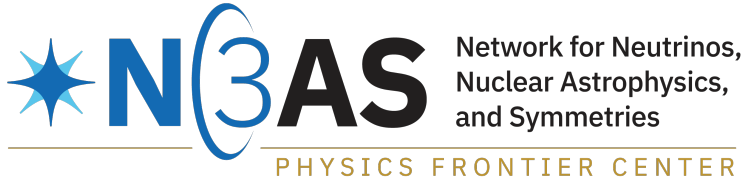
The impact of dark photons on the evolution of massive stars (pre-SN ν signal)

Ermal Rrapaj

with Andre Sieverding, Yong-Zhong Qian, and Gang Guo



Outline

- **Dark Photon Portal**
- **Core Collapse Supernovae**
- **Stellar evolution of massive stars**

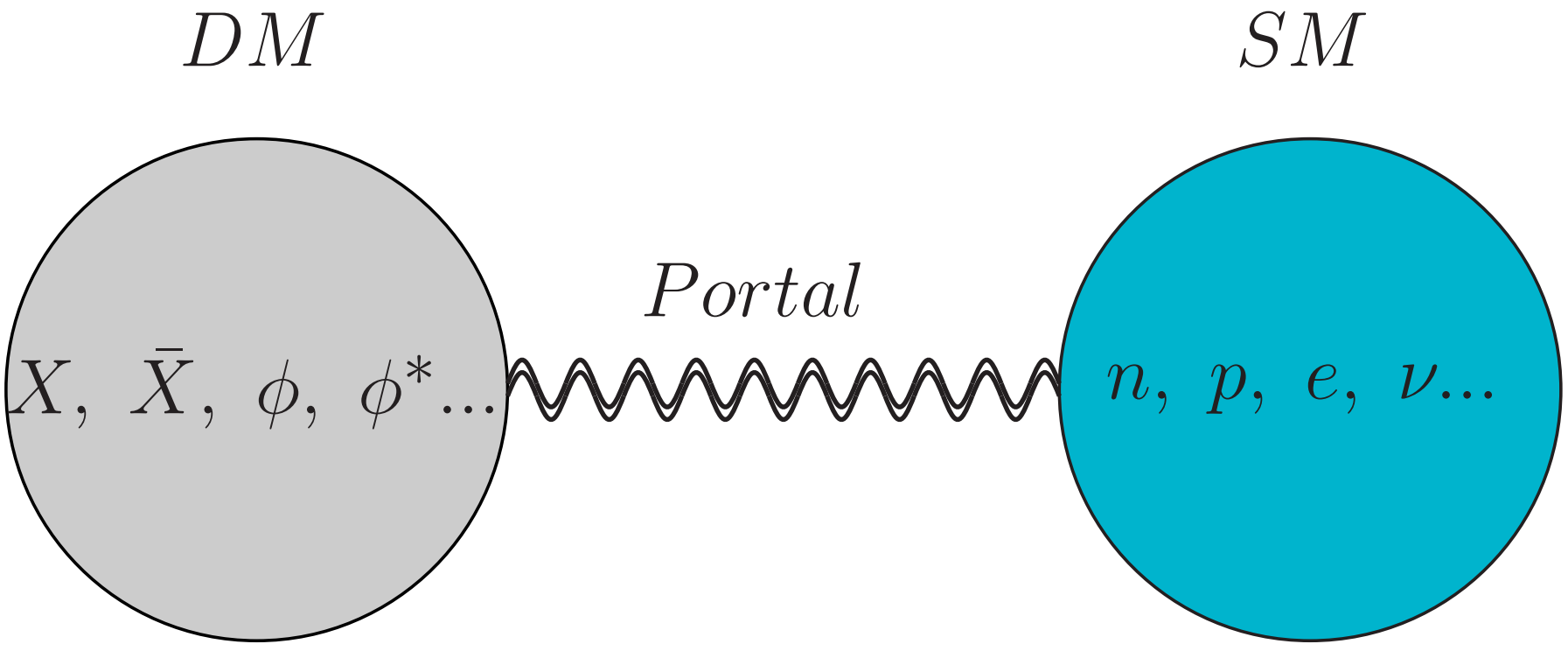
Dark matter

Astron.Astrophys. 571 (2014) A16

ΛCDM + Planck Data

- Dark Energy: 68.3%
- Dark Matter (DM): 26.8%
- Atomic Matter: 4.8%
- Light (Photons) + Neutrinos: $\lesssim 0.1\%$

Dark Sector



Essig et al, arxiv:1311.0029 (2013)

Portal

- **"Vector"**
- "Axion"
- "Higgs"
- "Neutrino"

Particle

- **Dark Photons**
- PseudoScalars
- Dark Scalars
- Sterile Neutrinos

Dark Photon

Lee, Yang PR. 98, 1501 (1955)
Batell, deNerville, McKeen, Pospelov, Ritz PRD 90, 115014 (2014)

Kinetic Mixing

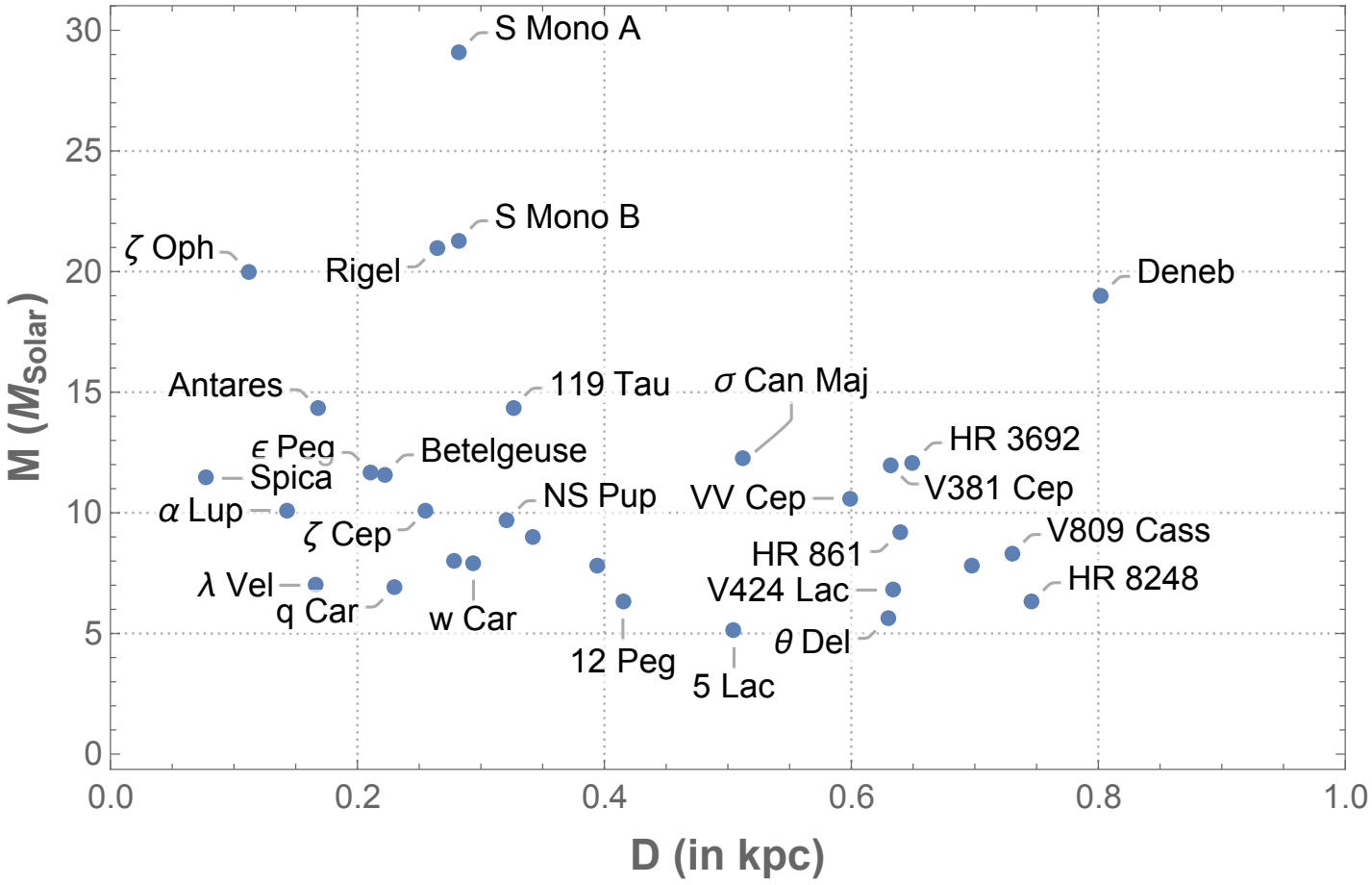
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F^{*}_{\mu\nu}F^{*\mu\nu} - \frac{\epsilon}{2}F^{*}_{\mu\nu}F^{\mu\nu} + \frac{m_A^2}{2}A_\mu A^\mu$$

Parameters

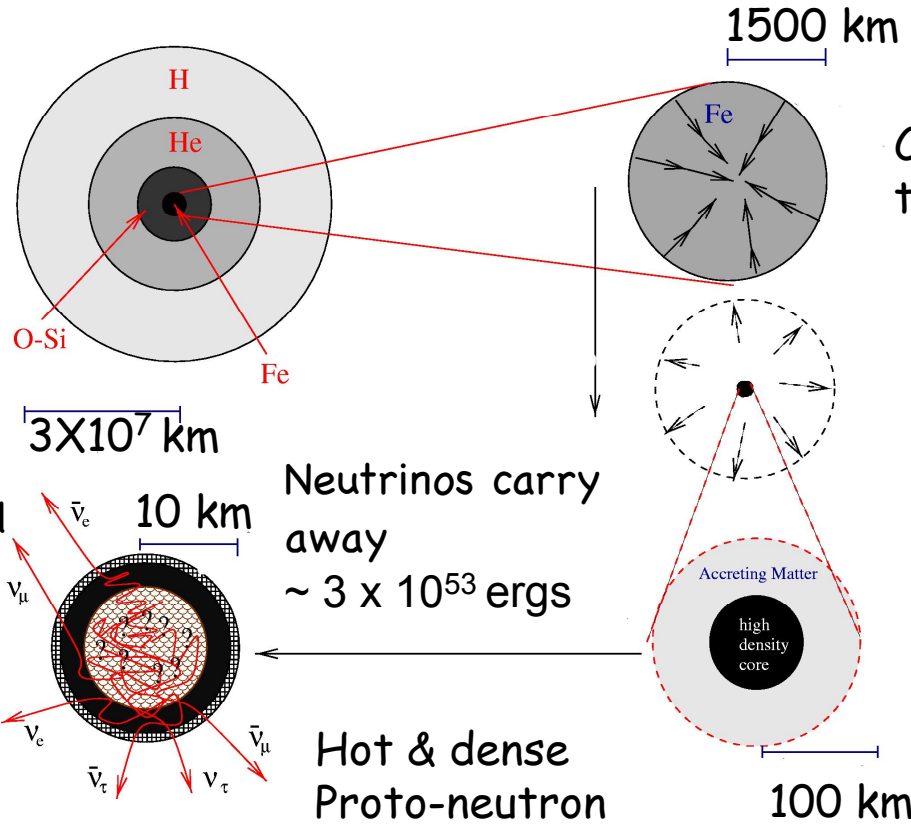
mass : m_A, relative strength: ϵ

Nearby Supernovae Candidates

Mainak Mukhopadhyay, Cecilia Lunardini, F. X. Timmes, Kai Zuber (2020) ApJ 899 153



Supernova Explosion



Neutrino flavor and energy distribution can impact explosion mechanism and r-process nucleosynthesis.

Annual Review of Nuclear and Particle Science, Adam Burrows

Supernova Constraints

Exotic matter cooling

1. Produced in the hot core (Nucleon Bremsstrahlung)
2. Small mass $\longrightarrow$ copious amounts!
3. Sap energy from the core
4. Soften energy spectra and reduce burst duration for neutrinos!

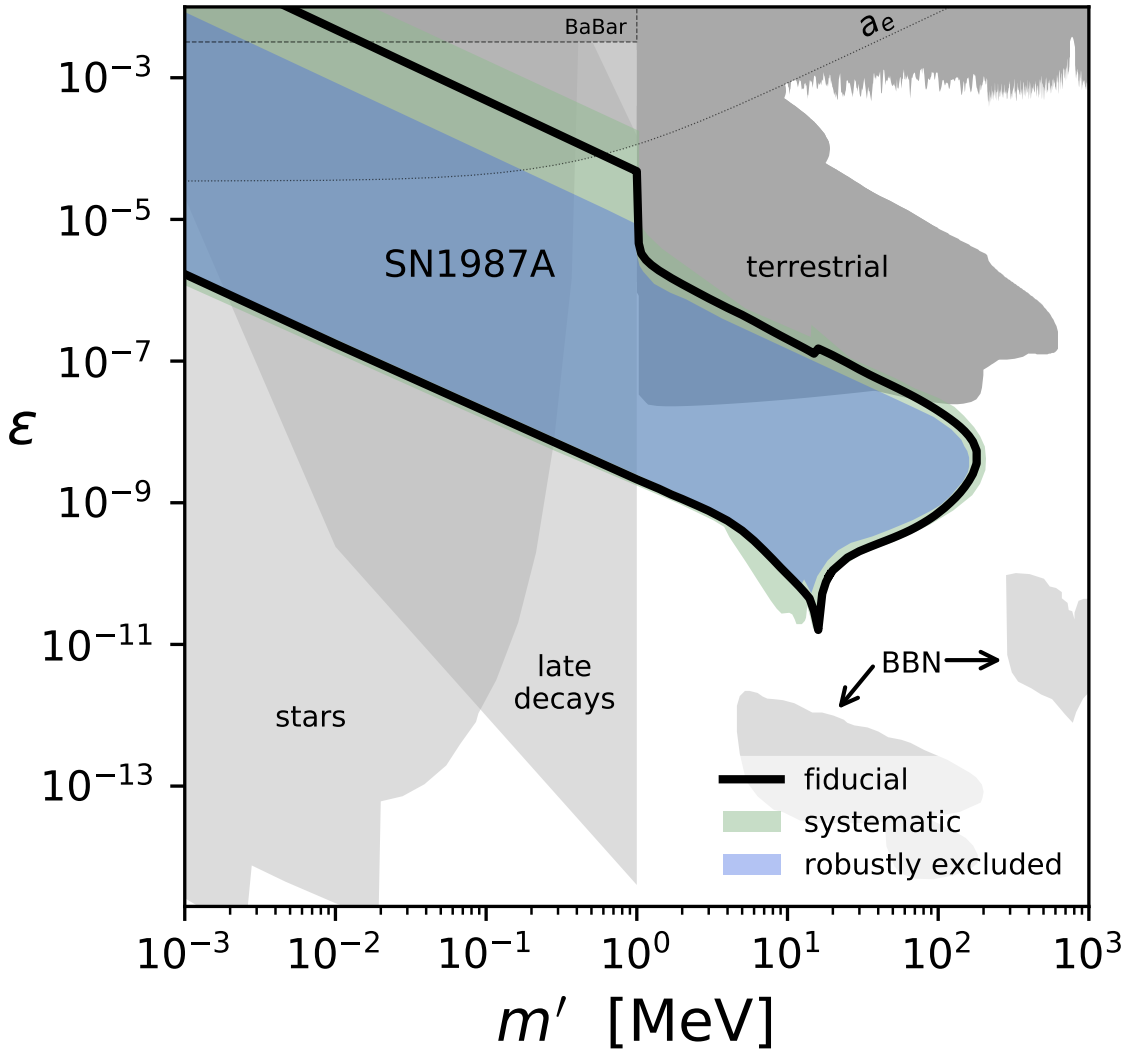
Raffelt's Criteria

$$\dot{E}(T = 30 \text{ MeV}, \rho = 3 \times 10^{14} \ \frac{\text{gram}}{\text{cm}^3}) \lesssim 10^{19} \frac{\text{erg}}{\text{gram s}} \implies \text{Burst duration is halfed!}$$

"Stars as laboratories for fundamental physics: The astrophysics of neutrinos, axions, and other weakly interacting particles" (University of Chicago Press, 1996)

Parameter Space and Constraints

Jae Hyeok Chang, Rouven Essig & Samuel D. McDermot, JHEP, 107 (2017)
A. Fradette, M. Pospelov, J. Pradler and A. Ritz, PRD 90 (2014) 035022
Haipeng An, Maxim Pospelov, Josef Pradler, PLB 725 (2013)
J. Redondo and M. Postma, JCAP 02 (2009) 005



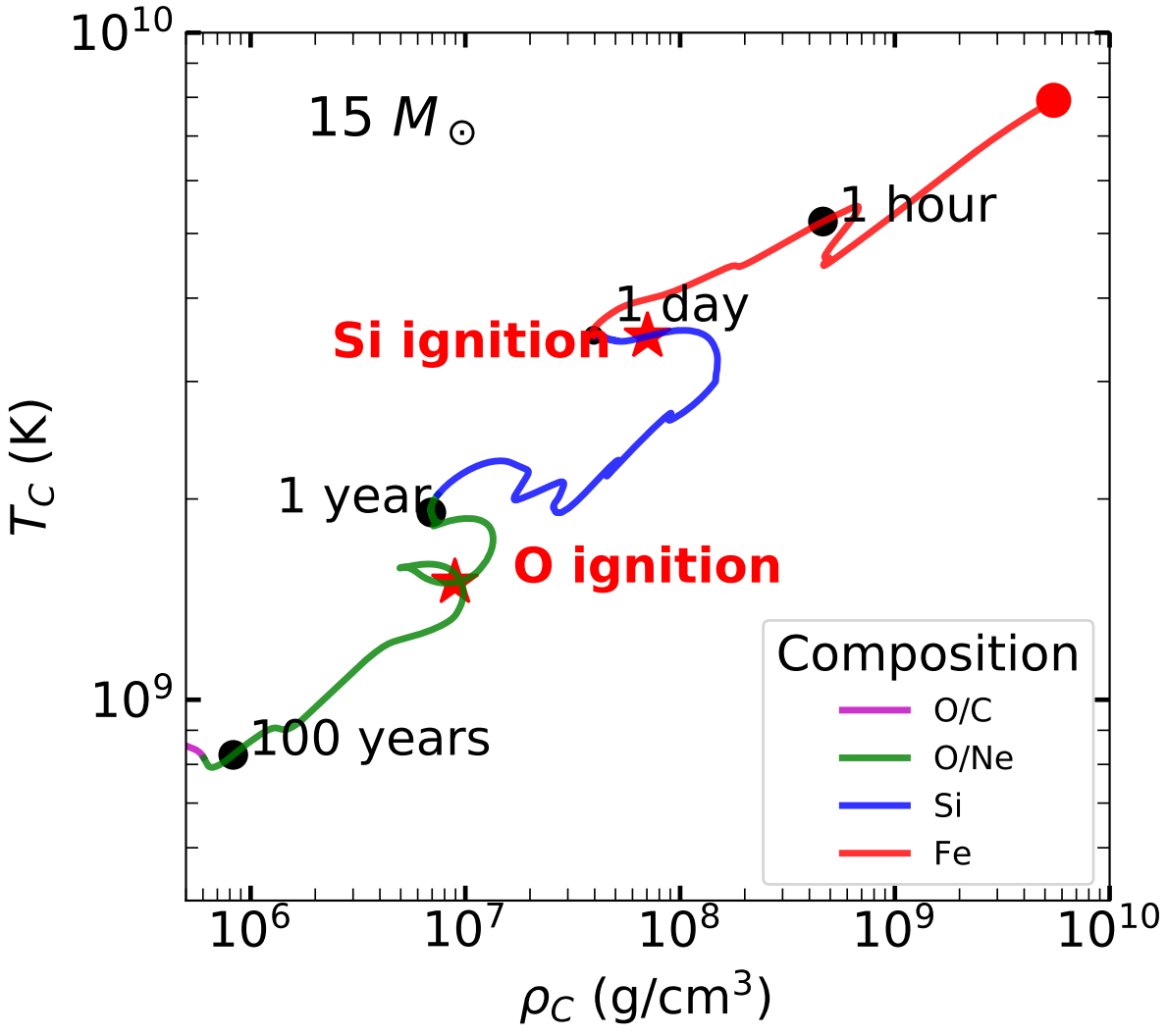
The core collapse is the end of the star

The core collapse is the end of the star

What happens to stellar evolution?

Supernova Progenitors

Andre Sieverding, **Ermal Rrapaj**, Yong-Zhong Qian, gang Guo, ApJ 912 13 (2021)

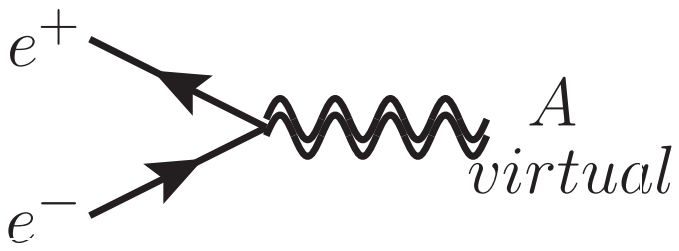


Pre-supernova neutrinos

- **ν cooling dominant in the late stages**
- **the only signature of core evolution**
- **information on progenitor core composition**
- **complementary information to supernovae neutrinos**

Dark Photons in Massive Stars

Ermal Rrapaj, Andre Sieverding, and Yong-Zhong Qian PRD 100, 023009(2019)

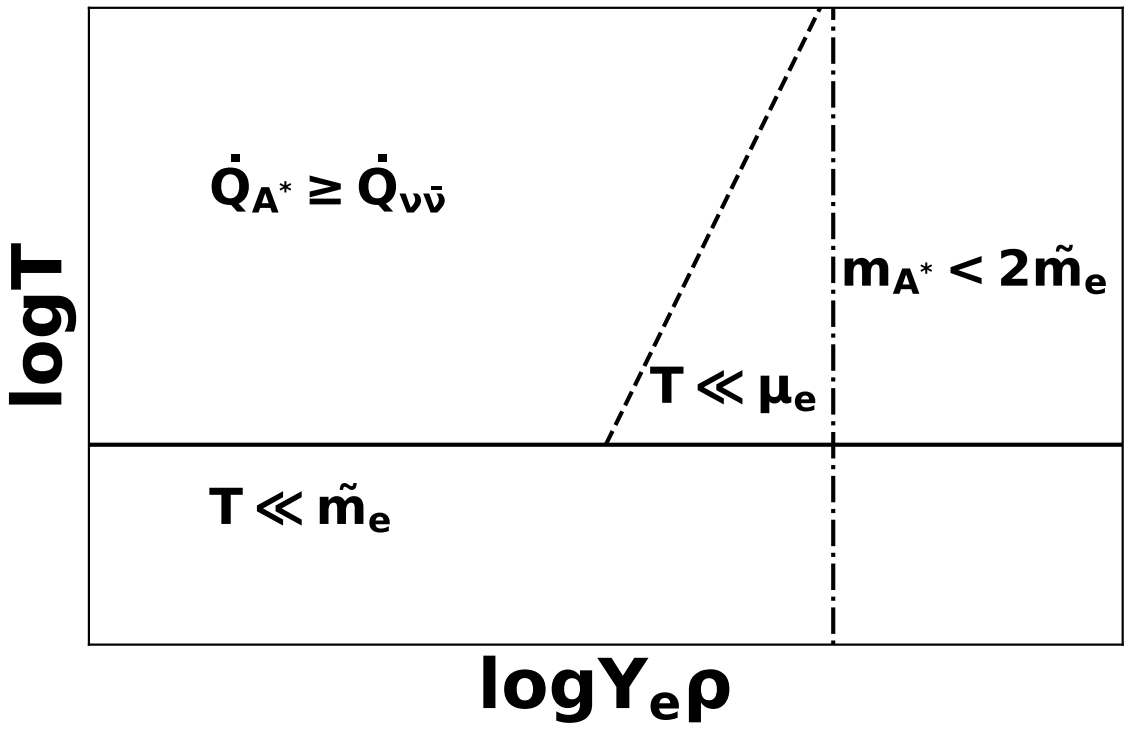


Electron - Positron pair annihilation

$$\dot{Q}_{A^D} = \int \frac{d^3k}{(2\pi)^3}\omega\Gamma_{A^D\text{ems}}, \;\; \Gamma_{A^D\text{ems}} = \frac{1}{3}\left(\Gamma^T_{A^D\text{ems}} + \Gamma^L_{A^D\text{ems}}\right)$$

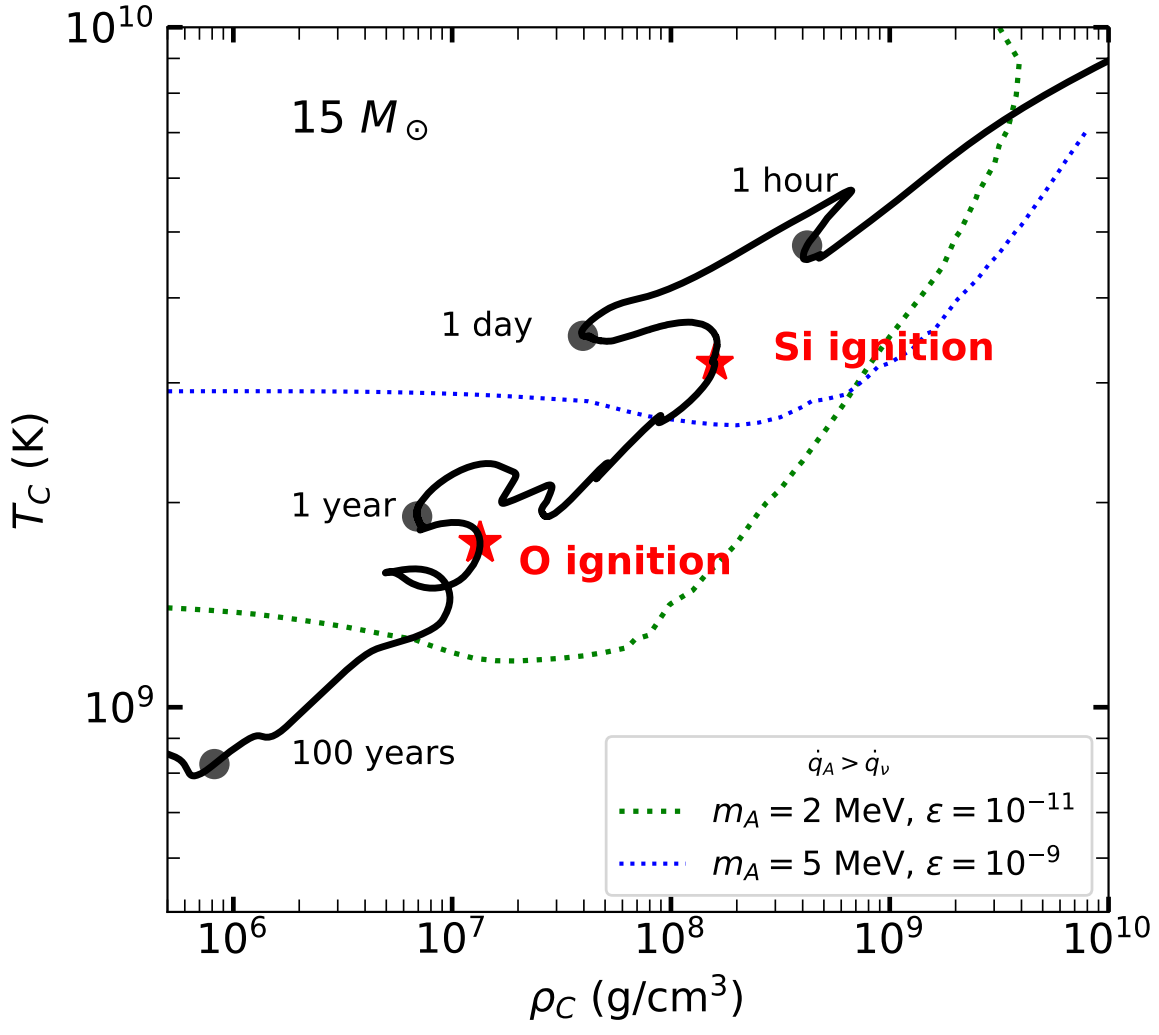
Dark photon vs Neutrino Emission

Ermal Rrapaj, Andre Sieverding, and Yong-Zhong Qian PRD 100, 023009(2019)



Dark photon vs Neutrino Emission

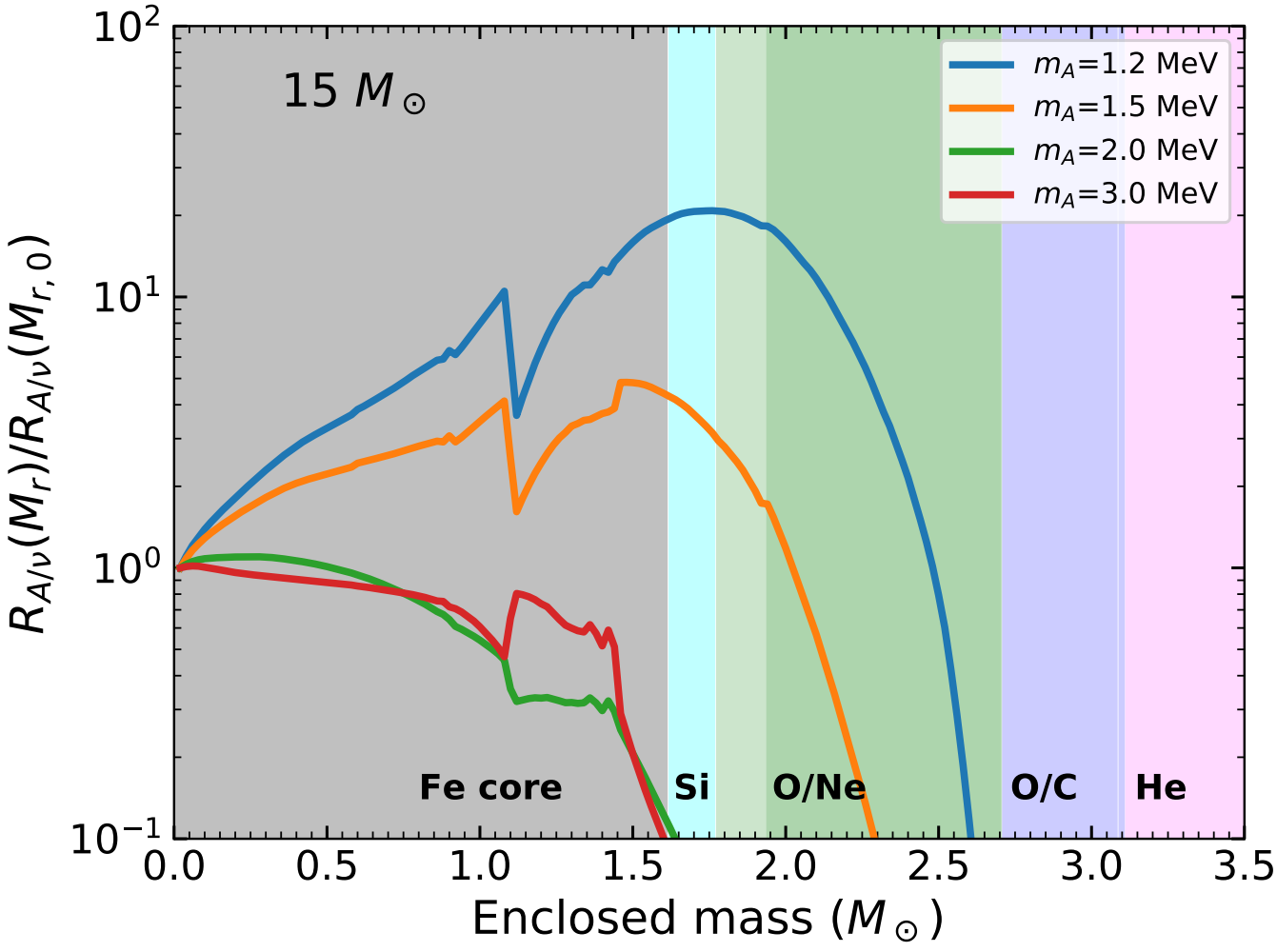
Ermal Rrapaj, Andre Sieverding, and Yong-Zhong Qian PRD 100, 023009(2019)
Andre Sieverding, **Ermal Rrapaj**, Yong-Zhong Qian, Gang Guo, ApJ 912 13 (2021)



Energy Loss Supernova Progenitor

Andre Sieverding, **Ermal Rrapaj**, Yong-Zhong Qian, Gang Guo, ApJ 912 13 (2021)

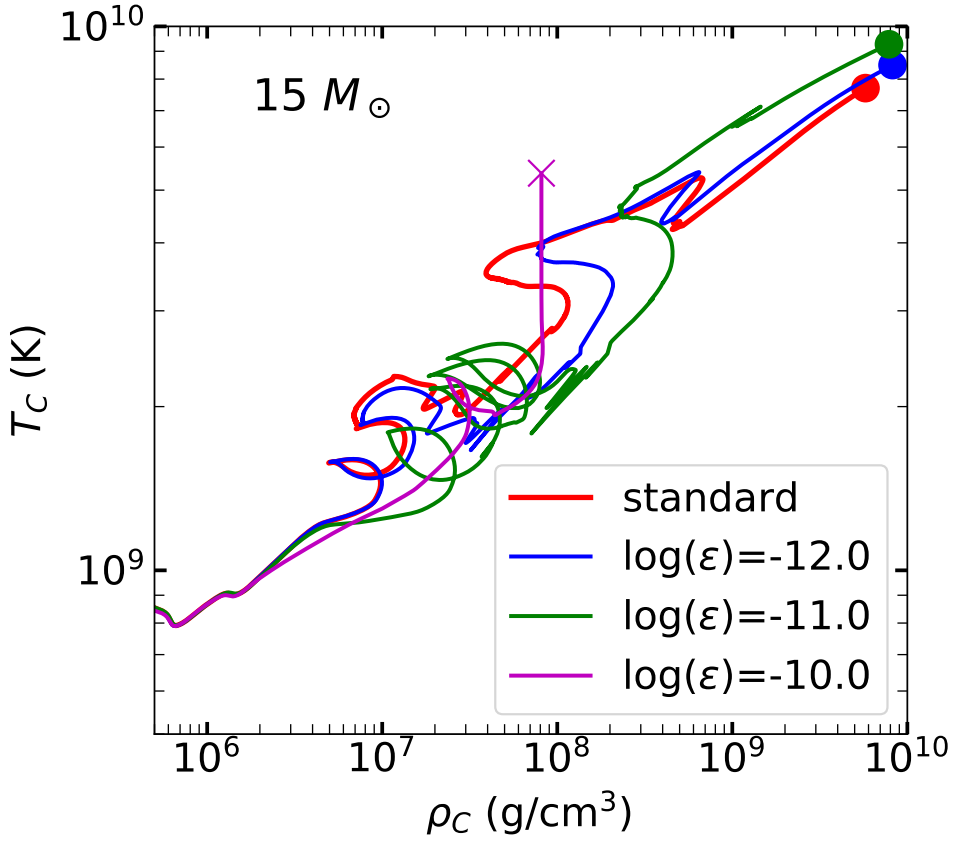
$$R_{A/\nu}(M_r) = E_{\mathrm{loss,A}}(M_r)/E_{\mathrm{loss},\nu}(M_r)$$



Lower mass $\Longrightarrow$ stronger nuclear burning in the lower density regions

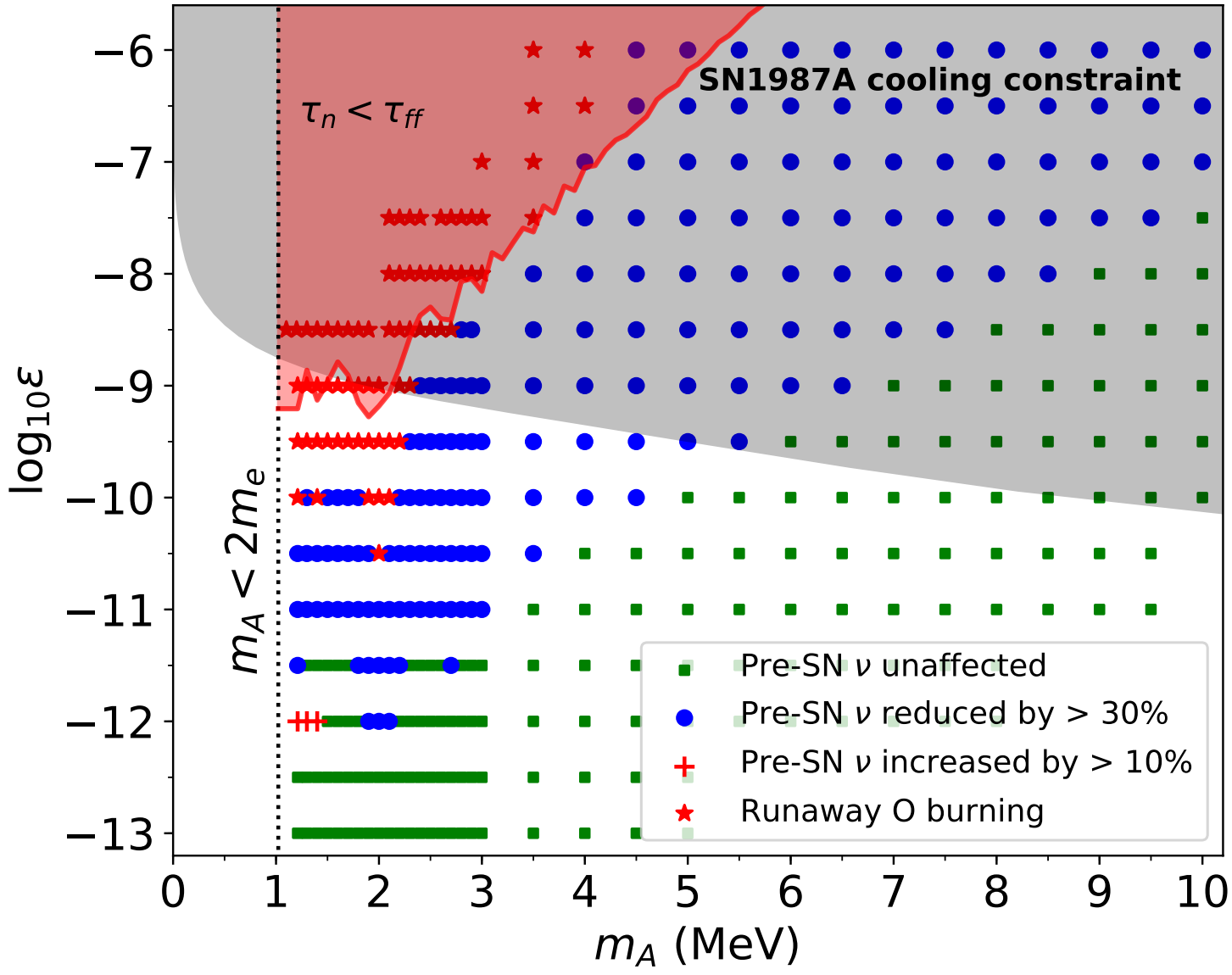
Impact on Stellar Evolution

Andre Sieverding, **Ermal Rrapaj**, and Yong-Zhong Qian, ApJ 912 13 (2021)



$m_A =$ 2 **MeV , "x": Thermonuclear runaway during Oxygen burning**

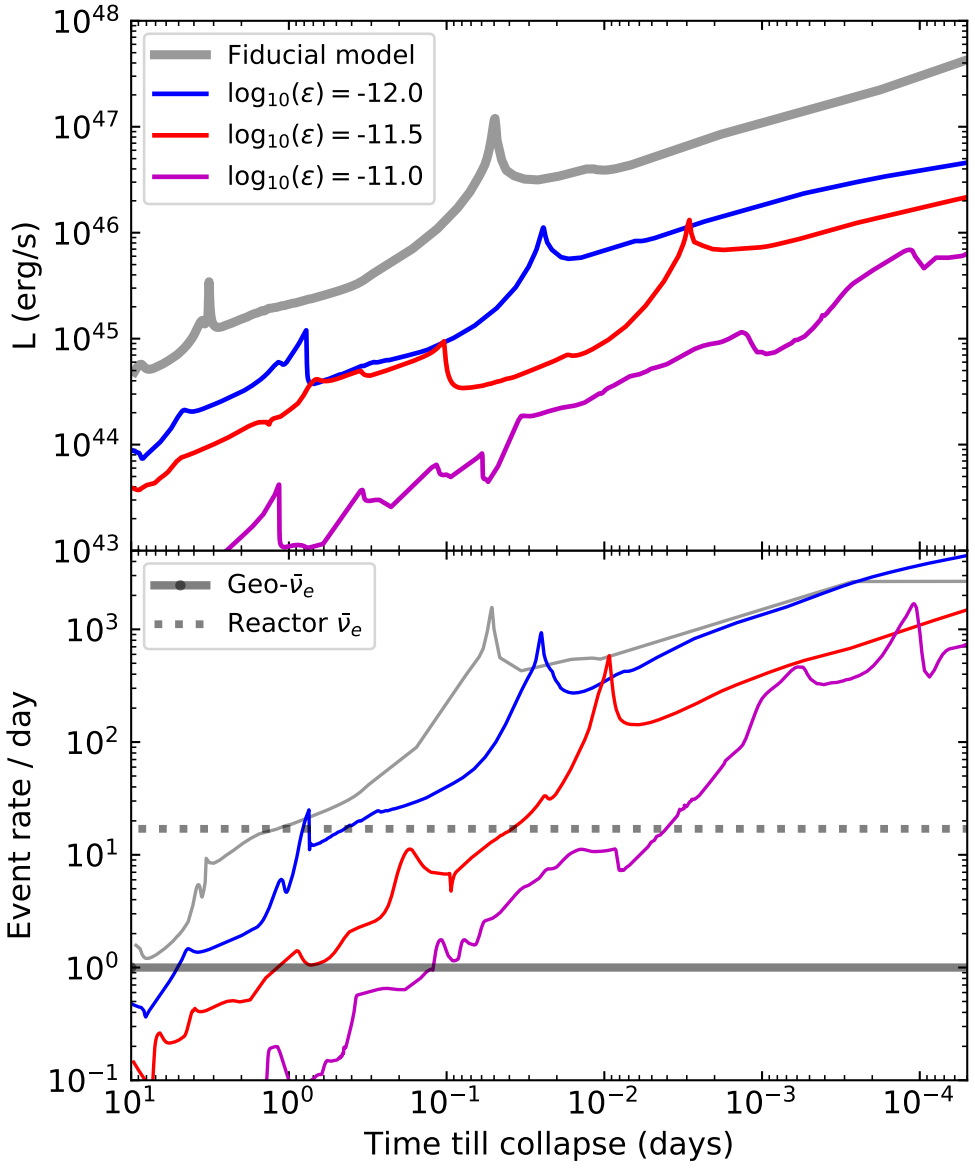
Impact on Stellar Evolution



$\overline{\nu}_e$ Detection at JUNO

($m_A = 2$ MeV, $d = 500$ pc)

Andre Sieverding, **Ermal Rrapaj**, and Yong-Zhong Qian, ApJ 912 13 (2021)



Summary

Dark photons in stellar evolution

- Mass range of $2m_e - 6$ MeV plays an important role
- Even very low couplings can have dramatic effects
- Pre-SN neutrino signal impacted by the dark photon

Thank you!

Collaborators

Andre Sieverding, Yong-Zhong Qian, and Gang Guo