Stellar Structure and Galactic probes of Modified Gravity

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w/ M. Banerji (in progress)
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Itzykson 17 Heart of Darkness

"... and a lot of Astrophysics is messy."

Mark Wyman

- Evading Solar System Bounds : Screening Mechanisms
- "Real" Astrophysical Probes : spectra/structure of galaxies, stars, HI regions.
- Stellar structure and modified Gravity
- Simulating stellar evolution in the presence of modified gravity

New Exotic Matter or New Gravity?

General Relativity is very strongly constrained on solar system scales.

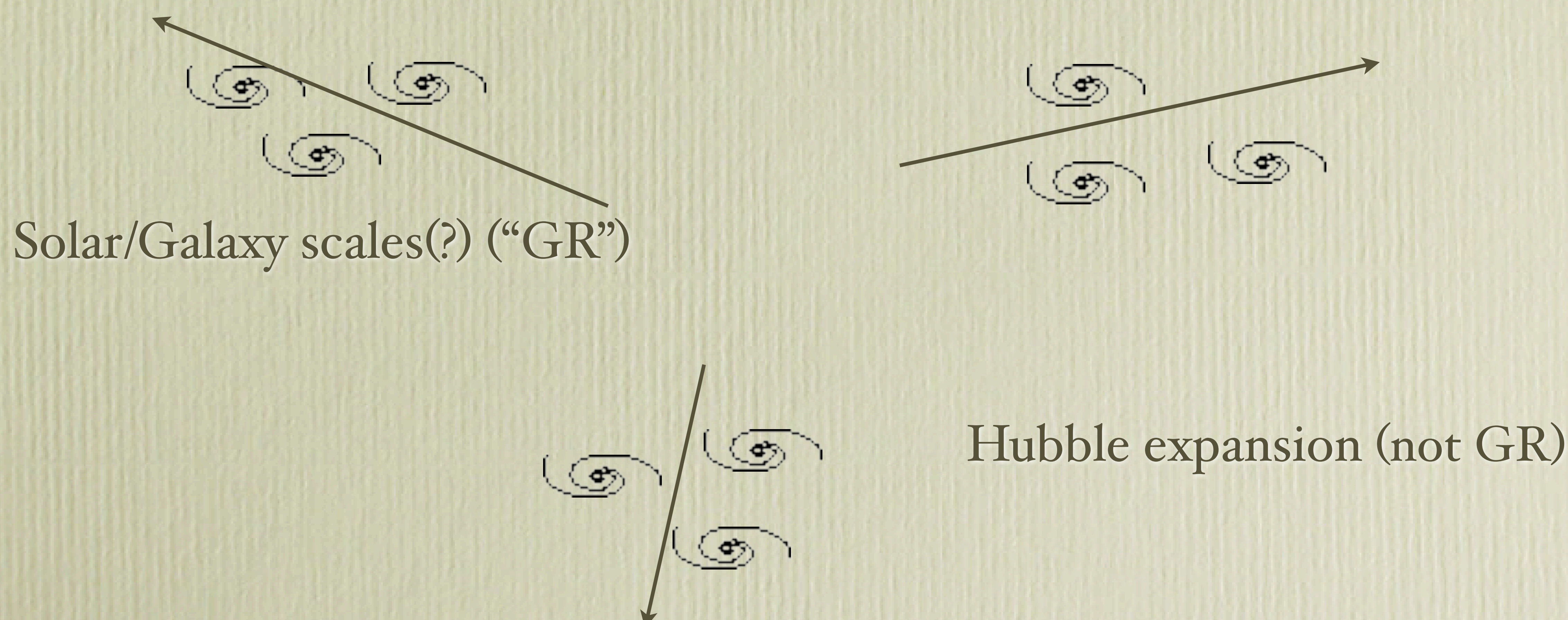
Large Scales (GR Broken?)		Solar System Scales (GR OK)
CMB, Large Scale Structure, Supernova Type Ia	*vs*	Mercury Precession, Torsion Tests, lensing by sun, Spacecraft trajectories lunar ranging etc.

Our Ingredients : gravity + 1 scalar d.o.f.

“Screening” Mechanisms

Loophole : change gravity at large scales, but keep gravity “the same” at small scales

Screening **:** suppress the effects of the extra scalar degree of freedom ‘locally’, while allowing it to change GR globally.



“Screening” Mechanisms

Our Ingredients : gravity + 1 scalar d.o.f.

Three known mechanisms :

Chameleons Khoury + Weltman (2004) Symmetrons Pietroni (2004), Hinterbichler + Khoury (2010) Brax et al (2010)	Relies on changing gravity as a function of *local ambient potential* e.g. $f(R)$

Vainshstein Mechanism
Vainshstein (1972)

operate via non-trivial scalar self-couplings (e.g. massive gravity)

Any viable theory of modified gravity must have some form of screening mechanism

Screened and Unscreened Objects

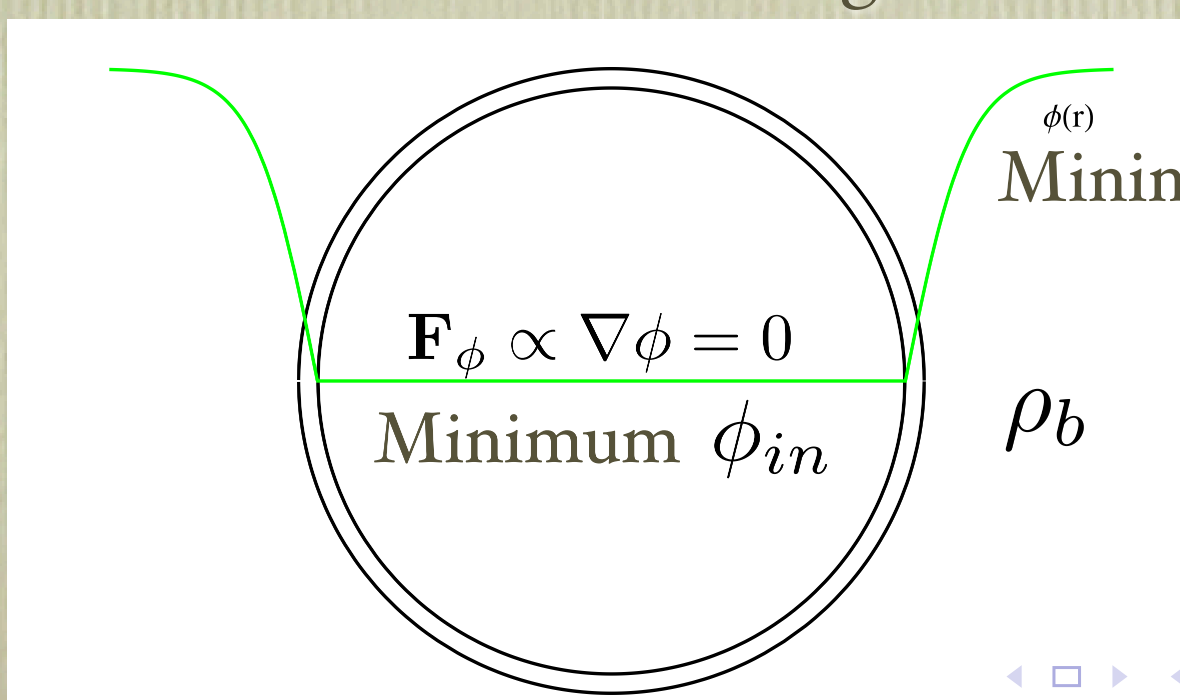
5th force is proportional to *gradient* of ϕ

$$\mathbf{F}_\phi \propto \sqrt{G}\beta(\phi)\vec{\nabla}\phi \qquad \beta(\phi) = \frac{d\ln A(\phi)}{d\phi}$$

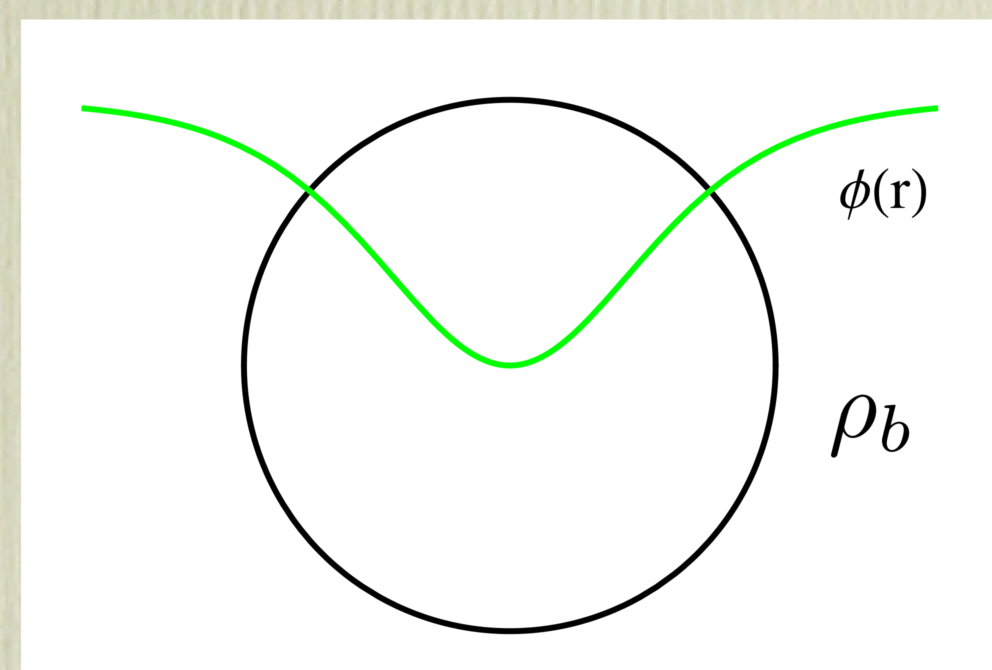
Homogenous ambient ρ_b = no gradients = no 5th force

Perturbation around ambient generates *gradients*

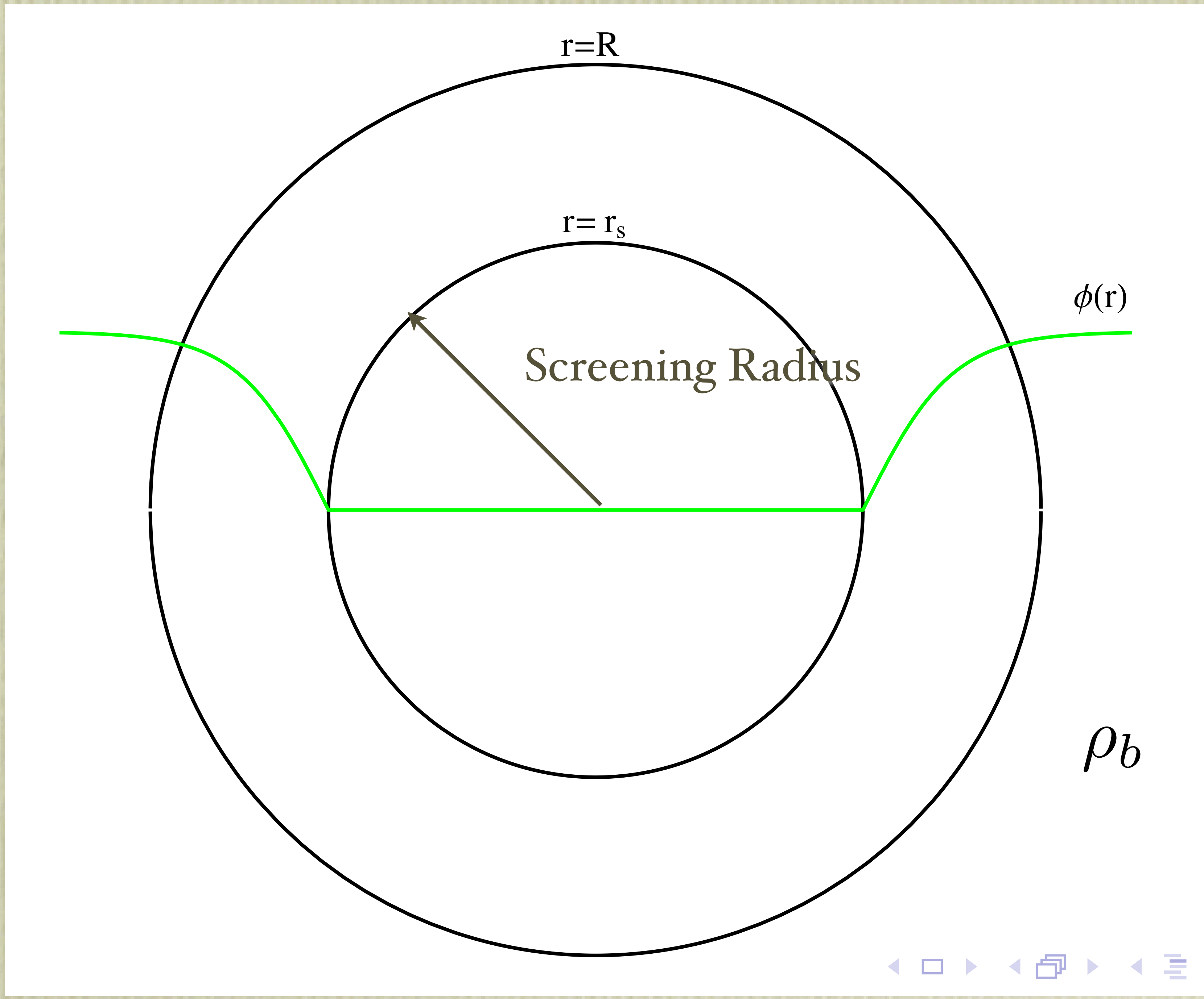
Big Perturbation from ambient density
"Thin Shell Screening"



Small Perturbation from ambient density
"Fully Unscreened"



Partially Screened Objects



$$\vec{\nabla}^2\phi \approx \begin{cases} \beta_0\rho(r)/M_{pl} & r_{\rm s} < r \ll m_0^{-1} \\ 0 & r < r_{\rm s} \end{cases} \quad \to \mathbf{f}_\phi \approx 2\beta_0\mathbf{f}_N$$

Parameterizing Modified Gravity

Two Parameters : χ_b , α_b

Is it unscreened? If it is, how strong is the fifth force?

$$\chi_b \equiv \frac{\phi_b}{2M_p\beta_b} > \text{Newtonian Potential } \Phi_N$$

Screening?

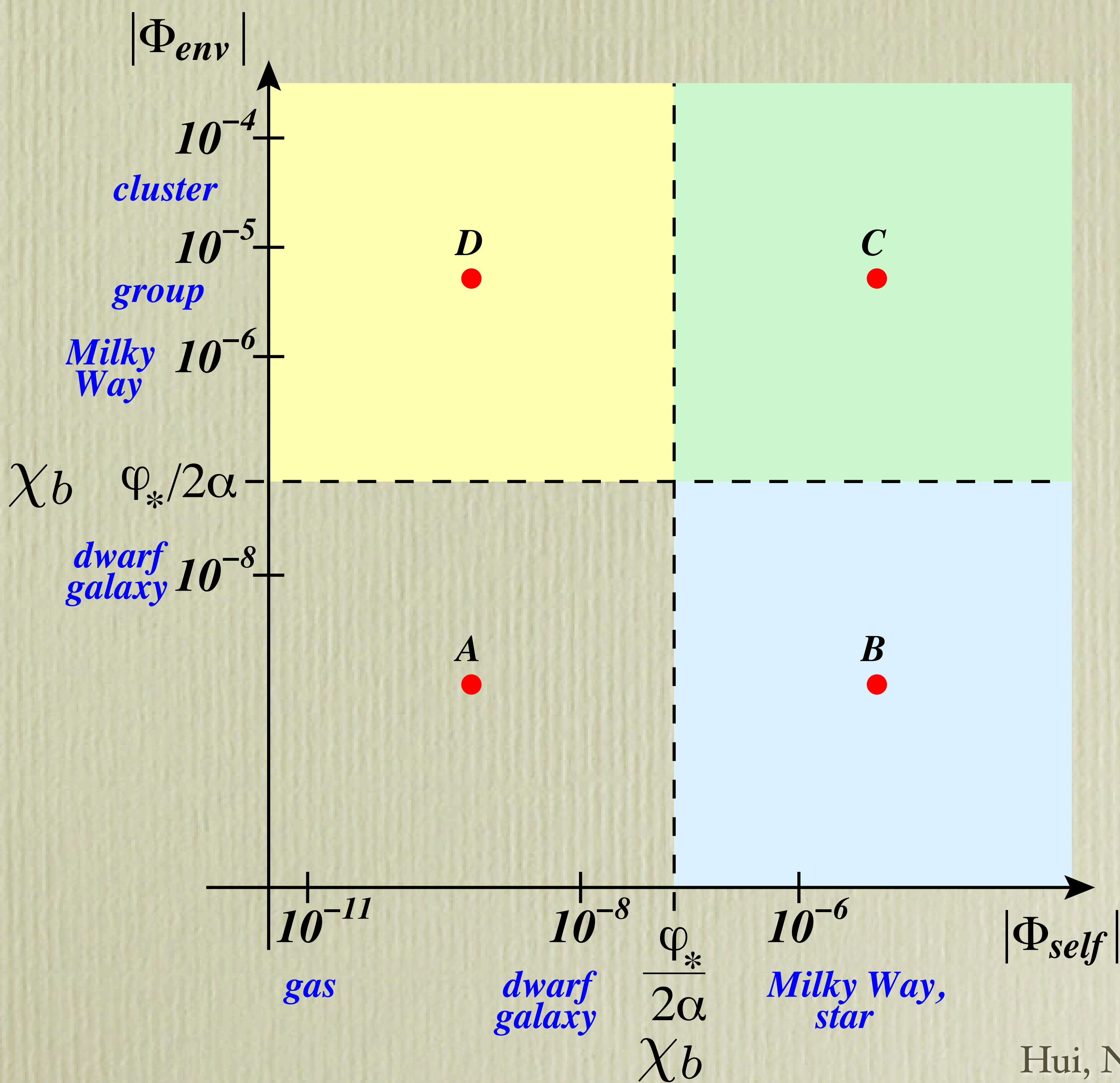
$$\alpha_b \equiv 2\beta_b^2 \quad \beta_b = \frac{d\ln A(\phi_b)}{d\phi}$$

If unscreened, how strong?

Example: $f(R)$ theories , $\alpha_b = 1/3$

Current constraints : $\chi_b < 10^{-4}$ (Halo Cluster, Schmidt (2009)) $\chi_b < 10^{-6}$ (Solar System (?))

Who screens What?



Hui, Nicolis + Stubbs (2009)

For MG to act, should be not self-screened or screened by other objects.

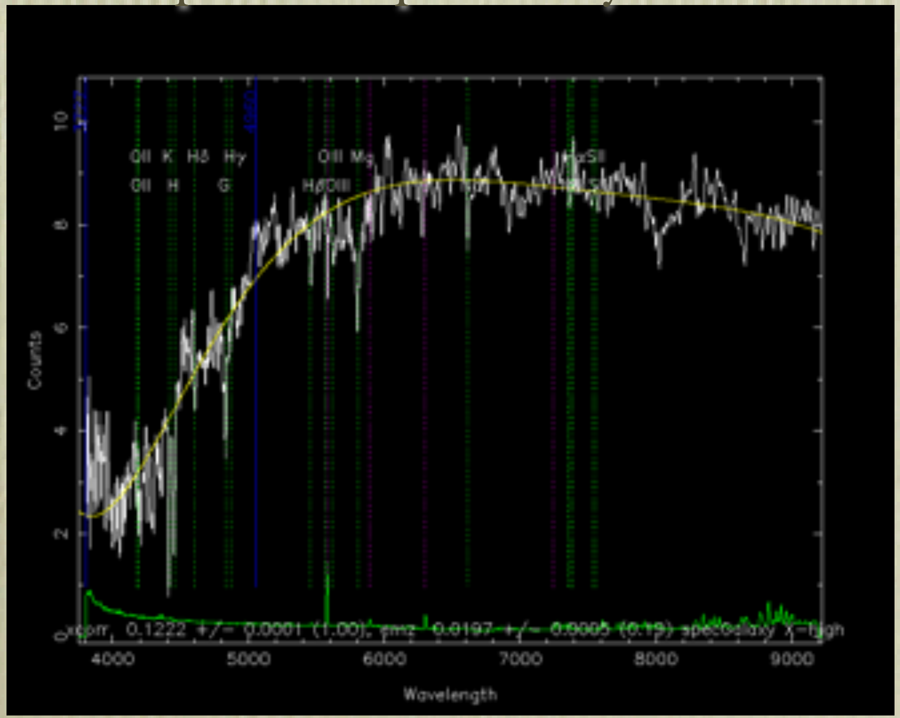
Some Assumptions/Fine Print

- Quasi-static Limit : $\frac{d\phi}{dt} \approx 0$
- Scalar field contributes little energy density
- Conformal/Coupling factor $A^2(\phi) \approx 1$

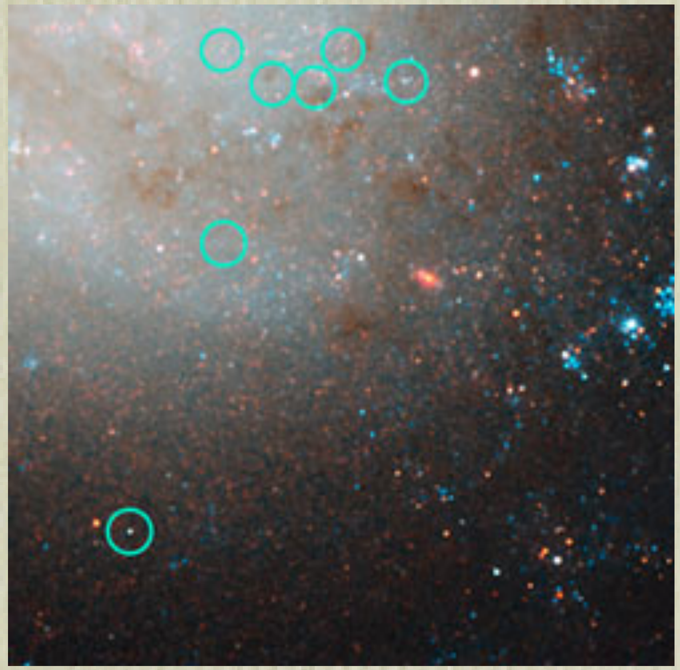
A ton of Astrophysical Data!!

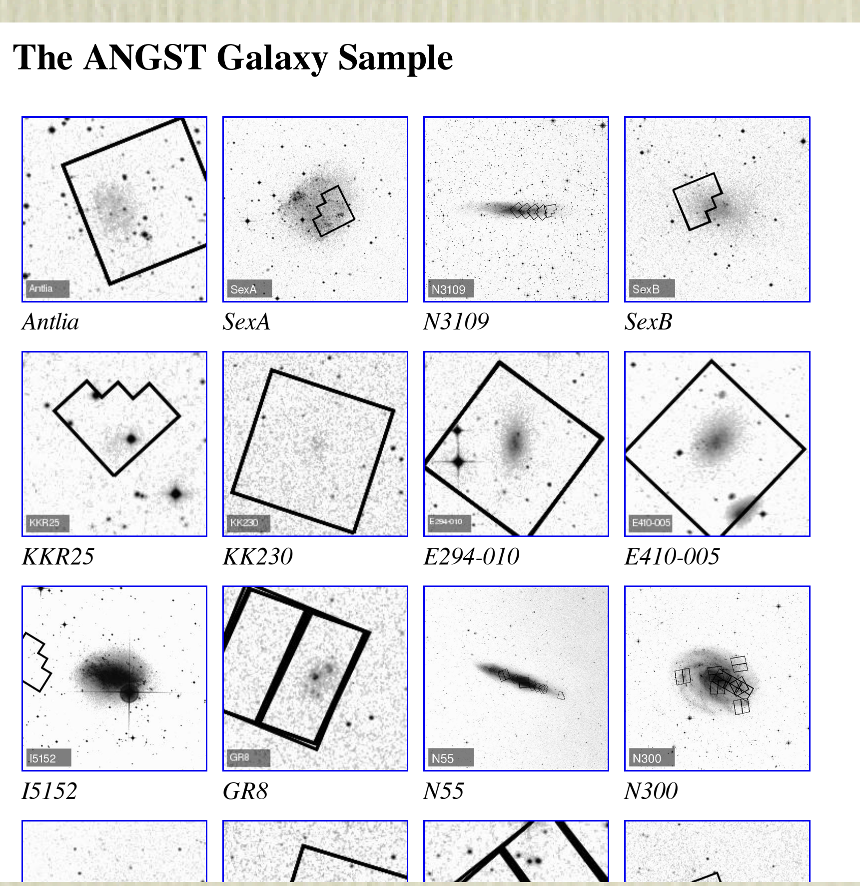
- Large Galaxy Surveys (SDSS/LSST) : galaxy *spectra*, metallicities, morphology
- Internal structure of galaxies : orbits of HI gas clouds, globular clusters, satellites
- Stellar census of globular clusters, nearby dwarfs (ANGST), Cepheids/RR Lyrae, red giants stars

SDSS Spectroscopic Survey



HST Cepheids Survey





Messy, but also a lot of information

- Complex interaction between different processes at many different energy scales
- Some *standard* physical processes not well understood (e.g. supernova feedback, effects of galactic B field, galaxy-galaxy interaction etc.)
- MG => O(1) effects! Problem are : *degeneracies* between modified gravity signatures and "regular observables".
- We want to figure out what are the signatures and how to break the degeneracies.

Next : Modified Gravity Changes Stellar Behavior

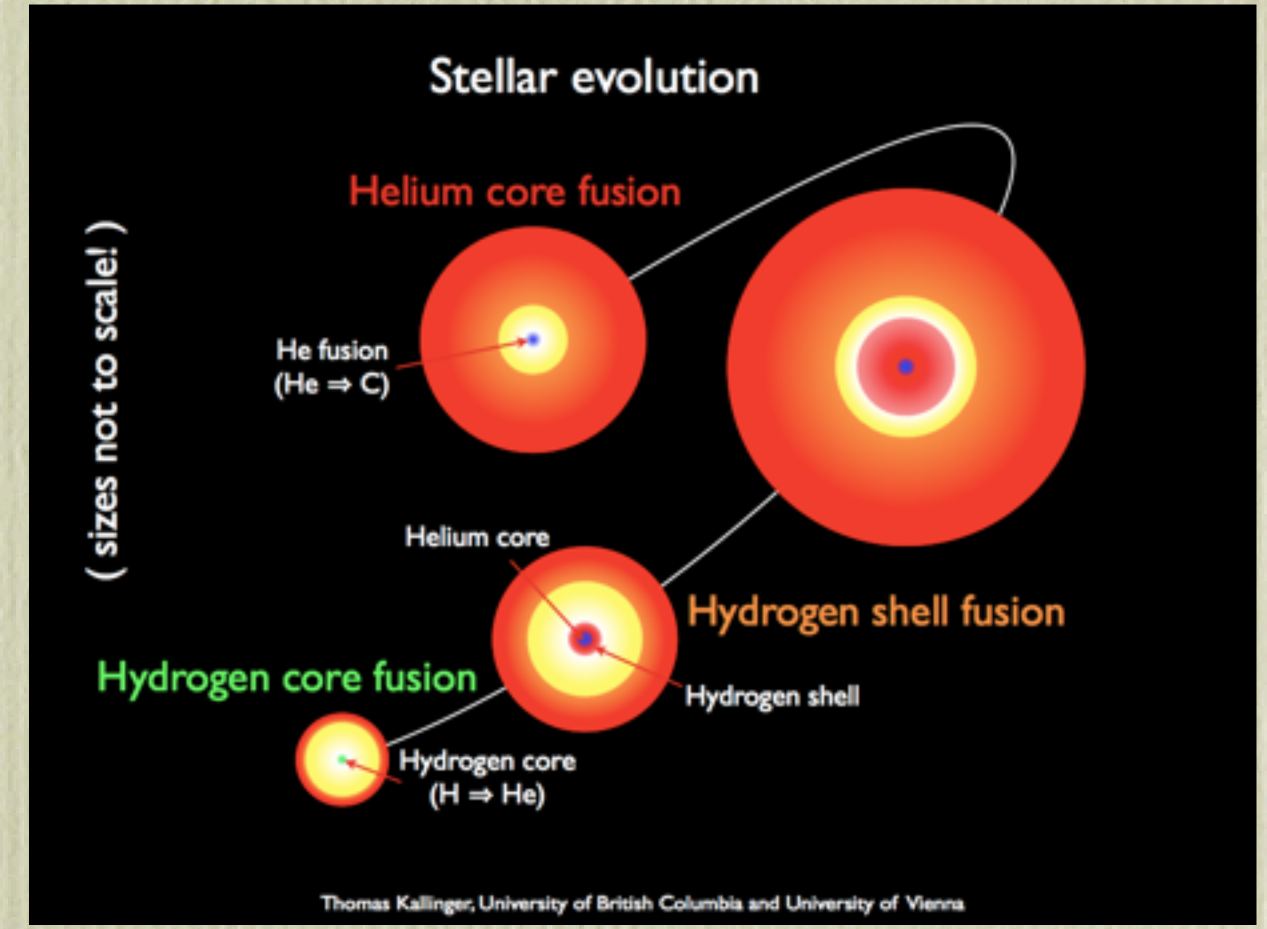
Chang + Hui (2010),
Davis, Lim, Sakstein, Shaw (2011)

- Modified Gravity makes gravity stronger
- To support itself, stars need higher pressures
- Hence it needs to be hotter and burns fuel at a higher rate
- Stars are then more luminous, but live shorter lives!

Rest of the Talk will be about Stars!

The Life of a Star

Astronomy-in-a-minute

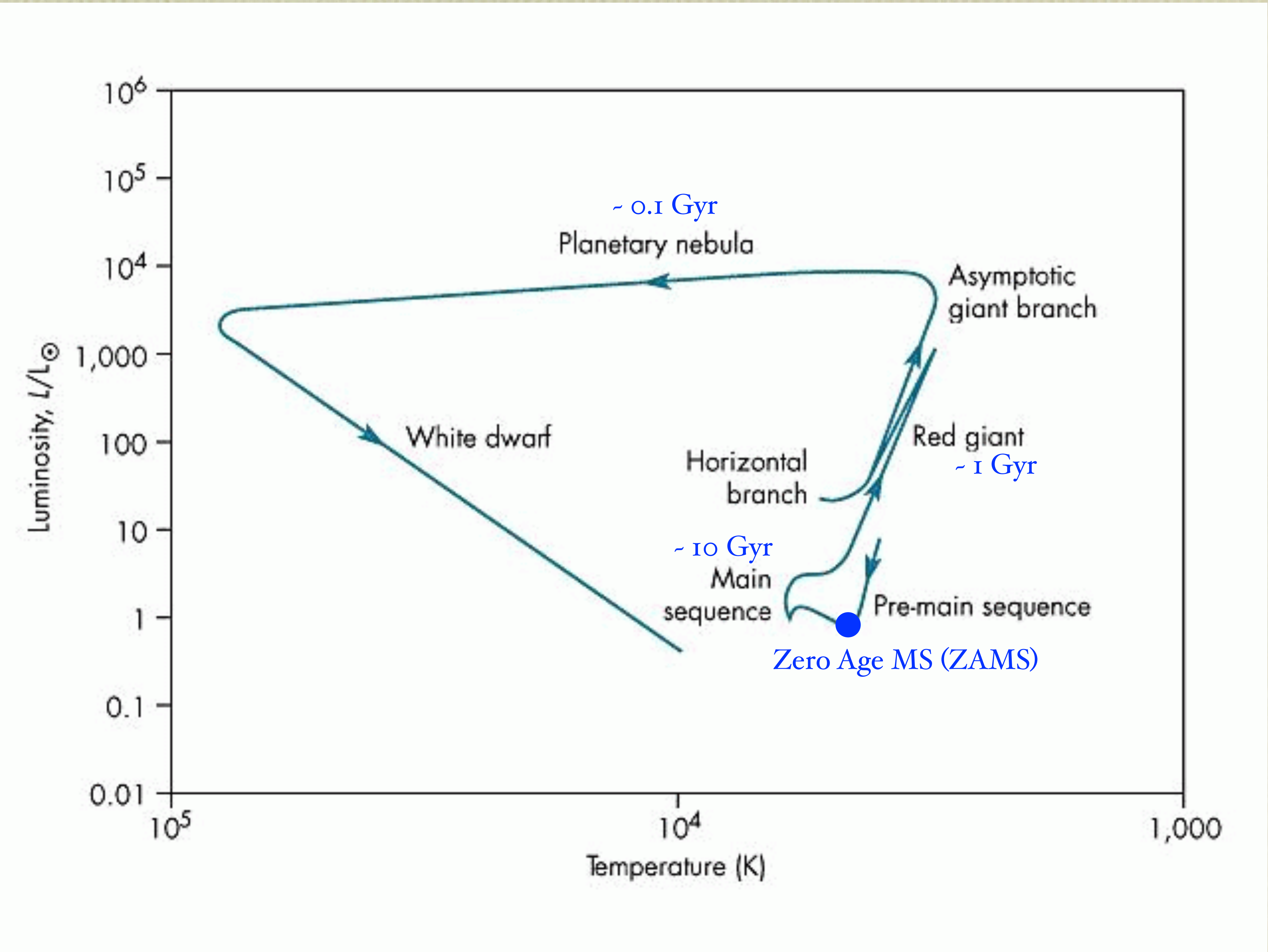


Log Luminosity

Sun lifetime ~ 10 Gyr

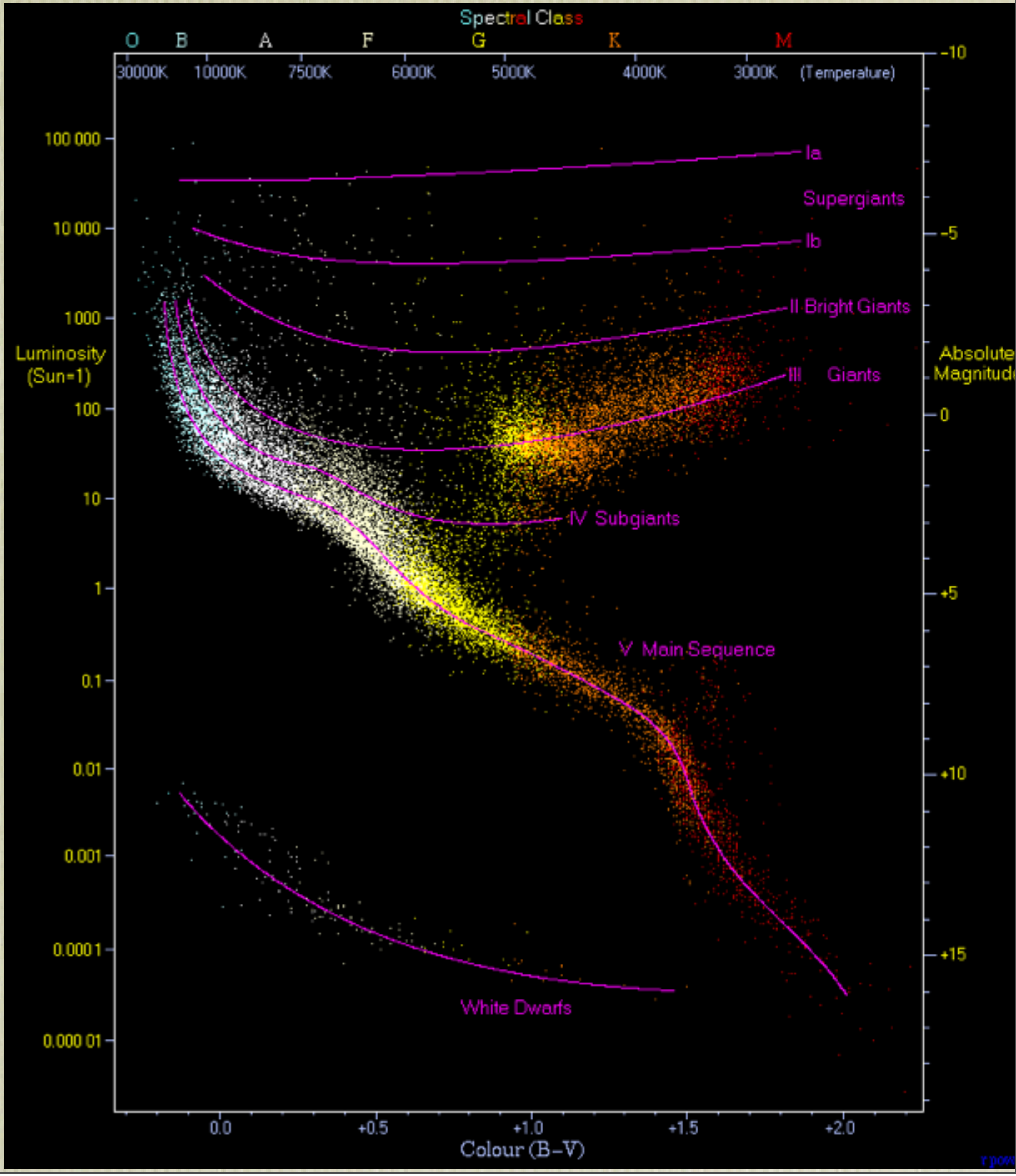
Roughly : Burn H to make He to make C to make N and O as Temperature increase

The Life of a Star



The Life of a Star

- Hertzrung-Russell Diagram (HR diagram)
- Evolutionary tracks (isochrones) depends on mass, composition and its environment. *And gravitational model!*
- Assumption (dangerous) : ambient density remains the same.



Stellar Structure Equations

$$\frac{dP}{dr} = -\frac{G\rho m}{r^2} \ , \ \ \frac{dm}{dr} = 4\pi r^2 \rho \qquad P = (\rho, T)$$

Hydrostatic Equilibrium   Mass Conservation   Equation of State

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L(r)}{4\pi r^2} \ , \ \ \frac{dL(r)}{dr} = 4\pi r^2 \epsilon(r)$$

Radiative Transfer   Energy Generation

Stellar Structure Equations

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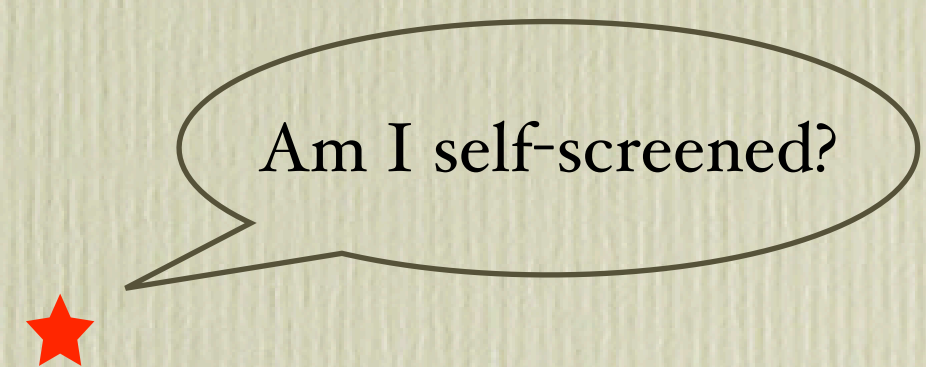
Radiative Transfer — Energy Generation

The only component of the system of equations that needs changing is the Hydrostatics Equilibrium Equation

Lonely Star Model



Solving the Stellar Structure Equations

- Dimension Analysis
- Analytic solution : Eddington Standard model
- Numerical solution (with MESA)

1. Dimension Analysis

See also Fred Adams (2008)

Assuming completely *unscreened* stars : $G_{eff} \to (1+\alpha_b)G$

$$P_{gas} \propto \rho T \ , \ P_{rad} \propto T^4 \ , \ \rho \sim M R^{-3}$$

Low Mass / Gas Supported Stars $L \propto G_{eff}^4 M^3$

High Mass / Radiation Supported Stars $L \propto G_{eff} M$

Example : $f(R)$ theories , $\alpha_b = 1/3$

2. Analytic solution : Eddington Standard Model

$$\frac{dP}{dr} = -\frac{G\rho m}{r^2} \,, \quad \frac{dm}{dr} = 4\pi r^2 \rho \qquad P = (\rho, T)$$

Hydrostatic Equilibrium — Mass Conservation — Equation of State

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Radiative Transfer — Energy Generation

2. Analytic solution : Eddington Standard Model

$$\frac{dP}{dr} = -F_{\rm total}(r)\rho \ , \ \ \frac{dm}{dr} = 4\pi r^2 \rho \qquad P = (\rho, T)$$

Hydrostatic Equilibrium — Mass Conservation — Equation of State

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L(r)}{4\pi r^2} \ , \ \ \frac{dL(r)}{dr} = 4\pi r^2 \epsilon(r)$$

Radiative Transfer — Energy Generation

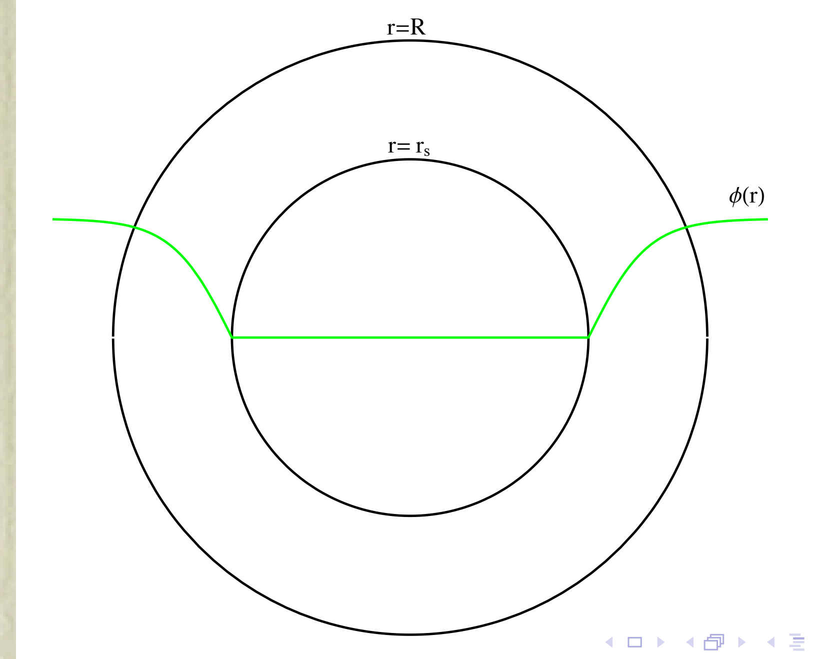
$$F(r) = f_{\rm grav} + f_\phi = \frac{{\rm d}\Phi_{\rm N}}{{\rm d}r} + \frac{\beta(\phi)}{M_{\rm pl}}\frac{{\rm d}\phi}{{\rm d}r}.$$

gravity — 5th force

2. Analytic solution : Eddington Standard Model

$$F(r) = f_{\rm grav} + f_\phi = \frac{\mathrm{d}\Phi_{\rm N}}{\mathrm{d}r} + \frac{\beta(\phi)}{M_{\rm pl}}\frac{\mathrm{d}\phi}{\mathrm{d}r}.$$

gravity 5th force



using $\vec{\nabla}^2\phi \approx \begin{cases} \beta_0\rho(r)/M_{pl} & r_{\rm s} < r \ll m_0^{-1} \\ 0 & r < r_{\rm s} \end{cases}$

$$\frac{\beta(\phi)}{M_{\rm pl}}\frac{\mathrm{d}\phi}{\mathrm{d}r} \approx \alpha_0 \left[\frac{G\left(m(r) - m(r_{\rm s})\right)}{r^2}\right] H(r - r_{\rm s}).$$

$$4\pi G \int_{r_{\rm s}}^{R} r\rho(r)\,\mathrm{d}r = \chi_0 \equiv \frac{\phi_0}{2\beta_0\, M_{\rm pl}}.$$

Implicit equation for screening radius

$$G_{eff} \to G(1 + \alpha_{eff}(r))$$

$$\alpha_{eff}(r) = \alpha_b\left(1 - \frac{m(r_s)}{m(r)}\right) H(r - r_s)$$

2. Analytic solution : Eddington Standard Model

$$\frac{dP}{dr} = -\frac{G_{eff}\rho m}{r^2}\ , \quad \frac{dm}{dr} = 4\pi r^2 \rho \qquad P = (\rho, T)$$

Hydrostatic Equilibrium — Mass Conservation — Equation of State

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L(r)}{4\pi r^2}\ , \quad \frac{dL(r)}{dr} = 4\pi r^2 \epsilon(r)$$

Radiative Transfer — Energy Generation

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Decoupled

Radiative Transfer — Energy Generation

Constant entropy gradient $T^3 \propto \rho$

2. Analytic solution : Eddington Standard Model

$$\frac{dP}{dr} = -\frac{G_{eff}\rho m}{r^2} \ , \ \ \frac{dm}{dr} = 4\pi r^2 \rho$$

$$P = K\rho^{4/3}$$

Hydrostatic Equilibrium   Mass Conservation   Equation of State

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Decoupled

Radiative Transfer   Energy Generation

Constant entropy gradient $T^3 \propto \rho$

Total gas + radiation pressure $P = P_{gas} + P_{rad} = \frac{P_{rad}}{(1 - b(\alpha_{eff}))}$

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Decoupled

Radiative Transfer — Energy Generation

Constant entropy gradient $T^3 \propto \rho$

Total gas + radiation pressure $P = P_{gas} + P_{rad} = \frac{P_{rad}}{(1 - b(\alpha_{eff}))}$

Opacity is constant $\kappa = \text{constant}$

Semi-Analytic Prescription

Modified Lane-Emden Equations

$$\frac{1}{\xi^2}\frac{d}{d\xi}\left(\xi^2\frac{d\theta(\xi)}{d\xi}\right) = -[1+\alpha_b\Theta(\xi-\xi_s)]\theta^3(\xi)$$

$$\xi \equiv r(P_c/\pi G\rho_c)^{-1/2}$$

$$P = P_c\theta^4(\xi)\ ,\ \rho = \rho_c\theta^3(\xi)\ ,\ T = T_c\theta(\xi)$$

(Totally screened star is an n=3 polytrope.)

Upshot : Luminosity as a function of stellar mass M and χ_b

$$L = \frac{4\pi c(1-b(\alpha_{eff}))[1+\alpha_{eff}(R)]GM}{\kappa}$$

Zeroth-order effect : Stellar Luminosity

$f(R)$ theories , $\alpha_b = 1/3$

Gas Supported $L \propto G_{eff}^4 M^3$

Radiation Supported $L \propto G_{eff} M$

χ_b — 10^{-4} — 10^{-5} — 5x 10^{-6} — 10^{-6}

Live Fast, Die Young

Main Sequence Lifetime $\tau_{MS} = 10 \left(\frac{M}{M_\odot}\right)\left(\frac{L_\odot}{L(M)}\right)$ Gyr

3 times increase in luminosity = 3 times shorter in life!

Stars make metals : MG galaxies more metal rich?

What about the Sun?

- The Sun must be screened, or almost screened. *Self-screening* bounds $\chi_b \sim 10^{-6}$
- Not self-screened, but screened by Milky Way bounds $\chi_b \sim 10^{-6}$
- But perhaps the Local Group dominates? I.e. the Sun is screened by a much deeper potential well?
- Most conservative constraints $\chi_b \sim 10^{-4}$ from galaxy cluster statistics. (Schmidt 2009)

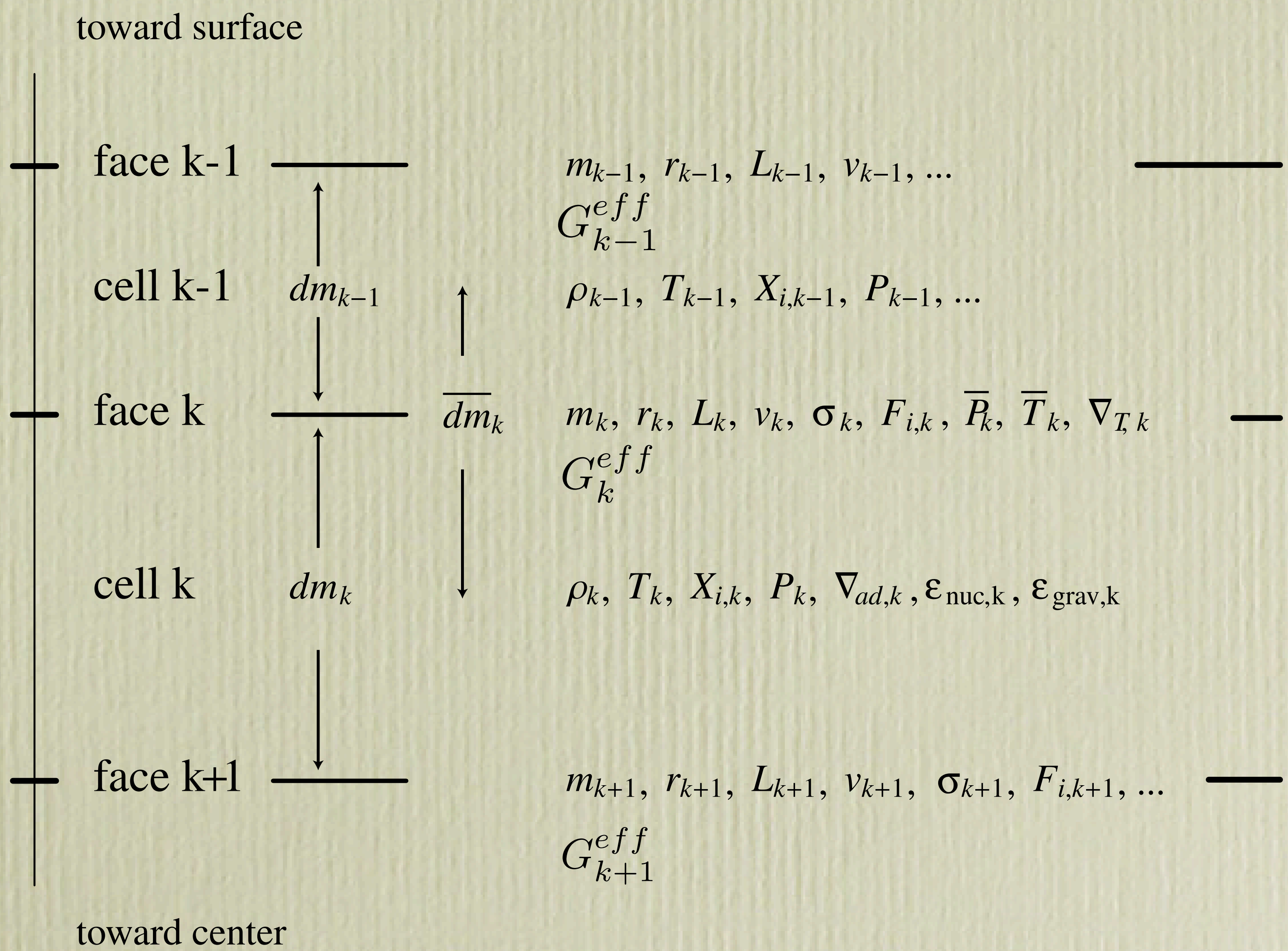
3. Building Realistic Stars/ Galaxies (Numerical)

- To test all this stuff, we need more precise predictions.
- Construct stars/isochrones using stellar simulator (modified MESA code). (w/ Bill Paxton)
- Construct galaxies with galaxy synthesis code (GALEV).

Modified MESA code

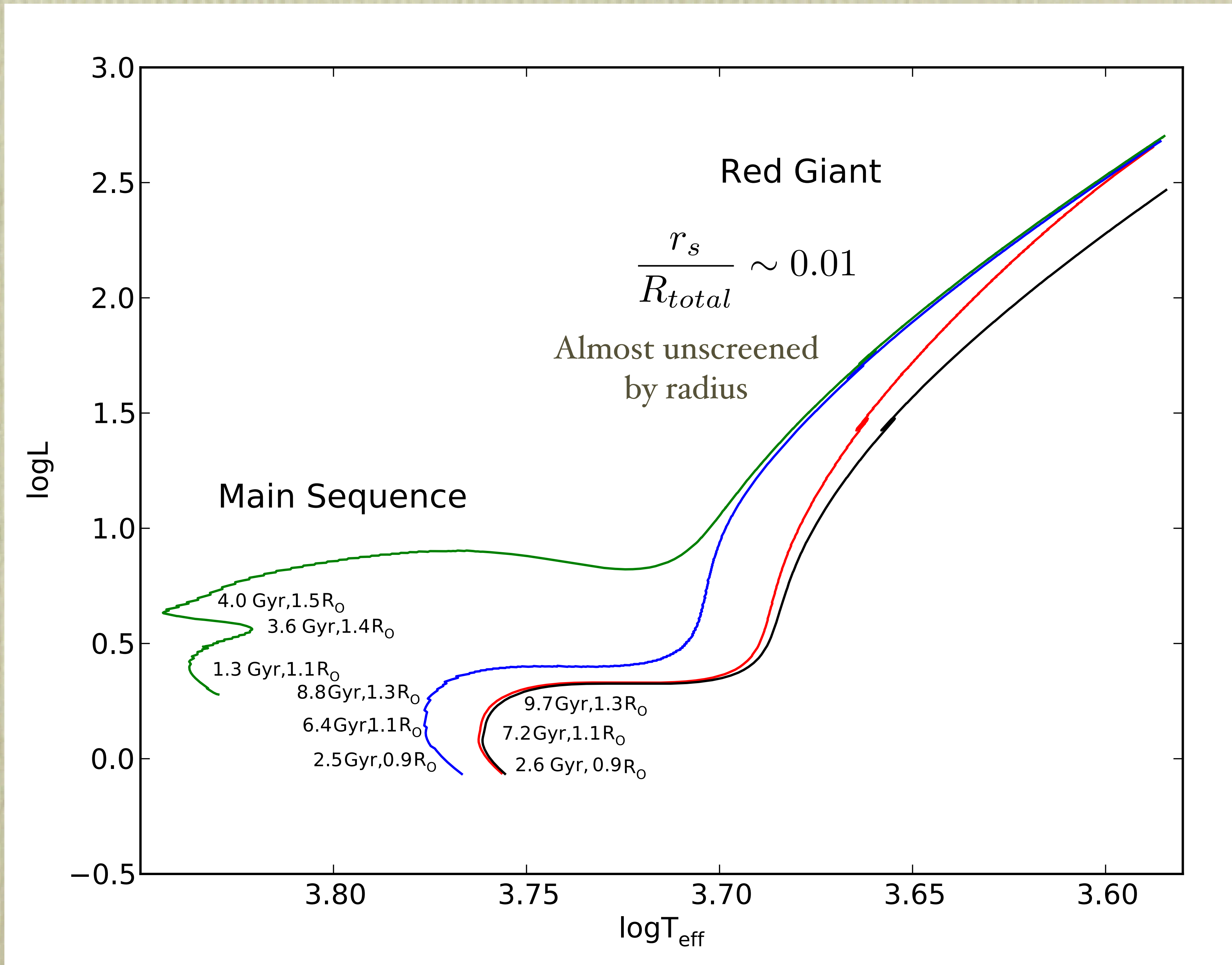
- MESA is a 1-D stellar evolution code with complete convective, nuclear energy generation, opacity modeling.

Bill Paxton (KITP)



Calculate G_{eff} and r_s using previous step $\rho(r)$

Evolution of screened and unscreened stars



Black : Unmodified

Red Blue Green : Modified

Compare Eddington Standard model prediction in the Main Sequence $\Delta T_{eff} \sim \mathcal{O}(100)$ K

$\chi_b = 10^{-6}$ ruled out?

- 65% Solar Mass *Main sequence* star unscreened, O(100) Kelvins temperature boost

- Degenerate with metallicities

- Degenerate with stellar lifetime

- Degenerate with stellar mass.

- Lonely star model breaks -- screening from environment?

Zeroth Order prediction : unscreened Galaxies are brighter

Total luminosity is the sum of all stars' output

$$L_{gal} = \int_{0.08M_\odot}^{100M_\odot} dM \; f_0(M, \tau_{age}) L_{star}(M; \chi_a) \Psi(M)$$

Initial Mass Function IMF

$$\Psi(M) = \frac{dN}{dM} \propto M^{-2.35}$$

Number of stars *born* in mass range dM

(Salpeter IMF)

Fraction of stars that have gone off main sequence

$$f_0(M, \tau_{age}) = \begin{cases} 1 & \tau_{age} < \tau_{MS} \\ \tau_{MS}/\tau_{age}(M) & \tau_{age} > \tau_{MS}(M) \end{cases}$$

Note $\tau_{MS} \propto L_{star}^{-1}$ so high mass (more luminous) stars scale out of the integral.

Galaxy Luminosity

stars burnt out too fast

Most stars screened

Most *additional* contribution comes from low mass stars : redder? But they are hotter : bluer?

Galaxy Clusters and Void Galaxies

- Galaxy Clusters are sitting in deep potential well $\chi_b \sim 10^{-6}$: galaxies and stars inside must be screened

- Milky Way Class galaxies $\chi_b \sim 10^{-6}$ possibly screening out all the stars inside.

- Dwarf Galaxies residing in intercluster voids only feel their own grav potential : $\chi_b \sim 10^{-8}$

Void Dwarf Galaxies should look very different from Cluster Dwarf Galaxies

Observational tests?

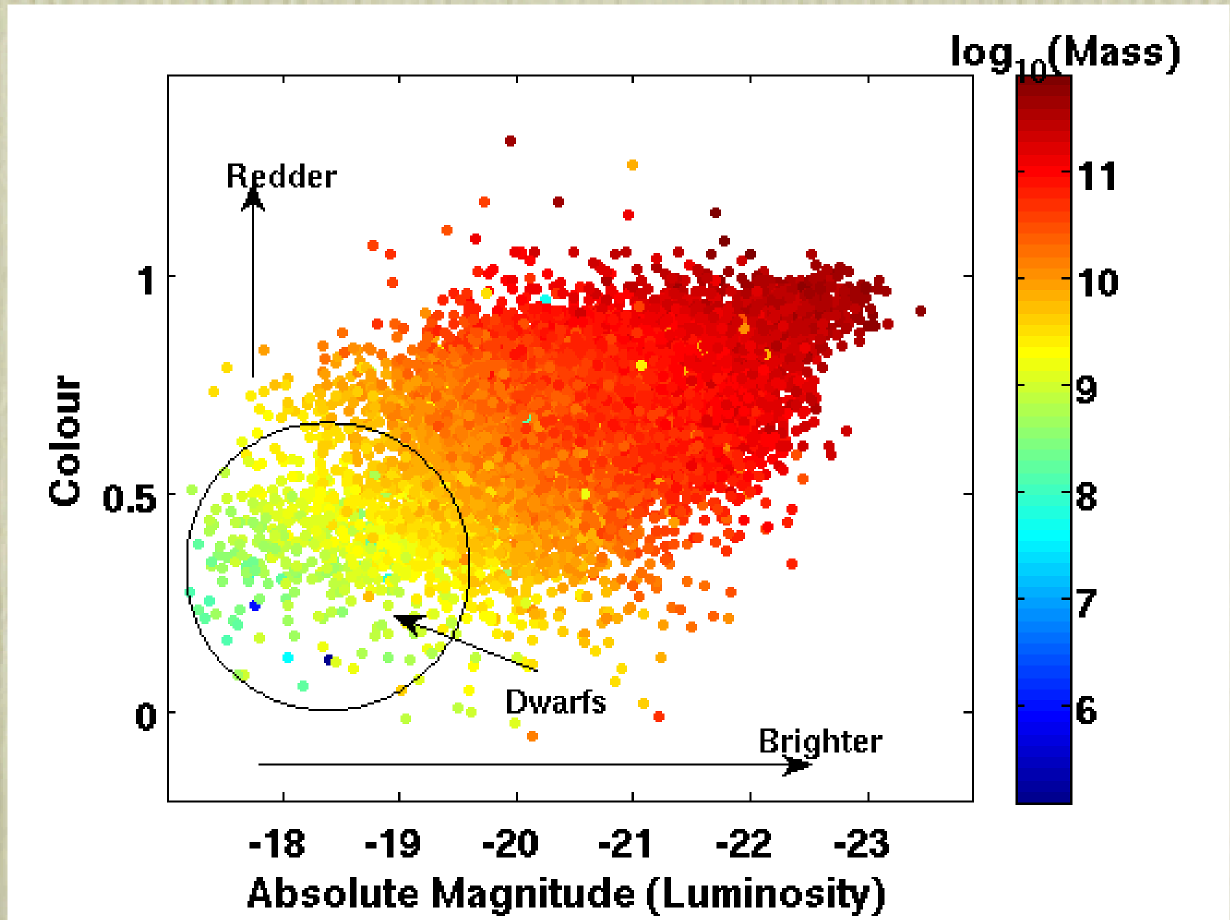
w/Davis, Sakstein, Banerji

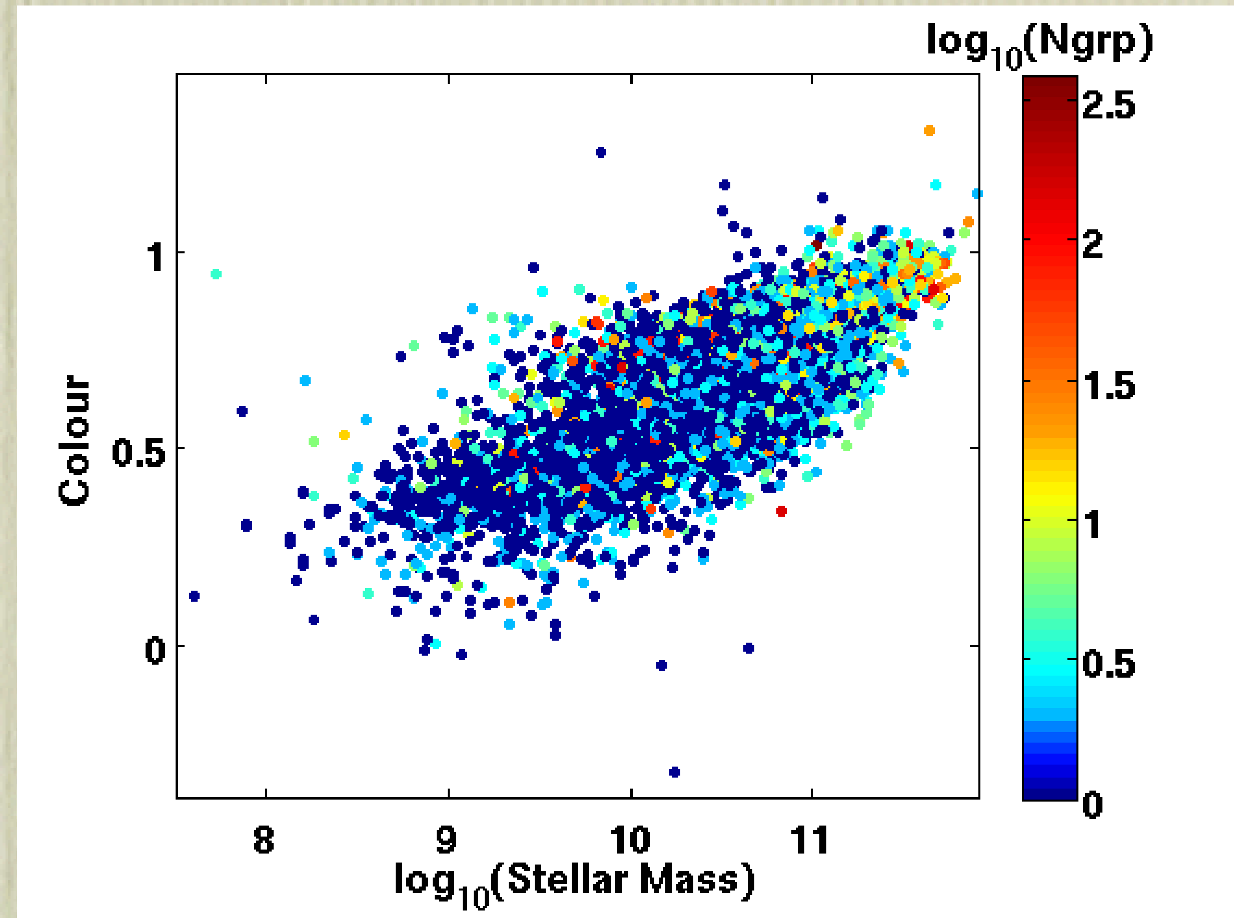
- Void Dwarf galaxies are *more luminous*
- Void Dwarf galaxies are roughly *redder*
- Hertzsprung-Russell diagram different
- Shorter life-cycles : higher metalicities (look older?)
- Look for deviations in populations of dwarfs in SDSS color-color diagrams.

Dwarf Populations in Voids

w/Davis, Sakstein, Banerji

SDSS Local Volume galaxies





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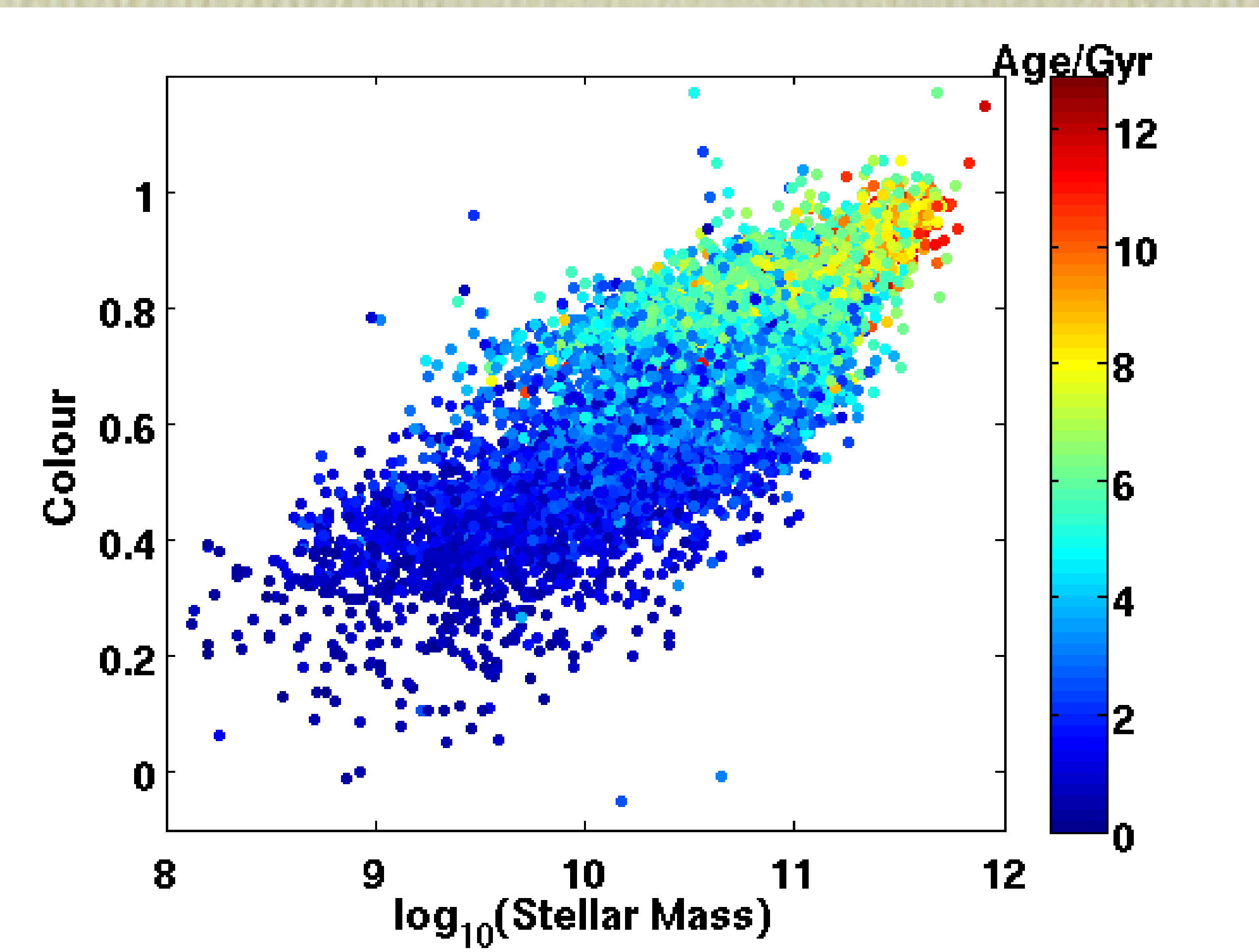
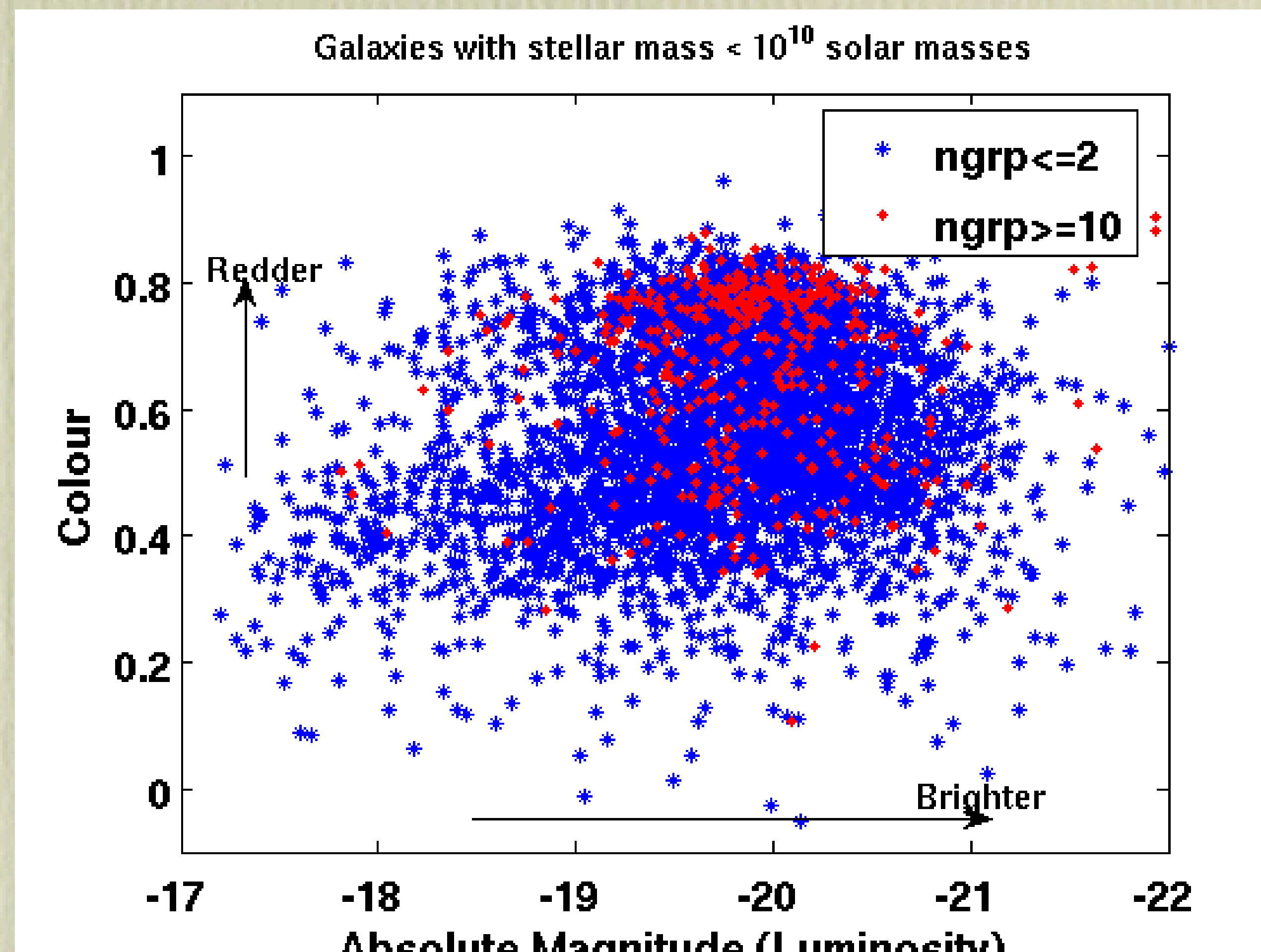


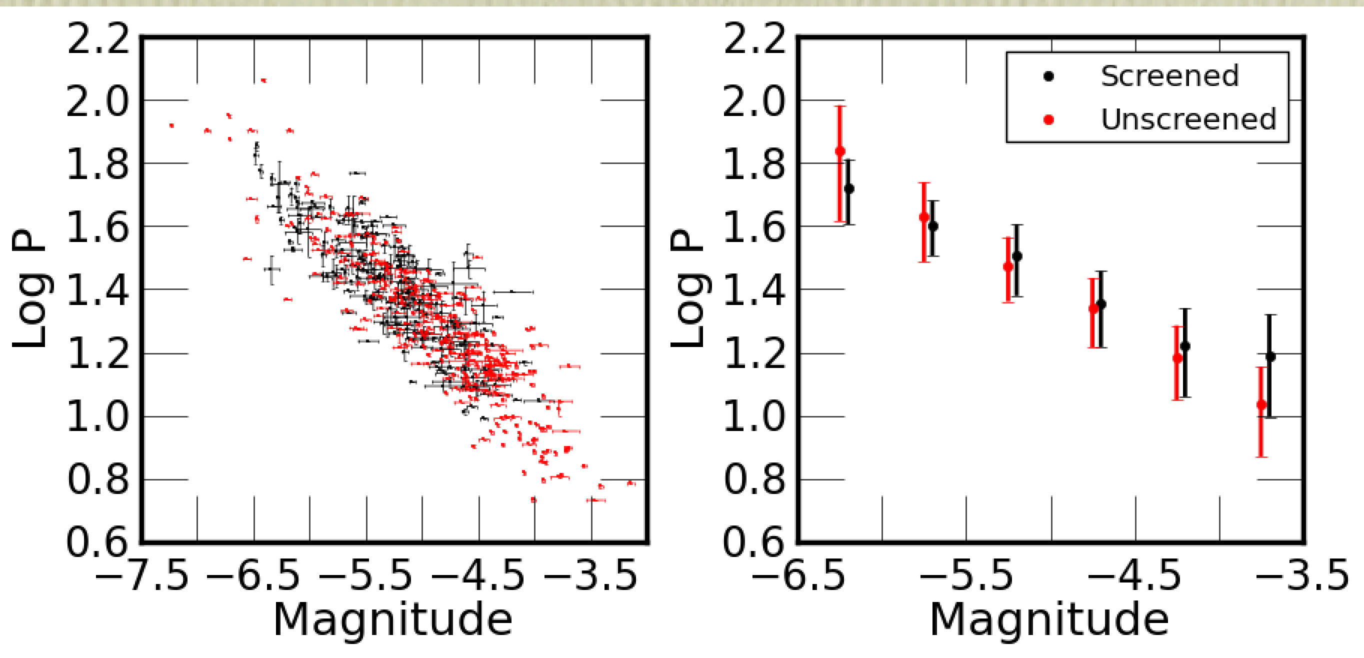


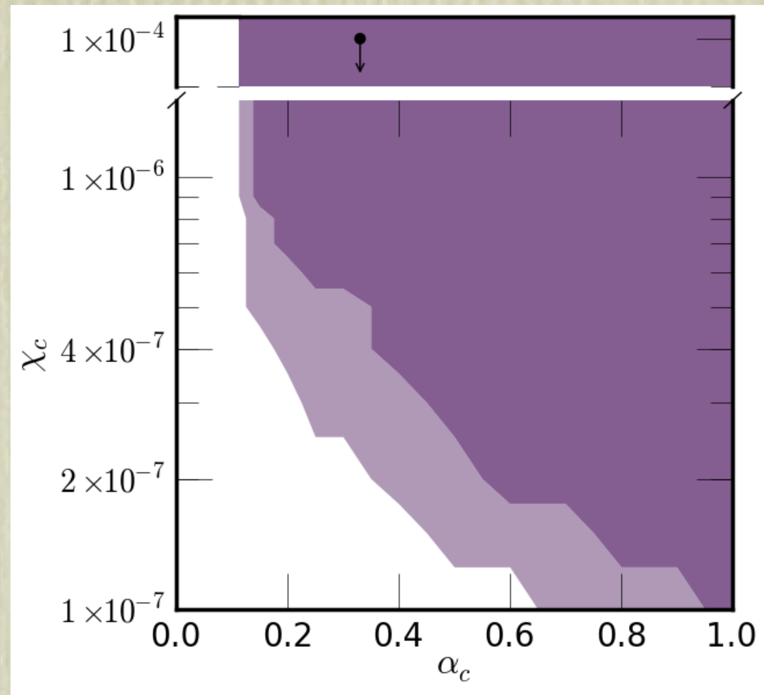
Other tests

- Stellar Pulsations (Cepheids) and distance indicators

$$\tau_{free} \propto (G_{eff}\rho)^{-1/2}$$

arXiv:1204.6044 Jain, Vikram, Sakstein,





- Angular momentum of Galactic Halos : MG halos have higher specific AM.

arXiv:1204.6608 Lee, Zhao, Li, Koyama

Understanding degeneracies

- Mass vs Modified Gravity
- Metallicities vs Modified Gravity
- Environmental evolution (void galaxies vs cluster galaxies) vs Modified Gravity
- Galactic Mass vs Modified Gravity
- Many others etc....

Summary

- MG = O(1) Effects! Stellar structure are modified.
- *Main sequence* stars are affected!
- MG stars are more luminous, more blue, smaller, and live shorter lifetimes.
- Individual stars are hard (no statistics), but galactic effects may be observable.

Thanks!