Cepheids as a dark matter detector

FLASY 2026

Aug 19, Gyeongju, Korea

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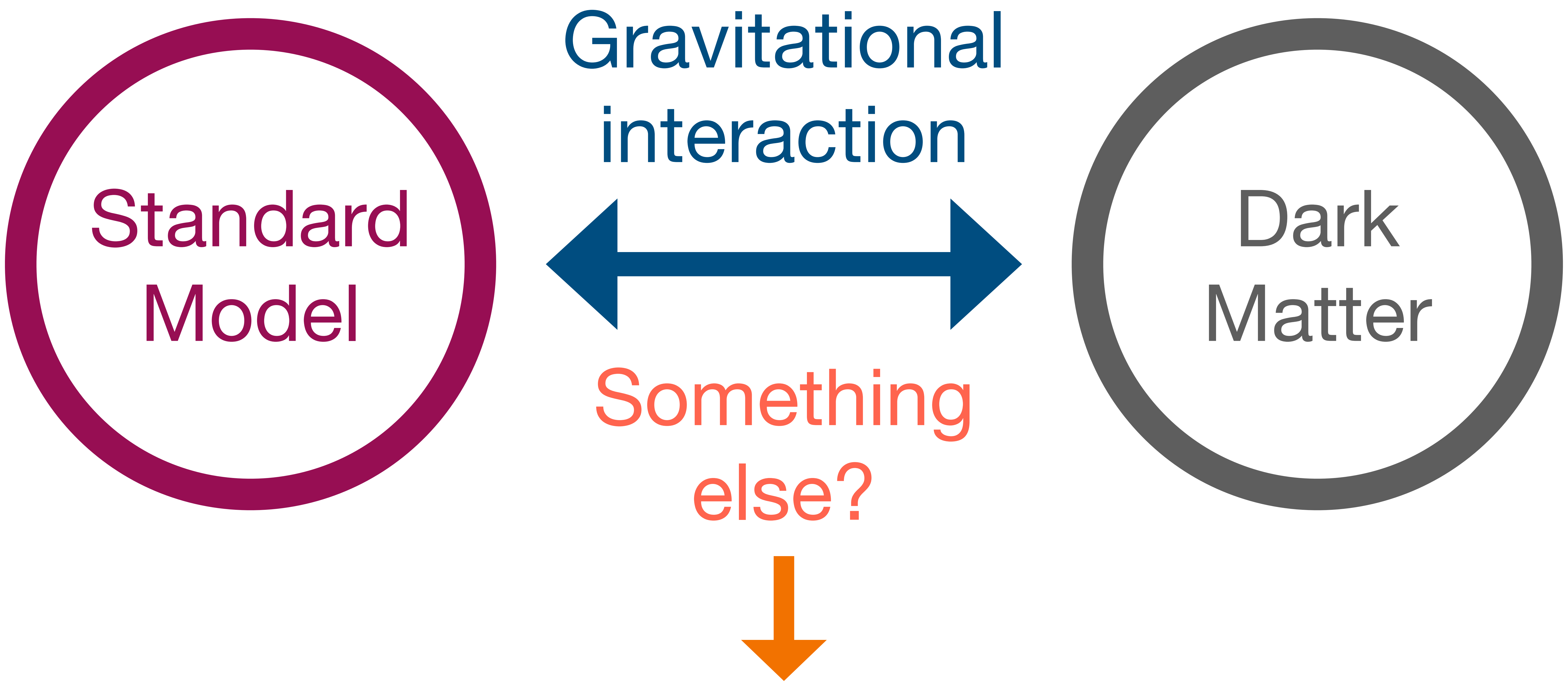
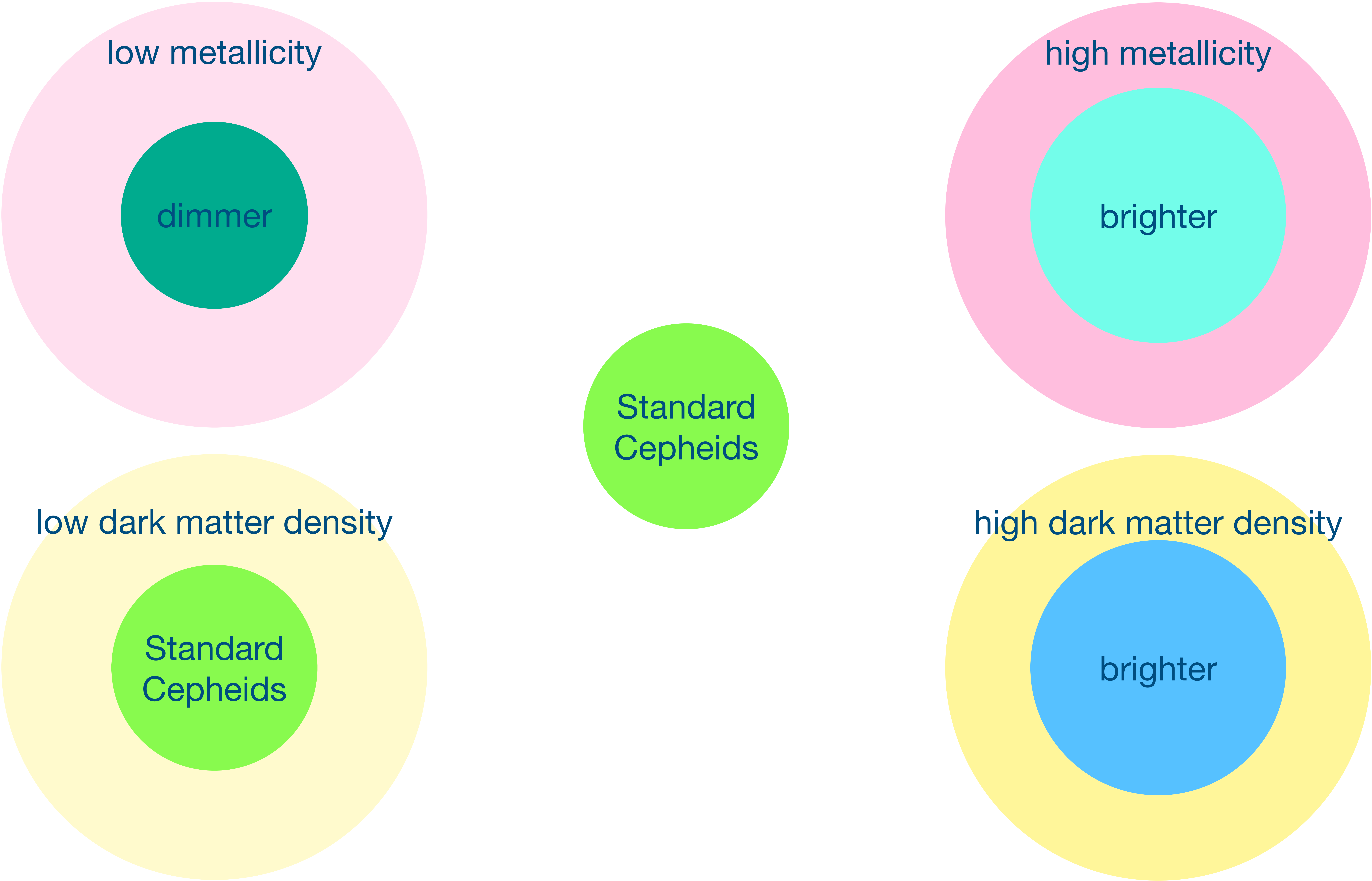
Standard
Model
Gravitational
interaction
Dark
Matter



Dark matter astrophysics beyond gravity


WIMP
Axion
Dark photon
Gravitational
Interaction
Dark Matter


WIMP
Axion, ALP,
Dark photon
Gravitational
Interaction
Dark Matter

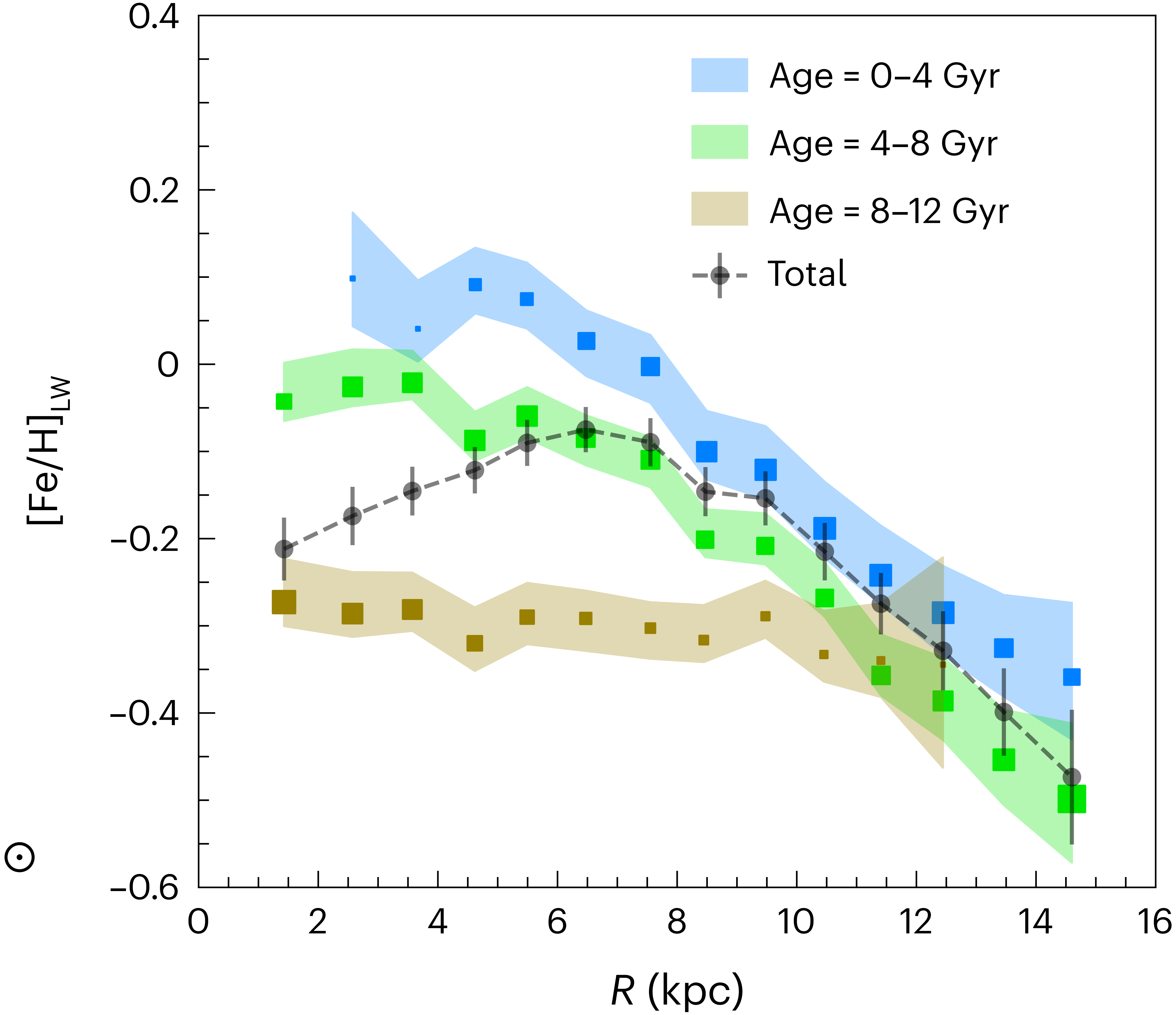

low metallicity
dimmer
high metallicity
brighter
Standard
Cepheids
low dark matter density
Standard
Cepheids
high dark matter density
brighter

Metallicity profile of Milky Way

J. Lian et al Nature Astronomy(2023)

Light weighted

- X: mass fraction of H
- Y: mass fraction of He
- Z: mass fraction of all the remaining elements (metals)
- X+Y+Z=1
- $Z_{\odot} = 0.014$
- $[Fe/H]_i = \log_{10}(\frac{N_{Fe}}{N_H})_i - \log_{10}(\frac{N_{Fe}}{N_H})_{\odot}$



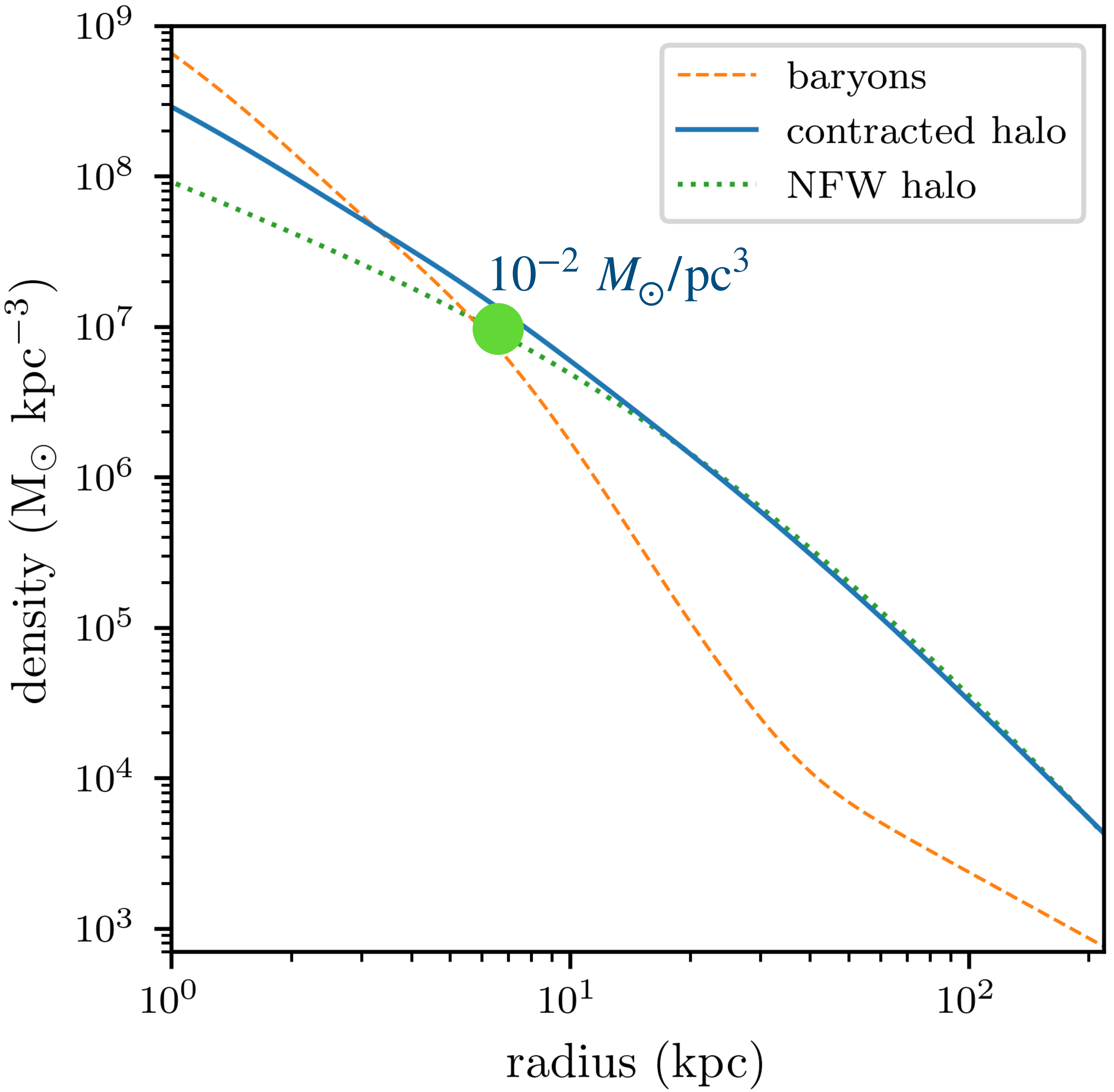
Dark matter profile

Galactocentric distance R

$$\rho_{\rm NFW} = \rho_H \frac{1}{\frac{r}{R_H}(1+\frac{r}{R_H})^2}$$

F Nesti et al (2013)

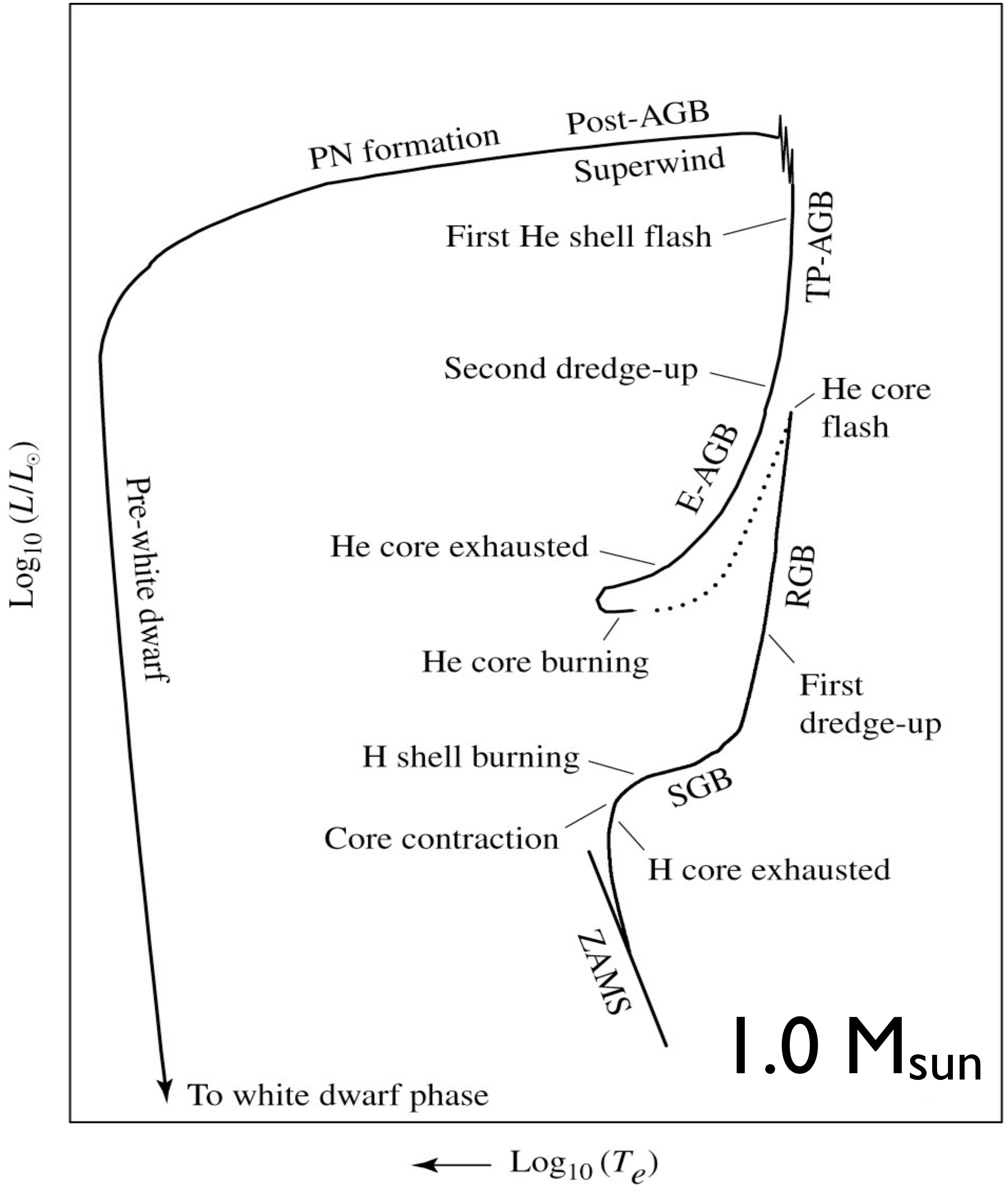
		BUR	NFW
ρ_H	$[10^7 M_\odot/\mathrm{kpc}^3]$	$4.13^{+6.2}_{-1.6}$	$1.40^{+2.9}_{-0.93}$
R_H	[kpc]	$9.26^{+5.6}_{-4.2}$	$16.1^{+17.}_{-7.8}$
$V_\odot$	[km/s]	$241.^{+11.}_{-7.4}$	$244.^{+6.3}_{-7.7}$
$R_\odot$	[kpc]	$7.94^{+0.36}_{-0.24}$	$8.08^{+0.2}_{-0.2}$
$\rho_\odot$	$[\mathrm{GeV/cm}^3]$	$0.487^{+0.075}_{-0.088}$	$0.471^{+0.048}_{-0.061}$
$M_{r<50\,\mathrm{kpc}}$	$[10^{12} M_\odot]$	$0.45^{+0.35}_{-0.20}$	$0.48^{+0.20}_{-0.15}$
$M_{r<100\,\mathrm{kpc}}$	$[10^{12} M_\odot]$	$0.67^{+0.67}_{-0.33}$	$0.81^{+0.60}_{-0.32}$
$M_{\rm vir}$	$[10^{12} M_\odot]$	$1.11^{+1.6}_{-0.61}$	$1.53^{+2.3}_{-0.77}$
$c_{\rm vir}$	$[\Delta=200]$	$31.4^{+13.}_{-5.3}$	$20.1^{+11.}_{-7.1}$



Color Magnitude Diagram

Solar mass initial condition : $M_\odot$

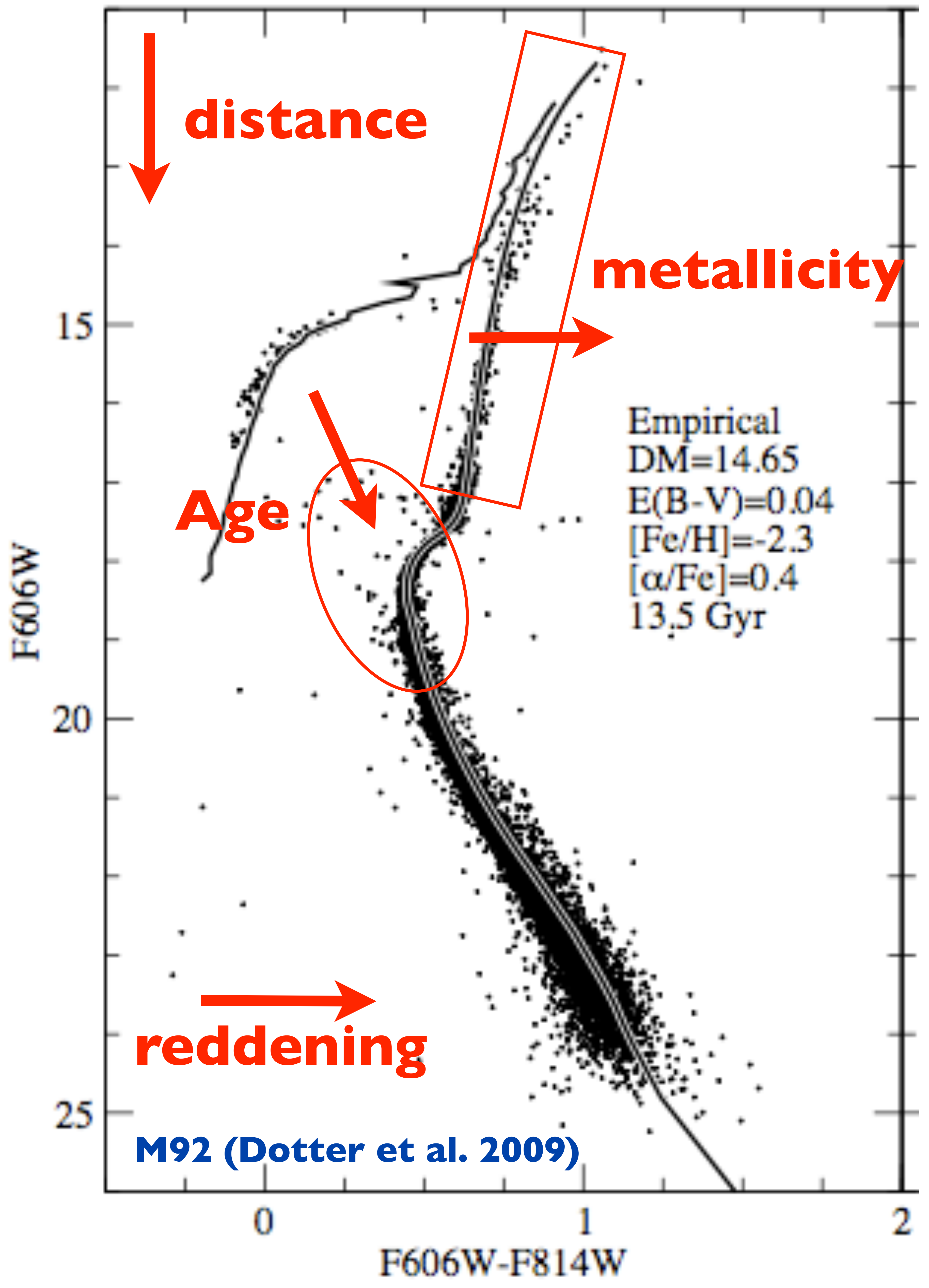
- Zero age main sequence (ZAMS)
- Red giant branch (RGB)
- Horizontal branch (HB)
- Asymptotic giant branch (AGB)
- White dwarf (WD)



Age and Metallicity

possible degeneracy

- M92 is a metal-poor globular cluster and can be an anchor for the red giant evolution
- Metal rich -> reddening
- Turn Off of Main Sequence -> Age is determined
- Red giant -> Metallicity is determined

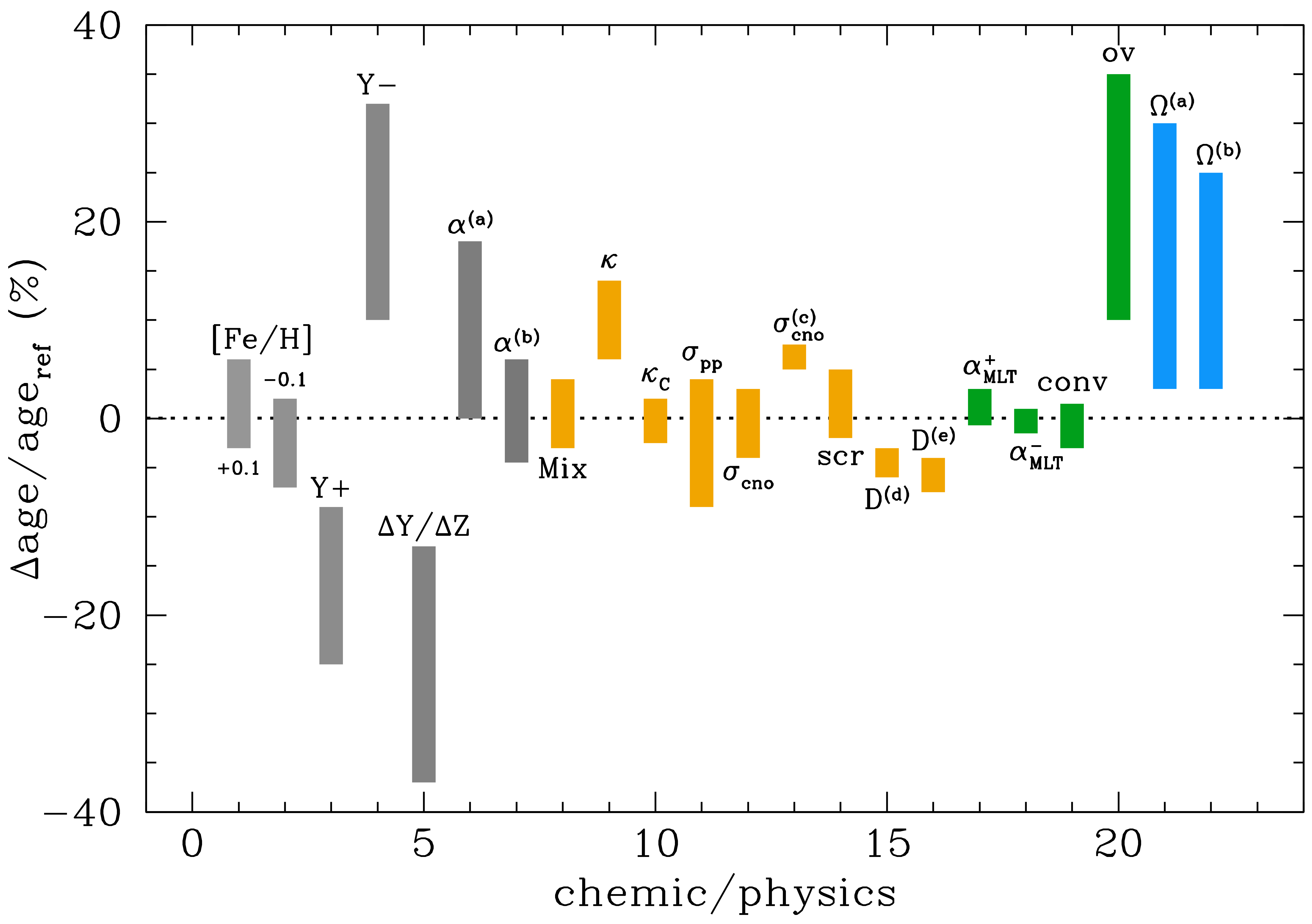


Uncertainties of Stellar Models

Y Lebreton et al (2014)

Age determination

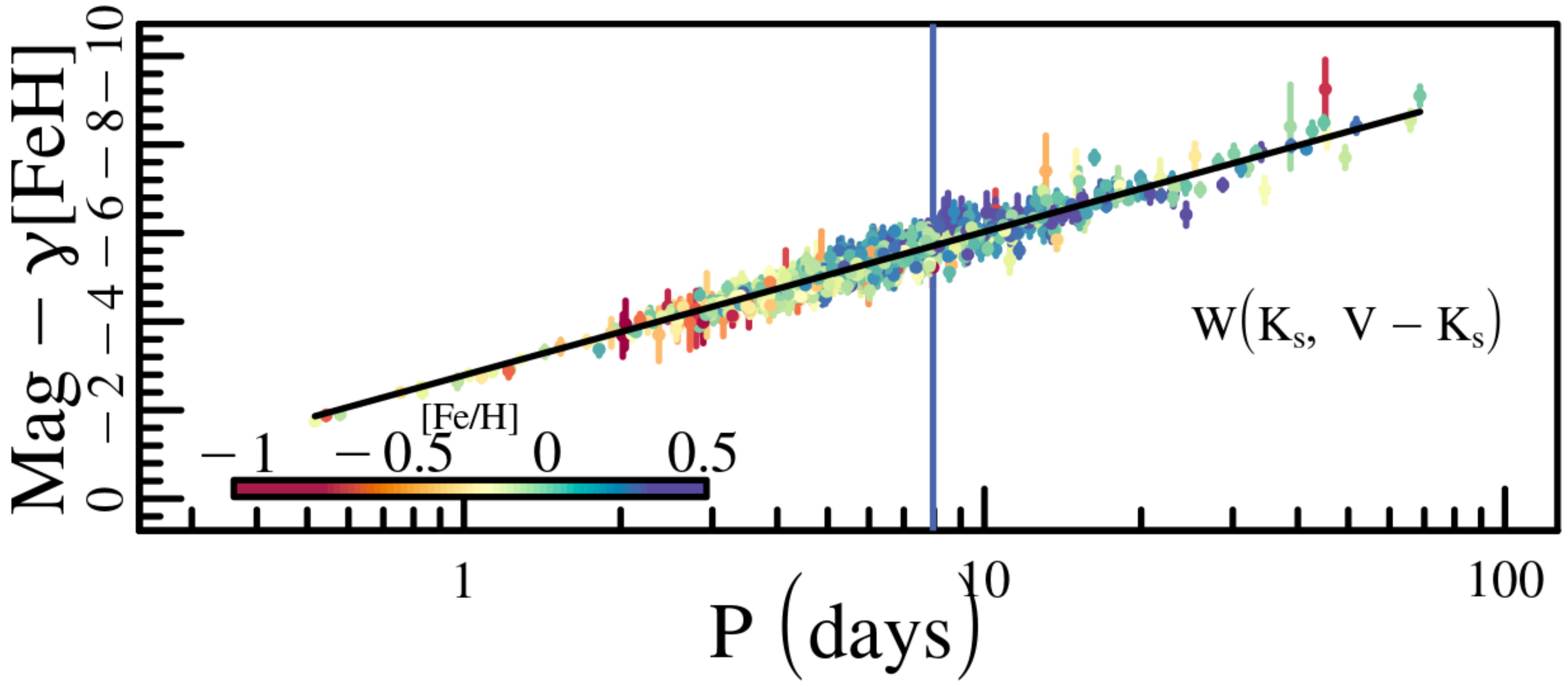
- Metallicity
- Helium
- O, N
- Opacity
- …

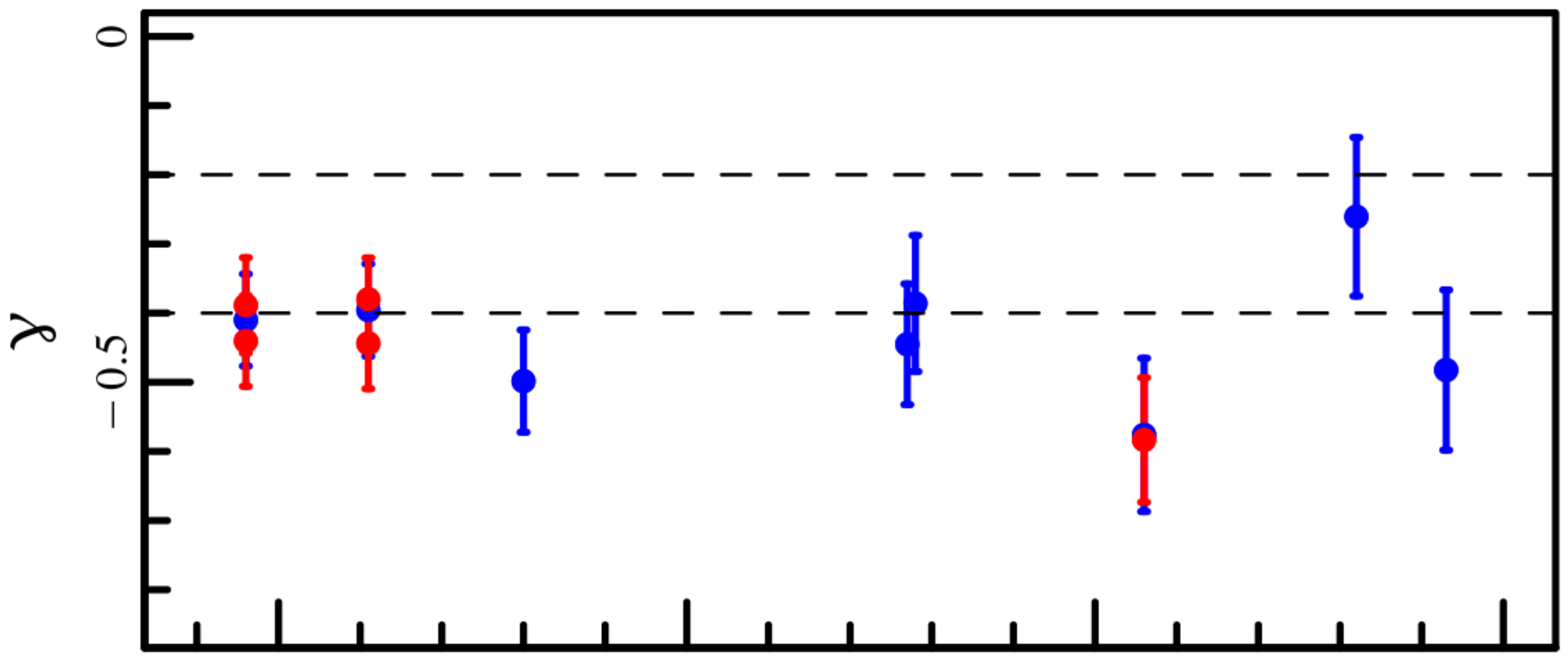


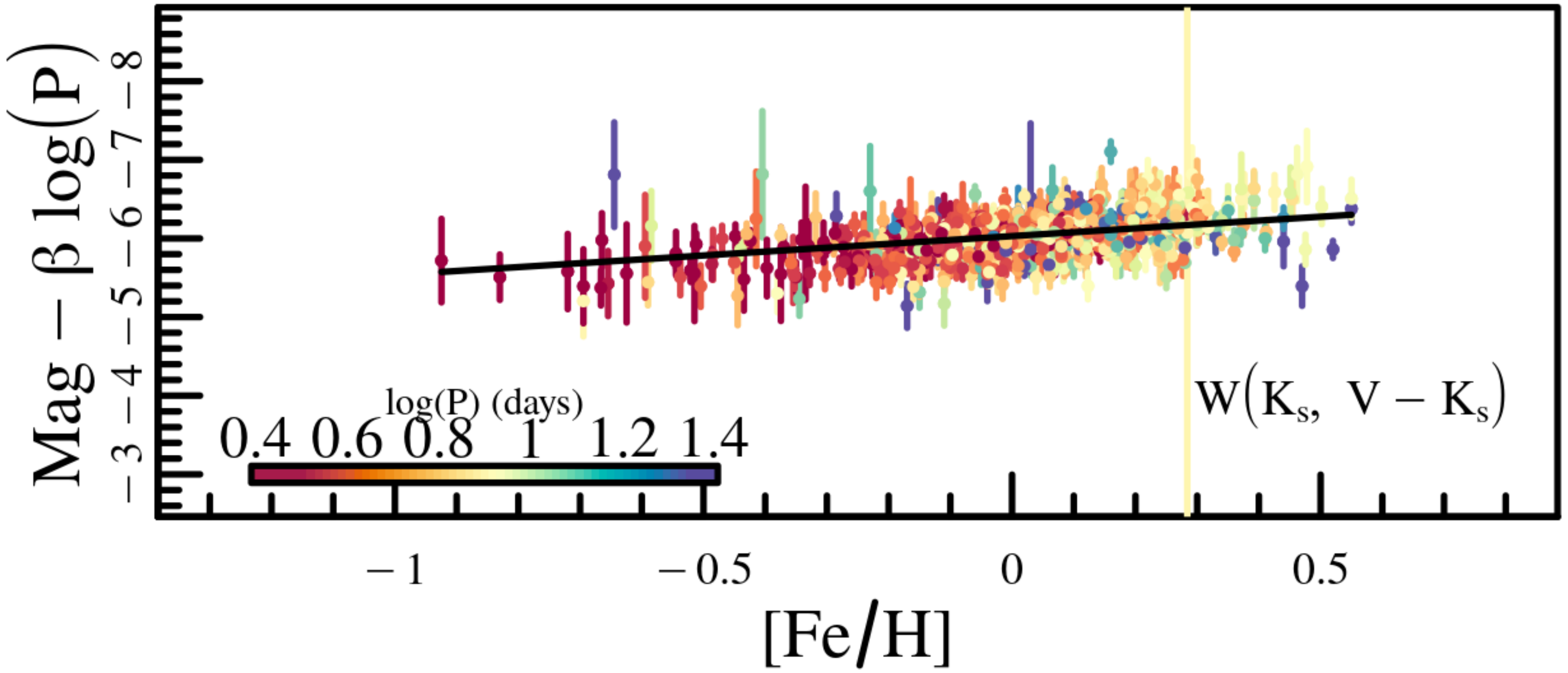
A&A, 683, A234 (2024)

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

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





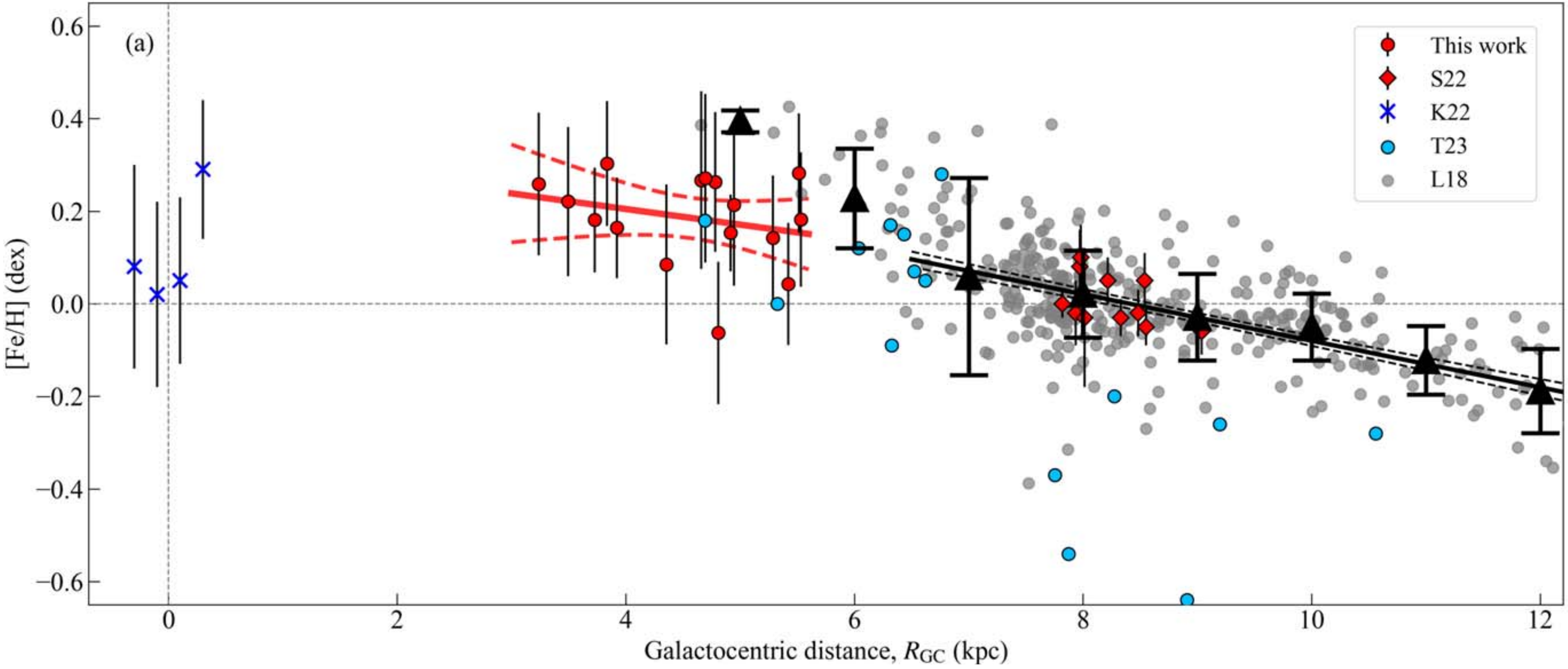


Cepheids and SN Ia

:Standardizable candle

Metallicity vs Galactocentric distance

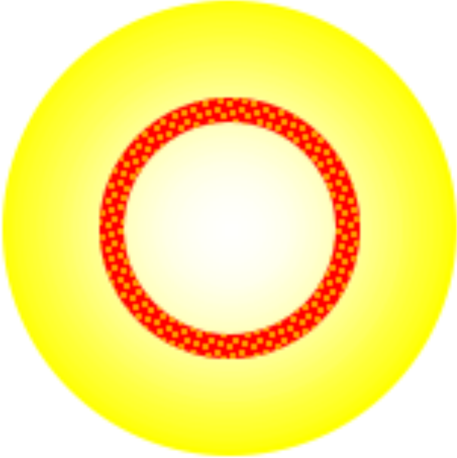
THE ASTROPHYSICAL JOURNAL, 954:198 (8pp), 2023 September 10 Matsunaga et al.



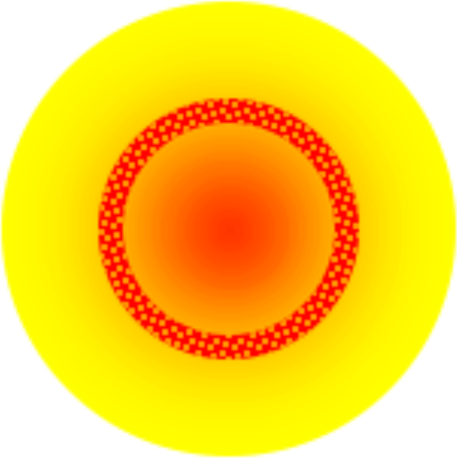
Cepheid as a Heat Engine

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

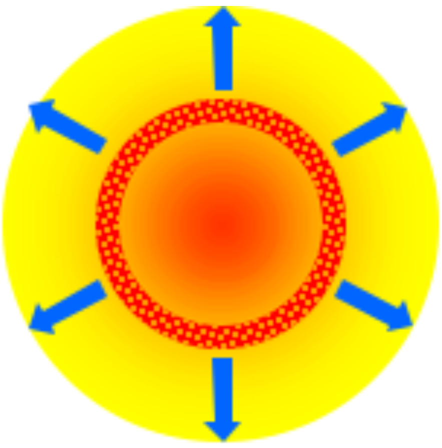
- 1. Valve open : radiation goes out and shrinks due to gravity



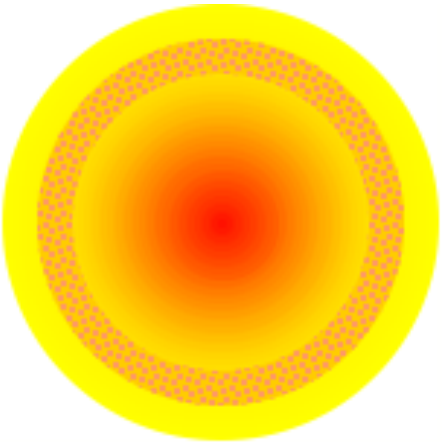
- 2. Compressed layer heats up and becomes opaque



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



- 4. Pressure pushes it outward

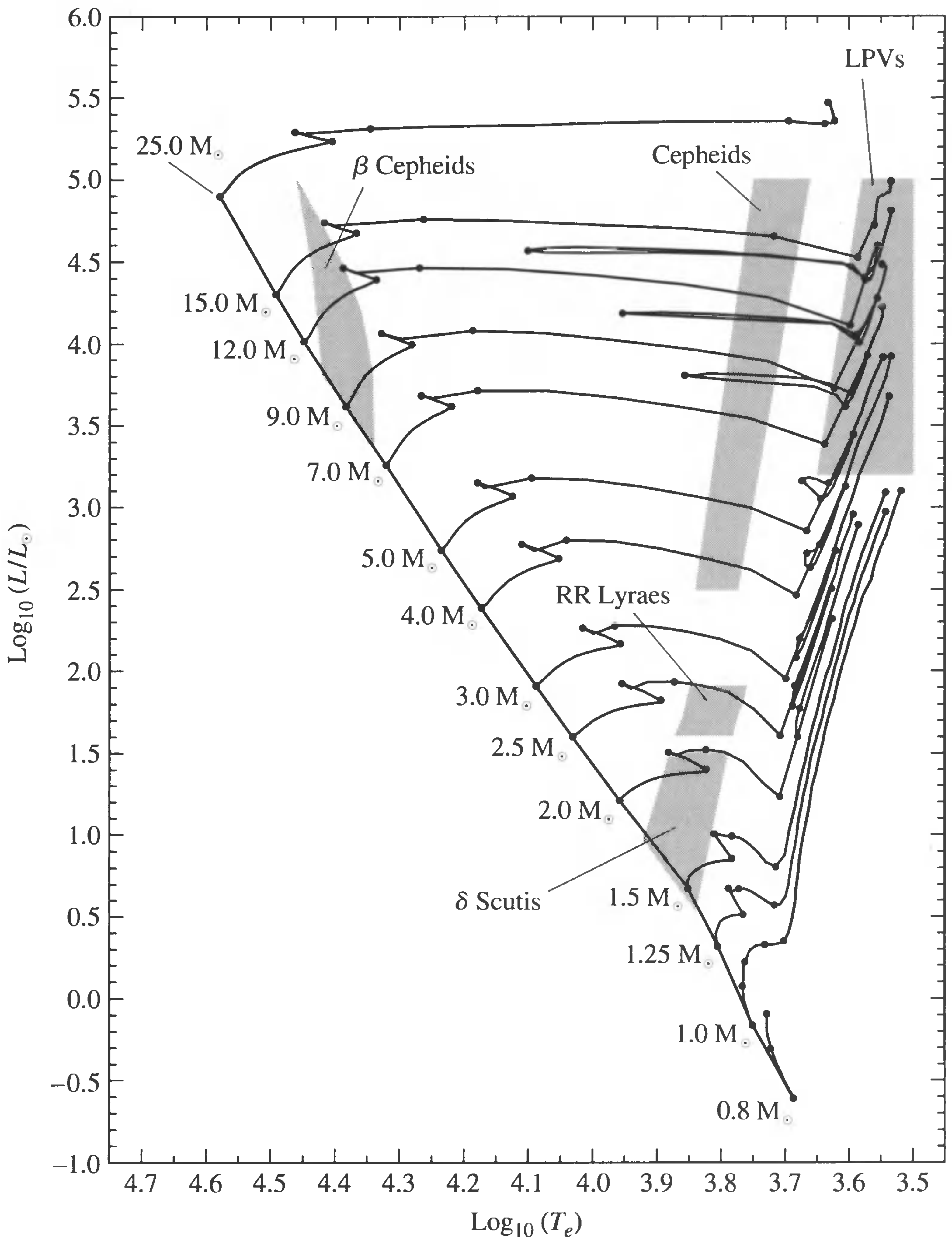


- 5. Valve starts to be open : layer expands and cools and opacity decreases

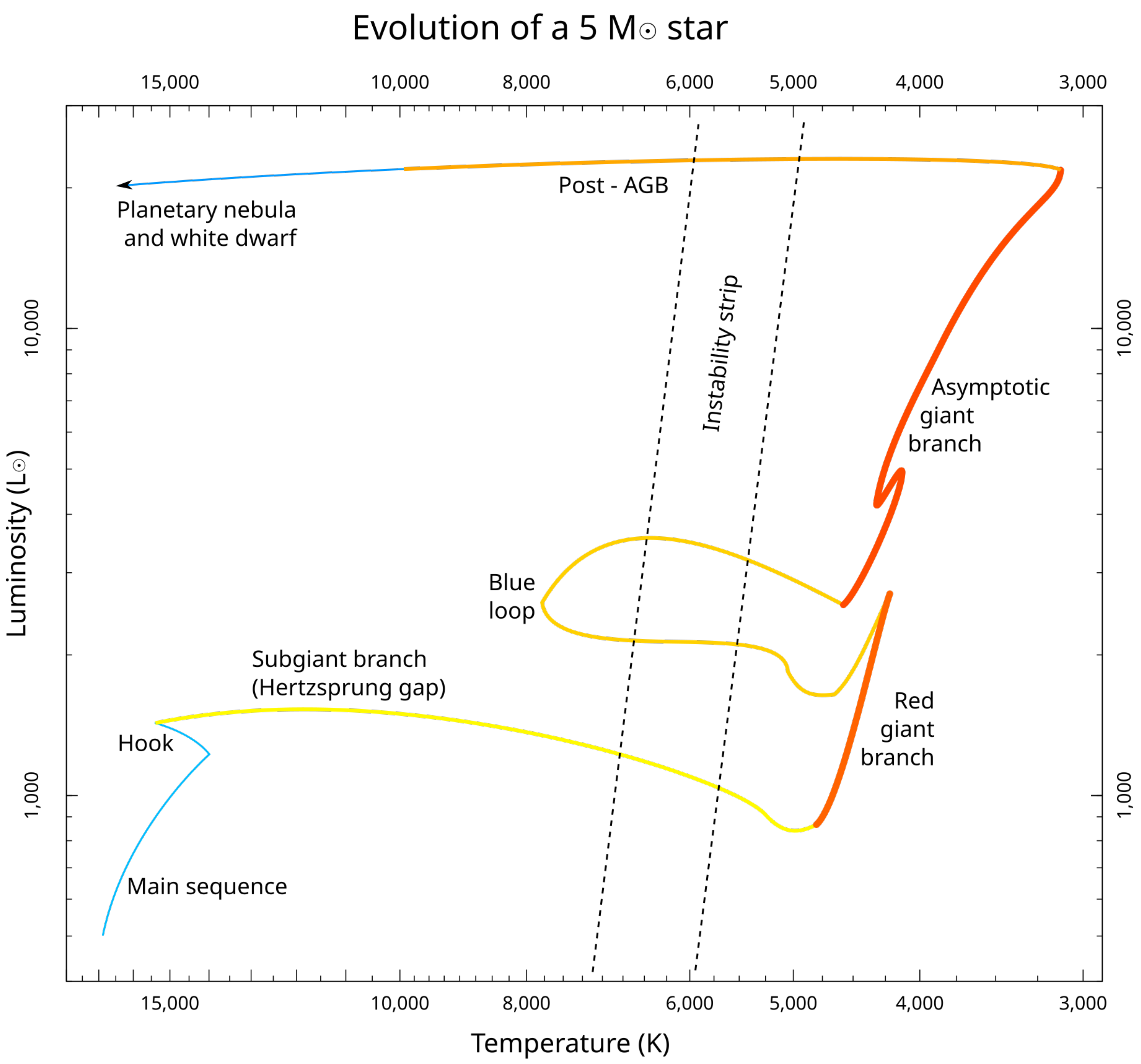
- 6. Valve open : back to 1

Blue loop

from red(or yellow) giant branch

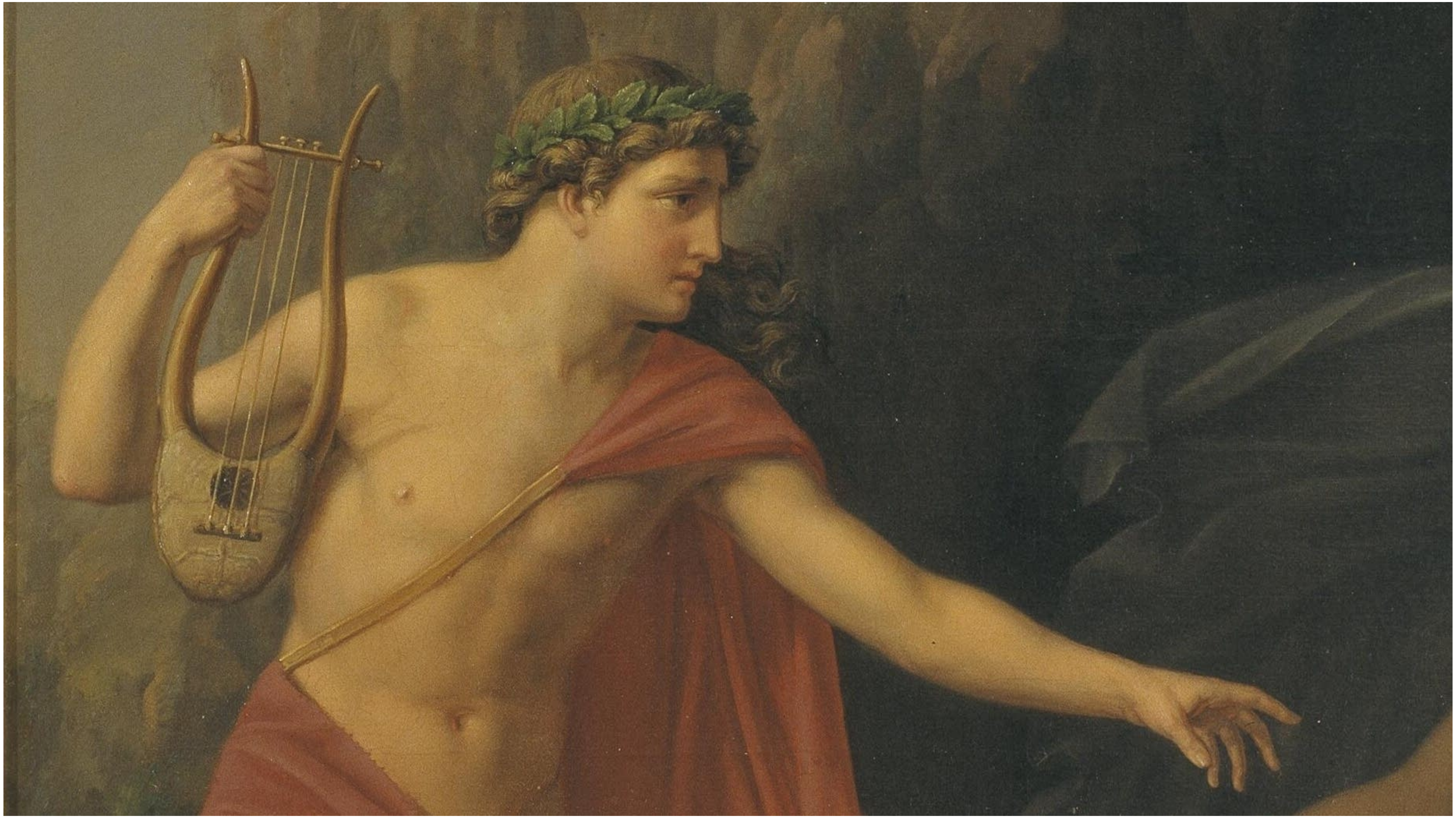


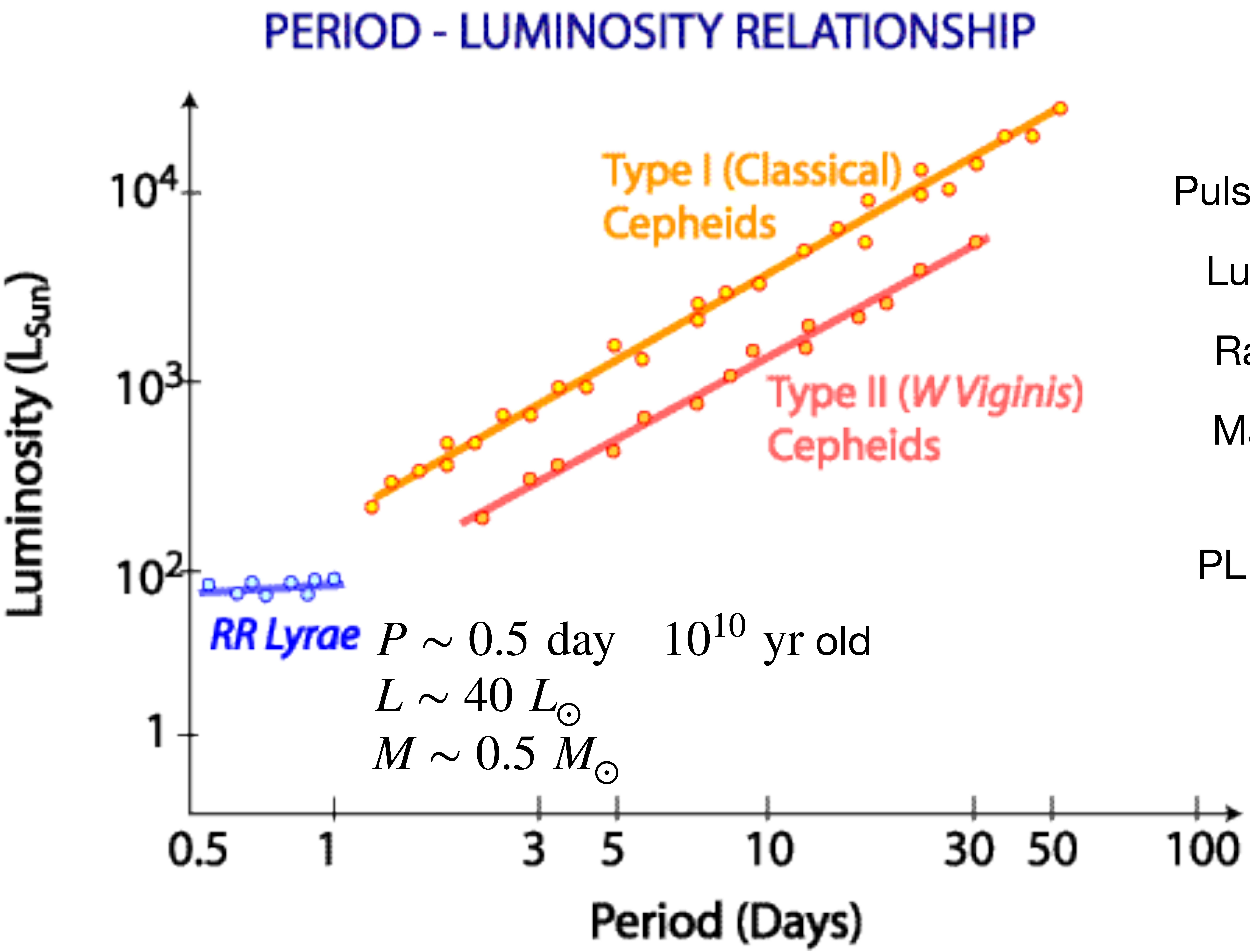
Smooth He burning for $M > 2.3\ M_{\odot}$ triggers the blue loop



Lyre(Lyra) of Orpheus

Lyrae=of Lyre





$P \sim 0.5$ day 10^{10} yr old

$L \sim 40\ L_\odot$

$M \sim 0.5\ M_\odot$

Pulsation Period : 1 - 50 days

Luminosity (L) : 300 - 26,000 $L_\odot$

Radius (R) : 14 - 200 $R_\odot$

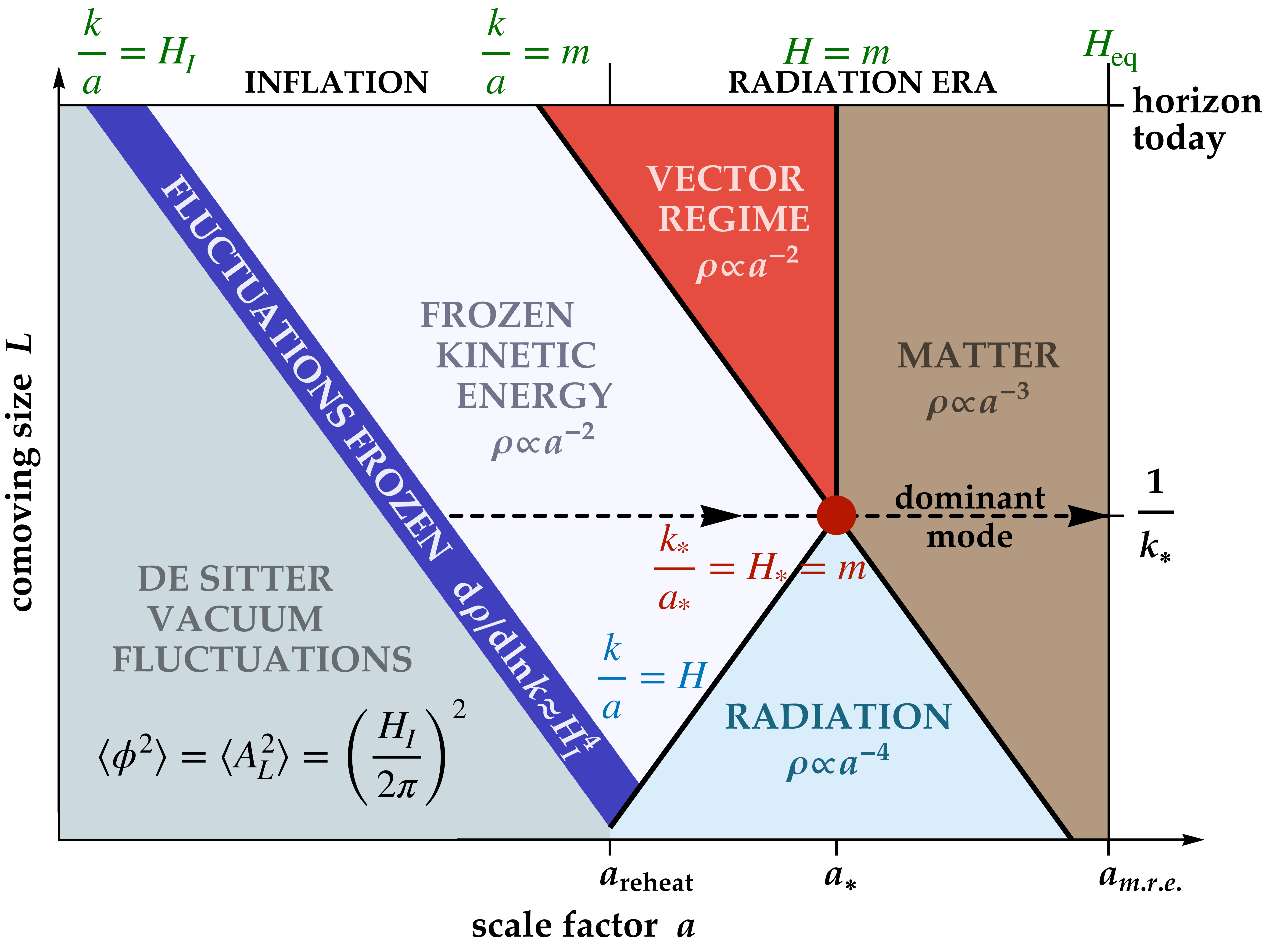
Mass (M) : 3.7 - 14 $M_\odot$

PL relation of Cepheids is used to measure the distance.

Standard candle

Dark Matter Relic Density

1504.02102



$k \ll k_*$

Stueckelberg mass

$$\frac{1}{a^2} \eta^{\mu\nu} m^2 (A_\mu + \frac{1}{m}\partial_\mu \phi)(A_\nu + \frac{1}{m}\partial_\nu \phi)$$

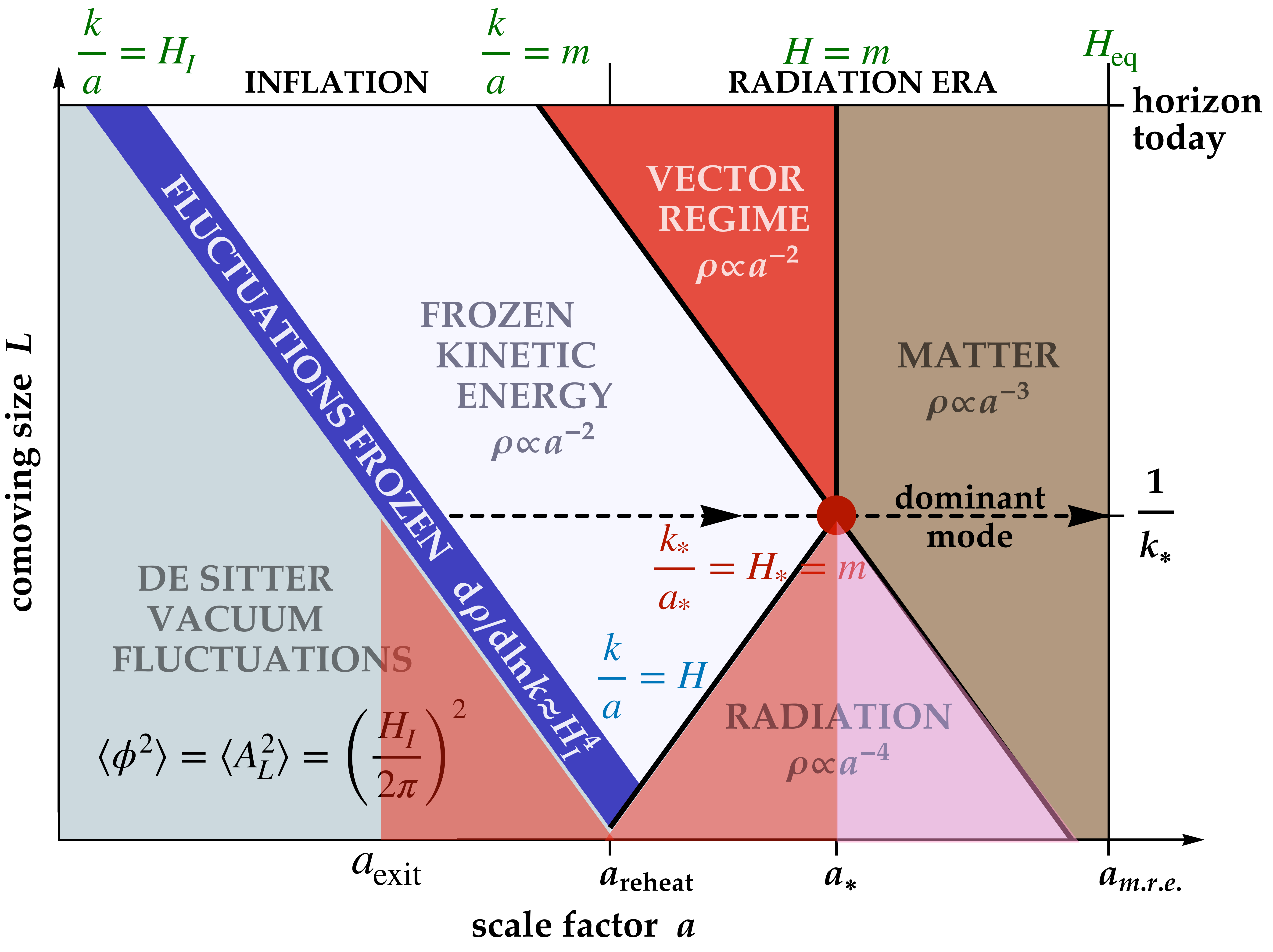
frozen kinetic energy

$$\left(\frac{k}{a} \right)^2 \langle \phi^2 \rangle \xrightarrow{\frac{k}{a} = m} m^2 \langle A^2 \rangle$$

vector regime (mass)

Dark Matter Relic Density

1504.02102



$k \gg k_*$

Radiation from $a_{\rm reheat}$ to a_* : $\dfrac{1}{a^4}$

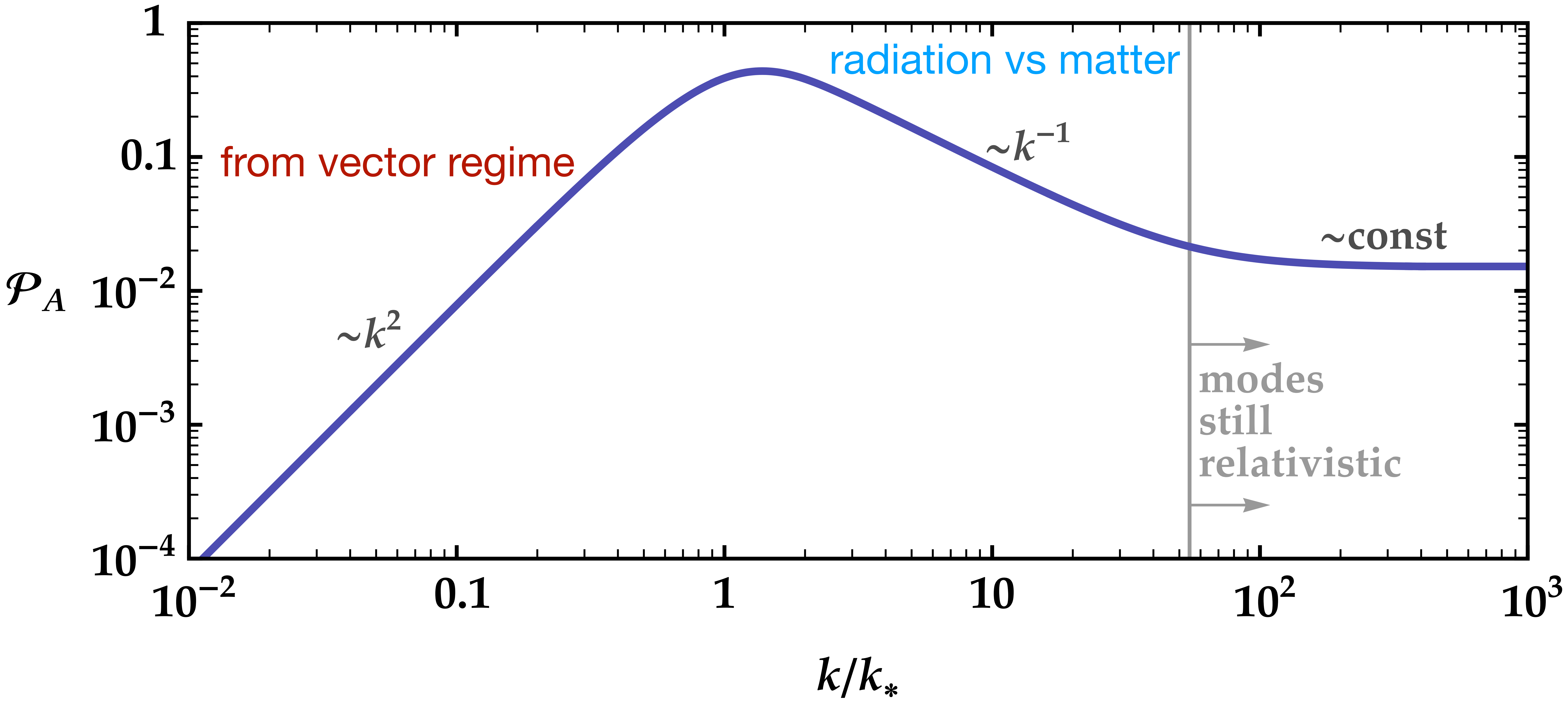
= $a_{\rm exit}$ to $a_{\rm reheat}$ and $a_{\rm reheat}$ to a_* : $\dfrac{1}{a^2}$

Radiation from a_* to a_m : $\dfrac{1}{a^4}$

Additional $\dfrac{1}{a} \sim \dfrac{1}{k}$ suppression

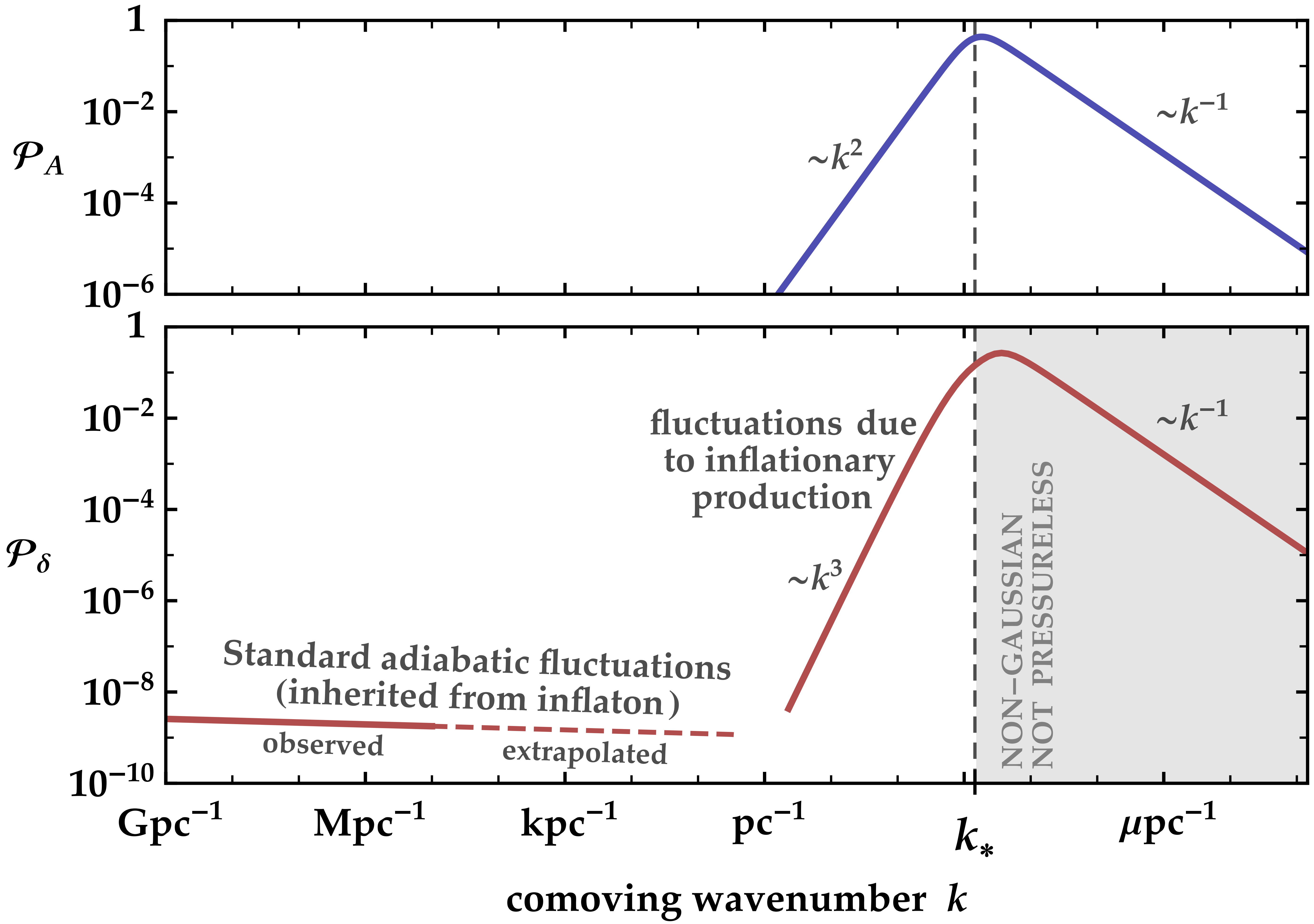
Dark Matter Relic Density

1504.02102



Vector dark matter from inflation (longitudinal)

1504.02102



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

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

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

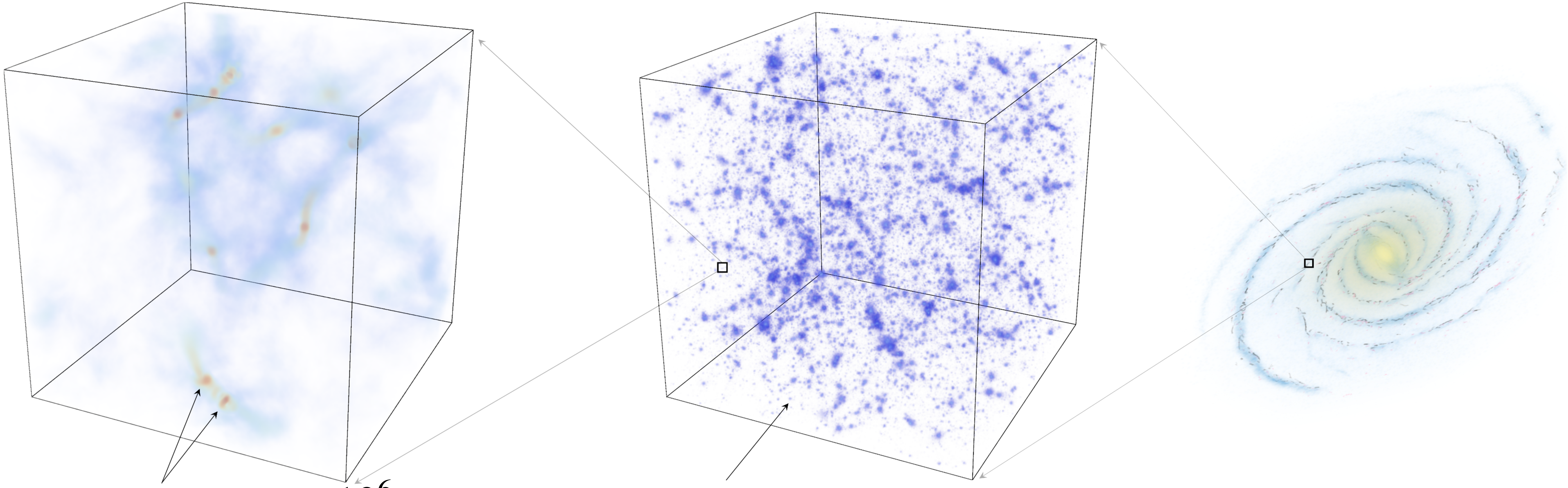
Dark Photon Stars

2203.10100

- Longitudinal component is produced during inflation.
- $$\frac{\Omega_A}{\Omega_{DM}} = \sqrt{\frac{m}{10^{-5}\ \mathrm{eV}}}\left(\frac{H}{10^{14}\ \mathrm{GeV}}\right)^2.$$
- Dark photon dark matter is possible for $10^{-5}\ \mathrm{eV} < m < 10^8\ \mathrm{GeV}$.
- Longitudinal component acts as a scalar during inflation by the Goldstone equivalence theorem.
- $\frac{1}{k_*} = \frac{1}{ma_*}$ is stretched to $\frac{1}{m}\frac{a_0}{a_*} \sim \frac{1}{m}\sqrt{\frac{T_0^2}{mM_{\mathrm{Pl}}}} \sim \frac{1}{m}\left(\frac{10^{-4}\ \mathrm{eV}}{m}\right)^{1/2} \times 10^{16}$

Dark photon stars

2203.10100



Solitons $\rho \sim 10^6 \rho_0$

Compact Halos

Solar system size

$$10^{11}\text{km}(10^{-5}\text{eV}/m)^{1/2}$$

Mass

$$10^{-16} M_\odot (10^{-5}\text{eV}/m)^{3/2}$$

$$\mathcal{N} \sim 10^{55} \left(10^{-5}\text{eV}/m\right)^{5/2}$$

Mass

$$10^{-11} M_\odot (10^{-5}\text{eV}/m)^{3/2}$$

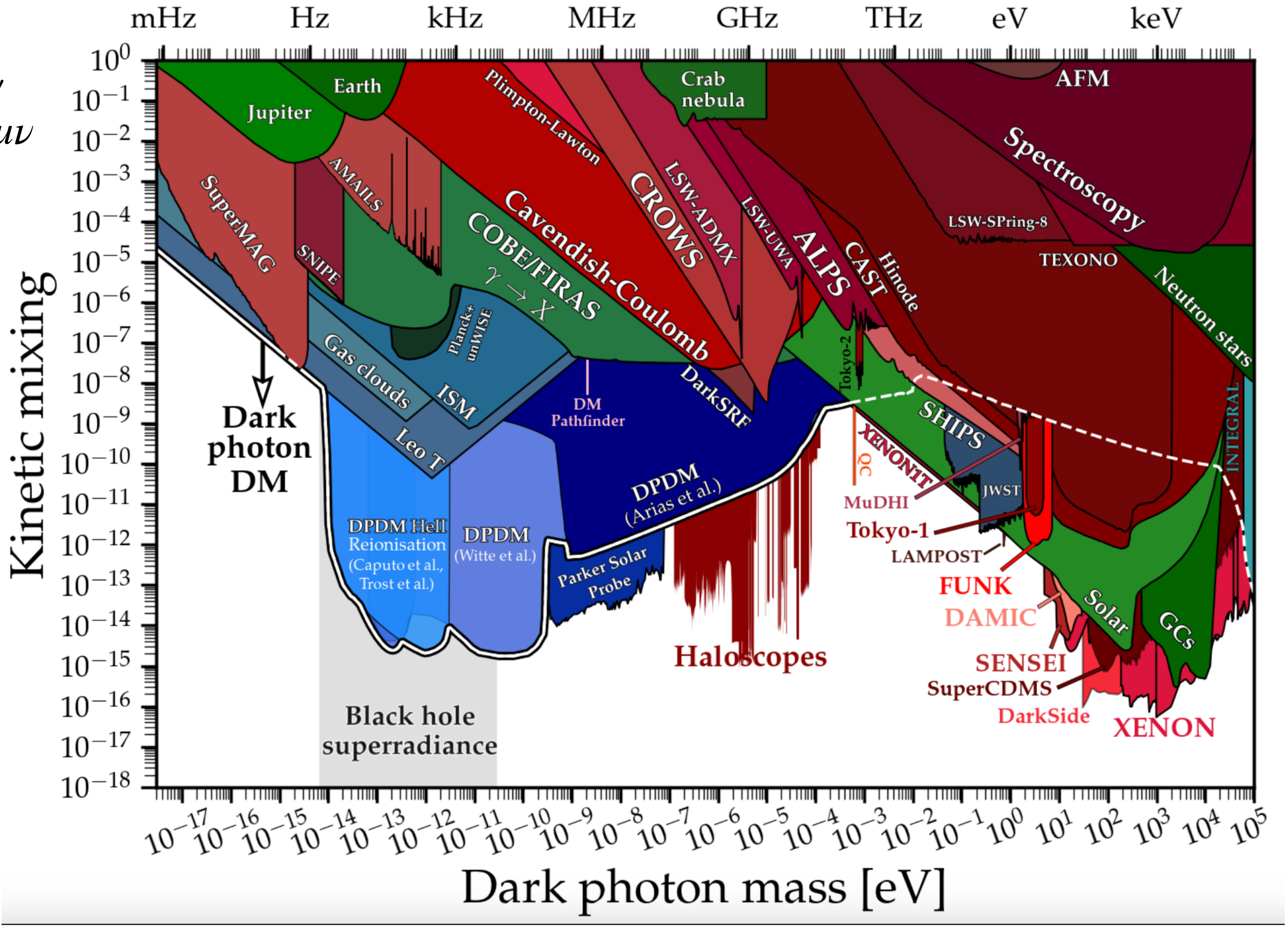
Quantum Dark Photon Stars

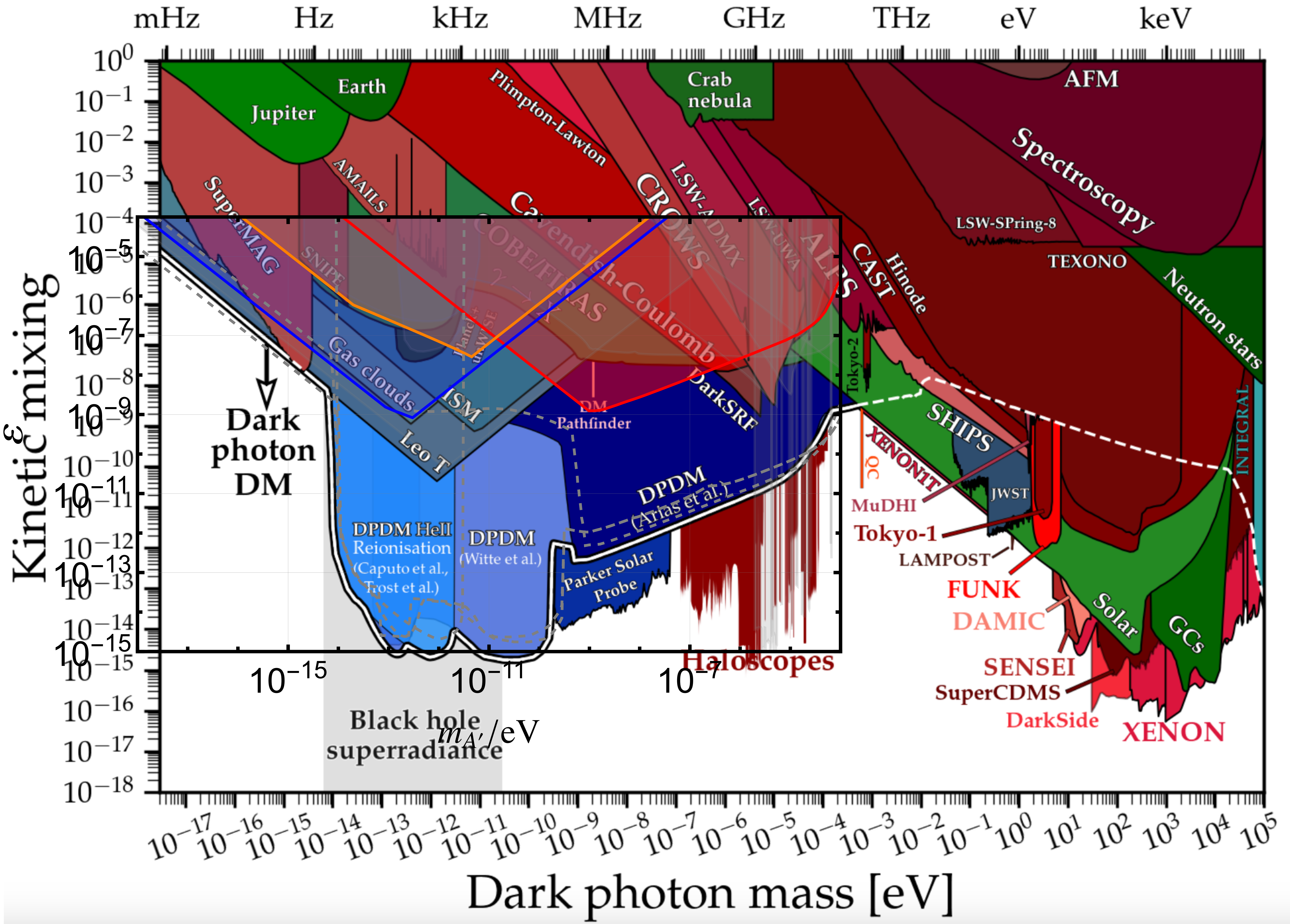
- $E_{\text{grav}} \sim -\dfrac{GM^2}{R} = -\mathcal{N}\dfrac{\mathcal{N}}{\mathcal{N}_*}\dfrac{1}{R} = -\mathcal{N}\dfrac{\alpha}{R}$ with $\mathcal{N}_* = \dfrac{1}{Gm^2}$ and $\alpha = \dfrac{\mathcal{N}}{\mathcal{N}_*}$.
- $E_{\text{kin}} \sim \mathcal{N}\dfrac{1}{2mR^2}$.
- $R \sim \dfrac{1}{m\alpha}$ is the minimum.
- α is a free parameter which should be determined from the relic density.

Will Dark Photon Stars survive?

- Jacobi radius : tidal force dominates over the local binding force,
- $r_{\mathrm{J}} \sim \left(\frac{M_{\text{soliton}}}{M}\right)^{1/3} R$ from $\frac{GM_{\text{soliton}}}{r_{\text{soliton}}^2} \sim \frac{GM_{\text{stellar}}}{R^2} - \frac{GM_{\text{stellar}}}{(R + r_{\text{solition}})^2}$.
- $\rho_{\text{soliton}} \sim \left(\frac{R_{\text{stellar}}}{R_J}\right)^3 \rho_{\text{stellar}}$
- Typically $R_{\mathrm{J}} \gg R$ and the dark photon stars will be tidally disrupted near astro stellar objects.
- Small fraction would be captured and will form a halo with size R_J.

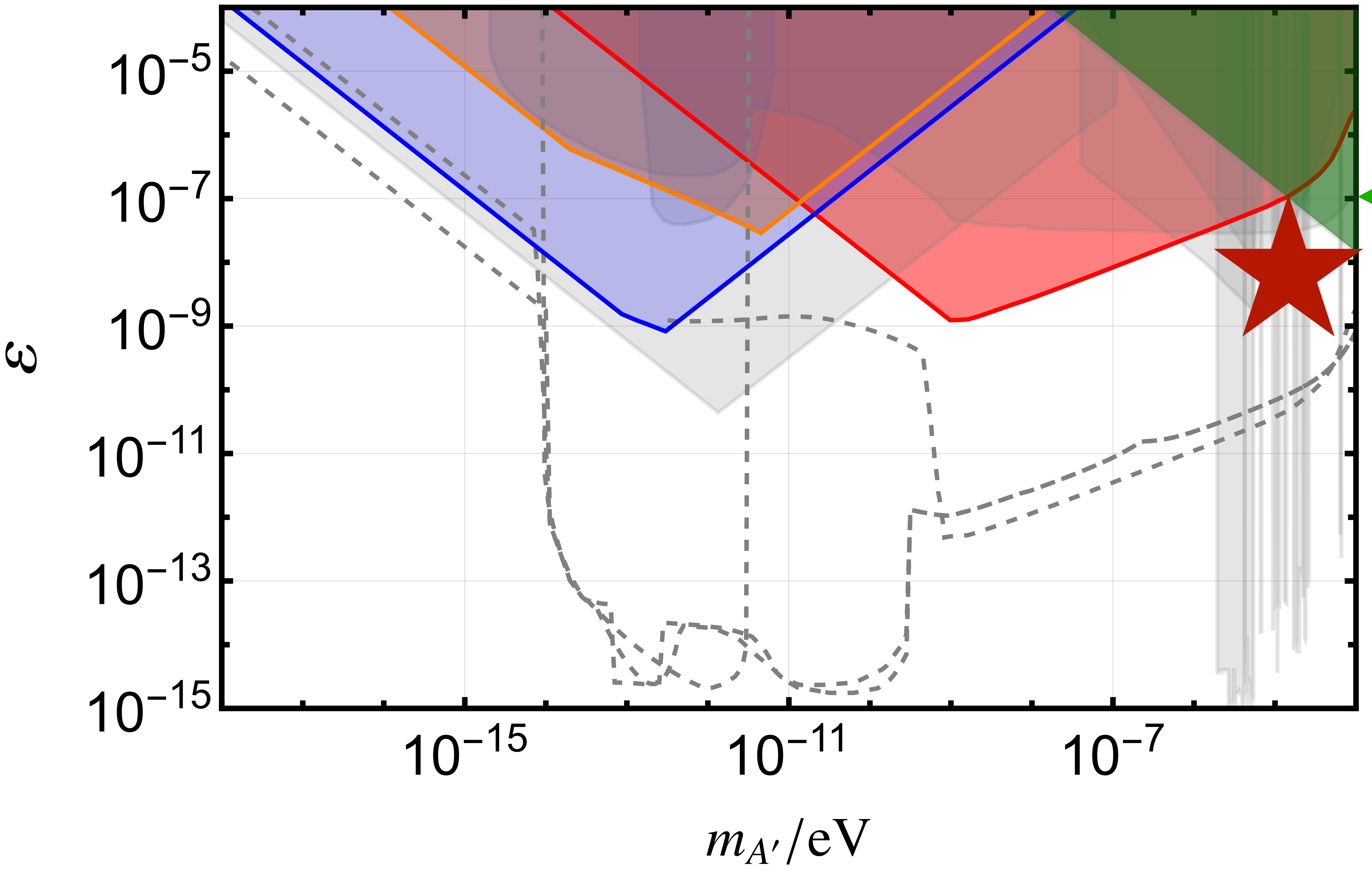
$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu}_{\rm EM} F'_{\mu\nu}$$




mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Kinetic mixing
Dark photon mass [eV]
Jupiter
Earth
Plimpton-Lawton
Crab nebula
AFM
Spectroscopy
LSW-SPring-8
TEXONO
Neutron stars
SuperMAG
AMAILS
Cavendish-Coulomb
COBE/FIRAS
CROWS
LSW-ADMX
LSW-UWA
ALPS
CAST
Hinode
SNIPE
Gas clouds
ISM
Leo T
DM Pathfinder
DarkSRF
Dark photon DM
DPDM HeII Reionisation (Caputo et al., Trost et al.)
DPDM (Witte et al.)
DPDM (Arias et al.)
Parker Solar Probe
Haloscopes
Tokyo-2
SHIPS
XENON1T
QC
MuDHI
JWST
Tokyo-1
LAMPOST
FUNK
DAMIC
Solar
GCs
INTEGRAL
SENSEI
SuperCDMS
DarkSide
XENON
Black hole superradiance
$m_{A'}$/eV
ε

The previous invalidated constraints are shown as gray dashed lines.

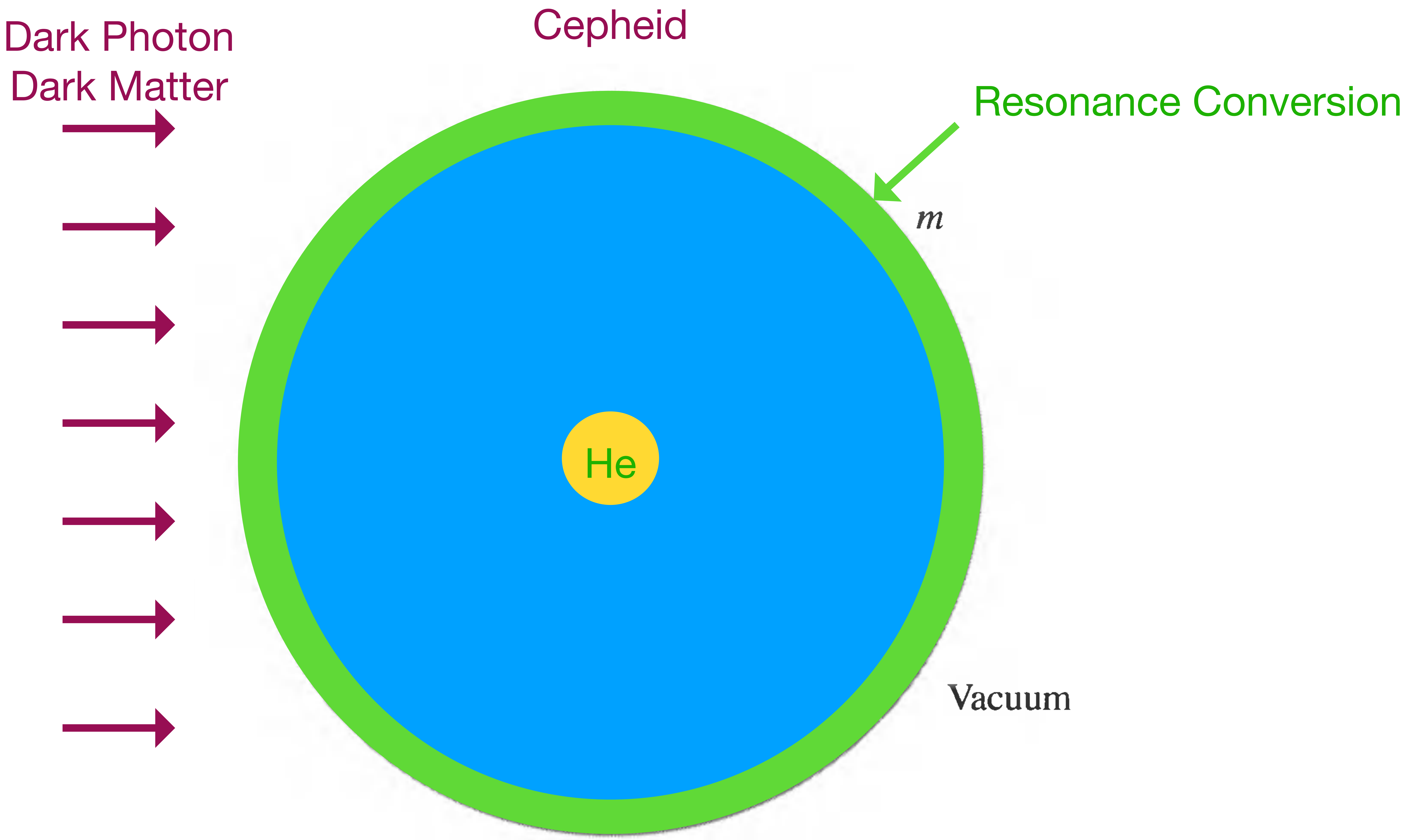
2510.13956 Anson Hook, Junwu Huang, Mohamad Shalaby



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

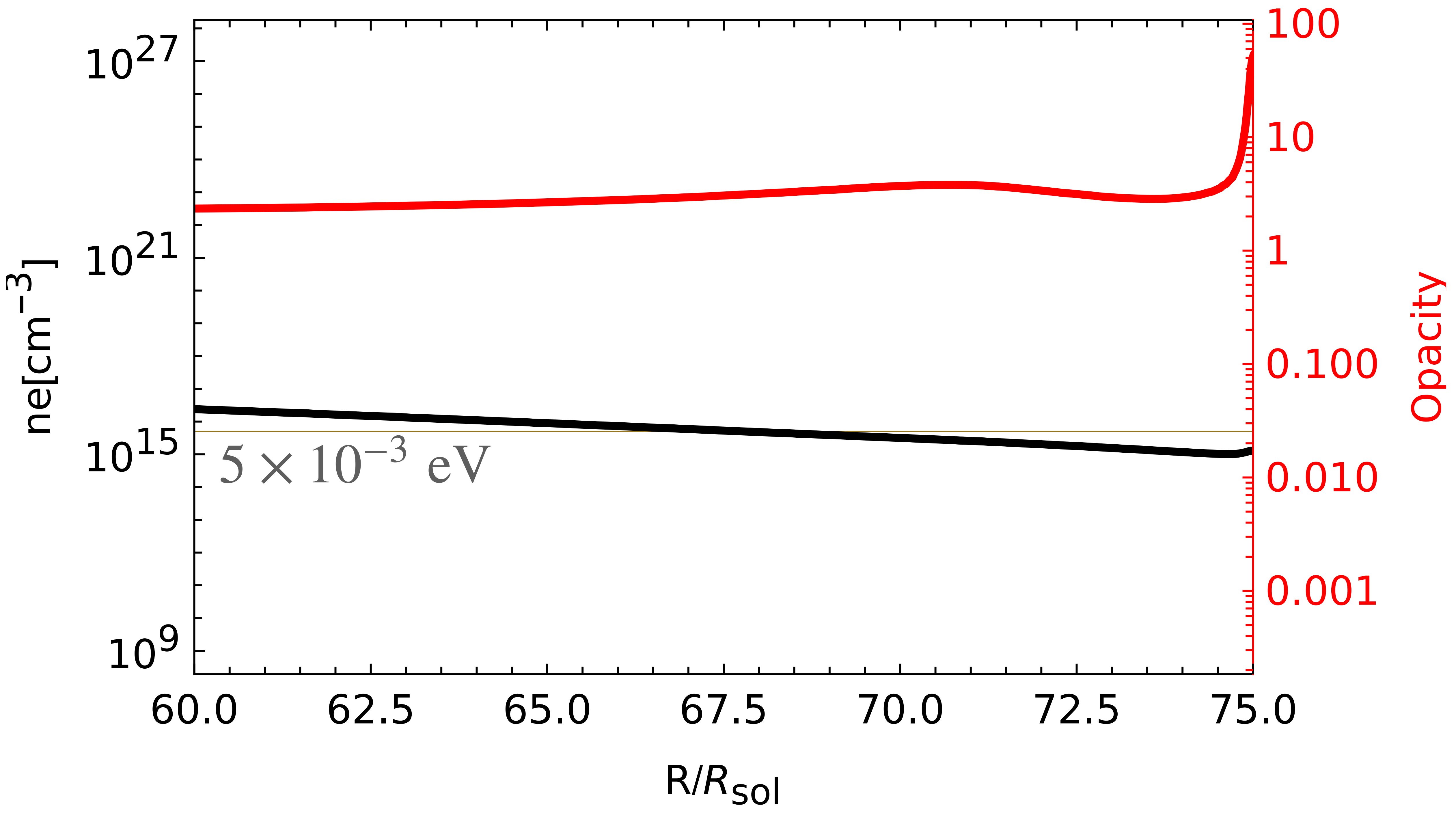
Solar cooling

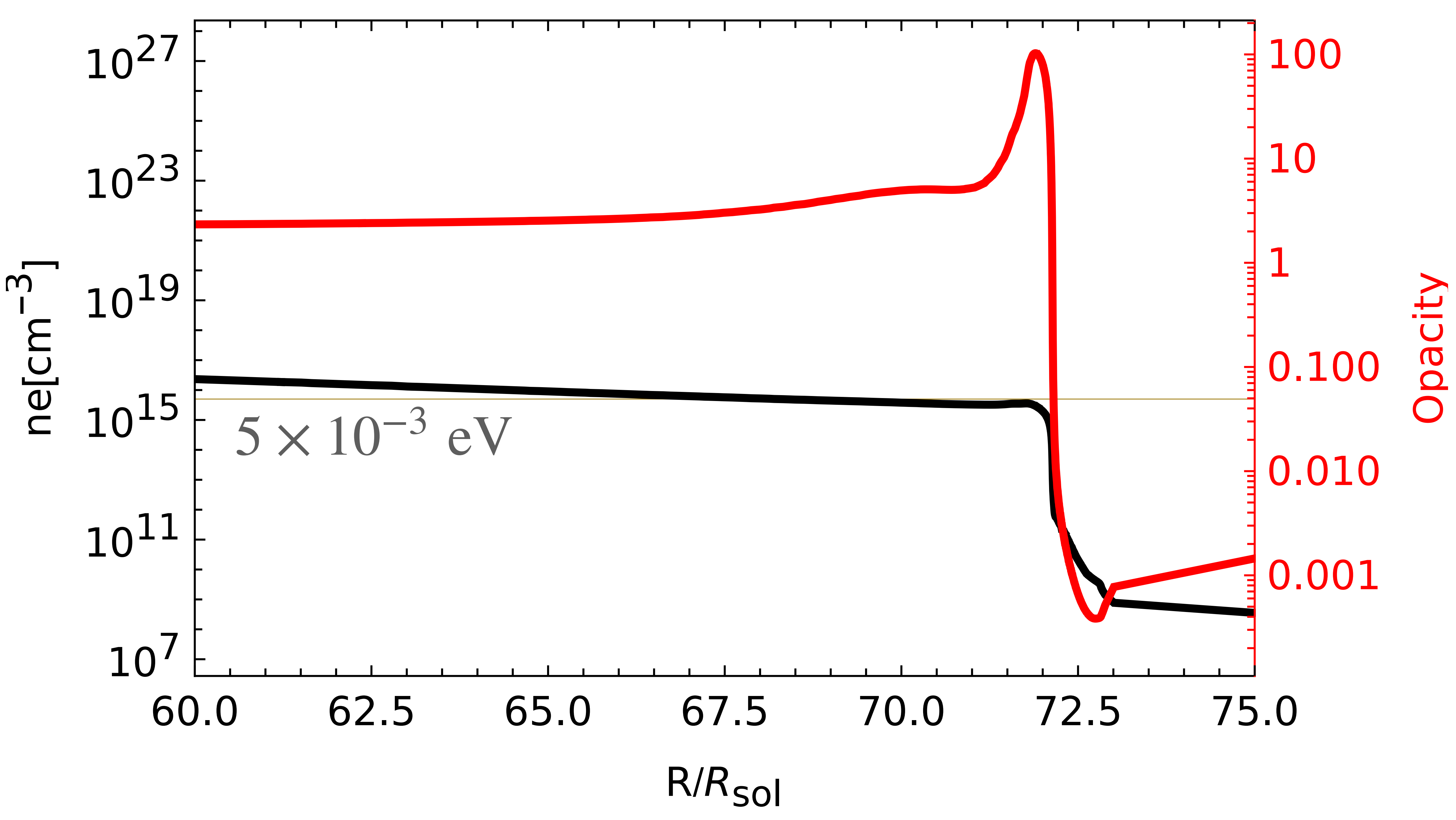
ALLOWED!!!



Dark Photon
Dark Matter
Cepheid
Resonance Conversion
m
He
Vacuum

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



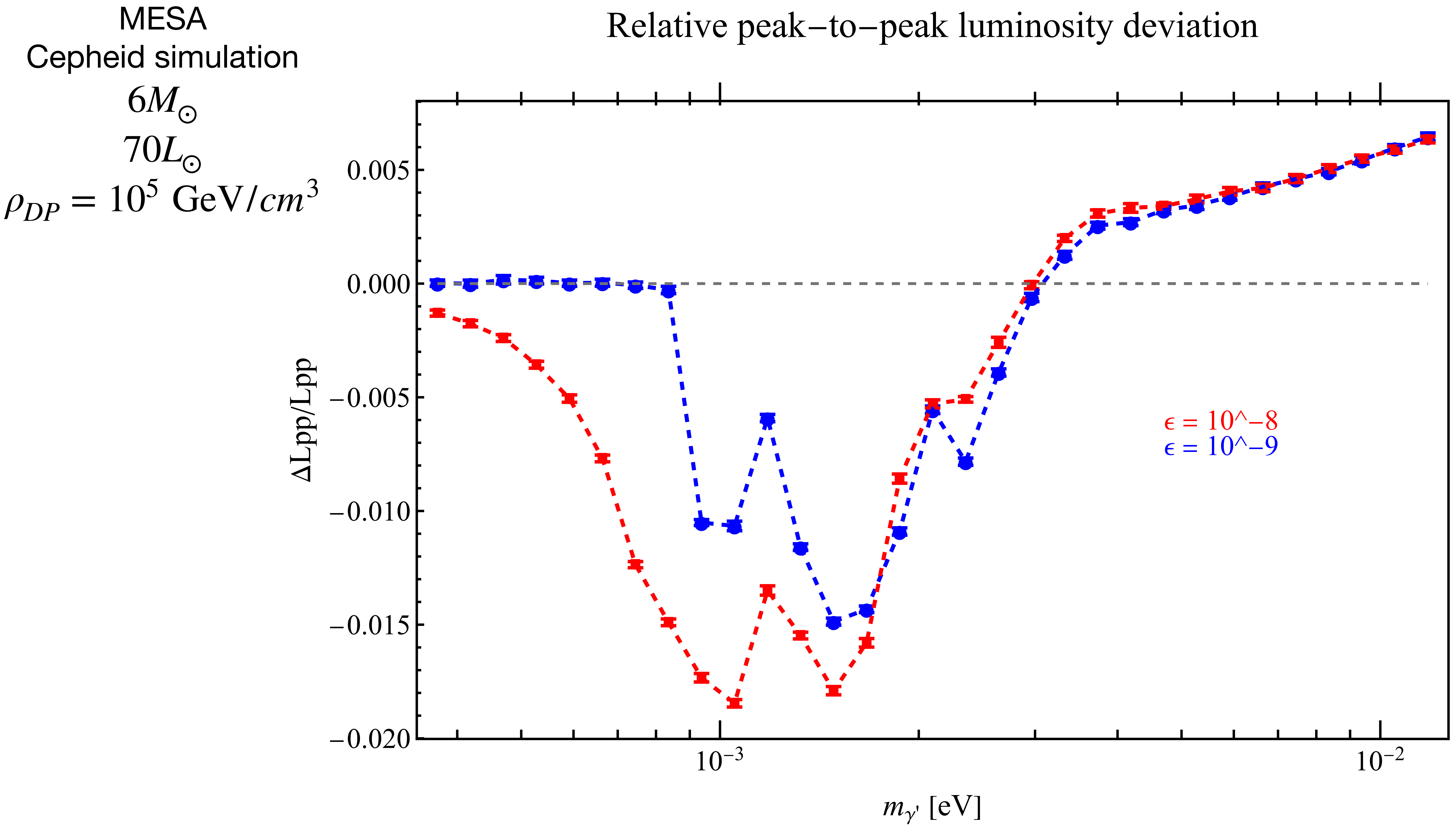


The result depends on whether the resonance occurs inside or outside of the valve (opacity peak)

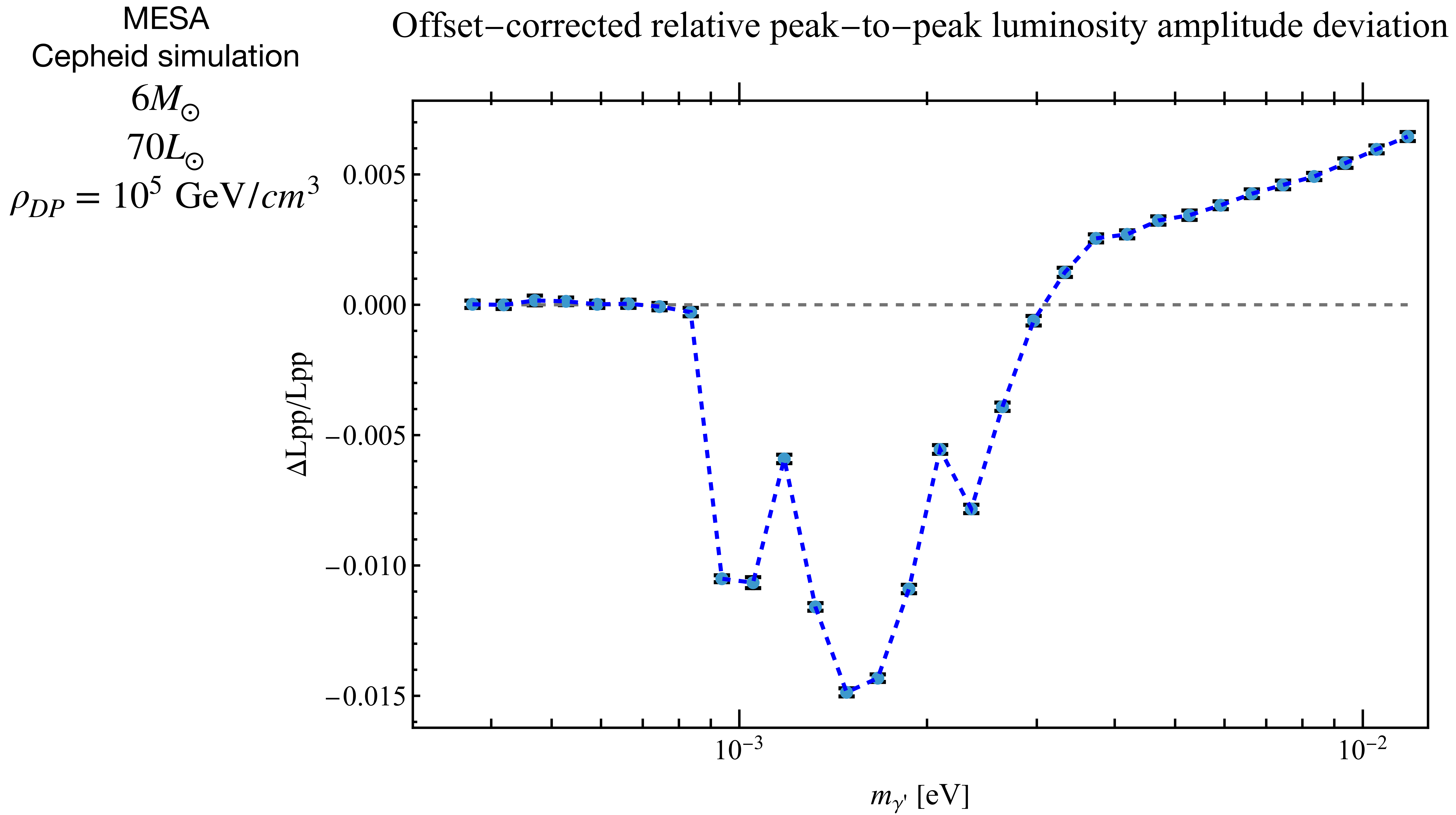
Summary

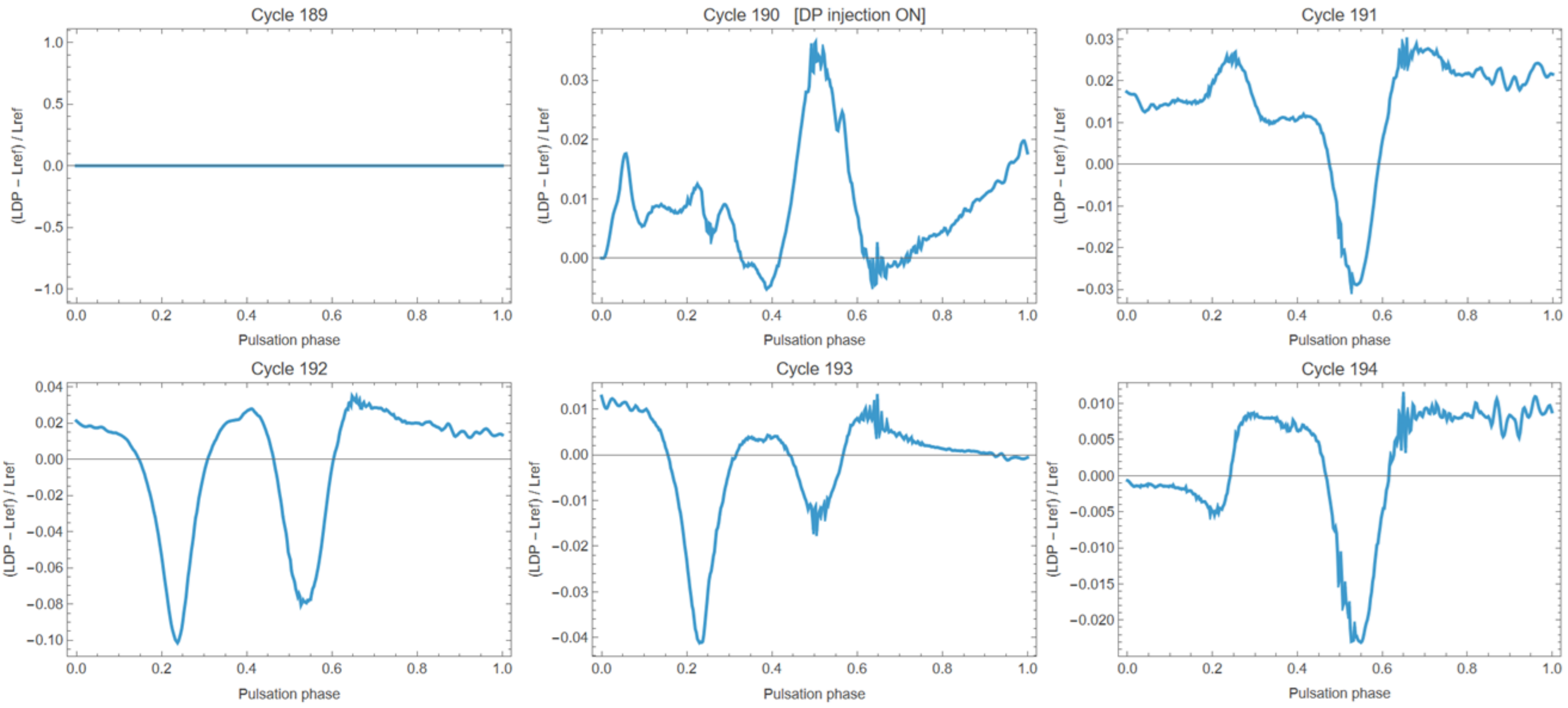
Waiting for new physics

- Breaking possible degeneracy in the presence of dark matter effects would be important.
- Resonance conversion of dark photon dark matter with $m \sim 10^{-3} eV$ can affect PLC relation of Cepheids variable → might affect the standard candle.
- RR Lyrae might be more suitable detectors than Cepheids.
- Dark photon stars (soliton supported by quantum pressure) might provide interesting phenomenological signatures.
- Local dark matter density can be different from NFW.


MESA
Cepheid simulation
$6M_\odot$
$70L_\odot$
$\rho_{DP} = 10^5$ GeV/cm^3
Relative peak−to−peak luminosity deviation
ΔLpp/Lpp
0.005
0.000
−0.005
−0.010
−0.015
−0.020
10^{-3}
10^{-2}
$m_{\gamma'}$ [eV]
ϵ = 10^−8
ϵ = 10^−9


MESA
Cepheid simulation
$6M_\odot$
$70L_\odot$
$\rho_{DP} = 10^5$ GeV/cm^3
Offset−corrected relative mean radius deviation
0.0006
0.0004
0.0002
0.0000
−0.0002
−0.0004
−0.0006
ΔR/R
10^{-3}
10^{-2}
$m_{\gamma'}$ [eV]


MESA
Cepheid simulation
$6M_\odot$
$70L_\odot$
$\rho_{DP} = 10^5$ GeV/cm^3
Offset−corrected relative peak−to−peak luminosity amplitude deviation
ΔLpp/Lpp
0.005
0.000
−0.005
−0.010
−0.015
10^{-3}
10^{-2}
$m_{\gamma'}$ [eV]


Cycle 189
Cycle 190 [DP injection ON]
Cycle 191
Cycle 192
Cycle 193
Cycle 194
(LDP – Lref) / Lref
Pulsation phase

Target minus reference around cycle 191 (DP heating only during cycle 190), $m_{A'} = 1.18\times10^{-3}$ eV, $\epsilon=10^{-9}$, $\rho_{DM}=10^{6}$GeV/cm^3