Make it: Stars as BSM factories

why stars (and their remnants)?

↳ temp ~ 10 keV (stars) or ~ 1 MeV (SNe) implies possibility of light particle production

↳ volume & age → rare processes that couldn't be seen elsewhere (e.g. colliders)

↳ observability / luminosity & ubiquity (stars) or proximity (sun)

Will rare & light physics even have any impact? (overwhelmed by SM processes? No!)

$M_\odot \sim 10^{30}$ kg $\quad R_\odot \sim 10^{9}$ m $\Rightarrow \bar{\rho}_\odot \sim 1 \text{ g/cm}^3$ (similar to H_2O!)

most mass is in protons (~10% neutrons)

$\Rightarrow n_p \sim 10^{24}/\text{cm}^3$ & same for electrons (charge neutral)

meanwhile, Thompson σ_T is $\sim 10^{-24} \text{ cm}^2$

⇒ rate of scattering of photons on electrons

$\Gamma \sim n\sigma v \sim 10^{10}/\text{second} \Rightarrow$ photon scatters every 10^{-10} s traveling $\ell_{mfp} \sim 1 \text{ cm} \ll R_\odot$

⇒ photons need to random walk out! $\Delta r \sim \sqrt{\underset{\nwarrow \text{steps}}{N}}\,\ell_{mfp}$

here $N \sim 10^{21}$ steps! takes $\sim 10^{11}$ s or $\sim 10^{4}$ years

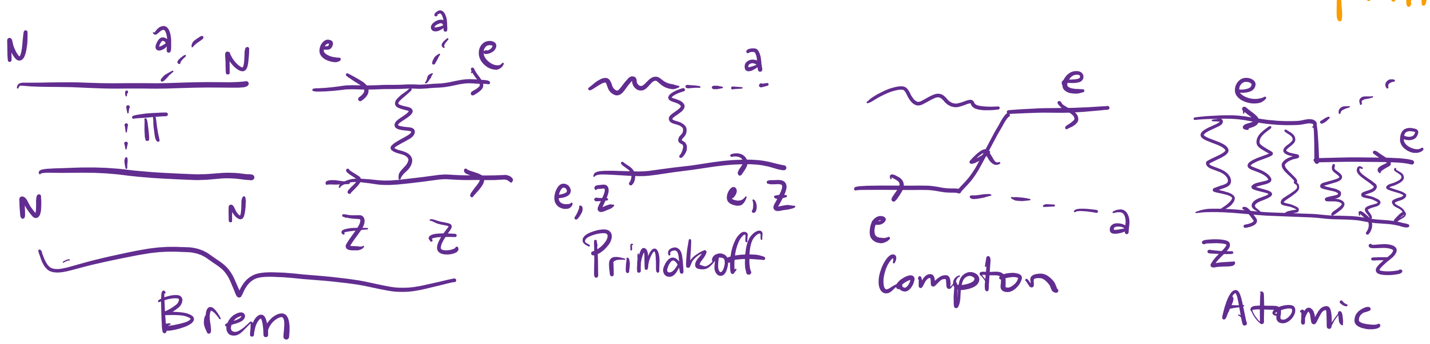
$R_\odot / c \sim 1$ second

∴ SM is slow at transporting energy in stars

(exception - neutrinos! BSM-neutrino degeneracy possible, possible differences in temp/density dependence are subtle)

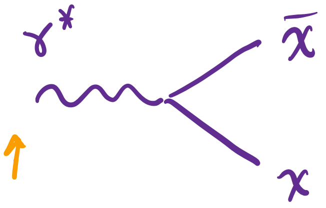
Meanwhile, there are BSM mechanisms for producing particles with long mean free path, including:

↳ Axions (and ALPs) $\mathcal{L} \supset \underbrace{\frac{i g_{aNN}}{2m_N}\partial_\mu a(\bar{N}\gamma^\mu\gamma_5 N)}_{\text{nucleophilic}} + \underbrace{\frac{i g_{aee}}{2m_e}\partial_\mu a(\bar{e}\gamma^\mu\gamma_5 e)}_{\text{electrophilic}} + \underbrace{g_{a\gamma\gamma} a(\vec{E}\cdot\vec{B})}_{\text{photo-philic}}$



↳ Millicharged particles (including neutrinos) $\mathcal{L} \supset Q\bar{\chi}\gamma^\mu\chi A_\mu$

*nothing 10^{-3} about this, also includes possible dark photon mediators



in a plasma photons have "mass" & can decay! Need to care about thermal field theory...

[SM analog:

has been observed in stars!]

↳ dark photons (e.g. kinetically mixed)

$$\mathcal{L} \supset -\frac{1}{4}FF - \frac{1}{4}F'F' + \frac{\varepsilon}{2}FF' + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$$

Can perform field redefinition to rotate away kinetic mixing

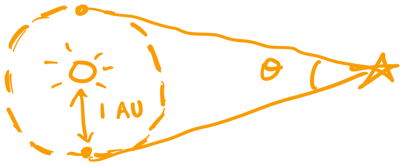
Stückelberg mass (Higgs possible too)

transition resonant when $m_{A'}$ = "m_A"
(emission peaked @ stellar radius)

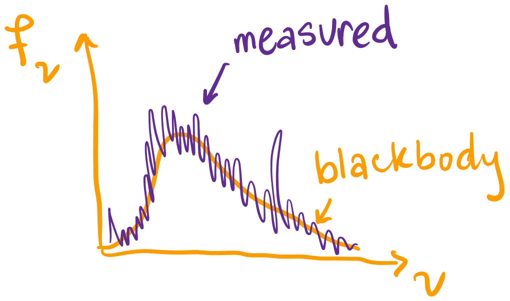
computing emission rate is nontrivial & involves a fair bit of thermal field theory... perhaps a future TASI lecture topic ☺

So what can we even observe about stars?

↳ parallax (distance)



↳ spectral flux density (energy/time/area/frequency)



→ integrate over ν to get total flux & combine w/ distance → Luminosity (energy/time)

→ effective blackbody temp T_* ← surface temp!

→ $$\underbrace{\frac{\pi^2 T_*^4}{60}}_{\text{flux coming out of blackbody}} = \frac{\text{Luminosity}}{4\pi r_*^2}$$ ← stellar radius

(can also get directly for eclipsing binaries)

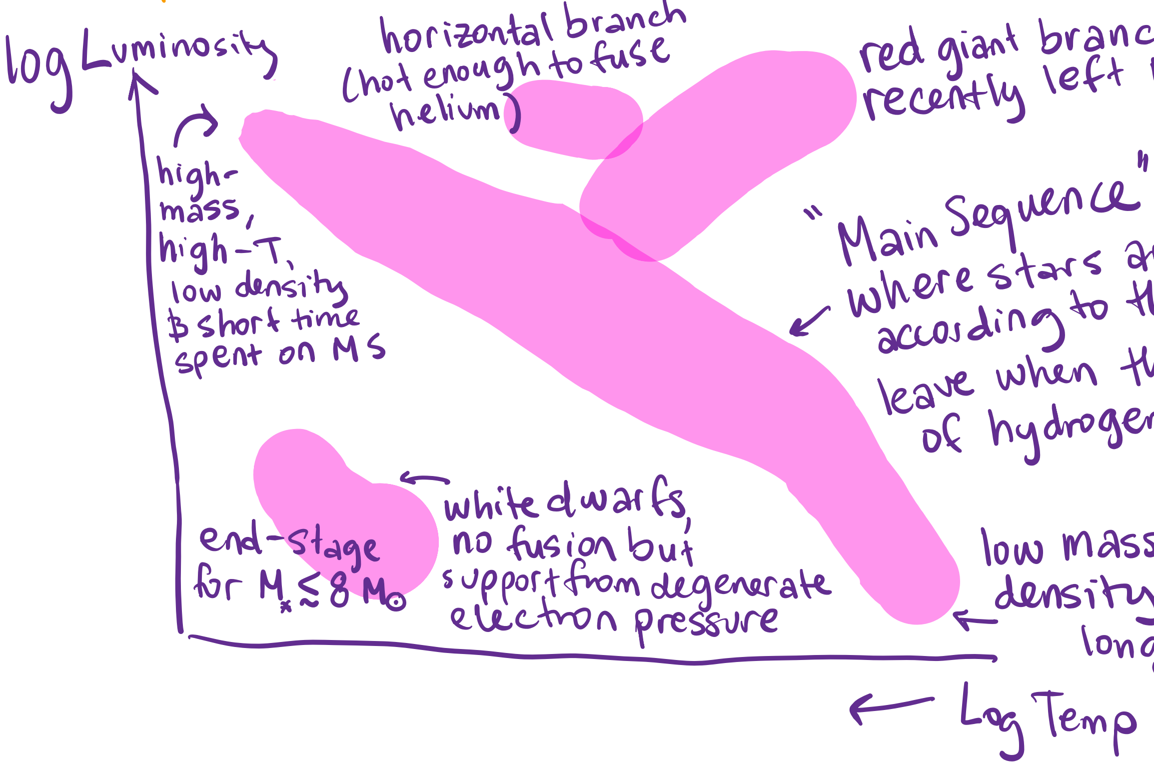
↳ mass (stellar binaries on Keplerian orbits)

- orbital period
- semi-major axes & orbital inclination (astrometric binary)
- velocities (spectroscopic or eclipsing binary)
- stellar radii (eclipsing binary)

↳ sound speed $c_s(r)$ from asteroseismology (e.g. Kepler)

Intrinsic properties of stars are correlated! (Hertzsprung-Russell)

not depicted: supernovae, neutron stars, black holes



horizontal branch (not enough to fuse helium)

red giant branch of stars that recently left MS

high-mass, high-T, low density & short time spent on MS

"Main Sequence" (MS) where stars are born according to their mass leave when they run out of hydrogen in core

end-stage for $M_* \lesssim 8 M_\odot$

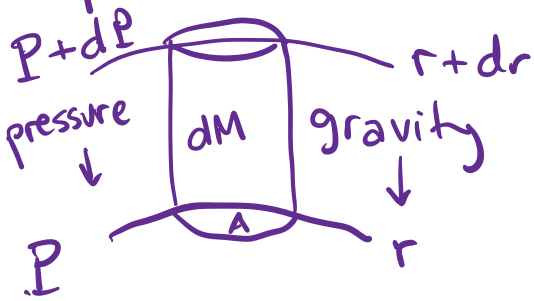
white dwarfs, no fusion but support from degenerate electron pressure

low mass, low temp, high density, stay on MS longest

How will BSM energy transport influence stars?

Need to understand governing dynamics... (Vogt-Russell uniqueness once mass & composition specified)

★ pressure balance



$$dM = \rho\, dV = \rho A\, dr$$

$$M_{enc.} = \int_0^r 4\pi r'^2 dr' \rho(r')$$

$$\vec{F}_P = -A\, dP\, \hat{r}$$

$$\vec{F}_{grav} = -\frac{GM_{enc.}\, dM}{r^2}\hat{r}$$

$$\Rightarrow \underset{\uparrow}{\frac{d^2r}{dt^2}} = -\frac{1}{\rho(r)}\frac{dP(r)}{dr} - \frac{GM_{enc.}(r)}{r^2}$$

ignore for stable stars in "hydrostatic equilibrium"

sources of pressure: $P = \underset{\nearrow}{nk_BT} + \underset{\uparrow}{\frac{\pi^2}{45}T^4} + \begin{cases} \# n^{5/3}/m_e & p_F \ll m_e \\ \# n^{4/3} & p_F \gg m_e \end{cases}$

ideal gas MS

radiation pressure matters in high-mass MS

↖ electron degeneracy in WD & HB core

★ energetics (luminosity)

$$\frac{dL}{dr} = 4\pi r^2 \rho(r)\, \varepsilon(r)$$

↖ power generated

↖ energy production rate per unit mass

$$\varepsilon_{tot} = \underset{\uparrow}{\varepsilon_{nuc.}} + \underset{\uparrow}{\varepsilon_{grav.}} + \varepsilon_{BSM}$$

↖ what we want to look for

reactions (including neutrino energy loss)

energy source/sink from contraction/expansion

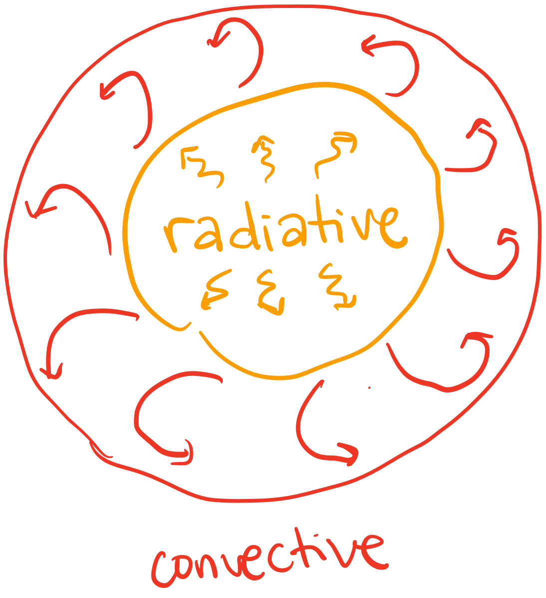
regarding $\varepsilon_{grav.}$ — virial theorem $\frac{1}{2}\frac{d^2I}{dt^2} = 2K + U$

in equilibrium $K = -\frac{U}{2}$ $E_{tot} = K + U = \frac{U}{2} = -K < 0$

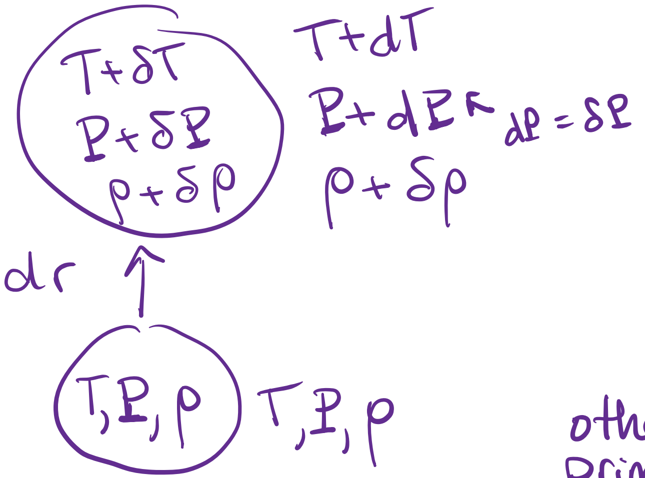
so energy loss $E_{tot}\downarrow \Rightarrow K\uparrow \Rightarrow T\uparrow$ (not stellar cooling!)

These are global considerations but what about local energy transport?

↳ conduction (mainly relevant for NS & WD)
↳ radiative diffusion (always active, not efficient)
↳ convection (efficient, conditions not always right)
(also affects composition through dredge-up effects)



Many stars have a mix of radiative & convective depending on conditions... For convection to occur, ask whether chunk of plasma moving upwards will float or sink



challenge: show that for adiabatic expansion with

$$P \sim \rho^{\underset{\text{adiabatic index}}{\gamma}}$$

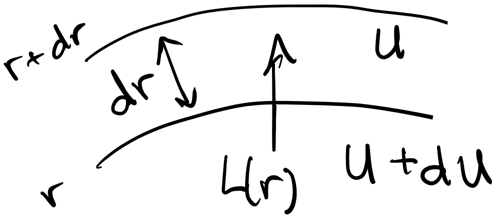
convection occurs if

$$\frac{dT}{dr} \leq \frac{(\gamma-1)}{\gamma}\frac{T}{P}\frac{dP}{dr}$$

otherwise, radiative transport is the primary mode of energy transport

Assuming local thermal equilibrium, $u = \frac{\pi^2}{15}T^4$ ← energy density

so $\frac{du}{dr} = \frac{du}{dT}\frac{dT}{dr} = \frac{4\pi^2 T^3}{15}\frac{dT}{dr}$



$$L(r) = -\underset{\substack{\uparrow \\ \langle\cos^2\theta\rangle \\ \text{relative to } \hat{r}}}{\frac{1}{3}} \underbrace{4\pi r^2 dr}_{\text{Volume of shell}} \cdot \underbrace{du}_{\text{diff. energy density}} \Big/ \left[\underset{\substack{\uparrow \\ \text{N steps}}}{\left(\frac{dr}{\ell_{mfp}}\right)^2} \cdot \underset{\substack{\uparrow \\ \text{time per step}}}{\frac{\ell_{mfp}}{c}} \right]$$

$$\ell_{mfp} = \frac{1}{\underset{\substack{\uparrow \\ \text{for photons,} \\ \text{Thomson scattering}}}{n\sigma}} \quad \text{so} \quad \frac{dT}{dr} = -\frac{45\, L(r)\, n(r)\, \sigma}{16\pi^3 r^2 T^3}$$

This was a lot... TL;DR is that BSM particles with long ℓ_{mfp} can get emitted and change ε

$$\begin{tikzcd}
\text{change } \varepsilon \arrow[r] & \text{change } \frac{dL}{dr} \arrow[r] & \text{change } \frac{dT}{dr} \arrow[r] \arrow[l, bend left] \arrow[ll, bend left] & \text{change } \frac{dP}{dr} \arrow[r] \arrow[l, bend left] & \text{change } \rho \arrow[ll, bend left] \arrow[lll, bend left] \arrow[llll, bend left]
\end{tikzcd}$$

- T-dependent or density-dependent BSM or nuclear processes
- gravitational energy storage/release

this is a headache... and we didn't even go beyond the spherical cow description... put it on a computer! (MESA, GARSTEC) This is especially true once stars leave MS (not really in hydrostatic equilibrium, new nuclear processes turn on...)

Story time:

Stars run out of H in core → loss of lumi/temp/pressure gradient → contraction due to lack of support → temp. increases (virial theorem) → outer layers previously at too low of a temp. for fusion now have fusion in a shell → overall lumi increases (more volume in shell)

→ shell gains new source of pressure & puffs up → radius of star increases → T_{eff} decreases since $T_{eff}^4 \sim \frac{L}{r_*^2}$ ← dominates over L

⇒ red giant branch!

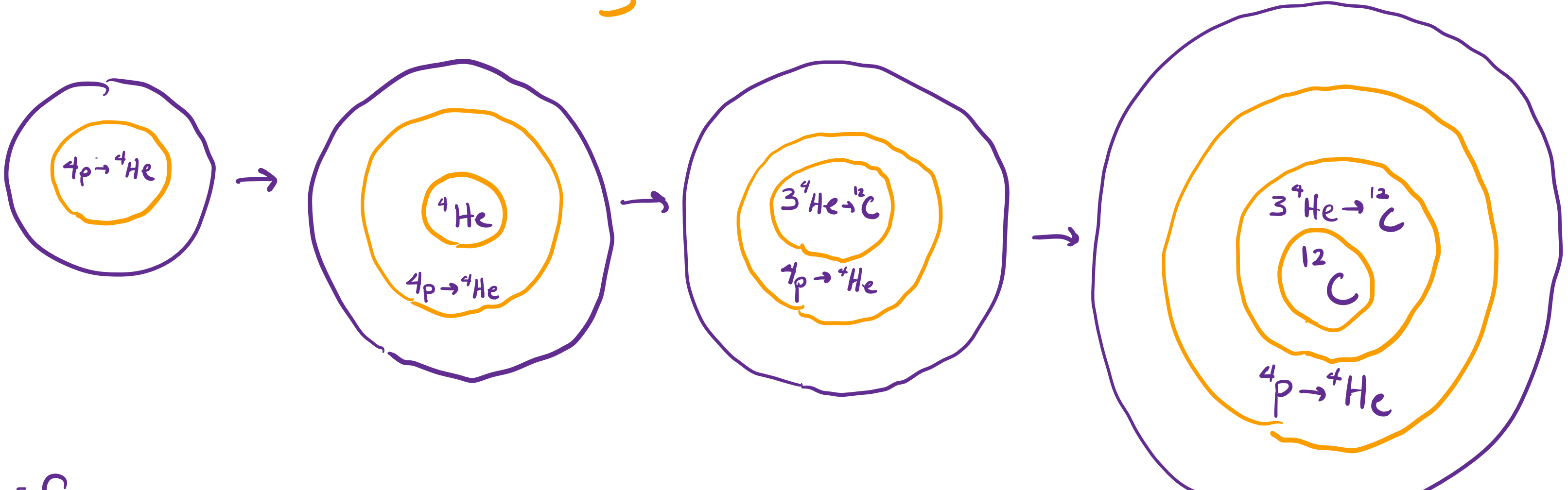
core continues to contract & heat up until eventually we get to the temp where triple-α $3\,{}^4He \to {}^{12}C$ becomes resonant "tip of the red giant branch"

Then we go to "helium burning / horizontal branch"

} * influenced by BSM!

Eventually we run out of helium in core so qualitatively a similar thing happens that gives RGB except now we have "double shell burning" on the "asymptotic giant branch"

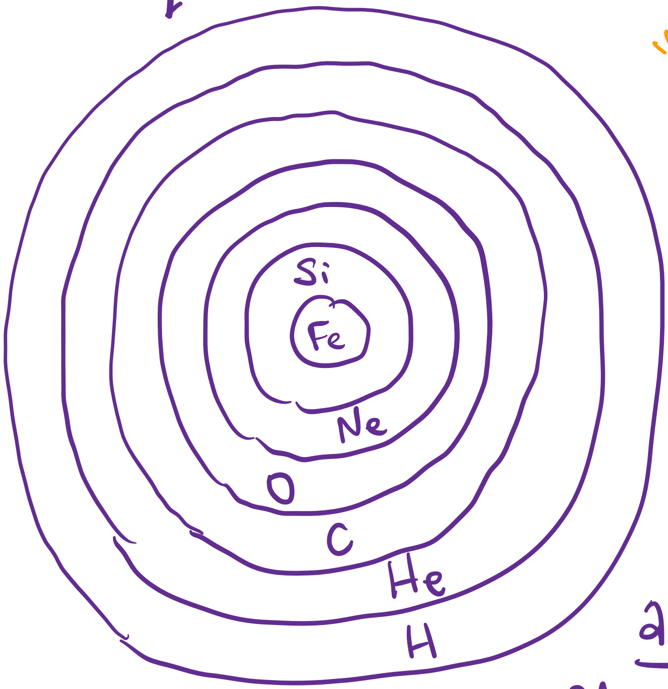
This whole time, due to puffed layers we have low surface gravity → mass loss → $r_* \downarrow$ → $T_{eff} \uparrow$ causing a "planetary nebula"



if $M_* < 8 M_\odot$, core virial temp doesn't get hot enough to ignite carbon & contraction of core occurs until quantum degeneracy pressure gives us "white dwarf"

* slow to cool, suceptible to BSM!

if $M_* \gtrsim 8 M_\odot$, we get a repeat of giant branch for subsequent nuclear reactions



"onion skin" stops w/ iron, the most tightly bound atomic nucleus (costs energy to fuse to heavier elements)

super high $T \rightarrow n_\gamma \sim T^3$ is high $\rightarrow$ photons in high energy tail can break Fe → uses up energy

also $e^- + p^+ \rightarrow n + \nu_e$ becomes efficient
ν_e can leave & carry away energy

Both of these energy loss channels mean loss of support → collapse → higher densities & temp. → more "neutronization" and iron photodissociation → (repeat cycle)

eventually we get "core collapse supernova"
if core mass $\lesssim$ 2-3 $M_\odot$ we get a neutron star supported by neutron degeneracy, otherwise a black hole (probably accompanied by soft gamma ray burst)

99% of energy emerging from CC SNe is in neutrinos due to their long mfp... ripe for BSM!