Imagining the Future: Gravitational Wave Astronomy

“What infrastructure will contribute to facilitating broad participation, community growth, and the best possible science?”

Barry Barish
Caltech
28-Oct-04
A "roadmap" is an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field.

R Galvin
Motorola
Creating a Roadmap for the Future

Gravitational Wave Astronomy

• What have we accomplished?

• Where are we now?

• Where are we going?

• What are the paths to get there?

• What tools do we need to reach our goals?
Comparing the Evolution of Two Fields

Neutrino Physics and Astronomy

Solar Neutrinos

Gravitational Wave Astronomy

Binary Black Hole Merger
Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, it's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

W. Pauli
Chadwick discovered the neutron, but neutrons are heavy and do not correspond to the particle imagined by Pauli.

Pauli responds ....

J Chadwick
Pauli responds at Solvang, in October 1933

“... their mass can not be very much more than the electron mass. In order to distinguish them from heavy neutrons, mister Fermi has proposed to name them "neutrinos". It is possible that the proper mass of neutrinos be zero... It seems to me plausible that neutrinos have a spin 1/2... We know nothing about the interaction of neutrinos with the other particles of matter and with photons: the hypothesis that they have a magnetic moment seems to me not founded at all."
Gravitational Waves

*the birth of the idea*

**Newton’s Theory**

“*instantaneous action at a distance*”

**Einstein’s Theory**

*information carried by gravitational radiation at the speed of light*
Gravitational Waves

*a glitch*

Early claims of gravitational wave detection were not confirmed.

J. Weber
"Since I first embarked on my study of general relativity, gravitational collapse has been for me the most compelling implication of the theory - indeed the most compelling idea in all of physics . . . It teaches us that space can be crumpled like a piece of paper into an infinitesimal dot, that time can be extinguished like a blown-out flame, and that the laws of physics that we regard as 'sacred,' as immutable, are anything but.”

– John A. Wheeler in Geons, Black Holes and Quantum Foam
Neutrinos

direct detection

Reines and Cowan
The target is made of about 400 liters of water mixed with cadmium chloride

The anti-neutrino coming from the nuclear reactor interacts with a proton of the target, giving a positron and a neutron. The positron annihilates with an electron of target and gives two simultaneous photons. The neutron slows down before being eventually captured by a cadmium nucleus, that gives the emission of photons about one 15 microseconds after those of the positron. All those photons are detected and the 15 microseconds identify the "neutrino" interaction.

Fred Reines
“Indirect” evidence for gravitational waves

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

Direct Detection

still waiting …..

Gravitational Wave Astrophysical Source

Terrestrial detectors
LIGO, TAMA, Virgo, AIGO

Detectors in space
LISA
The Birth of a Field

The evolving ‘roadmap’ for neutrino physics

- particle physics
- astrophysics
- neutrino properties
- neutrino beams
- neutrino interactions
- Reines-Cowan direct neutrino detection
The Birth of a Field

The evolving ‘roadmap’ for gravitational-wave astrophysics

- Physics
- Astrophysics

GW Properties

Improved Sensitivity

GW Observed

LIGO et al (soon ??)
direct grav. wave detection
In 1960, Lee and Yang are realized that if a reaction like

$$\mu^- \rightarrow e^- + \gamma$$

is not observed, this is because two types of neutrinos exist $\nu_\mu$ and $\nu_e$.
Mel Schwartz realized the possibility to produce an intense neutrino beam from the decay of pions, that are particles produced from the collision of a proton beam produced in accelerators.

\[ P + N \rightarrow \text{Nucleons } + n\pi's \]

\[ \pi \rightarrow \mu + \nu \]
Two Neutrinos

1962

AGS Proton Beam

Schwartz
Lederman
Steinberger

Neutrinos from $\mu$-decay only produce muons (not electrons) when they interact in matter.
Neutrinos
the modern era

High energy neutrino beams at CERN and Fermilab

15 foot Bubble Chamber At Fermilab
Neutrino Physics
weak neutral current

Gargamelle Bubble Chamber
CERN

First evidence for weak neutral current

$\nu_\mu + e \rightarrow \nu_\mu + e$
Neutrino Physics

**neutrino scattering**

\[ \nu_\mu + N \rightarrow \mu + X \]

- Quark Structure
- QCD
Neutrino Astrophysics

*solar neutrinos*

Homestake Detector

Ray Davis

Solar Neutrino Detection

600 tons of chlorine.

- Detected neutrinos of energy > 1 MeV
- Detection verifies fusion process in the sun
- The rate of solar neutrinos detected is three times less than predicted
The Development of the Field

The evolving ‘roadmap’ for neutrino physics

particle physics

astrophysics

weak neutral current
quark structure
QCD

ν properties
ν beams
ν interactions

νµ & νe

solar ν’s

Schwartz-BNL
HE CERN/Fermilab

Reines-Cowan
direct ν detection

ν interactions
Properties of Gravitational Waves

**The Speed**

If gamma ray burst (GRB) and gravitational waves arrive at same time to within ~ 1 sec

Then, speeds are the same to ~1 second / 2 billion yrs

~1 part in $10^{17}$
Properties of Gravitational Waves

The Polarization of Gravitational Waves

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}(\vec{r},t) \]

\[ h_+ = \varepsilon_+ h \ e^{i(k \cdot \vec{r} - \omega t)} \]

\[ h_\times = \varepsilon_\times h \ e^{i(k \cdot \vec{r} - \omega t)} \]

TAMA 300
LIGO
GEO 600
Virgo
Improved subsystems

Multiple Suspensions

Active Seismic

Sapphire Optics

Higher Power Laser
Advanced LIGO
Cubic Law for “Window” on the Universe

Improve amplitude sensitivity by a factor of 10x...
...number of sources goes up 1000x!

Virgo cluster
Event Localization With a Network

Global Distribution of Major Interferometer Sites

\[ \cos \theta = \frac{\Delta t}{c \, D_{12}} \]
\[ \Delta \theta \sim 0.5 \text{ deg} \]

\[ \Delta L = \frac{\Delta \theta}{c} \]

LIGO Transient Event Localization

LIGO - VIRGO - GEO Transient Event Localization

LIGO - VIRGO - GEO - TAMA Transient Event Localization

SOURCE

SOURCE

SOURCE

SOURCE
Advanced LIGO

2007 +

Enhanced Systems
- laser
- suspension
- seismic isolation
- test mass

Rate Improvement
\(~10^4\)

+ narrow band optical configuration
The Development of a Field

The evolving ‘roadmap’ for gravitational-wave astrophysics

- Strong Field GR
- GW Properties
- Speed
- Polarization
- Improved Sensitivity
- GW Observed
- LIGO et al. (soon ??) direct grav. wave detection

GW Observed

Improved Sensitivity

GW Properties

physics

astrophysics

Binary Inspiral
Pulsars

GW Networks
Adv Detectors
ν Oscillation Probability

★ The case with two neutrinos:

→ A mixing angle: \( \theta \)

→ A mass difference:

\[
\Delta m^2 = m_2^2 - m_1^2
\]

★ The oscillation probability is:

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left(1.27\Delta m^2 \frac{L}{E}\right)
\]

where \( L = \text{distance between source and detector} \)

\( E = \text{neutrino energy} \)
ν Oscillation Phenomena

\[ \Delta m^2 = 3 \times 10^{-3} \text{eV}^2 \]

\[ P(\nu_\alpha \rightarrow \nu_\alpha) \]

At large distance \( P \approx 1/2 \)
The Status of the Field

The evolving ‘roadmap’ for neutrino physics

- weak neutral current
- quark structure
- QCD

**particle physics**

- \( \nu \) properties
- \( \nu_{\mu} \) & \( \nu_e \)
- 3 \( \nu \) types
- \( \nu \) oscillations

**astrophysics**

- \( \nu \) beams
- solar \( \nu \)’s rate?

- Schwartz-BNL
- HE CERN/Fermilab

**interactions**

- Reines-Cowan
- direct \( \nu \) detection
Roadmap for the Future of Two Fields

**Neutrino Physics and Astronomy**

**Gravitational Wave Astronomy**

*High Energy Neutrino Astronomy*

LISA – Low Frequency Grav Waves
Goals: Dirac or Majorana particle?

Majorana: The neutrino is its own antiparticle

Ettore Majorana
Accelerators

neutrino factory – neutrinos from muon collider

Example
7400 km baseline
Fermilab → Gran Sasso
“world project”
Future Long Term Goals for the Field

The future ‘roadmap’ for neutrino physics

- Particle physics
- Astrophysics
- \( \nu \) properties
- \( \nu \) beams
- \( \nu \) interactions

Dirac vs Majorana

\( \nu \) osc parameters
CP violation

Superbeams
Neutrino Factories

the long term
Future Long Term Goals for the Field

The future ‘roadmap’ for neutrino physics

- Particle physics
  - ν properties
    - Dirac vs Majorana
    - ν osc parameters
  - ν interactions
- Astrophysics
  - ν beams
    - Cosmic rays
  - High energy physics
    - Solar
    - Supernovae
    - GRBs

WIMP
Dark matter
The evolving ‘roadmap’ for gravitational-wave astrophysics

- **New Physics**
- **Improved Sensitivity**
- **GW Observed**
  - LIGO et al (soon ??)
  - direct grav. wave detection
Multi-messenger Astronomy

**supernova**

- Pre-supernova star
- Collapse of the core
- Interaction of shock with collapsing envelope
- Explosive ejection of envelope
- Expanding remnant emitting X-rays, visible light, and radio waves.

**Nearby**

- Neutrinos
- Electromagnetic radiation
- Gravitational waves

Star brightens by $\approx 10^8$ times
Emerging Detector Technologies

- Cryogenic suspensions (LCGT Japan)
- Broadband (white light) interferometers (Hannover, UF)
- All-reflective interferometers (Stanford)
- Reshaped laser beam profiles (Caltech)
- Quantum non-demolition
  - Evade measurement back-action by measuring an observable that does not affect a later measurement
    - Speed meters (Caltech, Moscow, ANU)
    - Optical bars (Moscow)
  - Correlations between the SN and RPN quadratures
Sub-quantum-limited interferometer

Quantum correlations
(Buonanno and Chen)

Input squeezing
Ultimate Goal for the Field

The future ‘roadmap’ for neutrino physics

- **particle physics**
  - ν properties
    - Dirac vs Majorana
    - ν osc parameters
  - ν interactions
  - ν interactions
- **astrophysics**
  - ν beams
  - ν beams
  - High energy Solar Supernovae GRBs
  - ν cosmology
  - ν cosmology

- QCD
- WIMPS
Ultimate Goal for the Field

The evolving ‘roadmap’ for gravitational-wave astrophysics

- GW Observed
- Improved Sensitivity
- GW Properties
- Improved Sensitivity
- GW Observed

GW Observed

GW Properties

Improved Sensitivity

physics

astrophysics

New Physics

New Phenomena

Speed

Polarization

gw cosmology
Neutrino Signals from the Early Universe

The ultimate goal

Neutrinos decoupled just prior to big bang nucleosynthesis, when the age of the universe was around 1 s and the temperature around 1 MeV.

- Their momentum distribution subsequently redshifted to an effective temperature \( T_\nu \approx 1.9 \) K, and they have an average density of \( \sim 300/\text{cm}^3 \).

- The direct detection of such low-energy neutrinos remains an ultimate challenge.
Gravitational Waves from the Early Universe

Maybe a Special New Experiment

A. Vecchio
Ultimate GW Stochastic Probes

-11
-12
-13
-14
-15
-16

log Omega(f)

log f

LISA sensitivity limit (1yr)
3rd generation sensitivity limit (1yr)

WD-WD
NS-NS
BH-MBH
NS
CORRUPTED
CLEAN

\[ h_{(100)}^2 \Omega_p^{(\text{min})} \approx 8 \times 10^{-17} \left( \frac{f}{0.1 \text{ Hz}} \right)^{3/2} \left( \frac{T}{10^8 \text{ sec}} \right)^{-1/2} \left( \frac{h_{\text{rms}}}{10^{-24}} \right)^2 \]
Future experiments in the “gap” (?)
The morale of my story:
“Comparing roadmaps for neutrinos & gravitational waves

The key to the future will be investing enough resources in technological development and new detectors