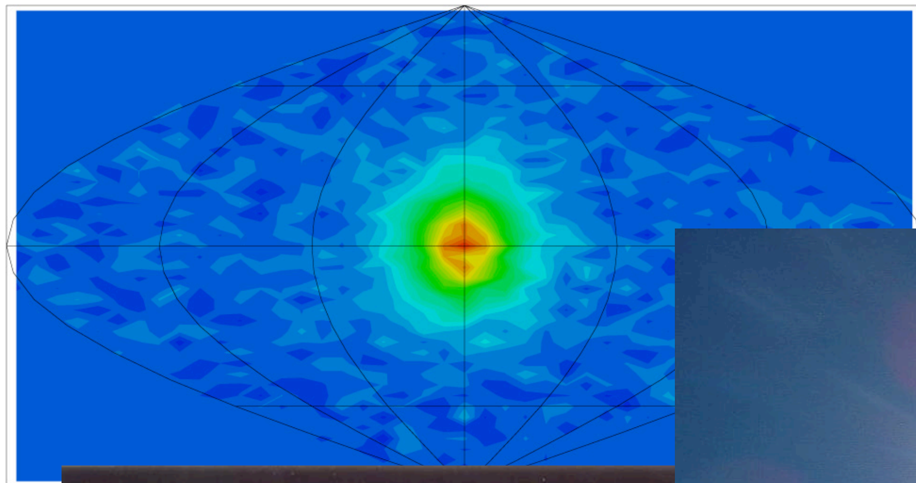
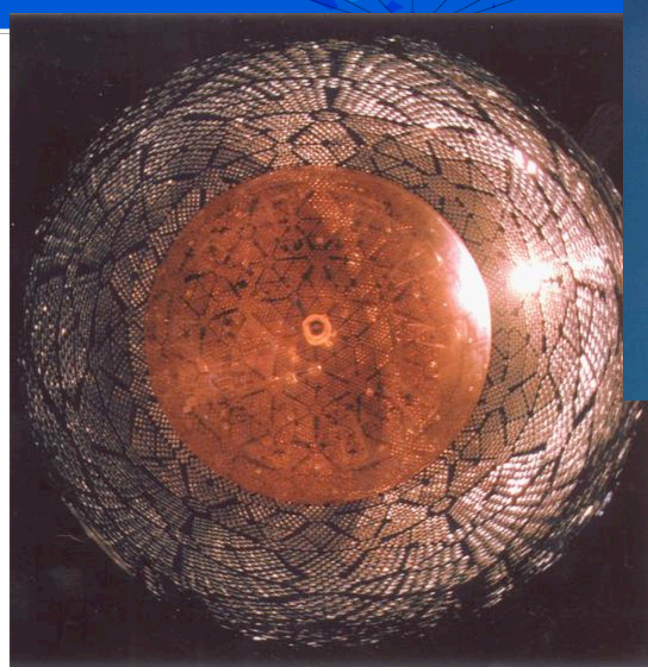
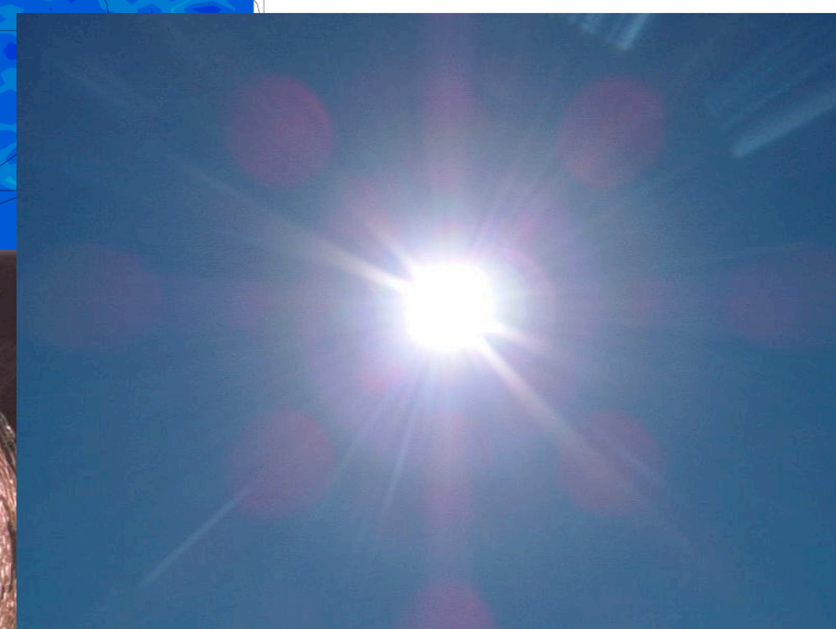
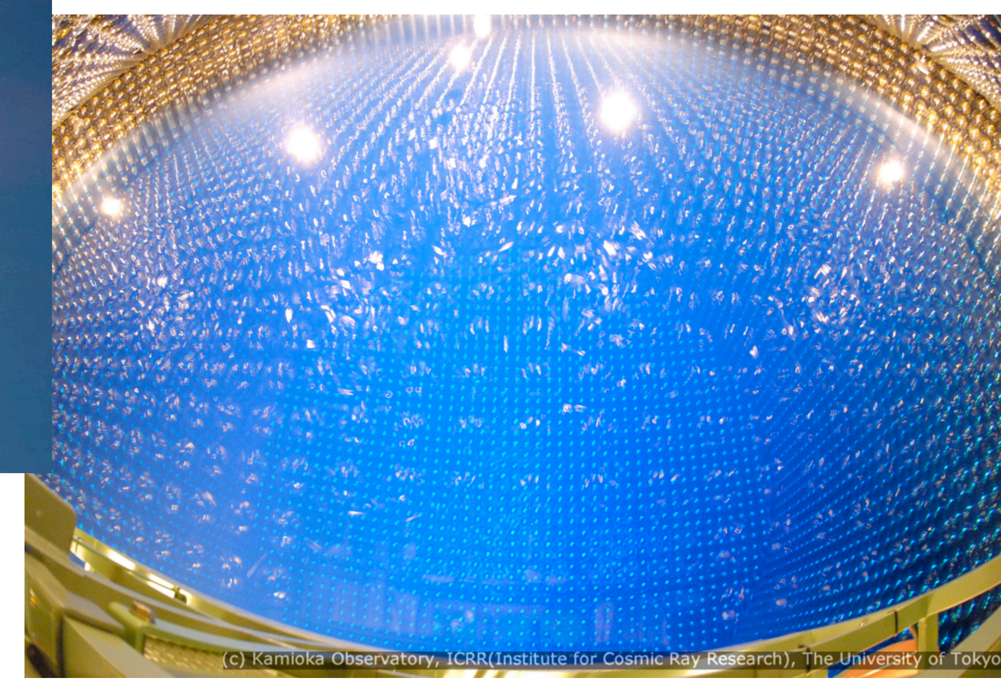
An Introduction to Stars







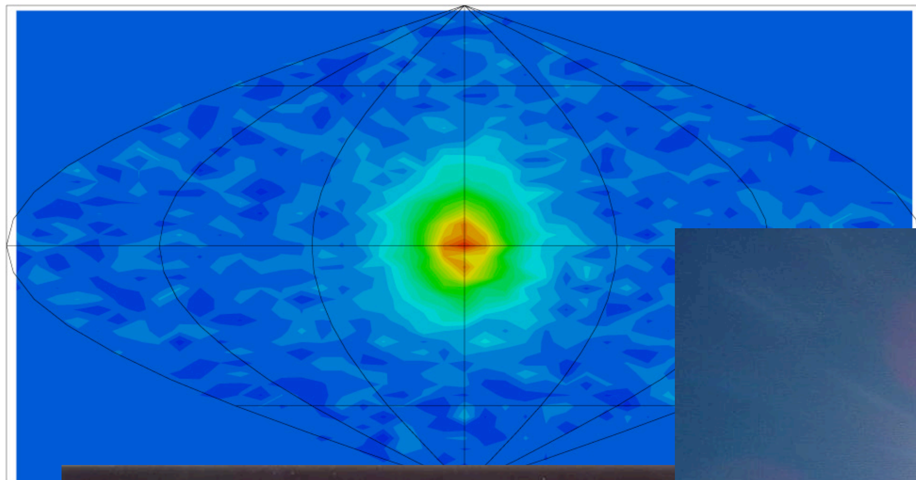


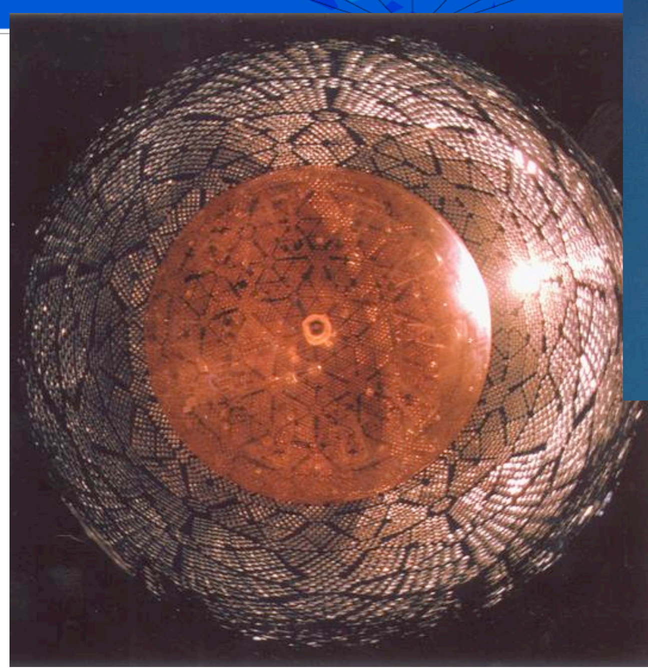
Brian Fields

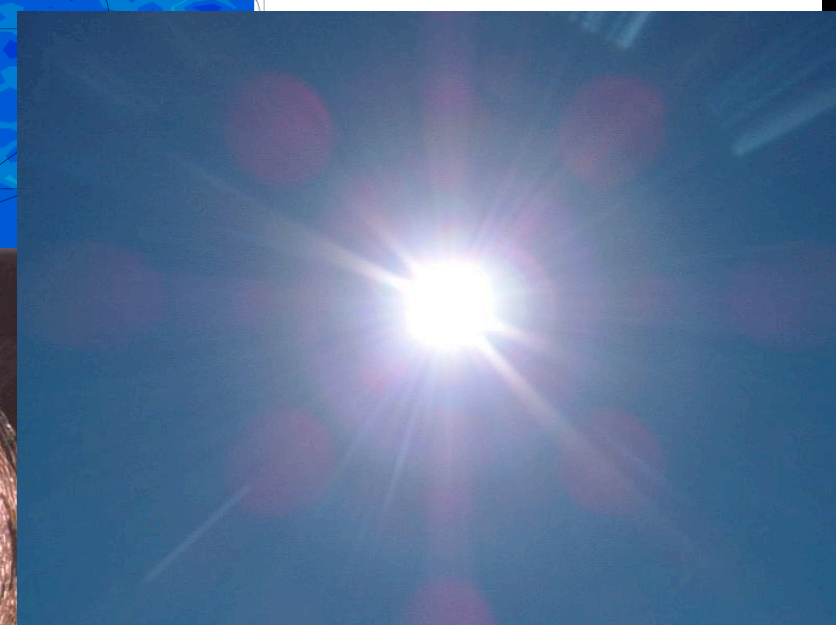
U. of Illinois

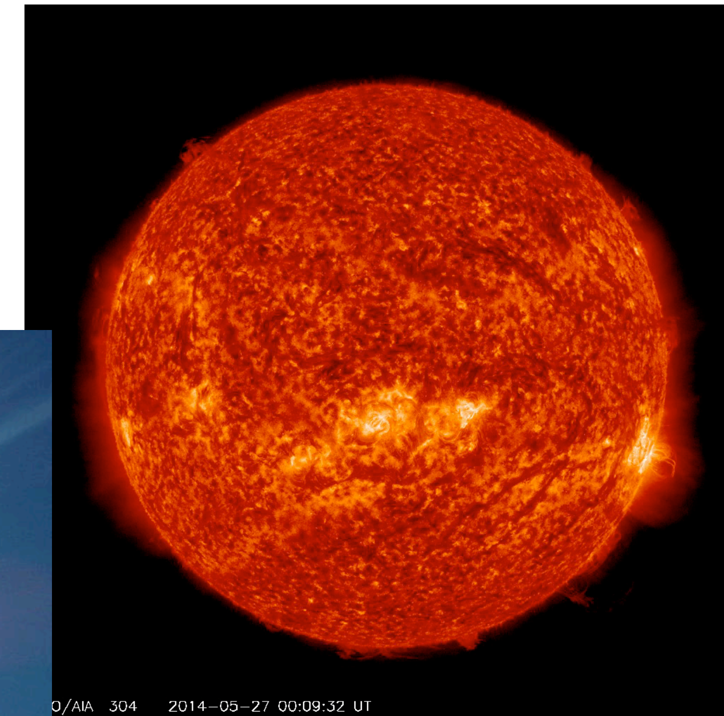
TALENT School, MSU, May 2014

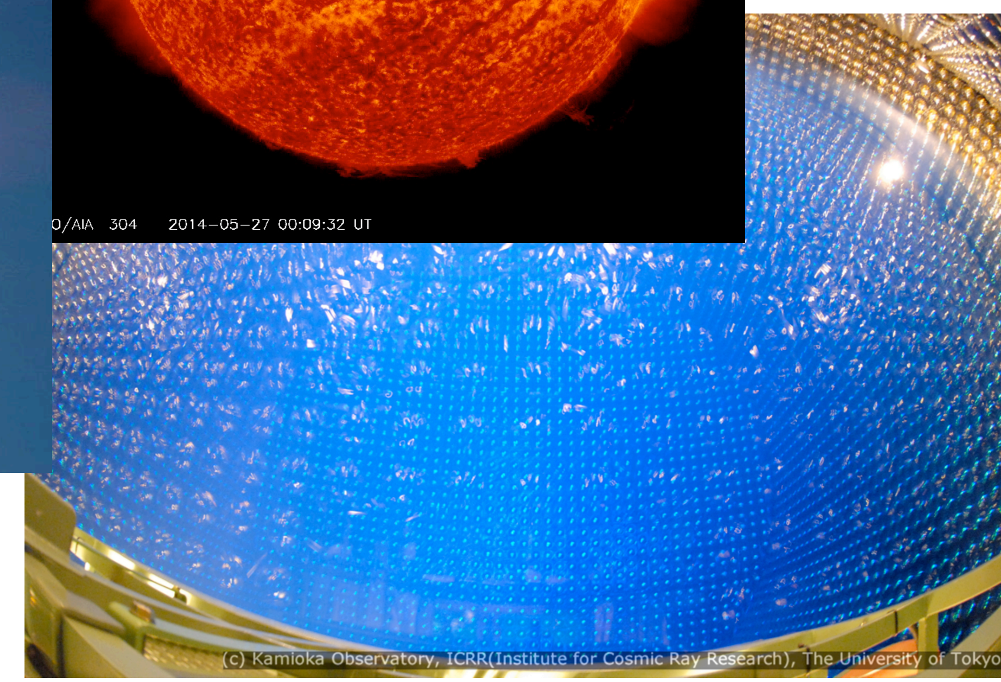
An Introduction to Stars









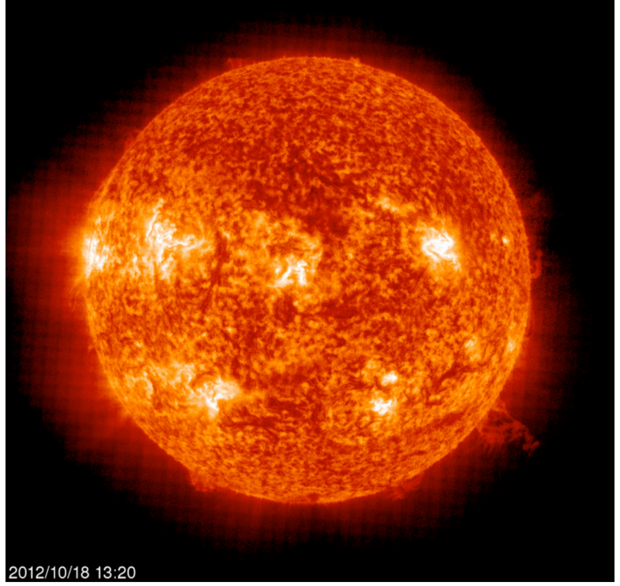


Brian Fields

U. of Illinois

TALENT School, MSU, May 2014

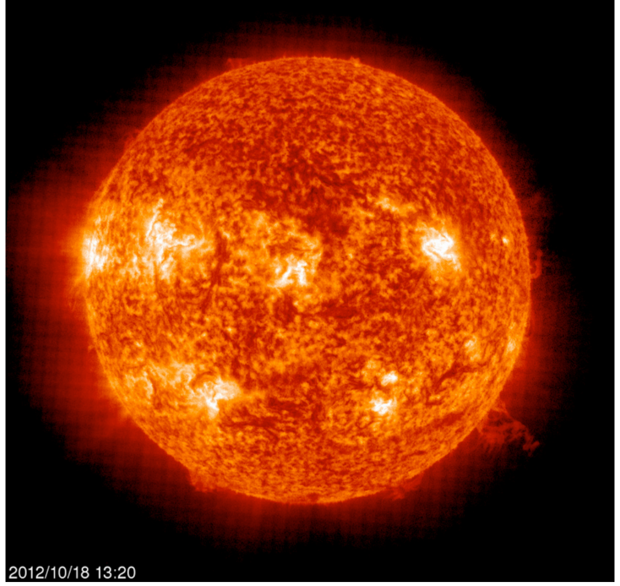
The Doomed Stars



the Sun and all stars:

- constantly emit energy, and
- have finite mass = finite fuel supply

The Doomed Stars

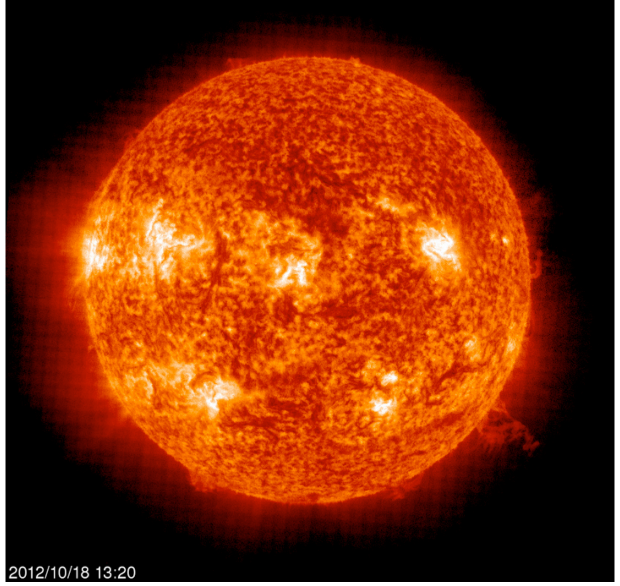


the Sun and all stars:

- constantly emit energy, and
- have finite mass = finite fuel supply

Thus?

The Doomed Stars



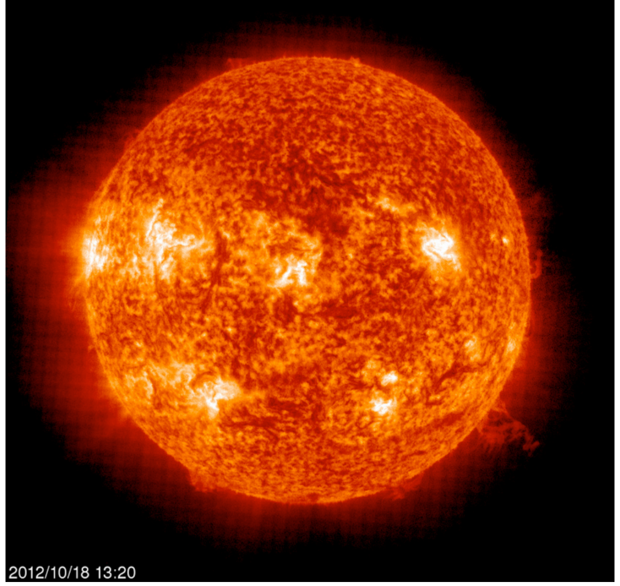
the Sun and all stars:

- constantly emit energy, and
- have finite mass = finite fuel supply

Thus?

- all stars – including the Sun – must eventually “burn out”

The Doomed Stars



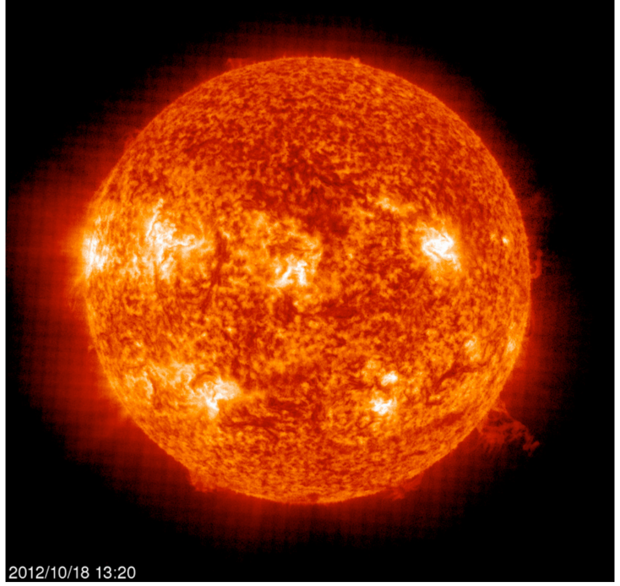
the Sun and all stars:

- constantly emit energy, and
- have finite mass = finite fuel supply

Thus?

- all stars – including the Sun – must eventually “burn out”
- = run out of energy = run out of fuel:

The Doomed Stars



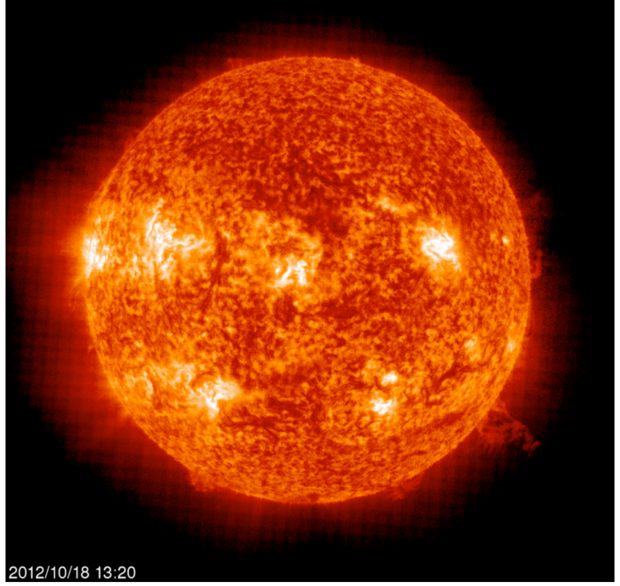
the Sun and all stars:

- constantly emit energy, and
- have finite mass = finite fuel supply

Thus?

- all stars – including the Sun – must eventually “burn out”
- = run out of energy = run out of fuel:
- the Sun all stars are doomed to die

The Doomed Stars



the Sun and all stars:

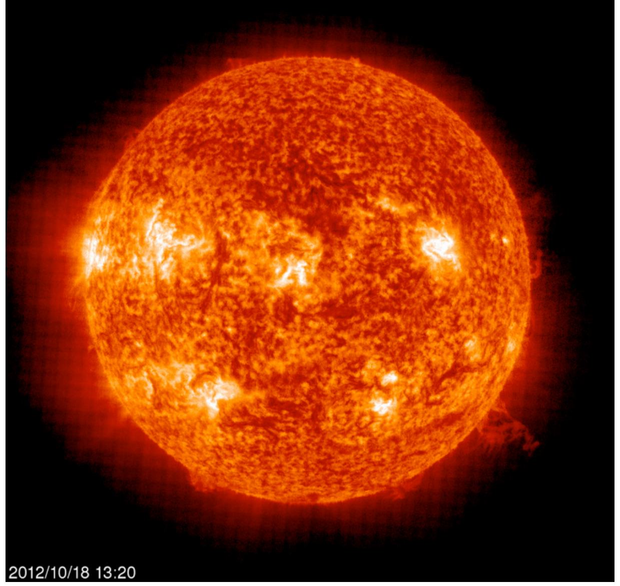
- constantly emit energy, and
- have finite mass = finite fuel supply

Thus?

- all stars – including the Sun – must eventually “burn out”
- = run out of energy = run out of fuel:
- the Sun all stars are doomed to die

the Sun cannot live forever!

The Doomed Stars



the Sun and all stars:

- constantly emit energy, and
- have finite mass = finite fuel supply

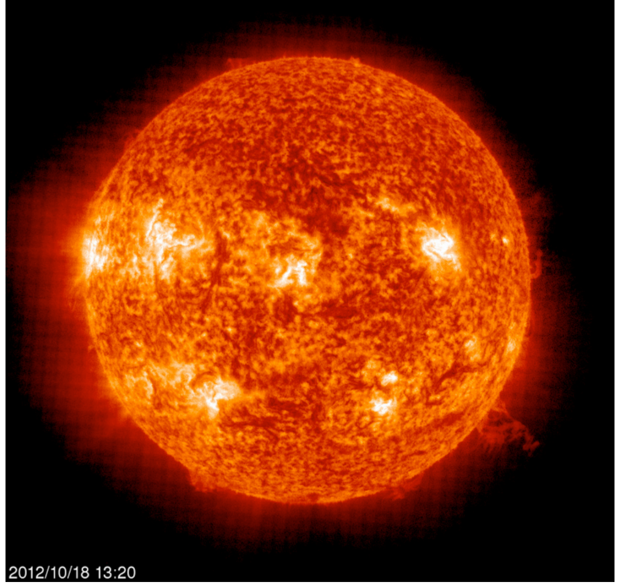
Thus?

- all stars – including the Sun – must eventually “burn out”
- = run out of energy = run out of fuel:
- the Sun all stars are doomed to die

the Sun cannot live forever!

But the Sun and other stars are alive today, so…?

The Doomed Stars



the Sun and all stars:

- constantly emit energy, and
- have finite mass = finite fuel supply

Thus?

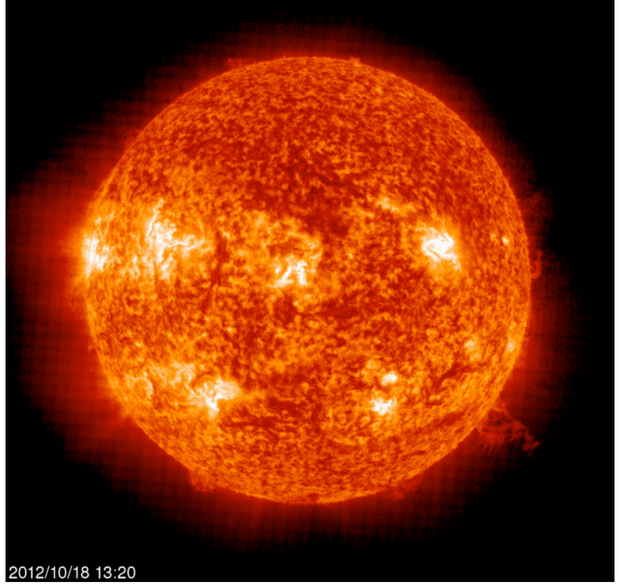
- all stars – including the Sun – must eventually “burn out”
- = run out of energy = run out of fuel:
- the Sun all stars are doomed to die

the Sun cannot live forever!

But the Sun and other stars are alive today, so…?

- stars alive today were not alive forever

The Doomed Stars



the Sun and all stars:

- constantly emit energy, and
- have finite mass = finite fuel supply

Thus?

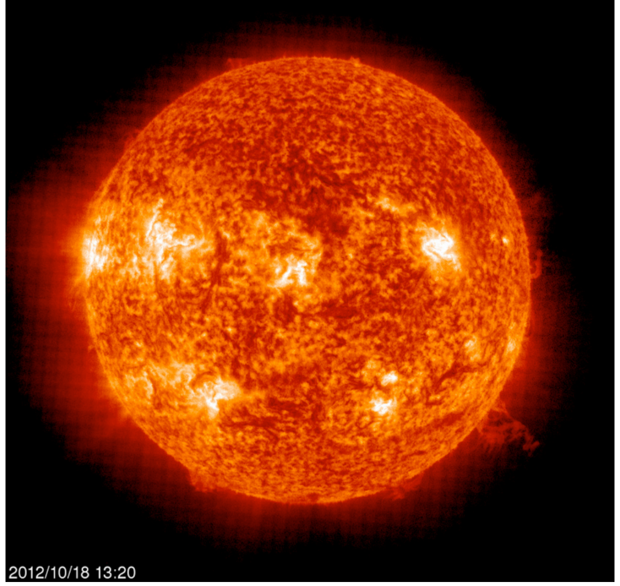
- all stars – including the Sun – must eventually “burn out”
- = run out of energy = run out of fuel:
- the Sun all stars are doomed to die

the Sun cannot live forever!

But the Sun and other stars are alive today, so…?

- stars alive today were not alive forever
- all stars must be born as well as die

The Doomed Stars



the Sun and all stars:

- constantly emit energy, and
- have finite mass = finite fuel supply

Thus?

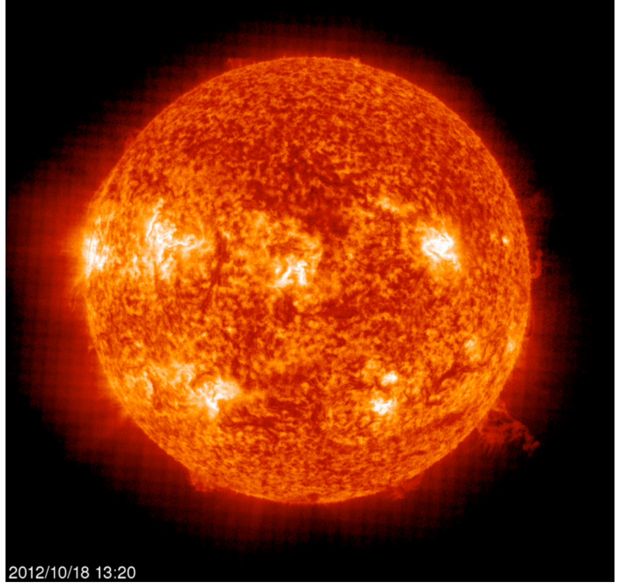
- all stars – including the Sun – must eventually “burn out”
- = run out of energy = run out of fuel:
- the Sun all stars are doomed to die

the Sun cannot live forever!

But the Sun and other stars are alive today, so…?

- stars alive today were not alive forever
- all stars must be born as well as die
- the Sun and stars have life cycles

The Doomed Stars



the Sun and all stars:

- constantly emit energy, and
- have finite mass = finite fuel supply

Thus?

- all stars – including the Sun – must eventually “burn out”
- = run out of energy = run out of fuel:
- the Sun all stars are doomed to die

the Sun cannot live forever!

But the Sun and other stars are alive today, so...?

- stars alive today were not alive forever
- all stars must be born as well as die
- the Sun and stars have life cycles
- stellar mortality also implies possibility of rebirth!

Astronomical Numbers

Astronomical Numbers

★ **Astronomical Unit:**

Earth-Sun distance

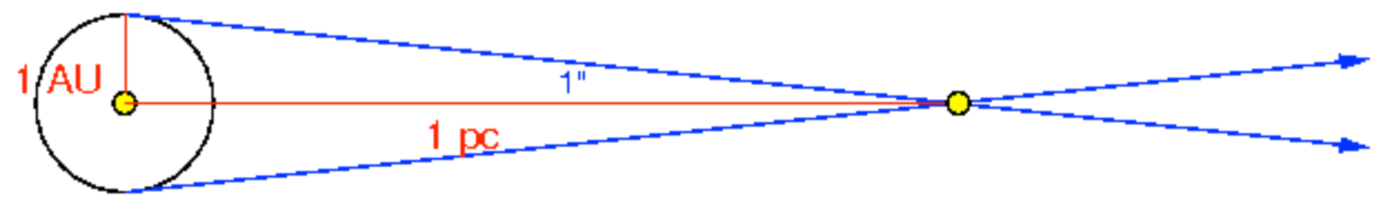
$$1\text{AU} = 1.5 \times 10^{13}\ \text{cm} \approx 500\ \text{light-seconds}$$

Astronomical Numbers

★**Astronomical Unit:**

Earth-Sun distance

$$1\text{AU} = 1.5 \times 10^{13}\ \text{cm} \approx 500\ \text{light-seconds}$$

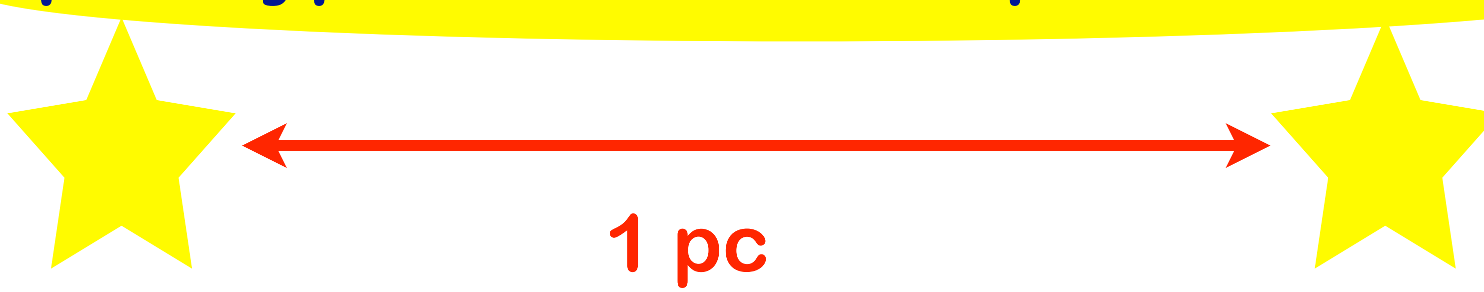


★**Parsec:**

$$1\ \text{pc} = \frac{1\text{AU}}{(1\text{arcsec})_{\text{radian}}} = 3.16 \times 10^{18}\text{cm} \approx 3\text{light-years}$$

nearest star: $d(\alpha\text{Cen}) = 1.3\ \text{pc} = 4\ \text{lyr}$

➡**1 pc ~ typical star-star separation**



Astronomical Numbers

★**Astronomical Unit:**

Earth-Sun distance

$$1\text{AU} = 1.5 \times 10^{13}\ \text{cm} \approx 500\ \text{light-seconds}$$

★**Parsec:**

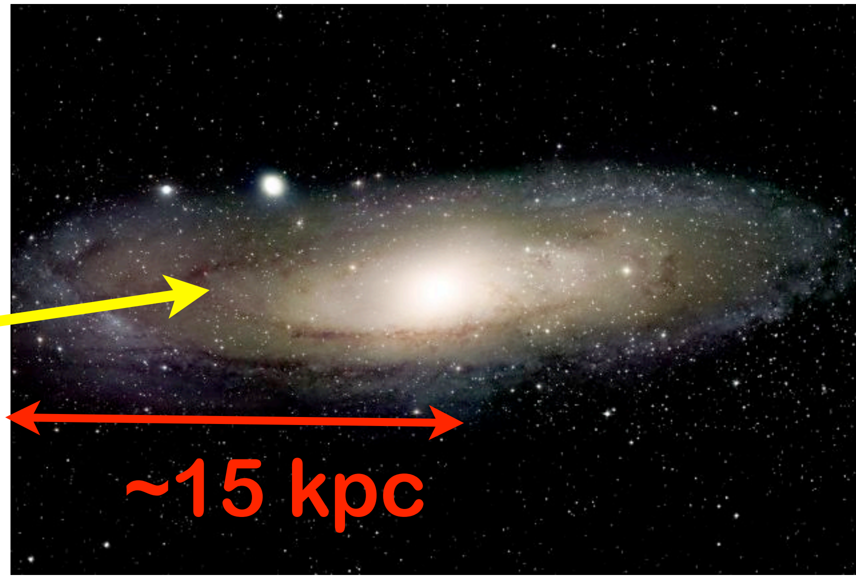
$$1\ \text{pc} = \frac{1\text{AU}}{(1\text{arcsec})_{\text{radian}}} = 3.16 \times 10^{18}\text{cm} \approx 3\text{light-years}$$

nearest star: $d(\alpha\text{Cen}) = 1.3\ \text{pc} = 4\ \text{lyr}$

➡**1 pc ~ typical star-star separation**

Milky Way Galaxy: R_{MW}~15 kpc

you are here: R_{sun}~8 kpc



An Introduction to Stars

- Star formation and gravitational instability
- Solar Structure
- Hydrogen burning in the Sun
- The Evidence: Solar Neutrinos

Star Formation

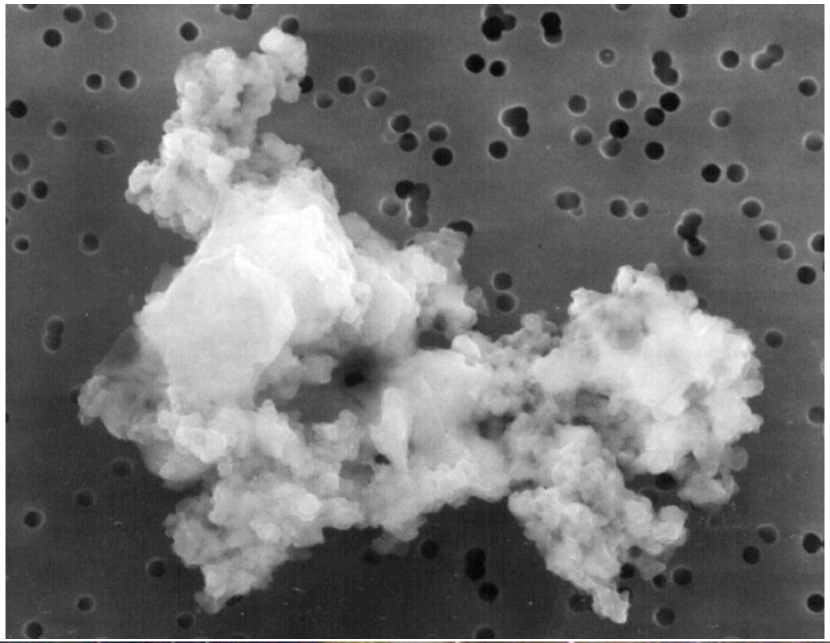
Star Formation

stars born in cold gas & dust clumps: molecular clouds

Initial protostellar material a small parcel of larger cloud

- • cold gas & dust
- • spinning: net angular momentum

Q: why is L>0 a reasonable assumption?



For simplicity: imagine first a cold cloud with zero spin i.e., zero angular momentum

Q: forces on particles in cloud?

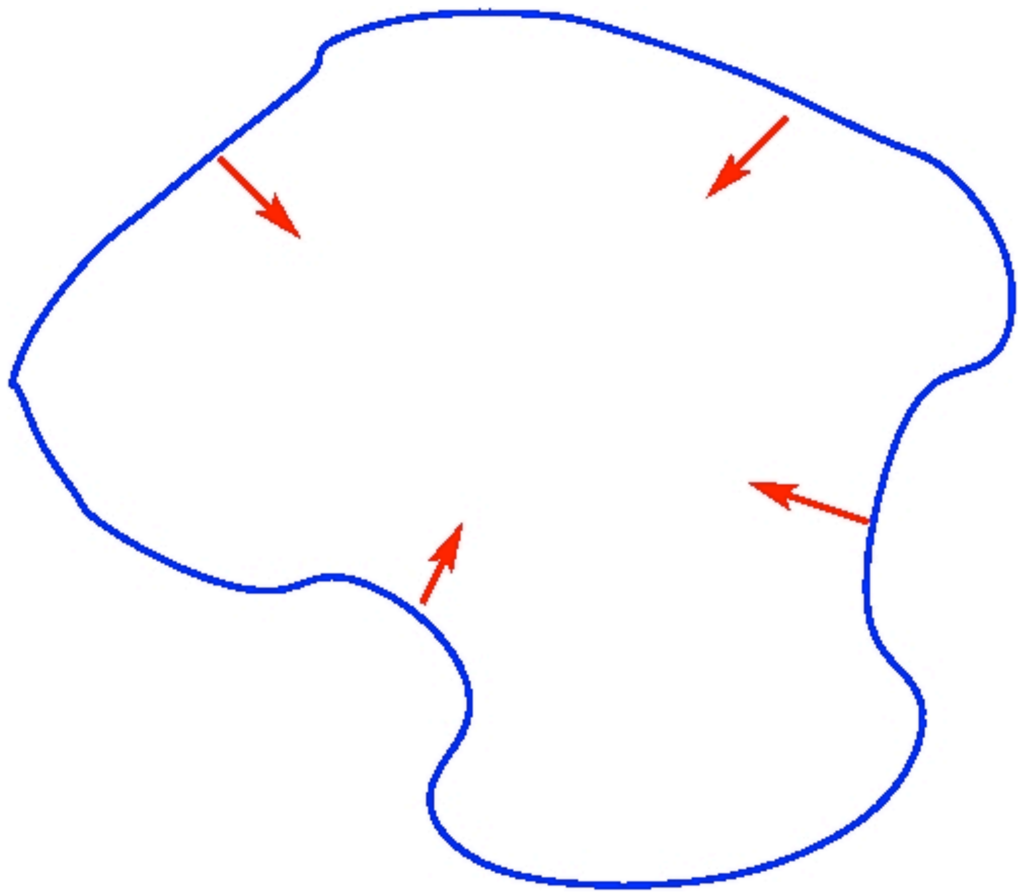
Q: response of particles to these forces?

Q: why is coldness important for this to work?

Gravitational Instability

ignoring spin: particles in cold cloud feel forces of

– gravity
– thermal pressure



but if cloud is cold: T low, pressure $P = \rho k T / m_{\text{particle}}$ small → only important force is gravity

gravity → inward motion → denser → stronger gravity → runaway!

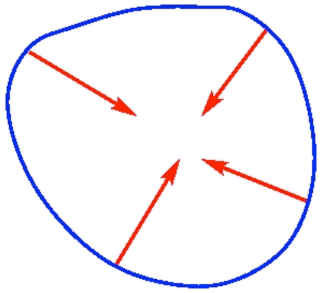
"gravitational collapse"

Q: why doesn't collapse continue until all matter → point?

Gravitational Instability

ignoring spin: particles in cold cloud feel forces of

- gravity
- thermal pressure



but if cloud is cold: T low, pressure $P = \rho kT/m_{\text{particle}}$ small → only important force is gravity

gravity → inward motion → denser → stronger gravity → runaway!

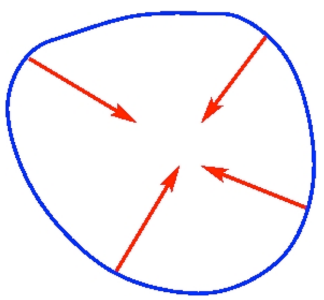
"gravitational collapse"

Q: why doesn't collapse continue until all matter → point?

Gravitational Instability

ignoring spin: particles in cold cloud feel forces of

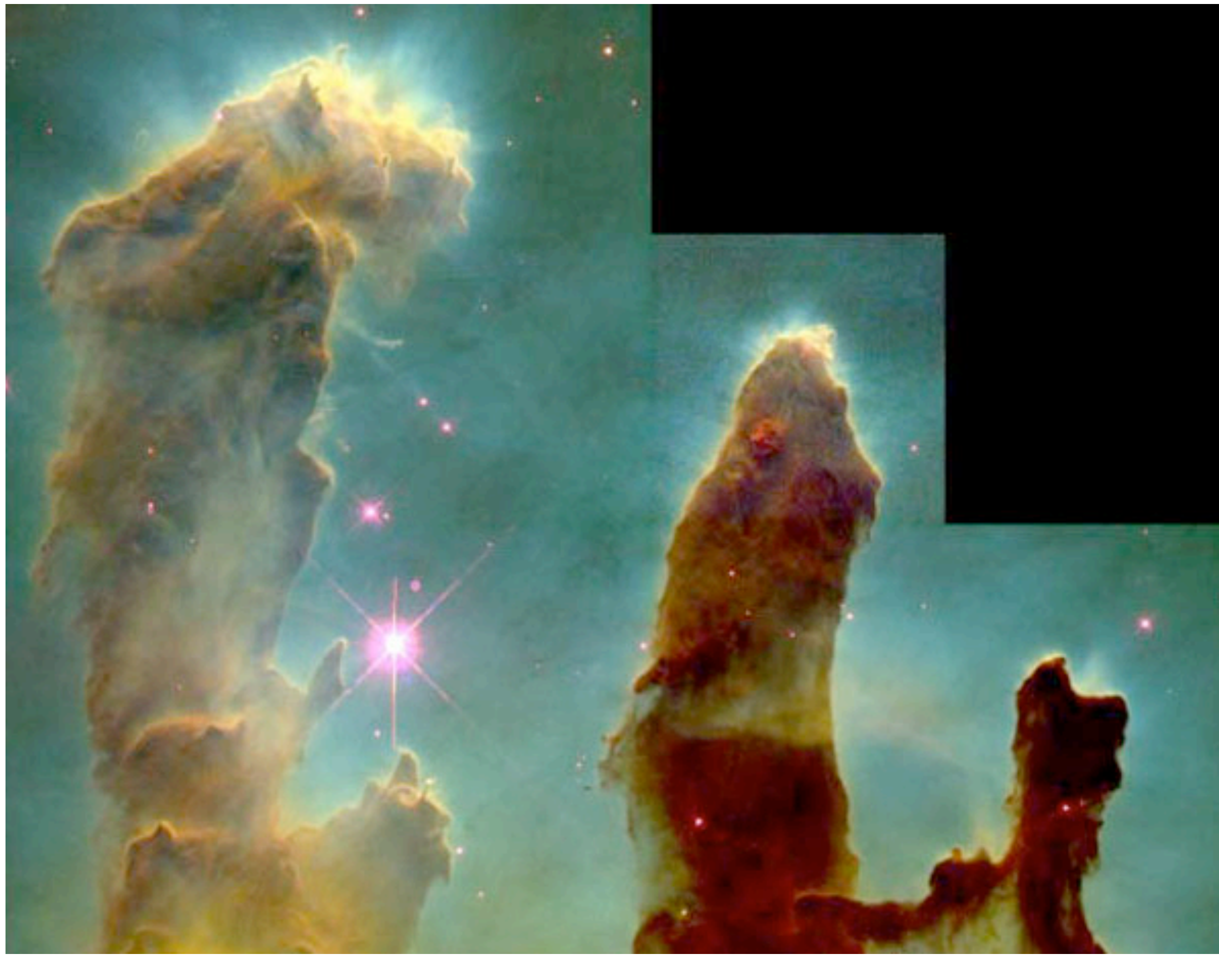
- gravity
- thermal pressure



but if cloud is cold: T low, pressure $P = \rho k T / m_{\text{particle}}$ small → only important force is gravity

gravity → inward motion → denser → stronger gravity → runaway!

"gravitational collapse"



Q: why doesn't collapse continue until all matter → point?

Nebular Collapse: Birth of Sun and Disk

indeed, most matter compressed → central "proto-Sun"

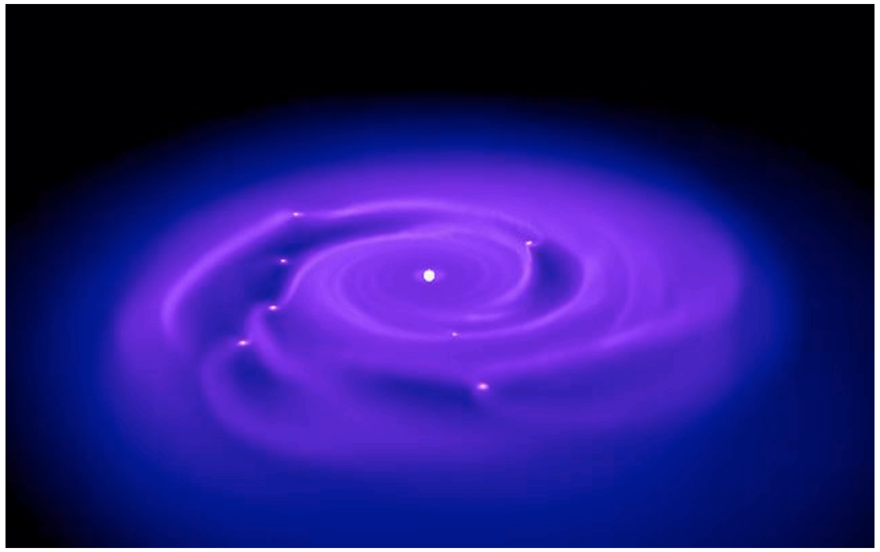
but real pre-stellar clouds are clumpy parts of larger nebulae

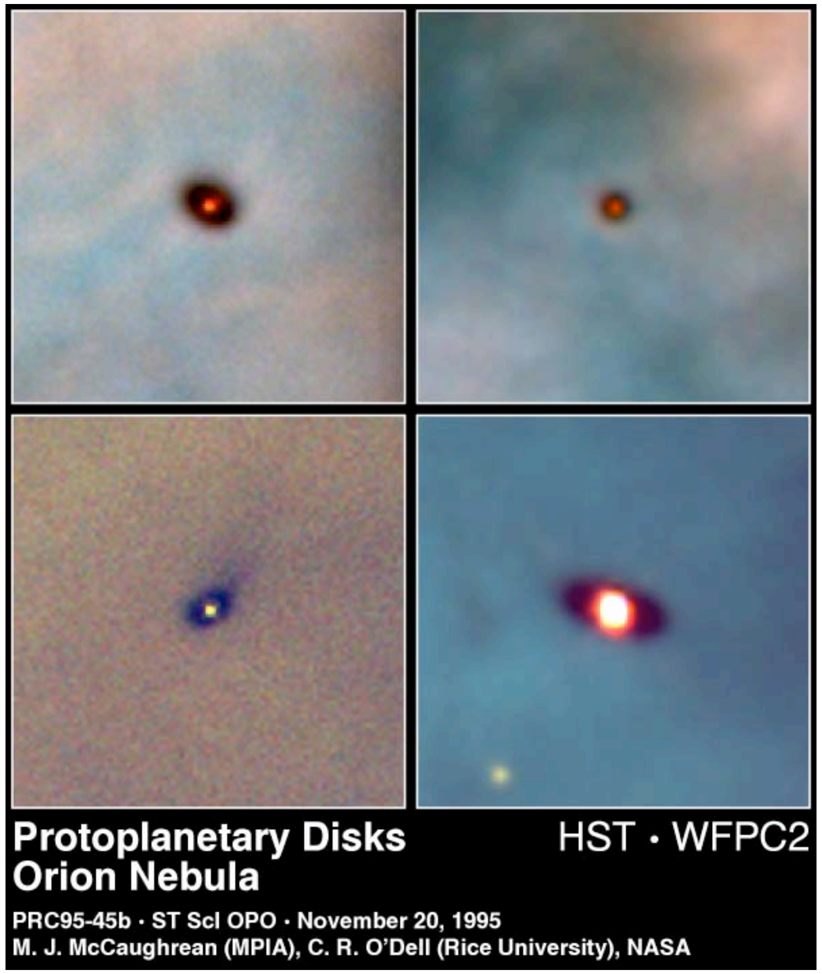
- turbulent motions
- clumps have random but nonzero spins: L>0

spin → axial but not spherical symmetry → collapse not spherical

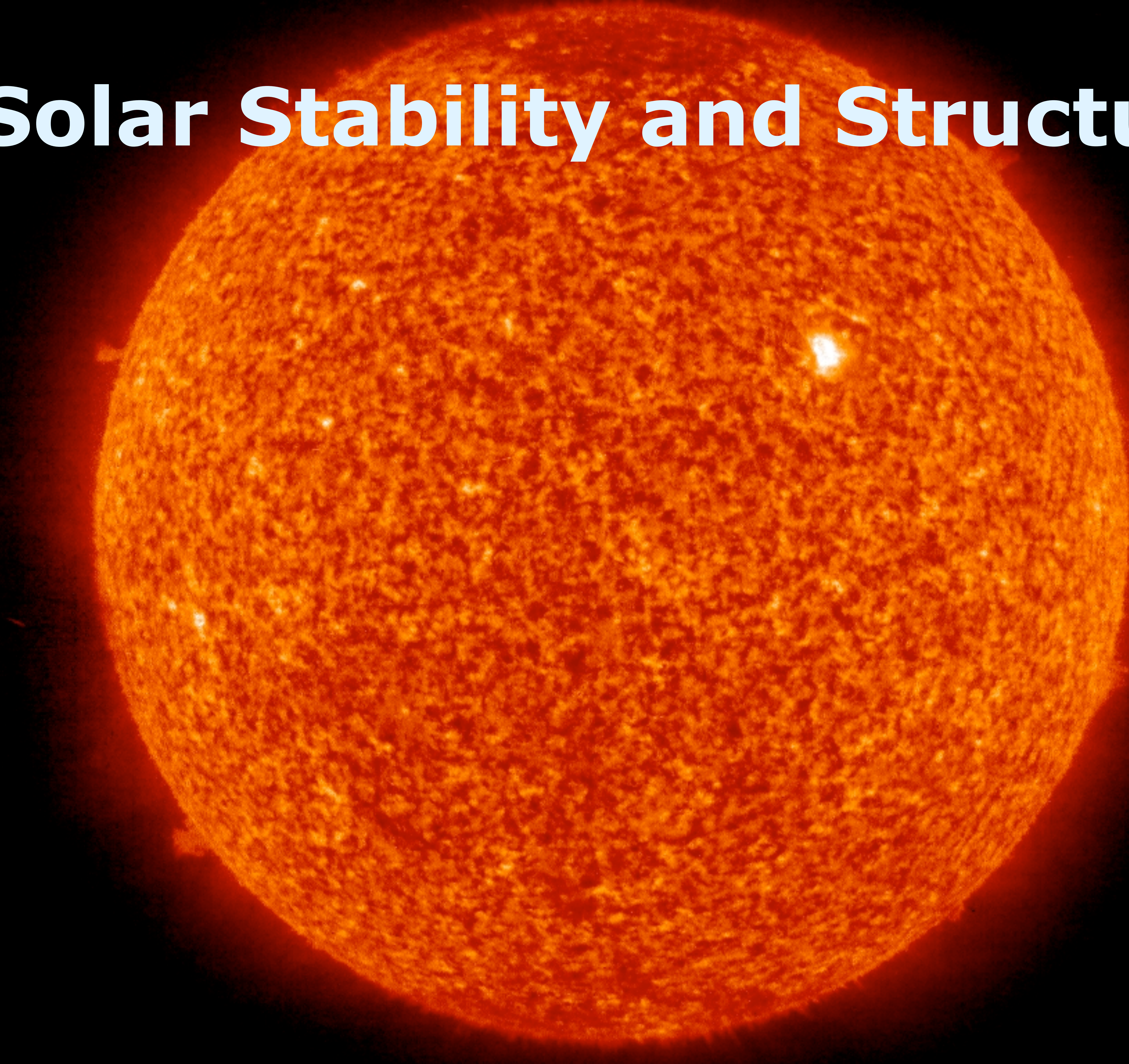
angular momentum "centrifugal barrier"

- collapse easier along z than along R
- protoplanetary disk





Solar Stability and Structure



The Sun: Stability

The Sun's size is constant.
Not expanding or collapsing
at least on human timescales

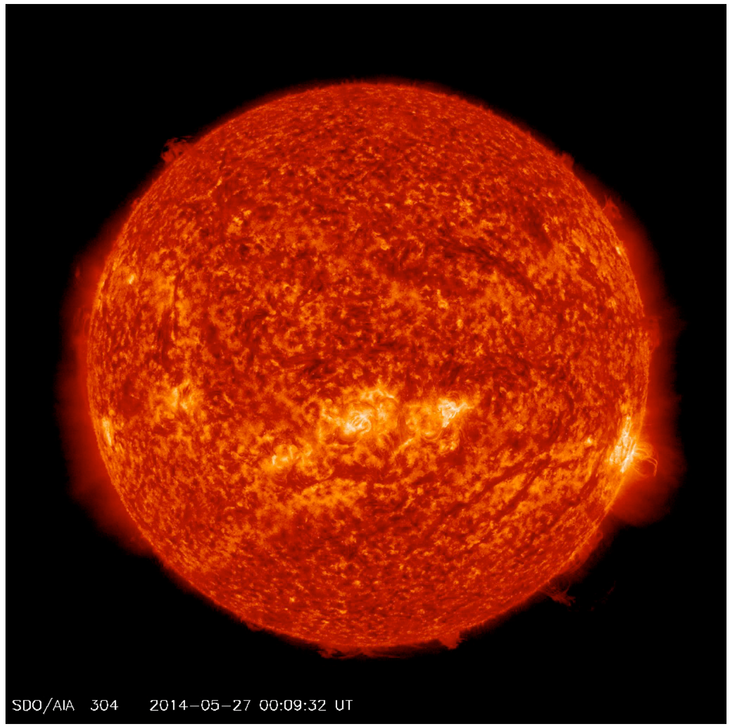
Q: What does this mean for every shell of gas in Sun?

net force: F = 0

- but Sun has mass and gravity
- so must be restoring force: pressure
- exactly balances gravity

The Sun: Stability

The Sun's size is constant.
Not expanding or collapsing
at least on human timescales

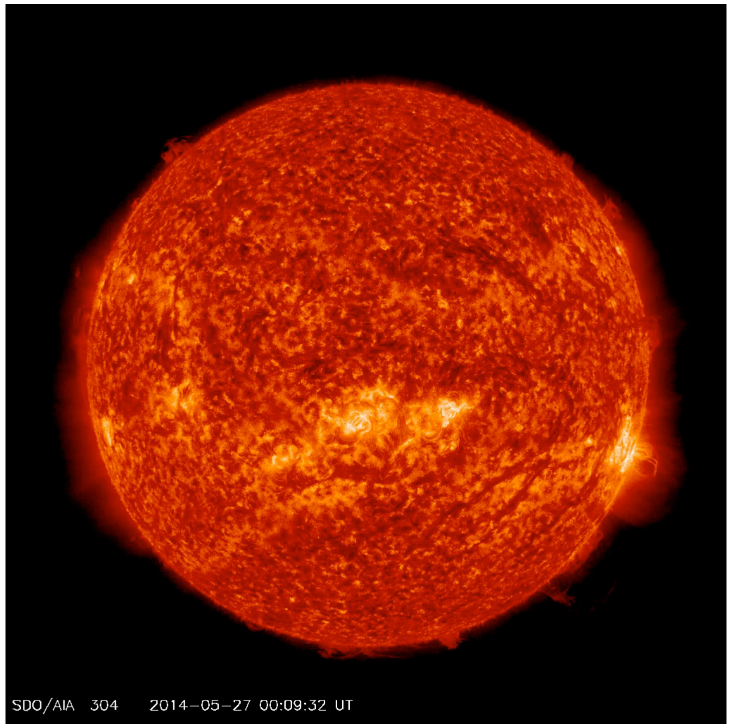


Q: What does this mean for every shell of gas in Sun?

net force: F = 0

- but Sun has mass and gravity
- so must be restoring force: pressure
- exactly balances gravity

The Sun: Stability

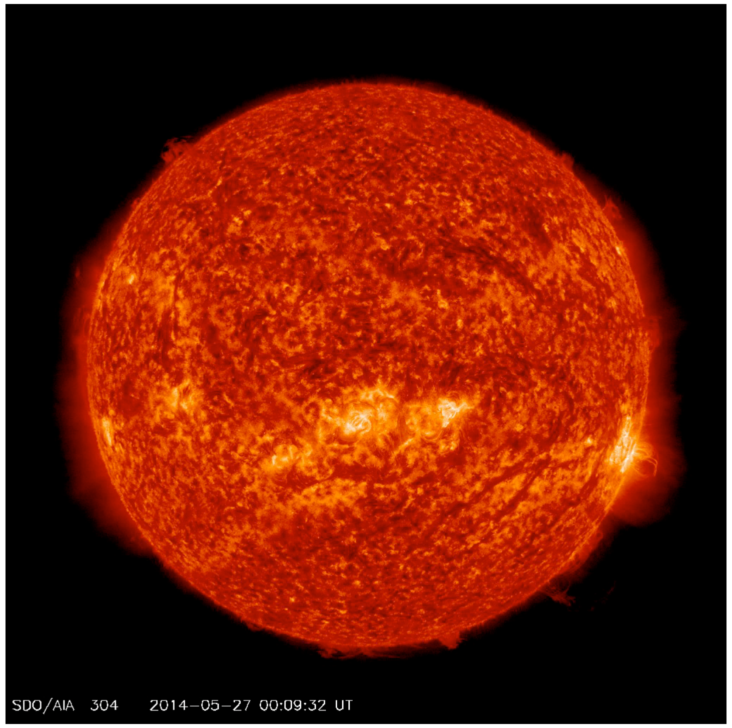


The Sun's size is constant.
Not expanding or collapsing
at least on human timescales

Q: What does this mean for every shell of gas in Sun?

The Sun: Stability

The Sun’s size is constant.
Not expanding or collapsing
at least on human timescales



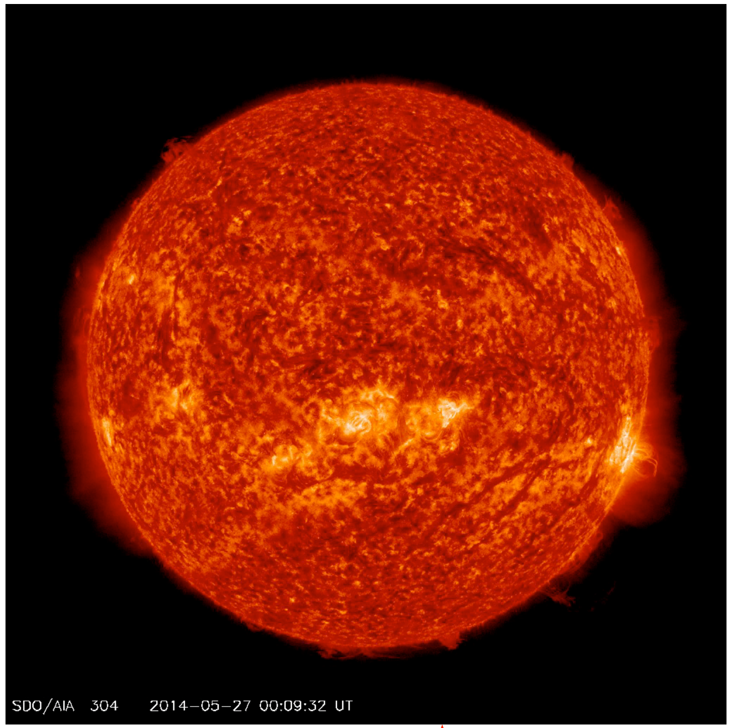
Q: What does this mean for every shell of gas in Sun?

net force: F = 0

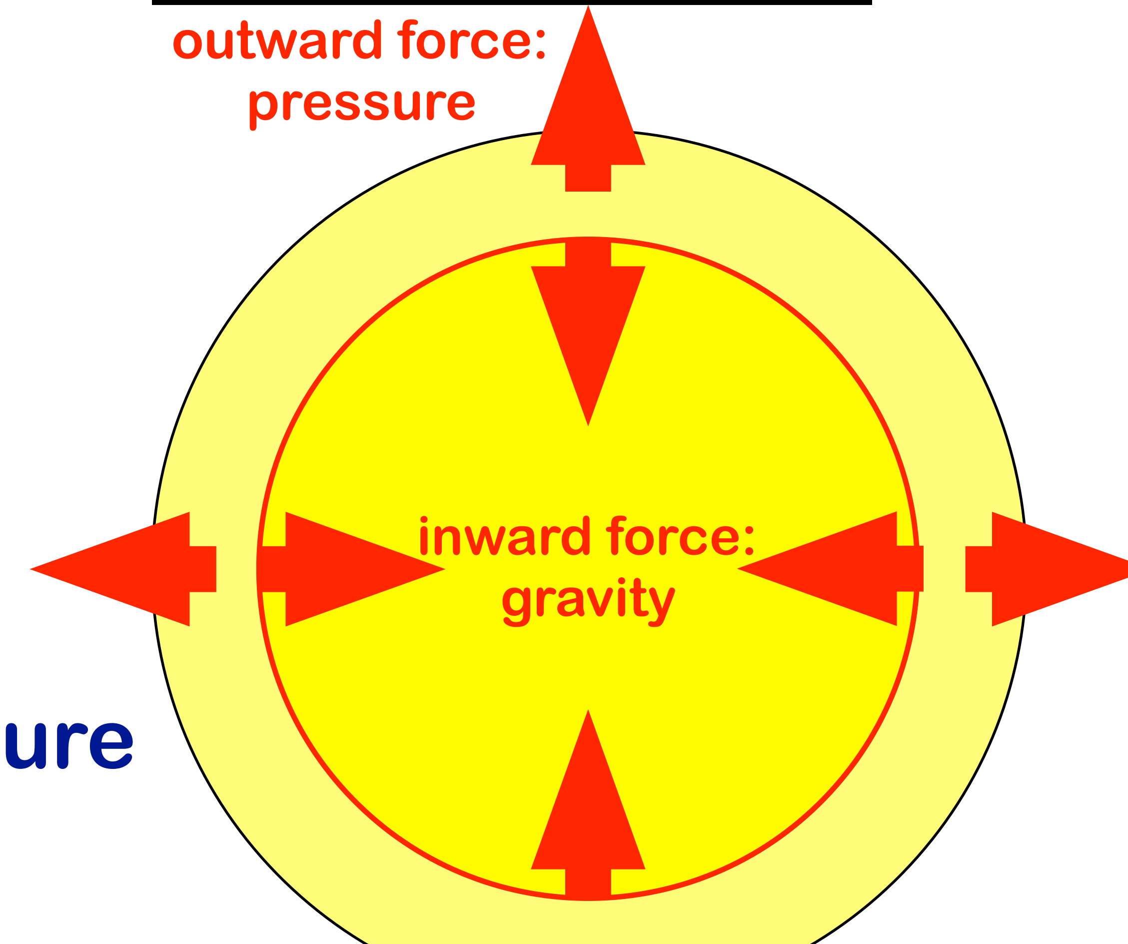
– but Sun has mass and gravity
– so must be restoring force: pressure
– exactly balances gravity

The Sun: Stability

The Sun's size is constant.
Not expanding or collapsing
at least on human timescales



Q: What does this mean for every shell of gas in Sun?



net force: F = 0

- but Sun has mass and gravity
- so must be restoring force: pressure
- exactly balances gravity

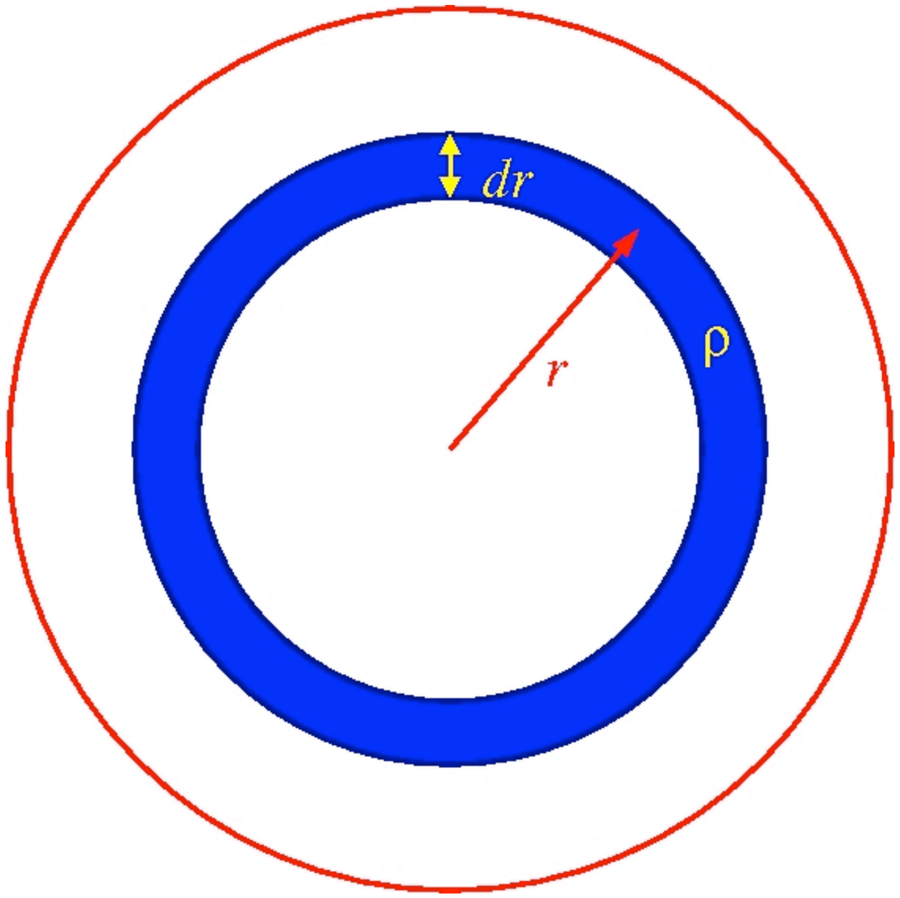
Hydrostatic Equilibrium

Consider a shell of gas in Sun, with with dr, volume $dV = 4\pi r^2 dr$

- net weight: $mg = \rho dV \; Gm(r)/r^2 = 4\pi G m(r) \rho dr$
- pressure difference:

  $P_{\text{net}} = -P(r+dr) + P(r) = -dP/dr \; dr$
- net pressure force:

  $F_p = P_{\text{net}} A = -4\pi r^2 P_{\text{net}}$ (up)



force balance:

$$-\frac{dP}{dr} = \frac{Gm(r)\rho}{r^2}$$

Q: equation of state?

Hydrostatic Equilibrium

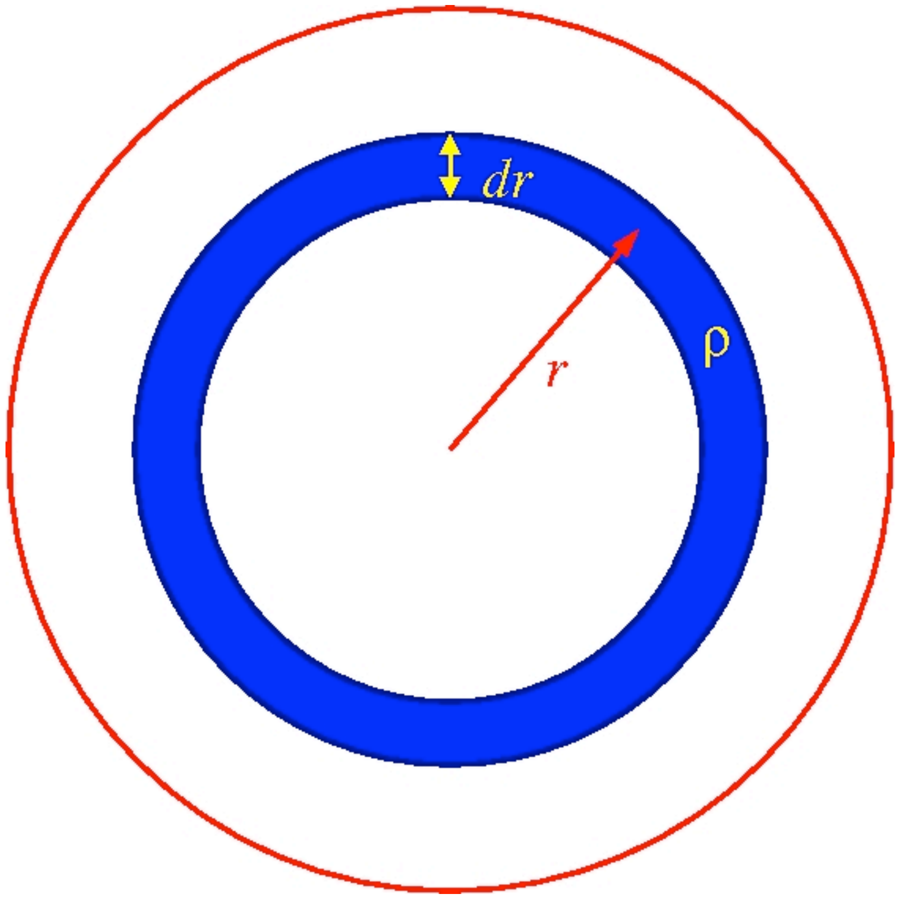
Consider a shell of gas in Sun, with with dr, volume $dV = 4\pi r^2 dr$

- net weight: $mg = \rho dV \ Gm(r)/r^2 = 4\pi Gm(r)\rho dr$
- pressure difference:

$$P_{\mathrm{net}} = -P(r+dr) + P(r) = -dP/dr \ dr$$

- net pressure force:

$$F_p = P_{\mathrm{net}} A = -4\pi r^2 P_{\mathrm{net}} \ (\mathrm{up})$$

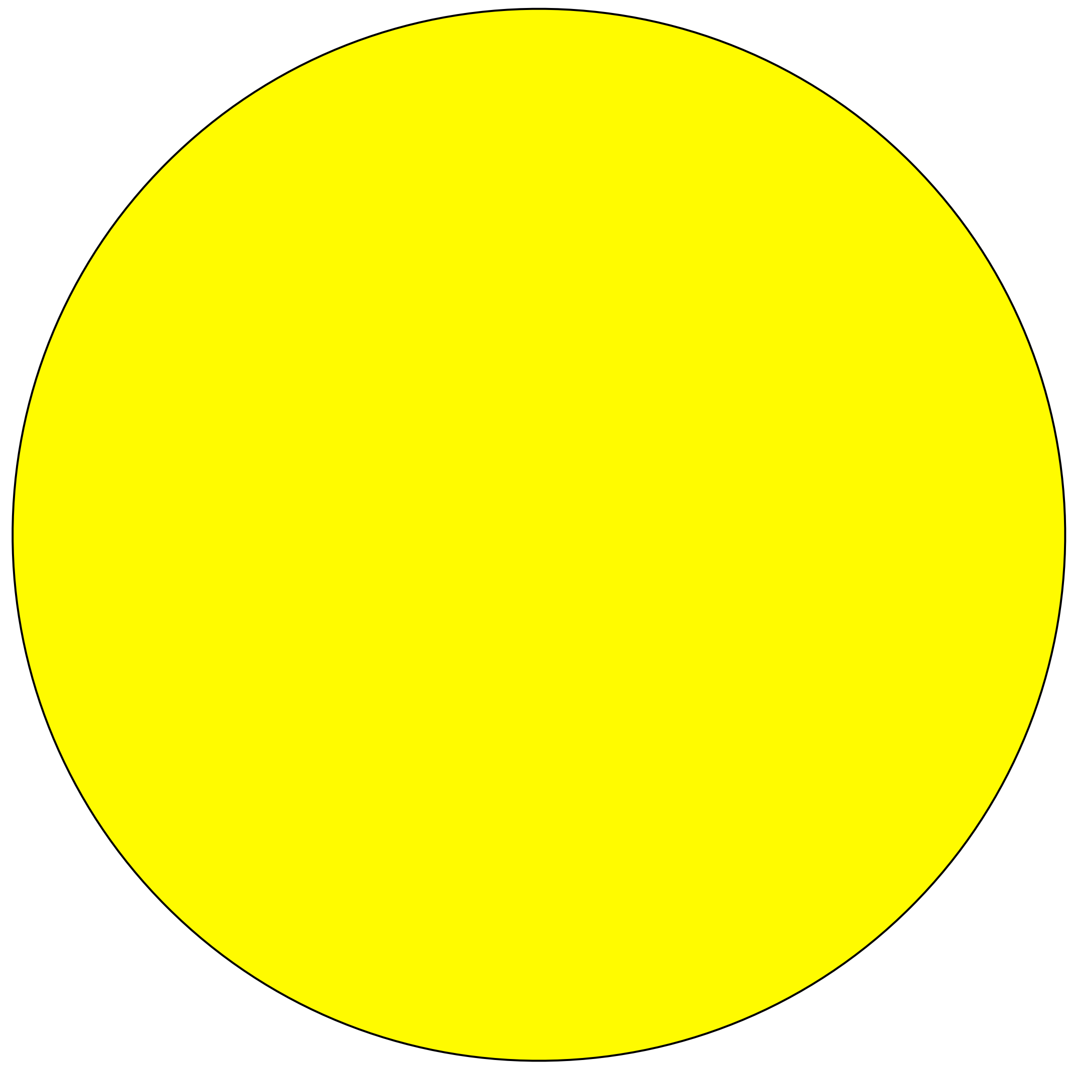


force balance:

$$-\frac{dP}{dr} = \frac{Gm(r)\rho}{r^2}$$

Q: equation of state? $p = \rho kT/m + aT^4/3$

The Battle of The Solar Titans
Gravity vs Pressure

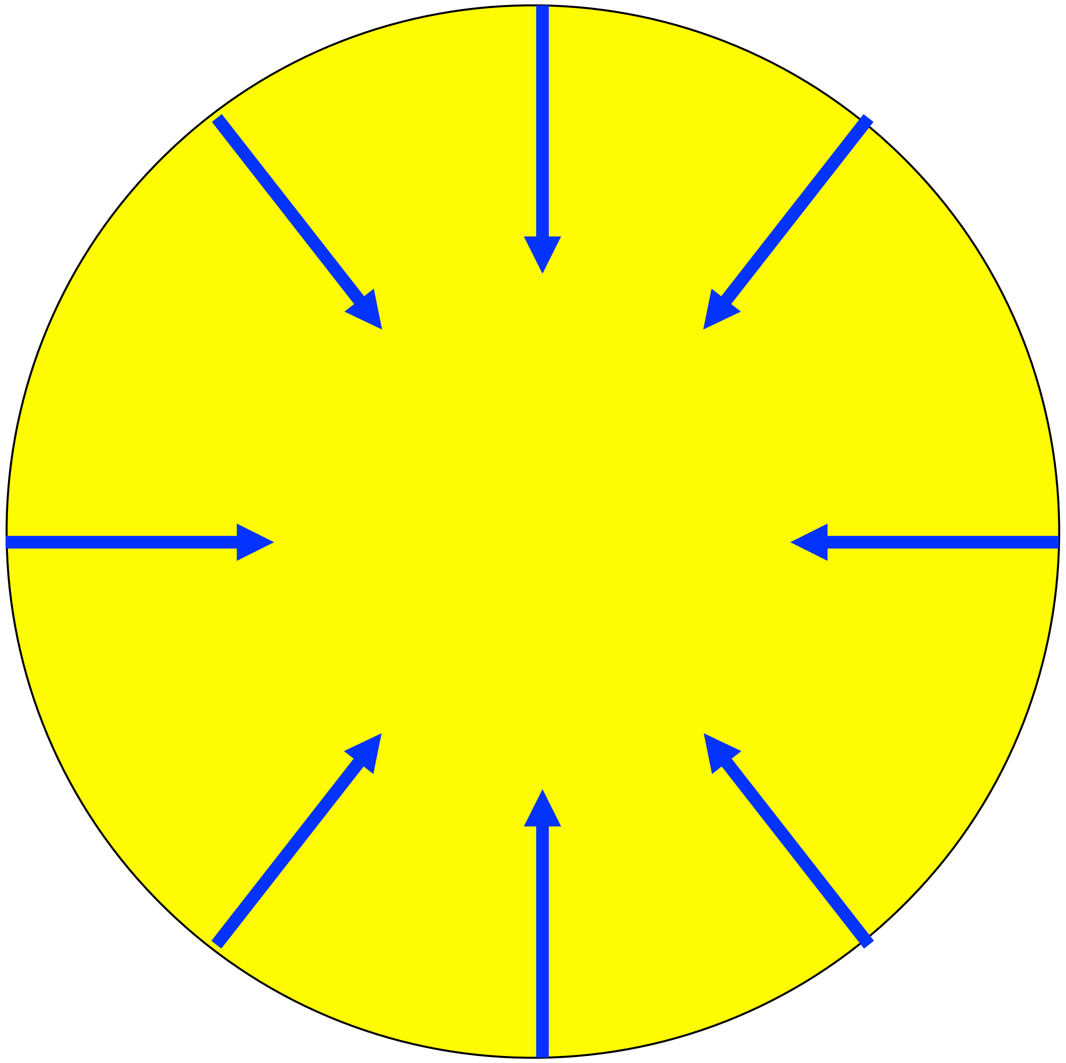


What would the Sun do if...

- pressure force > gravity ?
- pressure force < gravity ?

Lesson?

The Battle of The Solar Titans
Gravity vs Pressure

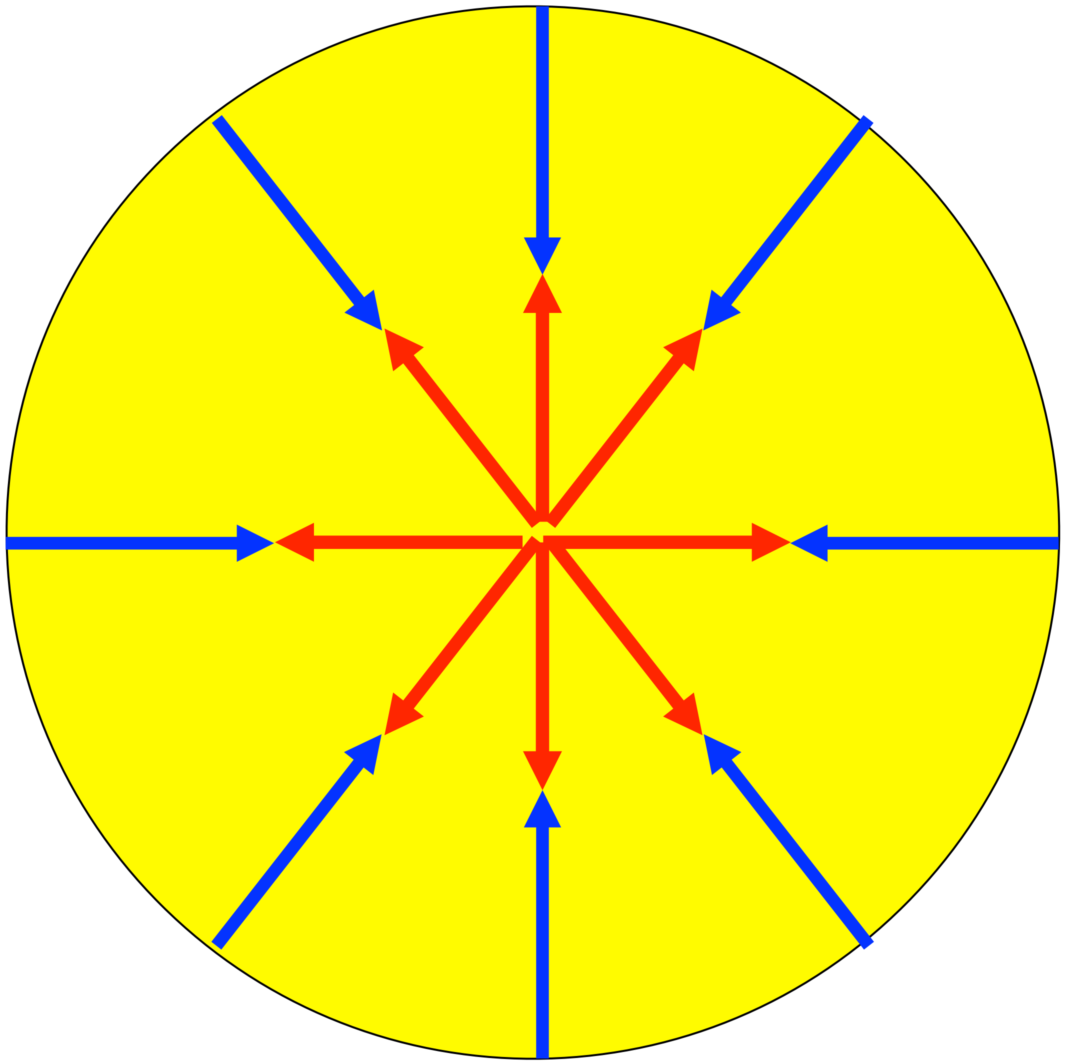


What would the Sun do if...

- **pressure force > gravity ?**
- **pressure force < gravity ?**

Lesson?

The Battle of The Solar Titans
Gravity vs Pressure



What would the Sun do if…

- pressure force > gravity ?
- pressure force < gravity ?

Lesson?

Energy Transport

at solar core: energy transport is via photon diffusion

photon energy density is $\varepsilon = aT^4$

radial flux is $F_r = \varepsilon c/3$

net flux at r: $F_{\rm net} = F(r+\delta r) - F(r) \simeq dF/dr\ \delta r$

diffusion: "stepsize" δr is mfp $\lambda = 1/n\sigma \equiv 1/\rho\kappa$

opacity $\kappa = \sigma n/\rho = \sigma/m$

local luminosity: $\ell = 4\pi r^2 F_{\rm net}$

$$\frac{\ell}{4\pi r^2} = \frac{1}{\rho\kappa}\frac{dF}{dr} = \frac{4acT^3}{3\rho\kappa}\frac{dT}{dr}$$

Energy Generation by Nuke Reactions

put $\rho\varepsilon =$ nuke energy production rate per unit vol

$$\begin{aligned} d\ell &= \rho\varepsilon dV = \rho\varepsilon 4\pi r^2 \, dr \\ \frac{d\ell}{dr} &= 4\pi r^2 \rho\varepsilon \end{aligned}$$

if $q = \langle \sigma_{ab} v \rangle n_a n_b$

$=$ nuke reaction rate per vol for $a + b \rightarrow c + d$

$\rho\varepsilon = Qq$, where energy release $Q = \Delta_a + \Delta_b - \Delta_c - \Delta_d$

Now have differential equations

but still need one more thing to solve them

What's that?

Boundary Conditions

$t_\odot = 4.6$ Gyr
$M_{\text{tot}} = M_\odot = 2.0 \times 10^{33}$ g
$R = R(t_\odot) = R_\odot = 7.0 \times 10^{10}$ cm
$L = L_\odot = 3.8 \times 10^{33}$ erg/s

With these, solve $m(r)$, $\ell(m)$, $T(m)$ (vs time)
for nuke rxns, we will need central ρ_c, T_c

Back of the Envelope

Order of magnitude estimation

$$-\frac{dP}{dr} = \frac{Gm(r)\rho}{r^2}$$

Consider 1-zone Sun:

- rho? T?
- dP/dr? P?

Back of the Envelope

Order of magnitude estimation

$$-\frac{dP}{dr} = \frac{Gm(r)\rho}{r^2}$$

Consider 1-zone Sun:

- rho? T?
- dP/dr? P?

Back of the Envelope

Order of magnitude estimation

$$-\frac{dP}{dr} = \frac{Gm(r)\rho}{r^2}$$

Consider 1-zone Sun:

- rho? T?
- dP/dr? P?

$$\frac{dP}{dR} \sim \frac{P_c}{R}$$
$$\sim \frac{GM\rho}{R^2}$$

ideal gas: $P = \rho kT/m$

$$T_c \sim \frac{(m_p/2)P_c}{\rho k} = \frac{GMm_p}{2kR} \sim 10^7 \text{ K}$$

Back of the Envelope

Order of magnitude estimation

$$-\frac{dP}{dr} = \frac{Gm(r)\rho}{r^2}$$

Consider 1-zone Sun:

- rho? T?
- dP/dr? P?

$$\frac{dP}{dR} \sim \frac{P_c}{R}$$
$$\sim \frac{GM\rho}{R^2}$$

ideal gas: $P = \rho kT/m$

$$T_c \sim \frac{(m_p/2)P_c}{\rho k} = \frac{GMm_p}{2kR} \sim 10^7 \text{ K}$$

why m=mp/2?

Back of the Envelope

Order of magnitude estimation

$$-\frac{dP}{dr} = \frac{Gm(r)\rho}{r^2}$$

Consider 1-zone Sun:

- rho? T?
- dP/dr? P?

$$\frac{dP}{dR} \sim \frac{P_c}{R}$$
$$\sim \frac{GM\rho}{R^2}$$

ideal gas: $P = \rho kT/m$

$$T_c \sim \frac{(m_p/2)P_c}{\rho k} = \frac{GMm_p}{2kR} \sim 10^7 \text{ K}$$

why m=mp/2?

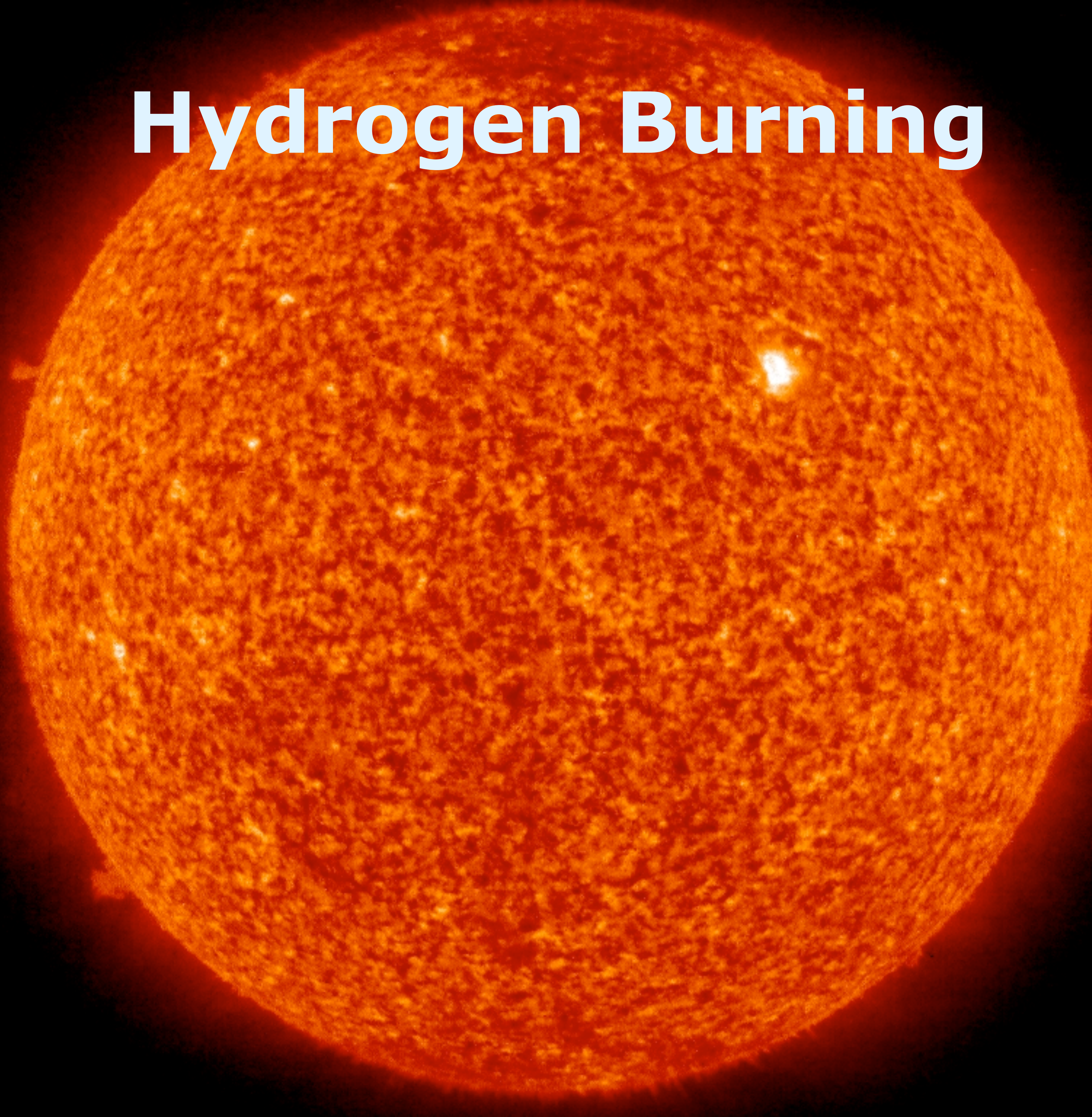
now compare to professional result...

Standard Solar Model (SSM)
Bahcall & Pinsonneault (2000,2004)

conditions at solar center:

$$
\begin{aligned}
T_c &= 1.57 \times 10^7 \text{ K} \\
\rho_c &= 152 \text{ g cm}^{-3} \\
X_c = \left(\frac{\rho_\mathrm{H}}{\rho_\mathrm{B}}\right)_c &= 0.34 \\
Y_c = \left(\frac{\rho_\mathrm{He}}{\rho_\mathrm{B}}\right)_c &= 0.64
\end{aligned}
$$

Hydrogen Burning



Solar Hydrogen Burning: Big Picture

Sun: main sequence, $4p \longrightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e$

Solar Hydrogen Burning: Big Picture

Sun: main sequence, $4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e$

Reaction chains usually begin with

$$p + p \rightarrow d + e^+ + \nu_e \tag{14}$$

Solar Hydrogen Burning: Big Picture

Sun: main sequence, $4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e$

Reaction chains usually begin with

$$p + p \rightarrow d + e^+ + \nu_e \tag{14}$$

weak rxn: slow; then

$$d + p \rightarrow {}^3\text{He} + \gamma \tag{15}$$

Solar Hydrogen Burning: Big Picture

Sun: main sequence, $4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e$

Reaction chains usually begin with

$$p + p \rightarrow d + e^+ + \nu_e \tag{14}$$

weak rxn: slow; then

$$d + p \rightarrow {}^3\text{He} + \gamma \tag{15}$$

Then: 3 branches

Solar Hydrogen Burning: Big Picture

Sun: main sequence, $4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e$

Reaction chains usually begin with

$$p + p \rightarrow d + e^+ + \nu_e \tag{14}$$

weak rxn: slow; then

$$d + p \rightarrow {}^3\text{He} + \gamma \tag{15}$$

Then: 3 branches

PP-I

${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + p + p$

Solar Hydrogen Burning: Big Picture

Sun: main sequence, $4p \to {}^4\text{He} + 2e^+ + 2\nu_e$

Reaction chains usually begin with

$$p + p \to d + e^+ + \nu_e \tag{14}$$

weak rxn: slow; then

$$d + p \to {}^3\text{He} + \gamma \tag{15}$$

Then: 3 branches

PP-I

$${}^3\text{He} + {}^3\text{He} \to {}^4\text{He} + p + p$$

$${}^3\text{He} + {}^4\text{He} \to {}^7\text{Be} + \gamma$$

PP-II

$${}^7\text{Be} + e \to {}^7\text{Li} + \nu_e$$
$${}^7\text{Li} + p \to {}^4\text{He} + {}^4\text{He}$$

PP-III

$${}^7\text{Be} + p \to {}^8\text{B} + \gamma$$
$${}^8\text{B} \to {}^8\text{Be} + e^+ + \nu_e$$
$${}^8\text{Be} \to {}^4\text{He} + {}^4\text{He}$$

The PP-II and PP-III Chains

$$^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$$

PP-II

$$^{7}\mathrm{Be} + e \rightarrow {}^{7}\mathrm{Li} + \nu_e$$
$$^{7}\mathrm{Li} + p \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

PP-III

$$^{7}\mathrm{Be} + p \rightarrow {}^{8}\mathrm{B} + \gamma$$
$$^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be} + e^{+} + \nu_e$$
$$^{8}\mathrm{Be} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

Q: what sets relative importance of PP-II vs III?

The PP-II and PP-III Chains

$$^{3}\text{He} + {}^{4}\text{He} \rightarrow {}^{7}\text{Be} + \gamma$$

PP-II	PP-III
$^{7}\text{Be} + e \rightarrow {}^{7}\text{Li} + \nu_e$	$^{7}\text{Be} + p \rightarrow {}^{8}\text{B} + \gamma$
$^{7}\text{Li} + p \rightarrow {}^{4}\text{He} + {}^{4}\text{He}$	$^{8}\text{B} \rightarrow {}^{8}\text{Be} + e^{+} + \nu_e$
	$^{8}\text{Be} \rightarrow {}^{4}\text{He} + {}^{4}\text{He}$

Q: what sets relative importance of PP-II vs III?

Other main pp chains: different ^{3}He fate

^{7}Be branching key:

e capture rate $\sim 1000\times$ p capture rate

- ^{7}Be: 15% of ν production
- ^{8}B $\sim 0.02\%$ of ν production

The CNO Cycle

pre-existing C, N, O act as $4p \rightarrow {}^4\mathrm{He}$ *catalyst*

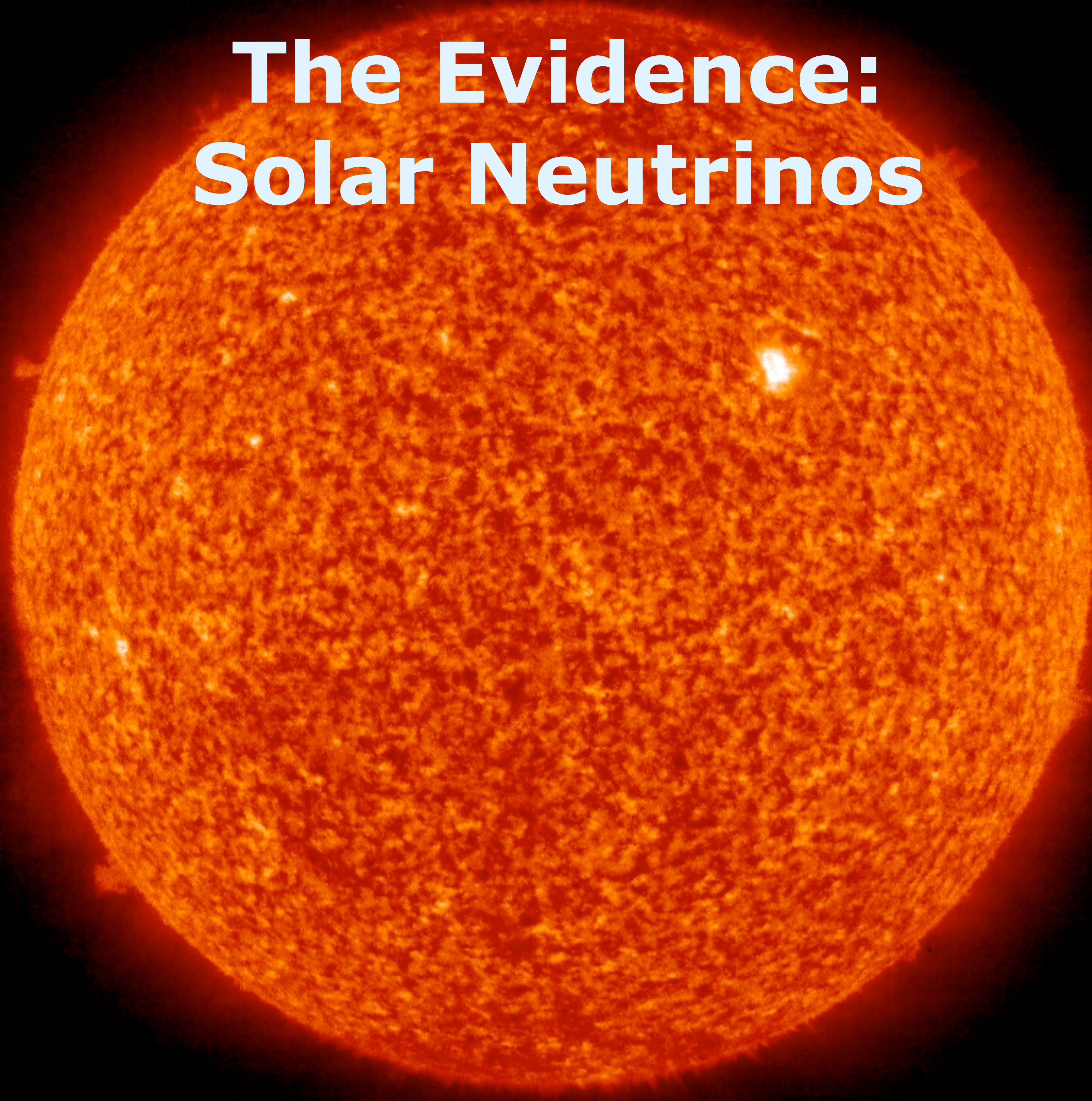
$$
\begin{array}{ccccc}
{}^{12}\mathrm{C} & \overset{(p,\gamma)}{\longrightarrow} & {}^{13}\mathrm{N} & \overset{e^+\nu_e}{\longrightarrow} & {}^{13}\mathrm{C} \\
(p,\alpha)\uparrow & & & & \downarrow(p,\gamma) \\
{}^{15}\mathrm{N} & \overset{e^+\nu_e}{\longleftarrow} & {}^{15}\mathrm{O} & \overset{(p,\gamma)}{\longleftarrow} & {}^{14}\mathrm{N}
\end{array}
$$

Coulomb barriers high ($Z = 6, 7, 8$): *need high* T_c to

$\Rightarrow$ CNO cycle minor in Sun (CNO $\rightarrow$1.6% $L_\odot$)

but main H-burner for $M \gtrsim 1.5 M_\odot$

The Evidence:
Solar Neutrinos



Solar Neutrino Production

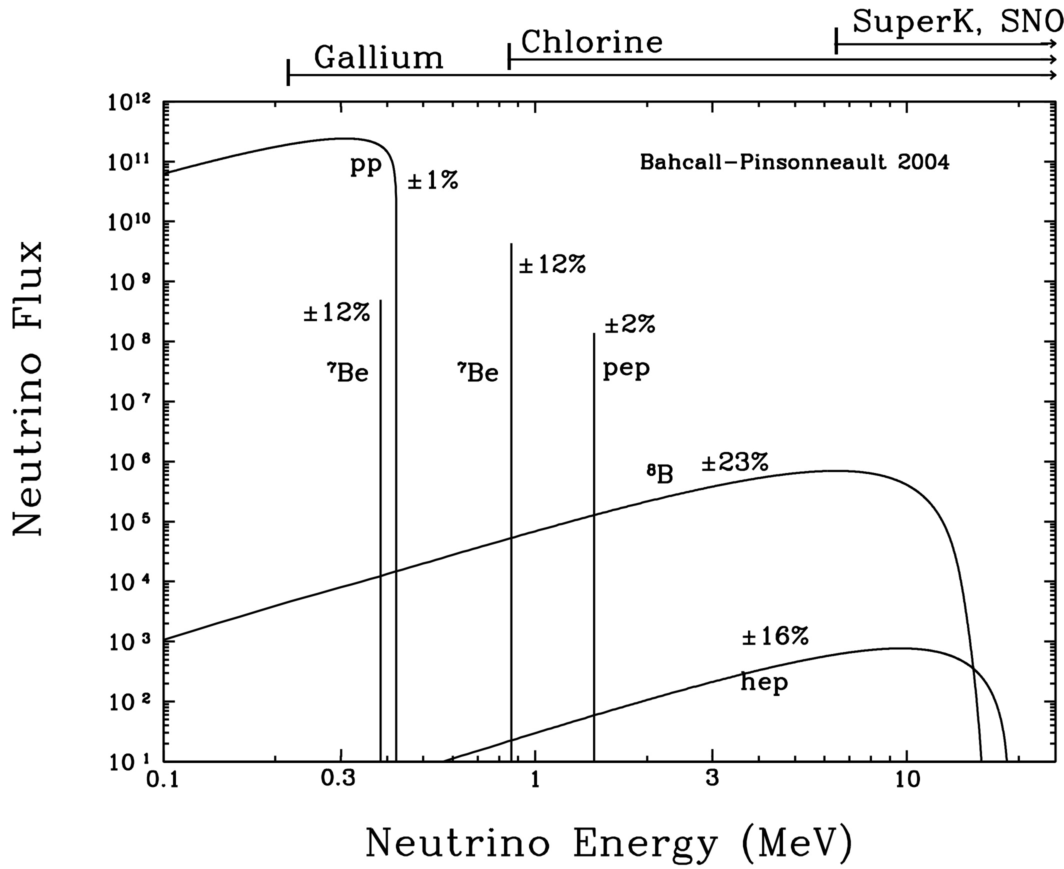
Rxn	$E_{\nu,\mathrm{max}} = Q$	$\langle E_\nu \rangle$	Total SSM Flux Φ_ν (10^{10} ν cm^{-2} s^{-1})
$pp \to de\nu$	0.420 MeV	0.265 MeV	6.0
^{7}Be $e \to {}^{7}$Li ν	lines: ^{7}Li^{gs} = 0.861 MeV; ^{7}Li* = 0.383 MeV		0.47
^{8}B $\to {}^{8}$Be e ν	17.98 MeV	9.63 MeV	5.8×10^{-4}

Q: Why are the ^{7}Be *neutrinos monoenergetic?*

Solar Neutrino Production

Rxn	$E_{\nu,\mathrm{max}} = Q$	$\langle E_\nu \rangle$	Total SSM Flux Φ_ν (10^{10} ν cm^{-2} s^{-1})
$pp \to de\nu$	0.420 MeV	0.265 MeV	6.0
^{7}Be $e \to {}^7$Li ν	lines: ^{7}Li^{gs} = 0.861 MeV; ^{7}Li* = 0.383 MeV		0.47
^{8}B $\to {}^8$Be e ν	17.98 MeV	9.63 MeV	5.8×10^{-4}

Q: Why are the ^{7}Be neutrinos monoenergetic?



Solar Neutrino Production

Rxn	$E_{\nu,\text{max}} = Q$	$\langle E_\nu \rangle$	Total SSM Flux Φ_ν (10^{10} ν cm^{-2} s^{-1})
$pp \to de\nu$	0.420 MeV	0.265 MeV	6.0
^{7}Be $e \to {}^7$Li ν	lines: ^{7}Li^{gs} = 0.861 MeV; ^{7}Li* = 0.383 MeV		0.47
^{8}B$\to{}^8$Be e ν	17.98 MeV	9.63 MeV	5.8×10^{-4}

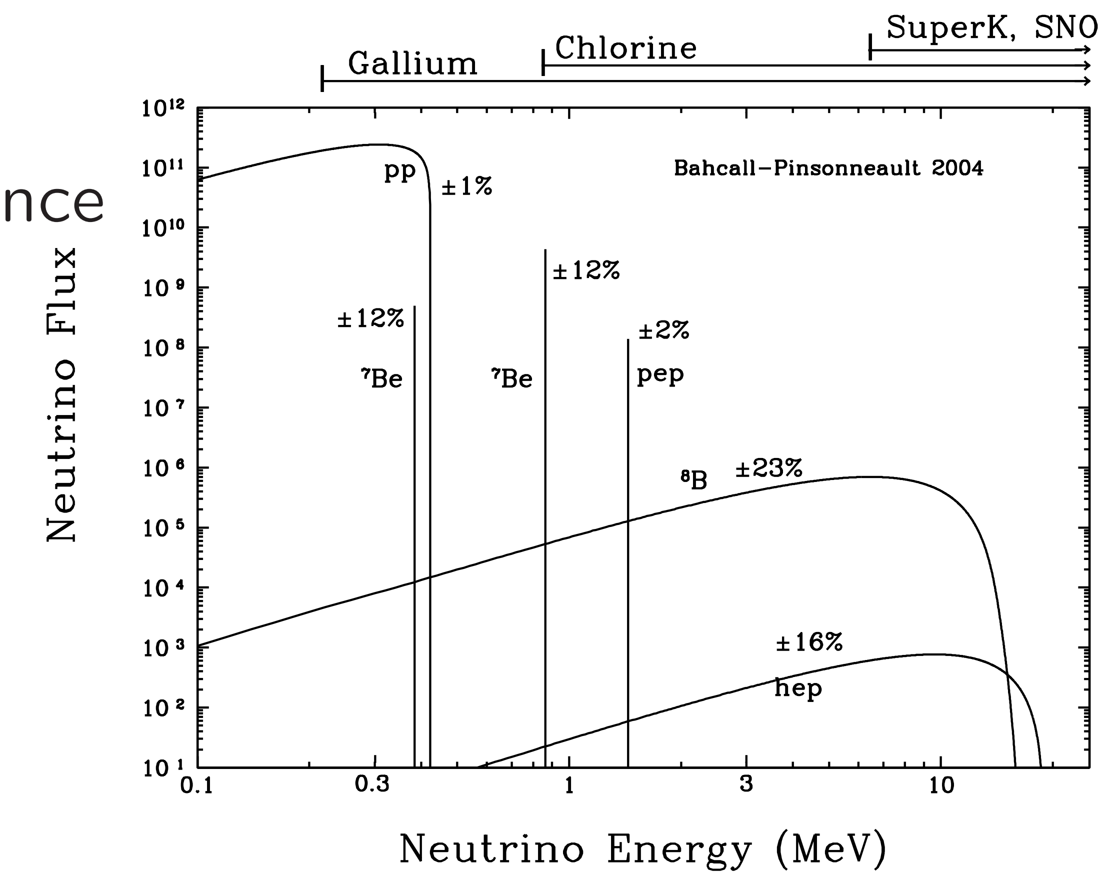
Q: Why are the ^{7}Be neutrinos monoenergetic?

pp neutrinos largest flux, but low energies

^{7}Be neutrinos monoenergetic, strong $\sim T_c^8$ dependence

^{8}B neutrinos continuum, ultrastrong $\sim T_c^{20}$ dep

What should this mean for production vs radius?



Solar Neutrino Production

Rxn	$E_{\nu,\text{max}} = Q$	$\langle E_\nu \rangle$	Total SSM Flux Φ_ν (10^{10} ν cm^{-2} s^{-1})
$pp \to de\nu$	0.420 MeV	0.265 MeV	6.0
^{7}Be $e \to {}^7$Li ν	lines: ^{7}Li^{gs} = 0.861 MeV; ^{7}Li* = 0.383 MeV		0.47
^{8}B $\to {}^8$Be e ν	17.98 MeV	9.63 MeV	5.8×10^{-4}

Q: Why are the ^{7}Be neutrinos monoenergetic?

pp neutrinos largest flux, but low energies

^{7}Be neutrinos monoenergetic, strong $\sim T_c^8$ dependence

^{8}B neutrinos continuum, ultrastrong $\sim T_c^{20}$ dep

What should this mean for production vs radius?