Introduction to Astronomy and Astrophysics - 1

IUCAA-NCRA Graduate School 2013

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August - September 2013

Coordinate Systems, Units and the Solar System

Locating Objects

- Angular position can be measured accurately; distance difficult
- Spherical Polar Coordinate System:

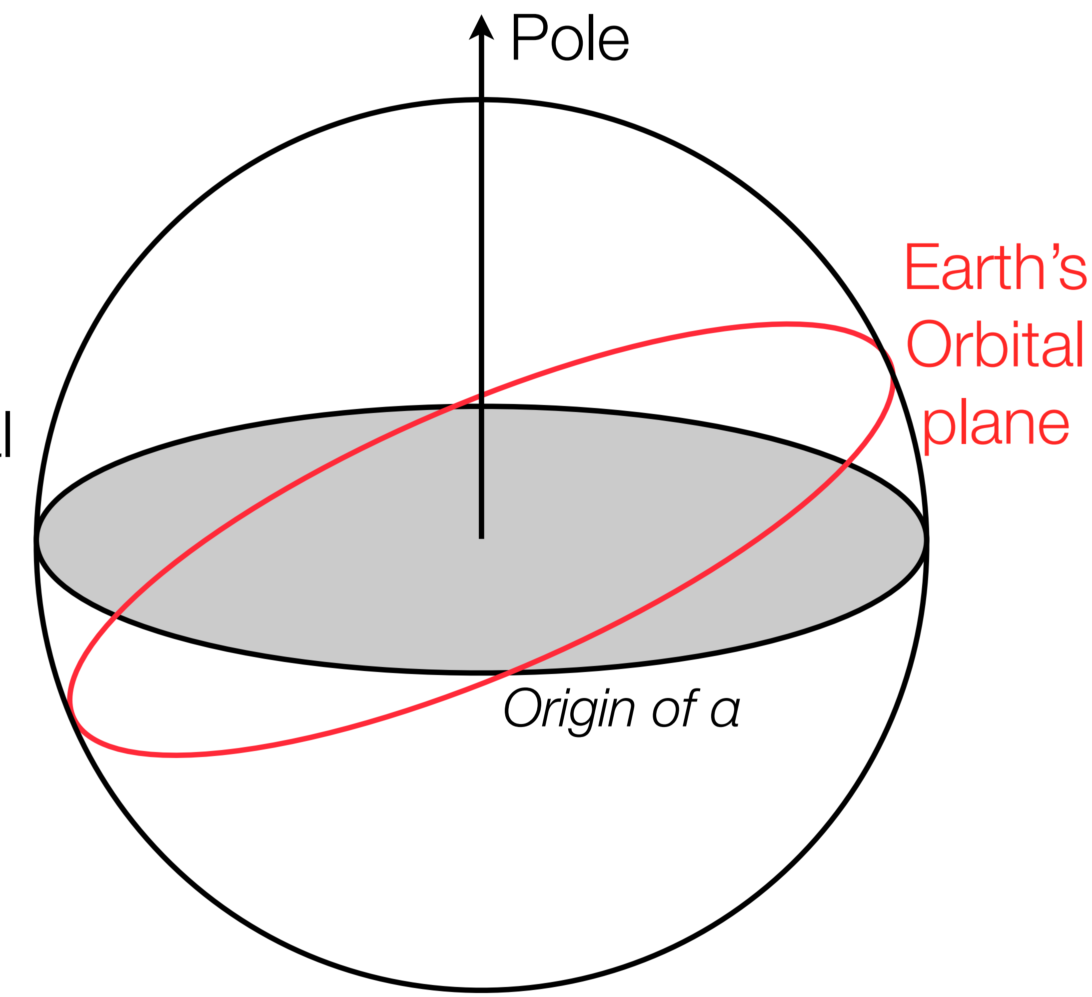
  latitude = Declination (δ)
  longitude = Right Ascension (α)

Time

Solar Day = 24 h
(*time between successive solar transits*)

Earth's Spin Period: 23h56m
(*time between successive stellar transits*)

24h "Sidereal Time" = 23h56m Solar Time

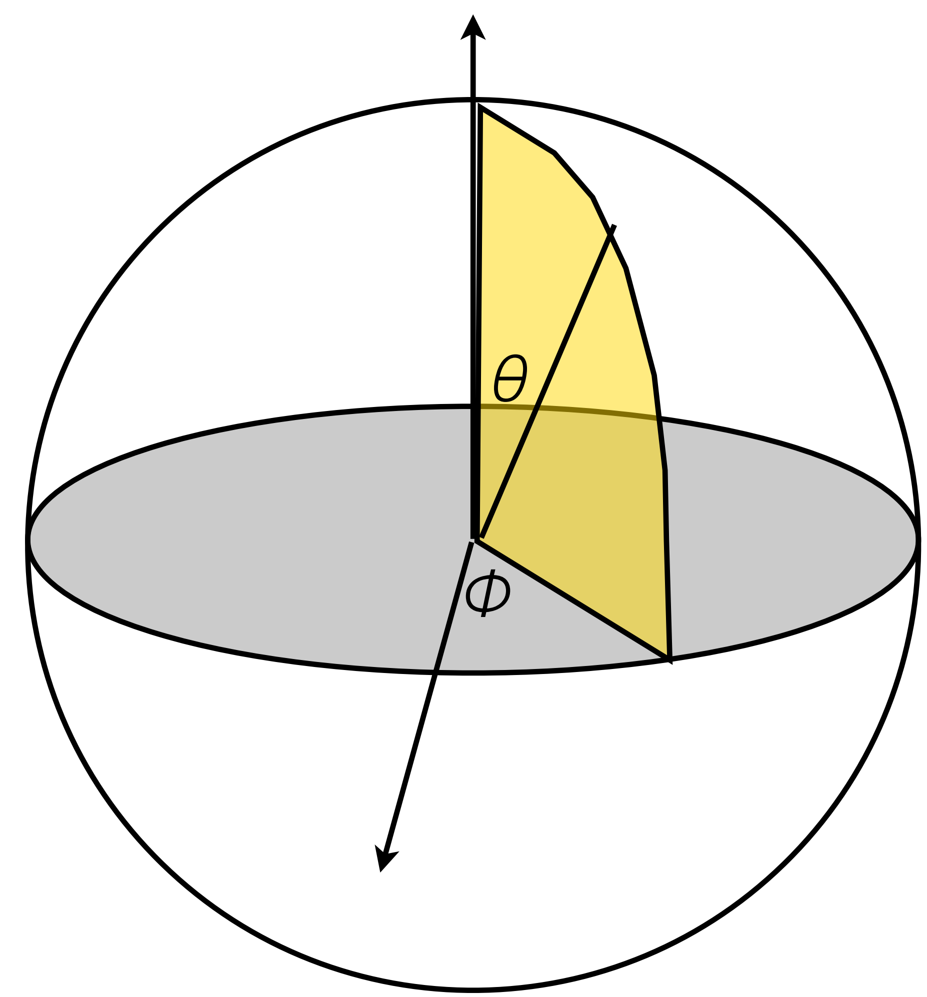


α is expressed in units of time
Transit time of a given α = Local Sidereal Time

Different coordinate systems

Convention: *Latitude: ($\pi/2 - \theta$) ; Longitude: Φ*

- **Equatorial:** Poles: extension of the earth's spin axis
- **Ecliptic:** Poles: Normal to the earth's orbit around the sun
- **Galactic:** Poles: Normal to the plane of the Galaxy



For Equatorial and Ecliptic: same longitude reference (ascending node - vernal equinox)

For Galactic coordinates: longitude reference is the direction to the Galactic Centre

Equatorial coordinates: larger Φ, later rise: RA (α)
latitude = Declination (δ)

Rise and Set

Horizon: tangent plane to the earth's surface at observer's location

geographic latitude λ

$OP = \sin\delta$; $QP = \cos\delta = PB$

$AP = OP\tan\lambda = \sin\delta\tan\lambda$

$\angle APB = \cos^{-1}(AP/PB) = \cos^{-1}\{\tan\delta\tan\lambda\}$

Total angle spent by the source above the horizon

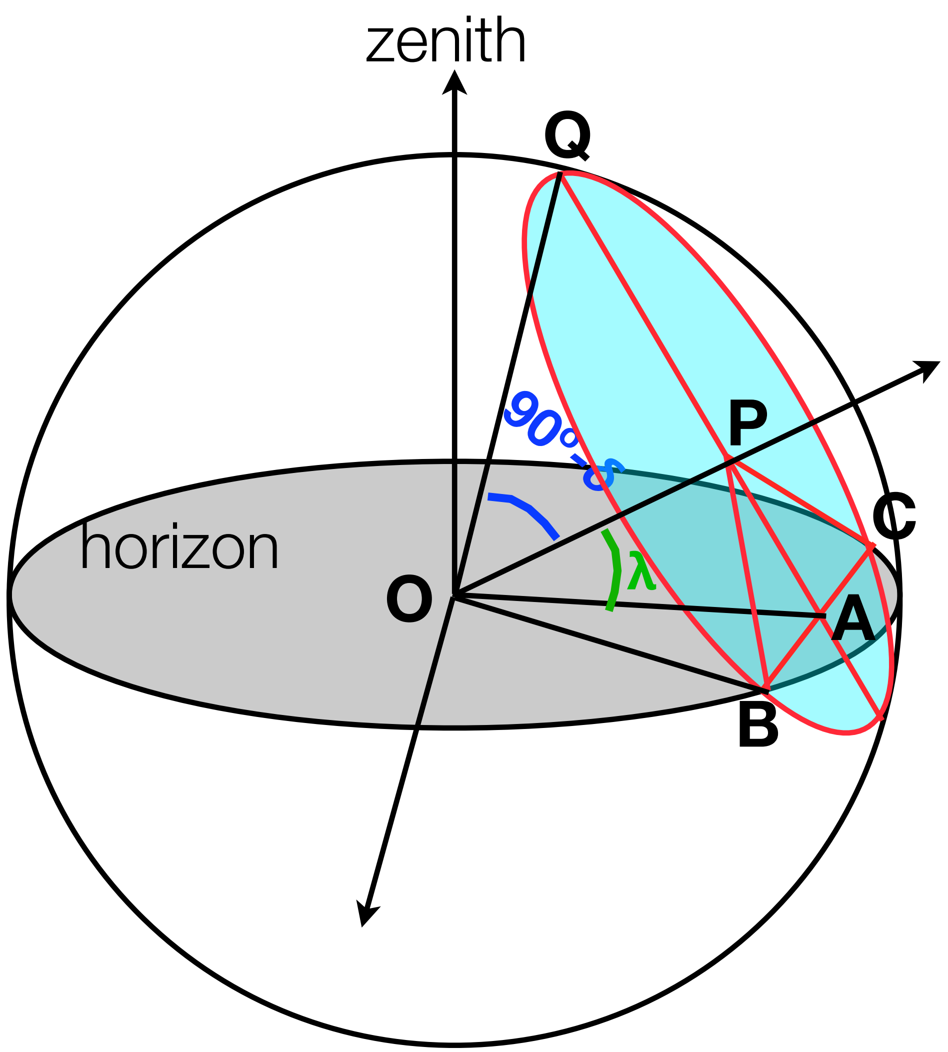
$= 360^o - 2\cos^{-1}\{\tan\delta\tan\lambda\}$

Time spent by the source above the horizon

$= ([360^o - 2\cos^{-1}\{\tan\delta\tan\lambda\}]/15)$ sidereal hours

$= (1436/1440)\,([360^o - 2\cos^{-1}\{\tan\delta\tan\lambda\}]/15)$

hours by solar clock

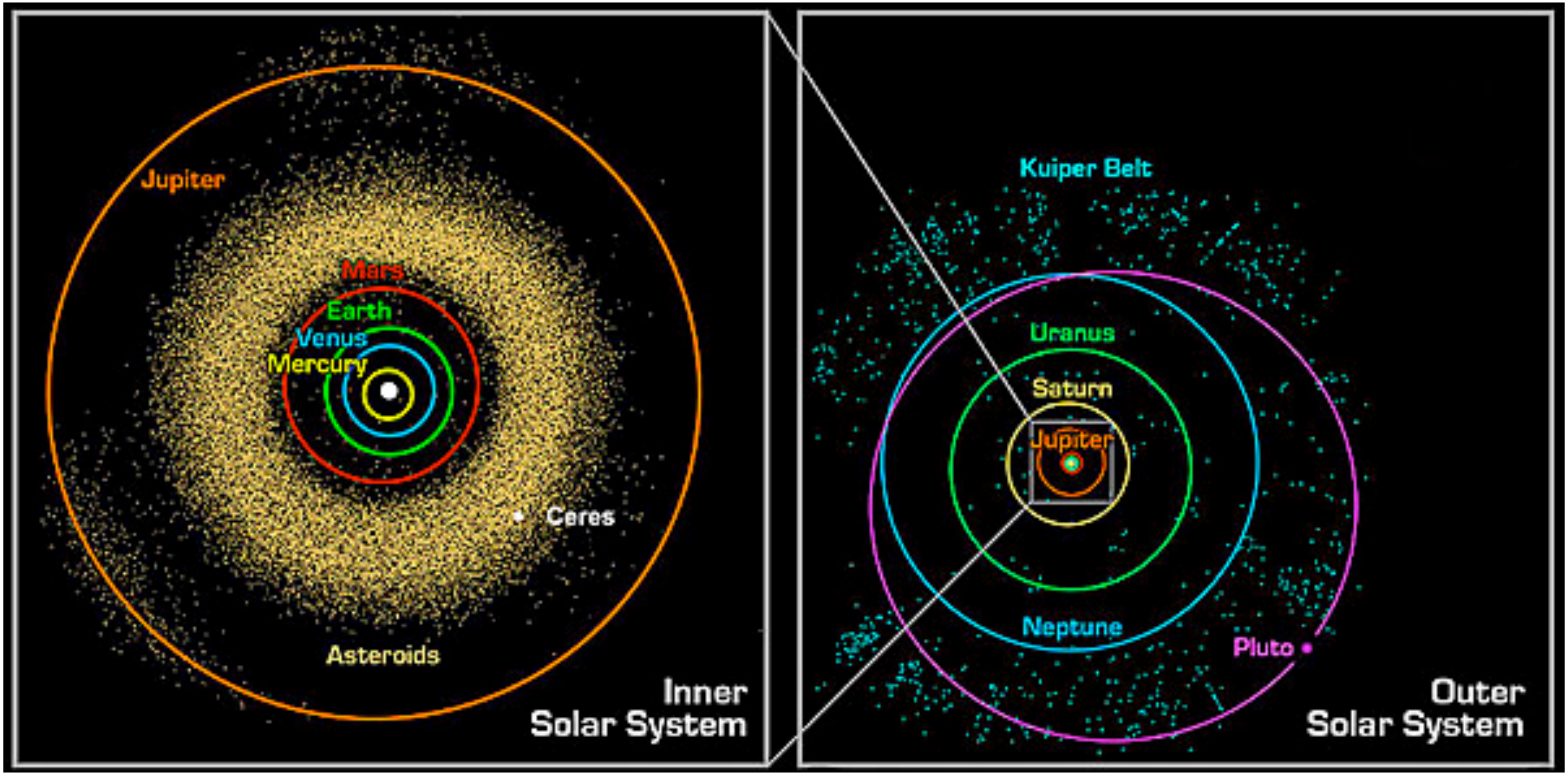


Earth-Moon system

- Tidally locked. Moon's spin Period = Period of revolution around the Earth
- $M_{earth} = 5.97722 \times 10^{24}$ kg ; $M_{moon} = 7.3477 \times 10^{22}$ kg
- Orbital eccentricity = 0.0549
- Semi-major axis = 384,399 km, *increasing by 38 mm/y* (1ppb/y)

  Earth's spin angular momentum being pumped into the orbit
- Origin of the moon possibly in a giant impact on earth by a mars-sized body; moon has been receding since formation.
- At present the interval between two new moons = 29.53 days
- Moon's orbital plane inclined at 5.14 deg w.r.t. the ecliptic
- Earth around the sun, Moon around the earth: same sense of revolution
- Moon is responsible for total solar eclipse as angular size of the sun and the moon are roughly similar as seen from the earth.

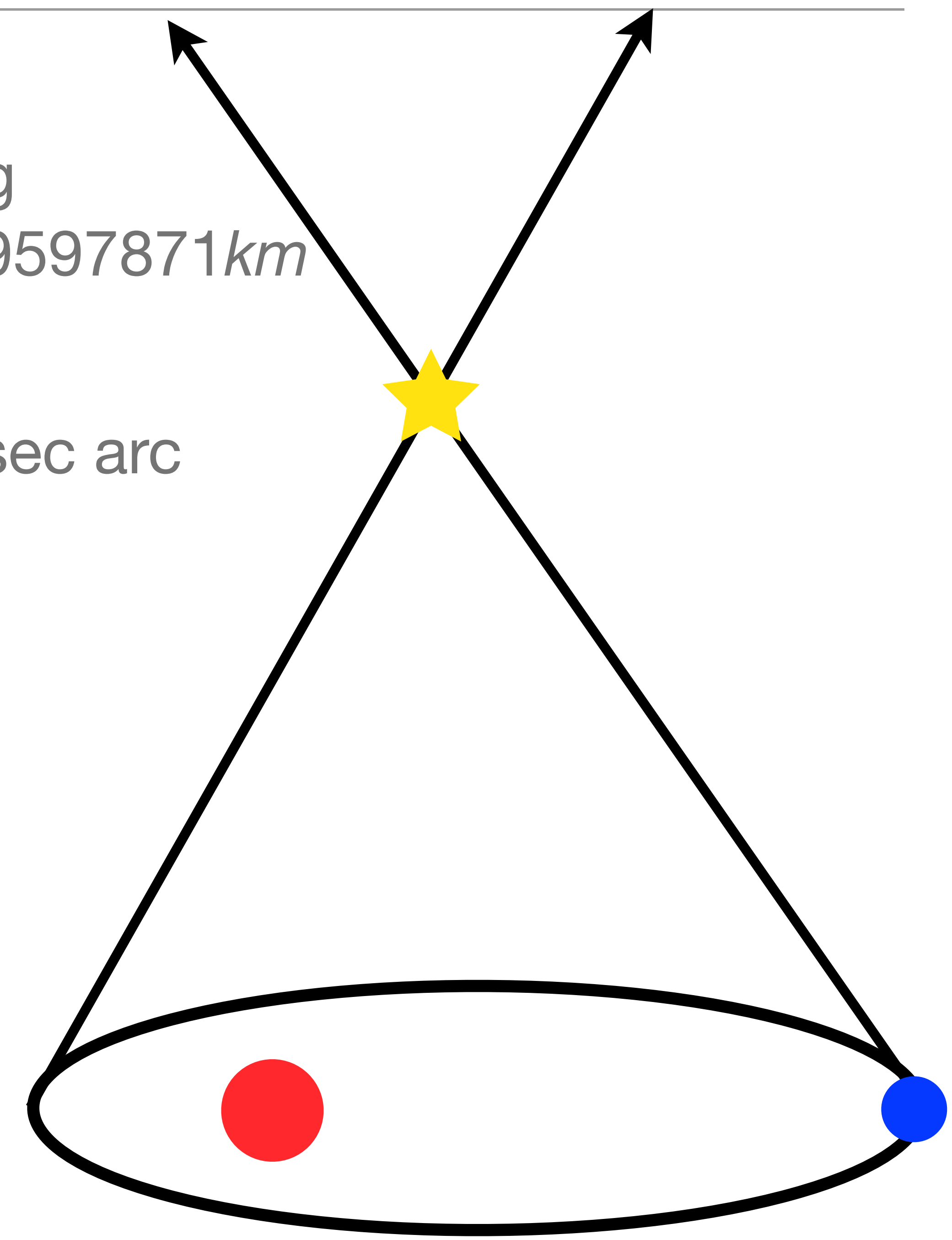
Bodies in The Solar System



A. Feild (STSCI)

Measuring Distance

- Inside solar system: Radio and Laser Ranging
  Earth-Sun distance: 1 Astronomical Unit = 149597871*km*
- Nearby stars: Parallax
  Parsec = distance at which 1 AU subtends 1 sec arc
  = 3.086×10^{13} *km* = 3.26 light yr
- Distant Objects: Standard Candles
  - Cepheid and RR Lyrae stars
  - Type Ia Supernovae
- Cosmological distance: Redshift



Linear size = angular size x distance

Measure of Intensity

1 Jansky = 10^{-26} W/m^2/Hz

Optical Magnitude Scale

Logarithmic Scale of Intensity: $m = -2.5 \log (I/I_0)$ *apparent magnitude*

Absolute Magnitude (measure of luminosity):

$$M = -2.5 \log (I_{10pc} / I_0)$$

The scale factor I_0 depends on the waveband, for example:

Band	$\mathbf{I_0}$
Johnson U	1920 Jy
B	4130
V	3690
R	3170
I	2550

References

- The Physical Universe : *Frank H. Shu*
- An Introduction to Modern Astrophysics : *B.W. Carroll & D.A. Ostlie*
- Astrophysical Quantities: *C.W. Allen*
- Astrophysical Formulae: *K.R. Lang*

Orbits

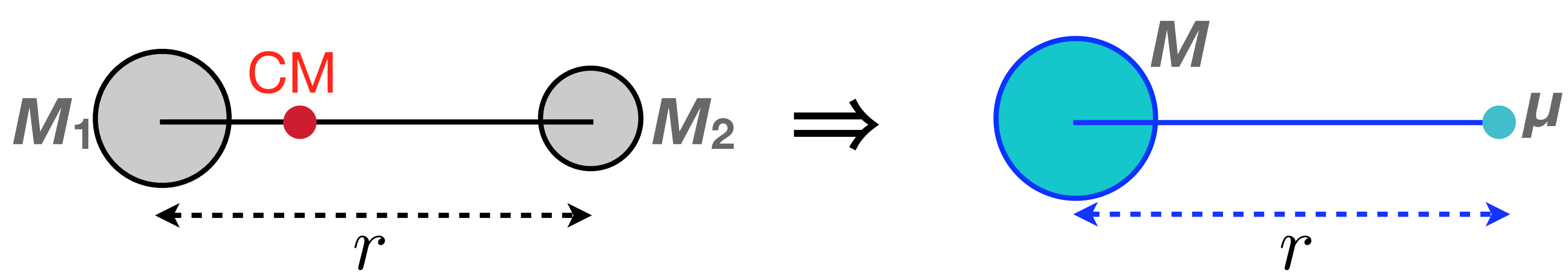
Kepler Orbit

1. Elliptical orbit with Sun at one focus
2. Areal velocity = constant
3. $T^2 \propto R^3$

Conserved Energy E
and Angular Momentum J

Dynamical time scale in gravity: $$\tau \approx \frac{1}{\sqrt{G\rho}}$$

Two body problem:



$$r = \frac{l}{1 + e\cos\phi}\,; \quad l = \frac{J^2}{GM\mu^2}\,; \quad e = \left[1 + \frac{2EJ^2}{G^2M^2\mu^3}\right]^{1/2}$$

$$M = M_1 + M_2$$

$$\mu = \frac{M_1 M_2}{M_1 + M_2}$$

$E < 0 \implies e < 1$; bound elliptical orbit:

$$a = \frac{GM\mu}{2|E|}\,; \quad J = \mu\sqrt{GMa(1-e^2)}$$

Motion in a Central Force Field

Energy $E = \frac{1}{2}\mu\dot{r}^2 + \underbrace{\boxed{\frac{J^2}{2\mu r^2} + U(r)}}_{U_{\mathrm{eff}}(r)}$; $\dot{r}^2 = \frac{2}{\mu}\left[E - U_{\mathrm{eff}}(r)\right]$

$$\phi = \int \frac{(J/r^2)dr}{\left[2\mu\left\{E - U_{\mathrm{eff}}(r)\right\}\right]^{1/2}} + \mathrm{const.}$$

Intersections of $U_{\mathrm{eff}}(r)$ with E give turning points in the orbit

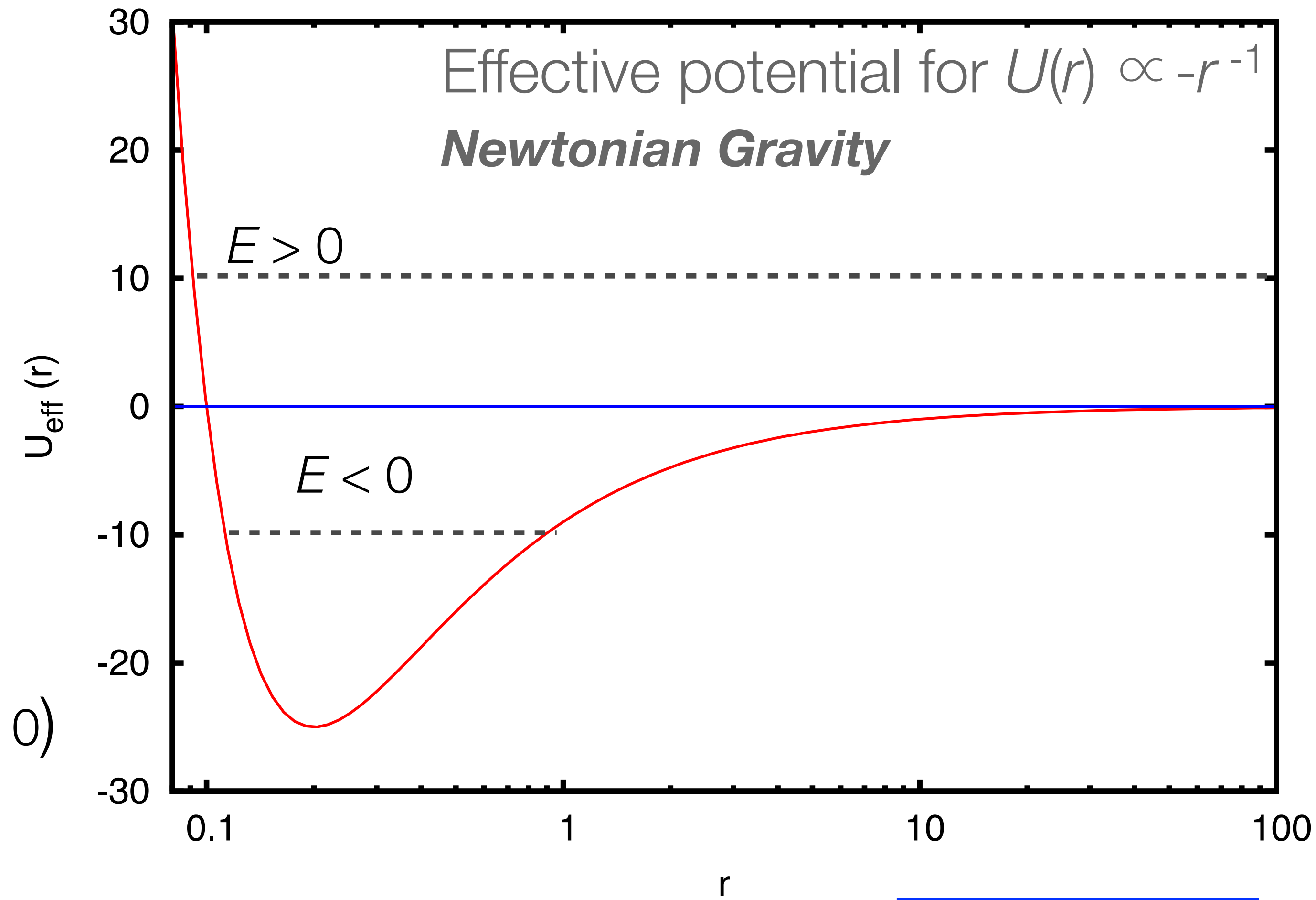
Newtonian Gravity: $U(r) = -\frac{GM\mu}{r}$

Setting $U_{\mathrm{eff}} = E$ gives turning points:

$$\frac{1}{r_{\substack{\min\\\max}}} = \frac{GM\mu^2}{J^2}\left[1 \pm \sqrt{1 + \frac{2J^2E}{GM^2\mu^3}}\right]$$

and for $E < 0$ ($r_{\max}$ does not exist for $E > 0$)

$$\Delta\phi = 2\left[\phi(r_{\max}) - \phi(r_{\min})\right] = 2\pi$$



i.e. orbit is closed. Departure from *1/r* or r^2 potential give $\Delta\phi \neq 2\pi$ $\Rightarrow$ **precession of periastron**

Departure from 1/r^2 gravity

Common causes of departure from 1/r form of gravitational potential:

- Distributed mass
- Tidal forces
- Relativistic effects

$$U = -\frac{\alpha}{r} + \frac{\beta}{r^2} \quad \Rightarrow \quad \underset{\text{per orbit}}{\delta\phi} = -2\pi\beta\mu/J^2$$

$$U = -\frac{\alpha}{r} + \frac{\gamma}{r^3} \quad \Rightarrow \quad \underset{\text{per orbit}}{\delta\phi} = -6\pi\alpha\gamma\mu^2/J^4$$

In relativity, effective potential near a point mass (including rest energy)

$$\bar{E} = \left[\left(1 - \frac{1}{\bar{r}}\right)\left(1 + \frac{\bar{a}^2}{\bar{r}^2}\right)\right]^{1/2}$$

$$\bar{E} = E/mc^2$$
$$\bar{a} = J/mcr_g$$
$$r_g = 2GM/c^2$$

Newtonian approximation $\bar{r} \gg 1$

Next order correction, upon expanding the square root: $-\dfrac{\bar{a}^2}{2\bar{r}^3}$

Gives $\underset{\text{per orbit}}{\delta\phi} = \dfrac{6\pi GM}{a(1-e^2)c^2}$ $\Rightarrow$ Precession of perihelion of Mercury

Schwarzschild Gravity: Equation of Motion & Effective Potential

$$\left(\frac{1}{1-1/\bar{r}}\right)\left(\frac{d\bar{r}}{d\tau}\right)^2 = \frac{1}{\bar{E}^2}\left[\bar{E}^2 - 1 + \frac{1}{\bar{r}} - \frac{\bar{a}^2}{\bar{r}^2} + \frac{\bar{a}^2}{\bar{r}^3}\right]$$

Effective potential by setting LHS = 0

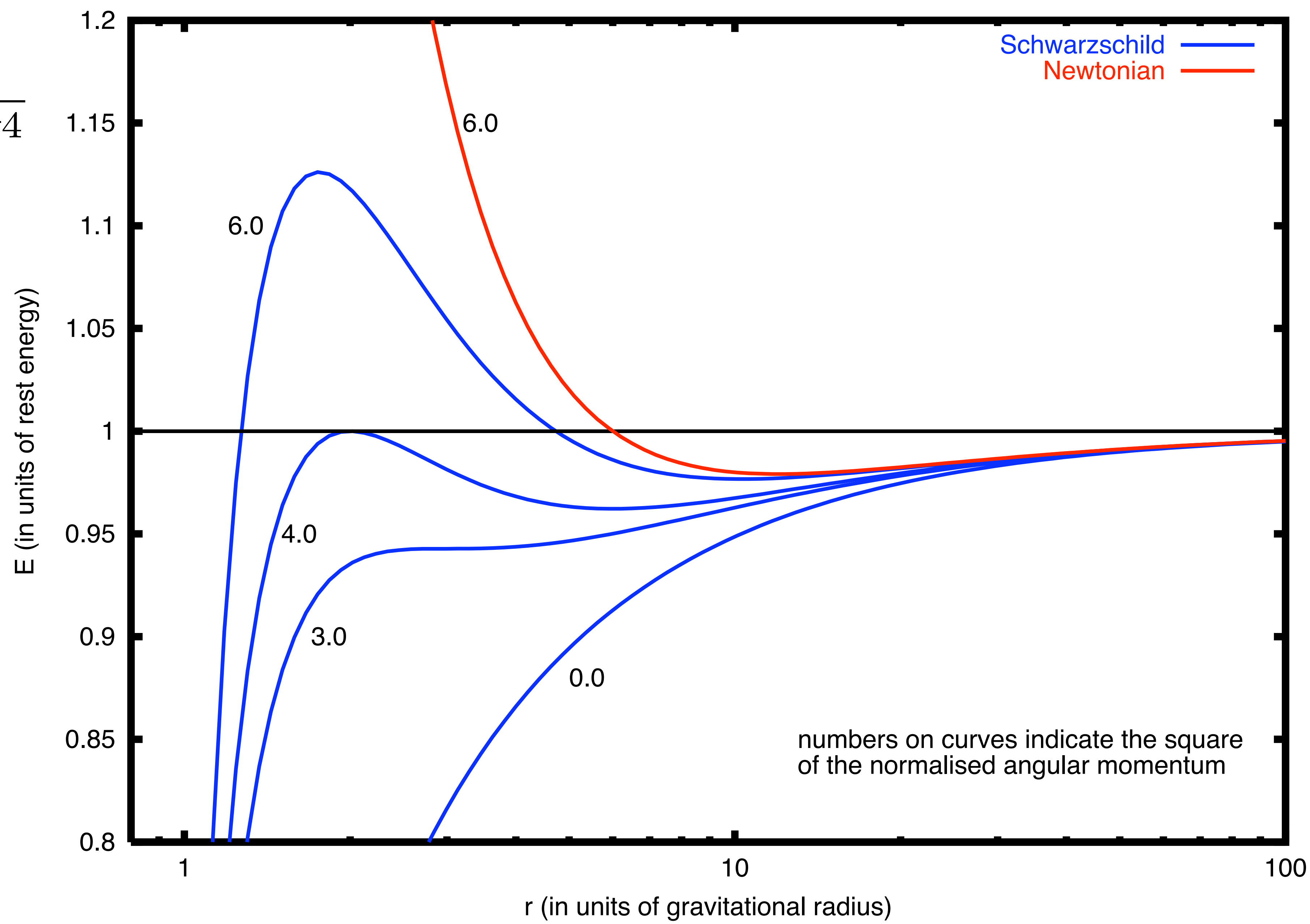
$$\left(\frac{1}{1-1/\bar{r}}\right)\left(\frac{d\phi}{d\tau}\right)^2 = \frac{\bar{a}^2}{\bar{E}^2\bar{r}^4}$$

A binary orbit decays due to Gravitational Wave radiation

$$-\frac{dE}{dt} = \frac{32}{5}\frac{G^4}{c^5a^5}M_1^2M_2^2 \times (M_1+M_2)f(e)$$

$$\frac{da}{dt} = \frac{2a^2}{GM_1M_2}\frac{dE}{dt}$$

$$\frac{de}{dt} = (1-e)\frac{1}{a}\frac{da}{dt}$$



Photon Orbit in Schwarzschild Gravity

setting $m = 0,\ \bar{E} \to \infty,\ \bar{a} \to \infty,\ \dfrac{\bar{a}}{\bar{E}} \to \dfrac{b}{r_g} \equiv \bar{b}$ $\quad b =$ impact parameter at ∞

$$\left(\frac{1}{1-1/\bar{r}}\right)\left(\frac{d\bar{r}}{d\tau}\right)^2 = 1 - \frac{\bar{b}^2}{\bar{r}^2} + \frac{\bar{b}^2}{\bar{r}^3}$$

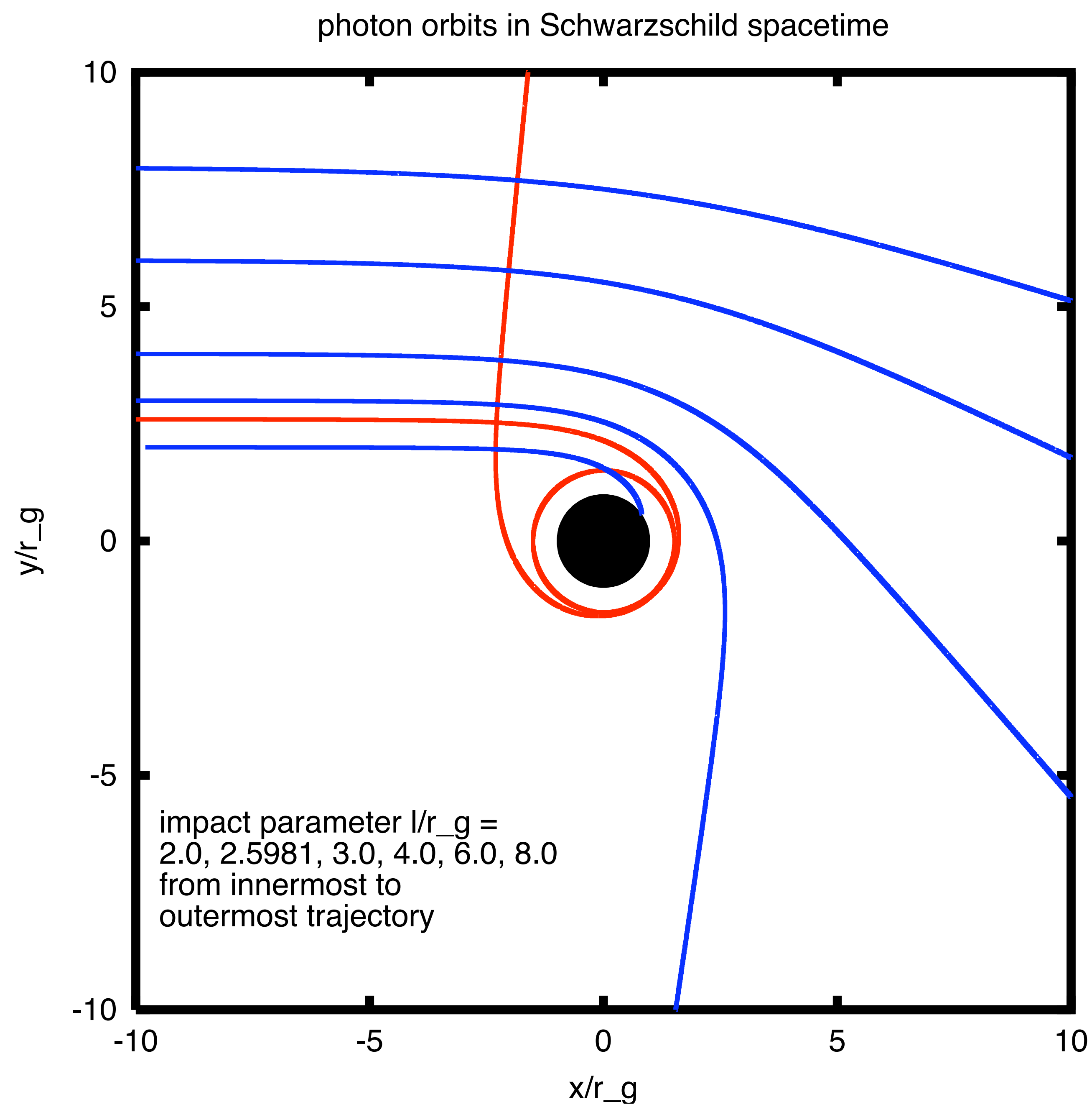
$$\left(\frac{1}{1-1/\bar{r}}\right)\left(\frac{d\phi}{d\tau}\right)^2 = \frac{\bar{b}^2}{\bar{r}^4}$$

hence

$$\left(\frac{dr}{d\phi}\right)^2 = \frac{r^4}{b^2}\left(1 - \frac{b^2}{r^2} + r_g\frac{b^2}{r^3}\right)$$

integrate to get orbit.
3rd term on RHS causes curvature of light path

Gravitational Lensing



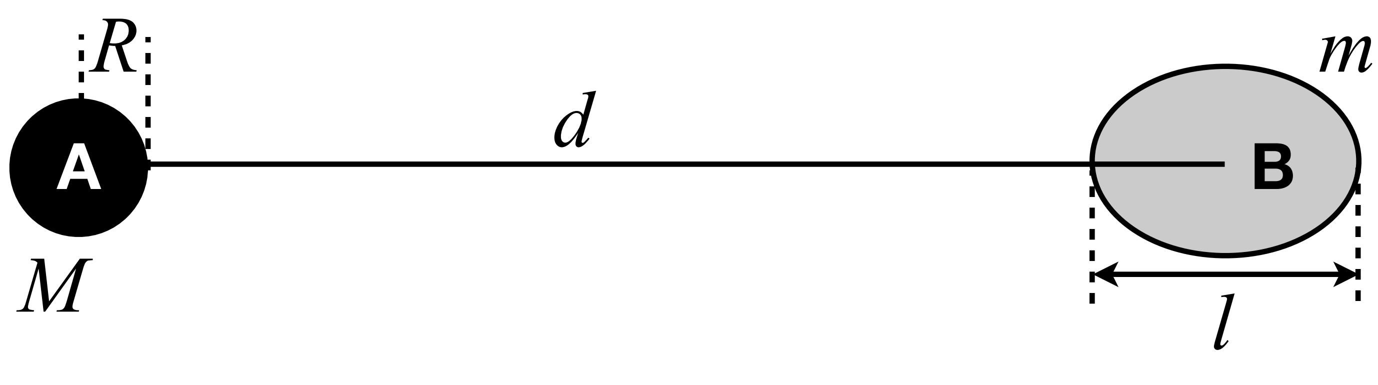
References

- Classical Mechanics : *H. Goldstein*
- Relativistic Astrophysics : *Ya B. Zeldovich & I.D. Novikov*
- Gravitation : *C. Misner, K.S. Thorne & J.A. Wheeler*
- Classical Theory of Fields : *L.D. Landau & E.M. Lifshitz*

Tidal forces and Roche Potential

Tidal effect

Gradient of external gravitational force across an extended body tends to deform the object - responsible for tides on Earth



Tidal Force: $F_T = \frac{2GMm}{d^3} l$

Self gravity of object B: $F_g = \frac{Gm^2}{l^2}$

Object B would not remain intact if $F_T > F_g$

$\therefore$ condition for stability: $l^3 < \frac{m}{2M} d^3$, or $\frac{l}{d} < \left(\frac{q}{2}\right)^{1/3}$, $q \equiv \frac{m}{M}$

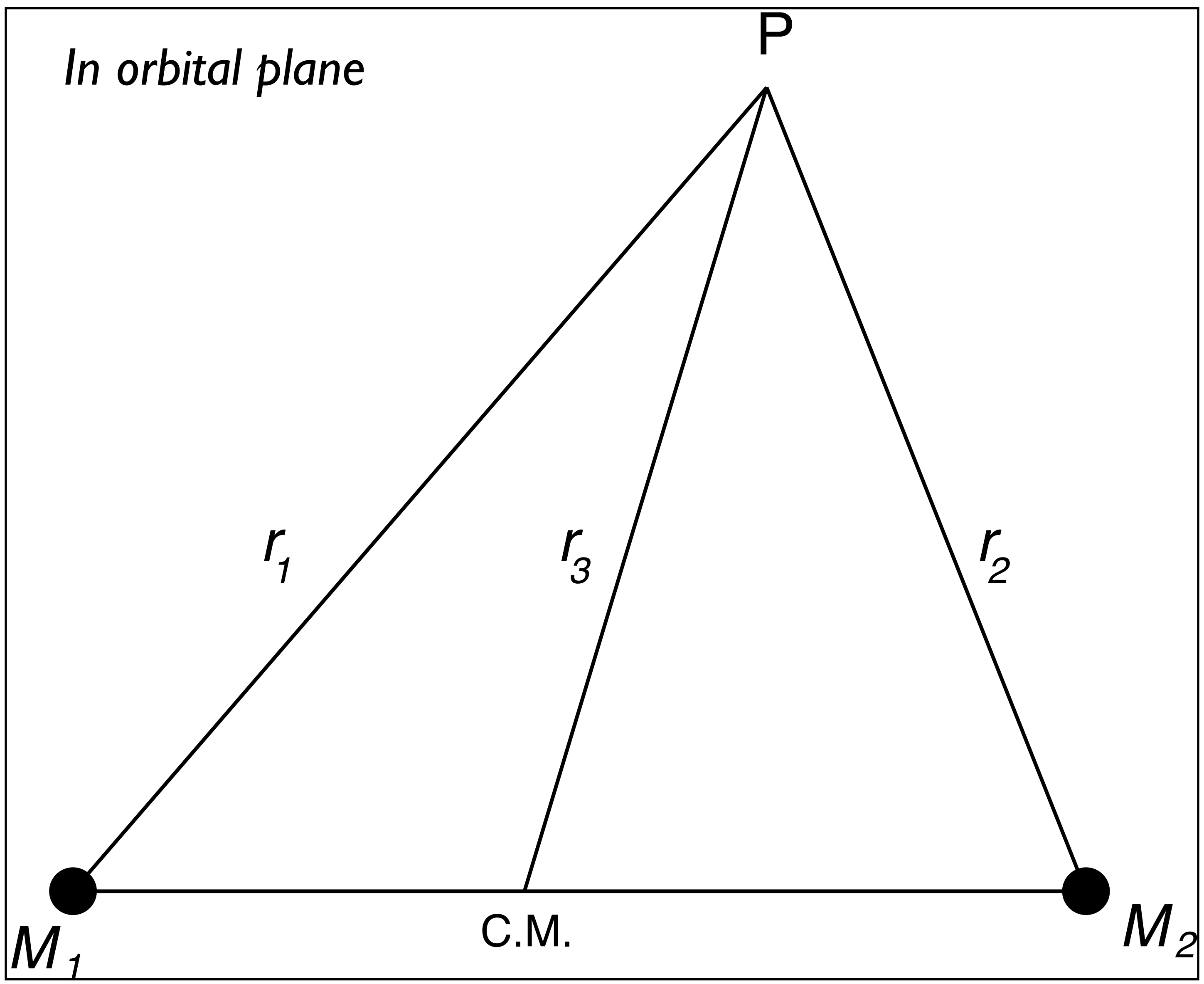
Disruption would occur if $d^3 < 2\frac{l^3}{m} M = 2R^3 \left(\frac{M}{4\pi R^3/3}\right) \left(\frac{m}{8 \times 4\pi (l/2)^3/3}\right)^{-1}$

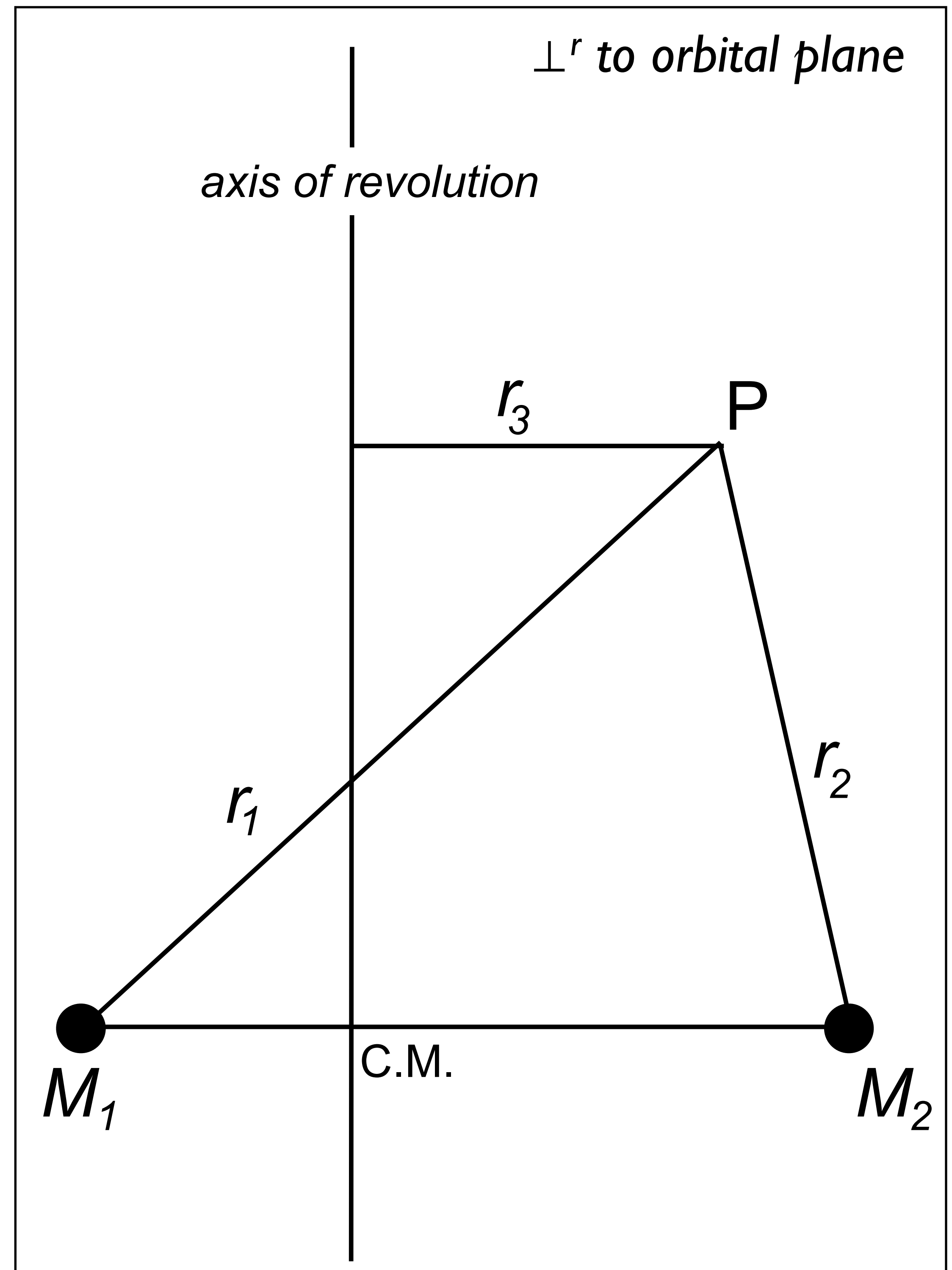
i.e. for $d < 2^{4/3} R \left(\frac{\rho_M}{\rho_m}\right)^{1/3}$ **: Roche limit**

Roche Potential in a binary system

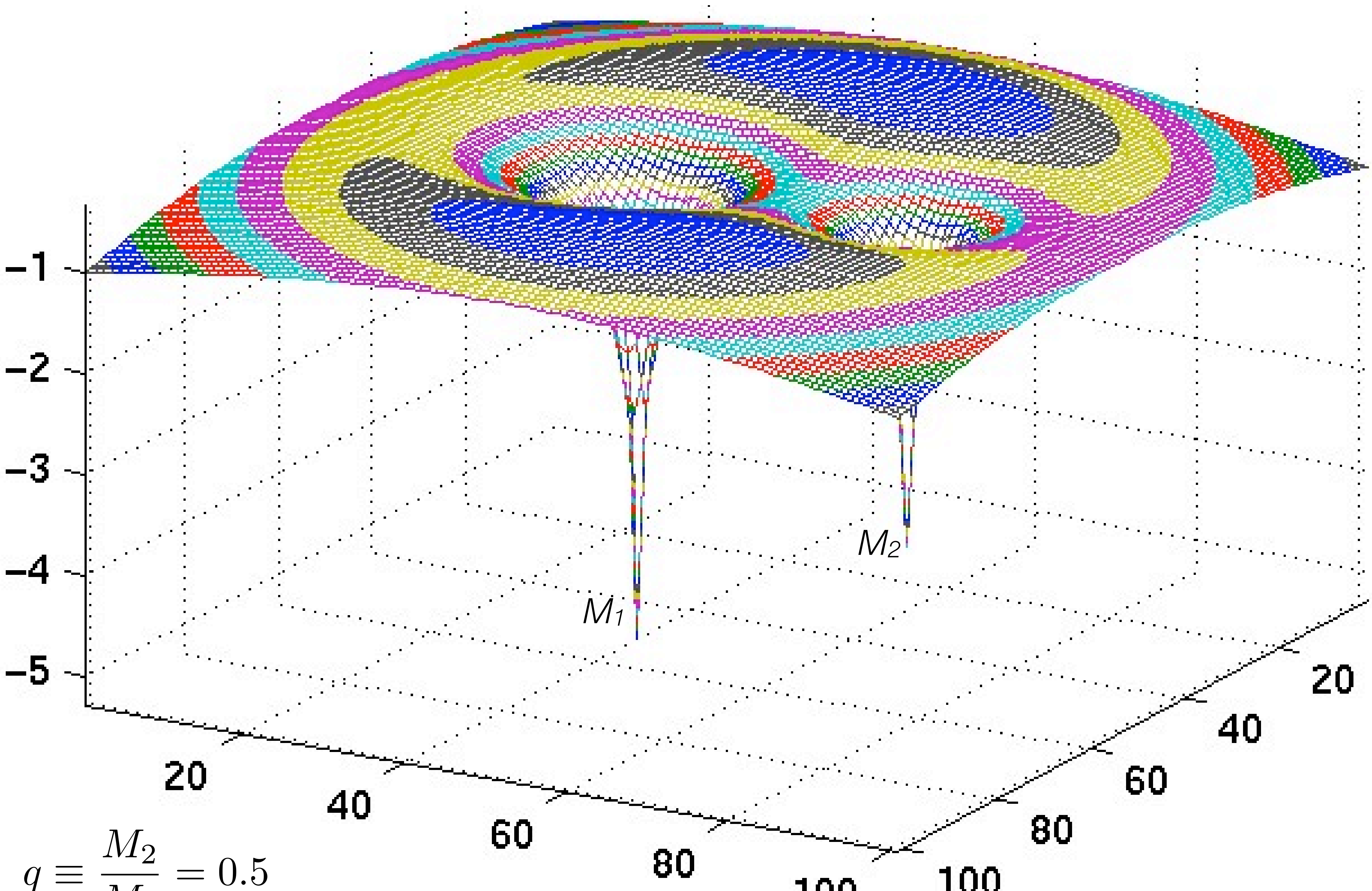
The surface of a fluid body is an equipotential

In corotating frame $$V = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \frac{\Omega^2 r_3^2}{2}$$





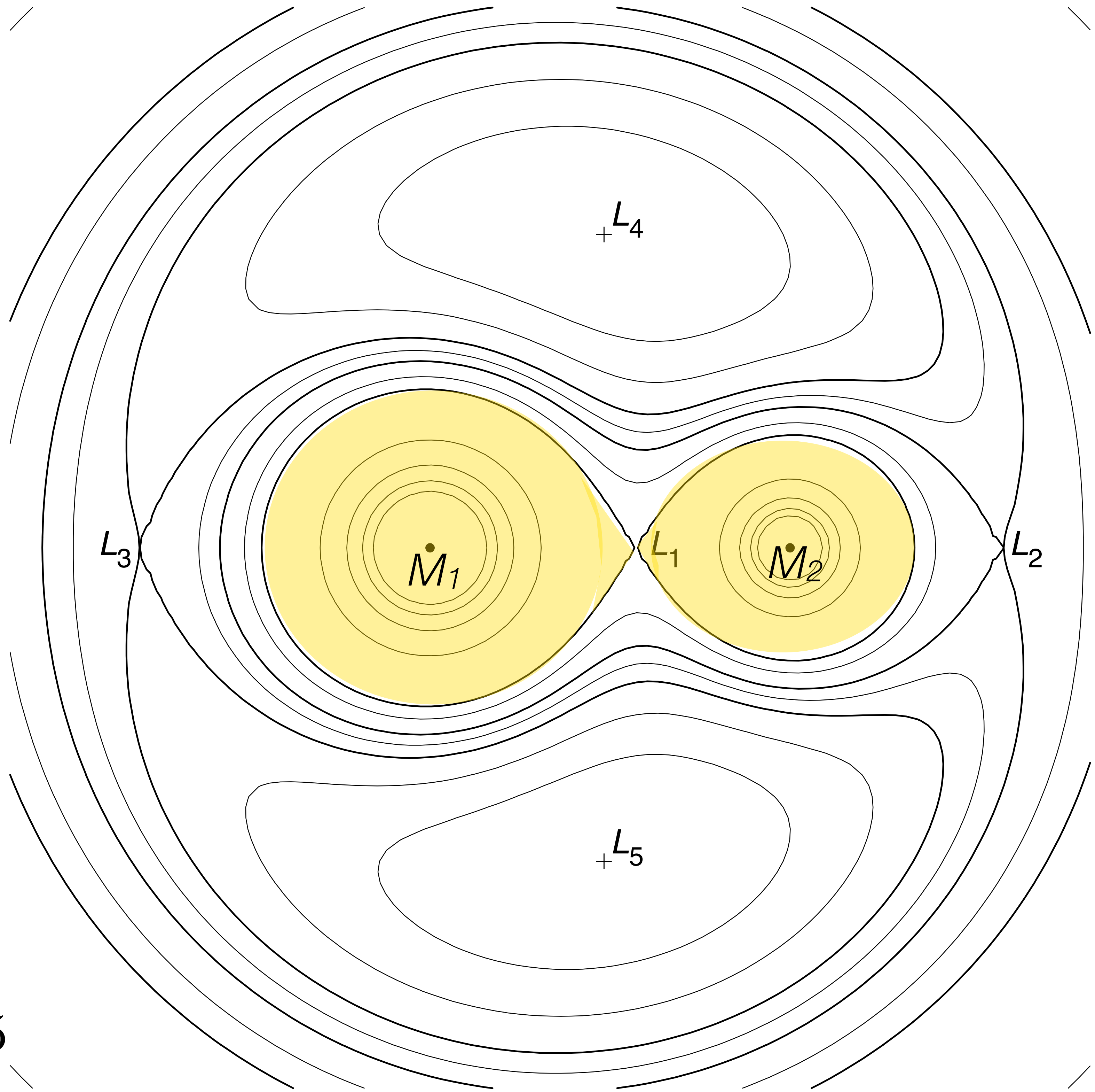
Roche Potential in the equatorial plane



$$q \equiv \frac{M_2}{M_1} = 0.5$$

Lagrangian points and the Roche Lobe

In orbital plane



A star overfilling its Roche Lobe would transfer matter to its companion

$$q \equiv \frac{M_2}{M_1} = 0.5$$

References

- Theoretical Astrophysics, vol. 1 sec. 2.3 : *T. Padmanabhan*
- Close Binary Systems : *Z. Kopal*
- Hydrodynamic and Hydromagnetic Stability: *S. Chandrasekhar*
- Astrophysical Journal vol. 55, p. 551 (1984) ; *S.W. Mochnacki*

Hydrostatic Equilibrium

Equations of Fluid Mechanics

Continuity Equation: $\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$

Euler Equation: $\rho \left[\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla}) \vec{v} \right] = -\vec{\nabla} P + \rho \vec{g}$

Equation of State: $P = P(\rho)$

The fluid is described by the quantities

$$\rho, \; P, \; \vec{v}$$

that are functions of space and time.

Viscosity is ignored

Stationarity follows by setting time derivatives $\frac{\partial}{\partial t}$ to zero

Hydrostatic equilibrium follows by setting both $\frac{\partial}{\partial t}$ and $\vec{v}$ to zero:

$$\vec{\nabla} P = \rho \vec{g}$$

Hydrostatic Equilibrium

$$\vec{\nabla} P = \rho \vec{g}$$

In spherical symmetry:

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

In relativity: (*Tolman, Oppenheimer, Volkoff*)

$$\frac{dP}{dr} = -\frac{G\left[M(r) + 4\pi r^3 \frac{P(r)}{c^2}\right]\left[\rho(r) + \frac{P(r)}{c^2}\right]}{r^2\left(1 - \frac{2GM(r)}{c^2 r}\right)}$$

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r)$$

Supplement with appropriate equation of state and solve for the structure of self-gravitating configurations such as stars, planets etc

Virial Theorem

$$\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2}$$ (hydrostatic equilibrium)

Multiply both sides by $4\pi r^3$ and integrate over the full configuration: $r = 0 \to R$

$$4\pi R^3 P(R) - \int_0^R 4\pi r^2 \cdot 3P dr = \int_0^R 4\pi r^2 dr \left[-\frac{GM(r)\rho(r)}{r} \right]$$

RHS = Total gravitational energy of the configuration E_g (< 0)

and since $P = (\gamma - 1)u_{\rm th}$, where $u_{\rm th}$ is the Thermal (kinetic) energy density,

the 2nd term in LHS = $3(\gamma - 1)E_{\rm th}$, $E_{\rm th}$ being the total thermal (kinetic) energy

Hence $E_g + 3(\gamma - 1)E_{\rm th} = 4\pi R^3 P(R)$: **Virial Theorem**

must be obeyed by all systems in hydrostatic equilibrium

For $\gamma = 5/3$ and $P(R) = 0$: $E_g + 2E_{\rm th} = 0$

Note: $E_{\rm tot} = E_g + E_{\rm th} = E_g/2 = -E_{\rm th}$

A Rough Guide to Stellar Structure

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

stellar radius R
central pressure P_c
total mass M

Using a linear approximation: $\frac{0 - P_c}{R} = -\frac{GM}{R^2} \cdot \frac{M}{\frac{4\pi}{3}R^3}$

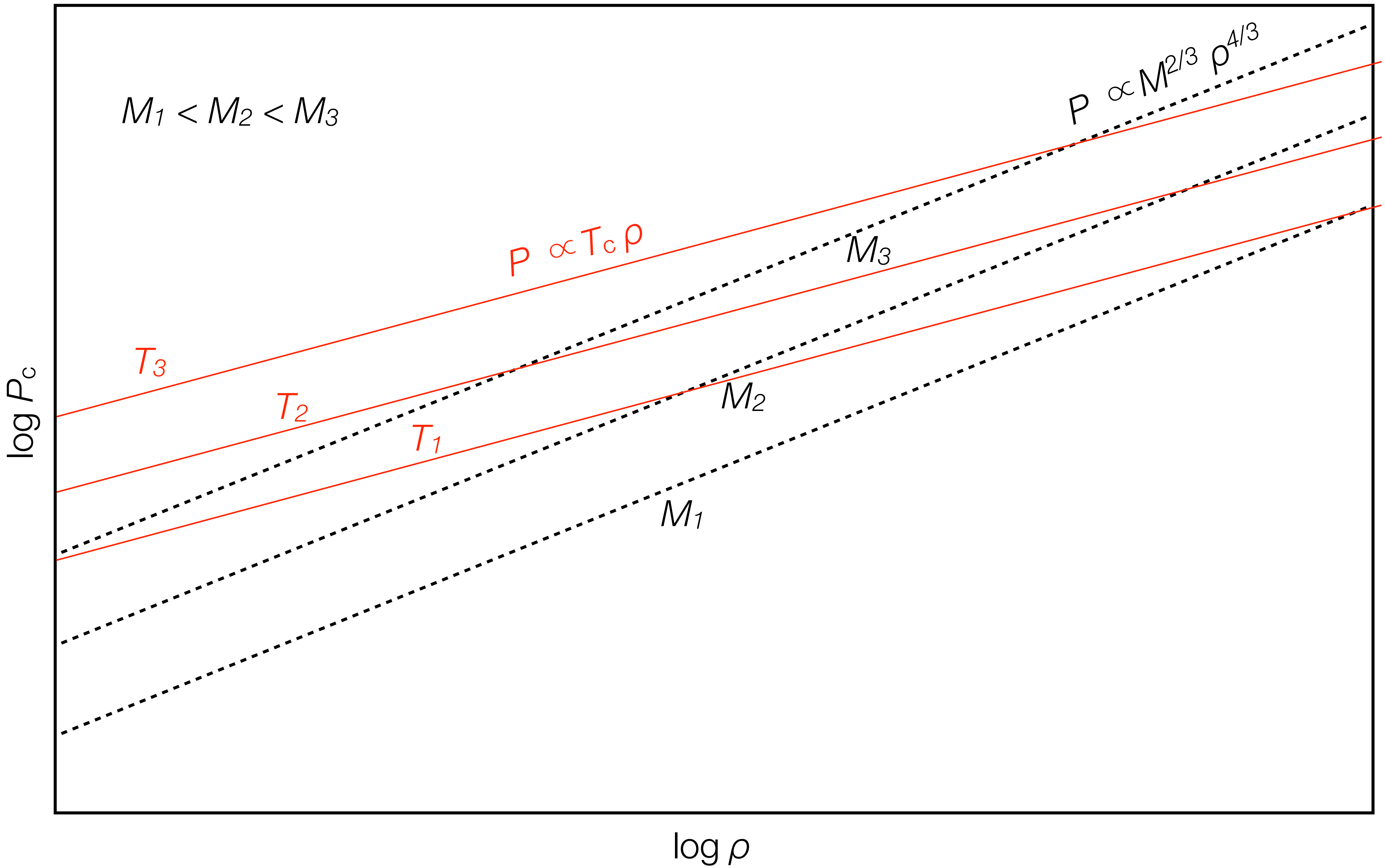
$$P_c = \frac{3}{4\pi}\frac{GM^2}{R^4} = \left(\frac{4\pi}{3}\right)^{1/3} GM^{2/3}\rho^{4/3}$$

(“gravitational pressure” $P_{\rm grav}$)

For equilibrium, this pressure needs to be matched by the Equation of State

e.g. Thermal Pressure: $P = \frac{kT}{\mu m_p}\rho$

Thermal pressure support



References

- Astrophysics I : Stars : *R.L. Bowers*
- The Physical Universe : *F.H. Shu*
- Stellar Structure and Evolution : *R. Kippenhahn and A. Weigert*
- Physics of Fluids and Plasmas : *A. Rai Choudhuri*

Stars

Main Sequence

Hydrogen burning star $T_\mathrm{c} \approx T_\mathrm{H}$

$$P_\mathrm{c} \approx GM^{2/3}\rho^{4/3} = \frac{kT_\mathrm{H}}{\mu m_\mathrm{p}}\rho \quad :: \quad \rho \propto M^{-2}\ ; \ R \propto M \text{ and } T_\mathrm{c} \propto \frac{M}{R}$$

Luminosity $L =$ Radiative Energy Content / Radiation Escape Time

Radiation Escape Time = $\left(\frac{R}{l}\right)^2 \cdot \frac{l}{c}$ where $l =$ mean free path $= \frac{1}{n\sigma} = \frac{1}{\rho\kappa}$

opacity

Hence $L \approx \frac{aT^4R^3}{(R^2/lc)} \approx aclT^4R$ In Main Sequence: $L \propto lR \propto lM$

High mass stars: opacity: Thomson scattering $\kappa =$ constant; $l \propto \frac{R^3}{M}$ :: $L_\mathrm{MS} \propto M^3$

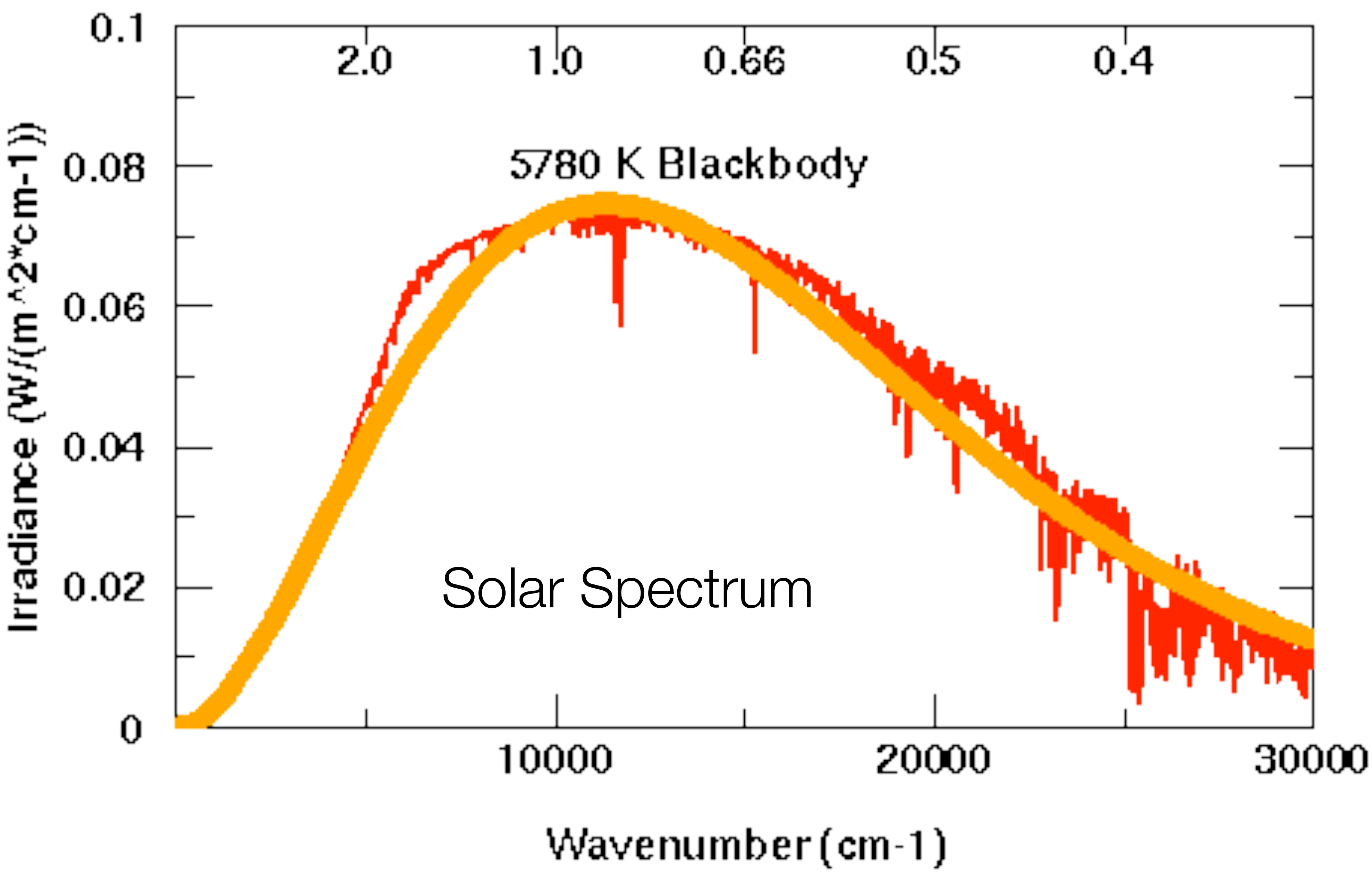
Low mass stars: $l \propto \frac{T^{3.5}}{\rho^2}$ :: $L_\mathrm{MS} \propto M^5$

On average

$$\boxed{\begin{aligned} L_\mathrm{MS} &\propto M^4 \\ t_\mathrm{MS} &\propto M^{-3} \end{aligned}}$$

Effective Temperature

A typical stellar spectrum is nearly a blackbody



Color Temperature = Temp. of best-fit Planck Function

Total Luminosity

$$L = 4\pi\sigma T_{\rm eff}^4 R^2$$

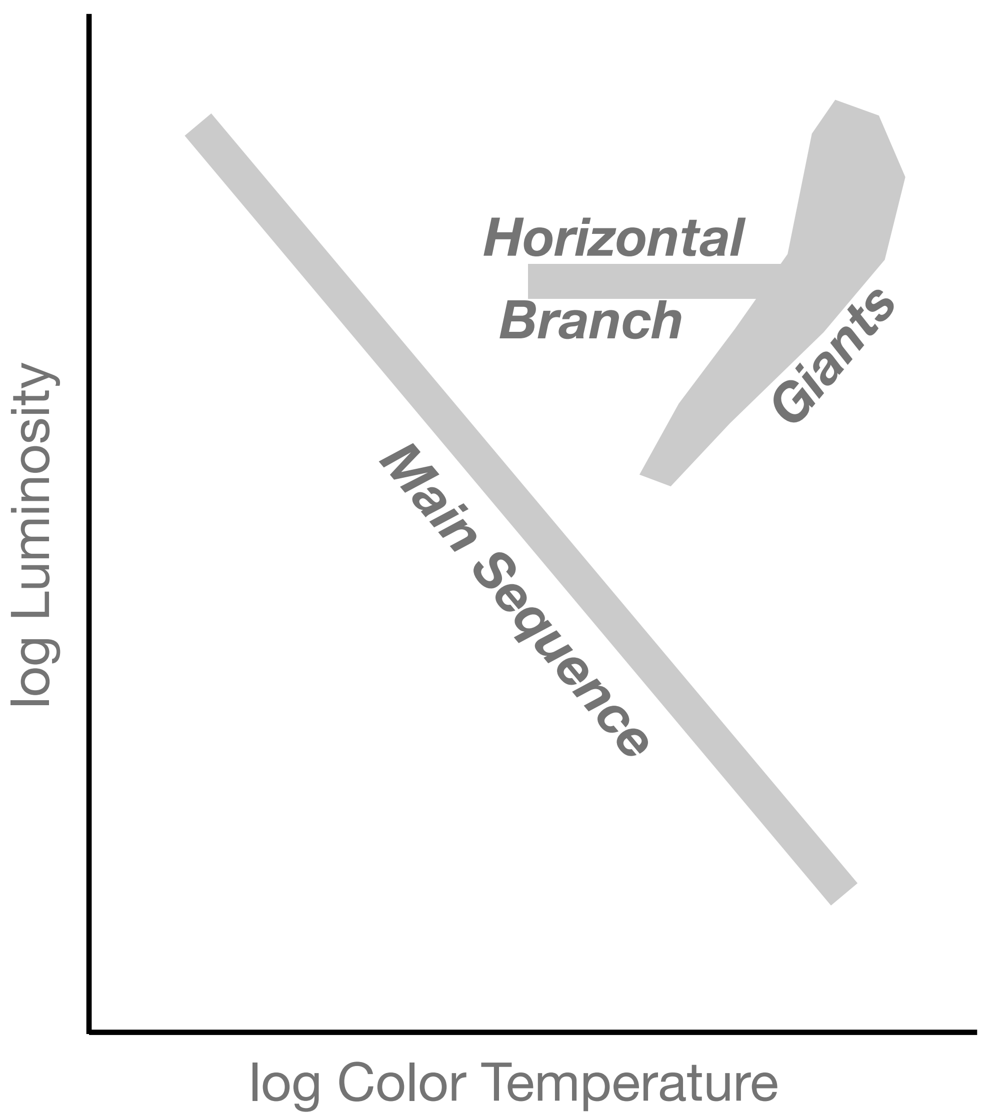
$T_{\rm eff}$ is defined as the Effective Temperature

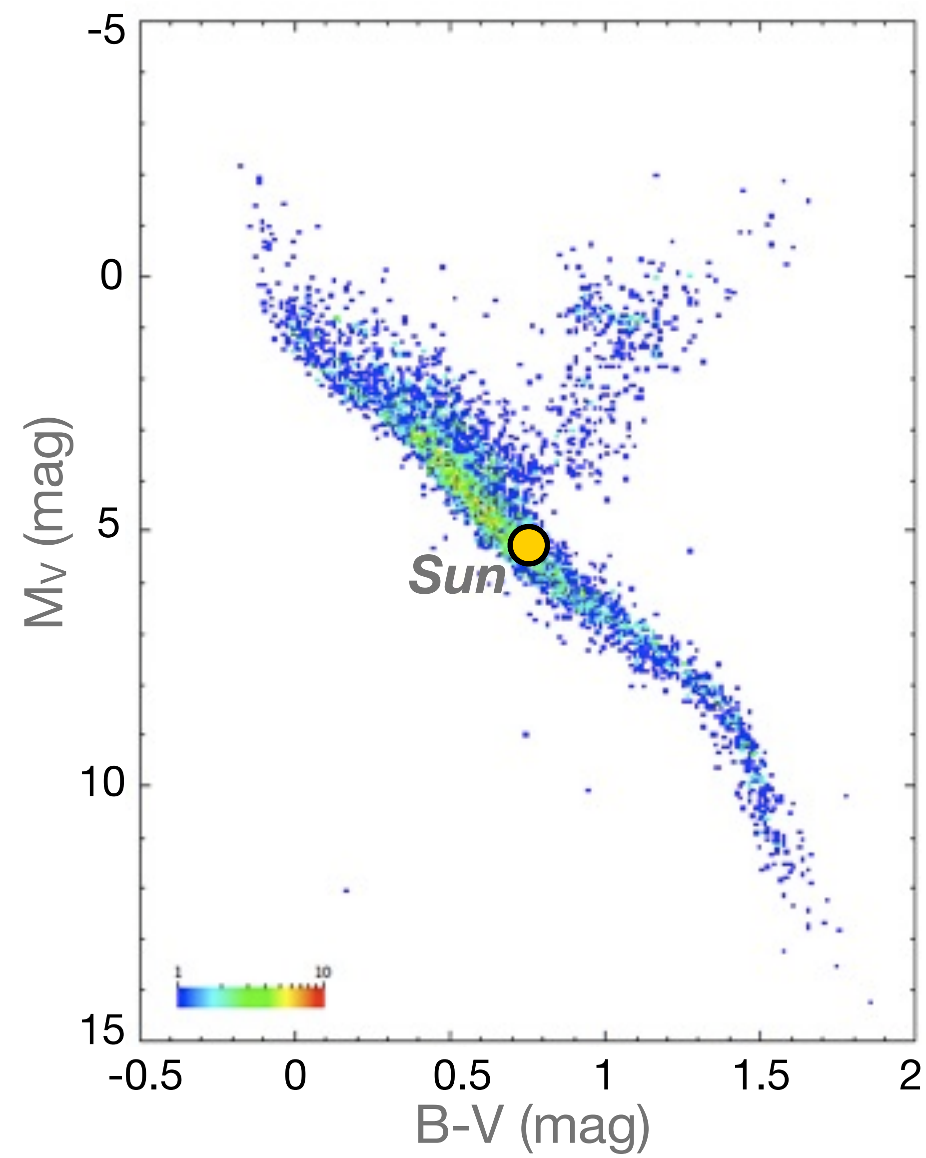
Hertzsprung Russell Diagram for Stars

A plot of Luminosity vs. Temperature
(Absolute Magnitude vs. Color)

Near Blackbody spectrum:
$T_{\rm eff} \approx T_{\rm col}$

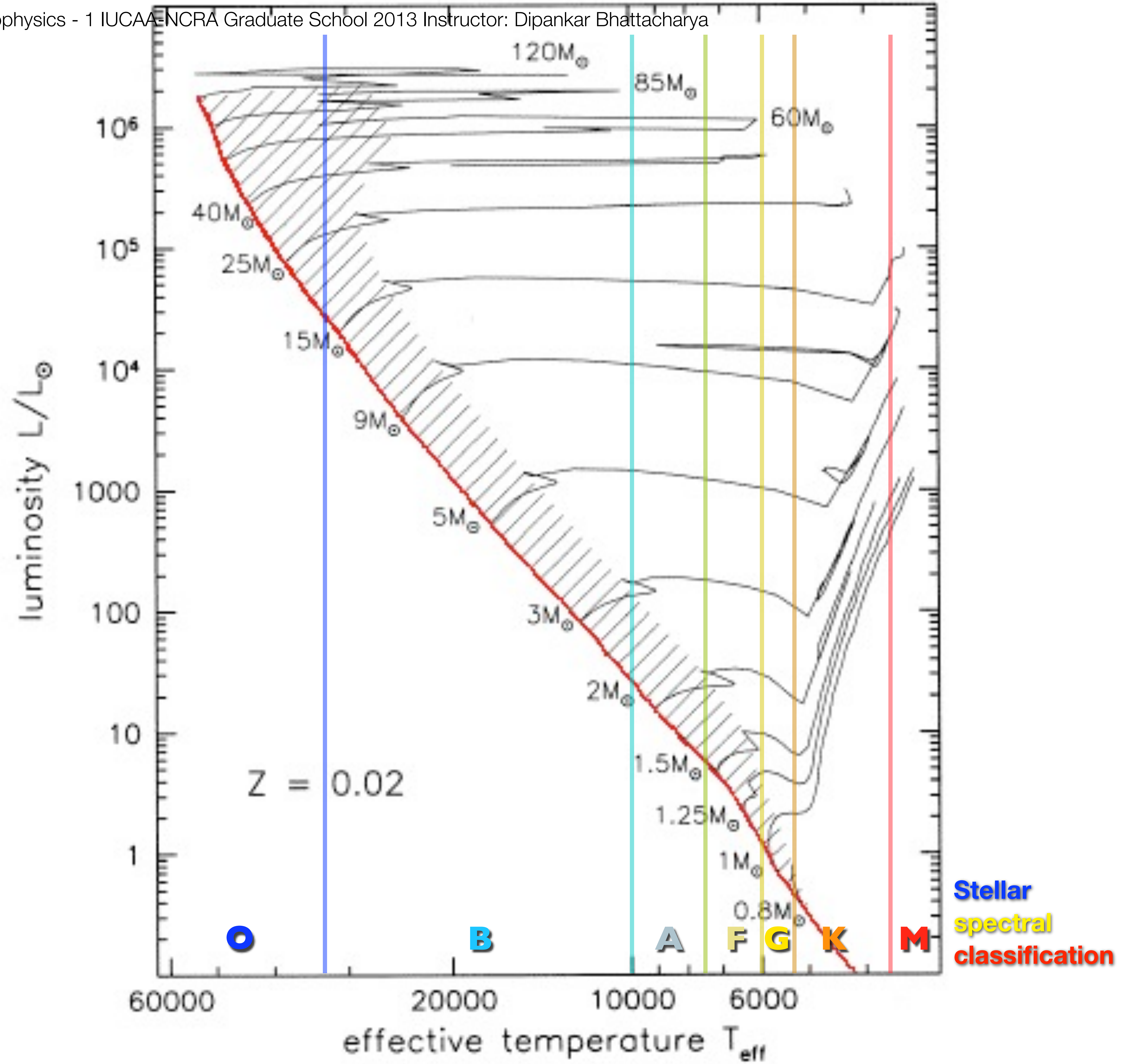
On Main Sequence $L \propto M^4; \;\; R \propto M \;\; \Rightarrow T_{\rm eff}^4 \propto \dfrac{L}{R^2} \propto M^2 \Rightarrow L_{\rm MS} \propto T_{\rm eff}^8 \sim T_{\rm col}^8$





Nearby stars measured by the Hipparcos satellite

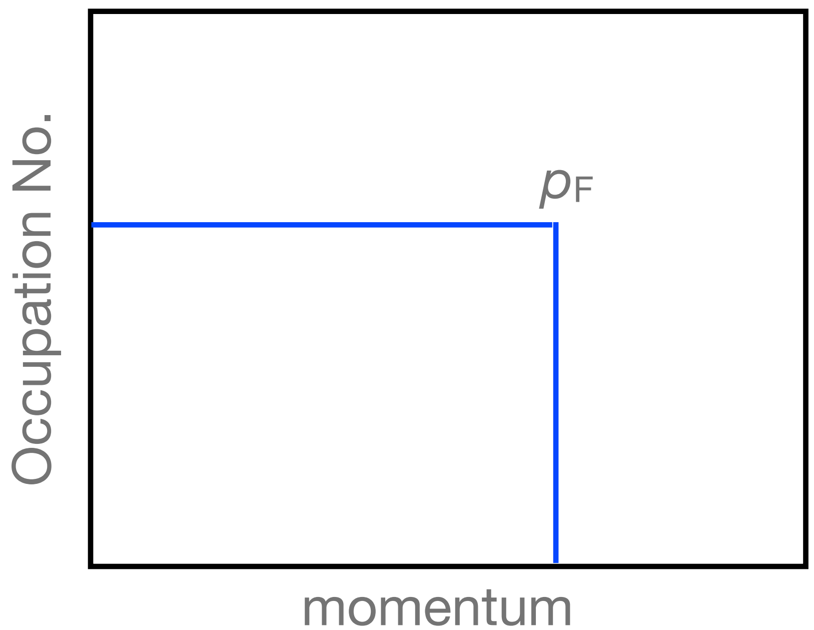
Theoretical H-R diagram



Stellar evolutionary tracks by Schaller et al 1992

Degeneracy Pressure

Momentum space occupation in cold Fermi gas



No. of particles per unit volume $n = \left(\frac{g}{h^3}\right) \frac{4\pi}{3} p_{\rm F}^3$

hence $p_{\rm F} = \left(\frac{3}{4\pi g}\right)^{1/3} h n^{1/3}$

Pressure $P \sim n \cdot v \cdot p_{\rm F} \propto v \cdot n^{4/3}$

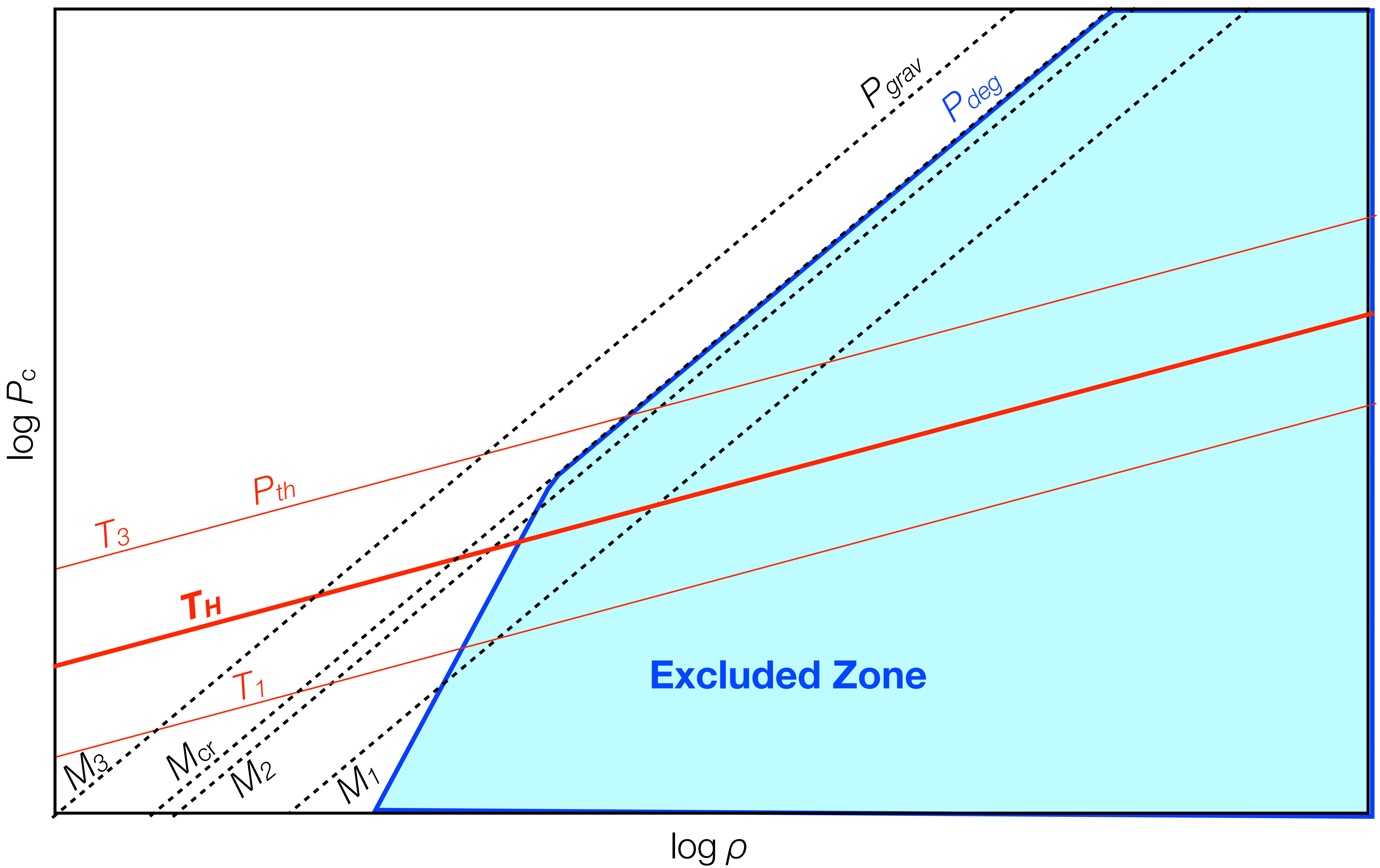
Electron degeneracy: $v = p_{\rm F}/m_{\rm e}$ (non-relativistic) and $v = c$ (relativistic)

$n_{\rm e} = \rho/(\mu_{\rm e} m_{\rm p})$ in both regimes

$\therefore$ Electron Degeneracy Pressure $\quad P_{\rm deg} \propto \rho^{5/3}$ (non-relativistic)

$\propto \rho^{4/3}$ (relativistic)

Stellar Equilibrium



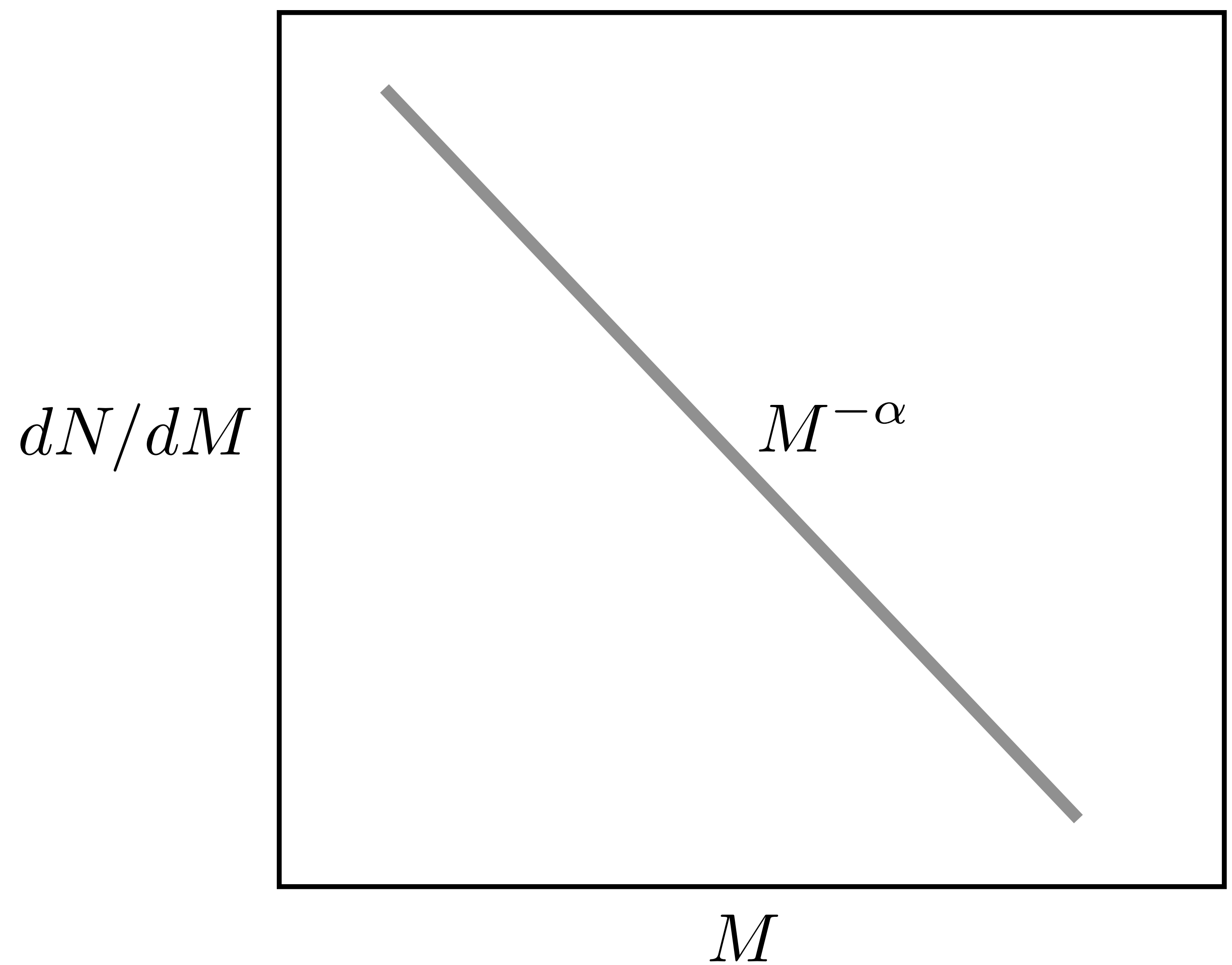
Stellar Mass Function

The mass distribution is typically a power-law.

In the Milky Way the index

$\alpha \approx 2.35$

Salpeter (1966)



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- Stellar Structure and Evolution : *R. Kippenhahn and A. Weigert*
- Structure and Evolution of the Stars: *M. Schwarzcshild*
- http://www.rssd.esa.int/index.php?project=HIPPARCOS&page=HR_dia

Compact Stars

White Dwarfs

Configurations supported by Electron Degeneracy Pressure

$P_{\rm deg} = K_1 m_{\rm e}^{-1} (\rho/\mu_{\rm e} m_{\rm p})^{5/3}$ (non-relativistic)

$P_{\rm deg} = K_2 (\rho/\mu_{\rm e} m_{\rm p})^{4/3}$ (relativistic) :: when $p_{\rm F} \gtrsim m_{\rm e} c$ ($\rho \gtrsim 10^6$ g cm^{-3})

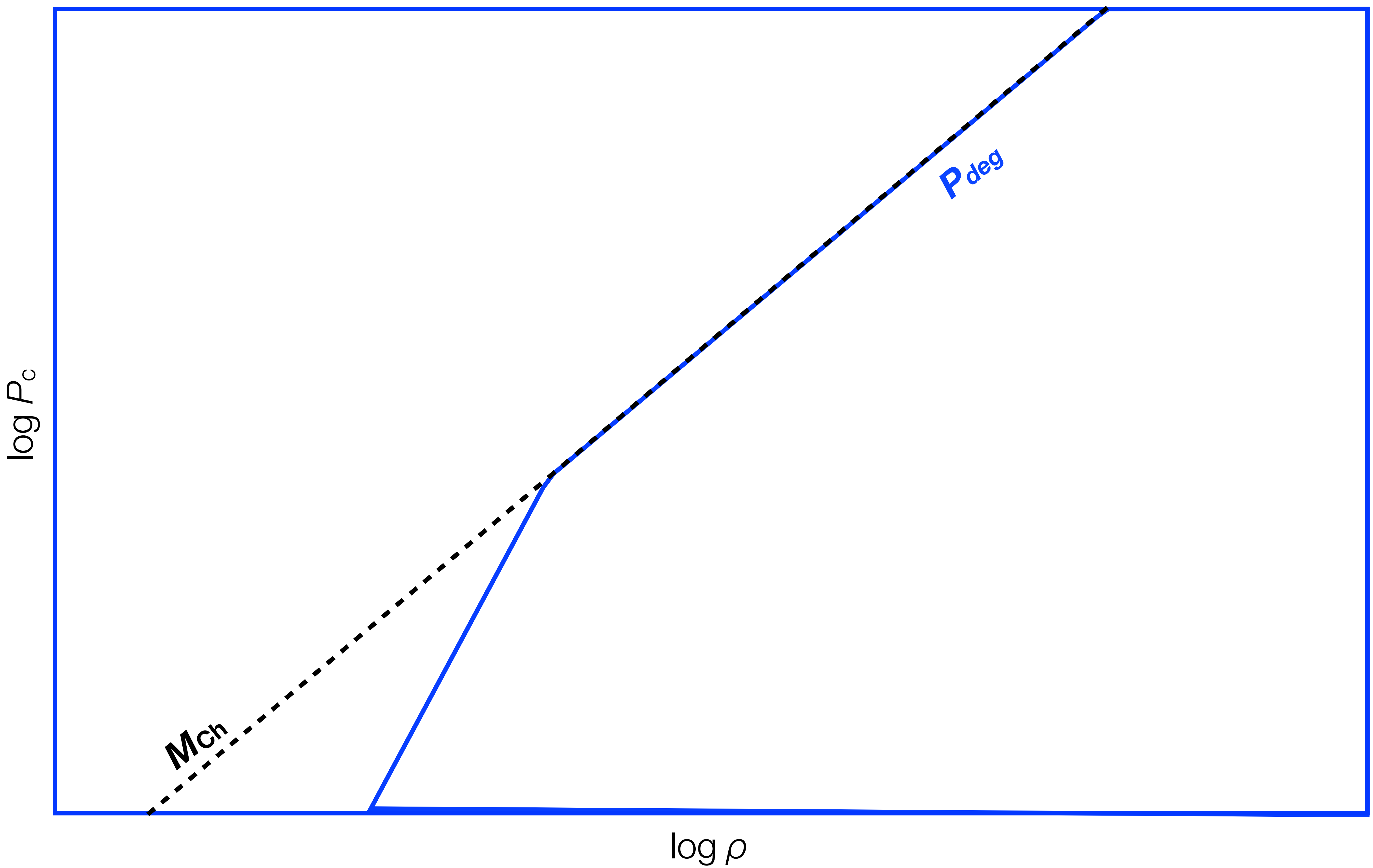
Equilibrium condition: $P_{\rm deg} \approx G M^{2/3} \rho^{4/3}$

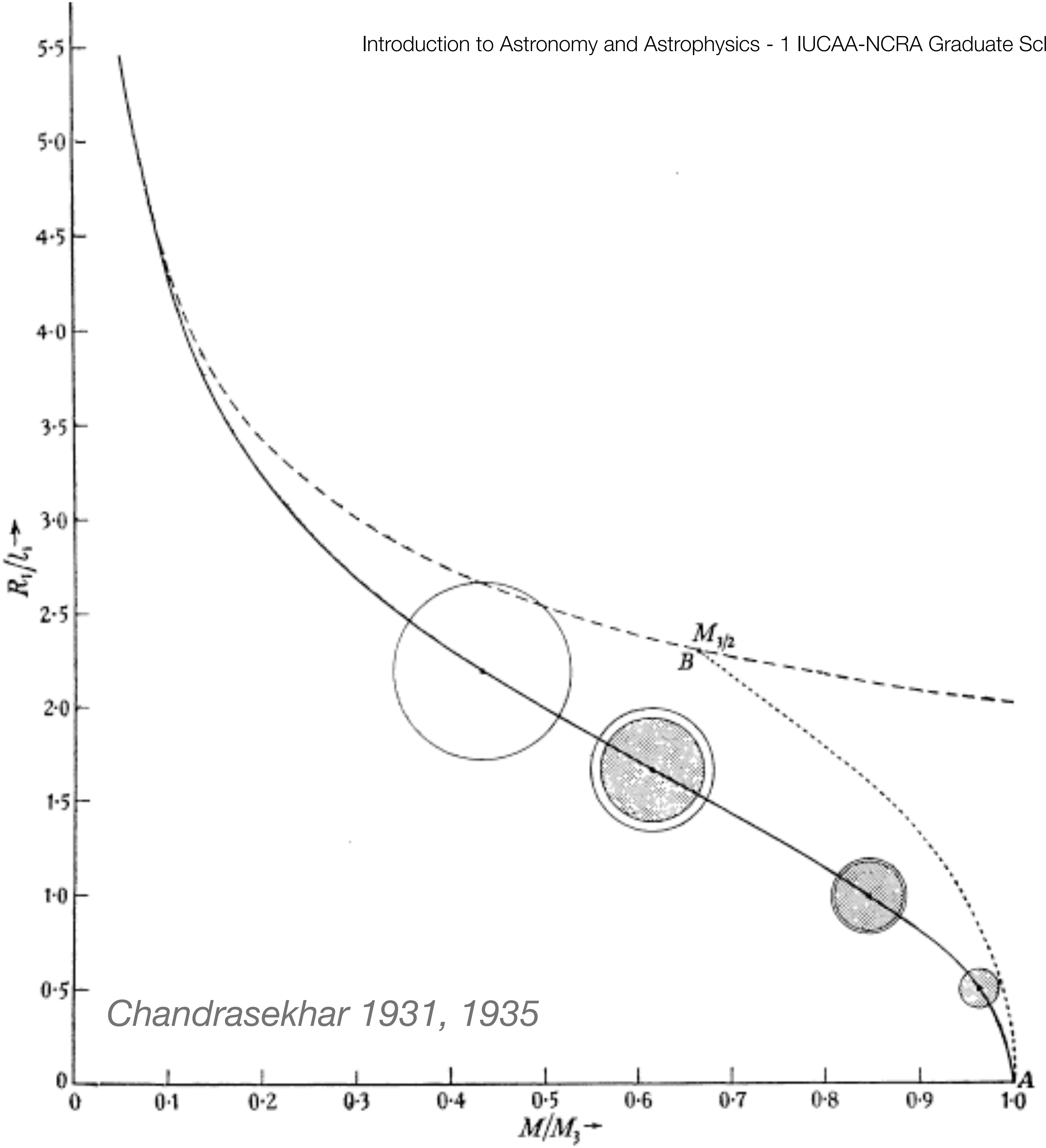
$\Rightarrow$ Non-relativistic: $R \propto m_{\rm e}^{-1} \mu_{\rm e}^{-5/3} M^{-1/3}$ (R ~ 10^4 km for M ~ 1 $M_{\rm sun}$)

Relativistic: $M \sim \left(\frac{K_2}{G}\right)^{3/2} (\mu_{\rm e} m_{\rm p})^{-2}$: Limiting Mass (Chandrasekhar Mass)

$$M_{\rm Ch} = 5.76 \mu_{\rm e}^{-2} \ M_\odot$$

Limiting Mass of White Dwarf





Chandrasekhar 1931, 1935

Neutron Stars

Supported by Neutron degeneracy pressure and repulsive strong interaction

TOV equation + nuclear EOS required for description

Beta equilibrium : > 90% neutrons, < 10% protons and electrons

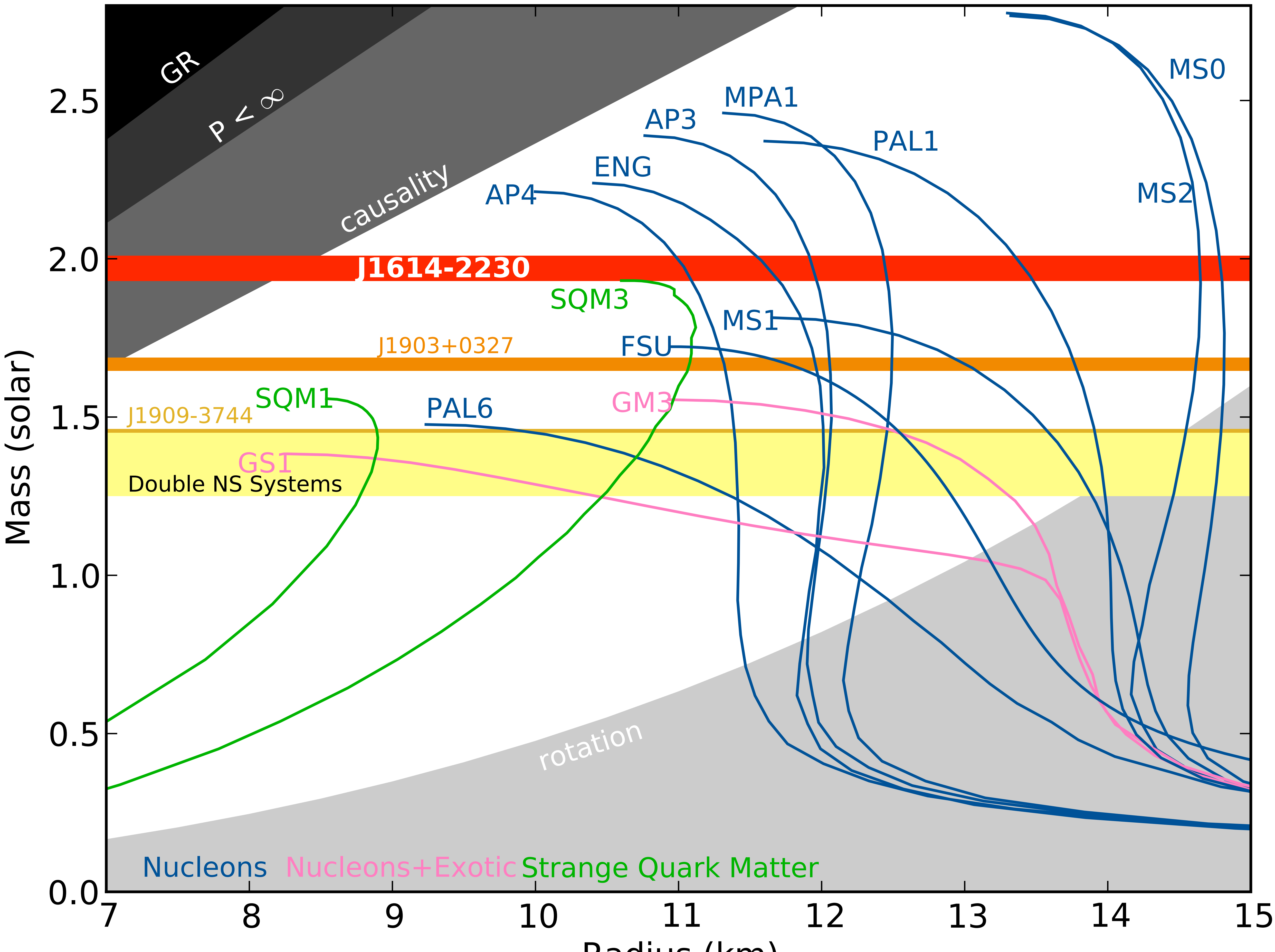
Uncertainty in the knowledge of nuclear EOS leads to uncertainty in the prediction of Mass-radius relation and limiting mass of neutron stars
(upon exceeding the max. NS mass a Black Hole would result)

Inter-nucleon distance ~ 1 fm $\Rightarrow n \sim 10^{39}$, $\rho \sim 10^{15}$ g cm^{-3}

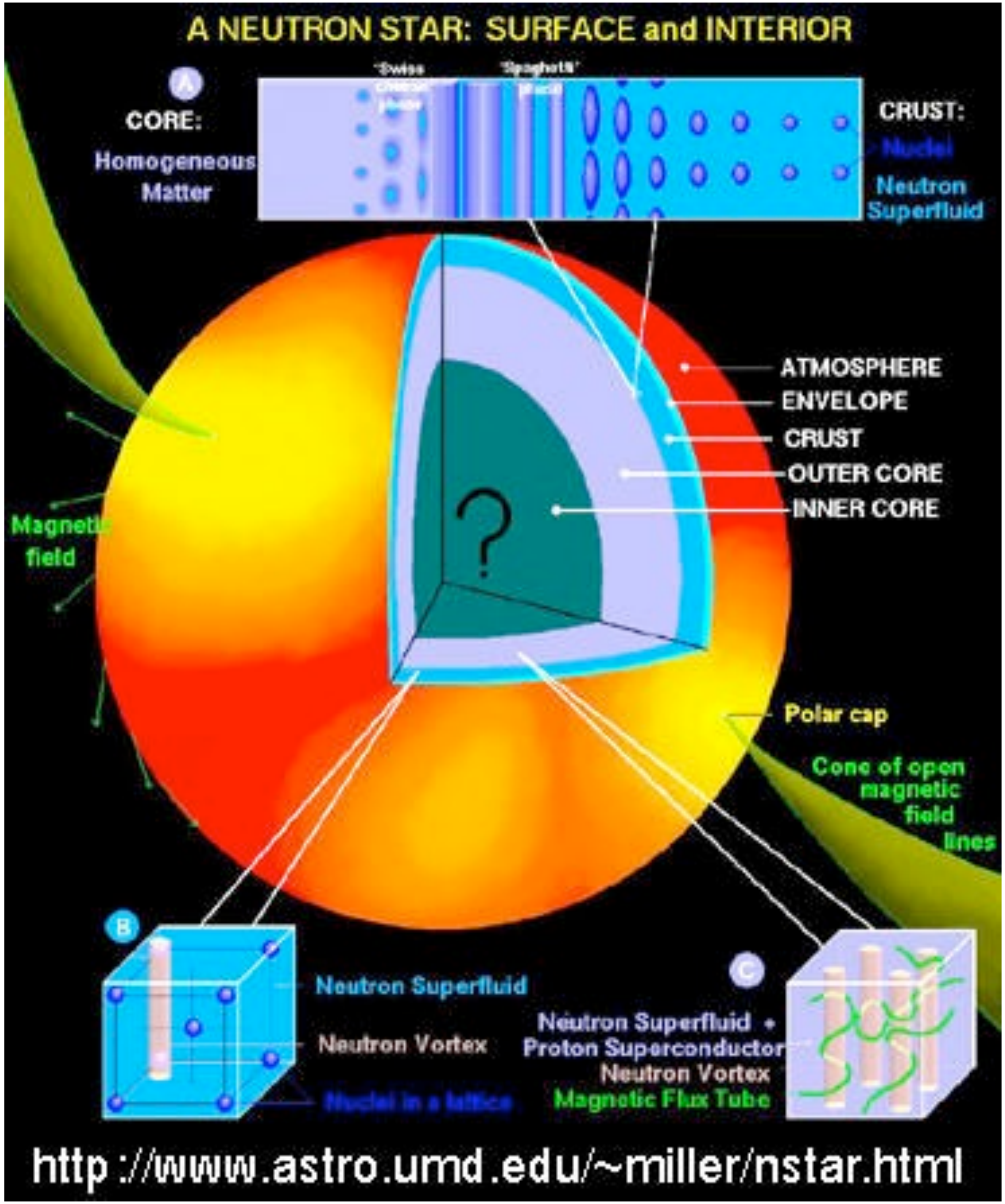
$R \sim 10$ km for $M \sim 1\ M_{sun}$

Neutron stars spin fast: $P \sim$ ms - mins
and have strong magnetic field: $B_{surface} \sim 10^8 - 10^{15}$ G

Exotic phenomena: *Pulsar, Magnetar activity*



Demorest et al 2010


A NEUTRON STAR: SURFACE and INTERIOR
A
CORE:
Homogeneous Matter
"Swiss cheese" phase
"Spaghetti" phase
CRUST:
Nuclei
Neutron Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines
B
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
C
Neutron Superfluid + Proton Superconductor
Neutron Vortex
Magnetic Flux Tube
http://www.astro.umd.edu/~miller/nstar.html

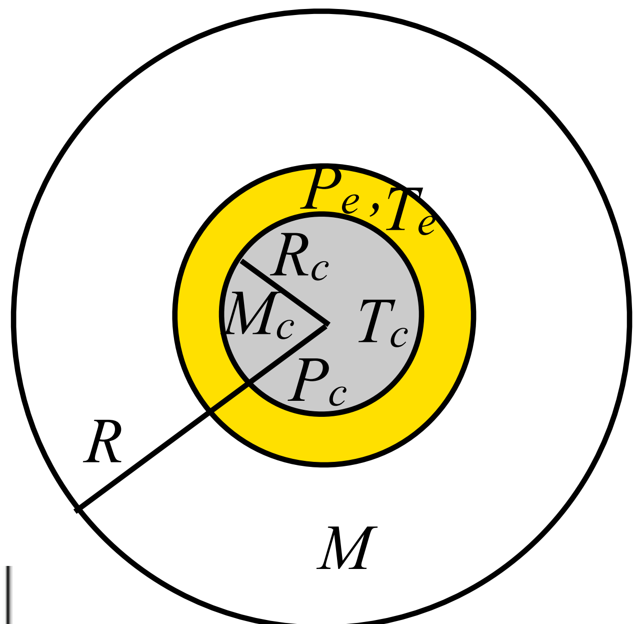
References

- The Physical Universe : *F.H. Shu*
- Stellar Structure and Evolution : *R. Kippenhahn and A. Weigert*
- An Introduction to the Study of Stellar Structure: *S. Chandrasekhar*
- White Dwarfs, Neutron Stars and Black Holes : *S.A. Shapiro and S.L. Teukolsky*

Stellar Evolution

Schönberg-Chandrasekhar limit

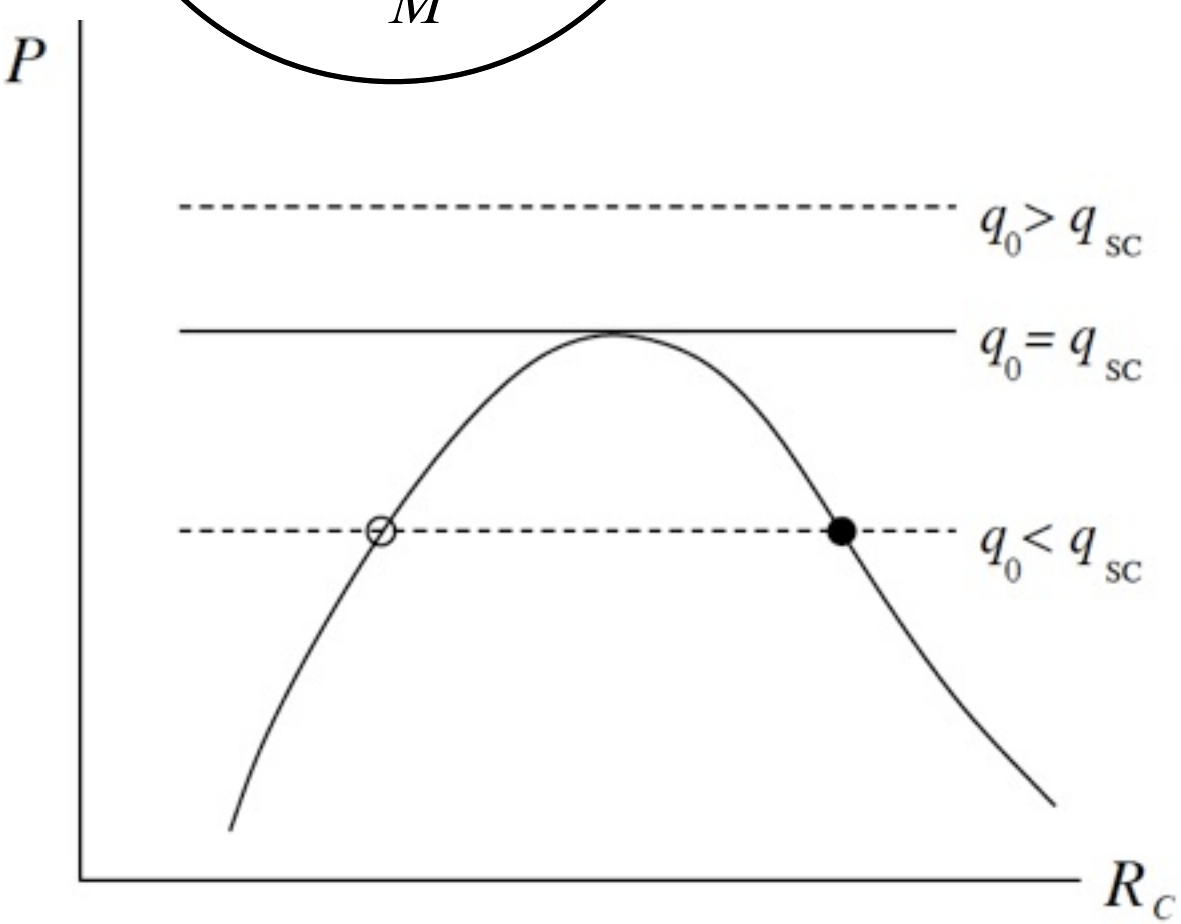
Core-envelope configuration: Inert core surrounded by burning shell



Core surface pressure $P_c = \dfrac{2E_{\rm th} + E_g}{4\pi R_c^3} = c_1 \dfrac{M_c T_c}{R_c^3} - c_2 \dfrac{M_c^2}{R_c^4}$

Envelope base pressure $P_e = c_3 \dfrac{T_e^4}{M^2}$

For mechanical and thermal balance $T_e = T_c$ and $P_e = P_c$



But P_c has a maximum as a function of R_c

$$P_{c,\rm max} = c_4 \frac{T_c^4}{M_c^2}$$

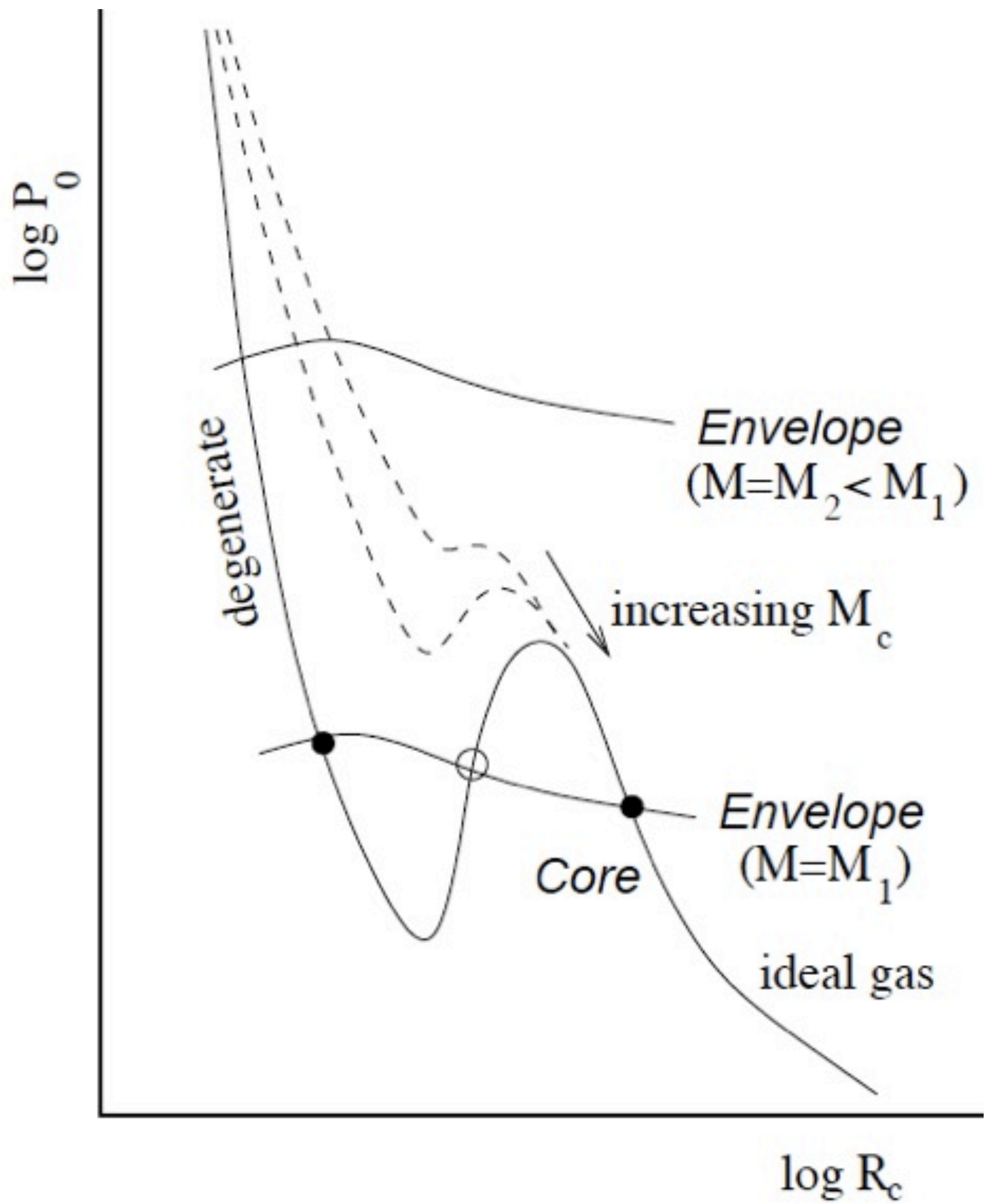
So balance is possible only if $P_e \leq P_{c,\rm max}$

i.e. $q_0 \equiv \dfrac{M_c}{M} \leq \sqrt{\dfrac{c_4}{c_3}} \equiv q_{\rm sc} \approx 0.37 \left(\dfrac{\mu_{\rm env}}{\mu_{\rm core}}\right)^2$

if core mass grows beyond this, then core collapse would occur.

⇒ *contraction until degeneracy support*

Post Main Sequence Evolution



Low mass star (< 1.4 $M_\odot$):

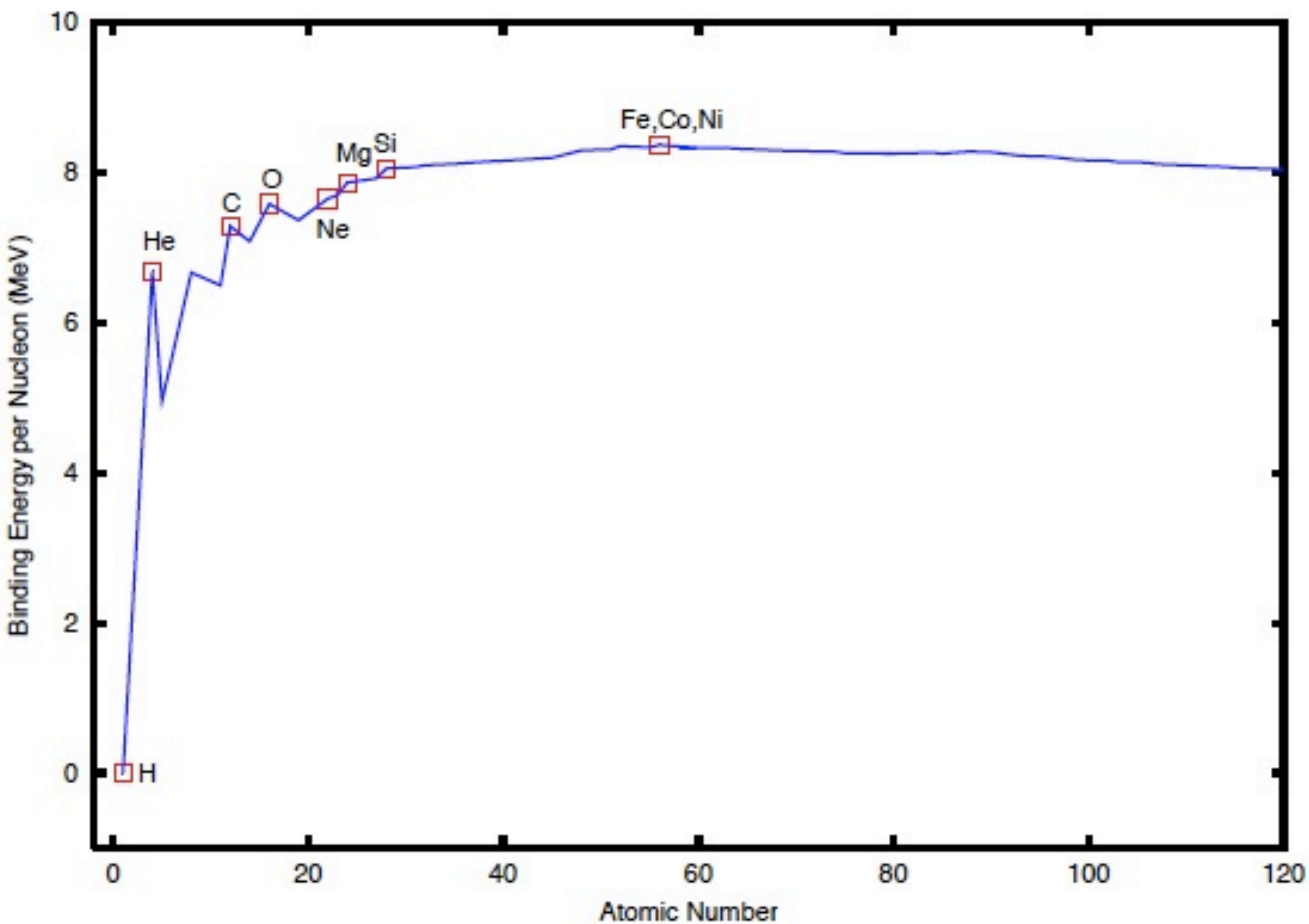
gradual shrinkage of the core to degenerate configuration
He ign at M_c = 0.45 $M_\odot$: L=100 $L_\odot$
varied mass loss; *horizontal branch*
later AGB ⇒ WD+*planetary nebula*

High mass star:

sudden collapse of the core from thermal to degenerate branch
⇒ quick progress to giant

Multiple burning stages
If final degen. support at M_c < M_{ch} , WD+PN will result
Else burning all the way to Fe core.
Once M_{ch} exceeded : collapse, neutronization, supernova

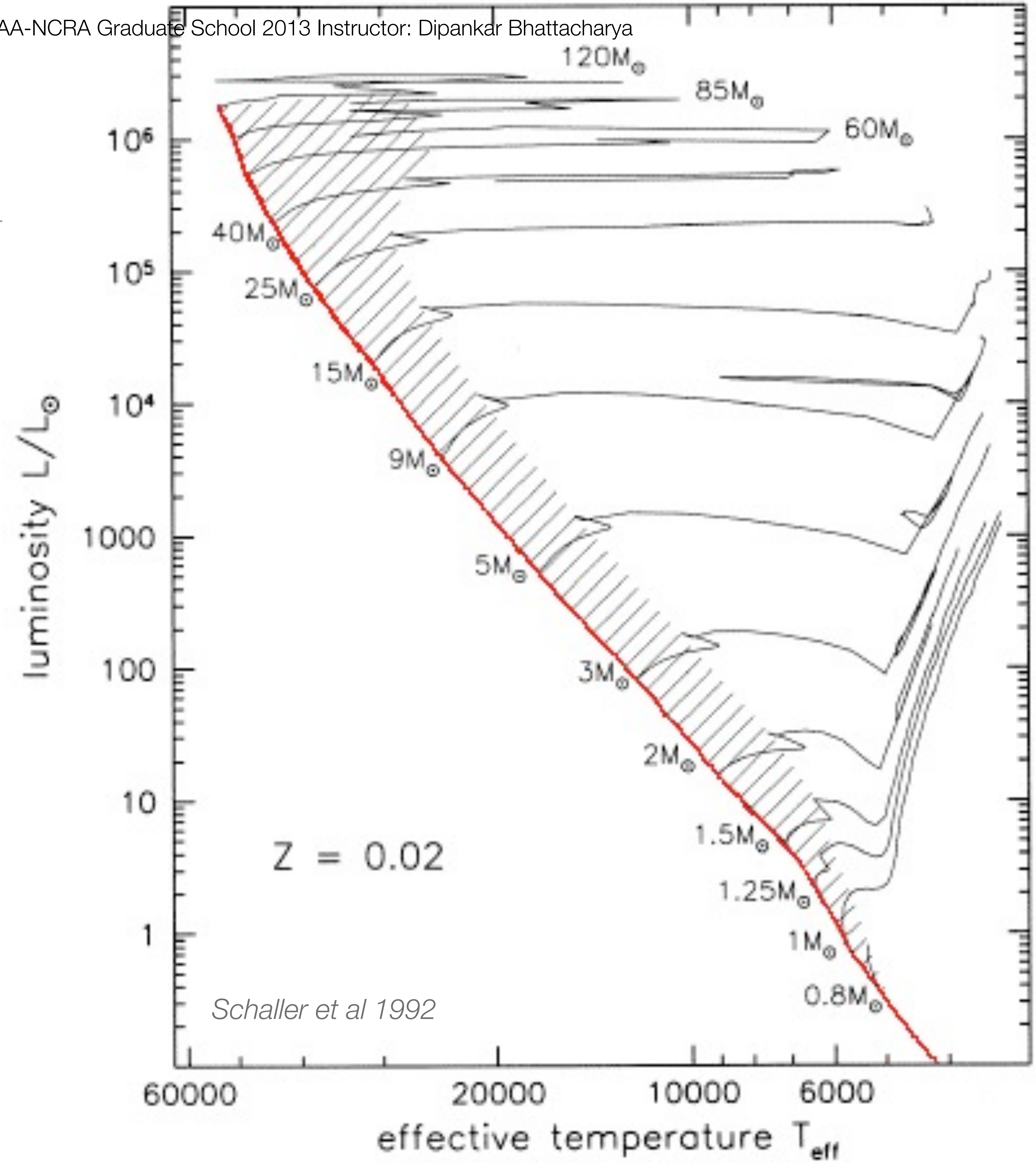
Nuclear burning stages



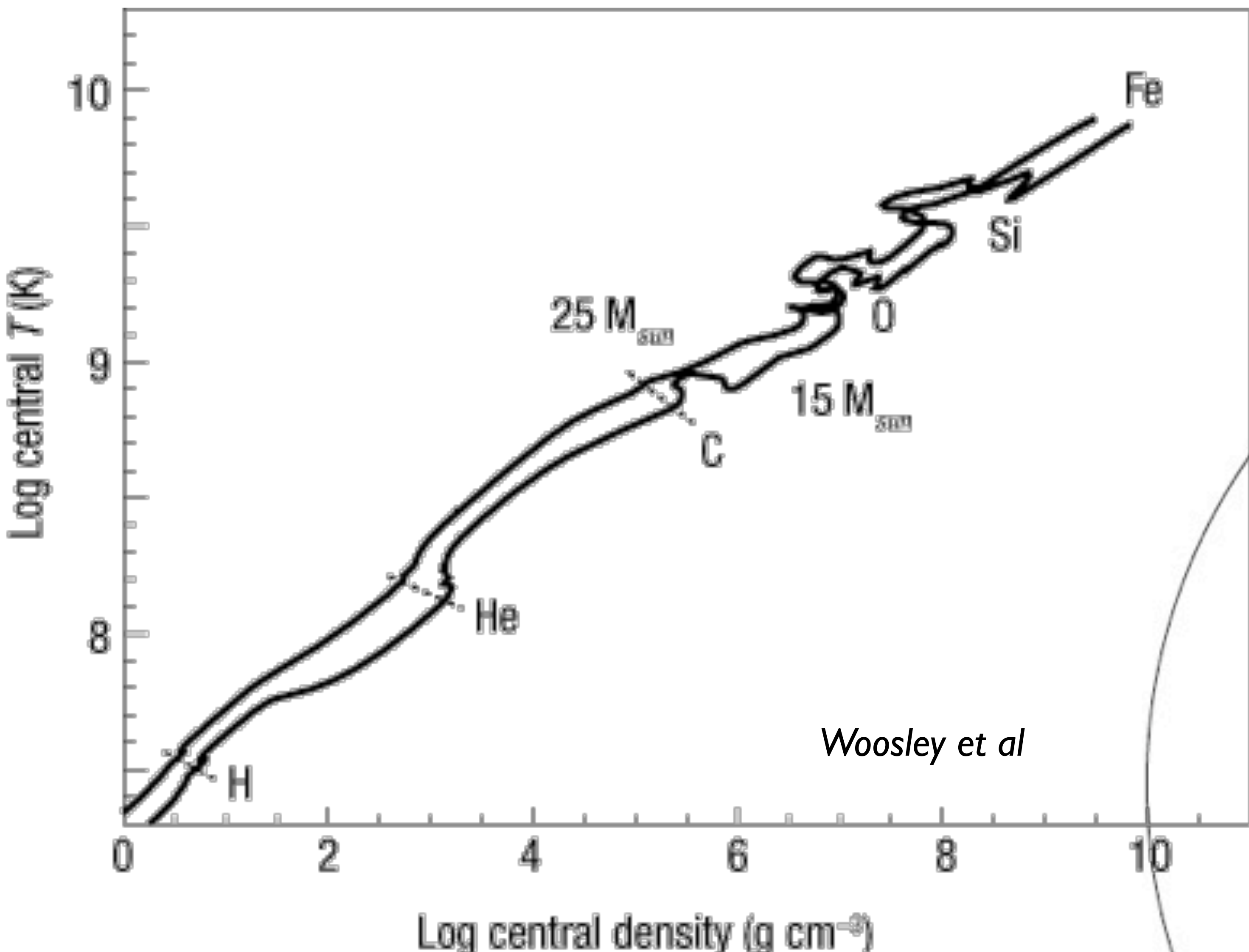
Stellar Evolutionary Tracks

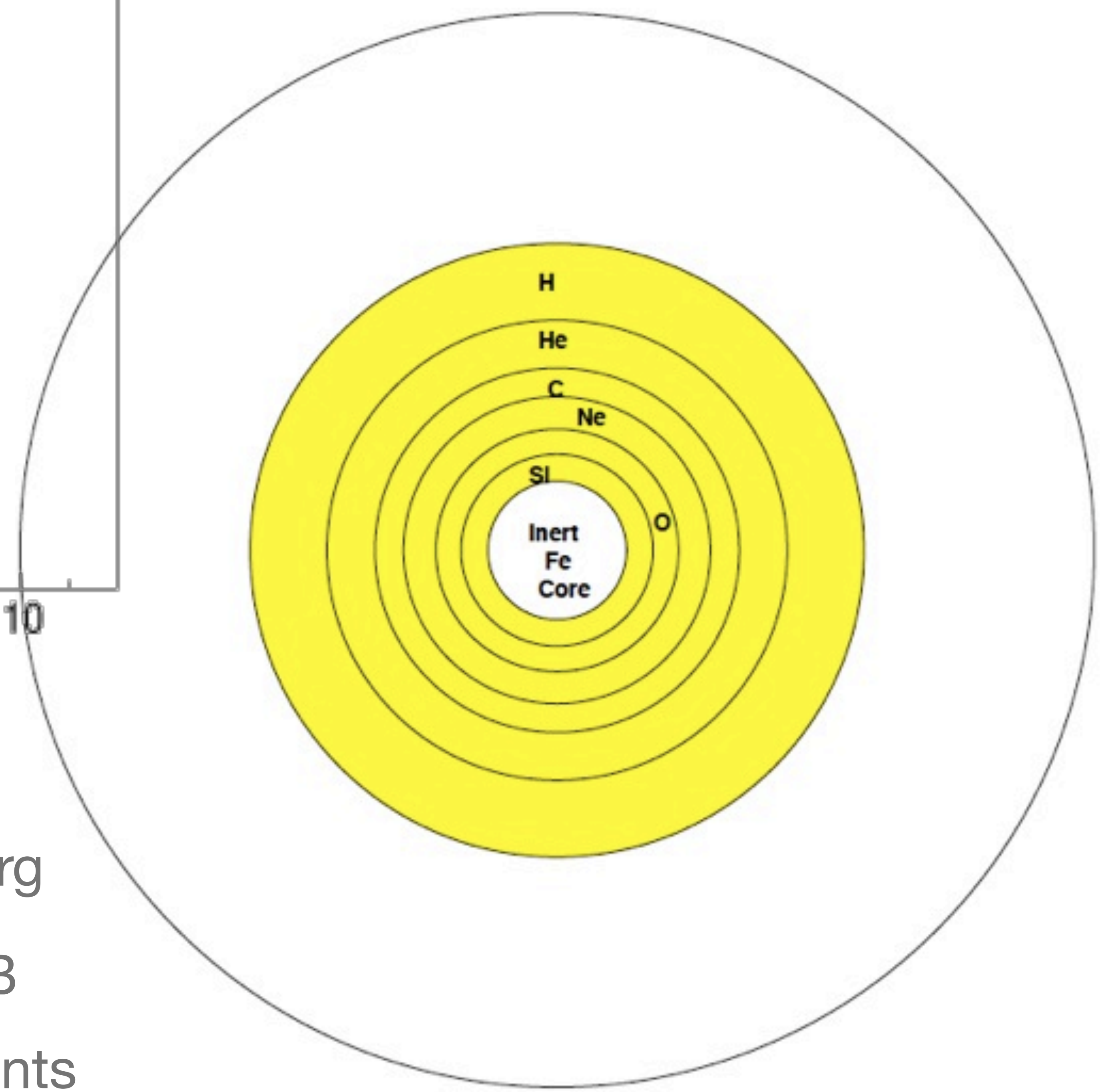
Star Cluster Studies

- Spectroscopic Parallax: *distance*
- Turnoff mass: *age*



A star's journey to a supernova





Core-collapse Supernovae:

$E_{tot} \sim 10^{53}$ erg; $E_{kin} \sim 10^{51}$ erg; $E_{rad} \sim 10^{49}$ erg

Massive, fast spinning stars ⇒ jets ⇒ GRB

r-process nucleosynthesis ⇒ heavy elements

Supernovae of Type Ia

Occur due to mass transfer in double WD binary followed by complete explosion.
No core collapse

WD composition: C+O
Accretion increases WD mass ⇒ M_{ch} approached ⇒ rapid contraction ⇒ heating

⇒ degenerate C-ignition ⇒ thermal runaway ⇒ explosion

$E_{tot} \sim 10^{51}$ erg ; Generates radioactive Ni which powers light curve

Standard conditions, standard appearance ⇒ Distance Indicators

References

- Stellar Structure and Evolution : *R. Kippenhahn and A. Weigert*
- Stars: Their Birth, Life and Death : *I.S. Shklovskii*
- An Introduction to the Theory of Stellar Structure and Evolution : *D. Prialnik*
- An Invitation to Astrophysics : *T. Padmanabhan*

Radiation

Radiative Transfer

Radiation is modified while propagating through matter

$$\frac{dI_\nu}{ds} = -\underbrace{\alpha_\nu}_{\text{absorption coef}} I_\nu + \underbrace{j_\nu}_{\text{emission coef}} \quad \Rightarrow \quad \frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

$$\Rightarrow I_\nu = S_\nu + (I_\nu^0 - S_\nu)e^{-\tau_\nu}$$

I_ν : Specific Intensity (energy/area/s/Hz/sr)

τ_ν : Optical Depth

S_ν : Source Function

For a thermal source S_ν = Planck function (blackbody) $B_\nu = \dfrac{2h\nu^3}{c^2}\dfrac{1}{\exp(h\nu/kT) - 1}$

$= 2\nu^2 kT/c^2$ $(h\nu \ll kT)$

$\tau_\nu \gg 1 \quad \Rightarrow$ Blackbody radiation
(optically thick)

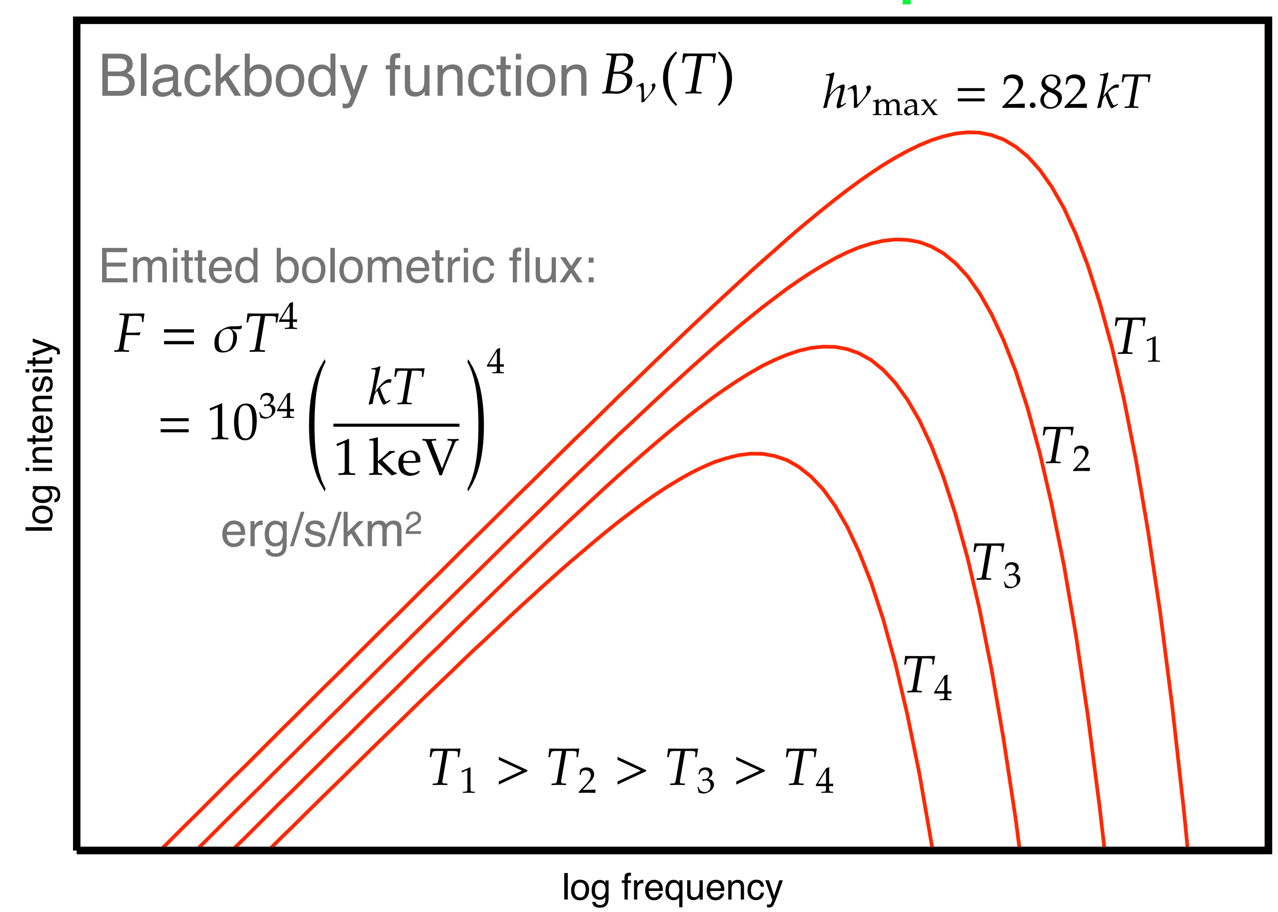
A source can be optically thick at some frequencies and optically thin at others

$\tau_\nu \ll 1 \quad \Rightarrow \quad I_\nu = I_\nu^0 + (S_\nu - I_\nu^0)\tau_\nu$
(optically thin)

$T_{\rm src} > T_{\rm bg}$: emission

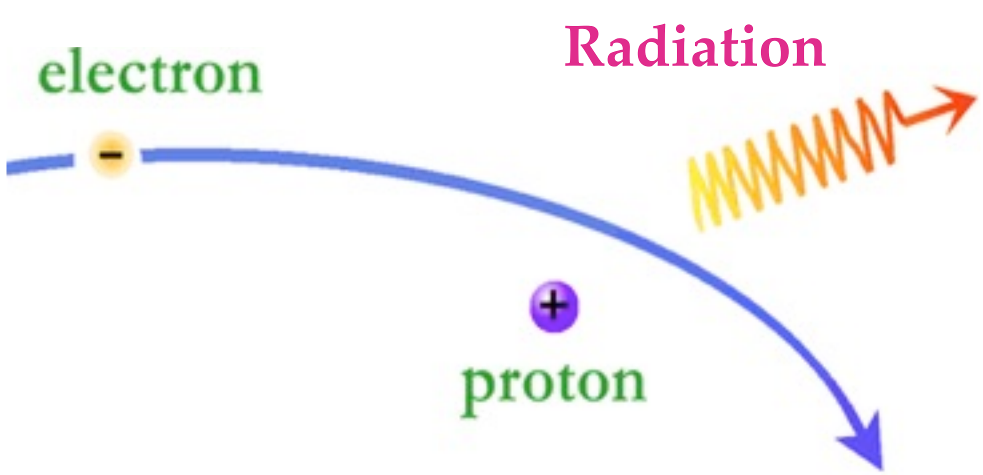
$T_{\rm src} < T_{\rm bg}$: absorption

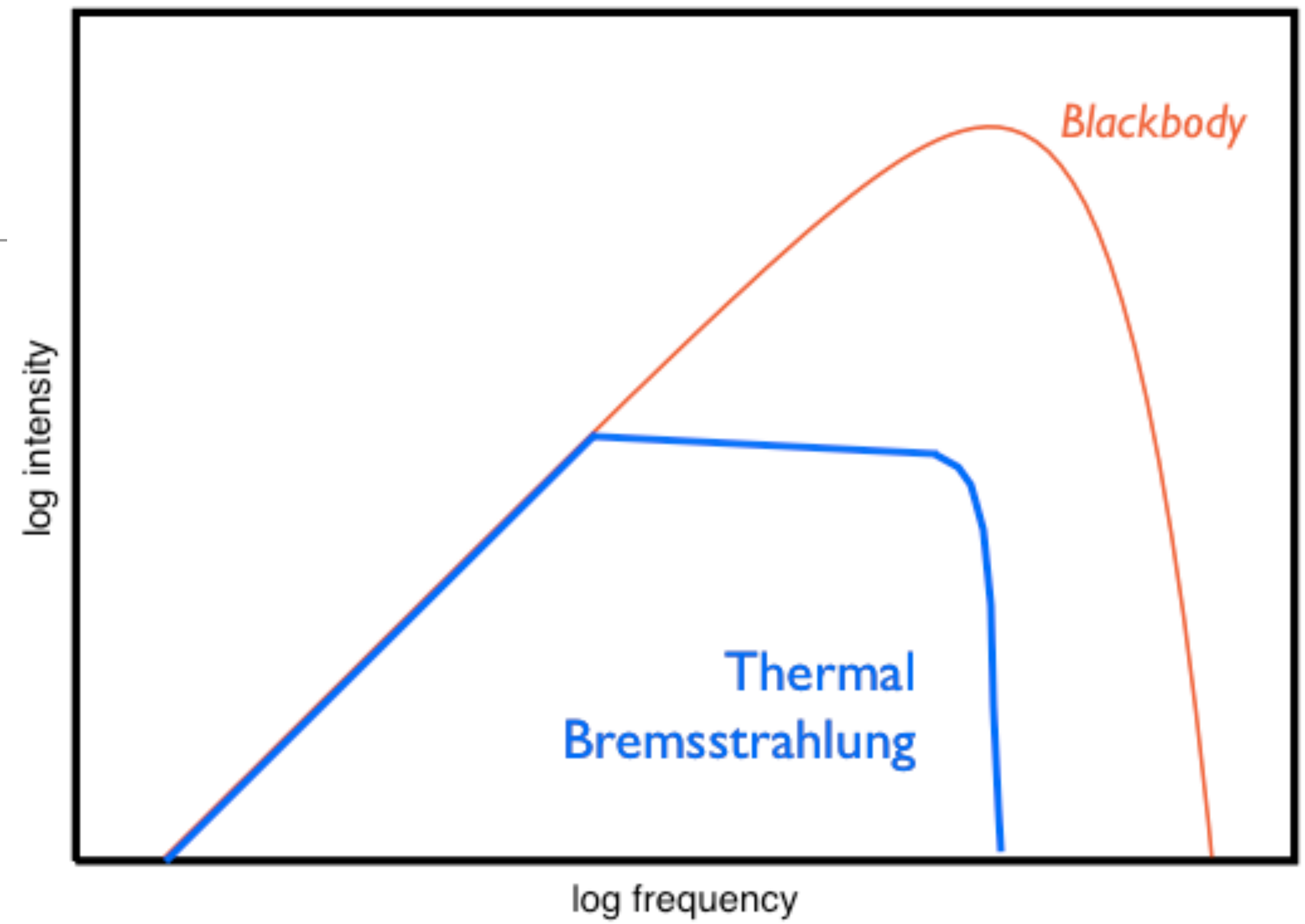
For non-thermal distribution of particle energies, $S_\nu \neq B_\nu$



Bremsstrahlung

(free-free process)





Emission coefficient :

$$\epsilon_\nu^{\rm ff} = 6.8\times10^{-38} Z^2 n_{\rm e} n_{\rm i} T^{-1/2} {\rm e}^{-h\nu/kT} \bar{g}_{\rm ff} \text{ erg s}^{-1}\text{ Hz}^{-1}\text{ cm}^{-3}$$

all n values in cm^{-3}

Bolometric: $$\epsilon^{\rm ff} = 1.4\times10^{-27} Z^2 n_{\rm e} n_{\rm i} T^{1/2} \bar{g}_{\rm ff} \text{ erg s}^{-1}\text{ cm}^{-3}$$

Free-free absorption coefficient:

$$\alpha_\nu^{\rm ff} = 3.7\times10^{8} Z^2 n_{\rm e} n_{\rm i} T^{-1/2} \nu^{-3} \left(1-{\rm e}^{-h\nu/kT}\right) \bar{g}_{\rm ff} \text{ cm}^{-1}$$

$$\approx 4.5\times10^{-25} Z^2 n_{\rm e} n_{\rm i} \,(kT)_{\rm keV}^{-3/2}\, \nu_{\rm MHz}^{-2} \bar{g}_{\rm ff} \text{ cm}^{-1}$$

Compare Thomson:

$$\alpha_{\rm T} = n_{\rm e}\sigma_{\rm T}$$
$$= 6.65\times10^{-25} n_{\rm e} \text{ cm}^{-1}$$

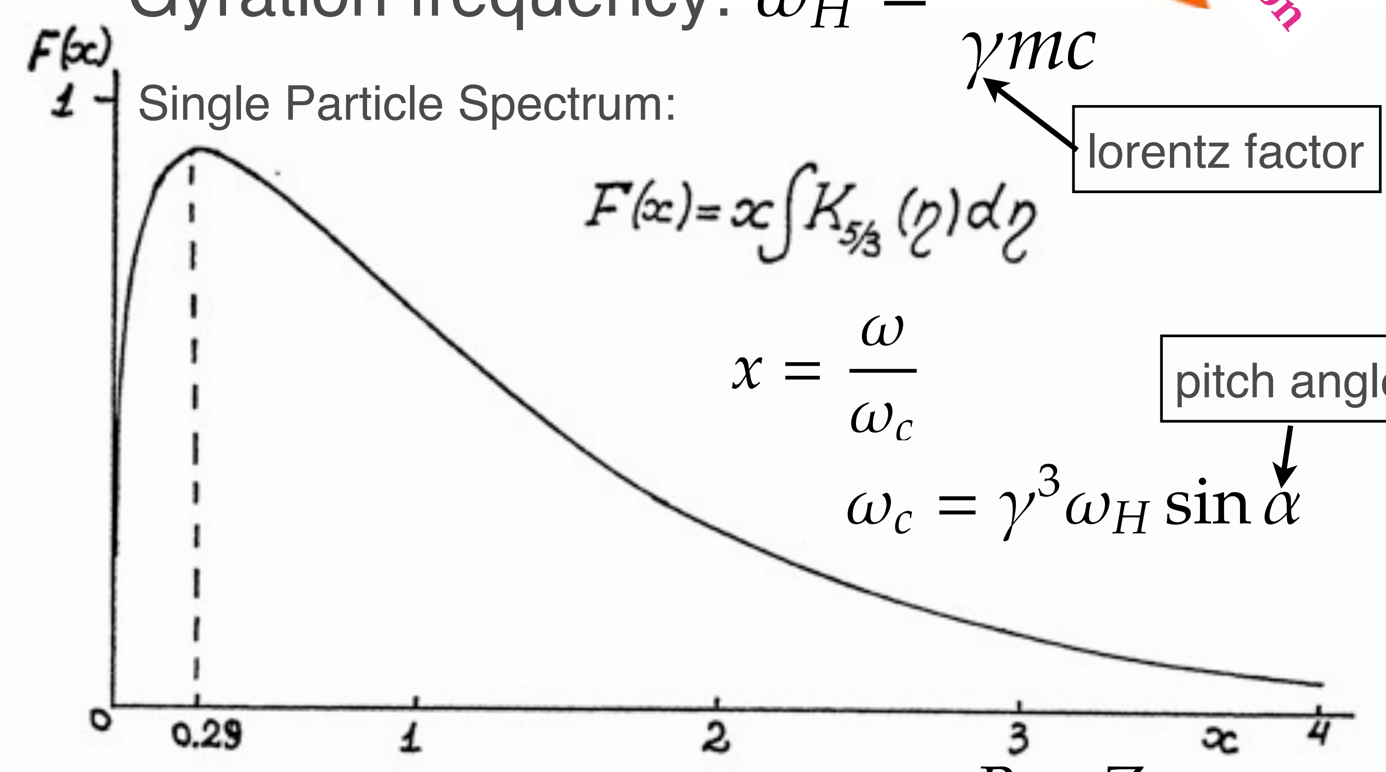
Synchrotron

(relativistically moving charged particle in a magnetic field)

Gyration frequency: $\omega_H = \frac{qB}{\gamma m c}$

Ze

lorentz factor



Single Particle Spectrum:

$F(x) = x \int K_{5/3}(\eta)\, d\eta$

$x = \frac{\omega}{\omega_c}$

$\omega_c = \gamma^3 \omega_H \sin\alpha$

pitch angle

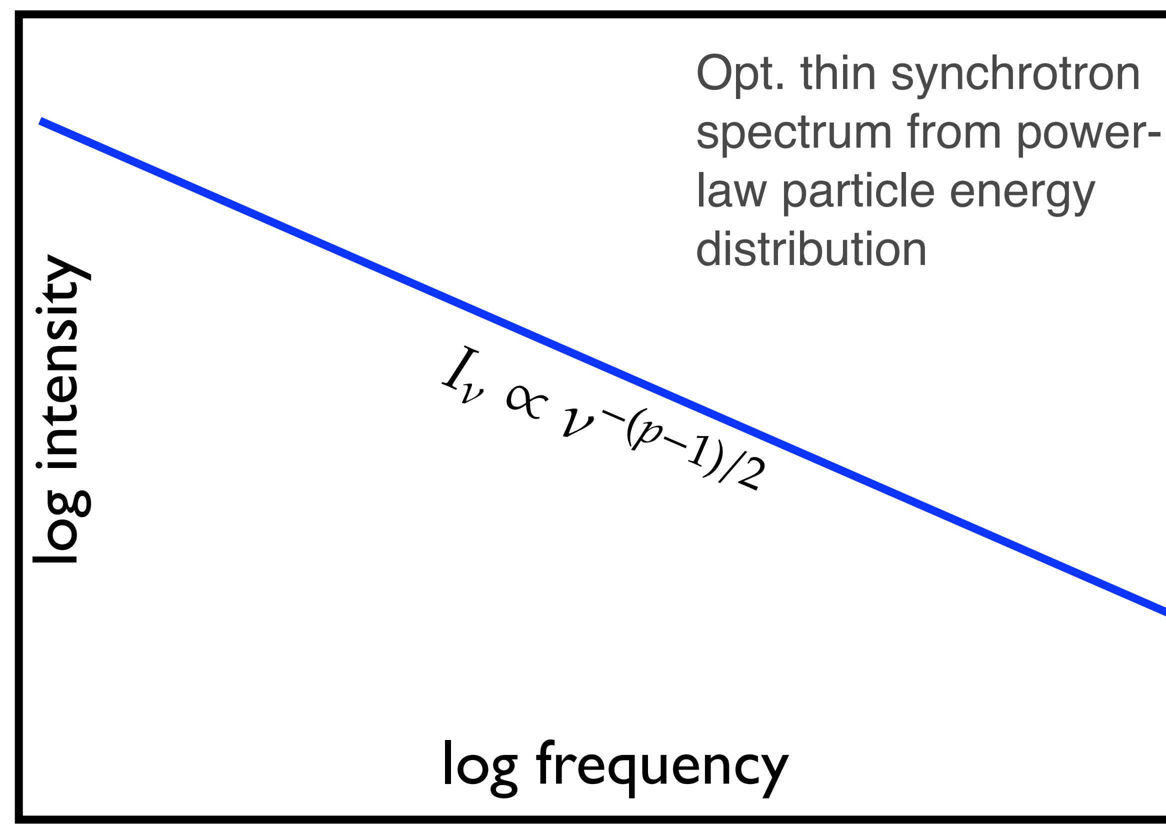
$\nu_{\rm peak} = 0.29 \frac{\omega_c}{2\pi} \approx 0.81 \gamma^2 \left(\frac{B}{1\,{\rm G}}\right) \frac{Z m_e}{m}$ MHz

Power = $\frac{4}{3} \sigma_T c \beta^2 \gamma^2 U_B \left(\frac{Z^2 m_e}{m}\right)^2$

$= 2.0 \times 10^{-14} \gamma^2 \left(\frac{B}{1\,{\rm G}}\right)^2 \left(\frac{Z^2 m_e}{m}\right)^2$ erg / s per particle

Particle acceleration process often generates *non-thermal*, power-law energy distribution of the relativistic charged particles: $N(\gamma) \propto \gamma^{-p}$

The radiation spectrum generated by such a distribution is also a power-law:

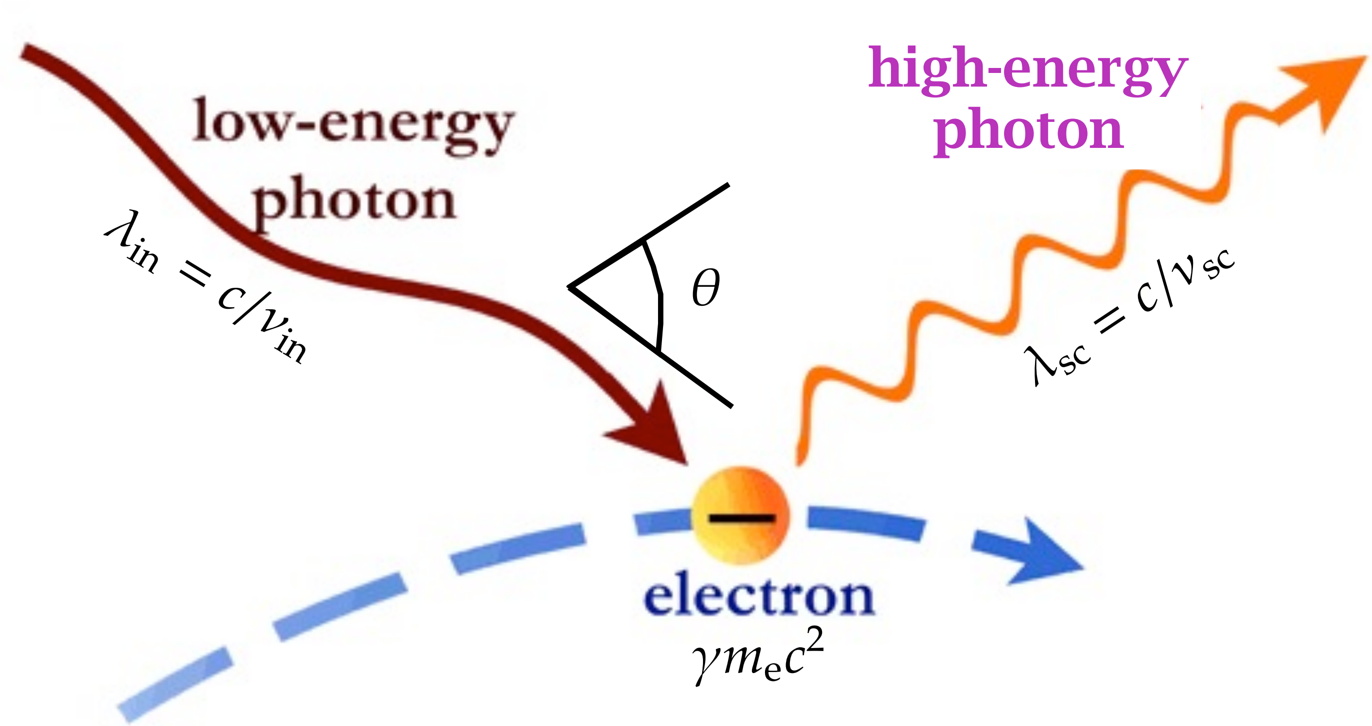


$j_\nu \propto \nu^{-(p-1)/2}$

$\alpha_\nu \propto \nu^{-(p+4)/2}$

$S_\nu \propto \nu^{5/2}$

Compton scattering



In the frame where the electron is initially at rest,

$$\lambda_{sc} - \lambda_{in} = \frac{h}{m_e c}(1 - \cos\theta)$$

and cross section: *Klein-Nishina*

$$\sigma_{KN} \approx \sigma_T \qquad (h\nu_{in} \ll m_e c^2)$$
$$\propto \nu_{in}^{-1} \qquad (h\nu_{in} \gg m_e c^2)$$

In the observer's frame, where the electron is moving with a lorentz factor γ,

$$\nu_{sc} \approx \gamma^2 \nu_{in} \qquad \text{for } h\nu_{in} \ll m_e c^2/\gamma$$

(inverse compton scattering)

Inverse compton power emitted per electron: $\frac{4}{3}\sigma_T c \beta^2 \gamma^2 U_{ph}$; U_{ph} = photon energy density

Non-thermal comptonization ⇒ spectral shape akin to synchrotron process

Thermal comptonization ⇒ number conserving photon diffusion in energy space
⇒ power-law, modified blackbody or Wien spectrum
(for different limiting cases of opt. depth and y-parameter)

Compton y parameter = (av. no. of scatterings) x (mean fractional energy change per scattering)

References

- Radiative Processes in Astrophysics : *G.B. Rybicki and A.P. Lightman*
- High Energy Astrophysics : *M. Longair*
- The Physics of Astrophysics vol. I: Radiation : *F.H. Shu*
- Theoretical Astrophysics vol. 1 : *T. Padmanabhan*

Diffuse Matter

Diffuse matter between stars: the ISM

Interstellar matter exists in a number of phases, of different temperatures and densities. Average density of Interstellar medium is ~ 1 atom / cm^3

At such low densities heat transfer between different phases is very slow.
So phases at multiple temperatures coexist at pressure equilibrium.

Cooling: free-free/free-bound continuum, atomic and molecular lines, dust radn.
Heating: Cosmic Rays, Supernova Explosions, Stellar Winds, Photoionization

Ionization fraction x: $\dfrac{x^2}{1-x} = \dfrac{2g_{\rm i}}{g_0 n}\left(\dfrac{2\pi m_{\rm e}kT}{h^2}\right)^{3/2} {\rm e}^{-\chi/kT}$ (*Saha equation*)

⇒ Hydrogen is fully ionized at T > 10^4 K

Ionization states are denoted by roman numeral: I: neutral, II: singly ionized.......

Gas around hot stars are photoionized by the stellar UV photons.
Ionization balance: *Recombination rate* = *Rate of supply of ionizing photons*

Strömgren sphere: $\dfrac{4\pi}{3}R^3 n_{\rm e} n_{\rm i} \underset{\uparrow}{\alpha} = \dot{N}_{\rm UV} \quad \Rightarrow \quad R = \left(\dfrac{3\dot{N}_{\rm UV}}{4\pi n_{\rm e}^2 \alpha}\right)^{1/3}$ (singly ionized: HII region)

$\boxed{\text{recombination coef}}$

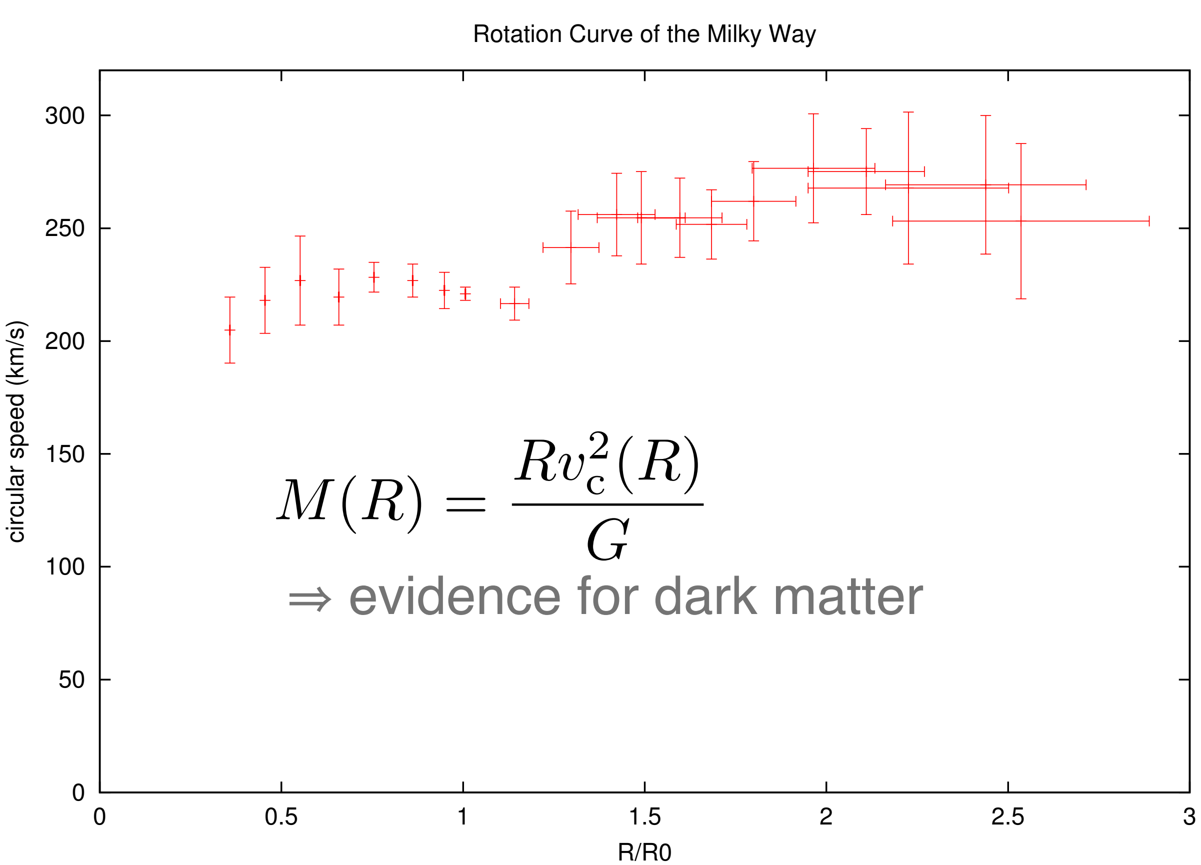
ISM phases and constituents

- Coronal Gas: T ~ 10^6 K
- Warm Ionized Medium: T ~ 8000 K
- Warm Neutral Medium: T ~ 6000 K
- Cold Neutral Medium: T ~ 80 K (HI clouds)
- Molecular Clouds: T < 20 K

Cosmic rays, diffuse starlight, magnetic field: ~ 1eV/cm^3 each

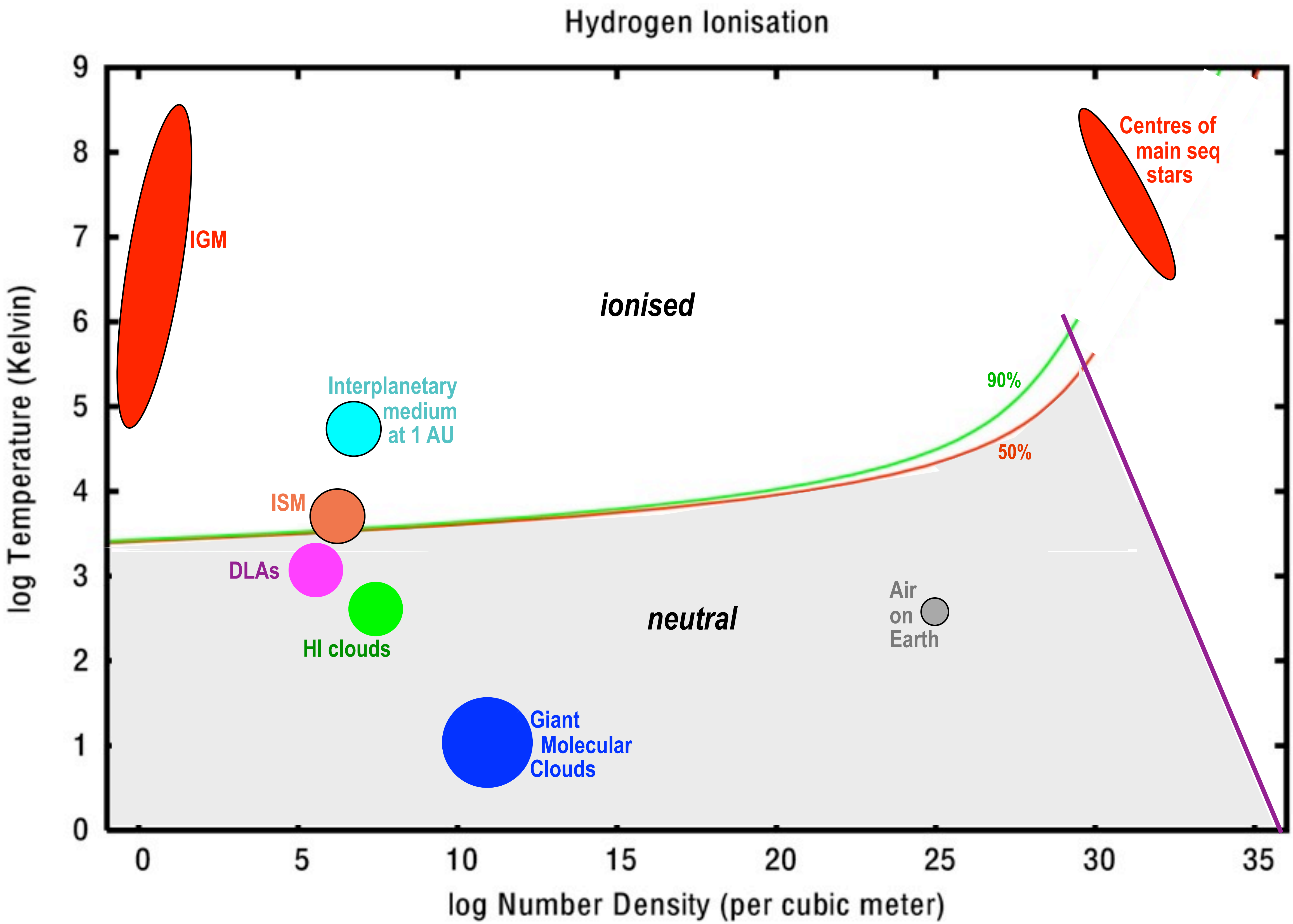
Dust: solid particles - graphite, silicates, PAHs etc.

Distributed HI gas produces 1420 MHz (21-cm) hyperfine transition line.
⇒ vital probe of density, temperature, kinematics (*e.g. rotation curve*)



Molecular regions can be studied through mm-wave rotational transitions, e.g. of CO

Dust causes extinction and reddening, re-radiates energy in Infrared, polarizes starlight, provides catalysis for molecule formation, shields molecular clouds from radiation damage, depletes the diffuse gas of some elements.



Hydrogen Ionisation
log Temperature (Kelvin)
log Number Density (per cubic meter)
0
1
2
3
4
5
6
7
8
9
0
5
10
15
20
25
30
35
IGM
Centres of main seq stars
ionised
Interplanetary medium at 1 AU
90%
50%
ISM
DLAs
HI clouds
neutral
Air on Earth
Giant Molecular Clouds

Star Formation

Stars form by gravitational collapse and fragmentation of dense molecular clouds

Gravitational Instability occurs at masses larger than the Jeans' scale $M_{\mathrm{J}} \sim \rho_0 L_{\mathrm{J}}^3$

where $\dfrac{GM_{\mathrm{J}}}{L_{\mathrm{J}}}\mu m_{\mathrm{p}} = kT_0 \quad \Rightarrow \; L_{\mathrm{J}} = \left[\dfrac{kT_0}{G\mu m_{\mathrm{p}}\rho_0}\right]^{1/2} \quad \Rightarrow \; M_{\mathrm{J}} = \left[\dfrac{kT_0}{G\mu m_{\mathrm{p}}}\right]^{3/2}\dfrac{1}{\rho_0^{1/2}}$

Collapse can proceed only in presence of cooling. Hence star formation rate is strongly dependent on cooling. Cooling is provided by atomic and molecular transitions. More molecules ⇒ faster cooling.

Dust aids the formation and survival of molecules.
Formation of dust needs heavy elements

In early epochs, star formation was slow; fewer, very massive stars formed
With enrichment, star formation rate (SFR) increased, many small stars produced

Infrared emission from hot dust is tracer of star formation activity
Ultra-Luminous Infra Red Galaxies (ULIRGs): example of high SFR

High SFR → High SN rate → More CR → stronger Sychrotron emission (radio)
⇒ *Radio - FIR* correlation

Free Electrons

Ionization provides free electrons in the ISM: $\langle n_\mathrm{e} \rangle \sim 0.03\,\mathrm{cm}^{-3}$

Propagation through this plasma causes Dispersion of e.m. radiation, measurable at radio wavelengths. Can be used to infer distances of, *e.g.* pulsars. Plasma frequency of the ISM $\omega_\mathrm{p} \sim 6\,\mathrm{kHz}$

Magnetic Field permeates the Interstellar Medium.
Polarized radio waves undergo Faraday Rotation while propagating through the magnetized plasma. ⇒ *key probe of distributed magnetic field*

Typical interstellar field strength: $\sim 1\,\mu\mathrm{G}$
Cyclotron resonance: $\omega_\mathrm{c} \sim 20\,\mathrm{Hz}$

Dispersion relation of circularly polarized eigenmodes:

$$k_{\mathrm{r,l}} = \frac{\omega}{c}\left[1 - \frac{\omega_\mathrm{p}^2}{2\omega^2}\left(1 \mp \frac{\omega_\mathrm{c}}{\omega}\right)\right] \qquad \text{for } \omega \gg \omega_\mathrm{p}, \omega_\mathrm{c}$$

Dispersion Measure:

$$DM = \int_0^L n_\mathrm{e}\, ds$$

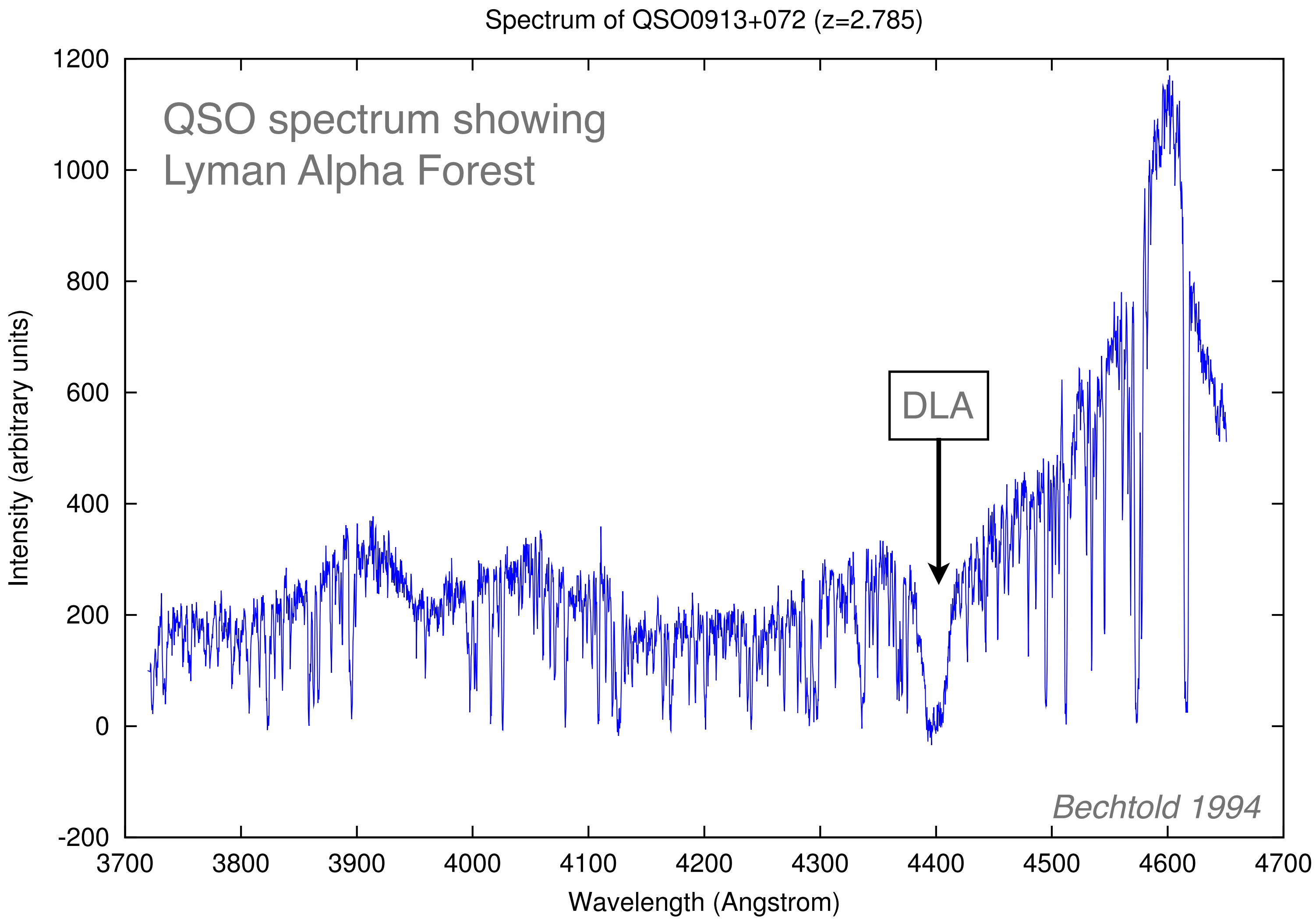
Rotation Measure:

$$RM = \int_0^L n_\mathrm{e} B_{||}\, ds$$

Intergalactic Medium

ISM of line-of-sight galaxies, gas clouds and the diffuse intergalactic medium can show up in absorption against the radiation of distant galaxies and QSOs

Lyman Alpha provides a strong absorption at 1216 Å in the rest frame of the absorbing gas. Due to cosmological redshift, absorption by different gas clouds in the line of sight occur at different wavelengths ⇒ Lyman Alpha Forest



Clouds with large Hydrogen content (e.g. galaxies) produce deep absorption with damping wings: Damped Lyman Alpha systems (*DLA*s)

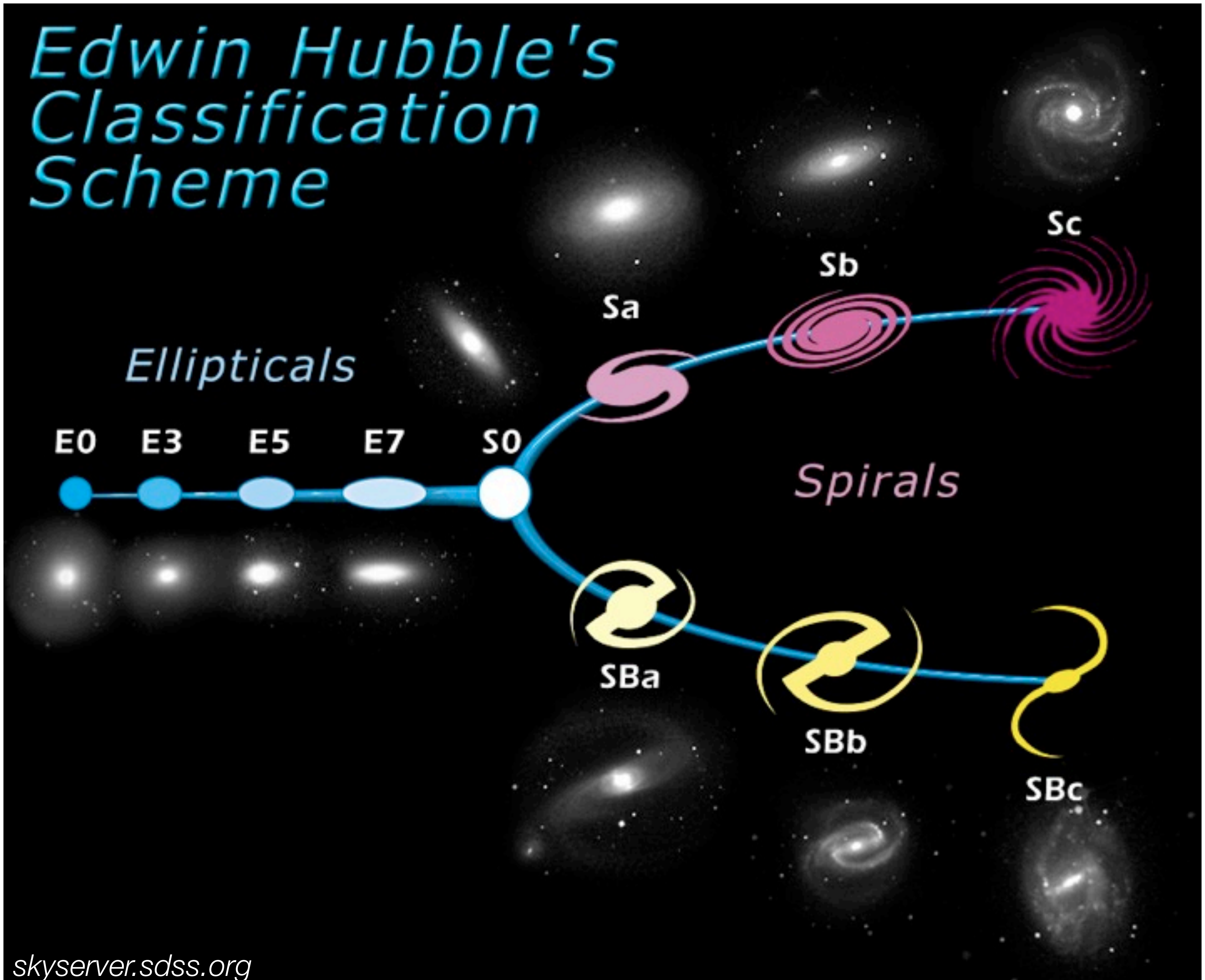
Diffuse Intercloud Medium is almost fully ionized. If not, then radiation shortward of emitted Ly-α would have been completely absorbed: *Gunn-Peterson* effect

References

- Physical Processes in the Interstellar Medium : *L. Spitzer Jr.*
- The Physical Universe: *F.H. Shu*
- An Invitation to Astrophysics : *T. Padmanabhan*

Galaxies

Hubble Classification



Galaxies are the basic building blocks of the universe

Various shapes and sizes:
- flattened **spirals** with high net ang. mom.
- **ellipticals** with lower net ang. mom.
- early galaxies mainly **irregular**

Baryon content $\sim 10^6\ M_\odot$ (dwarfs) to $\sim 10^{12}\ M_\odot$ (giant ellipt.)

Dark Matter $\sim$10-100 x Baryons

Properties of Galaxies

- Disk galaxies and irregulars are gas-rich, Ellipticals gas poor
- Star formation more prevalent in spirals/irregulars, more old stars in Ellipticals
- More Ellipticals found in galaxy clusters
- Ellipticals grow by merger: giants (cDs) found at centres of rich clusters
- Every galaxy appears to contain a central supermassive black hole
- Correlations:

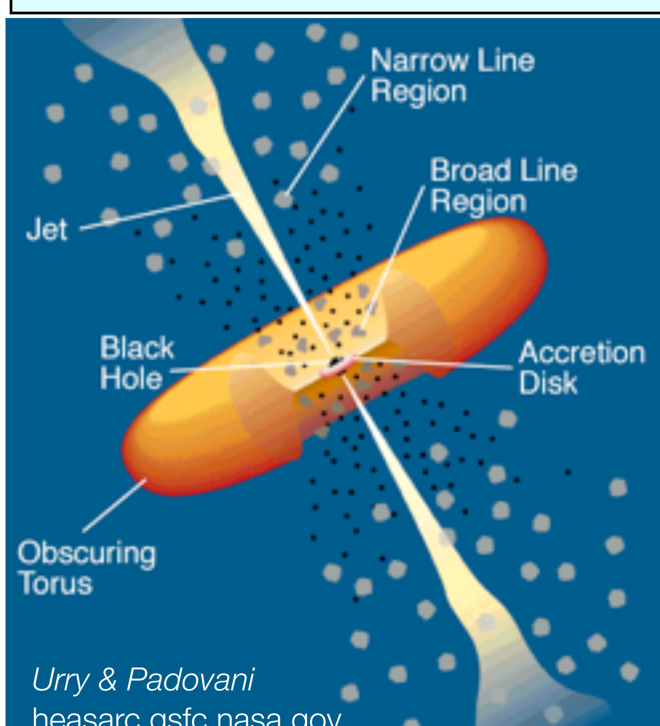
  Ellipticals: *Fundamental Plane*: $R \propto \sigma^{1.4\pm0.15} I^{-0.9\pm0.1}$

  Spirals: *Tully-Fisher relation*: $L \propto W^{\alpha}$

  $\alpha \sim 3-4$ depending on wavelength

  R : size
  σ : velocity dispersion
  I : surface brightness
  L : luminosity
  W : rotation velocity

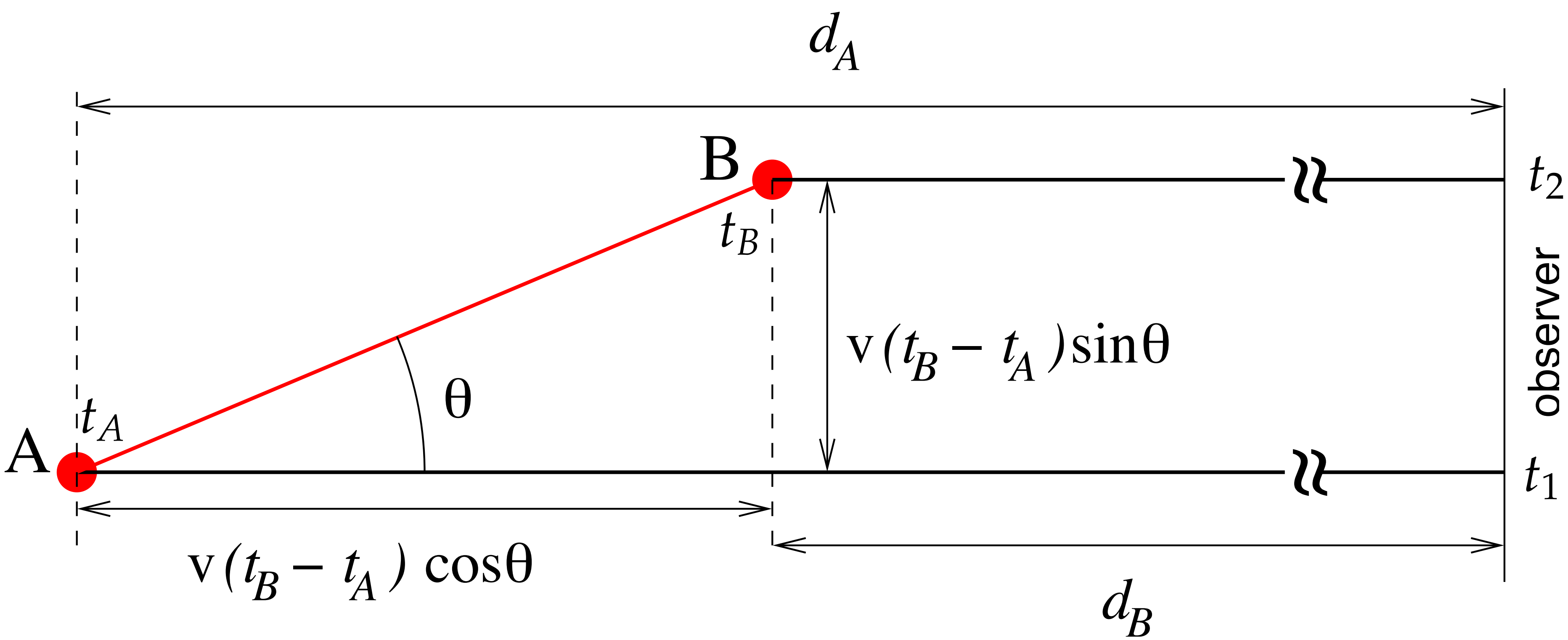
  Central Black Hole Mass: $M_{\rm BH} \propto \sigma^5$, $\sigma =$ velocity dispersion of elliptical galaxy or of central bulge in a spiral galaxy



- If central BH is fed by copious accretion, Active Galactic Nucleus (AGN) results: High nuclear luminosity, relativistic jets, non-thermal emission
  > Broad Line Region, Narrow Line Region, Disk, Torus
  > Diversity of appearance depending on viewing angle & jet strength: Seyferts, Radio Galaxies, QSOs, Blazars, LINERs......
- Emission is variable
- Reverberation mapping of BLR allows measurement of BH mass: light echo → R ; spectrum → v ; $M_{\rm BH} = Rv^2/G$

Superluminal Motion

Proof of relativistic bulk motion in AGNs



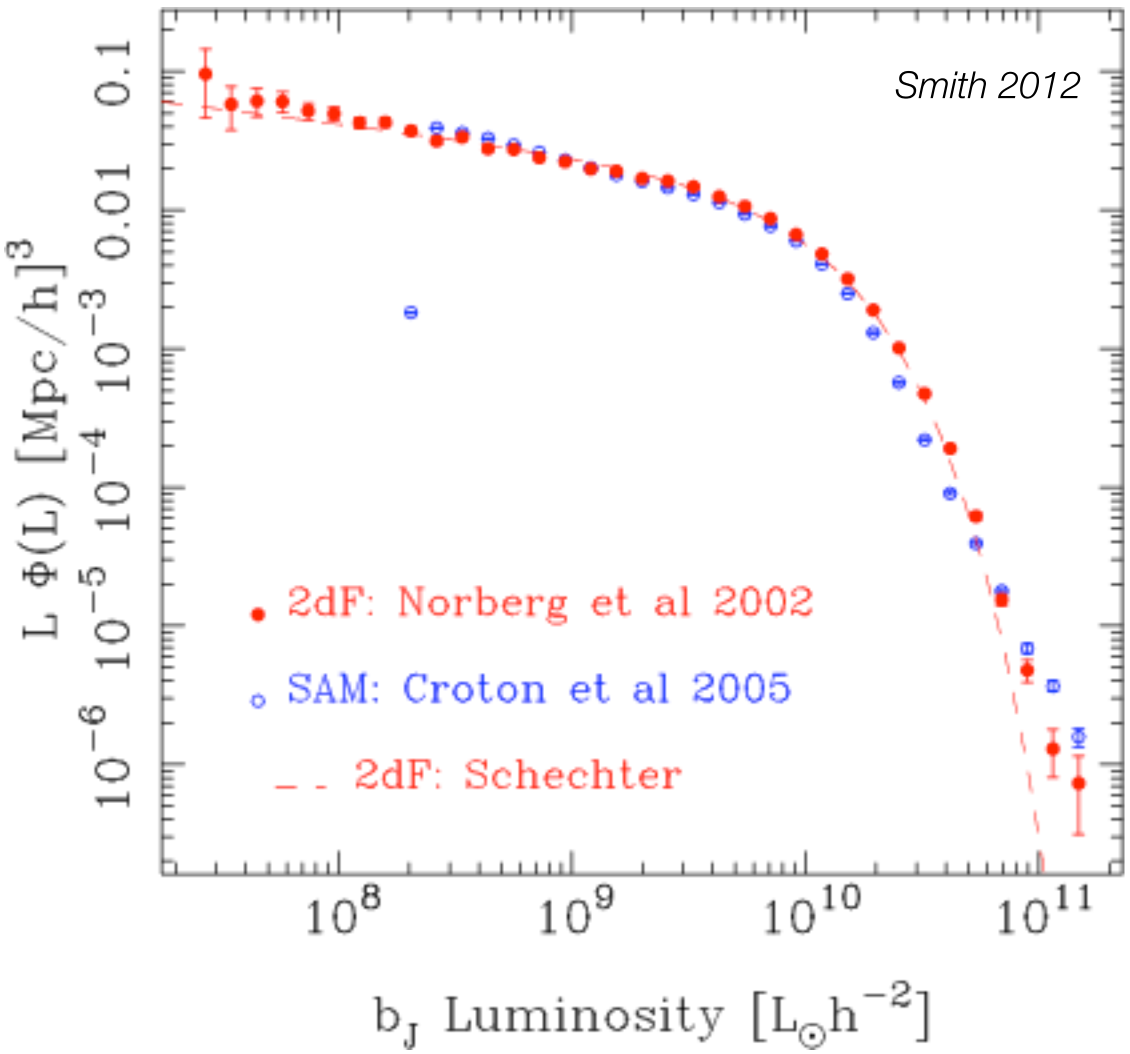
$$(t_2 - t_1) = (t_B - t_A) - \frac{(d_A - d_B)}{c} = (t_B - t_A)\left[1 - \frac{v\cos\theta}{c}\right]$$

$$v_{\mathrm{app}} = c\left(\frac{\beta\sin\theta}{1-\beta\sin\theta}\right) \quad \Rightarrow \quad \text{max. } v_{\mathrm{app}} = \gamma c\beta \quad \text{at } \cos\theta = \beta$$

faster than light
for $\beta \geq 0.71$

Galaxy Populations

Luminosity Function



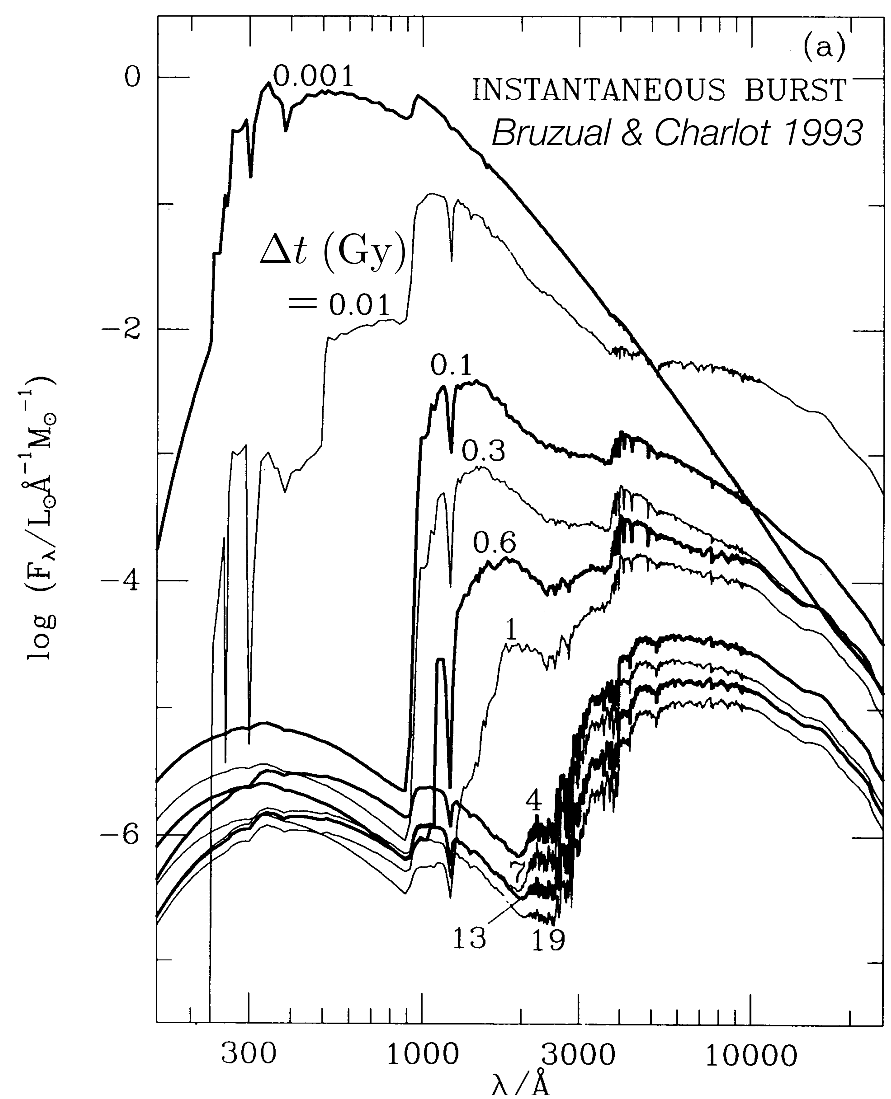
Analytical fit: *Schechter Function*

$$\Phi(L)dL = \Phi_*(L/L_*)^\alpha e^{-(L/L_*)}(dL/L_*), \qquad \alpha \sim -1.25$$

L_* depends on galaxy type and redshift

Luminosity and spectrum of a galaxy would change with time as stellar population evolves

Multiple starburst episodes may be required to characterize a galaxy

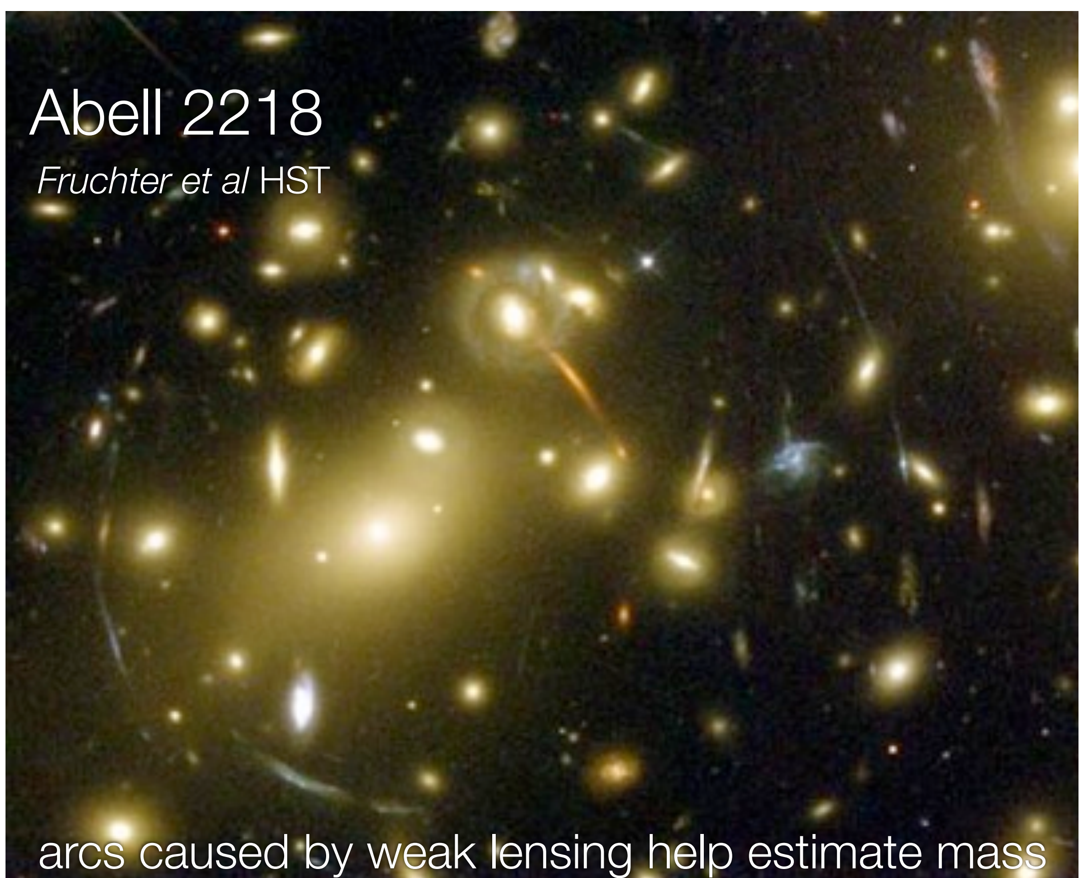


Large fraction of galaxies are found in groups and clusters. Interaction with other galaxies and with the cluster gas can strip a galaxy of gas and terminate star formation

Galaxy Clusters

- A rich cluster can contain thousands of galaxies bound to a large dark matter halo.
- Diffuse gas in clusters fall into the deep potential well, get heated and emit X-rays.
- Hot gas Compton scatters the cosmic microwave background: Sunyaev-Zeldovich.
- Gravitational lensing can be used to measure cluster mass, revealing dark matter.
- Groups and Clusters grow via collision and mergers.

Density profile of a DM halo: $\rho(r) = \rho_0 / \left[x(1+x)^2\right], \quad x \equiv r/R_s$ (*NFW*: from simulations)
Virial radius: $\bar{\rho}(r_{\rm vir}) = 200\rho_c(z)$. If hot gas at cluster core has time to cool then it will condense and flow inwards: *Cooling Flow*. Found to be rare: energization by AGN?



References

- Galactic Astronomy : *J. Binney & M. Merrifield*
- An Invitation to Astrophysics : *T. Padmanabhan*
- www.astr.ua.edu/keel/galaxies/

Cosmology

Hubble Expansion

Over large scales, the Universe is homogeneous and isotropic, and it is expanding. Scale factor $a(t)$ multiplies every coordinate grid.

Let object A receive radiation from object B. The coordinate (comoving) distance between them is d_c, which remains constant, and the proper distance is $d = a(t)d_c$. Due to cosmological expansion, the proper distance between these two points increases at a rate $v = \dot{a}(t)d_c$. This is an apparent relative velocity which causes a Doppler shift:

$$\frac{\delta\nu}{\nu} = -\frac{\dot{a}(t)d_c}{c} = -\frac{\dot{a}}{a}\left(\frac{d}{c}\right) = -\frac{\dot{a}}{a}\delta t = -\frac{\delta a}{a}\ ,$$ giving $\nu(t)a(t) = \text{constant} \Rightarrow \dfrac{\lambda_{\rm em}}{\lambda_{\rm obs}} = \dfrac{a_{\rm em}}{a_{\rm obs}}$

Thus redshift $z = \dfrac{\lambda_{\rm obs} - \lambda_{\rm em}}{\lambda_{\rm em}} = \dfrac{a_{\rm obs}}{a_{\rm em}} - 1$, or $1 + z = \dfrac{a_{\rm obs}}{a_{\rm em}} = \dfrac{a_0}{a(z)}$

subscript 0 denotes a quantity at present epoch

and $v = \left(\dfrac{\dot{a}}{a}\right)d = Hd$; $H \equiv \left(\dfrac{\dot{a}}{a}\right)$ = Hubble parameter. Present value: $H_0 \simeq 67$ km/s/Mpc

Hubble Time $t_H = \dfrac{a}{\dot{a}} = \dfrac{1}{H(t)}$ ~ age of the universe. Present value: $t_{H,0} \approx 14.5$ Gy

Dynamics of the Universe

Dynamical equations for cosmology follow from a fully relativistic framework. However a Newtonian analogy may be drawn to mimic the basic equations:

per unit mass K.E.+P.E. = const. : $\frac{1}{2}\dot{a}^2 - G\left(\frac{4\pi}{3}\rho a^3\right)\frac{1}{a}$ = const. = $-\frac{1}{2}k$

hence $\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho(t)$ or $H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho(t)$

$\Omega(t) \equiv \rho(t)/\rho_c(t)$

$\Omega(t) = 1 + k/a^2 = 1$ for $k = 0$

In our Universe $k \approx 0$, (flat geometry) *i.e.* $\rho = \rho_c \equiv \frac{3H^2}{8\pi G}$. At present $\rho_{c,0} \approx 0.84 \times 10^{-29}$ g/cm^3

Solution of the dynamical equation requires knowledge of $\rho(a)$: Equation of State

Adiabatic evolution: $P \propto V^{-\gamma} \propto a^{-3\gamma}$ while $P = (\gamma - 1)u = (\gamma - 1)\rho c^2$. Thus $\rho \propto a^{-3\gamma}$

Using this the dynamical equation yields the solution $a \propto t^{\frac{2}{3\gamma}}$ $(\gamma \neq 0)$ flat universe

- For non-relativistic matter $P \propto u_{\rm kin} \ll \rho c^2$, so $\gamma \approx 1. \Rightarrow \rho \propto a^{-3} \Rightarrow a \propto t^{\frac{2}{3}}$ matter dominated
- For relativistic matter or radiation $\gamma = 4/3$ $\Rightarrow \rho \propto a^{-4} \Rightarrow a \propto t^{\frac{1}{2}}$ radiation dominated
- For “Dark Energy” $\rho c^2 \approx$ const., *i.e.* $\gamma \approx 0$ $\Rightarrow \rho \propto a^0 \Rightarrow a \propto e^t$ acceleration, inflation

In cosmology the EoS is usually labelled by the parameter $w \equiv (\gamma - 1)$

Present day universe: $\Omega_{\rm tot} \approx 1,\ \Omega_{\rm m} \approx 0.3,\ \Omega_{\rm DE} \approx 0.7,\ \Omega_{\rm b} \approx 0.048,\ \Omega_{\rm rad} \approx 5 \times 10^{-5}$

Distance measures in Cosmology

Coordinate system: origin at the observer. Comoving (coordinate) distance to a source: r_c

Proper distance now: $d = a_0 r_c$, Redshift: z Light leaves source at t_c, received at t_0

Propagation from $r = r_c$ to $r = 0$: $-a\,dr = c\,dt$ *i.e.* $-\int_{r_c}^{0} dr = c\int_{t_c}^{t_0} \frac{dt}{a(t)}$

Hence $r_c = c\int_z^0 \frac{1}{a}\frac{dt}{da}\frac{da}{dz}dz = \frac{c}{a_0}\int_0^z \frac{a}{\dot{a}}dz$ and $d = a_0 r_c = c\int_0^z \frac{dz}{H(z)} = c\tau;$

τ = lookback time $= \int_0^z \frac{dz}{H}$

Luminosity distance d_L :

Received Flux $F \equiv \frac{L}{4\pi d_L^2} = \frac{L}{4\pi d^2}\left(\frac{1}{1+z}\right)\left(\frac{1}{1+z}\right)$ $\therefore\ d_L = d(1+z) = c(1+z)\int_0^z \frac{dz}{H}$

Luminosity

Reduction of photon energy

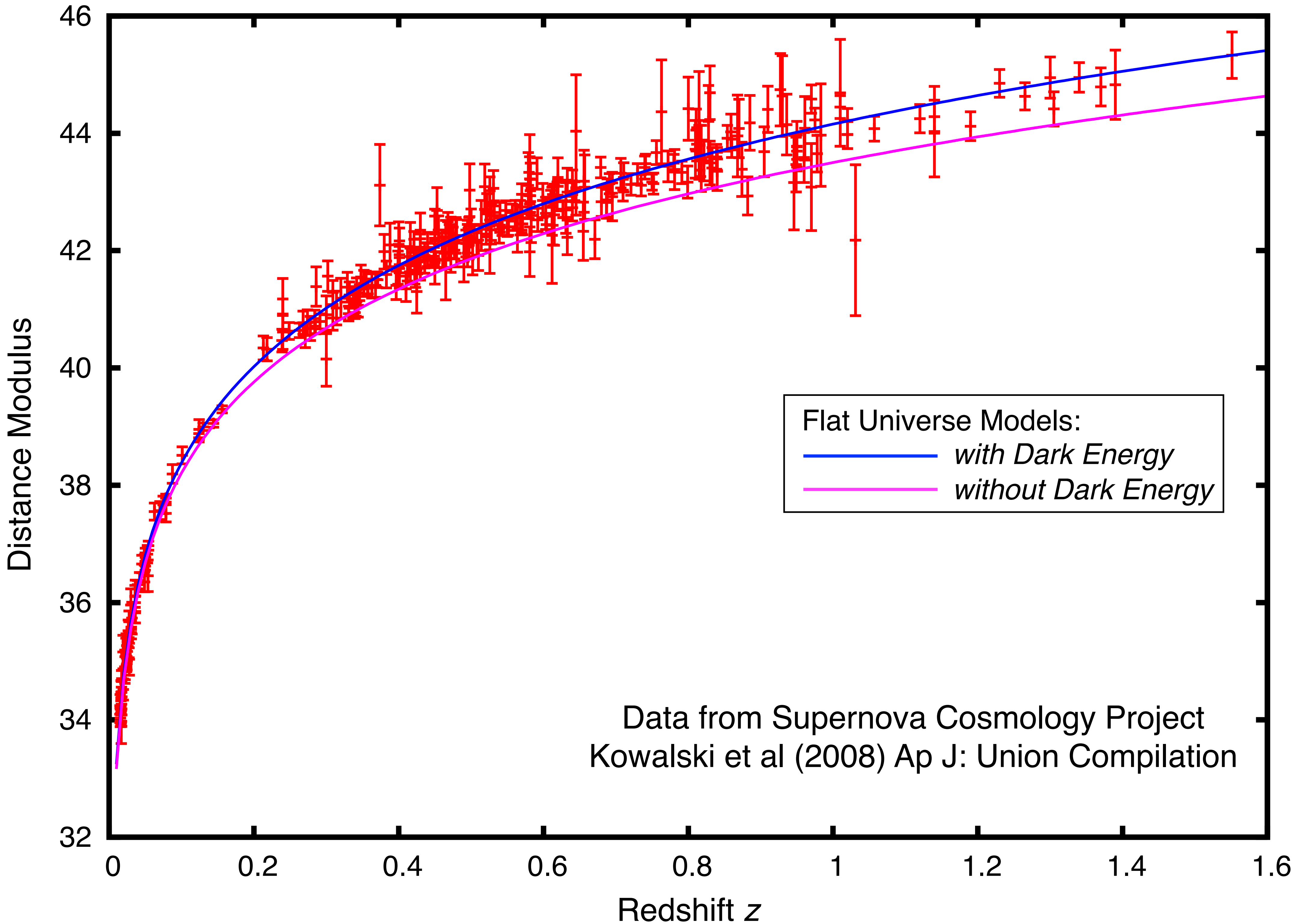
Reduction of photon arrival rate

Angular Diameter distance d_A :

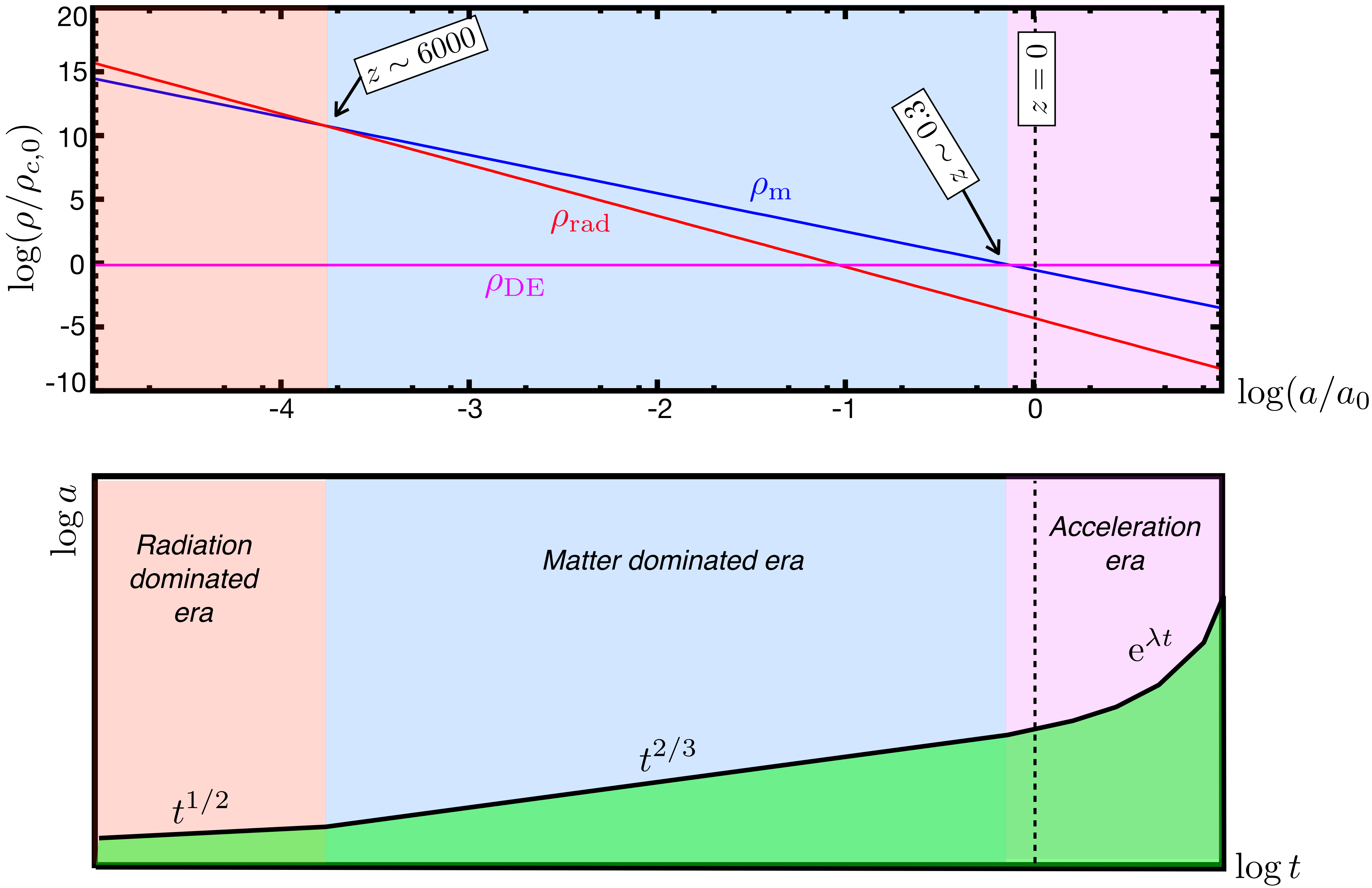
Angular size $\Delta\theta = \frac{\Delta l}{r_c a(t_c)}$; $d_A \equiv \frac{\Delta l}{\Delta\theta} = a(t_c) r_c = \frac{a_0 r_c}{1+z} = \frac{c}{1+z}\int_0^z \frac{dz}{H}$

Transverse linear size

Supernova Ia Hubble Diagram



Cosmological Expansion History



Thermal History of the Universe

Radiation and matter in thermal equilibrium in early universe, at a common temperature
Radiation is Planckian, with blackbody spectrum and energy density $\rho_{\rm rad} \propto T^4$

In cosmological evolution $\rho_{\rm rad} \propto a^{-4}$, thus $T \propto a^{-1}$; or $T = 2.73(1+z)$ K
Seen today at microwave bands: *Cosmic Microwave Background Radiation*

If $kT > 2mc^2$ for any particle species, relativistic pairs of the species can be freely created. All relativistic particle species behave similar to radiation in the evolution of their energy density. Total $\rho_{\rm rel}c^2 = \bar{g}a_R T^4$ where $\bar{g}$ =total stat wt of all rel. particle species

In the Early, radiation-dominated universe $a \propto t^{1/2}$. So $t = 1\,{\rm s}\,(kT/1{\rm MeV})^{-2}\,\bar{g}^{-1/2}$
[$\bar{g} \sim 100$ at $kT > 1$ GeV, ~ 10 at 1-100 MeV, ~ 3 at < 0.1 MeV]

Expansion → cooling → pair annihilation of relevant species → energy added to radiation
At $kT \lesssim 1$ GeV, nucleon-antinucleon annihilation → small no. of baryons survived
$\eta = \dfrac{n_\gamma}{n_{\rm b}} \sim 10^9$: “entropy per baryon”, photon-to-baryon ratio. “Baryon asymmetry” $\sim 10^{-9}$

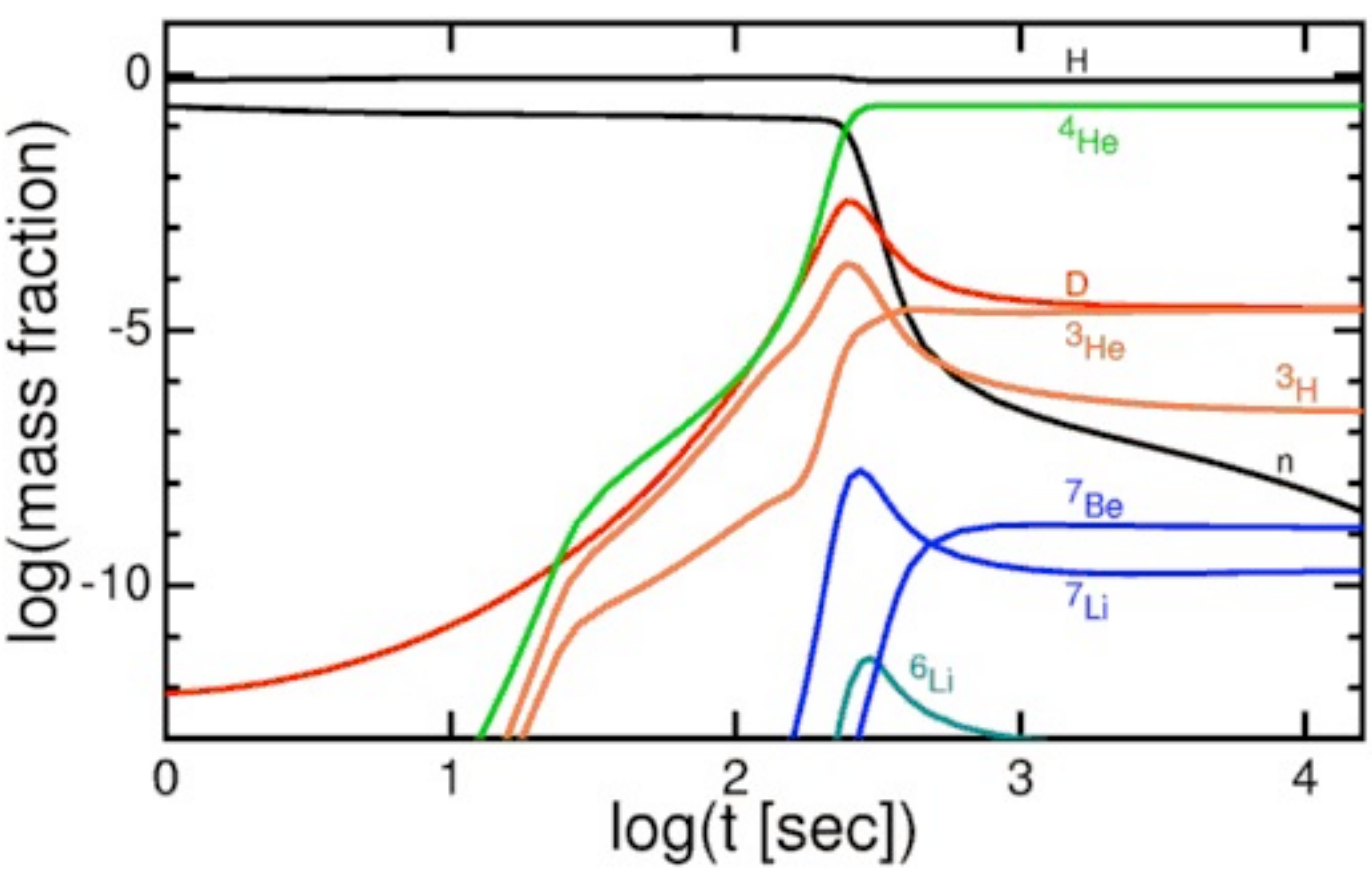
$kT \lesssim 1$ MeV: $e^{\pm}$ annihilation → $\sim 10^{-9}$ of the pop. left as electrons → charge neutrality
Contents at this stage: neutrons, protons, electrons, neutrinos, dark matter and photons

Primordial Nucleosynthesis

At $kT > 0.5$ MeV neutrons and protons are in beta equilibrium: $n_\mathrm{n}/n_\mathrm{p} = \exp(-1.3\,\mathrm{MeV}/kT)$
$kT \approx 0.5$ MeV: beta reactions become inefficient, n-p freeze at $n_\mathrm{n}/(n_\mathrm{n} + n_\mathrm{p}) \approx 15\%$
(no n-decay yet as $t_\mathrm{H} << t_\mathrm{decay}$)

Neutrons will then undergo decay with lifetime of 881 s until locked up in nuclei

Nucleosynthesis begins in earnest only after kT drops to ~0.07 MeV
(decided by the rate of first stage synthesis: that of Deuterium. Most of this ^2D then converts to ^4He)



http://www.astro.ucla.edu/~wright/BBNS.html

Neutron fraction drops to ~11% at this point, giving primordial mass fraction:

^4He : ~22%; ^1H : ~78%

Synthesis does not progress beyond this stage due to expansion and cooling

The entire nucleosynthesis takes place within approx. the first three minutes after Big Bang: $z \sim 3\text{x}10^8$

Recombination, CMB, Reionization

After nucleosynthesis the universe has ionized H and He, and electrons. Material is very optically thick due to electron scattering. Cooling continues as $T \propto a^{-1}$. There are also neutrinos, and leptonic Dark matter which do not interact with photons.

Once Dark Matter becomes non-relativistic, gravitational instability develops and self-gravitating collapsed halos start to form. Baryonic matter cannot collapse yet because of strong coupling with radiation.

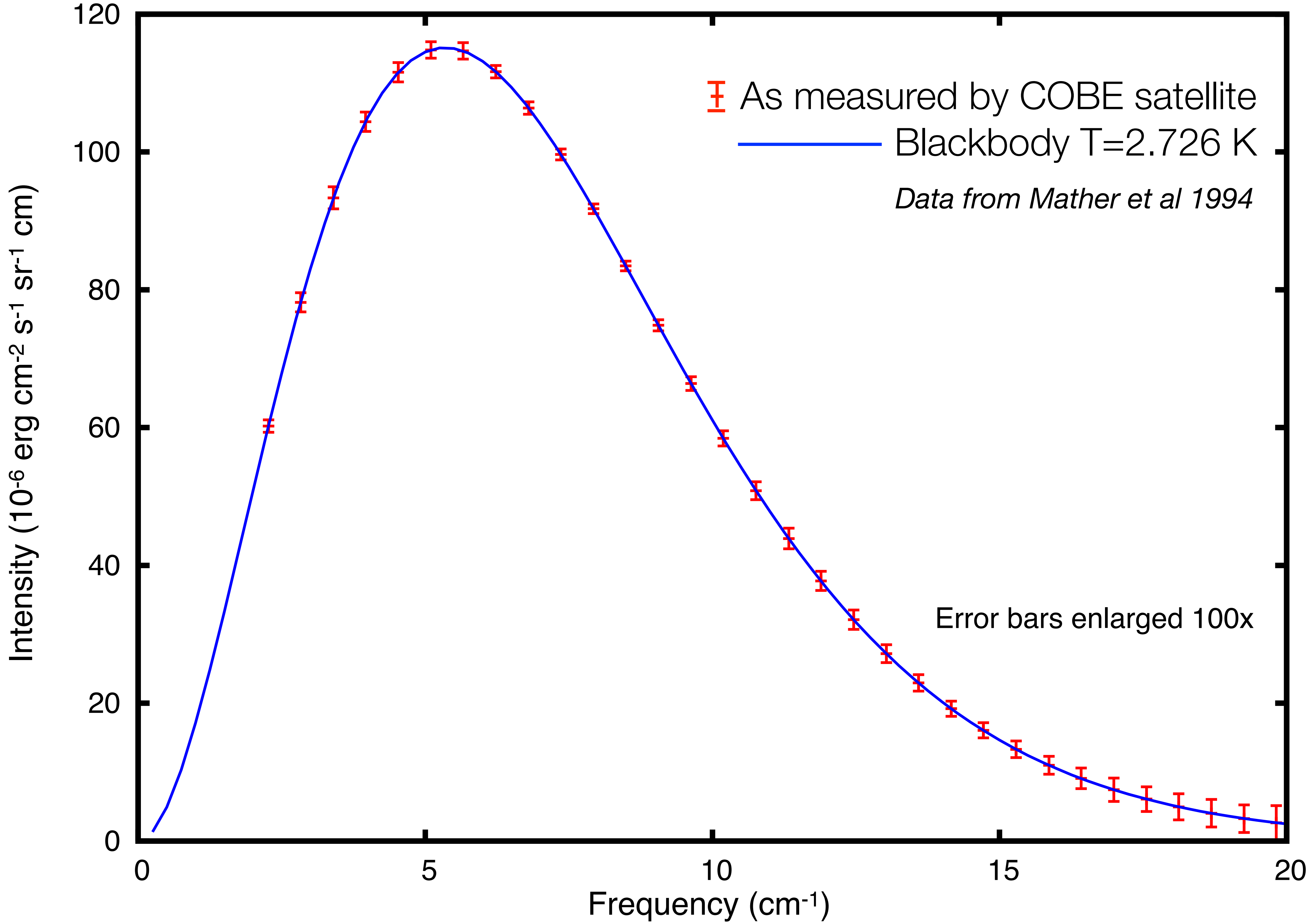
As temperature drops to ~3x10^3 K, electrons and ions ***recombine*** to form atoms. Universe becomes transparent to the Cosmic Background radiation. The ***CMB*** we see today comes from this “surface of last scattering” at z~1100. Diffuse gas is now neutral.

Decoupled from radiation, baryons now fall into the potential wells already created by Dark Matter, Luminous structures begin to form by z~20.

UV radiation from the luminous structures starts ionizing diffuse gas again. These “Stromgren sphere”s grow and overlap, completely ***reionizing*** the diffuse intergalactic medium by z~10.

Cosmic Background radiation temperature continues to fall as $1/a$, reaching 2.73 K at present epoch.

CMB spectrum

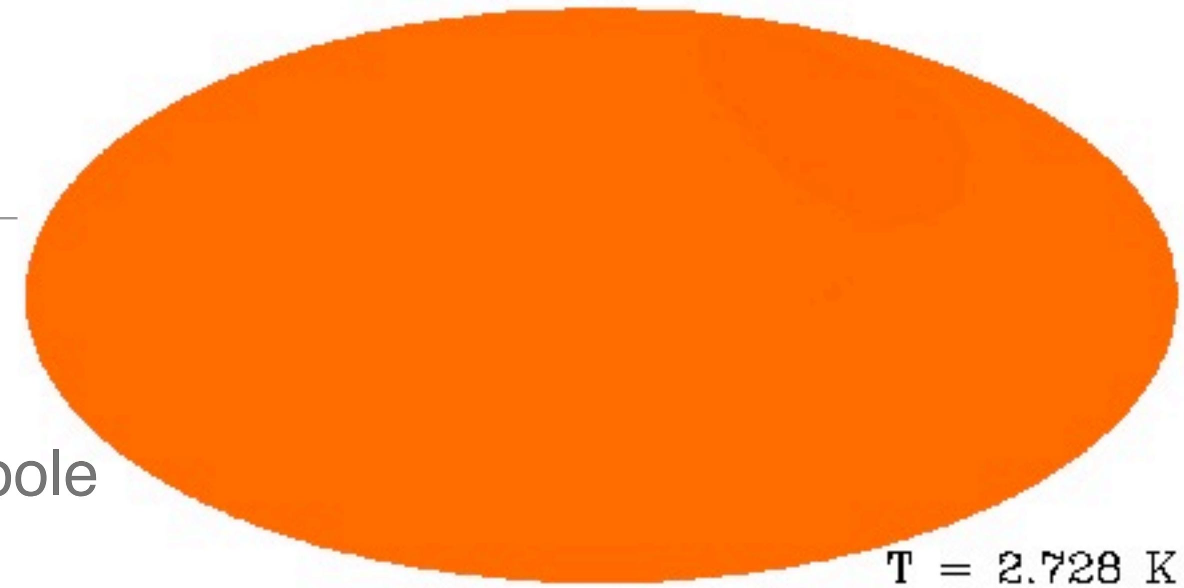


CMB sky distribution

COBE Satellite Maps

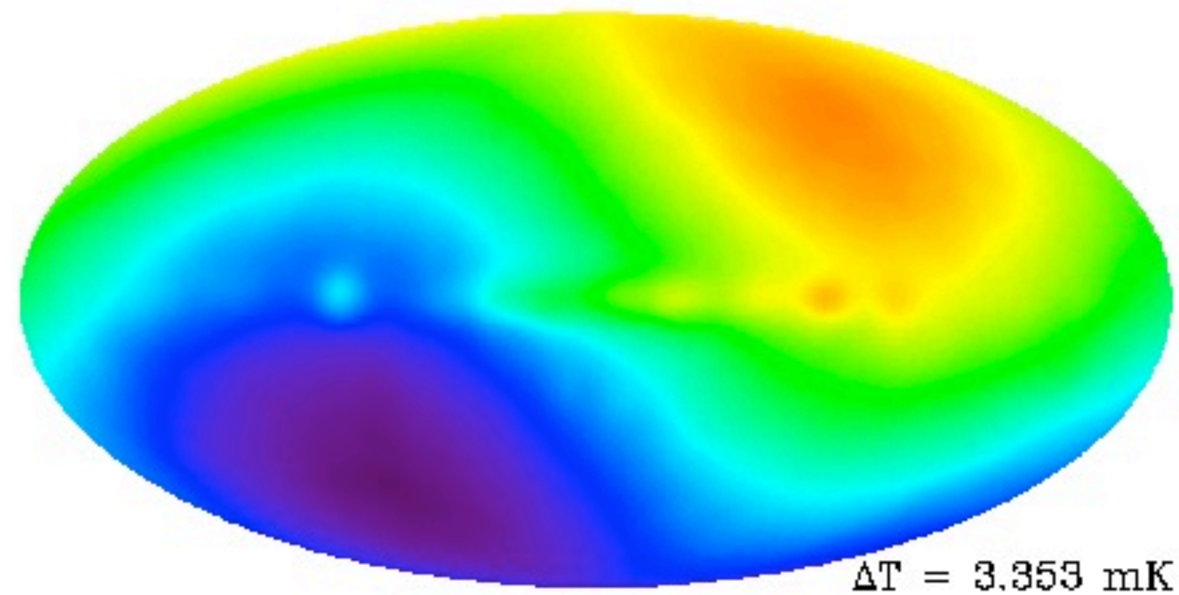
Bennett et al 1996

Monopole

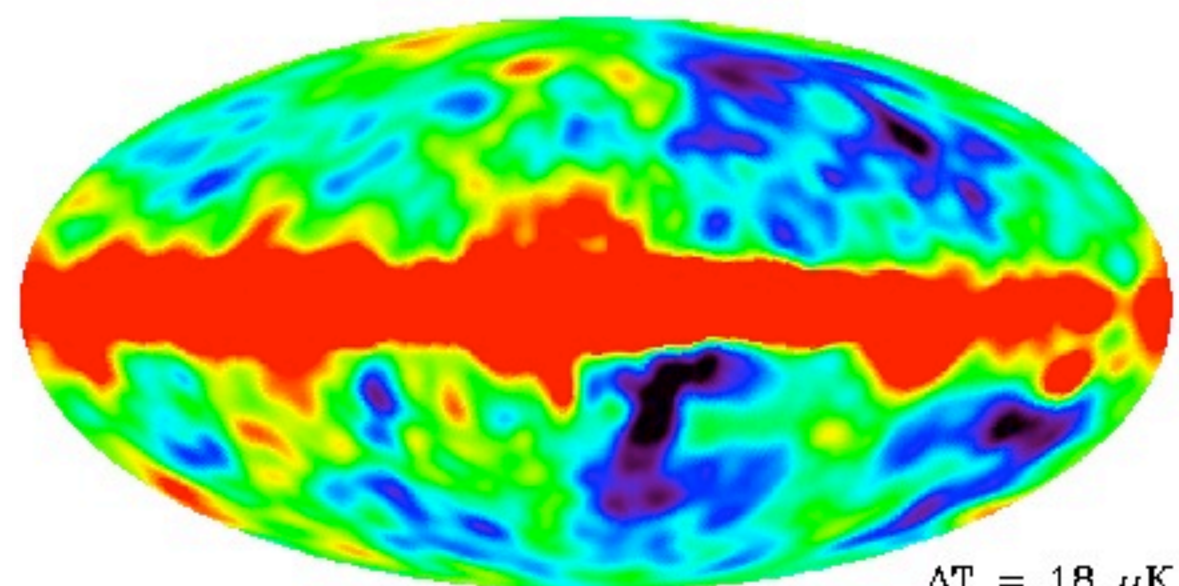


Dipole

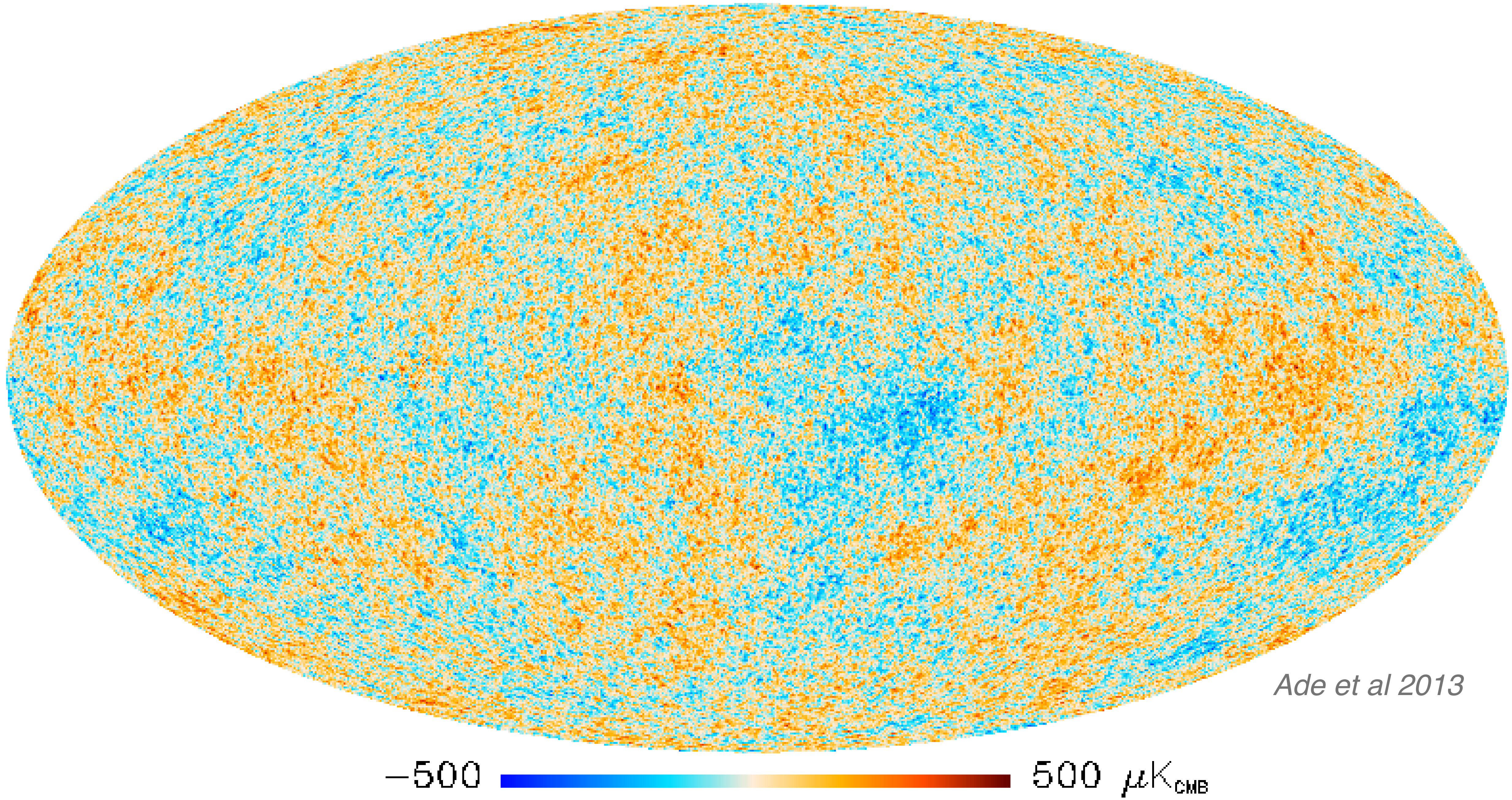
caused by our peculiar velocity
~ 370 km/s w.r.t. the Hubble flow



Higher order anisotropies



CMB sky distribution



CMB high-order anisotropy map from Planck Satellite

CMB Anisotropies

Epoch of Decoupling:

It follows from Saha equation that the universe recombines when the radiation temperature drops to ~3000 K. This corresponds to a redshift $z_{\rm dec} \simeq 1100$

Defines the last scattering surface (LSS)

In a flat universe $H(z) = H_0 \left[\Omega_{\rm rad,0}(1+z)^4 + \Omega_{\rm m,0}(1+z)^3 + \Omega_{\rm DE,0}\right]^{1/2} \Rightarrow \; H(z_{\rm dec}) \approx 22000\, H_0$

Age of the universe at decoupling $t_{\rm dec} \approx \frac{2}{3}\left(\frac{1}{H(z_{\rm dec})}\right) \approx 4\times 10^5$ y

CMB anisotropies developed until $t_{\rm dec}$: *Primary Anisotropy.* Later: *Secondary Anisotropy*

Sources of Primary Anisotropy:

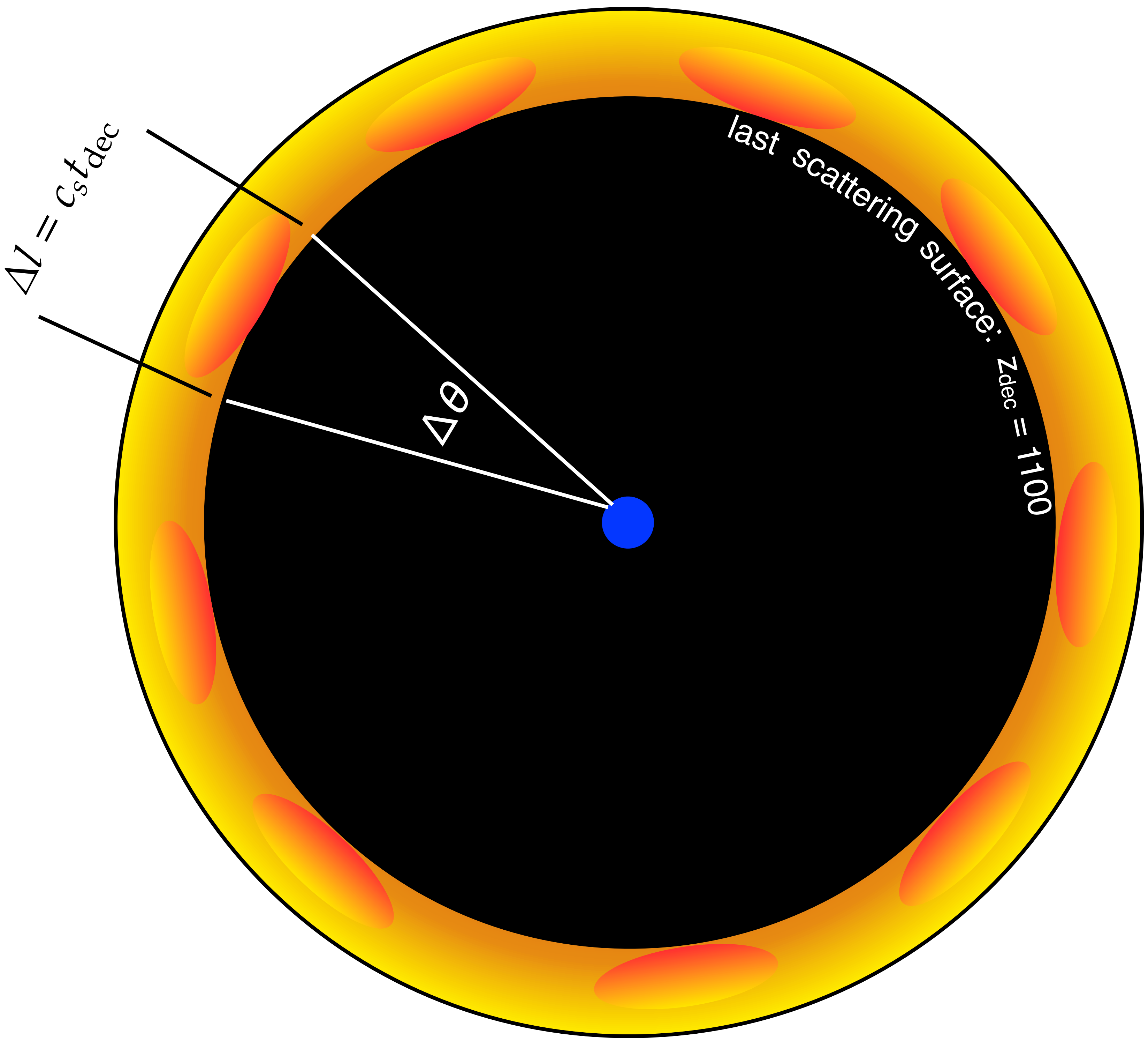
- *Intrinsic, from primordial perturbations*
- *Gravitational Redshift from fluctuating potential at LSS (Sachs-Wolfe effect)*
- *Doppler shifts due to scattering from moving gas*
- *Acoustic oscillations of the photon-baryon fluid*

Modified by:

- *Finite width of LSS*
- *Photon Diffusion (Silk Damping)*

Secondary Anisotropies from: *Integrated Sachs-Wolfe effect, Sunyaev-Zeldovich effect, Gravitational Lensing etc*

Acoustic Horizon Anisotropy Scale



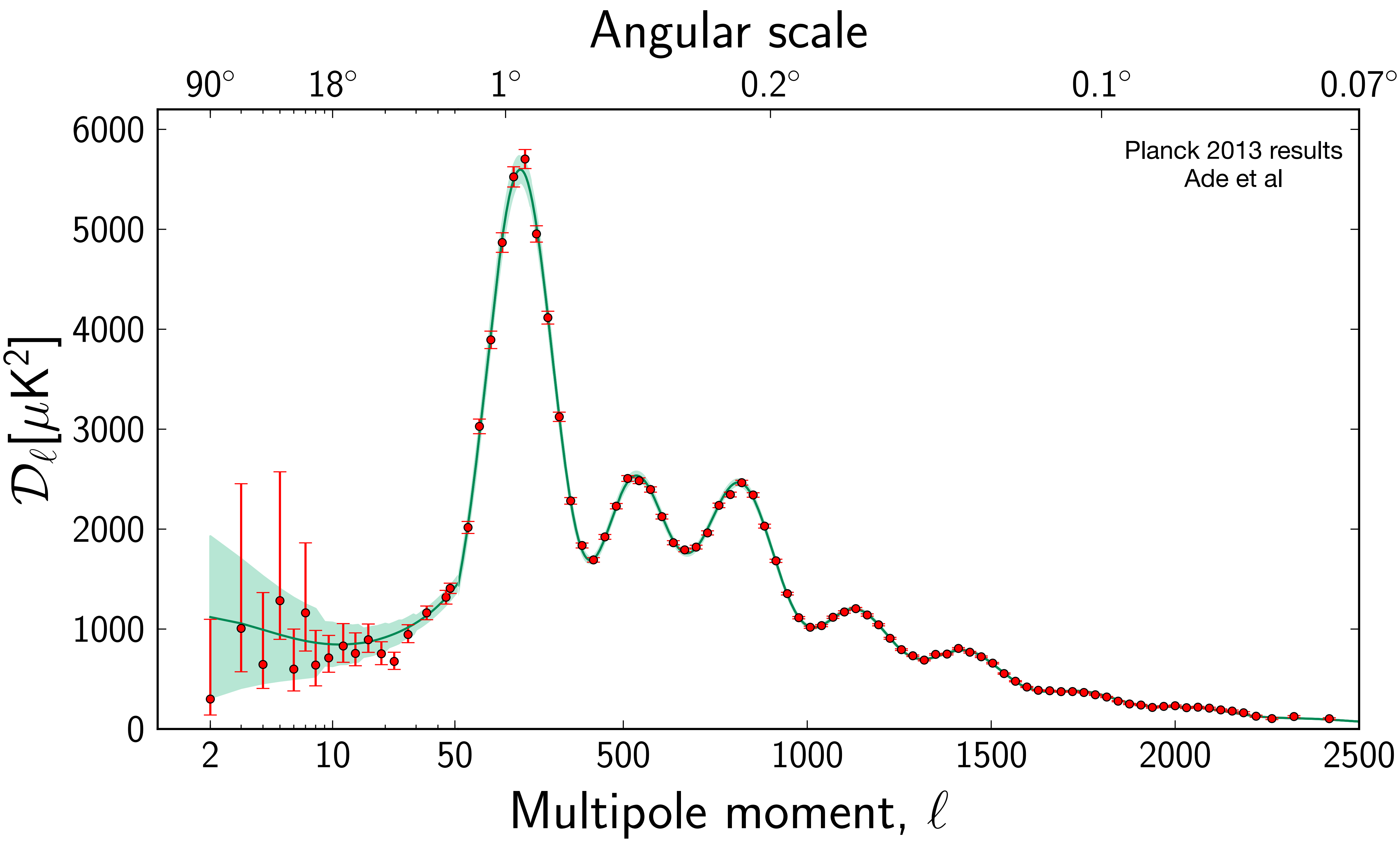
$$\Delta l = c_s t_{\rm dec} = \frac{c}{\sqrt{3}} t_{\rm dec}$$

$$d_A = \frac{c t_{\rm look-back}(z_{\rm dec})}{1 + z_{\rm dec}} \approx \frac{c t_0}{1 + z_{\rm dec}}$$

$$\Delta\theta = \Delta l / d_A$$

$$\therefore \Delta\theta = \frac{1 + z_{\rm dec}}{\sqrt{3}} \left(\frac{t_{\rm dec}}{t_0}\right) \approx 1^\circ$$

Anisotropy spectrum of the CMB



Formation of Structures

Gravitational Instability leads to growth of density perturbations of Dark Matter.

- overdense $[\rho = (1+\delta)\rho_{\rm bg}]$ regions expand less slowly than Hubble flow, eventually stop expanding, turn around and collapse to form halos.
- "critical overdensity" $\delta_{\rm c} \approx 1.68$
- Halo mass distribution at a redshift z : fraction of bound objects with mass $> M$:

$$f(>M, z) = \mathrm{erfc}\left[\frac{\delta_c(1+z)}{\sqrt{2}\,\sigma_0(M)}\right] \qquad \text{(Press-Schechter Formula)}$$

where $\sigma_0(M)$ is the *linearly extrapolated* rms δ at mass scale M at present epoch

Typical density contrast today at scale $8\,(100/H_0)$ Mpc is $\sigma_8 \approx (0.5 - 0.8)$

Initial density perturbations result from quantum fluctuations.

- However perturbations seen today would require scales much larger than horizon size in the early universe.
- Made possible by accelerated (exponential) growth of $a(t)$ for a brief period: ***inflation***
- Energy provided by a decaying quantum field, which also generates fluctuations

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