

Astrophysical Constraints On Light Dark Sectors

Seokhoon Yun

@ Light Dark World (LDW) 2025



Light Dark World 2025

Sep 16th - Sep 19th, 2025
IFT UAM-CSIC
Madrid, Spain

Confirmed speakers:

Paolo Cremonesi (Zurich, ETH)
Luc D'Amme (UPZ, Lyon)
Eleonora di Valentino (Sheffield U.)
Christina Gao (SUSTech, Shenzhen)
Enrico Grazzani (INFN, Roma Tre)
Jan Jerbott (MPP, Munich)
Felix Kling (DESY)
Maksim Ovchinnikov (CERN)
Jung Chul Park (Chungnam National U.)
Silvia Pascoli (Università di Bologna)
Elena Pinetti (Simons Foundation)
Javier Redondo (Zaragoza U.)
Yu-Dai Tsai (LANL)
Seokhoon Yun (IBS, Daejeon)
Renata Zukanowicz Puchals (Sao Paulo U.)

Organizing committee:

Adi Shmida (IFT)
Brian Hall (Pittsburgh U.)
David Gorbunov (IFT)
Ella Calzavara (IFT), chair
Patrick Huettenauer (IFT)
Felix Kahlhoefer (IFT)
Hao-Sheng Lee (SUSTech)
Jacobo Lopez-Paavola (IFT)
Laura Mota-Bueno (IFT), chair
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Outline

- 01 Preliminary**
- Current status of Feebly-Interacting Light Particles
 - Stages of Stellar Evolution

- 02 Low-M Stellar Evolution**
- **◎ Stellar Cooling Argument**
 - Sun (Main Sequence) - solar ν
 - Red Giants - luminosity @ tip
 - Horizontal Branches - lifetime

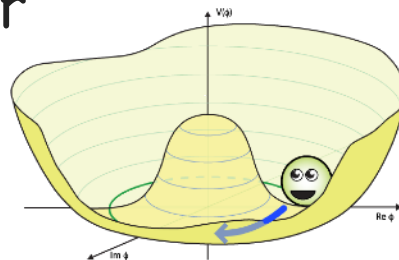
- 03 Supernova & Neutron Stars**
- Core-Collapse of massive stars
 - SN1987A Observations
 - Duration of ν signals & No prompt γ -ray & fireball
 - Phenomena associated with SN
 - ν -driven explosion
 - Neutron star cooling

Feebly-Interacting Light Bosons

- Ubiquitous in several extensions of the Standard Model
- Can be a good dark matter candidate

Axion / Axion-Like Particle

- ✓ Spin-0 Pseudoscalar
- ✓ Strong CP problem



$$g_{a\gamma\gamma} \frac{a}{4f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Dark Photon

- ✓ Spin-1 Vector
- ✓ $(g - 2)_\mu, \dots$

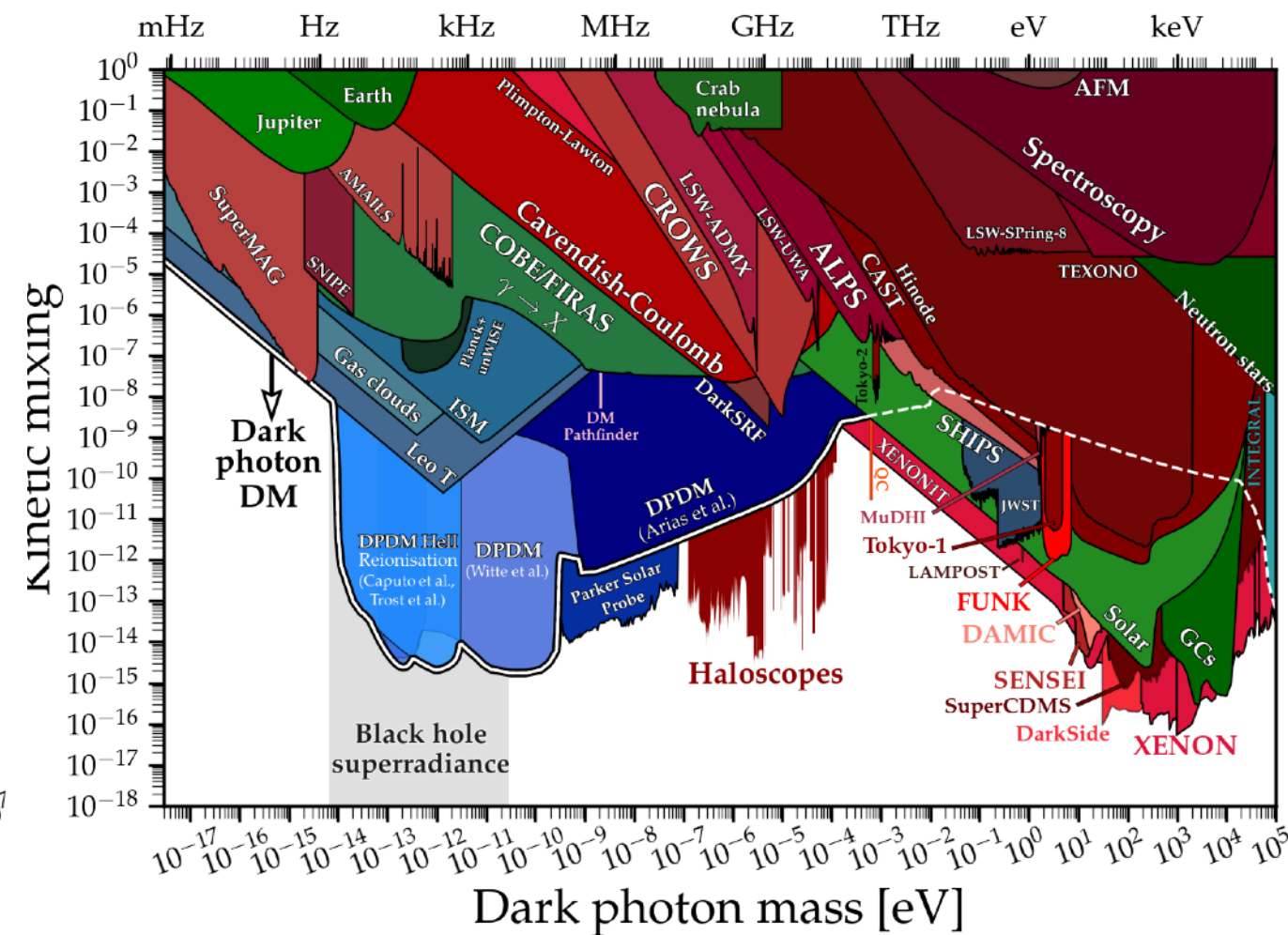
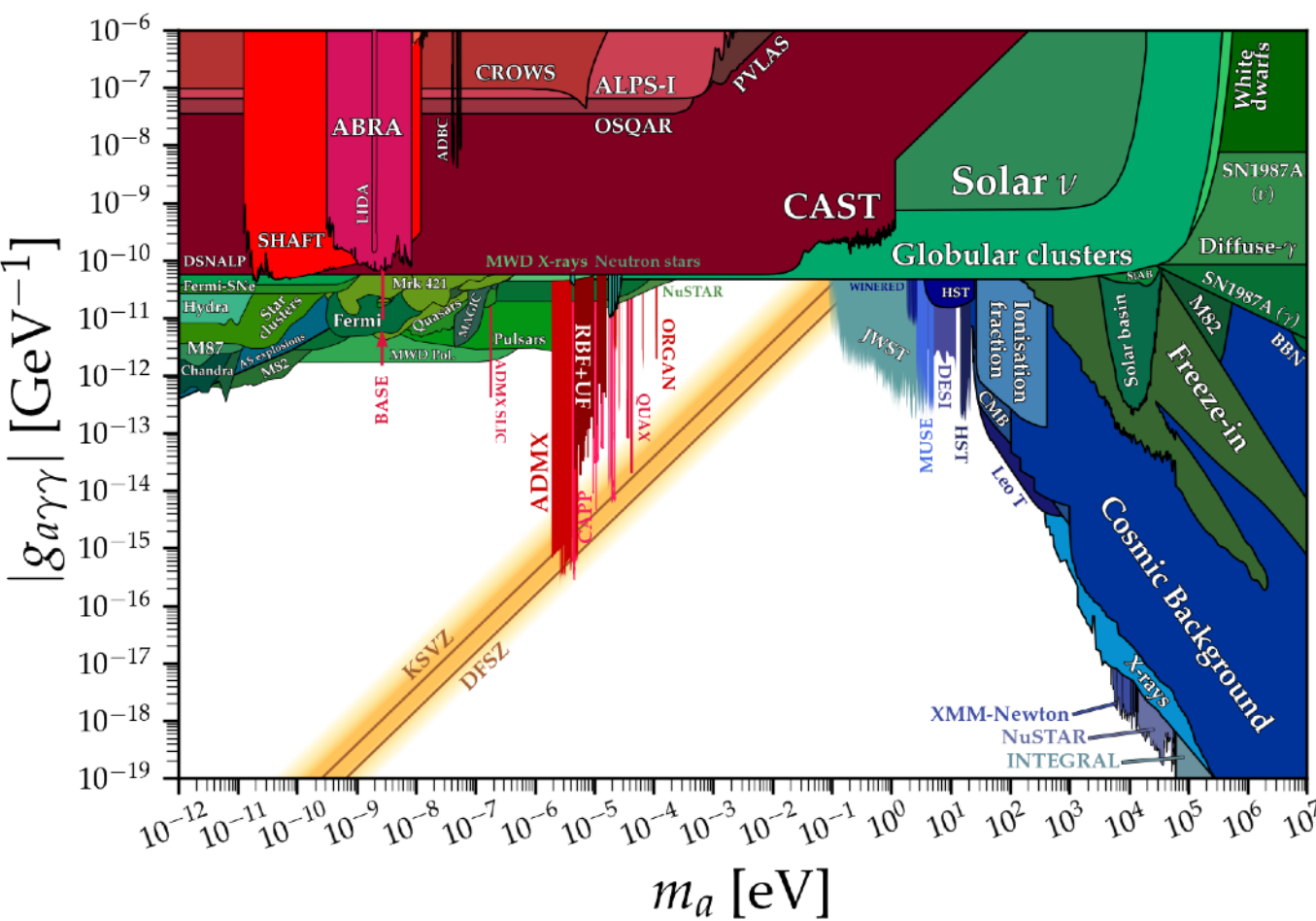
$$\frac{\varepsilon}{2} F_{\mu\nu} X^{\mu\nu}$$

Current Status

Experimental

Astrophysical

Cosmological



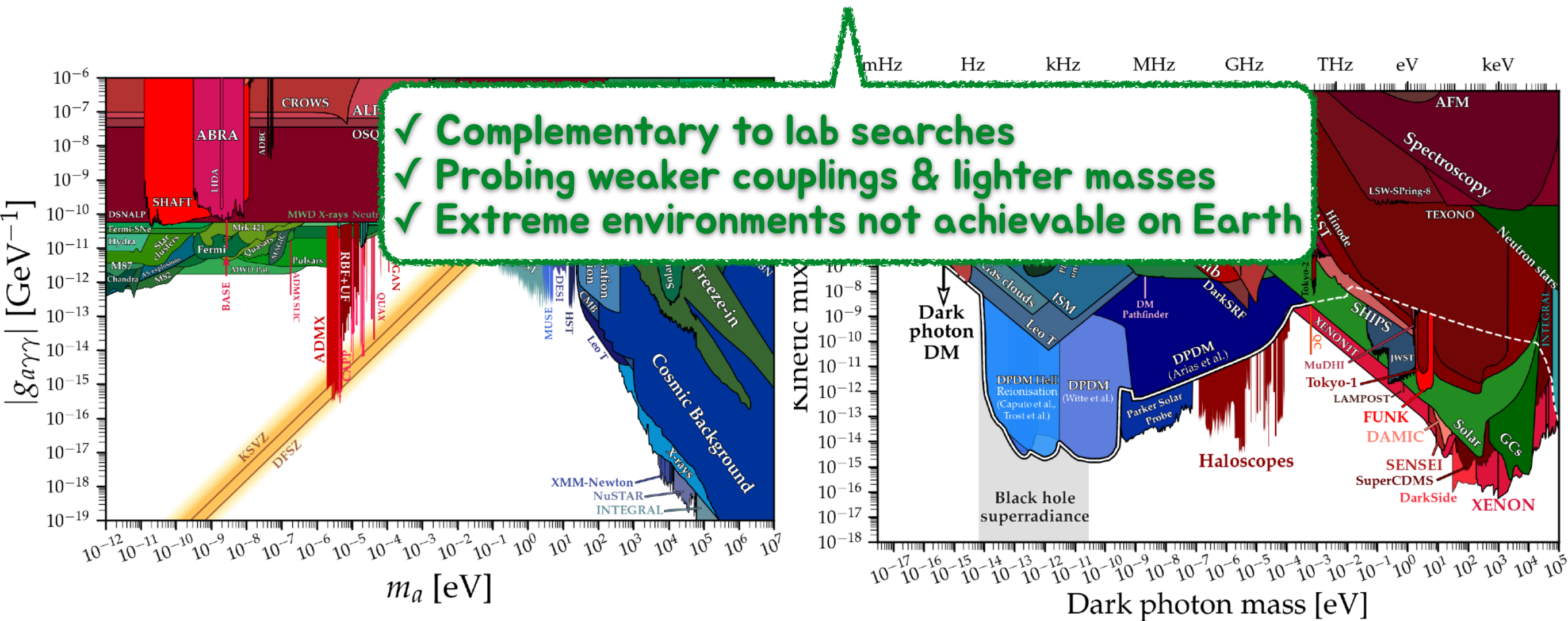
[<https://cajohare.github.io/AxionLimits/>]

Current Status

Experimental

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[<https://cajohare.github.io/AxionLimits/>]

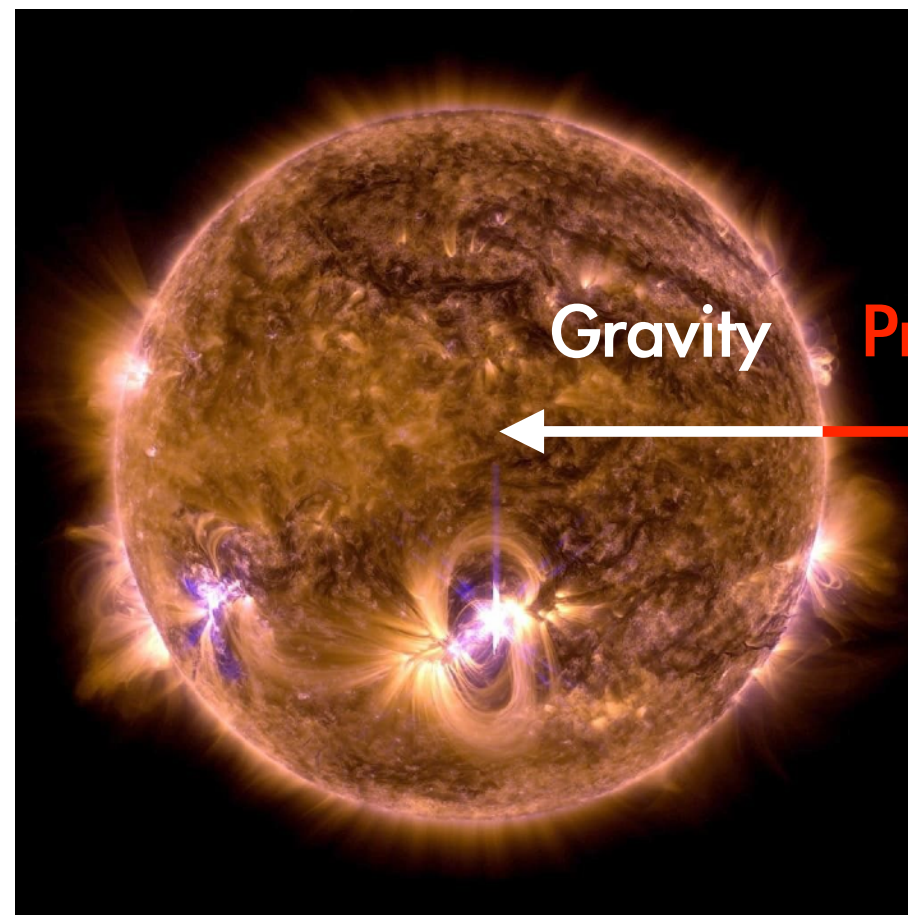
Stars

“ Star

From Wikipedia, the free encyclopedia

This article is about the astronomical object. For other uses, see [Star \(disambiguation\)](#).

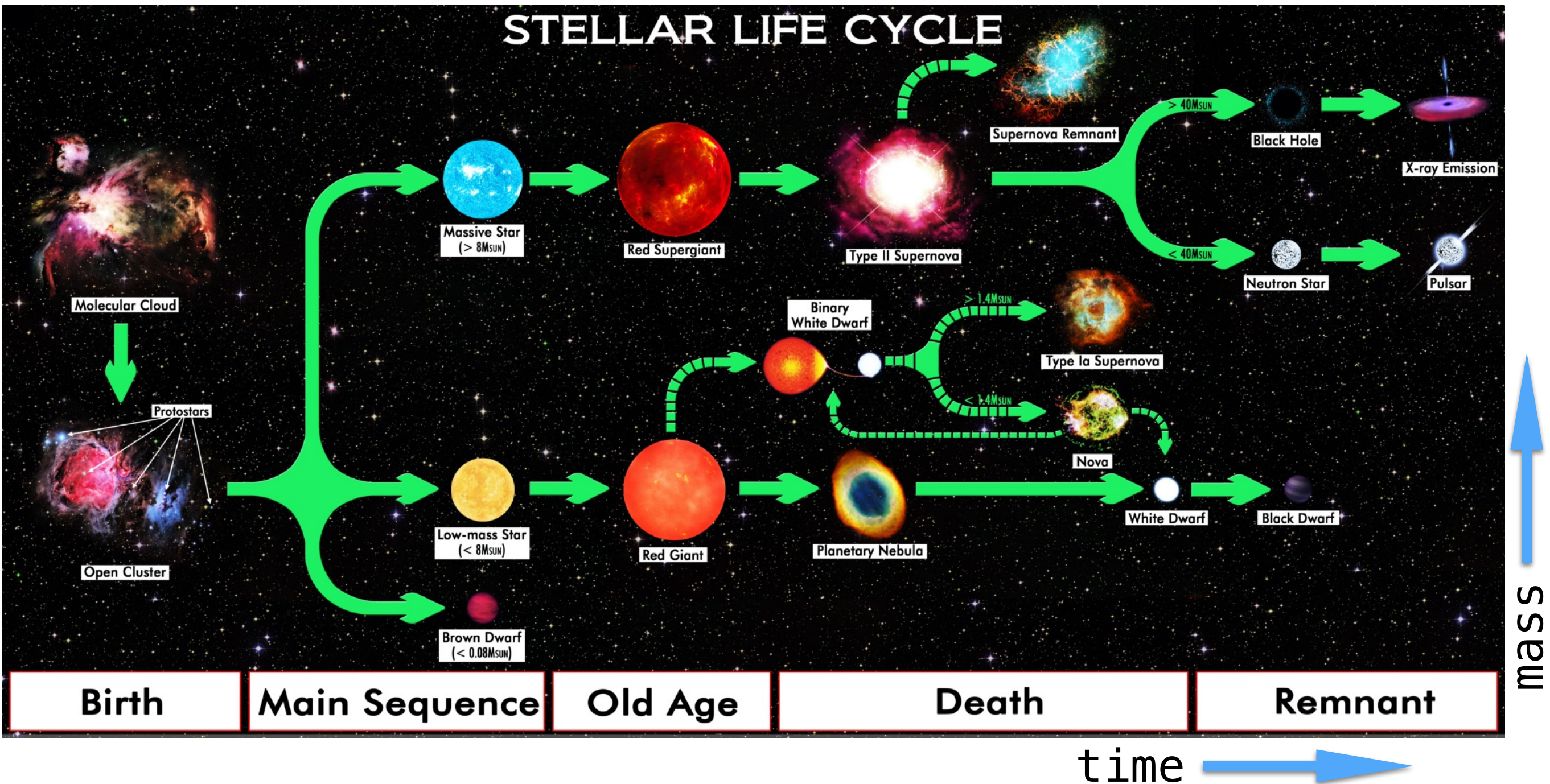
A **star** is an [astronomical object](#) consisting of a luminous [spheroid](#) of [plasma](#) held together by its own [gravity](#). ”



+ Energy conservation & transfer

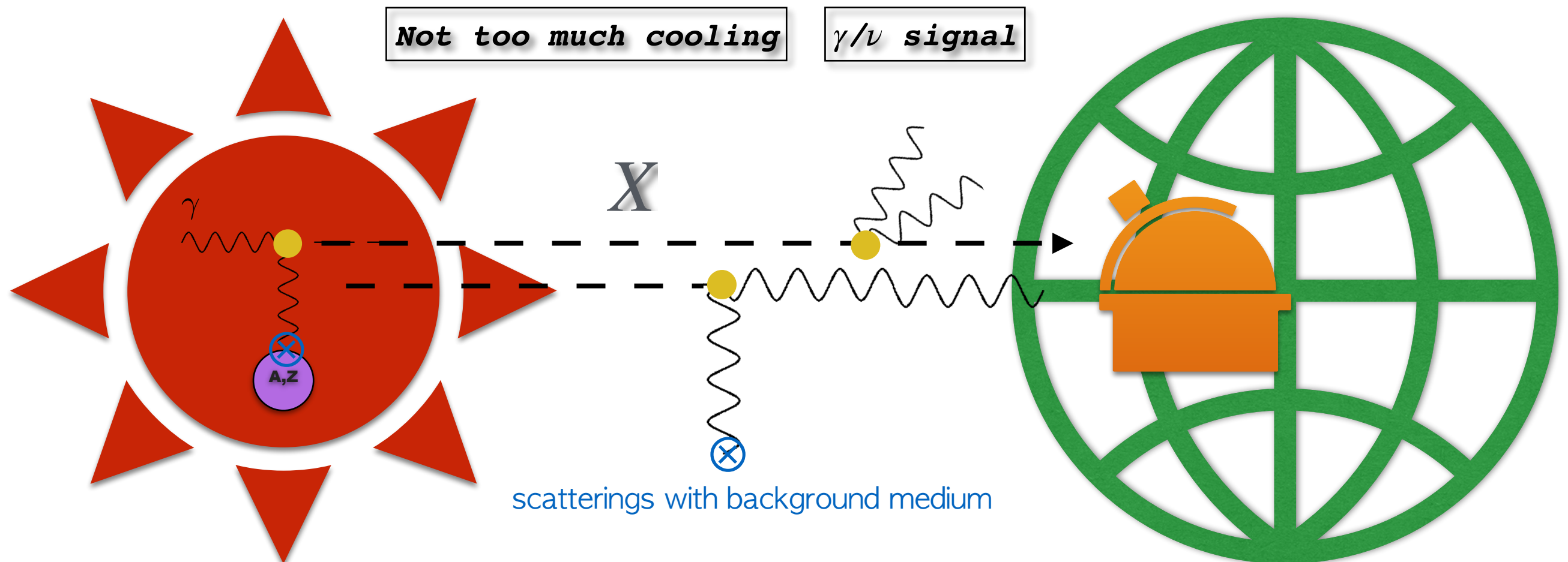
Stellar Evolution

[image from Wikipedia]



Astrophysical Searching Scheme

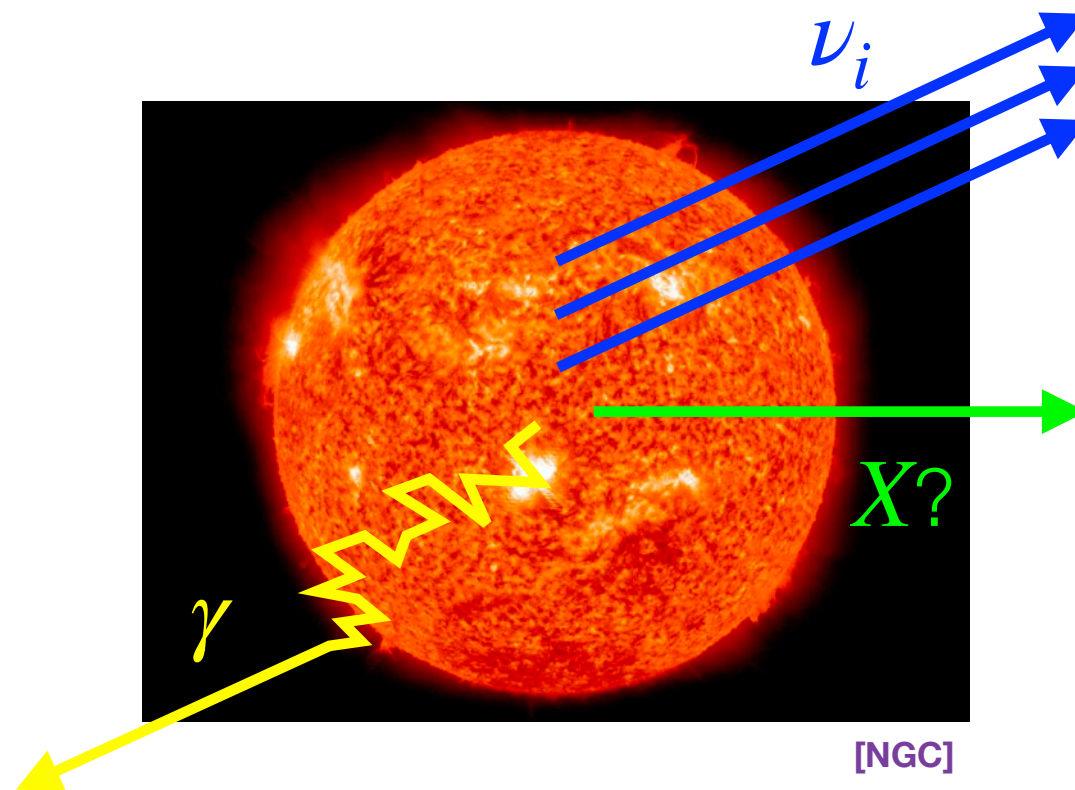
- Stars as ***laboratories*** to probe light bosons in extreme circumstances
 - ✓ Detection opportunity (e.g., ν spectrum from Sun or Supernovae)
 - ✓ Backreaction on stellar properties



Sun

- Thermal production & Nuclear transition
- Solar observables: helioseismology & solar neutrinos
- Terrestrial detectors: Helioscope & ν -detector

Stellar Cooling Argument on Sun



- Standard solar model calibrated to match the present-day solar radius & luminosity

$$R_{\odot} = 6.9598 \times 10^{10} \text{ cm} \quad L_{\odot} = 3.8418 \times 10^{33} \text{ erg s}^{-1}$$

- Observables:

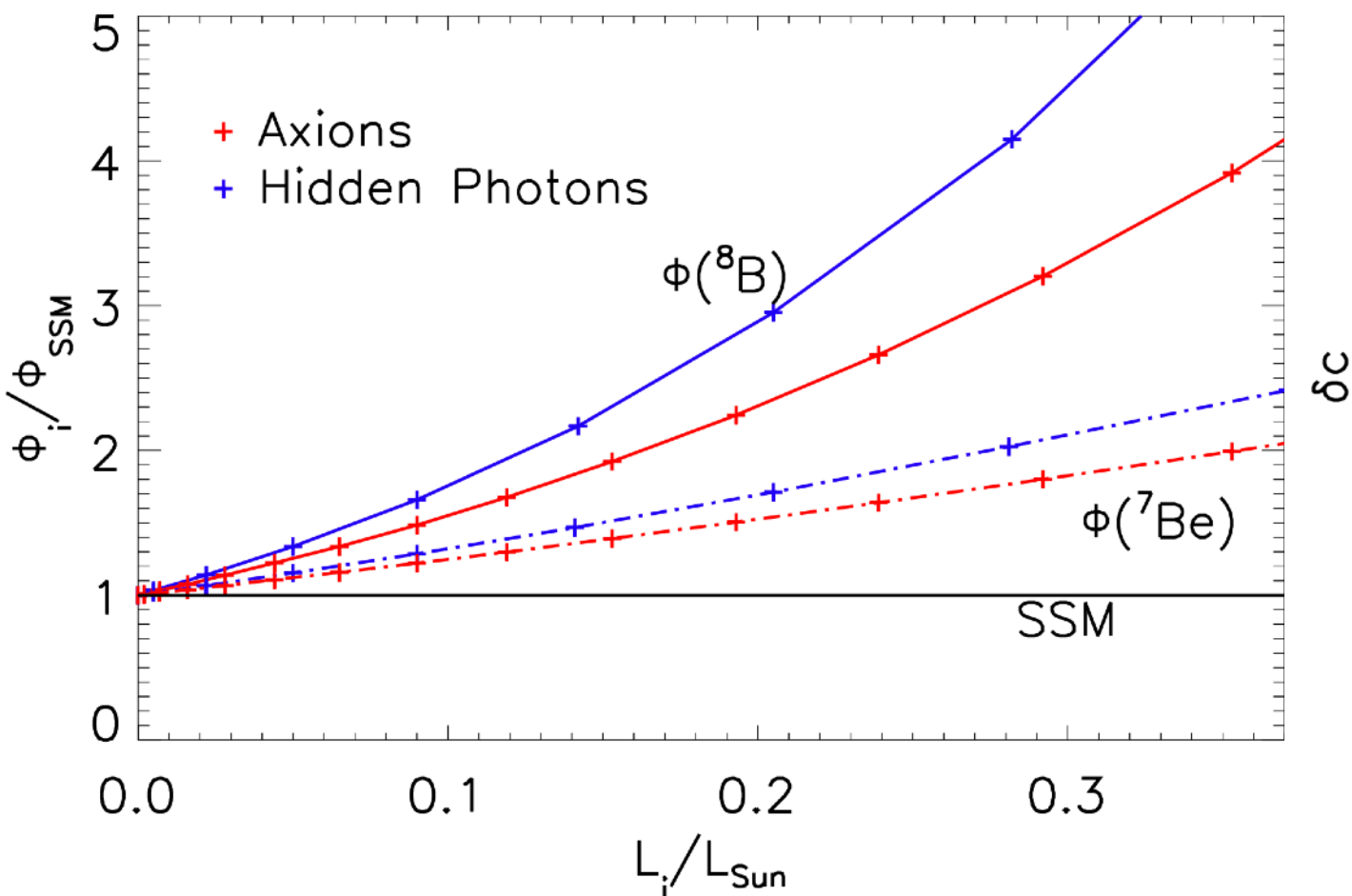
- 1) Helioseismology (sound speed, surface helium)
- 2) Solar neutrino fluxes $\Phi(^8\text{B})$ and $\Phi(^7\text{Be})$



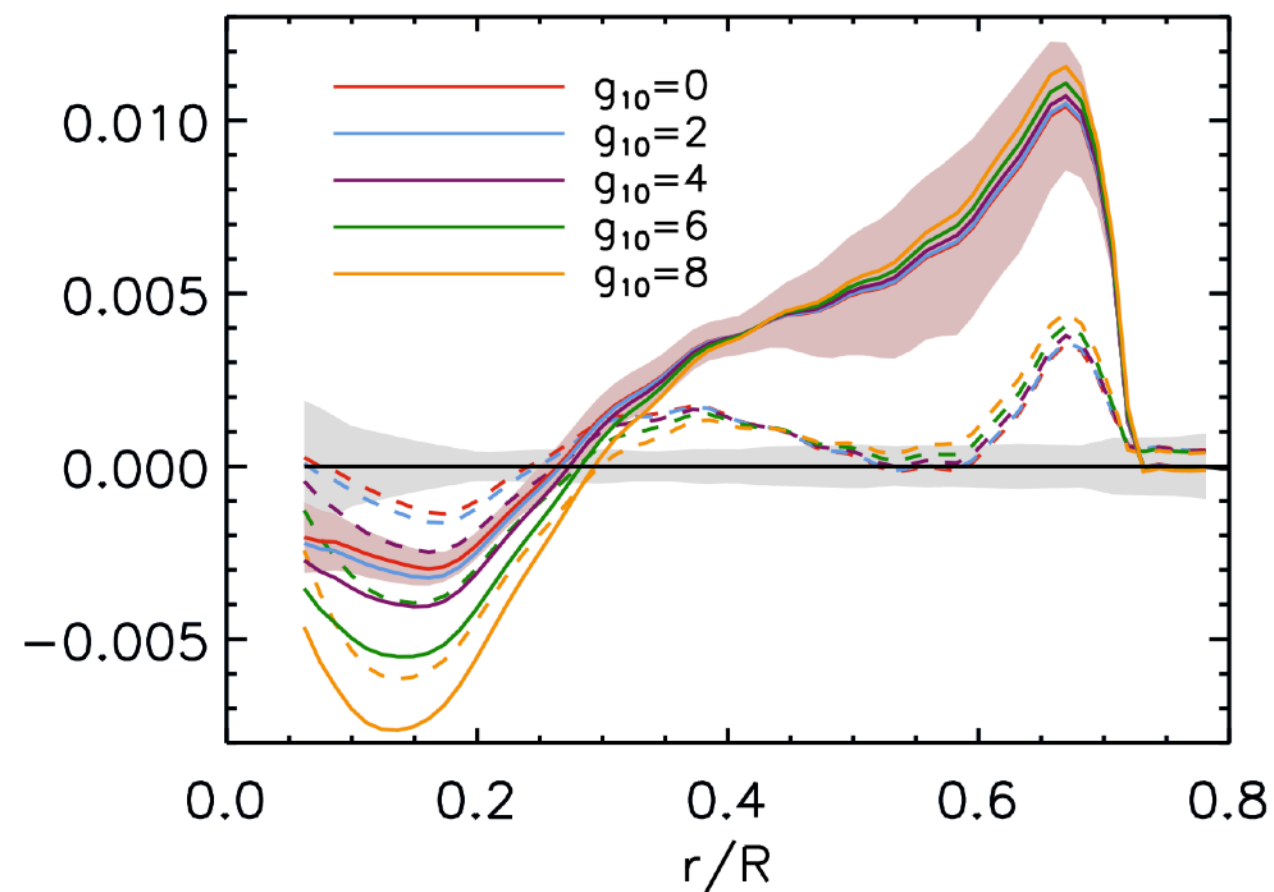
Extra cooling leading to observable deviations?!

Cooling Impacts on Solar Observables

✓ Increasing T_{core} to fit $L_{\odot}$



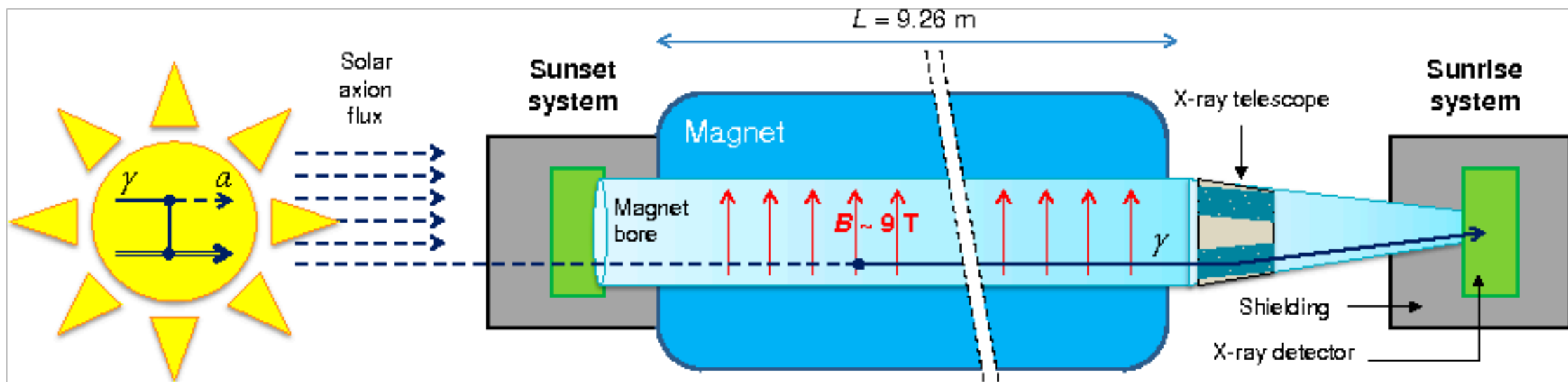
✓ Modifying interior structure
axions



[N. Vinyoles et al. 15]

Helioscope

[CAST, arXiv:1705.02290]

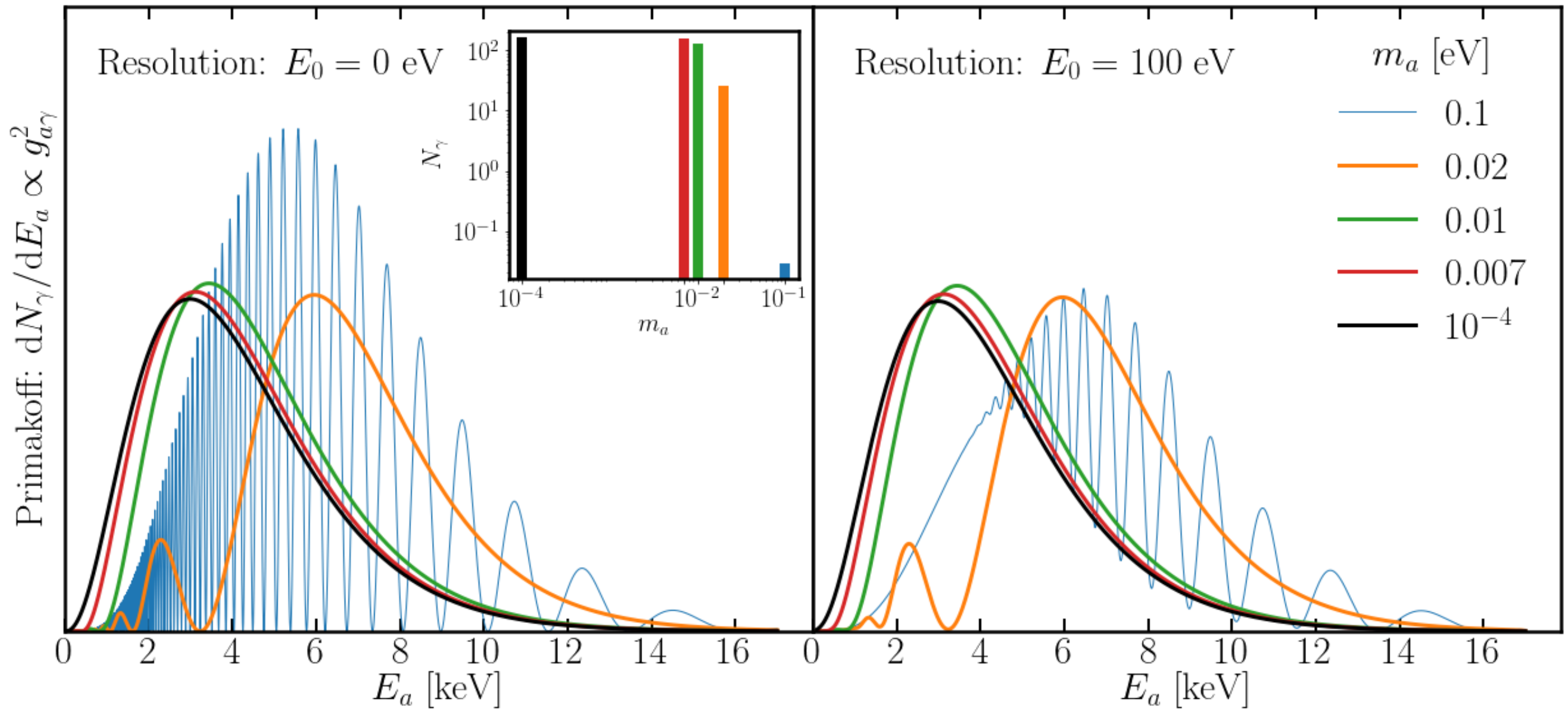


$$\Omega_a \times P_{a \rightarrow \gamma} = \text{X-ray}$$

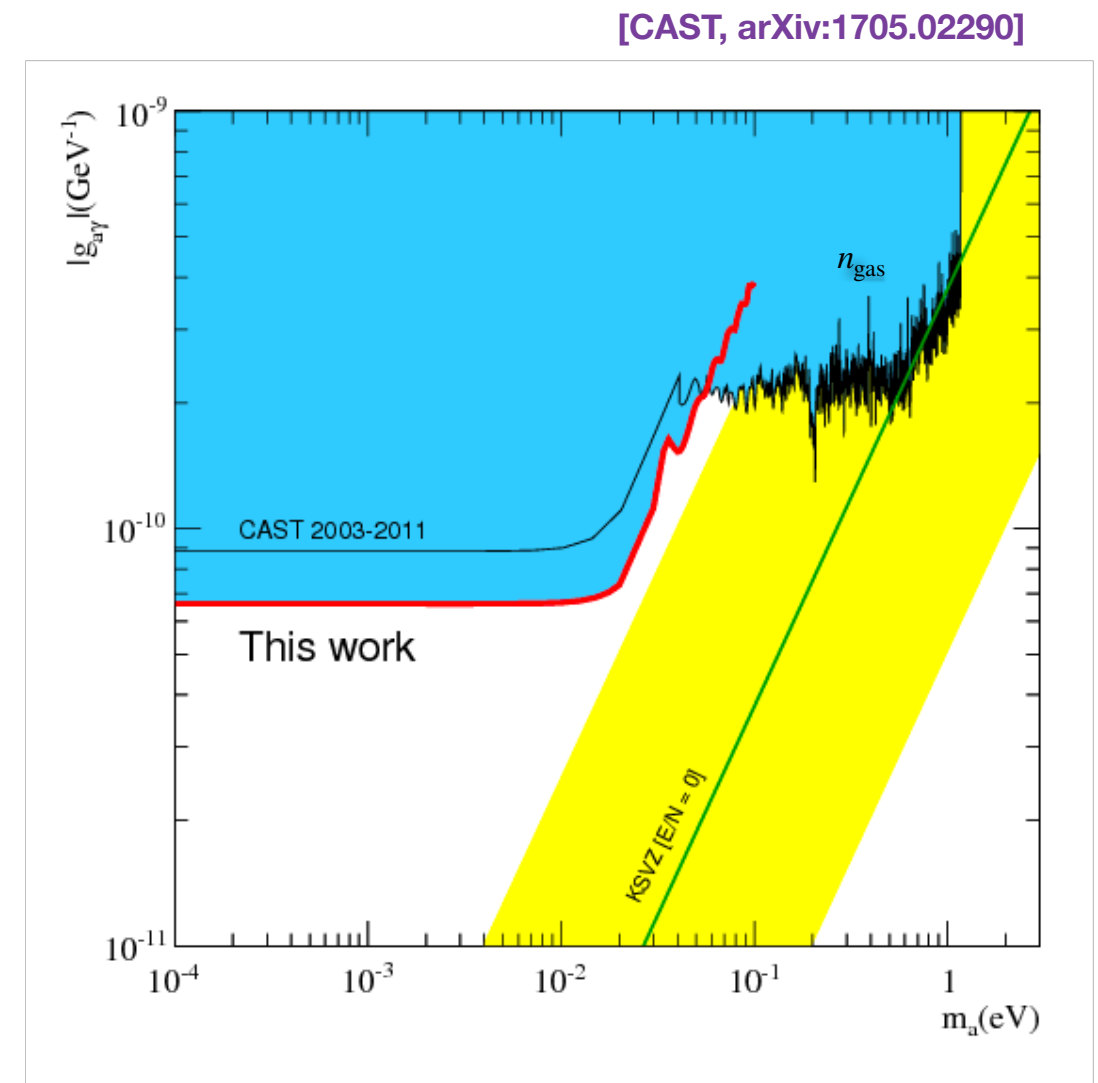
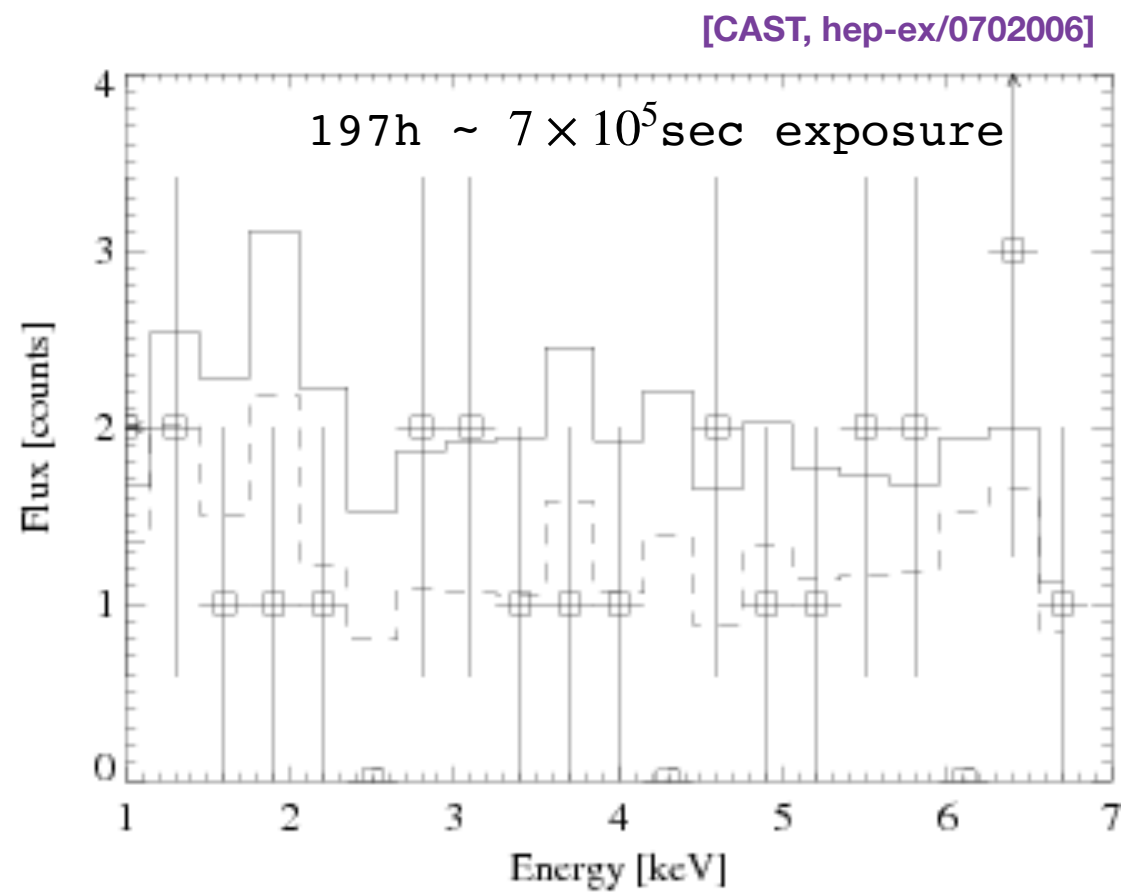
solar axion flux
axion $\rightarrow$ photon
in magnetic field

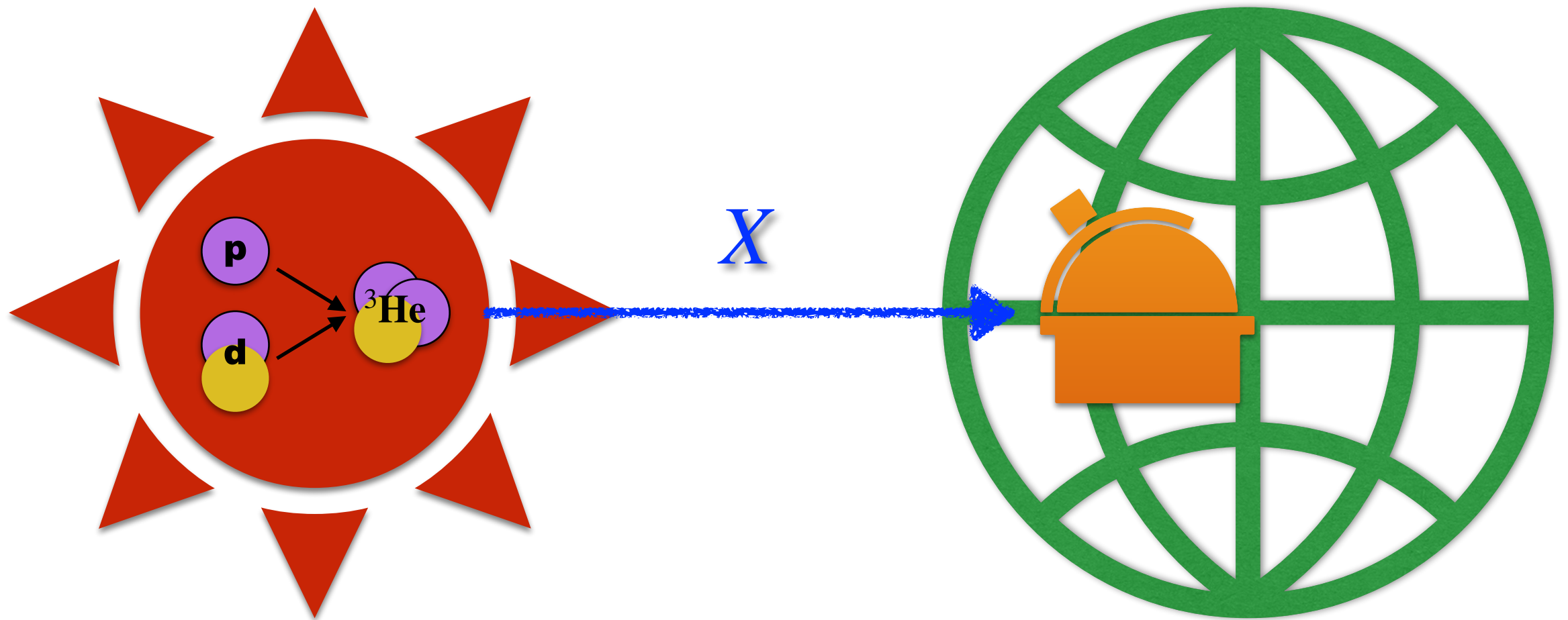
Expected X-ray Signals

[<https://cajohare.github.io/IAxOmass/>]



Helioscope Bounds



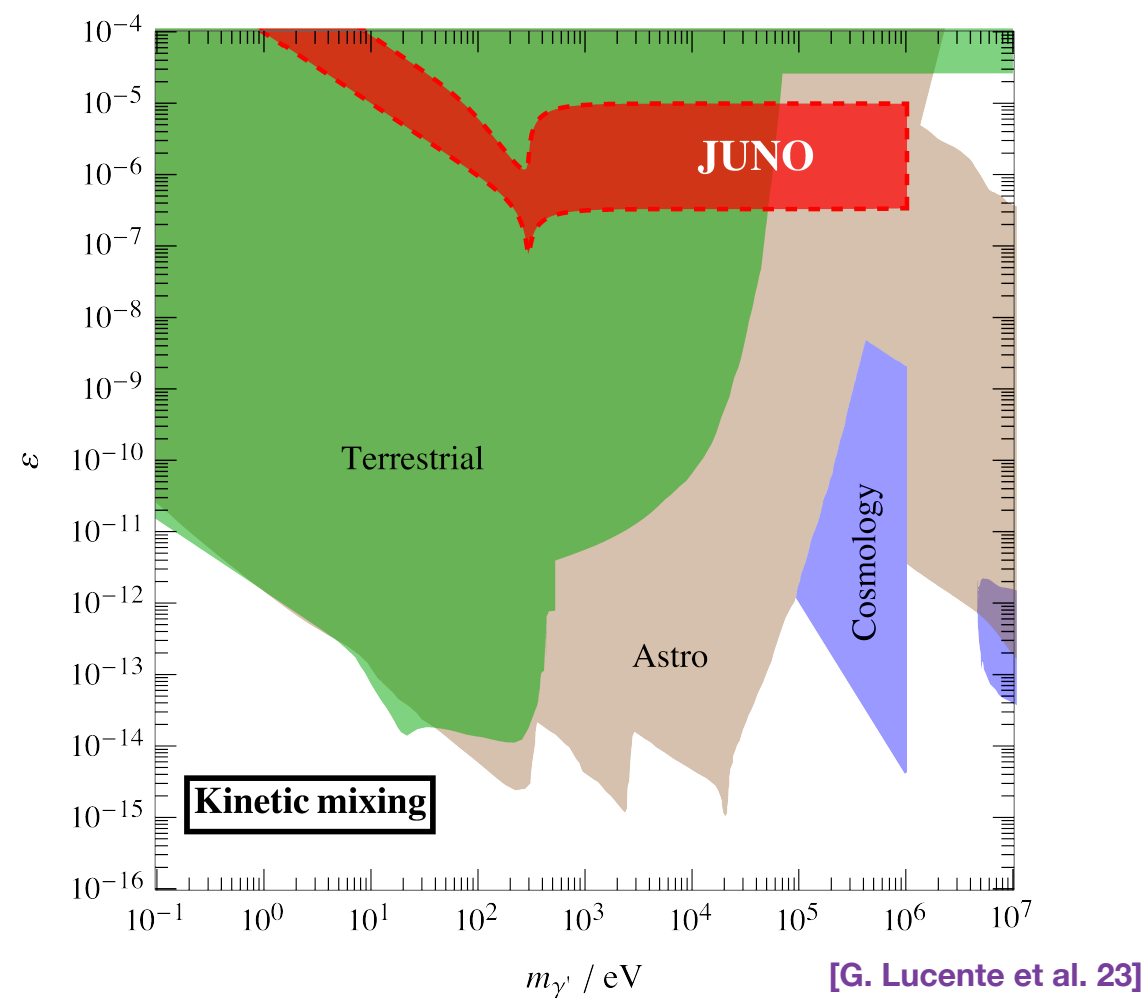
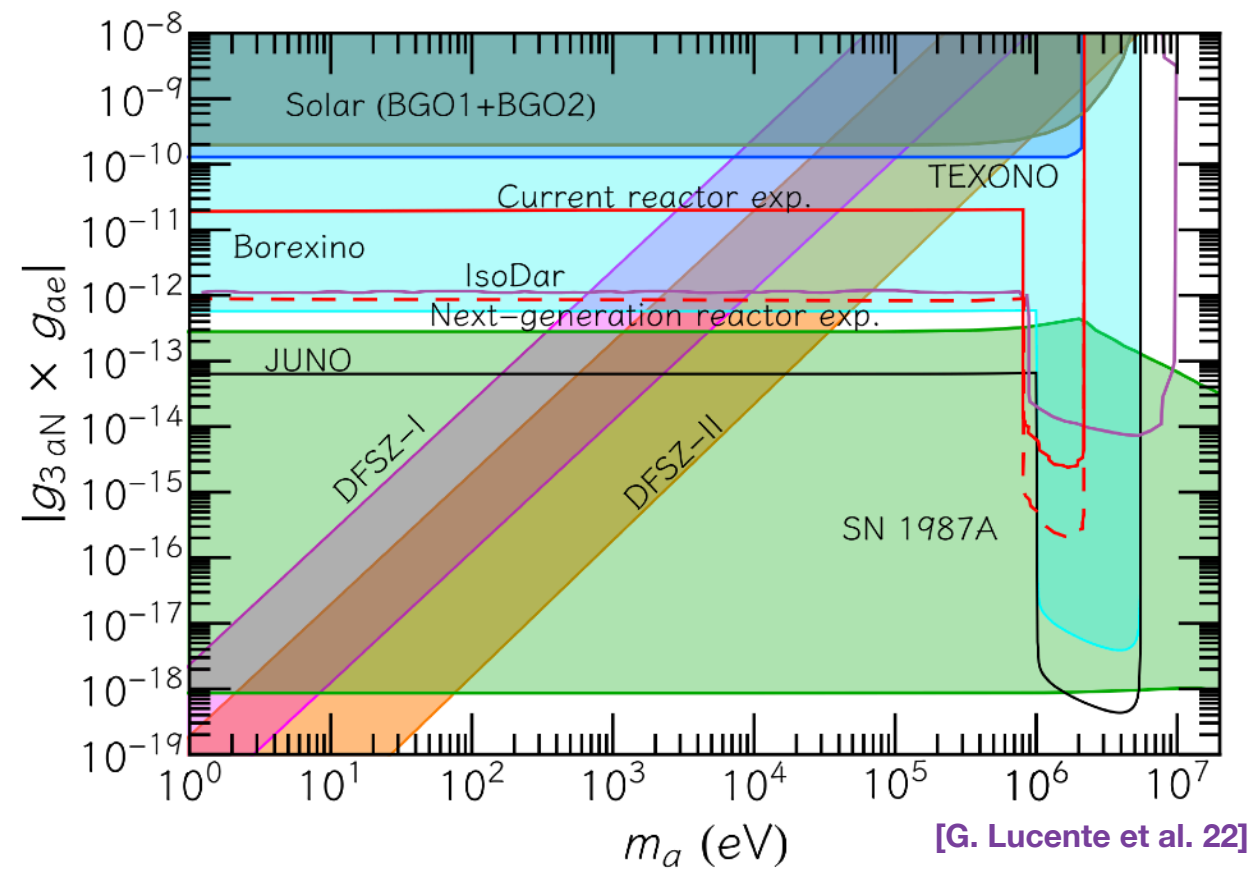
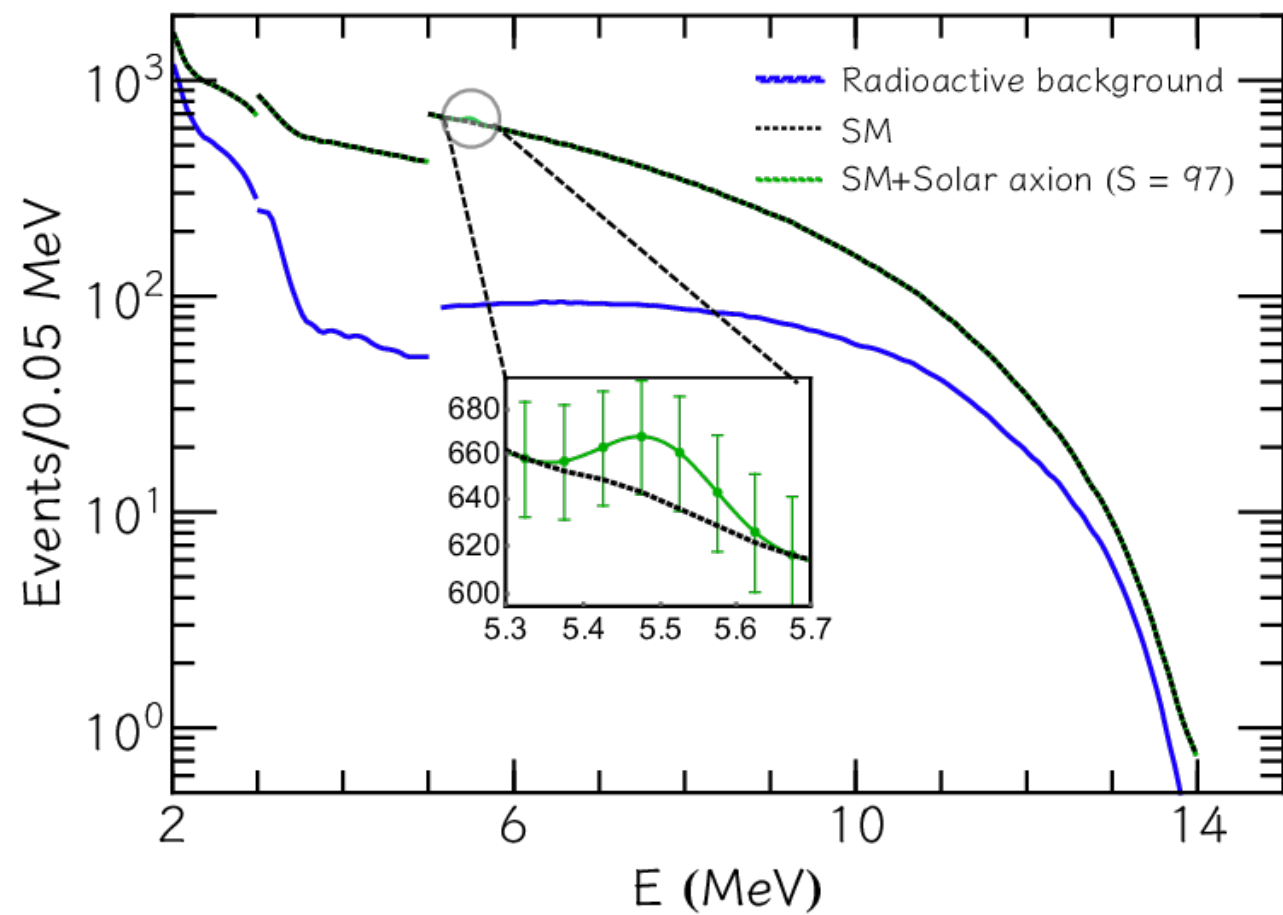


Production

- $p + d \rightarrow {}^3\text{He} + X \text{ (5.49 MeV)}$
 - ✓ *Multipole expansion - (E1 & M1)*
 - ✓ *Isovector*

Detection

- Compton-like $e^- X \rightarrow e^- \gamma$
 - ✓ *Polarized cross-section*
- In-flight decay $X \rightarrow e^- e^+$
 - ✓ *allowed for $m_X \geq 2m_e$*

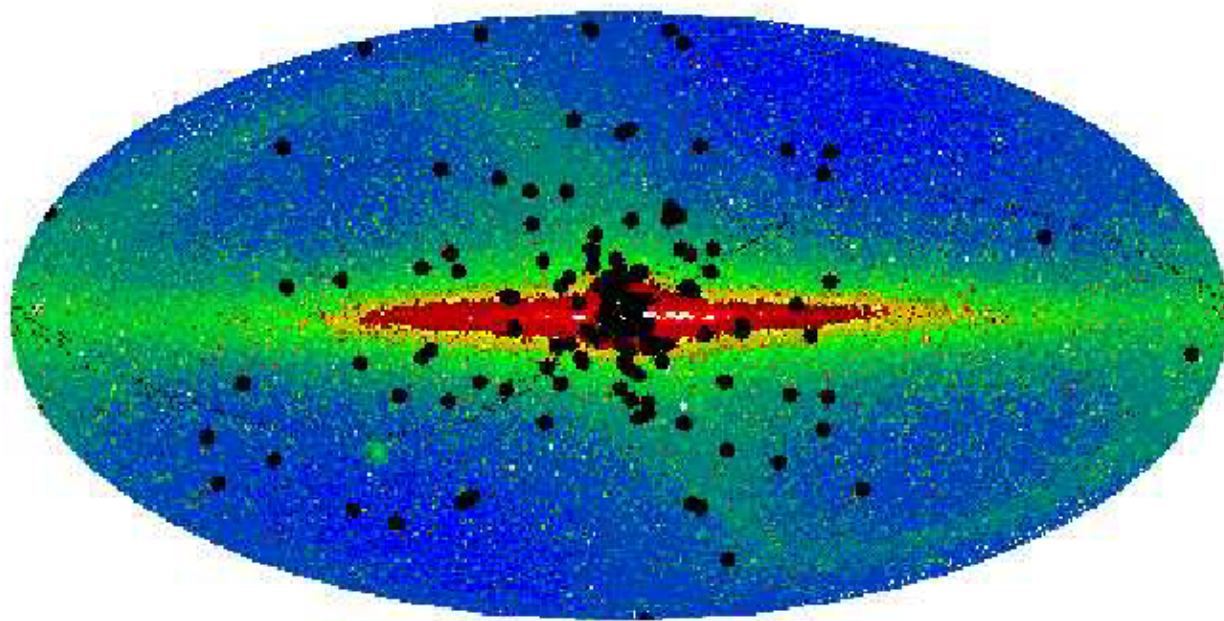


Low-Mass Stellar Evolution

- Stellar Cooling Argument
 - Red-Giant: luminosity at tip (just before helium flash)
 - Horizontal Branch: duration of helium burning
 - White Dwarf: luminosity function in time

Globular Cluster

- Very clean laboratories for studies of stellar evolution
- Coeval and almost equal chemical compositions
- Only different initial mass

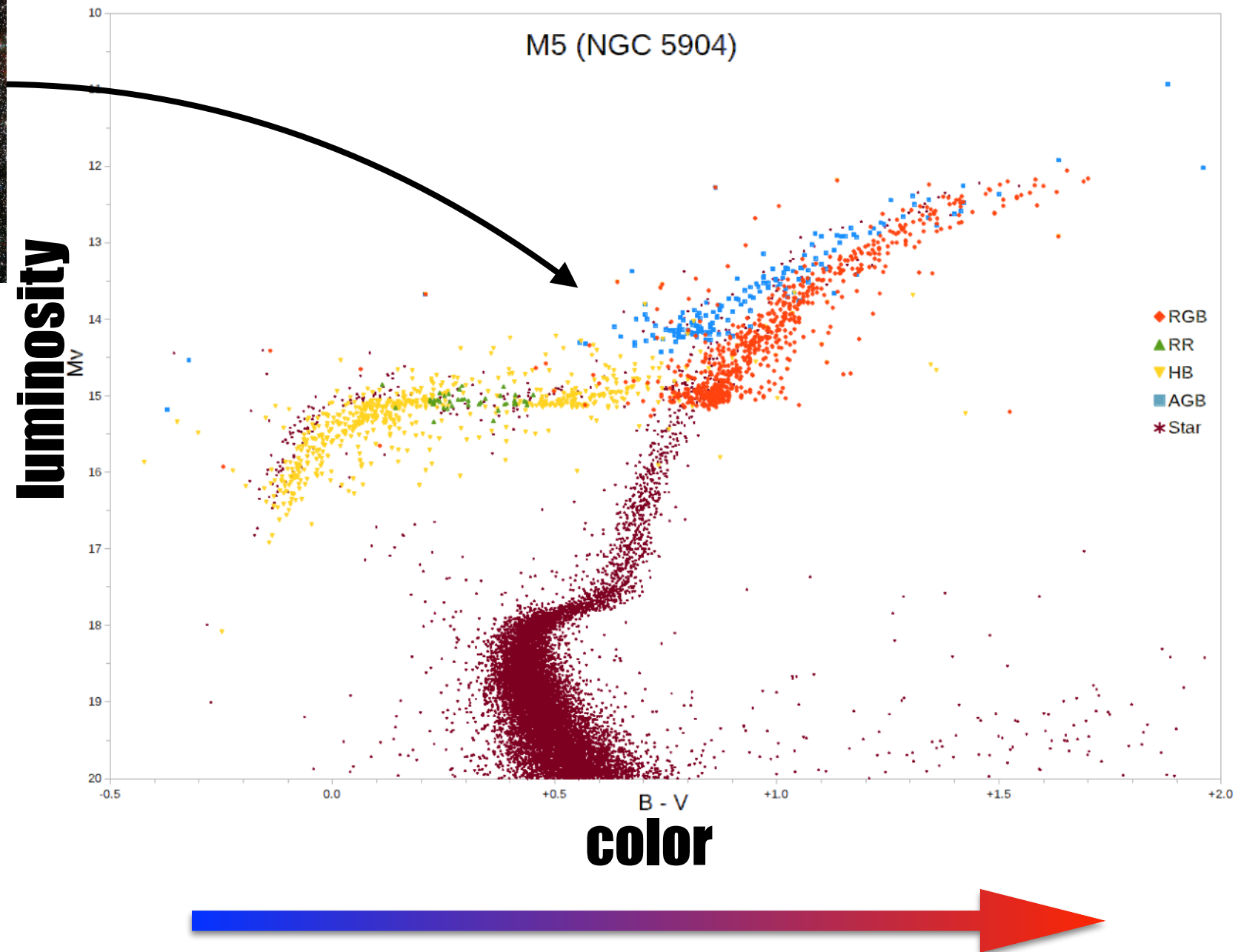
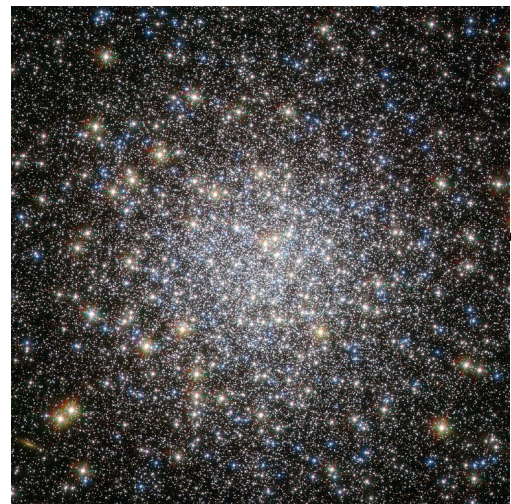


by Brian Chaboyer

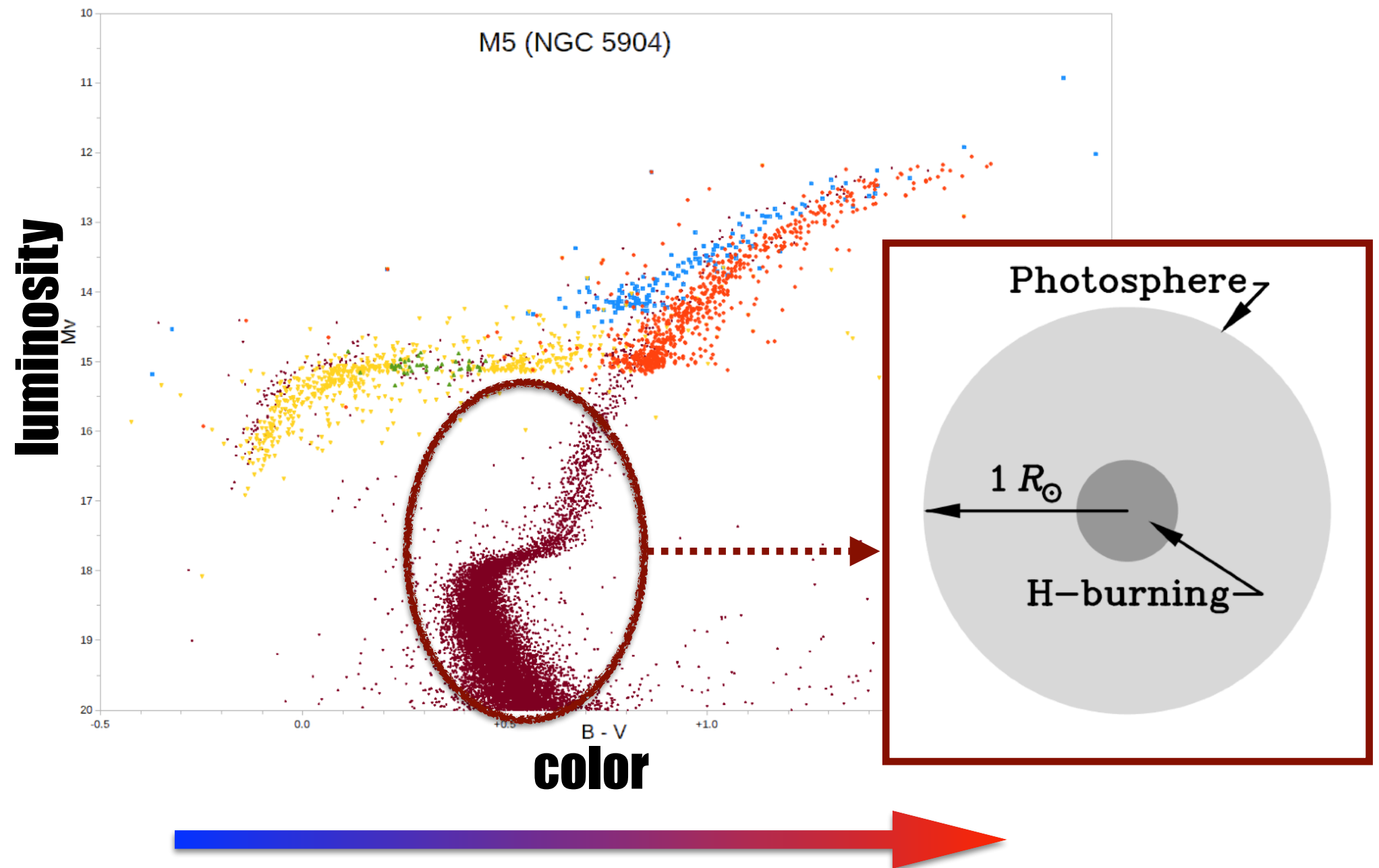


[Hubble]

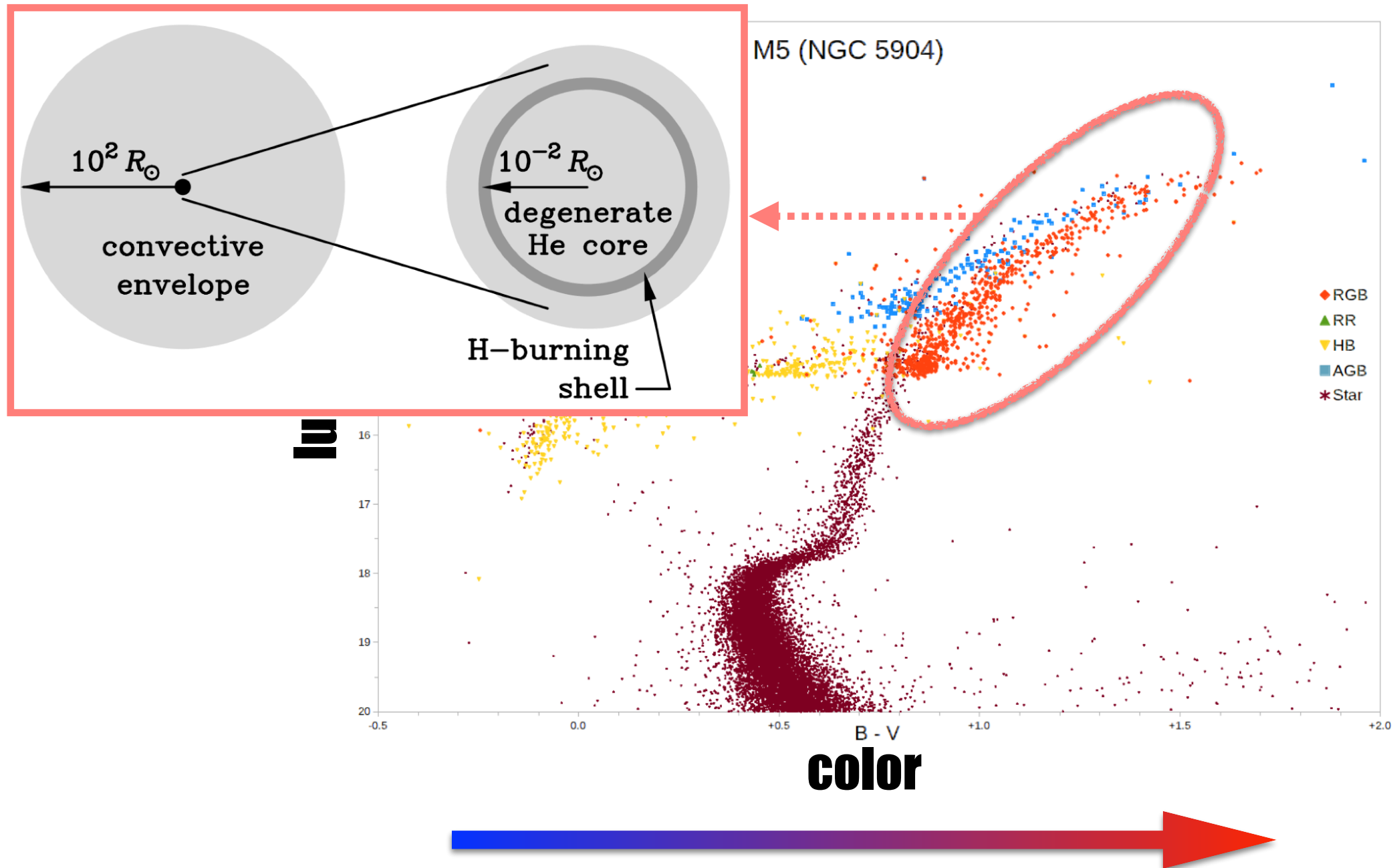
Color-Magnitude Diagram



Main-Sequence

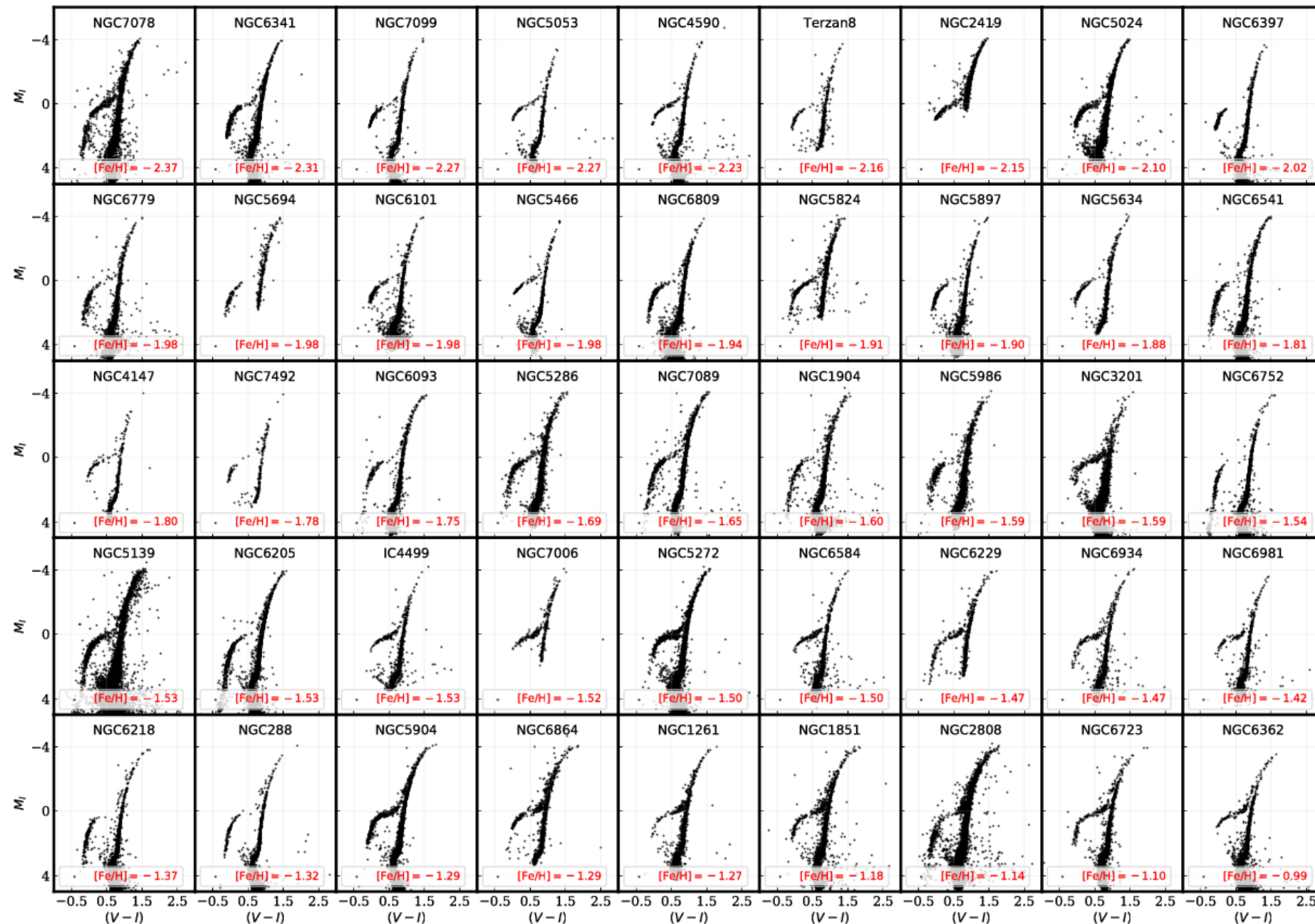


Red-Giant Branch

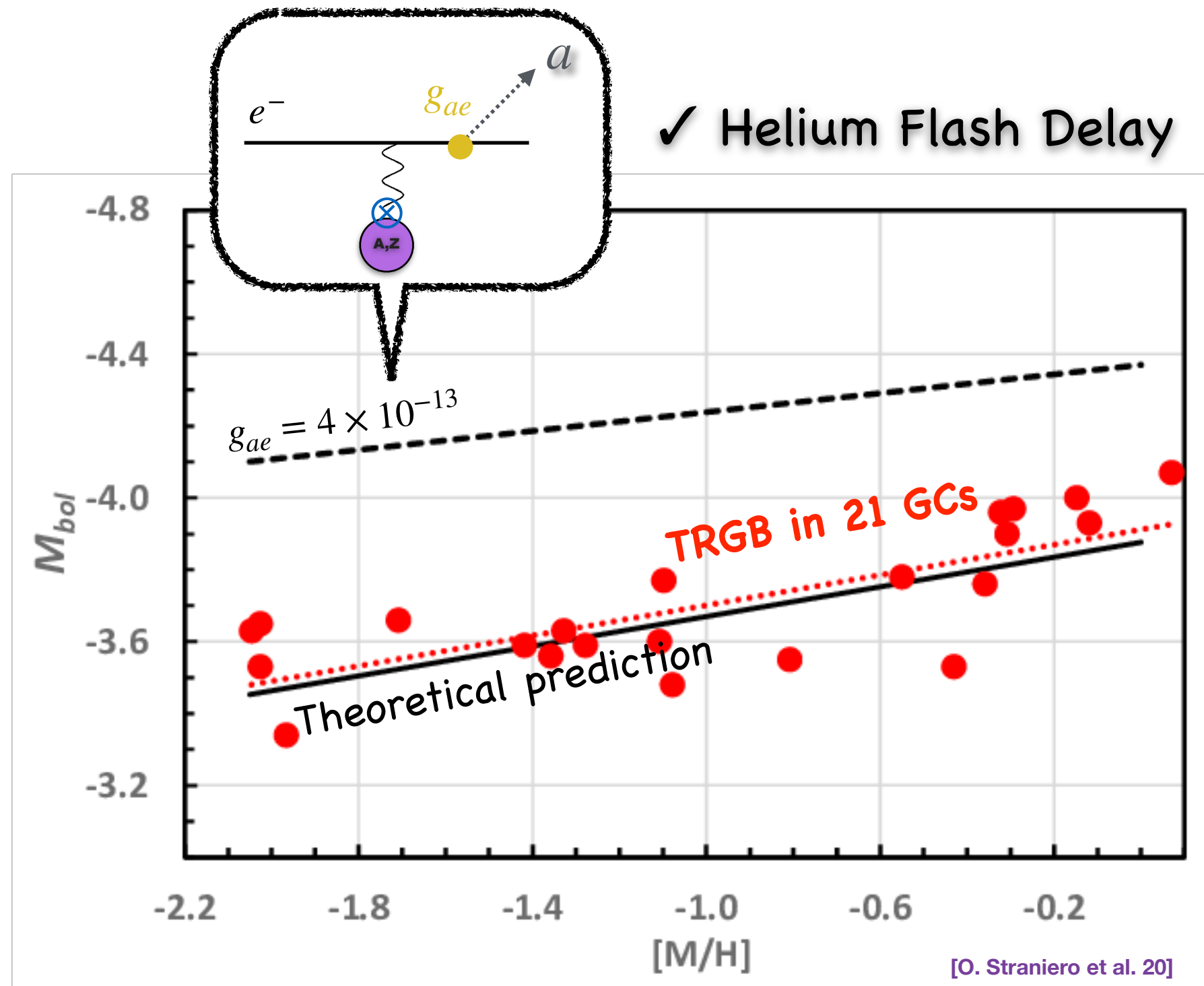


Tip of Red-Giant Branch (TRGB)

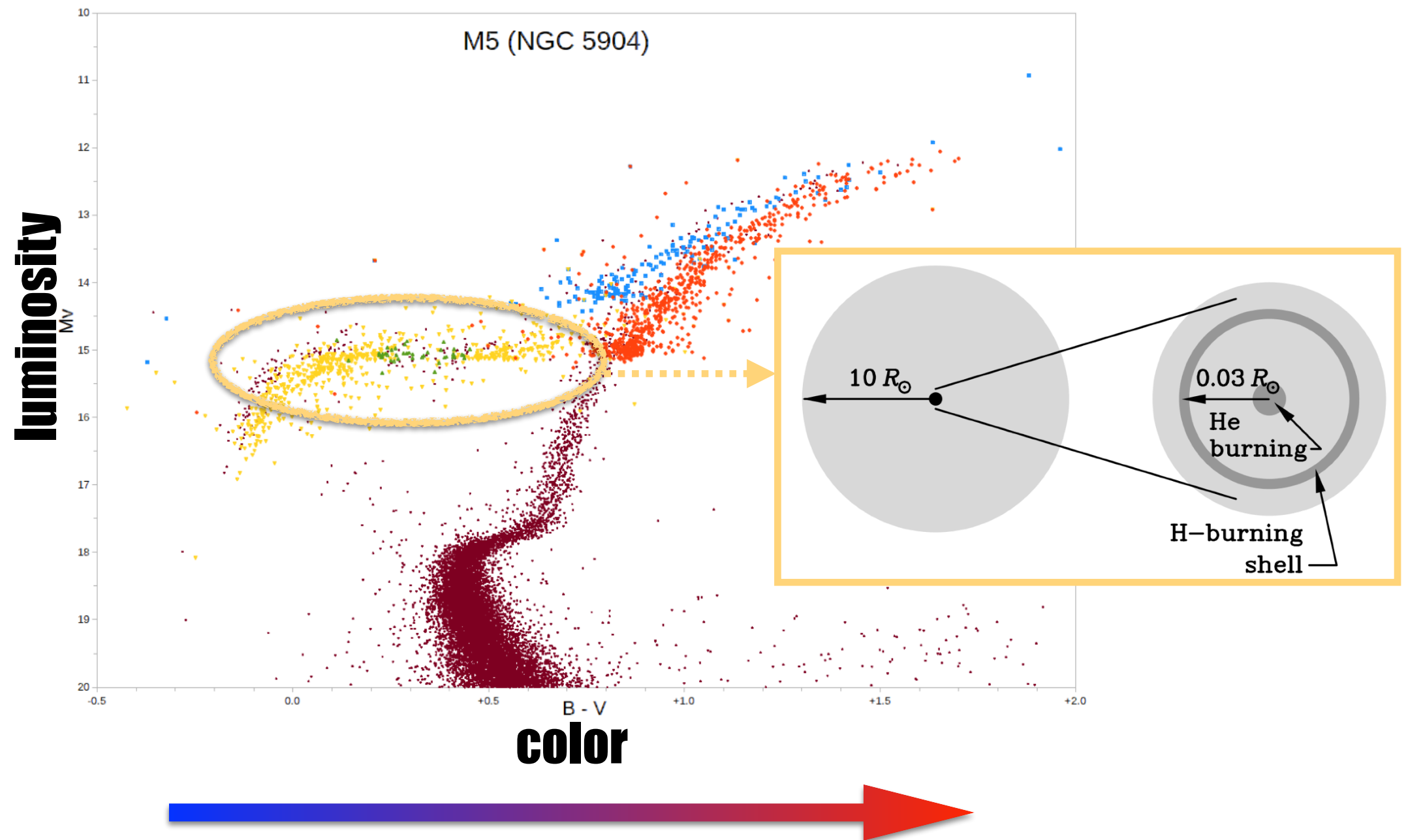
[W. Cerny et al. 20]



Core Mass Increase by Cooling



Horizontal-Branch

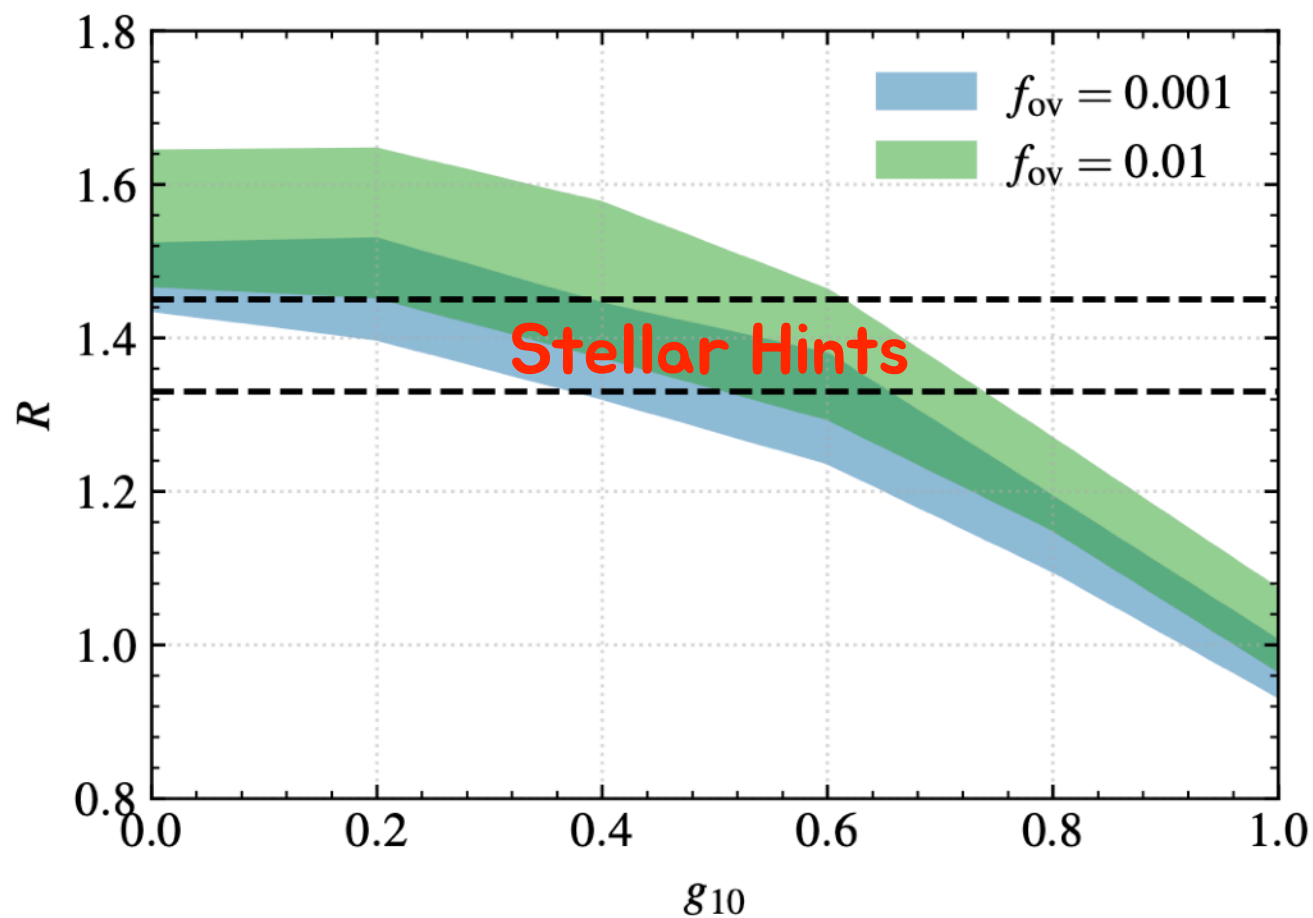


Stellar Cooling Argument on HB

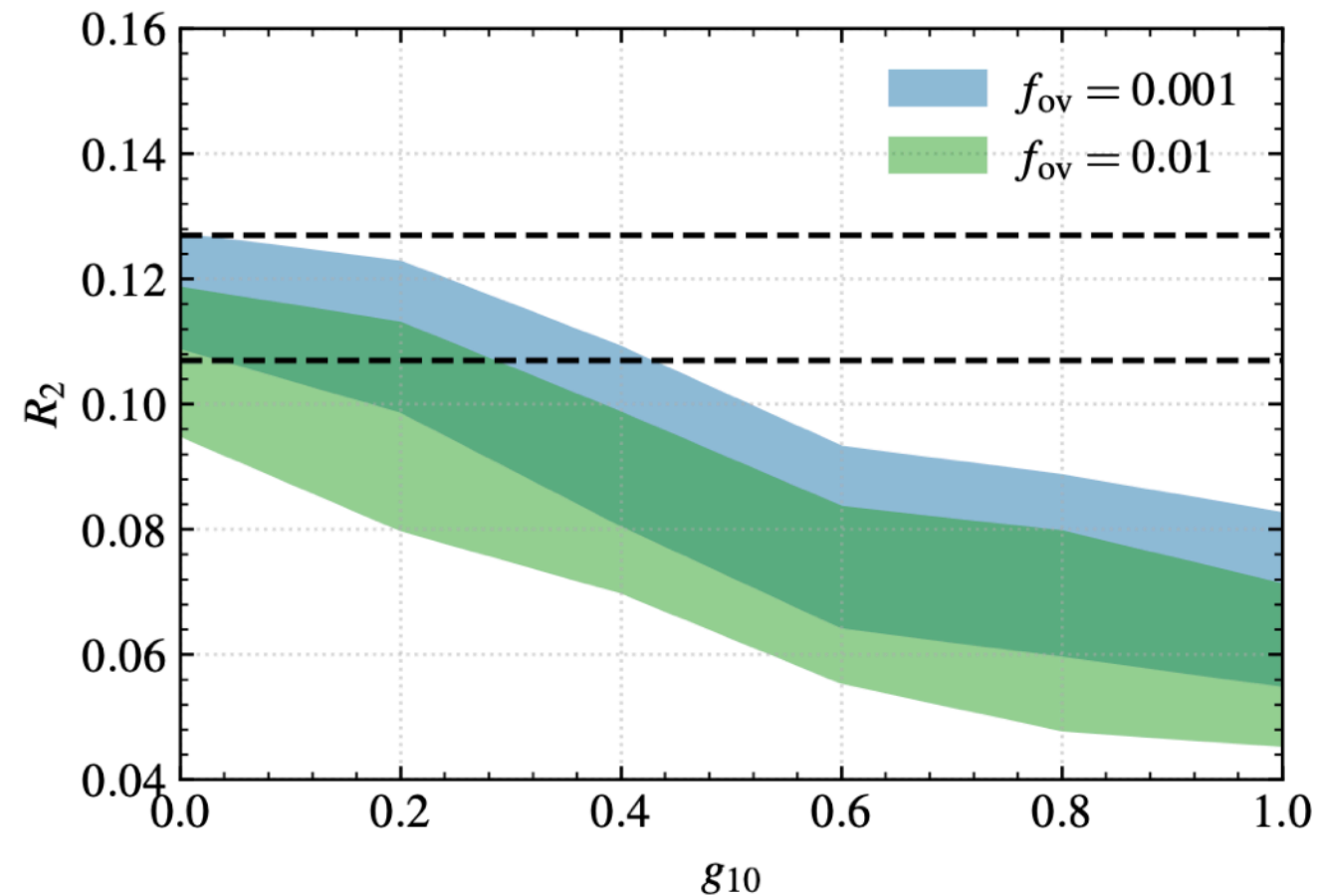
$$R = \frac{N_{\text{HB}}}{N_{\text{RGB}}}$$

Lifetime of HB

$$R_2 = \frac{N_{\text{AGB}}}{N_{\text{HB}}}$$

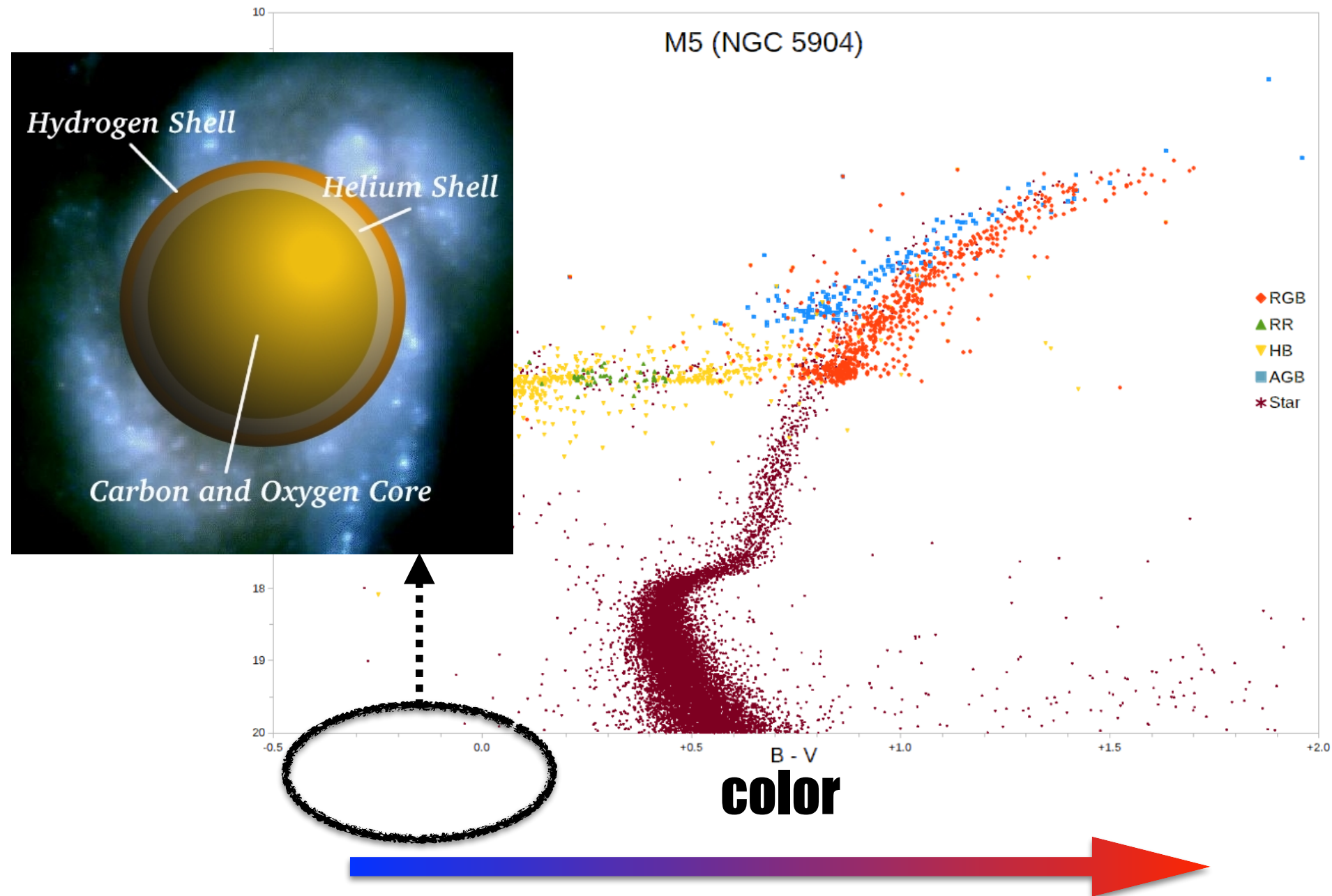


$$g_{10} = g_{ae} \times 10^{10}$$

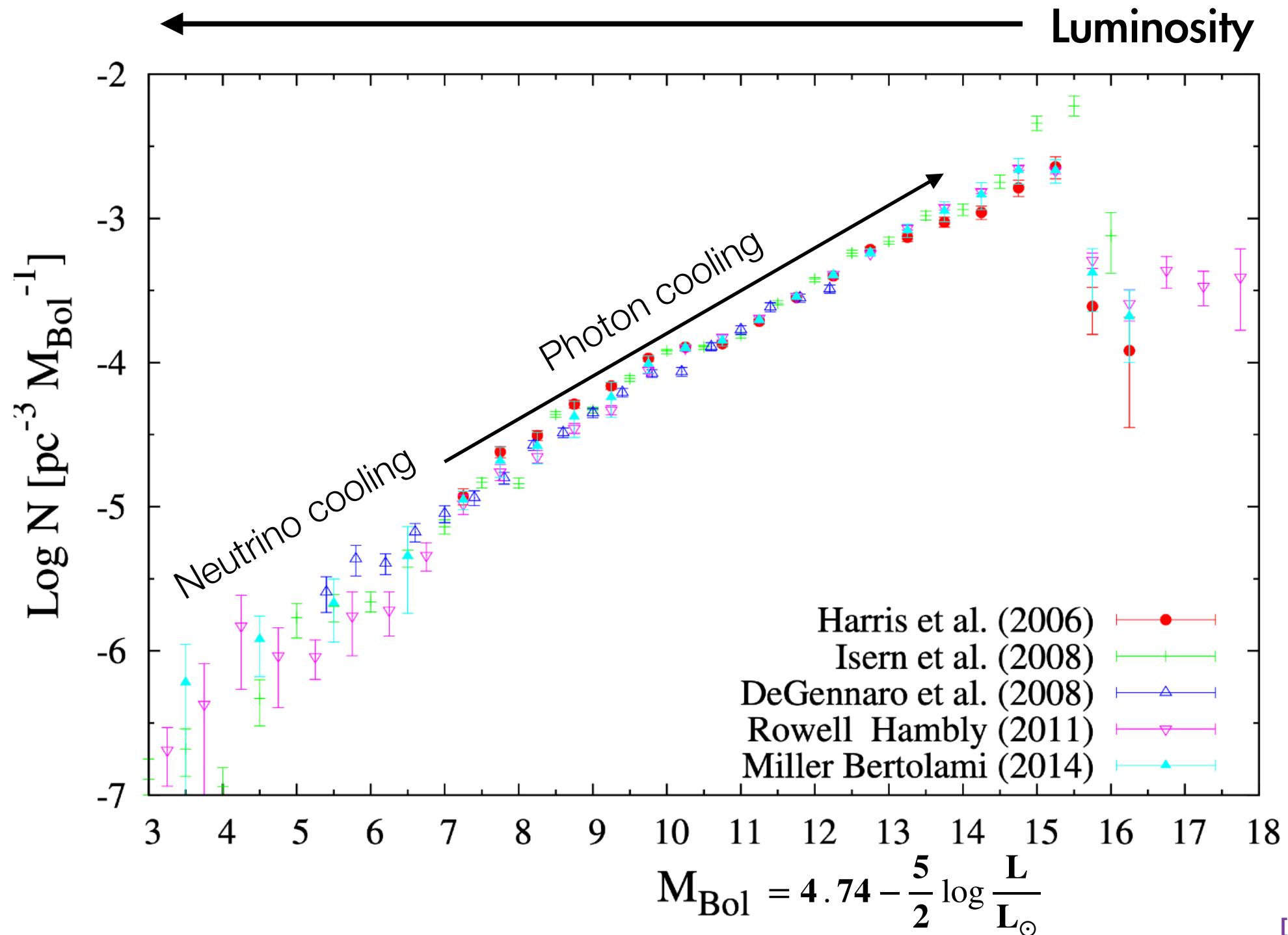


[M. Dolan et al. 22]

White Dwarf

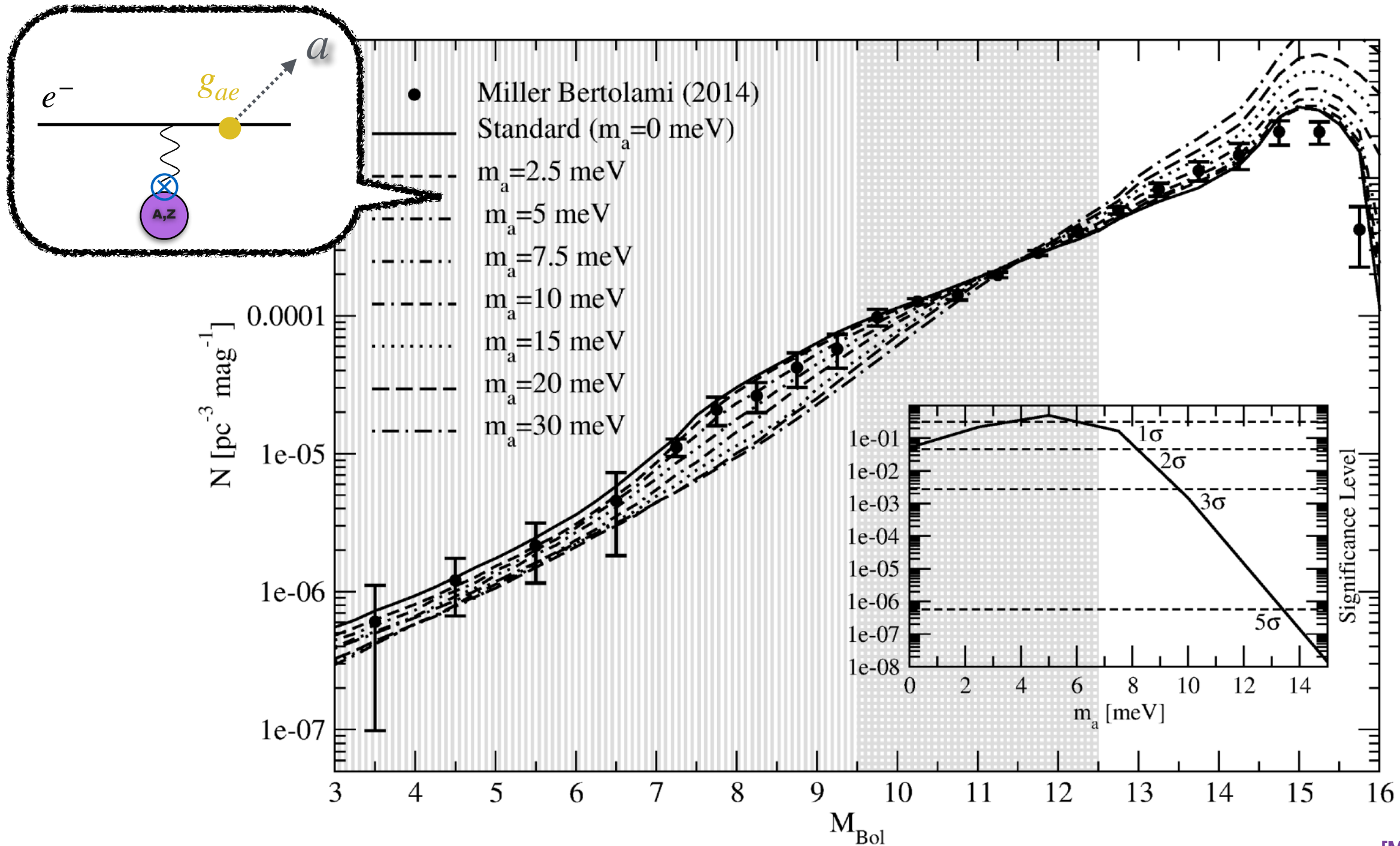


White Dwarf Luminosity Function



[M. Bertolami et al. 14]

White Dwarf Luminosity Function



[M. Bertolami et al. 14]

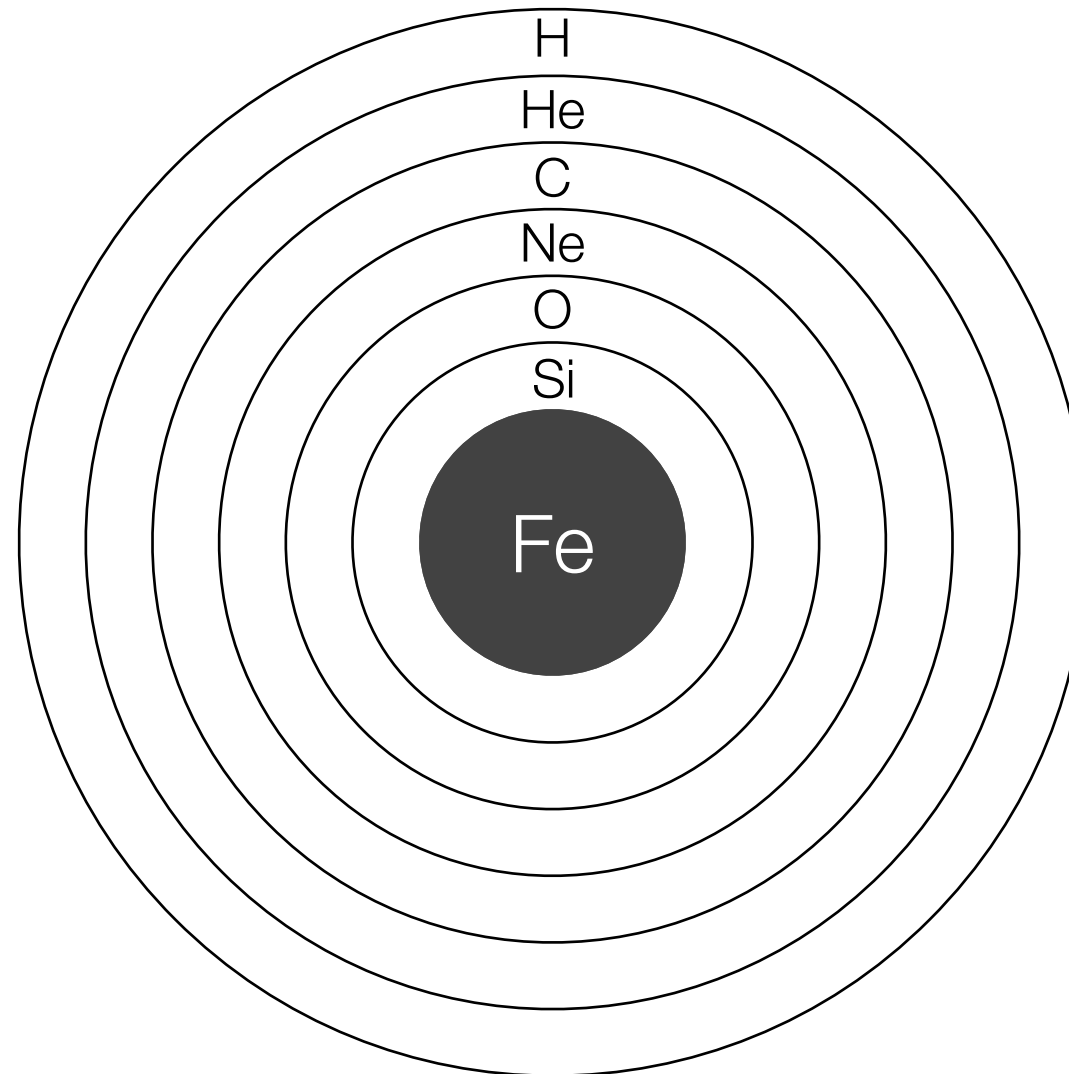
Core-Collapse Supernova

- For stars $> 8M_{\odot}$, iron core will collapse
- Formation of proto-Neutron Star
- Diffusive neutrino emission
- Shock wave (explosion) + delayed γ

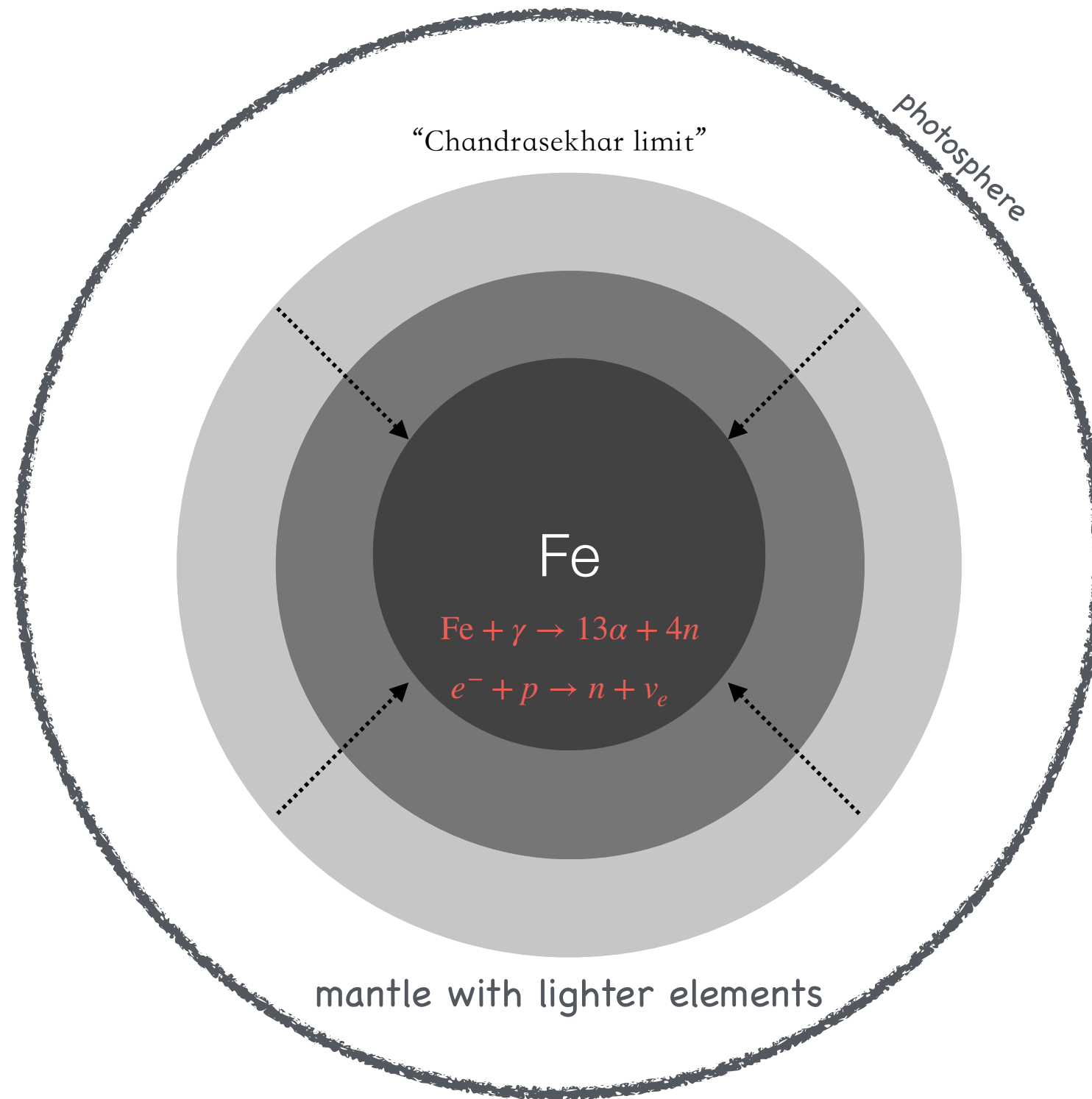
($> 8 M_{\odot}$)

Nuclear fusion in massive stars

progenitor like super red-giants



Onset of Iron Core-Collapse



$\mathcal{O}(1)$ second Post Core-Collapse

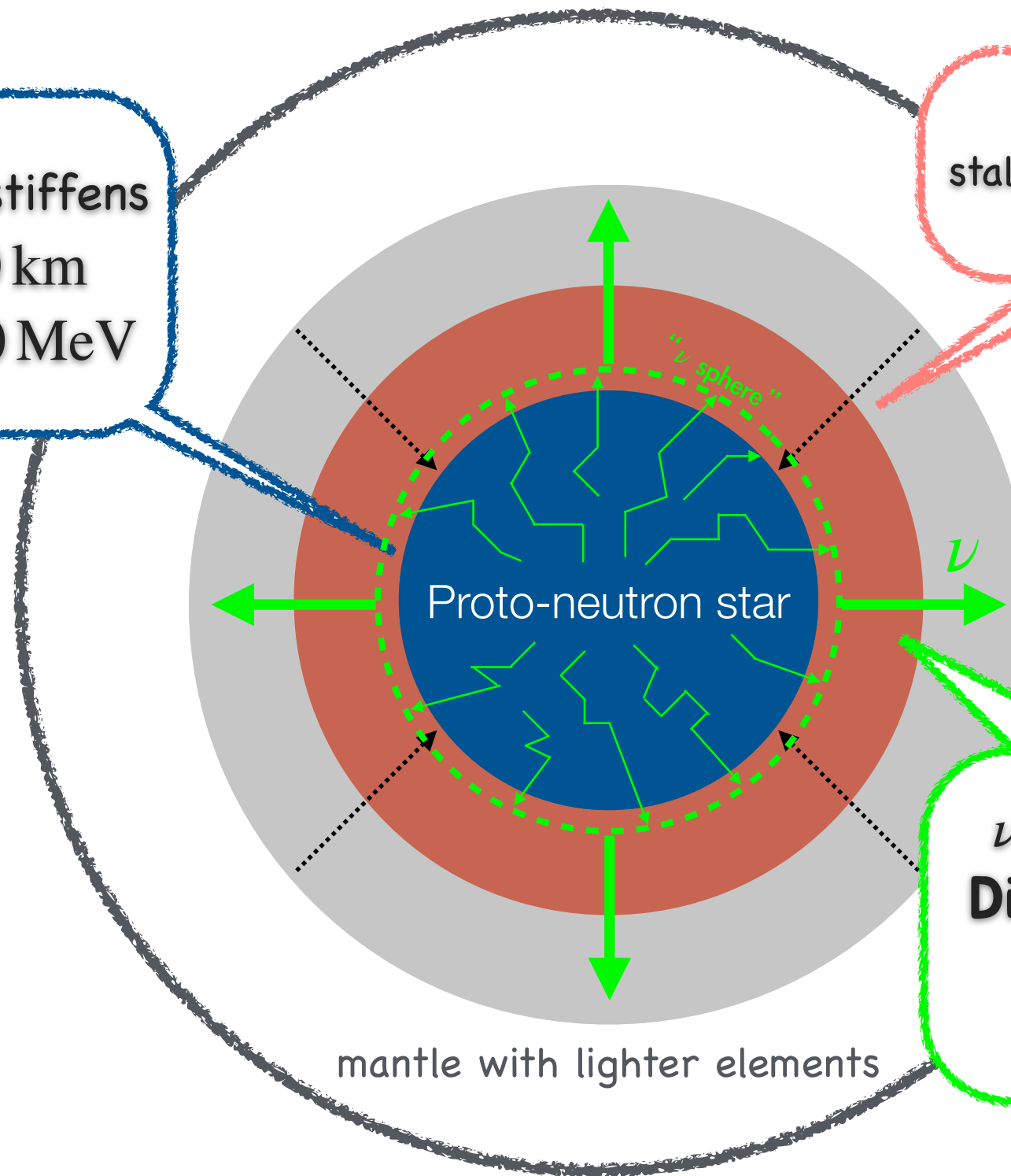
i.e., typical nucleon distance $\sim$ fm

At $\rho_c \sim \rho_{\text{sat}}$, EoS stiffens

Core size ~ 10 km

Temperature ~ 30 MeV

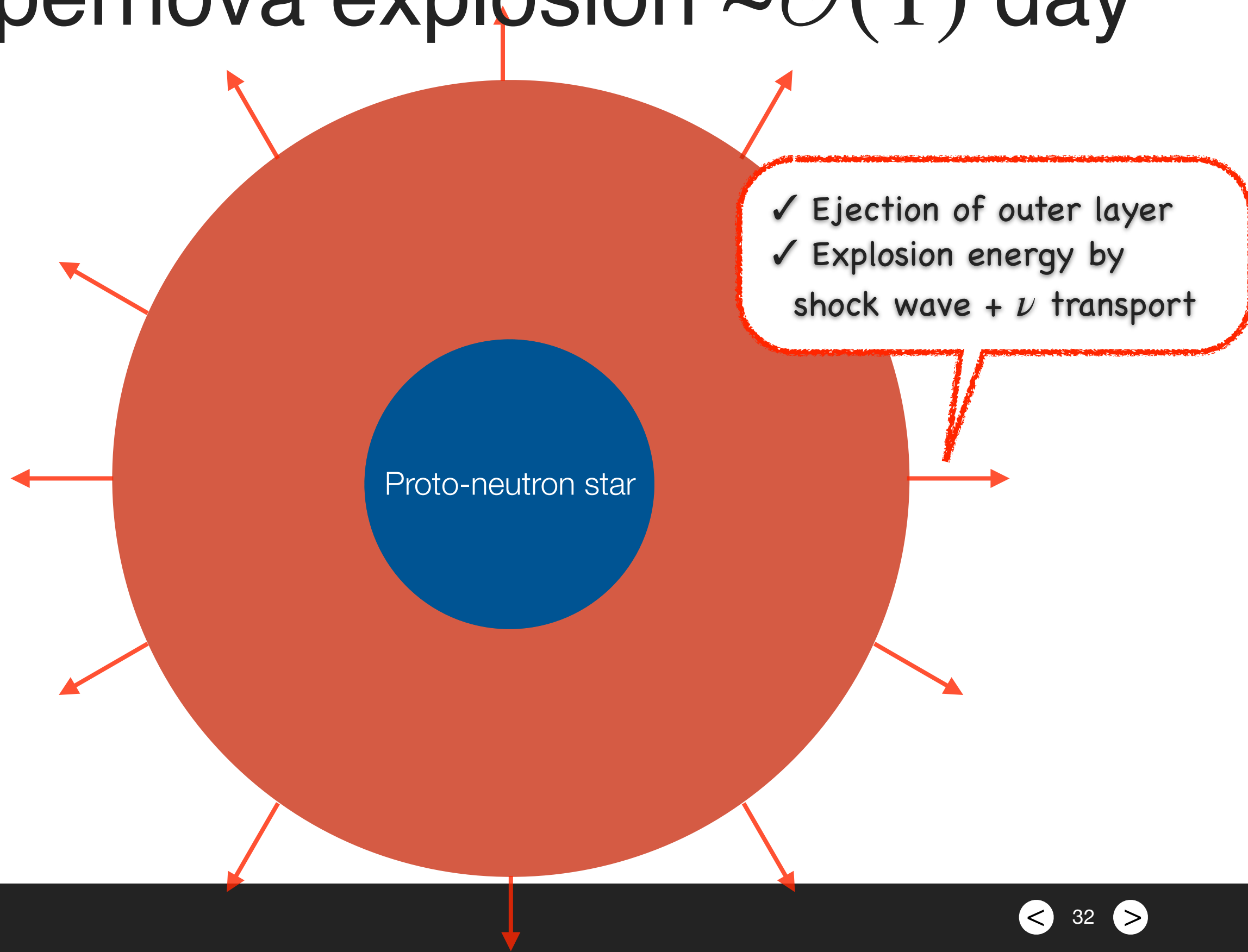
Bounce shock wave
stall by dissociation & accretion
revived by neutrinos



ν produced, but trapped
Diffusive surface emission

$$t_{\text{diff}} \sim \frac{R_c^2}{\lambda} \sim 10 \text{ sec}$$

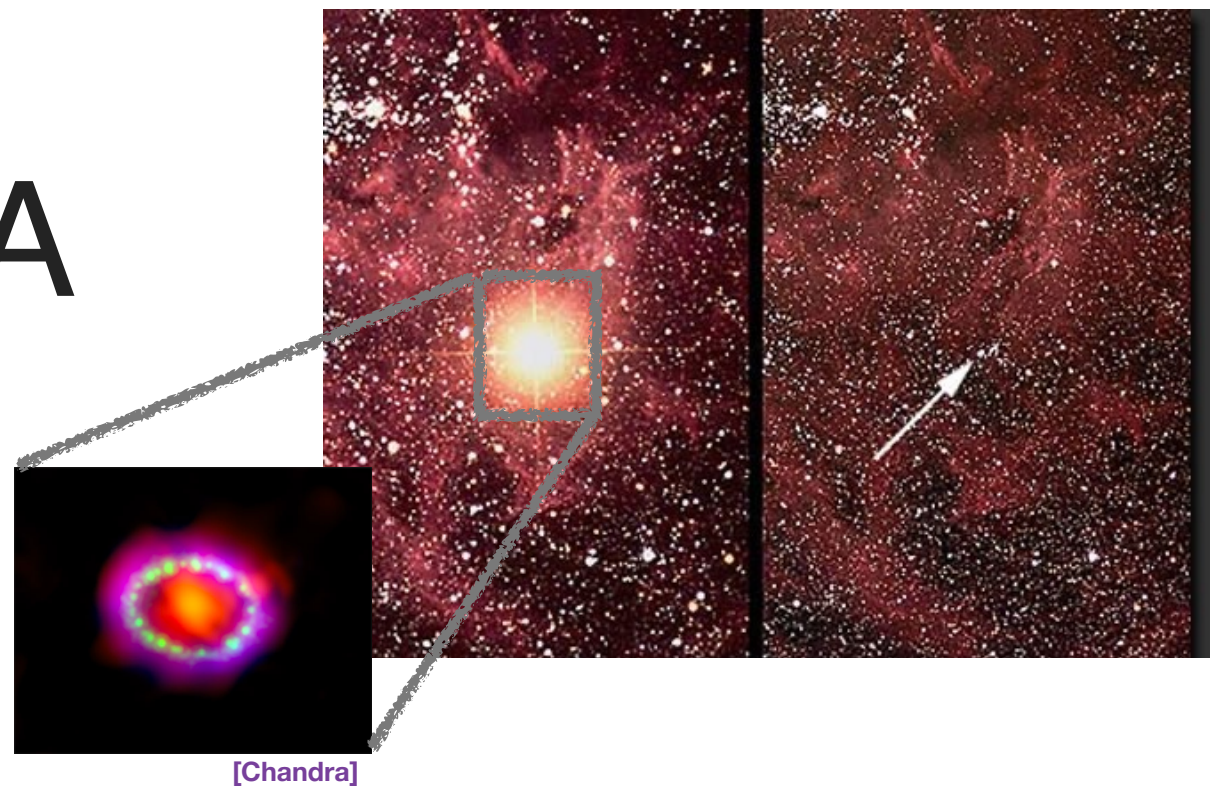
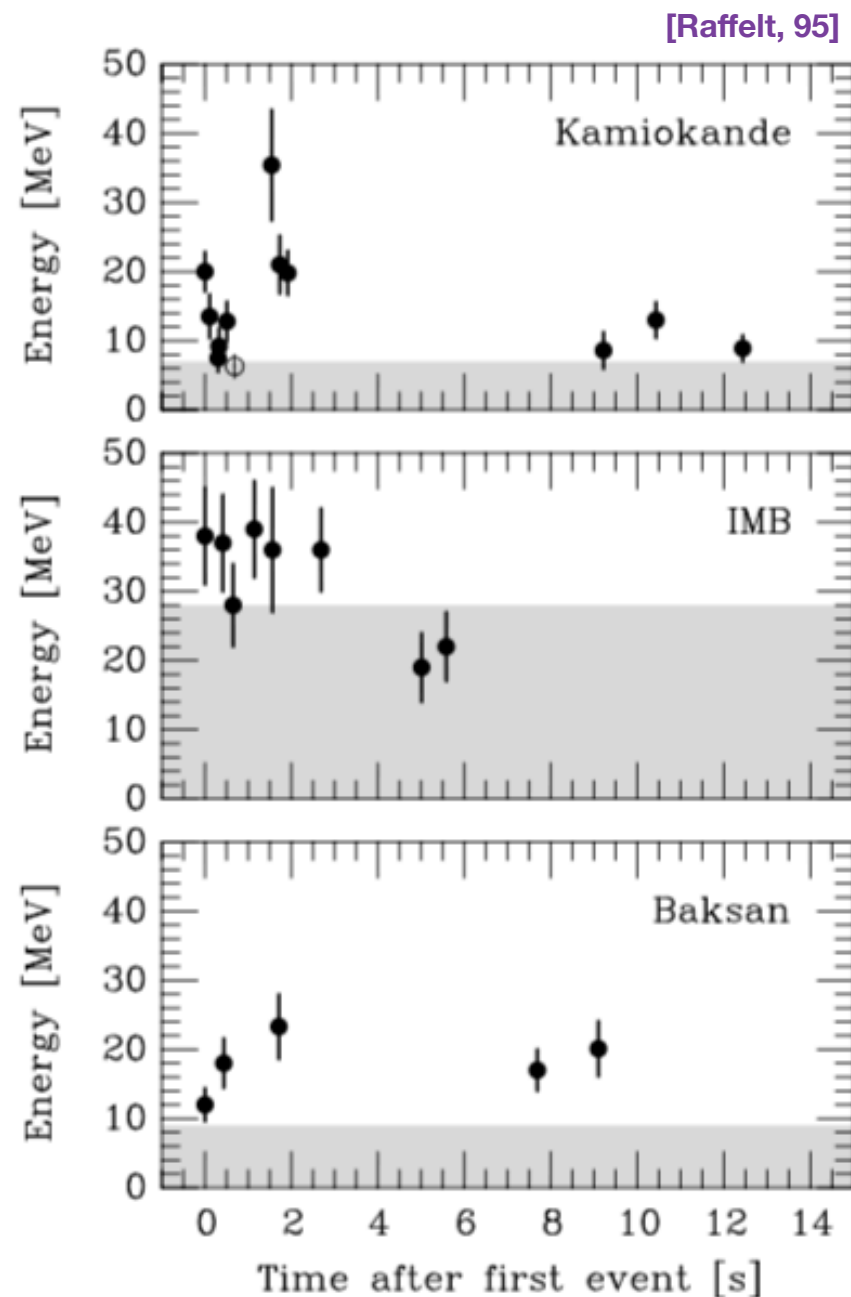
Supernova explosion $\sim \mathcal{O}(1)$ day



SN Implications

- Observables:
 - Neutrino & no prompt γ -ray signal of SN1987A
 - Low-energy supernova explosion
 - Fireball  γ -ray like signals
 - Galactic e^+ injection
 - Cosmic diffuse x-ray background

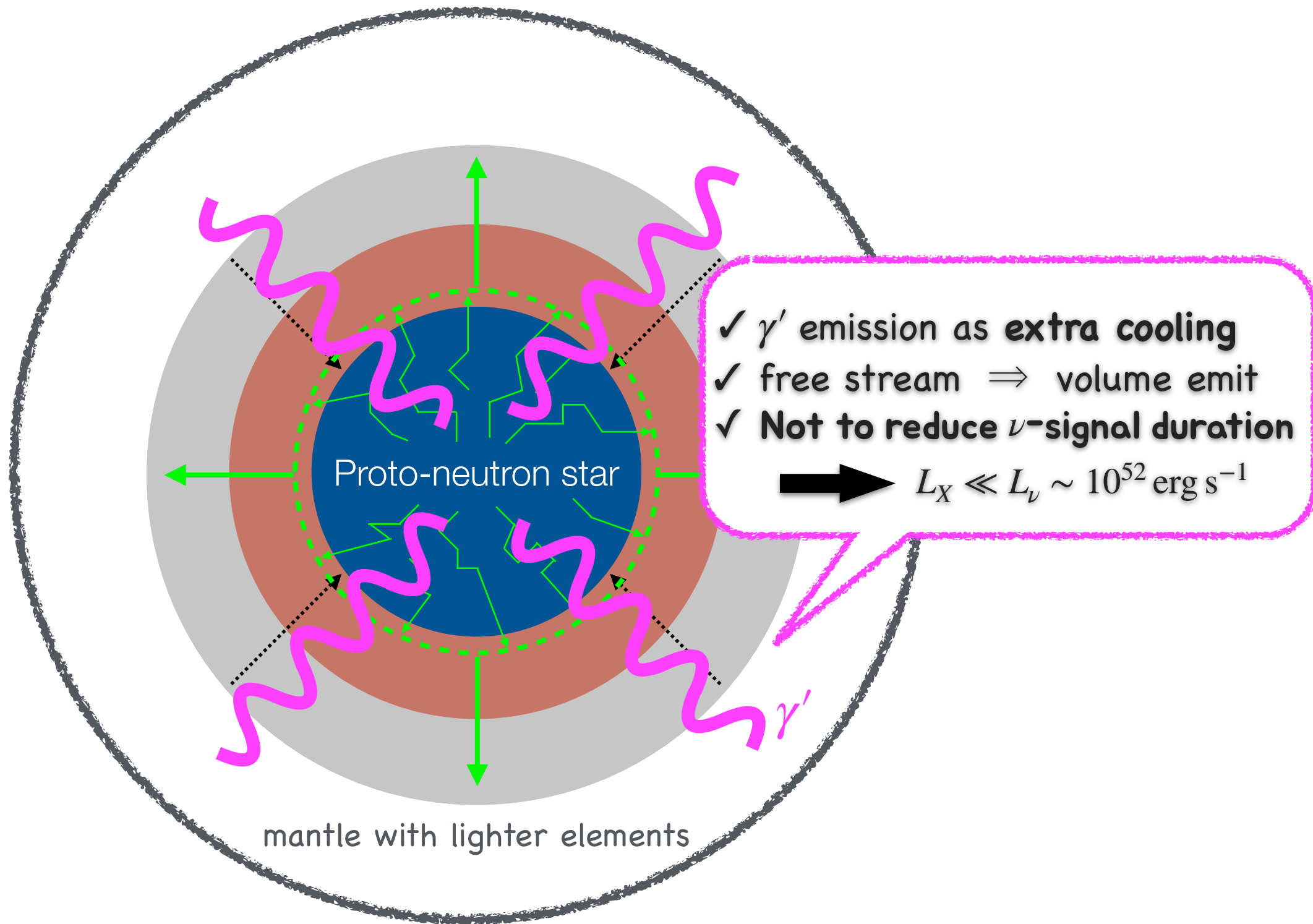
SN1987A



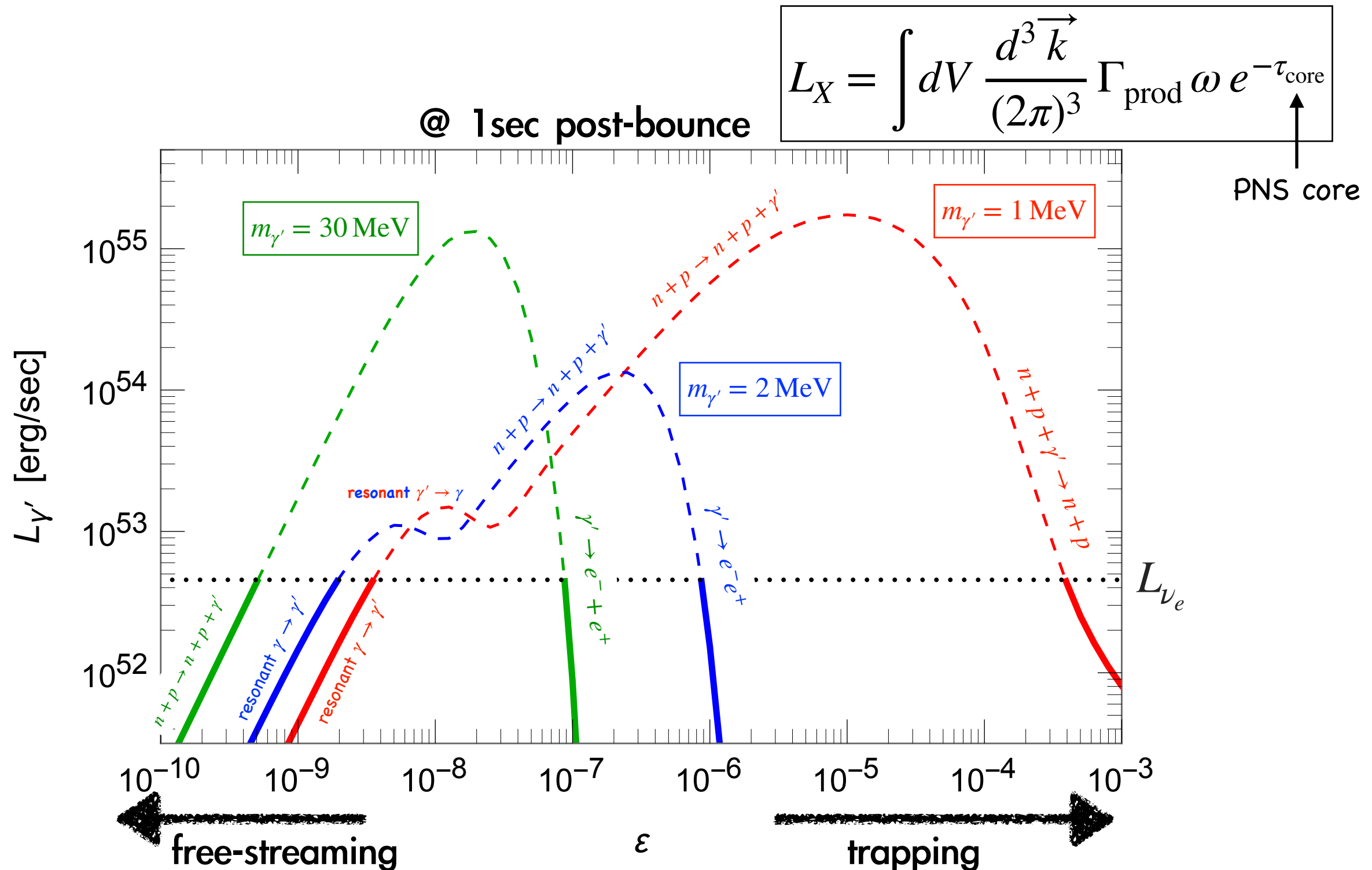
- The only direct observation of neutrinos occurred on 23 Feb 1987 when the blue supergiant Sanduleak–69 202 in the Large Magellanic Cloud exploded

**~ 10 seconds duration of
observational ν signals**

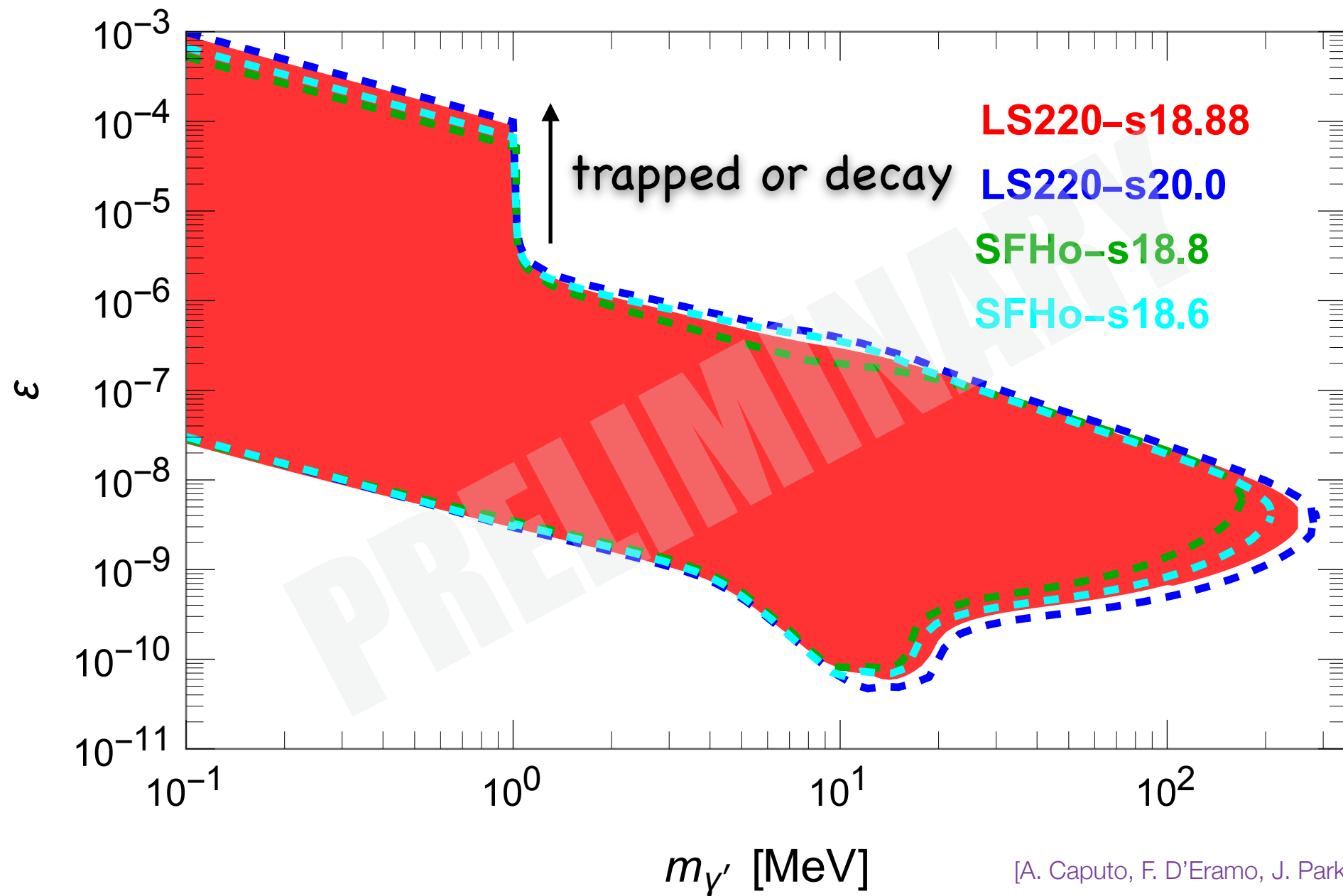
Cooling argument on SNe



SN Dark Photon Luminosity



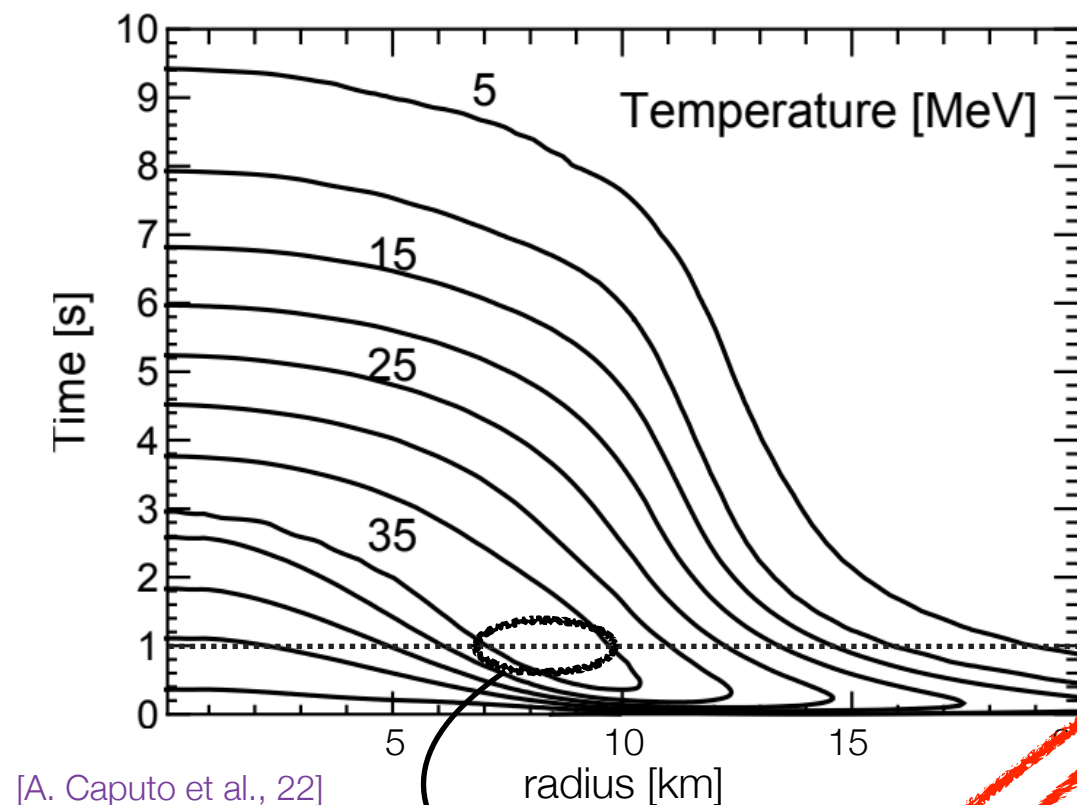
Cooling Constraints



[A. Caputo, F. D'Eramo, J. Park, **SY**, in progress]

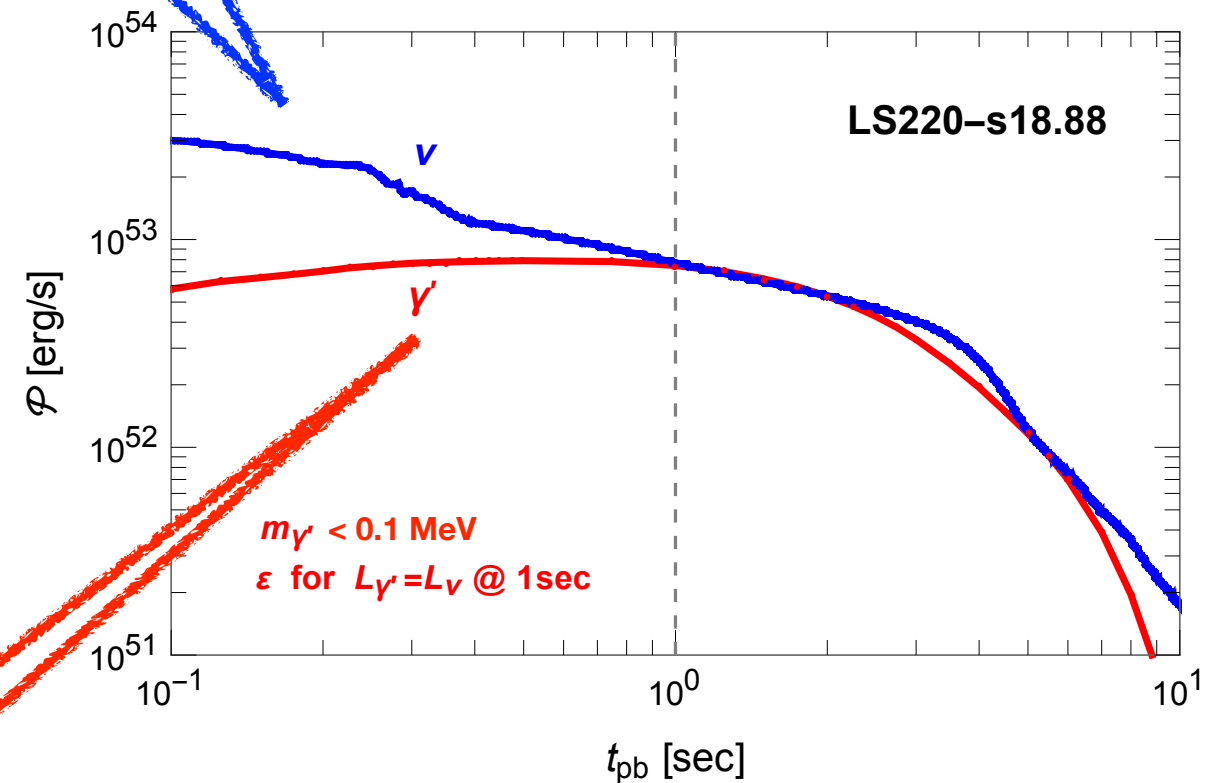
Remarks on SN Cooling Argument

Powered by accretion



[A. Caputo et al., 22]

Maximized @ $\sim 1\text{sec}$



✓ L_X VS L_{ν} @ 1sec **“Raffelt criterion”**

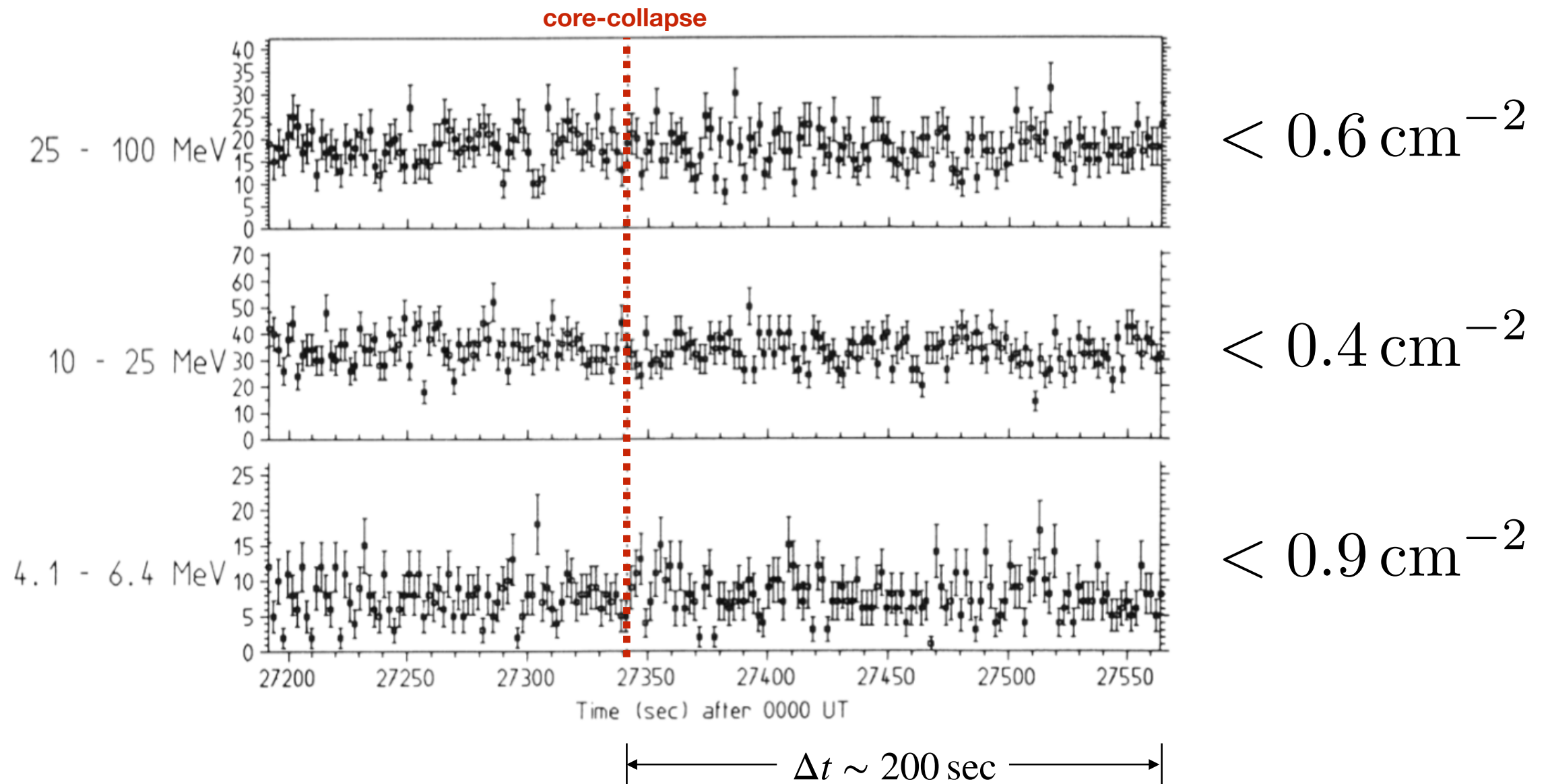
✓ No impact on earlier stage?

✓ Self-consistent simulations?

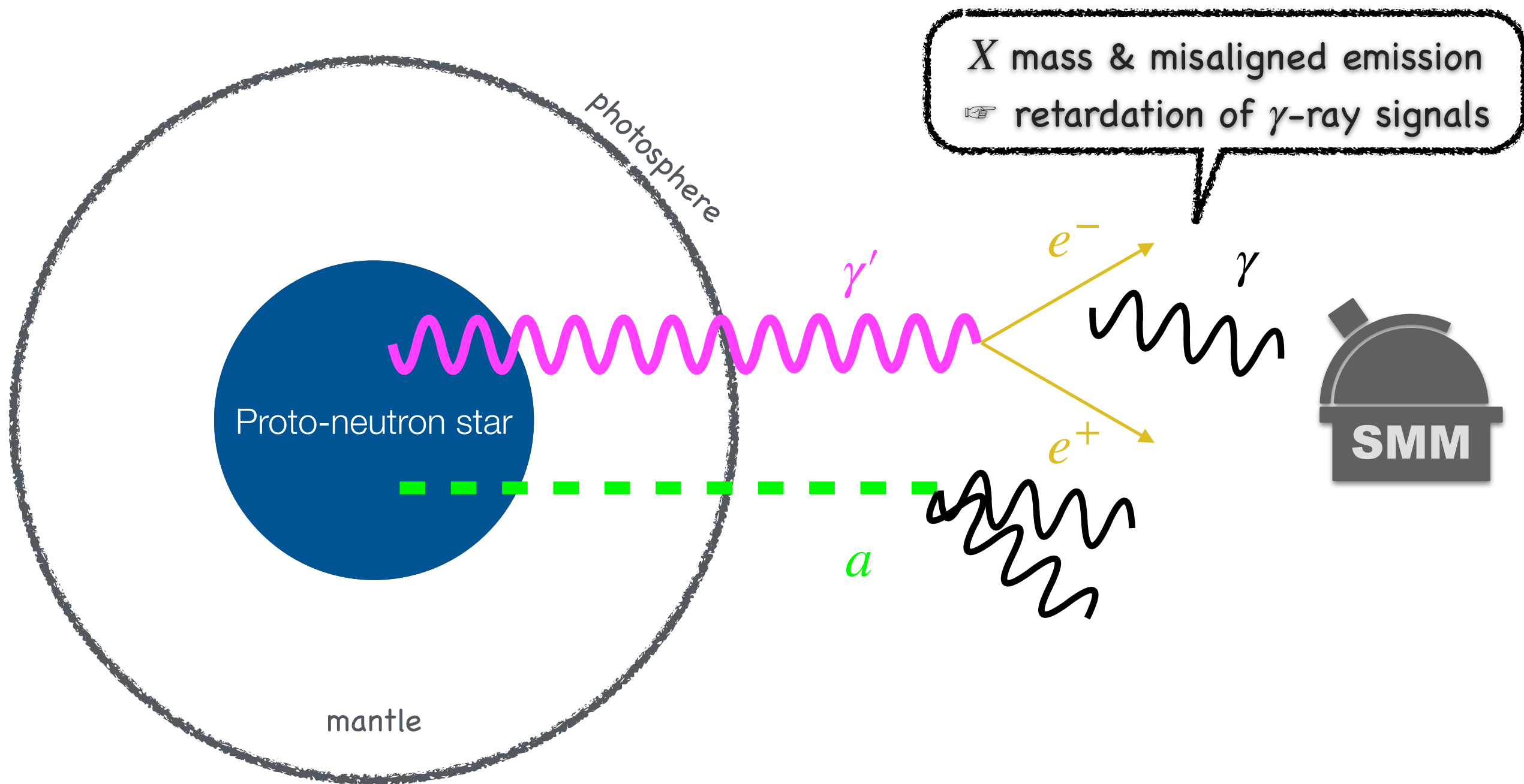
– in particular, explosion?

Absence of Prompt SN1987A γ -ray

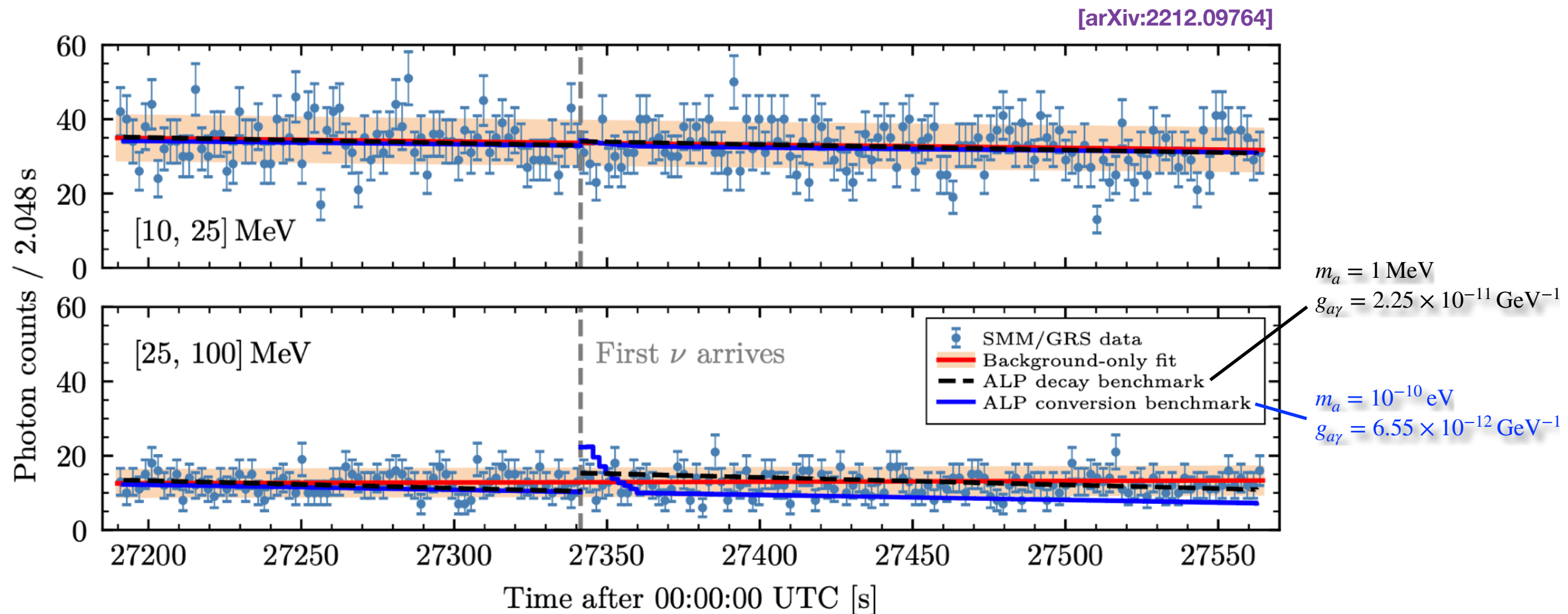
Even rates measured in the Gamma Ray Spectrometer of the Solar Maximum Mission



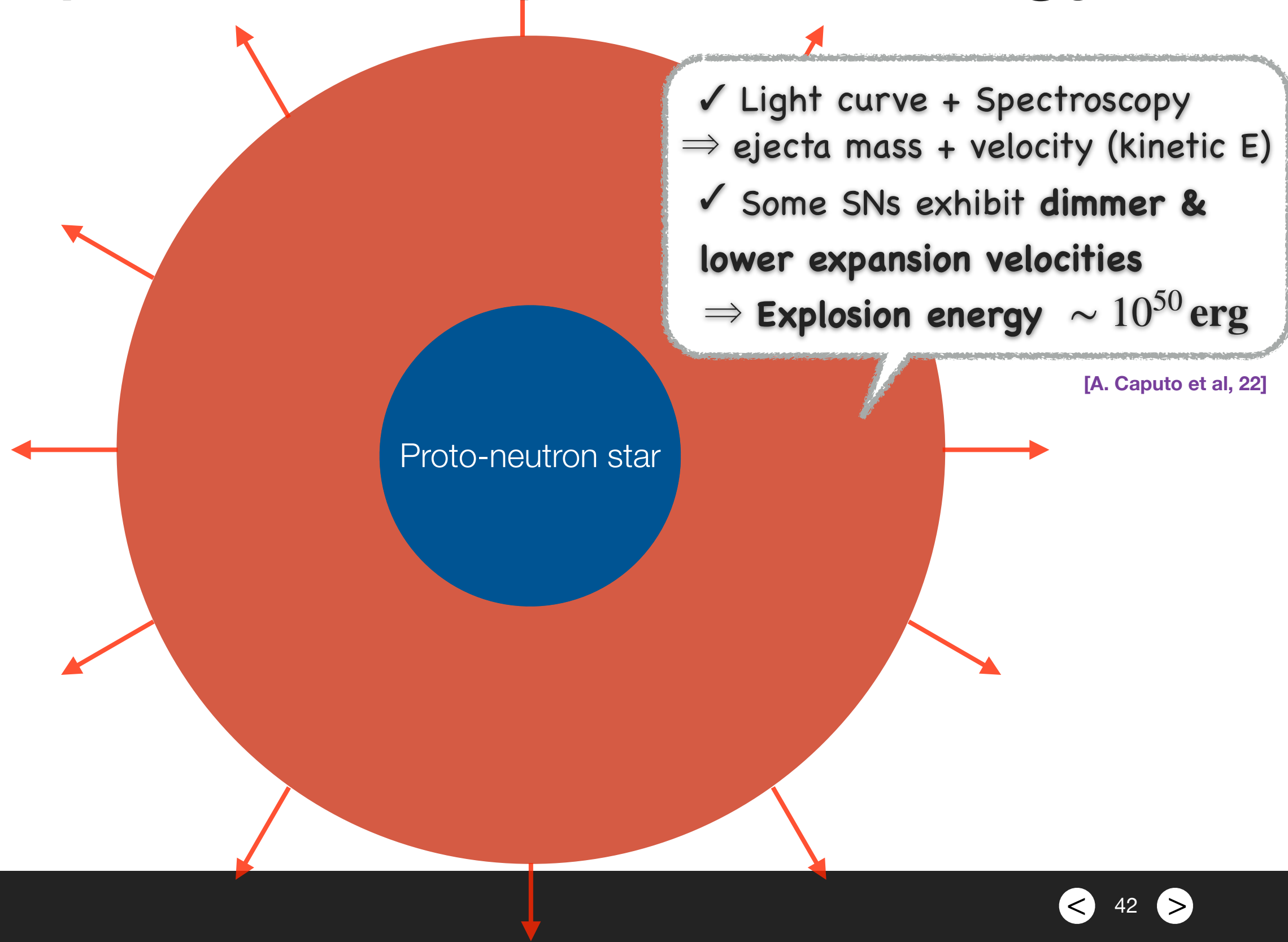
Prompt γ -ray from Novel Particles



Prompt γ -ray from Axions

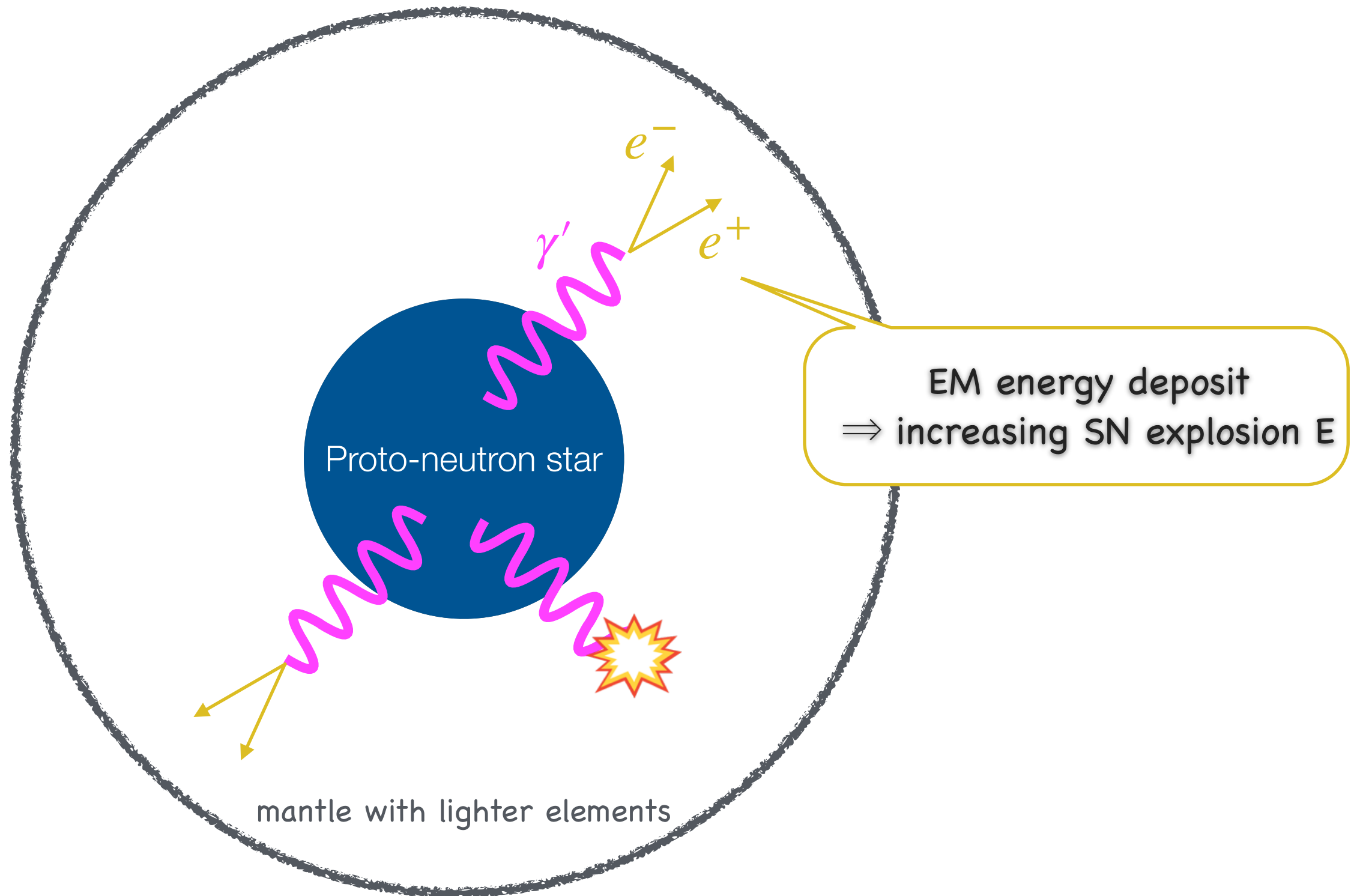


Supernova Explosion Energy

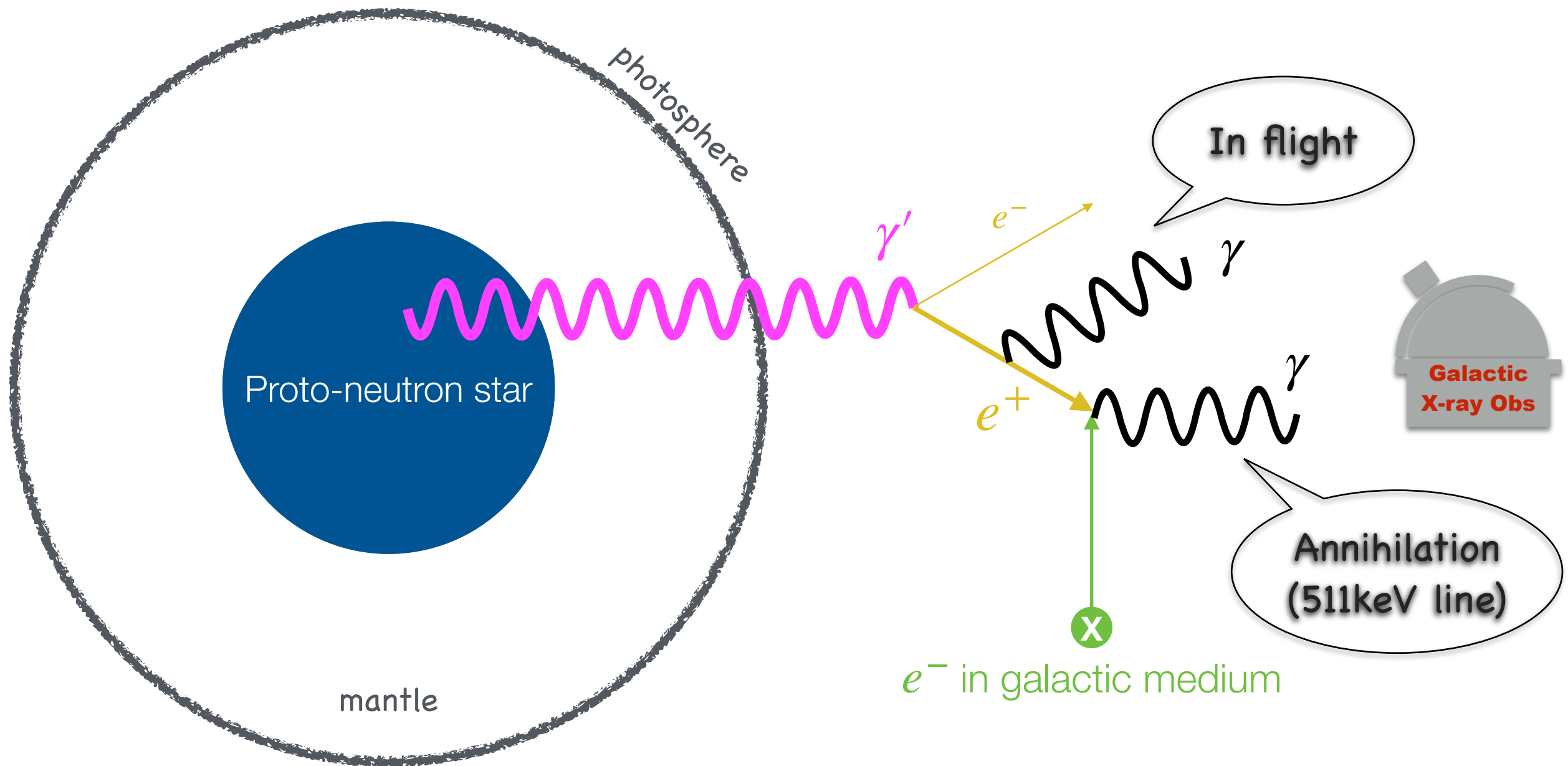


[A. Caputo et al, 22]

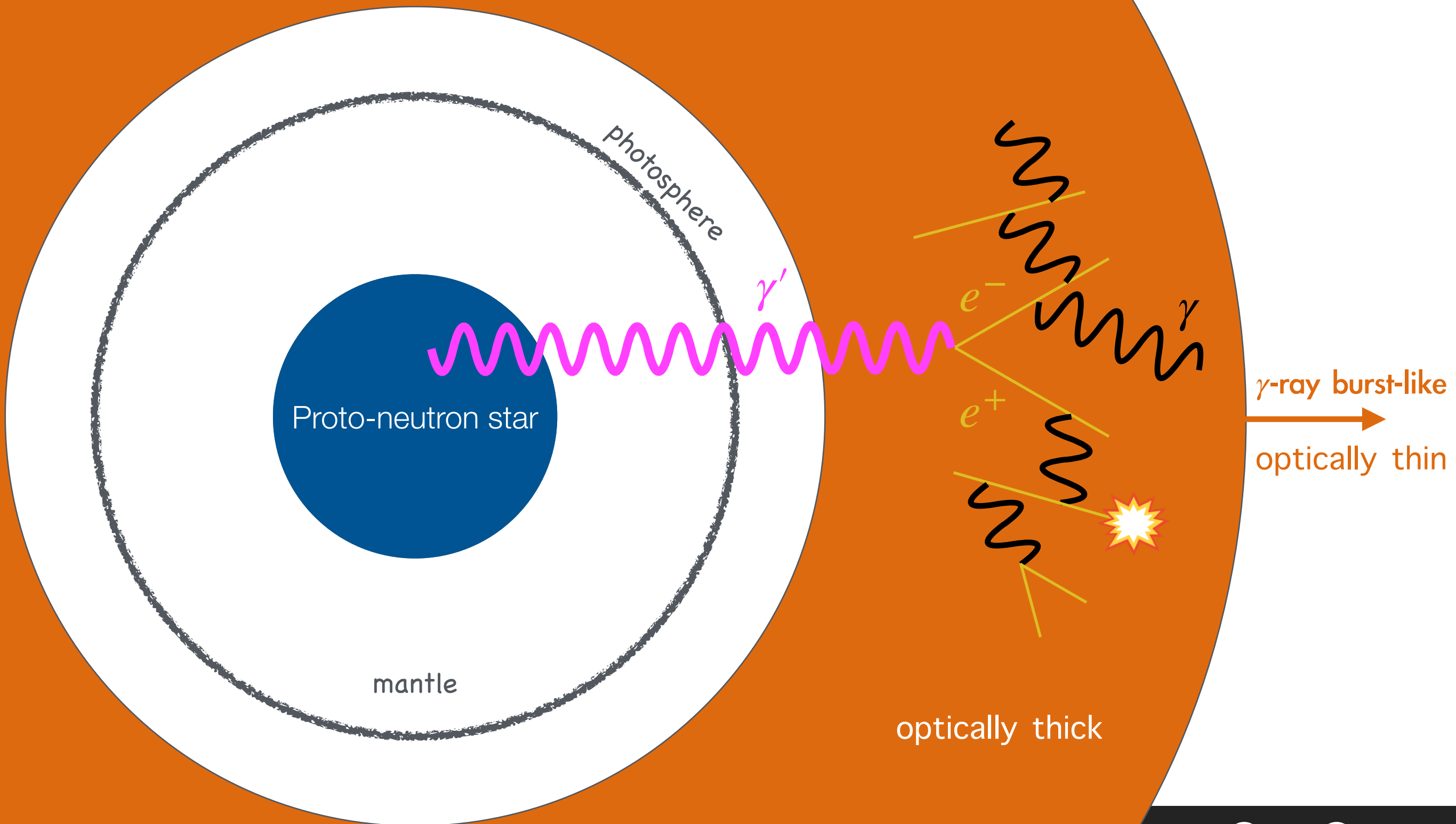
Energy Deposit by Decays



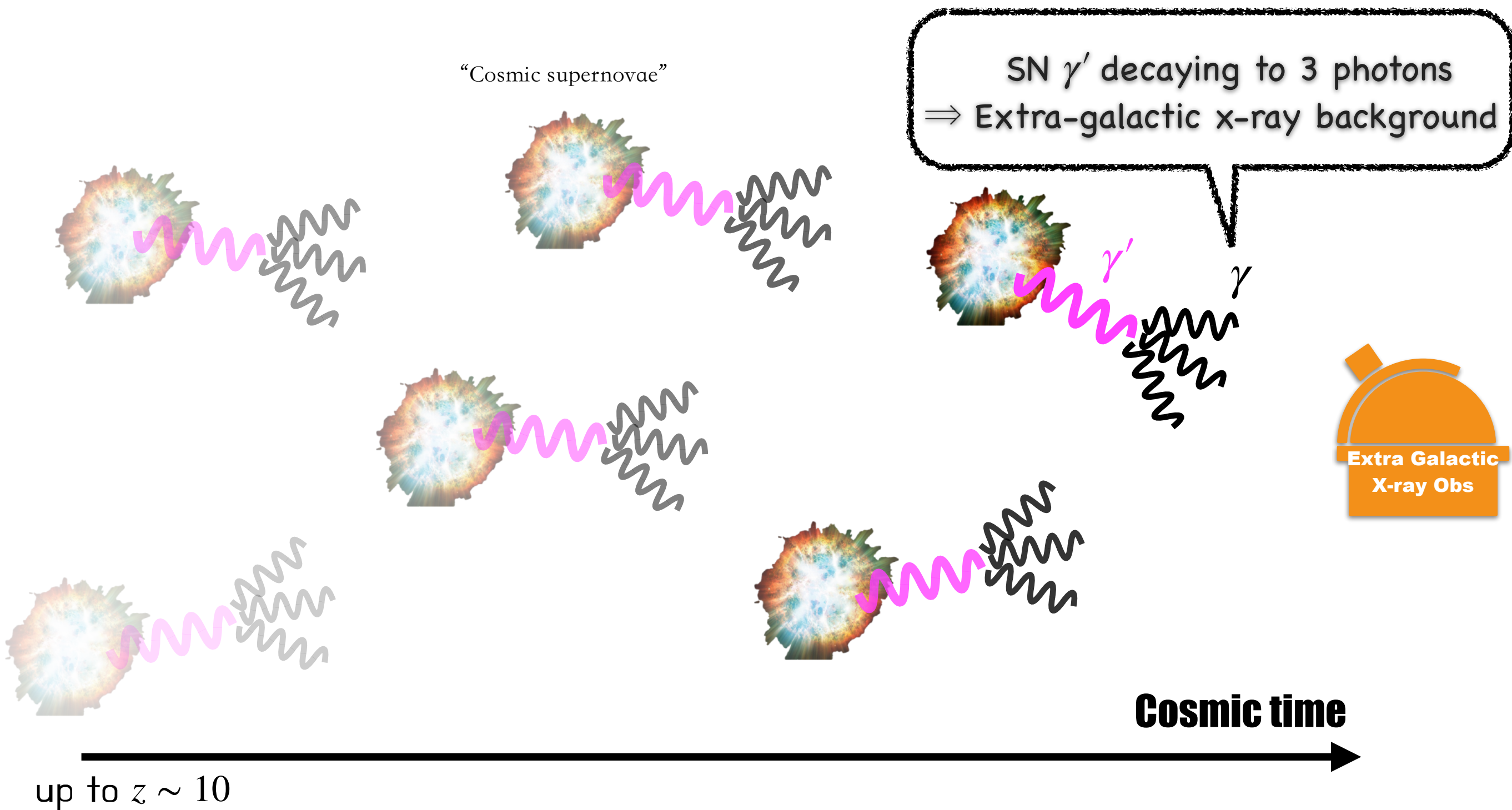
Supernova Galactic e^+ Injection



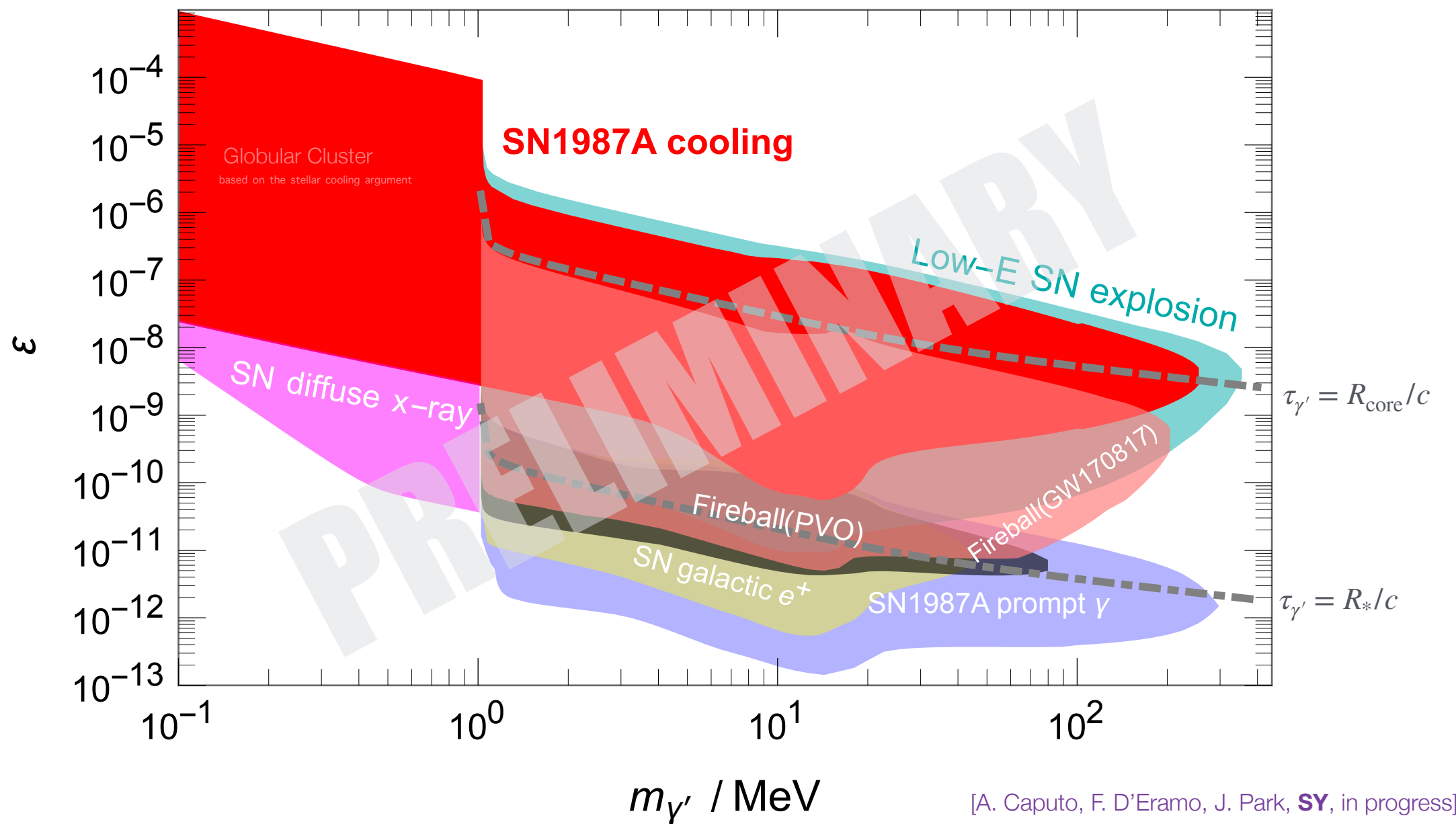
Fireball Formation by Decay



Cosmic Supernova & Novel Particles



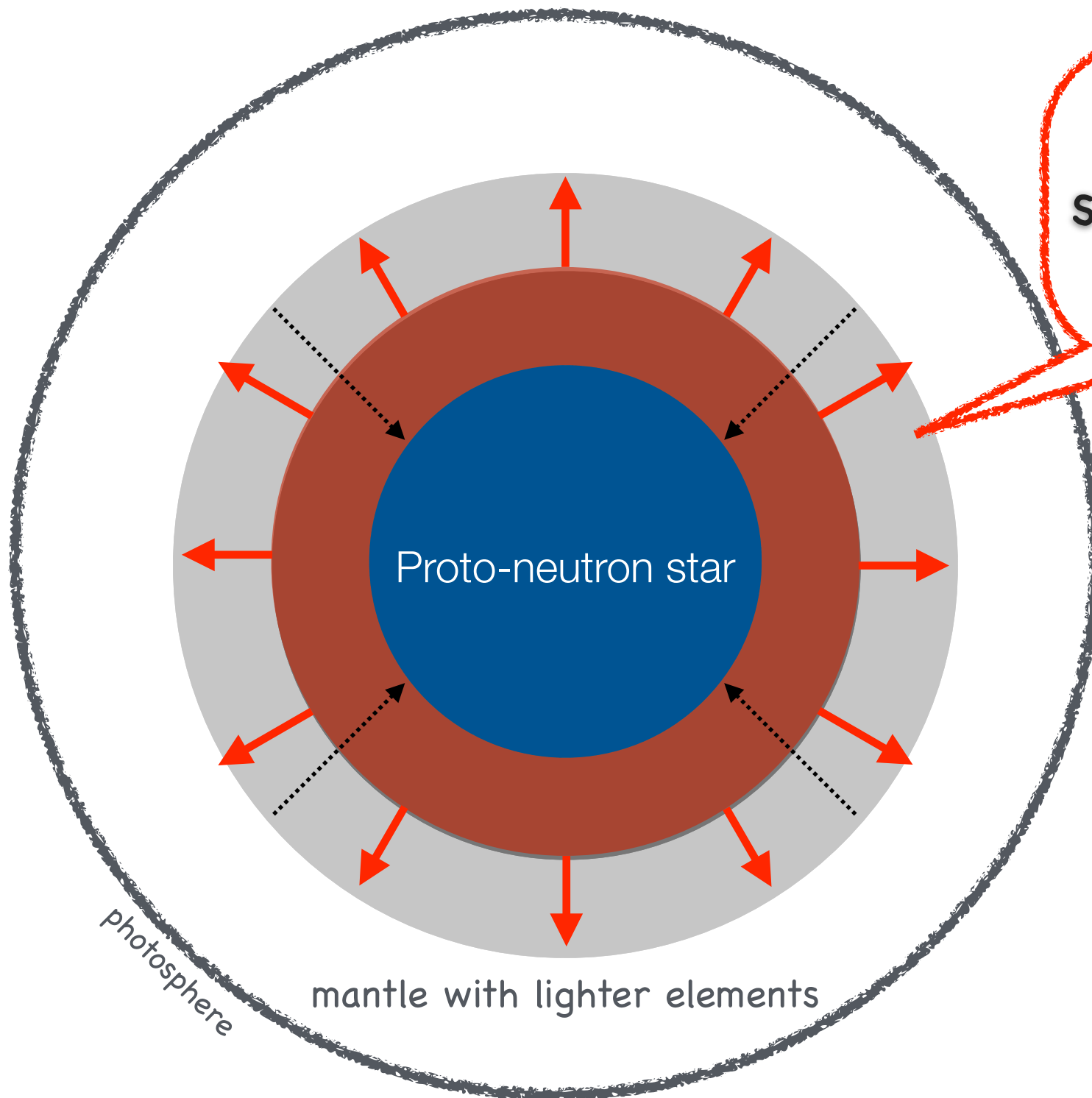
Supernova Constraints on γ'



Supernova Explosion

- Neutrino-driven explosion:
 - Shock wave revived by neutrino heating in the gain layer
 - Explosion can be failed by extra cooling

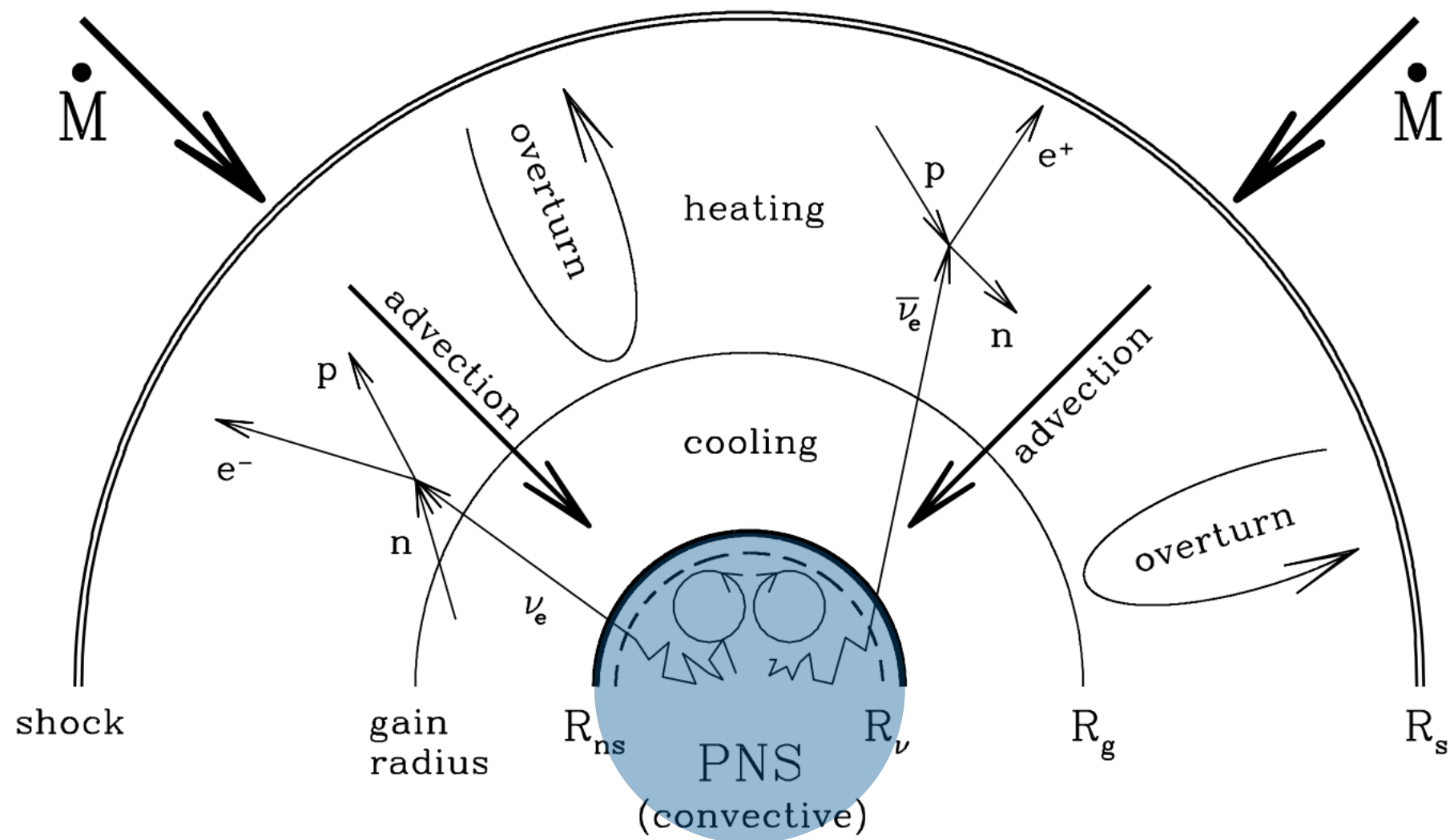
Shock Wave Stalls



Bounce shock wave
stall by dissociation & accretion
☞ revived by neutrinos

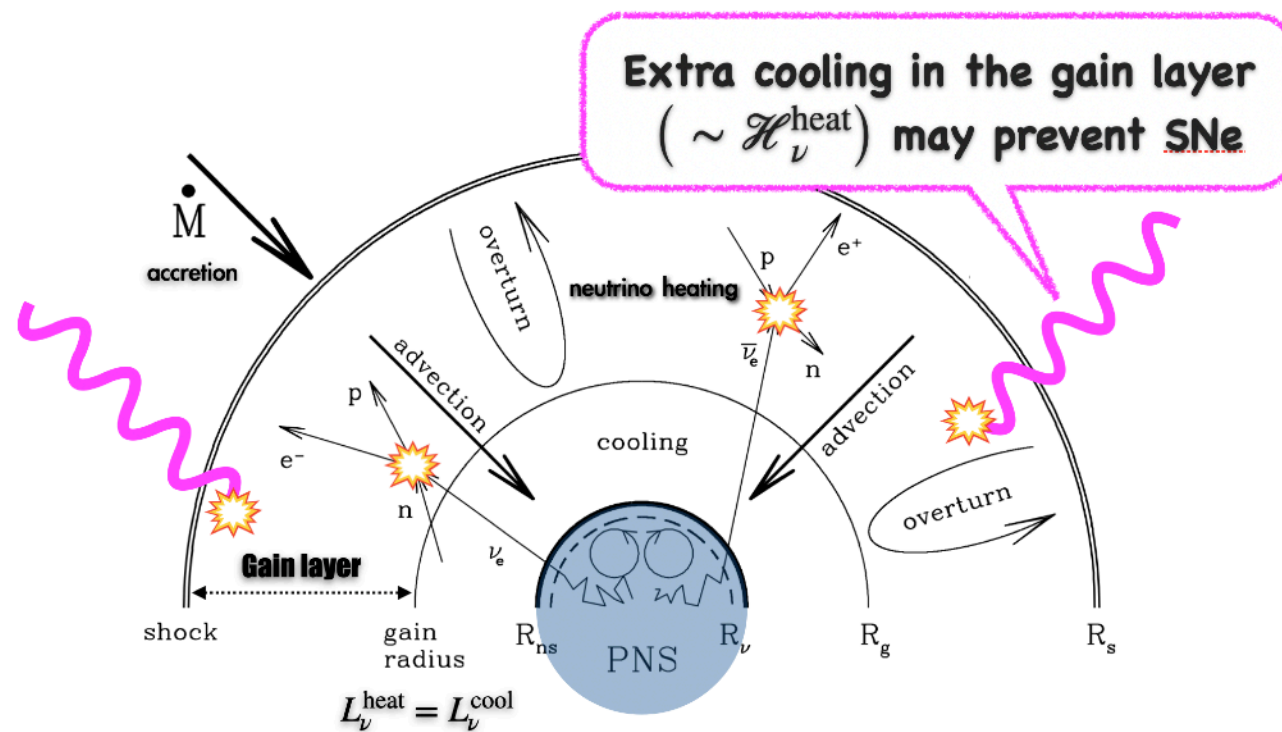
- ☉ $\mathcal{O}(0.1)M_{\odot}$ of iron material
 - ▶ Nuclear binding energy $\sim 10^{51}$ erg
 - ▶ Comparable to explosion energy

Shock Revival by ν -Heating

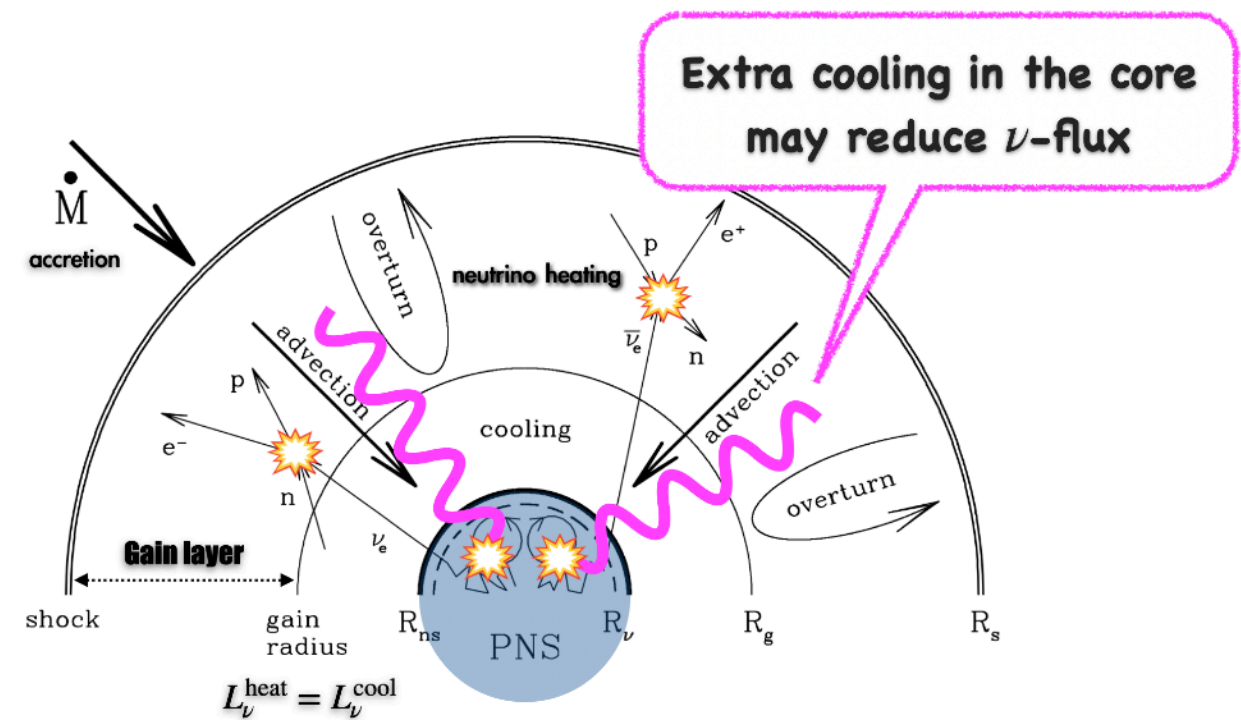


[T. Janka, 01]

Potential Ways to Impact on SNe

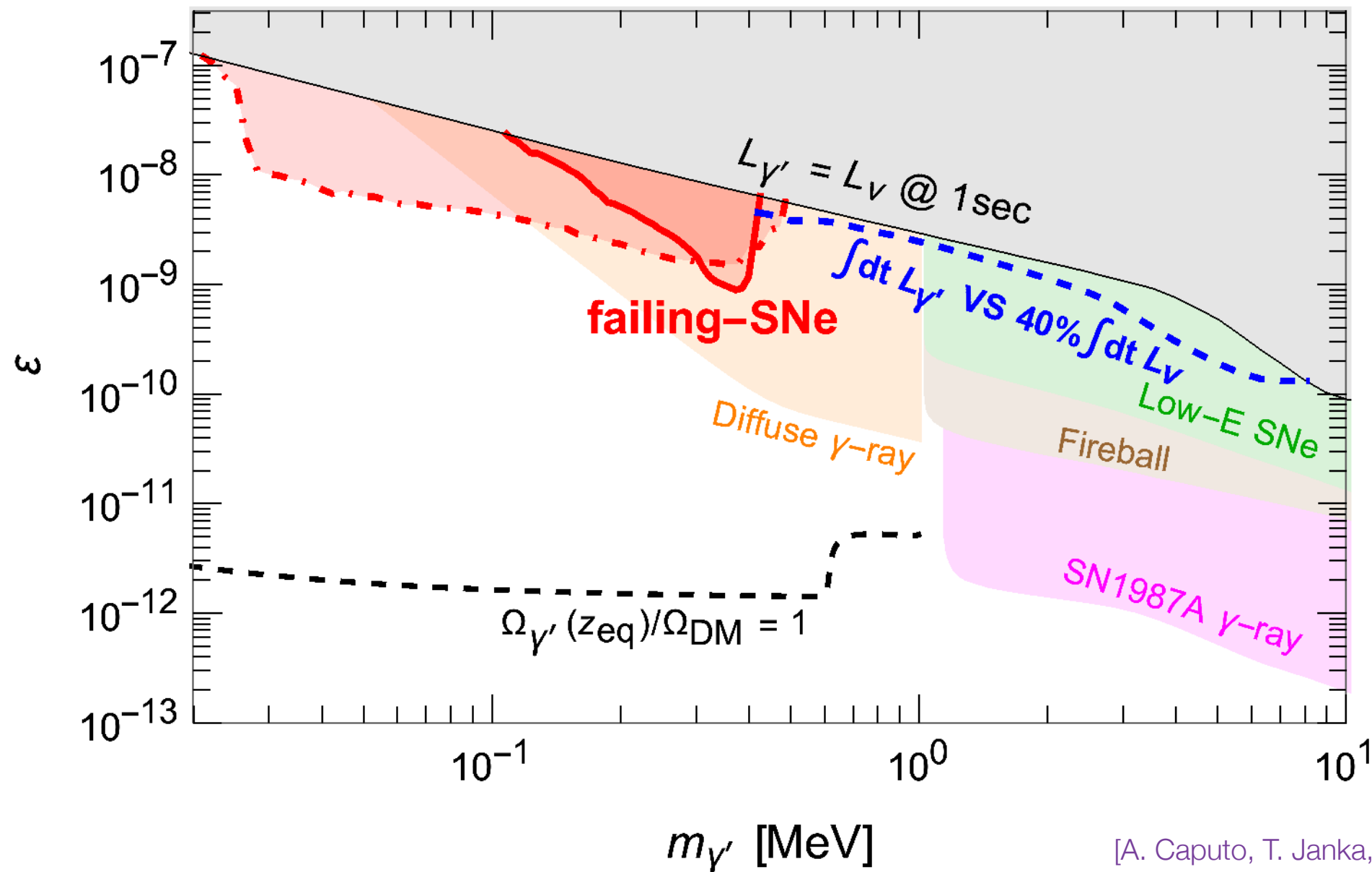


(Direct) Cooling in the Gain Layer



(Indirect) Cooling in the Core

SNe-Failing Constraints

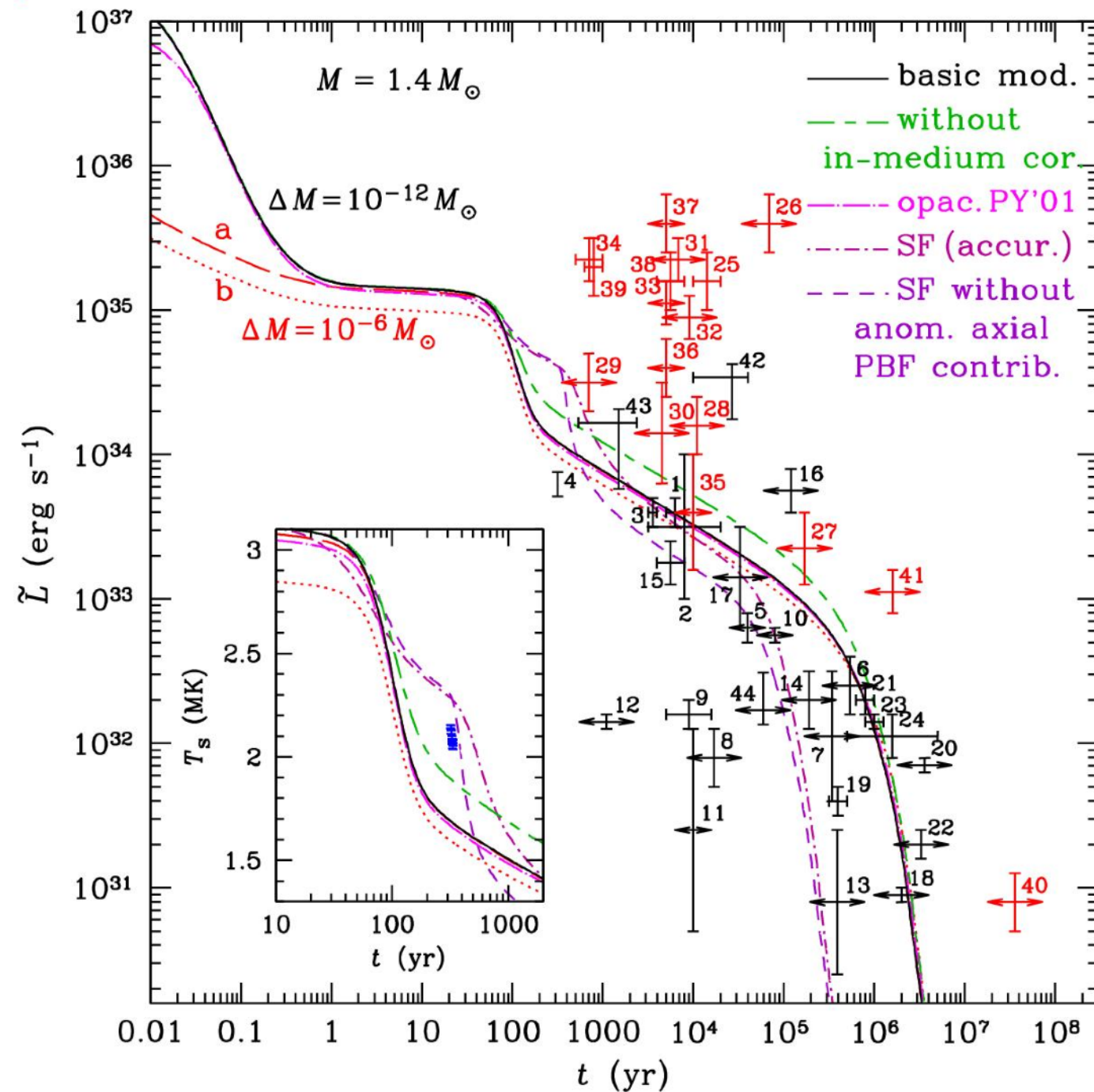


[A. Caputo, T. Janka, G. Raffelt, **SY**, 25]

Neutron Star Cooling

- Standard Cooling Scenario consistent w/ obs
- Observation of rapid cooling at early era (Cas-A)
 - evidence of superfluidity?

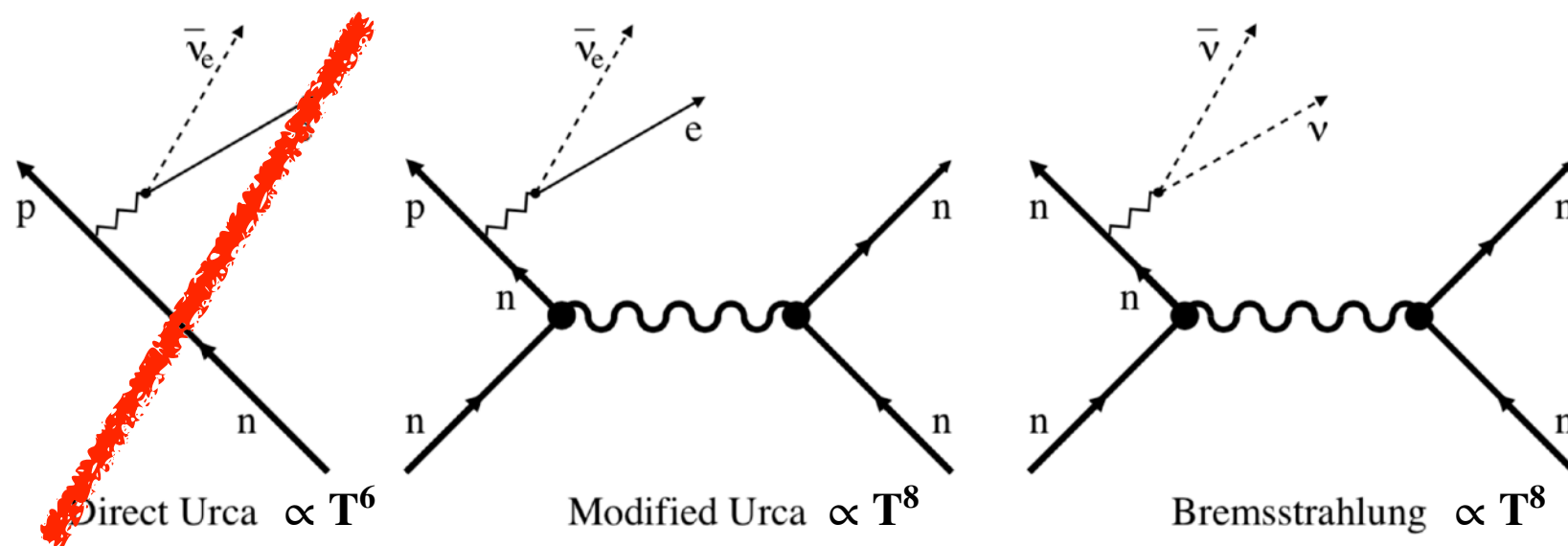
Standard Cooling Scenario



[A. Y. Potekhin, G. Chabrier, 18]

Young NS Cooling

- Neutrino (volume, mostly from core) emission



only when $> 2M_{\odot}$

© Energy balance equation

$$C \frac{dT}{dt} = -L_{\nu} - \cancel{L_{\gamma}} + \cancel{\dot{H}}$$

$C \propto T$ $\Rightarrow$ $\frac{\Delta T}{T} \sim -\frac{1}{6} \frac{dt}{t}$

~~• Photon (surface) emission~~ dominant when $> 10^5$ year

Cassiopeia A

[Chandra]

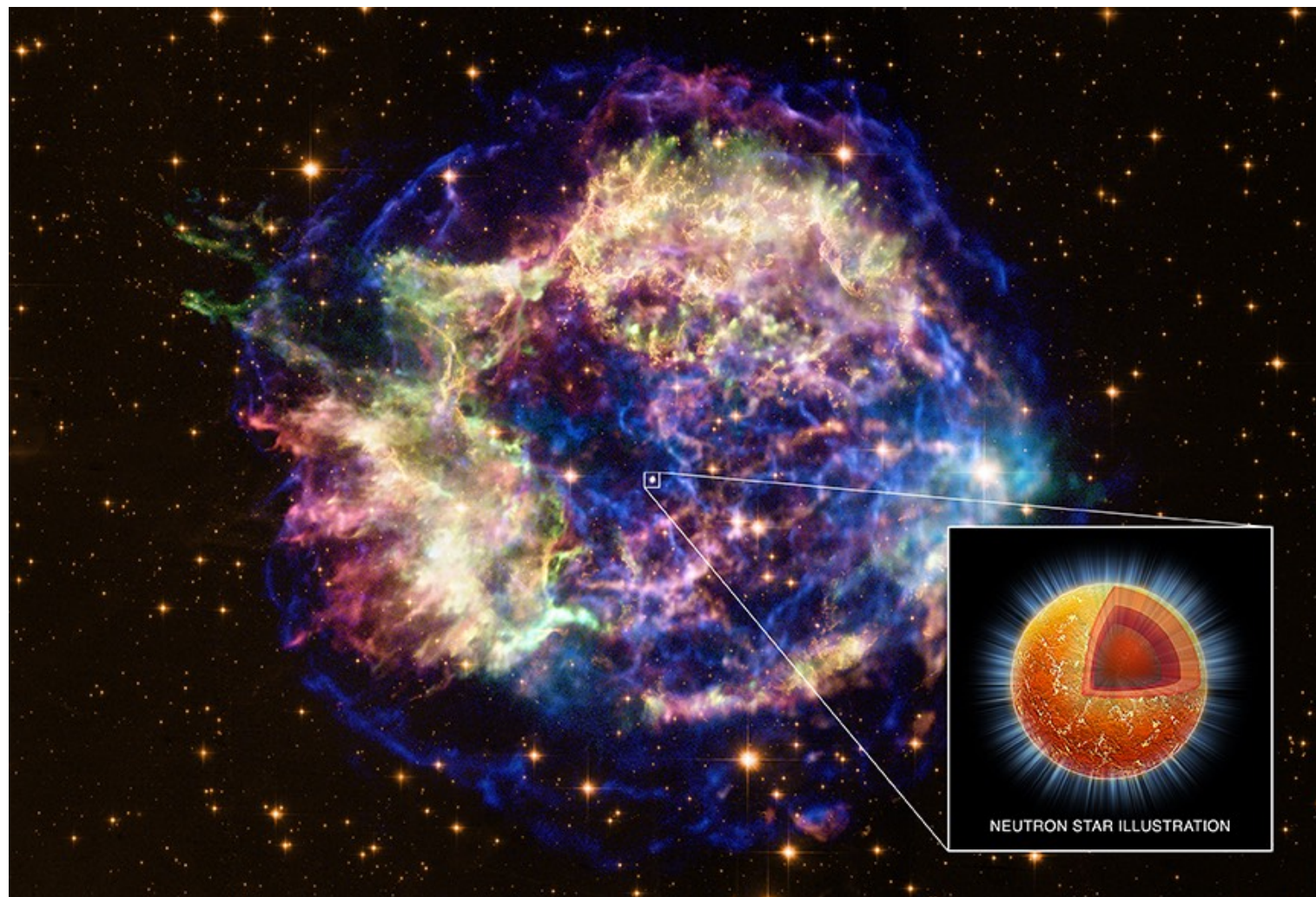
- Exploded 340 years ago
- Carbon (light element) atmosphere
- Rapid cooling of surface temperatures derived from X-ray observations

[M. J. P. Wijngaarden et al, 2019]

2~3% for 10 yr decline rate

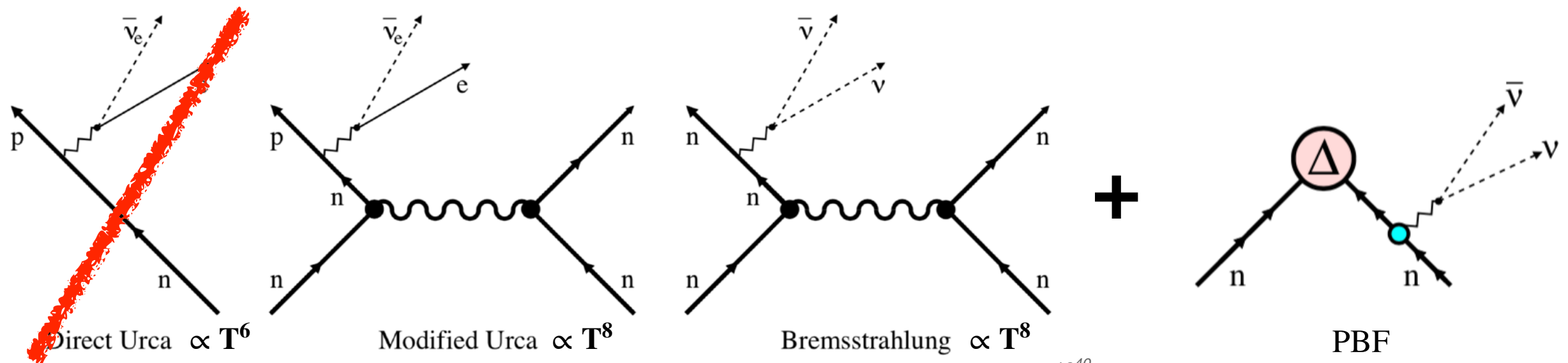
expectation w.o. superfluidity

$$\gg \frac{\Delta T}{T} \sim -\frac{1}{6} \frac{dt}{t} \sim 0.5 \%$$



Young NS Cooling

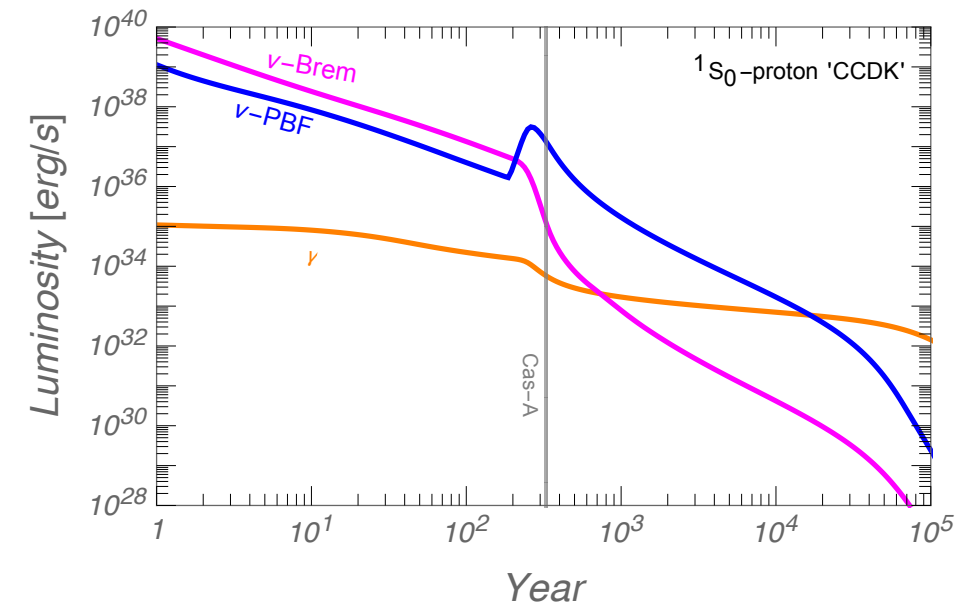
- Neutrino (volume) emission



only when $> 2M_{\odot}$

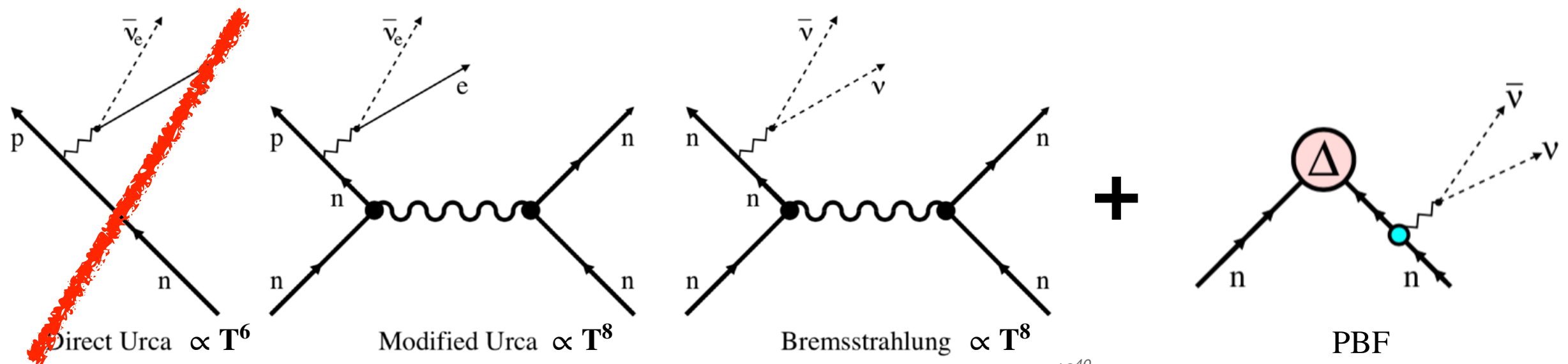
~~• Photon (surface) emission~~

dominant when $> 10^5$ year



Young NS Cooling

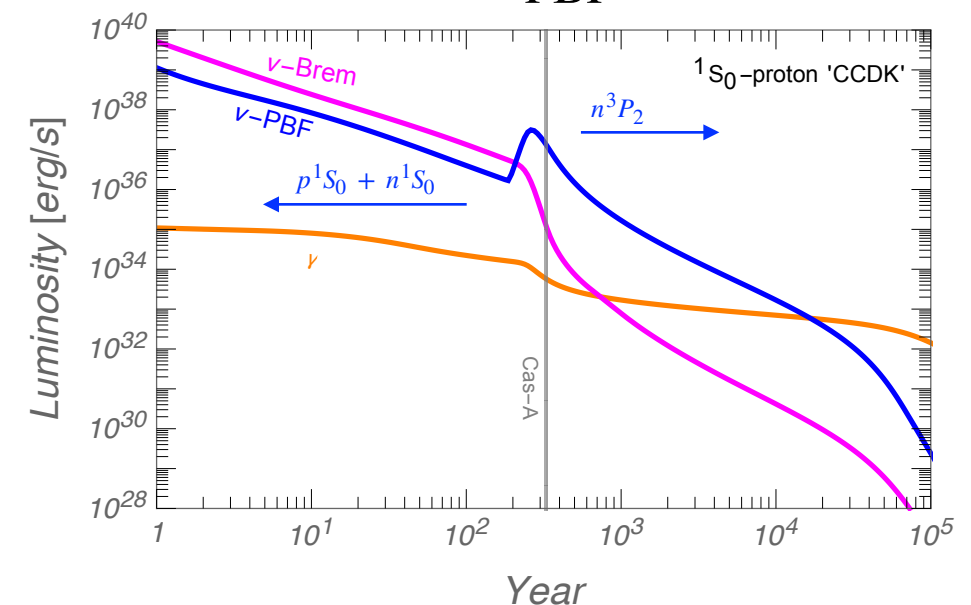
- Neutrino (volume) emission



only when $> 2M_{\odot}$

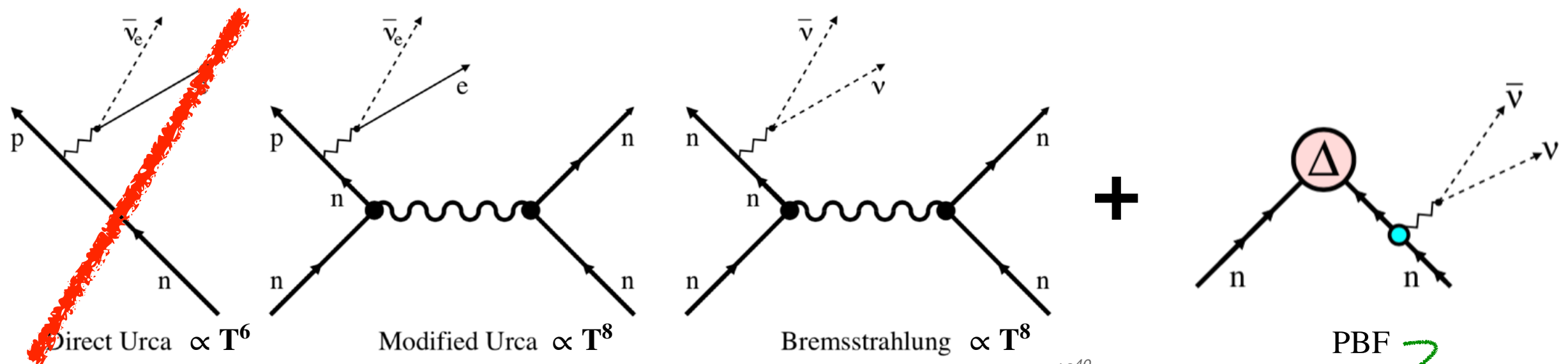
~~• Photon (surface) emission~~

dominant when $> 10^5$ year



Young NS Cooling

- Neutrino (volume) emission

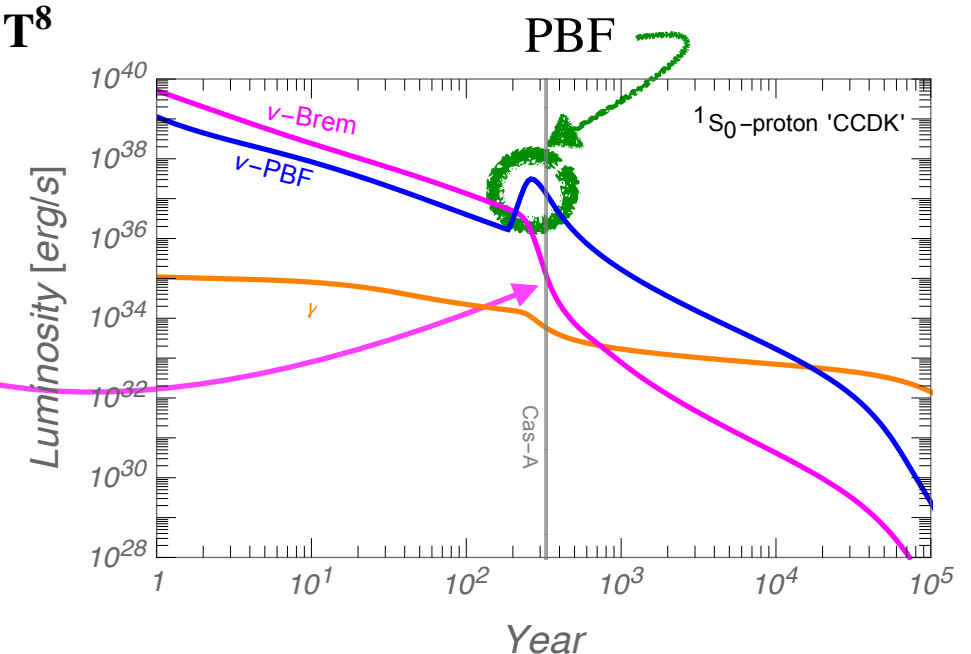


only when $> 2M_{\odot}$

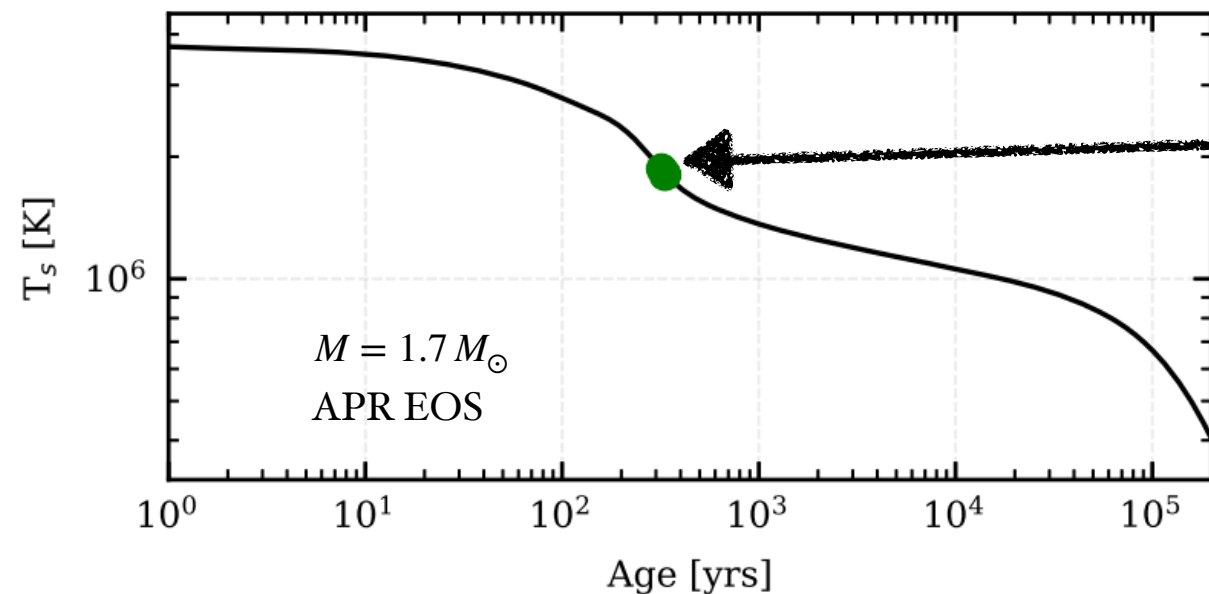
Suppressed at $T < T_c$

~~• Photon (surface) emission~~

dominant when $> 10^5$ year



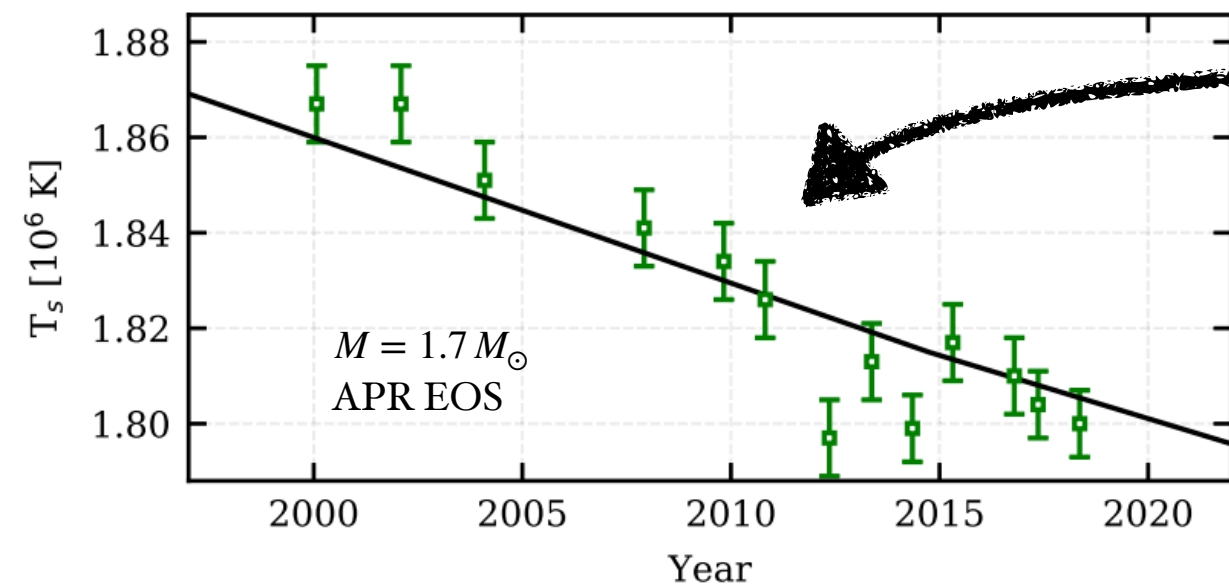
Evidence for superfluidity?



$$T = T_c \sim 5.9 \times 10^8 \text{ K for } {}^3P_2$$

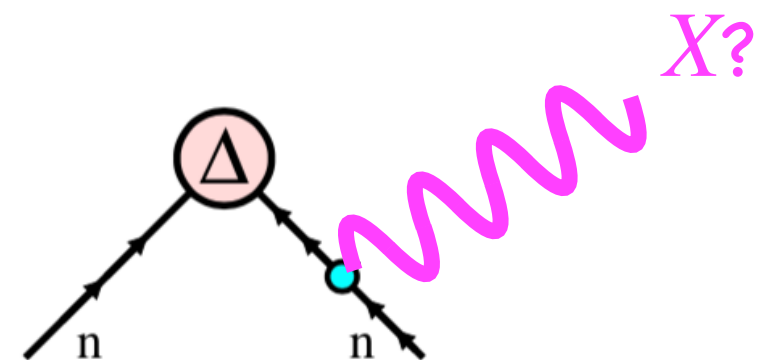


Rapid cooling by **PBF**



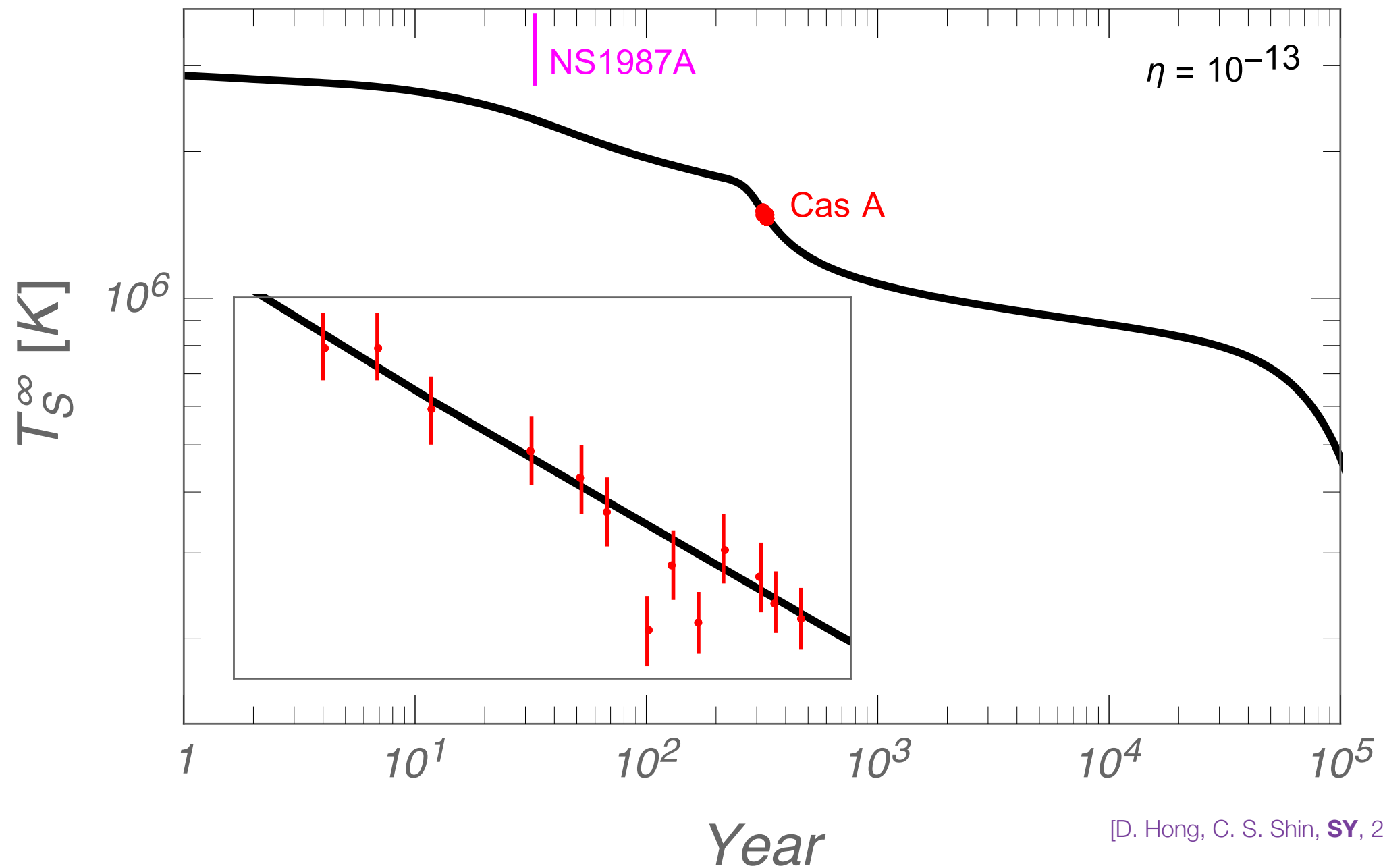
Minimal cooling scenarios with superfluidity fit well to the data

[M. J. P. Wijngaarden et al, 2019]

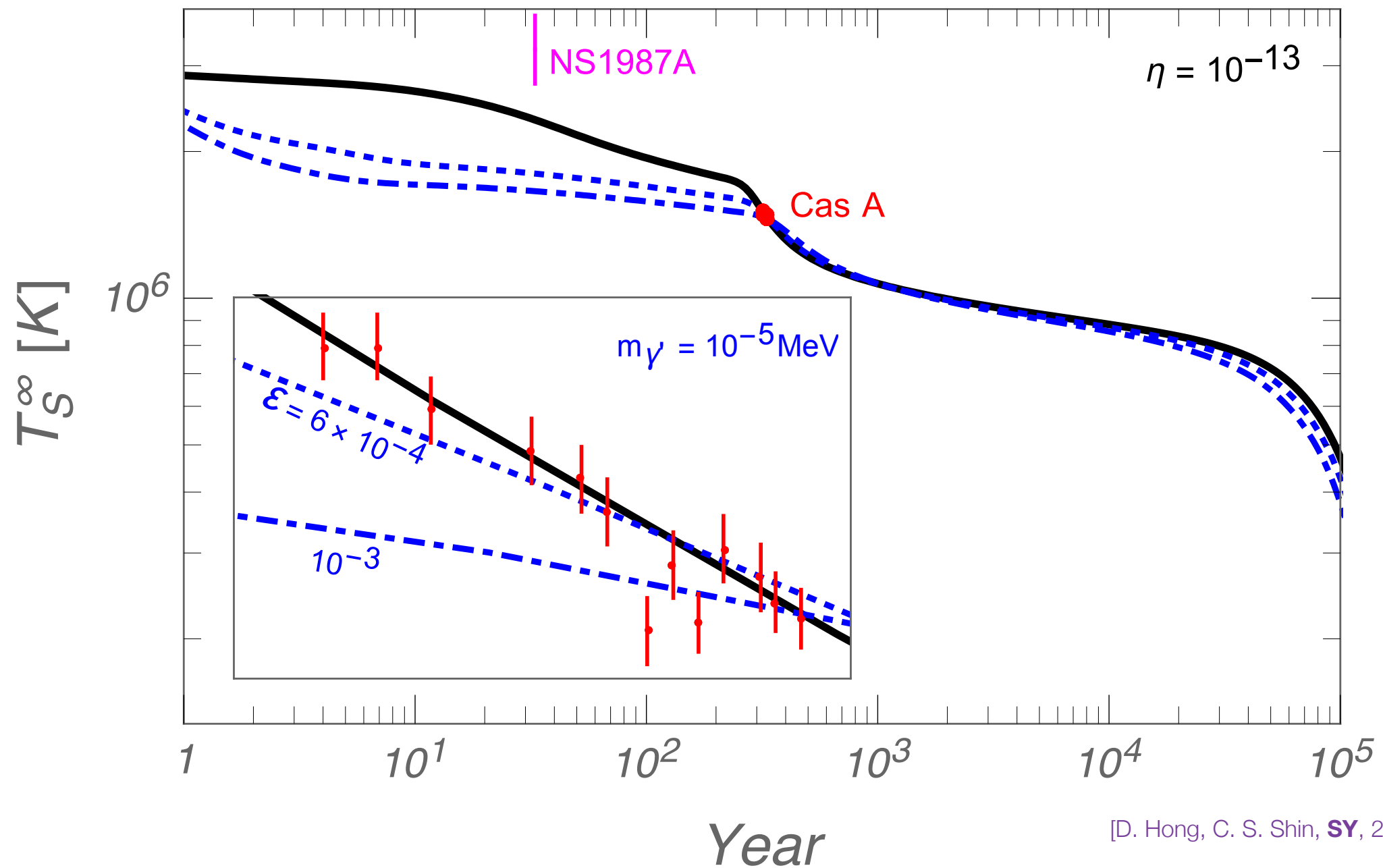


PBF

Dark Photon Cooling



Dark Photon Cooling



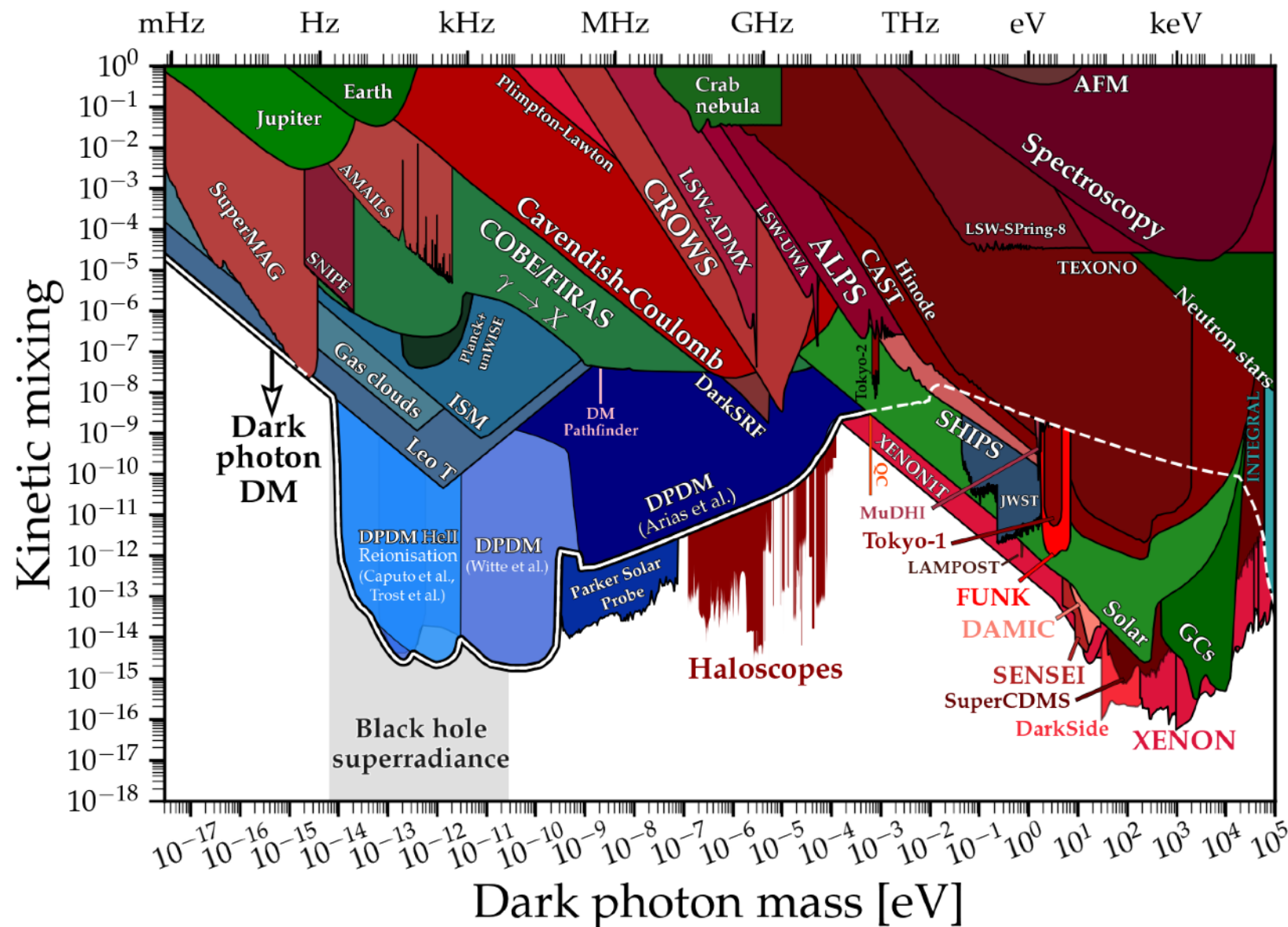
[D. Hong, C. S. Shin, **SY**, 21]

Current Status & More?

Experimental

Astrophysical

Cosmological

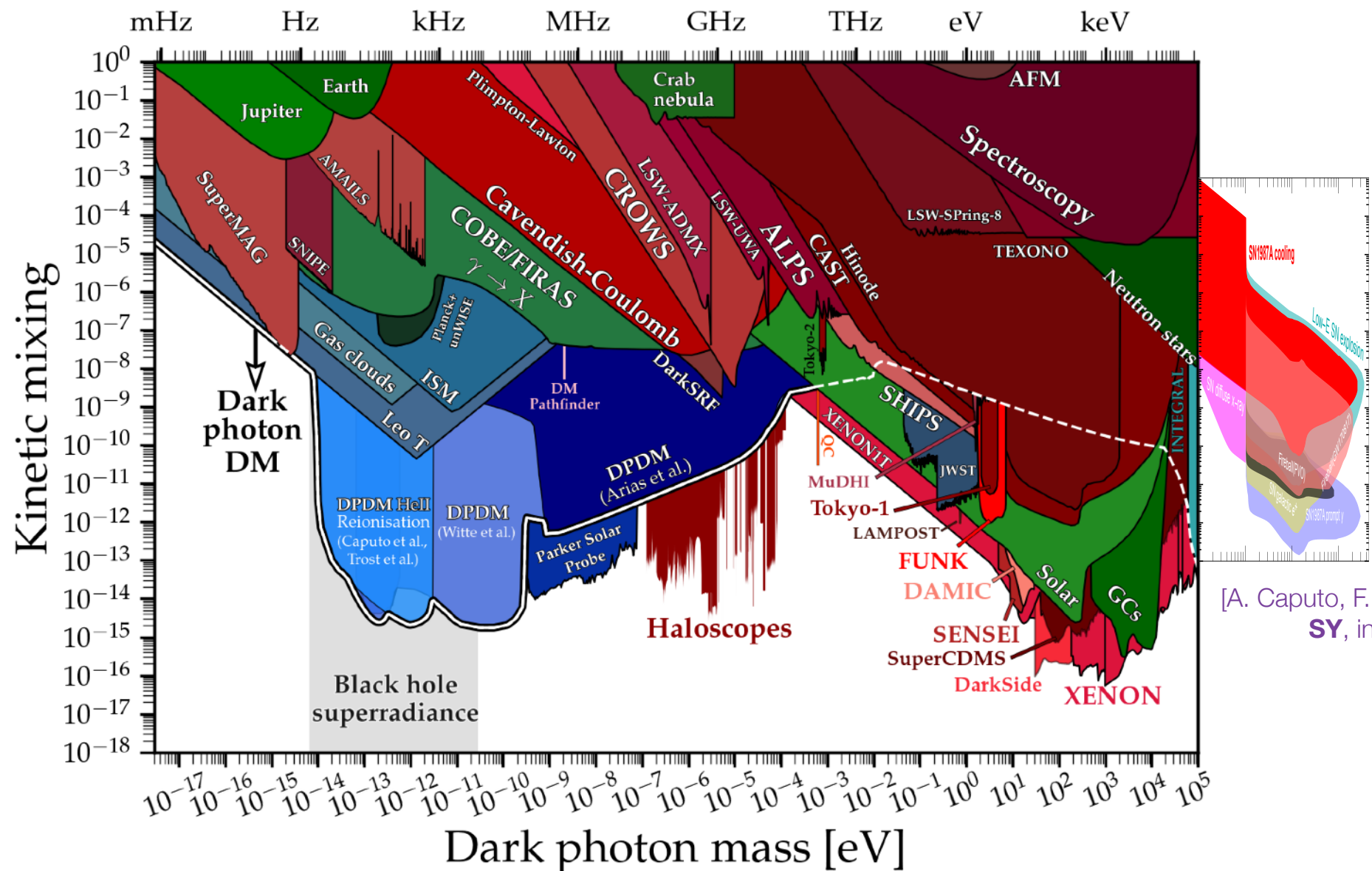


Current Status & More?

Experimental

Astrophysical

Cosmological



[A. Caputo, F. D'Eramo, J. Park, SY, in progress]

Summary

● Stars: powerful tools to probe BSM

- Sun: helioseismology & solar- ν
- Red giants: luminosity @ tip
- Horizontal branch: helium ignition lifetime (N_{HB} VS N_{RGB})
- White dwarfs: luminosity function
- Supernovae & Neutron stars: SN ν & γ -ray signal, explosion mechanism, neutron star cooling history

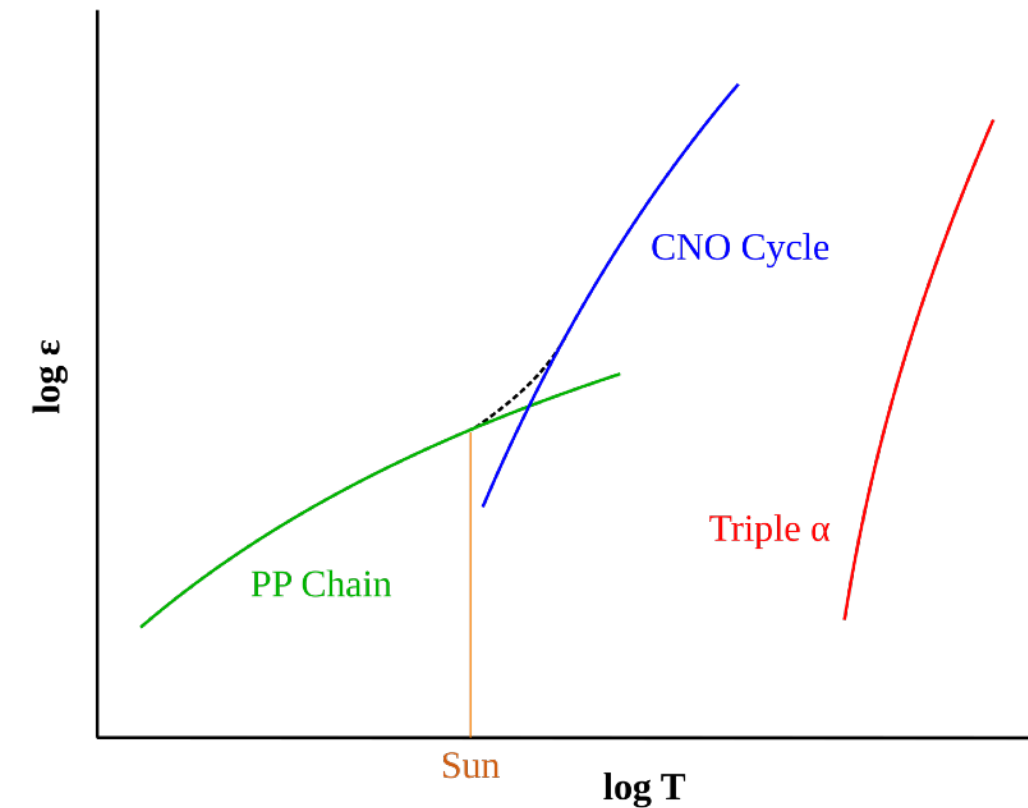
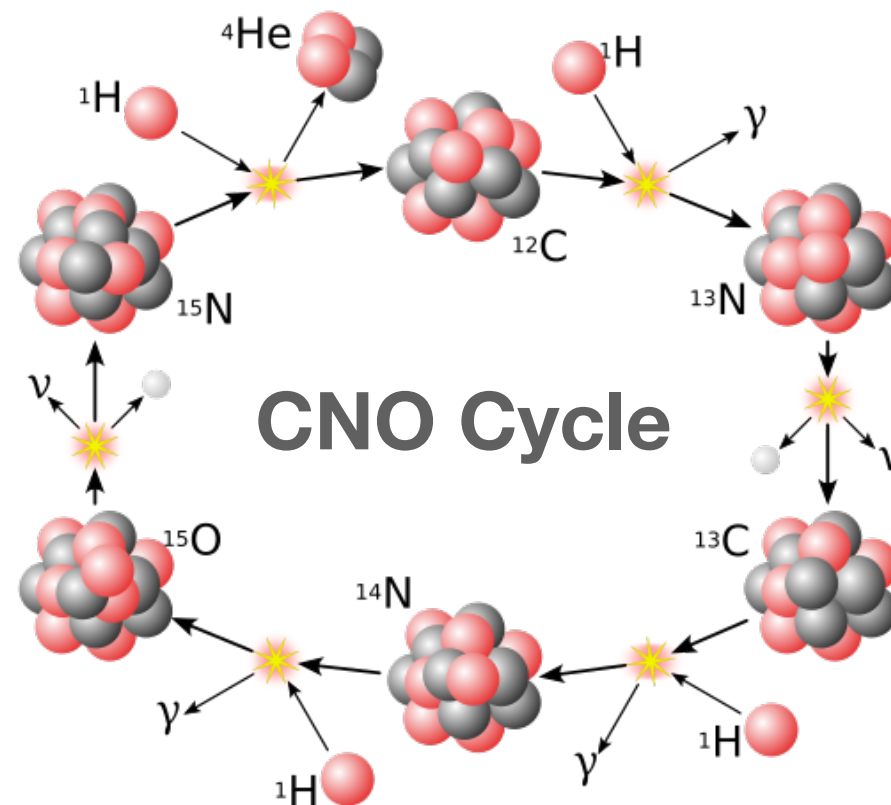
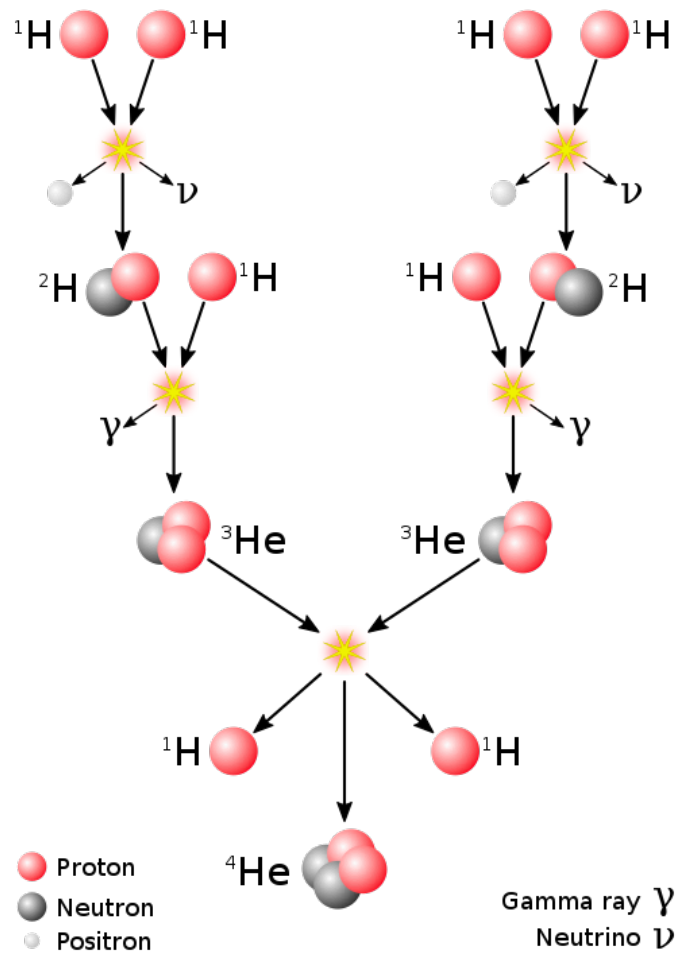
● What's next?

- More data ➡ better probes
- Sharpening theory ➡ robust & stronger constraints
- New ideas & strategies ➡ unexpected discoveries

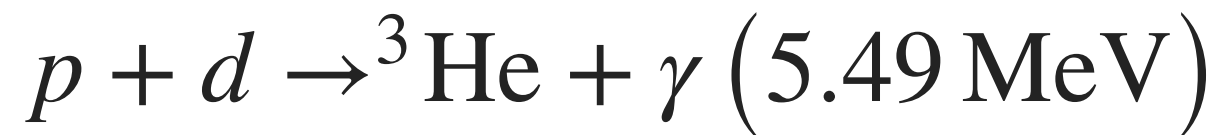
Back up

Hydrogen Burning in the Sun

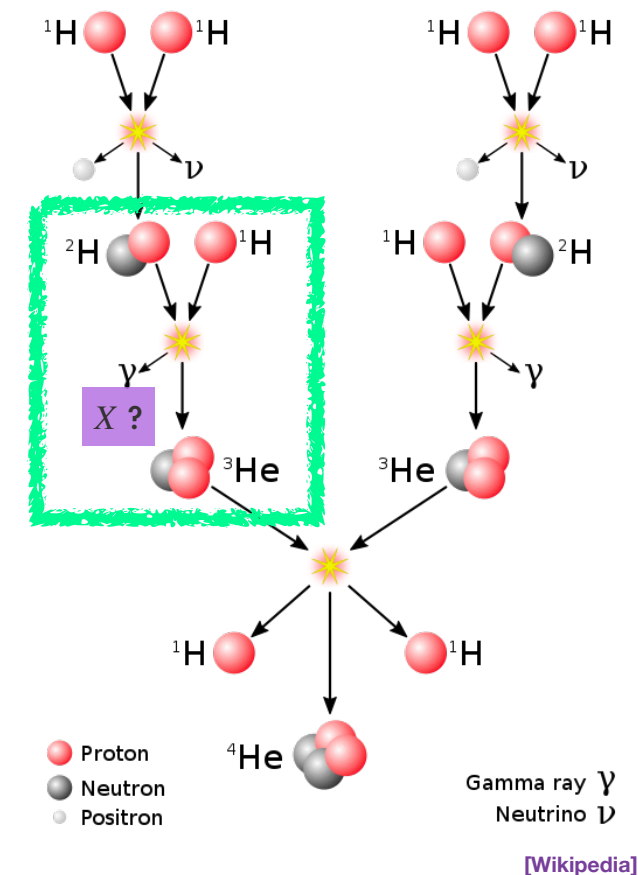
PP Chain



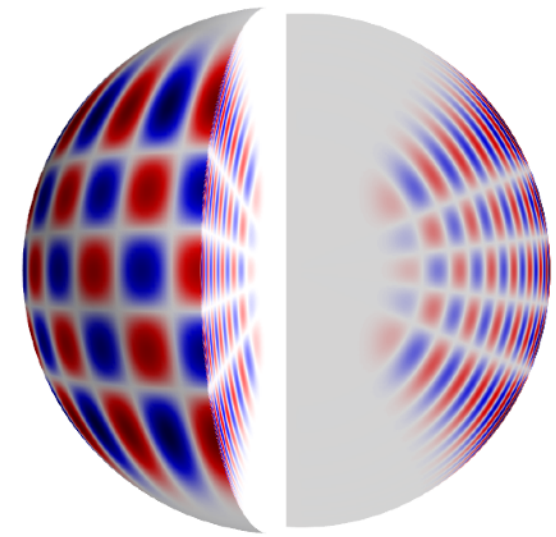
Deuterium fusion



- The second stage of solar pp fusion chain
 - $1.7 \times 10^{38} \text{ s}^{-1}$ at the innermost region (core) of the Sun
- 5.49 MeV energy release through the electromagnetic radiation
 - X instead of γ ? (possibility for axion & dark photon have been discussed)
- In terms of multipole expansion (relevant to non-relativistic regime)
 - Electric- & Magnetic-dipole transition dominant
 - Due to the proton and deuteron as the pure isospin eigenstates
 - Controlled by **isovector** charge (i.e., difference between the couplings to nucleons)



Helioseismology



The Convection Zone

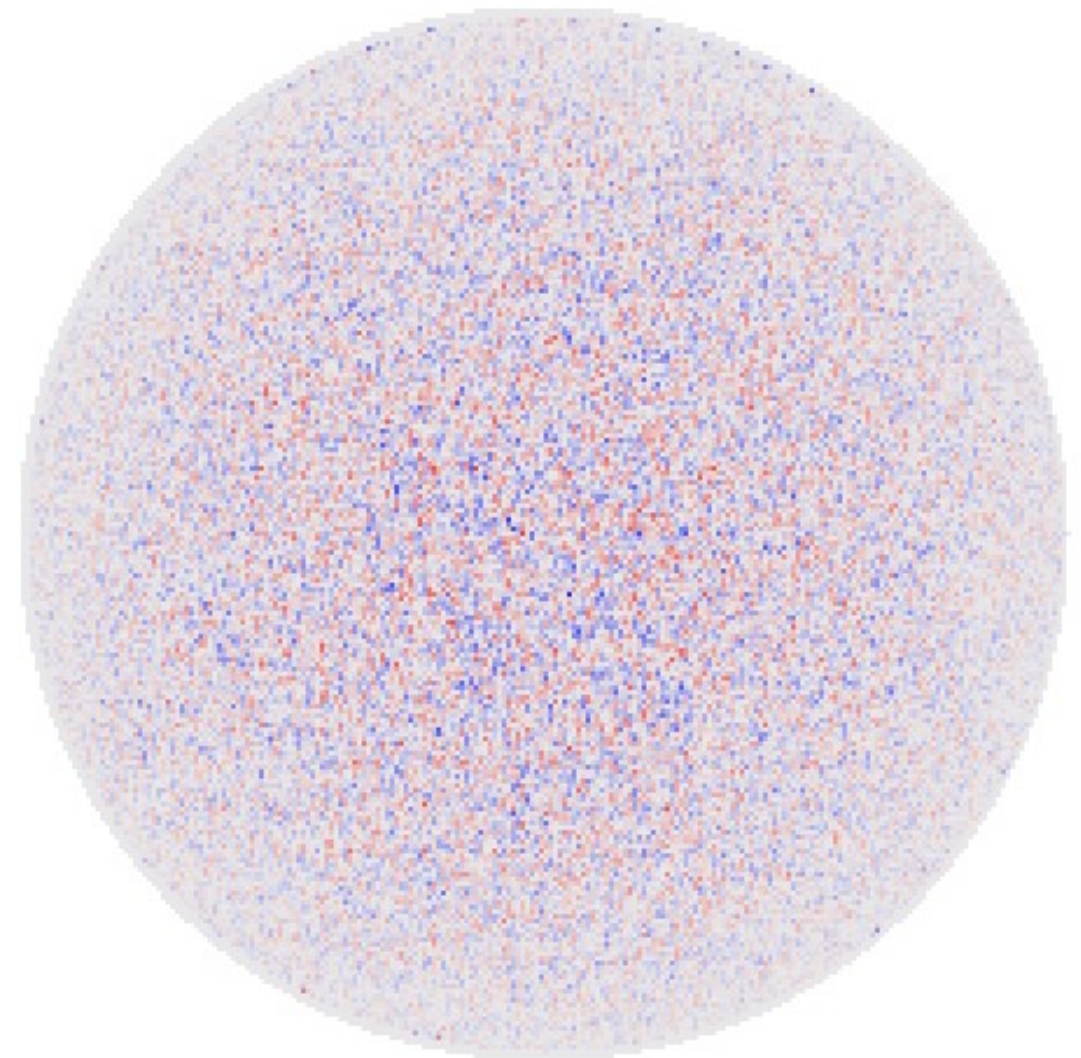
Energy continues to move toward the surface through convection currents of heated and cooled gas in the convection zone.

The Radiative Zone

Energy moves slowly outward—taking more than 170,000 years to radiate through the layer of the Sun known as the radiative zone.

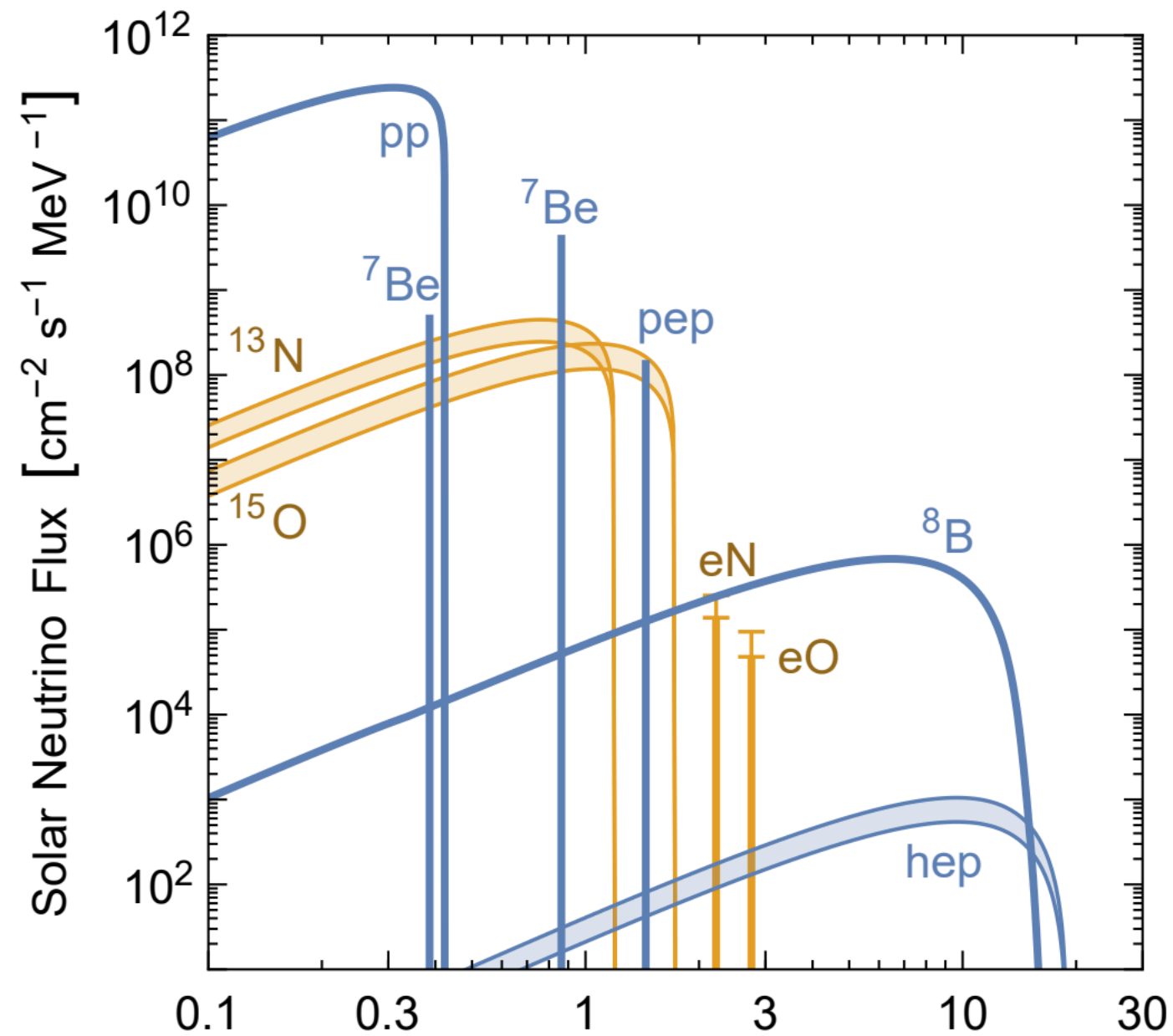
Sun's Core

Energy is generated by thermonuclear reactions creating extreme temperatures deep within the Sun's core.



[NASA]

Solar Neutrinos from Nuclear Reaction

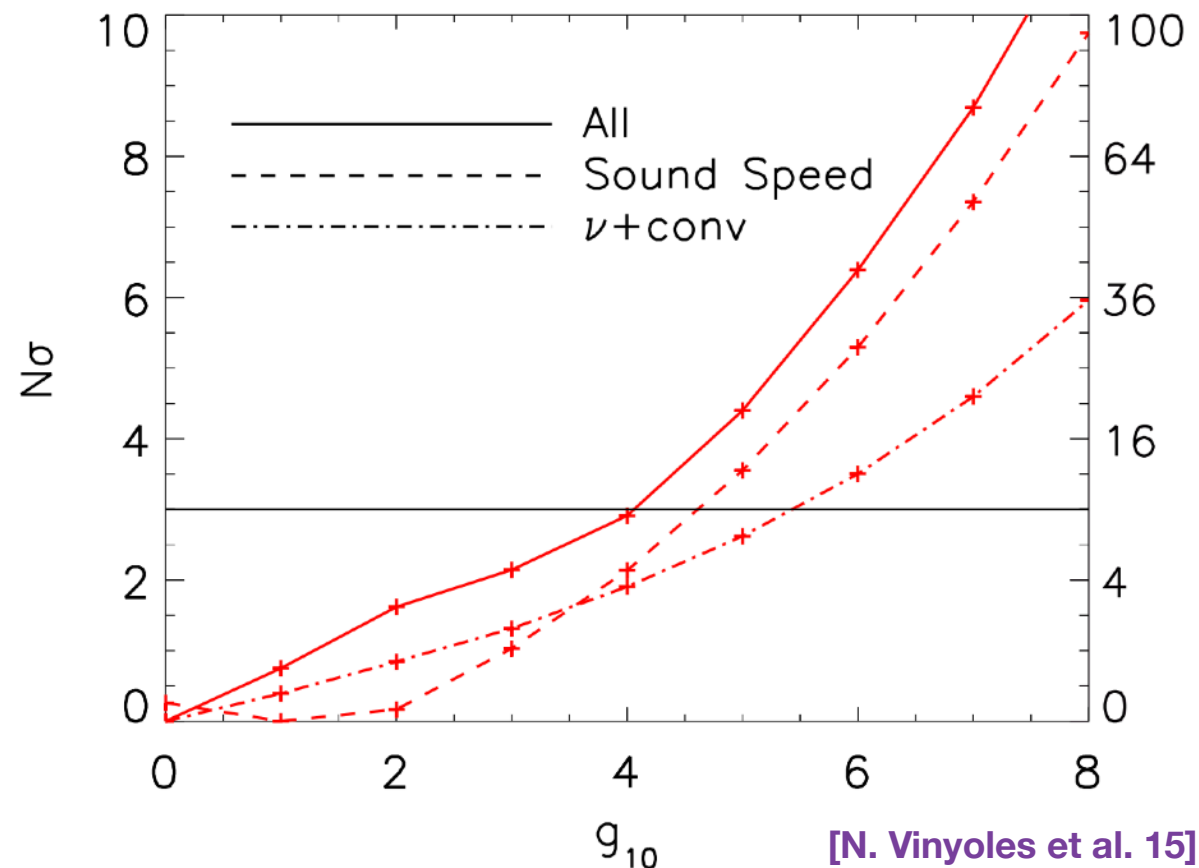


[E. Vitagliano et al. 20]

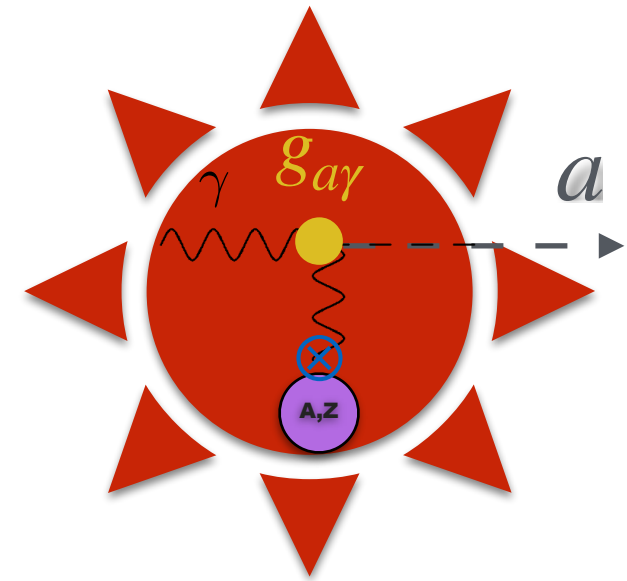
Stellar Cooling Argument on Sun

- Changes in the neutrino fluxes

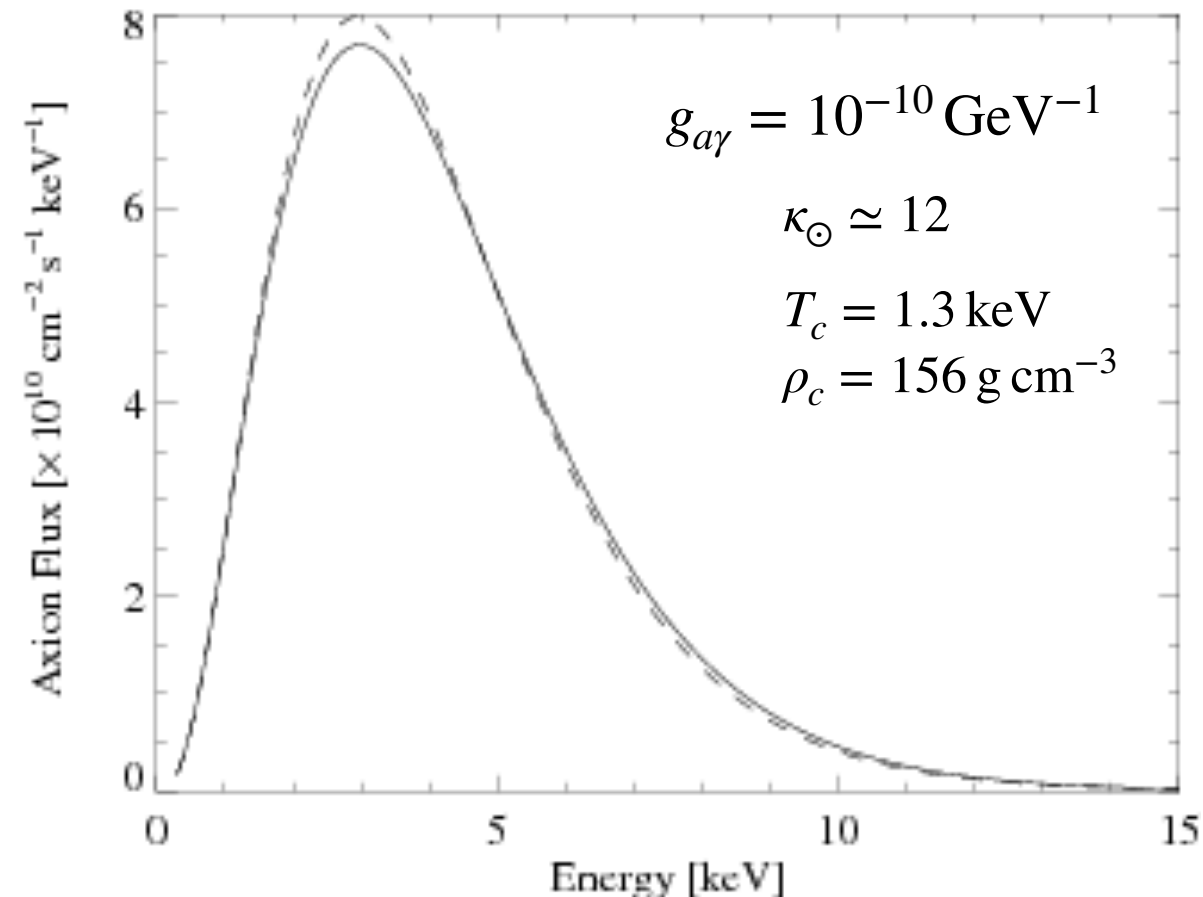
$$\frac{\Phi(^8\text{B})}{\Phi_{\text{SSM}}(^8\text{B})} = \left(\frac{L_a + L_{\odot}}{L_{\odot}} \right)^{4.4} < 150\% \quad \Rightarrow \quad L_a < 0.1 L_{\odot}$$



Solar Axion Flux



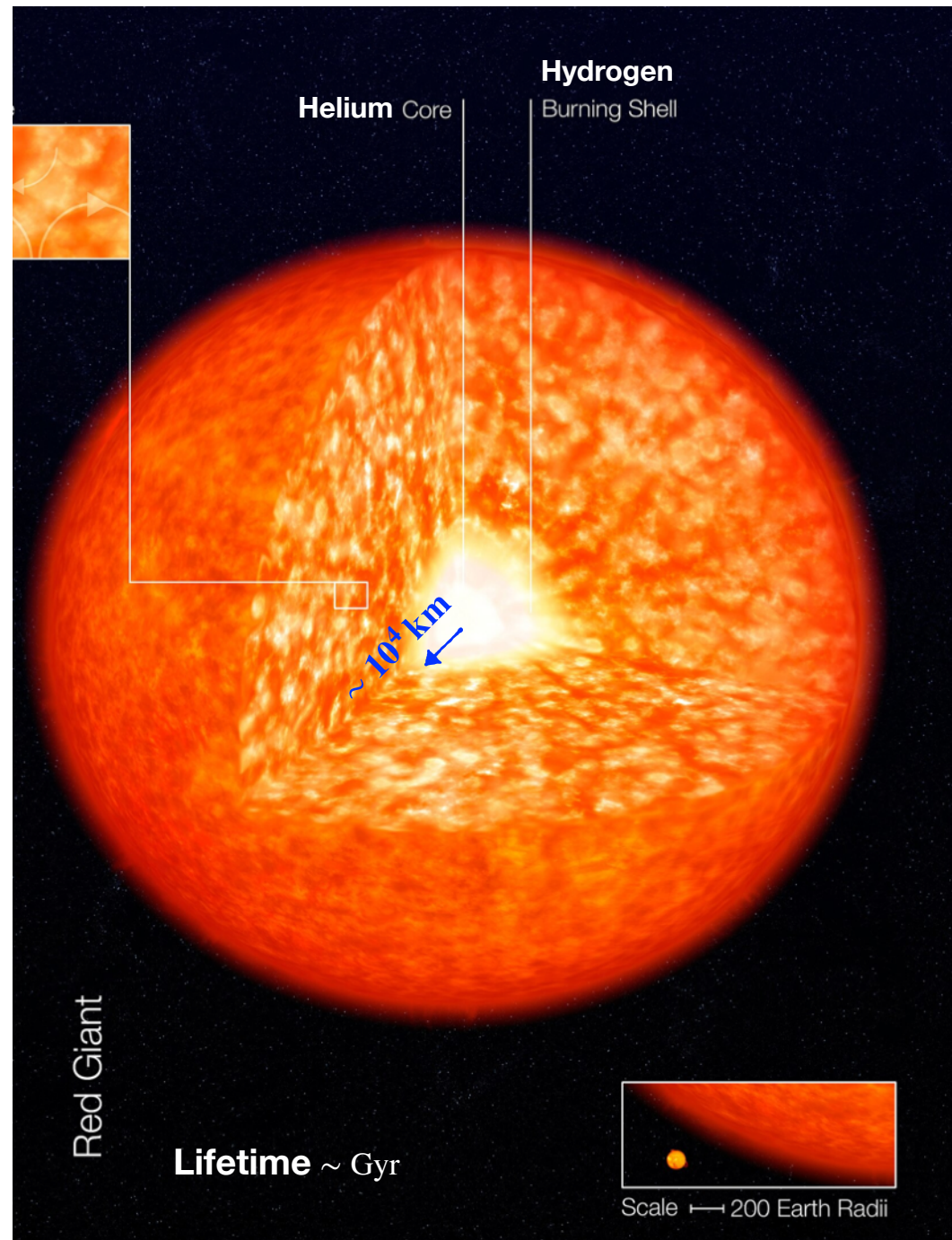
[CAST, hep-ex/0702006]



$$\frac{d\Phi_a}{d\omega} = 6.02 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \left(\frac{g_{a\gamma}}{10^{-10} \text{ GeV}^{-1}} \right)^2 \left(\frac{\omega}{\text{keV}} \right)^{2.481} e^{-\omega/1.205 \text{ keV}}$$

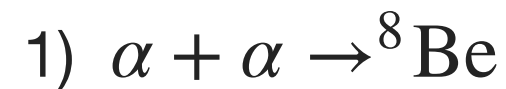
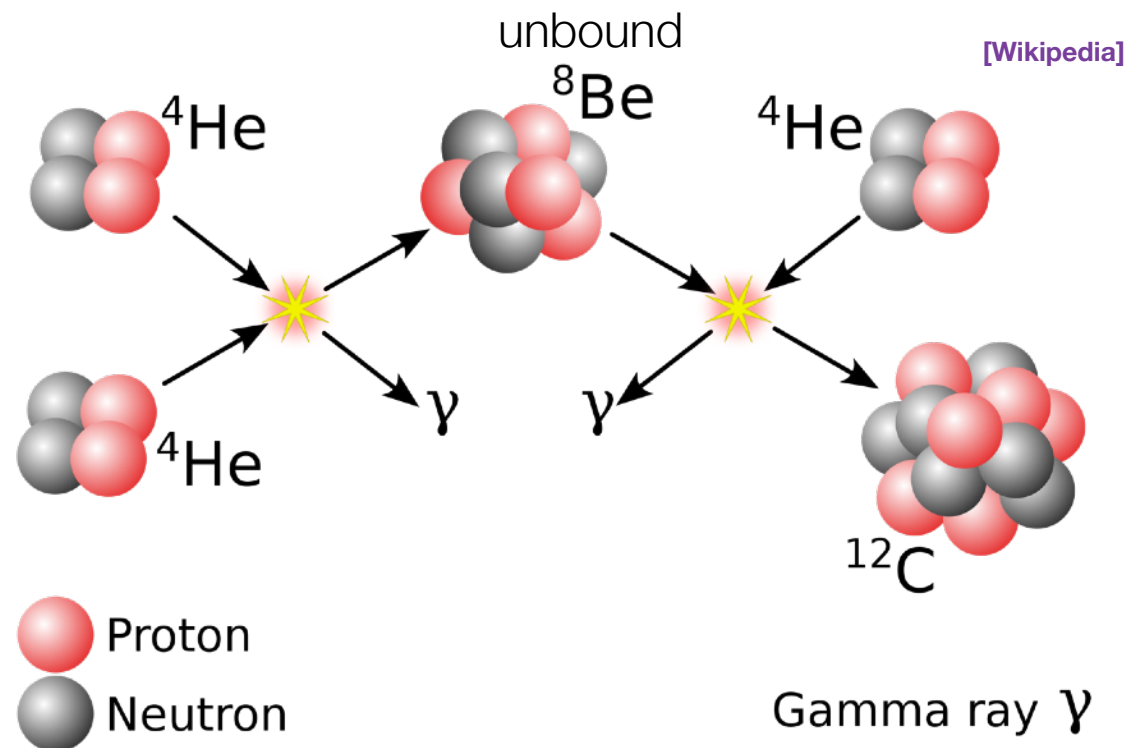
➡
$$L_a = 1.85 \times 10^{-3} L_{\odot} \left(\frac{g_{a\gamma}}{10^{-10} \text{ GeV}^{-1}} \right)^2$$

Red-Giant

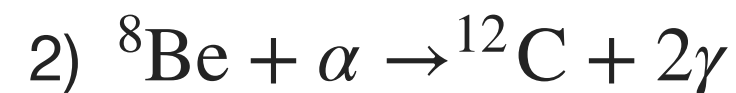


- Helium core governs properties of star
 - Sizable mass fraction $\mathcal{O}(1)M_{\odot}$
 - Very dense $\sim 10^6 \text{ g cm}^{-3}$
 - Degenerate electron pressure
 - Consistent burning condition ($r_{3\alpha} \propto T^{40}$ @ $T \sim 10^8 \text{ K}$)
- Hydrogen envelope
 - Dominant burning shell near core (pp-chain)
 - More dense core, more luminosity
 - Expanding via thermal pressure (redder)

Triple- α Process



- ${}^8\text{Be}$ is very unstable
- But, an equilibrium abundance of ${}^8\text{Be}$



- Resonant reaction

$$r_{3\alpha} \propto n_{\alpha}^3 e^{-43/T_8}$$

$$T_8 \equiv \frac{T}{10^8 \text{ K}}$$

$r_{3\alpha}$ reaction rate

Lifetime of Horizontal-Branch

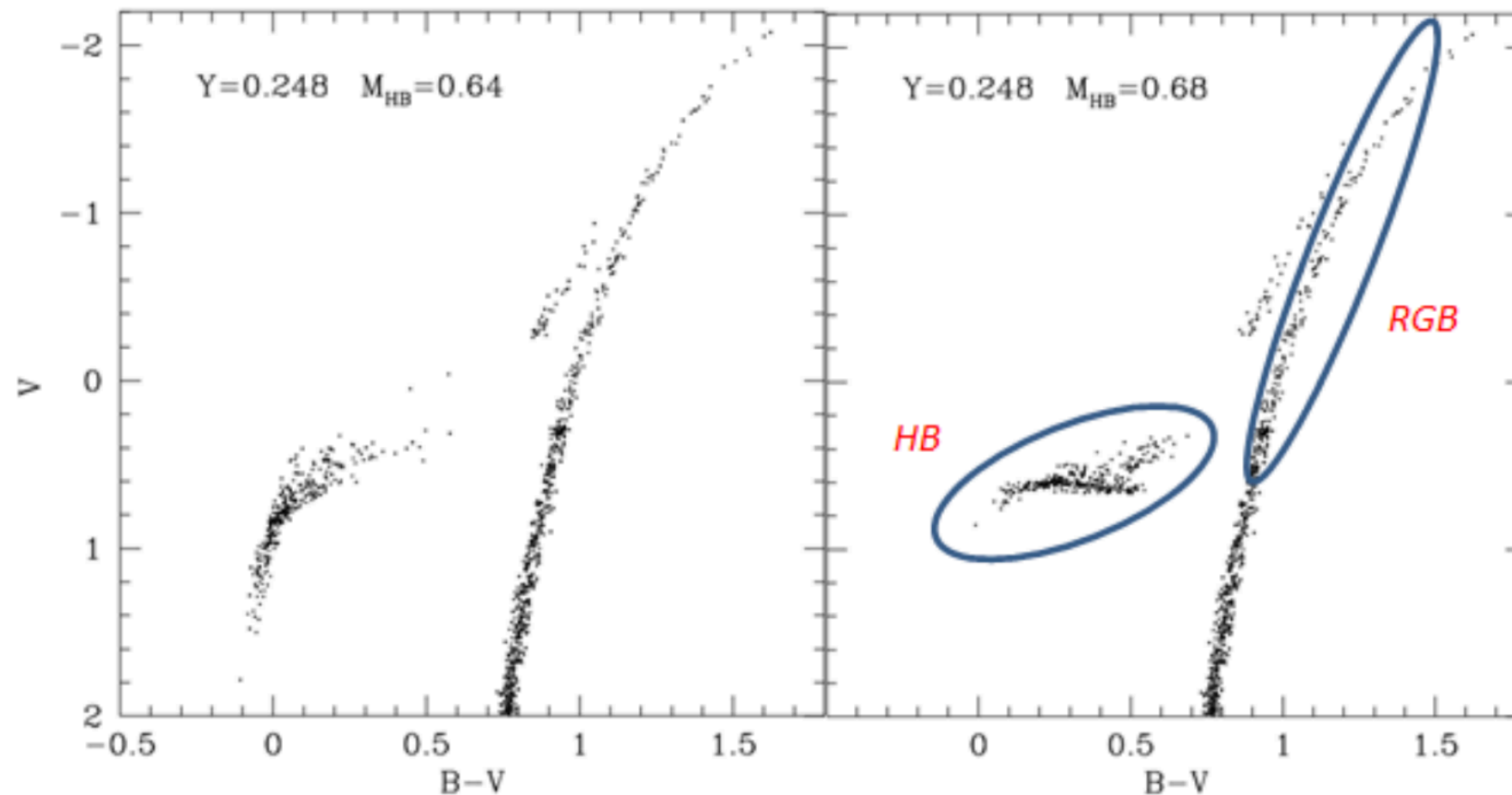
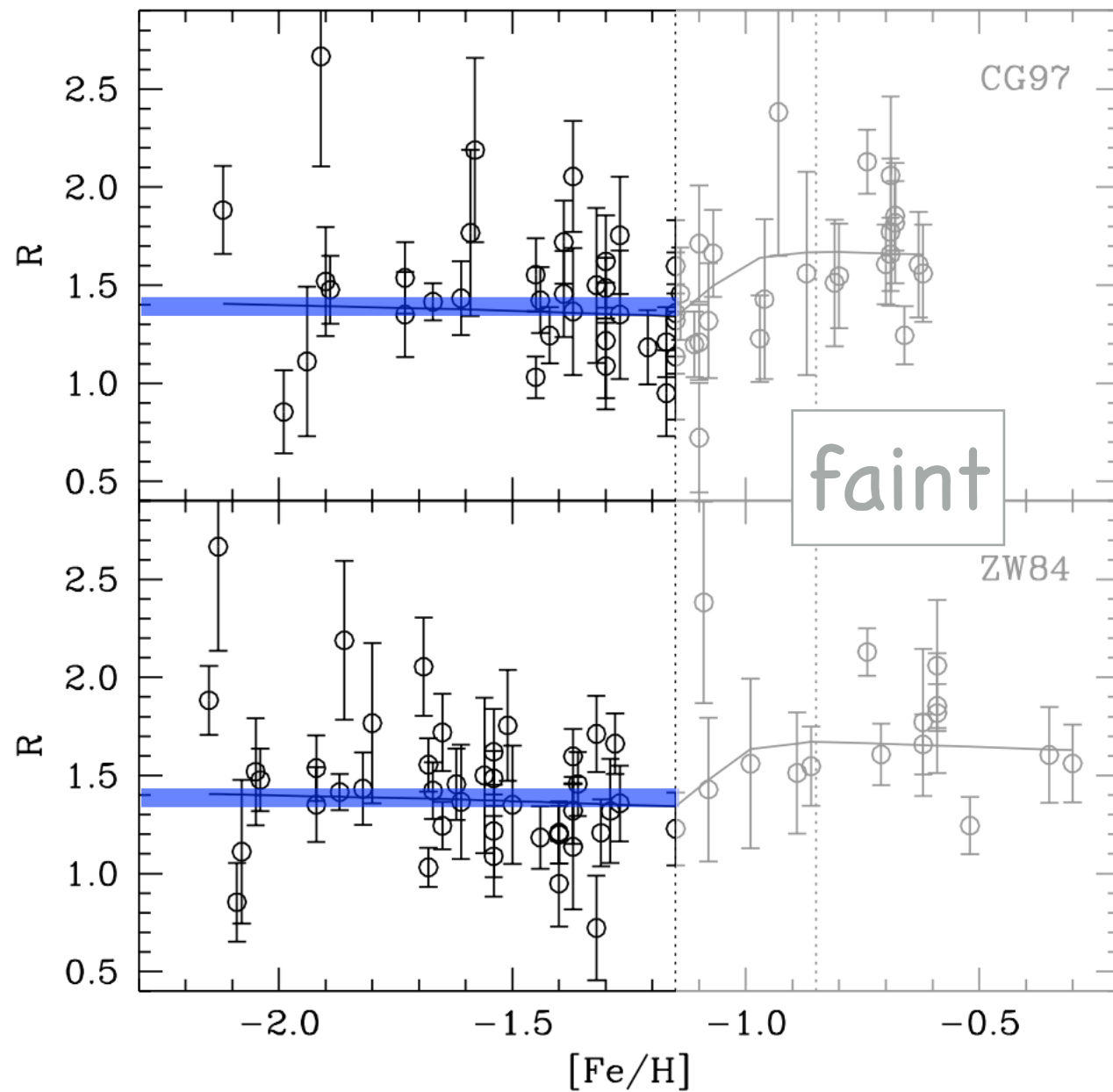


Figure 1: Example of synthetic CM diagrams. The diagram in the left panel has been obtained by assuming a stronger average mass loss rate during the RGB. As a result, the mean mass of HB stars (M_{HB}) is lower than that of the diagram in the right panel. The HB and the RGB portions used in the calculation of the R parameter are surrounded by ellipses.

[O. Straniero et al. 15]

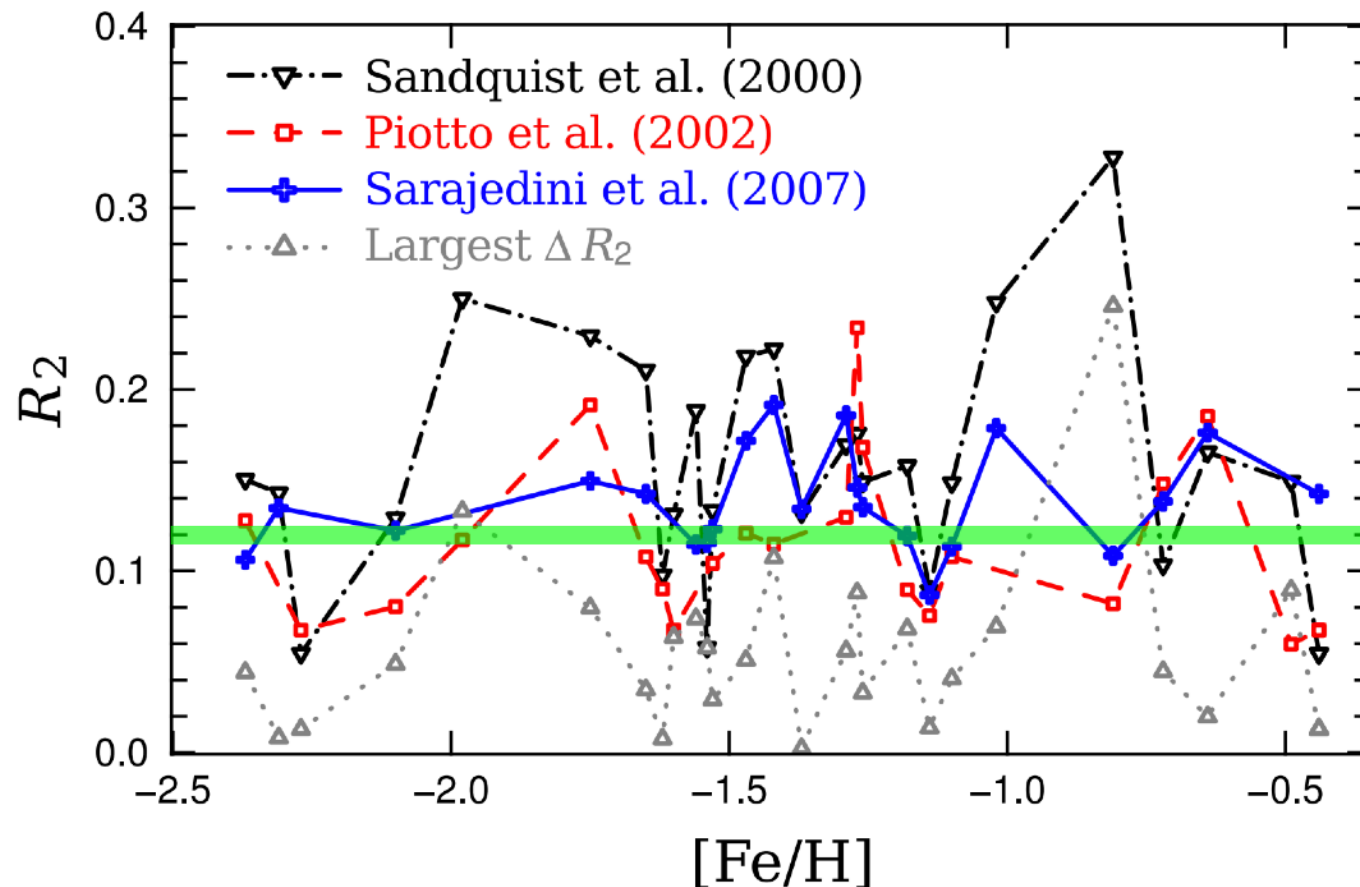
Lifetime of Horizontal-Branch

$$R = \frac{N_{\text{HB}}}{N_{\text{RGB}}}$$
$$= 1.39 \pm 0.03$$



[M. Salaris et al. 04]

Lifetime of Horizontal-Branch



$$R_2 = \frac{N_{\text{AGB}}}{N_{\text{HB}}} = 0.117 \pm 0.005$$

Figure 1. Comparison of R_2 for clusters shown in Table 1, limited to those with at least two different sources of photometry. The R_2 determined from the Sandquist (2000), Piotto et al. (2002), and Sarajedini et al. (2007) data are shown in black dash-dots, red dashes, and a blue solid line, respectively. The dotted grey line shows the maximum difference between R_2 determinations from different photometry.

[T. Constantino et al. 15]

Stellar Cooling Argument on HB

triple- α reaction

- A helium-burning core and a hydrogen-burning shell after the tip of red-giants

$$\rho \approx 10^4 \text{ g cm}^{-3} \quad T \approx 10^8 \text{ K}$$

- The number ratio R of HB vs. RGB in Globular clusters agreed with standard predictions to within 10%
- Lifetime of HB t_{He} (i.e., duration of helium burning phase) agrees within 10%

$$t_{\text{He}} \text{ reduced by } \frac{L_{3\alpha}}{L_a + L_{3\alpha}} \quad \Rightarrow \quad L_a \lesssim 10 \text{ erg g}^{-1} \text{ s}^{-1}$$

[Raffelt]

$$L_{3\alpha} \sim 20L_{\odot} \approx 8 \times 10^{34} \text{ erg s}^{-1}$$

$$M_c^{\text{HB}} \sim 0.5 M_{\odot}$$

Gauged U(1) Extension of the SM

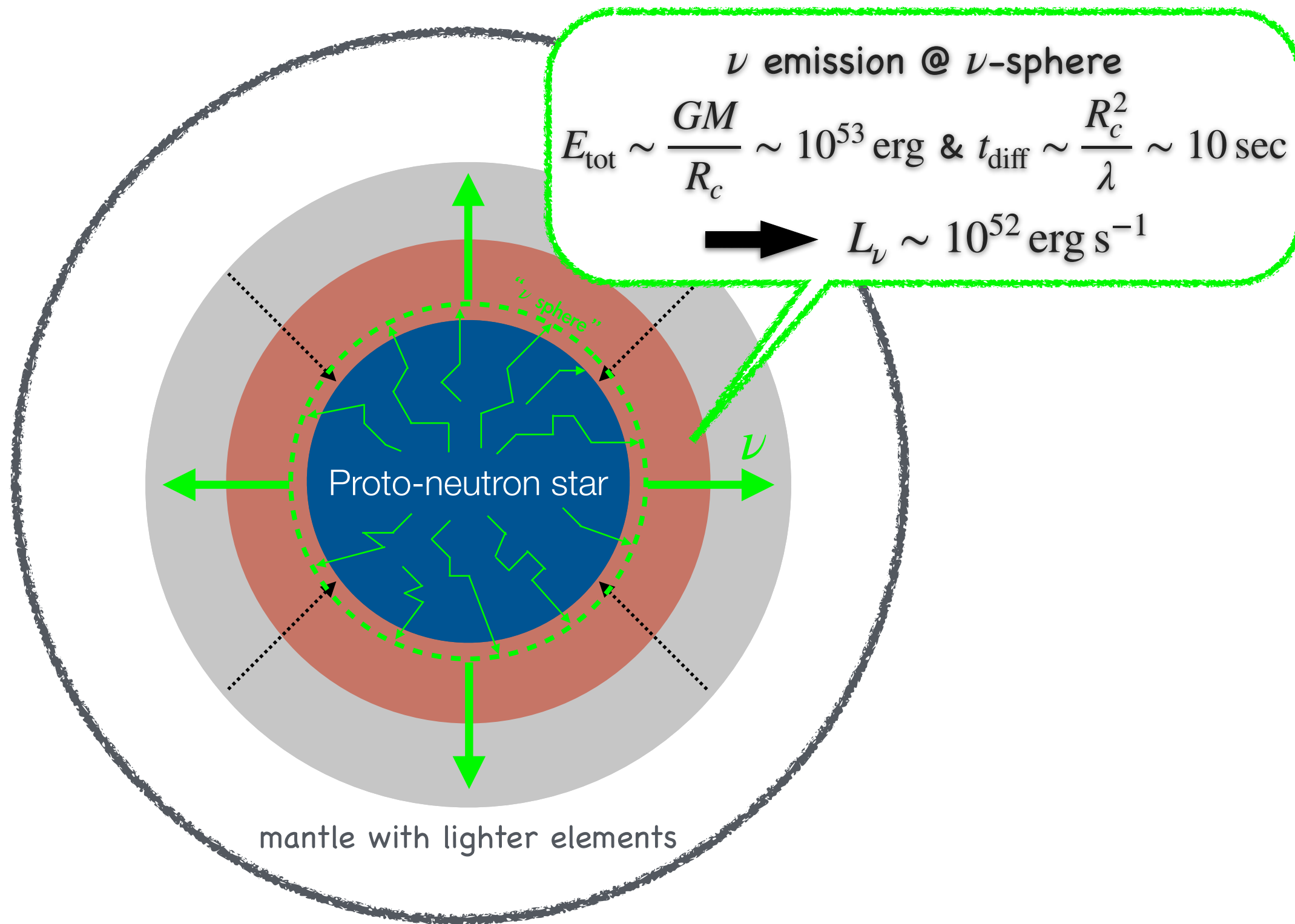
- General interactions of **dark gauge bosons** (γ' or A'_μ) to SM particles

- U(1) charge assignment $\mathcal{L}_{\gamma'-\psi} = g_\psi A'_\mu \bar{\psi} \Gamma^\mu \psi$ $\Gamma^\mu = [\gamma^\mu, \gamma^\mu \gamma^5, \dots]$

- Kinetic mixing $\mathcal{L}_{\gamma'-\gamma} = \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$ $\Rightarrow g_\psi = e\varepsilon q_\psi$ & $\Gamma^\mu = \gamma^\mu$ in vacuum

- Anomaly-free Abelian symmetries
 - flavor universal: $B - L, \dots$
 - flavor dependent: $L_e - L_\mu, L_e - L_\tau, L_\mu - L_\tau, \dots$
 - only kinetic mixing: dark photon

Neutrino Cooling of pNS



Diffusive Neutrino Transport

- *Neutral-Current cross-section*

- ▶ $\sigma(\nu + N \rightarrow \nu + N) \sim G_F^2 E_\nu^2 \sim 2 \times 10^{-41} \text{ cm}^2 (E_\nu/30 \text{ MeV})^2$

- Nucleon density

- ▶ $n_N = \rho_{\text{sat}}/m_N \sim 2 \times 10^{38} \text{ cm}^{-3}$

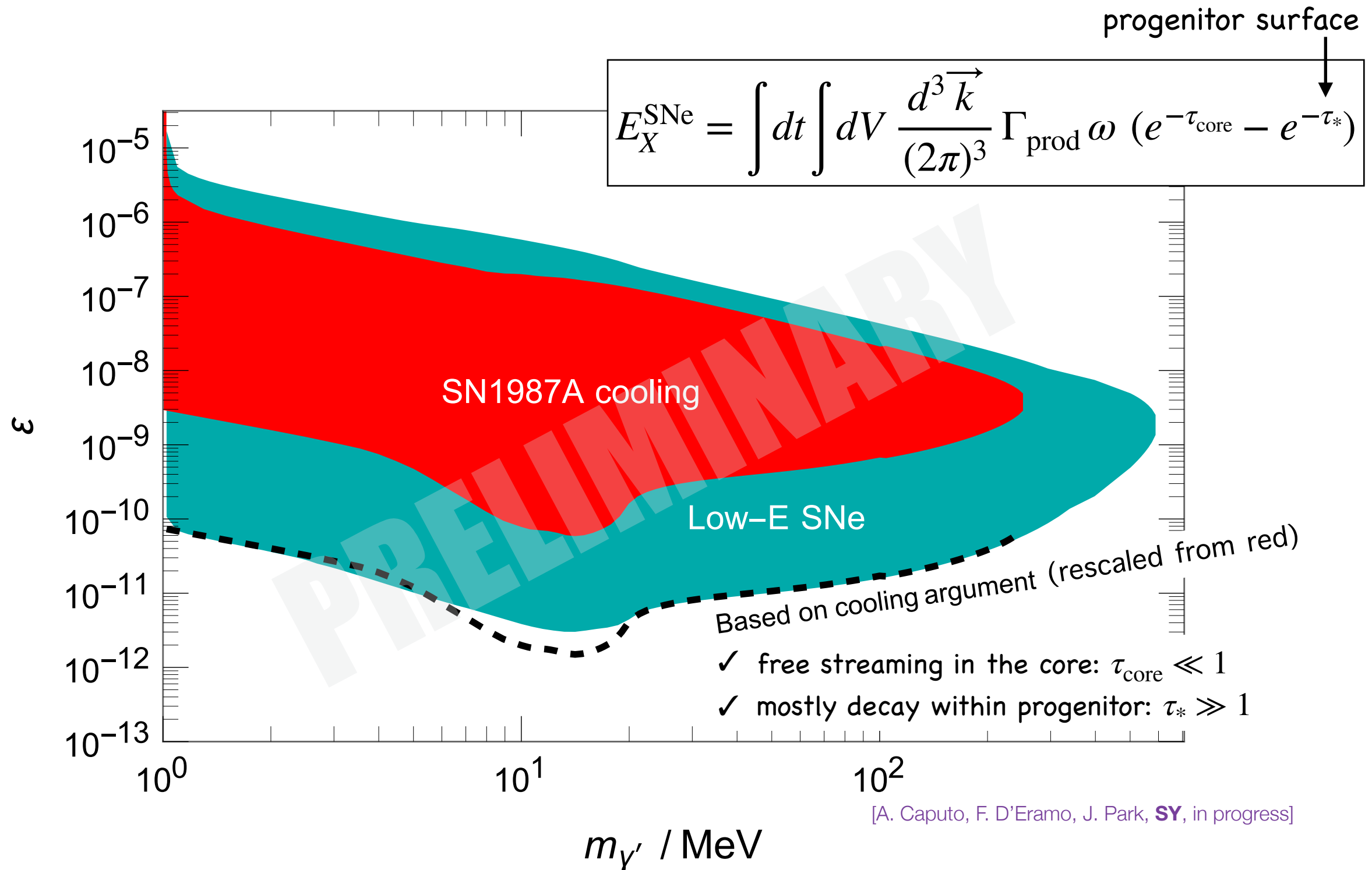
- Mean free path

- ▶ $\lambda = 1/n_N \sigma \sim 2.5 \text{ m} (E_\nu/30 \text{ MeV})^2 \ll R_{\text{NS}} \sim 10 \text{ km}$

- Diffusion time

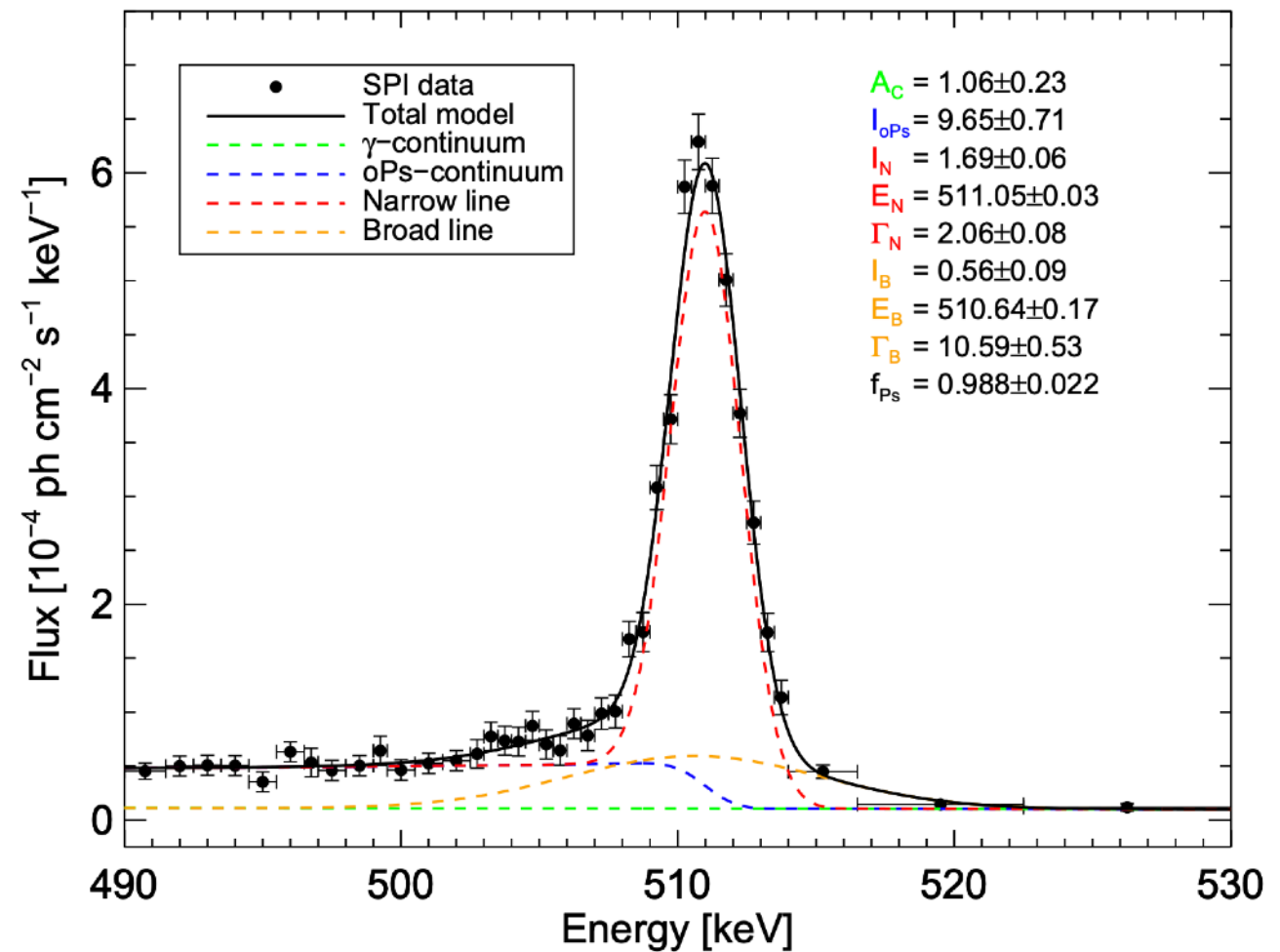
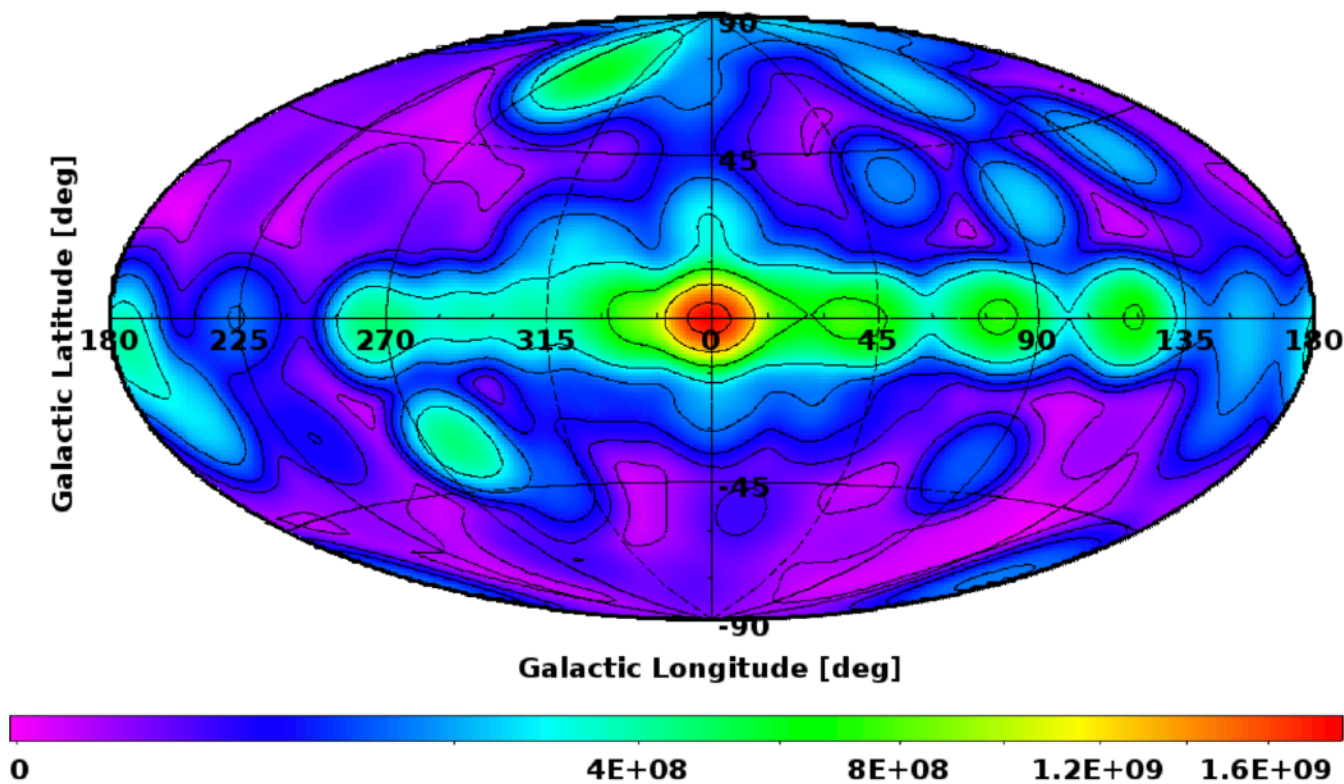
- ▶ $t_{\text{diff}} \approx R_{\text{NS}}^2/\lambda \sim 10 \text{ sec} (R_{\text{NS}}/10 \text{ km})^2 (E_\nu/30 \text{ MeV})^2$

Low-E SNe Constraints



Galactic 511keV signal

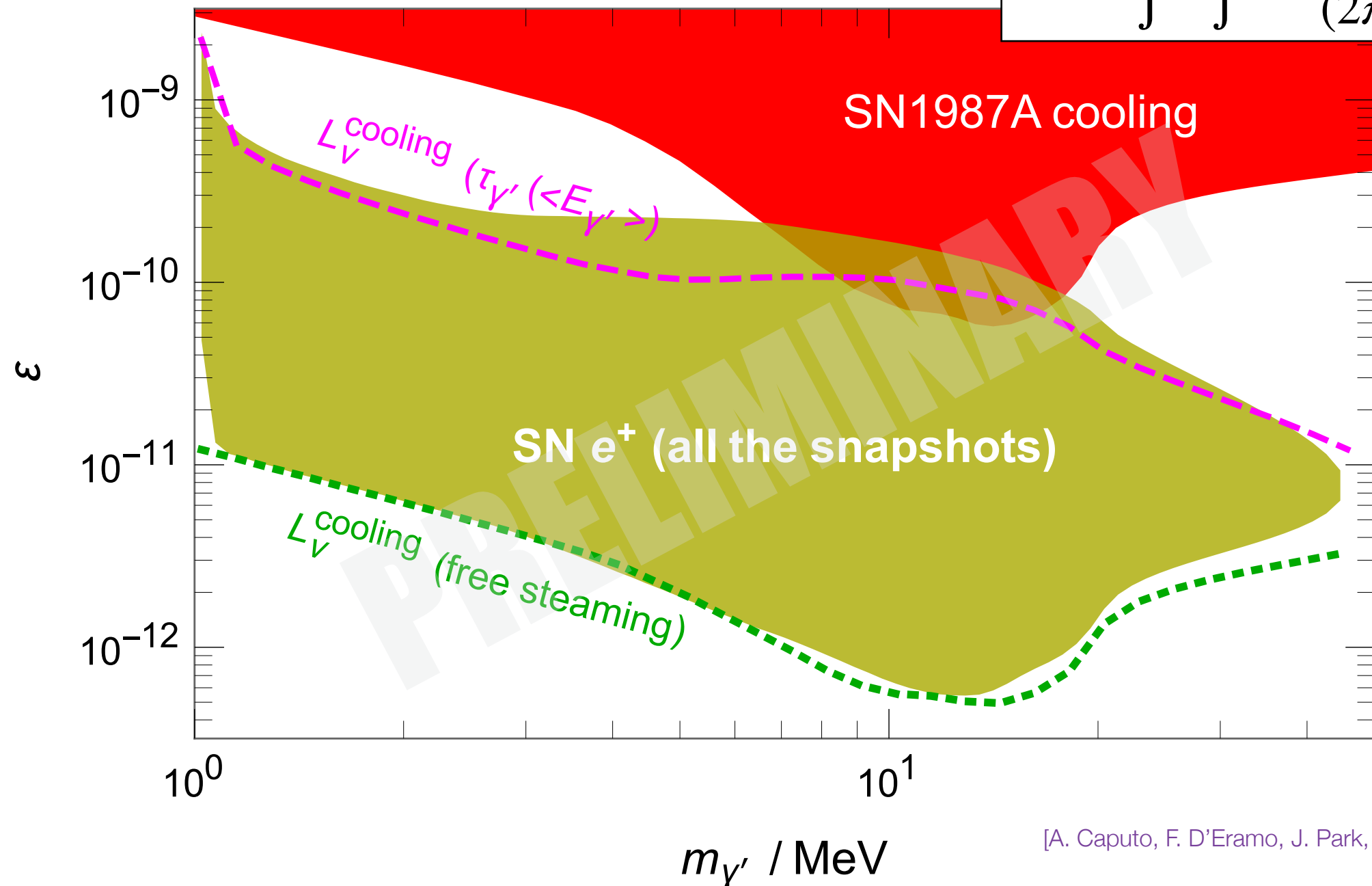
[T. Siegert et al, 19]



no larger than $4 \times 10^{43} e^+ \text{ sec}^{-1}$

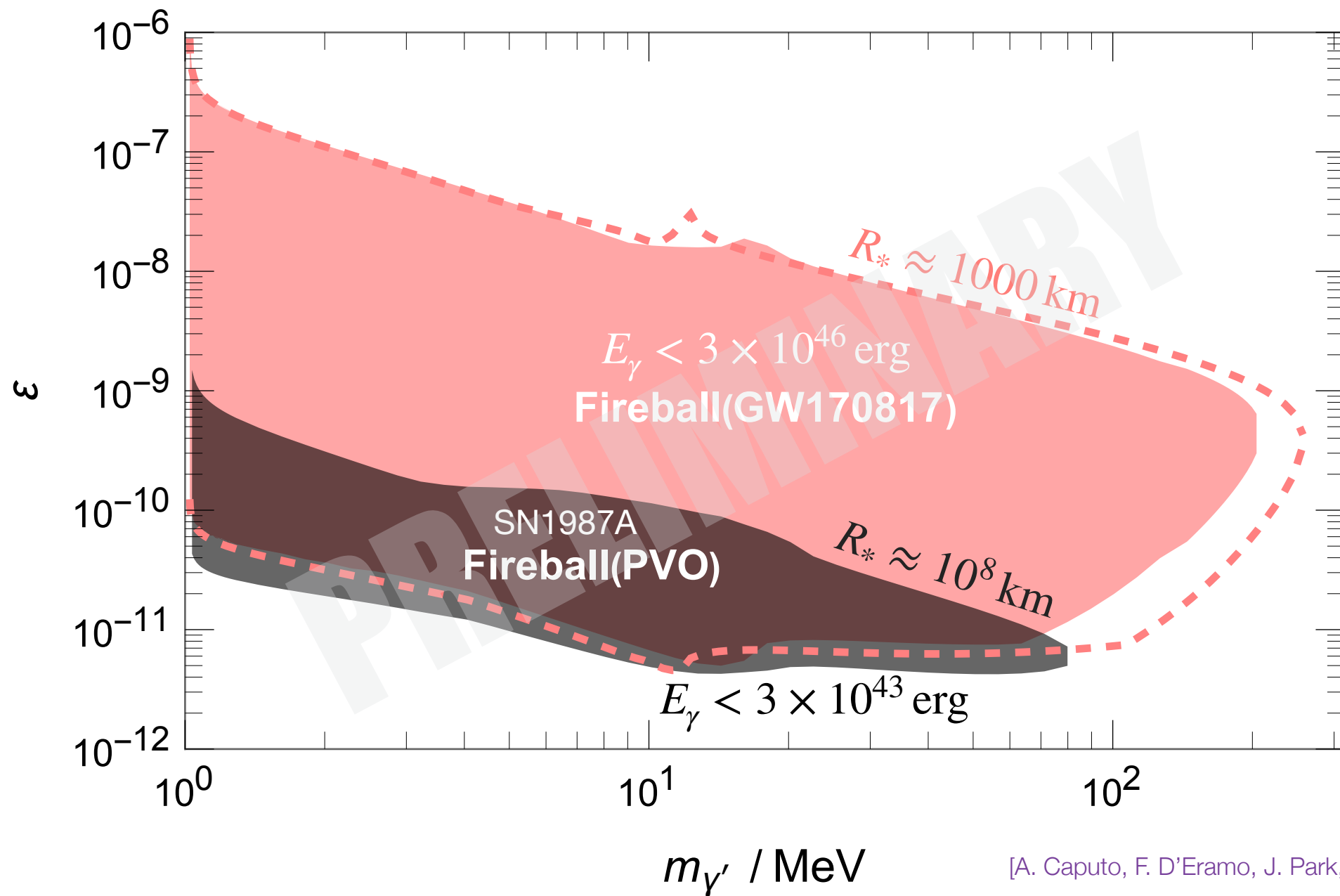
SN e^+ Injection Constraints

$$N_{e^+} \sim \int dt \int dV \frac{d^3 \vec{k}}{(2\pi)^3} \Gamma_{\text{prod}} e^{-\tau_*}$$



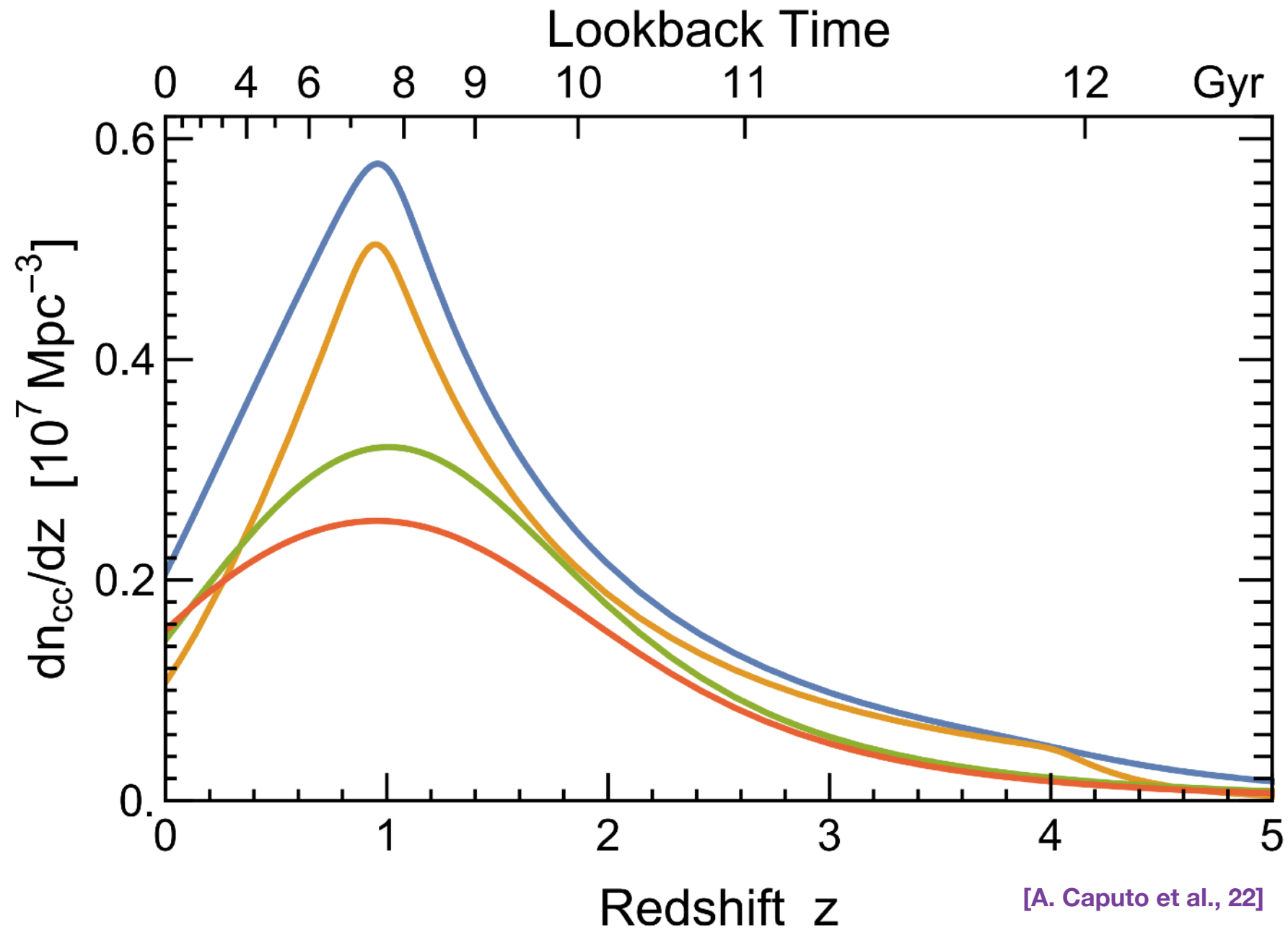
[A. Caputo, F. D'Eramo, J. Park, **SY**, in progress]

SN Fireball Constraints

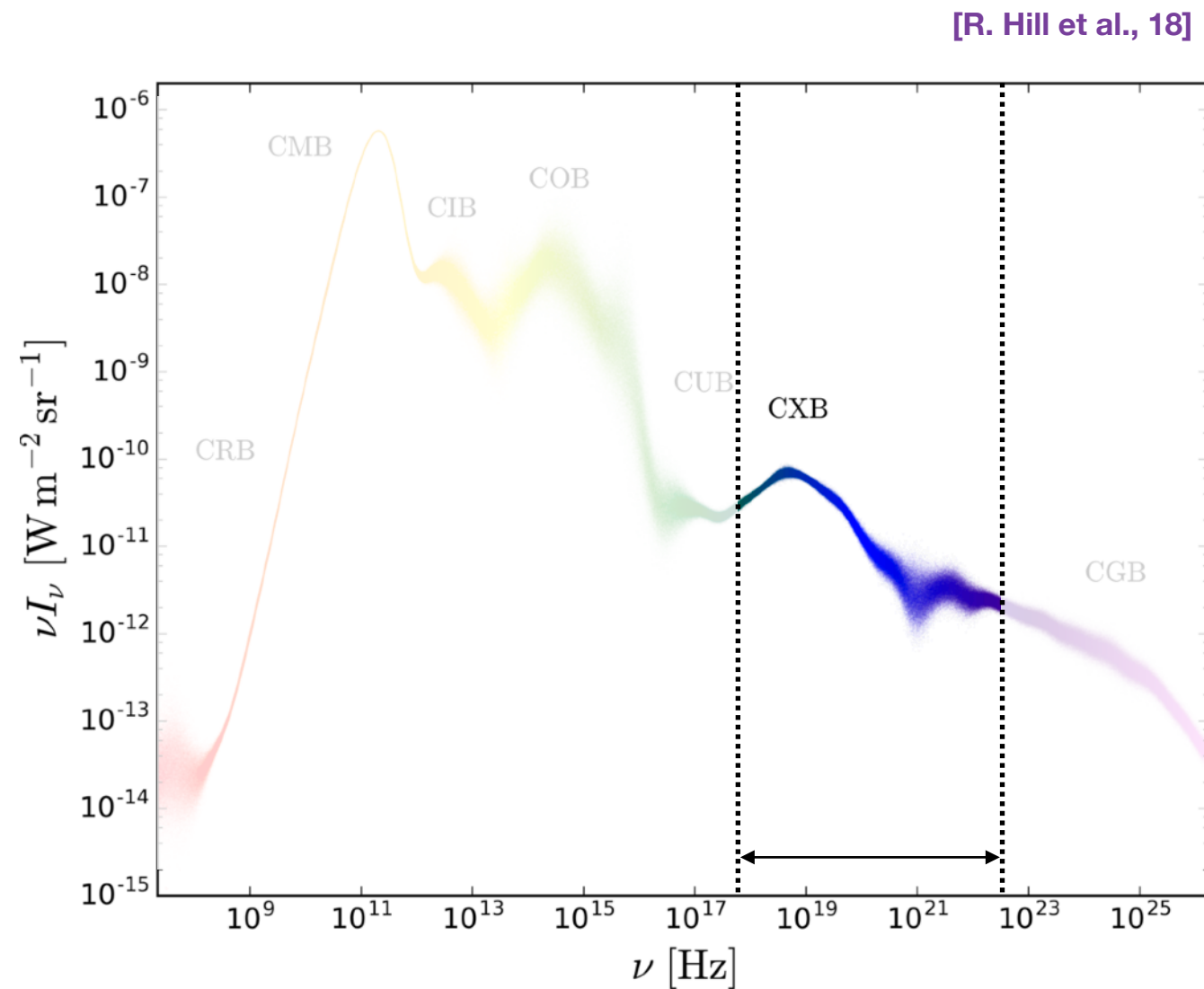


[A. Caputo, F. D'Eramo, J. Park, **SY**, in progress]

Cosmic Supernova rate

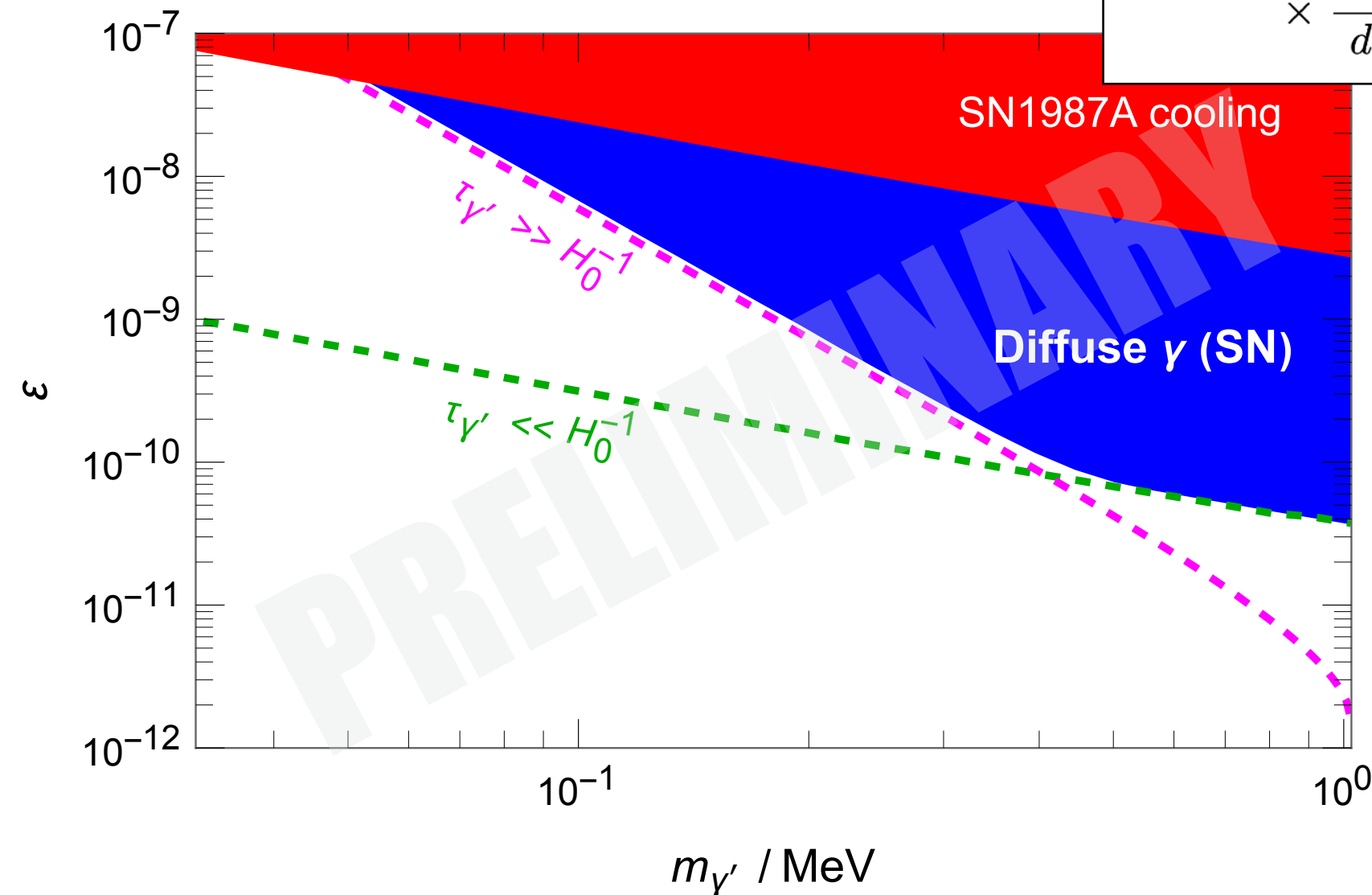


Cosmic diffuse X-ray background



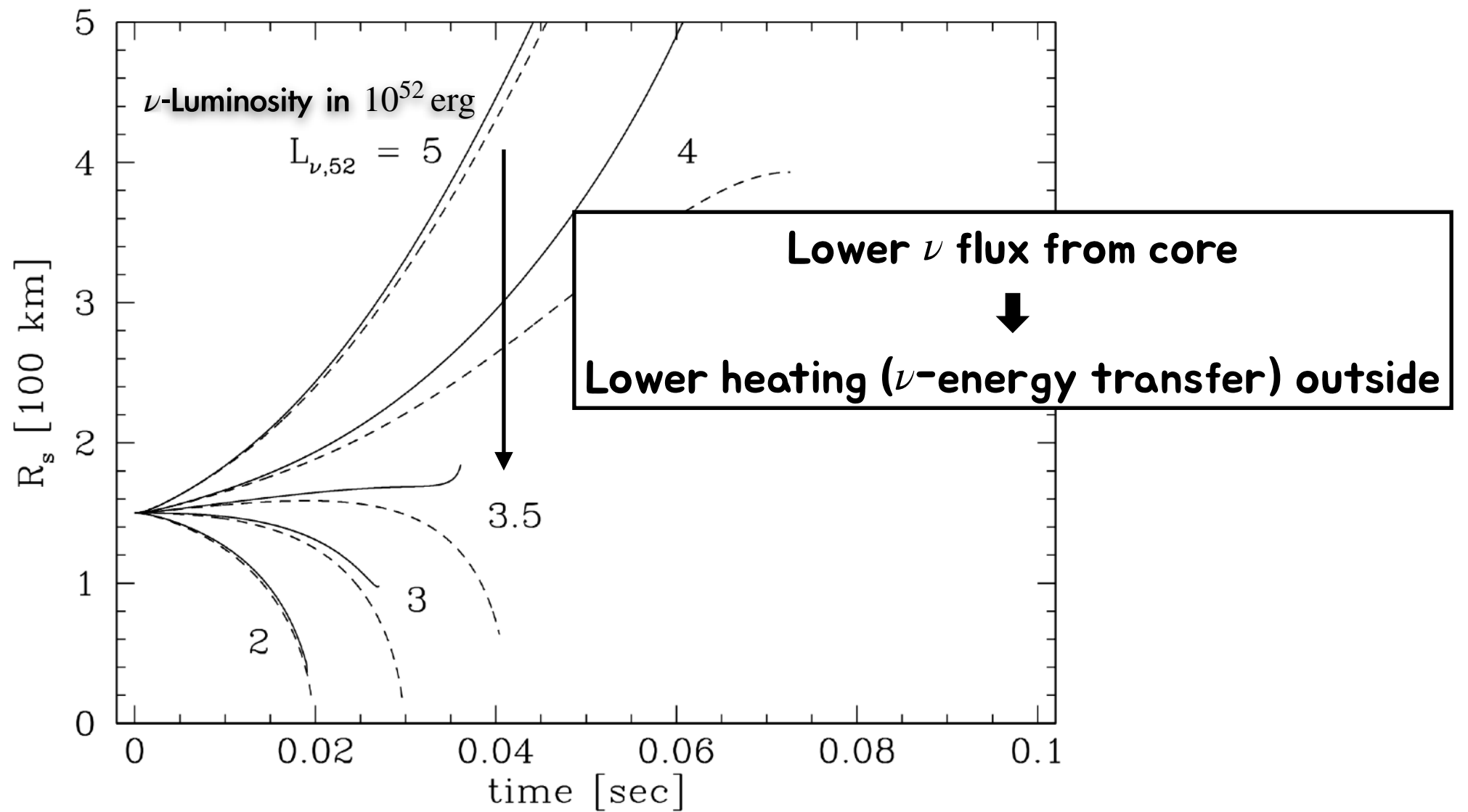
Diffuse X-ray Constraints

$$\begin{aligned} \frac{d\Phi_\gamma}{dE_\gamma} \simeq & \frac{c}{4\pi} \int_0^\infty dz \frac{dn_{\text{cc}}}{dz} \int_{E_\gamma(1+z)}^\infty d\omega \frac{d\mathcal{N}_{\gamma'}}{d\omega} \left(\frac{1+z}{\omega} \right) \\ & \times \left(1 - \exp \left[- \int_0^z dz' \Gamma_{\gamma'}(z') \left| \frac{dt}{dz'} \right| \right] \right) \left(\frac{\Gamma_{\text{rad}}}{\Gamma_{\gamma'}} \right) \\ & \times \frac{dN_\gamma}{dx} \Big|_{x=E_\gamma(1+z)/\omega} . \end{aligned} \quad (46)$$



[A. Caputo, F. D'Eramo, J. Park, **SY**, in progress]

R_{shock} in Time w.r.t. $\mathcal{L}_{\nu}$ -sphere



[T. Janka, 01]