# Cepheids as a DM detector

## meV dark photon dark matter

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(Seoul National University)

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## Preliminary

- Cepheids 101 : instability strip and blue loop
- HR diagram and physics of stellar pulsations
- PLC relation to PLZ relation : metallicity dependence
- Cosmic distance ladder
- One specific example : dark photon as a dark matter
- Resonance conversion at the Cepheids
- Summary

# The Discovery of Mira

## 1596 David Fabricius

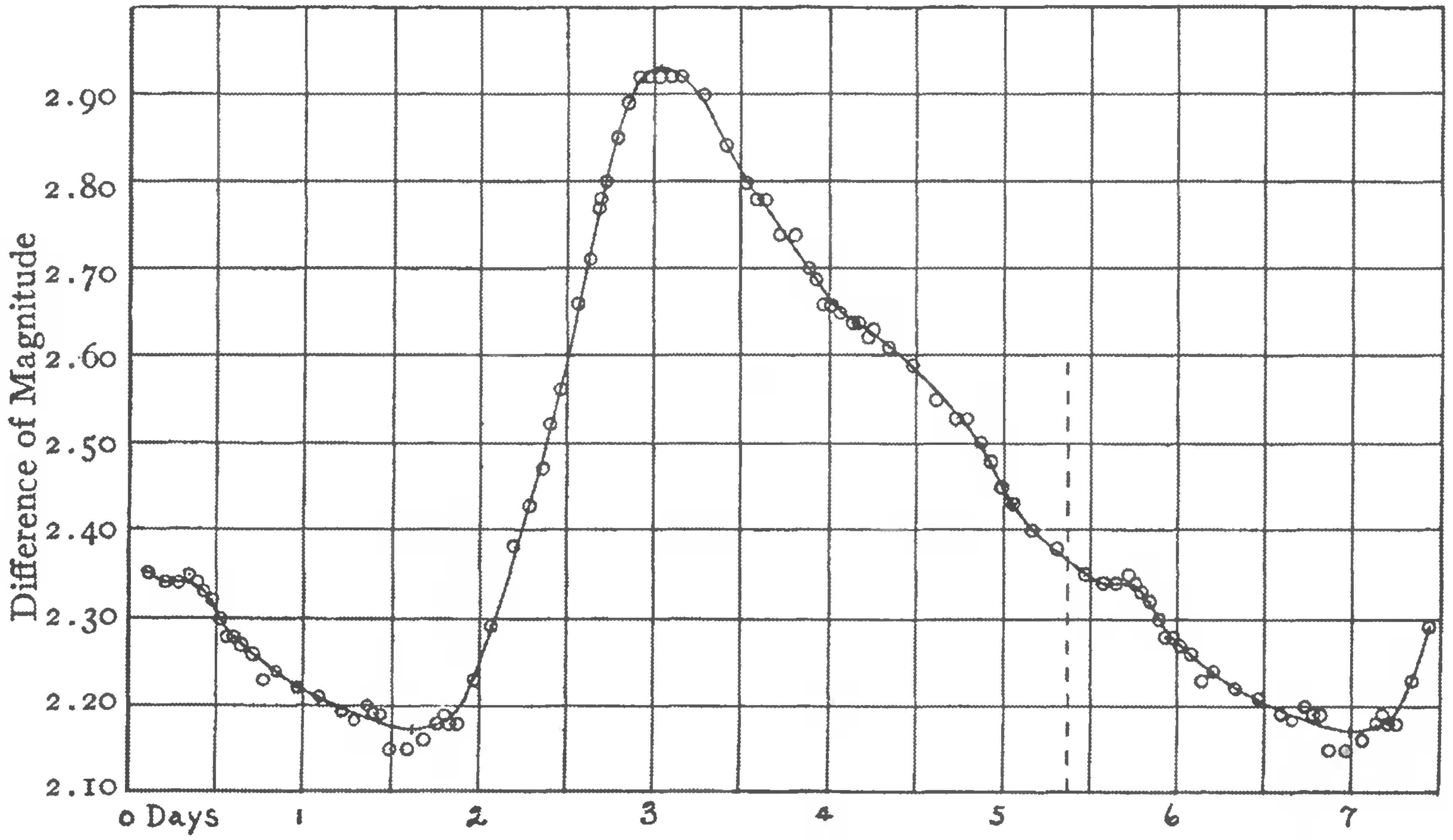
Over a period of 11 months, the bright second magnitude star faded, disappeared, and then finally returned to its former brightness.

o Ceti was later called ‘**Mira**’ (meaning ‘**wonderful**’) to describe its unusual behavior.

# $\delta$ Cephei

## 1784

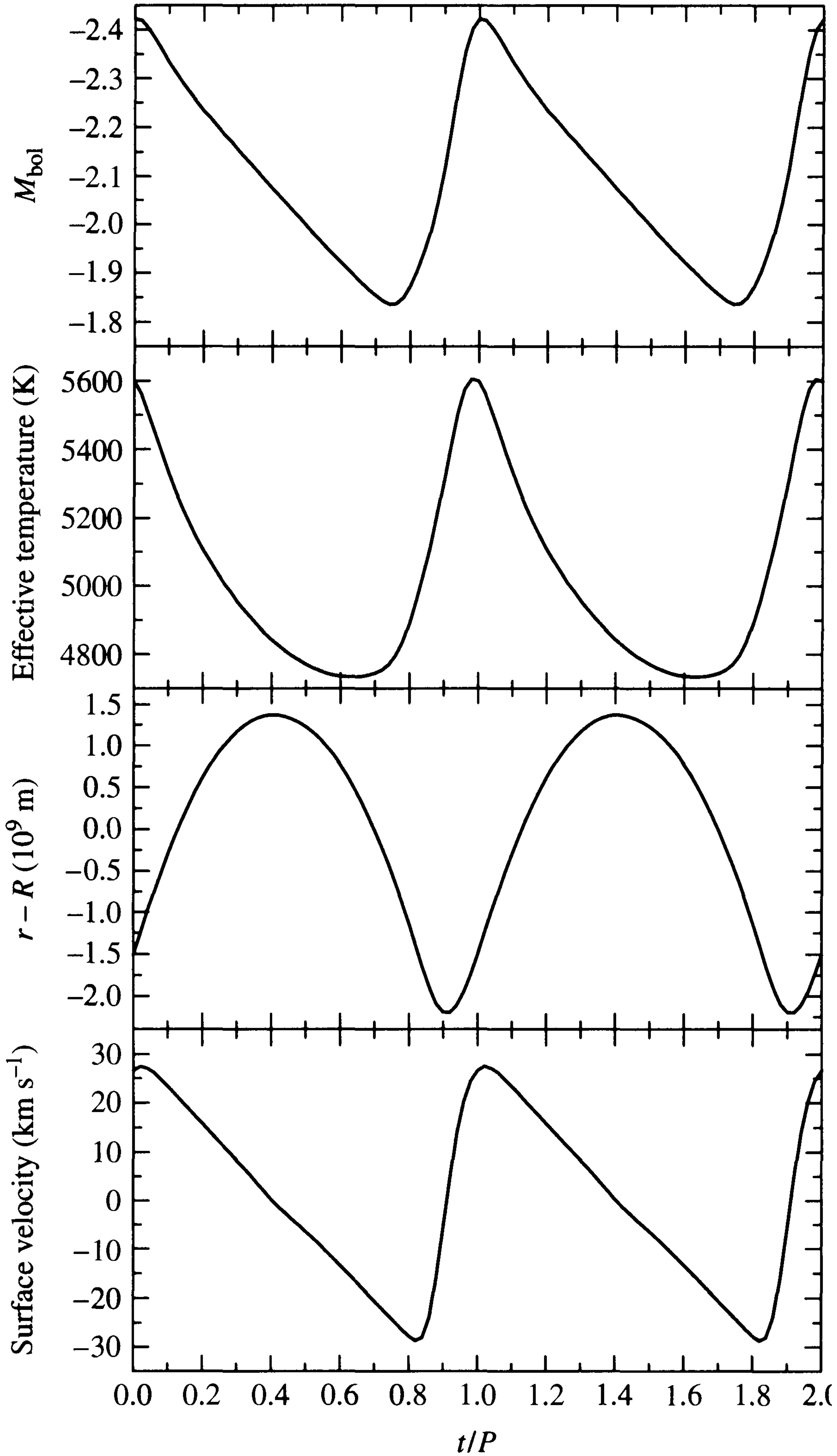
A pulsation period of 5 days, 8 hours and 37 minutes and exhibits magnitude variations of ~±1 mag. It is the prototype of a classical Cepheid, a pulsating variable.



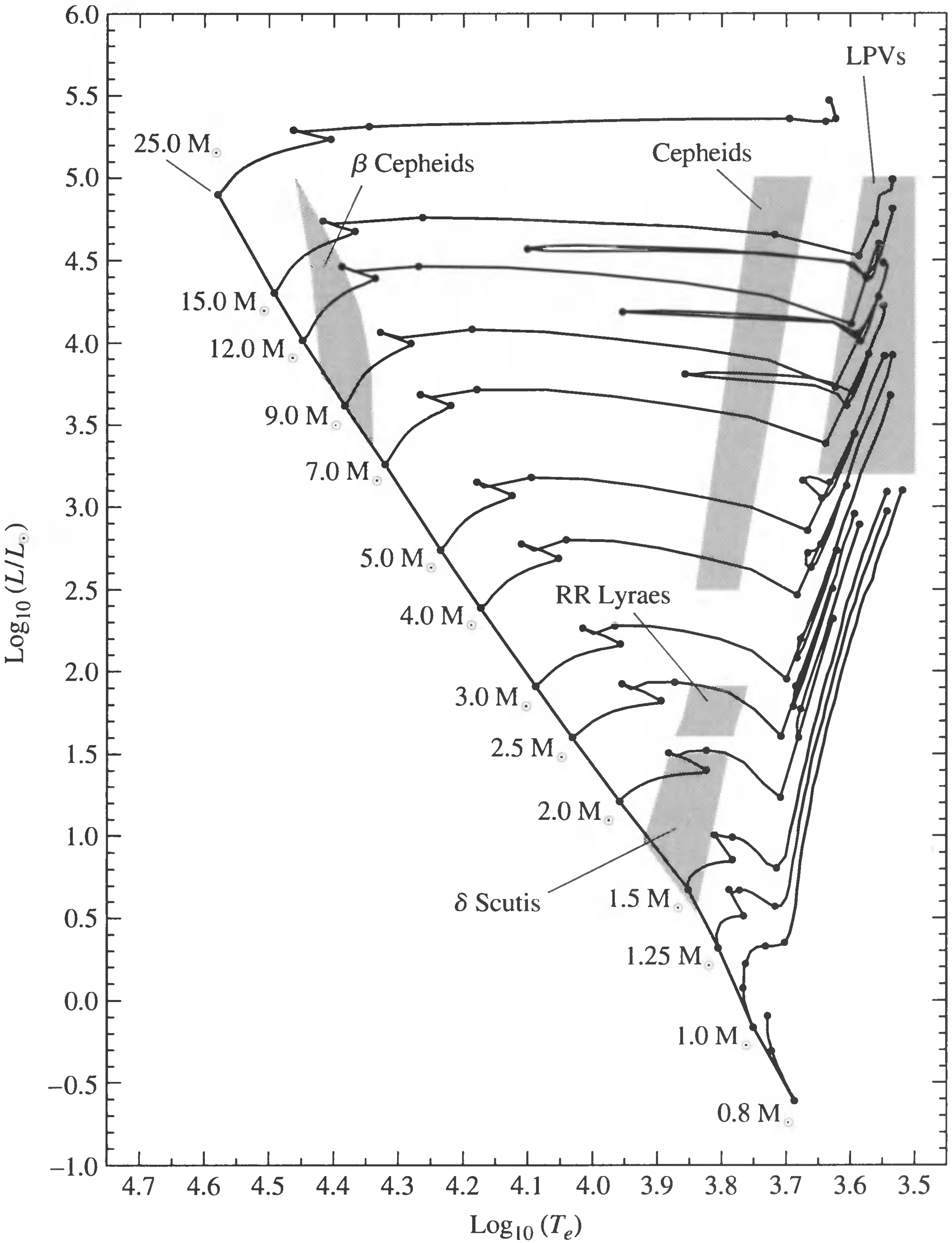
Henrietta
Swan
Leavitt
(1868-1921)

2400 variable stars are identified from the photographic plates

Period Luminosity relation has been found



$M_{\mathrm{bol}}$
−2.4
−2.3
−2.2
−2.1
−2.0
−1.9
−1.8
Effective temperature (K)
5600
5400
5200
5000
4800
$r - R$ ($10^9$ m)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
Surface velocity (km $\mathrm{s}^{-1}$)
30
20
10
0
−10
−20
−30
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.
$t/P$



LPVs
Cepheids
$\beta$ Cepheids
RR Lyraes
$\delta$ Scutis
25.0 $M_\odot$
15.0 $M_\odot$
12.0 $M_\odot$
9.0 $M_\odot$
7.0 $M_\odot$
5.0 $M_\odot$
4.0 $M_\odot$
3.0 $M_\odot$
2.5 $M_\odot$
2.0 $M_\odot$
1.5 $M_\odot$
1.25 $M_\odot$
1.0 $M_\odot$
0.8 $M_\odot$
$\mathrm{Log}_{10}(L/L_\odot)$
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
4.7
4.6
4.5
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
$\mathrm{Log}_{10}(T_e)$

# Explanation of Stellar Pulsation

## binary or radial pulsation?

Arthur Ritter (1879)
Harlow Shapley (1914)
Arthur Eddington (1918)
- sound waves in stellar medium might provide radial pulsations

Kelvin-Helmholtz to Francis William Aston (1920(?))

# Thermodynamic Heat Engine

## A Eddington

- Period $\Pi = \frac{2R}{v_s}$ in terms of the radius and the sound speed
- $v_s = \sqrt{\frac{\gamma P}{\rho}}$ for the pressure $P$ and the density $\rho$ & $(\gamma = \frac{5}{3})$
- $\frac{dP}{dr} = -\frac{4\pi G\rho^2}{3}r \Rightarrow P = \frac{2\pi G\rho^2}{3}\left(R^2 - r^2\right) \Rightarrow \Pi = \sqrt{\frac{3\pi}{2\gamma G\rho}}$

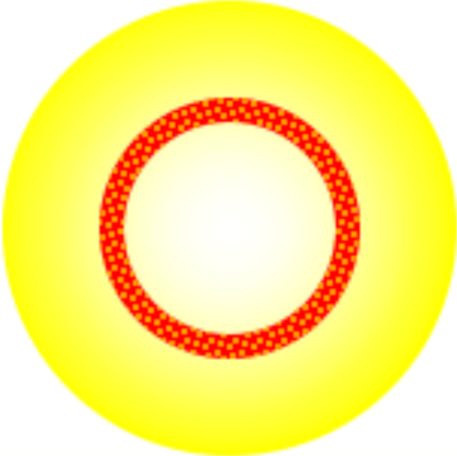
Harmonic oscillator

freefall time
(in the absence of radiation pressure)

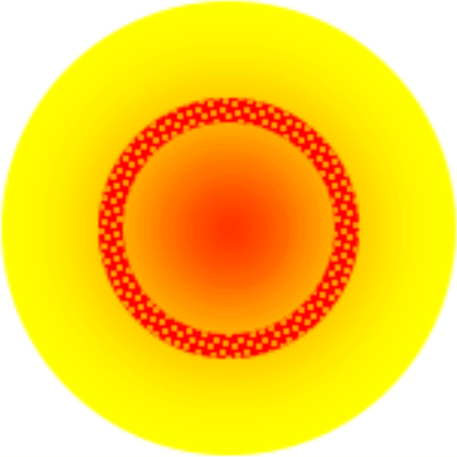
# Cepheid as a Heat Engine

## Pulsation cycle : opacity as a valve, layer as a piston

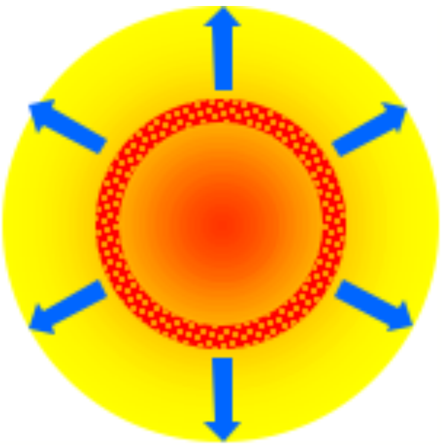
- 1. Valve open : radiation goes out and shrinks due to gravity



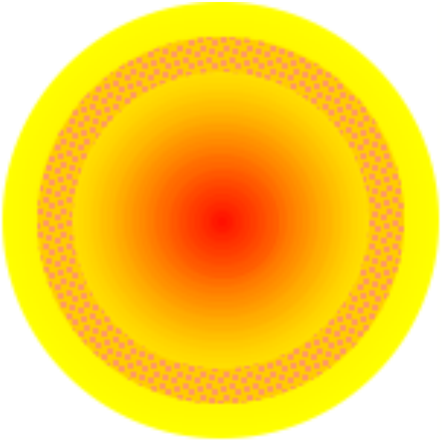
- 2. Compressed layer heats up and becomes opaque



- 3. Valve closed : opacity keeps radiation more and raises temperature

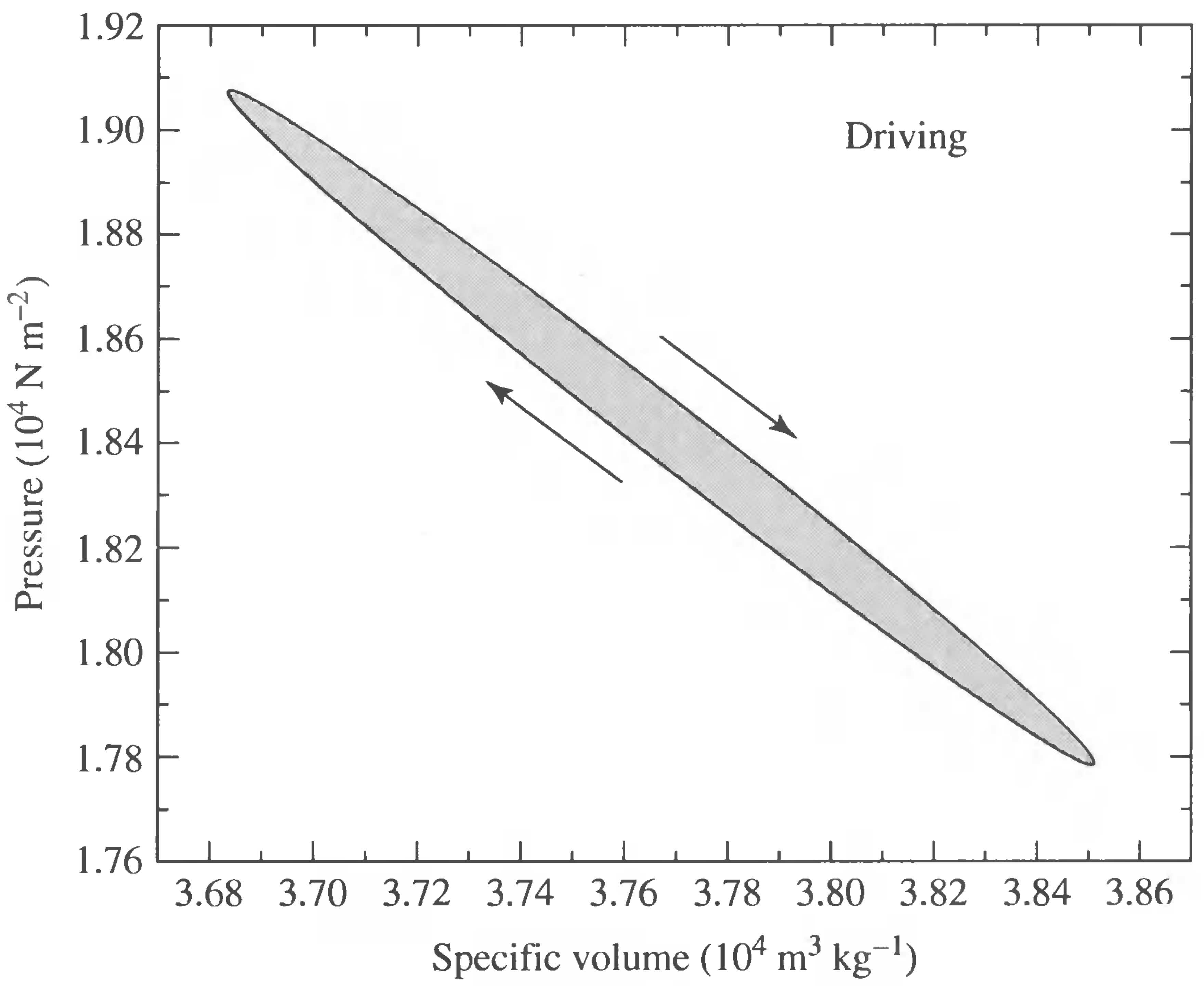


- 4. Pressure pushes it outward



- 5. Valve starts to be open : layer expands and cools and opacity decreases

- 6. Valve open : back to 1



$$\kappa \propto \frac{\rho}{T^{3.5}}$$

The opacity increases with compression

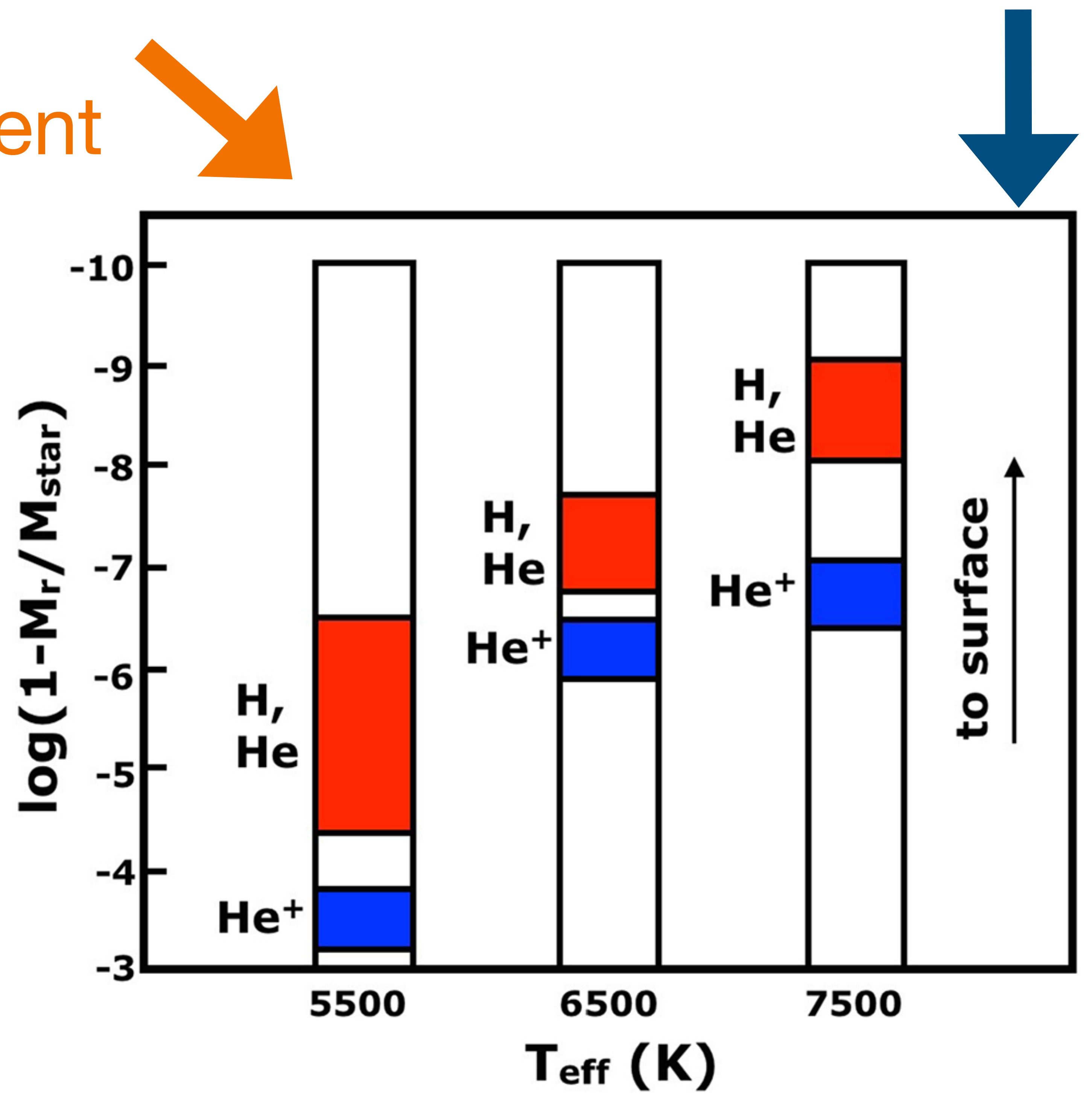
$$\oint P dV = 0$$

Equilibrium is reached.

Instability strip
5500 K < T < 7500 K

T is too low and convection is efficient

Not much left between the layer and the surface

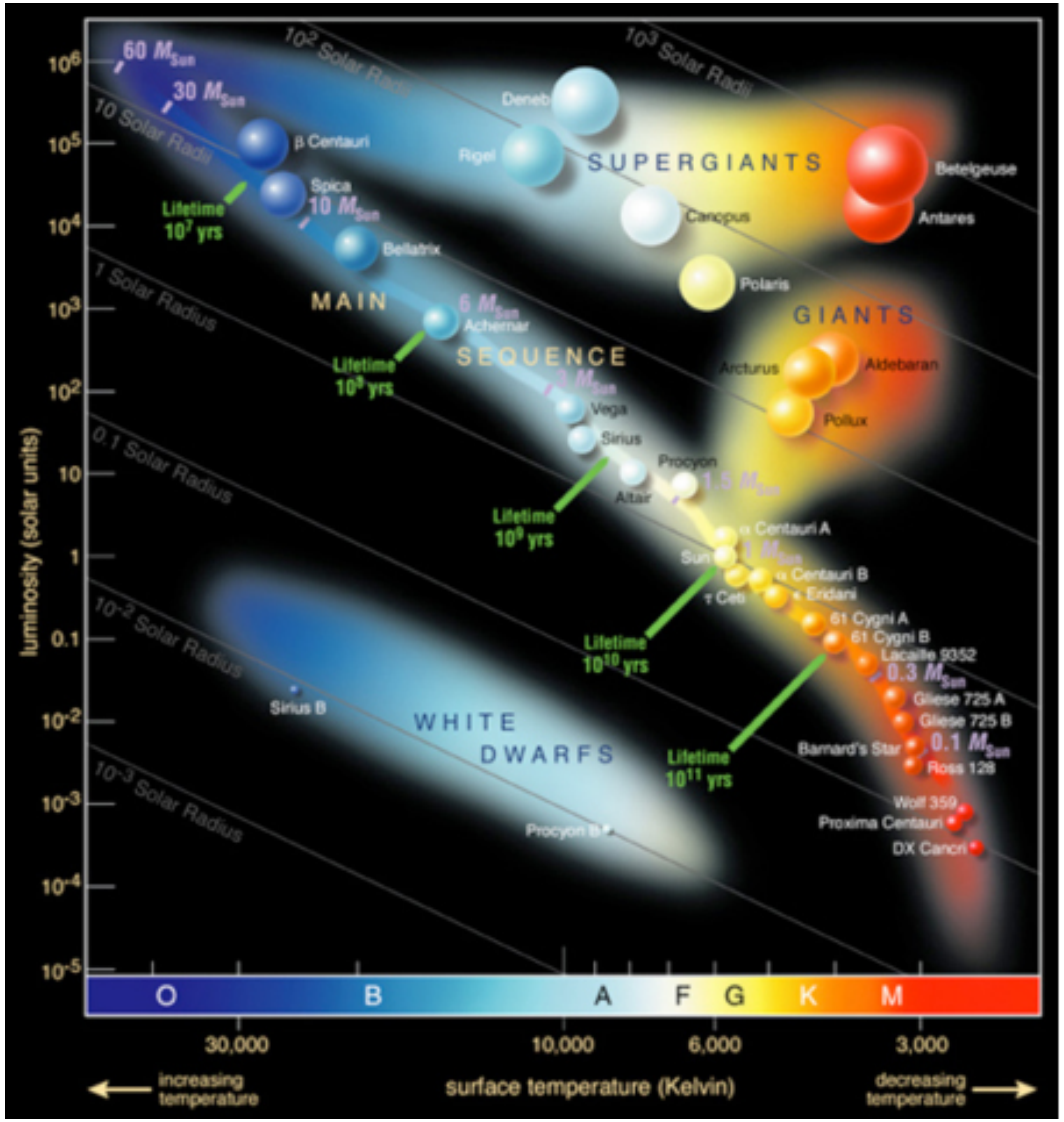


He II partial ionization zone : $4 \times 10^4$ K

Pulsation is observed only one in 10^5 stars

# Herzsprung-Russell Diagram

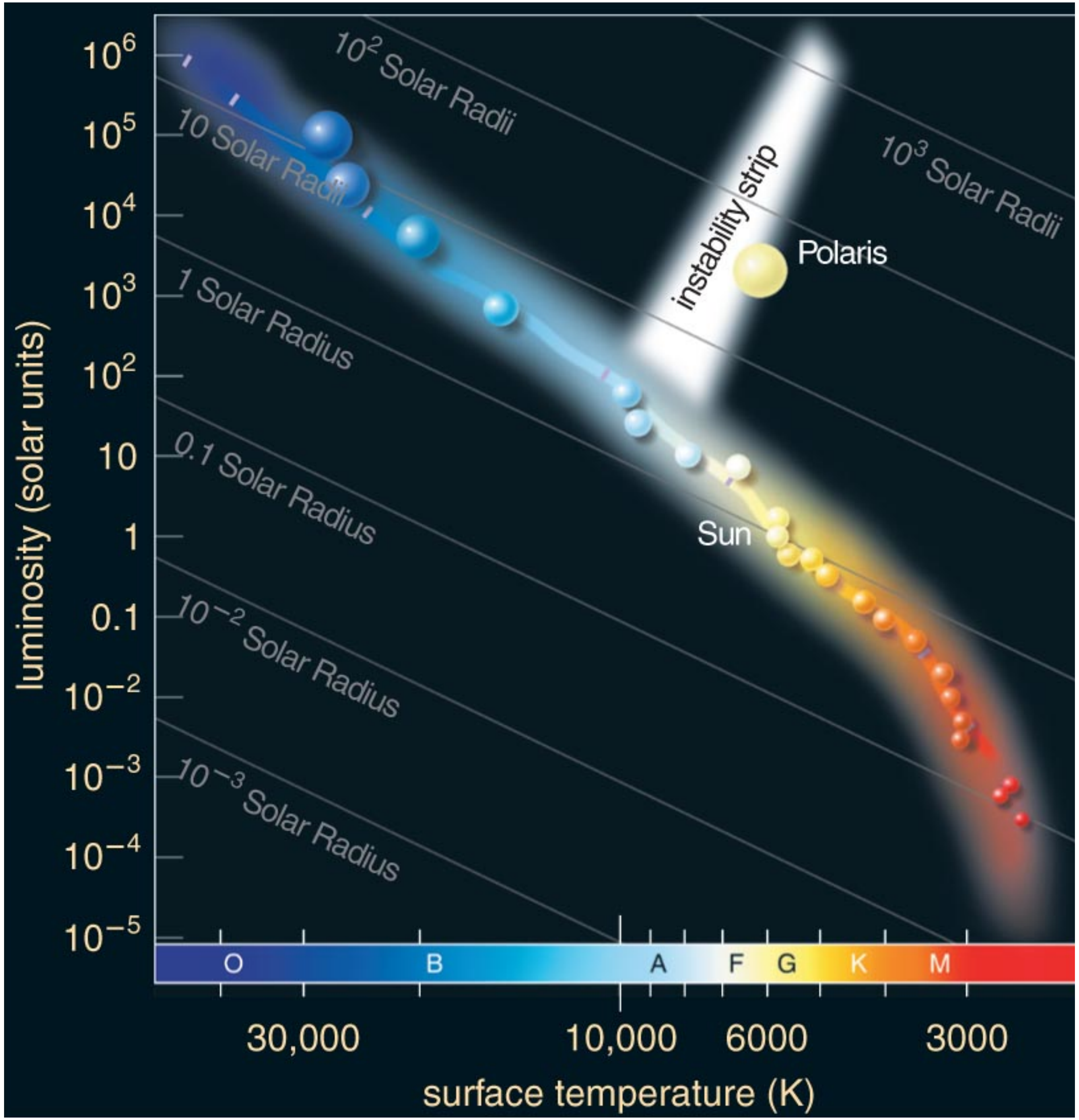
Luminosity

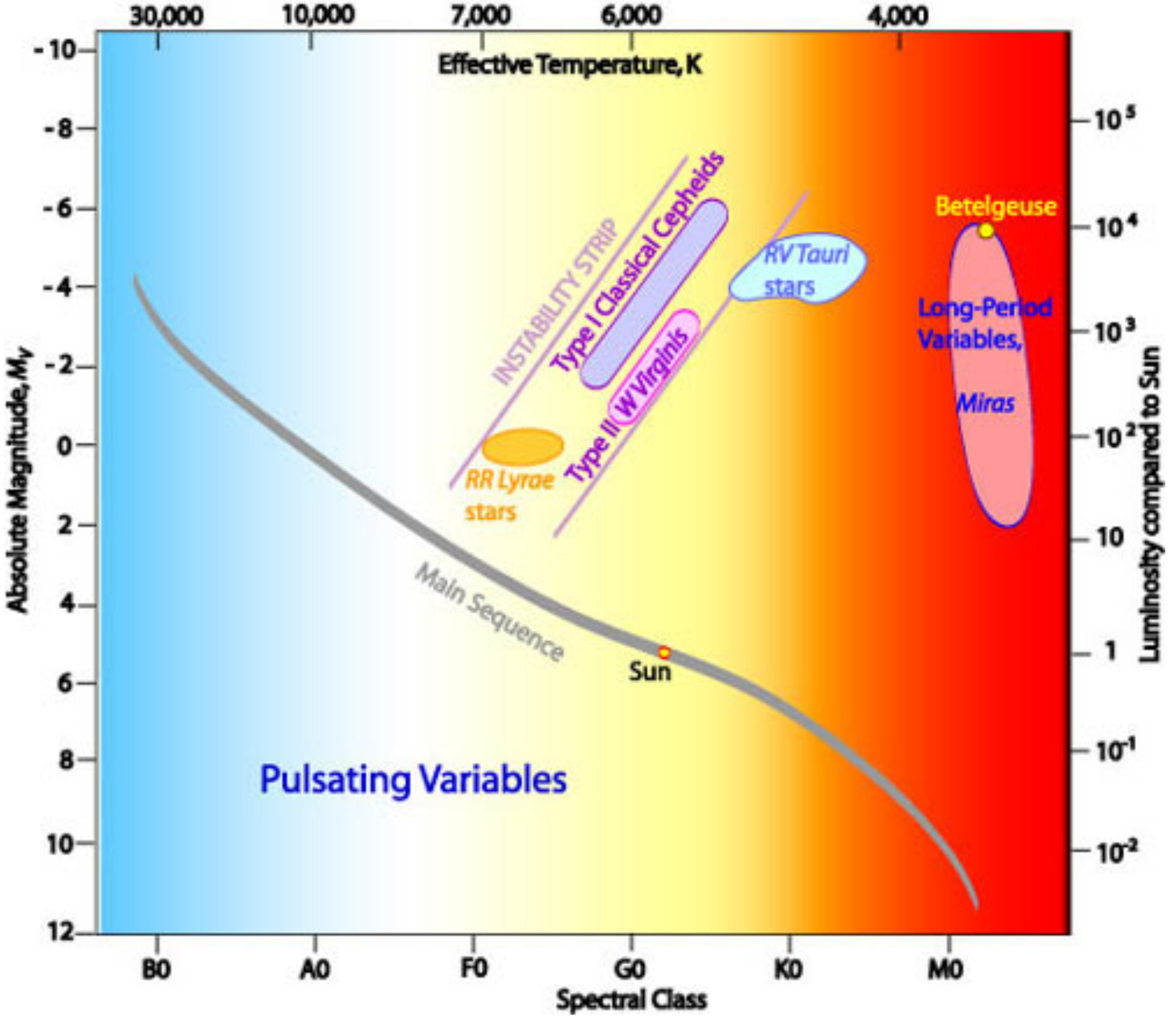


Mass

Color

(Temperature)

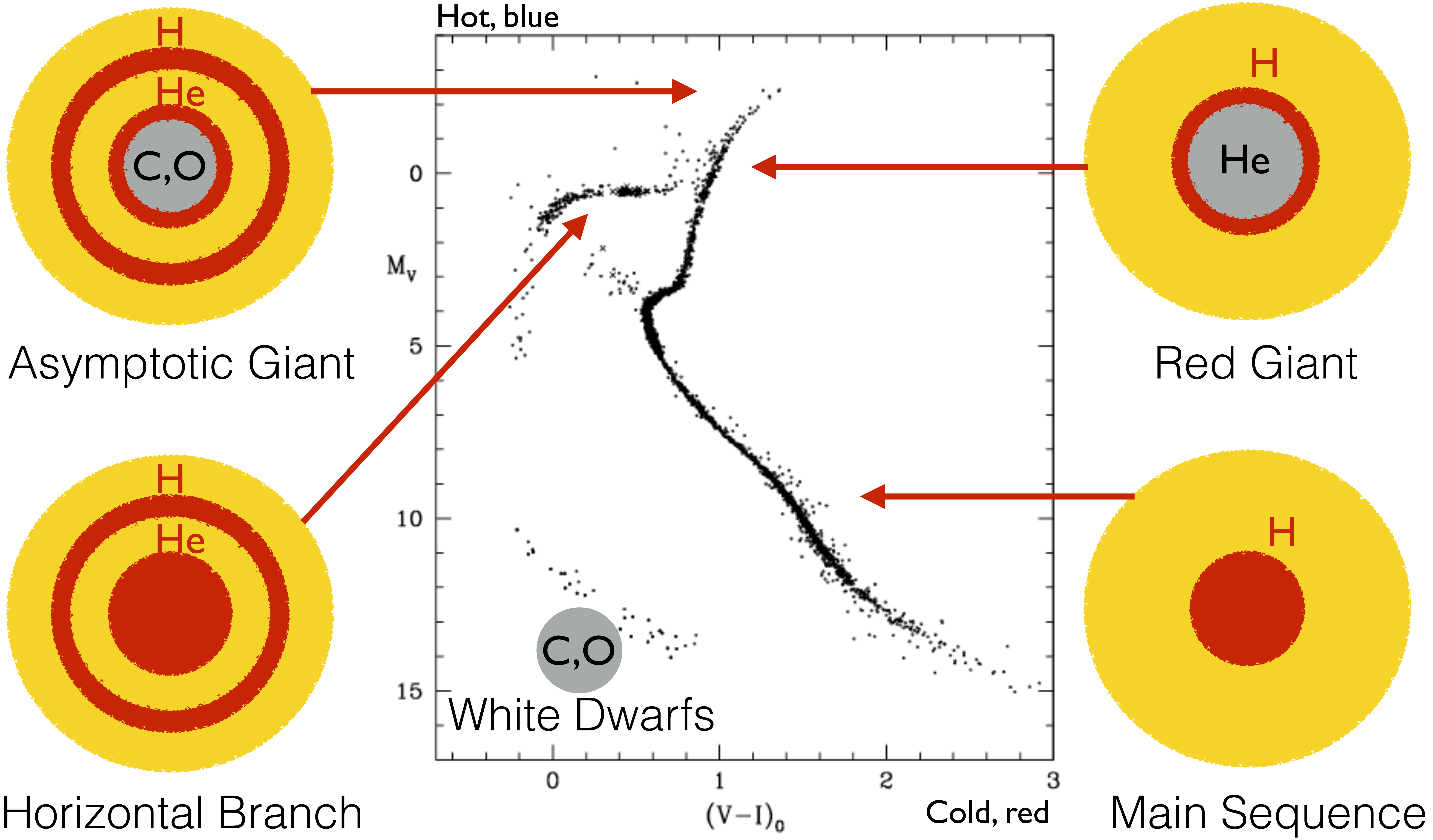

$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
10
1
0.1
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
luminosity (solar units)
$10^2$ Solar Radii
$10^3$ Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
$10^{-2}$ Solar Radius
$10^{-3}$ Solar Radius
instability strip
Polaris
Sun
O
B
A
F
G
K
M
30,000
10,000
6000
3000
surface temperature (K)


30,000
10,000
7,000
6,000
4,000
Effective Temperature, K
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
Absolute Magnitude, $M_V$
$10^5$
$10^4$
$10^3$
$10^2$
10
1
$10^{-1}$
$10^{-2}$
Luminosity compared to Sun
INSTABILITY STRIP
Type I Classical Cepheids
Type II W Virginis
RR Lyrae stars
RV Tauri stars
Betelgeuse
Long-Period Variables,
Miras
Main Sequence
Sun
Pulsating Variables
B0
A0
F0
G0
K0
M0
Spectral Class

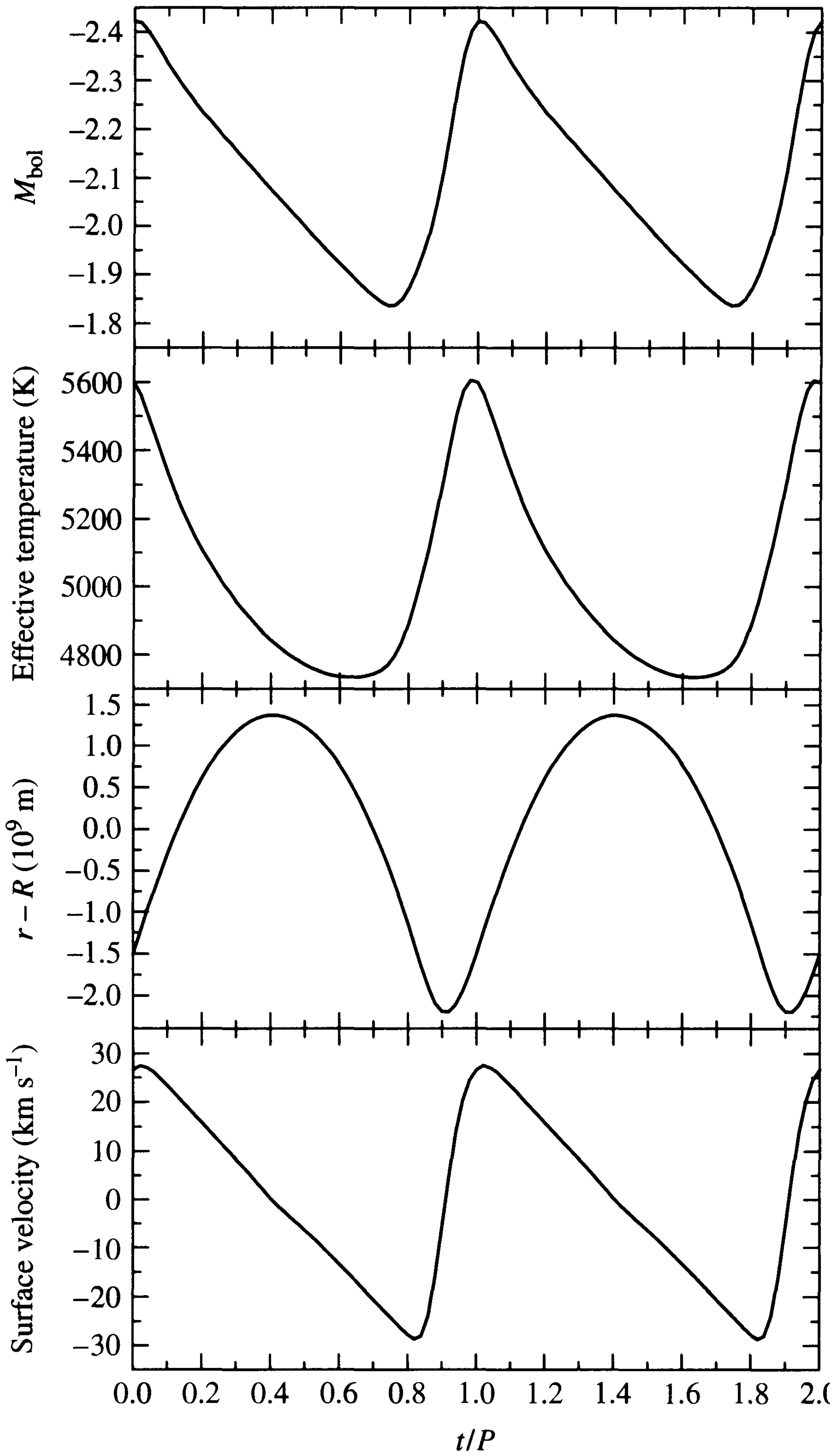
# Stars as laboratories

see e.g. Raffelt's excellent book

Pradler's talk 2015



Globular Cluster color-magnitude diagram



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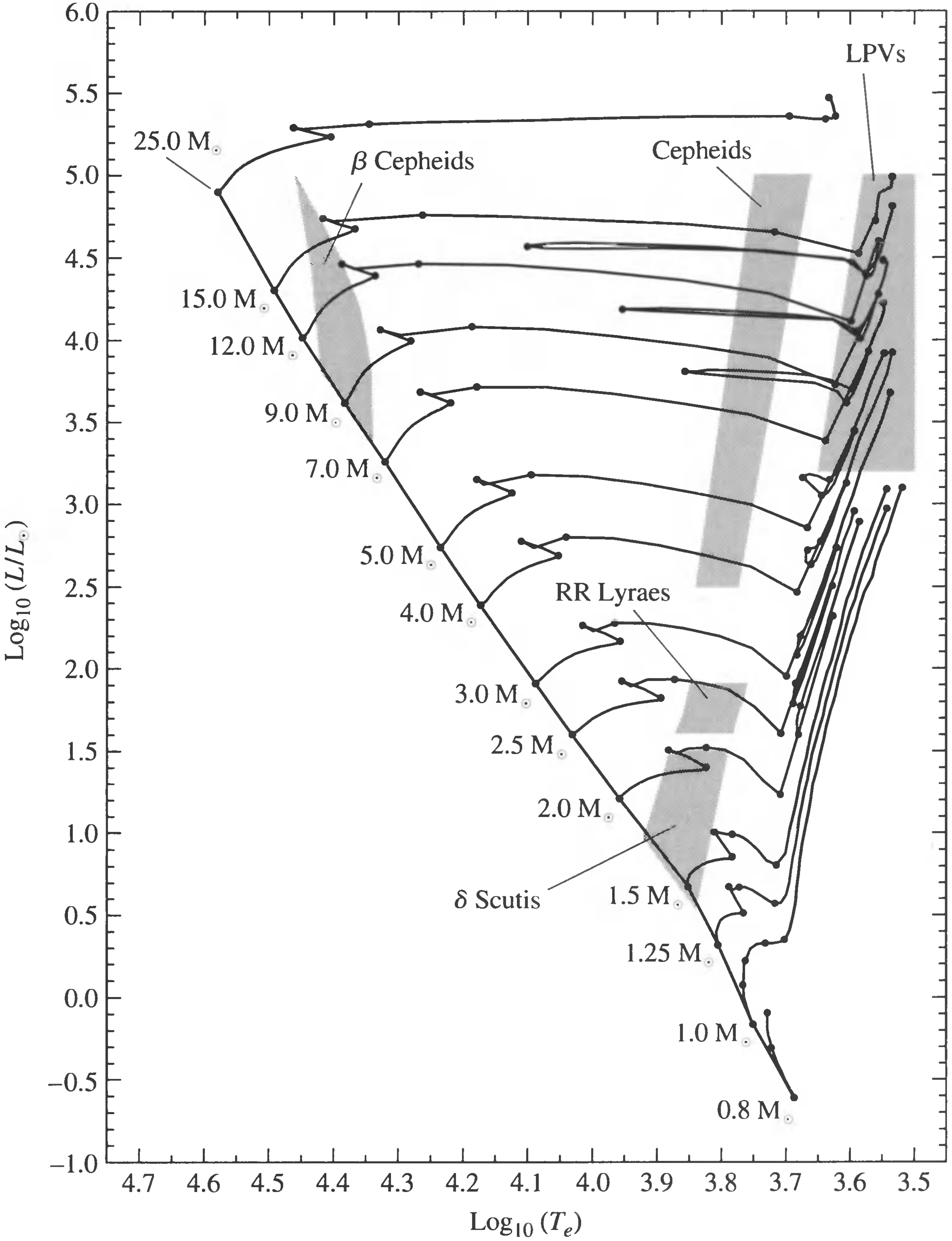
$t/P$



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RR Lyraes
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$\mathrm{Log}_{10}\,(L/L_\odot)$
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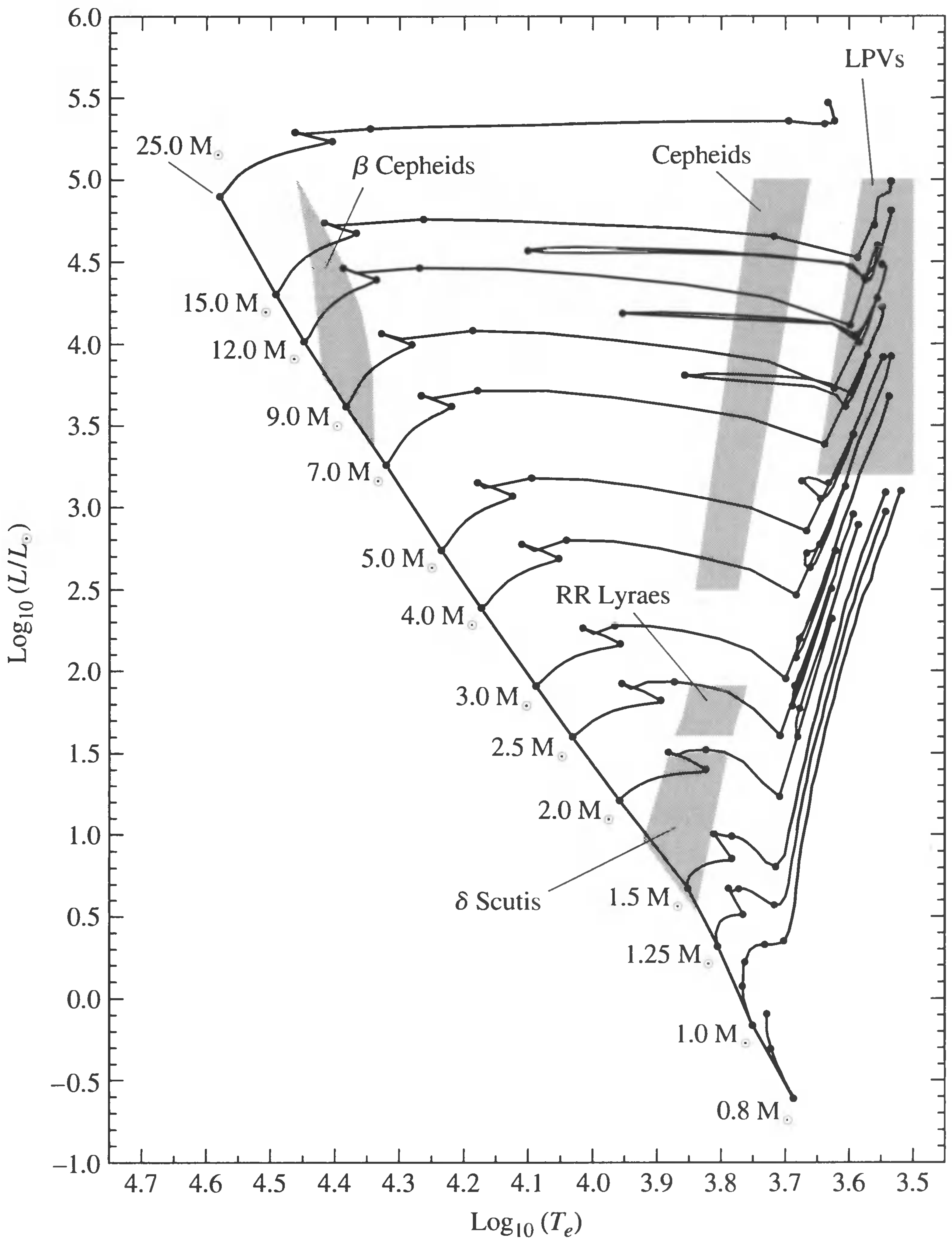
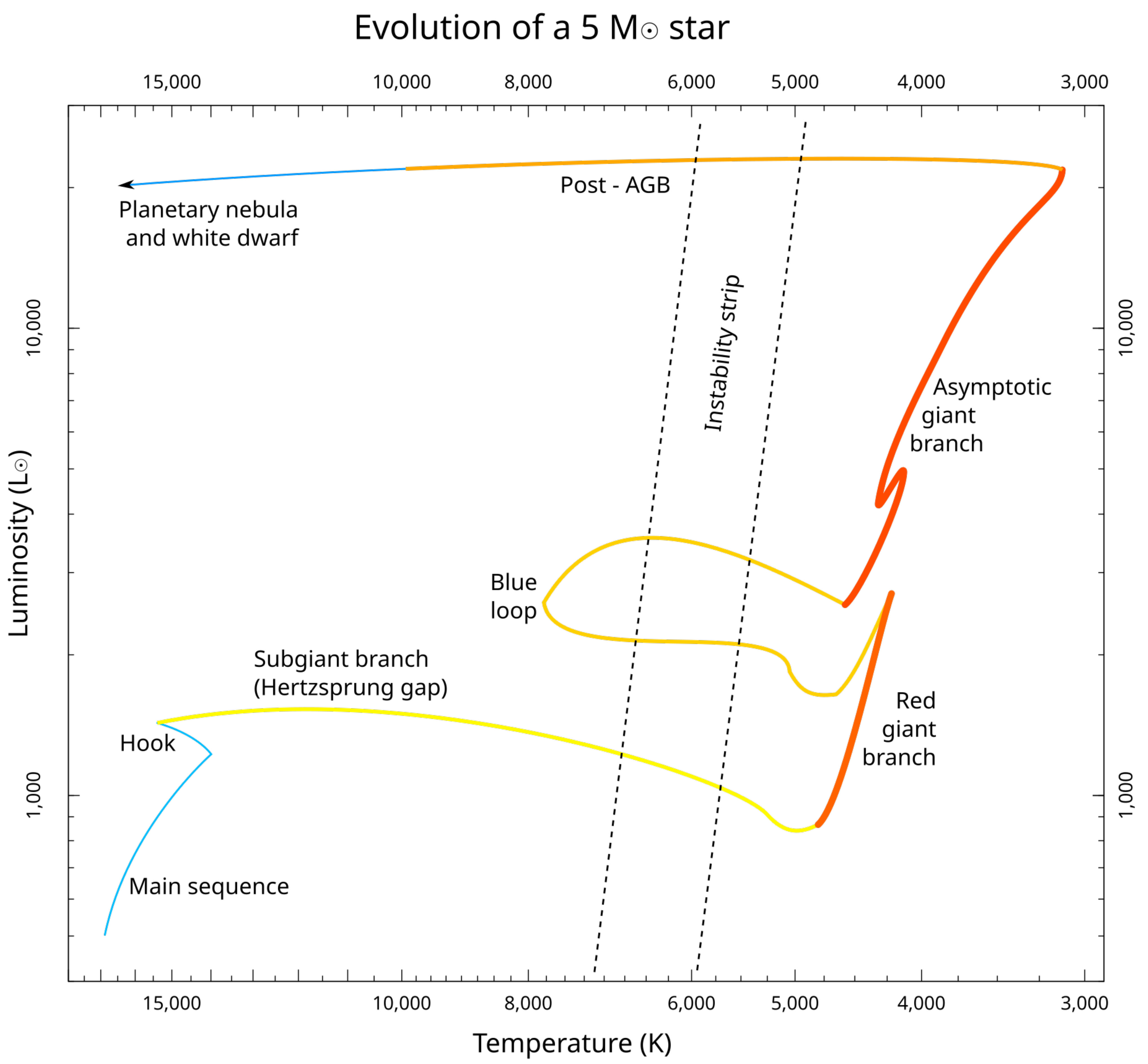
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
4.7
4.6
4.5
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
$\mathrm{Log}_{10}\,(T_e)$

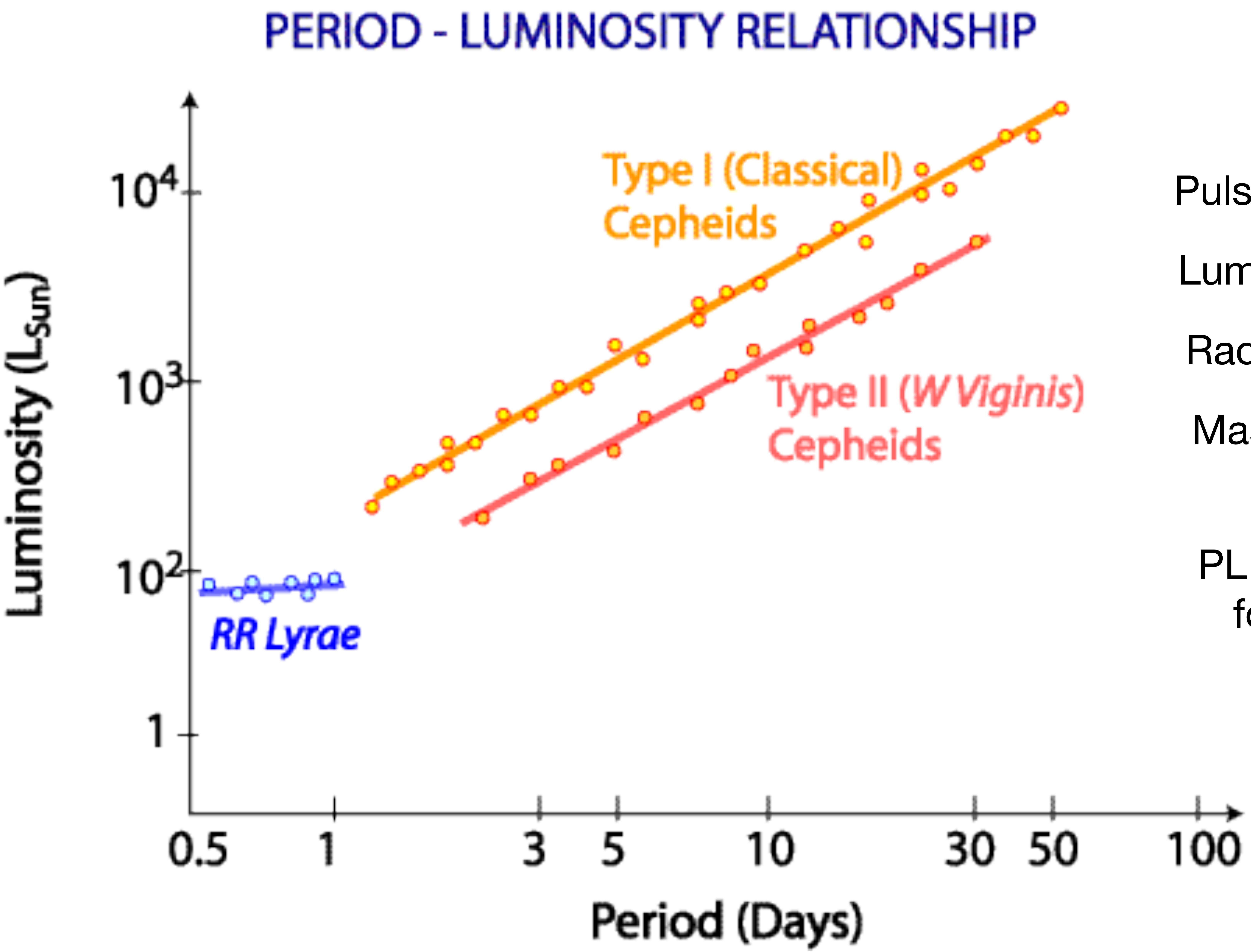
# Blue loop

## from red(or yellow) giant branch



Smooth He burning for $M > 2.3\ M_\odot$ triggers the blue loop





Pulsation Period : 1 - 50 days

Luminosity (L) : 300 - 26,000 L_sun

Radius (R) : 14 - 200 R_sun

Mass (M) : 3.7 - 14 M_sol

PL relation of Cepheids is used for measuring the distance.

Standard candle

# Magnitude and Distance Modulus

$$\frac{F_{10}}{F} = 100^{\frac{m-M}{5}} = (\frac{d}{10\mathrm{pc}})^2$$

(PL relation)
absolute
magnetiude

(observation)
apparent
magnitude

distance

$$M = m - 5\log_{10}\left(\frac{d}{10\mathrm{pc}}\right)$$

distance modulus

$$\mu = m - M$$

# PL(C) relation of Cepheids

$$L \propto R^2 T^4$$

Stefan-Boltzmann

$$\log L \propto 2 \log R + 4 \log T$$

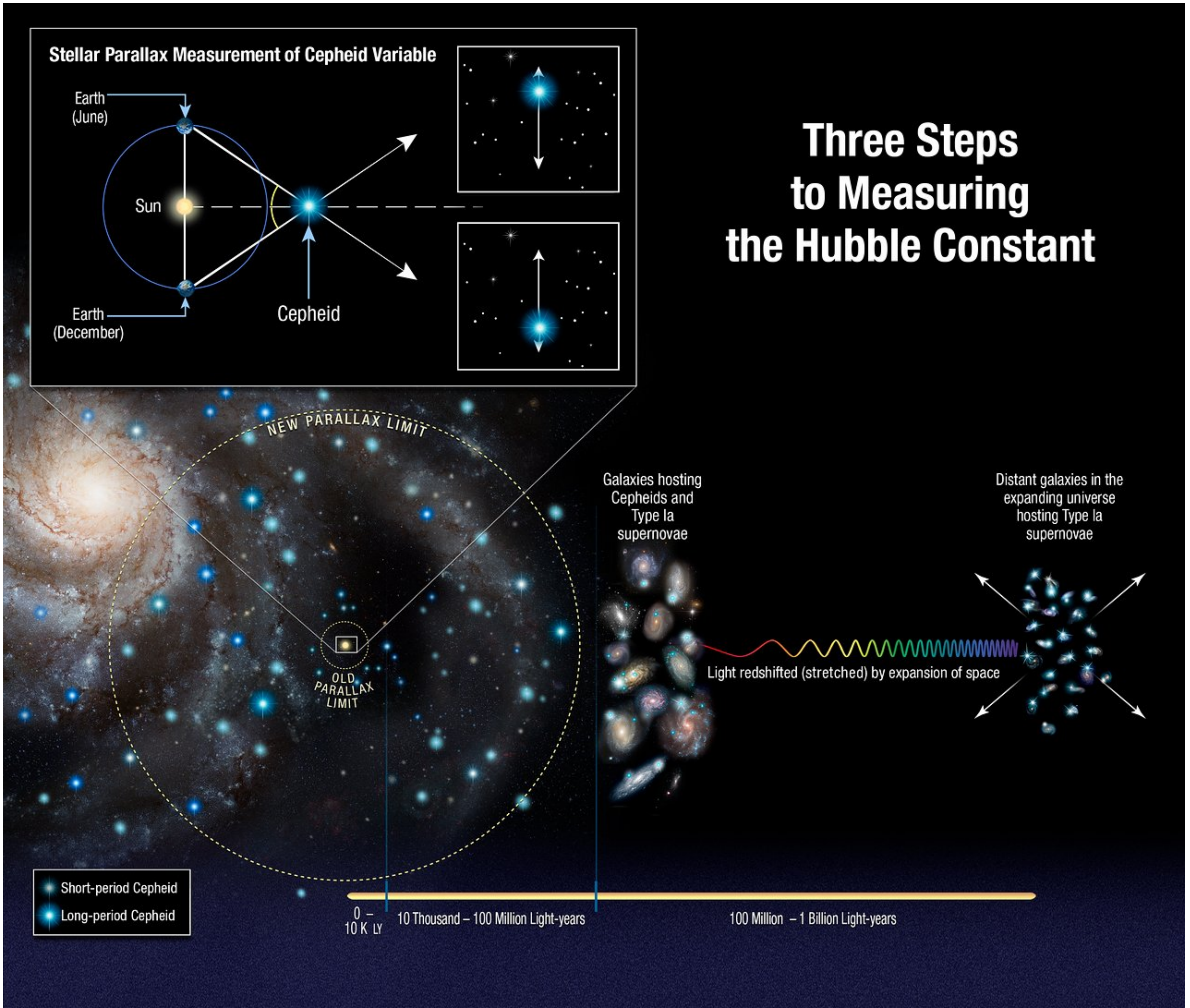
$$\propto \frac{4}{3} \log P + 4 \log T$$

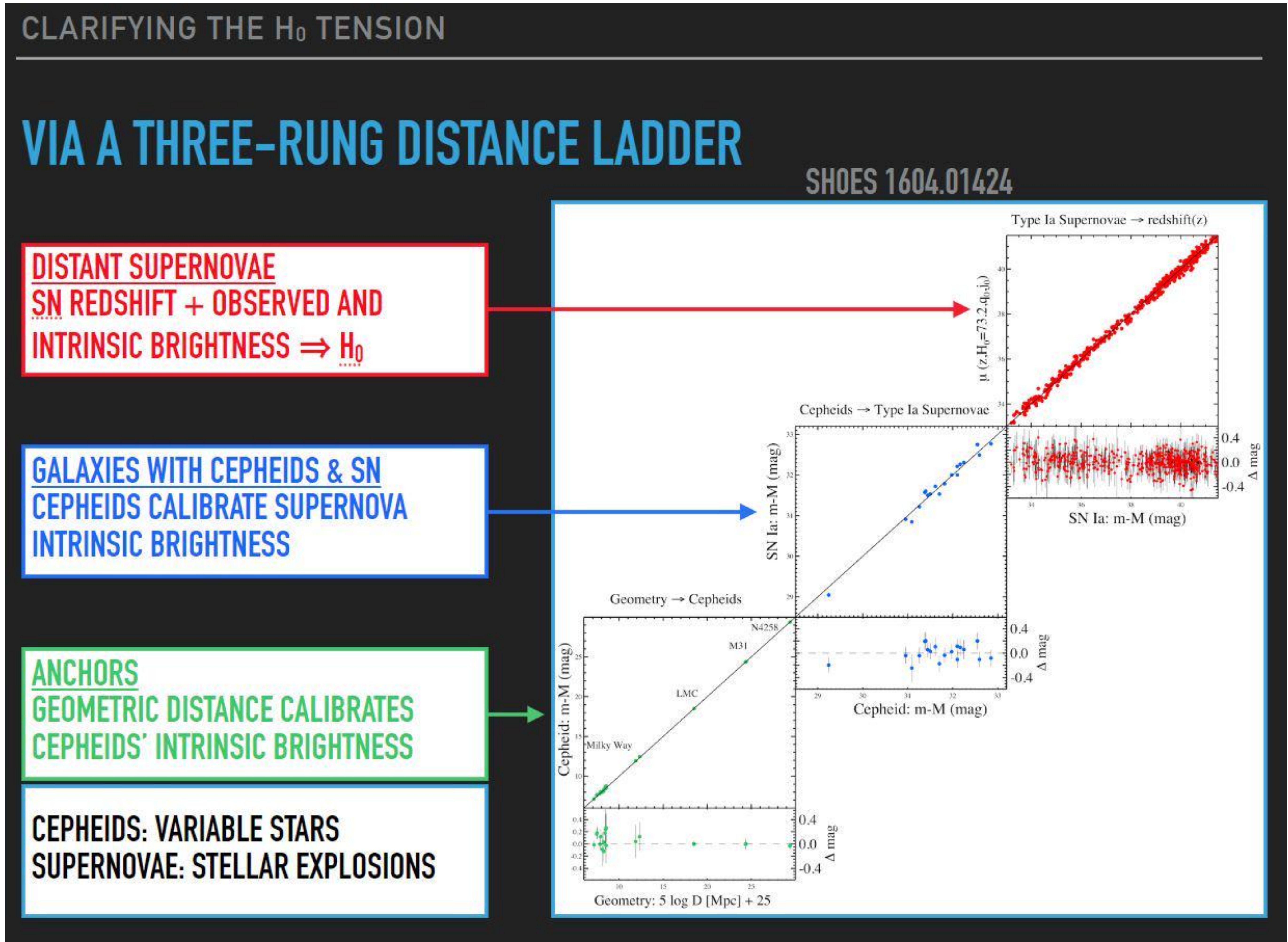
$$P = \Pi \propto \sqrt{\frac{1}{G\rho}} \propto R^{\frac{3}{2}}$$

$$M = \alpha \log P + \beta$$

Leavitt Law (1908)

# Cosmic Distance Ladder




CLARIFYING THE $H_0$ TENSION

VIA A THREE-RUNG DISTANCE LADDER

SHOES 1604.01424

DISTANT SUPERNOVAE
SN REDSHIFT + OBSERVED AND INTRINSIC BRIGHTNESS ⇒ $H_0$

GALAXIES WITH CEPHEIDS & SN
CEPHEIDS CALIBRATE SUPERNOVA INTRINSIC BRIGHTNESS

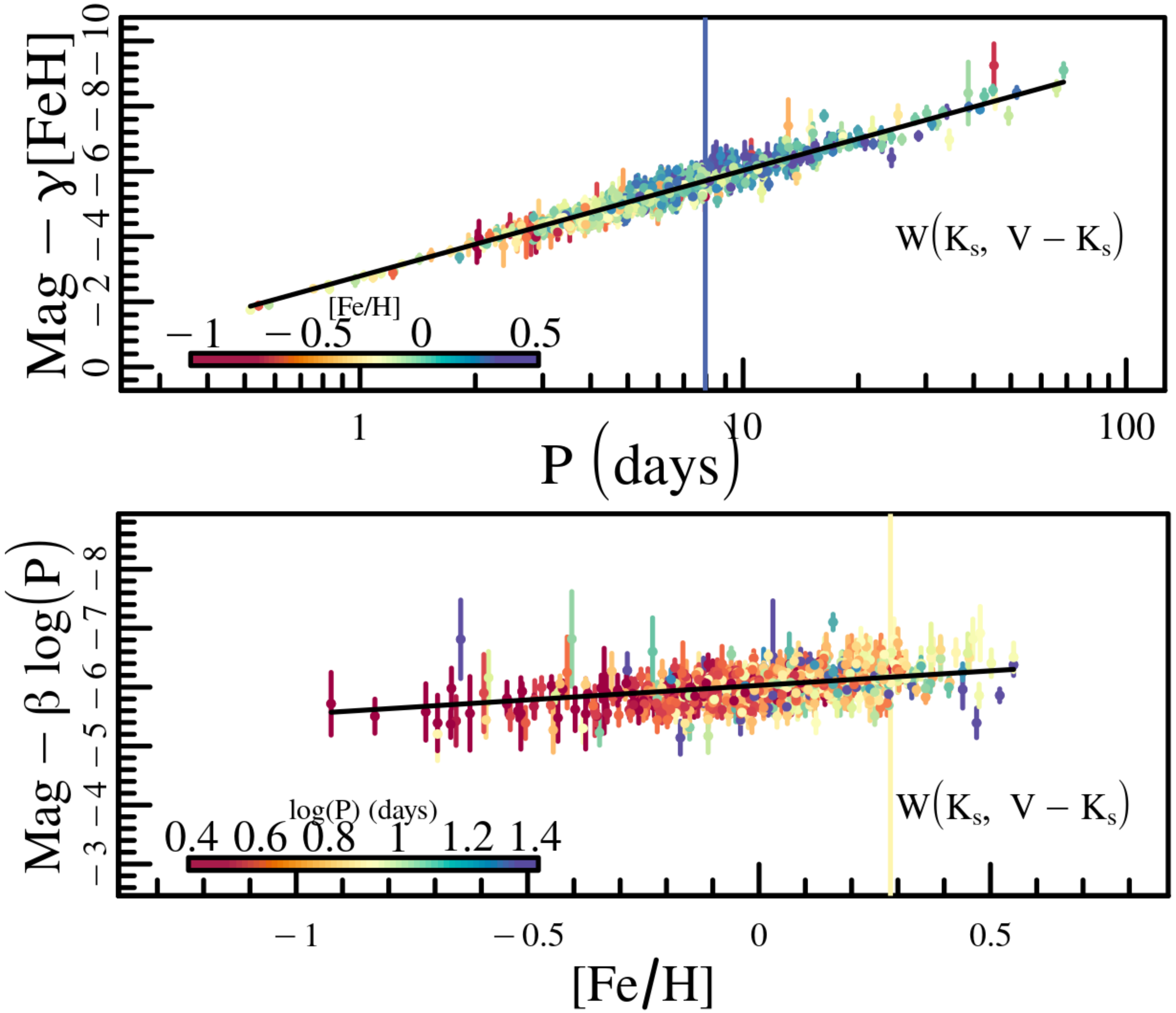
ANCHORS
GEOMETRIC DISTANCE CALIBRATES CEPHEIDS' INTRINSIC BRIGHTNESS

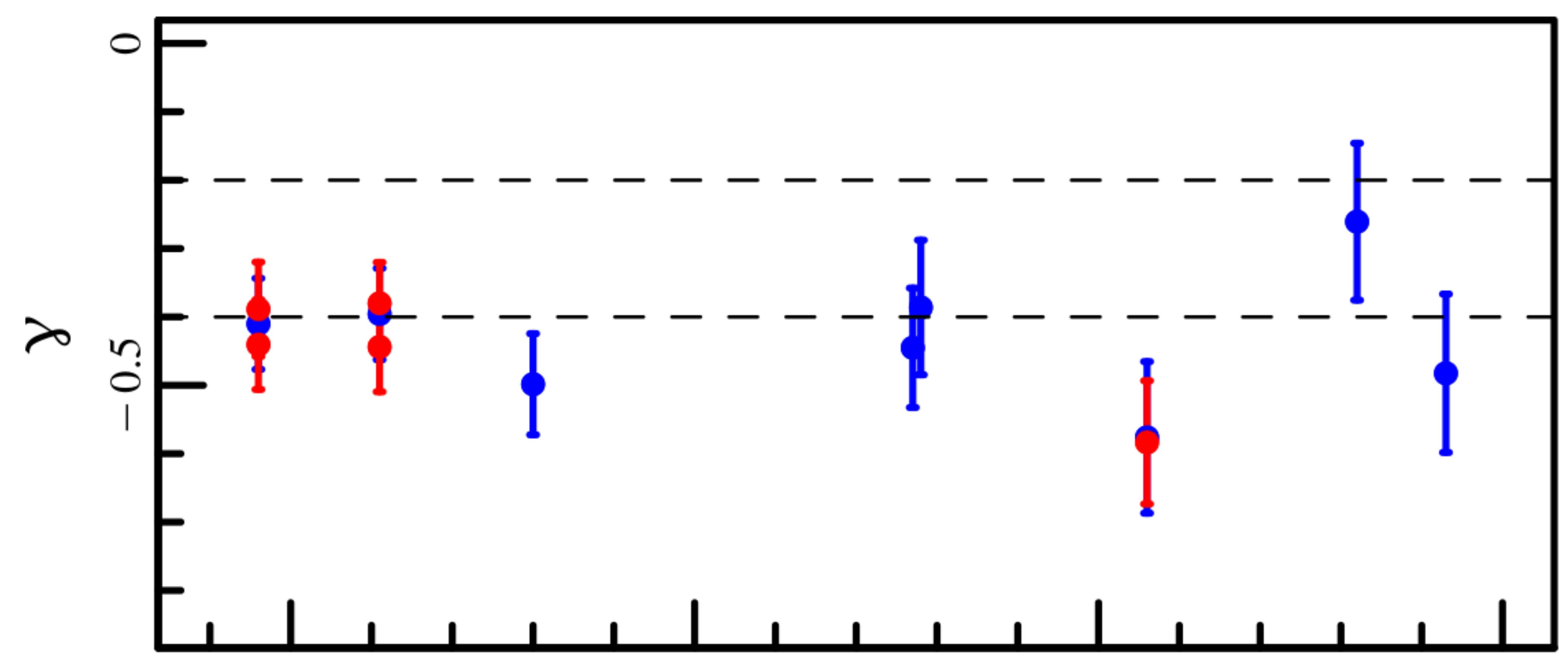
CEPHEIDS: VARIABLE STARS
SUPERNOVAE: STELLAR EXPLOSIONS

A&A, 683, A234 (2024)

# Cepheid Metallicity in the Leavitt Law (C-MetaLL) survey

## V. New multiband (*grizJHK*s) Cepheid light curves and period–luminosity relations⋆



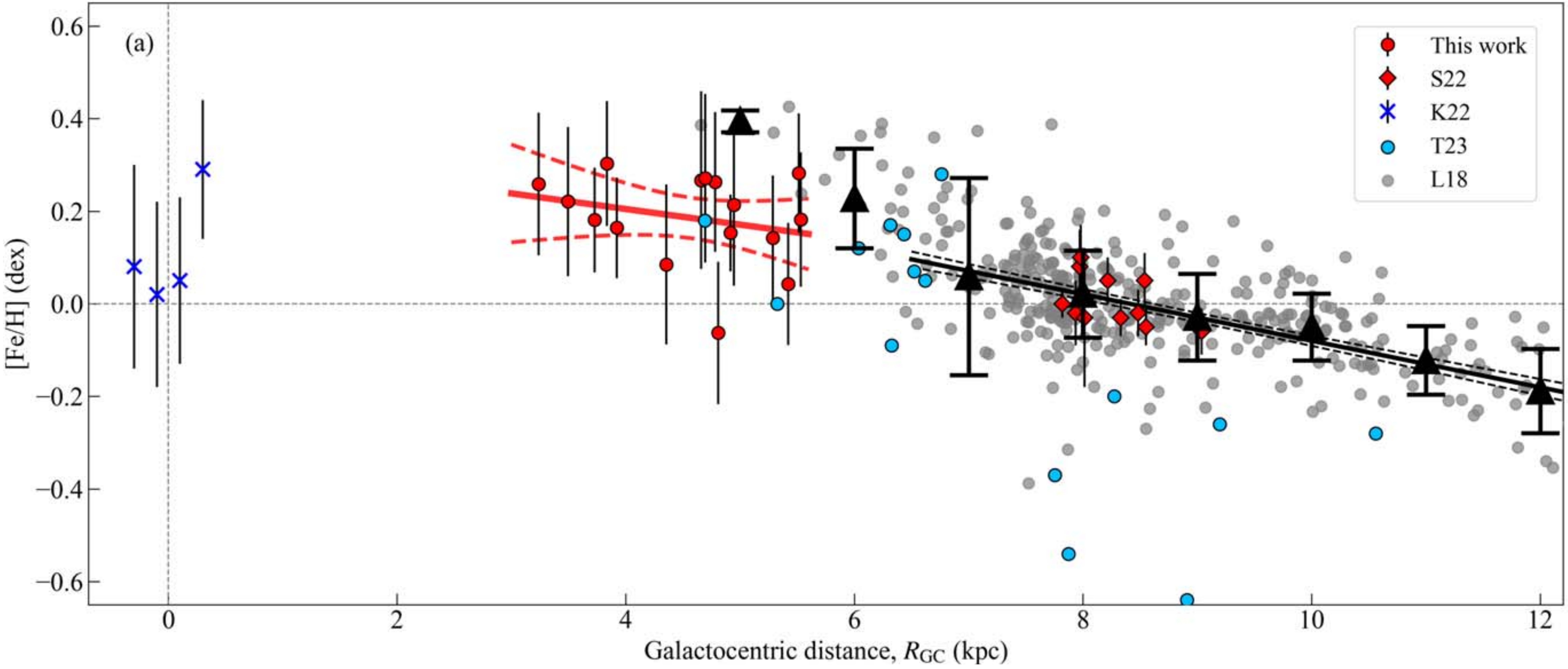


# Cepheids and SN Ia

# :Standizable candle

# Metallicity vs Galactocentric distance

THE ASTROPHYSICAL JOURNAL, 954:198 (8pp), 2023 September 10 Matsunaga et al.



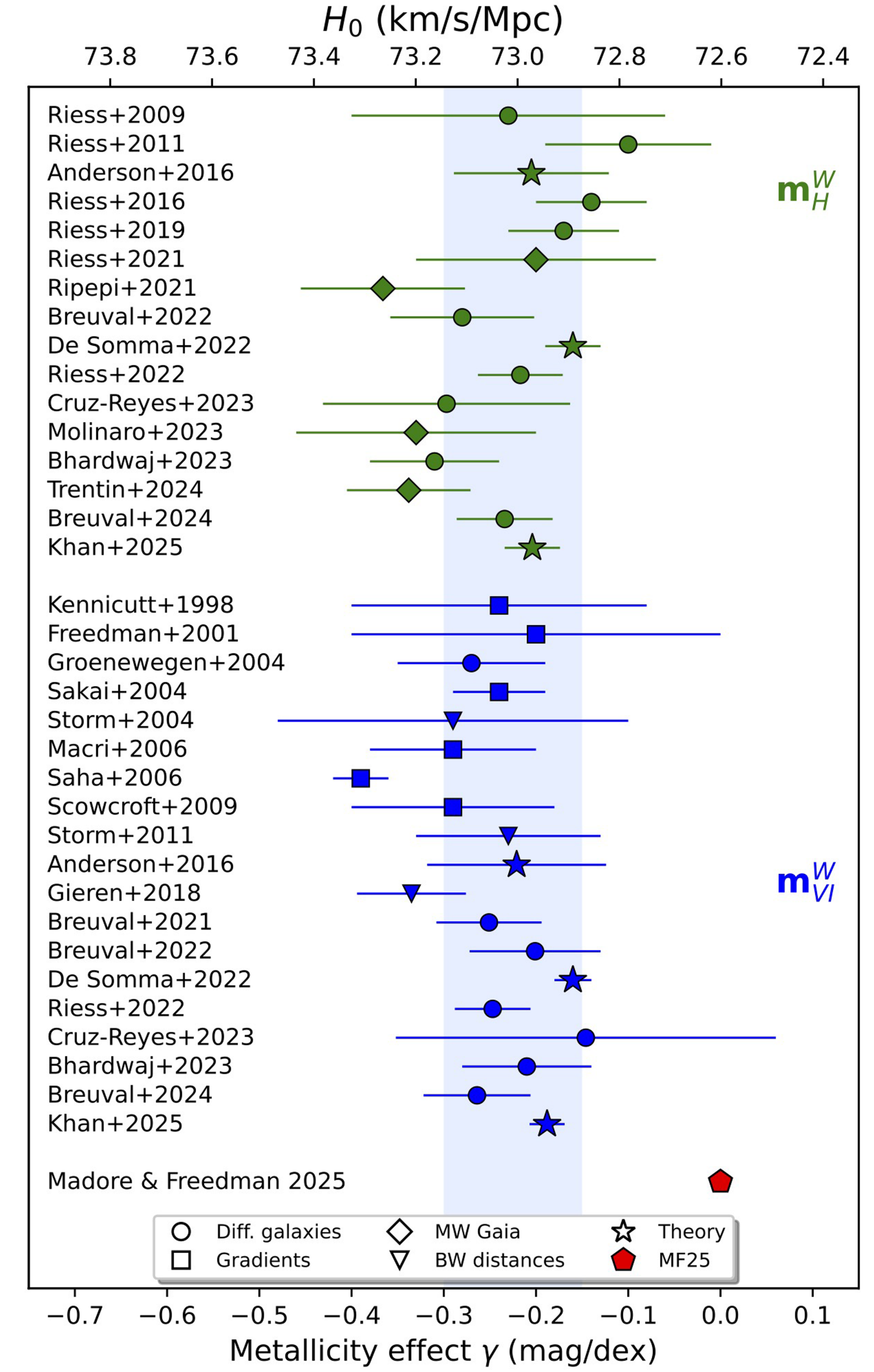
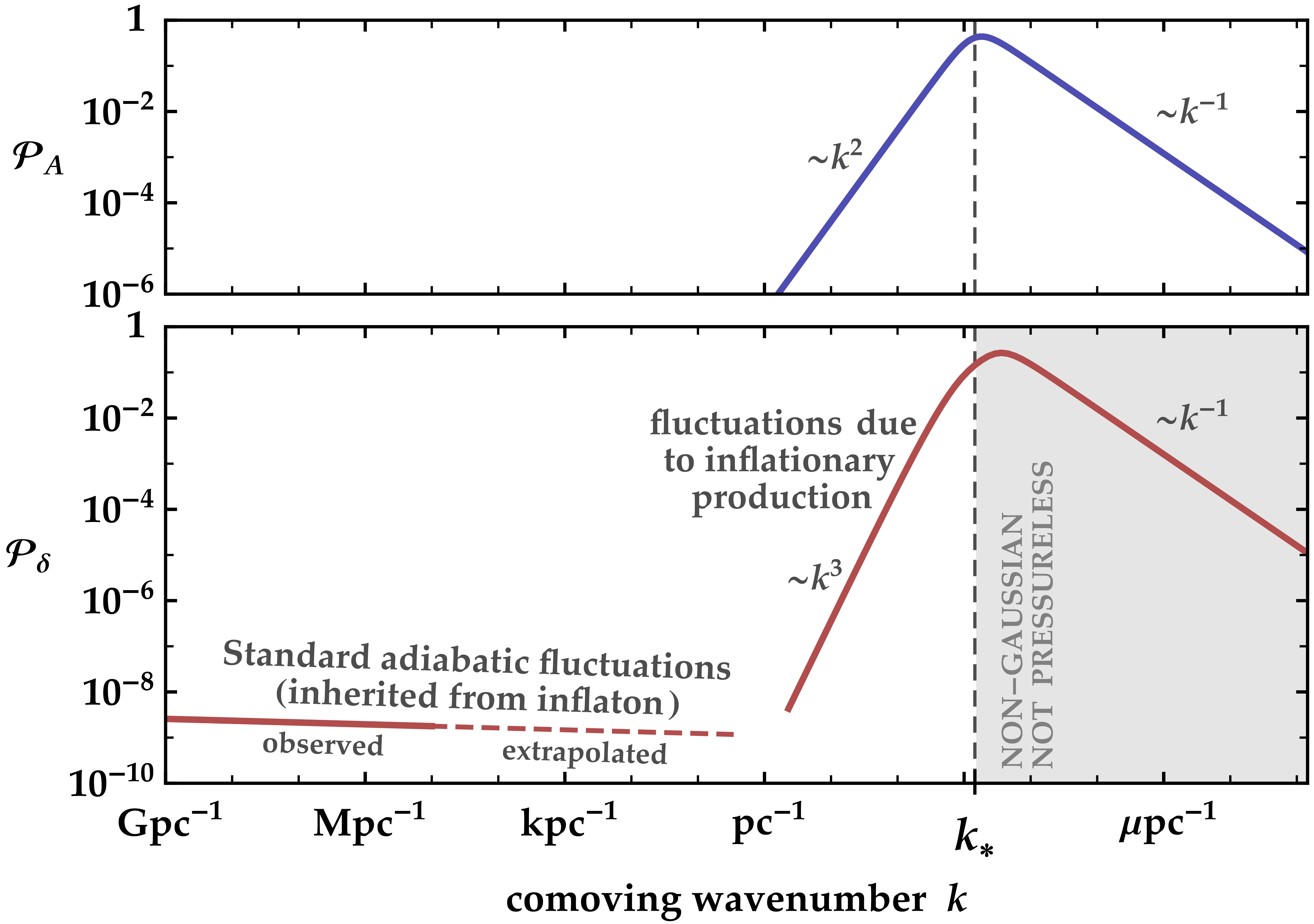


**Figure 1.** Recent empirical and theoretical estimates of the Cepheid metallicity dependence $\gamma$ from the literature in the $m_H^W$ and $m_{VI}^W$ Wesenheit indices. A few analyses were excluded from this plot (e.g., W. L. Freedman & B. F. Madore 2011; P. Wielgórski et al. 2017; K. A. Owens et al. 2022) due to issues that were identified and discussed in L. Breuval et al. (2022). The blue band shows broad agreement between $\gamma \sim -0.15$ and $-0.30$ mag dex$^{-1}$. The methods labeled with different shapes include comparison between P–L relations in different galaxies, metallicity gradients, Milky Way Cepheids with Gaia EDR3 parallaxes, Baade–Wesselink distances, and theoretical predictions. The red point indicates the $\gamma \sim 0$ multiwavelength result by MF25, based on a variety of methods. The metallicity dependence $\gamma$ in the $m_H^W$ Wesenheit magnitude and the Hubble constant $H_0$ are related as follows: $\gamma$ shifts the luminosity of Cepheids which show the largest metallicity difference with respect to Cepheids in SNIa hosts (i.e., in the SH0ES distance ladder, the metal-poor LMC, and SMC). This luminosity difference directly translates into a shift in $H_0$. We note that the $H_0$ values represented on the top x-axis are not actually measured in the quoted references but are derived from H0DN Collaboration et al. (2025).

# Vector dark matter from inflation (longitudinal)

**arXiv:1504.02102**



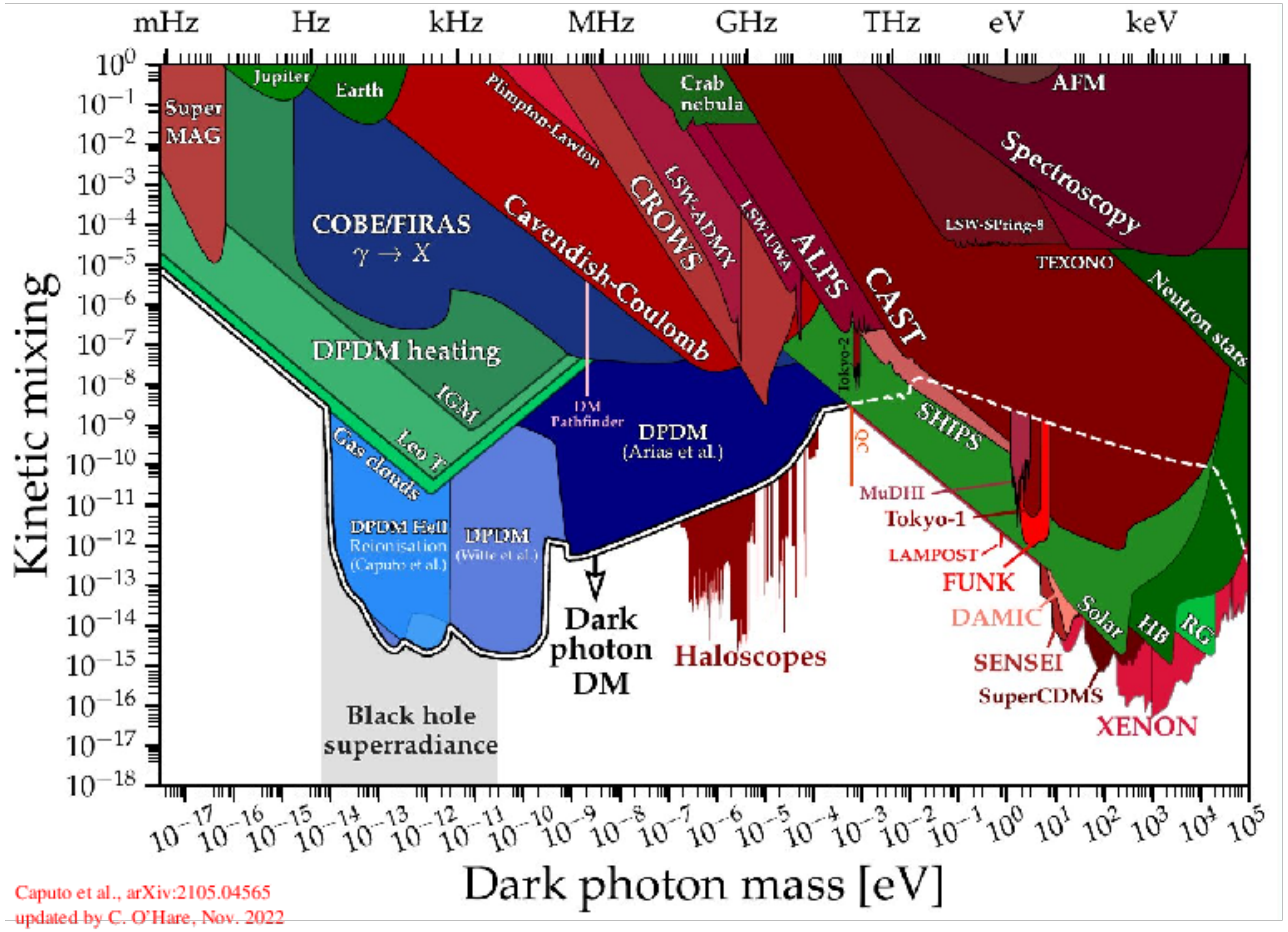
$$\frac{1}{k_*} \sim 10^{-10}\ \text{Mpc} \times \sqrt{\frac{10^{-3}\ \text{eV}}{m}}$$

$$\frac{\Omega_{\text{vector}}}{\Omega_{\text{cdm}}} = \sqrt{\frac{m}{10^{-3}\ \text{eV}}}\left(\frac{H_I}{3 \times 10^{13}\ \text{GeV}}\right)^2$$

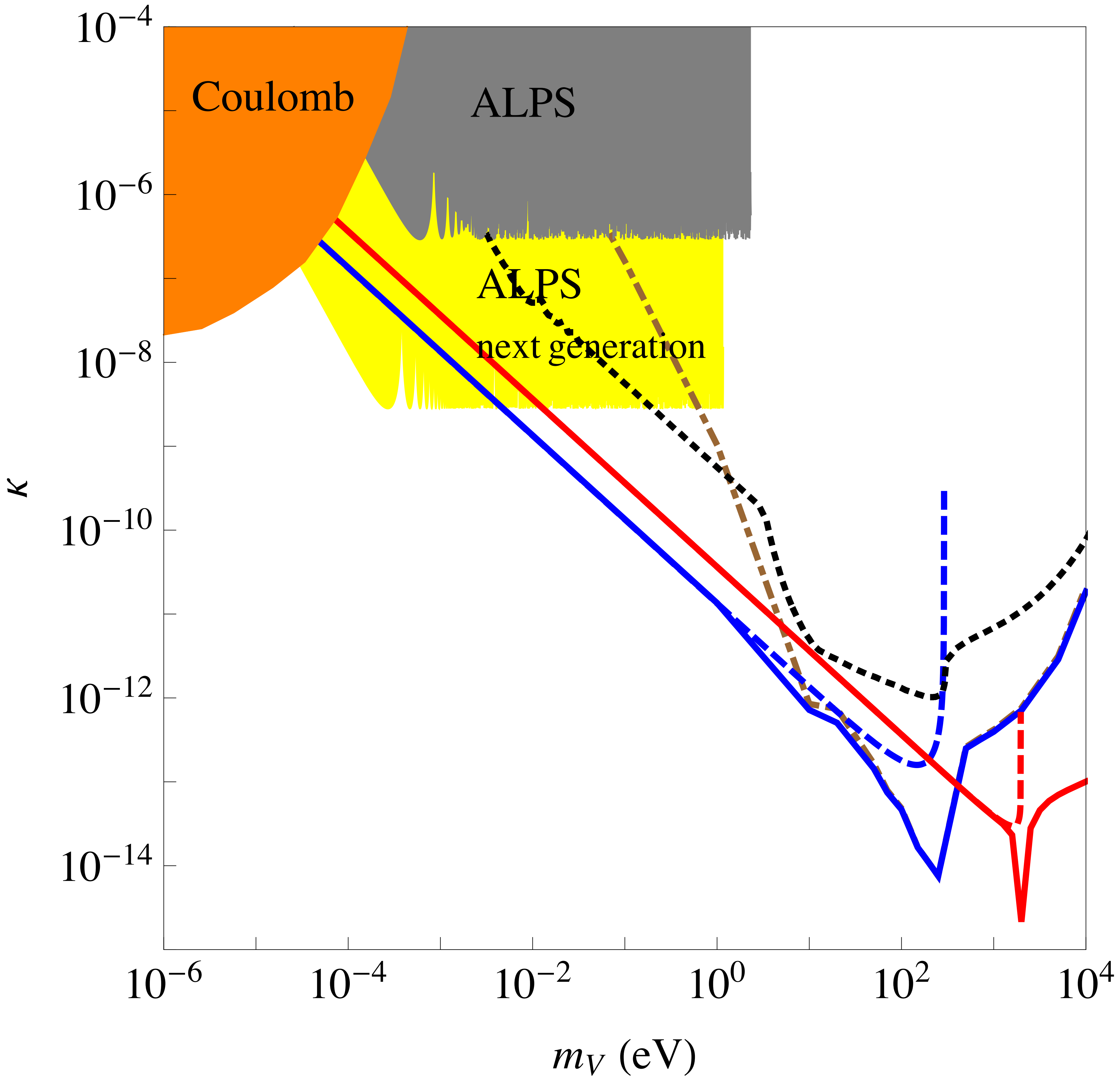
$$\mathscr{P}_\phi = \left(\frac{H_I}{2\pi}\right)^2 \xrightarrow[\phi \simeq \frac{m}{k} A_L]{} \mathscr{P}_{A_0} = \left(\frac{kH_I}{2\pi m}\right)^2$$

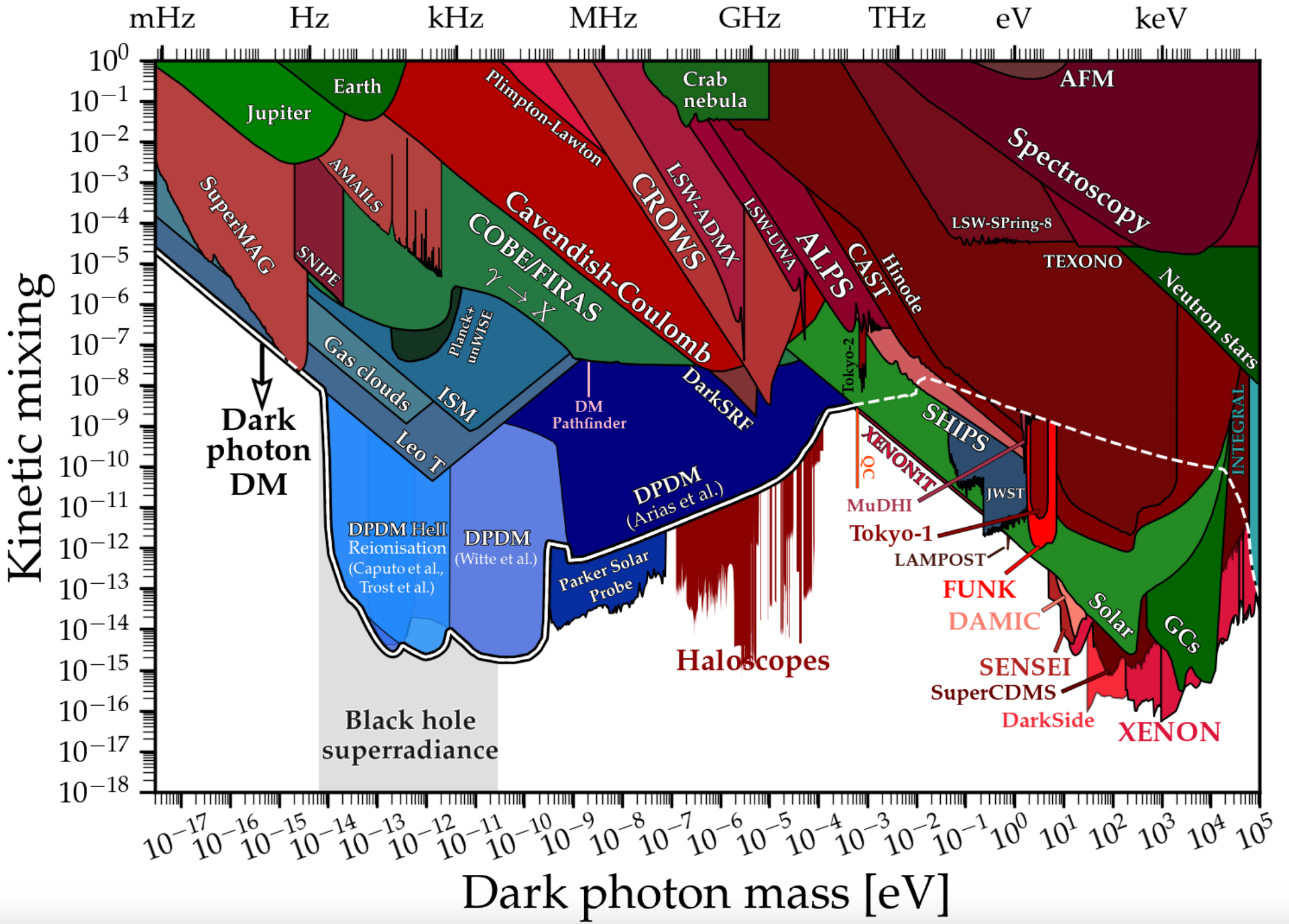
# Kinetic mixing of DPDM with photon

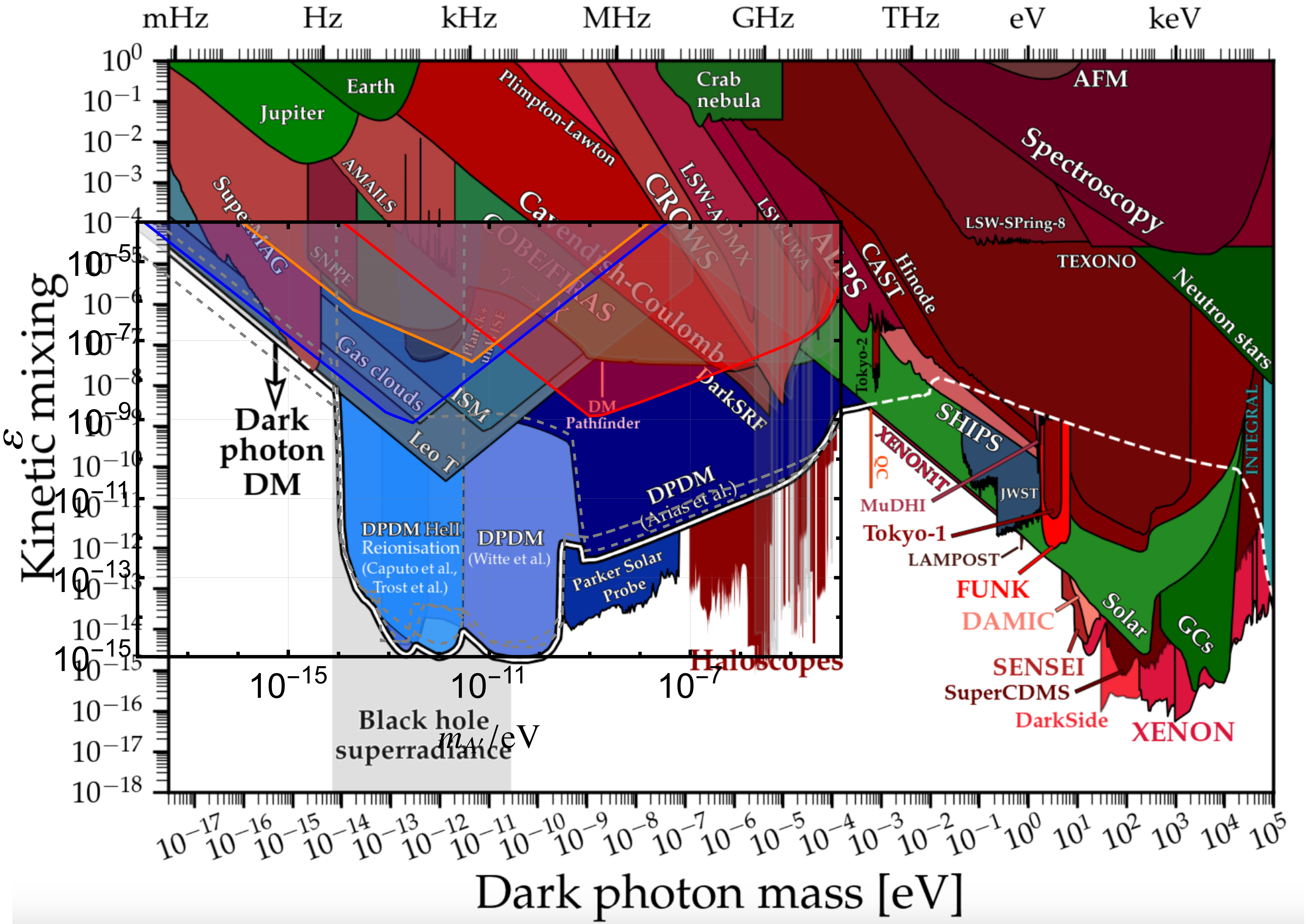
$$\mathscr{L} \supset \frac{\epsilon}{2} F^{\mu\nu}_{\mathrm{EM}} F'_{\mu\nu}$$



Caputo et al., arXiv:2105.04565
updated by C. O'Hare, Nov. 2022




mHz
Hz
kHz
MHz
GHz
THz
eV
keV
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
$10^{-17}$
$10^{-18}$
Kinetic mixing
Jupiter
Earth
Plimpton-Lawton
Crab nebula
AFM
Spectroscopy
SuperMAG
AMAILS
SNIPE
Cavendish-Coulomb
COBE/FIRAS
$\gamma \to X$
CROWS
LSW-ADMX
LSW-UWA
ALPS
CAST
Hinode
LSW-SPring-8
TEXONO
Neutron stars
Planck+ unWISE
Gas clouds
ISM
Leo T
DarkSRF
DM Pathfinder
Tokyo-2
SHIPS
INTEGRAL
XENON1T
QC
JWST
MuDHI
Tokyo-1
LAMPOST
FUNK
DAMIC
SENSEI
SuperCDMS
DarkSide
XENON
Solar
GCs
Dark photon DM
DPDM HeII Reionisation (Caputo et al., Trost et al.)
DPDM (Witte et al.)
DPDM (Arias et al.)
Parker Solar Probe
Haloscopes
Black hole superradiance
$10^{-17}$
$10^{-16}$
$10^{-15}$
$10^{-14}$
$10^{-13}$
$10^{-12}$
$10^{-11}$
$10^{-10}$
$10^{-9}$
$10^{-8}$
$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
$10^{4}$
$10^{5}$
Dark photon mass [eV]


mHz
Hz
kHz
MHz
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THz
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keV
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DPDM (Arias et al.)
DPDM HeII Reionisation (Caputo et al., Trost et al.)
DPDM (Witte et al.)
Parker Solar Probe
Dark photon DM
Kinetic mixing ε
Dark photon mass [eV]
$m_{A'}$/eV
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
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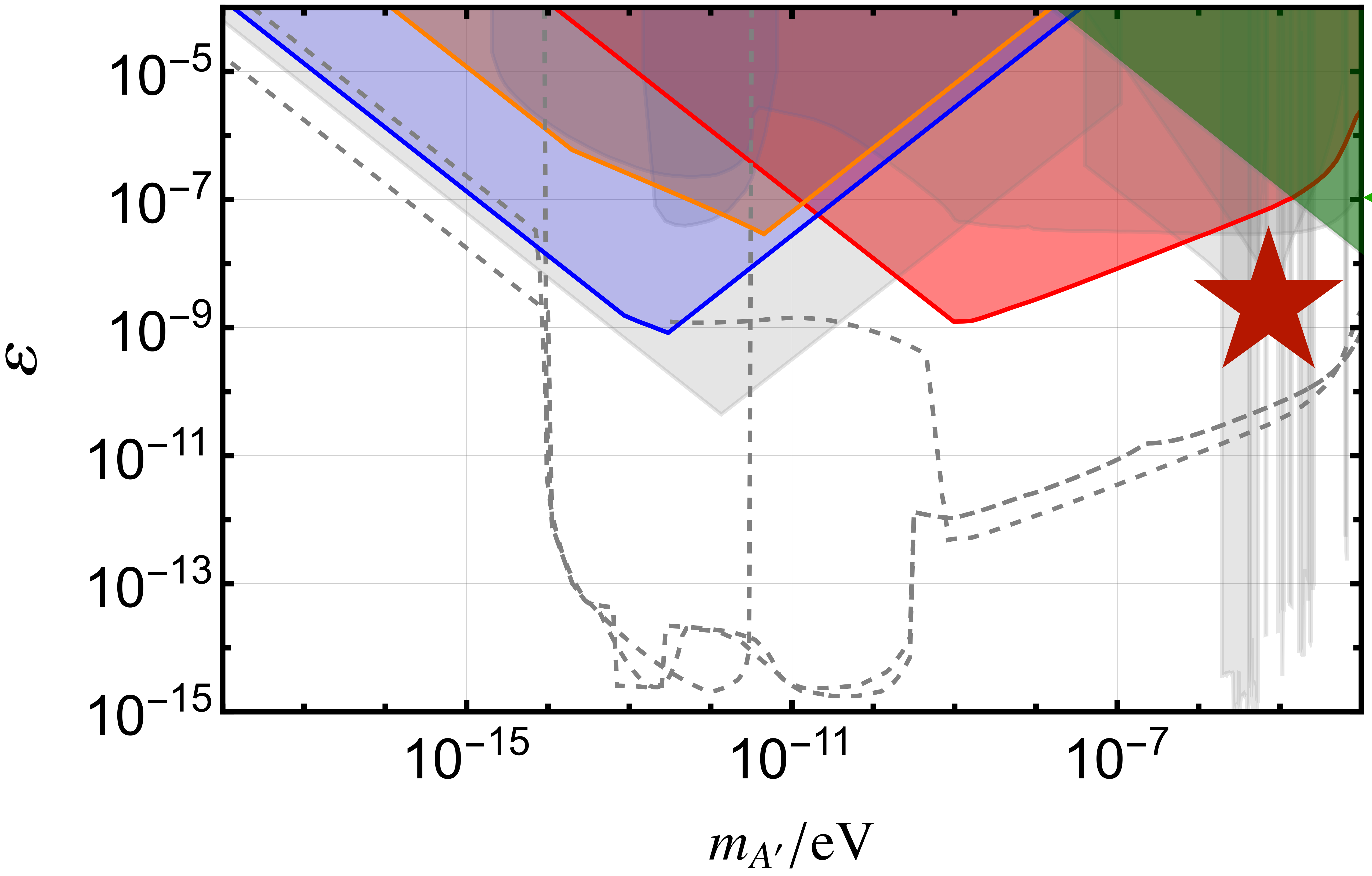
$10^{-11}$
$10^{-10}$
$10^{-9}$
$10^{-8}$
$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
$10^{4}$
$10^{5}$

The previous invalidated constraints are shown as gray dashed lines.

2510.13956 Anson Hook, Junwu Huang, Mohamad Shalaby



$$\epsilon m_D \leq 1.5 \times 10^{-12}\ \mathrm{eV}$$

Solar cooling

ALLOWED!!!

Dark Photon
Dark Matter

Cepheid

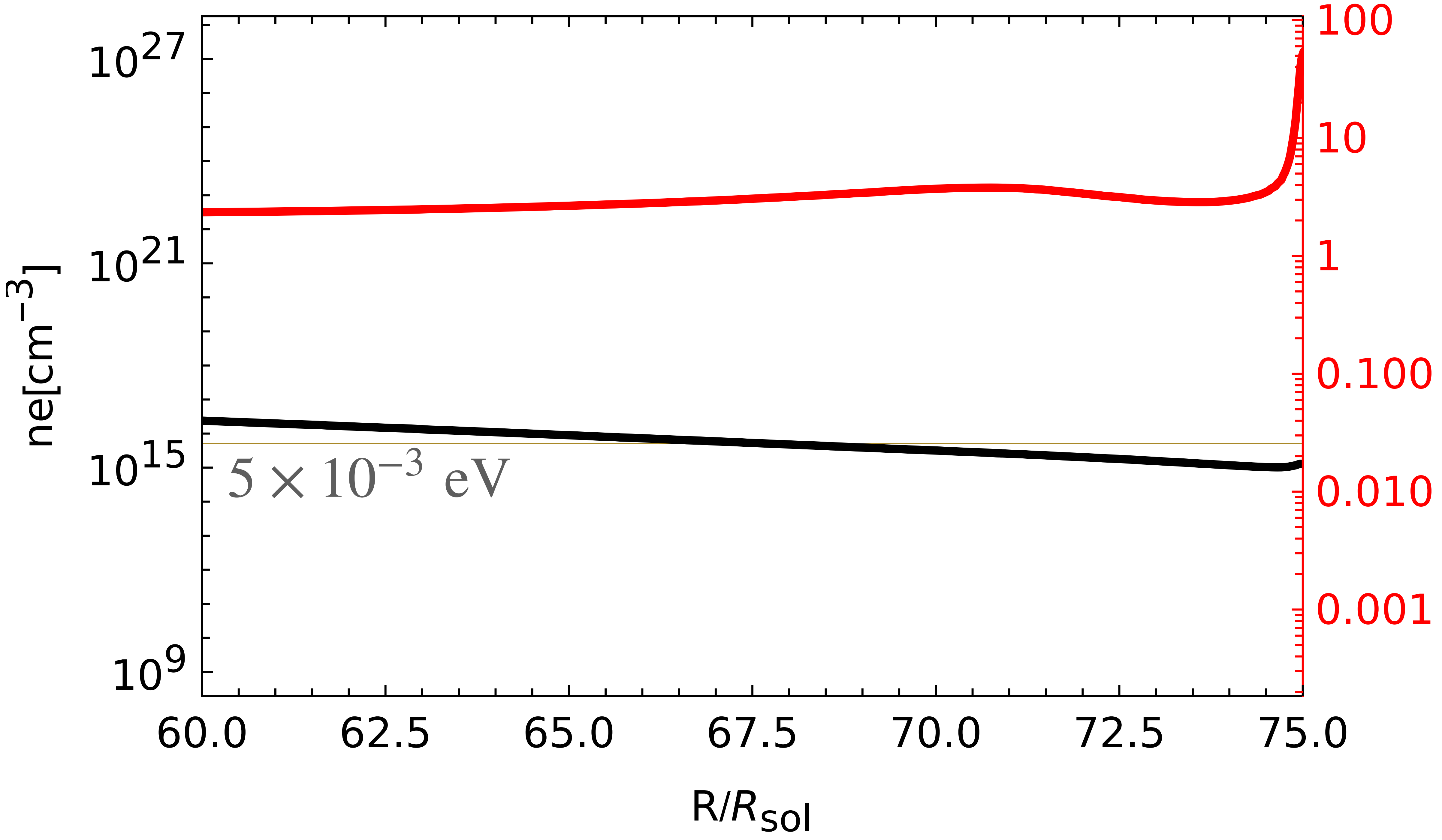
Resonance Conversion

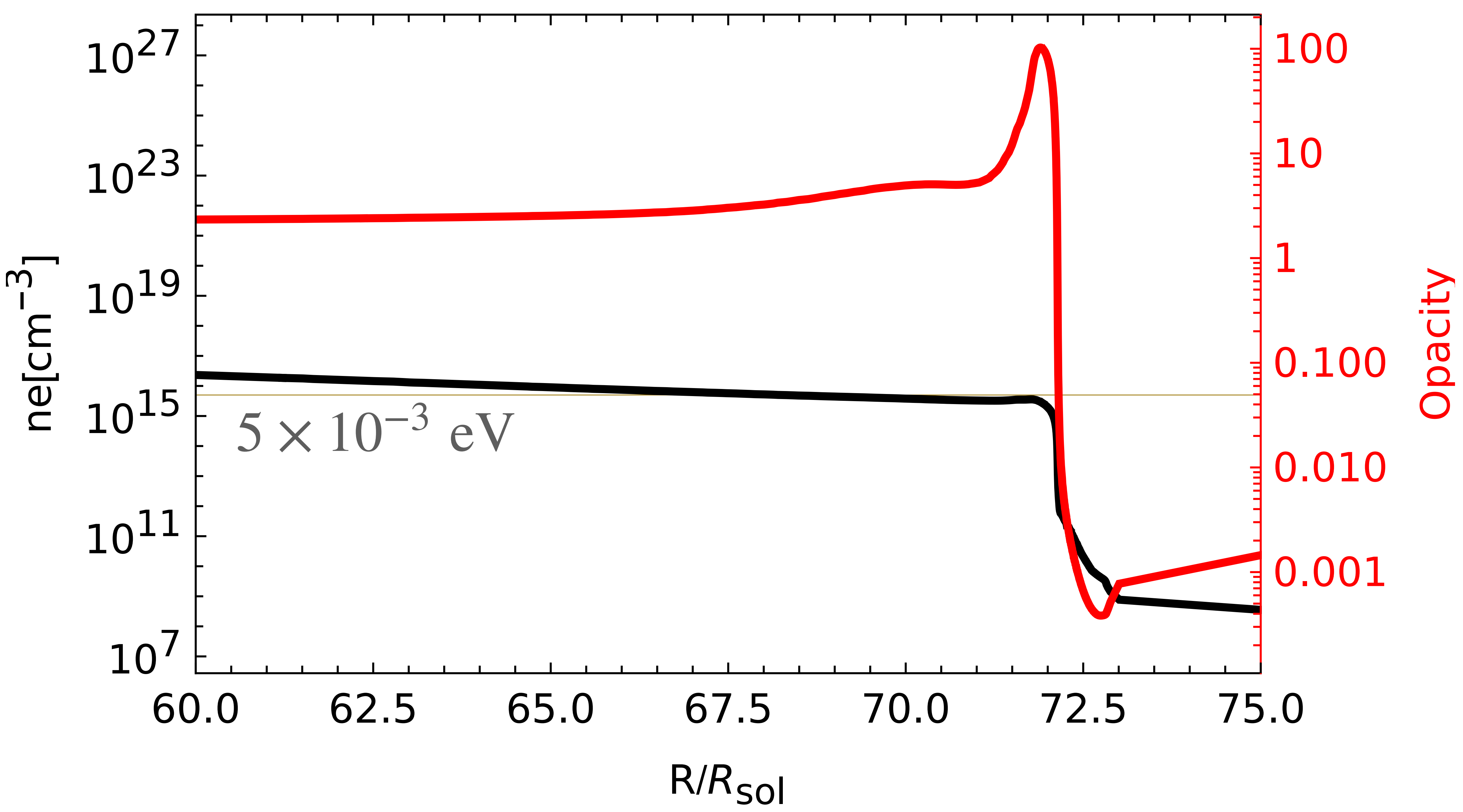
$m$

He

Vacuum

# $M = 6M_\odot,\ Y = 0.267,\ Z = 0.003$





The result depends on whether the resonance occurs inside or outside of the valve (opacity peak)

# Back of envelope calculation

$$\Gamma(\gamma' \to \gamma) = \frac{\pi \epsilon^2 m_{\gamma'}}{v \left| \frac{\partial \log \omega_P^2}{\partial \log r} \right|}$$

$$\frac{\omega_{\rm P}^{-1}}{L_{\rm shell}} \sim \frac{\rm mm}{10^8 \rm km} \sim 10^{-14}$$

Cepheid data

$L = 10^3 L_\odot \sim 4 \times 10^{36}$ erg/s

$R = 40 R_\odot \sim 2 \times 10^7$km

He II shell

$n_e \sim 10^{16}$ cm$^{-3}$

$T \sim 10^4$K

$$\omega_{\rm P} = \frac{4\pi\alpha n_e}{m_e} \sim \text{meV}$$

$$\Phi_{\rm DM} \Gamma_{\gamma'} A = \frac{\rho_{DM}}{m_{\gamma'}} v \Gamma_{\gamma'} \pi (40 R_\odot)^2$$

$$\sim \epsilon^2 \times 10^5 \text{GeV/cm}^3 \times 10^{15} \times 10^{25} \text{cm}^2 \times 10^{10} \text{cm/s}$$

$$\sim \left(\frac{\epsilon}{10^{-9}}\right)^2 \left(\frac{\rho_{\rm DM}}{10^5 \text{GeV}}\right) 10^{34} \text{erg/s}$$

# Summary

## Preliminary

- New era of dark matter astrophysics
- Dark matter beyond the gravitational source
- Many things to be understood in the stand(izable) candle stellar objects