Closing

2019 BUSAN KOREA

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Prediction of a neutron star

- L. Landau
  Physikalische Zeitschrift der Sowjetunion
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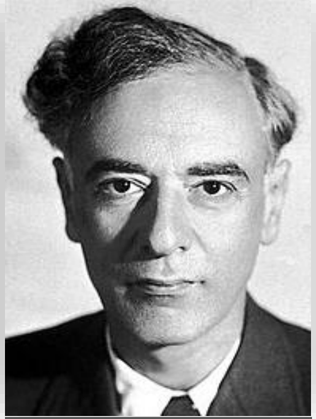


Lev Landau
(1908~1968)
Nobel Prize
in 1962

ON THE THEORY OF STARS.

By L. Landau.

(Received 7 January 1932).

From the theoretical point of view the physical nature of Stellar equilibrium is considered.

The astrophysical methods usually applied in attacking the problems of stellar structure are characterised by making physical assumptions chosen only for the sake of mathematical convenience. By this is characterised, for instance, Mr. Milne's proof of the impossibility of a star consisting throughout of classical ideal gas; this proof rests on the assertion that, for arbitrary L and M, the fundamental equations of a star consisting of classical ideal gas admit, in general, no regular solution. Mr. Milne seems to have overlooked the fact, that this assertion results only from the assumption of opacity being constant throughout the star, which assumption is made only for mathematical purposes and has nothing to do with reality. Only in the case of this assumption the radius R disappears from the relation between L, M and R necessary for regularity of the solution. Any reasonable assumptions about the opacity would lead to a relation between L, M and R, which relation would be quite exempt from the physical criticisms put forward against Eddington's mass-luminosity-relation.

It seems reasonable to try to attack the problem of stellar structure by methods of theoretical physics, i. e. to investigate the physical nature of stellar equilibrium. For that purpose we must at first investigate the statistical equilibrium of a given mass without generation of energy, the condition for which equilibrium being the minimum of free energy F (for given temperature). The part of free energy due to gravitation is negative and inversely proportional to some

Prediction of a neutron star

we have no need to suppose that the radiation of stars is due to some mysterious process of mutual annihilation of protons and electrons, which was never observed and has no special reason to occur in stars. Indeed we have always protons and electrons in atomic nuclei very close together, and they do not annihilate themselves; and it would be very strange if the high temperature did help, only because it does something in chemistry (chain reactions!). Following a beautiful idea of Prof. Niels Bohr's we are able to believe that the stellar radiation is due simply to a violation of the law of energy, which law, as Bohr has first pointed out, is no longer valid in the relativistic quantum theory, when the laws of ordinary quantum mechanics break down (as it is experimentally proved by continuous-rays-spectra and also made probable by theoretical considerations).[1] We expect that this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus.

On these general lines we can try to develop a theory of stellar structure. The central region of the star must consist of a core of highly condensed matter, surrounded by matter in ordinary state. If the transition between these two states were a continuous one, a mass $M < M_0$ would never form a star, because the normal equilibrium state (i. e. without pathological regions) would be quite stable. Because, as far as we know, it is not the fact, we must conclude that the condensed and non-condensed states are separated by some unstable states in the same manner as a liquid and its vapour are, a property which could be easily explained by some kind of nuclear attraction. This would lead to the existence of a nearly discontinuous boundary between the two states.

The theory of stellar structure founded on the above considerations is yet to be constructed, and only such a theory can show how far they are true.

February 1931, Zurich.

[1] L. Landau und R. Peierls, ZS. f. Phys. 69, 56, 1931.

made probable by theoretical considerations).[1] We expect that this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus.

- **May 1932**, James Chadwick discovered a new uncharged particle, which he called the **neutron**.

Prediction of a neutron star

- In Dec. 1933

Walter Baade (Mt. Wilson Observatory) &

Fritz Zwicky (Caltech)

Walter Baade
(1893-1960)

Fritz Zwicky
(1898-1974)

The American Physical Society Meeting
(Stanford, December 15-16, 1933)
Published in Physical Review 46, 76 1934)

38. Supernovae and Cosmic Rays. W. Baade, *Mt. Wilson Observatory*, and F. Zwicky, *California Institute of Technology*.—Supernovae flare up in every stellar system (nebula) once in several centuries. The lifetime of a supernova is about twenty days and its absolute brightness at maximum may be as high as $M_{vis} = -14^M$. The visible radiation L_ν of a supernova is about 10^8 times the radiation of our sun, that is, $L_\nu = 3.78 \times 10^{41}$ ergs/sec. Calculations indicate that the total radiation, visible and invisible, is of the order $L_\tau = 10^7 L_\nu = 3.78 \times 10^{48}$ ergs/sec. The supernova therefore emits during its life a total energy $E_\tau \geqq 10^5 L_\tau = 3.78 \times 10^{53}$ ergs. If supernovae initially are quite ordinary stars of mass $M < 10^{34}$ g, E_τ / c^2 is of the same order as M itself. In the *supernova* process *mass in bulk is annihilated*. In addition the hypothesis suggests itself that *cosmic rays are produced by supernovae*. Assuming that in every nebula one supernova occurs every thousand years, the intensity of the cosmic rays to be observed on the earth should be of the order $\sigma = 2 \times 10^{-3}$ erg/cm² sec. The observational values are about $\sigma = 3 \times 10^{-3}$ erg/cm² sec. (Millikan, Regener). With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.

First calculation of neutron star models

FEBRUARY 15, 1939 PHYSICAL REVIEW VOLUME 55

On Massive Neutron Cores

J. R. OPPENHEIMER AND G. M. VOLKOFF
Department of Physics, University of California, Berkeley, California

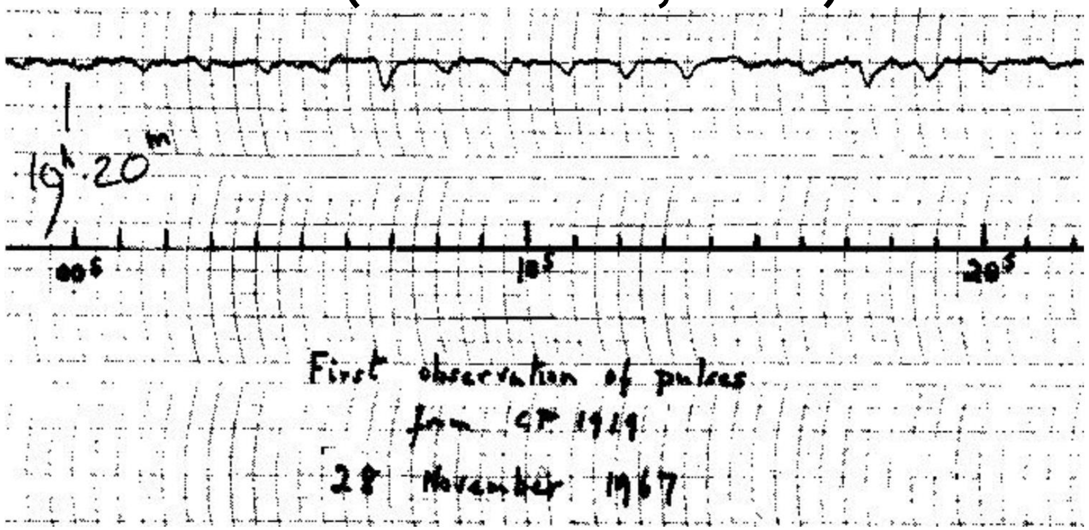
(Received January 3, 1939)

~ 30 years later.. Discovery of pulsars

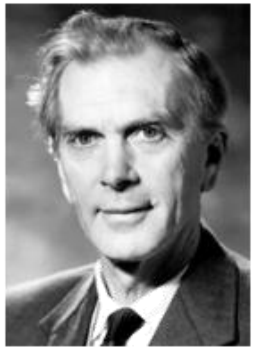
- Nov. 1967, S. J. Bell (Cambridge) and A. Hewish

Susan Jocelyn Bell

(PSR B1919+21, LGM-1)



The Nobel Prize in Physics 1974



Sir Martin Ryle
Prize share: 1/2

Antony Hewish
Prize share: 1/2

Little Green Man

~ 30 years later.. Discovery of pulsars

- Nov. 1967, S. J. Bell (Cambridge) and A. Hewish

Susan Jocelyn Bell

NATURE, VOL. 217, FEBRUARY 24, 1968

Observation of a Rapidly Pulsating Radio Source

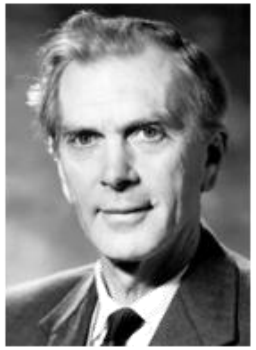
by

A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

The Nobel Prize in Physics 1974



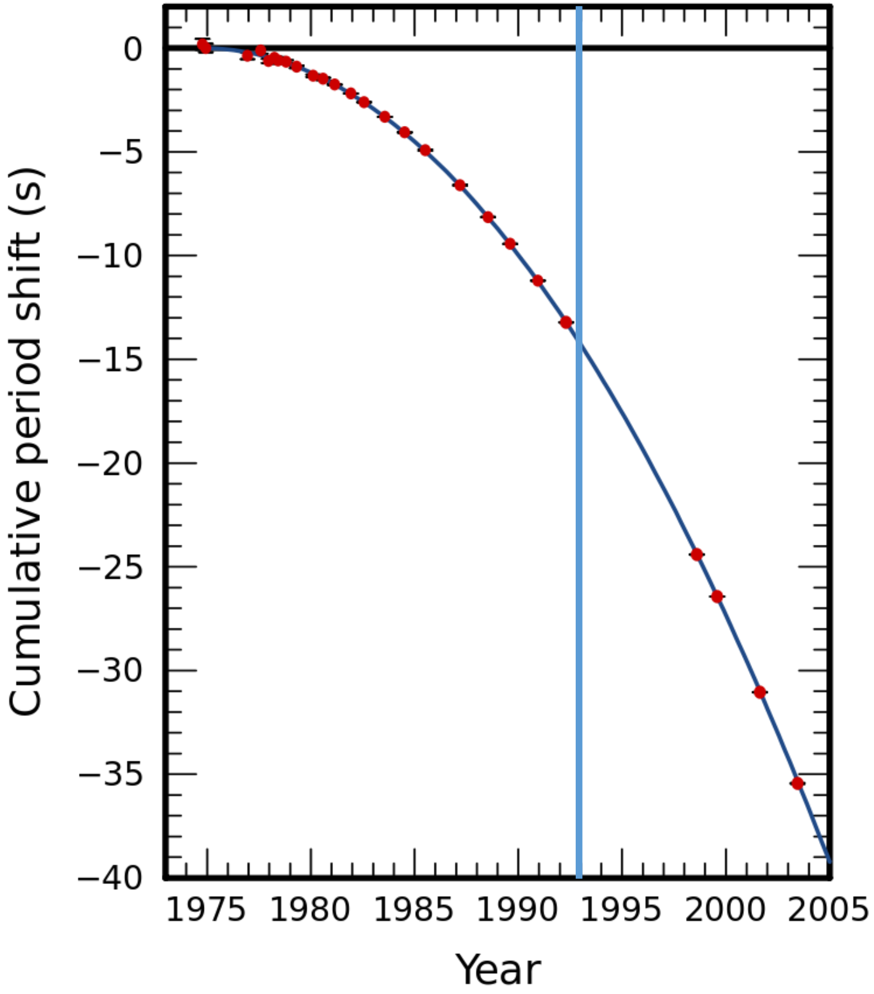
Sir Martin Ryle
Prize share: 1/2

Antony Hewish
Prize share: 1/2

Little Green Man

~7 years later .. Binary Pulsar PSR 1913+16

In 1974, Russell Hulse and Joseph Taylor observed a binary pulsar



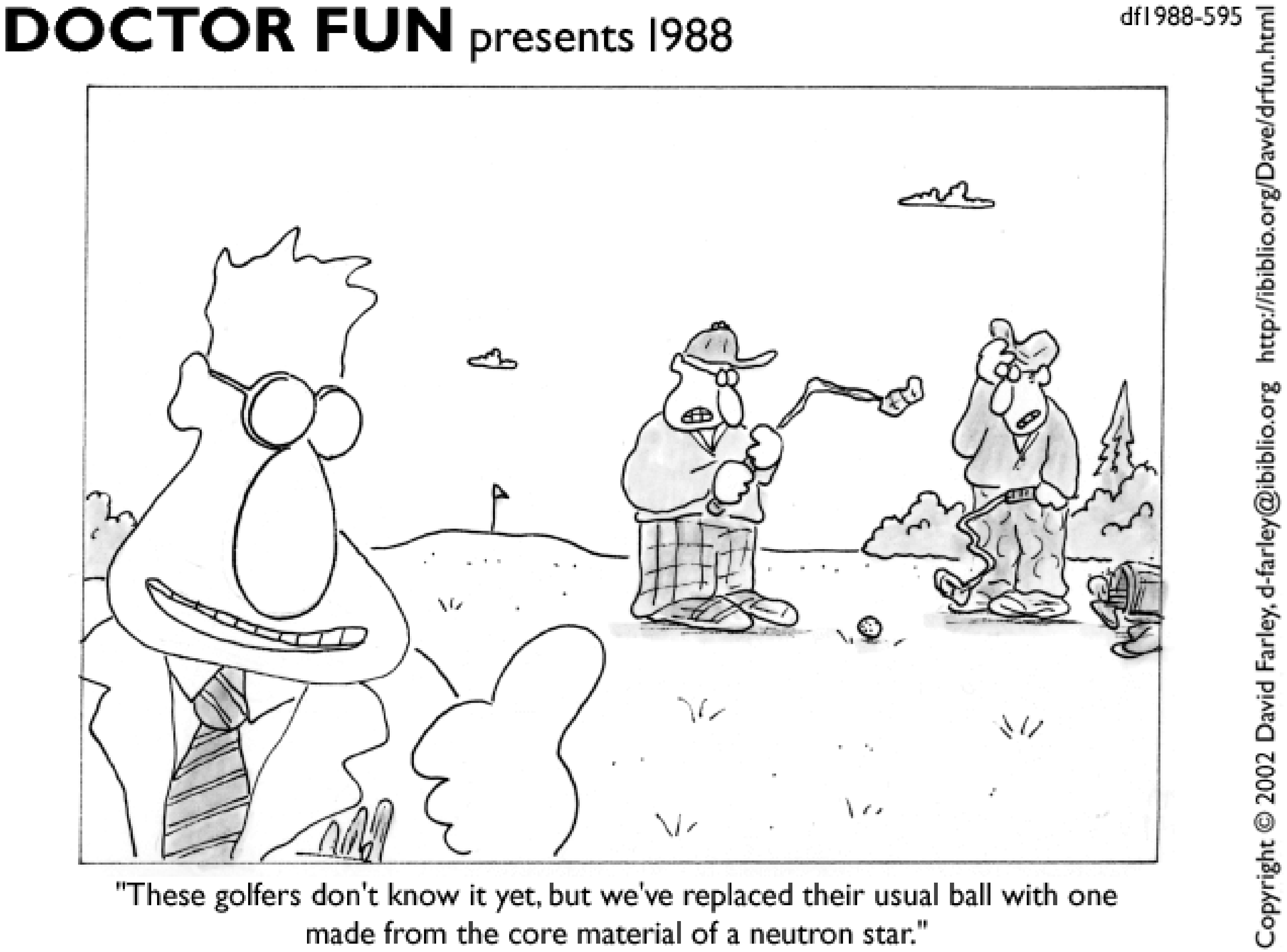
Arecibo radio telescope
in Puerto Rico

The Nobel Prize in Physics 1993

Russell A. Hulse
Prize share: 1/2

Joseph H. Taylor Jr.
Prize share: 1/2

In 1988, a neutron star became a layman's term!



"These golfers don't know it yet, but we've replaced their usual ball with one made from the core material of a neutron star."

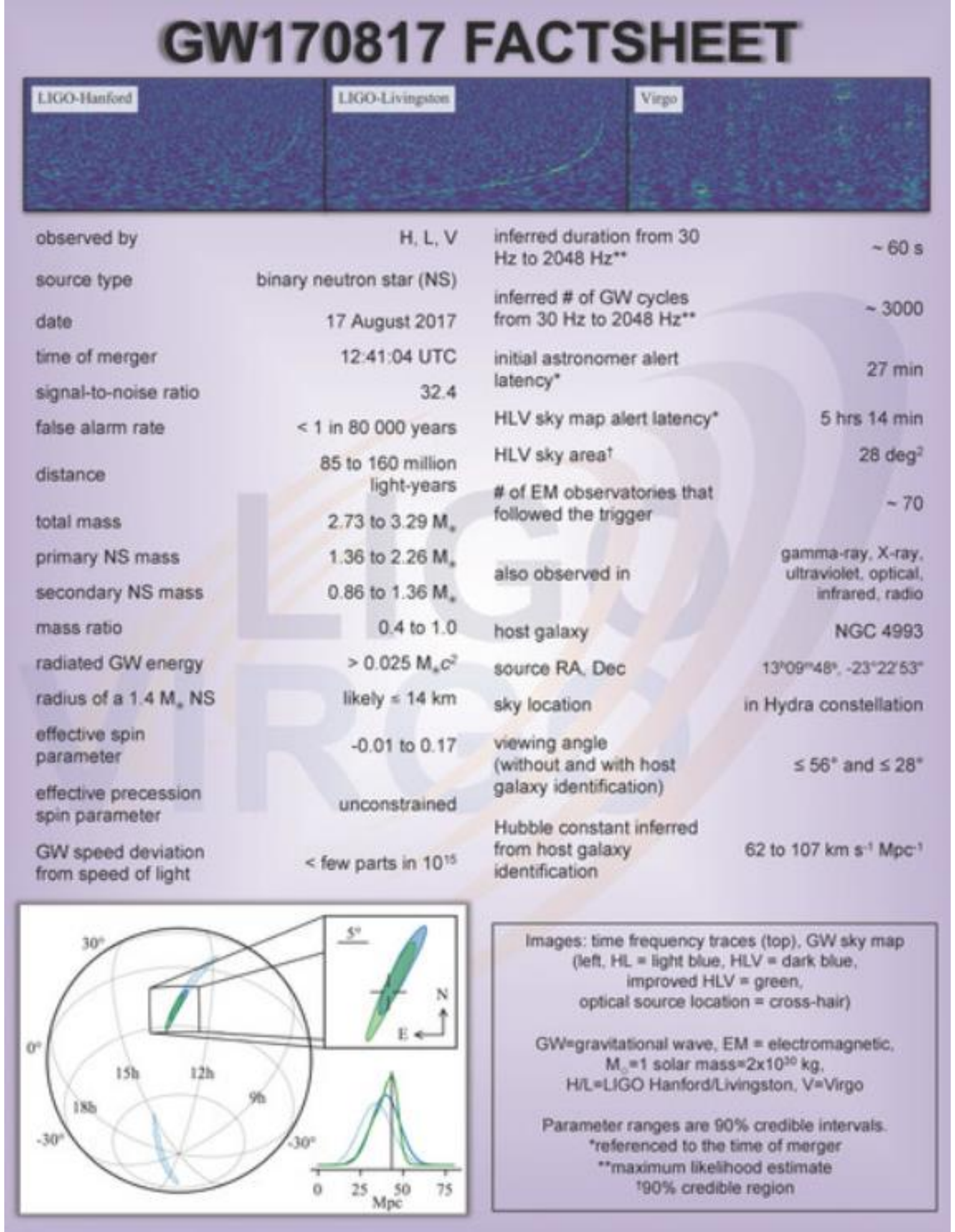
We've replaced their usual ball with one made from **the core material of a neutron star.**

~30 years later .. LIGO

A new era of multi-messenger astronomy and astrophysics!

Revolution!

Really an exciting time for astronomy, astrophysics, nuclear physics, & particle physics, etc



GW170817 FACTSHEET

observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≤ 14 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}

inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	13^{h}09^{m}48^s, -23°22'53"
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}

Images: time frequency traces (top), GW sky map (left, HL = light blue, HLV = dark blue, improved HLV = green, optical source location = cross-hair)

GW=gravitational wave, EM = electromagnetic, $M_\odot$=1 solar mass=2x10^{30} kg, H/L=LIGO Hanford/Livingston, V=Virgo

Parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
†90% credible region

Problems discussed ..

Hyperon puzzle

NNN interactions at high densities

Hyperon interactions

Symmetry energy

Superfluidity and Superconductivity

Nuclear matter vs quark matter

Fully 3-D calculations & internal structures

Thermal evolution and cooling

Tidal deformation

Magnetar and decay of magnetic fields

and many others ..

Laboratory probes of the nuclear matter EOS

RAON

Rare isotope
Accelerator complex for
ON-line experiments

RAON: Rare Isotope accelerator complex for ON-line experiment

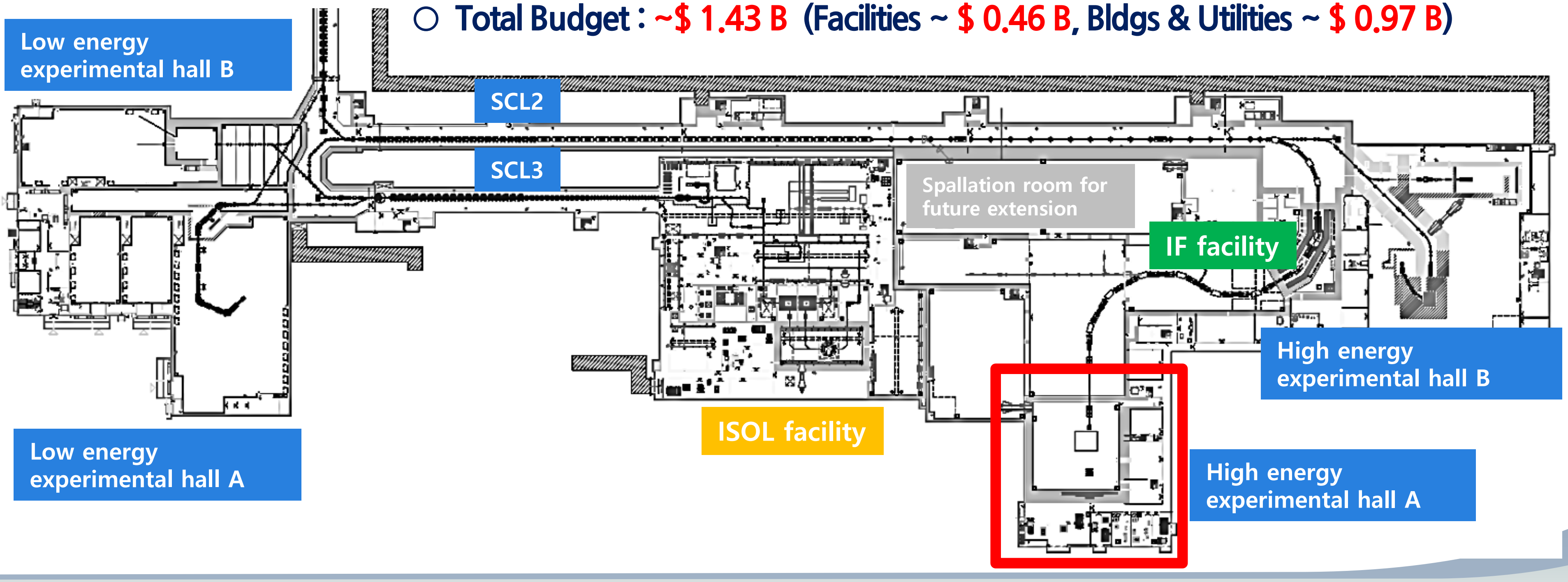
❖ **high intensity RI beams by ISOL and IF**
ISOL: direct fission of ^{238}U by 70 MeV proton
IF: 200 MeV/u ^{238}U (intensity: 8.3 pμA)

❖ **high quality neutron-rich beams**
e.g., ^{132}Sn with up to 250 MeV/u, up to 10^9 particles per second

❖ **More exotic RI beam production by combination of ISOL and IF (ISOLIF)**

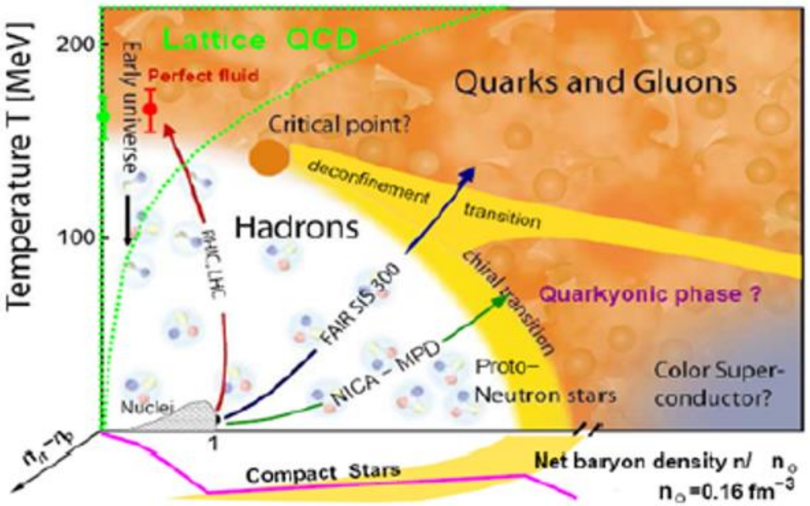
○ **Project period : 2011.12 - 2021.12**

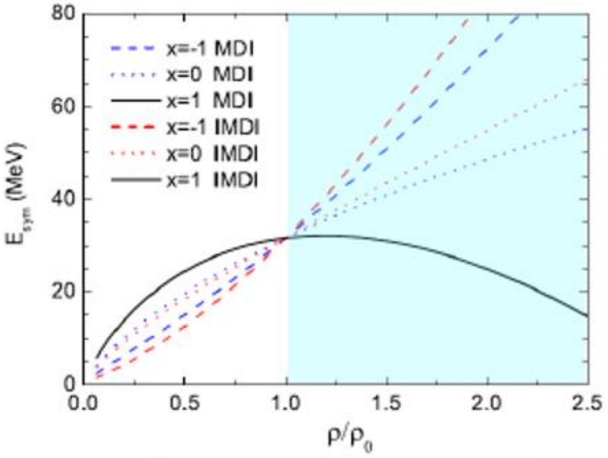
○ **Total Budget : ~$ 1.43 B (Facilities ~ $ 0.46 B, Bldgs & Utilities ~ $ 0.97 B)**



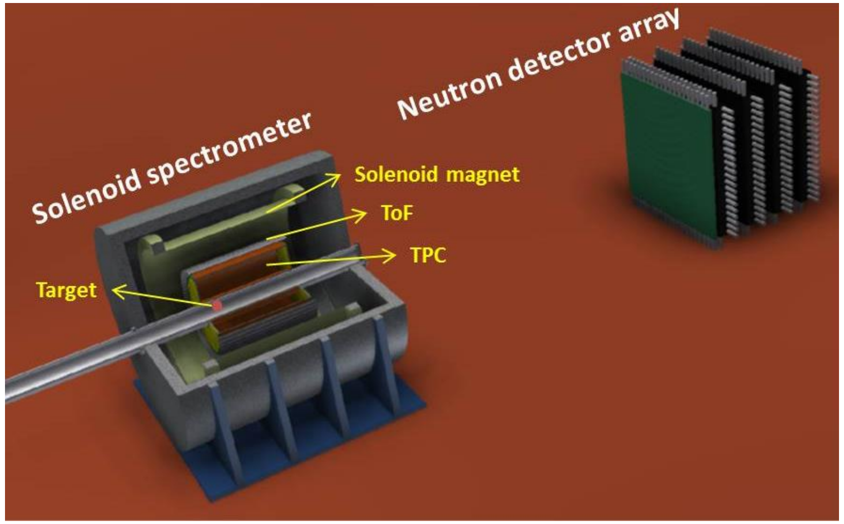
LAMPS (Large Acceptance Multi-Purpose Spectrometer)

- Exploring the nuclear phase diagram via heady-ion collisions including the isospin axis using RI beams
- Role of isospin degree of freedom in strong interaction
  - Nuclear symmetry energy from sub- to supra-saturation densities
  - Characterization of the core of neutron stars





C. Xu and B. A. Li, PRC 81, 044603(2010)



- Beam Energy: up to 250 MeV/u
- Solenoid Spectrometer
  - Max. 1T solenoid magnet
  - TPC (~ 3π sr acceptance,
  - charged particle tracking)
  - Scintillation counter (trigger & ToF)
- Neutron Wall (neutron tracking)


Oct. 2018
Area ~ 1M m2


Sep. 2019
Area ~ 1M m^2

Installation of the First Superconducting Cavites and Cryomodules

See you in China in 2021