TERRA INCOGNITA
in
Contemporary Nuclear Physics

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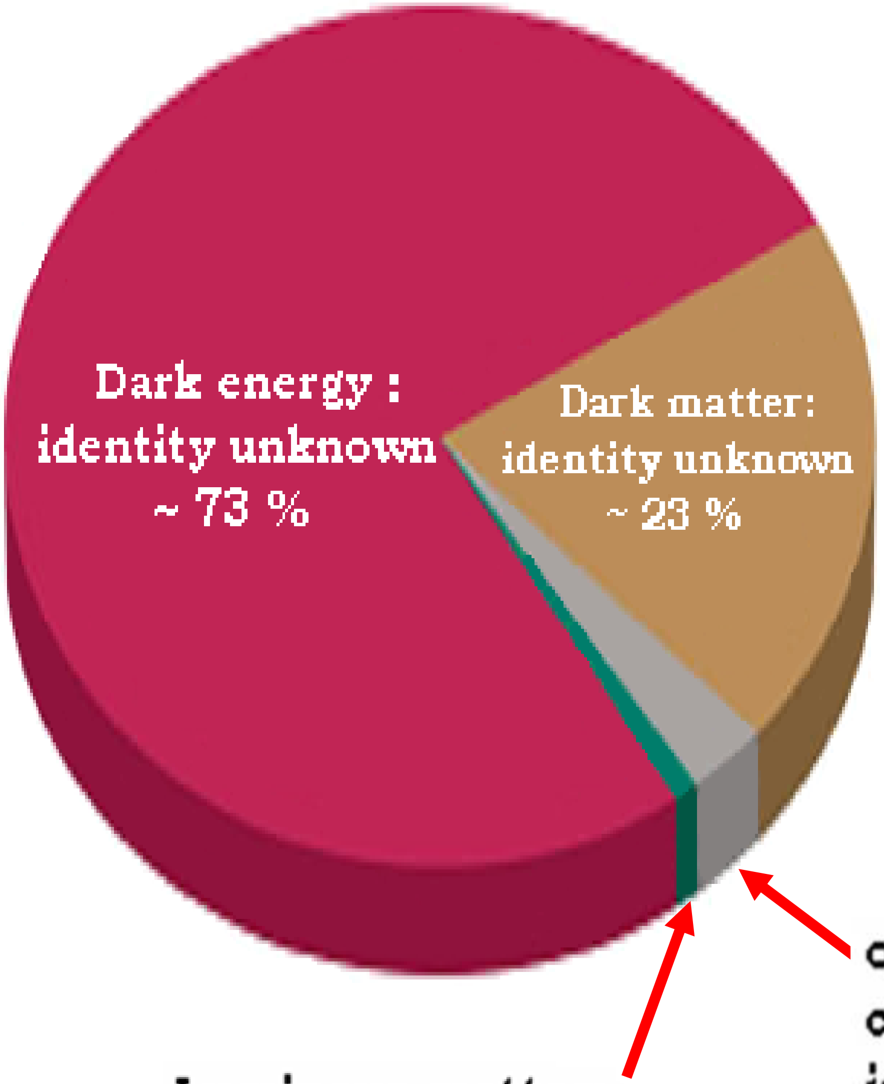
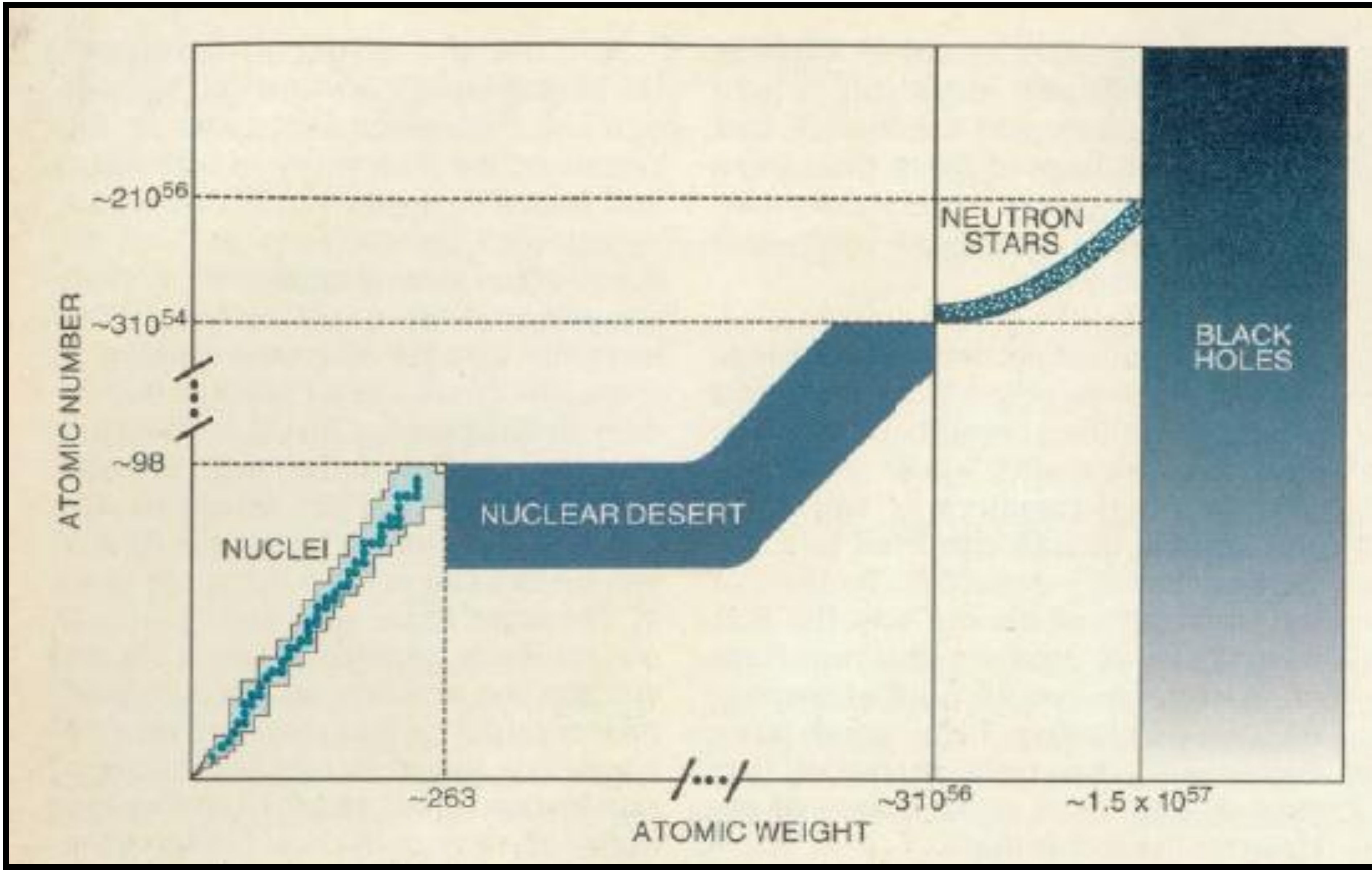
Department of Atomic Energy

International Workshop on Future Plan with Radioactive Ion Beam,
Saha Institute of Nuclear Physics, Kolkata
April 16, 2012

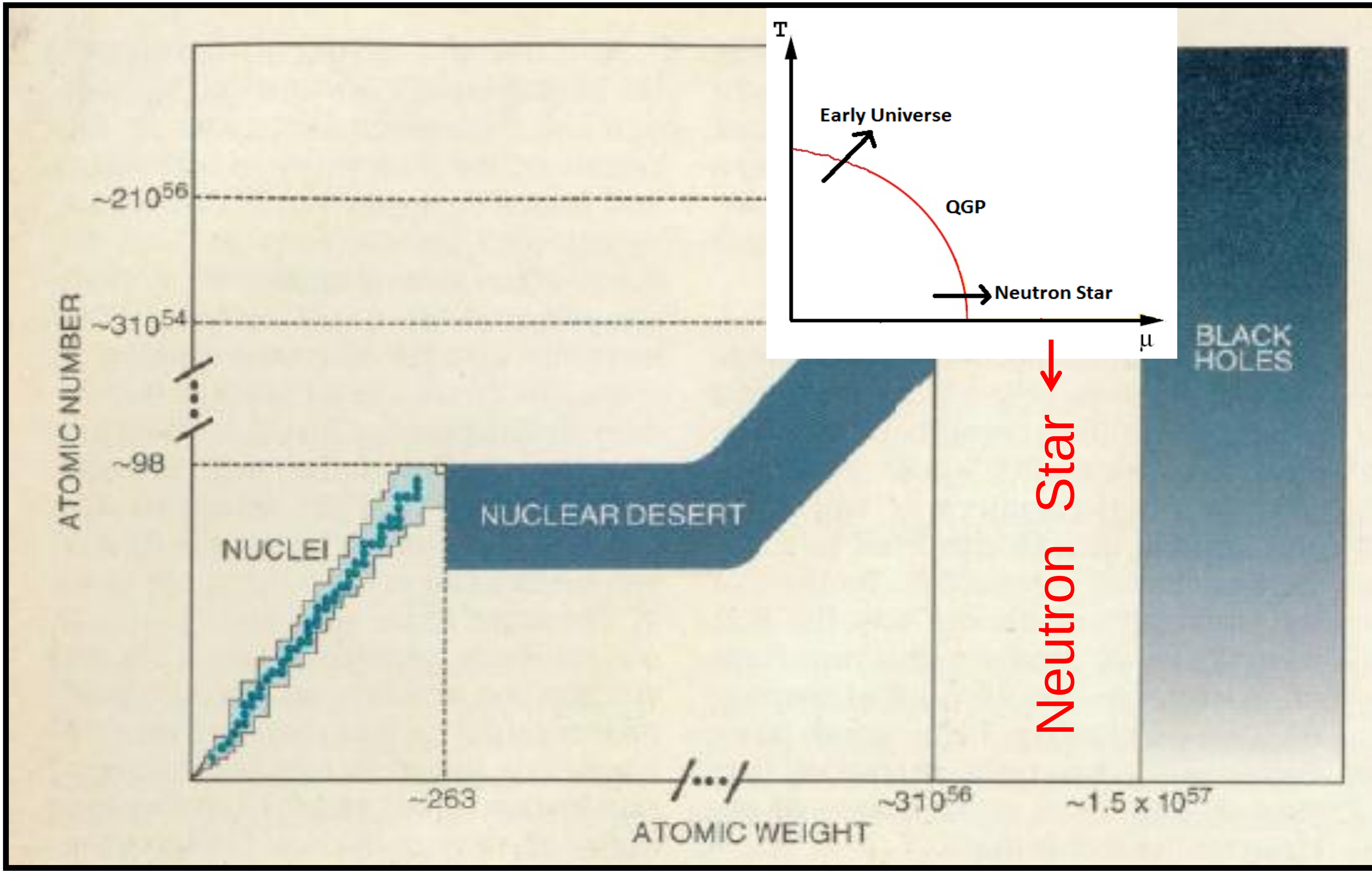


Luminous matter:
stars and luminous
gas ~ 0.4 % ;
radiation 0.005 %

other nonluminous
components:
intergalactic gas 3.6 % ;
neutrinos 0.1 % ;
supermassive black
holes 0.004 %



Charts of nuclides shows all known forms of stable matter. Between the heaviest atomic elements and neutron stars, which are giant nuclei, lies a vast, unpopulated nuclear desert. This void may actually be filled with strange quark matter.



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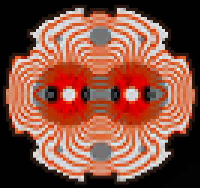
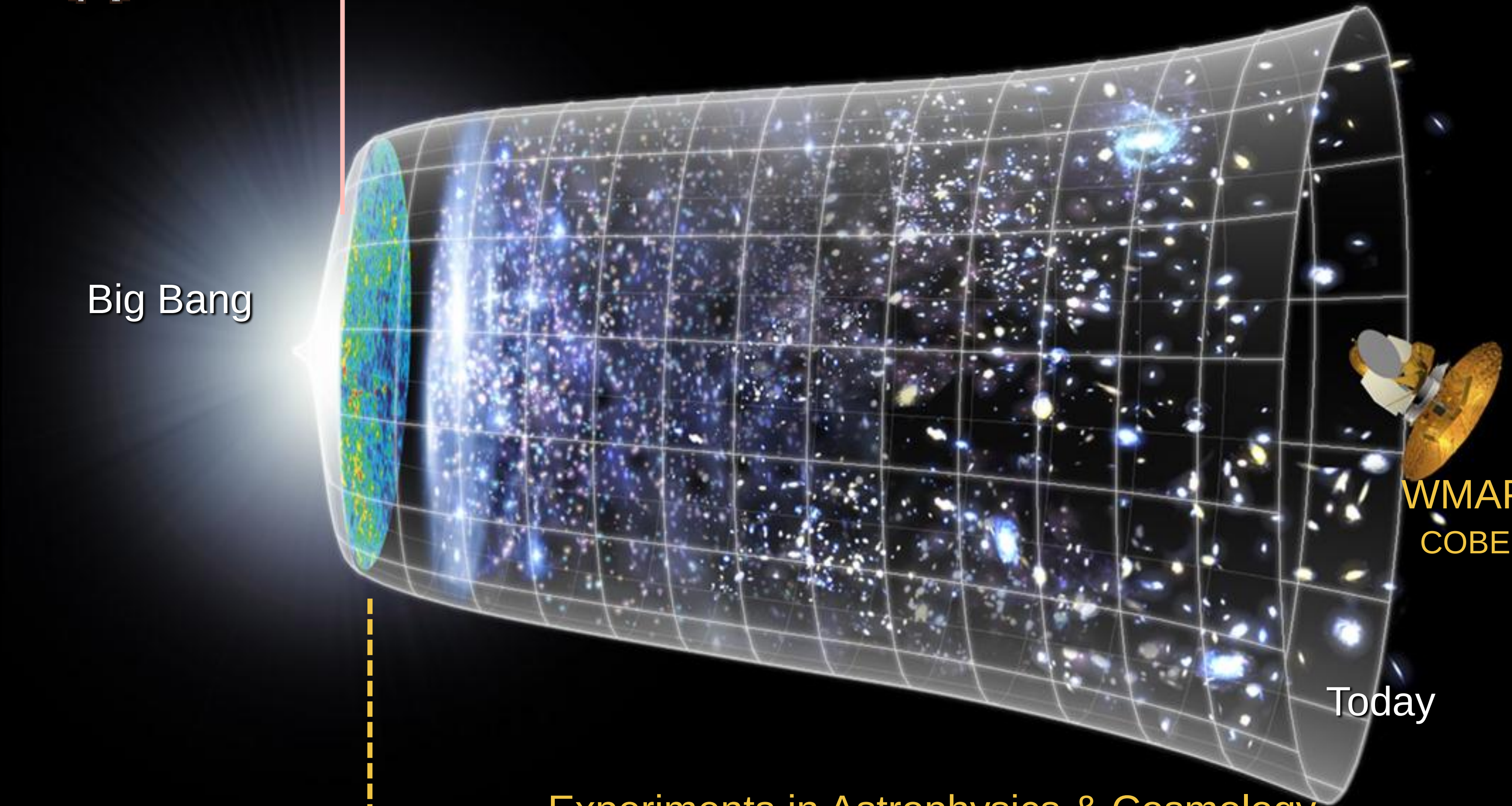


LHC: ~ 10^{-12} seconds (p-p)

~ 10^{-6} seconds (Pb-Pb)



Big Bang

WMAP (2001)

COBE (1989)

Today

Experiments in Astrophysics & Cosmology

~300‘000 years

$$\Psi = \Phi + \Phi \frac{G}{e} \Psi$$

$$\mathrm{G}\,\Phi = \mathrm{V}\,\Psi \qquad : \qquad \omega = \int (\Psi - \Phi)\, \mathrm{d}^3\mathrm{X}$$

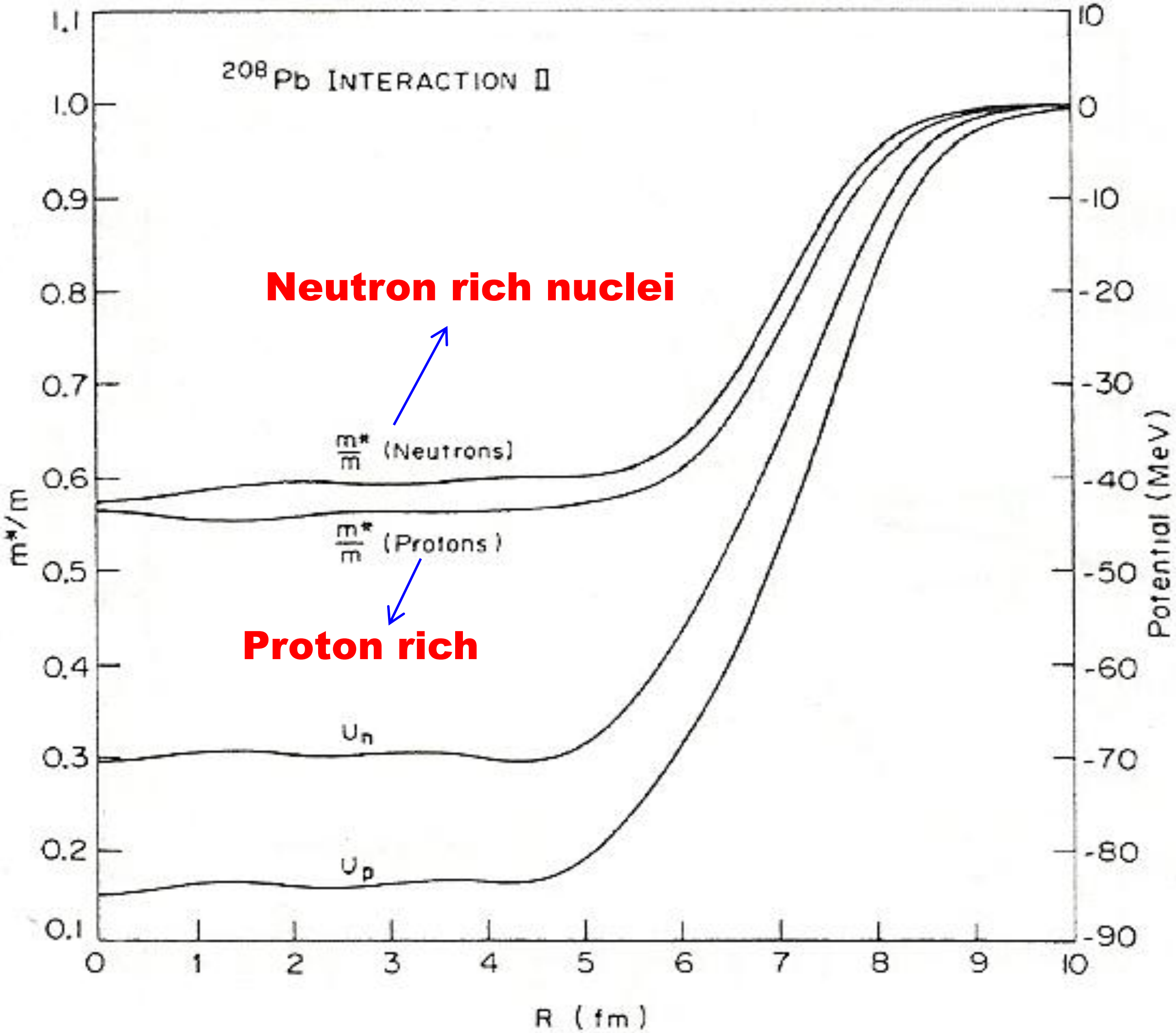
$$\mathrm{E} = \frac{\mathrm{k}^2}{\mathrm{m}} + \sum (\mathrm{k}, \mathrm{E}) \quad \Longleftarrow \quad \text{self energy}$$

$$\sum(\mathrm{k}, \mathrm{E}) \equiv \mathrm{U}(\mathrm{k}, \mathrm{E}) + \mathrm{i}\mathrm{W}(\mathrm{k}, \mathrm{E})$$

$$\frac{\mathrm{k}}{\mathrm{m}^*} \equiv \frac{dE}{dk} = \frac{k}{m} + \frac{\partial \mathrm{U}}{\partial \mathrm{k}} + \frac{\partial U}{\partial \mathrm{E}} \frac{\partial \mathrm{E}}{\partial \mathrm{k}} = \frac{\mathrm{k}}{\mathrm{m}} (1 + \frac{\mathrm{m}}{\mathrm{k}} \frac{\partial \mathrm{U}}{\partial \mathrm{k}}) \, (1 - \frac{\partial \mathrm{U}}{\partial \mathrm{E}})^{-1}$$

$$\frac{\mathrm{m}_{\mathrm{e}}^{*}}{\mathrm{m}} \equiv (1 - \frac{\partial \mathrm{U}}{\partial \mathrm{E}})$$

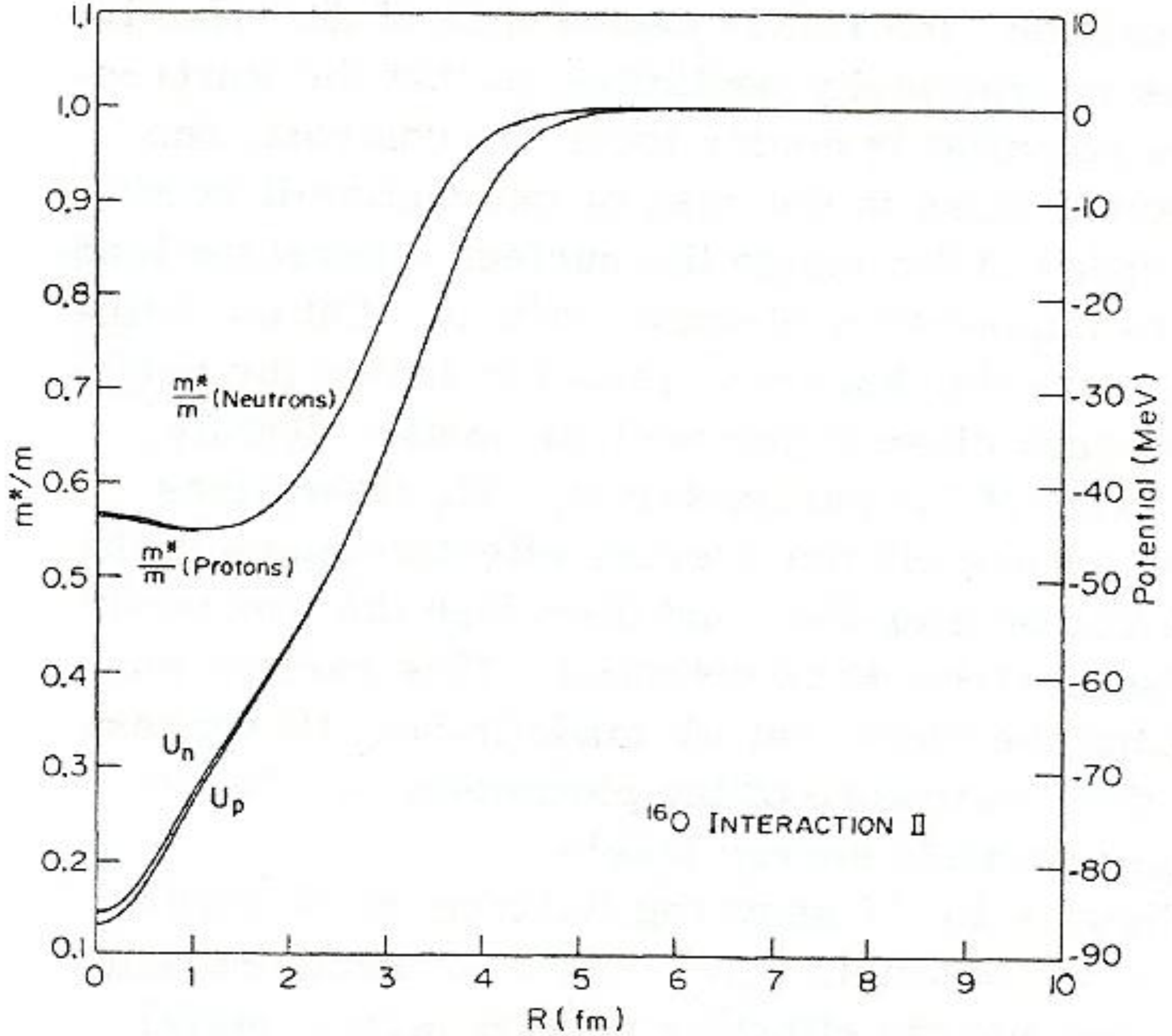
$$\frac{\mathrm{m}_{k}}{\mathrm{m}} = (1 + \frac{\mathrm{m}}{\mathrm{k}} \frac{\partial \mathrm{U}}{\partial \mathrm{k}})^{-1}$$



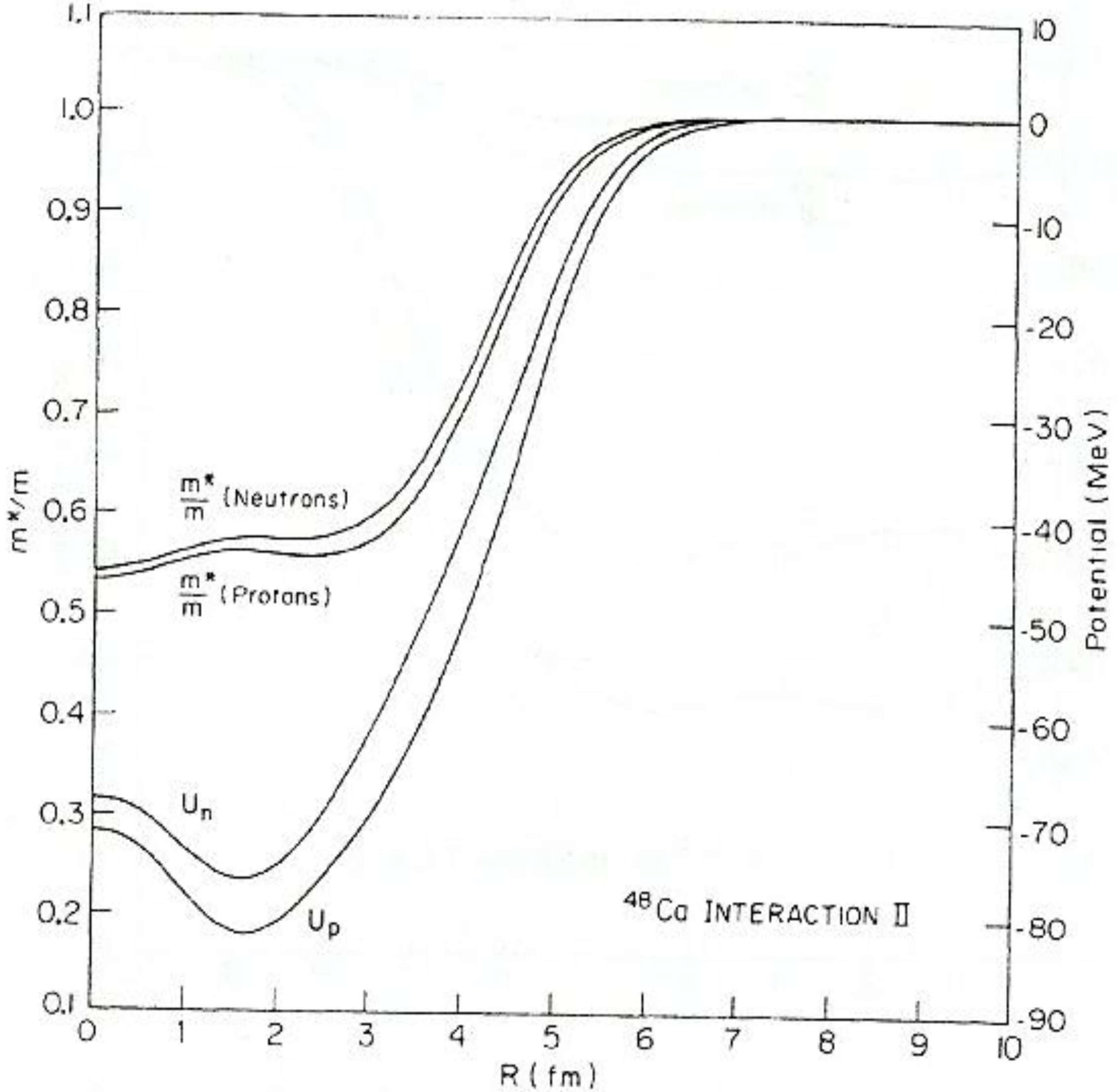
Neutron rich nuclei

Proton rich

Effective mass m^*/m and potential U calculated in ^{208}Pb with interaction II.



Effective mass m^*/m and potential U calculated in ^{16}O with interaction II.

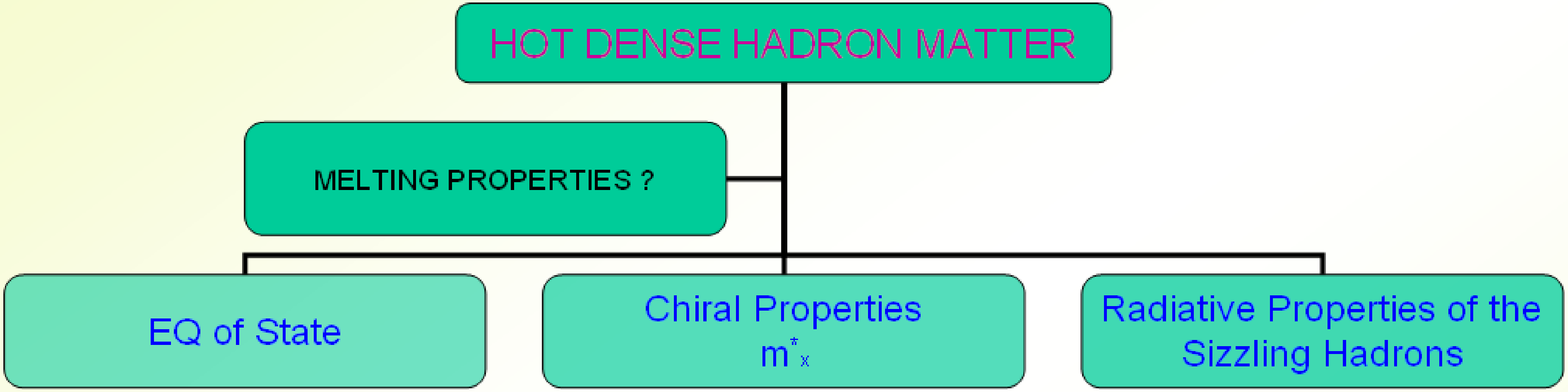


Effective mass m^*/m and potential U calculated in ^{48}Ca with interaction II.

1. What about m^* in halo nuclei e. g. ^{11}Li ?

2. m^*_N : Neutron rich ?

3. m^*_P : Proton rich ?



HOT DENSE HADRON MATTER

MELTING PROPERTIES ?

EQ of State

Chiral Properties
m^*_x

Radiative Properties of the Sizzling Hadrons

(Decay widths)
Chiral Hadrodynamics

Mesons, Vector mesons, Baryons
No Universal law of m^*_x
Brown – Rho Scaling law does not seem to hold
Ie,

$$\frac{m_N^*}{m_N} \neq \frac{m_\omega^*}{m_\omega} \neq \frac{m_p^*}{m_p}$$

Medium effects : (Finite Temp Field th.)

P. Roy, S. Sarkar, J. Alam, B.S., Nucl Physics A 653 (1999)
S. Sarkar, P. Roy, J. Alam, B. S.
Phys. Rev. C (1999) & Annals of Phys 2000

$$\frac{m_v^*}{m_v} = \frac{f_v^*}{f_v} = \frac{\omega_o^*}{\omega_o}\left[1 - \frac{T^2}{T_c^2}\right]^{1/2}$$

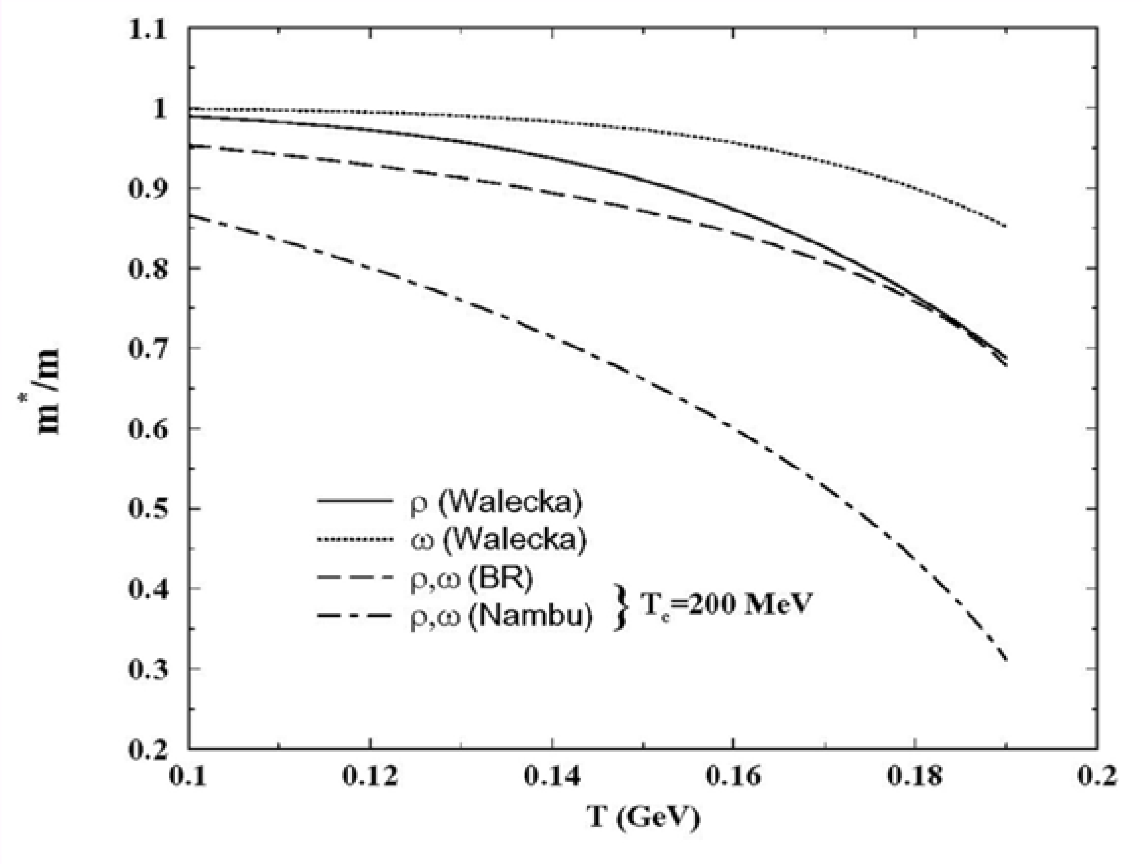
f_v Coupling between electromagnetic current & vector meson Field , ω_0 Continuim Threshold

Should not

$$\frac{m_v^*}{m_v} \neq \frac{m_N^*}{m_N}$$

J. Alam
S. Sarkar
T. Hatsuda
T. Nayak
B. S. (2000)

VARIATION OF NUCLEON MASS WITH TEMPERATURE AND BARYON DENSITY



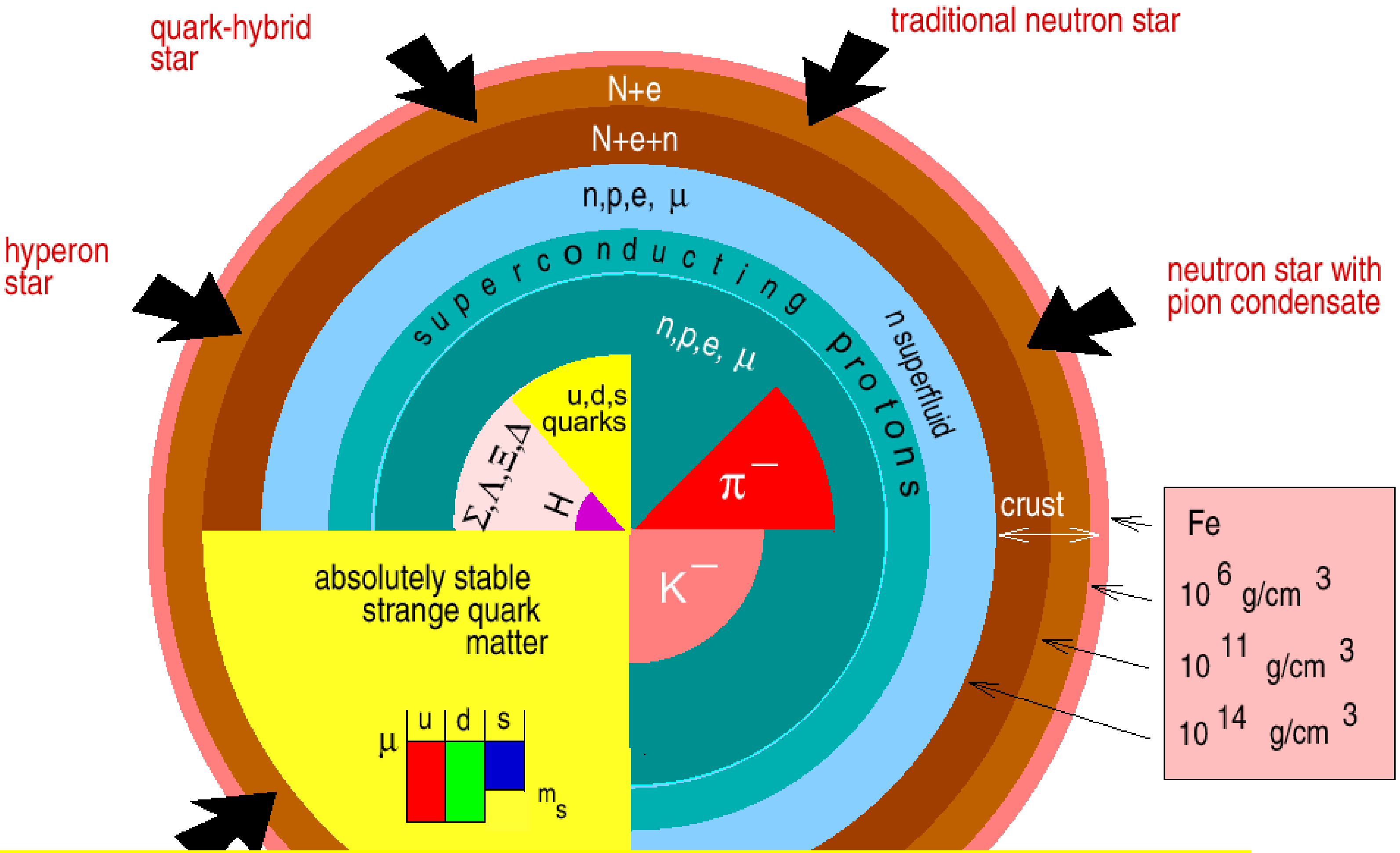
S Sarkar
J Alam
P Roy
A Dutta-Majumder
B Dutta-Roy
B Sinha
Nucl. Phys.A (1998)

$$\rho_O = 0.15 baryon / fm^3$$

Tc (=200 MeV) is just a parameter

At T= 200 MeV the nucleon mass decreases by ~ 230 MeV when ρ/ρ0 = 0 and by ~ 440 MeV when ρ/ρ0 = 2

Strongly interacting matter in neutron stars



"Strangeness" of dense matter ?
In-medium properties of hadrons ?
Compressibility of nuclear matter?
Deconfinement at high baryon densities ?

The Universe

4th century BC(Greek Philosophers) to 16th century

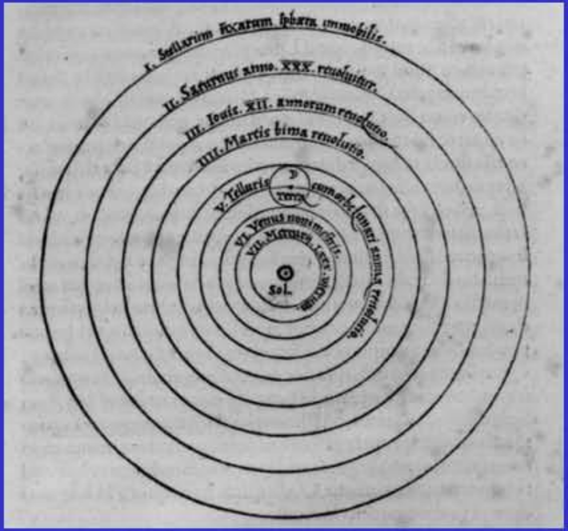
Schema huius præmiſſæ diuiſionis Sphærarum.

Geocentric view : Ptolemaic System


Schema huius præmiſſæ diuiſionis Sphærarum.

Galileo development of the telescope

Copernicus 1543

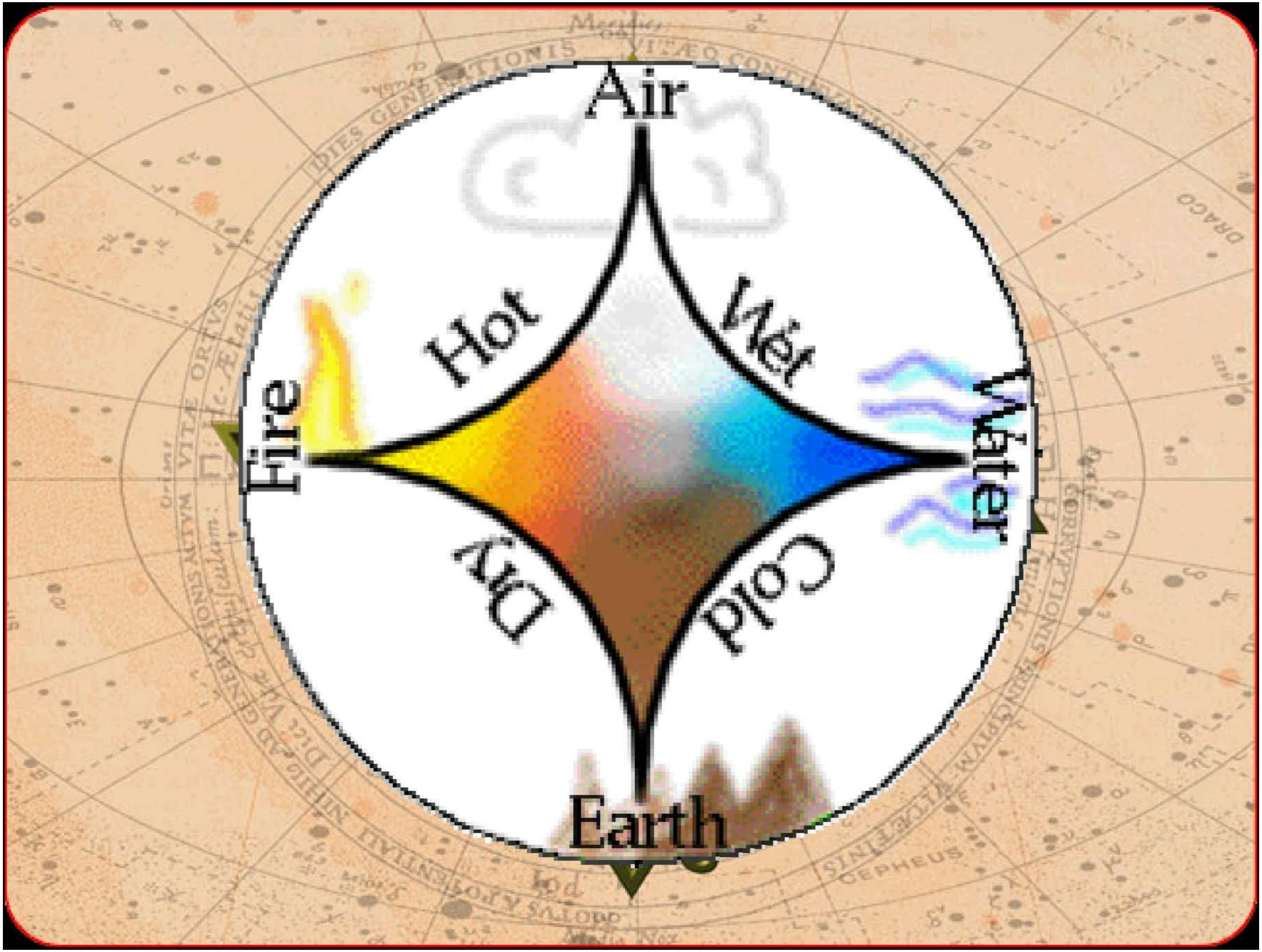


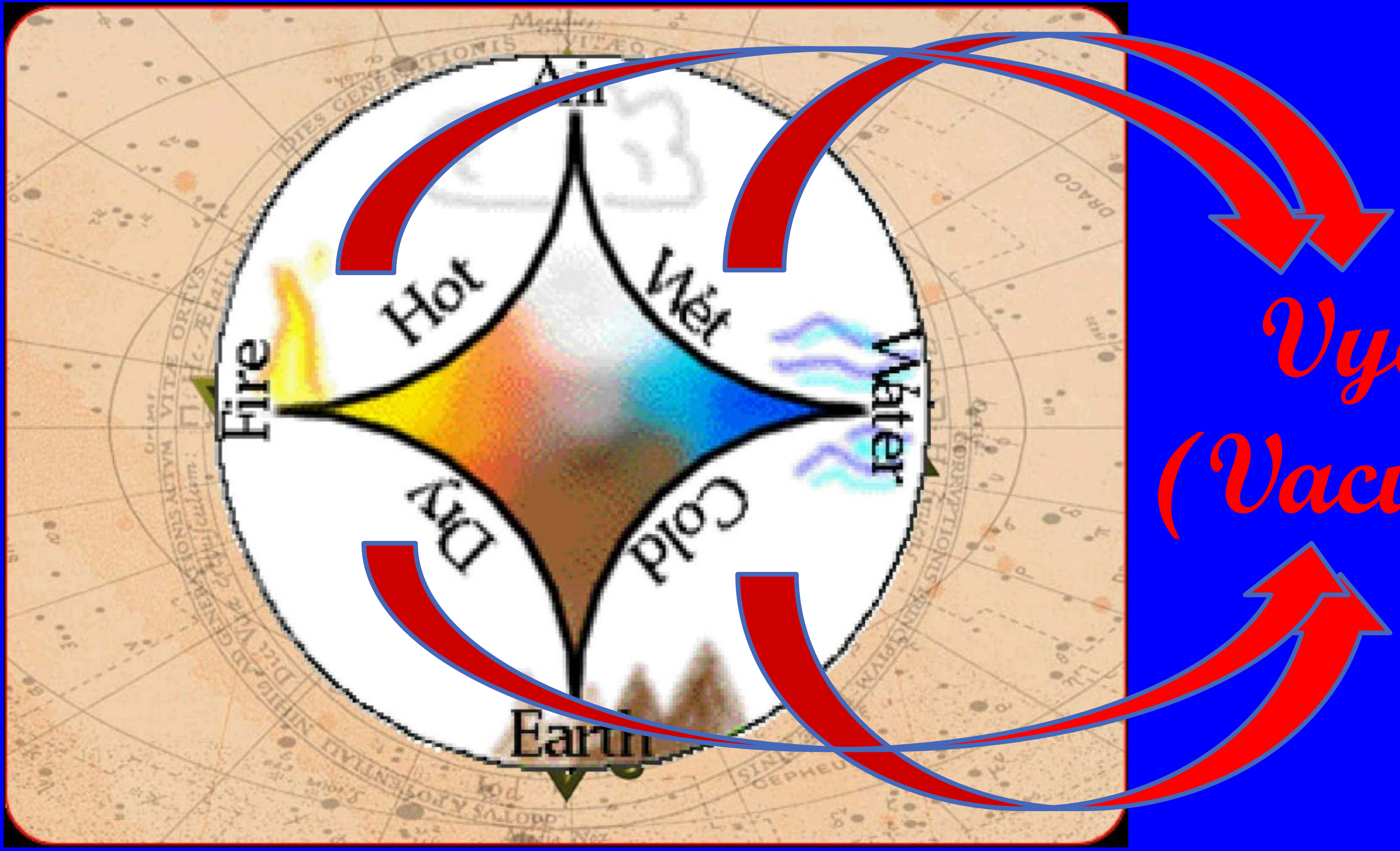
Heliocentric view


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
GALILEO GALILEO
PATRITIO FLORENTINO
PERSPICILLI
QVATVOR PLANETIS
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

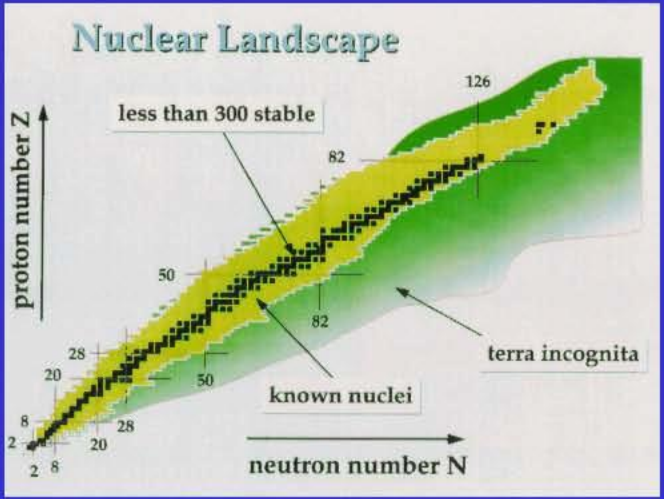
VENETIIS, M DC X.

Published 1610

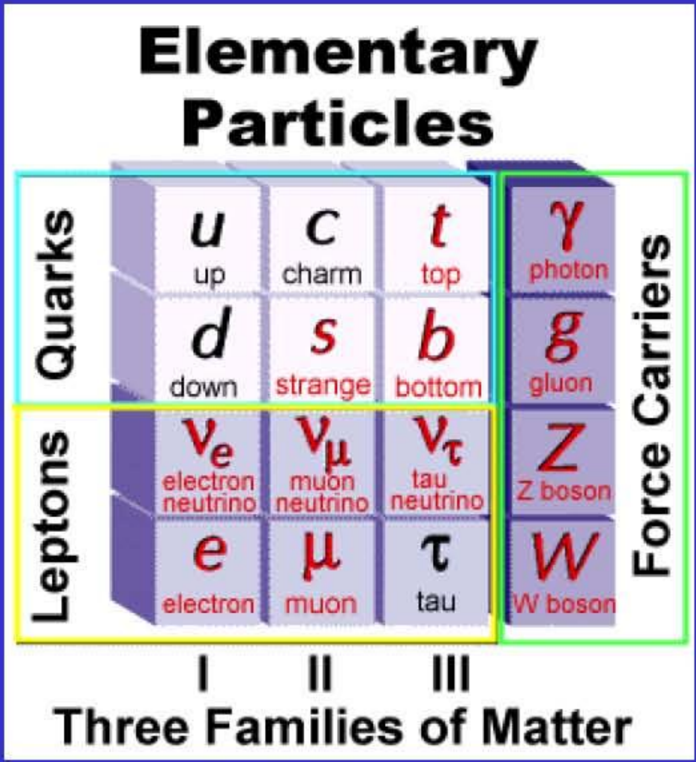

Air
Hot
Wet
Fire
Water
Dry
Cold
Earth



Vyom
(Vacuum)



Particle accelerators



Elementary Particles

	I	II	III	Force Carriers
Quarks	u up	c charm	t top	γ photon
Quarks	d down	s strange	b bottom	g gluon
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
Leptons	e electron	μ muon	τ tau	W W boson

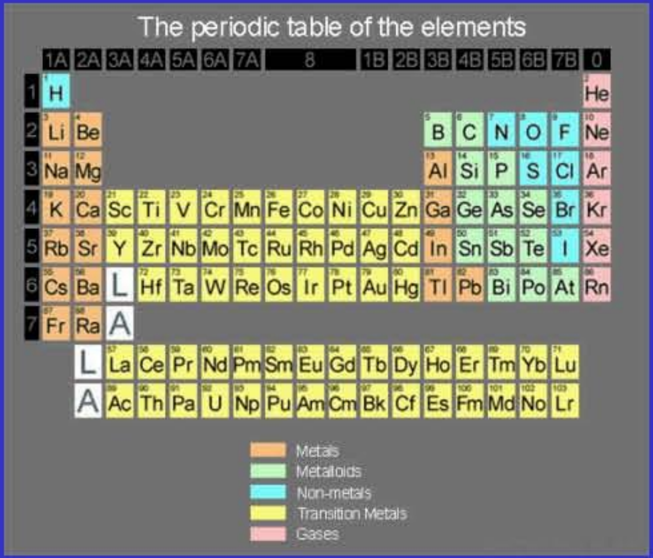
Three Families of Matter

New accelerators

LHC, ILC

Deeper Understanding

Of space/Matter

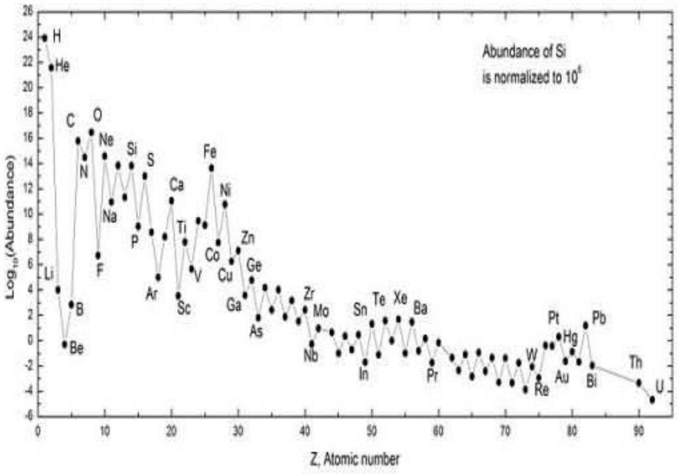


The periodic table of the elements

	1A	2A	3A	4A	5A	6A	7A	8			1B	2B	3B	4B	5B	6B	7B	0
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	L	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	A															
			L	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			A	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

🟧 Metals
🟩 Metalloids
🟦 Non-metals
🟨 Transition Metals
🟥 Gases

Abundance curve elements

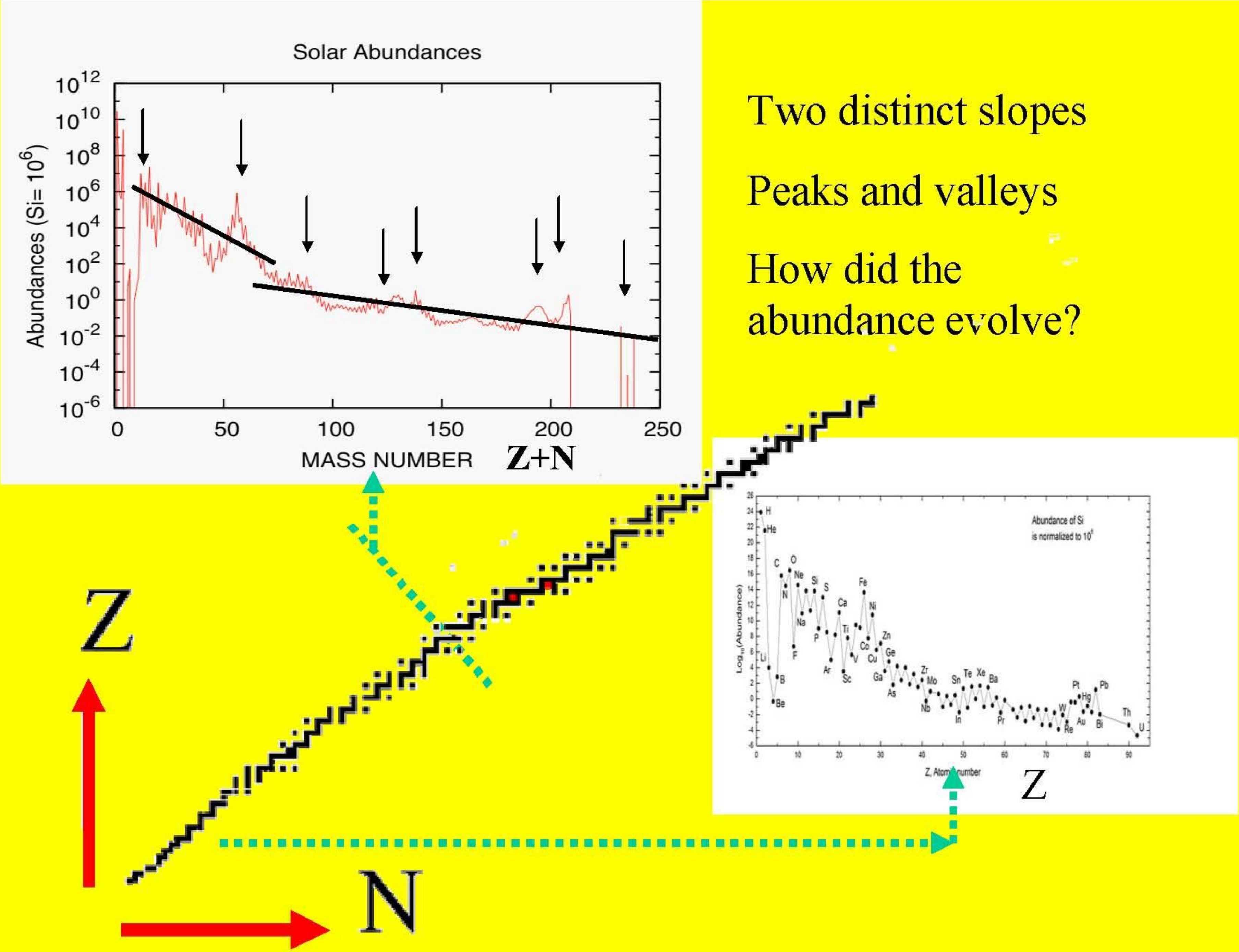


Searching for “SHE”

Two distinct slopes

Peaks and valleys

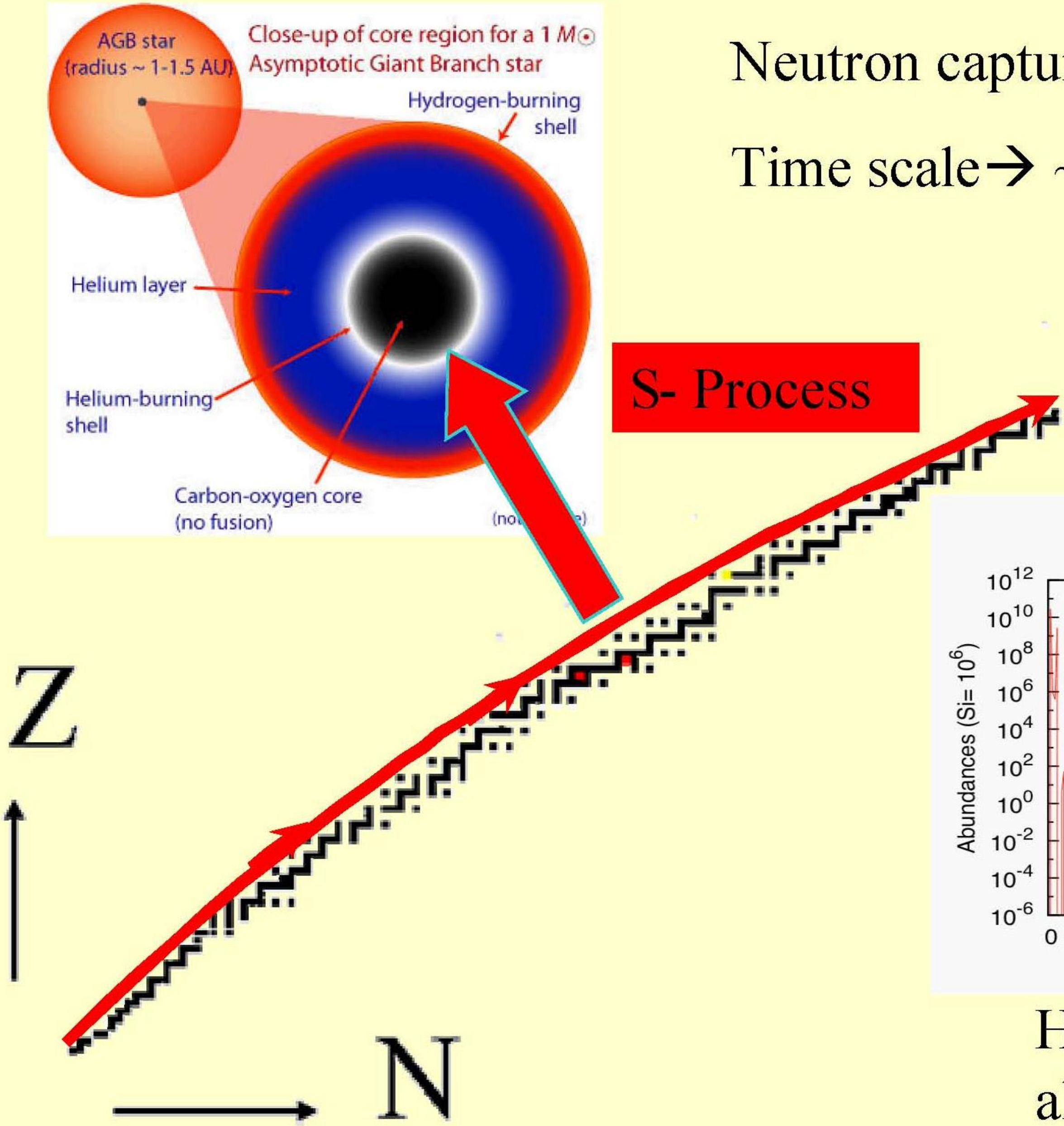
How did the abundance evolve?

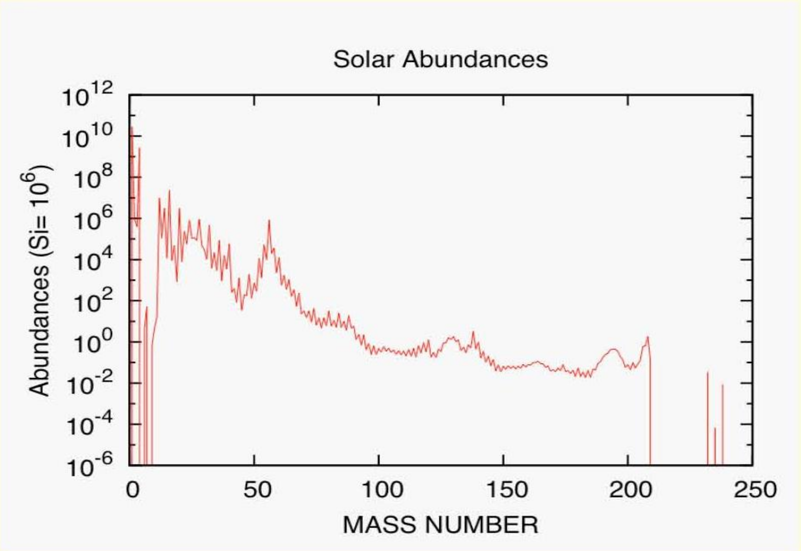


End stage Main sequence stars

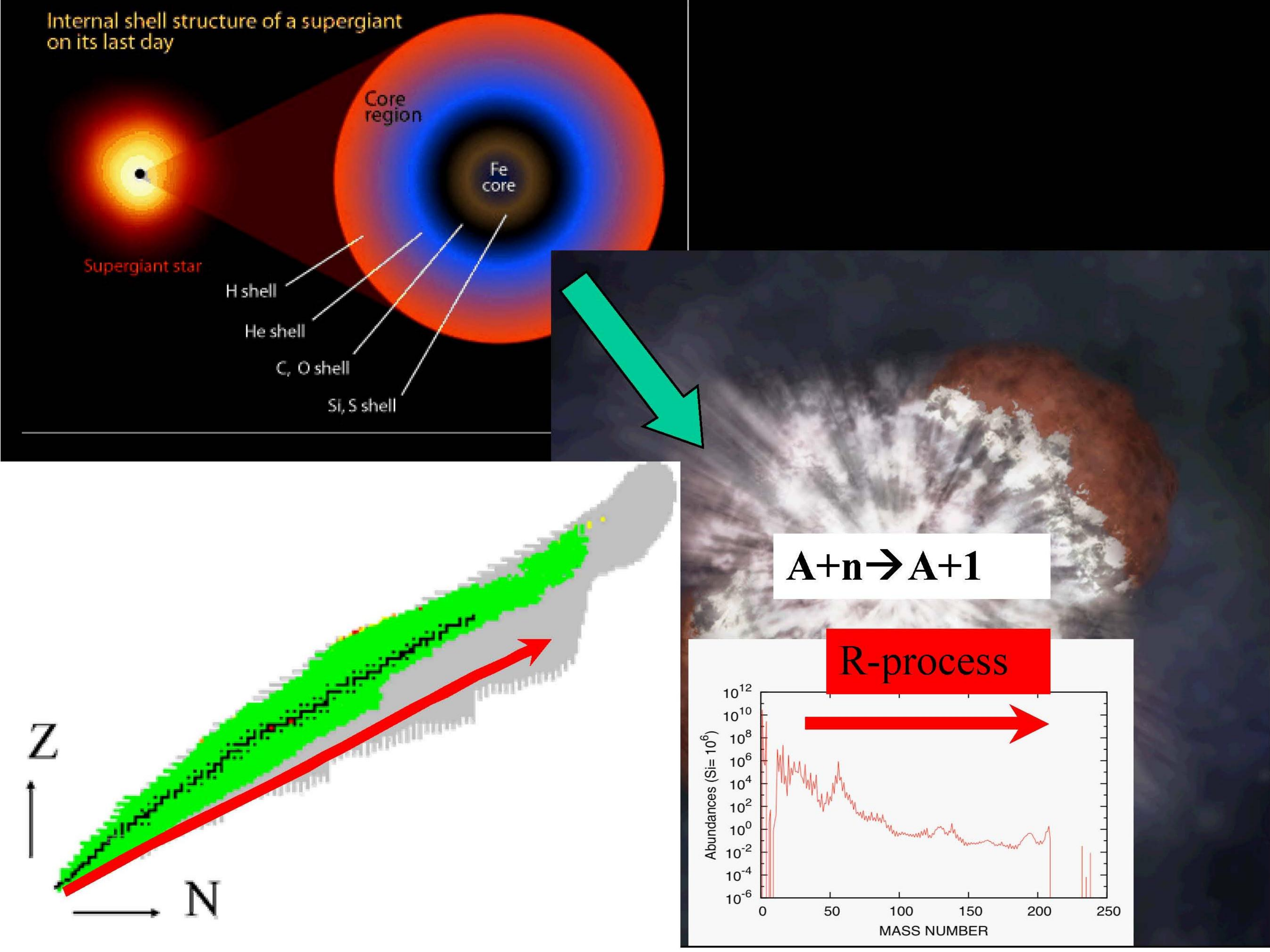
Neutron capture A+n→A+1

Time scale→ ~ 10^6 years





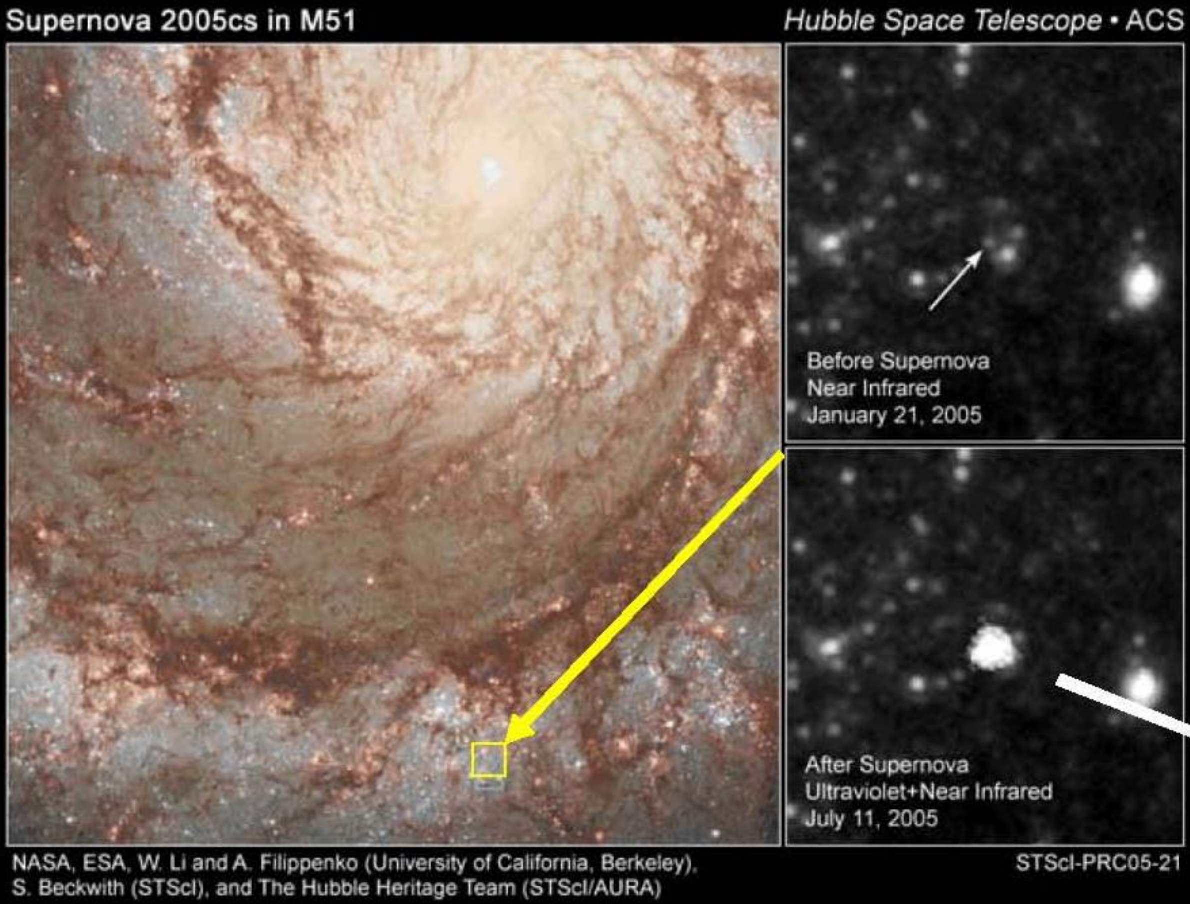
However cannot explain
all features A> 60



A+n→A+1

R-process

Massive star evolution → ends as supernova explosion

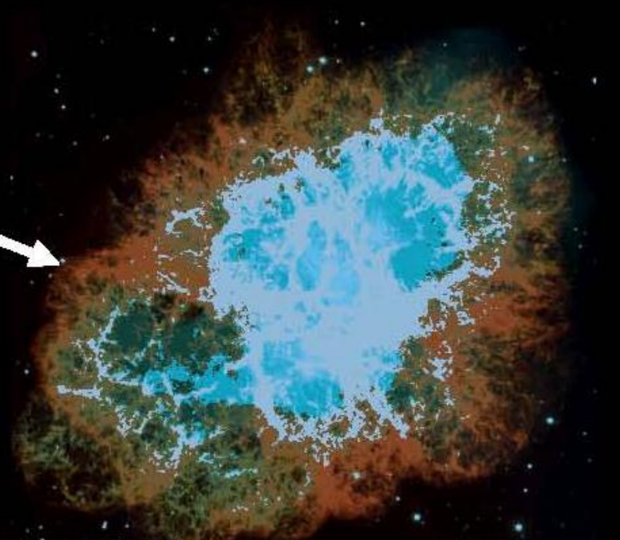


Supernova 2005cs in M51

Hubble Space Telescope • ACS

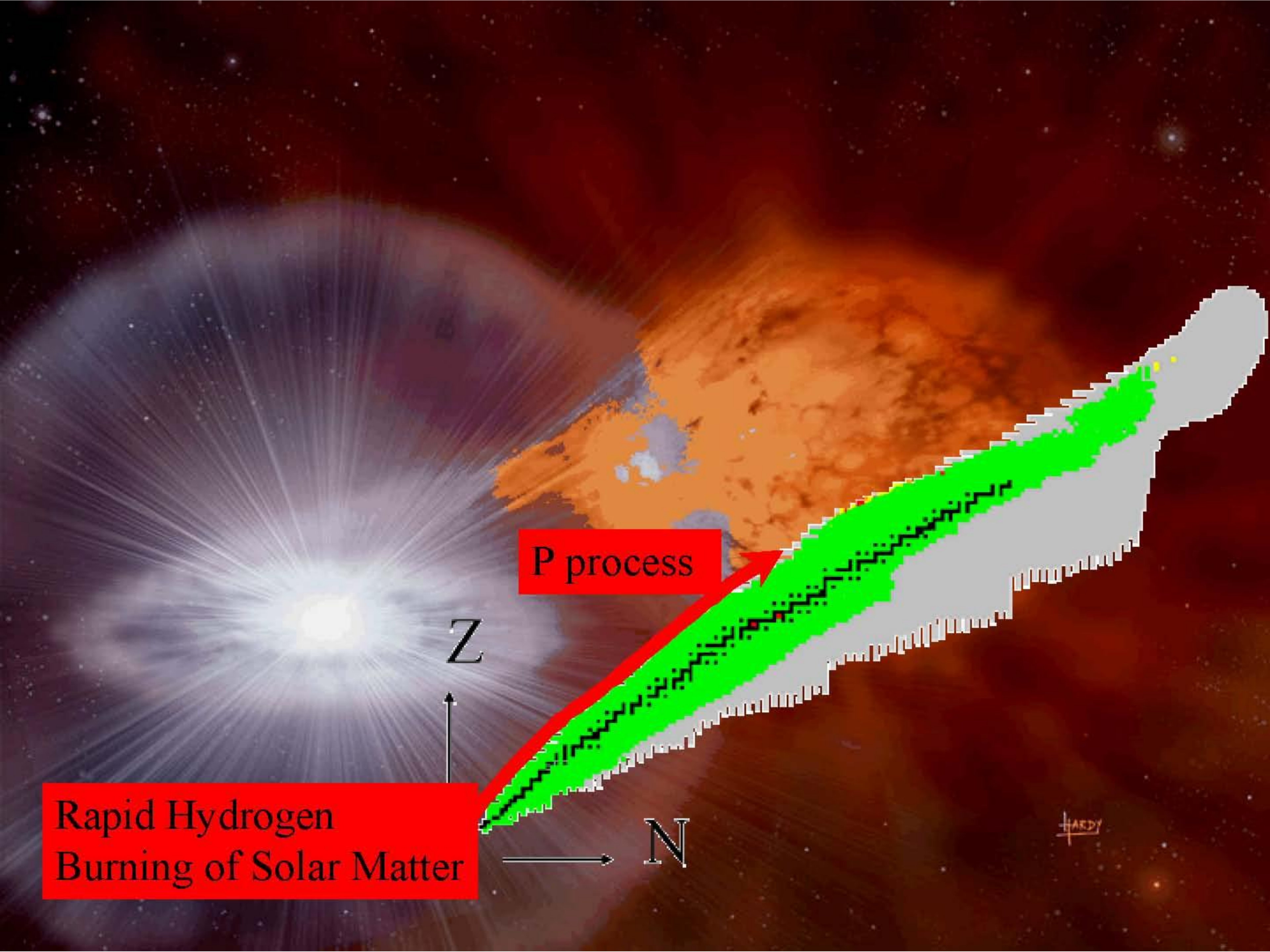
NASA, ESA, W. Li and A. Filippenko (University of California, Berkeley), S. Beckwith (STScI), and The Hubble Heritage Team (STScI/AURA)

STScI-PRC05-21



During the explosion heavy elements are produce < sec

Elements are blasted into space



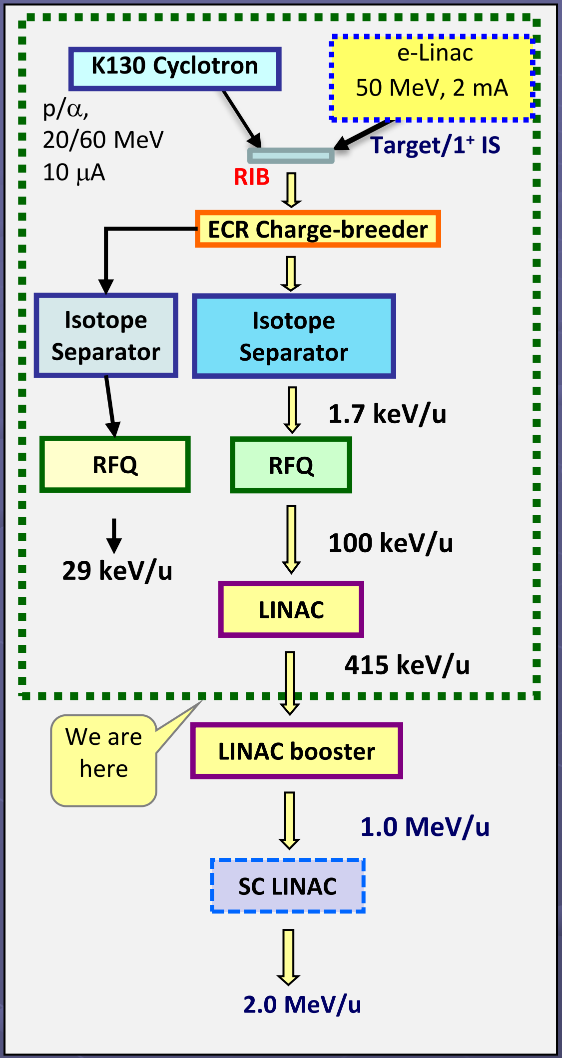
P process

Rapid Hydrogen
Burning of Solar Matter

RIB beyond Nuclear Physics

1. Medical Application
2. Condensed matter physics and related areas
3. New horizon for security
4. Biophysics Research

Radioactive Ion Beam project at VECC



K130 Cyclotron

p/α,
20/60 MeV
10 μA

e-Linac
50 MeV, 2 mA

Target/1⁺ IS

RIB

ECR Charge-breeder

Isotope Separator

Isotope Separator

1.7 keV/u

RFQ

RFQ

29 keV/u

100 keV/u

LINAC

415 keV/u

We are here

LINAC booster

1.0 MeV/u

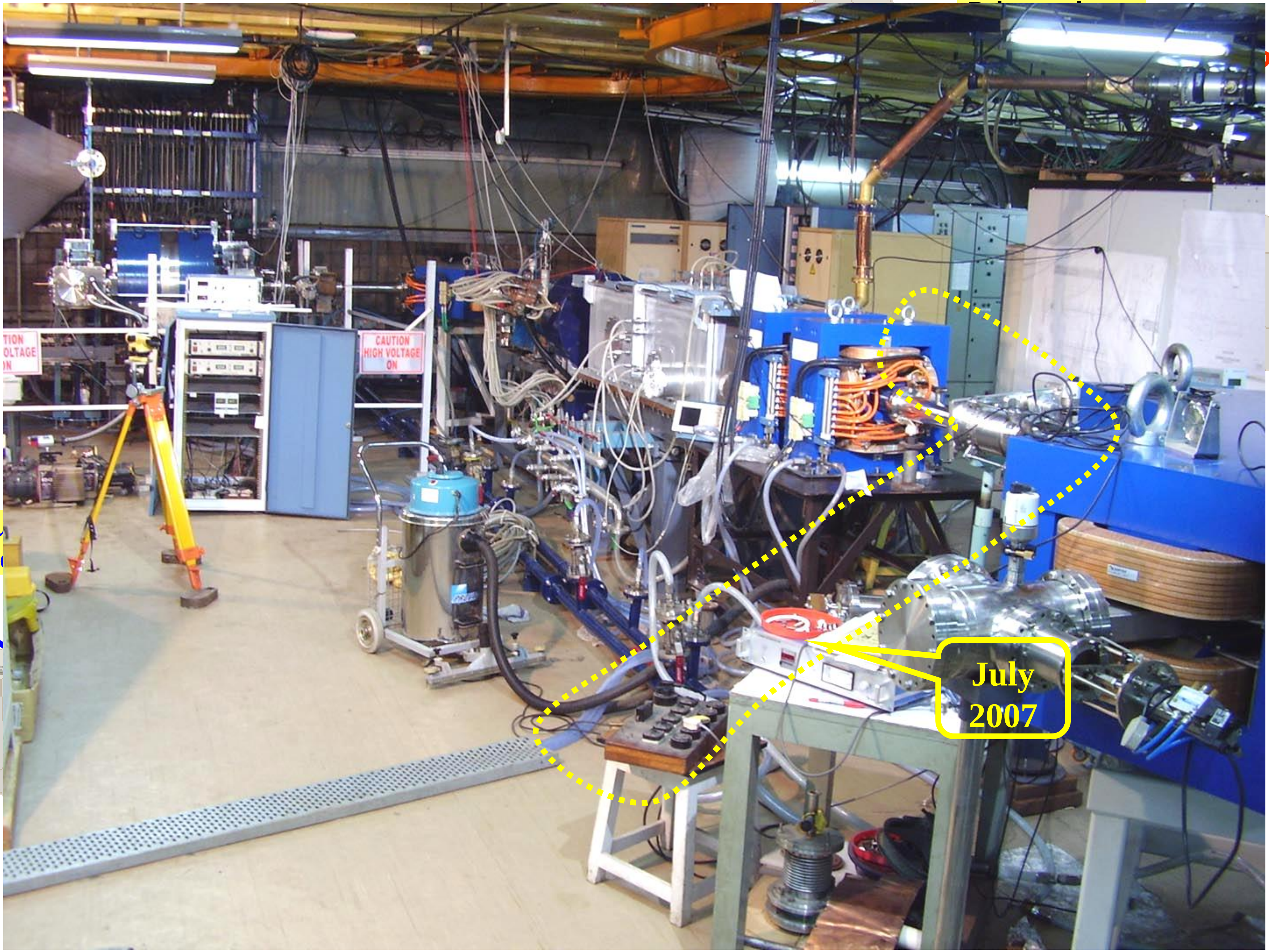
SC LINAC

2.0 MeV/u

Schematic Layout of RIB Facility

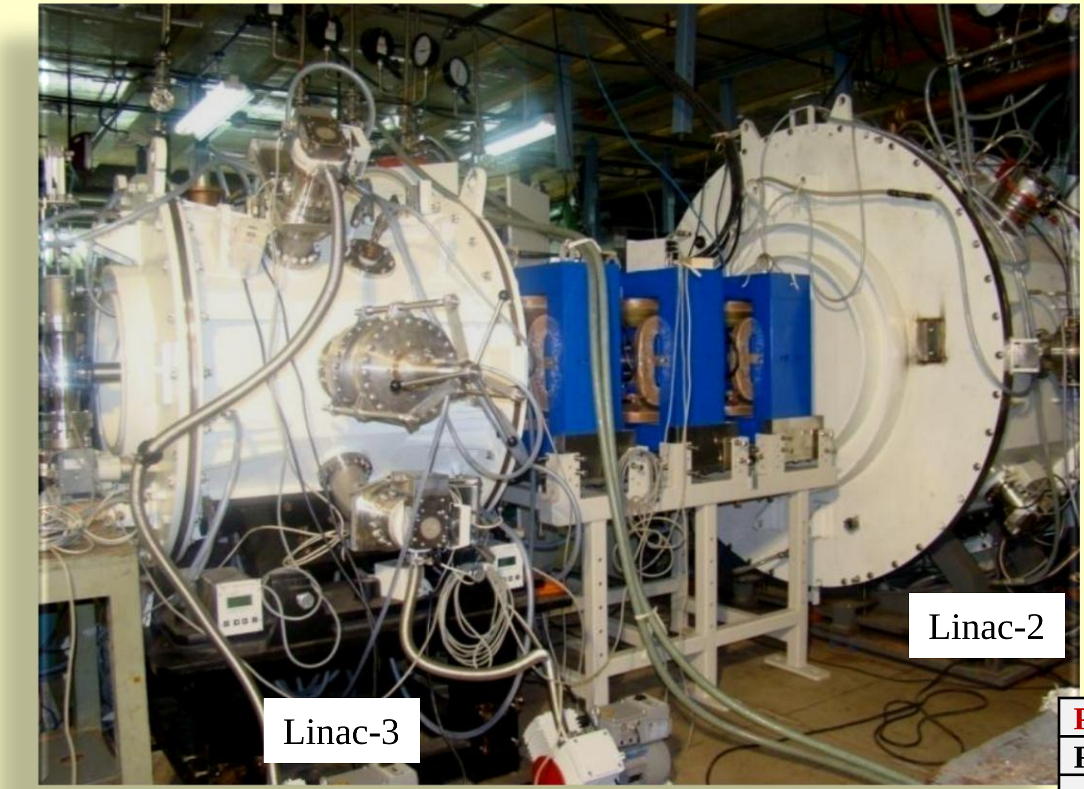
on

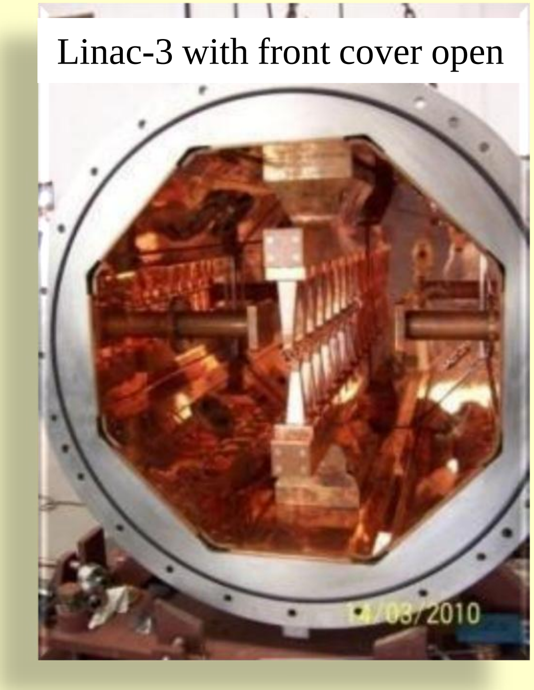
Fu
fa



July
2007

414 keV/u (5.8 MeV) $^{14}N^{4+}$ beam accelerated through LINAC-3




Linac-3 with front cover open

Parameter	Unit	Linac-2	Linac-3
Frequency	MHz	37.8	75.6
q/A	>=	1/14	1/14
E(in)	KeV/u	186.2	289.1
E(out)	KeV/u	289.1	413.9
Peak Vol.	kV	±107.8	±75.8
Length	m	0.871	0.913
Inner Dia	m	1.72	0.8
Accln. Grad.	MV/m	1.79	1.99
Power (Calc)	kW	9.84	11.5

A photograph of Linac-3 installed downstream of Linac-2 for beam test; Eventually will be moved to adjacent cave

Radiolanthanides at ISOLDE

spallation or fission

1 or 1.4 GeV protons

pulsed beam, $3\ 10^{13}$ p/pulse (~1μA)

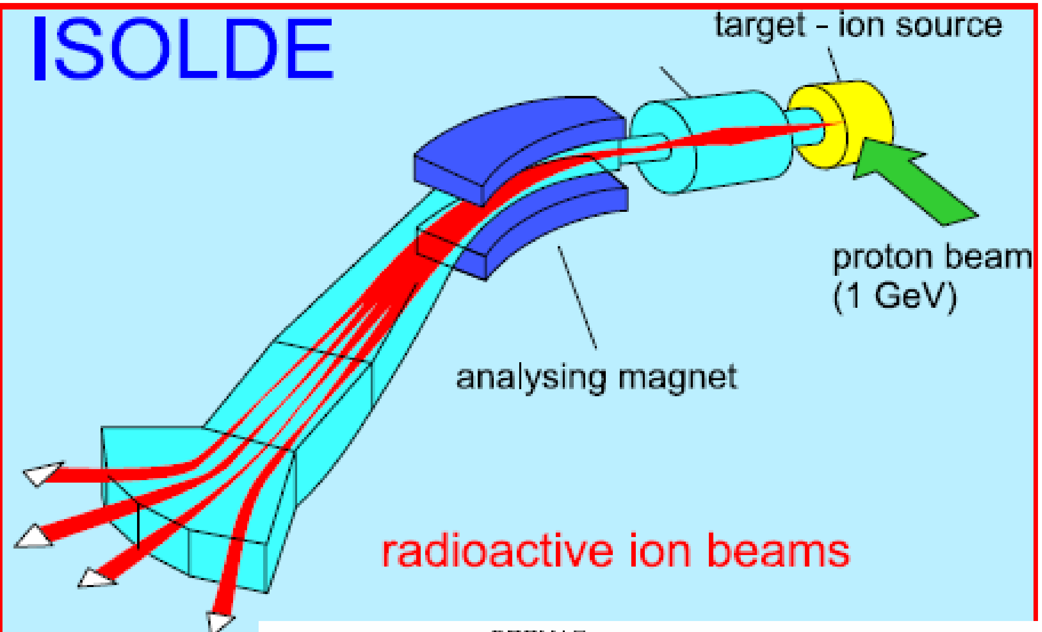
Ta-foil- or U-carbide target

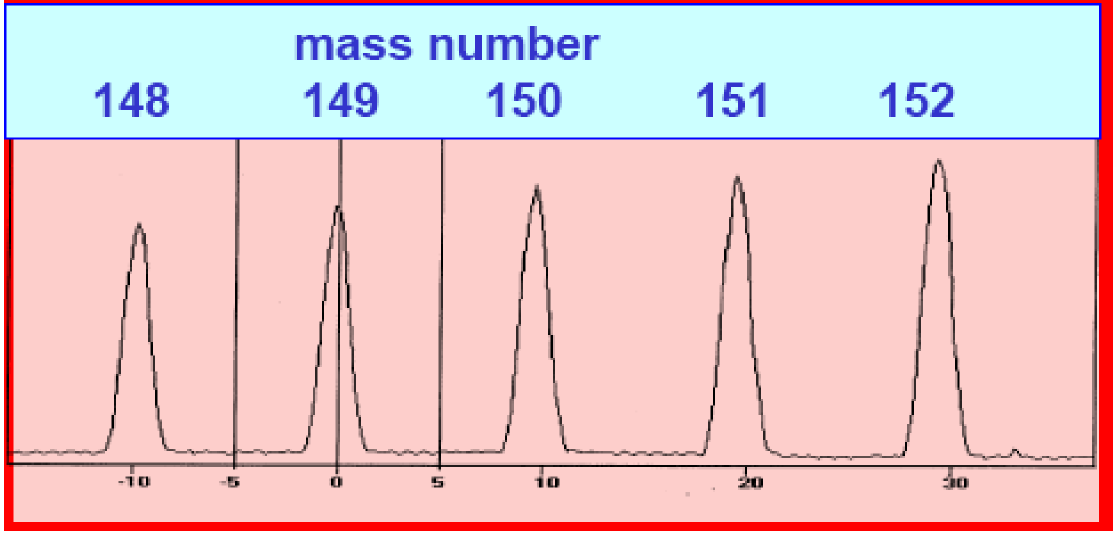
Surface ionization ion source

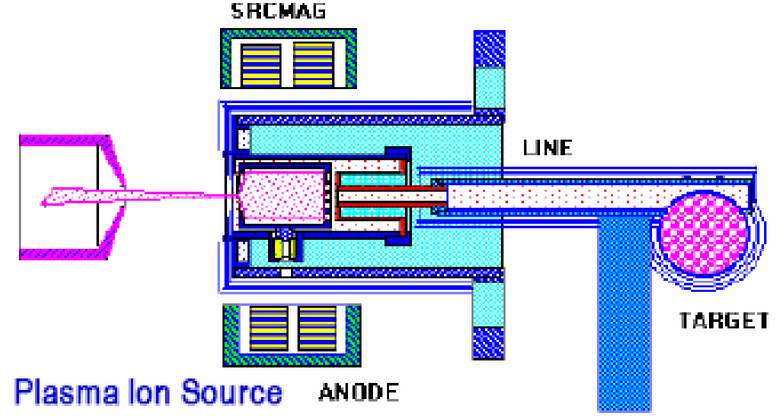
122 g/cm^{2} Ta (rolls of 25 μm foils) at 2400 ^{o}C

W-tube as ionizer at 2800^{o}C

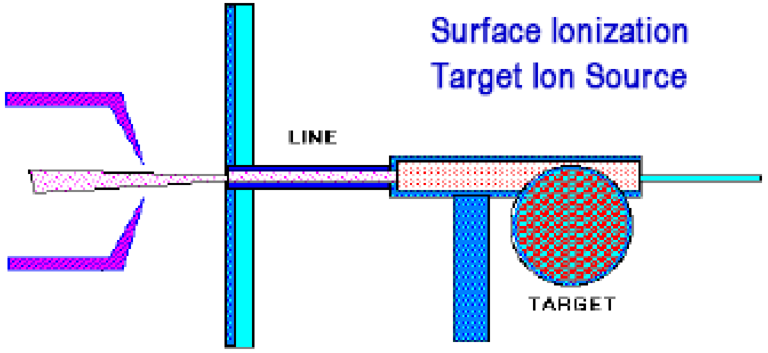
Radioactive Ion Beams of 40 elements possible today



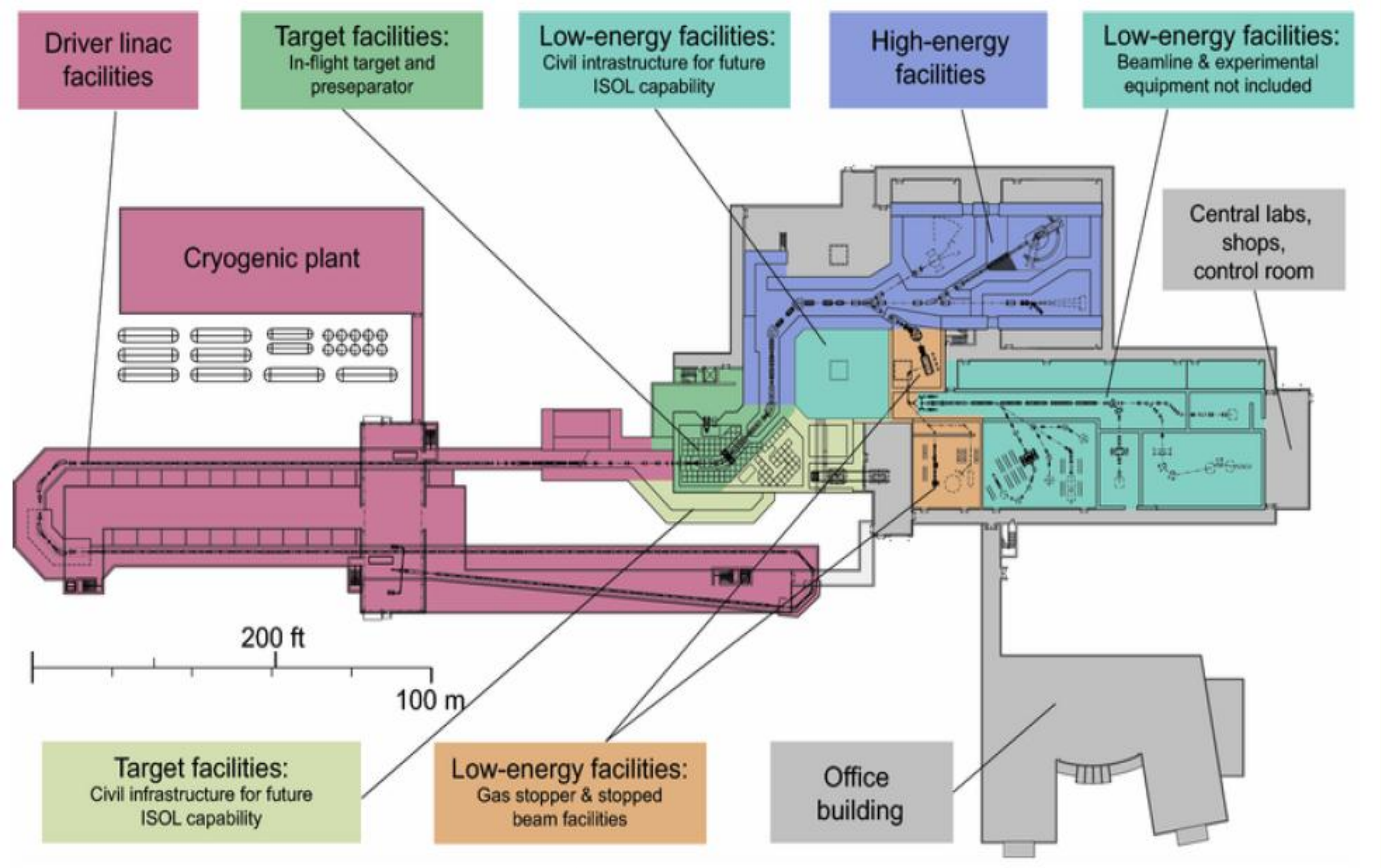




Plasma Ion Source



Surface Ionization Target Ion Source



Layout of the Isotope Science Facility,
Michigan States proposed next generation RIB facility

It is expected that such a facility will allow for the first time, any experimental measurements on many isotopes that are very far from stability. For the first time it may explore experimentally isotopes that are relevant to the r-process and explore near the neutron drip line for heavy mass systems.

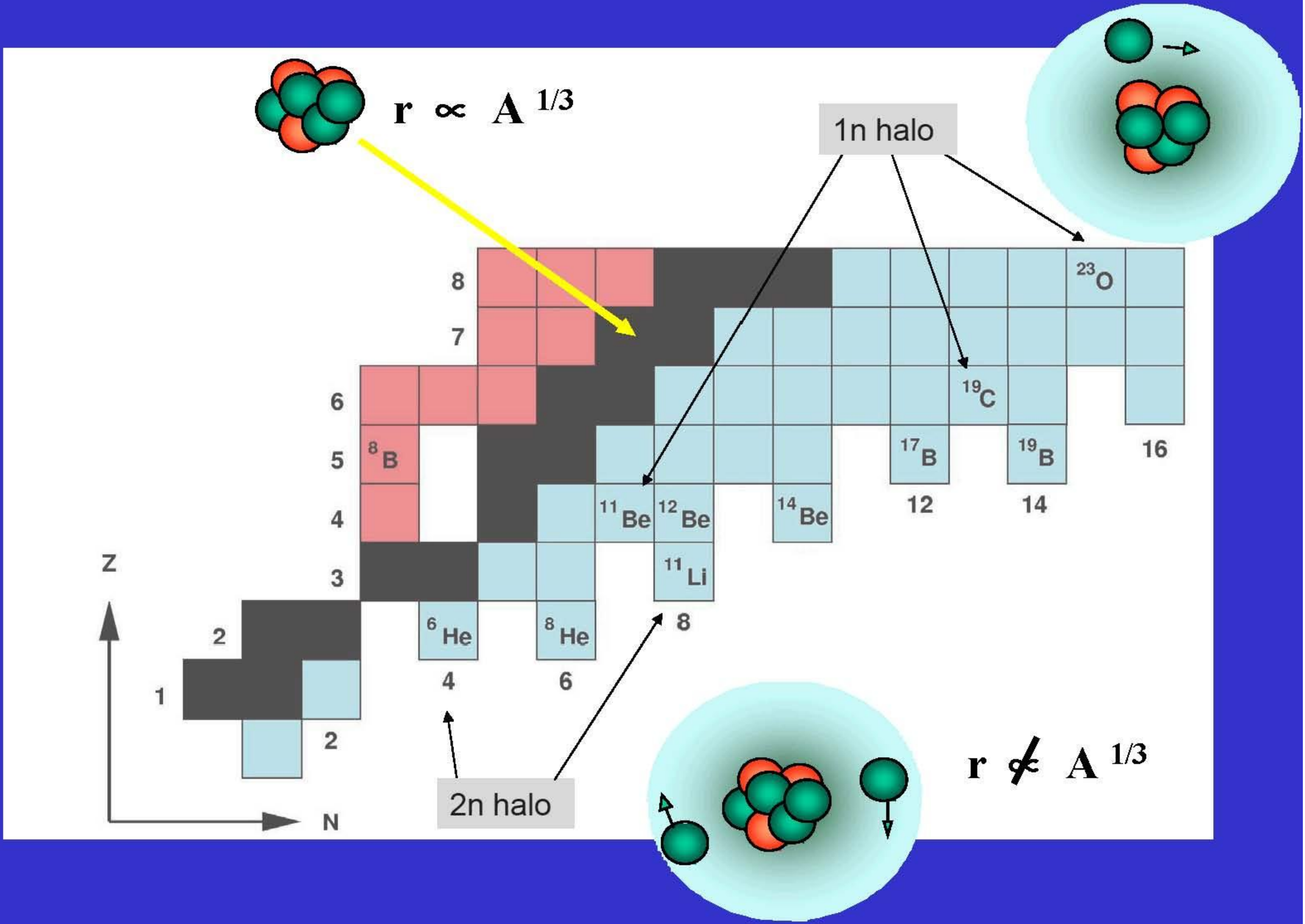
This facility will also provide much large production rates for isotopes near stability, which will enable many more types of experiments than were previously possible.

How radioactive ion beam facilities could impact medical isotopes

G. Beyer et al., conducted an experiment using to study the effectiveness of using the alpha emitter ^{149}Tb (Terbium) in treating lymphoma in mice. ^{149}Tb has a 4.12 hour half-life and was made at the ISOLDE radioactive ion beam facility in CERN.

The ^{149}Tb was attached to an antibody that is specific for the infected cells. Thus, the ^{149}Tb was delivered in close proximity to the infected cells, necessary for the alpha particle to affect those cells. The study divided the effect mice in the four groups. One received no treatment, the other two received just the antibodies, and the fourth received the antibody doped with ^{149}Tb. All the mice in the first three groups died. While, only 11% of the mice died in the group that received the ^{149}Tb.

This was the first in vivo experiment to demonstrate the efficiency of alpha target therapy using ^{149}Tb. It is exactly this kind of research that would be greatly expanded when the next generation radioactive ion beam facilities come on line.



$r \propto A^{1/3}$

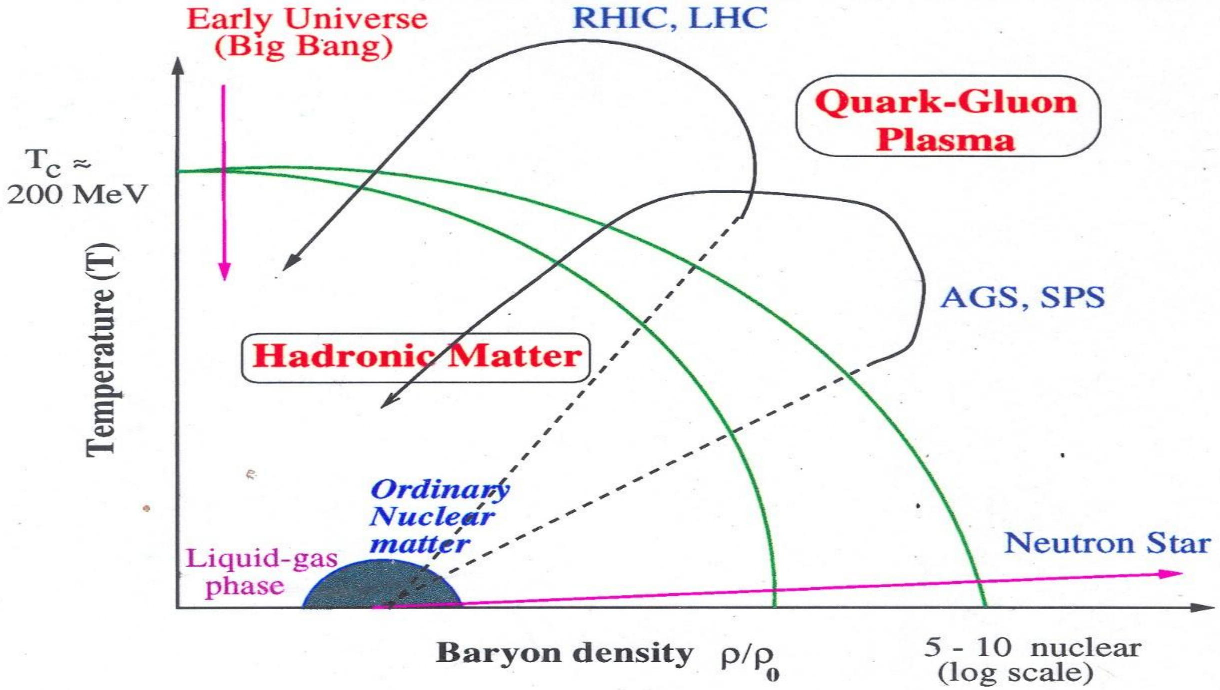
1n halo

2n halo

$r \not\propto A^{1/3}$

What about
Colliding RIB’s
and
the discovery of
new happy islands

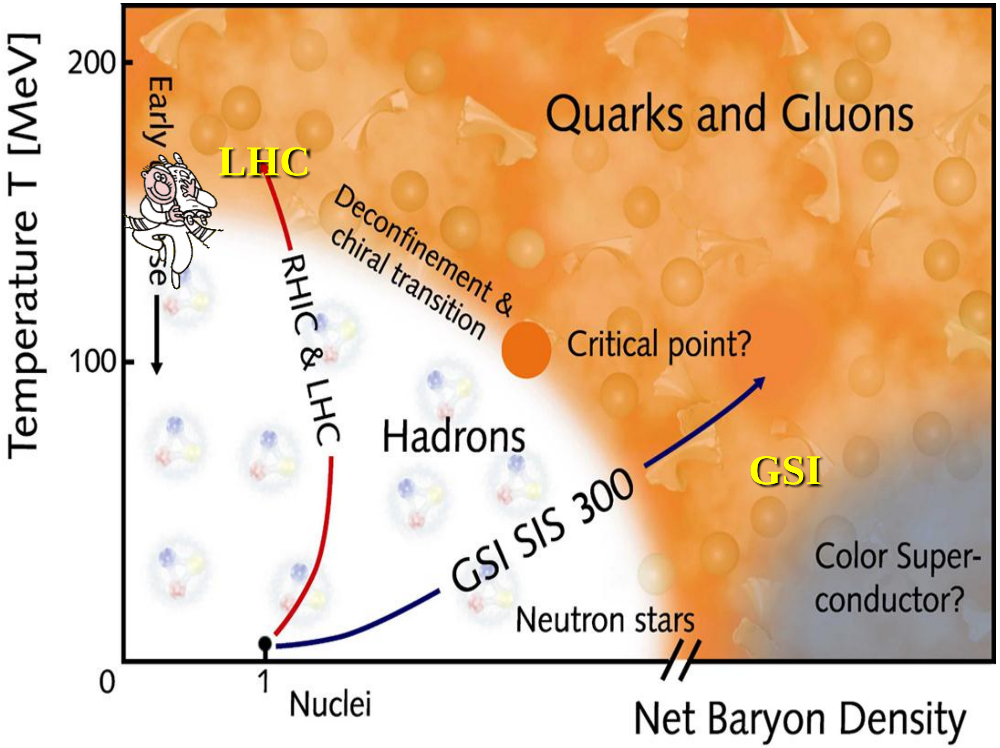
Phase Diagram of Nuclear Matter



QCD Transitions:

- Deconfinement
- Chiral Symmetry Restoration

QCD Phase Diagram



What does the theory expect?
→ mainly predictions from lattice QCD:

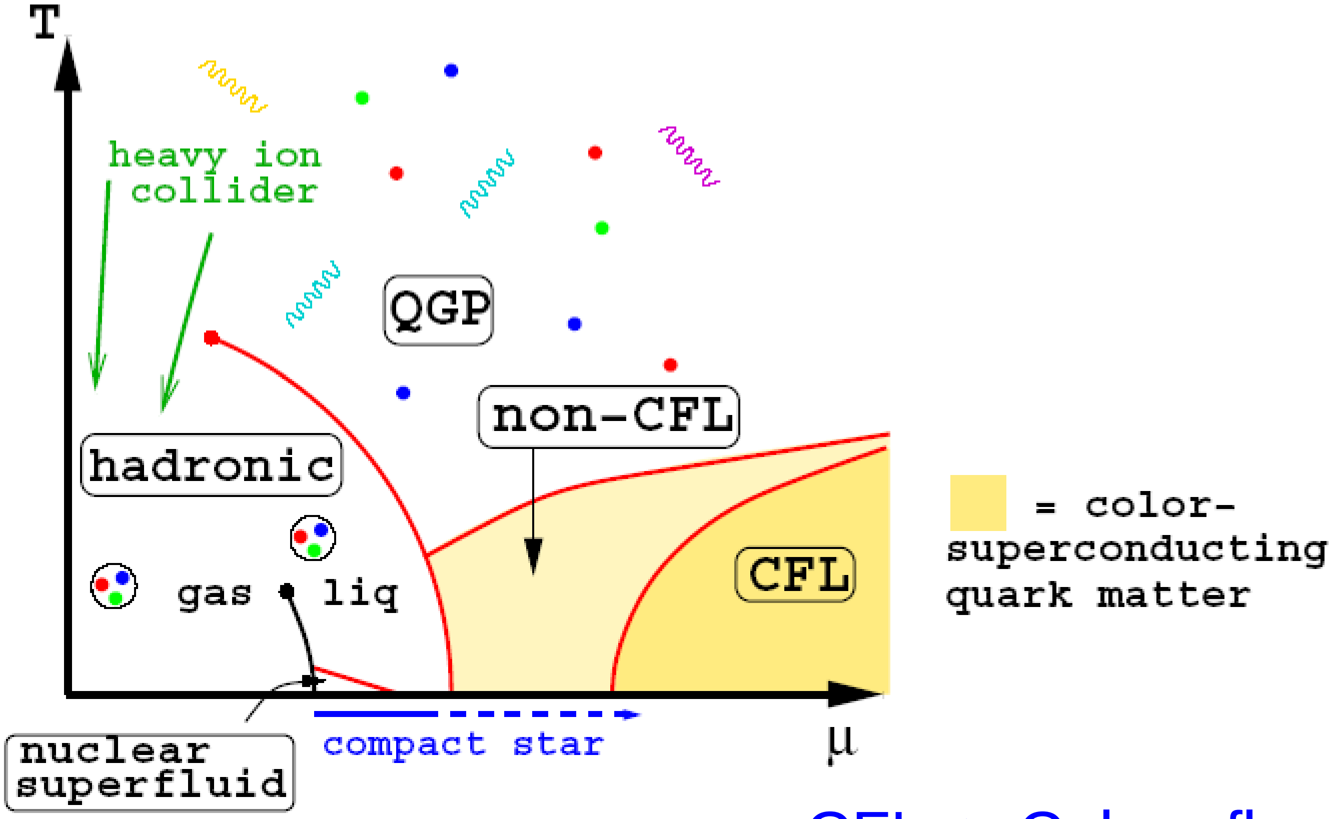
- crossover transition from partonic to hadronic matter at small μ_B and high T
- critical endpoint in intermediate range of the phase diagram
- first order deconfinement phase transition at high μ_B but moderate T

The Compressed Baryonic Matter (CBM) experiment : Exploration of the phase diagram at very high baryon densities and moderate temperatures to look for :

- **De-confinement phase transition at high temperature & baryon density**
- **In-medium modification of hadrons – signal of the onset of chiral symmetry restoration.**
- **Location of the critical end point**

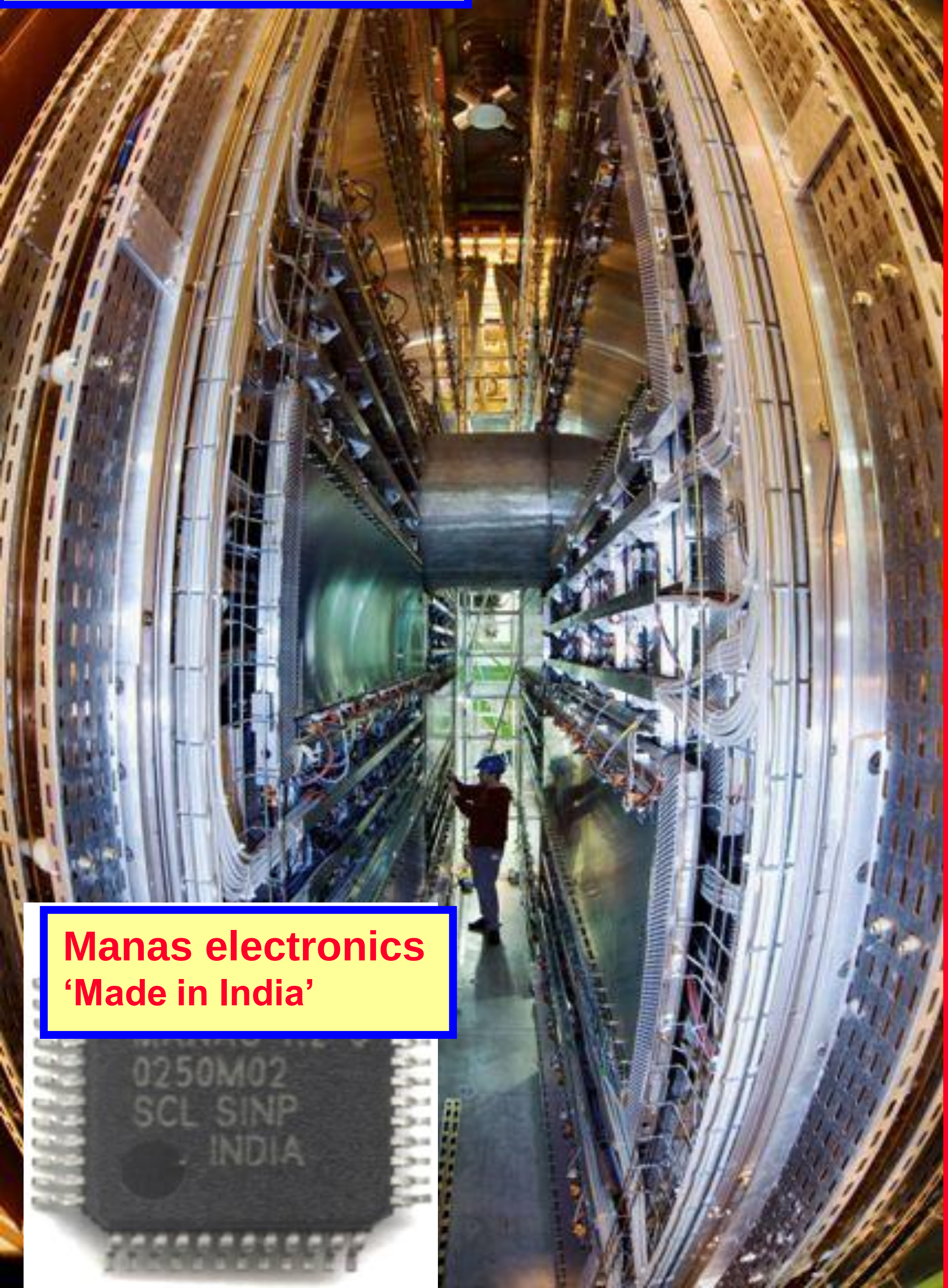
Quark matter in neutron stars

Conjectured QCD phase diagram



CFL -> Colour flavour Locked

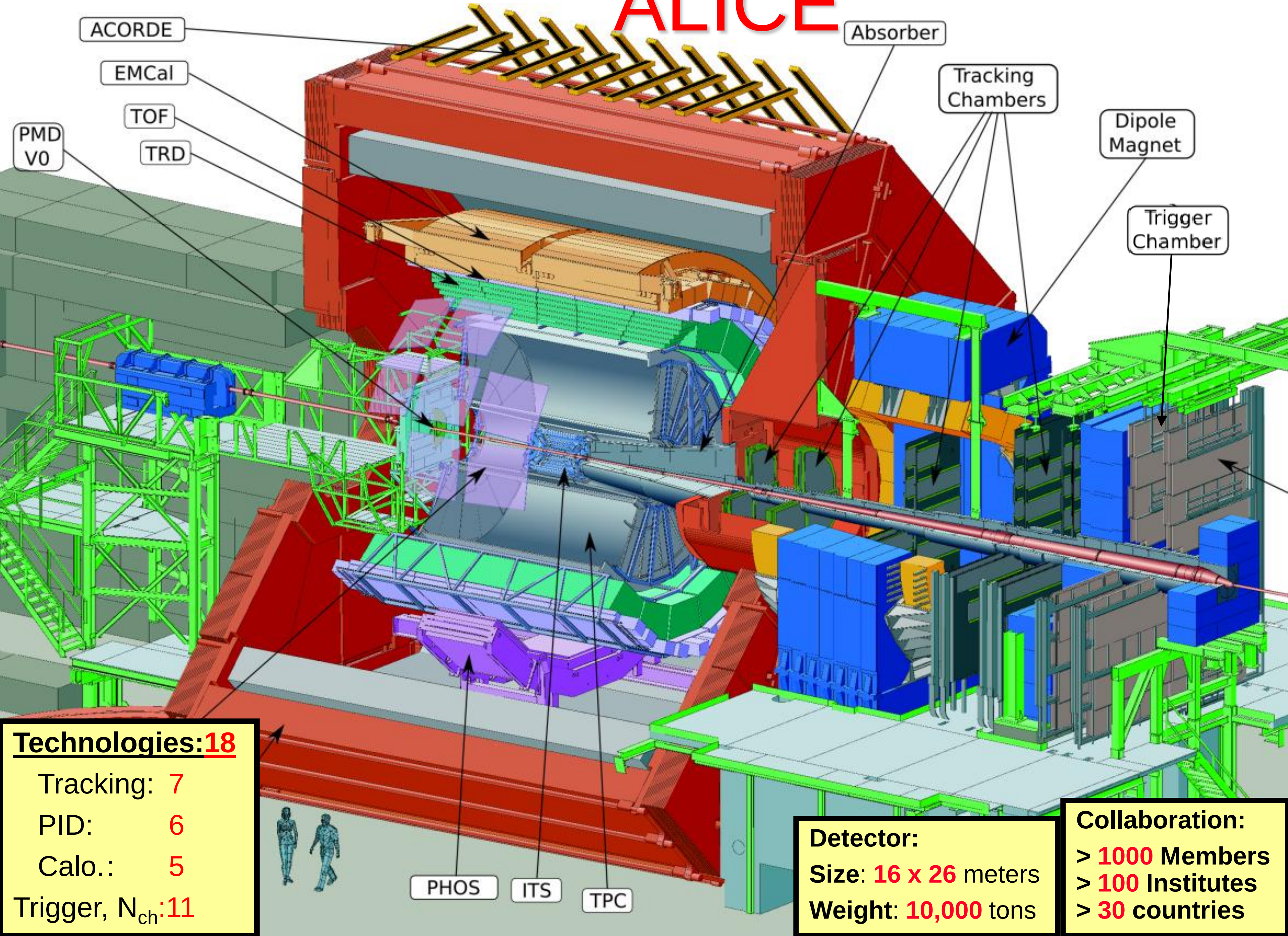
Muon Chambers
~ 100 m2, > 106 channels



Manas electronics
‘Made in India’

PMD

ALICE



Technologies:18

Tracking: 7

PID: 6

Calo.: 5

Trigger, N_{ch}:11

Detector:

Size: 16 x 26 meters

Weight: 10,000 tons

Collaboration:

> 1000 Members

> 100 Institutes

> 30 countries

Au + Au Collisions
RHIC

$$\sqrt{s_{NN}} = 250\ \mathrm{GeV}$$

Perfect fluid

$\eta/S = 0.08$

Classical Nuclear Physics

Collective Phenomena

η/s in Finite Nucli

1. Giant Resonances/proton & neutron fluids Hydro dynamical model => widths of resonances to the viscosity of the proton – neutron fluids

2. Fission process

At high temp : $T >> \hbar\omega$

$$\frac{\eta}{S} = \frac{\hbar}{4\pi k_B} \frac{16}{5\pi} \left(\left(\frac{\in_F}{T} \right)^2 \frac{\alpha}{T} \right) \longrightarrow \text{Neutron Star?}$$

$$T \approx {}^{\in_F}\!/_{2} \longrightarrow {}^{\eta}\!/_{S} \sim {}^{\hbar}\!/_{4\pi k_B}$$

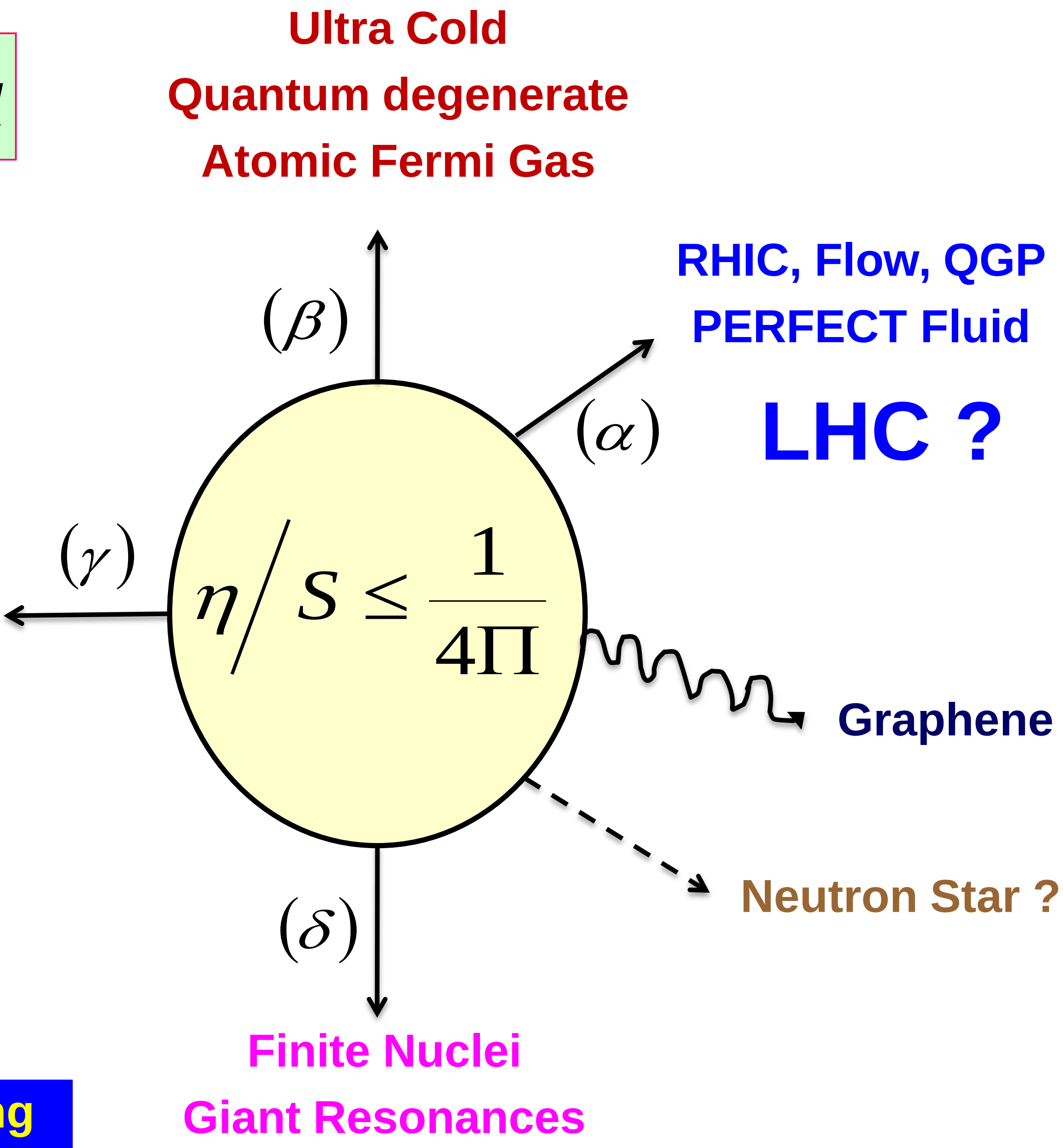
Unusually similar to RHIC results

What about Giant dipole resonances on highly excited state $\longrightarrow \dfrac{\eta}{S}$

Giant Resonance in Radioactive Nuclei

The values of η found in the studies of the fission process agree generally with the ones found from the work on giant resonances.

η/S *Saga*



Ultra Cold
Quantum degenerate
Atomic Fermi Gas

(β)

RHIC, Flow, QGP
PERFECT Fluid

(α)

LHC ?

(γ)

Microsecond
Universe : QGP
String Theory

$$\eta/S \leq \frac{1}{4\Pi}$$

Graphene

Neutron Star ?

(δ)

Finite Nuclei
Giant Resonances

Strongly interacting System

RIB (TERRA INCOGNITA)

➡ **EXOTIC COGNITA**

- LHC is a fantastic 'Big Bang' machine
  - ⇨ even for LHC standards, quality of first ion run was outstanding
  - ⇨ very powerful and complementary set of detectors (Atlas/CMS/Alice)
  - ⇨ physics looks to be even more interesting than anticipated

There is plenty of
exciting physics (and fun)
at the LHC
exploring QCD in a new domain,
where the strong interaction is
really strong !

- Looking forward to the 'terra incognita' of HI at LHC

G. Blaeu (Dutch School)

Hic sunt Leones !