Midterm Topics (this Friday, Feb. 20)

1. Scientific units, notations
2. Exponents, trigonometry
3. Length scales in the universe, astronomy units
4. Eratosthenes: radius of the Earth
5. Earth's axis tilt, seasons, precession
6. Important stars and constellations
7. Kepler's Laws
8. Galileo's & Newton's contributions
9. Newton's laws
10. Conservation laws: Energy, momentum, angular momentum
11. Kinetic & Potential Energy

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10. Conservation laws: Energy, momentum, angular momentum
11. Kinetic & Potential Energy
12. Gravity
13. Circular Motion
14. Escape velocity
15. Tides
16. Electromagnetic waves
17. Electromagnetic spectrum
18. Blackbody radiation
19. Photons
20. Electronic structure of atoms
21. Spectroscopy
22. Doppler effect
23. Nuclear particles
24. P-P chain solar fusion

Formula Sheet

$$\varepsilon = \frac{d}{2a}$$

$$T^2 = a^3$$

$$\frac{v_p}{v_a} = \frac{1+\varepsilon}{1-\varepsilon}$$

$$x = vt$$

$$v = at$$

$$x = \frac{1}{2}at^2$$

$$F_{A\to B} = -F_{B\to A}$$

$$E_k = \frac{1}{2}mv^2$$

$$F_G = \mathrm{G}\frac{M_A M_B}{r^2}$$

$$a_c = \frac{v^2}{r}$$

$$F_c = \frac{mv^2}{r}$$

$$T^2 = \frac{4\pi^2}{G(M_1+M_2)}a^3$$

$$M_1 r_1 = M_2 r_2$$

$$r_2 = a\frac{M_1}{M_1+M_2}$$

$$p = mv$$

$$L = p \times r$$

$$L = mvr$$

$$E_{potential} = -\mathrm{G}\frac{M_1 M_2}{r}$$

$$E_{total} = E_{potential} + E_{kinetic}$$

$$v_{escape} = \sqrt{\frac{2GM_E}{R_E}}$$

$$f = \frac{1}{T}$$

$$\lambda f = c$$

$$\lambda_{max} = \frac{2.9\times 10^6}{T}$$

$$L = \sigma T^4$$

$$I = \frac{1}{2}c\varepsilon_0 E^2$$

$$B = E/c$$

$$P = \frac{I}{c}$$

$$I(r,\theta) = \frac{\pi^2 p_0^2}{2\epsilon_0 c^3}\cdot f^4 \cdot \frac{\sin^2\theta}{r^2}$$

$$p_\gamma = \frac{h}{\lambda} = \frac{E_\gamma}{c}$$

$$M_\gamma = 0$$

$$f' = f + \Delta f$$

$$\frac{\Delta f}{f} = -\frac{\Delta\lambda}{\lambda} = \frac{v_\parallel}{c}$$

$$v_\parallel = v\cos\theta$$

$G = 6.6743 \times 10^{-11}$ m^3/kg.s^2

1 eV = 1.602×10^{-19} J

$\sigma = 5.67 \times 10^{-8}$ W/(m^2·K^4)

$h = 6.626 \times 10^{-34}$ J·s

$\varepsilon_0 = 8.85 \times 10^{-12}$ C^2/(N·m^2)

$c = 3.0 \times 10^8$ m/s

$m_p = 1.67265 \times 10^{-27}$ kg

$m_n = 1.67495 \times 10^{-27}$ kg

$m_e = 9.11 \times 10^{-31}$ kg

1 AU = 149.6×10^6 km

$M_{Earth} = 5.97 \times 10^{24}$ kg

R_{Earth} = 6371 km

$M_{Sun} = 1.99 \times 10^{30}$ kg

$R_{Sun} = 6.96 \times 10^5$ km

$M_{Moon} = 7.34 \times 10^{22}$ kg

R_{Moon} = 1737 km

Midterm Format

- 4 questions (or if two are really easy then 5 questions).
- Formula sheet will be included in test.
- Mix of quantitative and qualitative questions.
- Time: 9 am – 9:50 am.
- Write legibly. Points will be taken off for messy and unreadable test answers.

Midterm Rules

- Closed book test.
- No internet searches ... No internet usage.
- No artificial intelligence assistance.
- No computers
- No phones
- No use of course website, Blackboard course notes, or OpenStax Astronomy book.
- Calculator recommended (with trig functions).

Today's Topics

Monday, February 16, 2026 (Week 4, lecture 11) – Chapter 5.

A. Doppler effect -- continued

B. Nuclear particles

C. Nuclear Isotopes

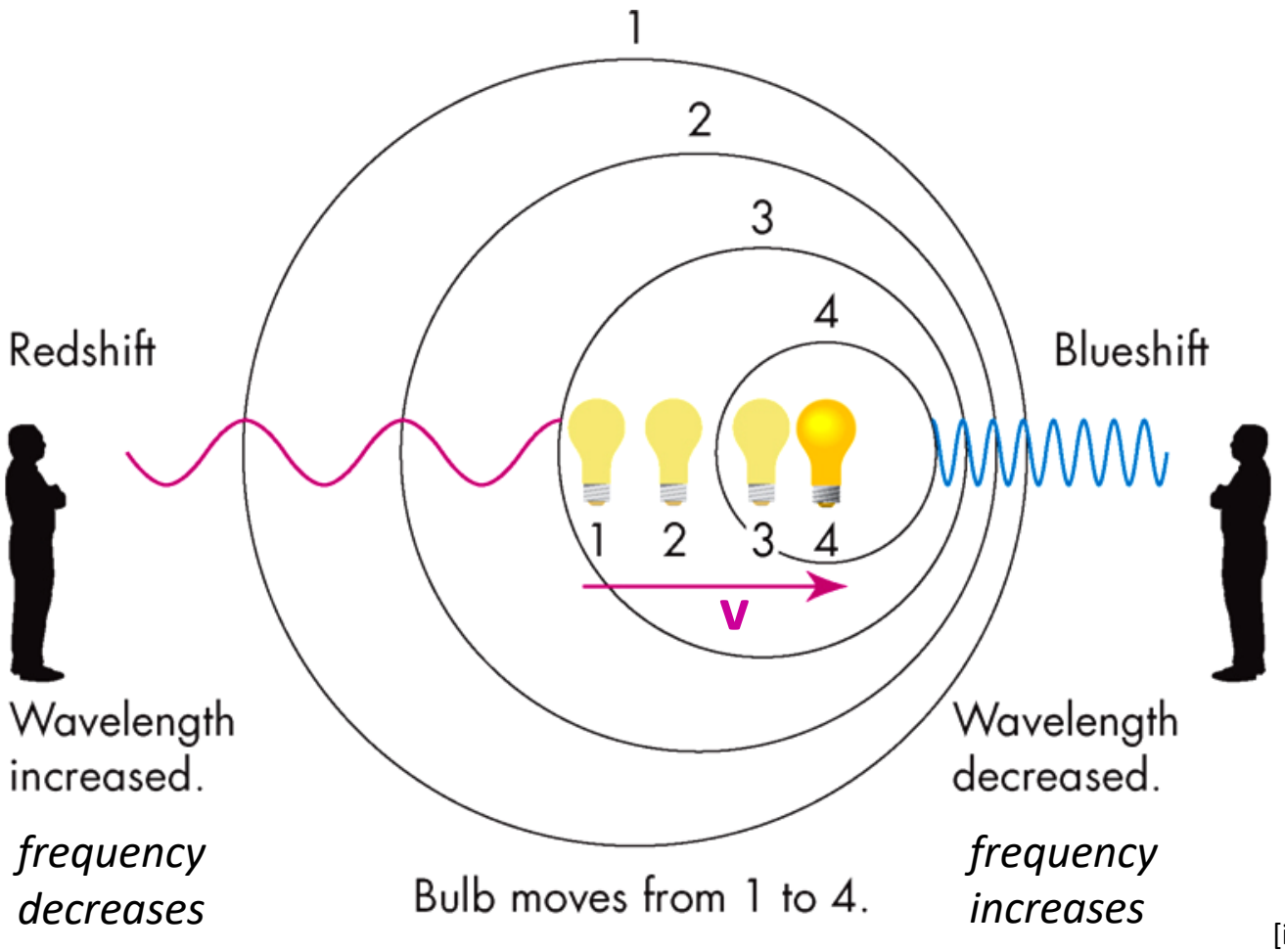
D. Solar fusion

REMINDER #1: ***Problem Set #4*** is due on ExpertTA by Wednesday, February 18, 9:00 AM.

REMINDER #2: **Midterm #1** is on Friday, February 20.

Doppler Effect

A **moving source** cannot change the speed of its emitted light, but it does change its **frequency & wavelength**.



[image source: J. Nelson]

Doppler Shift Calculation

Doppler frequency shift: $\frac{\Delta f}{f} = -\frac{\Delta \lambda}{\lambda} = \frac{v}{c}$ with $f' = f + \Delta f$

frequency of stationary source

perceived frequency of moving source

If source is moving towards you, then light is blue shifted.

$v > 0$

$\Delta f > 0$, f' goes up

$\Delta \lambda < 0$

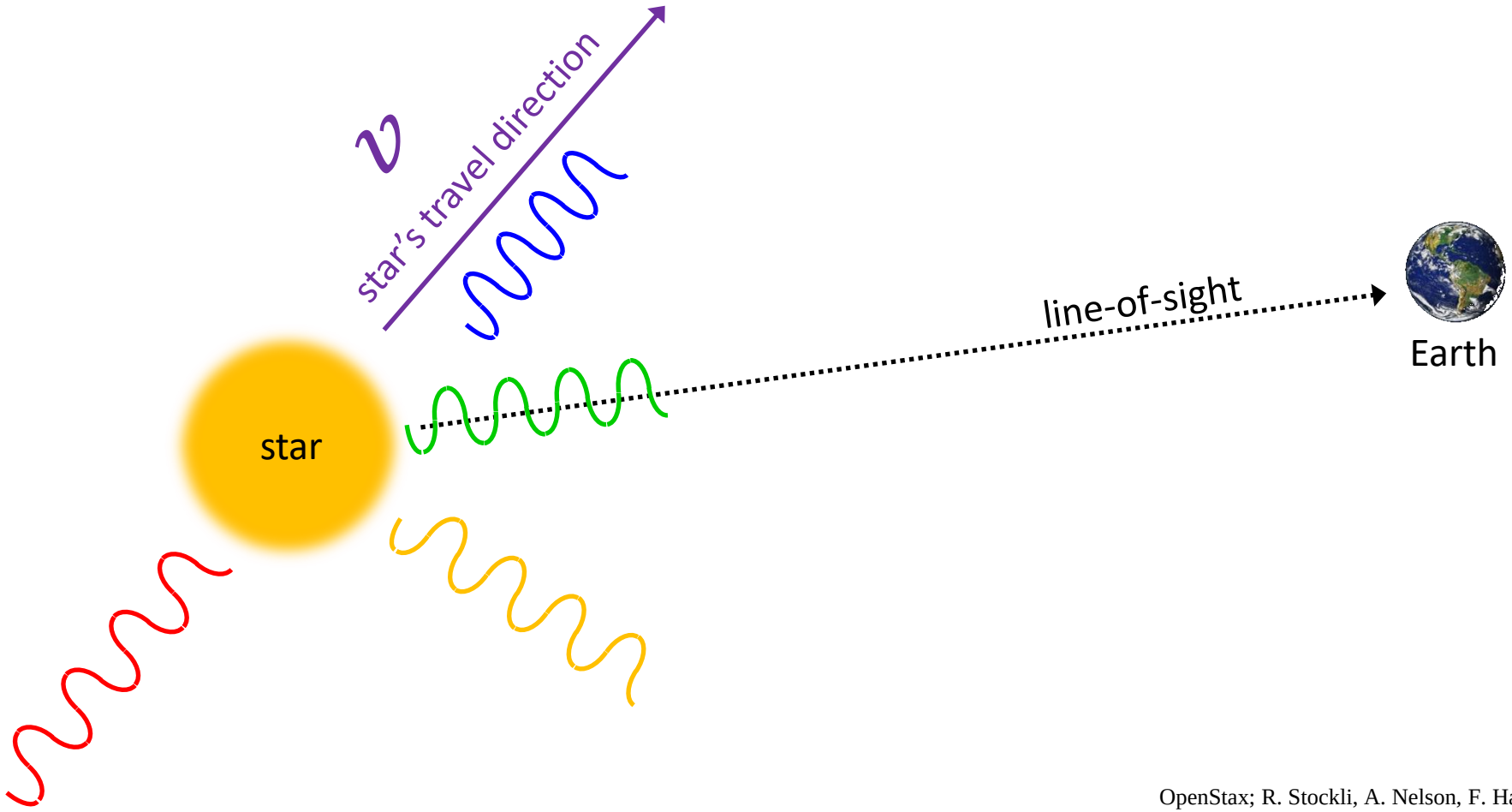
If source is moving away from you, then light is red shifted.

$v < 0$

$\Delta f < 0$, f' goes down

$\Delta \lambda > 0$

Doppler Shift
is for
Line-of Sight Velocity Component



OpenStax; R. Stockli, A. Nelson, F. Hasler, NASA/GSFC/NOAA/USGS)

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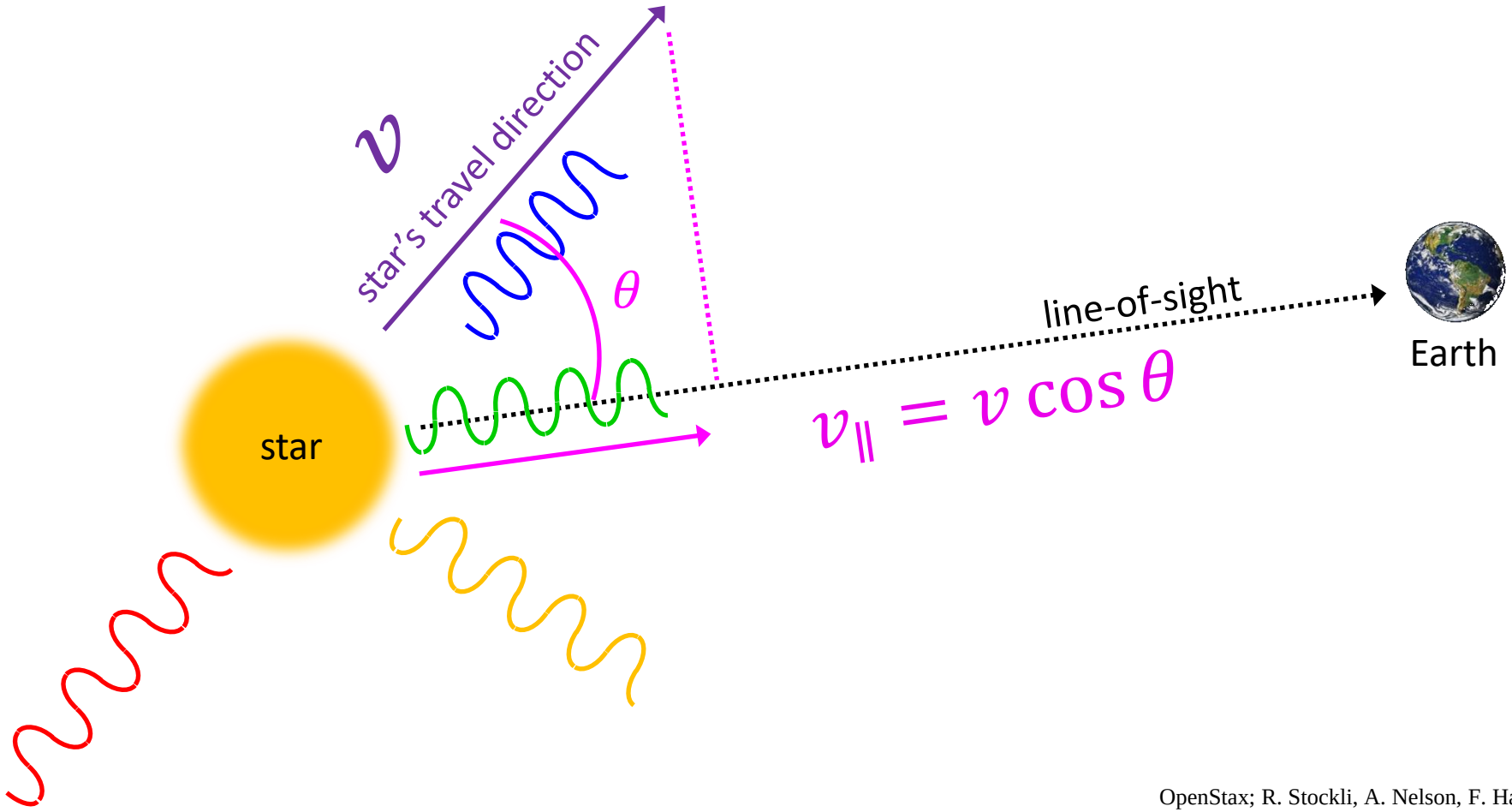

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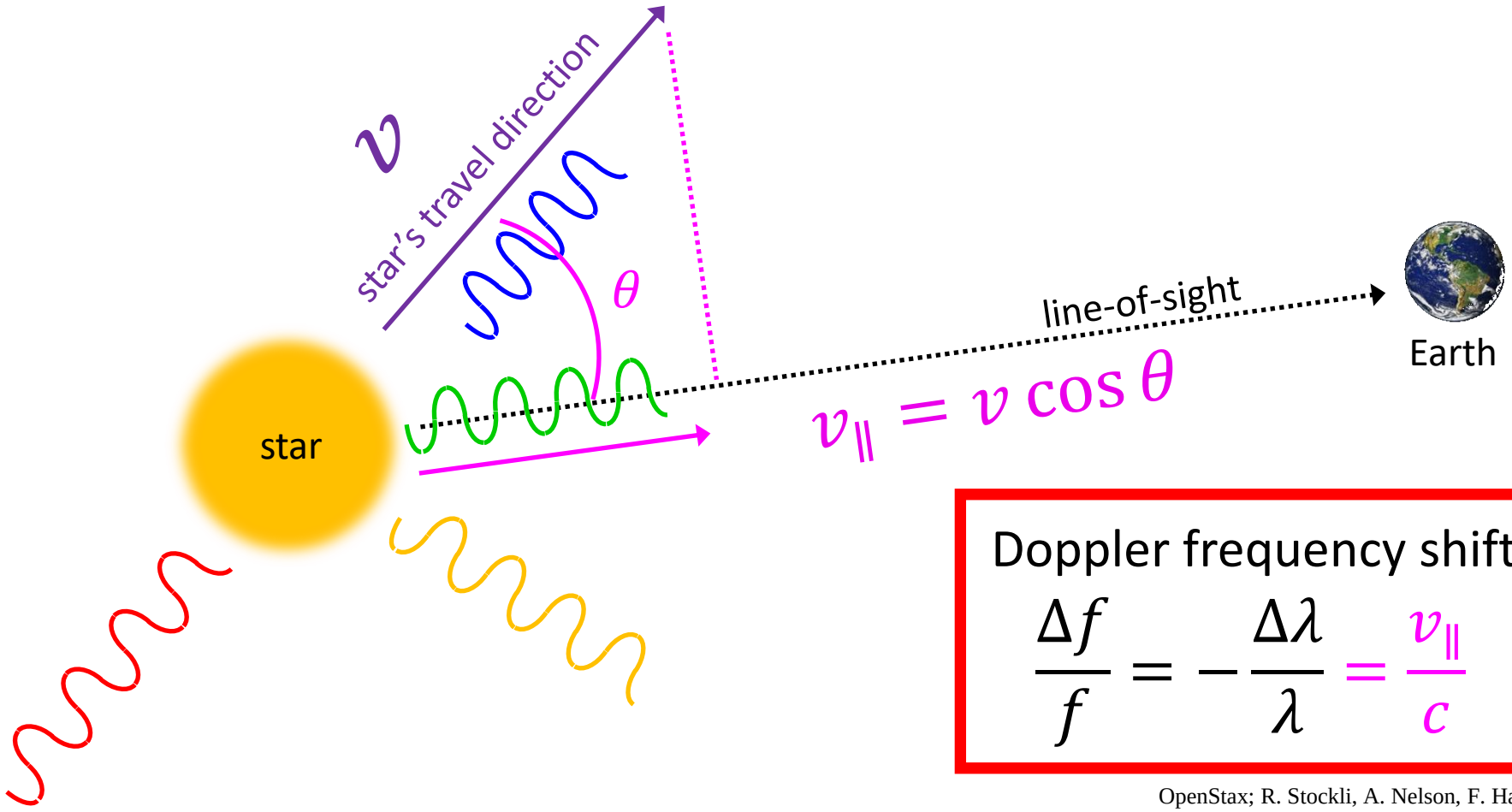
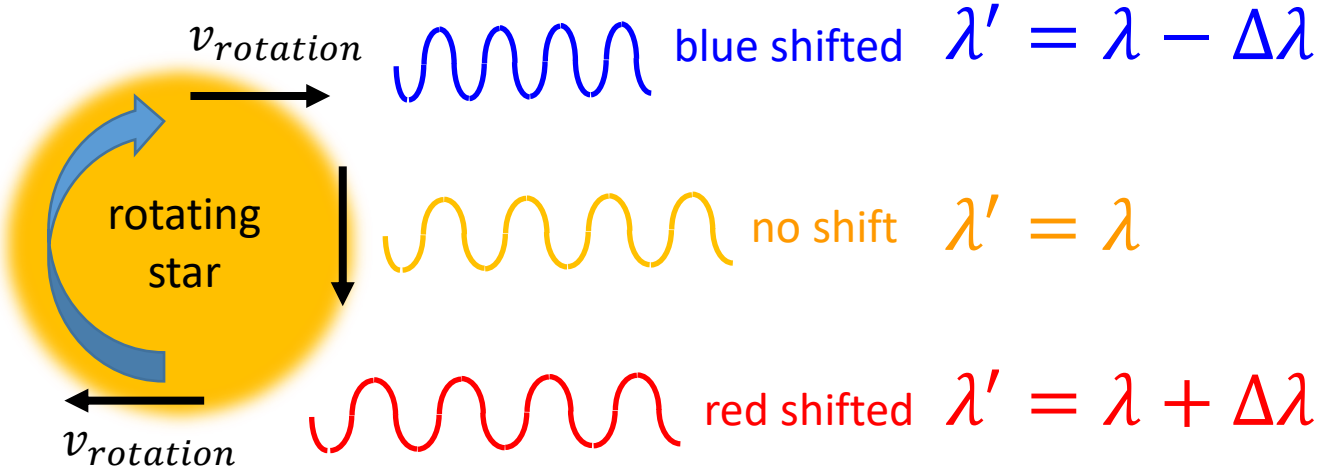


Doppler frequency shift:

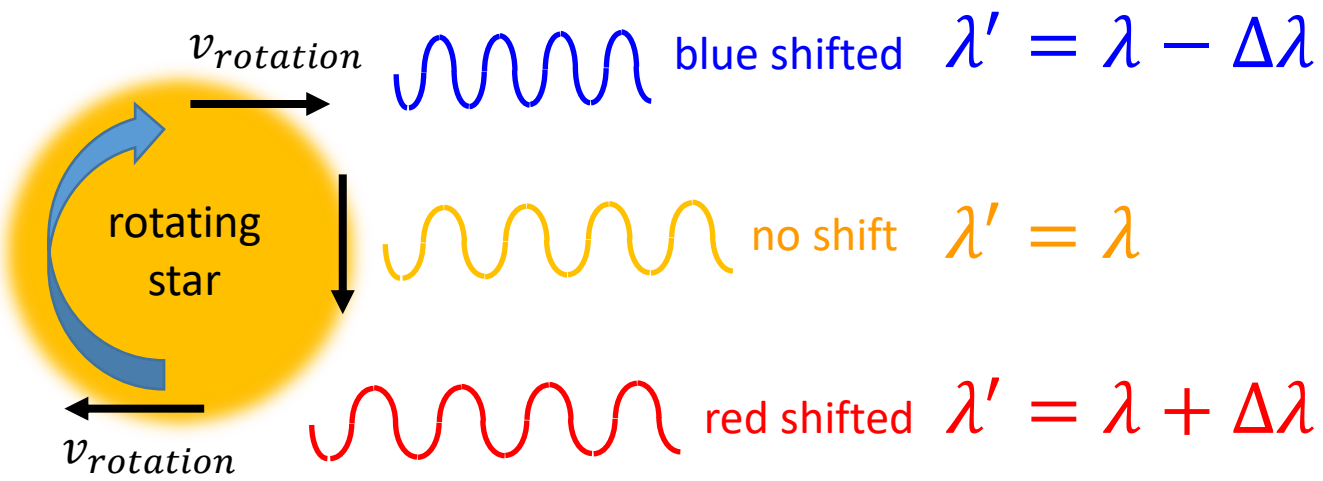
$$\frac{\Delta f}{f} = -\frac{\Delta \lambda}{\lambda} = \frac{v_{\parallel}}{c}$$

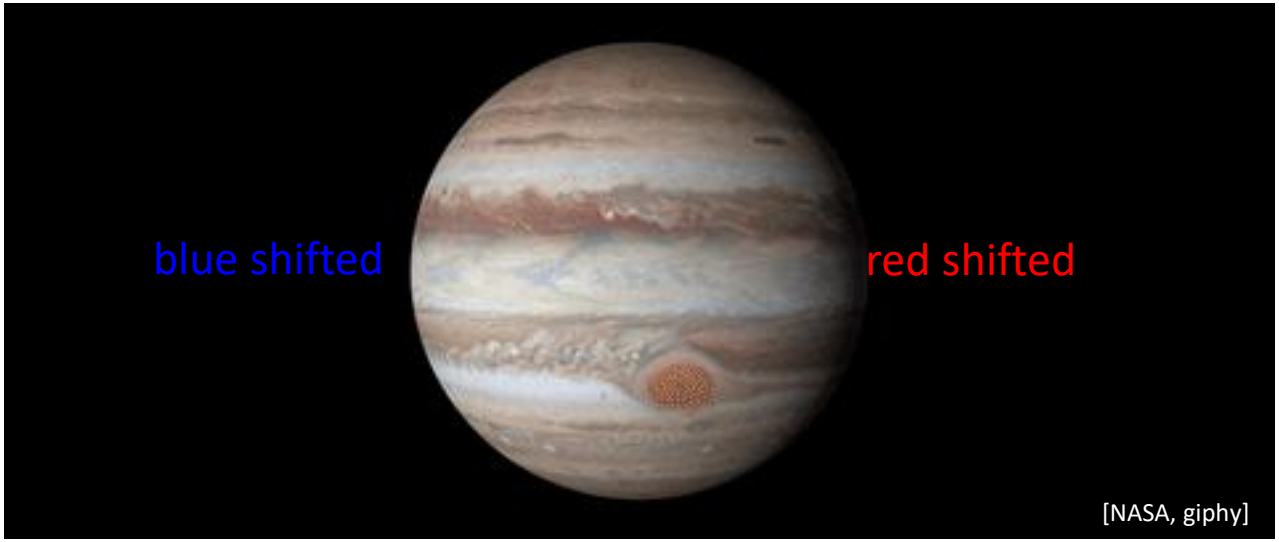
OpenStax; R. Stockli, A. Nelson, F. Hasler, NASA/GSFC/NOAA/USGS)

Doppler Shifts for Rotating Sources



Doppler Shifts for Rotating Sources





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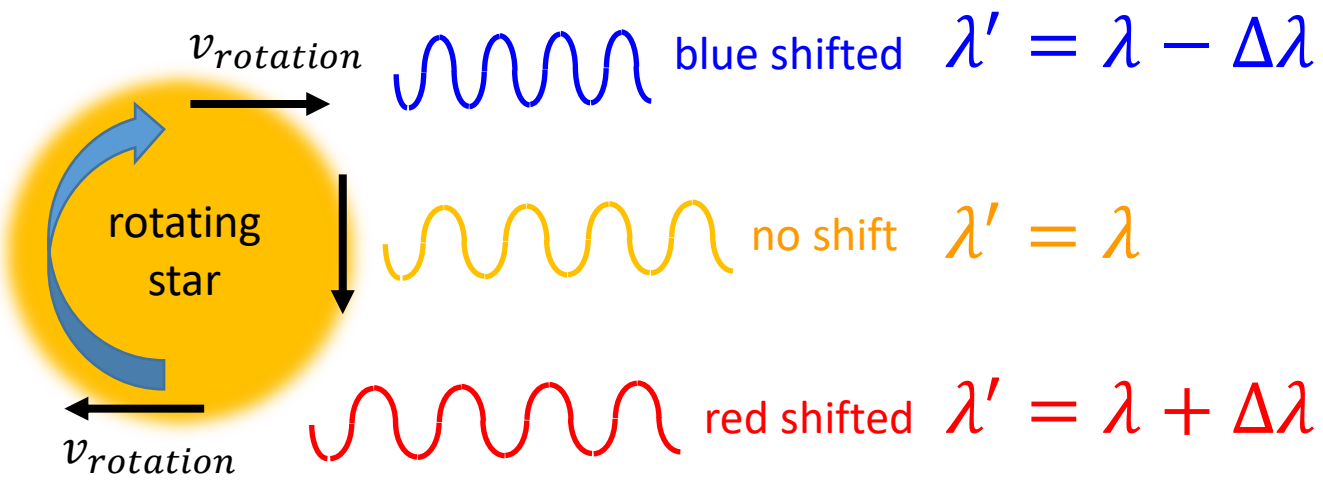

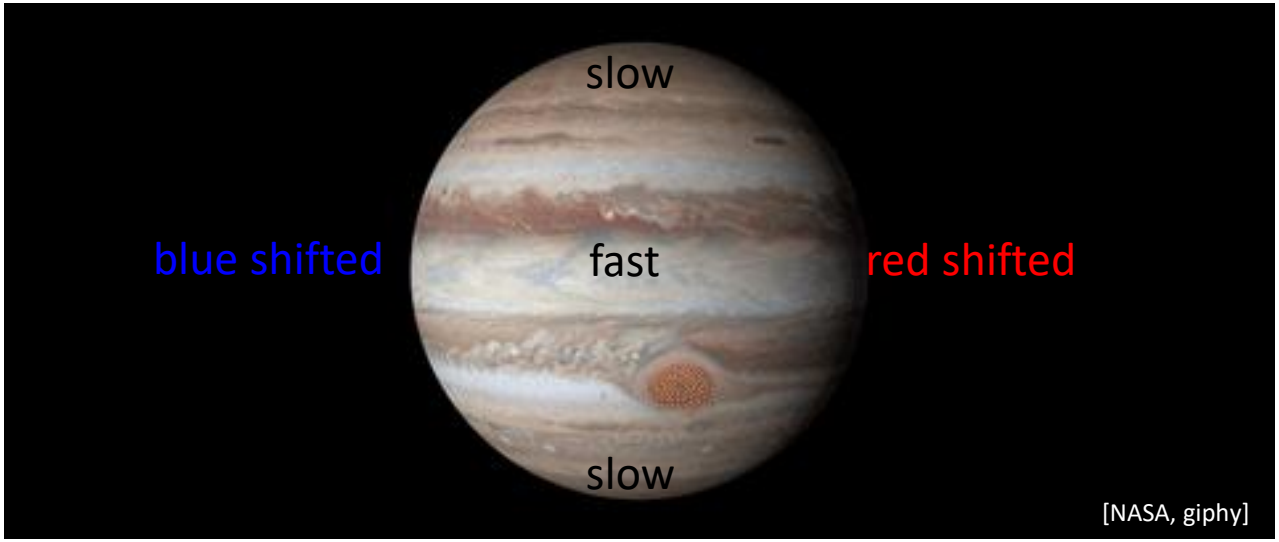

Nuclear Particles

Photons are the easiest particles with which to view space, but they are not the only ones

- Protons (p or p^+), electrons (e or e^-), neutrons (n)
- Alpha particles (α)
- Neutrinos (ν)
- Anti-particles: Positrons (e^+) & anti-protons (p^-)
- Cosmic rays (high energy p^+, p^-, e^+, e^-, α, etc)

Particle Properties

Particle	Mass (kg)	Electric charge	Forces
Proton	1.67265×10^{-27}	+1	Strong, EM, weak, gravity
Neutron	1.67495×10^{-27} $m_n \sim m_p$	0	Strong, weak, gravity
Electron	9.11×10^{-31} $m_e \sim 1/2000\ of\ m_p$	-1	EM, weak, gravity
Neutrino	$< 2 \times 10^{-36}$	0	weak, gravity

barely interacts with anything !!! (very hard to detect)

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Fundamental forces

There are only 4 fundamental forces that we know of:

Strong nuclear force, electromagnetic force, weak nuclear force, gravity.

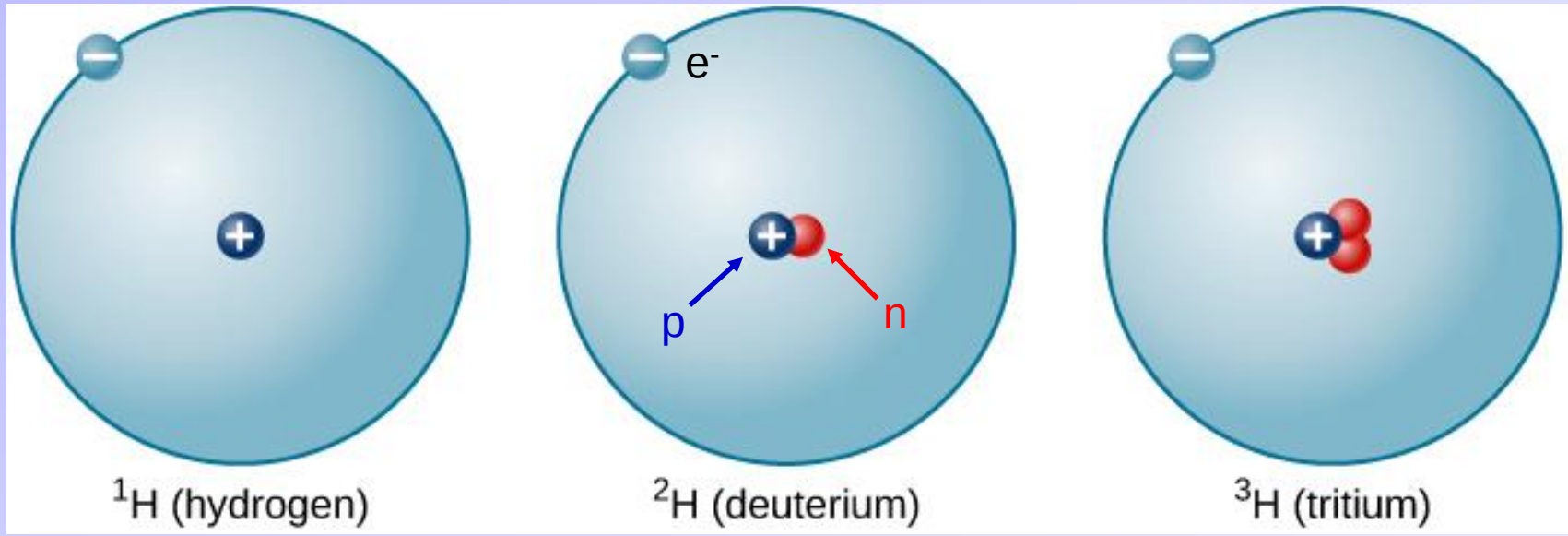
(holds nucleus together) [short range]

(generates radioactive decay) [short range]

(very very weak)

Nuclear Isotopes: hydrogen

- Number of neutrons affects the properties of nucleus, but not chemistry.
- 3 hydrogen isotopes:



(stable)

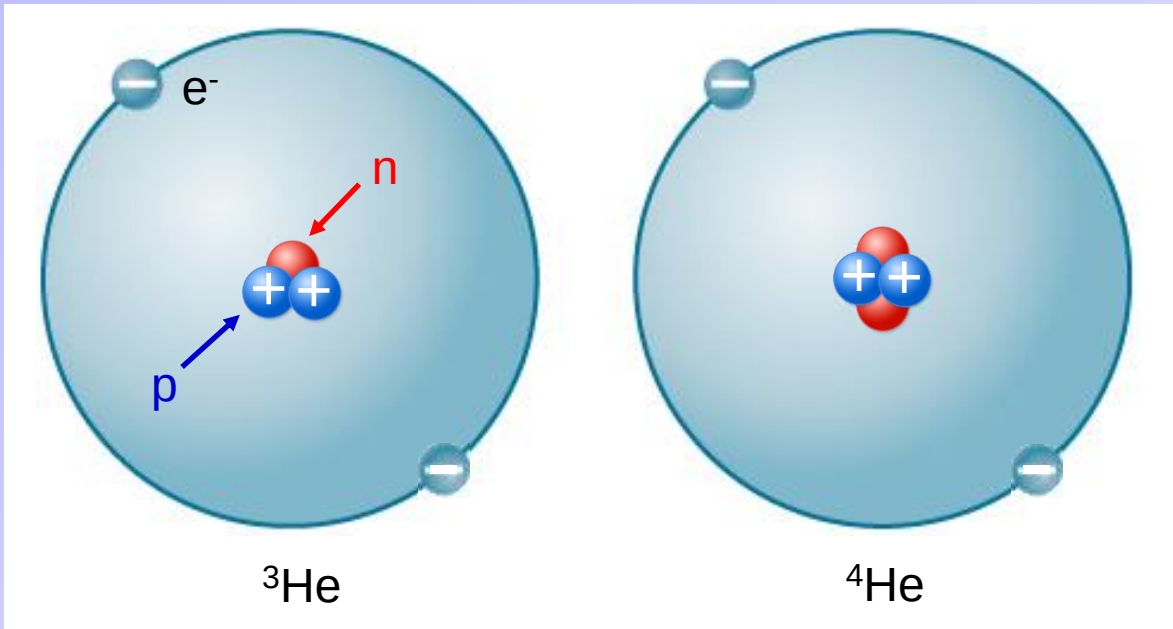
"heavy hydrogen"
(stable)

(unstable: 12 year half-life)

[OpenStax: Astronomy]

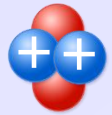
Nuclear Isotopes: helium

2 stable isotopes of helium:



[OpenStax: Astronomy]

^{3}He	^{4}He
1 neutron	2 neutron
2 protons	2 protons

Note: an alpha particle (α) is a helium-4 nucleus 

Solar Fusion

Proton-proton chain

Step 1: $p + p \rightarrow {}^{2}H + e^{+} + \nu$ + energy

Step 2: ${}^{2}H + p \rightarrow {}^{3}He + \gamma$ + energy

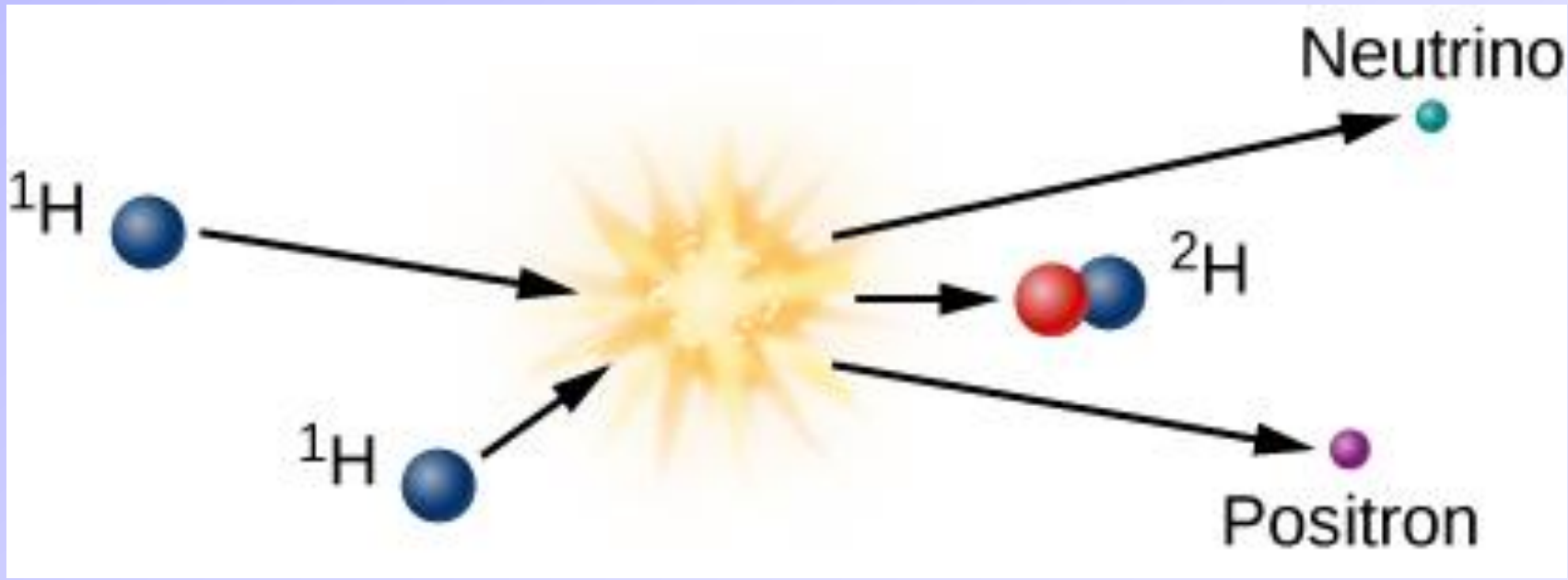
Step 3: ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p$ + energy

Step 1: p + p

Step 1: $p + p \rightarrow {}^{2}H + e^{+} + \nu$ + energy of 1.442 MeV

weak force

Note: 1 eV = 1.602×10^{-19} J

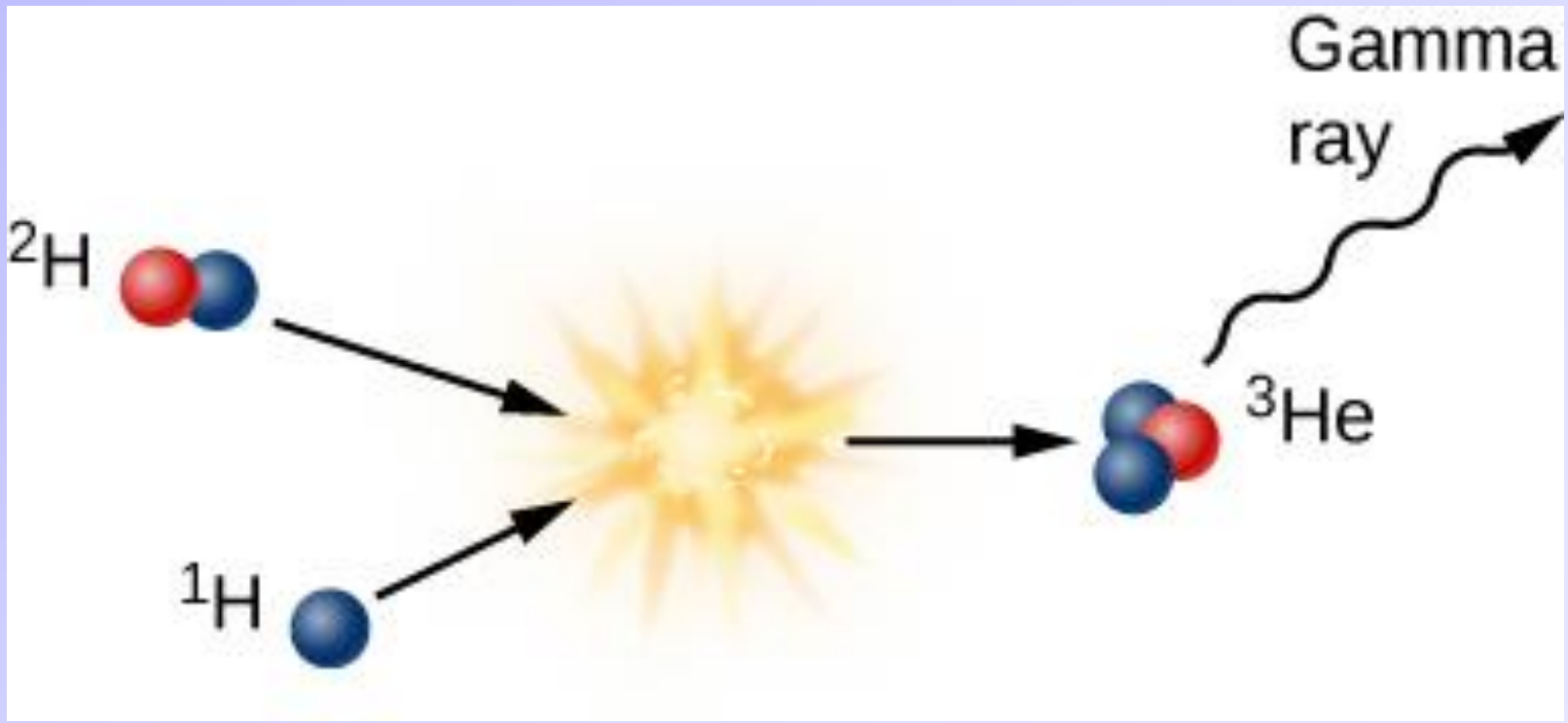


Note: This reaction is very slow … protons are estimated to wander around for 9 billion years (on average) in Sun's core before this process occurs.

Step 2: ^{2}H + p

Step 2: $^2H + p \rightarrow {}^3He + \gamma$ + energy of 5.49 MeV

strong force

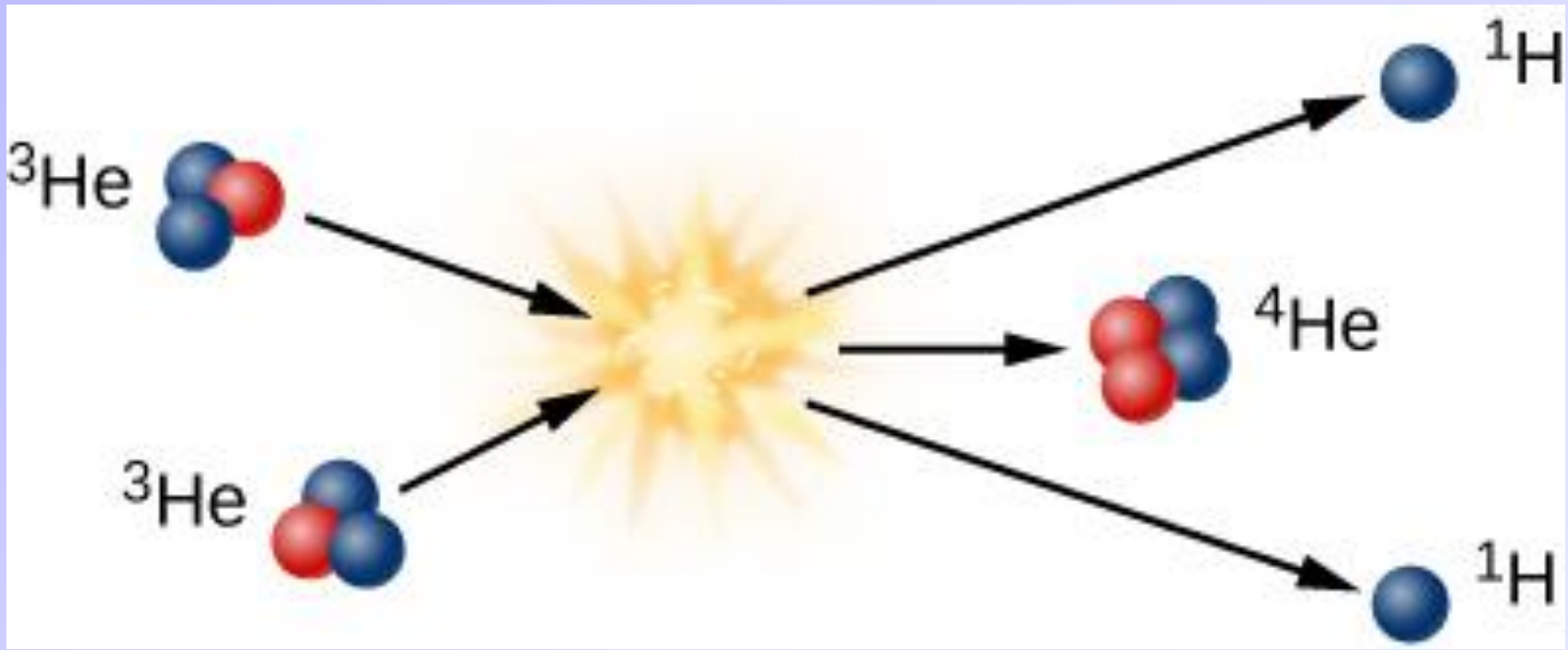


Note: This reaction is very fast … each ^{2}H nucleus lasts about 4 seconds.

Step 3: ^{3}He + ^{3}He

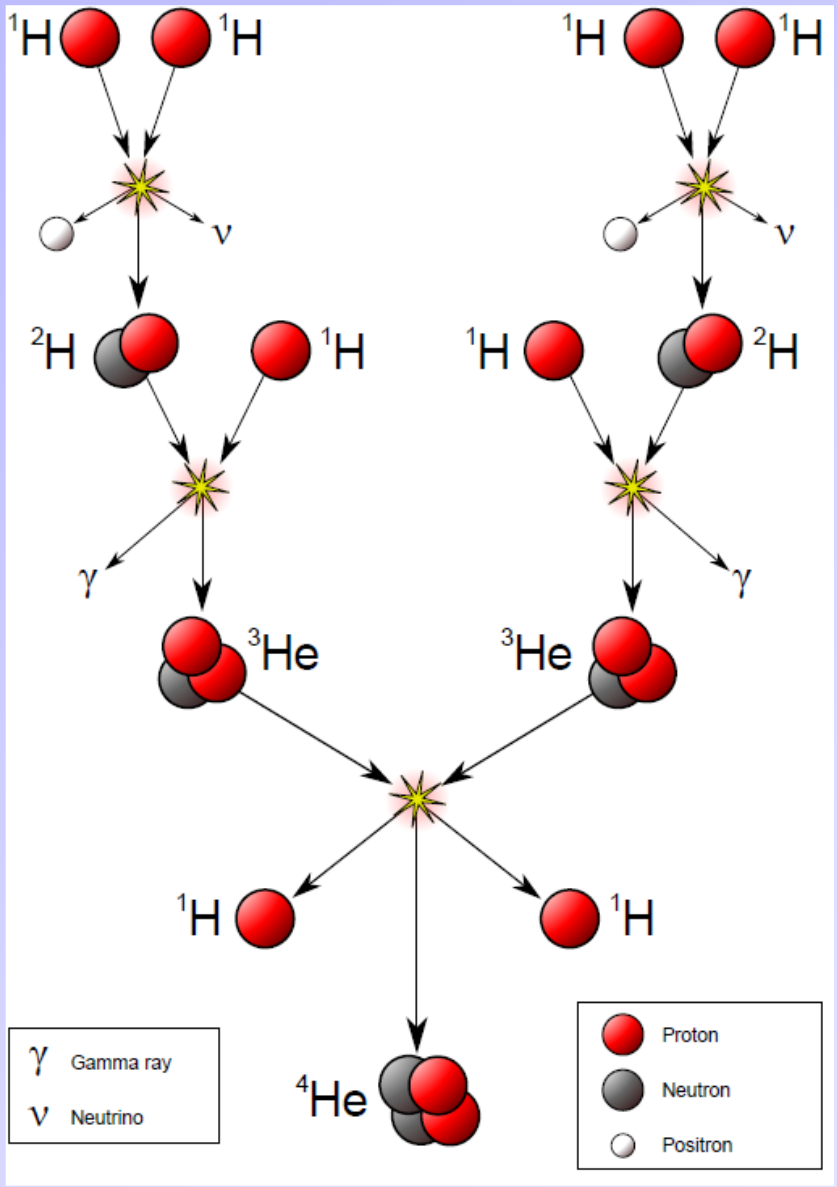
Step 3: $^3He + {}^3He \rightarrow {}^4He + p + p$ + energy of 12.86 MeV

strong force



Note: each helium-3 nucleus lasts about 400 years in the Sun's core.

Summary of proton-proton chain



2×1.442 MeV

\+ 2×5.49 MeV

\+ 12.86 MeV

= 26.7 MeV total

$= 4.28 \times 10^{-12}$ J

Charged Particle Astronomy

Protons and electrons (and anti-protons & positrons) + **α-particles**

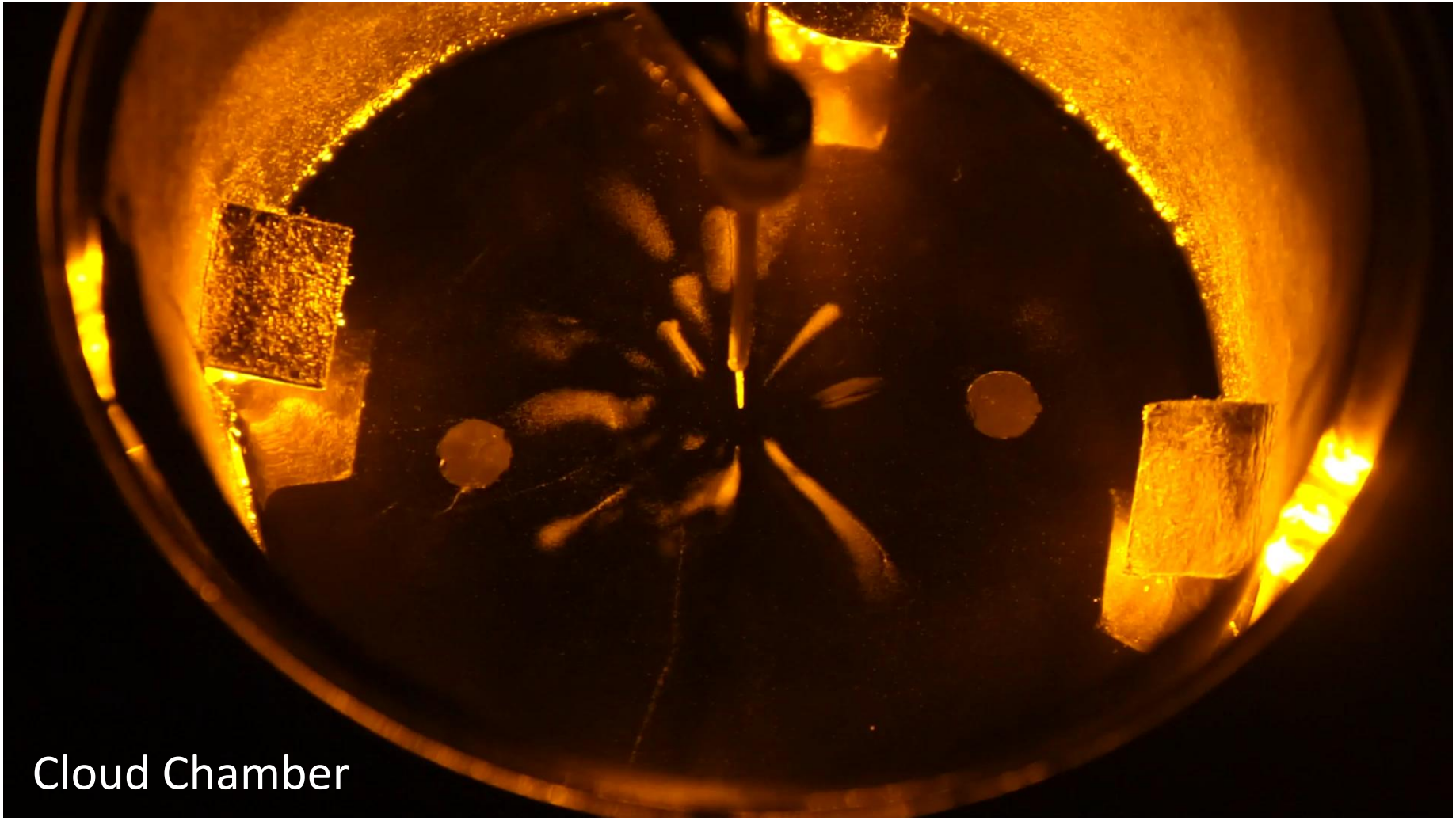
(charge = +2)

Good: lots of them, easy to detect (in space).

→ Stars emit p+ and e- as **solar wind**.

→ **Cosmic rays** from violent stellar events.

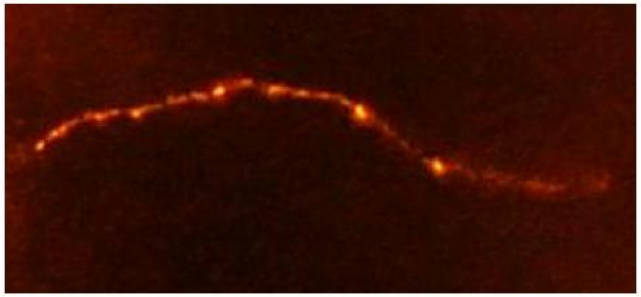
Alphas, electrons, muons (muon = heavy electron) from radioactive Lead-210

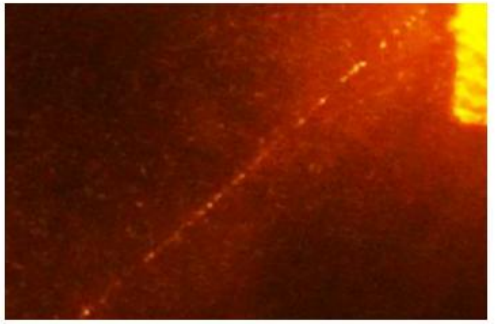


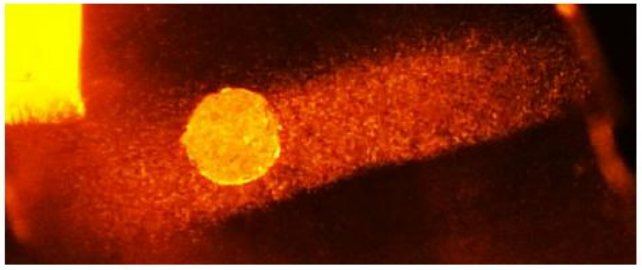
[video by Megan Frayser, W&M 2019]

Alphas, electrons, muons (muon = heavy electron) from radioactive Lead-208

Type of Particle	Particle Track
electron	
muon or fast electron	
alpha or proton	

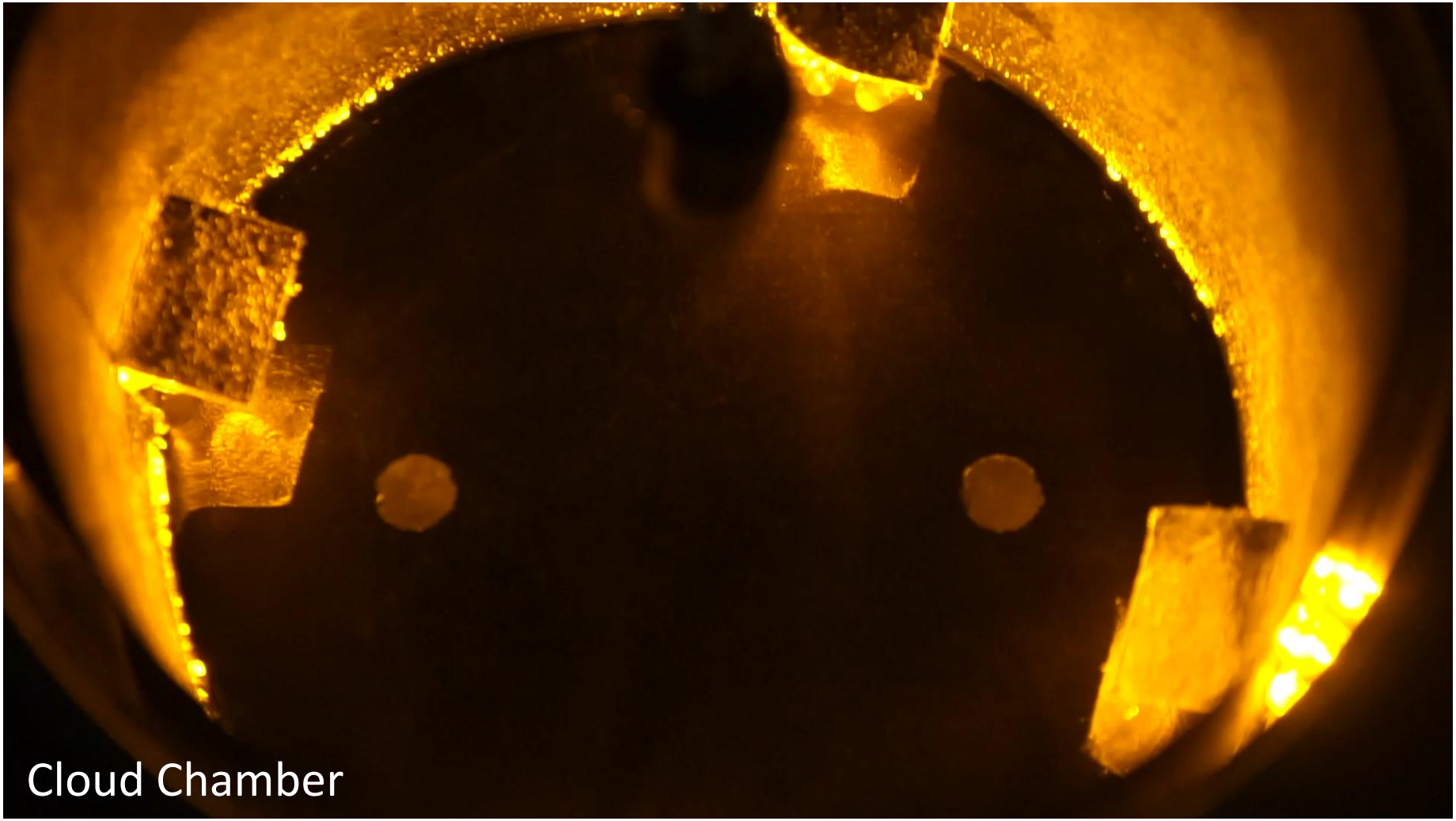






[photos by Megan Frayser, W&M 2019]

Alphas, electrons, muons (muon = heavy electron) from background cosmic rays & radioactivity



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(charge = +2)

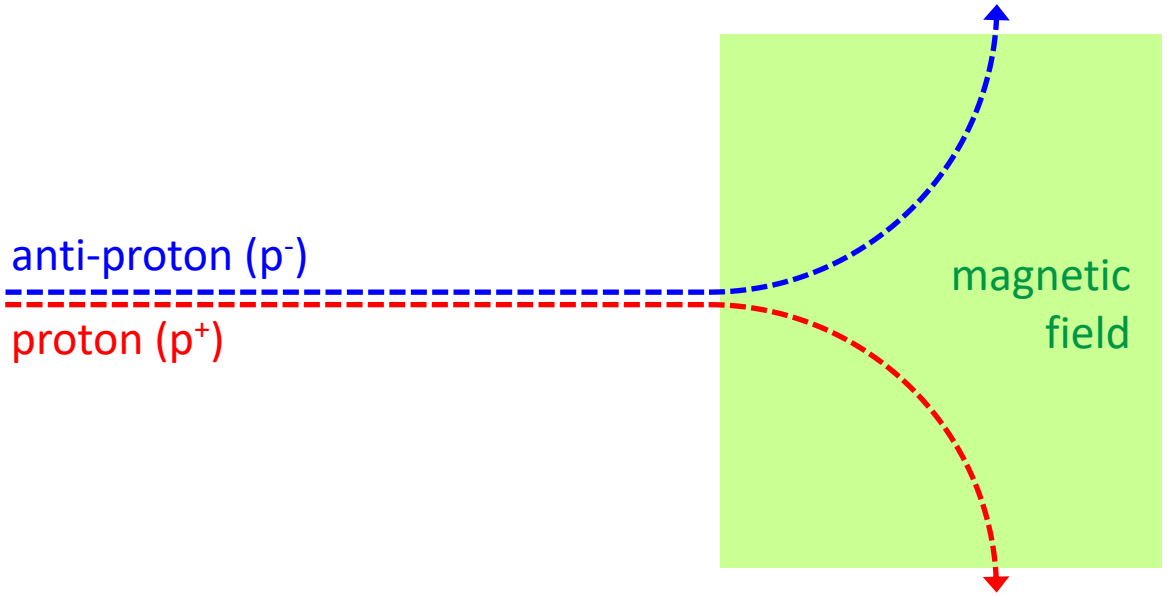
Good: lots of them, easy to detect (in space).

→ Stars emit p+ and e- as **solar wind**.

→ **Cosmic rays** from violent stellar events.

Bad: Strongly affected by planetary, solar, and galactic **magnetic fields**.

→ Hard to identify origin/source of particle.



Particle does not "point back" to its origin.

→ not useful for imaging.

What are anti-particles ?

- **Antiprotons** are protons with negative charge (q=-1).
- **Positrons** (anti-electrons) are electrons with positive charge (q=+1).
- **Antineutrons** are neutrons with opposite magnetic moment.

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Antimatter

You can build nuclei and atoms using antiprotons, positrons, and antineutrons.

- Anti-hydrogen consist of an anti-proton + positron.
  → Anti-hydrogen still feels attractive gravity.
- Anti-helium consists of anti-alpha particle + 2 positrons.
  (charge = -2)

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Matter-Antimatter Annihilation

When matter and antimatter meet they **annihilate** each other to ultimately produce **gamma rays** and **neutrinos**.