LECTURE II:

How Studying the Future Evolution of the Cosmos Affects our Understanding of the Universe

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Five Ages of the Universe

- Primordial Era $n < 6$
- Stelliferous Era $n = 6 - 14$
- Degenerate Era $n = 14 - 40$
- Black Hole Era $n = 40 - 100$
- Dark Era $n > 100$

$$\textit{where} \quad n \quad \textit{defined by} \quad t = 10^n \; \textit{years}$$

The Primordial Era

- The `Big Bang Moment'
- Inflation
- Matter > Antimatter
- Quarks --- protons & neutrons
- Dark matter abundances are frozen
- Nuclear synthesis of the light elements
- Cosmic Microwave Background
- Universe continues to expand

The Stelliferous Era

- Stars dominate energy production
- Lowest mass stars increasingly important
- Biosphere ends in 3.5 Gyr
- Earth as a planet ends in 7 Gyr
- Odds of Earth escape (capture) are about one part in 10^5 (3x10^6)
- Most liquid water found inside frozen planets
- Star formation and stellar evolution end near (by) cosmological decade n = 14

The Degenerate Era

The Black Hole Era

- Black holes are brightest stellar objects
- Generation of energy via Hawking radiation
- Every galaxy contributes one supermassive and about one million stellar black holes
- Black hole lifetime is mass dependent:

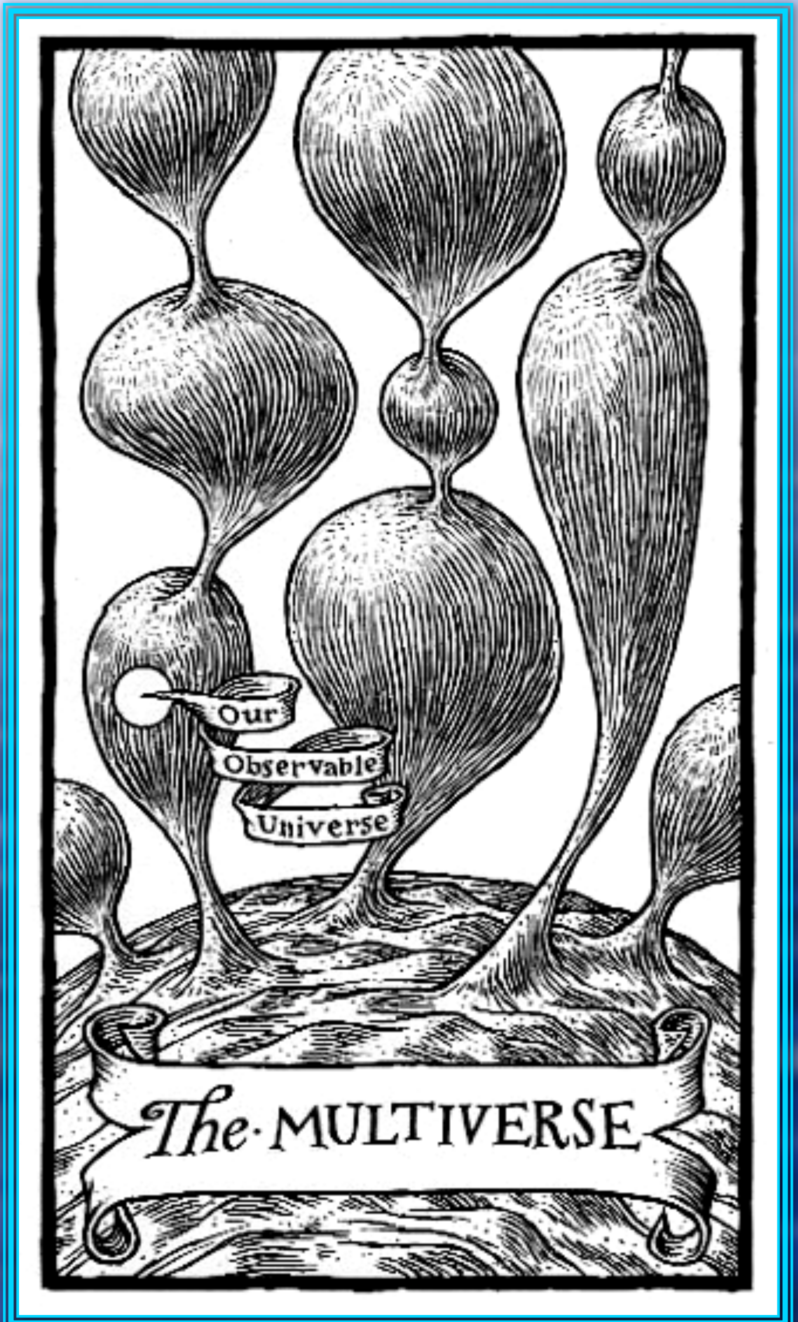
One solar mass:	n=65
Million solar mass:	n=83
Galactic mass:	n=98
Horizon mass:	n=131

$$t_T \propto M_{bh}^3$$

The Dark Era

- No stellar objects of any kind
- Inventory of elementary particles: electrons, positrons, neutrinos, & photons
- Positronium formation and decay
- Low level annihilation
- Vacuum tunneling events?

Ashes to ashes,
Dust to dust,
Particles to particles,
Our universe will
evolve through a
a one-way time-line.
Other universes can
live through their own
time-lines, as parts of
The MULTIVERSE.



Lecture I Summary

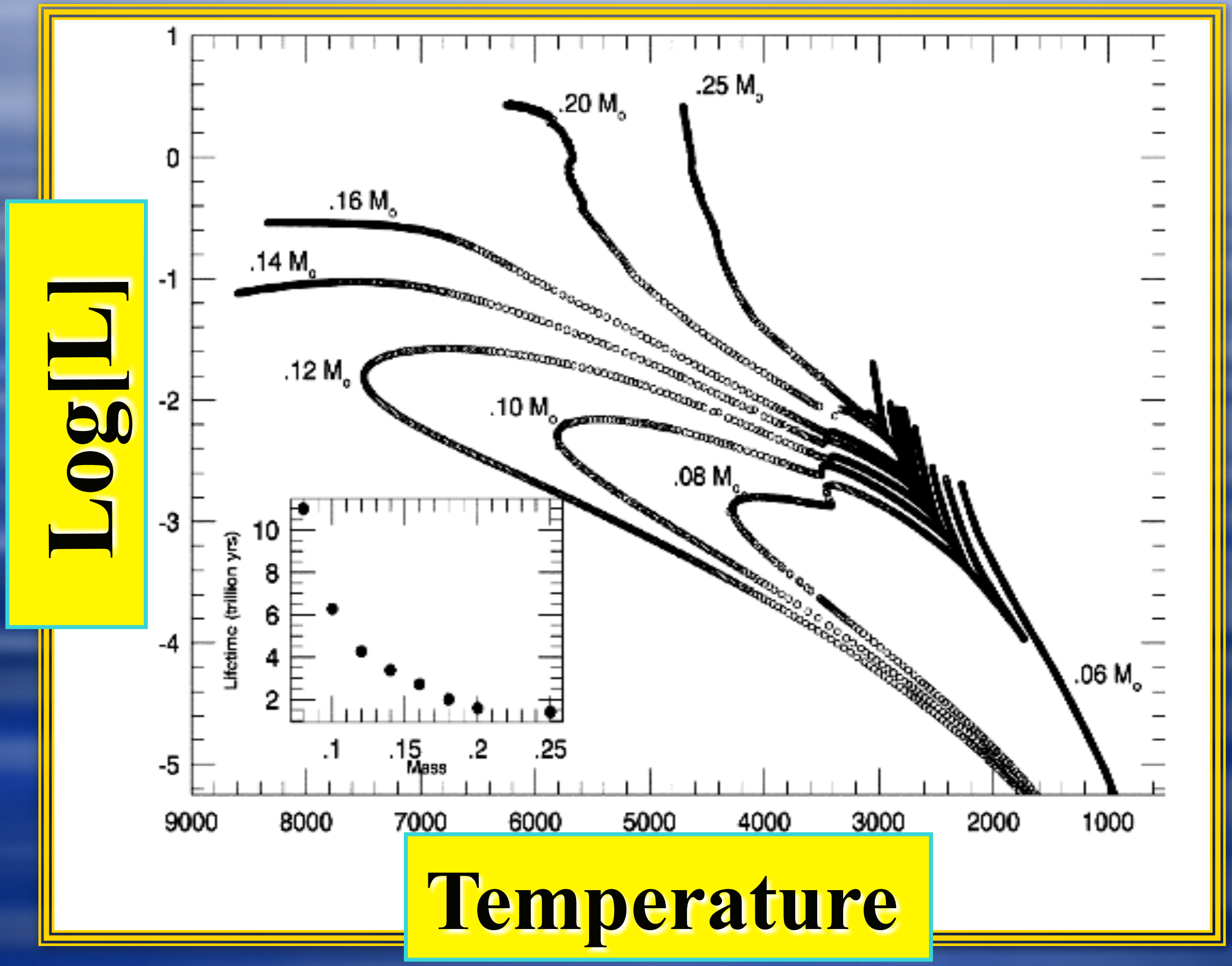
- Our current understanding of the laws of physics and astrophysics allow us to construct a working picture of the future.
- Studying physical processes of the future provides insight into current astrophysical problems, e.g., the reason for red giants, structure of dark matter halos, dynamical scattering problems, defining the masses of galaxies, etc.

Outline for Lecture II

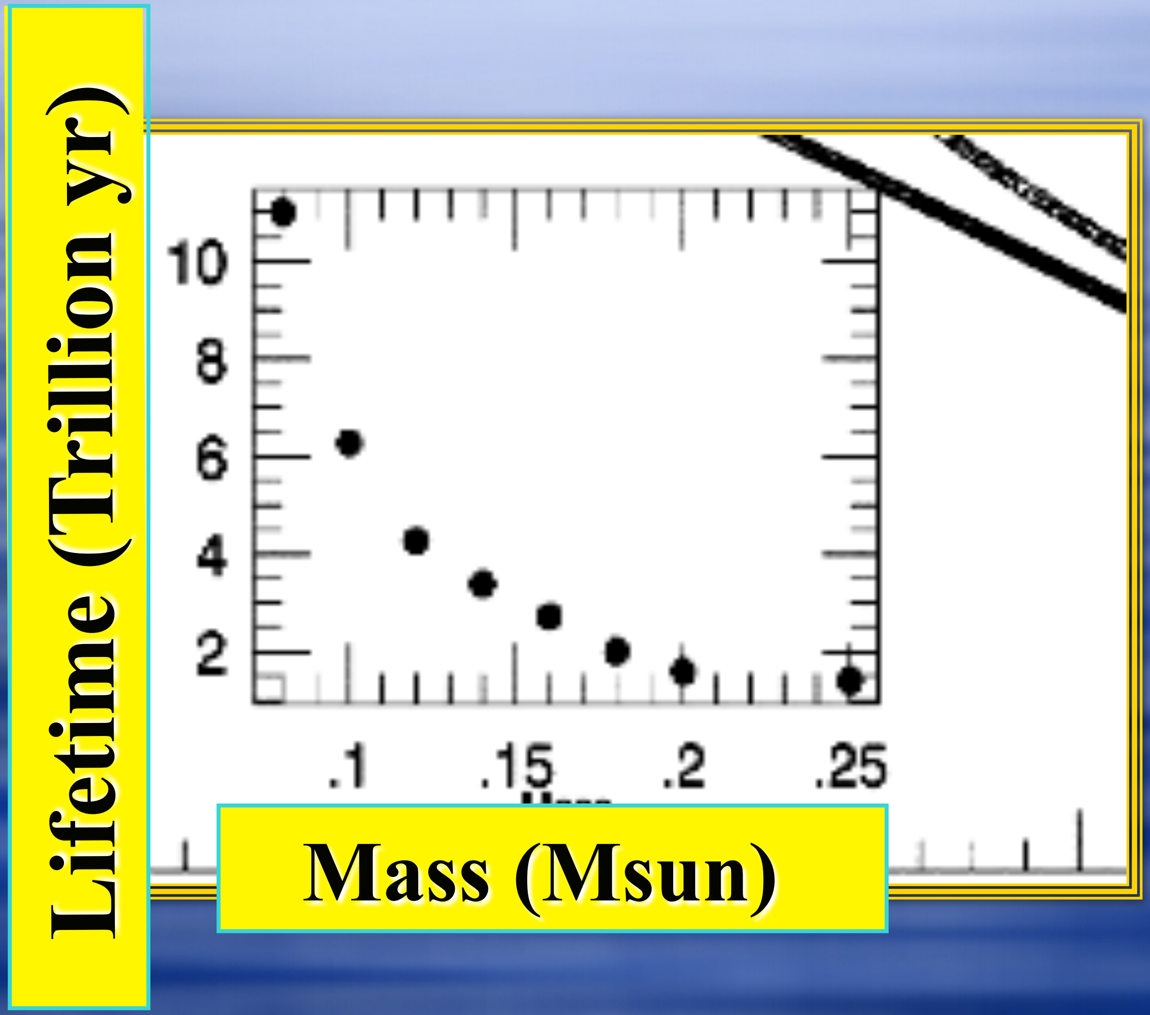
- Why stars become red giants
- How to define the mass of a galaxy
- The asymptotic form of galactic halos
- How common are stars in alternate universes (other parts of the multiverse)
- Time-varying constants of nature
- Even longer term astrophysical processes
- Discussion issues

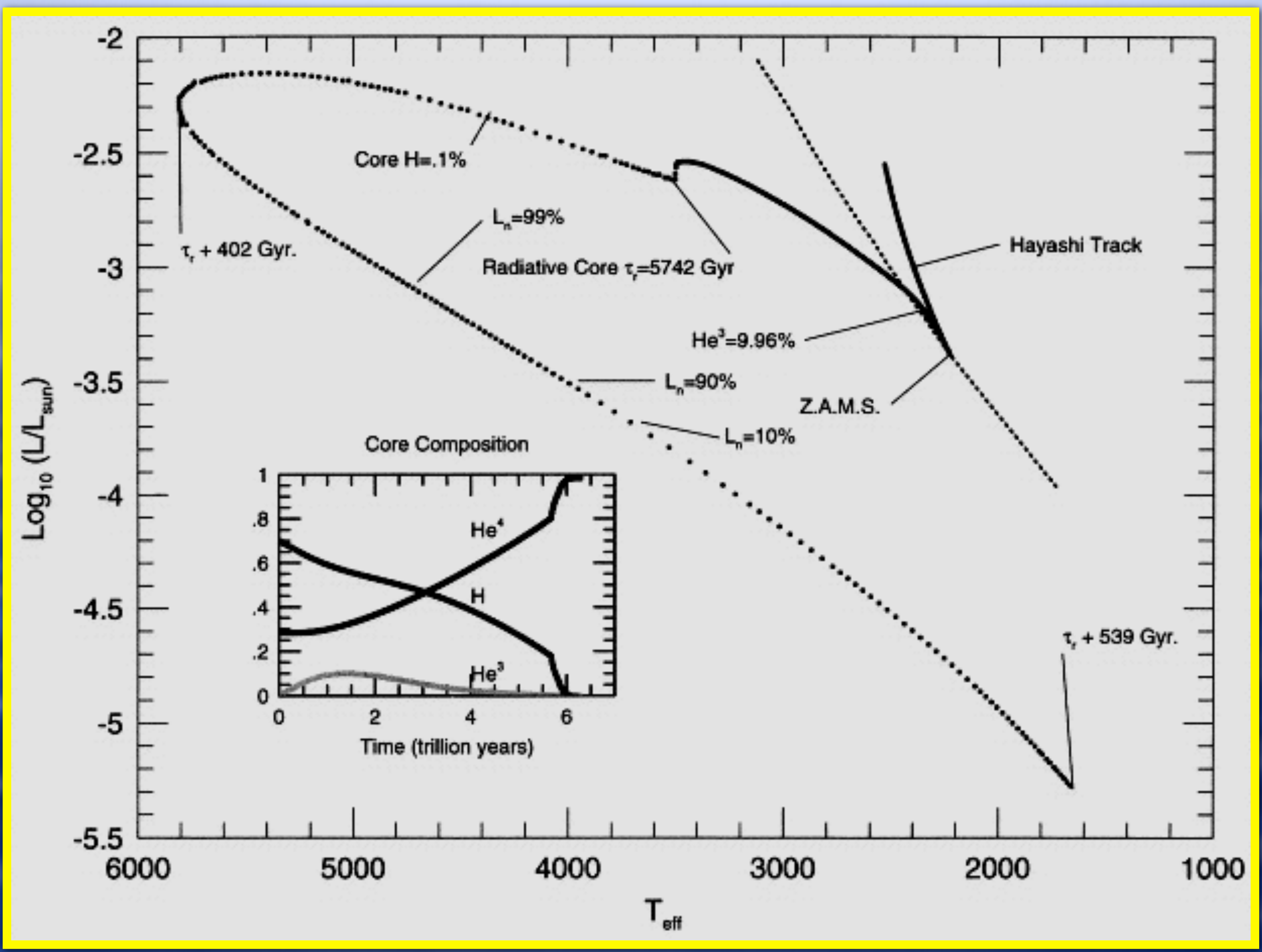
Why do stars become RED GIANTS ?

Long term Evolution of Red Dwarfs



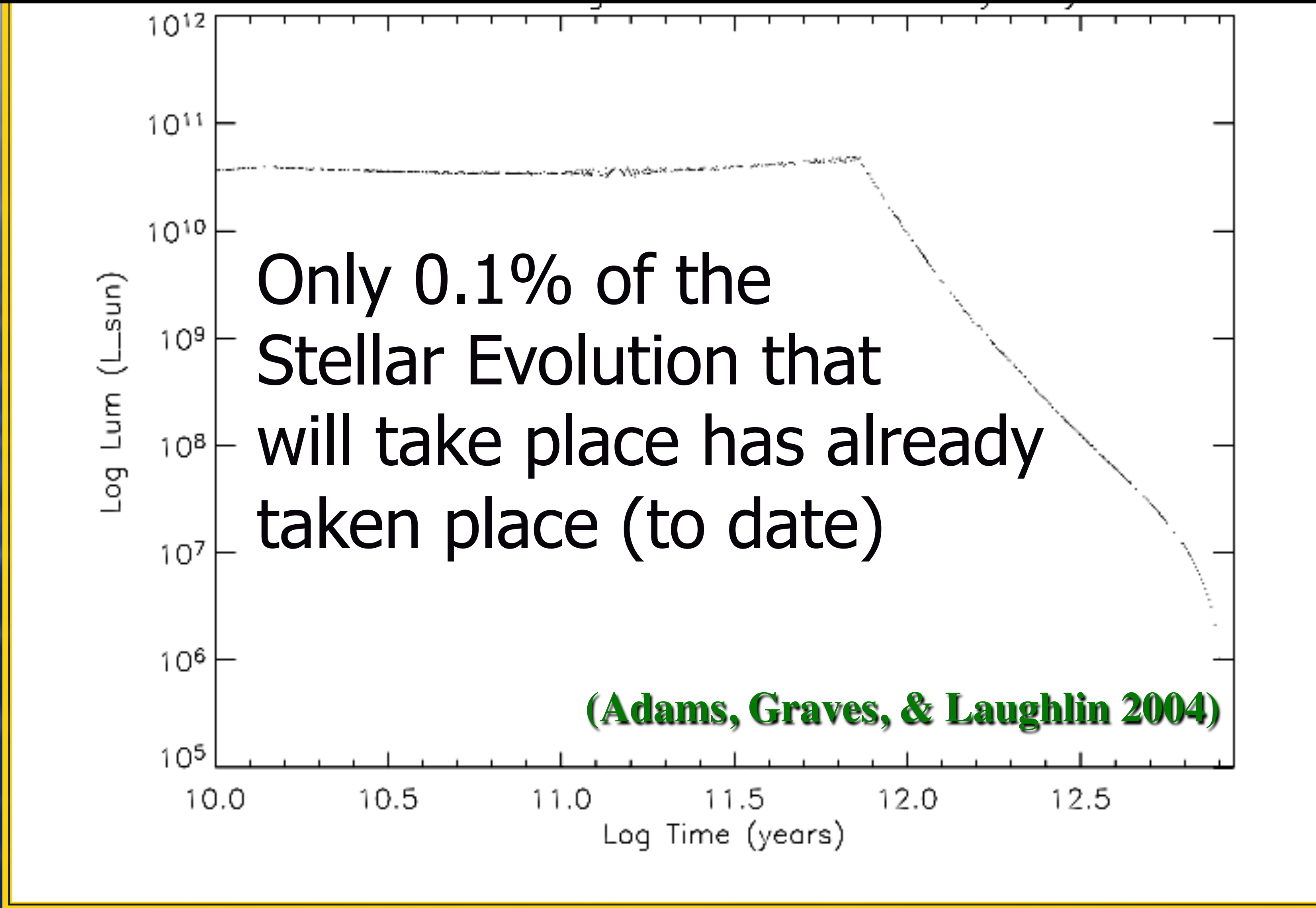
Life Span of Red Dwarfs



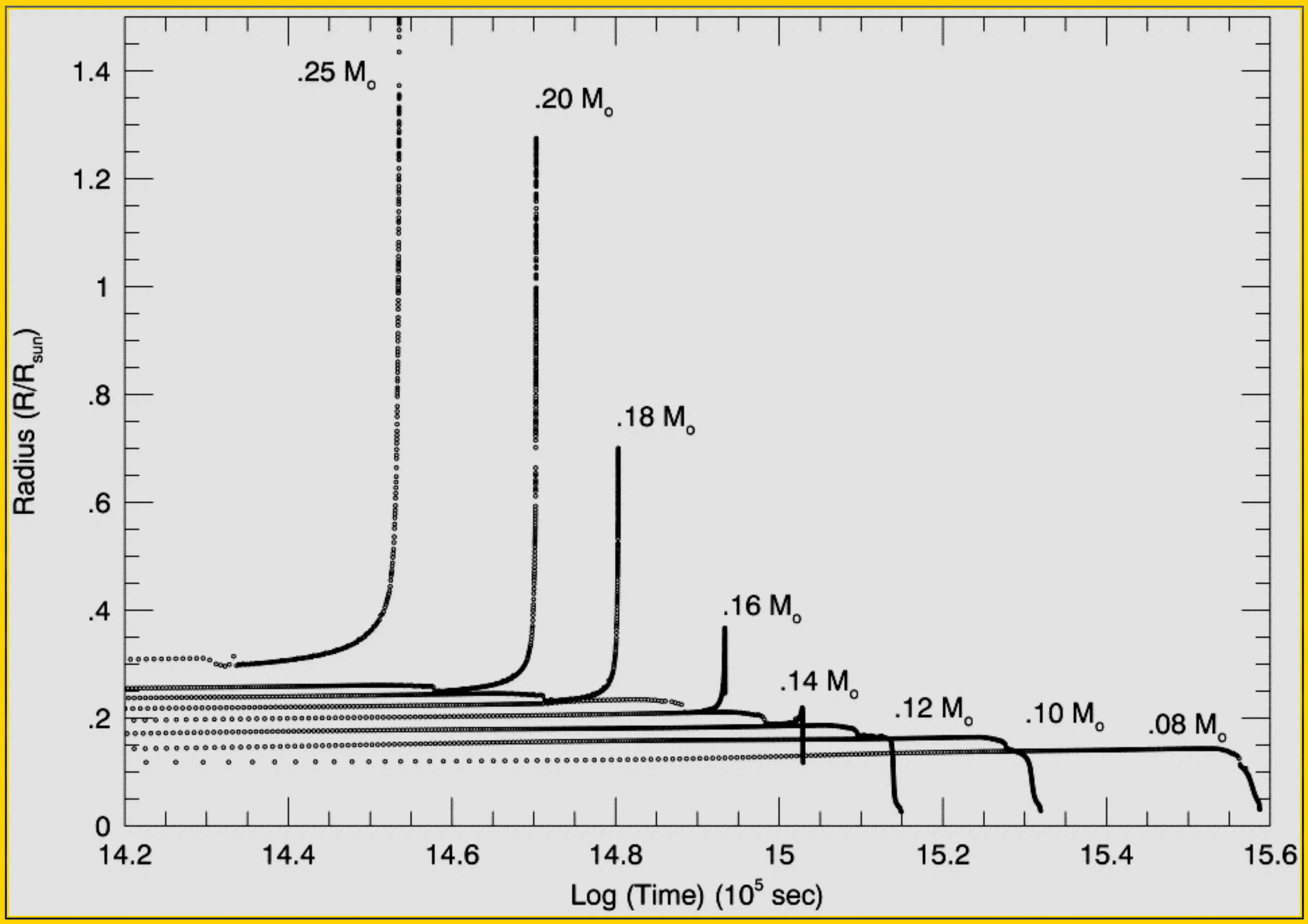


Evolution of star with m = 0.10

Late time light curve for Milky Way



Radial size vs time for varying masses



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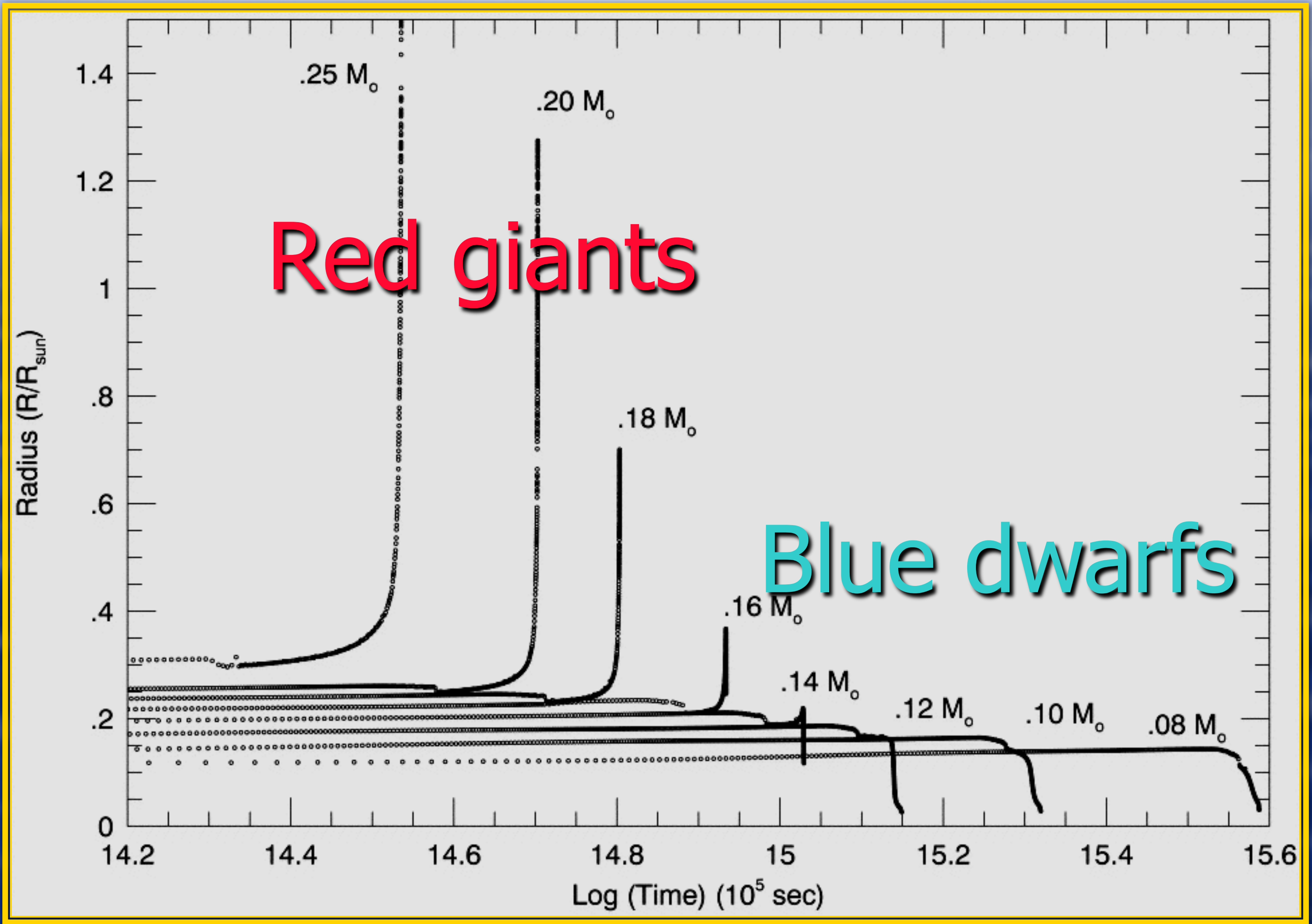
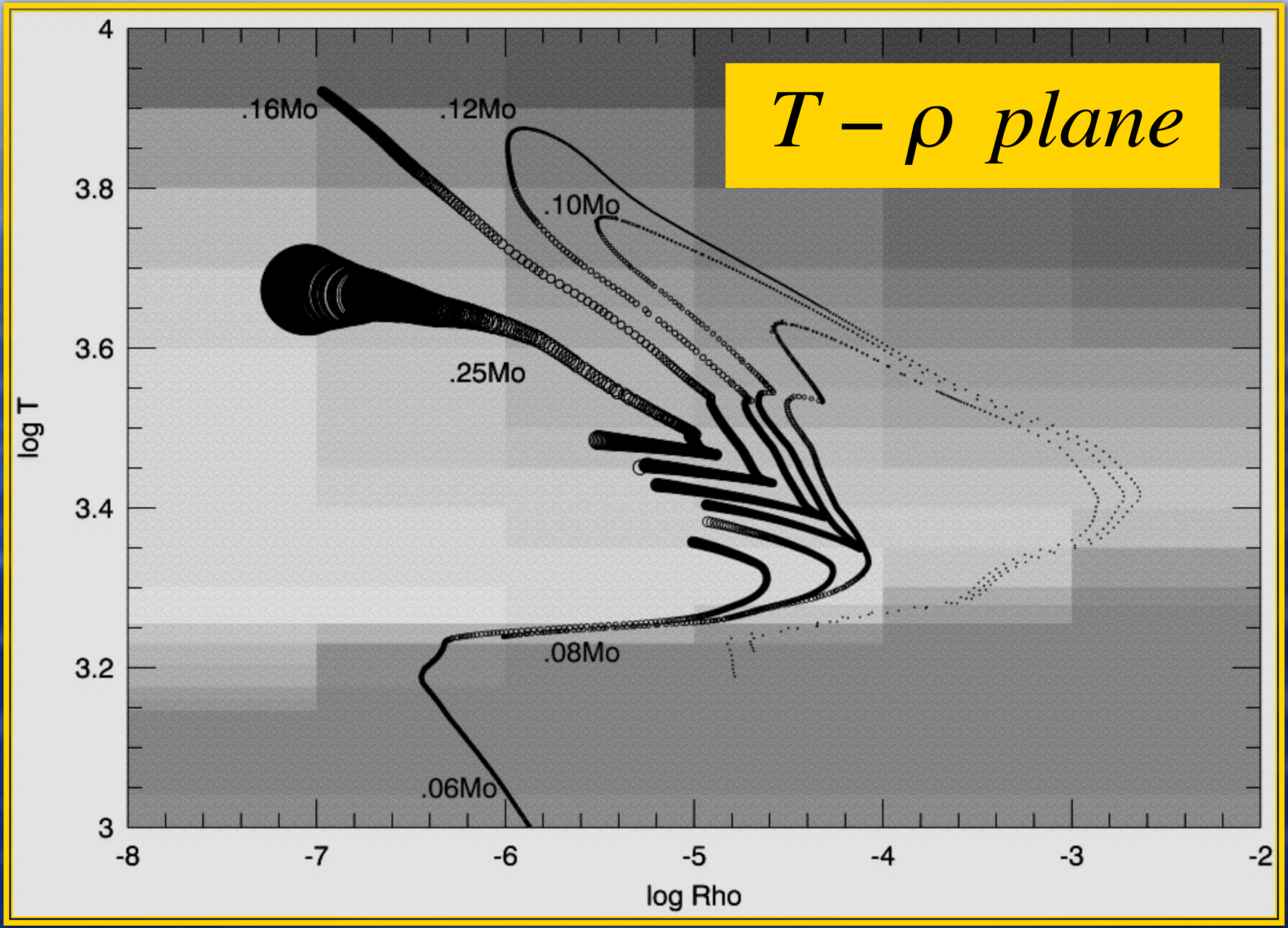
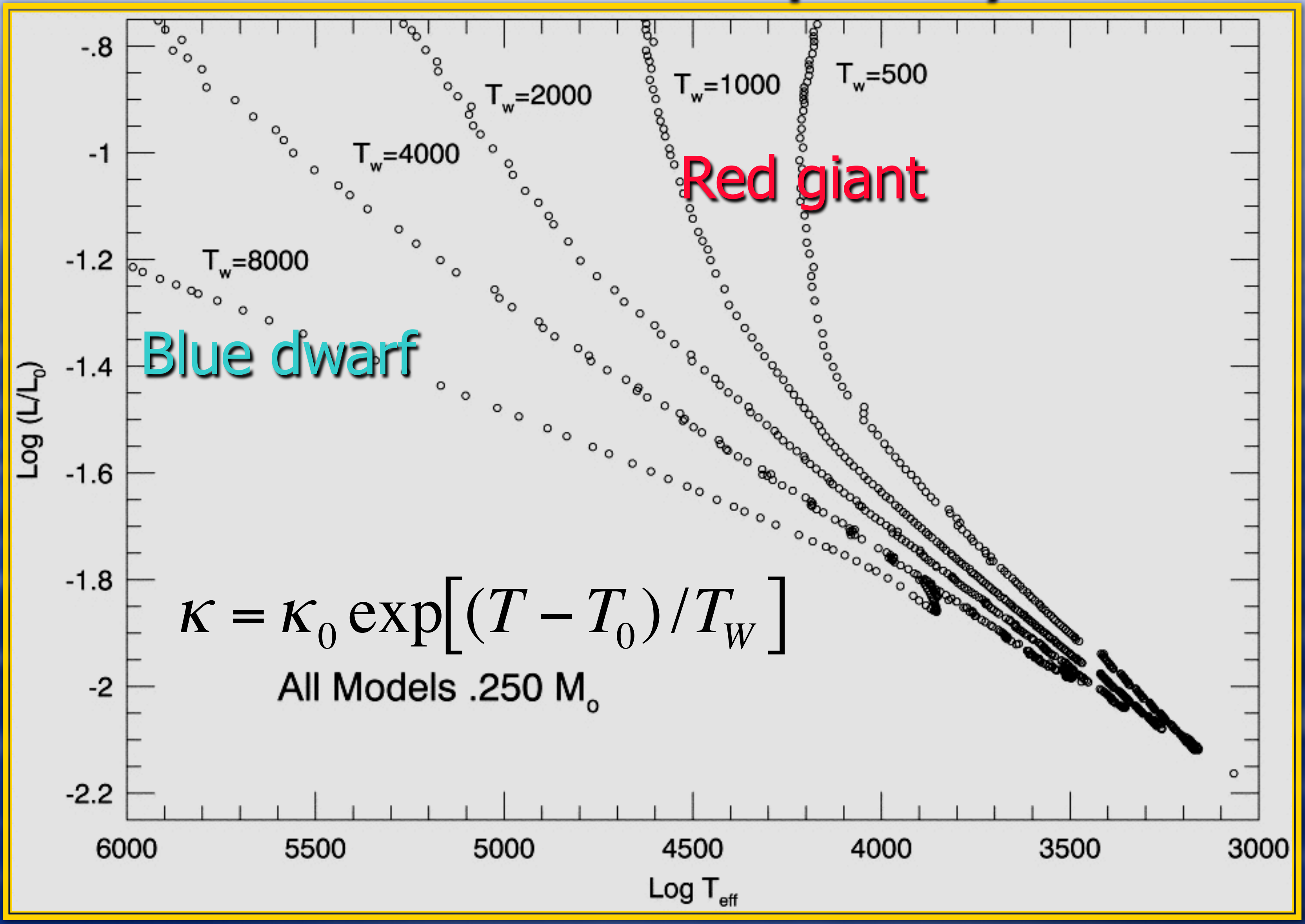


Photosphere evolution:



Effects of the "Opacity Wall"



Why Do Stars Become **RED GIANTS** ?

Luminosity increases $L_* = 4\pi R_*^2 \sigma T_*^4$

Star can either become large or hot.

If photosphere has an opacity wall, then the star cannot become hot, so it must become large => **Giant!**

Opacity Analysis

Radiation equation $$L = -4\pi\, r^2 \frac{4acT^3}{3\kappa\rho}\frac{dT}{dr}$$

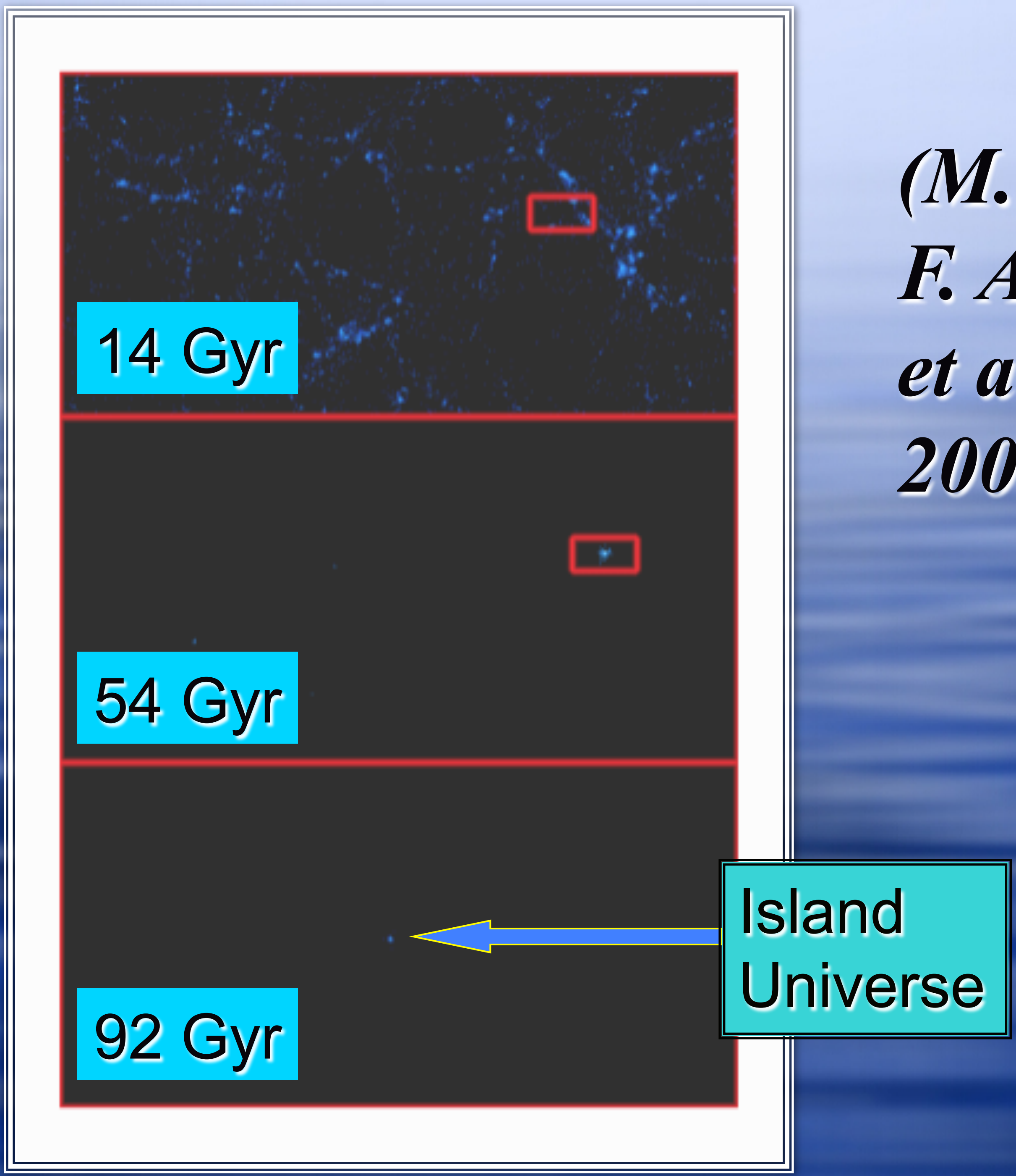
Hydrostatic equilibrium $$\frac{dT}{dr} = -\frac{1}{1+n}\frac{\mu G M_r}{r^2 R_g}$$

$$\Rightarrow \quad L_* = \frac{16\pi}{3}\frac{acG}{R_g}\frac{\mu M_*}{1+n}\frac{T_*^3}{\kappa\rho}$$

$$\kappa = C\rho^\alpha T^\omega,\ \rho \propto R_*^{-\gamma},\ \&\ L_* = 4\pi R_*^2 \sigma T_*^4 \quad \Rightarrow$$

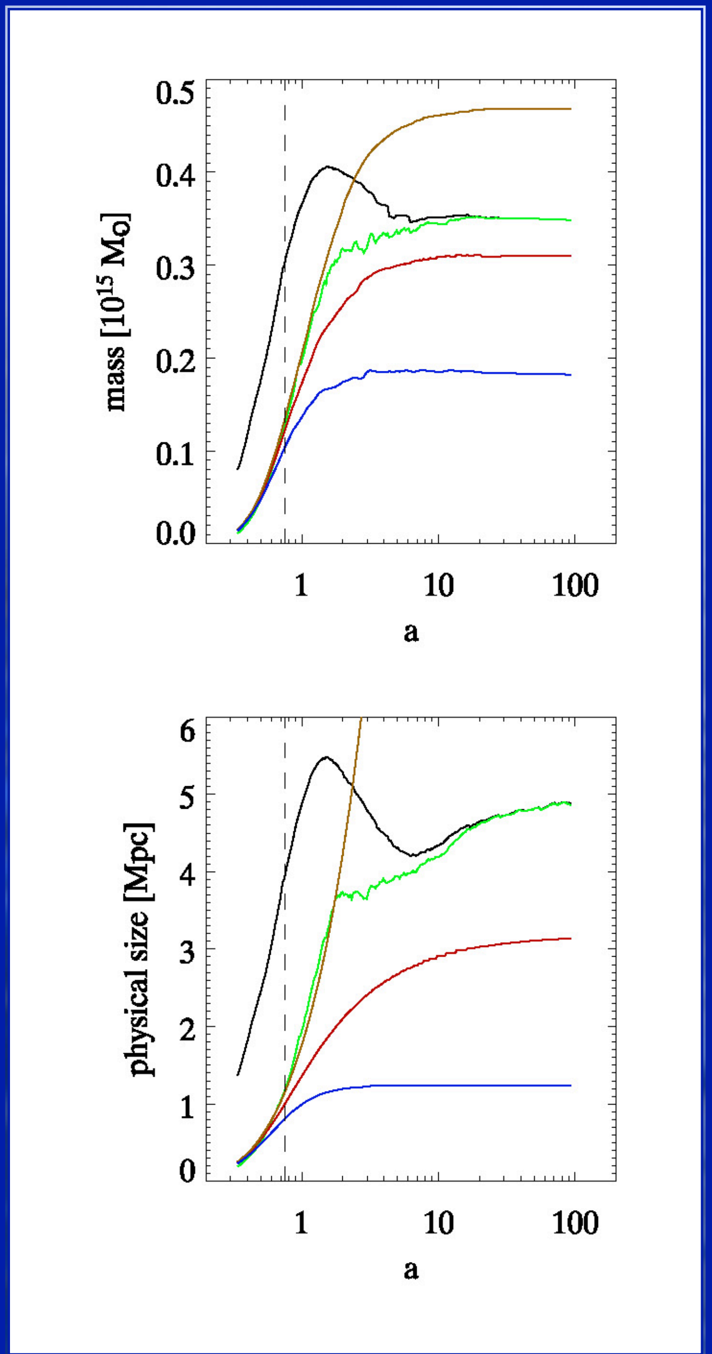
$$\frac{\Delta T_*}{T_*} = \frac{\alpha}{\omega+1+4\alpha}\frac{\Delta L_*}{L_*}, \qquad \frac{\Delta R_*}{R_*} = \frac{\omega+1}{2(\omega+1+4\alpha)}\frac{\Delta L_*}{L_*}$$

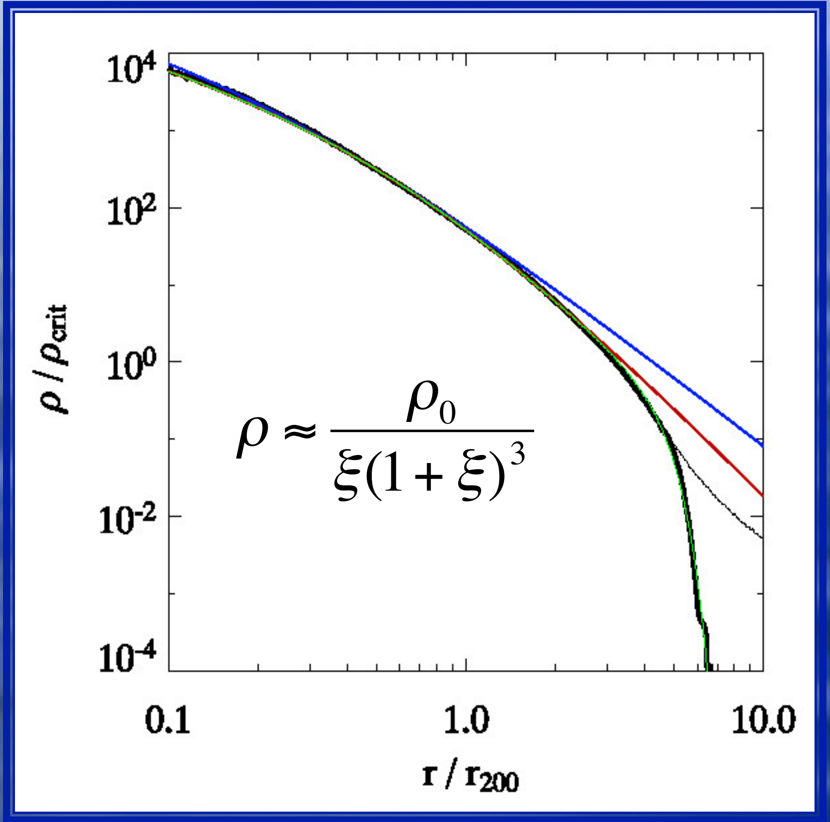
What is the total mass of a galaxy? Why do dark matter halos have a nearly universal form?



(M. Busha, F. Adams, et al. 2003, 2005, 2007)

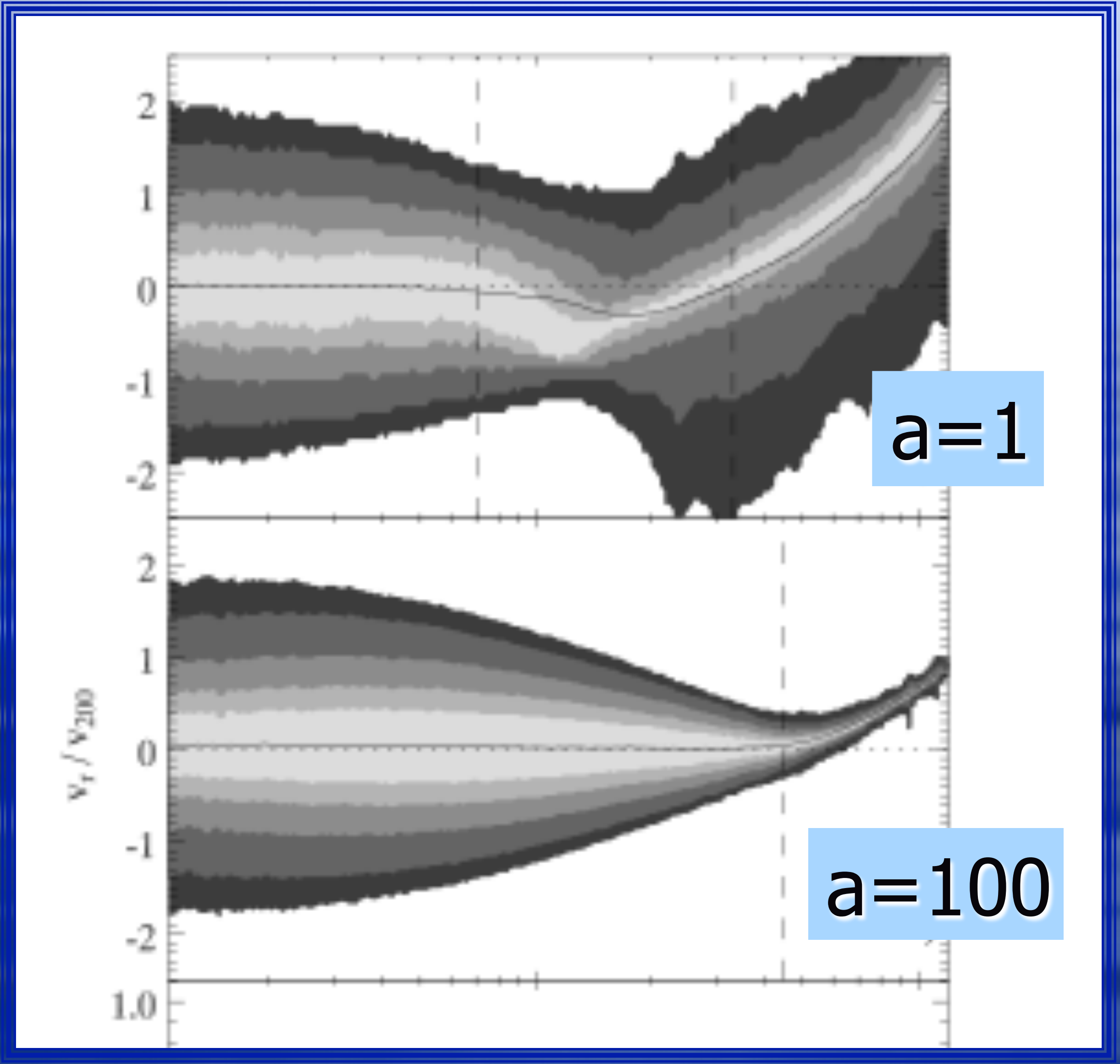
Dark matter halos approach a well-defined asymptotic form with unambiguous total mass, outer radius, & density profile





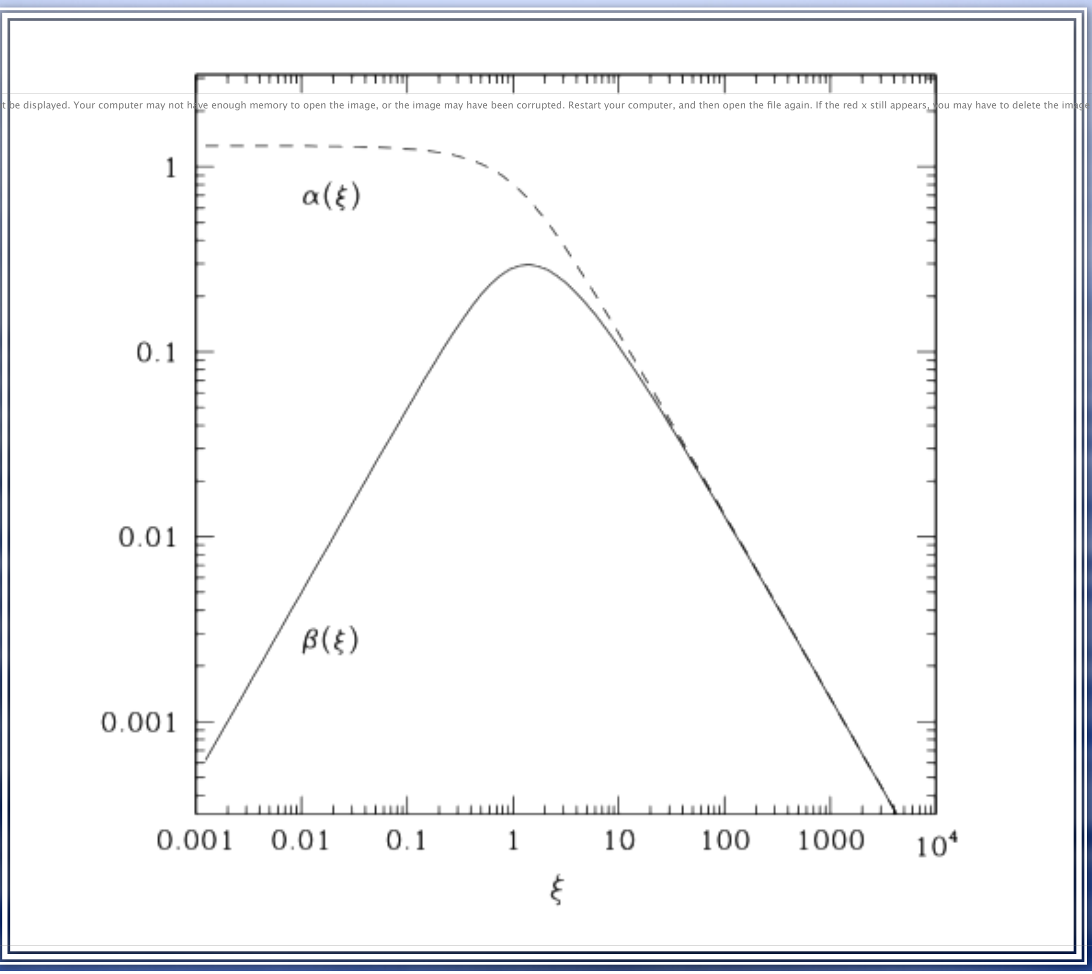
(Busha et al. 2005)

Phase Space of Dark Matter Halo



(M. Busha et al. 2005)

Spacetime Metric Attains Universal Form



$$ds^2 = -[1 - A(r) - \chi^2 r^2]dt^2 + \frac{dr^2}{[1 - B(r) - \chi^2 r^2]} + r^2 d\Omega^2$$

ORBITS?

- Most of the mass is in dark matter
- Most dark matter resides in these halos
- Halos have the universal form found here (nfw/hq) for most of their lives
- Most orbital motion that will EVER occur will be THIS orbital motion in DM halos

$$\left(factor \quad of \quad 10^{74} \right)$$

Triaxial Forces

$$F_x = \frac{-2\,\mathrm{sgn}(x)}{\sqrt{\left(a^2-b^2\right)\left(a^2-c^2\right)}} \ln\left(\frac{2G(a)\sqrt{\Gamma}+2\Gamma-a^2\Lambda}{2a^2\xi G(a)+\Lambda a^2-2a^4\xi^2}\right)$$

$$F_y = \frac{-2\,\mathrm{sgn}(y)}{\sqrt{\left(a^2-b^2\right)\left(b^2-c^2\right)}} \left[\sin^{-1}\left(\frac{\Lambda-2b^2\xi^2}{\sqrt{\Lambda^2-4\Gamma\xi^2}}\right)-\sin^{-1}\left(\frac{2\Gamma/b^2-\Lambda}{\sqrt{\Lambda^2-4\xi^2\Gamma}}\right)\right]$$

$$F_z = \frac{-2\,\mathrm{sgn}(z)}{\sqrt{\left(a^2-c^2\right)\left(b^2-c^2\right)}} \ln\left(\frac{2G(c)\sqrt{\Gamma}+2\Gamma-c^2\Lambda}{2c^2\xi G(c)+\Lambda c^2-2c^4\xi^2}\right)$$

$$G(u) = \xi^2u^4-\Lambda u^2+\Gamma$$

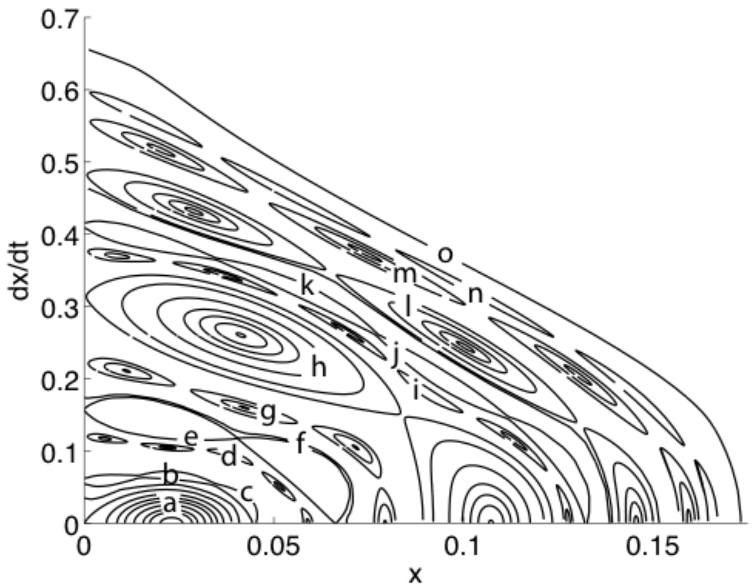
$$\xi^2 = x^2+y^2+z^2$$

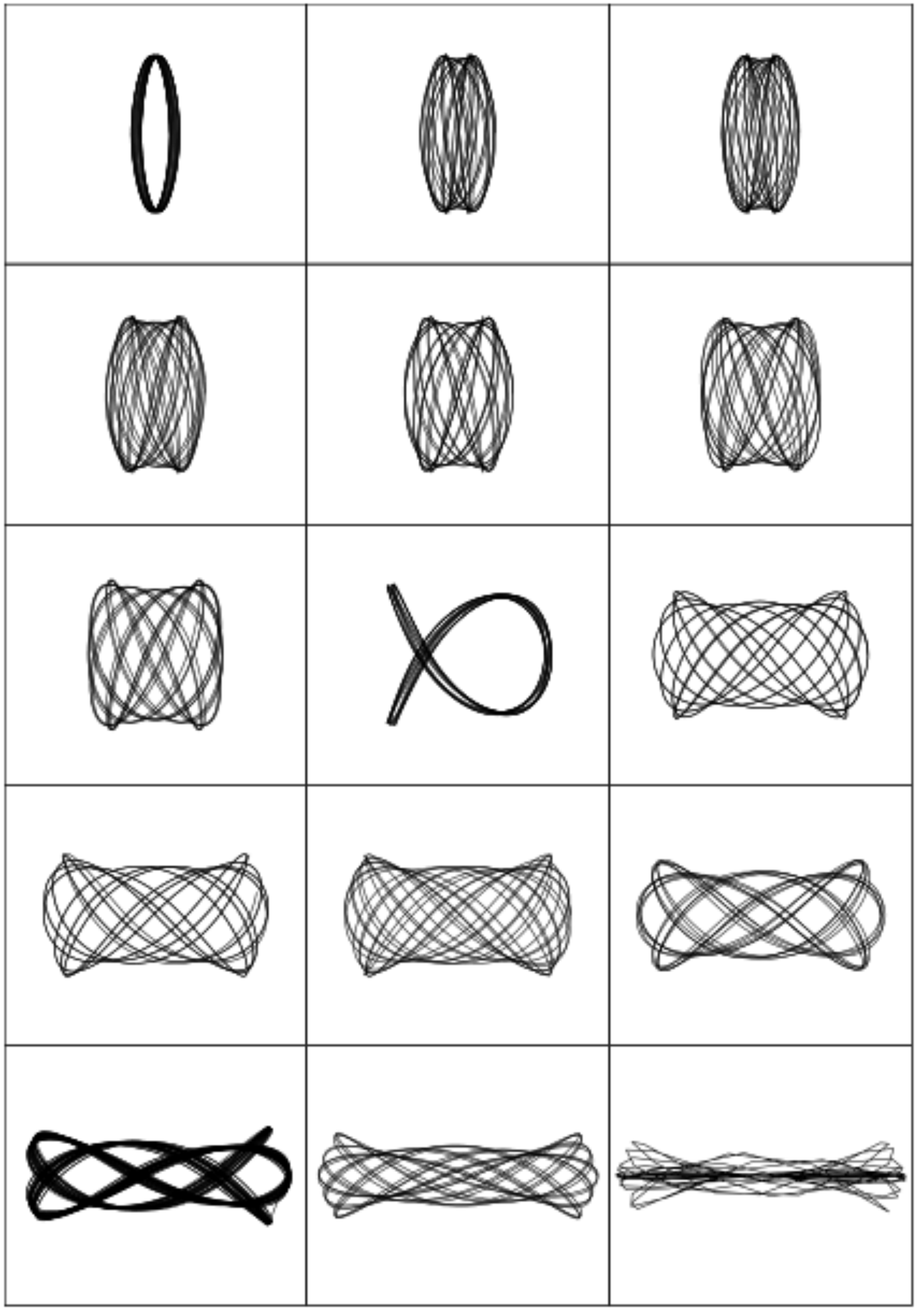
$$\Lambda = \left(b^2+c^2\right)x^2+\left(a^2+c^2\right)y^2+\left(a^2+b^2\right)z^2$$

$$\Gamma = b^2c^2x^2+a^2c^2y^2+a^2b^2z^2$$

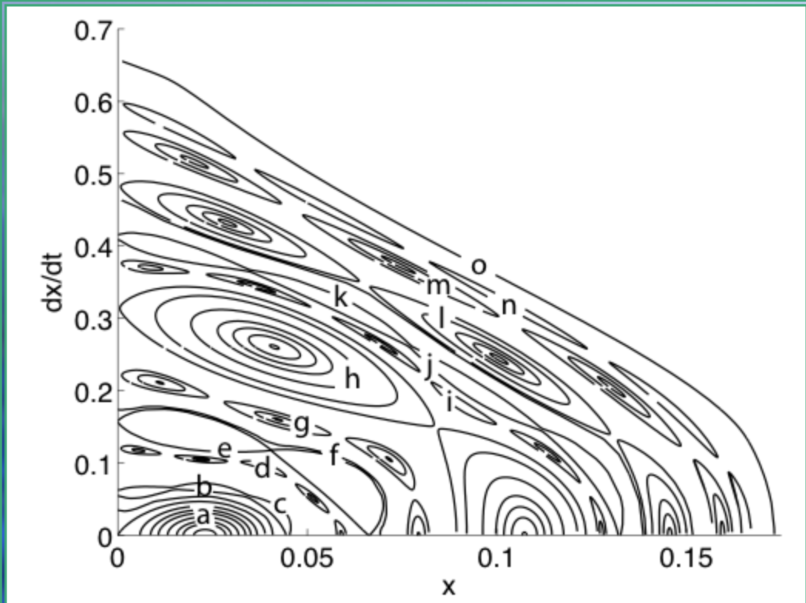
(Adams, Bloch, Butler, Druce, Ketchum 2007)

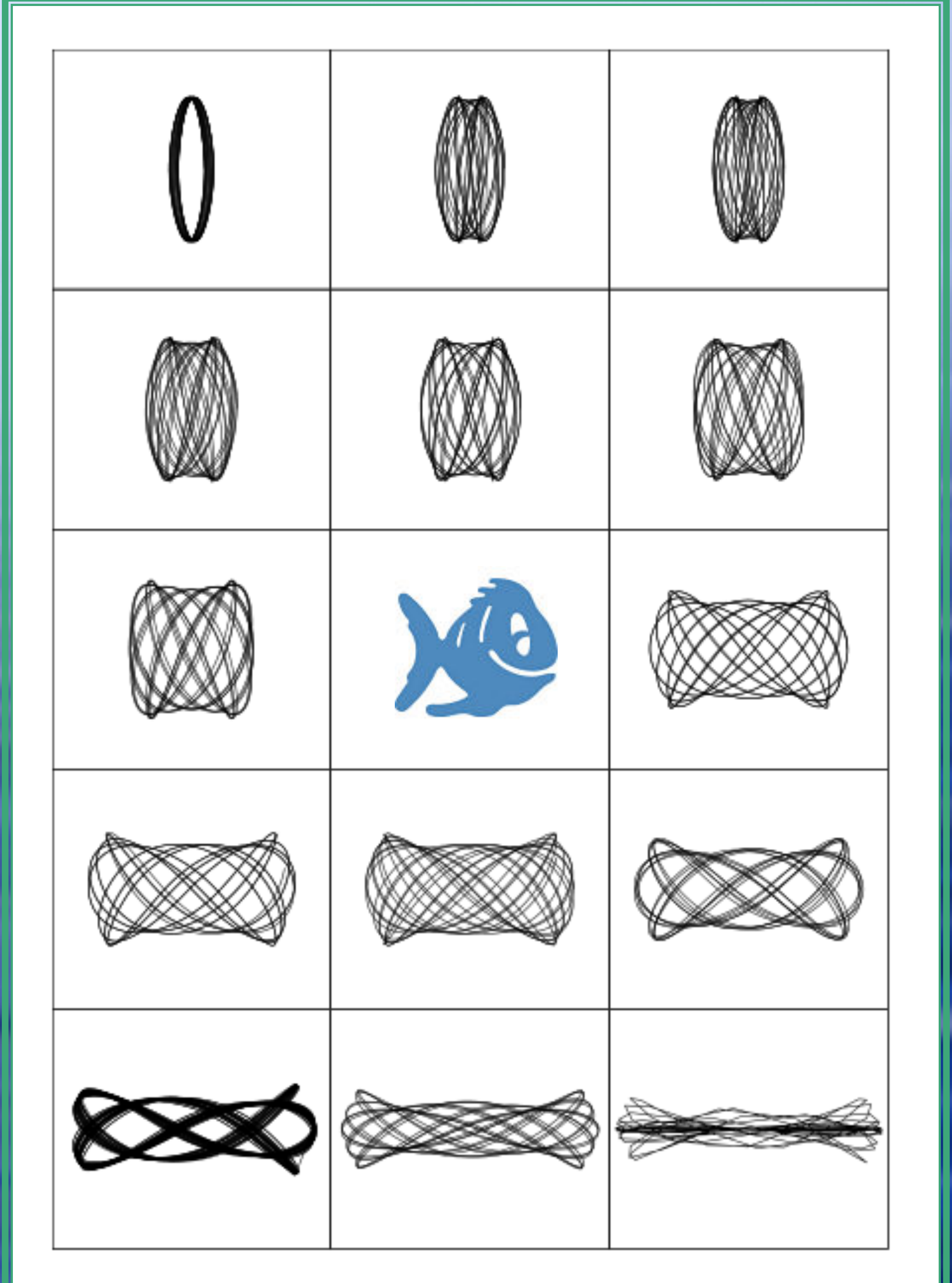
Orbit Gallery





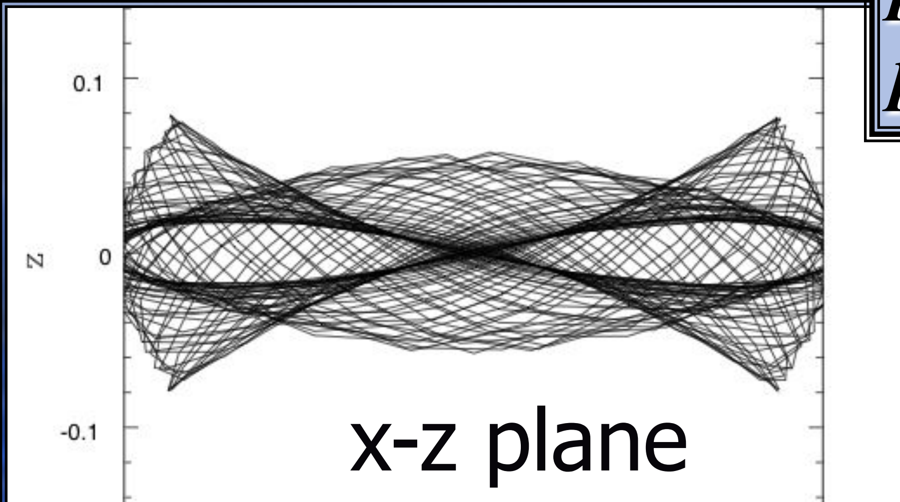
Orbit Gallery

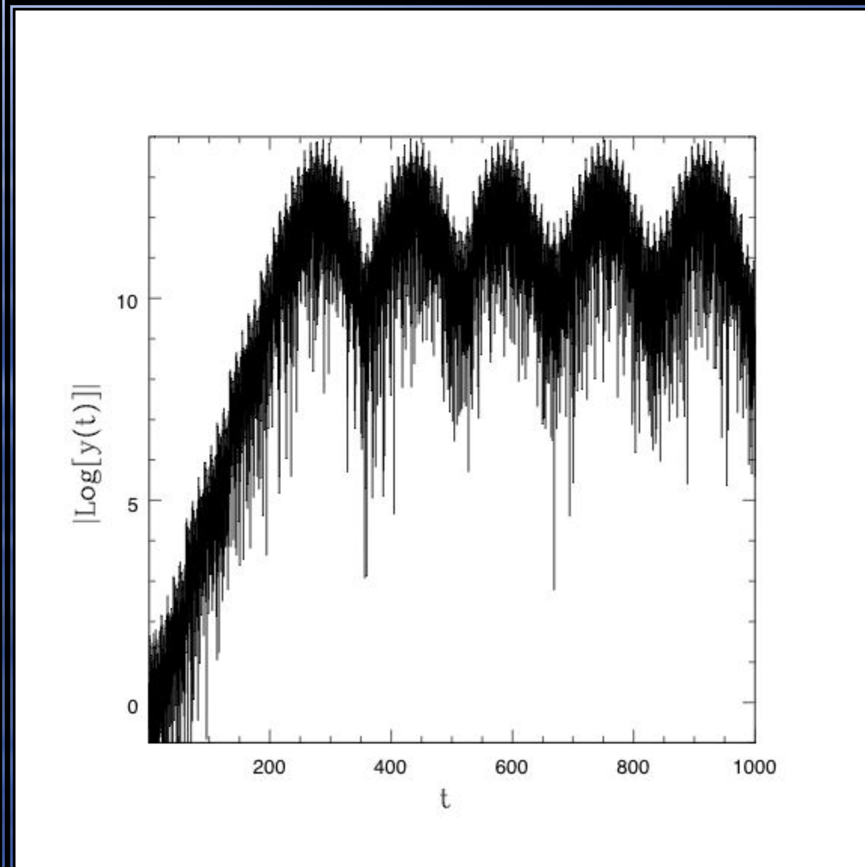




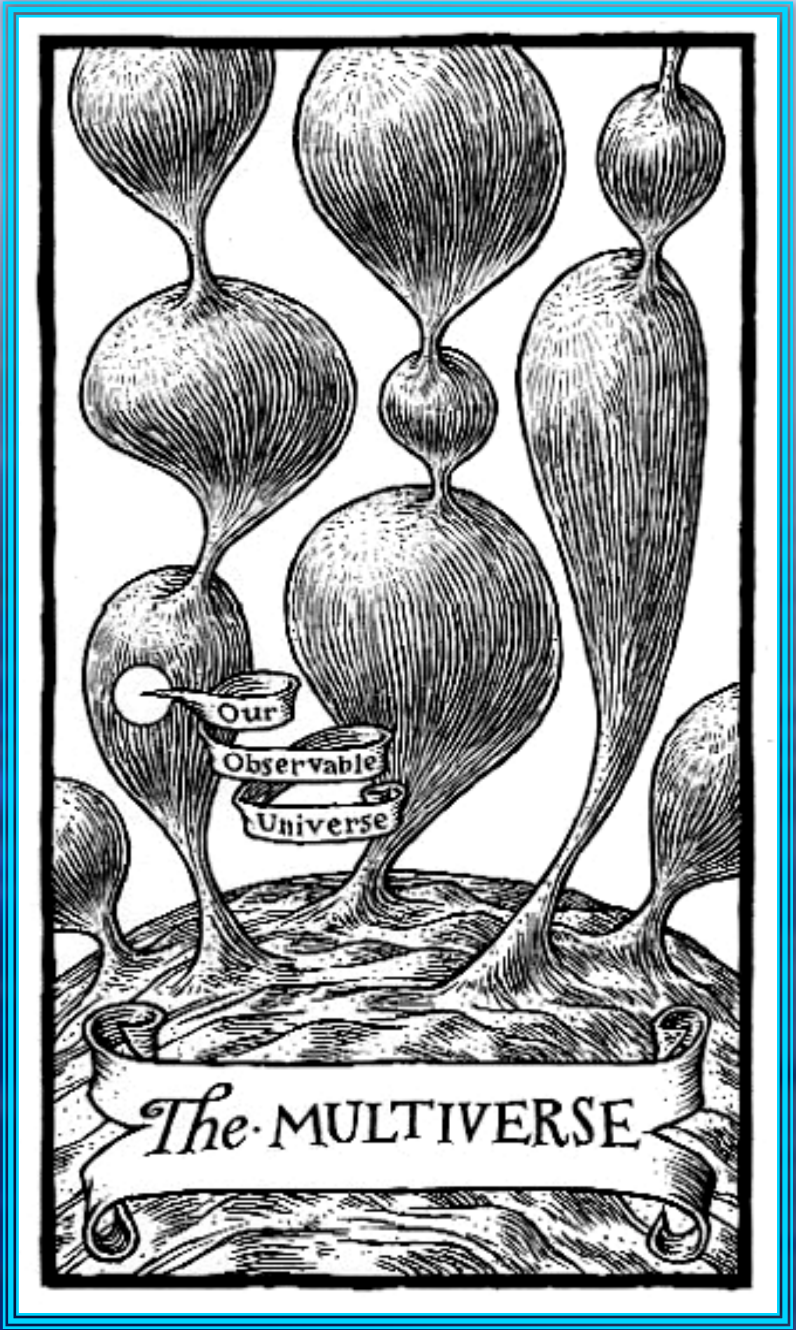
INSTABILITIES

Orbits in any of the principal planes are unstable to motion perpendicular to the plane.





Unstable motion shows:
(1) exponential growth,
(2) quasi-periodicity,
(3) chaotic variations,
(4) eventual saturation



Given the possible existence of multiple universes, we face the question:
Do other universes have different versions of the laws of physics?
Do other versions of the laws of physics allow life to develop?

Stars and Stellar Structure in Other Universes

F. Adams (2008) JCAP, 08010

OVERVIEW

- Build robust, analytic stellar model
- Polytropic model of mechanical structure
- Only one nuclear burning species
- Radiative energy transport
- Define solution space: 4 forces of nature reduced to 3 parameters: (G, α, C)

Large fraction of this parameter space allows for the existence of working stars

Stellar Structure Equations

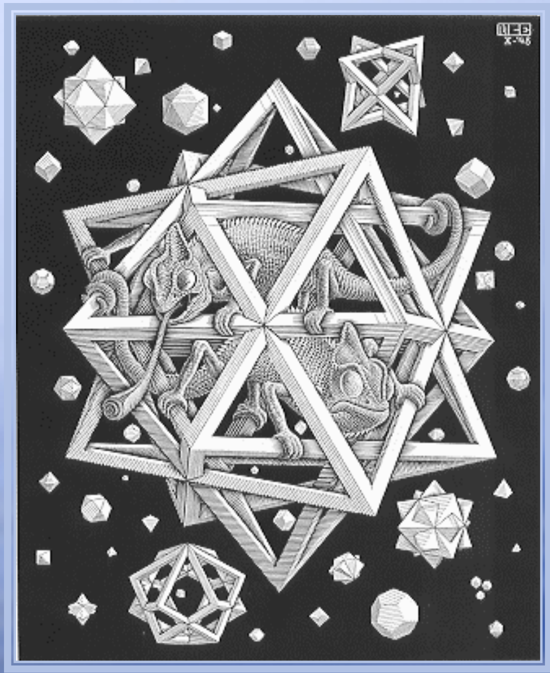
$$\frac{\partial P}{\partial r} = -\frac{GM(r)\rho}{r^2}, \qquad \frac{\partial M}{\partial r} = 4\pi r^2 \rho$$

$$\frac{\partial \ell}{\partial r} = 4\pi r^2 \left(\varepsilon - \varepsilon_\nu\right), \qquad \frac{\partial T}{\partial r} = -\frac{3\kappa\rho\ell}{64\pi r^2 \sigma T^3}$$

$$P\left(\rho, T, \ldots\right) \qquad \kappa\left(\rho, T, \ldots\right) \qquad \varepsilon\left(\rho, T, \ldots\right)$$

Polytropic Stars

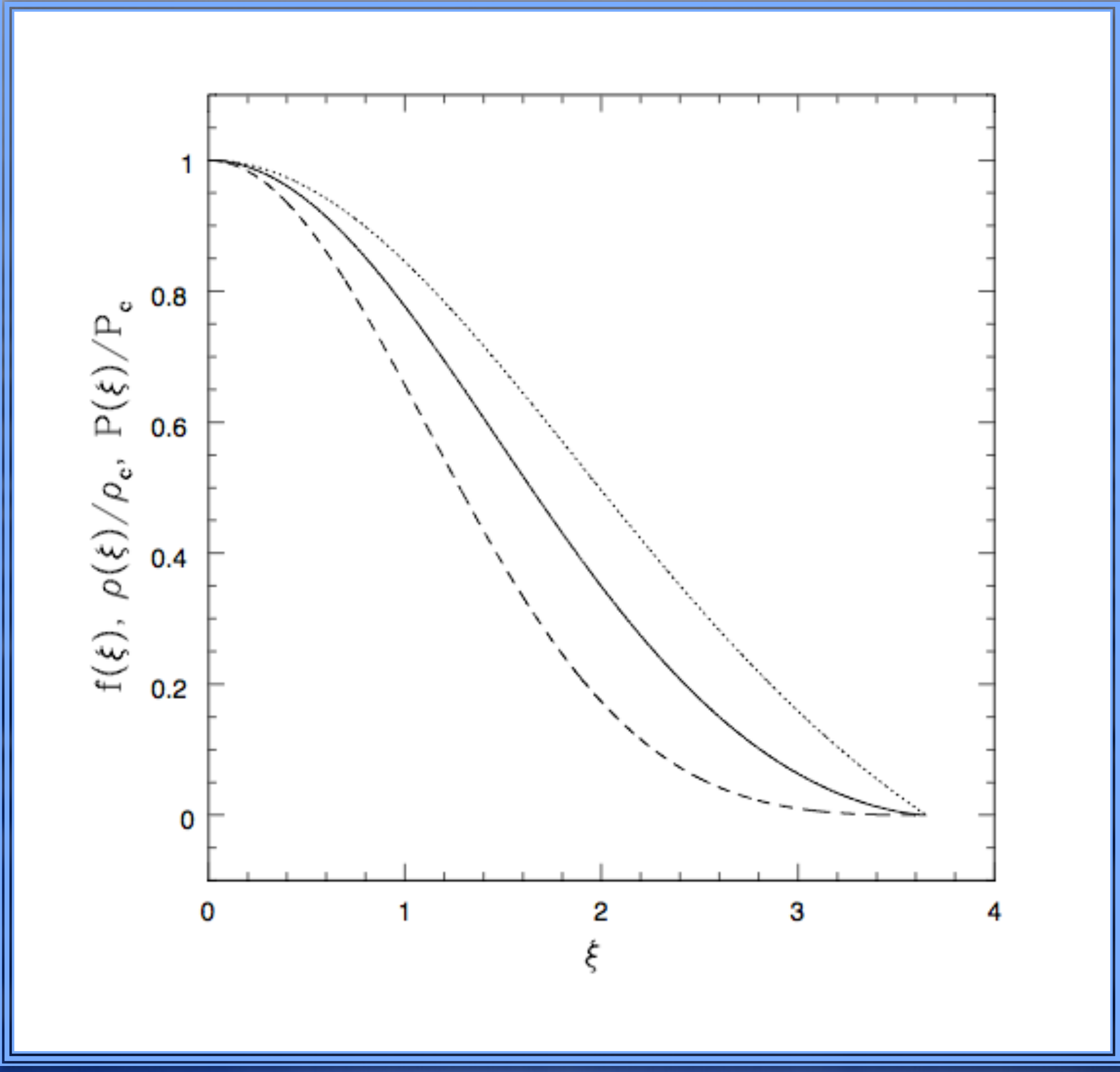
$$P = K\ \rho^{\Gamma} = K\ \rho^{1+1/n}$$



$$\xi = r/R,\ \ \rho = \rho_C f^{\,n},\ \ R^2 = \frac{K\Gamma/(\Gamma-1)}{4\pi G\rho_C^{2-\Gamma}}$$

$$\frac{d}{d\xi}\left(\xi^2 \frac{df}{d\xi}\right) + \xi^2 f^{\,n} = 0$$

Radial Profiles: Mechanical Structure

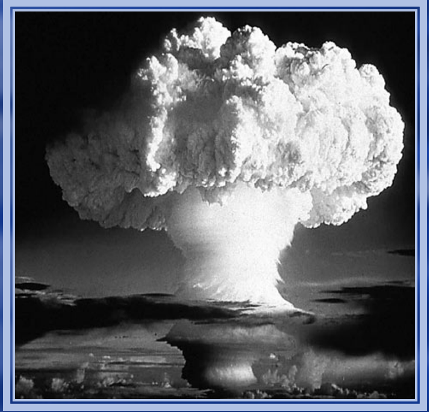


Nuclear Reaction Rates

$$\sigma(E) = \frac{S(E)}{E} \exp\left[-\left(\frac{E_G}{E}\right)^{1/2}\right] \qquad E_G = \left(\pi\ \alpha\ Z_1 Z_2\right)^2 2 m_R c^2$$

$$\varepsilon = C\rho^2\Theta^2 \exp\left[-3\Theta\right] \qquad \Theta = \left(E_G / 4kT\right)^{1/3}$$

$$where \quad C = \frac{8(\Delta E) S(E_0)}{\sqrt{3}\ \pi\ \alpha\ m_1 m_2 Z_1 Z_2 m_R c}$$



(thermal distribution of particle energies
+ Coulomb barrier + quantum tunneling)

Central Temperature

$$specify \quad opacity: \quad \kappa \approx A\rho\, T^{-7/2} \quad (Kramer)$$

after some algebra:

$$\Theta_C I(\Theta_C) T_C^3 = \frac{(4\pi)^3 ac}{3\beta\kappa_c C}\left(\frac{M_*}{\mu_0}\right)^4 \left[\frac{G}{(n+1)R_{gas}}\right]^7$$

$$where \quad I(\Theta_C) \equiv \int_0^{\xi_*} f^{2n}\xi^2\Theta^2 \exp[-3\Theta]\, d\xi$$

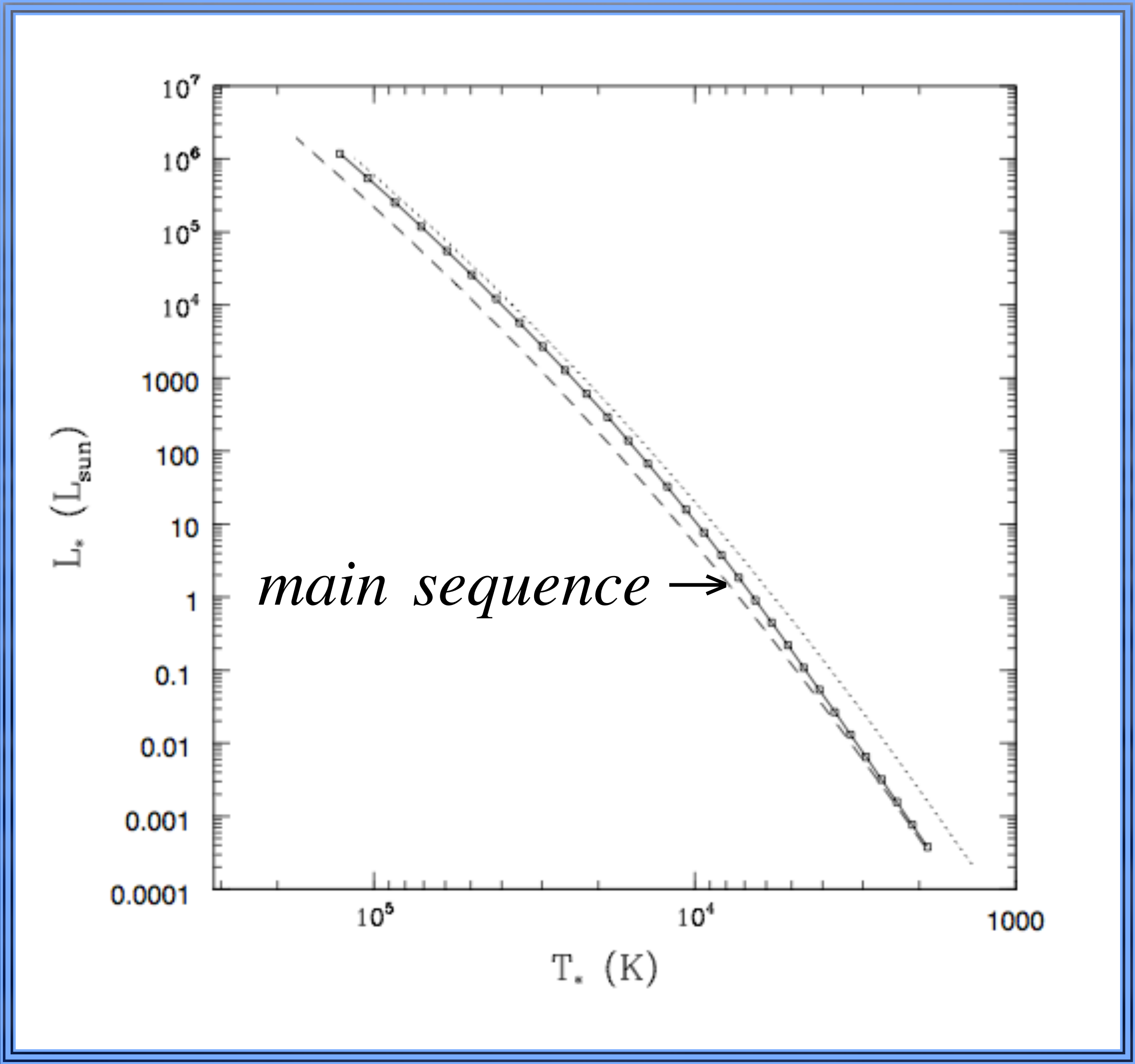
Stellar Structure Solutions

$$R_* = \frac{GM_*\langle m \rangle}{kT_C}\frac{\xi_*}{(n+1)\mu_0}$$

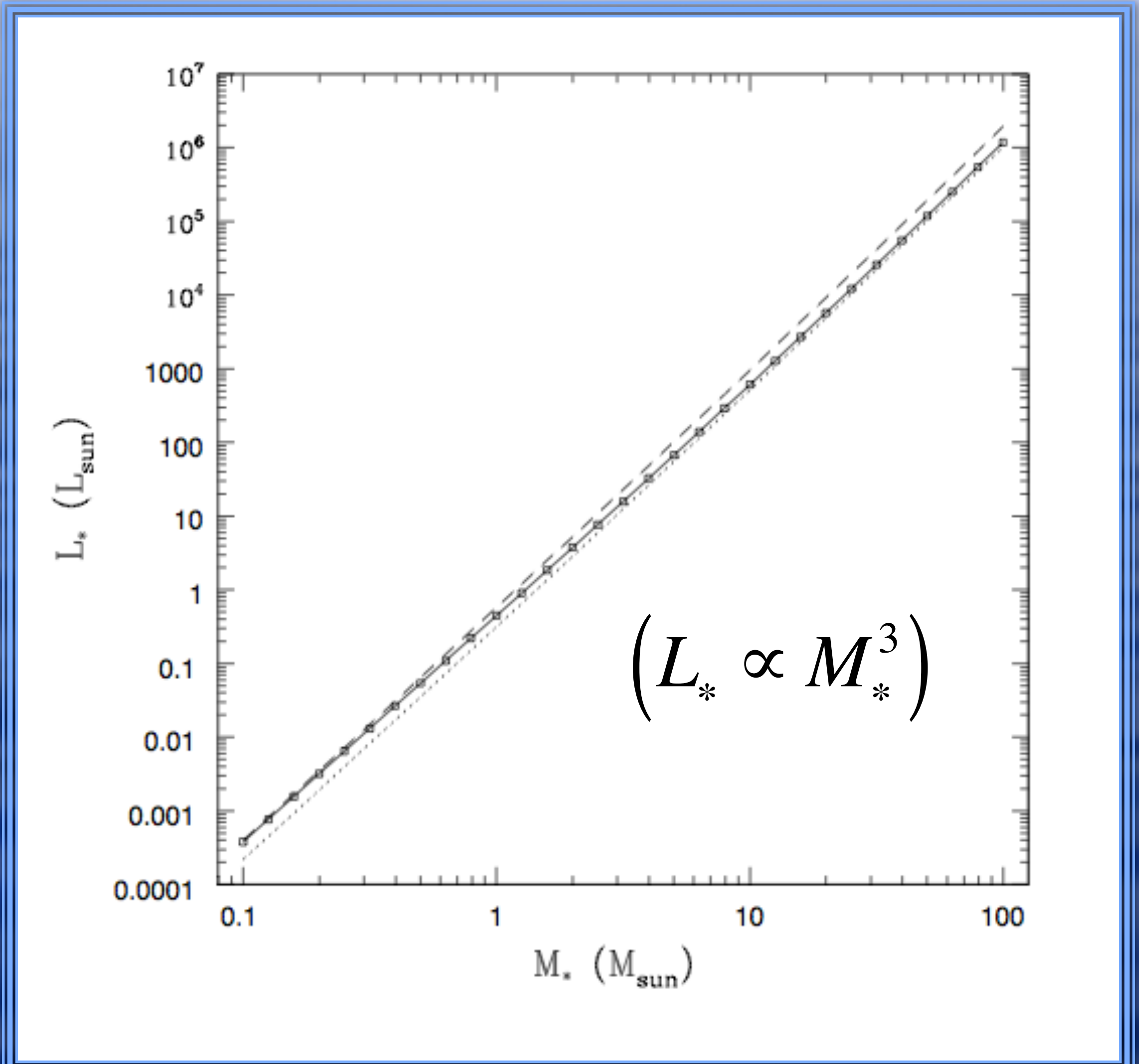
$$L_* = \frac{(2\pi)^7}{15h^3c^2\beta\kappa_0\Theta_C}\left(\frac{M_*}{\mu_0}\right)^3\left[\frac{G\langle m \rangle}{(n+1)}\right]^4$$

$$T_* = \left[\frac{L_*}{4\pi R_*^2\sigma}\right]^{1/4}$$

Hertzsprung-Russell Diagram



Luminosity-Mass Relationship



Minimum & Maximum Masses

characteristic mass scale:

$$M_0 \equiv \left(\frac{hc}{2\pi G}\right)^{3/2} m_P^{-2} = \frac{M_{Pl}^3}{m_P^2} \approx 1.85\, M_{SUN}$$

$$M_{*\min} = 6(3\pi)^{1/2}\left(\frac{4}{5}\right)^{3/4}\left(\frac{m_P}{m_{ion}}\right)^2\left(\frac{kT_{nuc}}{m_e c^2}\right)^{3/4} M_0 \approx 0.07\, M_0$$

$$M_{*\max} = \left(\frac{18\sqrt{5}}{\pi^{3/2}}\right)^{3/4}\left(\frac{1-f_g}{f_g^4}\right)^{1/2}\left(\frac{m_P}{\langle m\rangle}\right)^2 M_0 \approx 56\, M_0$$

$$Chandrasekhar: \quad M_{Ch} = \frac{1}{5}(2\pi)^{3/2}\left(Z/A\right)^2 M_0 \approx 0.76\, M_0 \approx 1.4\, M_{SUN}$$

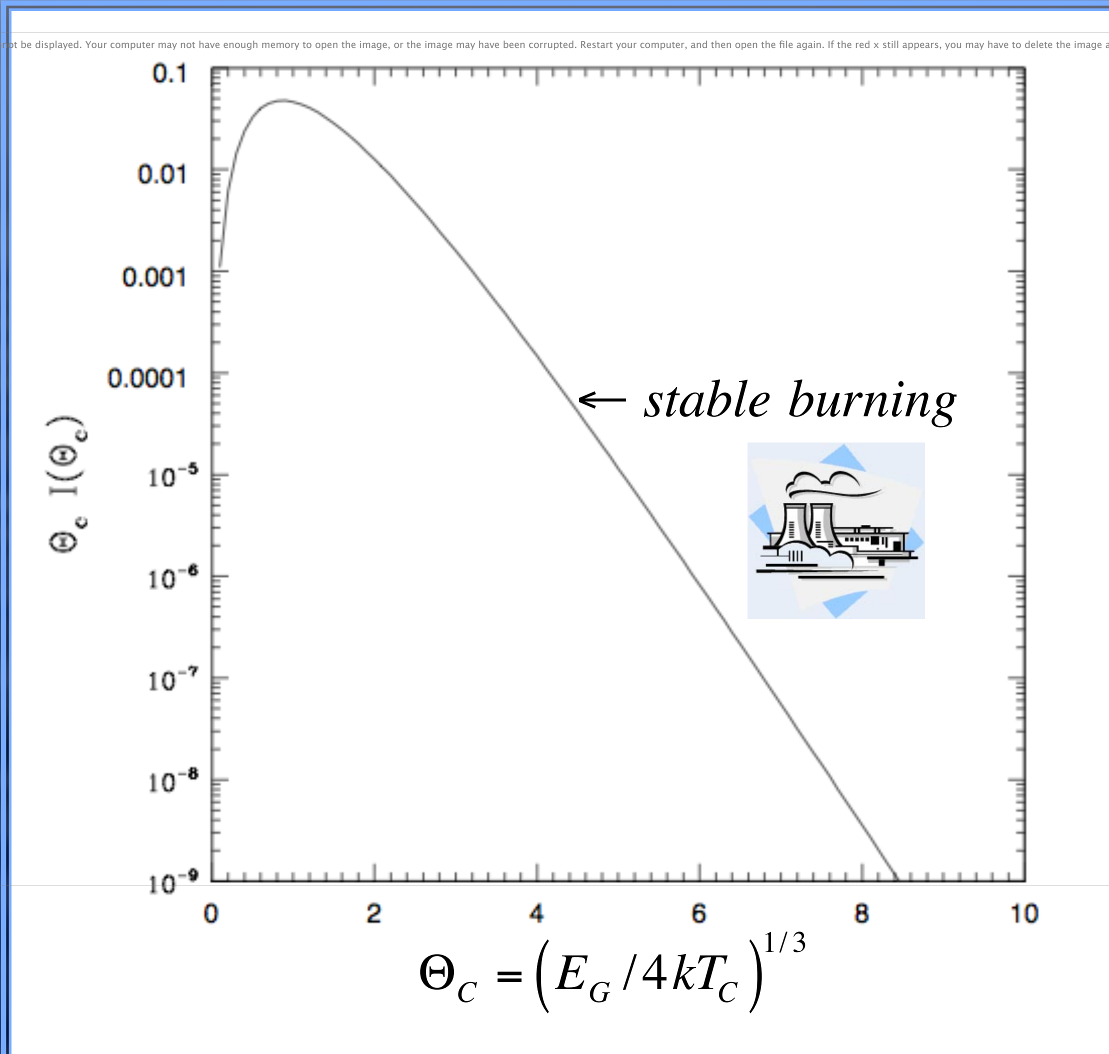
Combined Constraint

We have required central temperature as function of stellar mass, and the relation between minimum stellar mass and given nuke-burning temperature. Combine to eliminate mass, get constraint:

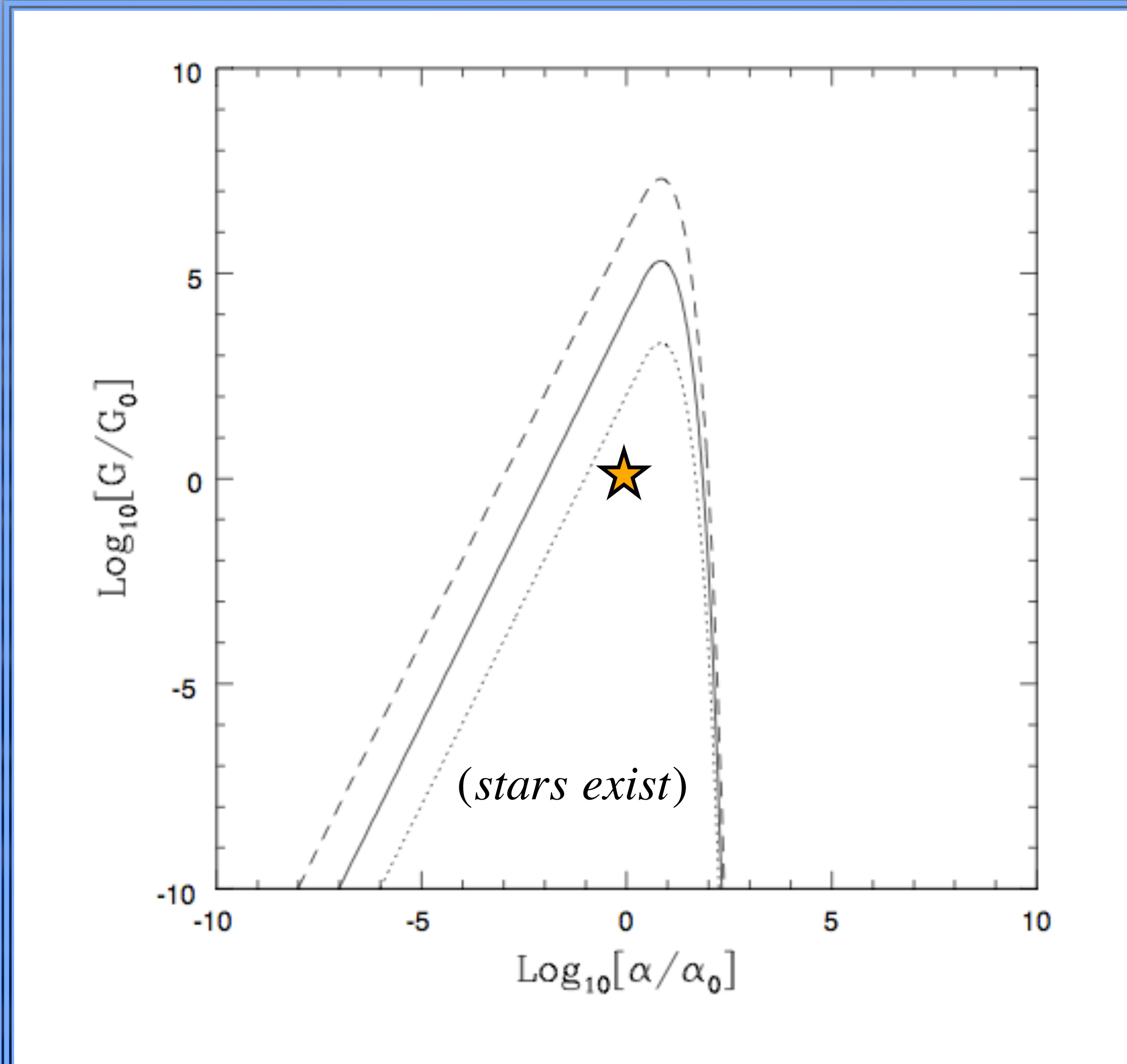
$$\Theta_C I(\Theta_C) = \left(\frac{2^{20}\pi^4 3^4}{5^{11}}\right)\left(\frac{h^3}{c^2}\right)\left(\frac{1}{\beta\mu_0^4}\right)\left(\frac{1}{m\ m_e^3}\right)\left(\frac{G}{\kappa_0 C}\right)$$

$$I(\Theta_C) \equiv \int_0^{\xi_*} f^{2n}\xi^2\Theta^2 \exp[-3\Theta]\,d\xi \quad \& \quad \Theta = \left(E_G / 4kT\right)^{1/3}$$

Central Temperature Solution



Allowed Region of Parameter Space



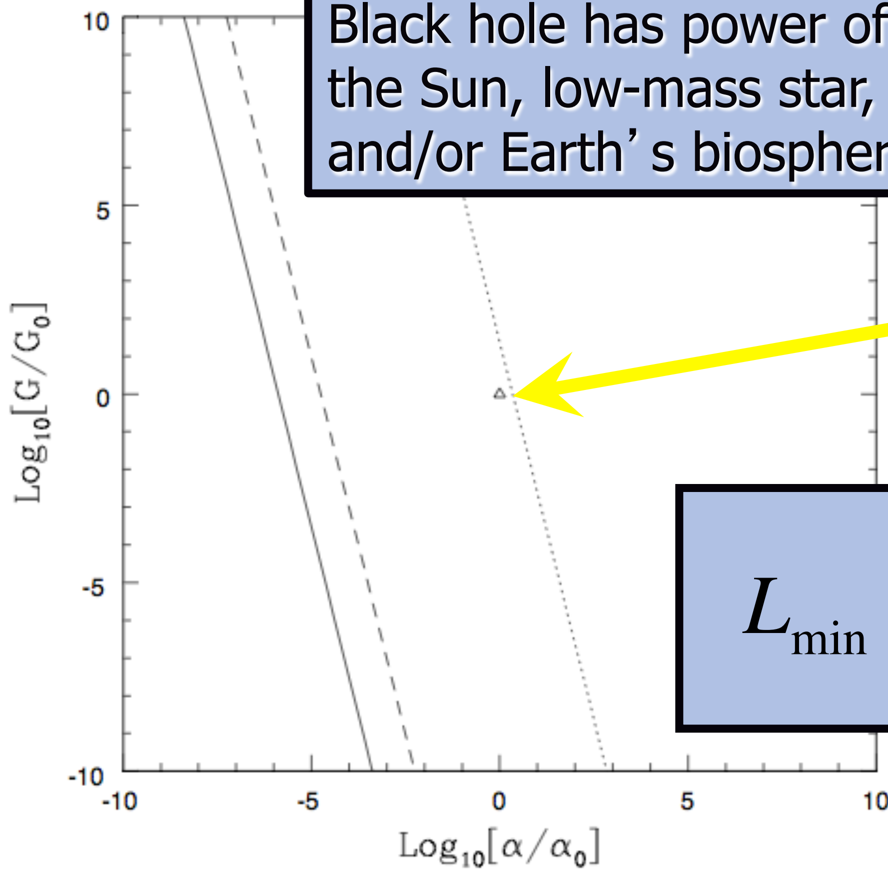
CONCLUSION

Stars in other universes are not as rare as sometimes claimed: Substantial fraction of parameter space allows for the existence of working stars.

This result is only the first step:

- Habitable universes require more constraints
- Expand parameter space (particle masses)
- Need the probability of realizing parameters
- Consider more complicated stellar models
- Some universes could have alternative stars, including dark matter stars and black holes

Region of Parameter Space where Black Holes act as Stars



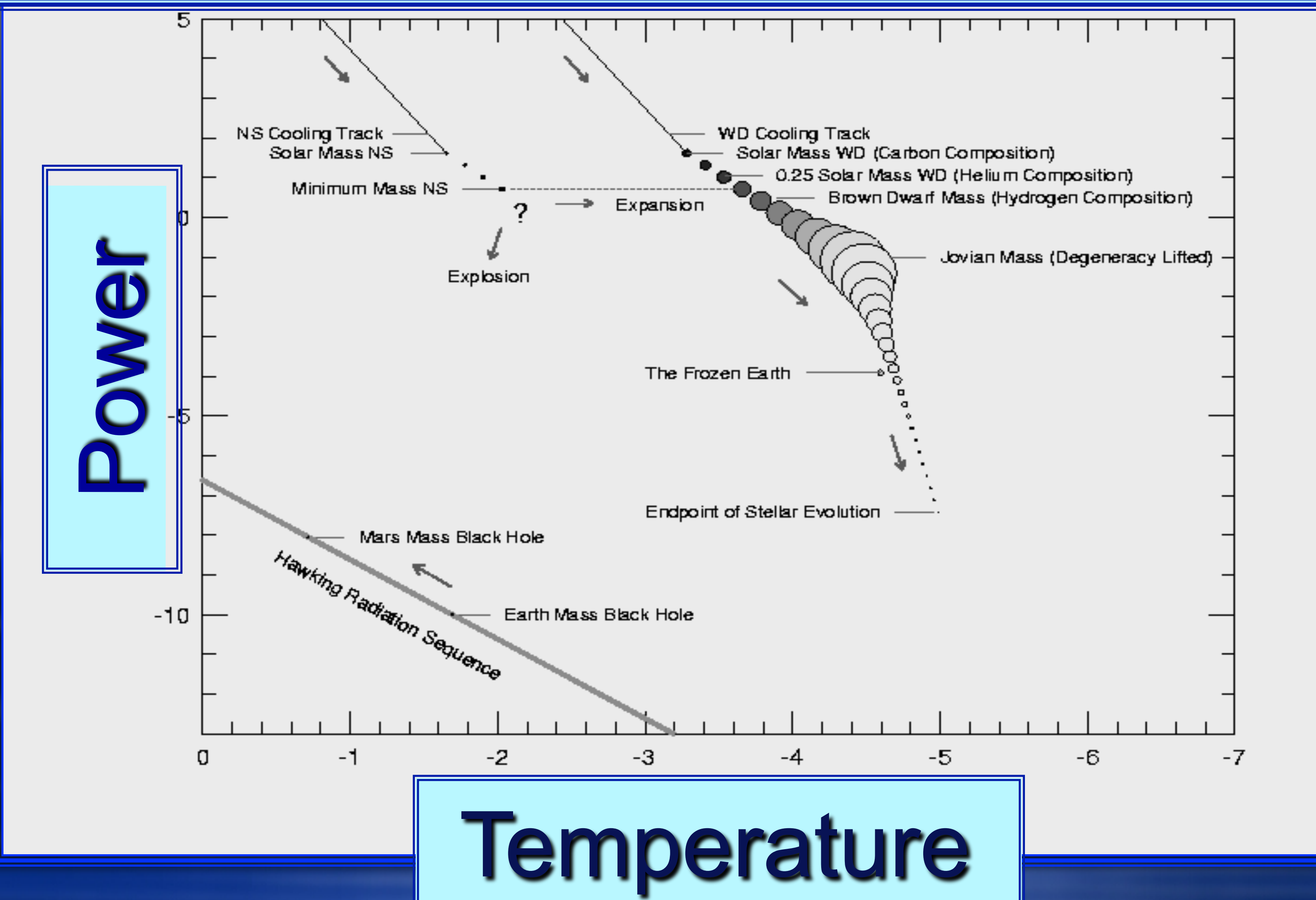
Black hole has power of the Sun, low-mass star, and/or Earth's biosphere.

$$M_{bh} = 10^{14}\,g$$

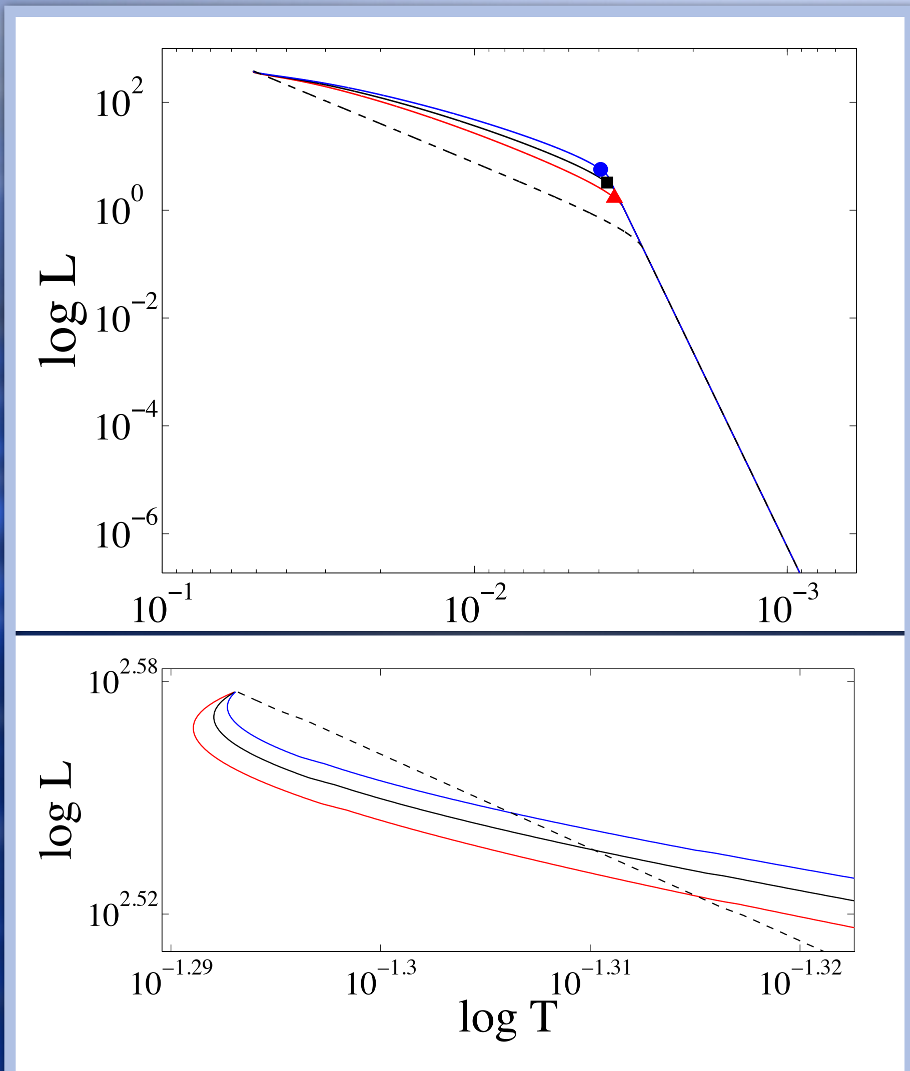
$$L_{\min} = L_{\min(0)}\left(\alpha / \alpha_0\right)^4$$

Instead of having different values in other universes, the fundamental constants can have time-varying values within our own universe

Fate of Degenerate Objects



White Dwarf Evolution with Proton Decay and Time-varying G



$$G(t) = G_0 (1 + t / t_*)^{-p}$$

three regimes:

$$t_* >> \Gamma^{-1} \quad (old\ track)$$

$$t_* << \Gamma^{-1} \quad (horz\ track)$$

$$t_* \approx \Gamma^{-1} \quad (new\ track)$$

$$here: p = 0,\ 0.25,\ 0.5$$

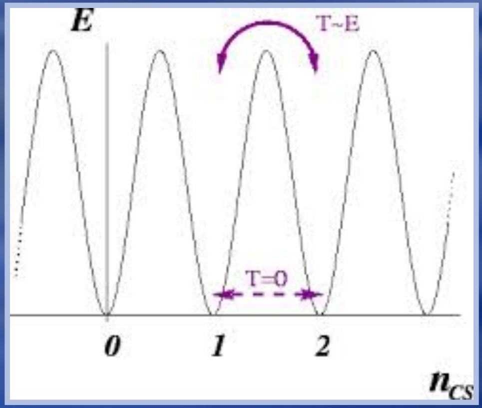
Ketchum & Adams 2008

Uncertainties

- As one journeys deeper into future time, projections necessarily become more uncertain (our basic timeline stops at cosmological decade $n = 100$).
- As we learn more about the fundamental laws of physics, or if the laws change with cosmological time, corrections (both large and small) to this timeline must be made.

Higher Order Proton Decay

- If baryon decay is suppressed at leading order, it can still (sometimes) take place at higher order: n = 100 – 160
- The vacuum state of the standard model of particle physics allows tunneling transitions – sphalerons – that have timescale: n = 141



NOTE: Higher order proton decay is hard to observe

- The universe contains `only' about 10^78 protons in total. If the proton decay timescale is n = 100, e.g., then the probability that a single proton has decayed in the whole universe, thus far in time, is only about 0.000000000001

Liquid Rocks

- Since atoms within a lattice can tunnel via quantum mechanics, they can change places, so that any solid is really a liquid over the long term. Time required for rock to be a liquid:

$$t = 10^{65}\, yr$$

$$n = 65$$

Infinite Monkey Theorem

- Given enough time, a hypothetical monkey typing at random would, as part of his output, almost surely, produce all of the plays of Shakespeare

$$t = 10^{500}\, yr$$

$$n = 500$$

The Iron Age

- Because iron nuclei have the highest binding energy per particle, all nuclei will decay to iron if you wait long enough:

$$t = 10^{1500}\,yr \;\rightarrow\; n = 1500$$

Tunneling to Black Holes

- In the absence of proton decay, white dwarfs would live forever in the absence of a lower energy state, i.e., a black hole state. But it takes a long time for a white dwarf to tunnel into a black hole:

$$t = 10^{10^{76}}\, yr \rightarrow n = 10^{76}$$

A Basic Lesson

- The time scales of the last three processes are much longer than the time scales considered thus far.
- None of the last three processes are likely to happen – ever. Another process, in this case proton decay, will occur first (most likely) and thereby prevent them from happening.

Vacuum Tunneling Time Scales

$$P = K\exp[-S_4]$$

$$V(\phi) = \lambda\phi^4 - a\phi^3 + b\phi^2 + c\phi + d$$

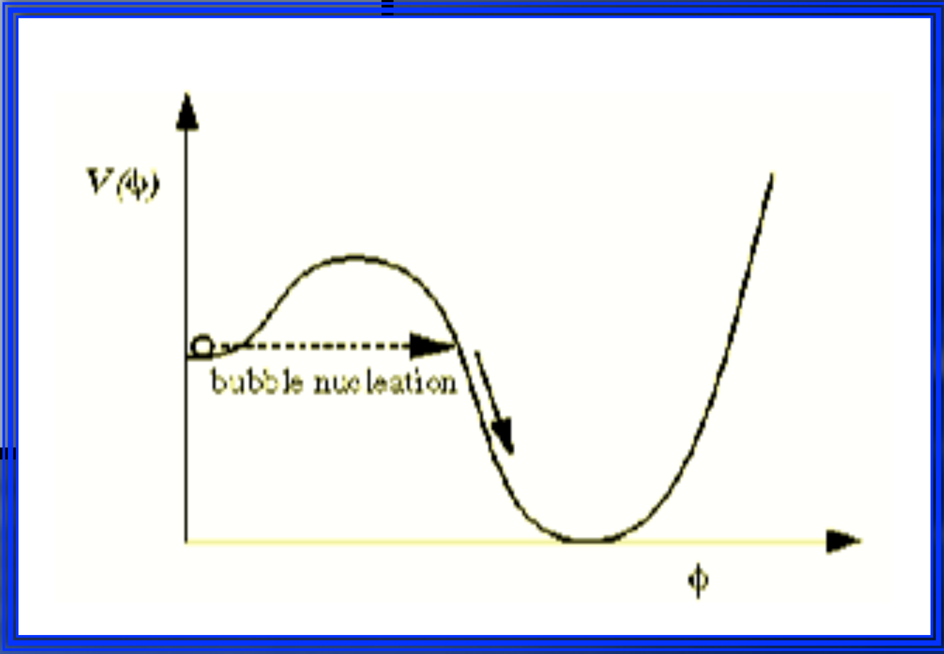
$$need\ \ S_4 \geq 231\ \log 10 \approx 532\ \ (survival)$$

$$for\ \ \lambda = 0.1 - 1:$$

$$0.5 < S_4 < 30{,}000$$

$$t_{\max} \approx 10^{12{,}800}\, yr$$

$$n \approx 12{,}800$$



Wrapping Up

- The future evolution of the universe is a rich subject – many many topics
- Studies of the future universe provide us with a deeper understanding of the present-day universe
- As our theories get farther from the experimental constraints: Be careful!

Discussion Question

- We have introduced the concept of a Copernican Time Principle. But: The cosmos does indeed evolve with time, so that life – as we know it – is certainly more likely to arise in a particular range of epochs (maybe n = 6 – 30). To what extent is such a principle valid or useful?

Discussion Question

- What happens to this (or any) projection of the future history of the universe if the laws of physics are time dependent?
- Experiments => we are good up to cosmological decade $n = 15$ or so; but there is a lot of real estate at later times

Discussion Question

- Given the uncertainties inherent in studying the future universe, at what point does the exercise stop being science?
- Similarly, as we go back in time toward the moment of the Big Bang, at what point does that exercise stop being science?
- (in both cases, one moves farther away from experimental confirmation/refutation)

Discussion Question

- There is an asymmetry between the past history and future history of the universe. We can look for signatures of past events but not for future events. To what extent does this asymmetry affect the answers to the previous questions?