?

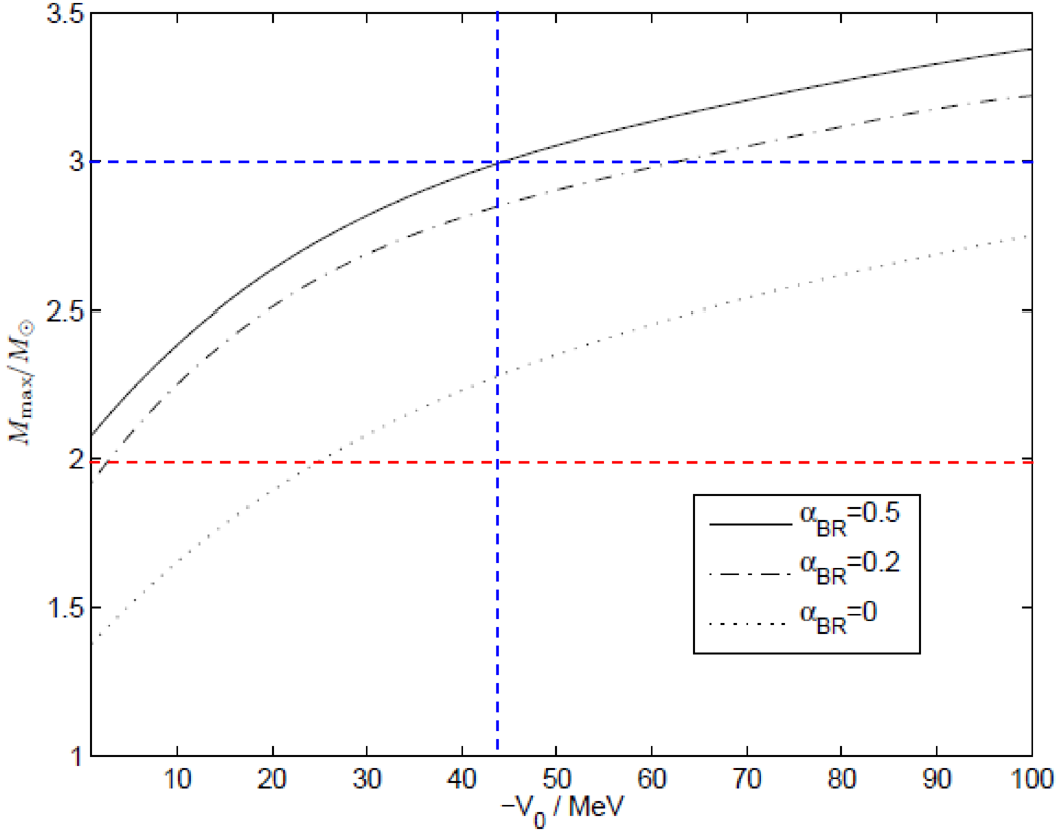
- A realistic quark cluster: ***H-star***?

Assuming ***interaction*** between H's is mediated by σ-ω mesons,



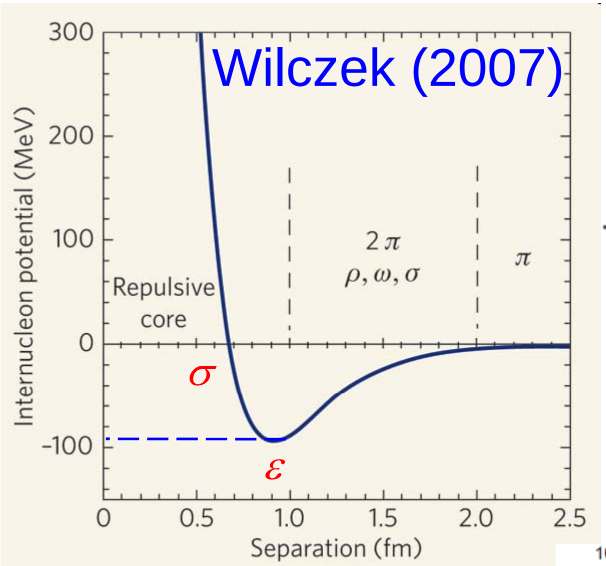
M-R, M-ρ_c

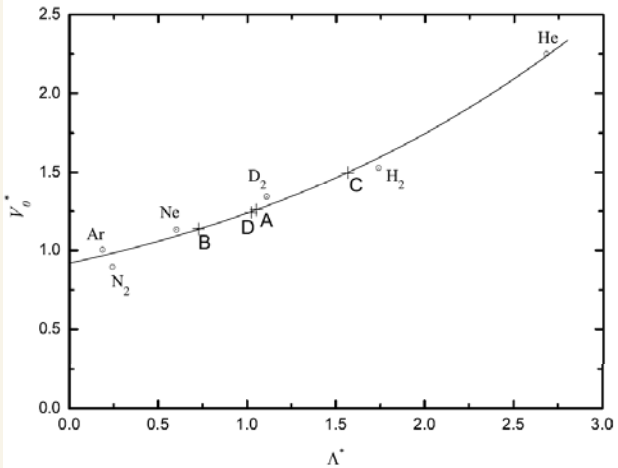
$M_{\rm max}$-V_0

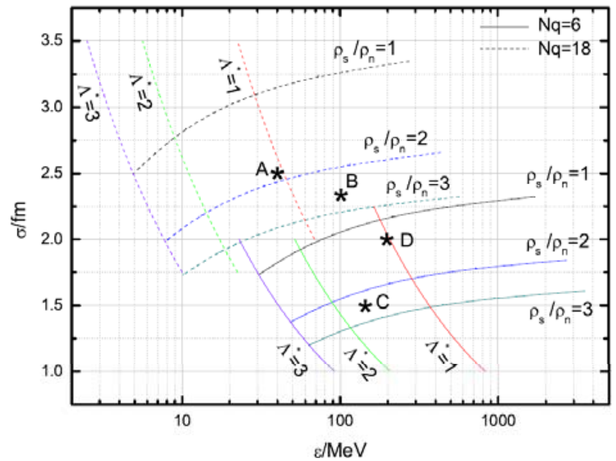


What if CBM is made of quark-cluster matter?

• A ***corresponding-state*** approach to …







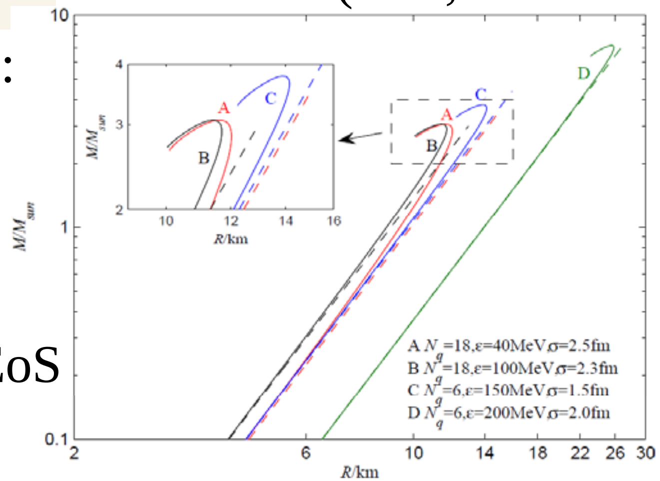
• The results (Guo, Lai & Xu; arXiv1209.3688):

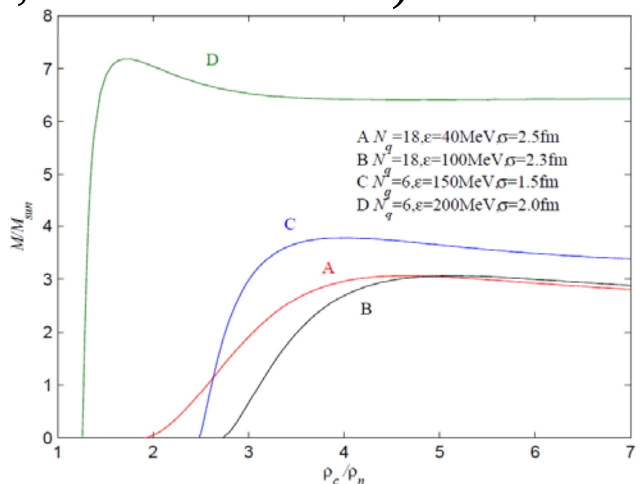
• Dimensionless parameters:

$$P^* = P\sigma^3/\varepsilon$$
$$V^* = V/(N\sigma^3)$$
$$T^* = kT/\varepsilon$$
$$\Lambda^* = h/(\sigma\sqrt{m\varepsilon})$$

• Corresponding state law EoS

$$P^* = f(V^*, T^*, \Lambda^*)$$





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What can observations teach us?

- Observational hints for the nature of CBM:
  - $2M_{\rm sun}$ psr: Stiff EoS!

A mass gap?

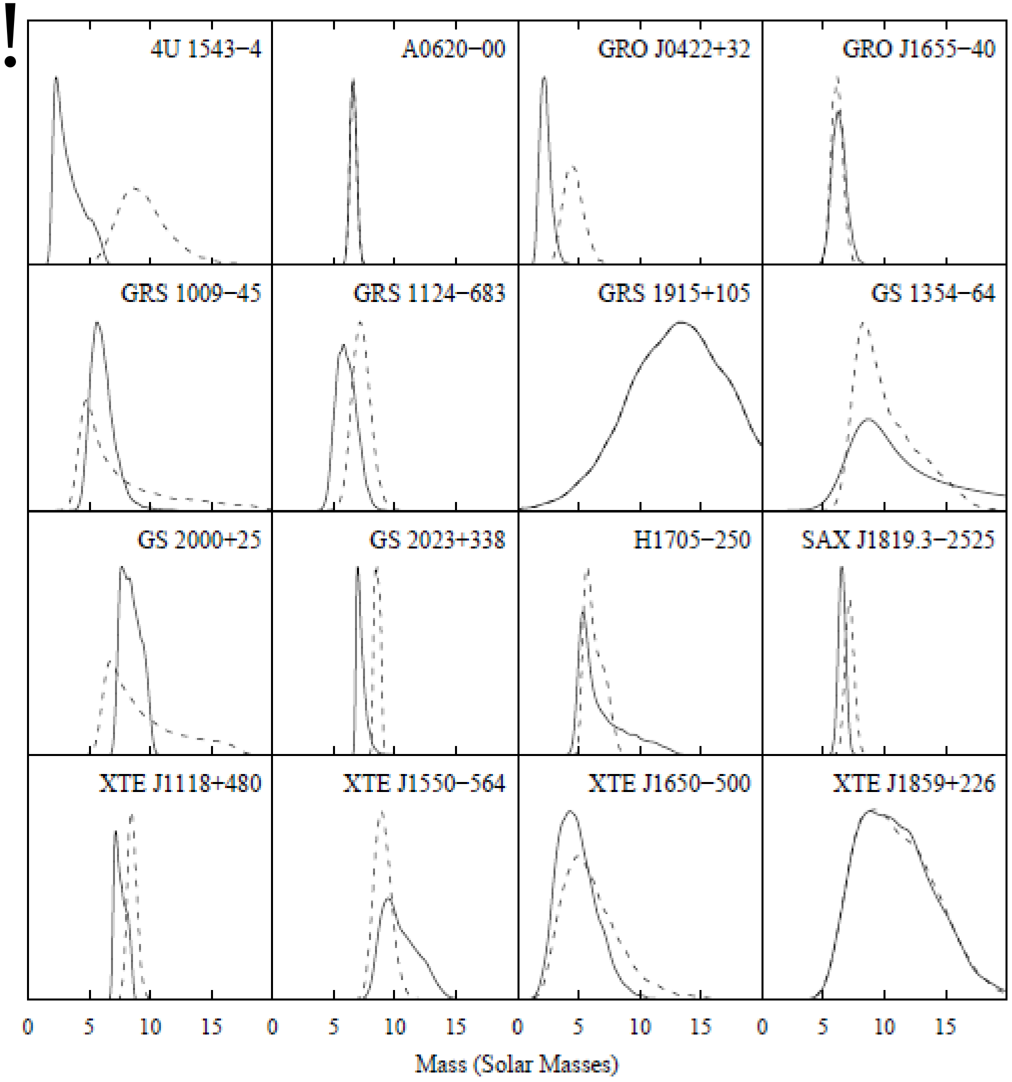
$M_{\rm psr}$ detected < 2 $M_{\rm sun}$

$M_{\rm BH}$ detected > 5 $M_{\rm sun}$

$$m_{\rm BH} = \frac{f(1+q)^2}{\sin^3 i}$$

GRO J0422+32

4U1543-47



Kreidberg et al. (2012)

What can observations teach us?

- Observational hints for the nature of CBM:
  - * Self-bound surface

Subpulse drifting: strong B-field vs. self-bound on surface (Xu et al. 1999, Qiao et al. 2004)

Nonatomic spectra: strong B-field vs. self-bound (Xu. 2002)

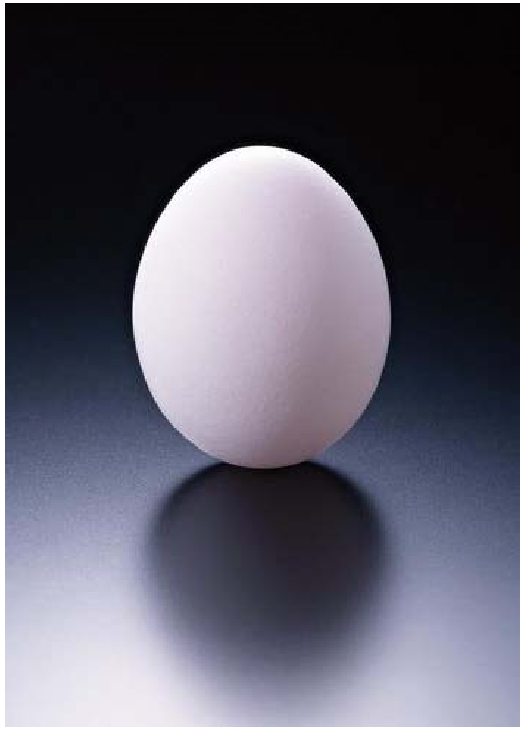
Clean fireball for SNE & GRB? (Ouyed et al. 2005; Paczynski & Haensel 2005; Chen et al. 2007)

Linear **poln**% (B, ∇T)!

What can observations teach us?

- Observational hints for the nature of CBM:
  - * Precession, free or forced

(Xu. 2003)

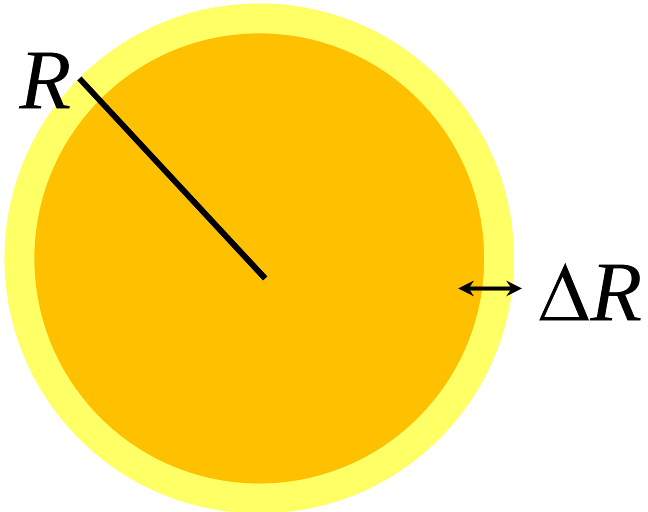


Pulsars B1821-11: *precession* or even *free precession*?

(Stairs, Lyne & Shemar, 2000, Nature, 406, 484)

What can observations teach us?

- Observational hints for the nature of CBM:
  - ∗Huge free energy: B-field vs. quake? (Xu et al. 2006)



$$E_{\rm stored} \approx \frac{GM^2}{R} \sim 10^{53} \frac{\Delta R}{R}\ \text{ergs}$$

for $M \sim M_\odot$

AXP/SGRs: bursts/glitches, flares, even superflares

magnetars vs. *solid quark-cluster stars*?

What can observations teach us?

•Observational hints for the nature of CBM:

∗Low-mass compact stars? (KRCS, PMCS)

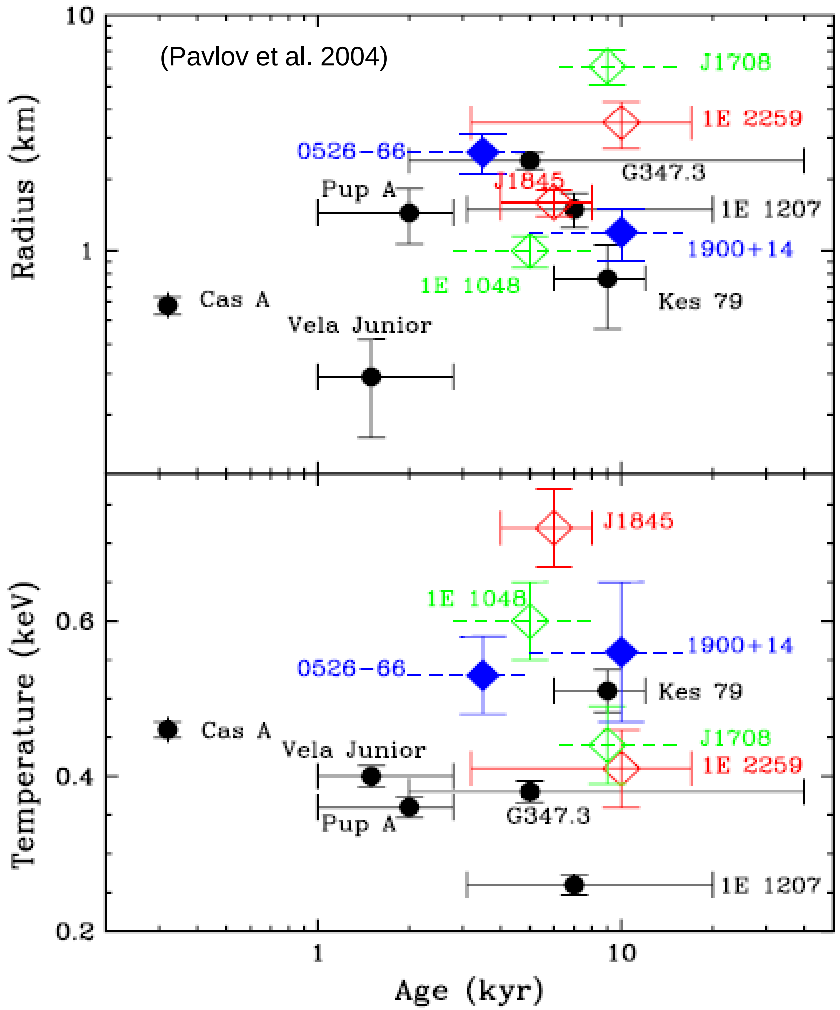


Figure 1. Age dependences of BB radius and BB effective temperature for CCOs (filled circles), AXPs (open diamonds) and SGRs (filled diamonds). For objects with known SNR association, estimated SNR ages are used (solid horizontal error-bars) while for four magnetars (marked with horizontal dash lines) we use spin-down ages.

Km-radius compact star?

Planet-mass compact star?

PSR J1719-1438

(Horvath 2012)

PSR B1257+12

(Xu et al. 2003)

What can observations teach us?

- Observational hints for the nature of CBM:
  - *X-ray bursts on surface: evidence for crust?

    Elaborate modeling in NS model!

    Can it be reproduced in quark-cluster star model?

    The key is to have unstable energy release during accretion: either thermal nuclear flash on crust formed above quark-cluster star or star-quake-induced burst.

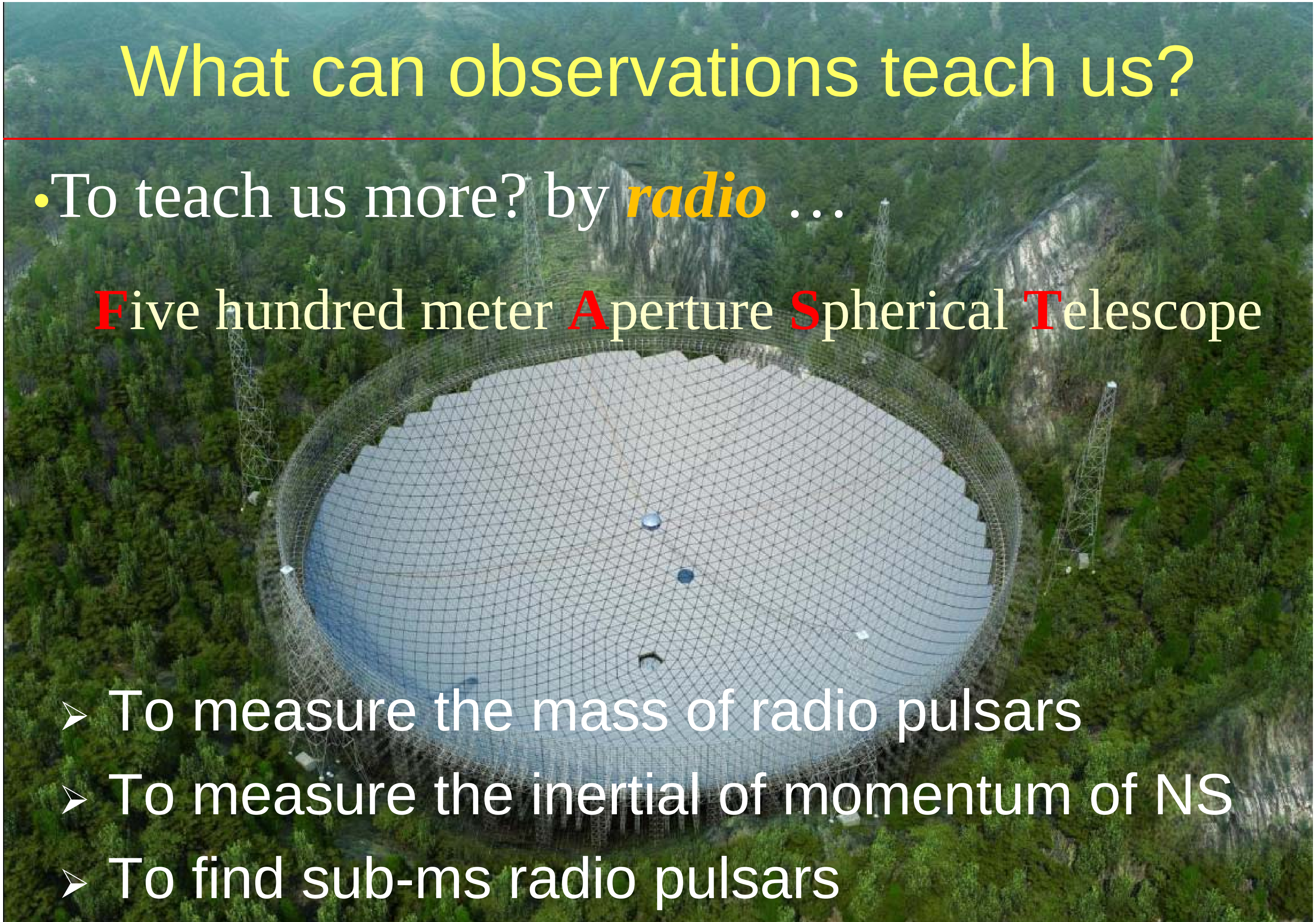
  - *Others: cooling, glitch and braking…?

(Blaschke et al. 2012; Negreiros et al. 2012; Glendenning, Pei ,Weber 1997)

What can observations teach us?

•To teach us more? by ***radio*** …

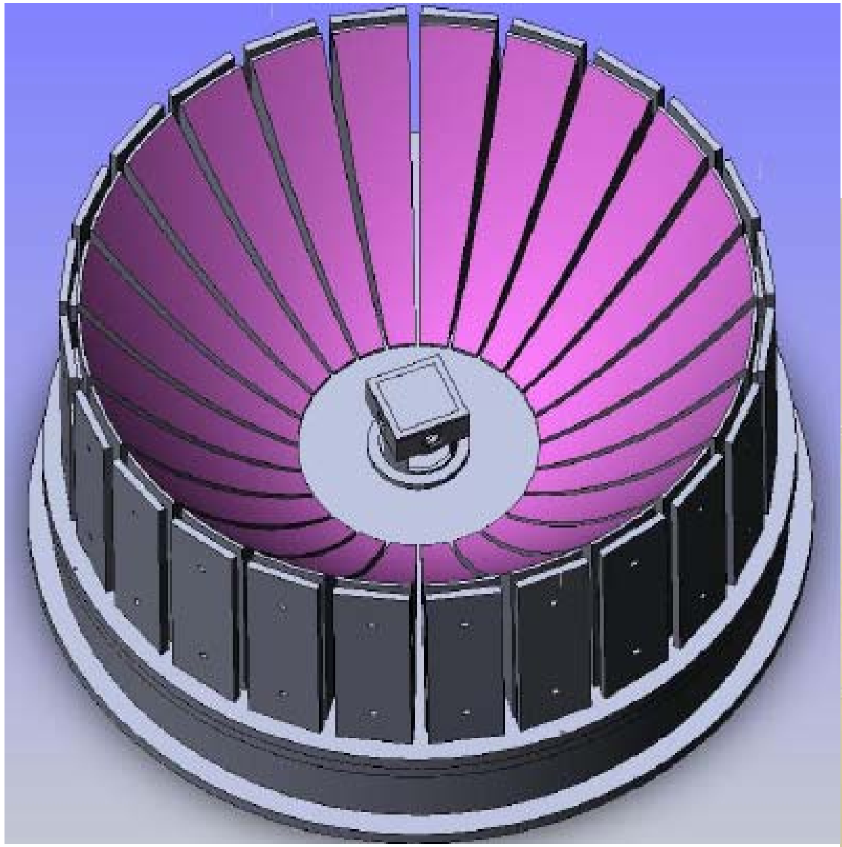
Five hundred meter **A**perture **S**pherical **T**elescope



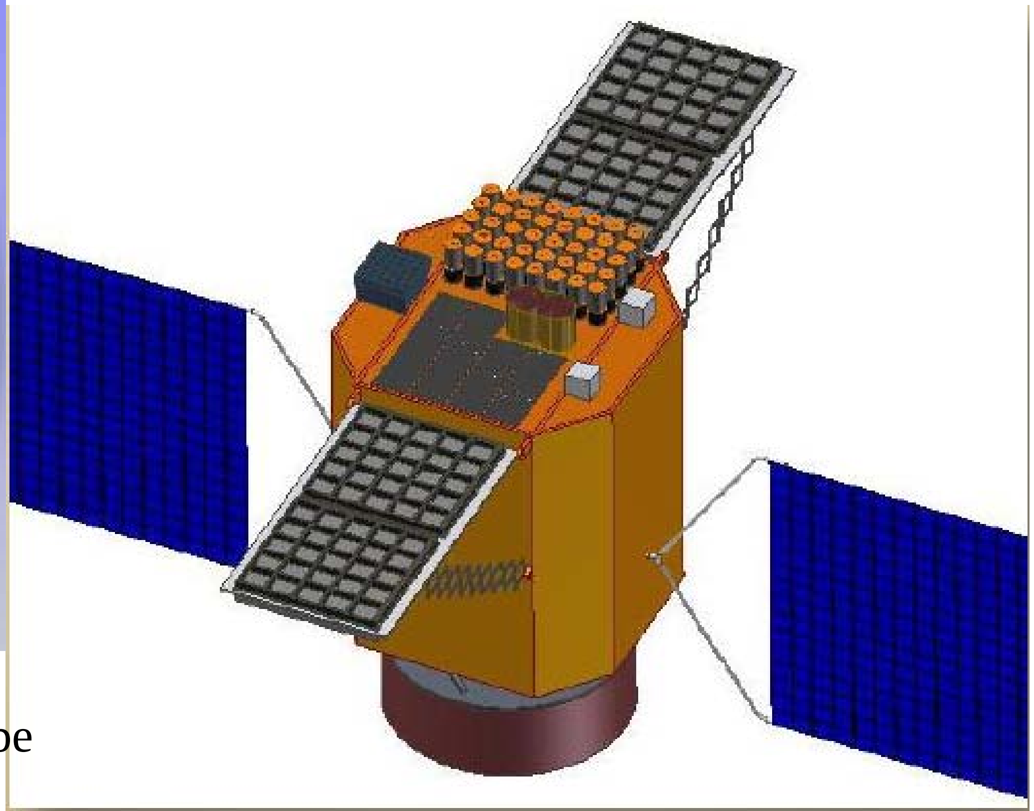
- To measure the mass of radio pulsars
- To measure the inertial of momentum of NS
- To find sub-ms radio pulsars

A new answer: quark-cluster matter?

- To teach us more? by X-ray ***polarization*** …



X-ray **T**iming and **P**olarization



Lightweight **A**symmetry and **M**agnetism **P**robe

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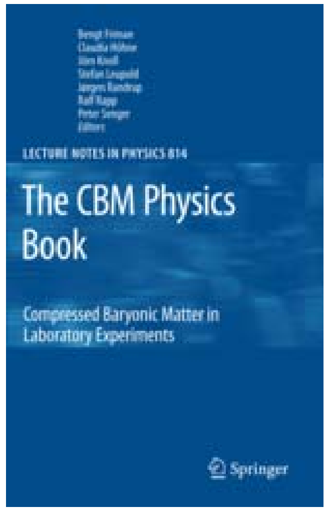
Why study **C**ompressed **B**aryonic **M**atter, or more generally strongly interacting matter at high densities and temperatures? Most obviously, ***because it's an important piece of Nature.*** The whole universe, in the early moments of the *big bang*, was filled with the stuff. Today, highly compressed baryonic matter occurs in neutron stars and during crucial moments in the development of *supernovae*. Also, working to understand compressed baryonic matter gives us new perspectives on ordinary baryonic matter, i.e. the matter in *atomic nuclei*. But perhaps the best answer is a variation on the one George Mallory gave, when asked why he sought to scale Mount Everest: Because, as a prominent feature in the landscape of physics, it's there. Compressed baryonic matter is a material we can *produce in novel, challenging experiments* that probe new extremes of temperature and density. On the theoretical side, ***it is a mathematically well-defined domain*** with a wealth of novel, challenging problems, as well as wide-ranging connections. Its challenges have already inspired a lot of very clever work, and revealed some wonderful surprises, as documented in this volume.

------ Frank Wilczek (2011)

"*Prelude to compressed baryonic matter*"

《The CBM Physics Book》

(Springer-Verlag Berlin Heidelberg)



Conclusions