Astroparticle physics

- Big Bang and the particle physics and the dark size of the universe
  - dark energy
  - dark matter (axioins, sterile neutrinos, SUSY Q-balls, WIMPs, WIMPZILLAS, etc.)
- a smaller bang: the supernova (some of the above particles)
- Even smaller bangs: the cosmic rays (and some other particles)
Supernova: another lab of an astroparticle physicists

Term *supernova* was coined by Baade and Zwicky in 1930s. "Brighter than nova".

Types of supernova

- **Type I**: absence of hydrogen lines
  - Type Ia: no H line, strong Si line
  - Type Ib: no H line, no Si line, strong He line
  - Ic: no H line, no Si line, no (or weak) He line

- **Type II**: presence of hydrogen lines
Physics:

- Type Ia: probably thermonuclear explosion of a white dwarf accreting matter from a binary companion

- Type II: core collapse supernova
High-density stard can be stable only if their masses are less than $M_{\text{Ch}}$.

At high pressure matter $\Rightarrow$ degenerat Fermi gas.

$E_F \sim p_F^2/m_e$, for non-relativistic electrons

$E_F \sim p_F$, for relativistic electrons

Consider an equilibrium configuration (Landau, 1932)

$N$ fermions in asphere of radius $R$.

\[ n \sim \frac{N}{R^3} \]

Volume per fermion: $\sim 1/n$ (Pauli principle)
By Heisenberg uncertainty principle,

\[ p_F \sim \hbar n^{1/3} \sim n^{1/3} \]

\[ E_F \sim \begin{cases} 
  p_F^2 \sim n^{2/3}/m_e \sim \frac{N^{2/3}}{m_e R^2}, & \text{for non-relativistic electrons} \\
  p_F \sim n^{1/3} \sim \frac{N^{1/3}}{R}, & \text{for relativistic electrons}
\end{cases} \]

Gravitational energy per fermion:

\[ E_G \sim -\frac{GMm_B}{R}, \text{ where } M = Nm_B. \]

NB: even though the pressure comes from electrons, all the mass is in baryons.
Total energy:

\[ E_{\text{tot}} = E_F + E_G \sim \begin{cases} 
\frac{N^{2/3}}{m_e R^2} - \frac{G M m_B}{R}, & \text{for non-relativistic} \\
\frac{N^{1/3}}{R} - \frac{G M m_B}{R}, & \text{for relativistic}
\end{cases} \]

\[ E_{\text{tot}} = \min \Rightarrow \text{equilibrium.} \]

In the non-relativistic case, \( \left( \frac{1}{R^2} - \frac{1}{R} \right) \) always has a minimum.

In the relativistic case,

\[ E_{\text{tot}} = \frac{\text{const}}{R} \]

If \( \text{const} > 0 \), \( E_{\text{tot}} \) can be decreased by increasing \( R \) until the system enters non-relativistic regime, the previous case. \( \Rightarrow \) STABLE.

If \( \text{const} > 0 \), \( E_{\text{tot}} \) can be decreased without bound by decreasing \( R \). \( \Rightarrow \) COLLAPSE.
The critical mass is determined by setting to zero the coefficient of $1/R$.

$$E \sim (N^{1/3} - GNm_B^2) \frac{1}{R}$$

$$N_{\text{max}}^{1/3} - GNm_B^2 = 0 \Rightarrow$$

$$N_{\text{max}} \sim \left( \frac{1}{Gm_B^2} \right)^{3/2} = \left( \frac{m_{\text{Pl}}}{m_B} \right)^3 = \left( \frac{10^{19}\text{GeV}}{1\text{GeV}} \right)^3 = 10^{57}$$

$$M_{\text{max}} = N_{\text{max}}m_B = 10^{57}\text{GeV} \sim M_\odot$$

More precisely, $M_{\text{max}} = M_{\text{Chandra}} = 1.4M_\odot$
This depends only on fundamental constants!
What is the radius? It is determined by the onset of degeneracy:

\[ E_F \sim \frac{N^{1/3}}{R} = m \]

where \( m \) is the mass of the fermion.

\[ R \sim \frac{N_{\text{max}}^{1/3}}{m} = \frac{1}{m} \left( \frac{10^{19}\text{GeV}}{1\text{GeV}} \right) = \frac{10^{19}}{m} \]

Two special cases of interest:

- “normal” matter: \( m = m_e, R \sim 10^{19}/m_e \sim 10^8\text{cm} \) (white dwarf)

- nuclear matter \( m = m_n, R \sim 10^{19}/m_n \sim 5 \times 10^5\text{cm} \) (neutron star)
A more precise calculation gives the following relation between the mass and the density:
Type Ia Supernova

Thermonuclear explosion: WD made of CO burns into Fe. Total energy:

\[ E = \left( m_C - \frac{12}{56} m_{\text{Fe}} \right) \frac{M_{\text{WD}}}{m_C} \sim 3 \times 10^{51}\text{erg} \]

where \( m_C \) and \( m_{\text{Fe}} \) are the masses of \(^{12}\text{C}\) and \(^{56}\text{Fe}\).

Most energy is released in light, heat. Neutrinos carry only a negligible fraction of energy.
Core collapse supernova (Type II)

A massive star, $M > M_\odot$, burns H, He into Si core, into Fe core. When the mass of the Fe core exceeds the Chandrasekhar mass, the core collapses into a neutron star ($\rho \sim 10^{14} \text{g/cm}^3$). Initial temperature $\sim$ MeV, so the weak interactions are important: $pe \rightarrow n\nu_e$.

Is there enough time to produce neutrinos? Compare $\tau_{\text{weak}}, \tau_{\text{grav}}$

$$\tau_{\text{weak}} \sim \frac{1}{\sigma n}$$

$$\sigma \sim G_F^2 T^2, n \sim \rho/m_n$$
\[ \tau_{\text{weak}} \sim 8 \times 10^{-8} \, s \left( \frac{10 \text{MeV}}{T} \right)^2 \left( \frac{\rho}{10^{14} \text{g/cm}^3} \right) \]

\[ \tau_{\text{grav}} \sim \frac{1}{\sqrt{G_N \rho}} \sim 0.4 \, ms \left( \frac{\rho}{10^{14} \text{g/cm}^3} \right)^{-1/2} \]

Since \( \tau_{\text{weak}} \ll \tau_{\text{grav}} \), produce a lot of neutrinos!!
Total energy:

\[ E_{\text{total}} = -\frac{GM^2}{R} \bigg|_{R=R_{NS}}^{R=R_{Fe}} \sim 10^{53}\text{erg} \]

10^{53}\text{erg} \rightarrow \text{neutrinos}

10^{51}\text{erg} \rightarrow \text{kinetic energy of outgoing envelope}

10^{49}\text{erg} \rightarrow \text{light}
Core collapse supernova

A wonderful tool for setting bounds on particles with mass below 50 MeV (axions, sterile neutrinos).
A place to discover new physics!
SN1987A: neutrinos observed
supernova asymmetries and the pulsar velocities.
Discuss on the example of sterile neutrinos
Supernova asymmetries and new physics

- Weakly interacting particles, e.g. sterile neutrinos are emitted from a supernova with anisotropy

- Example: terile neutrinos with masses and mixing angles consistent with dark matter can explain the pulsar velocities

[AK, Segrè; Fuller, AK, Mocioiu, Pascoli]
The pulsar velocities.

Pulsars have large velocities, $\langle v \rangle \approx 250 - 450 \text{ km/s}$. [Cordes et al.; Hansen, Phinney; Kulkarni et al.; Lyne et al.]

A significant population with $v > 700 \text{ km/s}$, about 15% have $v > 1000 \text{ km/s}$, up to 1600 km/s. [Arzoumanian et al.; Thorsett et al.]
A very fast pulsar in Guitar Nebula

HST, December 1994

HST, December 2001
Map of pulsar velocities
Proposed explanations:

- asymmetric collapse [Shklovskii] (small kick)
- evolution of close binaries [Gott, Gunn, Ostriker] (not enough)
- acceleration by EM radiation [Harrison, Tademaru] (kick small, predicted polarization not observed)
- asymmetry in EW processes that produce neutrinos [Chugai; Dorofeev, Rodinov, Ternov] (asymmetry washed out)
- “cumulative” parity violation (it’s not cumulative)
Asymmetric collapse

“...the most extreme asymmetric collapses do not produce final neutron star velocities above 200km/s” [Fryer ’03]
Supernova neutrinos

Nuclear reactions in stars lead to a formation of a heavy iron core. When it reaches $M \approx 1.4 M_\odot$, the pressure can no longer support gravity. $\Rightarrow$ collapse.

Energy released:

$$\Delta E \sim \frac{G_N M_{\text{Fe core}}^2}{R} \sim 10^{53}\text{erg}$$

99% of this energy is emitted in neutrinos.
Pulsar kicks from neutrino emission?

Pulsar with $v \sim 500 \text{ km/s}$ has momentum

$M_\odot v \sim 10^{41} \text{ g cm/s}$

SN energy released: $10^{53} \text{ erg} \Rightarrow$ in neutrinos. Thus, the total neutrino momentum is

$P_{\nu; \text{total}} \sim 10^{43} \text{ g cm/s}$

A 1% asymmetry in the distribution of neutrinos is sufficient to explain the pulsar kick velocities.

But what can cause the asymmetry??
Magnetic field?

Neutron stars have large magnetic fields. A typical pulsar has surface magnetic field $B \sim 10^{12} - 10^{13} \text{ G}$. Recent discovery of soft gamma repeaters and their identification as magnetars $\Rightarrow$ some neutron stars have surface magnetic fields as high as $10^{15} - 10^{16} \text{ G}$. $\Rightarrow$ magnetic fields inside can be $10^{15} - 10^{16} \text{ G}$. Neutrino magnetic moments are negligible, but the scattering of neutrinos off polarized electrons and nucleons is affected by the magnetic field.
Core collapse supernova

Onset of the collapse: $t = 0$
Shock formation and “neutronization burst”: $t = 1 - 10 \text{ ms}$

Protoneutron star formed. Neutrinos are trapped. The shock wave breaks up nuclei, and the initial neutrino come out (a few %).
Core collapse supernova

Thermal cooling: $t = 10 - 15 \text{ s}$

Most of the neutrinos emitted during the cooling stage.
Electroweak processes producing neutrinos (urca),

\[ p + e^- \leftrightarrow n + \nu_e \quad \text{and} \quad n + e^+ \leftrightarrow p + \bar{\nu}_e \]

have an asymmetry in the production cross section, depending on the spin orientation.

\[ \sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu) \]

The asymmetry:

\[ \tilde{\epsilon} = \frac{g^2_V - g^2_A}{g^2_V + 3g^2_A} k_0 \approx 0.4 k_0, \]

where \( k_0 \) is the fraction of electrons in the lowest Landau level.
In a strong magnetic field, $k_0$ is the fraction of electrons in the lowest Landau level.

Pulsar kicks from the asymmetric production of neutrinos? [Chugai; Dorofeev, Rodionov, Ternov]
Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

No

Neutrinos are trapped at high density.
Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

No

Rescattering washes out the asymmetry.

In approximate thermal equilibrium the asymmetries in scattering amplitudes do not lead to an anisotropic emission. Only the outer regions, near neutrinospheres, contribute (a negligible amount).

However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!
Sterile neutrinos leave the star without scattering. Hence, they give the pulsar a kick.

Sterile neutrinos emitted asymmetrically by oscillations: [D’Olivo, Nieves, Pal; Semikoz]
The bounds on sterile neutrinos

The figure shows the bounds on sterile neutrinos, with the axes labeled as follows:

- \( m_s \) (keV) on the y-axis
- \( \sin^2 \theta \) on the x-axis

Key features include:
- The excluded region for x-rays is highlighted.
- The pulsar kicks (allowed) region.
- The Lyman-\( \alpha \) bound for production above 100 GeV.
- Dark matter produced via DW.

DW = Dodelson + Widrow; for discussion of the bounds, see hep-ph/0609081.
Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK]
Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK]
Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK]

- **No** \( B - \nu \) **correlation** is expected because
  - the magnetic field *inside* a hot neutron star during the *first ten seconds*
    is very different from the surface magnetic field of a cold pulsar
  - rotation washes out the \( x, y \) components

- **Directional** \( \vec{\Omega} - \vec{\nu} \) **correlation** is expected, because
  - the direction of rotation remains unchanged
  - only the \( z \)-component survives
Gravity waves

Rotating “beam” of neutrinos is the source of GW

Artist’s conception by Roulet [Summer School lectures in Trieste]
Gravity waves

Artist’s conception by Roulet [Summer School lectures in Trieste]

Rotating “beam” of neutrinos is the source of GW

Predicted correlation: direction of $\vec{v}$ and $\vec{\Omega}$. 
Gravity waves at LIGO and LISA

[<cite>Loveridge, PR D 69, 024008 (2004)</cite>]
• Ultrahigh-energy cosmic rays

• Ultrahigh-energy neutrinos
Spectrum of cosmic rays
Spectrum of cosmic rays

Perhaps galactic origin
Spectrum of cosmic rays

- Probably galactic origin
- Definite prediction
Spectrum of cosmic rays

- Probably galactic origin
- Greisen–Zatsepin–Kuzmin cutoff
- Definite prediction
Greisen-Zatsepin-Kuzmin cutoff

Cosmic microwave background radiation has temperature $2.7K = 10^{-4}eV$

Protons interact with the CMBR and lose energy to pion photoproduction:

$$p\gamma \rightarrow n\pi^+, \ p\pi^0$$

Threshold: $\sqrt{s} = \sqrt{m_p^2 + 2E_\gamma E_p} > m_p + m_\pi$ or

$$E_p > 5 \times 10^{19} eV$$

Nucleon loses about 20% of its energy in each interaction. Energy attenuation length:

$$R_{GZK} \sim 50 Mpc$$
Cross section of $p\gamma \rightarrow N\pi$ rises rapidly at the $\Delta$ resonance
nucleon interaction length (dashed line) and energy attenuation length (solid line)
nucleon interaction length (dashed line) and energy attenuation length (solid line)
nucleon interaction length (dashed line) and energy attenuation length (solid line)
expect a sharp drop in the flux of cosmic rays:

\( E < 5 \times 10^{19} \text{eV} \) – should see sources from entire universe

\( E > 5 \times 10^{19} \text{eV} \) – should see sources only within 50 Mpc
What about photons?

\[ \lambda_{\text{Attenuation}} \]

- Local Supercluster
- HALO
- CBR

\[ E_\gamma (\text{eV}) \]

- \( \gamma_{\text{Earth}} \rightarrow e^+e^- \)
- \( \gamma_{\text{Gal}} \rightarrow e^+e^- \)
- \( 2e^+e^- \)

Distance:
- 10 kpc
- 1 Mpc
- 100 Mpc
AGASA events beyond the cutoff...
Air showers
Detection techniques

Fluorescent detection: Fly’s Eye, Hi Res, EUSO
Surface array: AGASA
Both: Pierre Auger
Pierre-Augur Observatory

Northern Auger in Utah

Southern Auger in Argentina

50km

Astronomy Colloquium at UCLA
Water tanks
Fluorescence detector

Schmidt Telescope at Los Leones

- aperture box
- filter
- reference point
- corrector ring
- camera
- mirror system

[Diagram of Schmidt Telescope at Los Leones]
Lidar is used to monitor the atmosphere
Events (preliminary)
Platinum Event
#673411
(10 tanks in fit)
2-Telescope
Golden Hybrid
Event #668949

Los Leones
The GZK puzzle is two-fold

- what are the sources of UHECR?
- Why no GZK cutoff (assuming AGASA results are correct)?
Cosmic accelerators

Can accelerate particles to $10^{20}$ eV?
Cosmic accelerators
Acceleration in AGN and radio galaxies
Fermi acceleration
New physics?

- Supermassive relic particles
- Topological defects (cosmic strings, etc.)
- New exotic particles
Supermassive relic particles

• Could be copiously produced at the end of inflation, during reheating, from gravity or other interactions at the high scale.

• Can be the dark matter.
  Long lifetime is difficult to explain,
  but models exist [e.g., Kolb et al.; Kuzmin, Rubakov]

• Decays can produce UHECR in our galactic halo, hence no GZK cutoff
Superheavy dark-matter particles producing UHECR

Observational signature: North-South asymmetry.
Topological defects

High energy density in the core. Decays can produce high-energy particles. Long lifetimes.
AGASA vs HiRes
Pierre Auger will clarify the experimental situation

Fitting even HiRes data alone might require exotic nearby sources

However, regardless of whether the GZK cutoff is there, there is great physics one can do with detectors like Pierre Auger and EUSO.
Extreme Universal Space Observatory (EUSO)

EUSO is designed to observe fluorescent air showers initiated by extremely high energy cosmic rays - and neutrinos.
EUSO is designed to observe fluorescent air showers initiated by extremely high energy cosmic rays - and neutrinos.
Ultrahigh-energy neutrinos
UHE neutrinos are out there!

- Astrophysical sources

- $p\gamma$ interactions imply a (predictable) flux of cosmogenic UHE neutrinos.

- Additional sources can provide additional flux.

**Hopefully, they will be discovered in the near future**

Pierre Auger, [ANITA](http://www.anita-icecube.org), [ICE CUBE](http://www.icecube.wisc.edu), [EUSO](http://www.euso-bubble.org), [OWL](http), ...
UHECR are deflected by magnetic fields
UHE neutrino astronomy

Neutrino error box is limited only by the EUSO angular resolution while the proton error box is dominated by the intergalactic magnetic field.

\[ <B> = 1 \text{ nGauss} \]

\[ <d> = 30 \text{ Mpc} \]
Pierre Auger can detect UHE neutrinos
"Certain" predictions and limits
Limits from AMANDA-B

\[ \log_{10}(E^2 \Phi_\nu(E)) \left[ \text{cm}^2 \text{s}^{-1} \text{sr}^{-1} \text{GeV} \right] \]

-6.8 -6.6 -6.4 -6.2 -6.0
3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8
\( \log_{10}(E_{\nu}) \) [GeV]

AMANDA-B10 \( E^2 \nu_e \)
MACRO \( E^2 \nu_\mu \)
SS QC pred.
A-B10 lim.
Baikal \( E^2 \nu_e \)
Frejus \( \nu_\mu \) (diff. at \( E_{\nu} = 2.6 \) TeV)
Charm D pred.
Charm D A-B10 lim.
Atmospheric neutrinos
Detection strategy relies on the knowledge of the neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$ GeV

Calculations of $\sigma_{\nu N}$ at $10^{20}$ eV necessarily use extrapolations of PDF and standard model parameters.

[Gandhi, Reno, Quigg, Sarcevic]
Several approved and proposed experiments plan to detect UHE neutrinos by observations of nearly horizontal air showers. Neutrinos are the only particles that interact weakly enough to produce horizontal air showers (assuming the cross section $\sigma_{\nu N} \sim 10^{-31}\text{cm}^2$ at $10^{20}\text{eV}$) Hence, particle ID is straightforward.

How well do we know the neutrino-nucleon cross section? New physics contributions? Can saturation affect the cross section at high energy?

Is it possible to measure the neutrino-nucleon cross section at these energies?
Calculations of neutrino-nucleon cross section at $\sqrt{s} \sim 10^6 \text{GeV}$

Calculations of $\sigma_{\nu N}$ at $10^{20}\text{eV}$ necessarily use extrapolations of PDF and standard model parameters.

![Graph showing neutrino energy versus cross section.](image)
Calculations of neutrino-nucleon cross section at $\sqrt{s} \sim 10^6 \text{GeV}$

Calculations of $\sigma_{\nu N}$ at $10^{20}\text{eV}$ necessarily use extrapolations of PDF and standard model parameters.

![Graph showing the cross section as a function of neutrino energy for different mass scales.](image-url)
Calculations of neutrino-nucleon cross section at \( \sqrt{s} \sim 10^6 \text{GeV} \)

Calculations of \( \sigma_{\nu N} \) at \( 10^{20}\text{eV} \) necessarily use extrapolations of PDF and standard model parameters.
Neutrino-nucleon cross section at $\sqrt{s} \sim 10^6\text{GeV}$

Calculations necessarily use extrapolations of PDF and standard model parameters.

SM calculation [Quigg et al.] is most likely right, but we want to measure this cross section.
If the cross section is smaller, the Earth becomes more transparent to neutrinos. More neutrinos can get through the Earth, interact just below the surface and produce a charged lepton that originates an up-going air shower (UAS).

- The increase in UAS rate compensates for the decrease in HAS.

- The comparison of the two rates allows a measurement of the cross section at $10^{11}$ GeV

- Angular distribution of UAS can provide an additional independent information about the cross section
The probability of a neutrino conversion into an up-going $\tau$ grows with the mean free path $\lambda_\nu$, for $\lambda_\nu < R_\oplus$, because the shadowing by the Earth decreases.
UAS requires a neutrino to interact and produce a $\tau$ below the surface.
UAS requires a neutrino to interact and produce a $\tau$ below the surface. The number of UAS is higher for a smaller cross section.
The shower probability per incident neutrino:

The energy threshold for detection of UAS was assumed $E_{th} = 10^{18}\text{eV}$ for curve 1 and $E_{th} = 10^{19}\text{eV}$ for curve 2. Additional UAS events, not included here, can be detected by EUSO or OWL via Cerenkov radiation of tau leptons.
In addition, the angular distribution depends on the cross section.

Most probable UAS corresponds to chord length close to mean free path.
Can one disentangle the *unknown flux* from the *unknown cross section*?

Rate of HAS: $\propto F_\nu \sigma_{\nu N}$

Rate of UAS: $\propto F_\nu / \sigma_{\nu N}$

Angular distribution: $\cos \theta_{\text{peak}} \propto 1 / \sigma_{\nu N}$

$\Rightarrow$ *can determine* $\sigma_{\nu N}$ and $F_\nu$ *independently*

All one needs is enough statistics. Need neutrino telescopes.

Possible to do particle physics experiments using cosmic ray detectors
Conclusion

- Astrophysical observations can yield information about particle physics. These data are complementary to the collider experiments.

- Knowledge of astrophysical objects is important. In contrast with traditional astrophysics, particle physicists ask different questions about the same objects.

- Dark matter implies that new physics is out there to be discovered. Other signs of new physics (baryogenesis, cosmic rays, etc.).