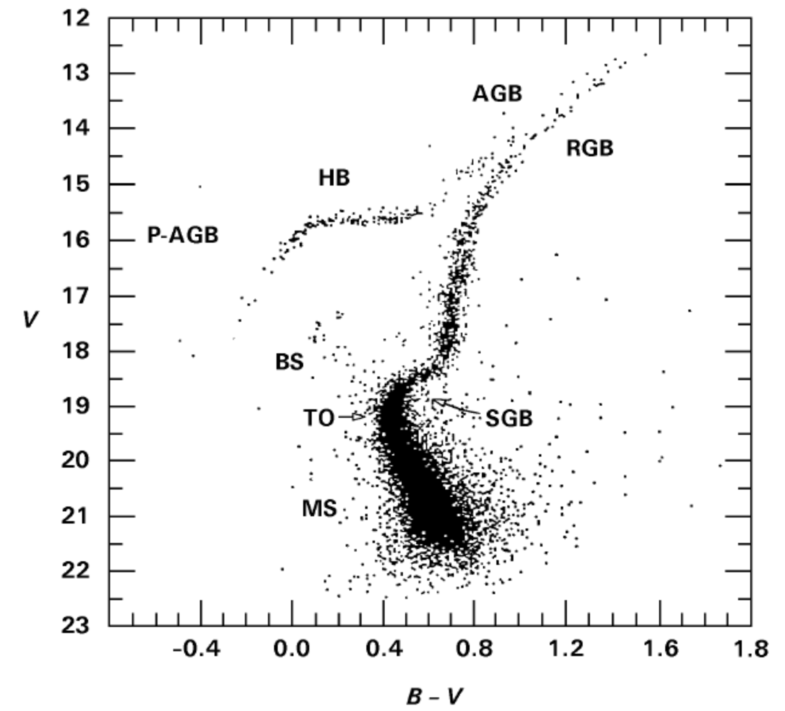


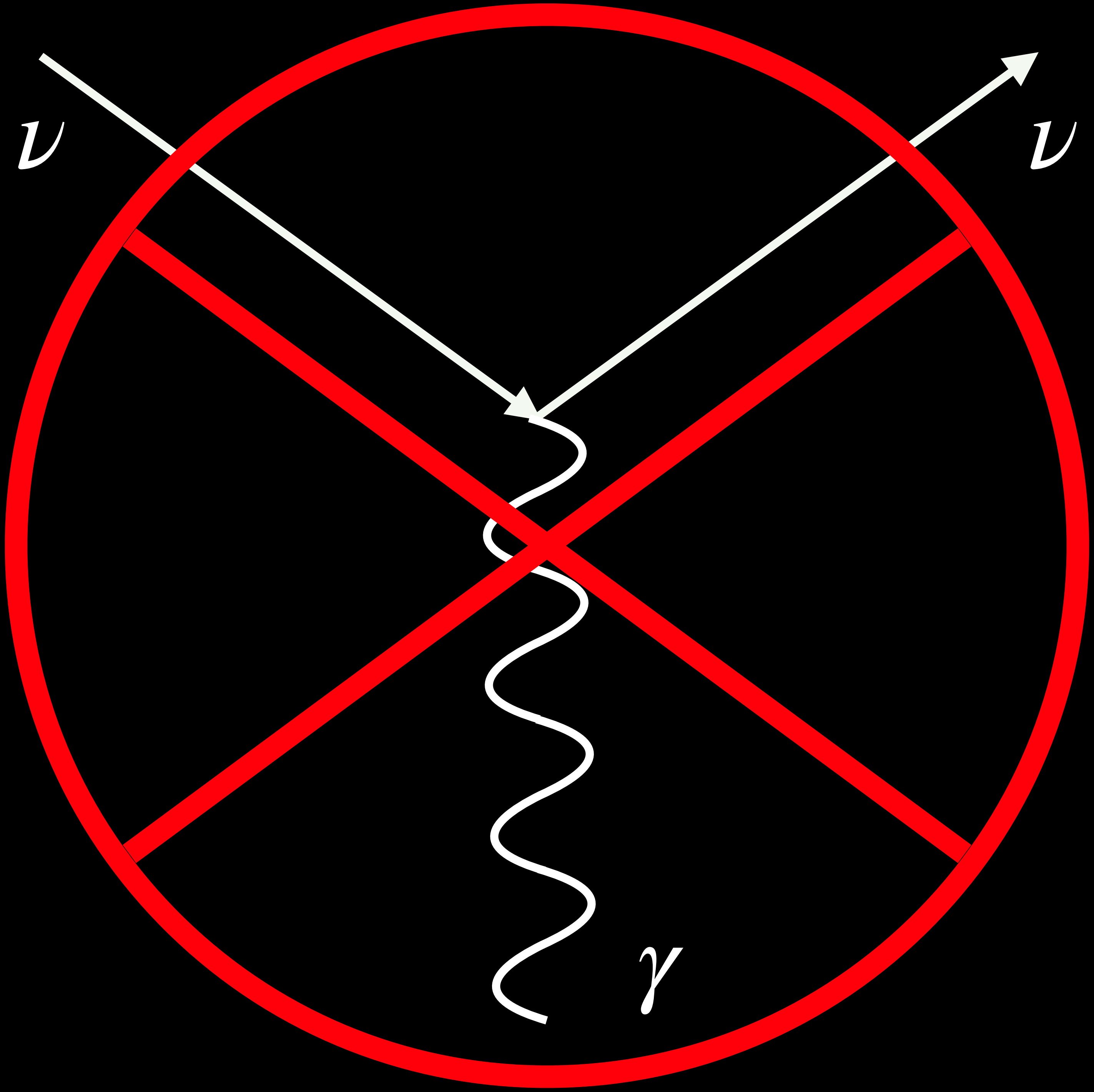
Astrophysical constraints on the neutrino magnetic moment

FRANCESCO CAPOZZI

based on Phys. Rev. D 102 (2020) no.8, 083007, in collaboration with G. Raffelt

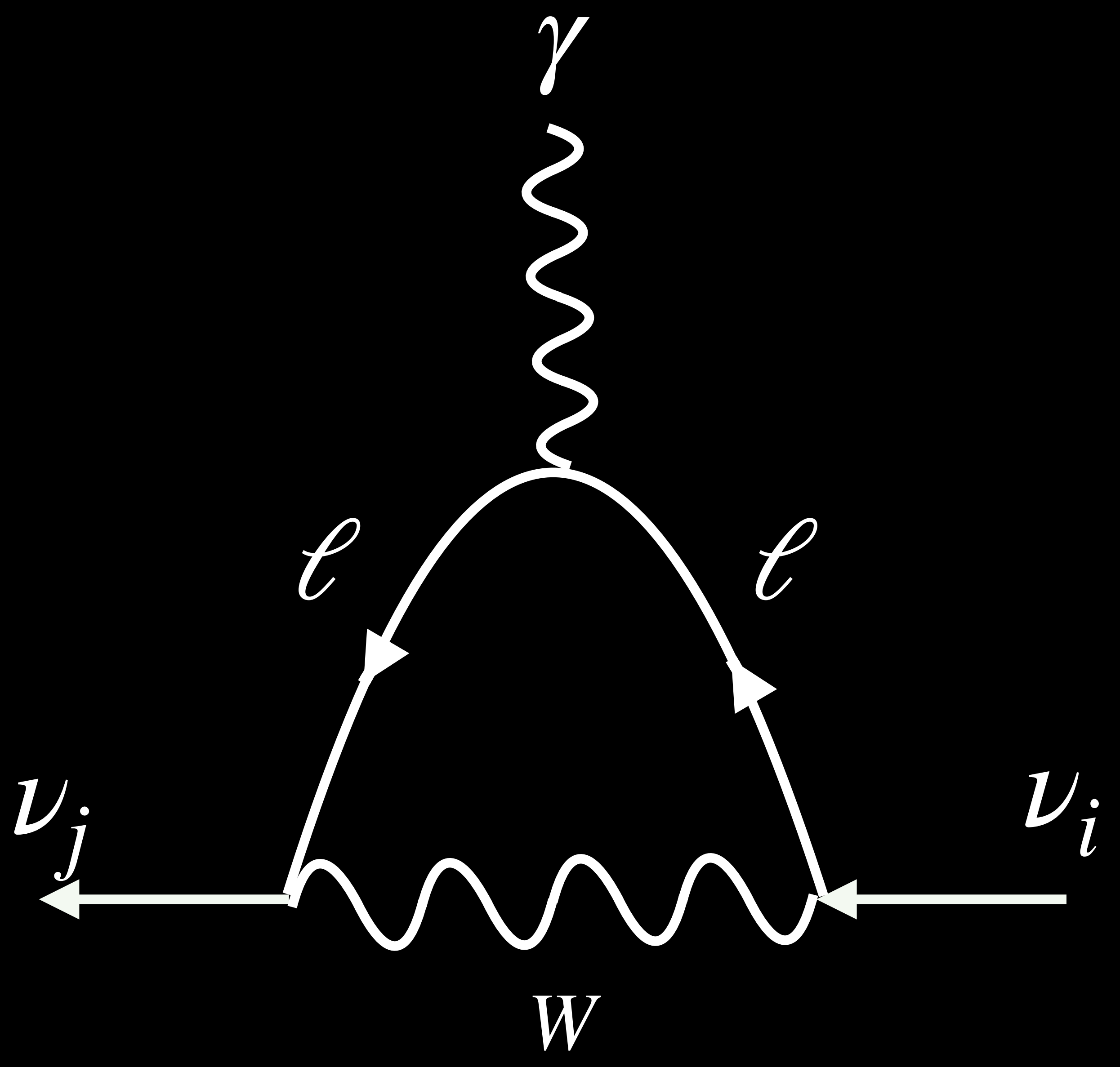
INSTITUT DE FÍSICA CORPUSCULAR

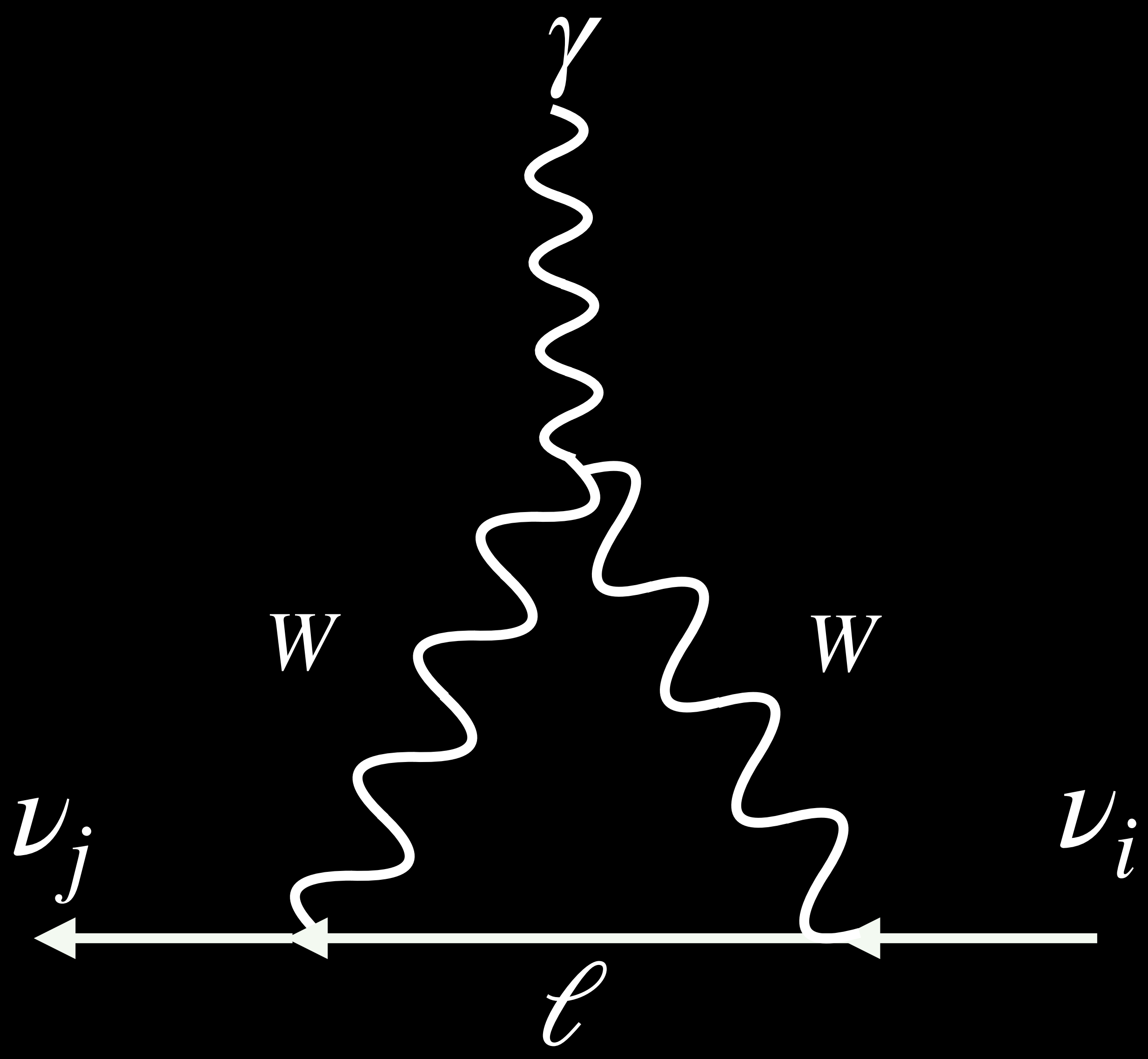
Neutrino magnetic moment



Neutrinos have no EM charge. Diagram not allowed in the Standard Model

Neutrino magnetic moment





Coupling to photon possible at the loop level: **neutrino magnetic moment**

Neutrino magnetic moment

$$\mathscr{L} \supset \mu_{ij}^{D}\, \bar{\nu}_i\, \sigma_{\mu\nu} \nu_j\, F^{\mu\nu}$$

Dirac

Fujikawa, Shrock, Phys. Rev. Lett. **45**, 963

$$\mu_{ij}^{\rm D} = \frac{eG_F}{8\sqrt{2}\pi^2}(m_i + m_j) \sum_{l=e,\mu,\tau} f(a_l) U_{li}^{*} U_{lj}$$

$$a_l = \left(\frac{m_l}{m_W}\right)^2$$

$$\mu_{ii}^{\rm D} \simeq 3.2 \times 10^{-19} \left(\frac{m_i}{\rm eV}\right) \mu_{\rm B}$$

$$\mathscr{L} \supset \mu_{ij}^{M}\, \nu_i\, \sigma_{\mu\nu} \nu_j\, F^{\mu\nu}$$

Majorana

$$\mu^{\rm M} = -\left(\mu^{M}\right)^{T}$$

$$\mu_{ii}^{\rm M} = 0$$

Only off-diagonal (transition) magnetic moments can exist

Neutrino magnetic moment

$$\mathscr{L} \supset \mu_{ij}^{D}\, \bar{\nu}_i \sigma_{\mu\nu} \nu_j F^{\mu\nu}$$

Dirac

PHENOMENOLOGY:

- $\nu + e$ cross section
- $\nu_i \to \nu_j + \gamma$
- $\nu_{\alpha,L} \to \nu_{\beta,R}$ in scattering or B
- $\gamma^* \to \nu\bar{\nu}$

$$\mathscr{L} \supset \mu_{ij}^{M}\, \nu_i \sigma_{\mu\nu} \nu_j F^{\mu\nu}$$

Majorana

PHENOMENOLOGY:

- $\nu + e$ cross section
- $\nu_i \to \nu_j + \gamma$
- $\nu_\alpha \to \bar{\nu}_\beta$ in scattering or B
- $\gamma^* \to \nu\bar{\nu}$

Neutrino magnetic moment

Regardless of the nature of neutrinos, if we measure

$$\mu_\nu > 10^{-19}\mu_B$$

We have direct evidence of new physics

Constraints: ν - e scattering

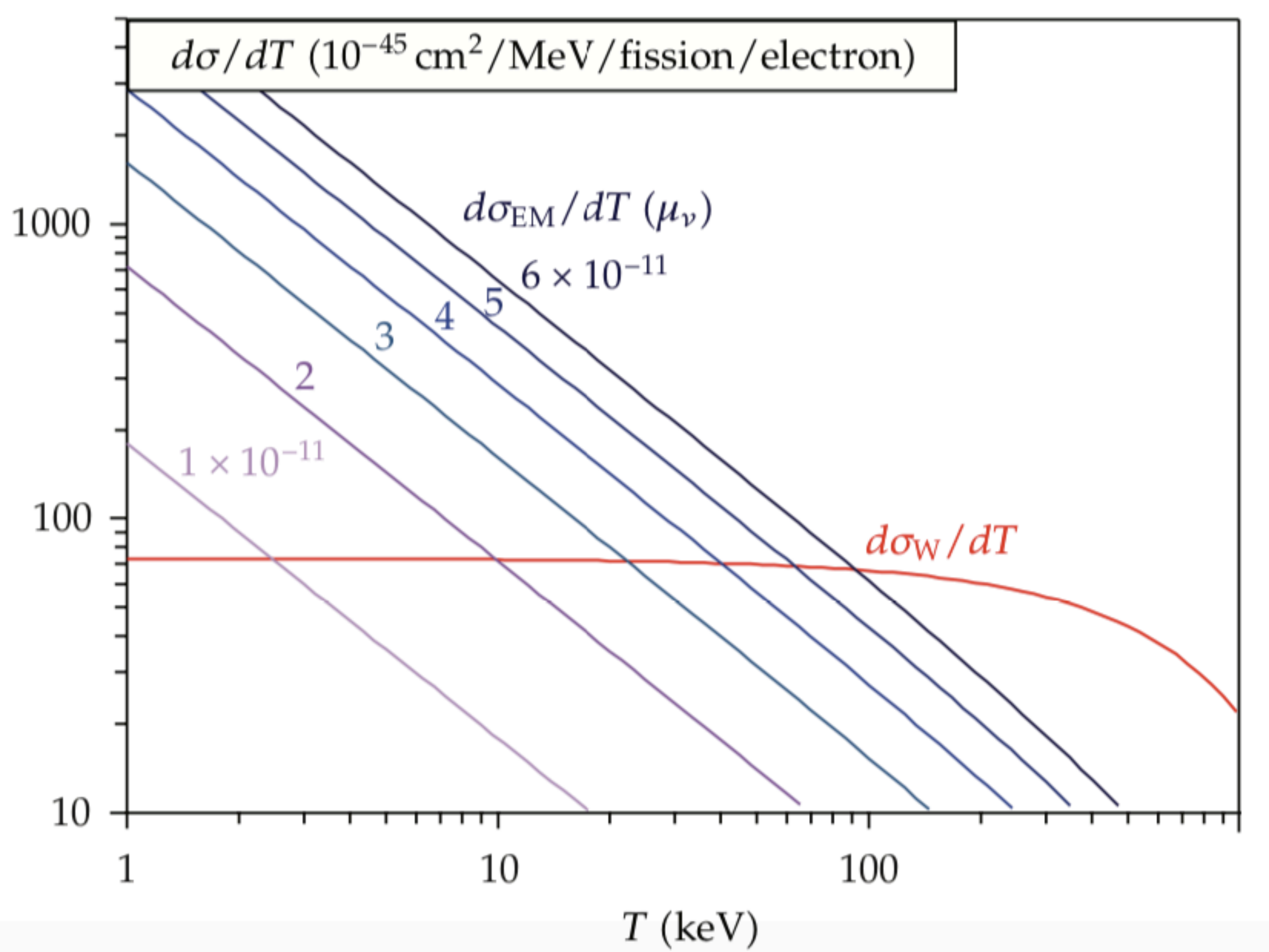
$$\frac{d\sigma}{dT} = \left(\frac{d\sigma}{dT}\right)_{\mathrm{SM}} + \left(\frac{d\sigma}{dT}\right)_{\mu}$$

Assuming ν_R to be light

$$\left(\frac{d\sigma}{dT}\right)_{\mu} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_B}\right)^2$$

Constraints: ν - e scattering

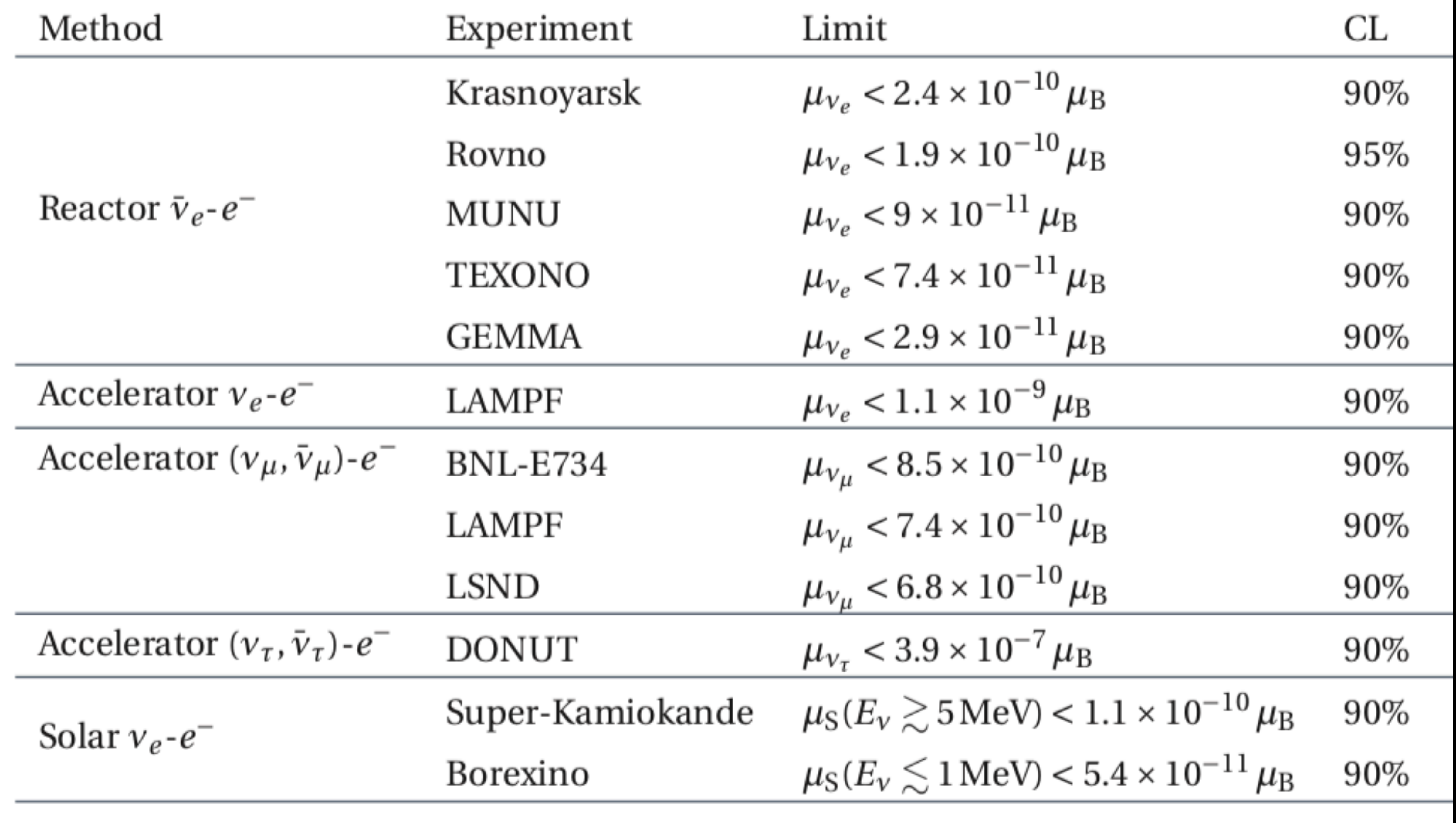
Broggini, Giunti, Studenikin, Adv. High Energy Phys.2012 (2012), 459526



Extra contribution from μ dominates at low T (recoil energy of electrons)

Constraints: ν - e scattering

Giunti, Kouzakov, Li, Lokhov, Studenikin, Zhou, Annalen Phys. 528, 198-215 (2016)



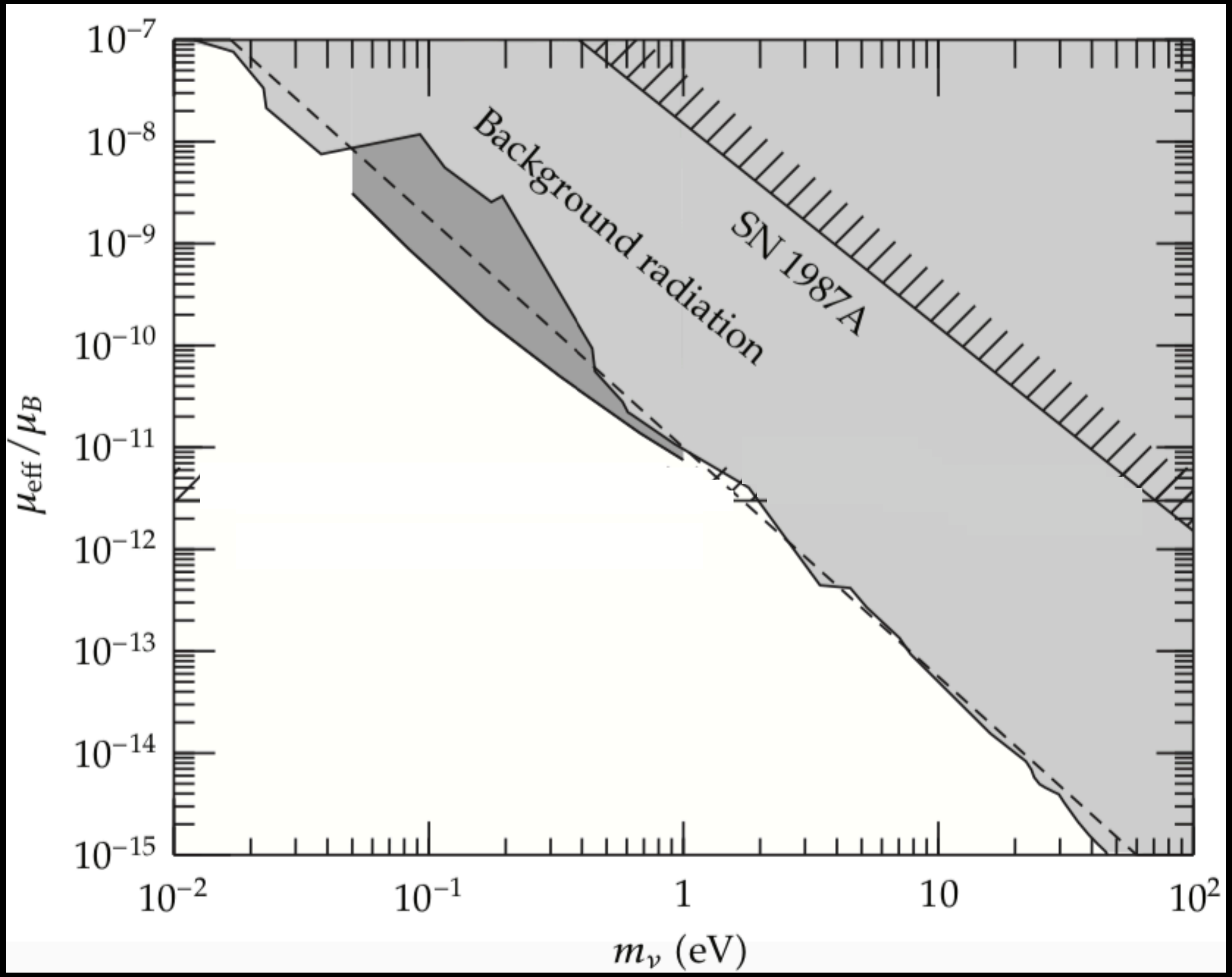
Method	Experiment	Limit	CL
Reactor $\bar{\nu}_e$-e^-	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}\, \mu_B$	90%
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}\, \mu_B$	95%
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}\, \mu_B$	90%
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}\, \mu_B$	90%
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}\, \mu_B$	90%
Accelerator ν_e-e^-	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}\, \mu_B$	90%
Accelerator $(\nu_\mu, \bar{\nu}_\mu)$-e^-	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}\, \mu_B$	90%
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}\, \mu_B$	90%
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}\, \mu_B$	90%
Accelerator $(\nu_\tau, \bar{\nu}_\tau)$-$e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}\, \mu_B$	90%
Solar ν_e-e^-	Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}\, \mu_B$	90%
	Borexino	$\mu_S(E_\nu \lesssim 1\,\text{MeV}) < 5.4 \times 10^{-11}\, \mu_B$	90%

Constraints: radiative decay

Radiative neutrino decay affects SN1987a and background radiation

$$\Gamma_{\nu_i\to\nu_j+\gamma} = 5.3\left(\frac{\mu_\nu}{\mu_B}\right)^2\left(\frac{m_i^2-m_j^2}{m_j^2}\right)^3\left(\frac{m_i}{1\,\mathrm{eV}}\right)^3\,\mathrm{s}^{-1}$$

Raffelt, Phys. Rept. 320, 319-327 (1999)

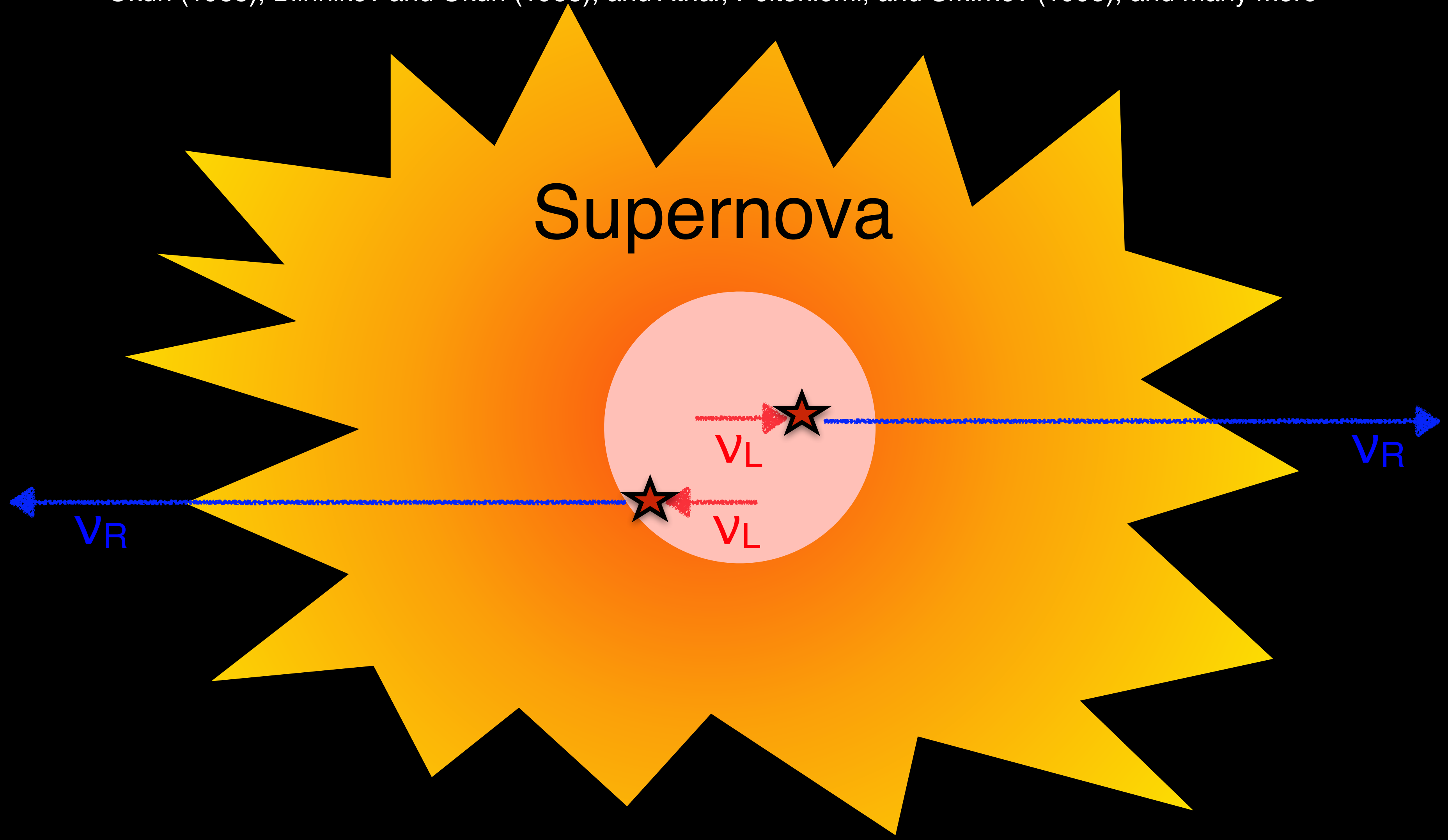


Francesco Capozzi - Instituto de Fisica Corpuscular

Constraints: spin-flip

Neutrinos can flip chirality: $\nu_L + e^- \rightarrow \nu_R + e^-, \nu_L + p \rightarrow \nu_R + p$

Dar (1987), Nussinov and Rephaeli (1987), Goldman et al. (1988), Voloshin (1988),
Okun (1988), Blinnikov and Okun (1988), and Athar, Peltoniemi, and Smirnov (1995), and many more

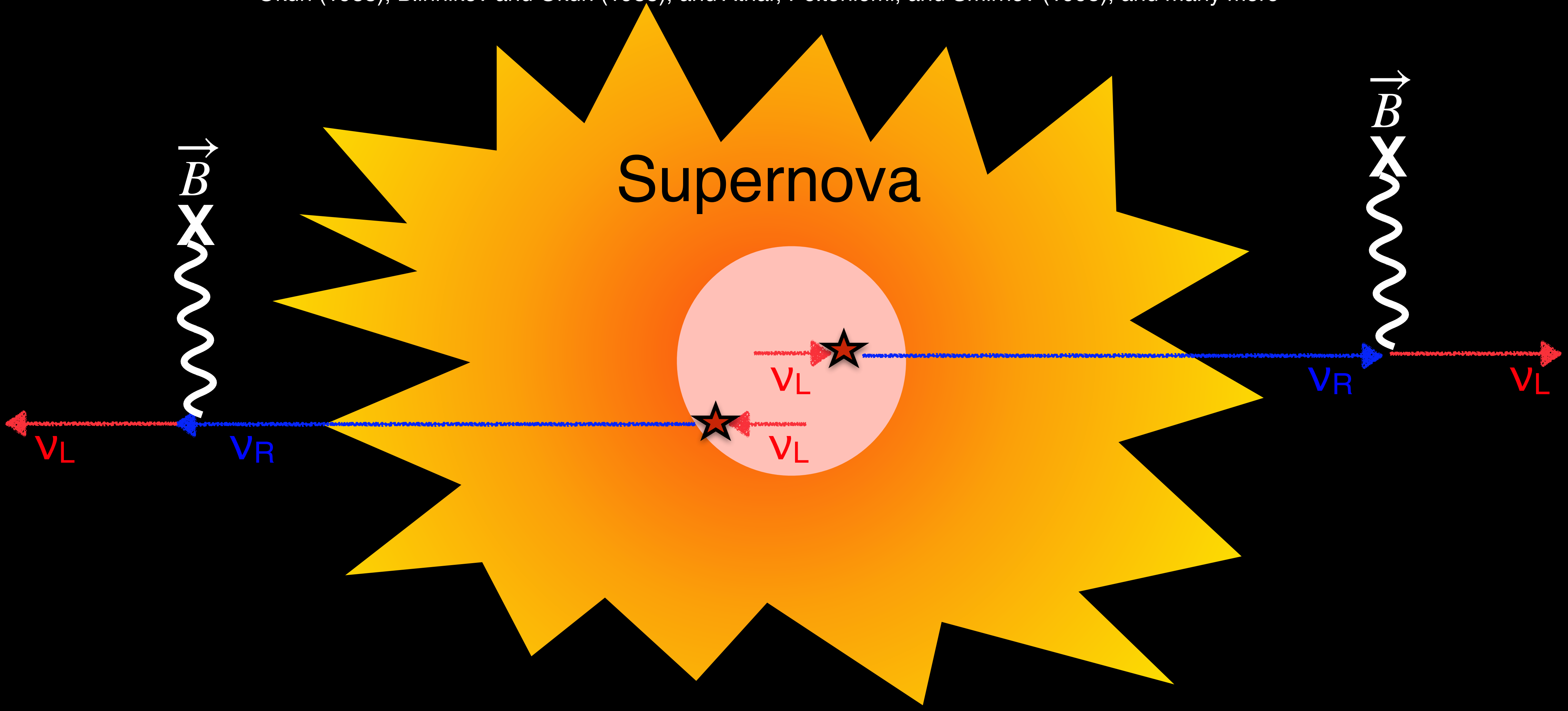


Luminosity emitted in ν_R cannot be larger than 10^{53} erg

Constraints: spin-flip

Neutrinos can flip chirality: $\nu_L + e^- \rightarrow \nu_R + e^-, \nu_L + p \rightarrow \nu_R + p$

Dar (1987), Nussinov and Rephaeli (1987), Goldman et al. (1988), Voloshin (1988), Okun (1988), Blinnikov and Okun (1988), and Athar, Peltoniemi, and Smirnov (1995), and many more

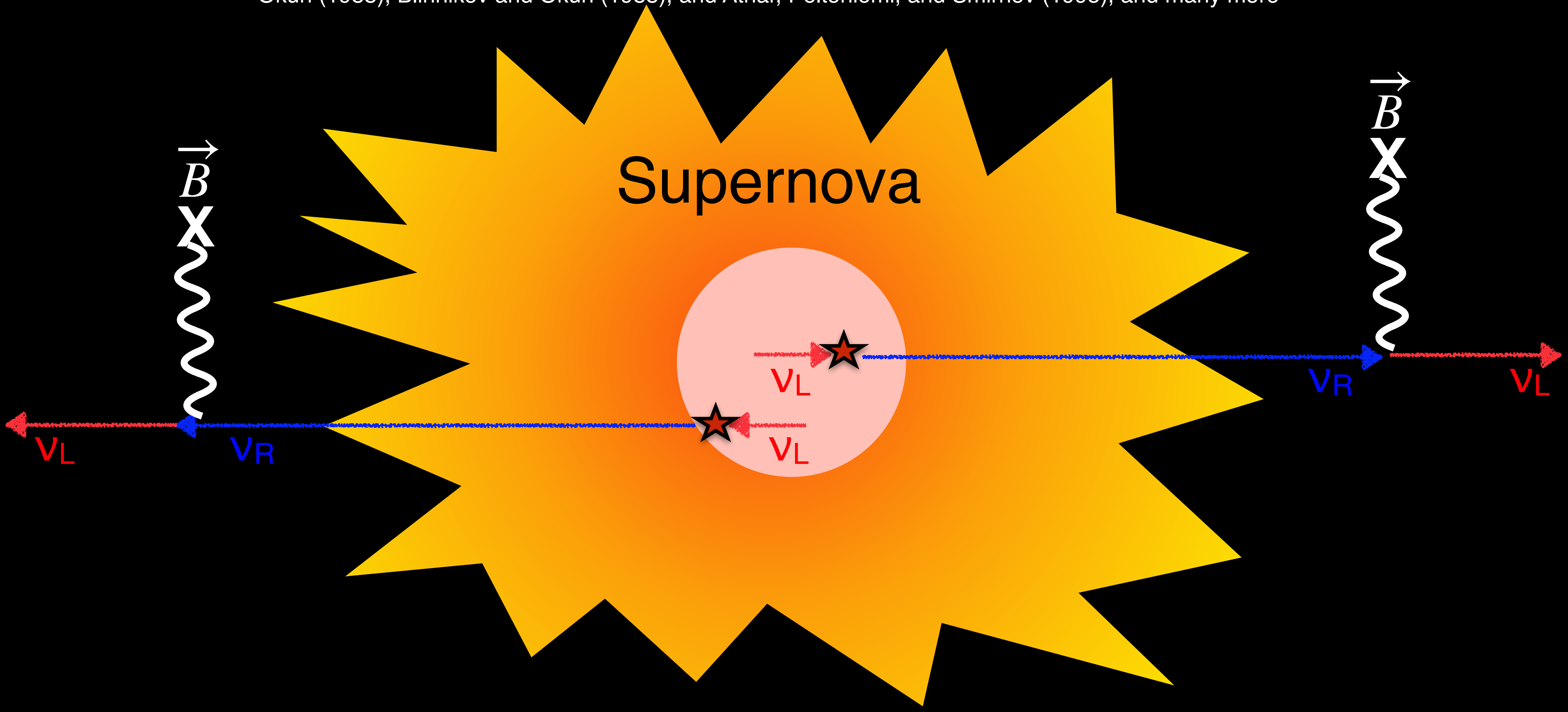


ν_R could rotate back into ν_L ones in magnetic fields outside the supernova

Constraints: spin-flip

Neutrinos can flip chirality: $\nu_L + e^- \rightarrow \nu_R + e^-, \nu_L + p \rightarrow \nu_R + p$

Dar (1987), Nussinov and Rephaeli (1987), Goldman et al. (1988), Voloshin (1988), Okun (1988), Blinnikov and Okun (1988), and Athar, Peltoniemi, and Smirnov (1995), and many more

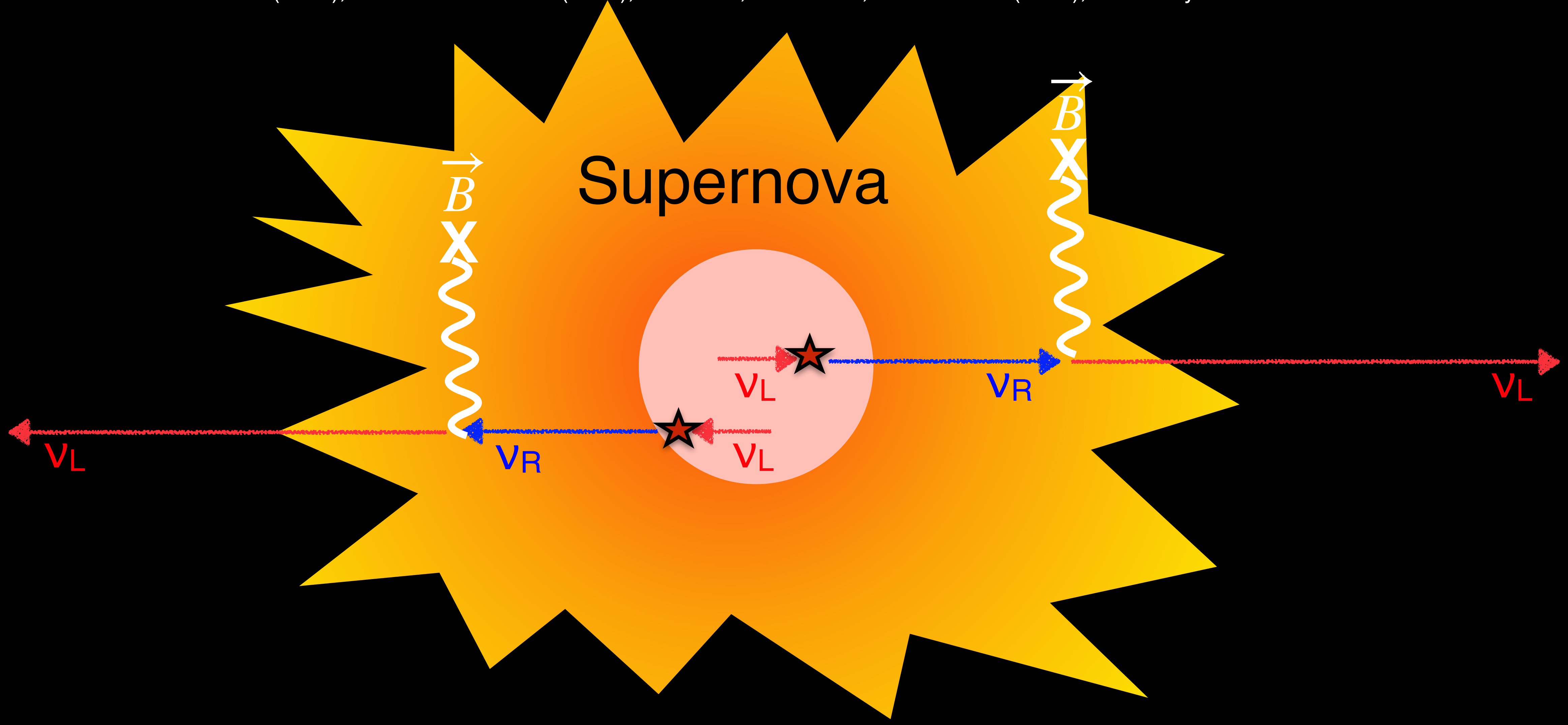


Back conversion to ν_L would lead to high energy events

Constraints: spin-flip

Neutrinos can flip chirality: $\nu_L + e^- \rightarrow \nu_R + e^-, \nu_L + p \rightarrow \nu_R + p$

Dar (1987), Nussinov and Rephaeli (1987), Goldman et al. (1988), Voloshin (1988),
Okun (1988), Blinnikov and Okun (1988), and Athar, Peltoniemi, and Smirnov (1995), and many more

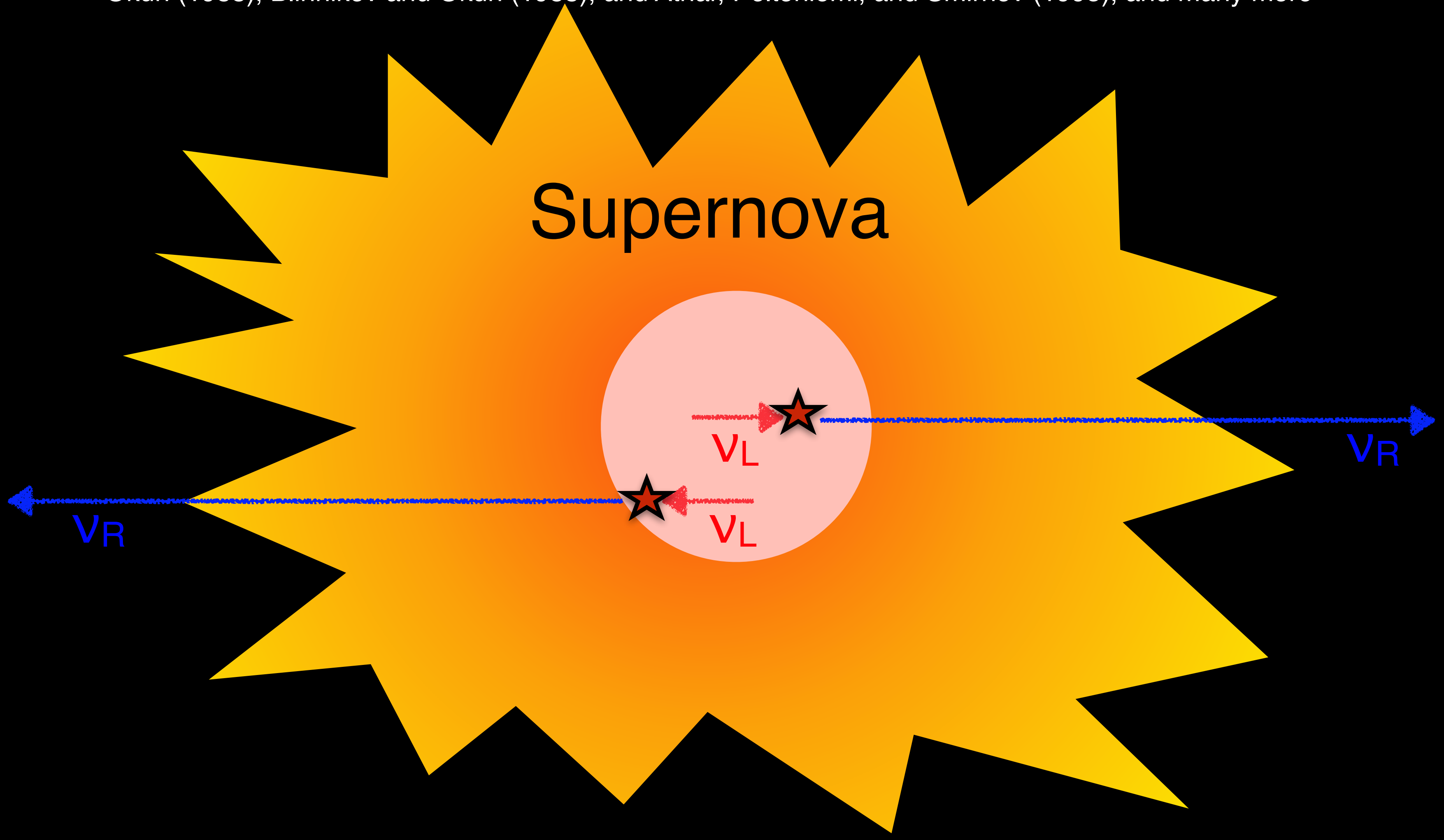


Conversion to ν_R may happen inside the supernova, with impact on explosion

Constraints: spin-flip

Neutrinos can flip chirality: $\nu_L + e^- \rightarrow \nu_R + e^-, \nu_L + p \rightarrow \nu_R + p$

Dar (1987), Nussinov and Rephaeli (1987), Goldman et al. (1988), Voloshin (1988), Okun (1988), Blinnikov and Okun (1988), and Athar, Peltoniemi, and Smirnov (1995), and many more



In general $\mu_\nu \lesssim 10^{-12}\mu_B$ can influence supernova physics, but many effects come into play at the same time

Constraints: spin-flip

Neutrinos can flip chirality: $\nu_L + e^- \rightarrow \nu_R + e^-, \nu_L + p \rightarrow \nu_R + p$

$$N_{\text{eff}} \simeq 2.85 \pm 0.28 \ (\text{BBN})$$

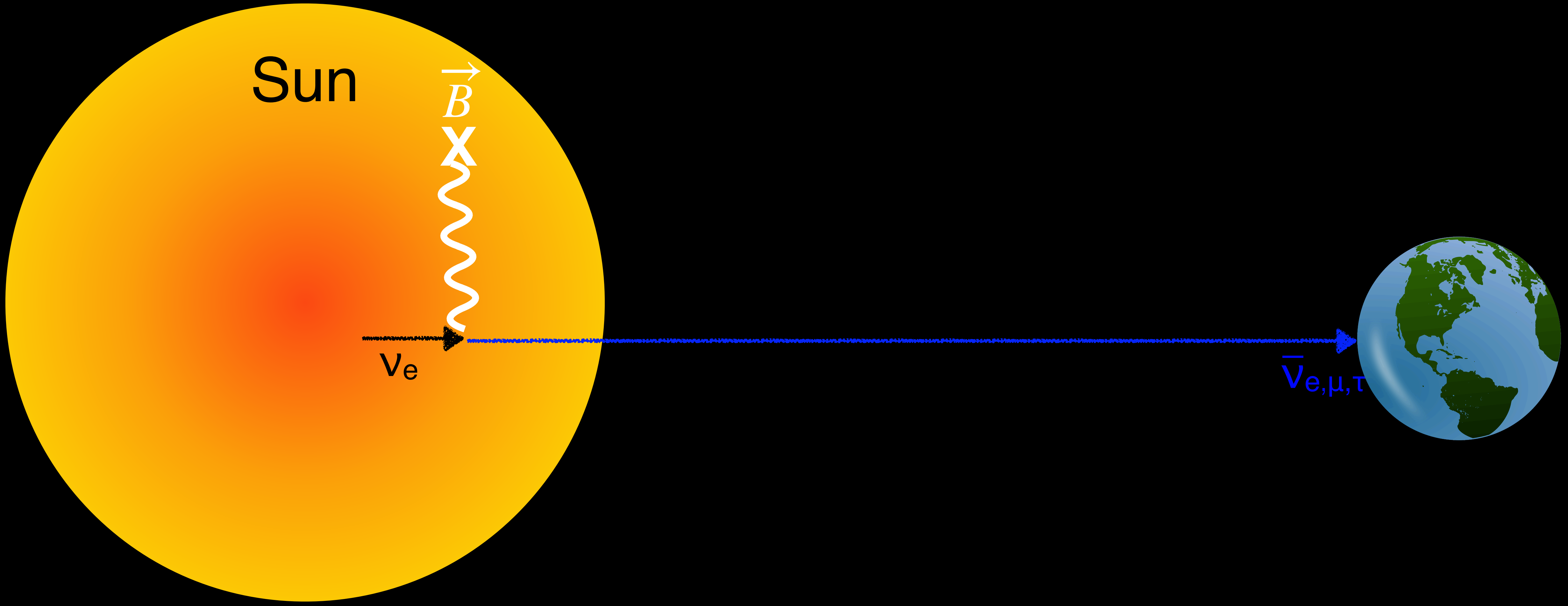
Cyburt, Fields, Olive and Yeh, Rev. Mod. Phys. 88, 015004 (2016)
Morgan, J. 1981a, Phys. Lett. B, 102, 247
Morgan, J. 1981b, Mon. Not. R. astr. Soc., 195, 173
Fukugita and Yazaki, Phys. Rev. D 36, 3817 (1987)
Elmfors, Enqvist, Raffelt and Sigl, Nucl. Phys. B 503 (1997) 3

Extra thermalised light degree of freedom is excluded: $\mu_\nu \lesssim 6 \times 10^{-11} \mu_B$

Constraints: spin-flavour oscillation

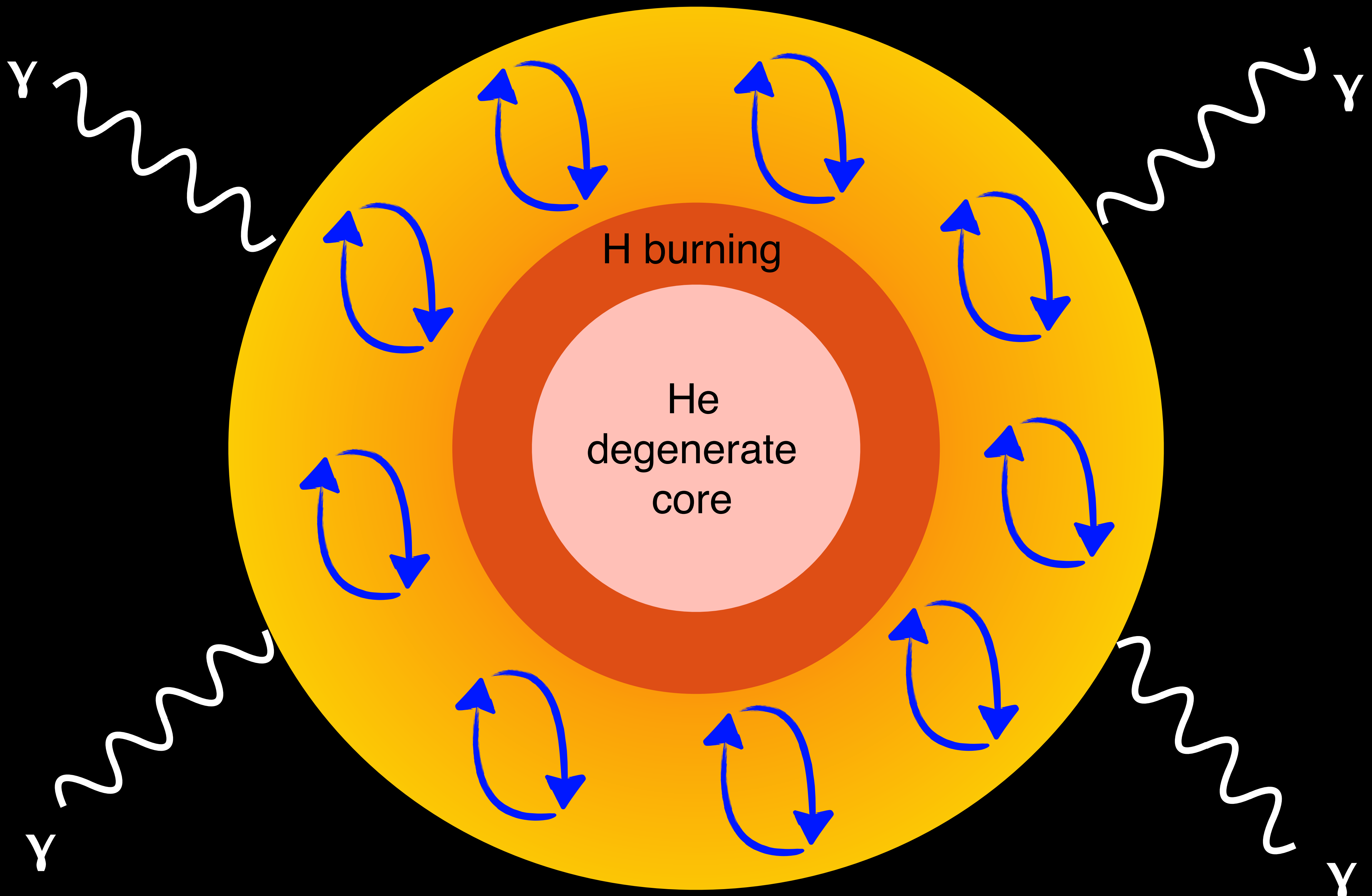
Majorana neutrinos: $\nu_\alpha \to \bar{\nu}_\beta$ through μ_ν interaction with magnetic field

Ahkmedov, Pulido, Phys. Lett. B 553, 7-17 (2003)
Miranda, Rashba, Rez Valle, Phys. Rev. Lett. 93, 051304 (2004)
Agostini et al., Astropart. Phys. 125, 102509 (2021)

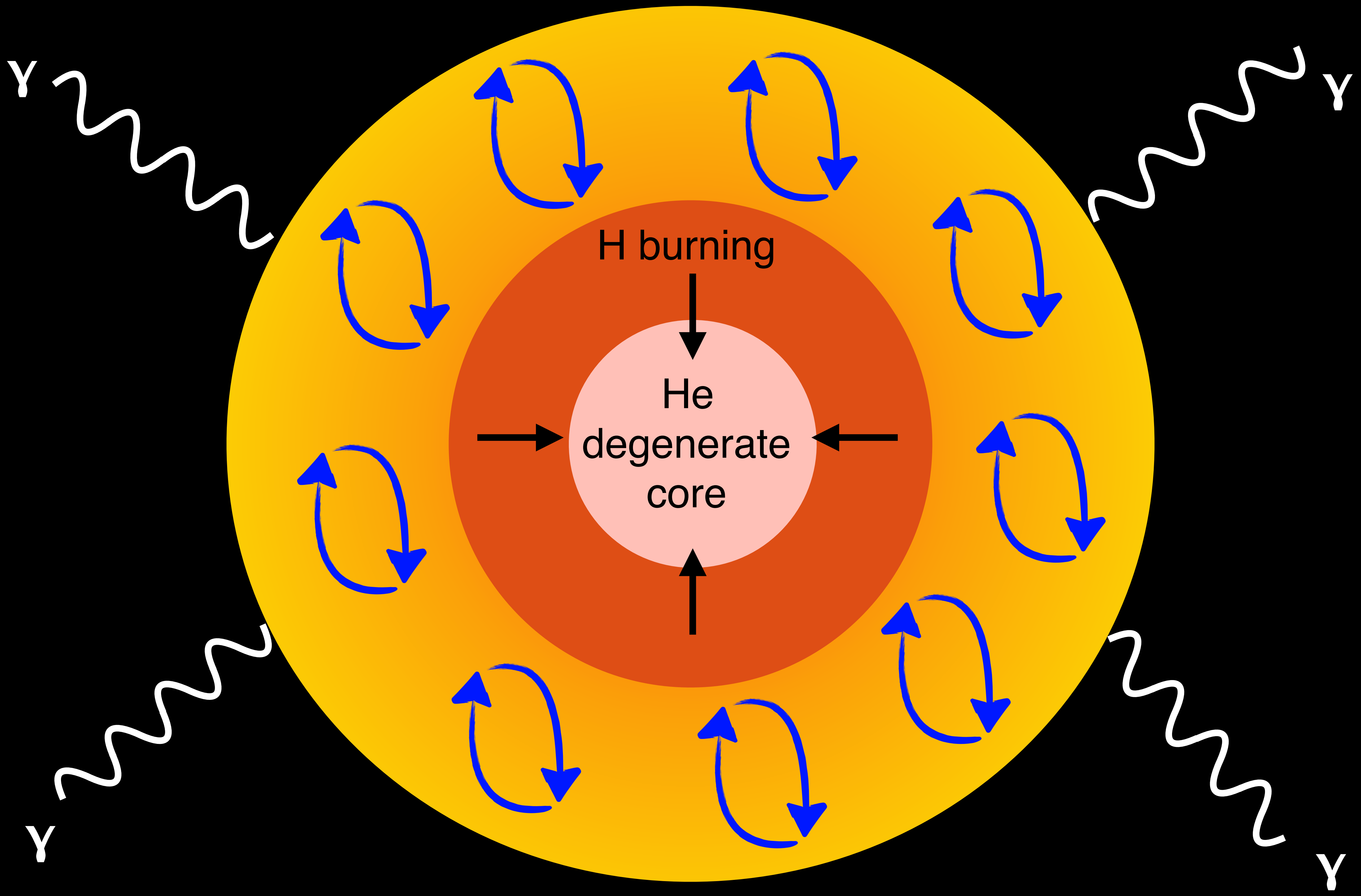


Borexino: $\mu_\nu \lesssim 3 \times 10^{-11} \mu_B$ assuming B ~ 10^4 G in convective zone

Constraints: cooling of RGB stars

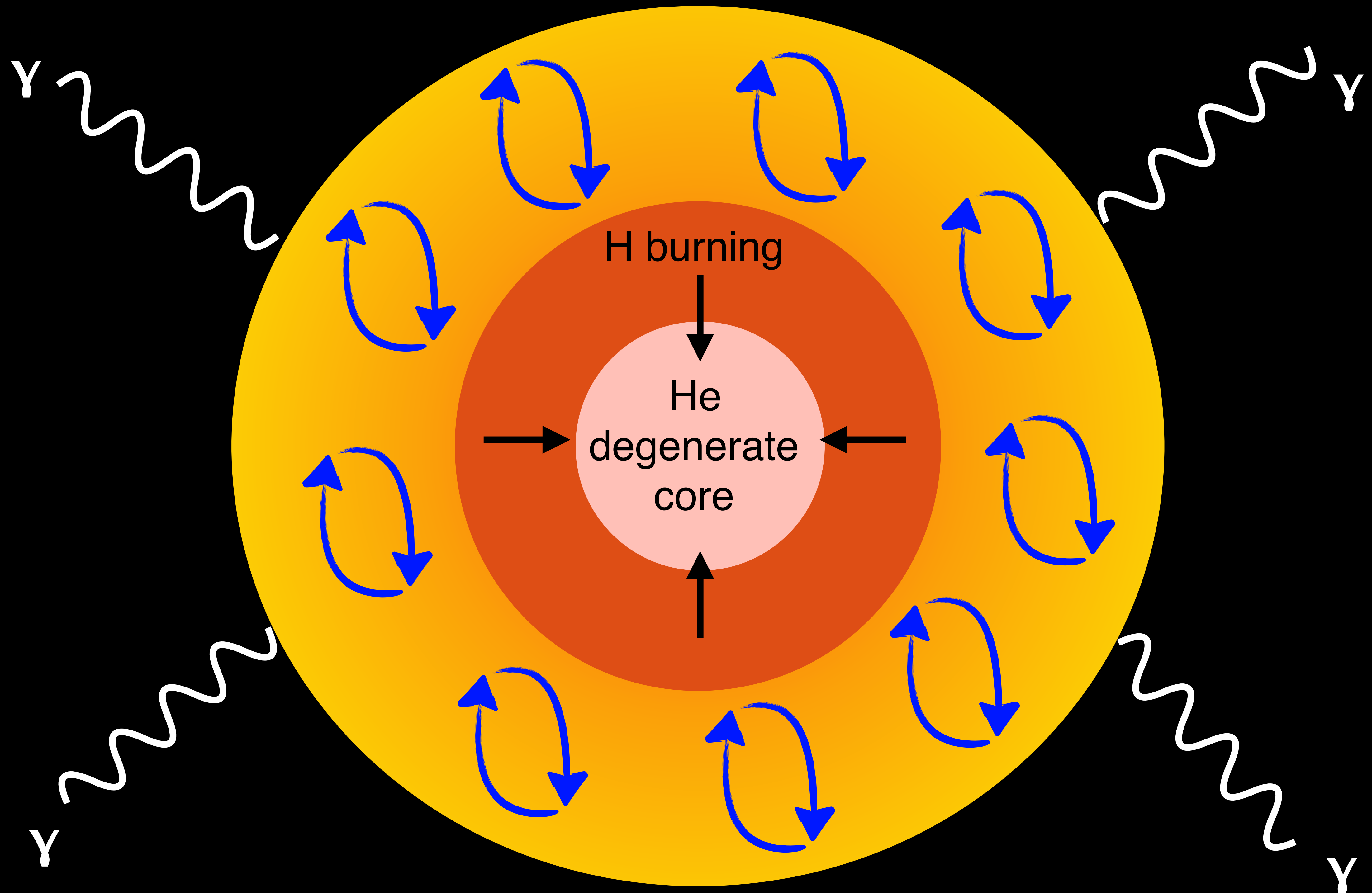


Constraints: cooling of RGB stars



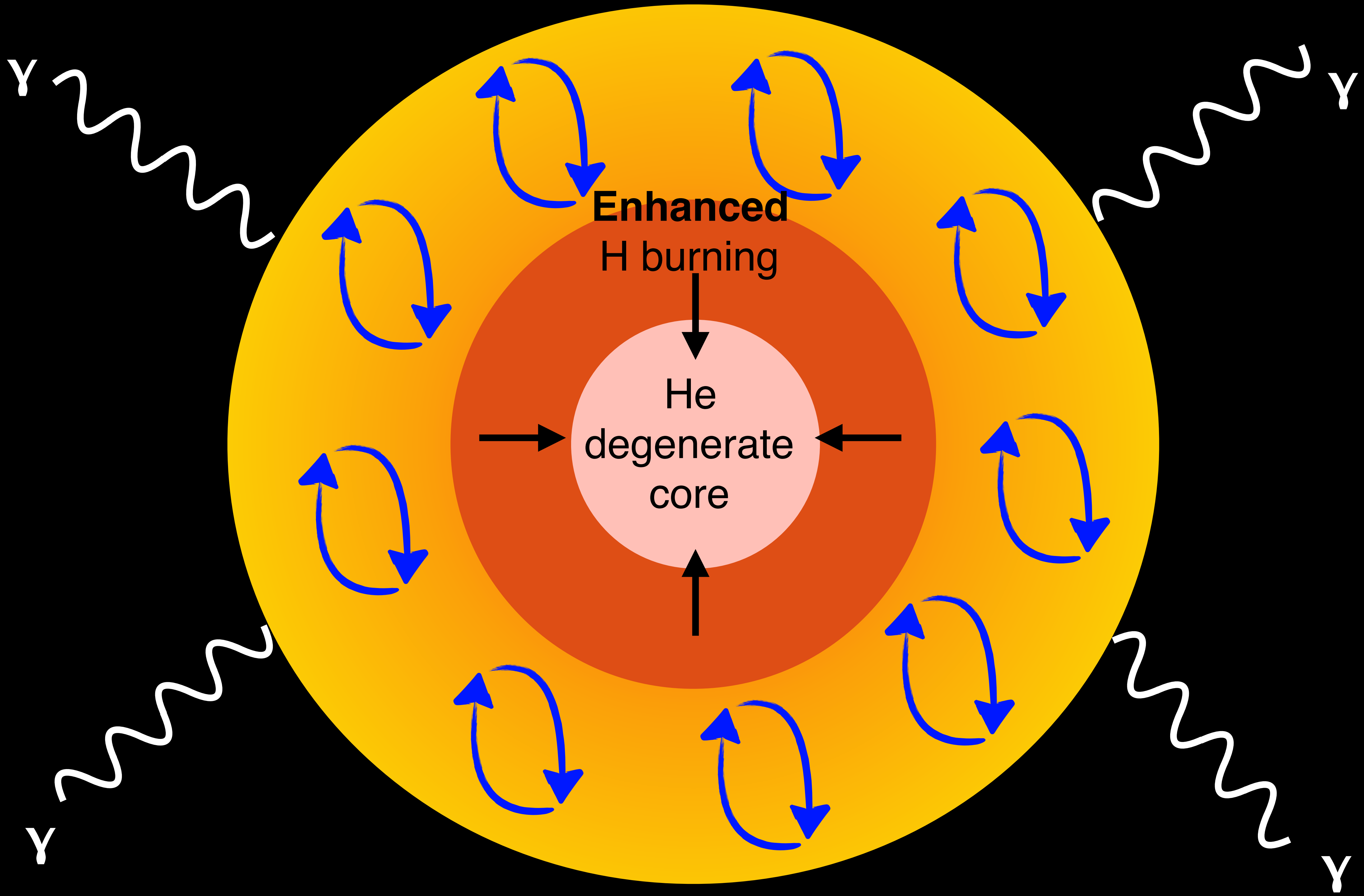
Hydrogen burning produces more He falling on the core.
The core increases its mass and it shrinks ($R \sim M^{-1/3}$)

Constraints: cooling of RGB stars



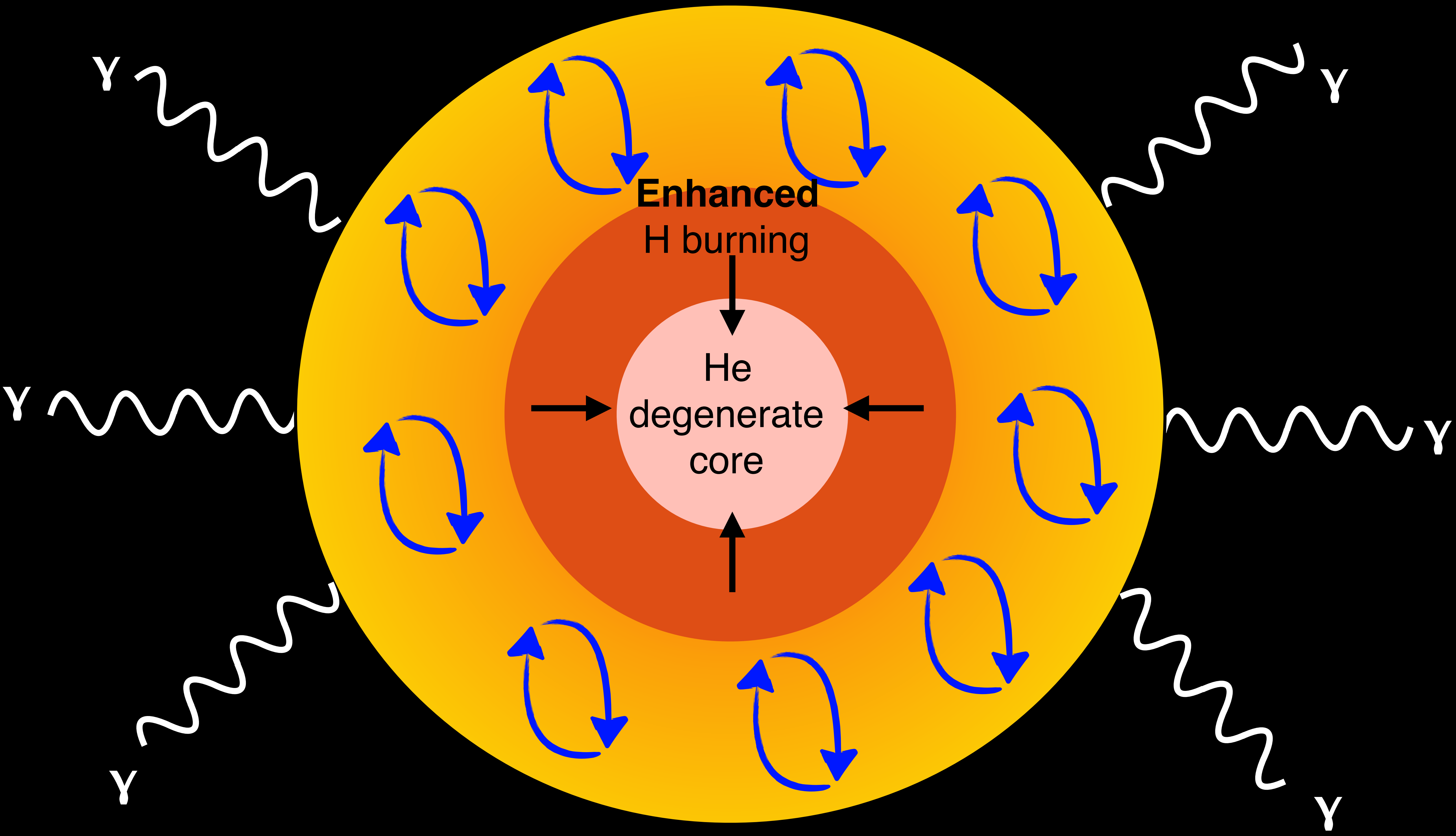
The core provides a larger gravitational potential $\Phi \sim M / R$

Constraints: cooling of RGB stars



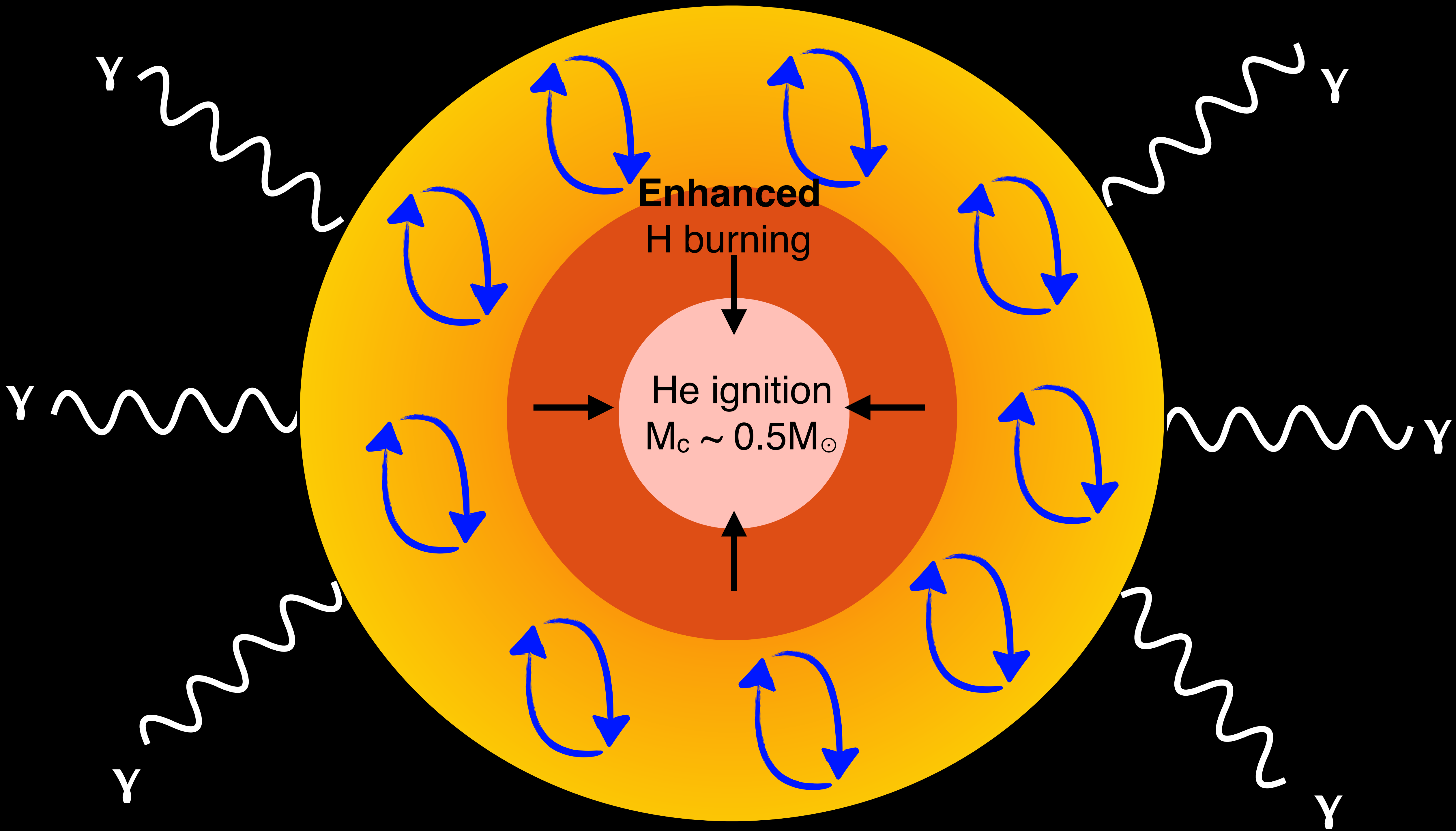
To compensate Φ more pressure from H burning is required

Constraints: cooling of RGB stars



The enhanced H burning raises the temperature and the luminosity

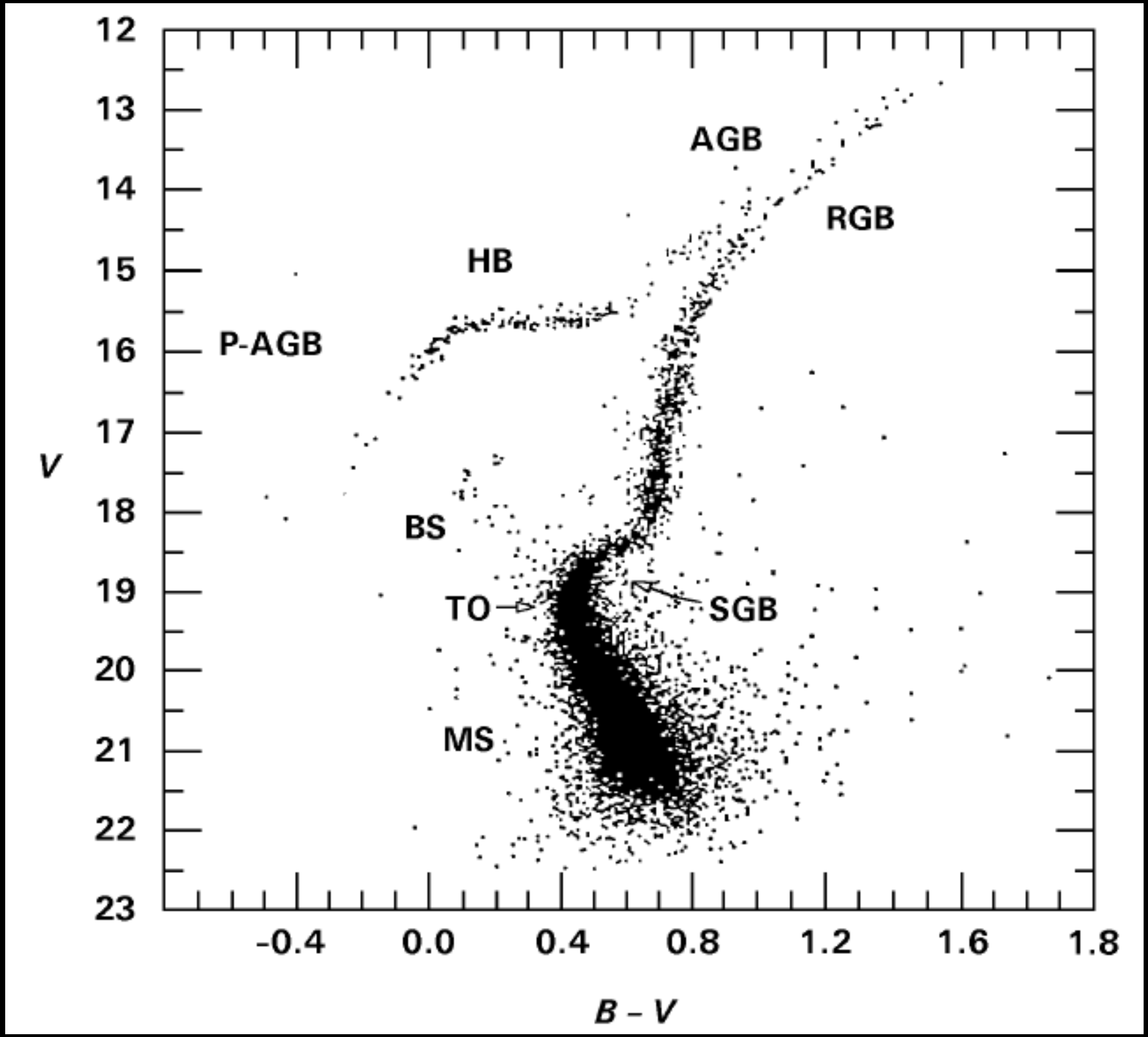
Constraints: cooling of RGB stars



The star reaches the maximum luminosity (Tip of the RGB) when the core becomes so hot and dense that helium ignites

Constraints: cooling of RGB stars

G. Raffelt, Lect. Notes Phys. 741 (2008), 51-71

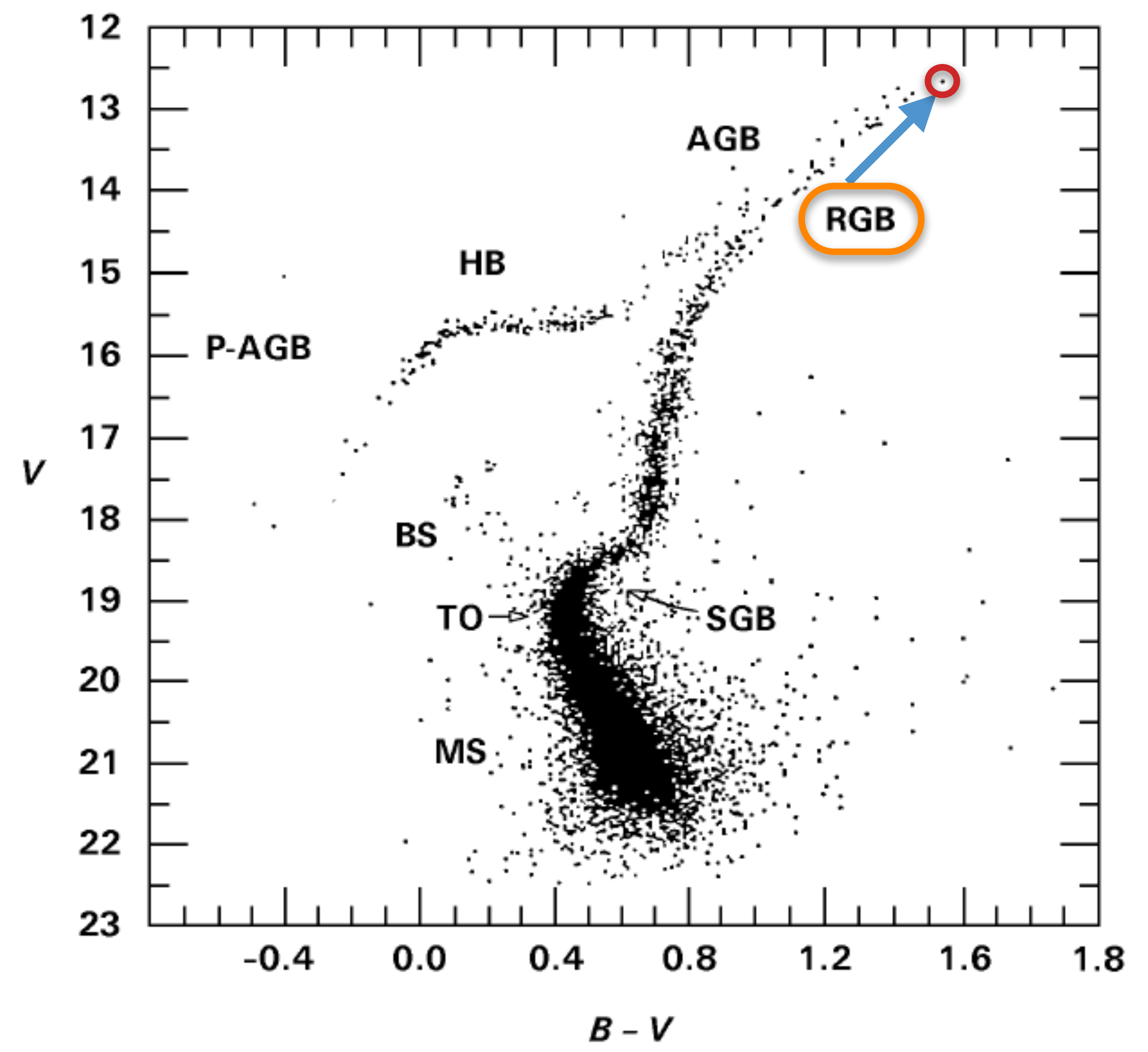


Luminosity

Blue Color Red

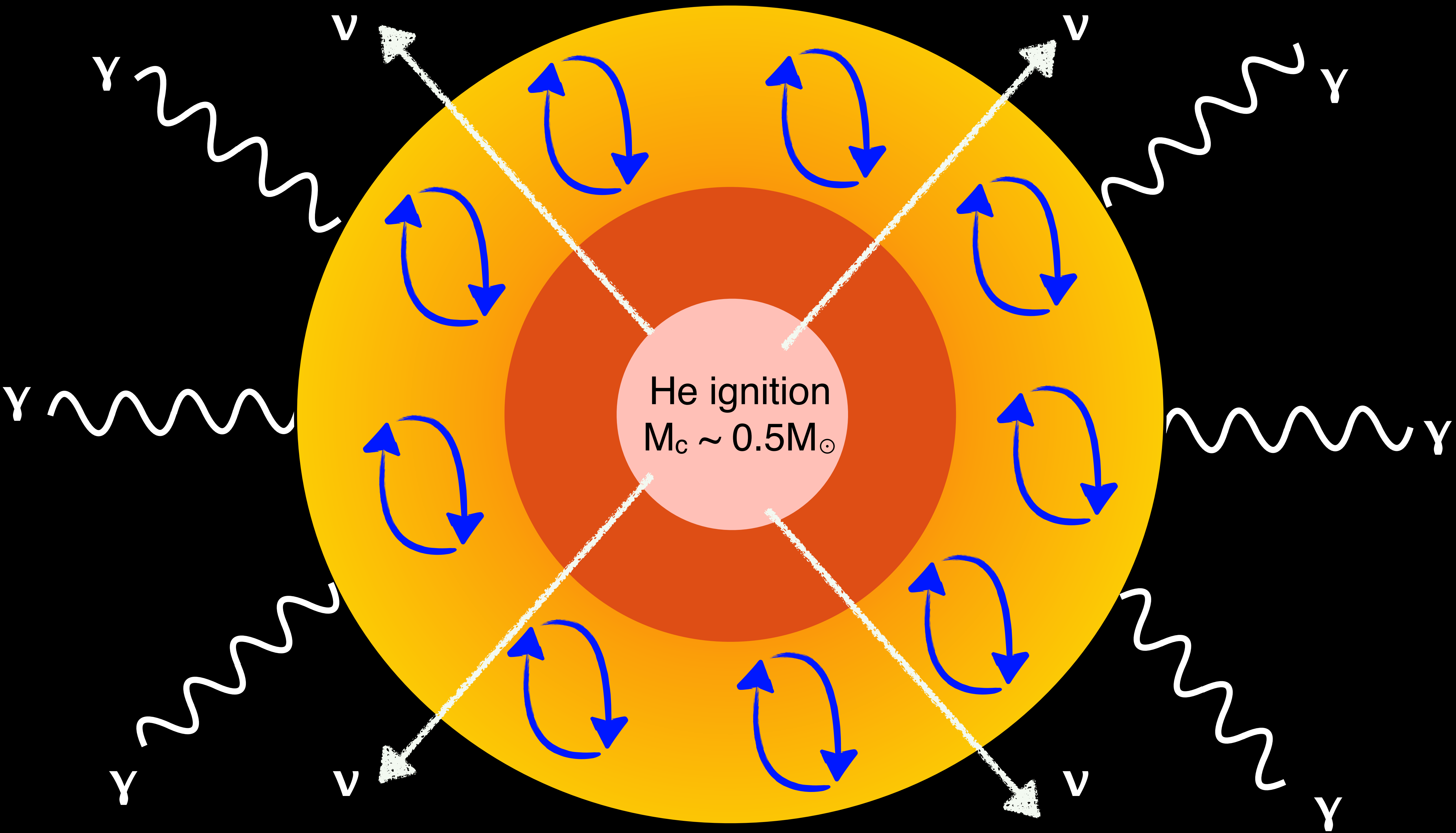
Constraints: cooling of RGB stars

G. Raffelt, Lect. Notes Phys. 741 (2008), 51-71



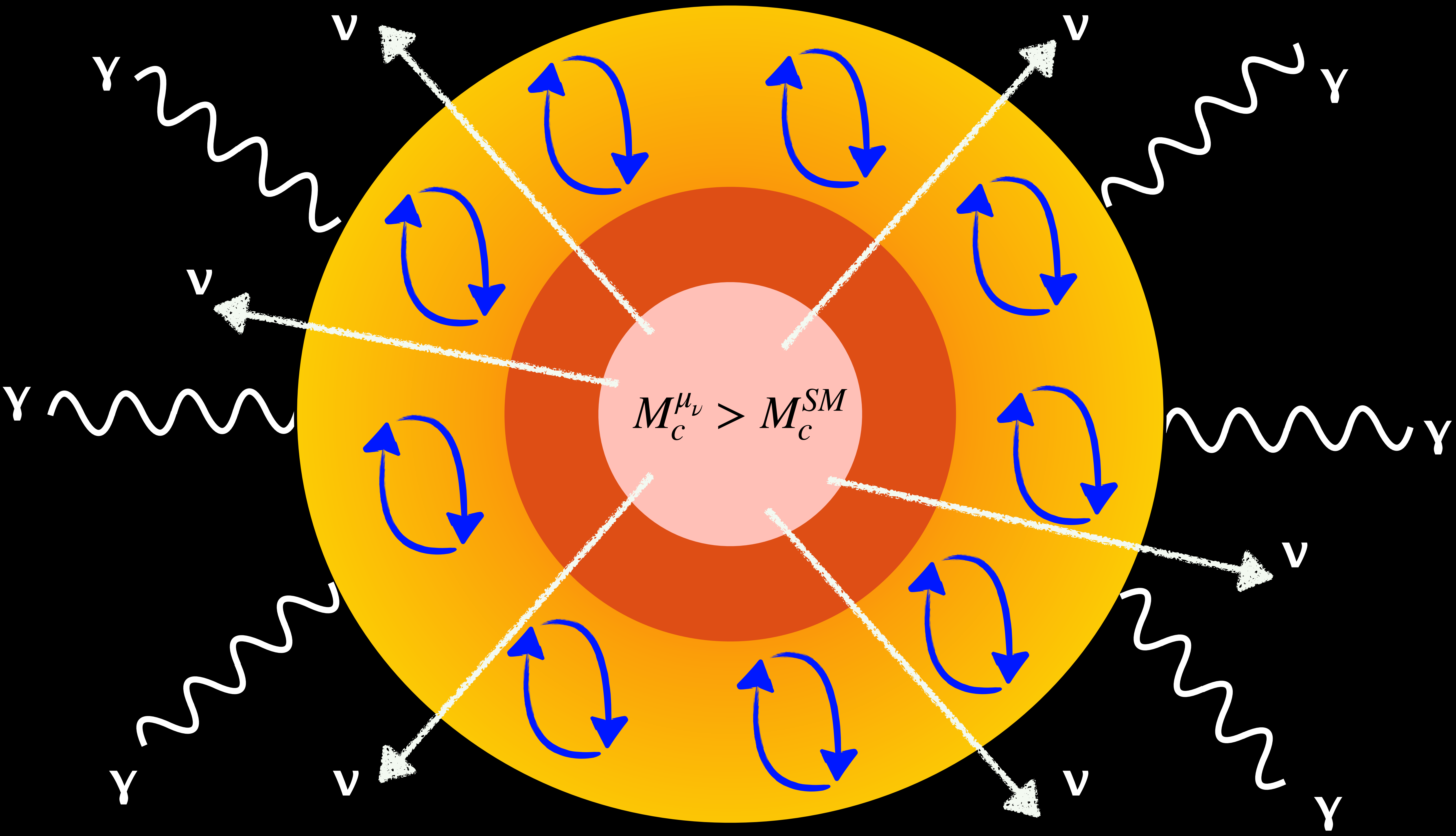
The **TIP** is the RGB star with maximum luminosity

Constraints: cooling of RGB stars



In the SM the core cools through plasmon decay into neutrinos ($\gamma^* \rightarrow \nu + \bar{\nu}$)

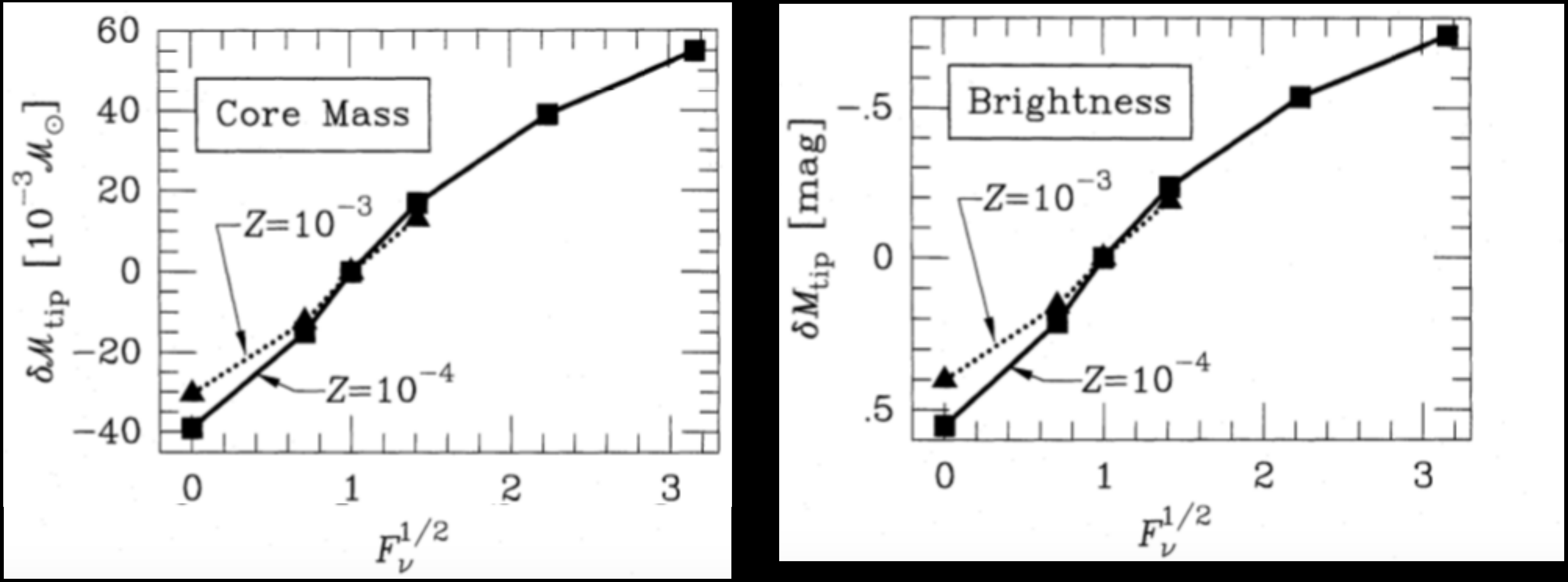
Constraints: cooling of RGB stars



The larger μ_ν, the more neutrinos are emitted, the later He ignition happens, the bigger M_c and the gravitational potential. **The Tip is more luminous.**

Constraints: cooling of RGB stars

Raffelt, Weiss, Astron. Astrophys. 264 (1992), 536-546



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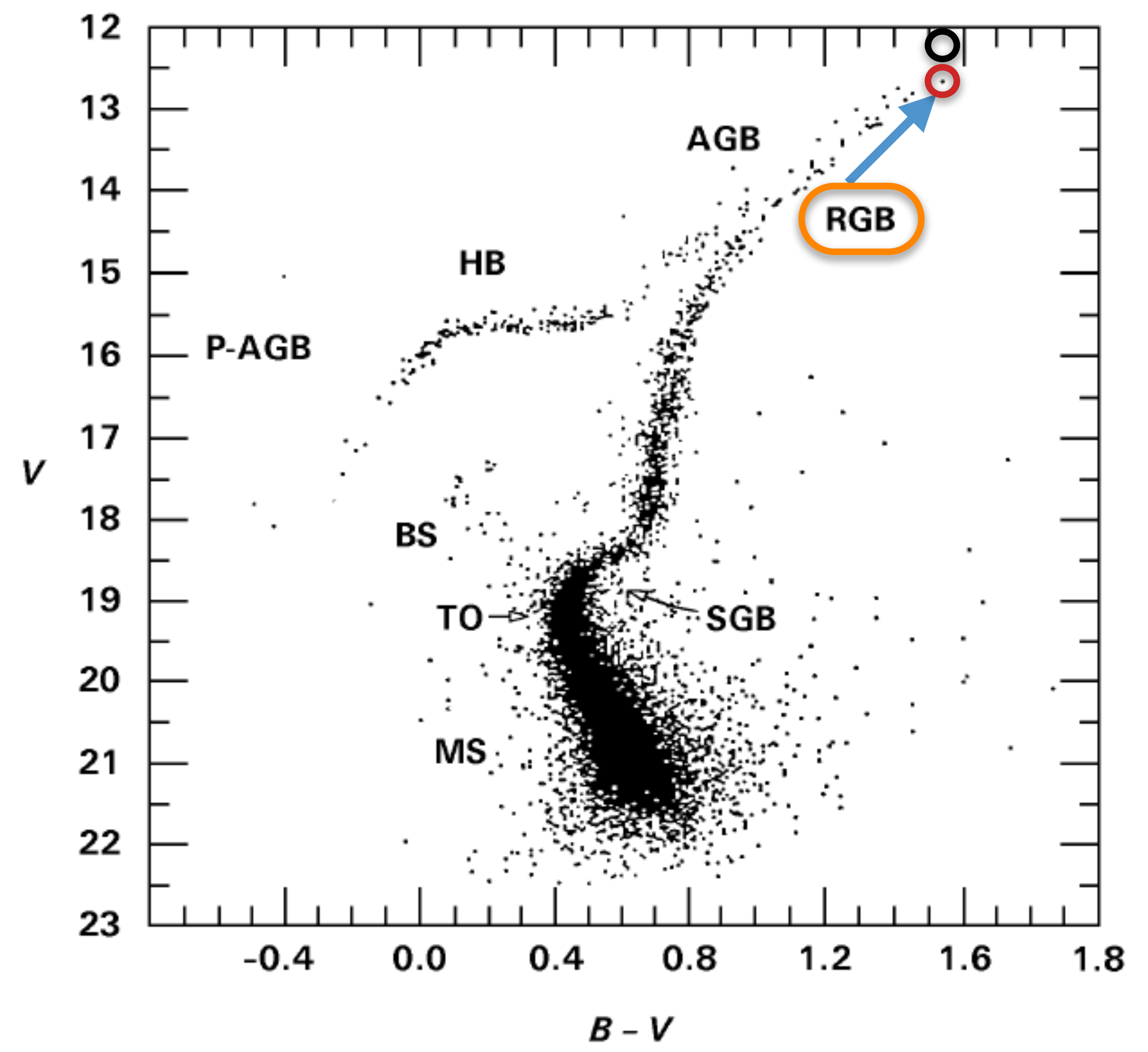
G. Raffelt, Lect. Notes Phys. 741 (2008), 51-71



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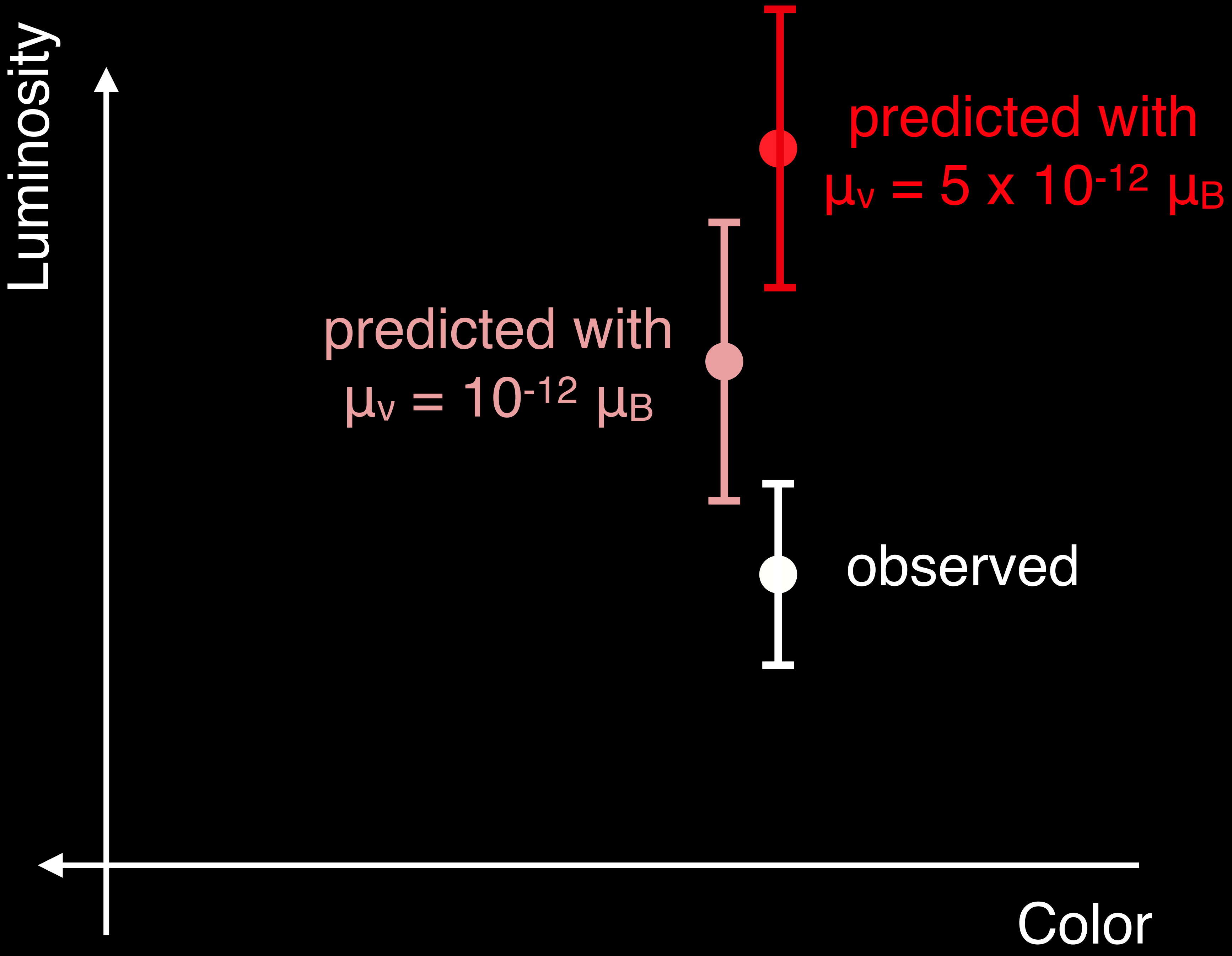
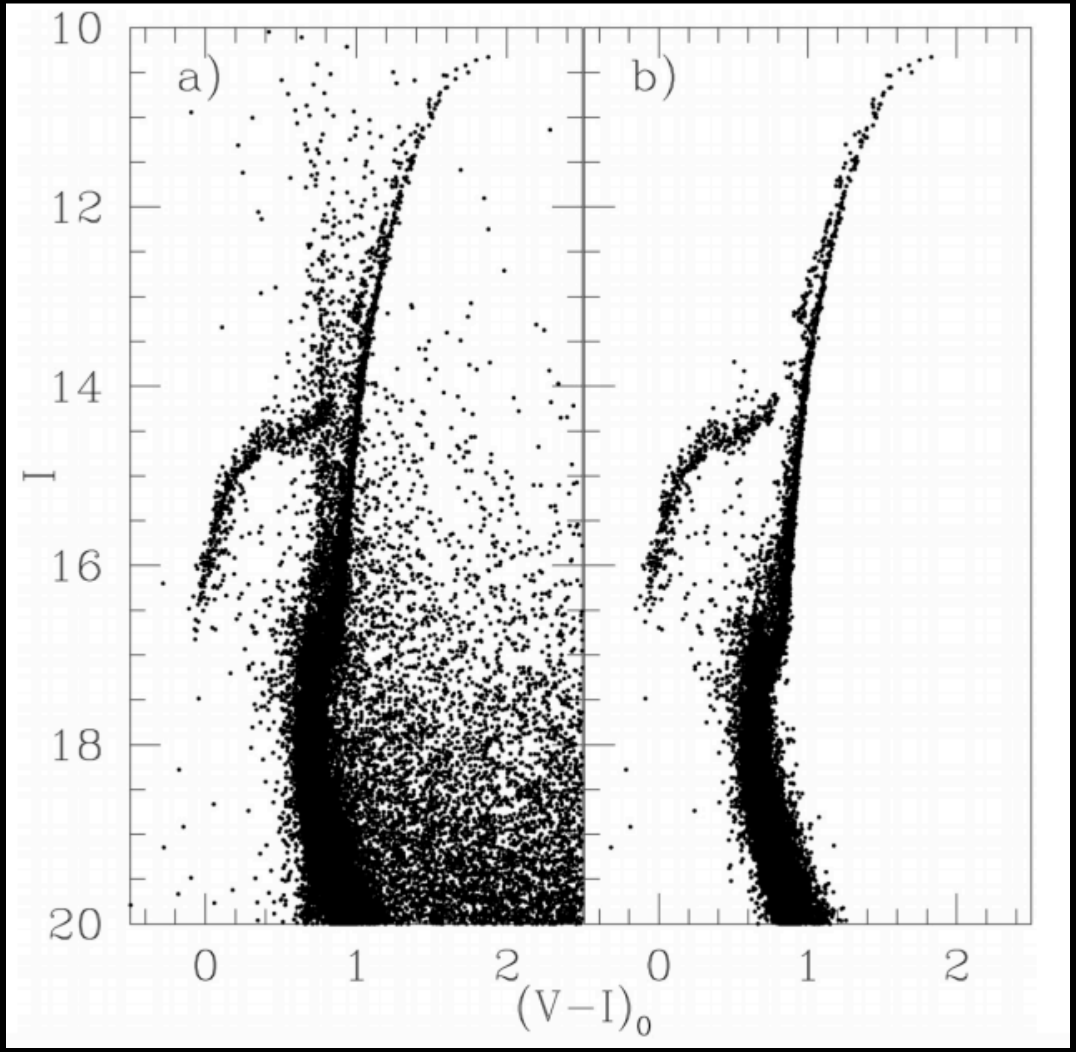


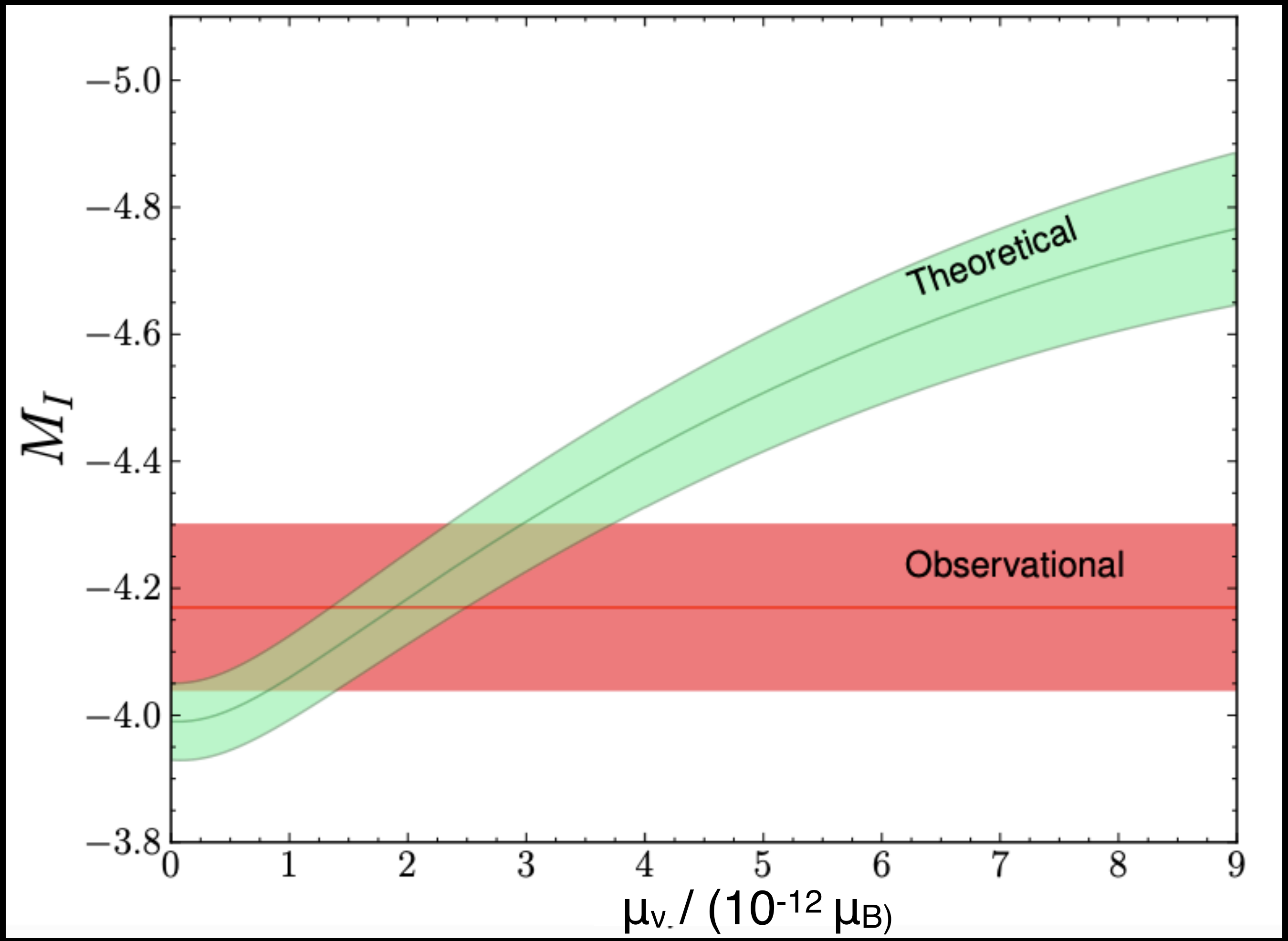
We can compare theory and observation to constrain extra cooling (axions-electron coupling g_{ae}, neutrino anomalous magnetic moment μ_ν, …)

Constraints: cooling of RGB stars

Example: globular cluster M5

Viaux et al., AA 558 (2013), A12

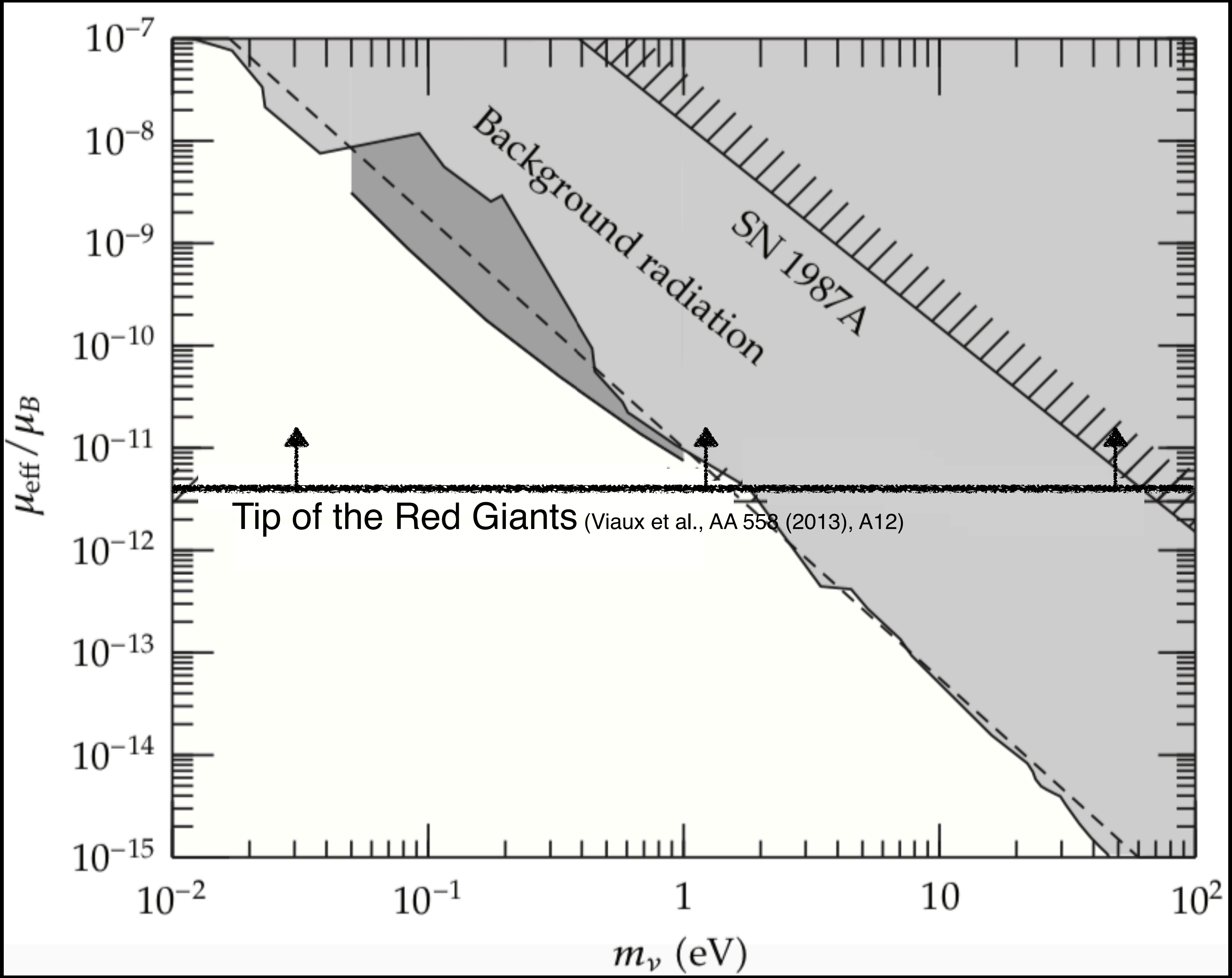




Slight preference for extra cooling

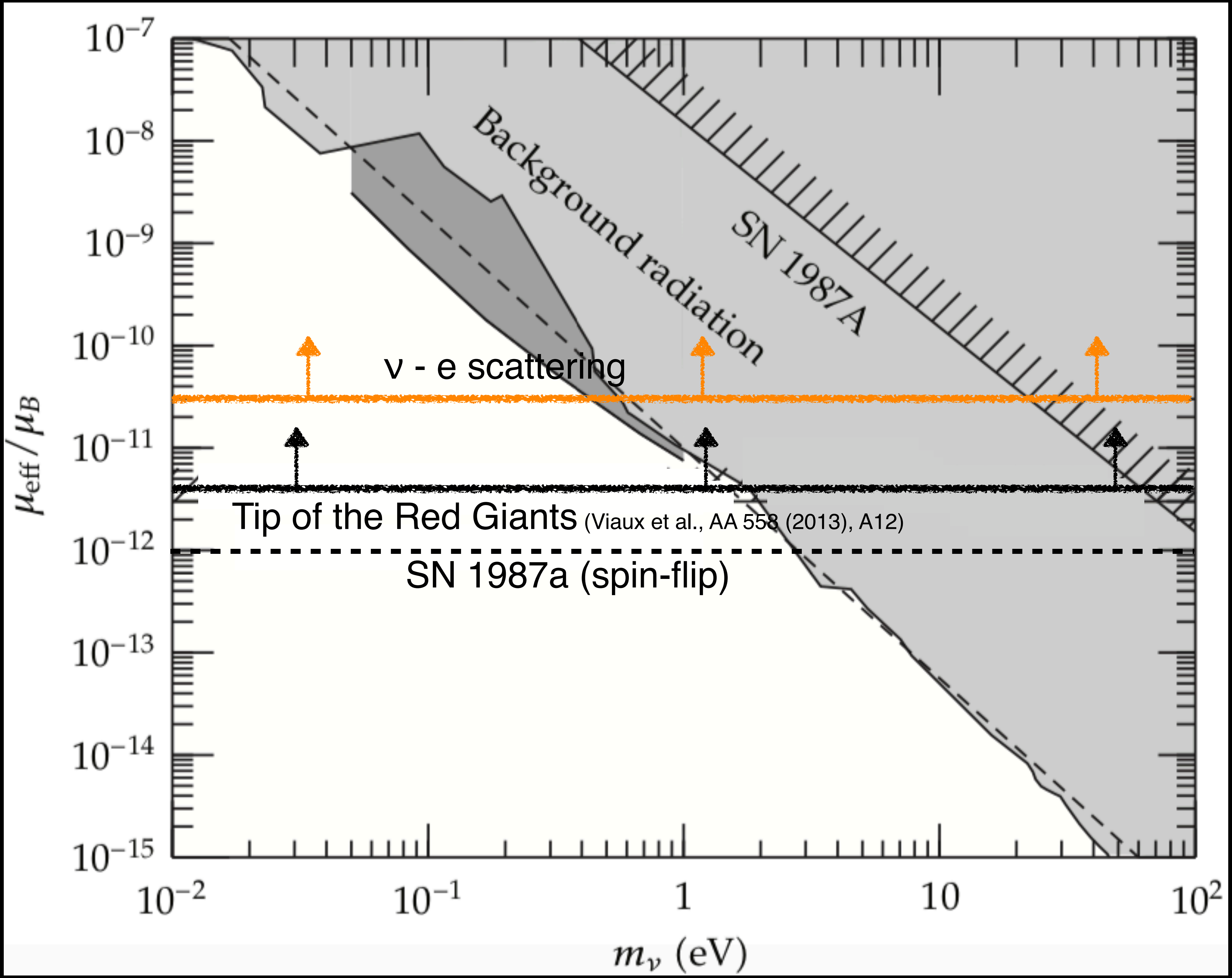
Constraints: astrophysical

Raffelt, Phys. Rept. 320, 319-327 (1999)



Constraints: summary

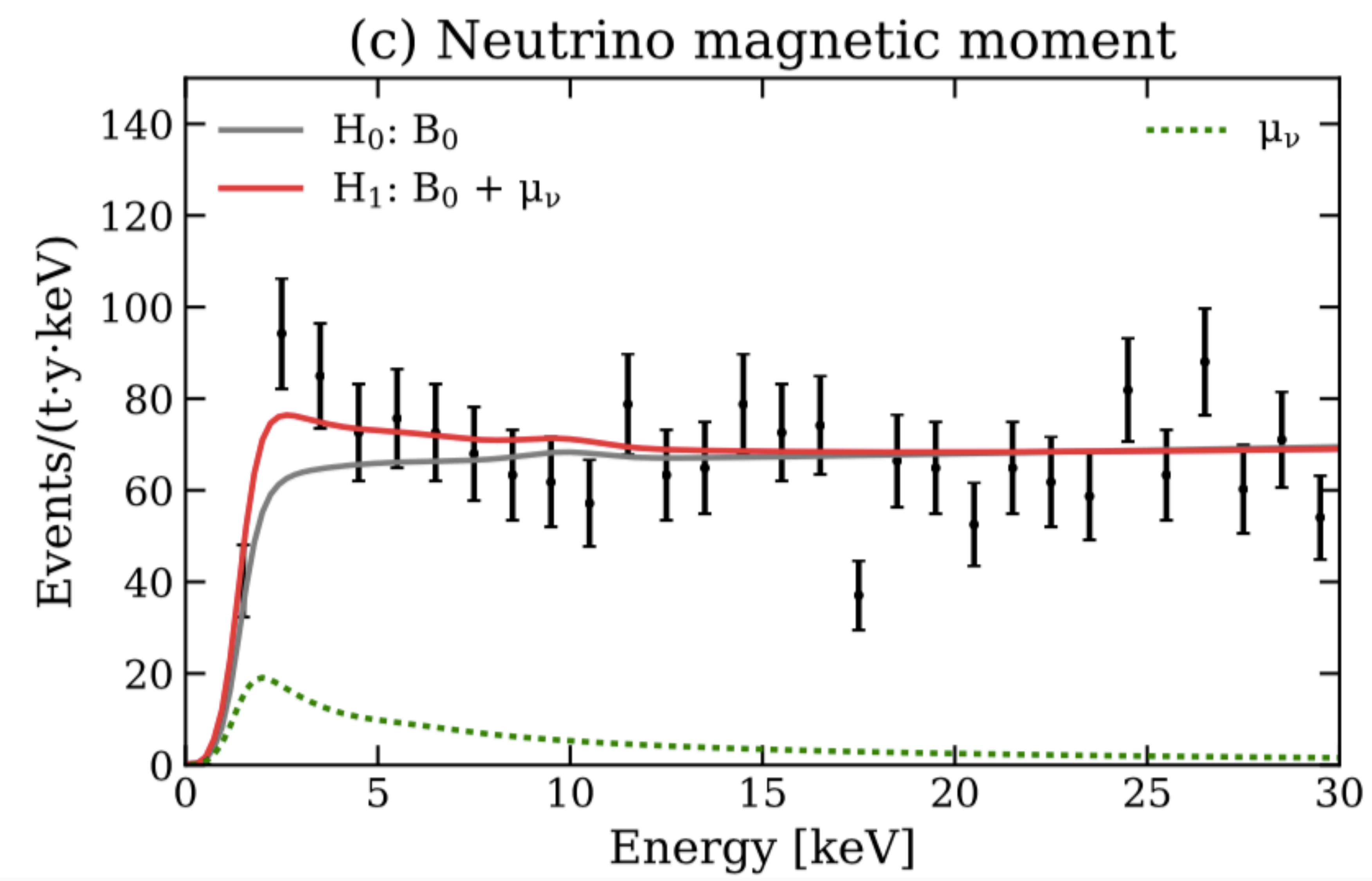
Raffelt, Phys. Rept. 320, 319-327 (1999)



Xenon1T excess

Xenon1T observed an excess in low-energy electronic recoil data

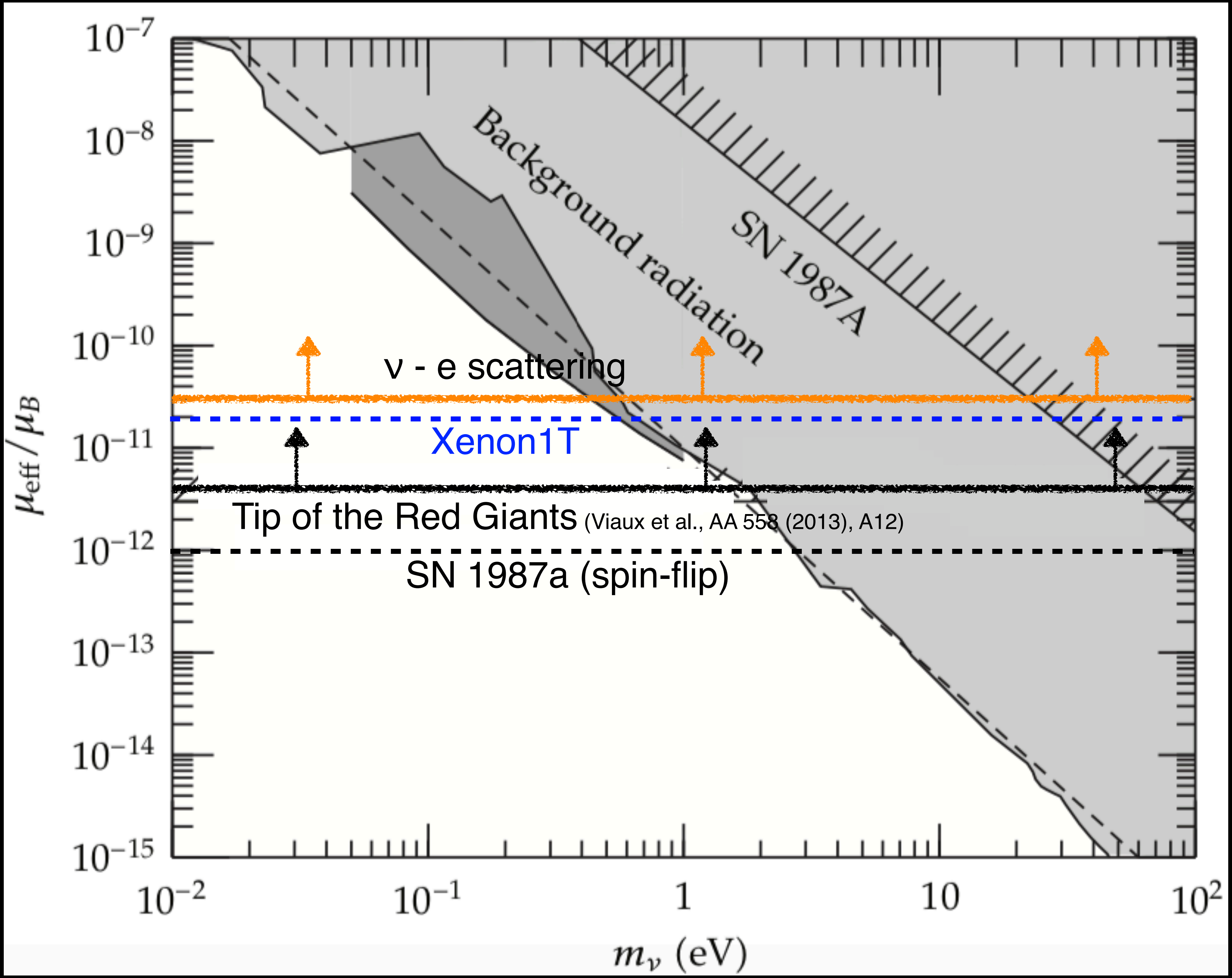
Aprile *et al.*, Phys. Rev. D 102 (2020) no.7, 072004



The excess can be explained by solar neutrinos with $\mu_\nu \simeq 2 \times 10^{-11} \mu_B$

Xenon1T excess

Raffelt, Phys. Rept. 320, 319-327 (1999)



What next?

SN1987a constraints are the strongest, but depend on many unknowns

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TRGB bounds are reliable, but affected by large experimental uncertainties

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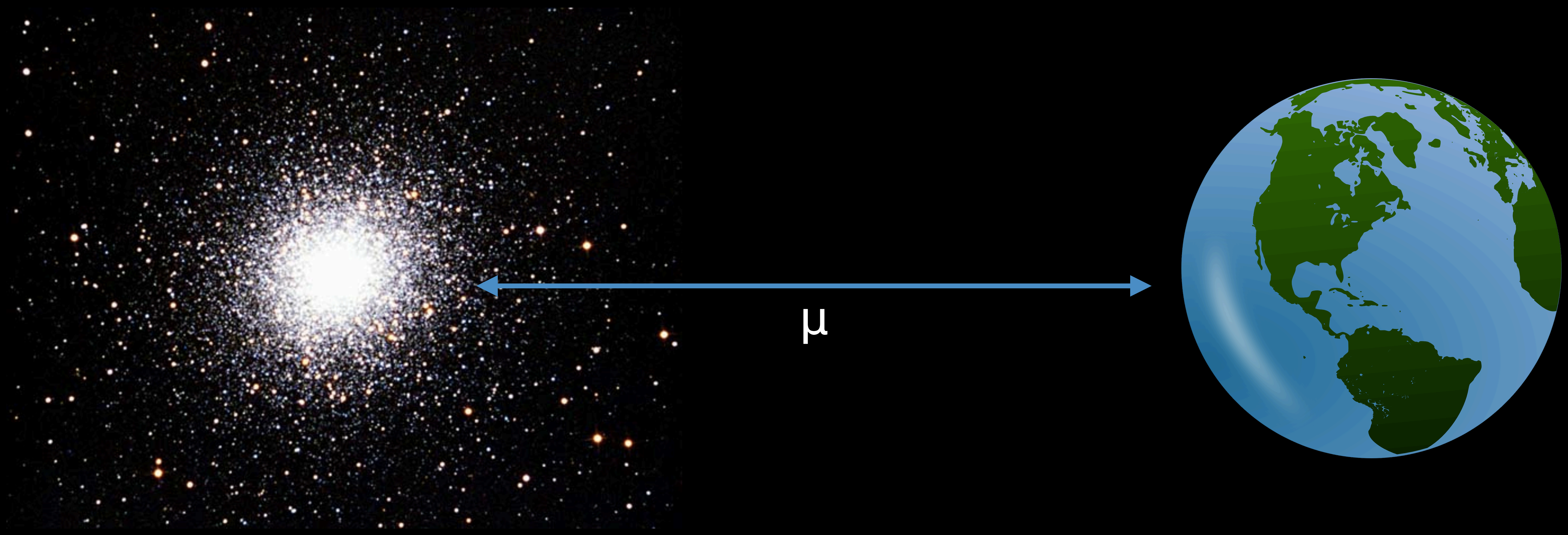
SN1987a constraints are the strongest, but depend on many unknowns

TRGB bounds are reliable, but affected by large experimental uncertainties

Can we improve TRGB bounds wrt Viaux et al., AA 558 (2013) A12?

What is new for TRGB?

Usually RGB stars in Globular Clusters are used



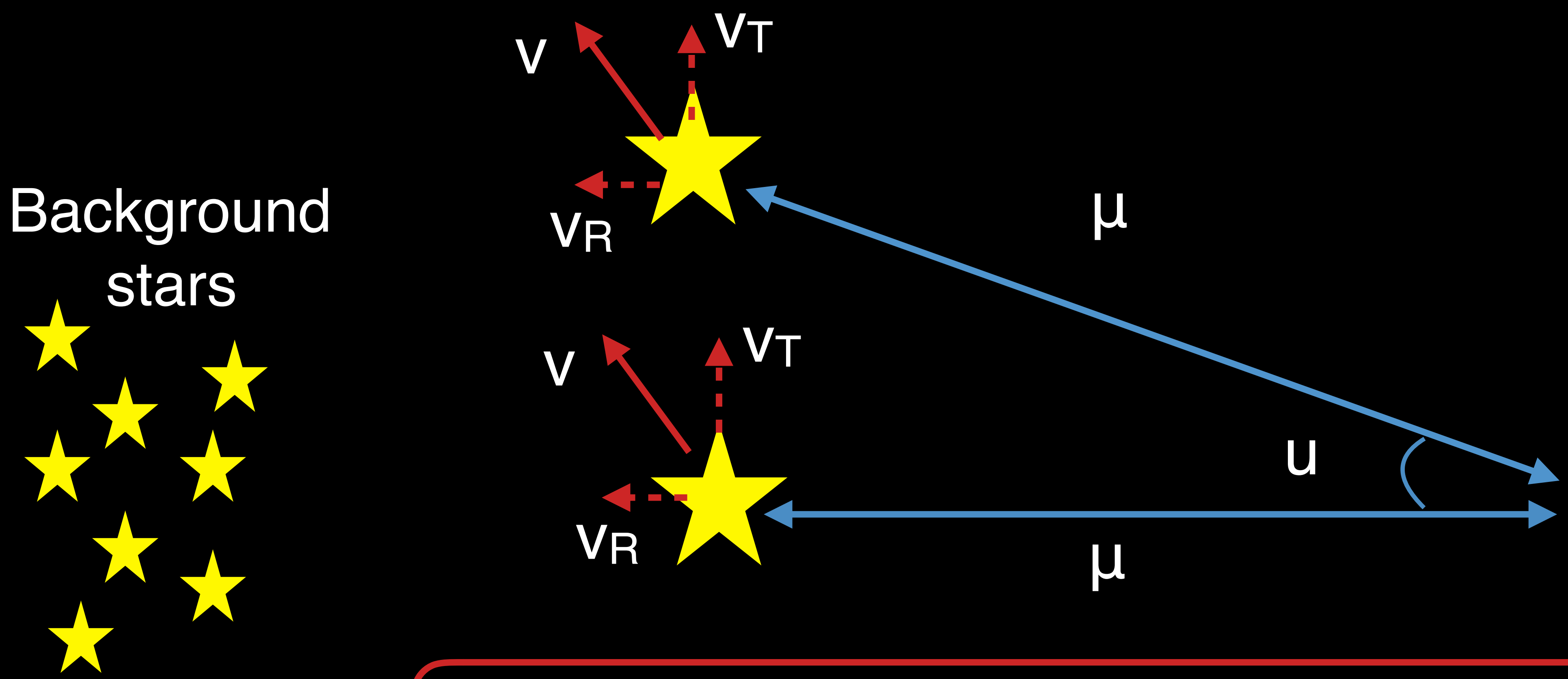
M13, Wikimedia Commons

$$M_{TRGB} = m_{TRGB} - \mu$$

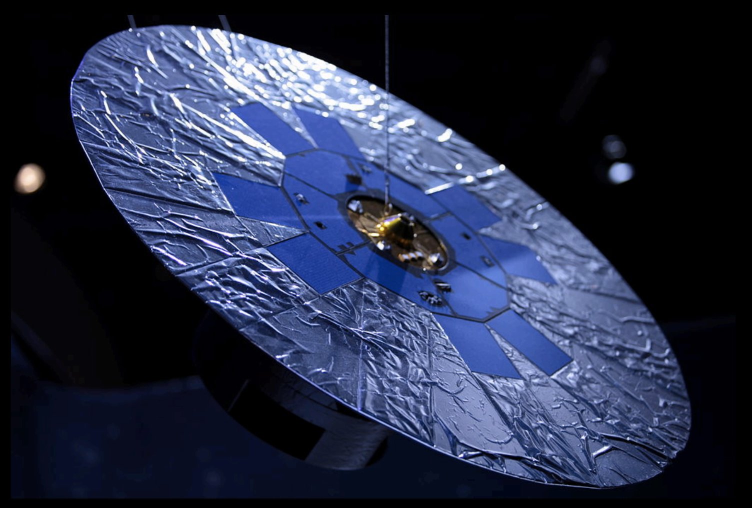
The main uncertainty has usually been the distance μ

What is new for TRGB?

Usually RGB stars in Globular Clusters are used



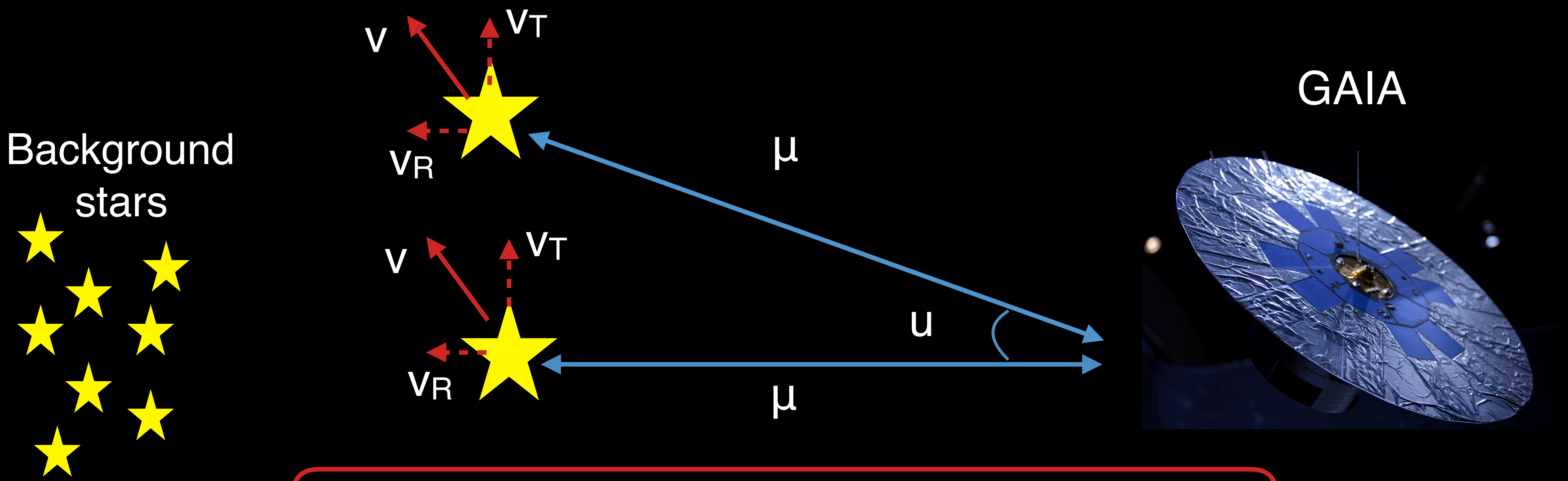
GAIA



- measure v_R from star spectrum and Doppler effect
- measure u (proper motion) with observation in time

What is new for TRGB?

Usually RGB stars in Globular Clusters are used



- measure v_R from star spectrum and Doppler effect
- measure u (proper motion) with observation in time

Get μ from N-body simulation that reproduce observed kinematics of cluster

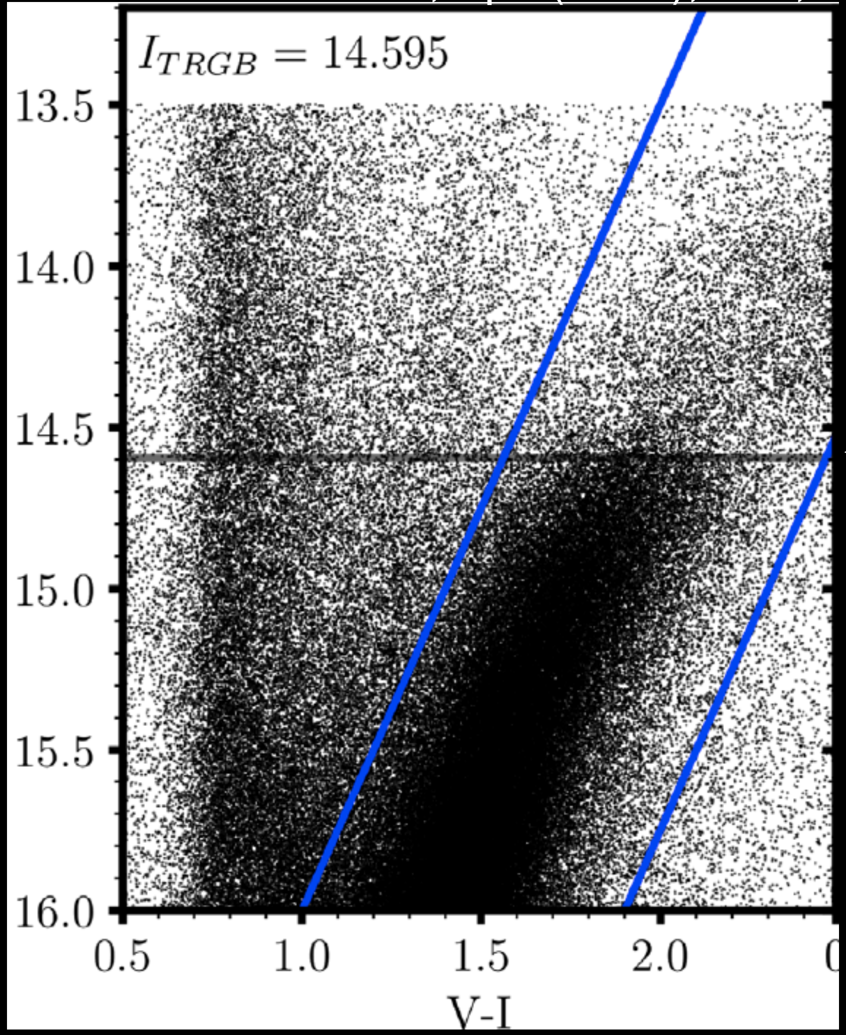
H. Baumgardt, et al, Mon. Not. R. Astron. Soc. 482

What is new for TRGB?

Precise calibration of TRGB from galaxies: Large Magellanic Cloud

W. L. Freedman et al., ApJ (2019), 882, 34

m_I

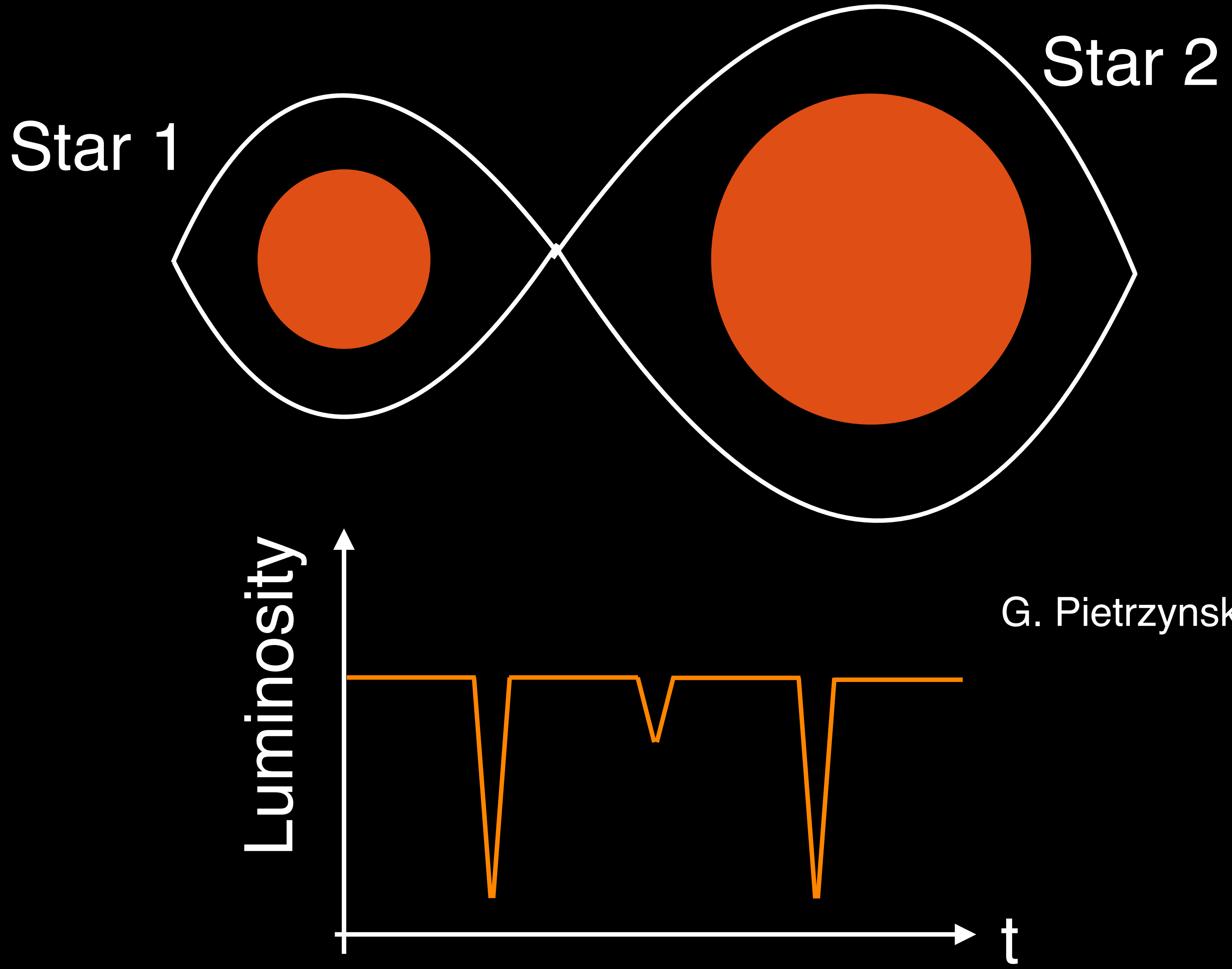


TRGB line

New precise distance from **detached eclipsing binary stars**.
Nice alternative to Globular Clusters!

What is new for TRGB?

Detached eclipsing binaries as distance indicators



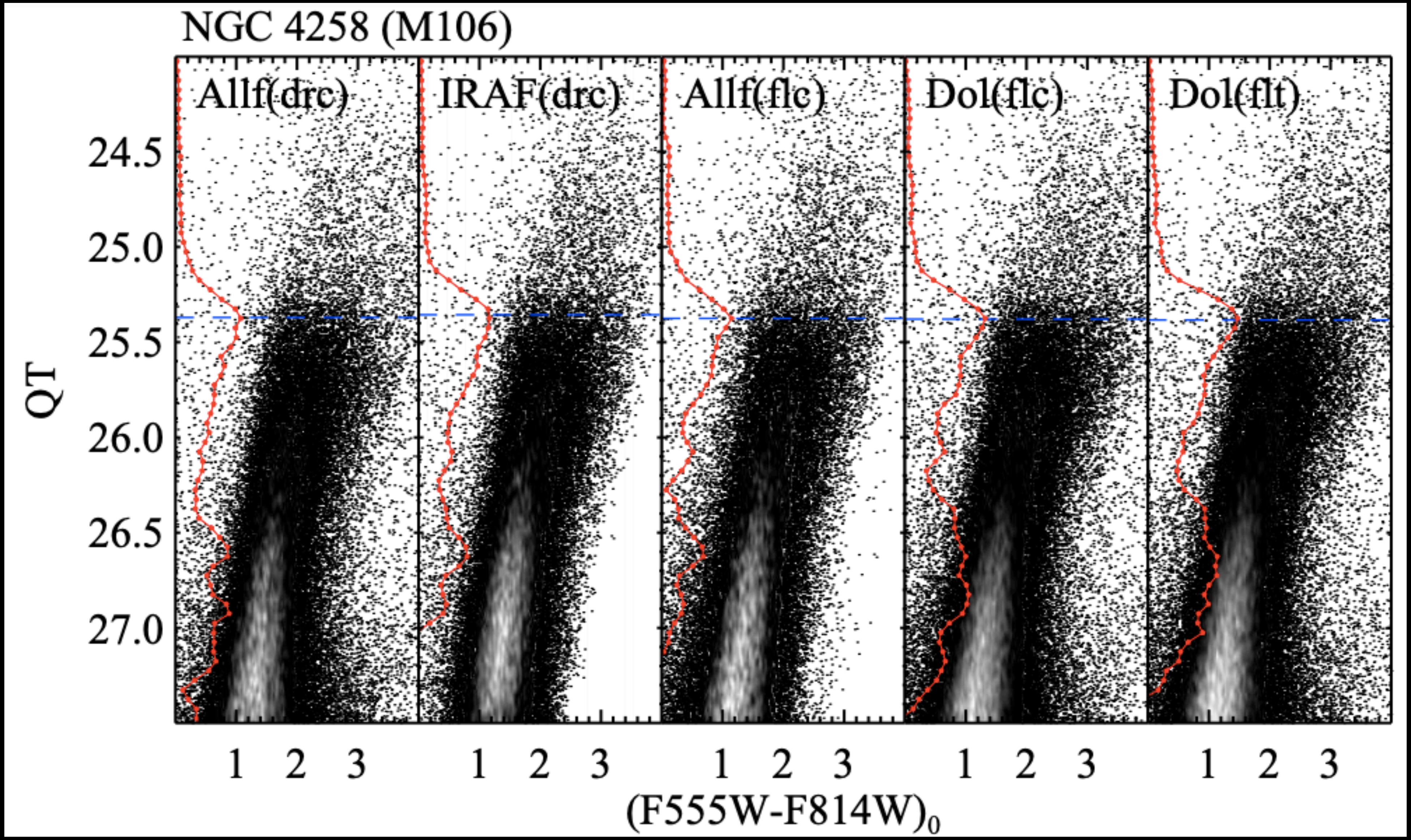
For LMC, see
G. Pietrzynski et al., Nature 567 (2019) 200

Radii of stars from eclipses time, masses from radial velocities, surface brightness from empirical relations or atmosphere models

What is new for TRGB?

Precise calibration of TRGB from galaxies: NGC 4258

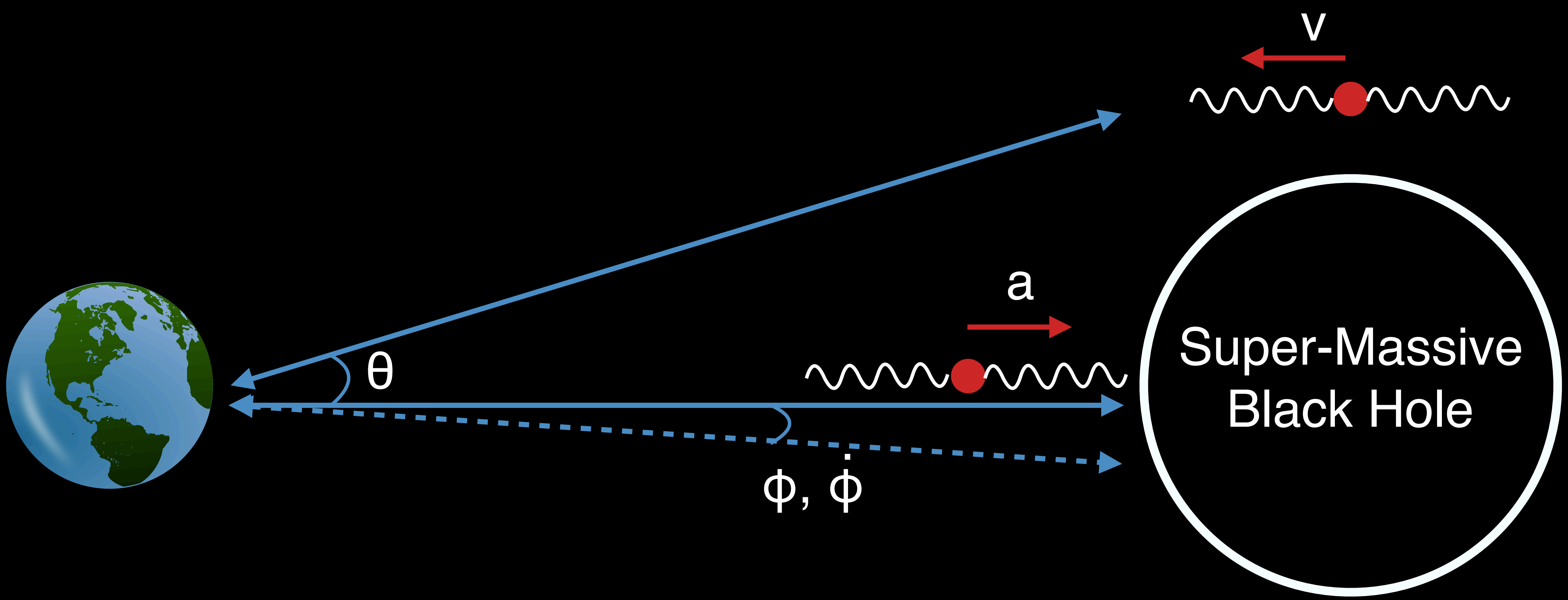
I. S. Jang and M. G. Lee, Astrophys. J. 835 (2017) 28



New precise distance from **Megamasers**.
Nice alternative to Globular Clusters!

What is new for TRGB?

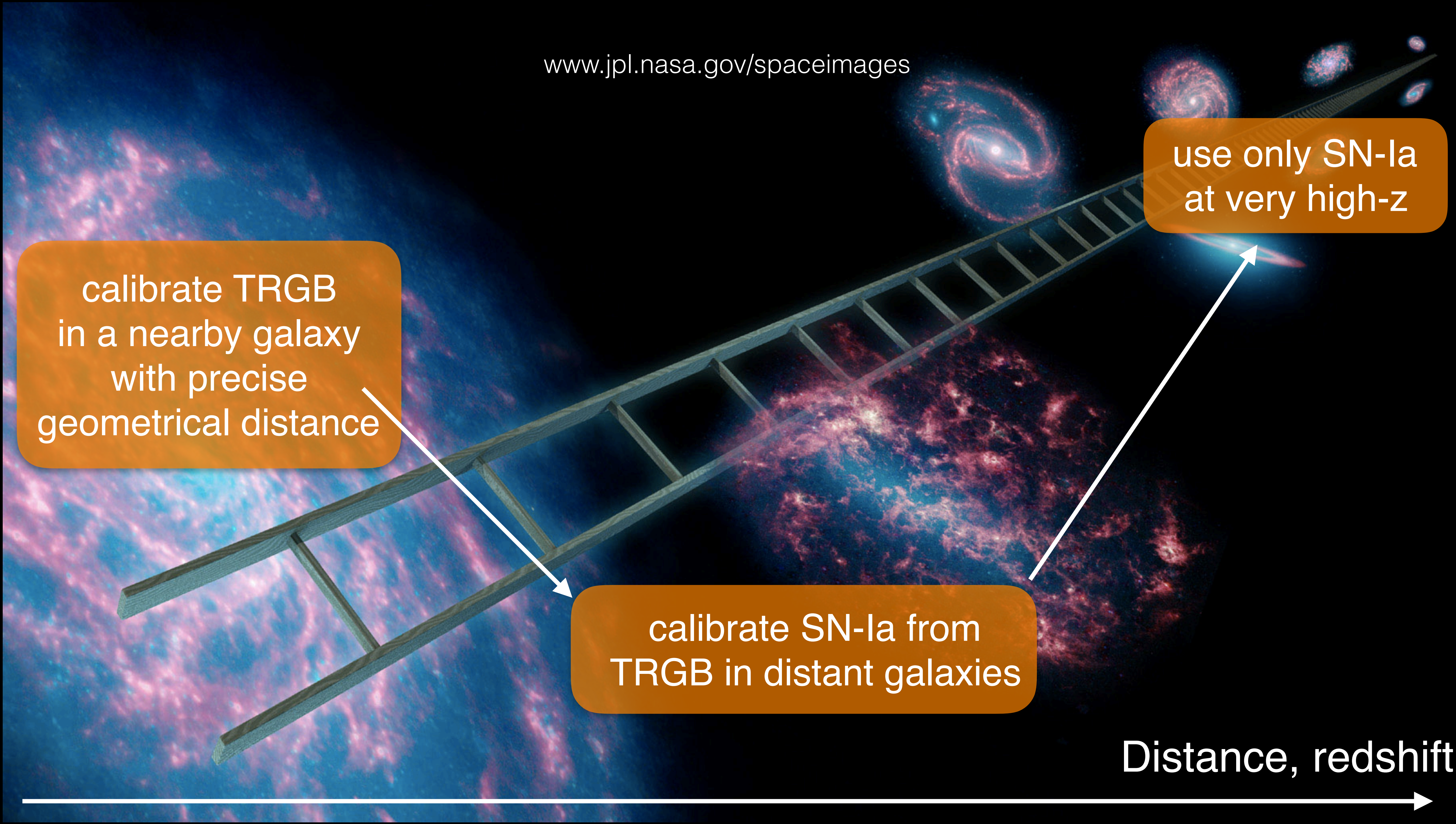
Megamasers from accretion disks of SMBH as distance indicators



For NGC 4258, see
M. Reid et al., Astrophys. J. Lett. 886 (2019) L27

Very long baseline interferometry can measure v, a, θ, ϕ.
This is enough for getting the distance of the galaxy

What is new for TRGB?



www.jpl.nasa.gov/spaceimages

calibrate TRGB
in a nearby galaxy
with precise
geometrical distance

calibrate SN-Ia from
TRGB in distant galaxies

use only SN-Ia
at very high-z

Distance, redshift

Final goal of new precise distances is actually measuring H_0 with SN-Ia

What is new for TRGB?

Important developments for the theoretical predictions of TRGB

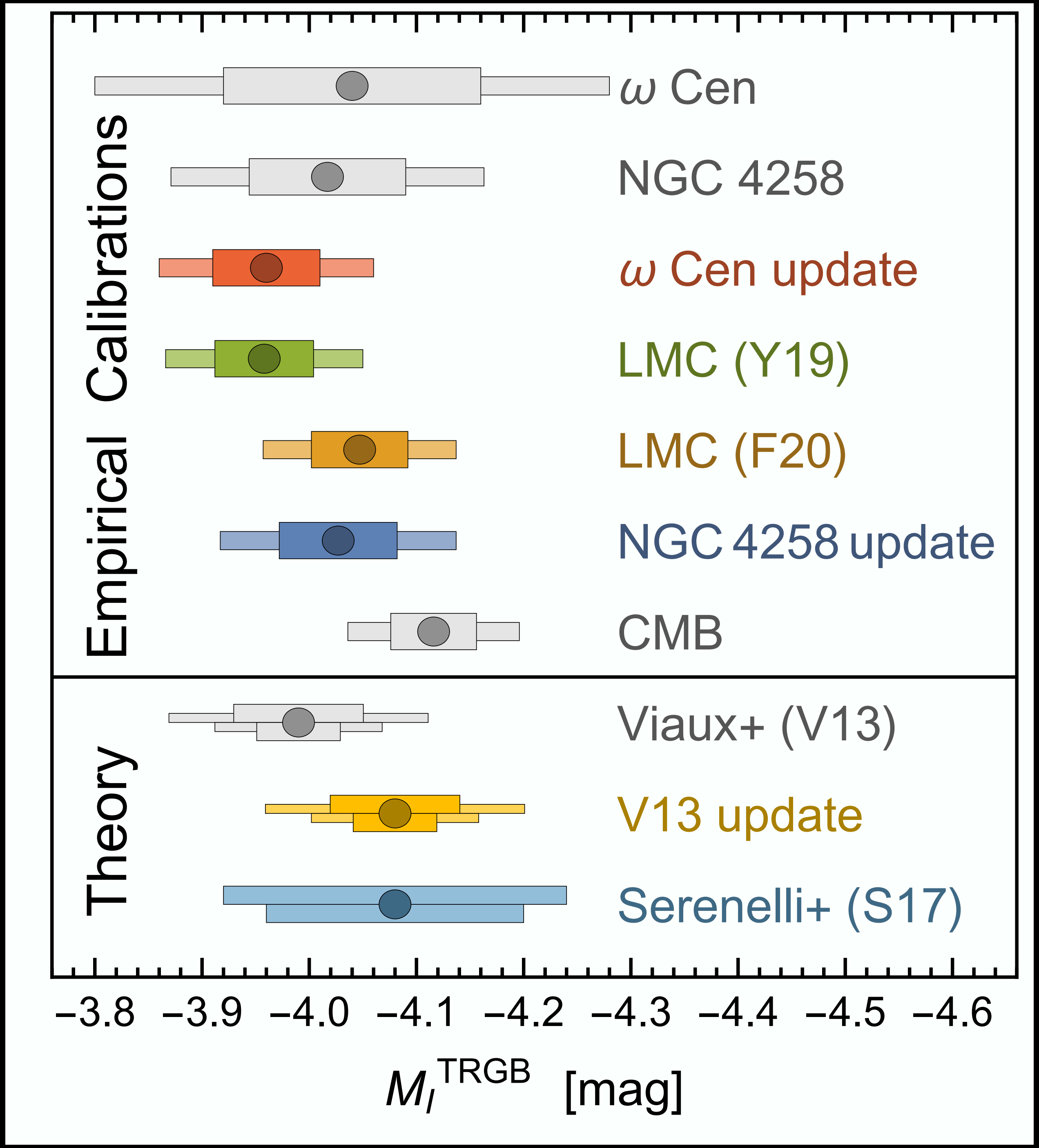
A. Serenelli et al., , Astron. Astrophys. 606 (2017) A33

$$M_{TRGB} = -4.090 + 0.017[(V-I)^{TRGB} - 1.4] + 0.036[(V-I)^{TRGB} - 1.4]^2$$

Detailed assessment of theoretical uncertainties also available

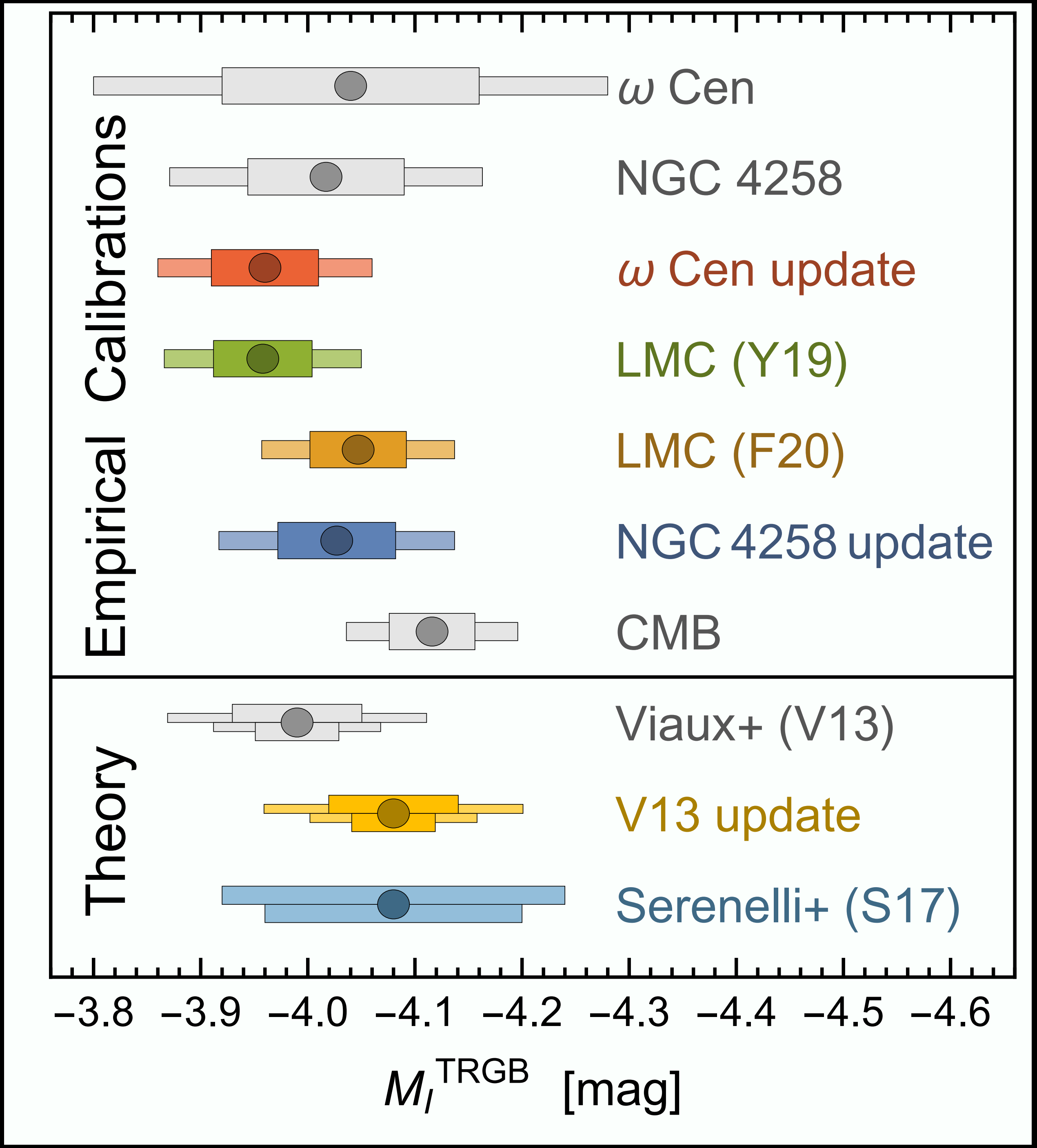
Theoretical error sources: nuclear reaction rates, nuclear reaction screening, mixing length, equation of state, radiative opacities, conductive opacities, neutrino emission, diffusion

Current TRGB calibrations



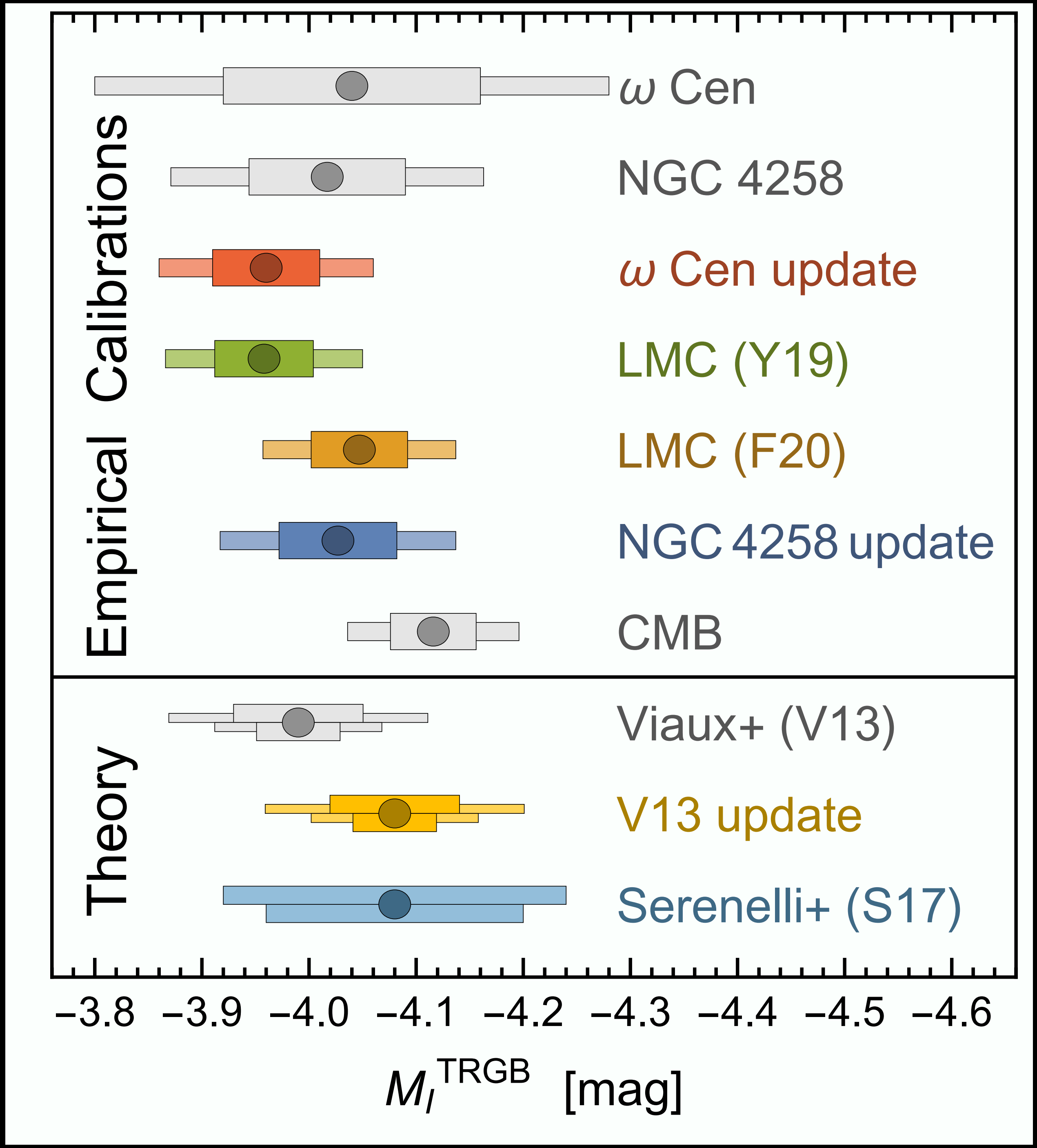
old calibrations

Current TRGB calibrations



new calibrations

Current TRGB calibrations



aggressive bounds

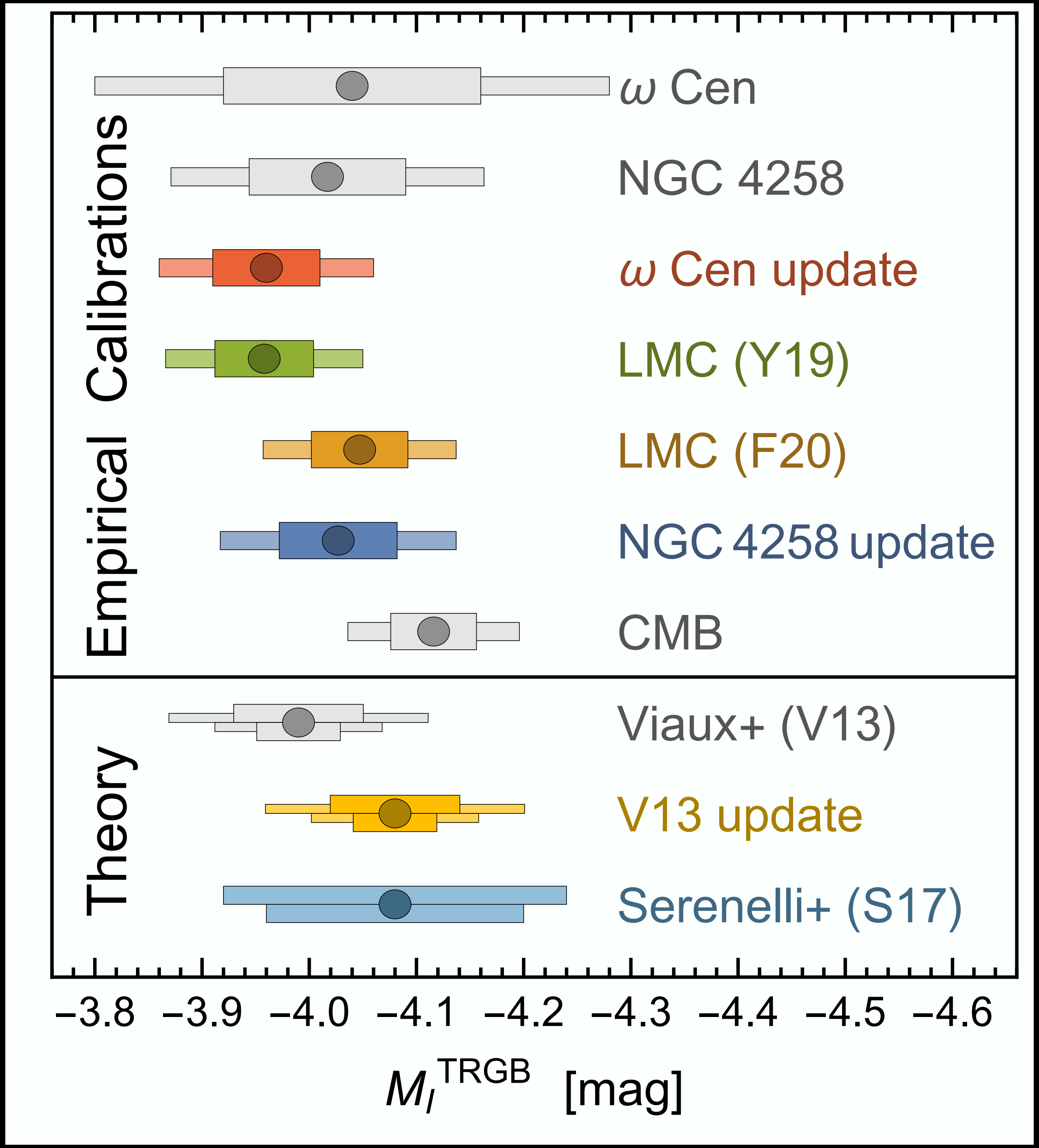
conservative bounds

Debate on the extinction of the LMC

F20: W. L. Freedman et al. , Astrophys. J. 891 (2020) 57

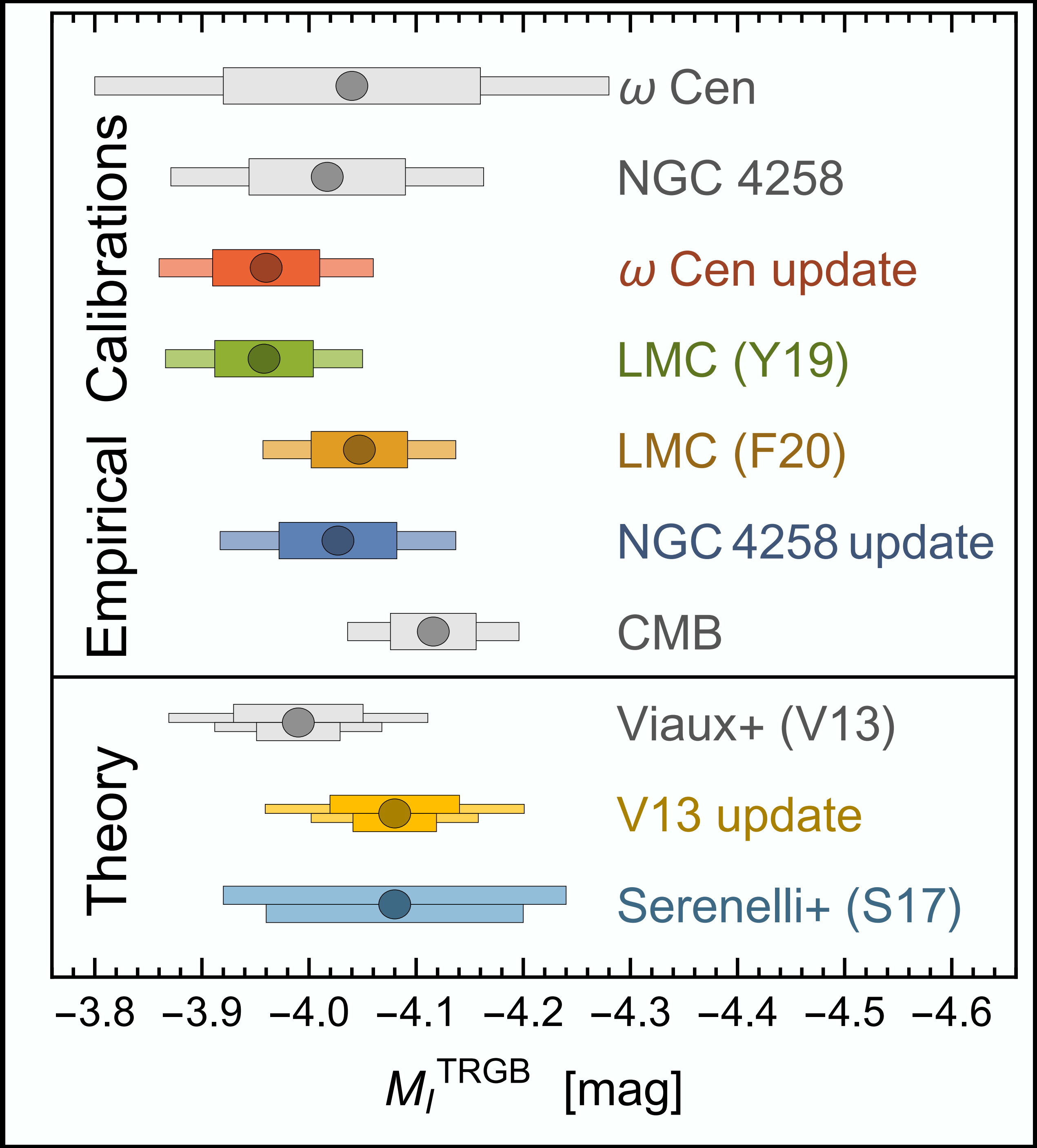
Y19: W. Yuan et al., Astrophys. J. 886 (2019) 61

Current TRGB calibrations



← inverted LMC calibration adopting H_0 from PLANCK measurements

Current TRGB calibrations

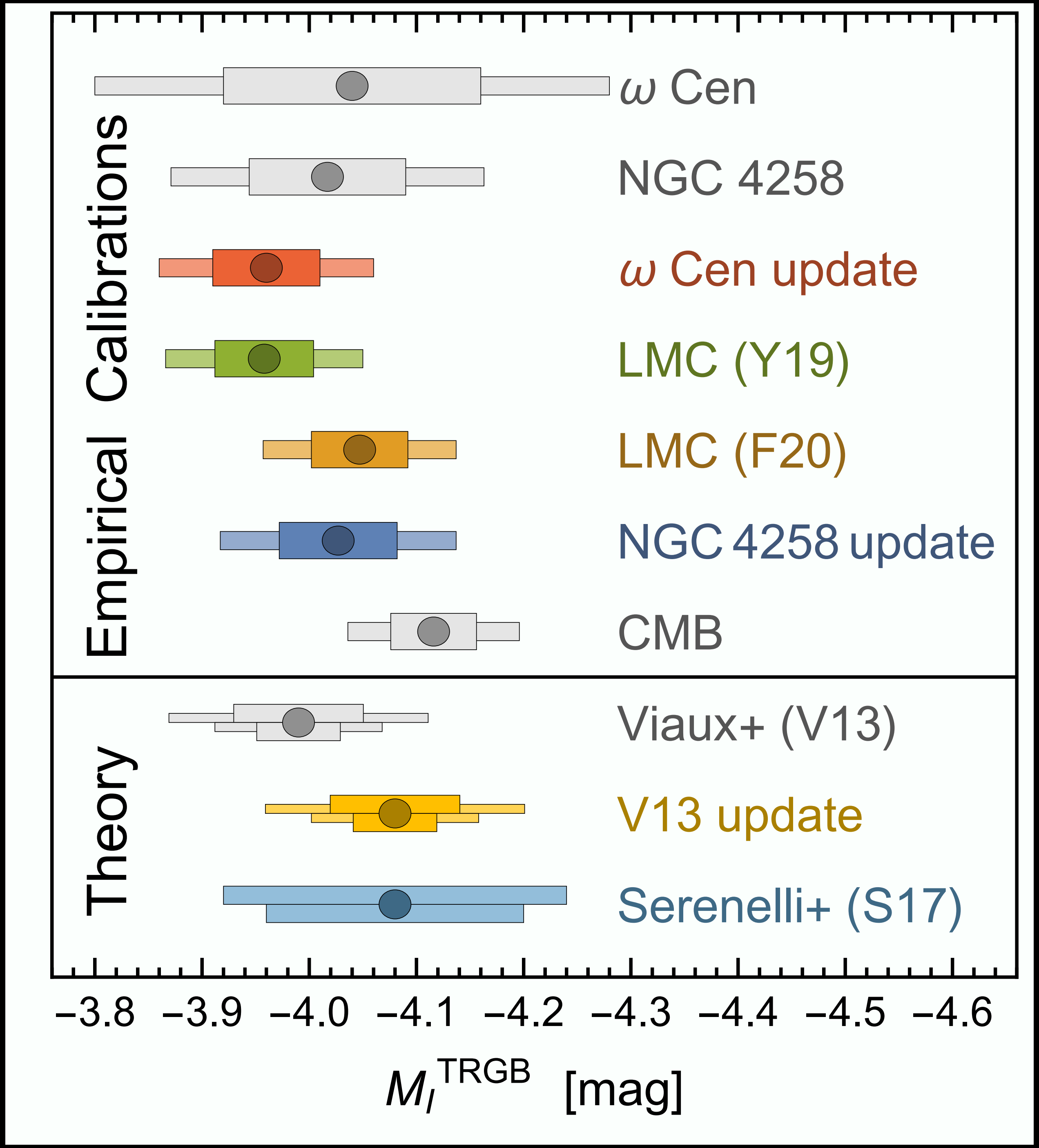


V13
Viaux et al., AA 558 (2013), A12

S17
A. Serenelli et al., AA 606 (2017) A33

Theoretical error sources: nuclear reaction rates, nuclear reaction screening, equation of state, radiative opacities, conductive opacities, neutrino emission, diffusion

Current TRGB calibrations



V13
Viaux et al., AA 558 (2013), A12

S17
A. Serenelli et al., AA 606 (2017) A33

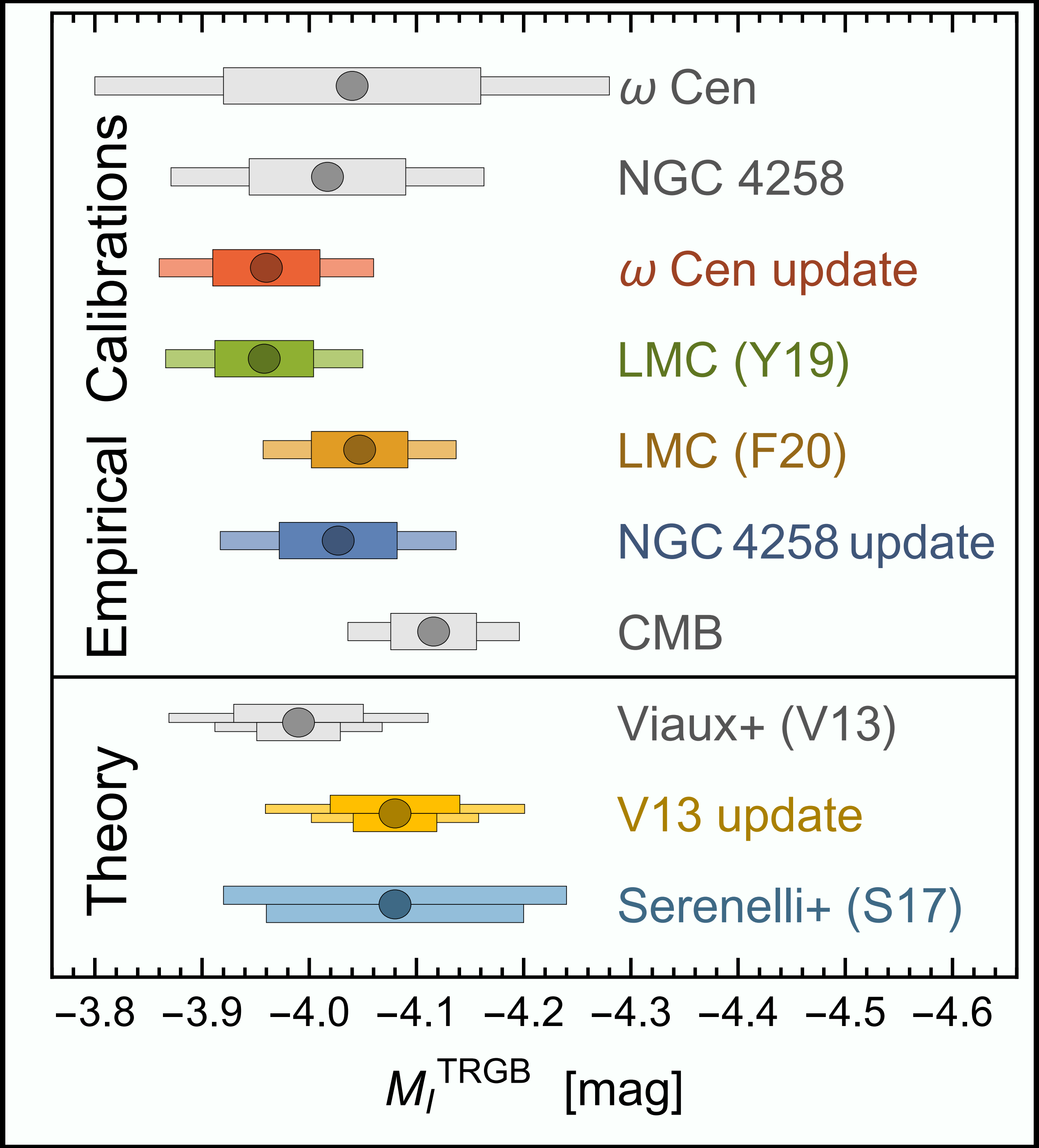
← old V13 prediction

← new V13 prediction following S17 prescription

V13 intend errors as Gaussian

Theoretical error sources: nuclear reaction rates, nuclear reaction screening, mixing length, equation of state, radiative opacities, conductive opacities, neutrino emission, diffusion

Current TRGB calibrations



V13
Viaux et al., AA 558 (2013), A12

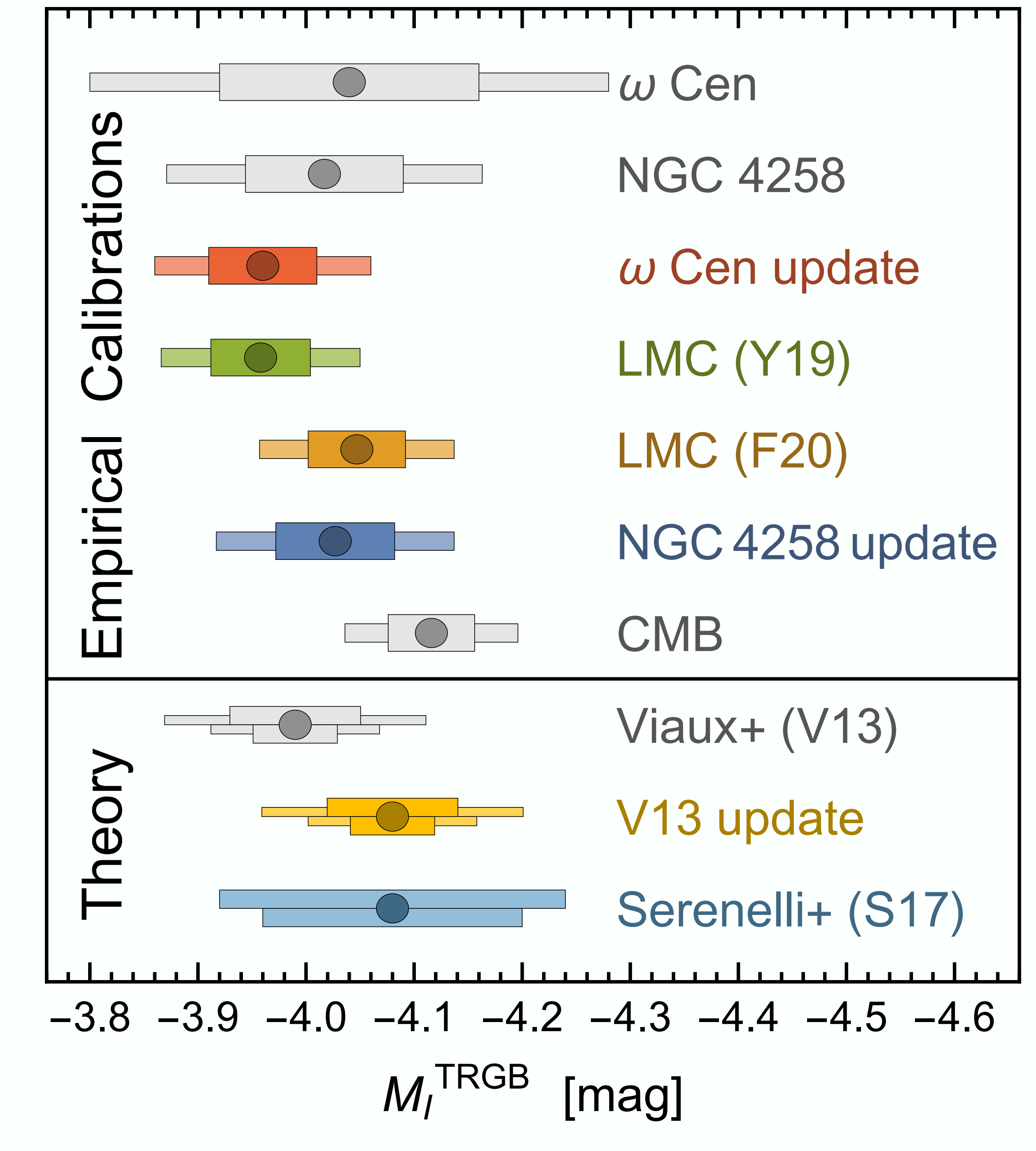
S17
A. Serenelli et al., AA 606 (2017) A33

← latest calibration

S17 intend errors as maximal range

Theoretical error sources: nuclear reaction rates, nuclear reaction screening, equation of state, radiative opacities, conductive opacities, neutrino emission, diffusion

Current TRGB calibrations



V13
Viaux et al., AA 558 (2013), A12

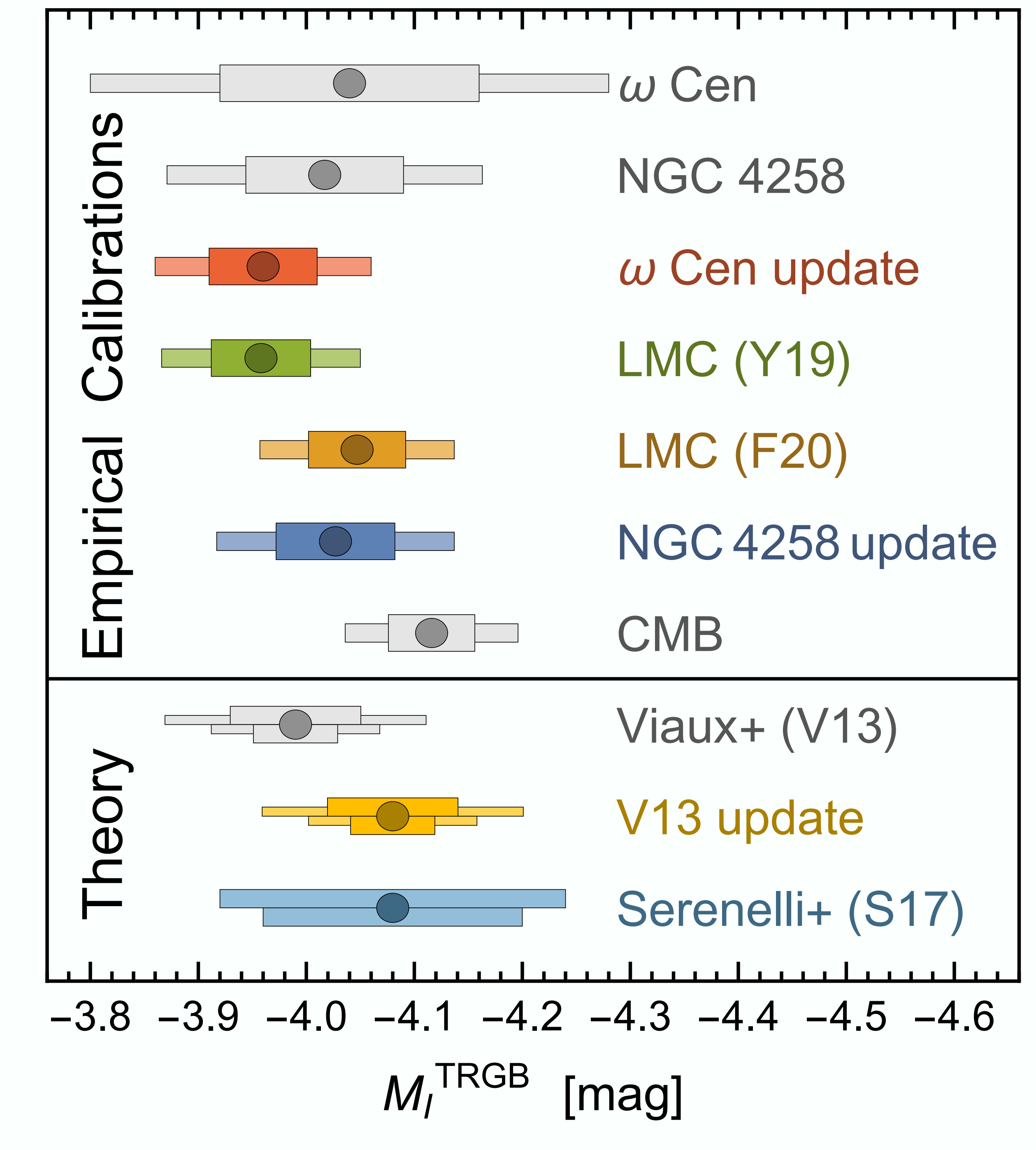
S17
A. Serenelli et al., AA 606 (2017) A33

Top bar include bolometric correction

$BC = M_{bol} - M_I$

Theoretical error sources: nuclear reaction rates, nuclear reaction screening, equation of state, radiative opacities, conductive opacities, neutrino emission, diffusion

Current TRGB calibrations



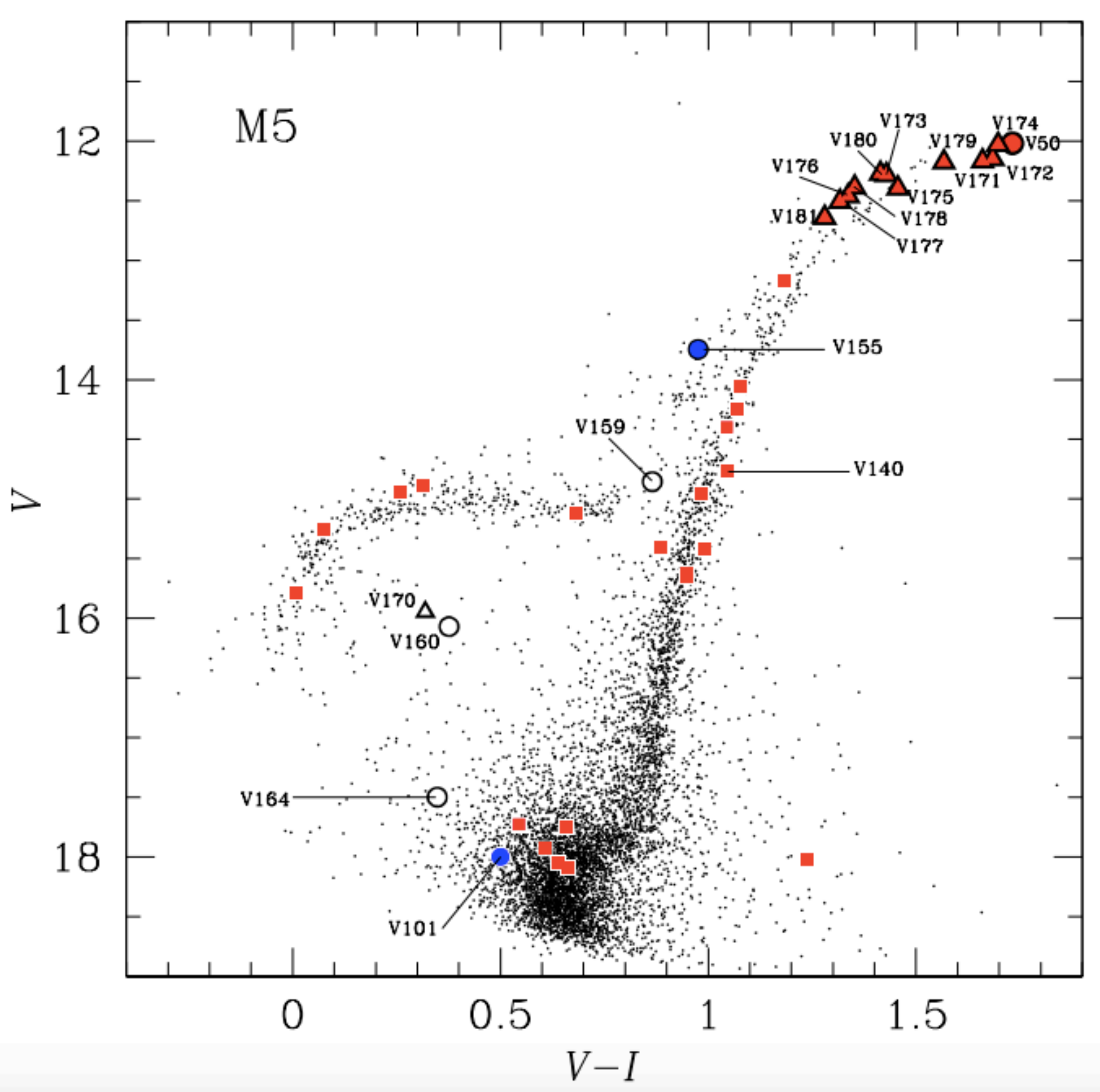
Theory and observations in agreement.

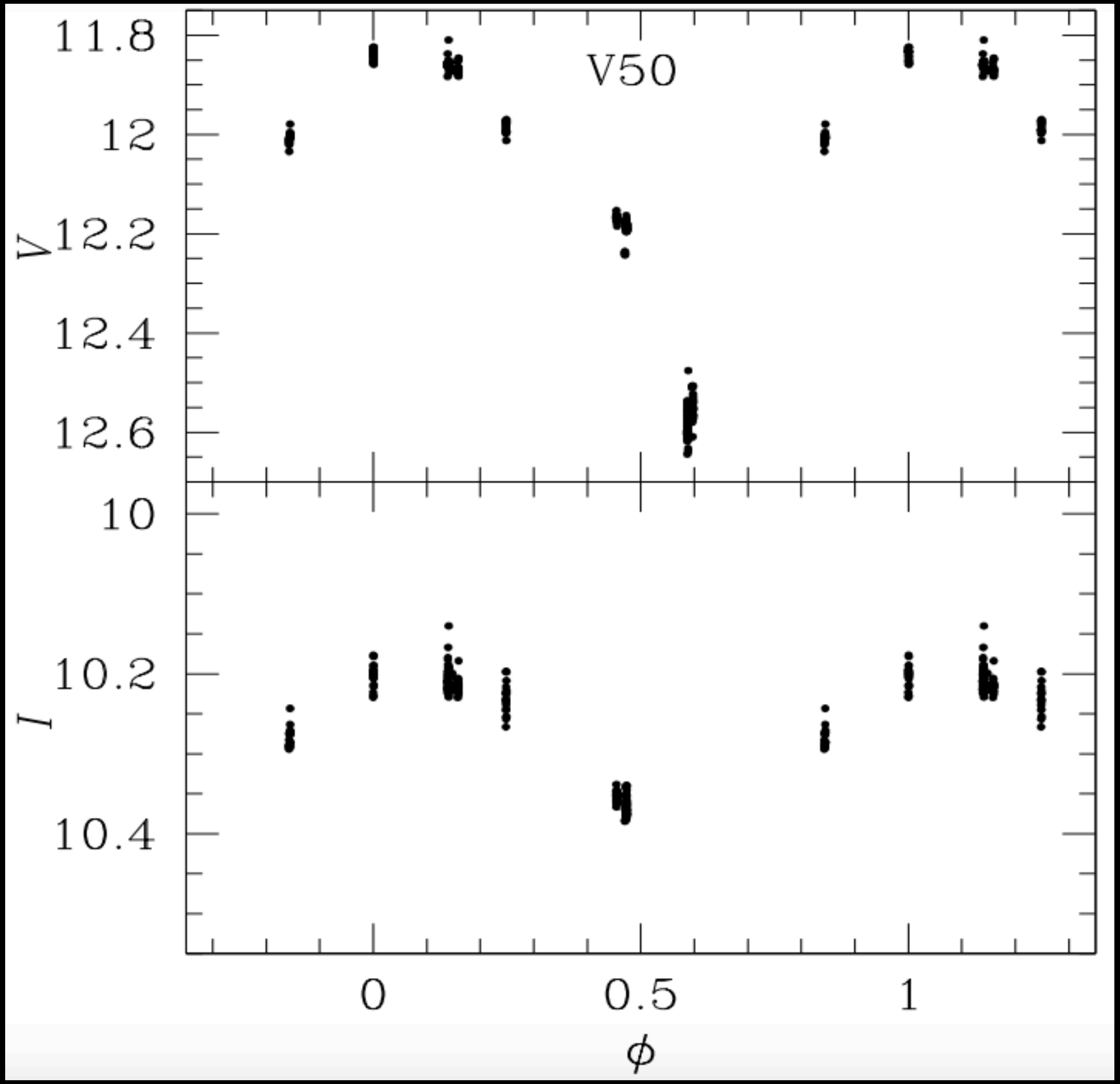
Errors dominated by theory and bolometric corrections

What has been left out?

M5 has been previously used in literature in Viaux et al., AA 558 (2013), A12

Arellano Ferro et al., Information Bulletin on Variable Stars 6137 (2015) 1



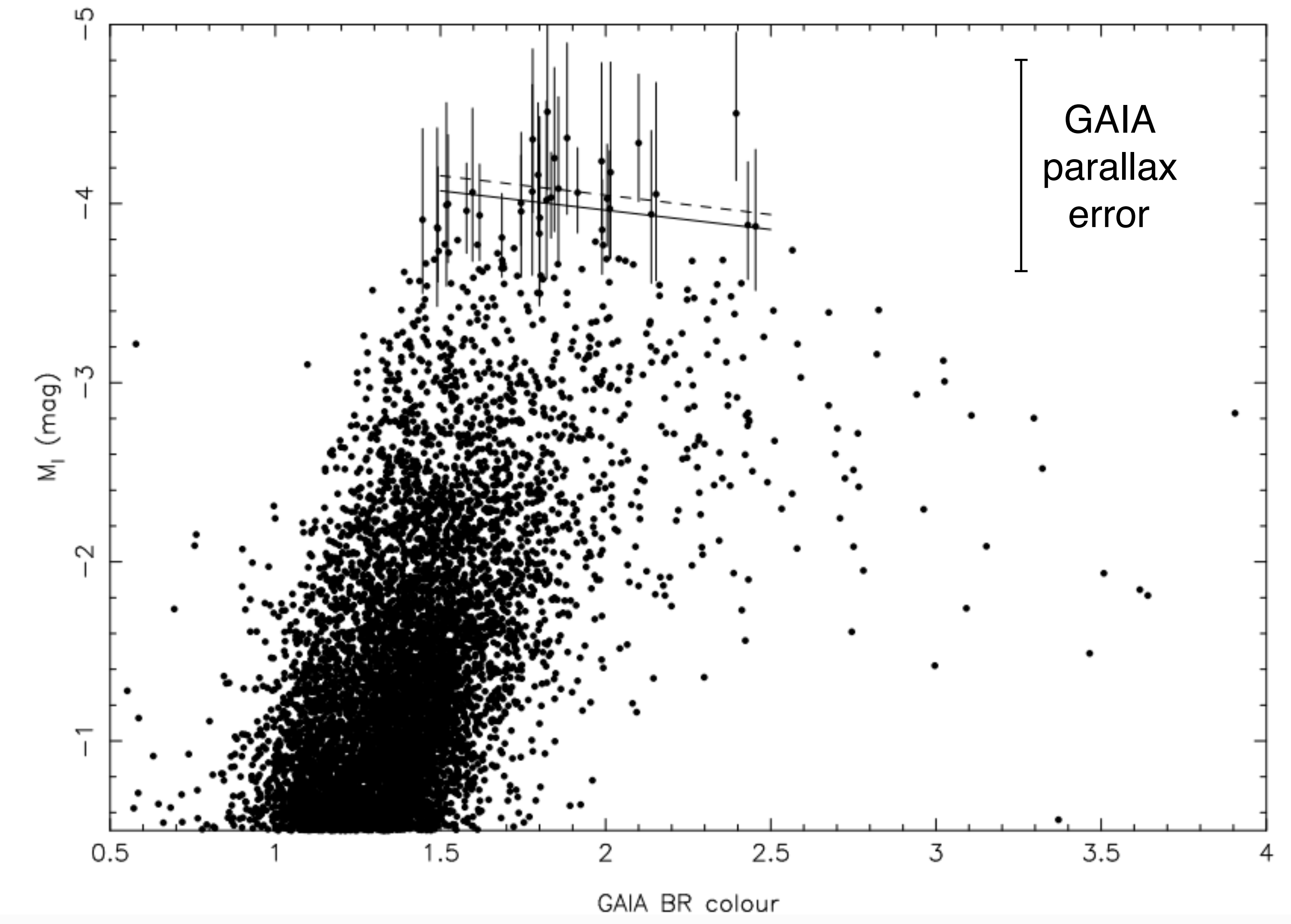


However the brightest star seems to be a variable star (V50)

What has been left out?

Red giant stars in the halo of the Milky Way

J. Mould et al., Publ. Astron. Soc. Australia 36 (2019) E001



Not yet competitive, but future GAIA data will improve the uncertainties

Bounds on extra cooling

We express neutrino magnetic moment bounds with $\mu_{12} = \mu_\nu / (10^{-12}\,\mu_B)$

We consider theoretical predictions at (V-I) = 1.8

Bounds on extra cooling

Theoretical predictions of TRGB are modified by extra cooling

N. Viaux et al., AA 558 (2013), A12 (V13)

$$M_{TRGB}(th) = -4.08 - \delta M \pm \sigma_{th}$$

$$\delta M = -0.25\, [(\mu^2_{12} + 0.80)^{0.5} - 0.80 - 0.18\, \mu^{1.5}_{12}]$$

$$\sigma_{th} = [0.039^2 + (0.046 + 0.0075\, \mu_{12})^2]^{0.5}$$

We need to compare theoretical and empirical calibrations

Bounds on extra cooling

Assuming Gaussian errors:

$$\text{Likelihood} = \frac{e^{-\frac{(M^{\rm th}_{\rm TRGB} - M^{\rm emp}_{\rm TRGB})^2}{2(\sigma^2_{\rm th} + \sigma^2_{\rm emp})}}}{\sqrt{2\pi(\sigma^2_{\rm th} + \sigma^2_{\rm emp})}}$$

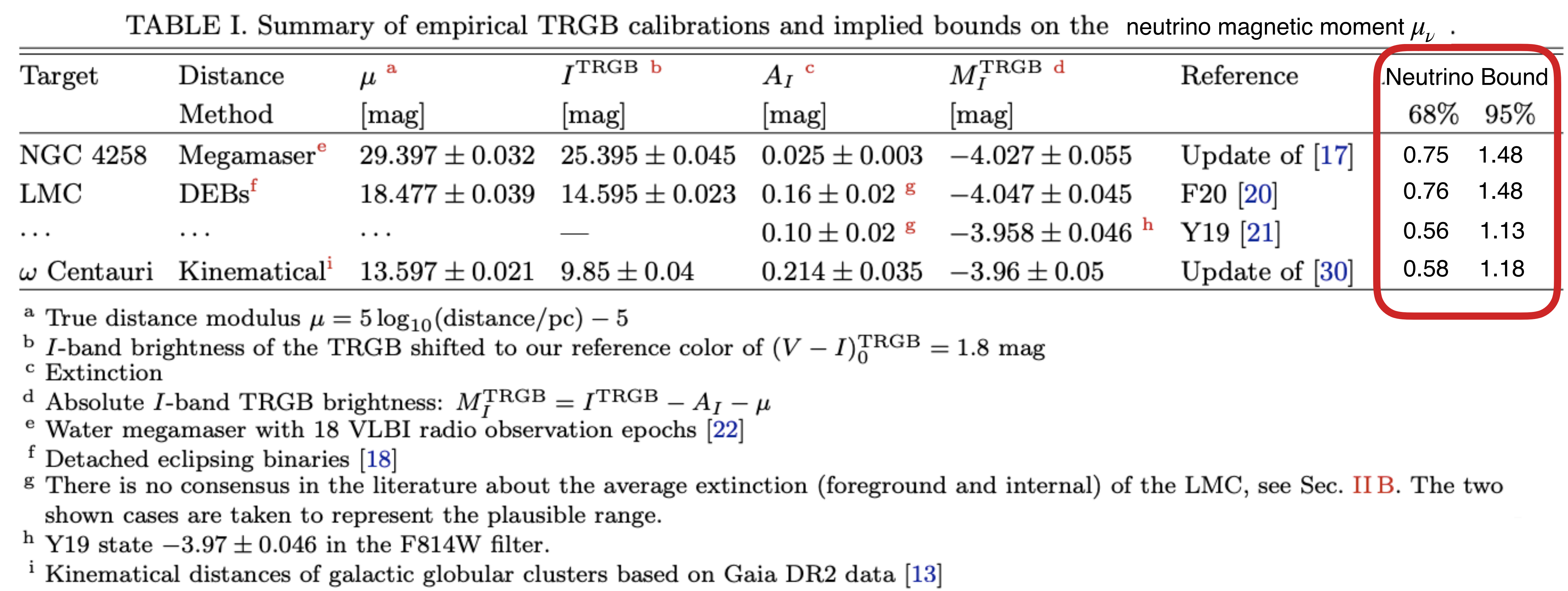


TABLE I. Summary of empirical TRGB calibrations and implied bounds on the neutrino magnetic moment μ_ν .

Target	Distance Method	μ [a] [mag]	$I^{\rm TRGB}$ [b] [mag]	A_I [c] [mag]	$M_I^{\rm TRGB}$ [d] [mag]	Reference	Neutrino Bound 68%	95%
NGC 4258	Megamaser[e]	29.397 ± 0.032	25.395 ± 0.045	0.025 ± 0.003	-4.027 ± 0.055	Update of [17]	0.75	1.48
LMC	DEBs[f]	18.477 ± 0.039	14.595 ± 0.023	0.16 ± 0.02 [g]	-4.047 ± 0.045	F20 [20]	0.76	1.48
...	...	...	—	0.10 ± 0.02 [g]	-3.958 ± 0.046 [h]	Y19 [21]	0.56	1.13
ω Centauri	Kinematical[i]	13.597 ± 0.021	9.85 ± 0.04	0.214 ± 0.035	-3.96 ± 0.05	Update of [30]	0.58	1.18

[a] True distance modulus $\mu = 5\log_{10}(\text{distance/pc}) - 5$

[b] I-band brightness of the TRGB shifted to our reference color of $(V-I)_0^{\rm TRGB} = 1.8$ mag

[c] Extinction

[d] Absolute I-band TRGB brightness: $M_I^{\rm TRGB} = I^{\rm TRGB} - A_I - \mu$

[e] Water megamaser with 18 VLBI radio observation epochs [22]

[f] Detached eclipsing binaries [18]

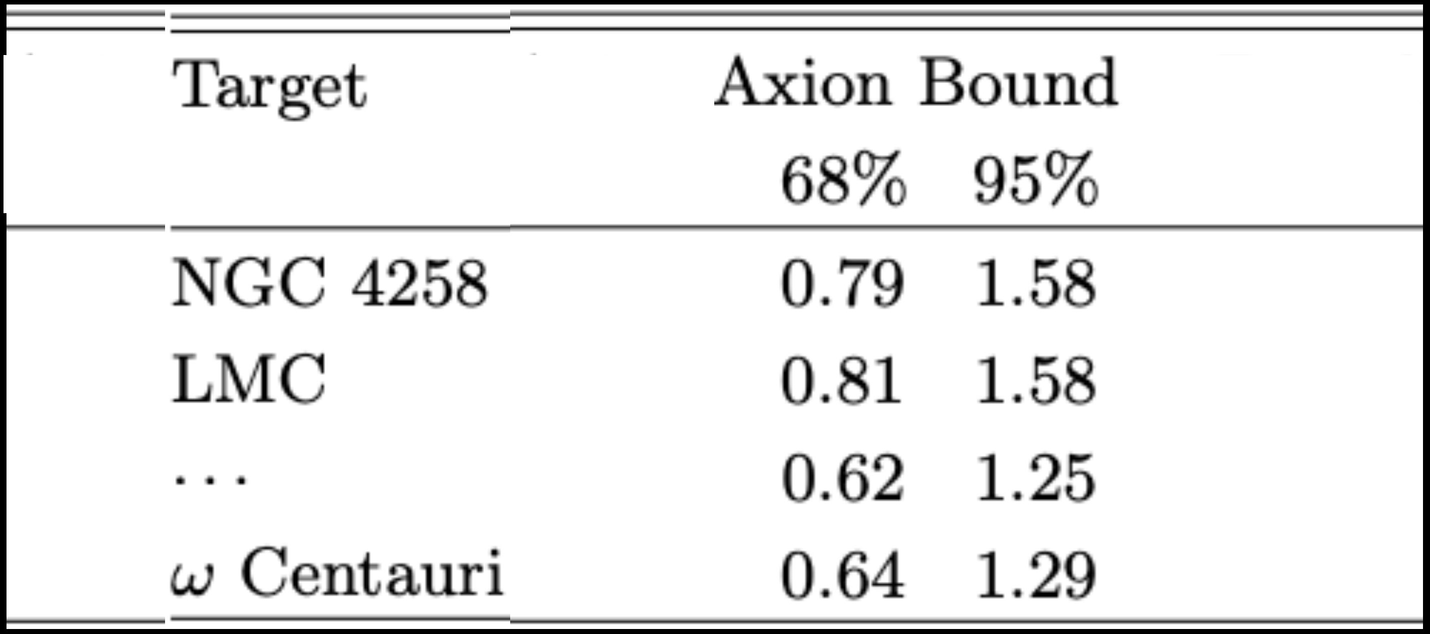
[g] There is no consensus in the literature about the average extinction (foreground and internal) of the LMC, see Sec. II B. The two shown cases are taken to represent the plausible range.

[h] Y19 state -3.97 ± 0.046 in the F814W filter.

[i] Kinematical distances of galactic globular clusters based on Gaia DR2 data [13]

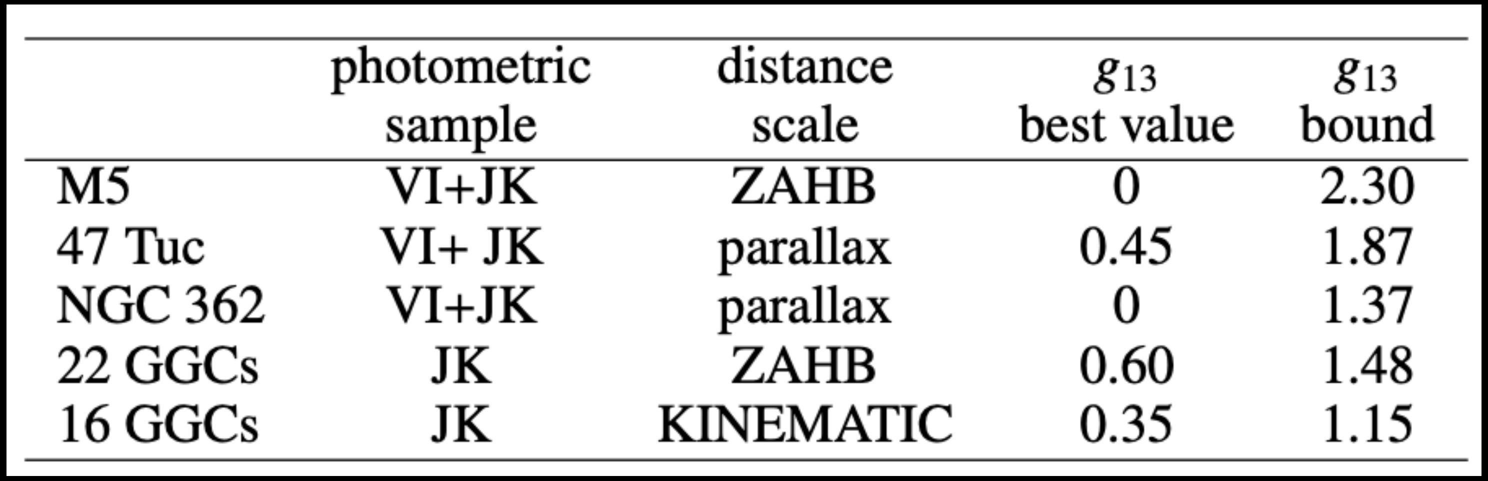
Bounds on extra cooling

Comparison with Straniero et al., arXiv:2010.03833



Target	Axion Bound	
	68%	95%
NGC 4258	0.79	1.58
LMC	0.81	1.58
$\cdots$	0.62	1.25
ω Centauri	0.64	1.29

Straniero et al., arXiv:2010.03833



	photometric sample	distance scale	g_{13} best value	g_{13} bound
M5	VI+JK	ZAHB	0	2.30
47 Tuc	VI+ JK	parallax	0.45	1.87
NGC 362	VI+JK	parallax	0	1.37
22 GGCs	JK	ZAHB	0.60	1.48
16 GGCs	JK	KINEMATIC	0.35	1.15

Similar constraints recently obtained using a compound of globular clusters

Conclusions

- With new distances extra cooling bounds dominated by theory

- Extragalactic calibrations are competitive with Globular Clusters

- Improvements expected with GAIA DR3 and its precise distances