- Nighttime observing makeup was cloudy. Another night? Not sure.
- Next homework due Oct 24th.
- Astronomy Club: http://www.astro.uiuc.edu/~uias/



# What some extra credit?

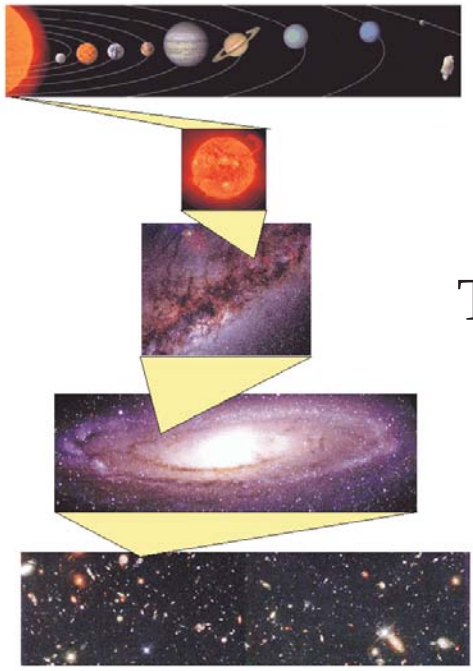
- Attend the general public Icko Eben Jr. Lecture on November 5th at 4:00pm.
- Fill out a short sheet (available later) and have me sign it– show-up early.
- Worth 50% of a homework grade on your final grade.
- http://www.astro.uiuc.edu/events/iben.shtml



# Outline

- Some more background
  - Pressure
- Hydrostatic Equilibrium
- Liquid Nitrogen
- How does the Sun shine?
- 4 Forces
- Fusion reaction in the Sun
- Neutrino astronomy





# Astronomy: The Big Picture

# Pressure

- What is pressure?
  - Pressure $= \frac{Force}{Area}$

Pressure of Earth's atmosphere is 14.7 pounds per square inch

- Explain blowing up a balloon?

- http://www.phy.ntnu.edu.tw/java/idealGas/idealGas.html



# Hydrostatic Equilibrium

- Gravity vs. Pressure in the Sun– also stars.

- Gravity from the mass of the Sun– $r^2$ gravity law.
- Like Jupiter, gravity raises the temperature of the interior hot gas– even more.
- Pressure pushes out and gravity pulls in-- equilibrium
- This is why the Sun isn't shrinking even though it's a big ball of gas.



The sun is a mass of incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into helium
At a temperature of millions of degrees

Yo ho, it's hot, the sun is not
A place where we could live
But here on Earth there'd be no life
Without the light it gives

We need its light
We need its heat
We need its energy
Without the sun, without a doubt
There'd be no you and me

The sun is a mass of incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into helium
At a temperature of millions of degrees

The sun is hot

It is so hot that everything on it is a gas: iron, copper, aluminum, and many others.



The sun is large; if the sun were hollow, a million Earths could fit inside. And yet, the sun is only a middle-sized star.

The sun is far away

About 93 million miles away, and that's why it looks so small.

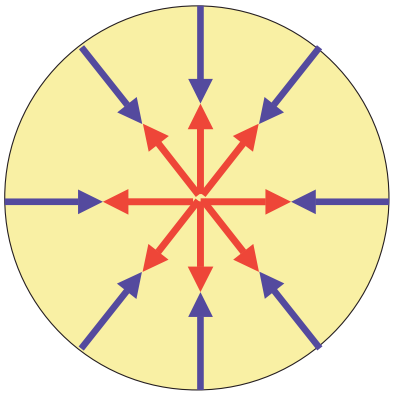
And even when it's out of sight
The sun shines night and day

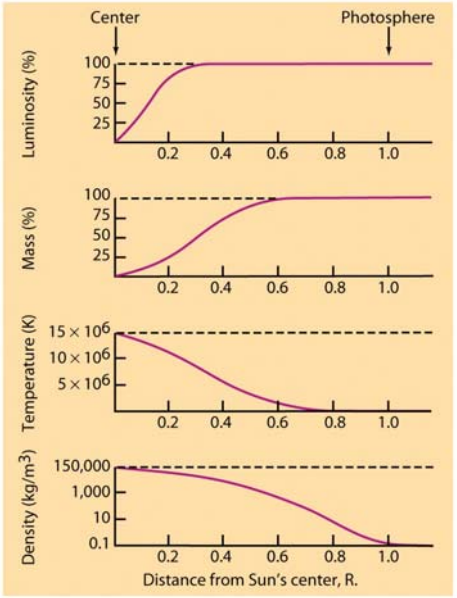
The sun gives heat
The sun gives light
The sunlight that we see
The sunlight comes from our own sun's
Atomic energy

Scientists have found that the sun is a huge atom-smashing machine. The heat and light of the sun come from the nuclear reactions of hydrogen, carbon, nitrogen, and helium.

The sun is a mass of incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into helium
At a temperature of millions of degrees

## The Battle between Gravity and Pressure







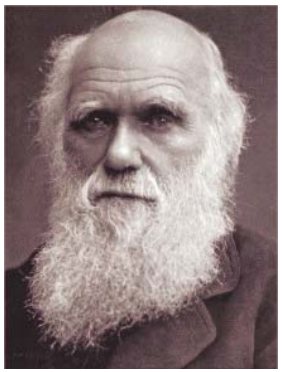

# But how does the Sun shine?

- And how old is the Sun? Coupled questions.
- The energy output of the Sun is large, and it has been doing it for years, and years, and years…



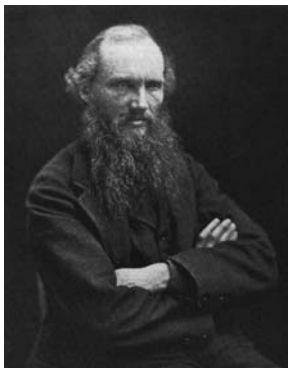
## What Holds Up the Sun?

- Without an energy source, Sun would rapidly cool & contract
- Mid-1800s:
  - Darwin: evolution needs Sun & Earth to be > $10^8$ years old
  - Lyell: geological changes also needs > $10^8$ years
  - Kelvin: gravitational heating gives only a few million years!
- No physical process then known would work!



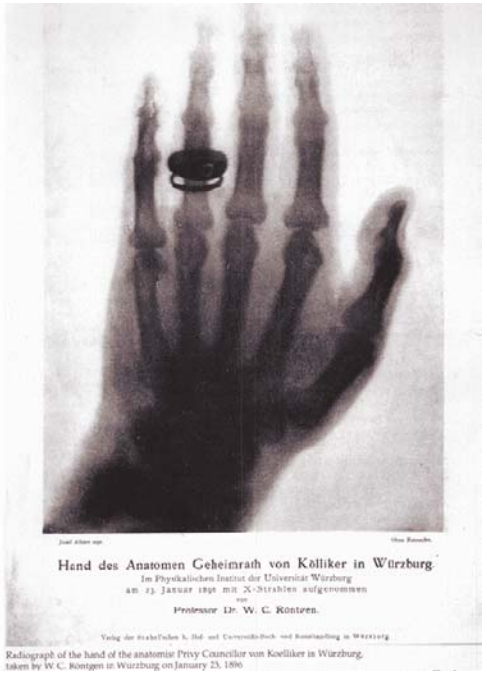
Charles Darwin

Charles Lyell



William Thomson, Lord Kelvin



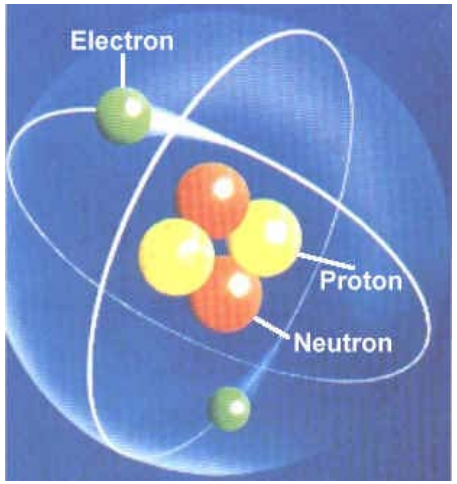



Radiograph of the hand of the anatomist Privy Councilor von Koelliker in Würzburg, taken by W. C. Röntgen in Würzburg on January 23, 1896

Eyes begin to turn to the nuclear processes of the Atoms

# Back to Atoms

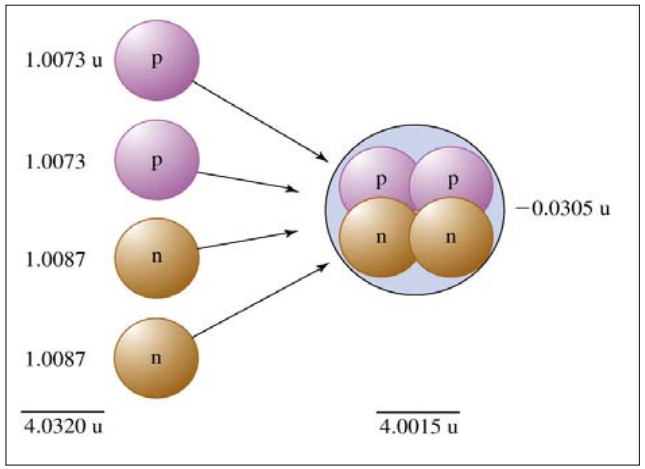
Remember that the atom consists of a nucleus and electrons moving around the nucleus.






# The Nucleus

- Okay, so we know that the nucleus can have numerous protons very close.
- Why doesn't the nucleus of the atom fly apart?






# 4 Fundamental Forces

- Gravity
- Electromagnetic
- Strong Nuclear
- Weak Nuclear



# Gravity

- As described by Newton
- The weakest of the forces, yet it is the dominant force in the universe for shaping the large scale structure of galaxies, stars, etc.
- Only purely attractive force
- Arguably the least understood force
- Infinite range

# Electromagnetic

- Similar to the gravitation force (inverse square law)
- Electric and Magnetic fields
- Both attractive and repulsive force
- Only acts on charges particles
- Responsible for all electric and magnetic phenomena we observe
- Infinite range



# Strong Nuclear

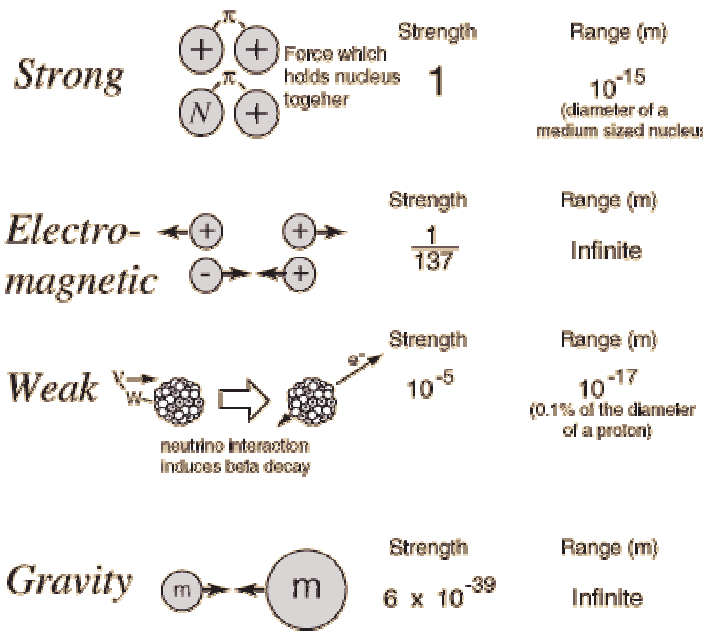
- The strongest of the 4 forces
- The force which holds an atom's nucleus together, in spite of the repulsion between the protons.
- Does not depend on charge
- Not an inverse square law– very short range.



# Weak Nuclear

- Moderates certain kinds of nuclear decays such as the neutron decay
- The most common particle which interacts only via the Weak Force is the *neutrino*
- Very short range





# The Source of Solar Energy

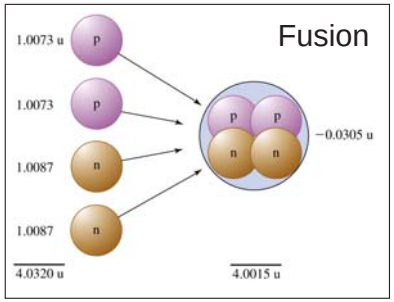
**The Sun is powered by nuclear energy**

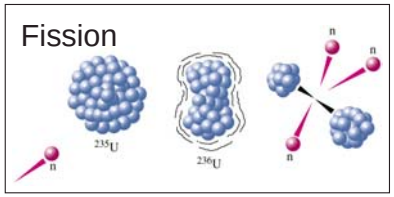
How do we know this?

- Energy conservation: $E = L \times t$
- Nuclear energy is the only energy source ($E$: "fuel supply" / "battery") that can supply the tremendous light power output ($L$: "luminosity") of the Sun for a time $t$ = 4.6 billion years or more
- Note: can figure this out **without** knowing the details of how nuclear energy released
- But what happens in the solar core to generate nuclear energy?

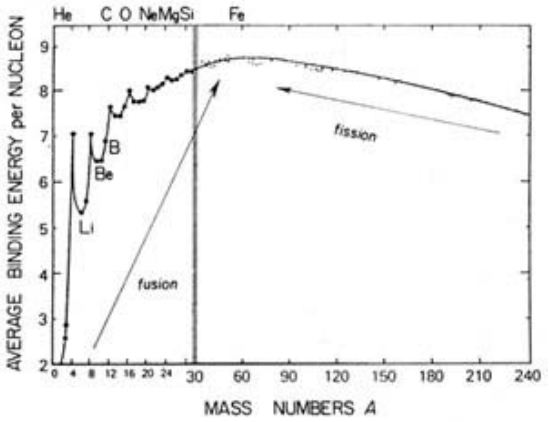


## Nuclear Reactions




- Atomic nuclei can combine or split
- Release energy in process ($E = mc^2$)
- Light nuclei: fusion
- Heavy nuclei: fission






# *Nuclear Fusion in the Sun*

- Sun core $T$ = 16 million K
  - collisions violent:
  - e stripped from atoms (ionized)
  - nuclei collide, react
- thru series (chain) of reactions
- 4 protons ⟹ helium (2p,2n) nucleus + energy
- **Fusion:** light nuclei combine ⟹ heavier nuclei

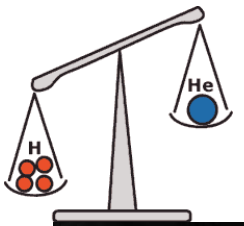


# Why does fusion release energy?

Solar Fusion: $4\ p \rightarrow {}^4\mathrm{He}\ (2\ p, 2\ n)$

fact: **$4m(p) > m(^4\mathrm{He})$** !

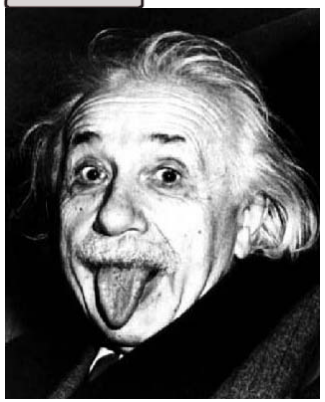
mass of whole < mass of parts!




Einstein says **$E = mc^2$**:

- mass is a form of energy!
- each $^4$He liberates energy:

$$E_{1\mathrm{fusion}} = m_{\mathrm{lost}}c^2 = 4m(p)c^2 - m(^4\mathrm{He})c^2 > 0!$$



# Nuclear Reactions in the Sun

- Chain: 4 protons ⟹ helium

- first step in chain:

$$p + p \rightarrow [np] + e^{+} + \nu$$

- start with 2 particles (protons)
- end up with 4 (two of which are glued together)
- each of products is very interesting in its own right....



# *Nuclear Reactions in the Sun*

$$p + p \rightarrow [np] + e^{+} + \nu$$

$[np]$ = **deuterium**

- 1 proton + 1 neutron bound together into nucleus of element…
- hydrogen, but has n, so 2 times mass of normal H
  - "Heavy Hydrogen"
- Simplest composite nucleus

Discovery of D in lab: *Nobel Prize*

about 0.01% of all H on earth is D

✓ including in your body:
you contain about 10 kilos (20 lbs) of H, and about 2 grams of D

✓ Water (normally $H_2O$) with D is $D_2O$ : "heavy water"



# *Nuclear Reactions in the Sun*

$$p + p \rightarrow [np] + e^{+} + \nu$$

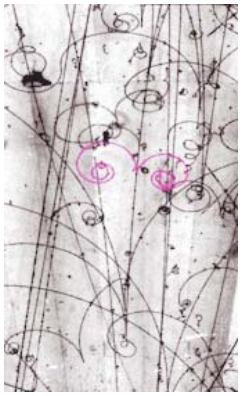
$e^{+}$ = **positron**

- Exactly the same as electron but charge **+1**:
- **antimatter**
- combines with normal $e^{-}$
  - Both gone, release energy
  - ***annihilation***

Discovery of positron in lab: *Nobel Prize*

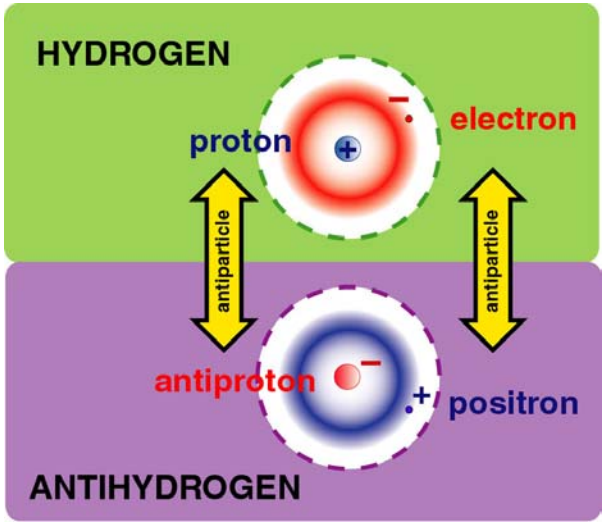
Because of this reaction

➢ The Sun contains a small amount of antimatter!





# Antimatter Atoms



# *Nuclear Reactions in the Sun*

$$p + p \rightarrow [np] + e^{+} + \nu$$

ν (Greek letter "nu") = **neutrino**

- particle produced in nuclear reactions ***only***
- tiny mass: $m(\nu) < 10^{-6} m(e)$ !
- moves at nearly the speed of light
- ***very*** weakly interacting

Discovery of neutrino in lab: *Nobel Prize*

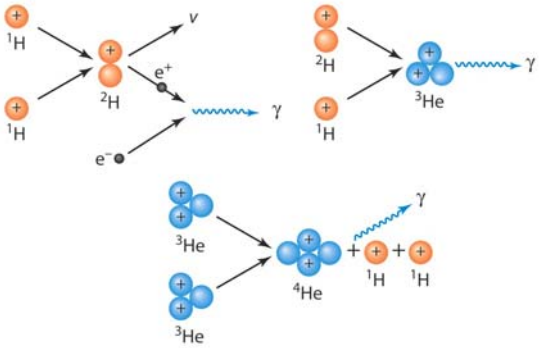
10 billion from Sun go through hand every sec

- reach out!
- go through your body, Earth, but almost never interact

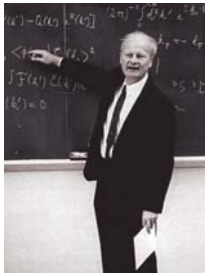


## Nuclear Fusion in the Sun's Interior

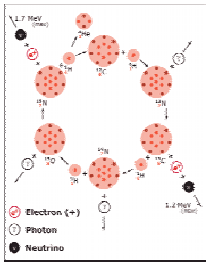
- Proton-proton in stars like the Sun
  - Hydrogen fused to make helium
  - 0.7% of mass converted to energy
- CNO cycle in more massive stars




The Proton-Proton Cycle



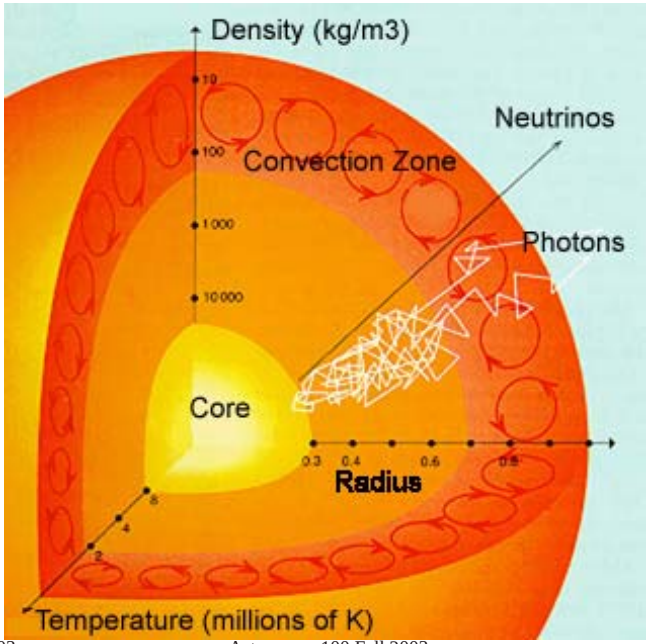
Hans Bethe




The CNO Cycle



## The Interior of the Sun






# The Evidence

How do we know these nuclear reactions occur in the Sun?

Neutrinos from Sun are ***observed***

Detect in huge underground experiments

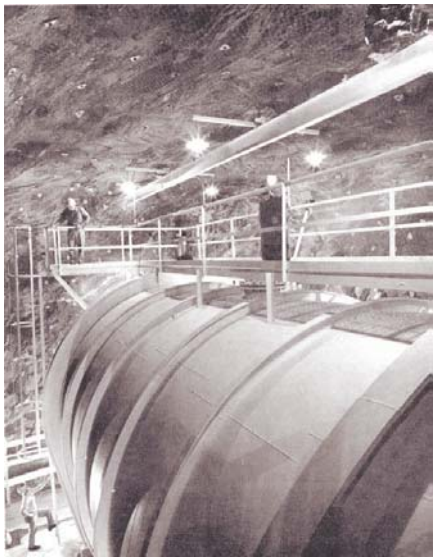
- *Why huge?*
- *Why underground*?

# Neutrino Observatories

I. vats of chlorine (cleaning fluid!) in S. Dakota gold mine

$\nu + \text{chlorine} \rightarrow \text{argon}$

collect argon atoms: radioactive!





# *Neutrino Observatories*

II. vats of gallium metal under mountain in Italy

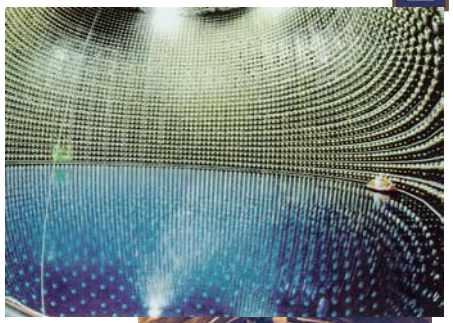
$\nu + \text{gallium} \rightarrow \text{germanium}$

collect germanium atoms



# Neutrino Observatories

III. vats of pure water in Japanese, Canadian mines



$\nu + e$ at rest $\rightarrow$ $e$ moving fast

- see tiny flashes of light from "kicked" electrons

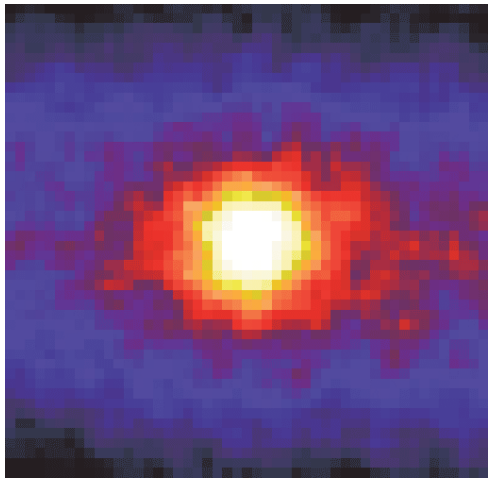


# Results and Implications: *Neutrino Astronomy*

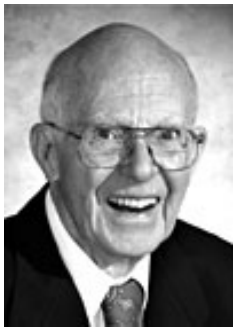
Results:

- All experiments detect neutrinos
- Water experiments show they come from the Sun!

1. **Proof** that Sun powered by nuclear fusion
   - *Why?*
2. Neutrino experiments are telescopes
   - Open new window to cosmos!



# *Nobel Prize 2002*



Ray Davis,
USA

Masatoshi Koshiba,
Japan

"for the detection of cosmic neutrinos"