Nuclear Astrophysics: From The Beginning of Time to the End of the Universe

Nuclear Physics, the Core of Matter, the Fuel of Stars (Schiffer Fest)

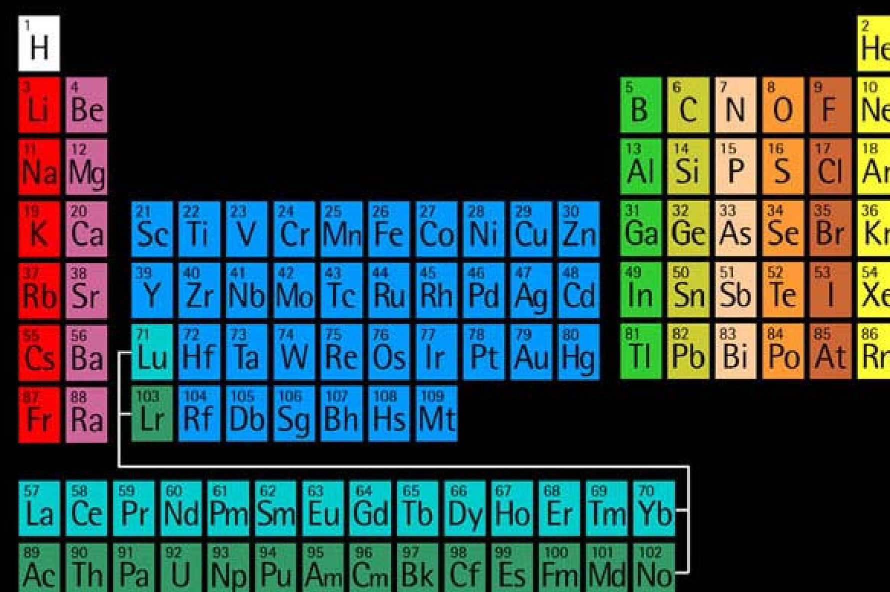
September 22, 2006

Michael S. Turner
Kavli Institute for Cosmological Physics

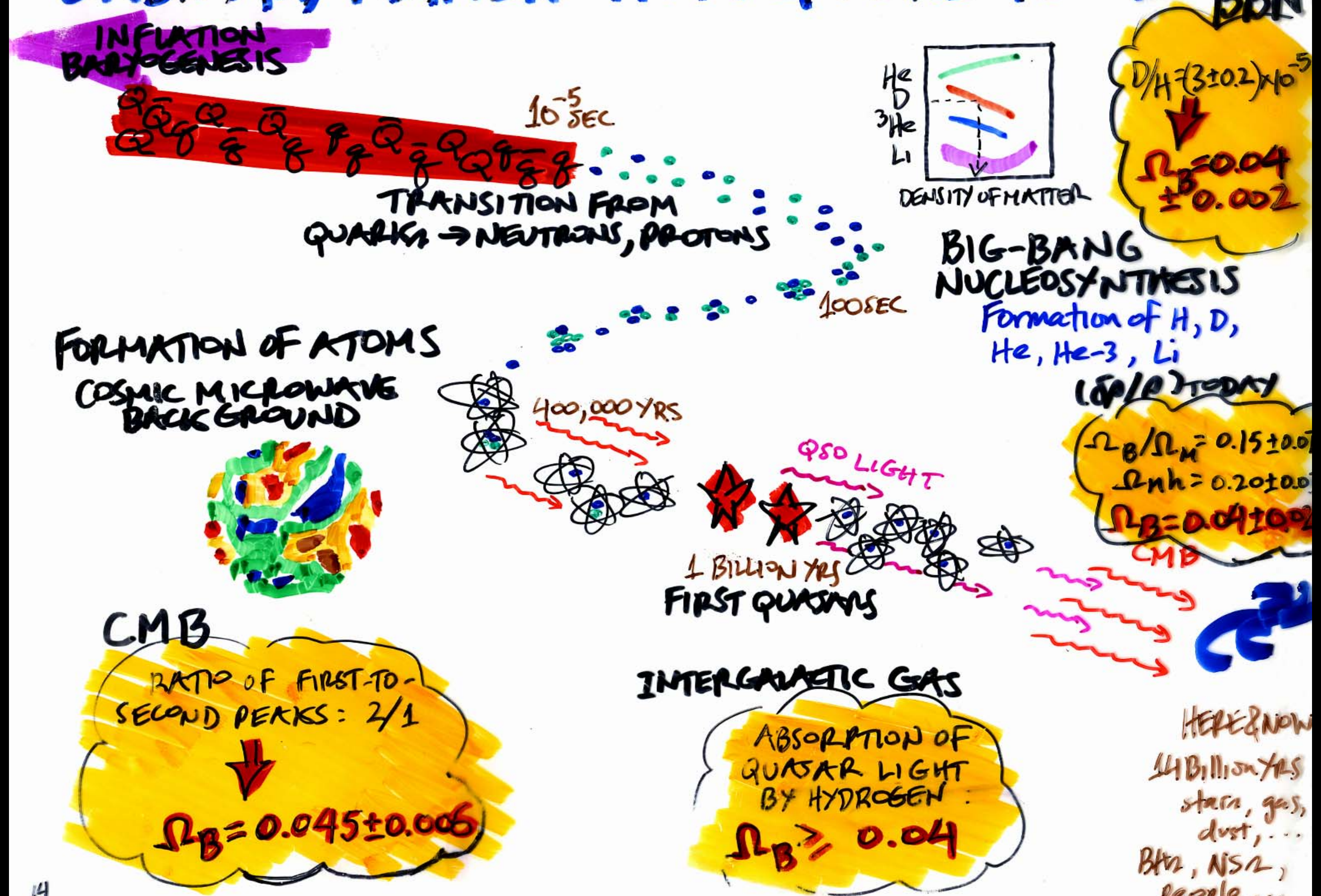
Chemists like to say,
“Chemistry makes the world run, from energy and materials to life here and beyond”

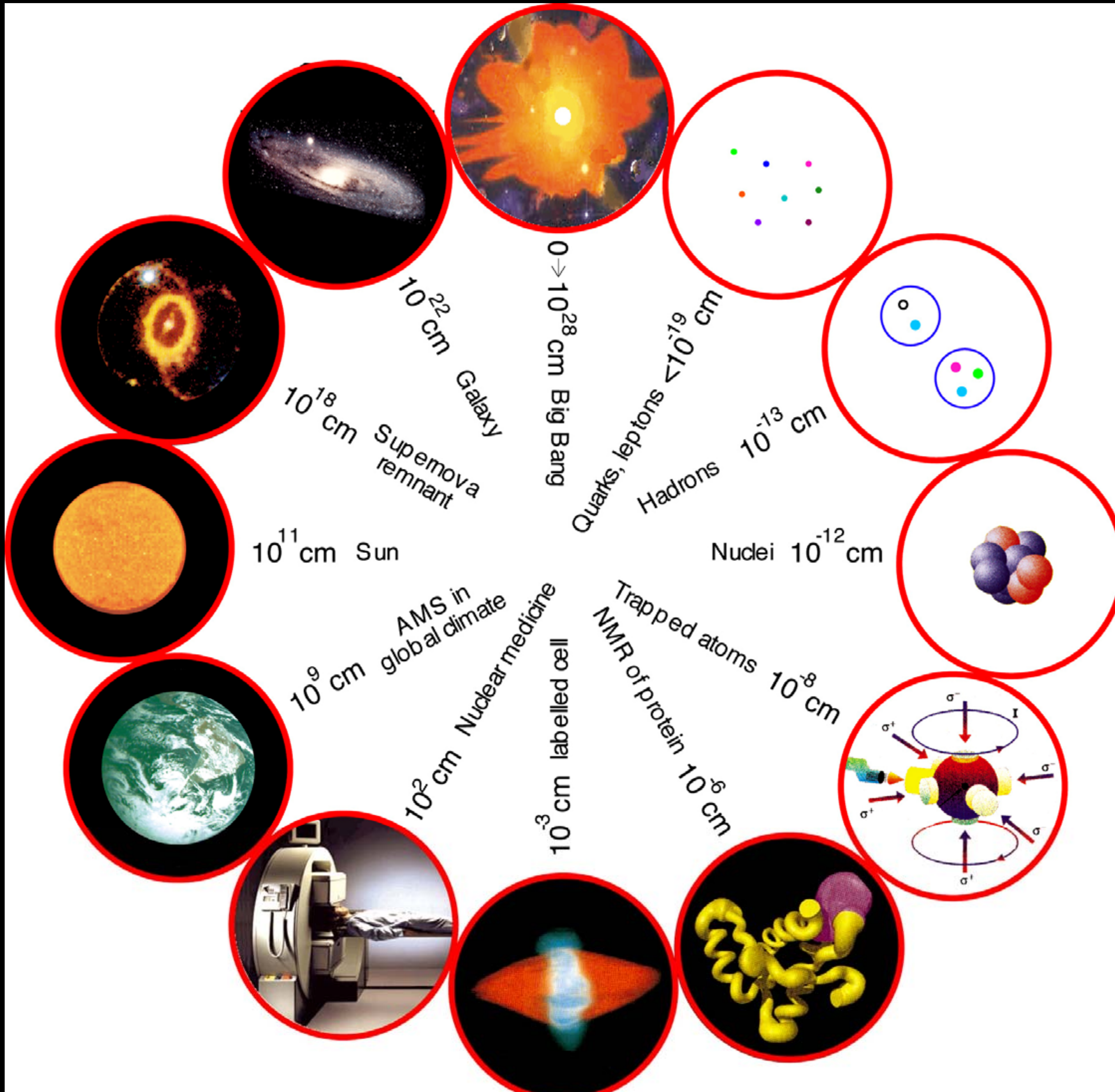
However, without Nuclear Physics there would only be Hydrogen and not much chemistry. And nuclear energy is million times as powerful as chemical energy!

Nuclear Astrophysics: The Interesting Journey from Quarks to the Periodic Table



ORDINARY MATTER: FROM QUARKS TO US

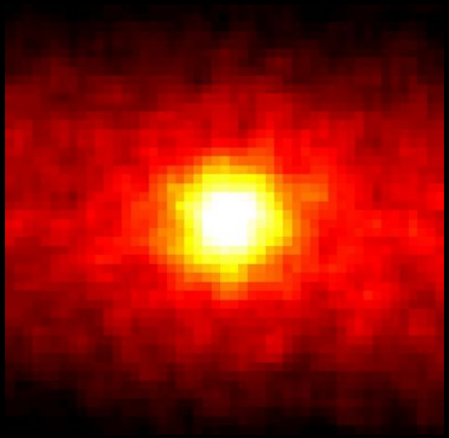


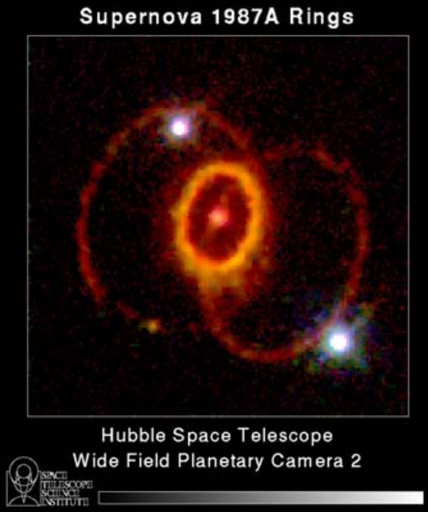


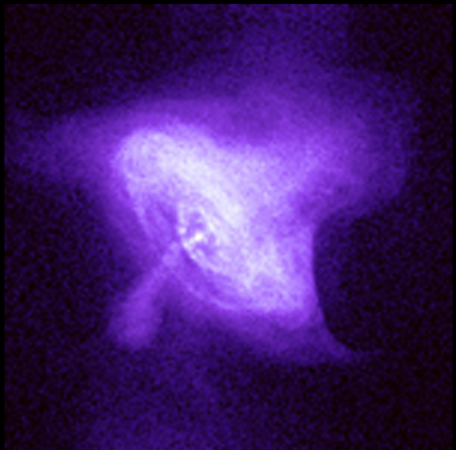
$0 \to 10^{28}$ cm Big Bang
Quarks, leptons $<10^{-19}$ cm
Hadrons 10^{-13} cm
Nuclei 10^{-12} cm
Trapped atoms 10^{-8} cm
NMR of protein 10^{-6} cm
10^{-3} cm labelled cell
10^{2} cm Nuclear medicine
10^{9} cm AMS in global climate
10^{11} cm Sun
10^{18} cm Supernova remnant
10^{22} cm Galaxy

Successes

- Origin of the Periodic Table
  - Big bang; cosmic rays; main-sequence stars; novae and supernovae
- Standard Solar Model
  - Fusion power plant tested to better than 1%
- Macroscopic nuclear matter
  - Neutron stars, pulsars, highest T_c superconductor
- Nuclear power plants (stars) and explosions
- Big Bang Nucleosynthesis
  - Nuclear physics in an old, quenched reactor
- Neutrinos!: SN87a, solar, atmospheric, reactors
- Quark/Gluon Plasma on the lattice and in the lab(?)

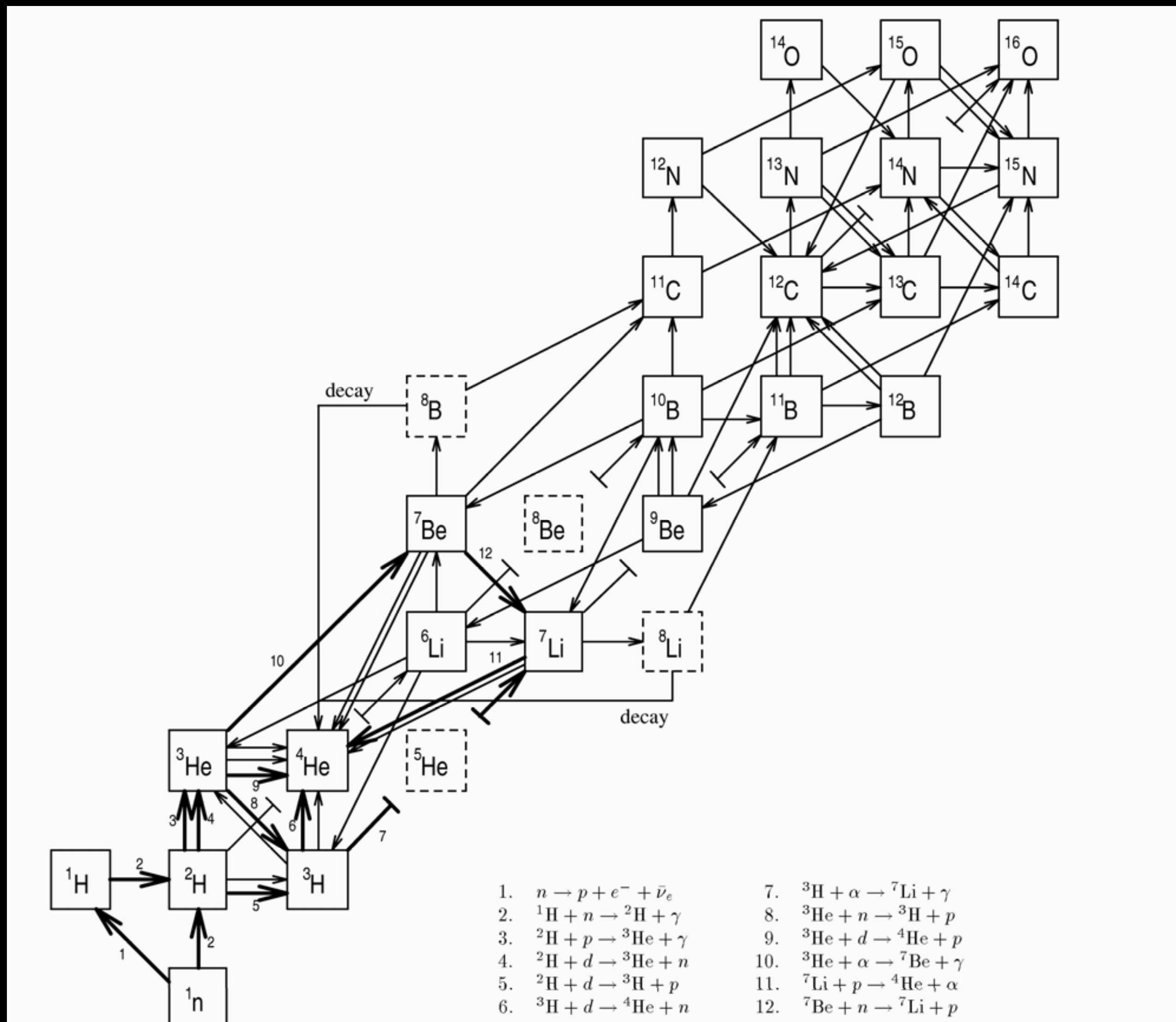


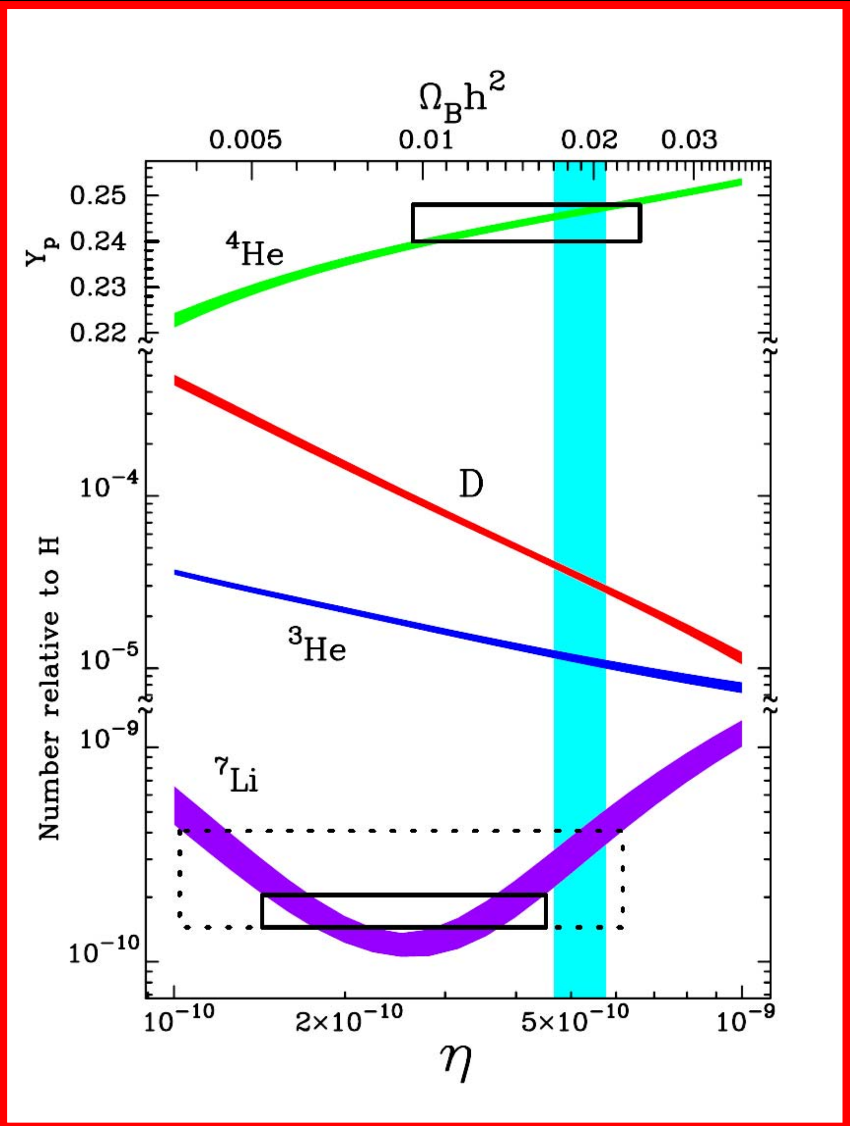


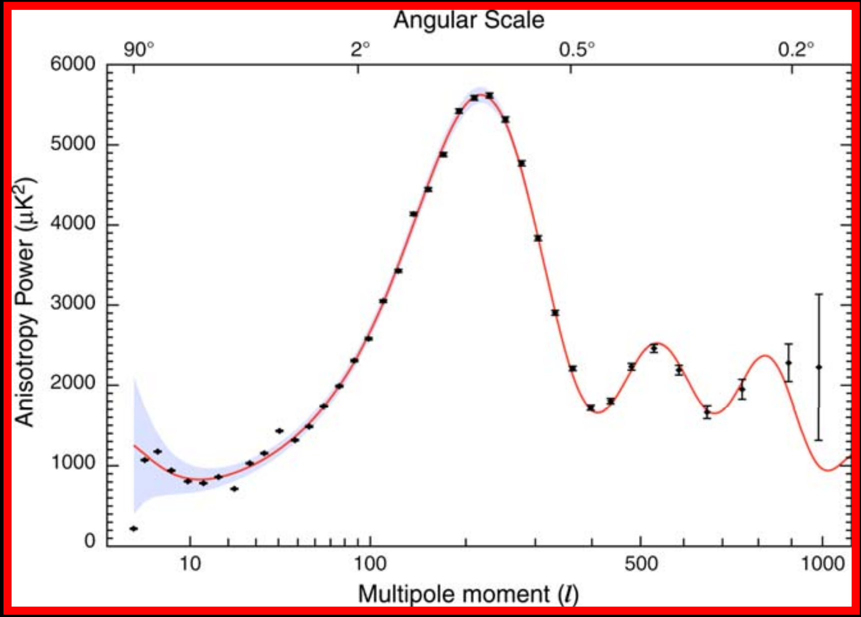


BBN: Quenched Nuclear Reactor

T ~ 10^9 K, ρ ~ g/cm^3, t ~ sec







CMB (first to second peak)
$\Omega_b h^2 = 0.022 \pm 0.001$

BBN (Deuterium)
$\Omega_b h^2 = 0.020 \pm 0.001$

Ω_b = 4% to 5%!

TWO COSMIC ACCTING

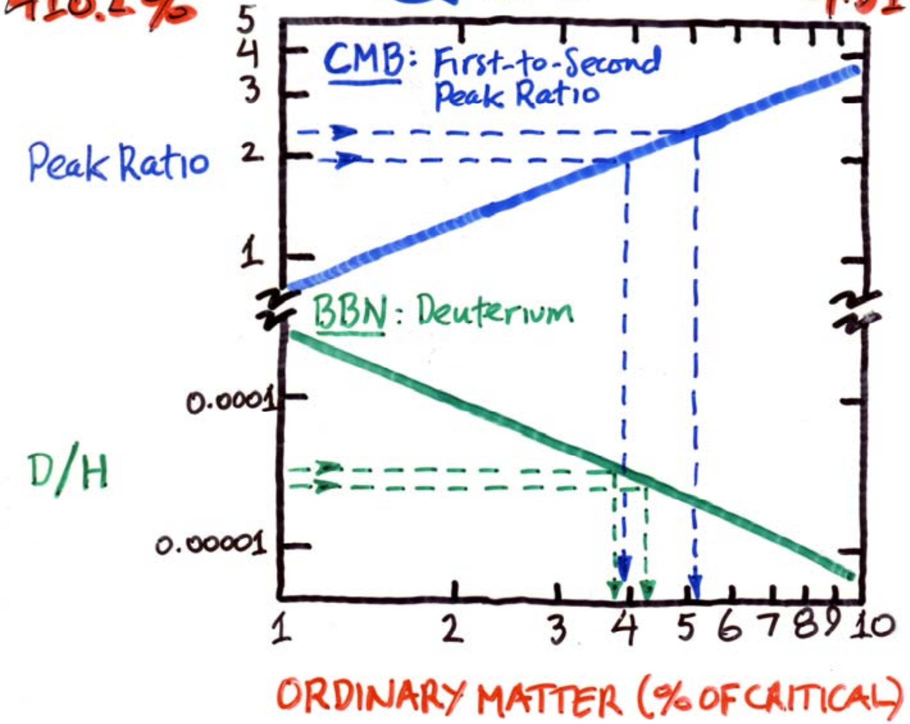
NUCLEAR PHYSICS @ 1 SEC

AGREE

GRAVITY @ 400,000 YRS

4±0.2 %

4.5±0.6 %

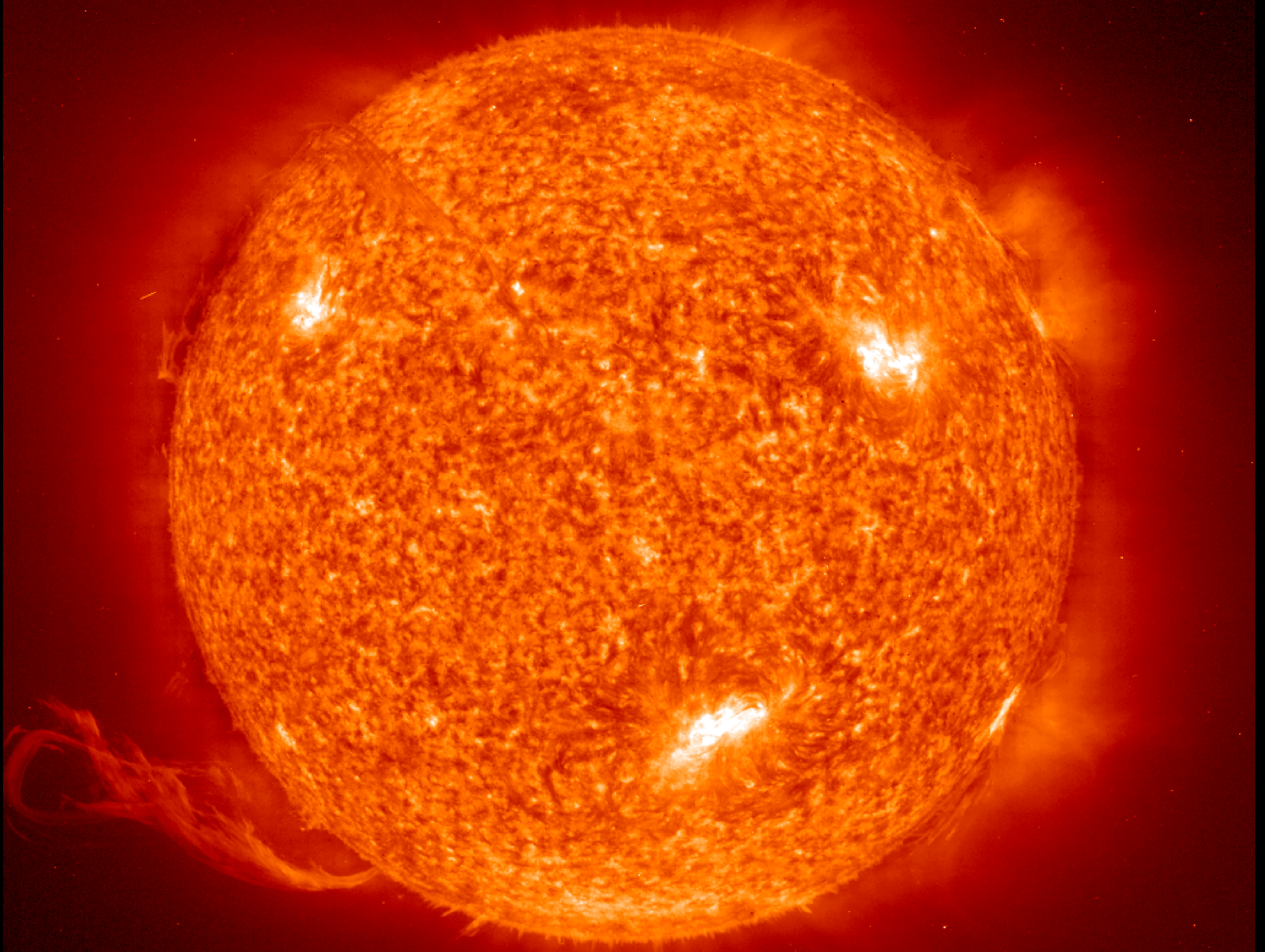


$H_0 = 70.7$ km s^{-1} Mpc^{-1}

ORDINARY MATTER ACCTS FOR 1/8th DARK MATTER

Consistency!

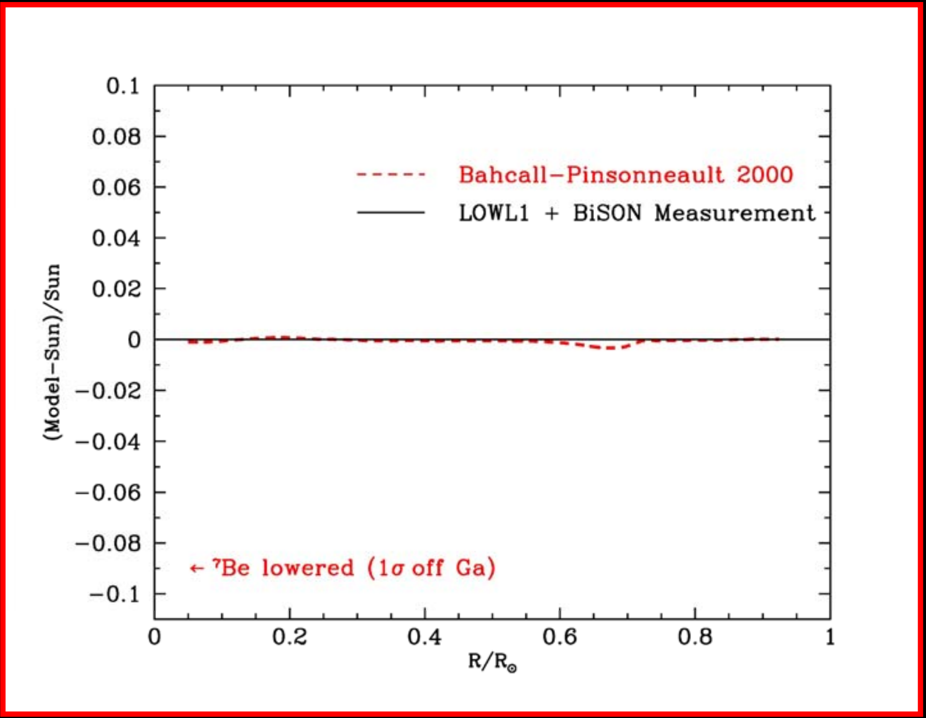
- Earliest test of big-bang cosmology
- Stringent test of constancy of laws of physics (gravity, nuclear, and otherwise)
- Probe of fundamental physics ($N_\nu < 3.2$)
- Probe of cosmology: Ω_B = 4% to 5%



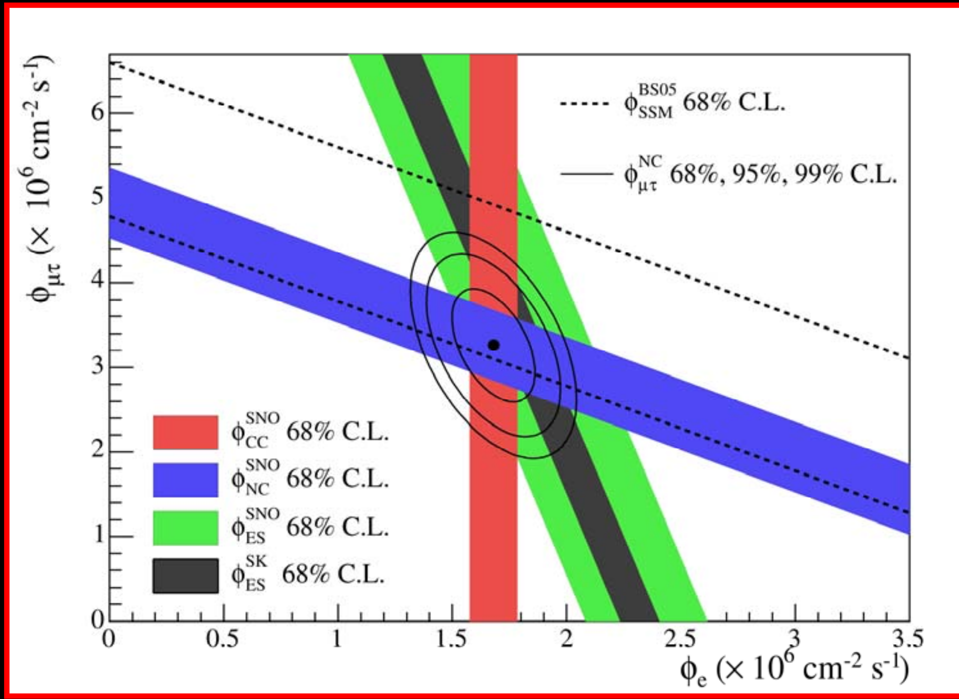
REACTION	TERM. (%)	ν ENERGY (MeV)
$p + p \rightarrow {}^2H + e^+ + \nu_e$	(99.96)	≤ 0.423
or		
$p + e^- + p \rightarrow {}^2H + \nu_e$	(0.44)	1.445
${}^2H + p \rightarrow {}^3He + \gamma$	(100)	
${}^3He + {}^3He \rightarrow \alpha + 2p$	(85)	
or		
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$	(15)	
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	(15)	$\begin{cases} 0.863 & 90\% \\ 0.385 & 10\% \end{cases}$
${}^7Li + p \rightarrow 2\alpha$		
or		
${}^7Be + p \rightarrow {}^8B + \gamma$	(0.02)	
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$		< 15
${}^8Be^* \rightarrow 2\alpha$		
or		
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	(0.00003)	<18.8

John Bahcall

Gravitational Confined Fusion Reactor



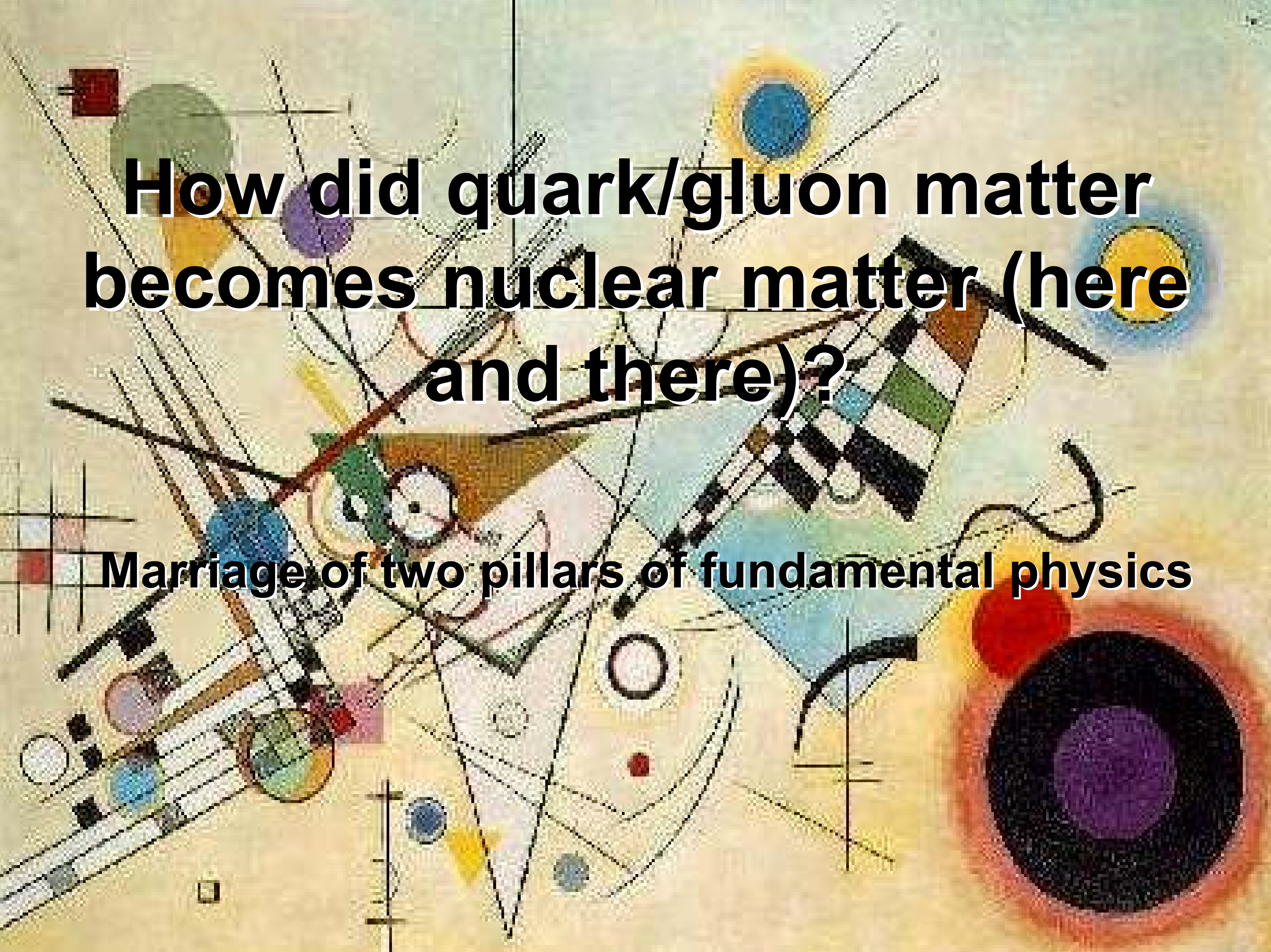
Standard Solar Model vs. Helioseismology



Standard Solar Model vs. Neutrinos

The Very Bright and Exciting Nuclear Frontier: Quarks to the Cosmos

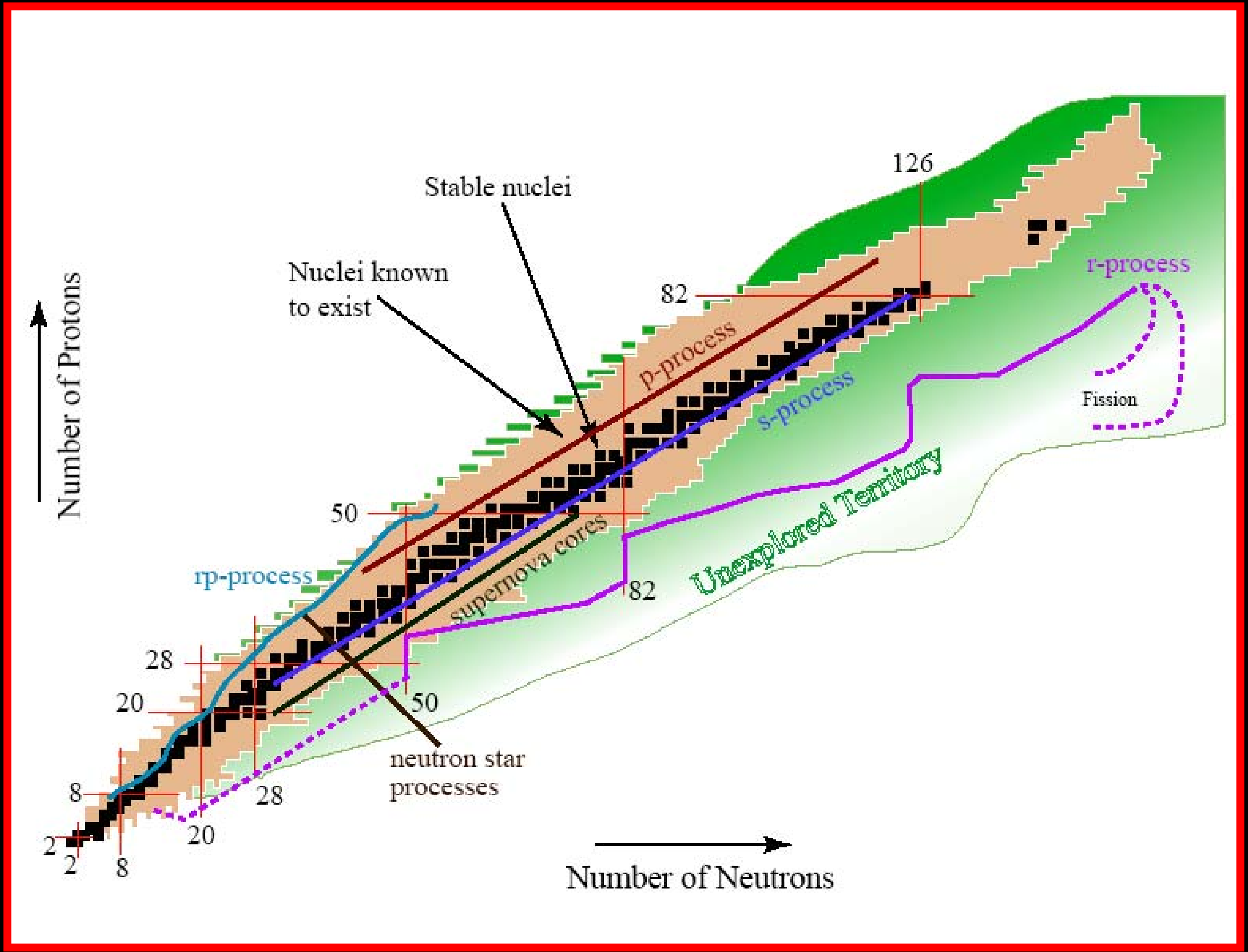
Bright enough to continue to attract the next generation of John Schiffers



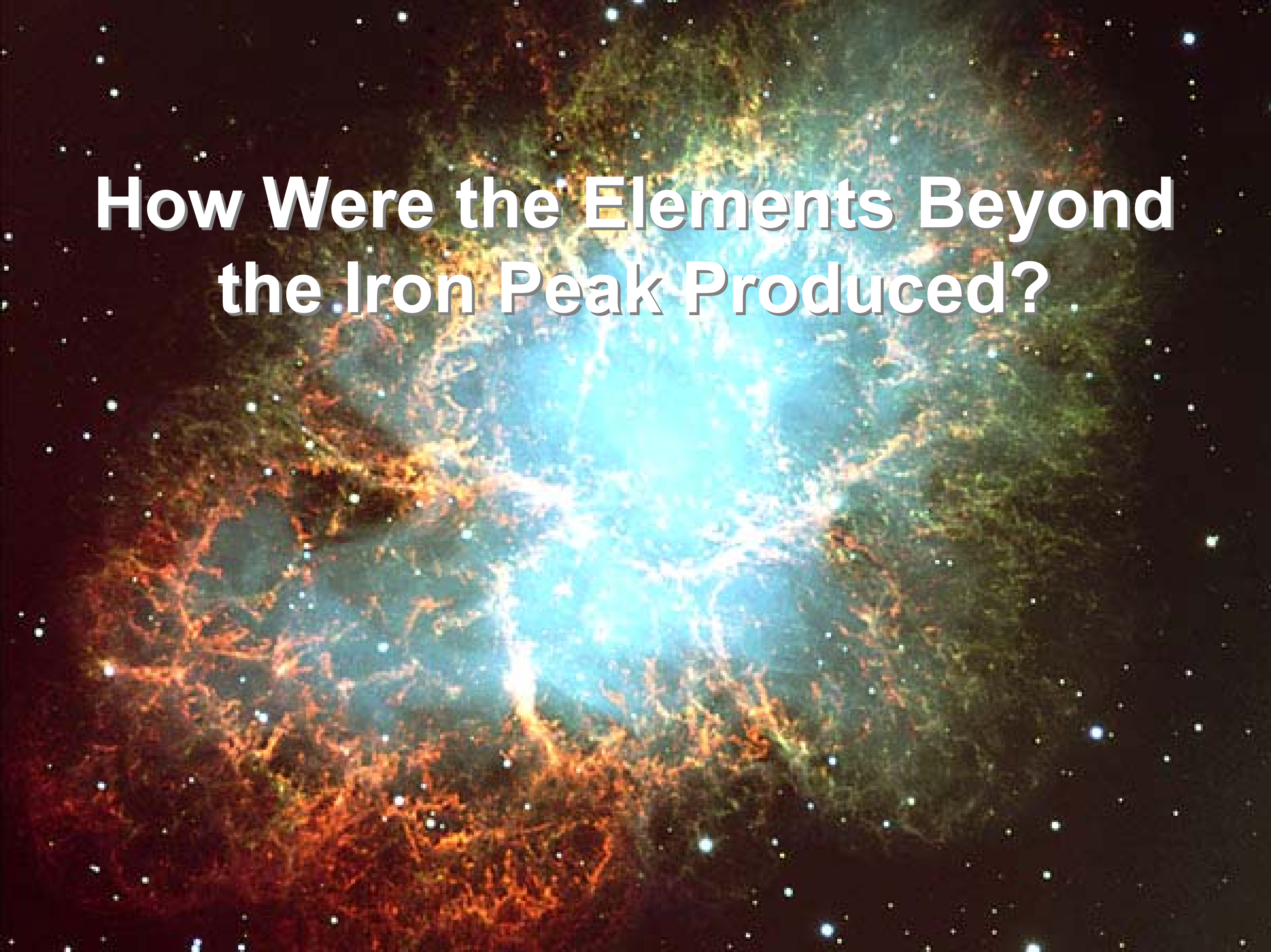
How did quark/gluon matter becomes nuclear matter (here and there)?

Marriage of two pillars of fundamental physics

What is the Complete Periodic Table of Elements and Nuclides?

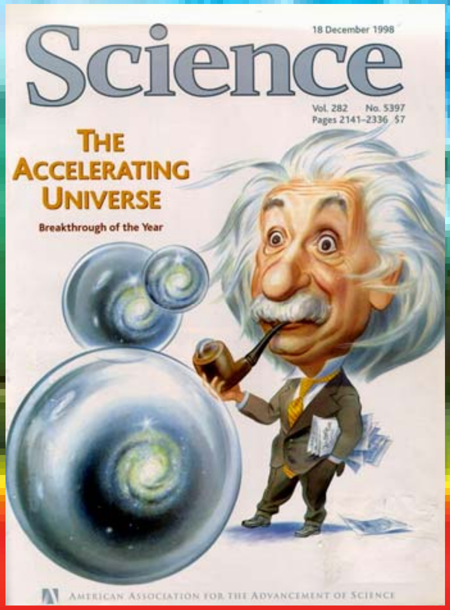


How Were the Elements Beyond the Iron Peak Produced?



How Do Massive Stars Explode?

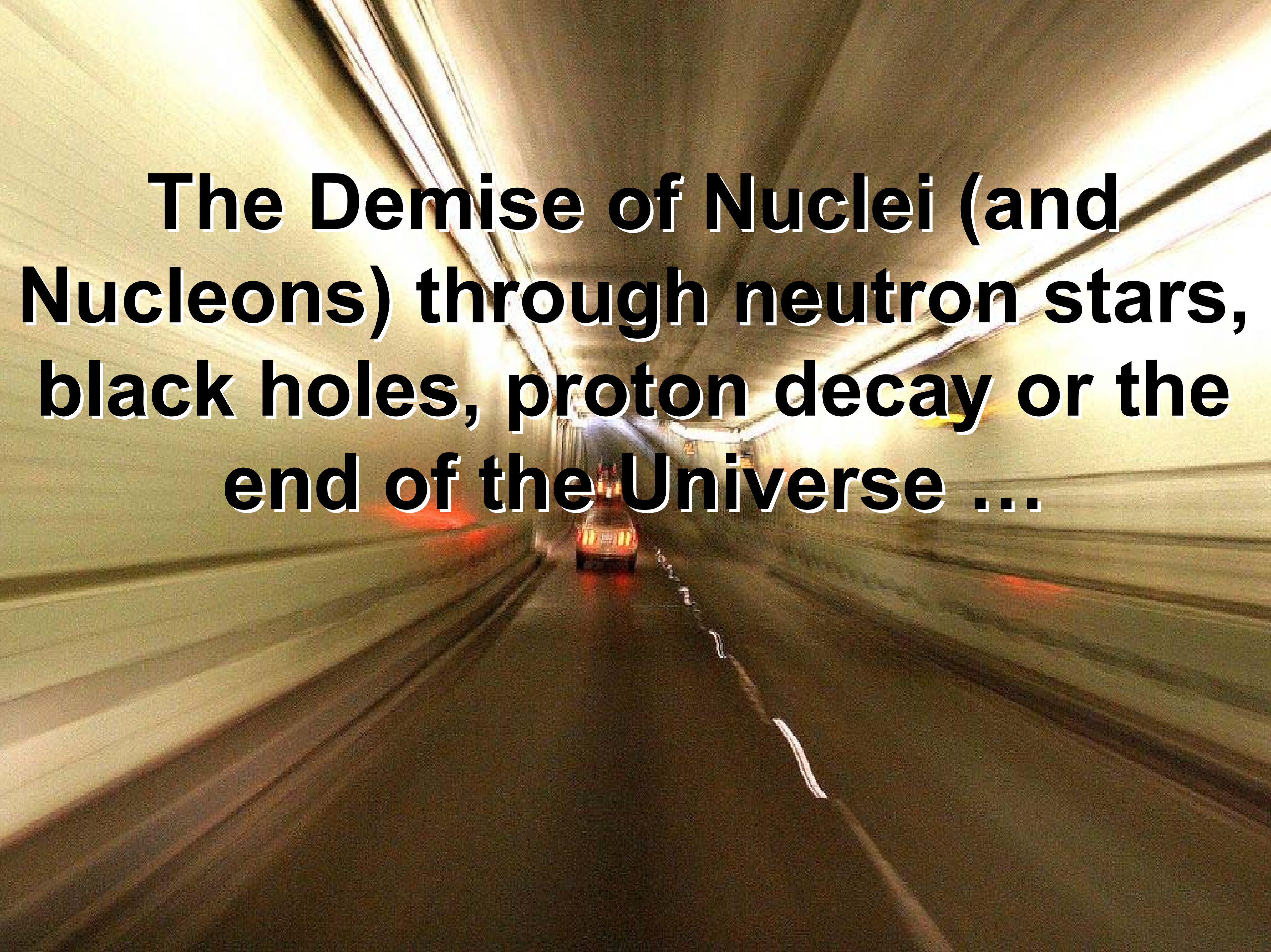
Both thermonuclear and gravitational explosions



How Do Neutrinos Shape the Universe?

Origin of baryons, large-scale structure, stellar explosions, stellar nucleosynthesis, …

Measuring Critical Nuclear Properties for Applied Science, Astrophysics and National Security


The Demise of Nuclei (and Nucleons) through neutron stars, black holes, proton decay or the end of the Universe …