Dark Photons
Lessons from Astrophysics

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Outline

- Dark photon portal
- Parameter constraints from supernovae
- Stellar evolution of massive stars

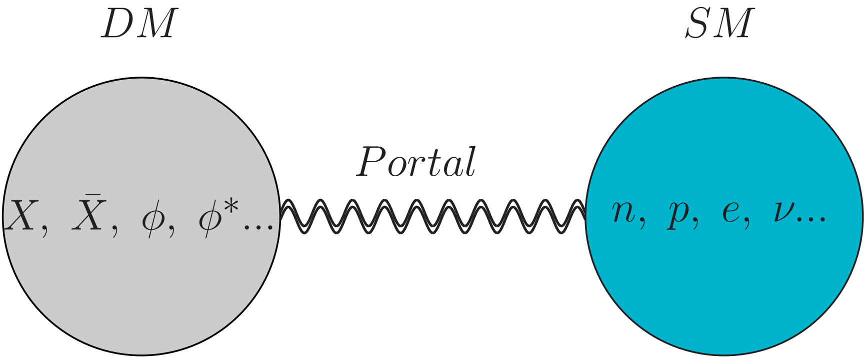
Dark matter

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 portal



Essig et al, arxiv:1311.0029 (2013)

Portal

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

Particle

- Dark Photons
- PseudoScalars
- Dark Scalars
- Sterile Neutrinos

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

Kinetic Mixing

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F^D_{\mu\nu}F^{D\,\mu\nu} - \frac{\epsilon}{2}F^D_{\mu\nu}F^{\mu\nu} + \frac{m^2_{A^D}}{2}A^D_\mu A^{D\,\mu}$$

Parameters

mass : m_{A^D}, relative strength: ϵ

Supernova Constraints

Exotic matter cooling of PNS

1. produced in the hot core (Nucleon Bremsstrahlung)
2. light in mass $\longrightarrow$ copious amounts!
3. sap energy from the core
4. soften energy spectra and reduce burst duration for neutrinos!

Raffelt's Criteria

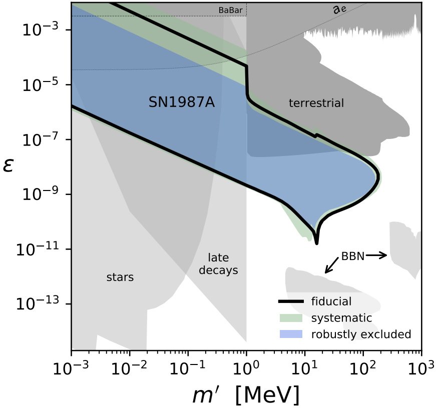
$\dot{E}(T = 30 \text{ MeV}, \rho = 3 \times 10^{14} \frac{\text{gram}}{\text{cm}^3}) \lesssim 10^{19} \frac{\text{erg}}{\text{gram s}} \implies$ Burst duration is halfed!

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

Supernova 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
J. Redondo and M. Postma, JCAP 02 (2009) 005

Cooling Constraint



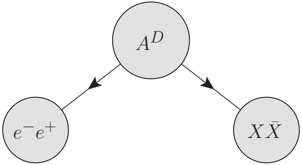
Additional supernova constraints

Allan Sung, Huitzu Tu,and Meng-Ru Wu PRD 99, 121305(R) (2019)
William DeRocco, Peter W. Graham, Daniel Kasen, Gustavo Marques-Tavares, Surjeet Rajendran, JHEP, 171 (2019)

$$A^D \longrightarrow e^- e^+ (\gamma)$$

- Energy deposition in the envelope
- Galactic positrons
- Gamma rays

Non trivial dark sector



$$\lambda^{-1}_{A^D\to e^- e^+} = \alpha\epsilon^2 \frac{(m^2_{A^D} + 2m_e^2)}{3k}\sqrt{1 - \frac{4m_e^2}{m^2_{A^D}}} \leftrightarrow$$

$$\frac{\lambda_{A^D\to X\overline{X}}}{\lambda_{A^D\to e^- e^+}} = \left(\frac{\epsilon}{\epsilon_X}\right)^2 \left(\frac{m^2_{A^D} + 2m_e^2}{m^2_{A^D} + 2m_X^2}\right)\sqrt{\frac{m^2_{A^D} - 4m_e^2}{m^2_{A^D} - 4m_X^2}},$$

$$m_X \sim m_e \to \frac{\lambda_{A^D\to X\overline{X}}}{\lambda_{A^D\to e^- e^+}} = \left(\frac{\epsilon}{\epsilon_X}\right)^2 \implies A^D \to X\overline{X} \text{ dominant decay mode}$$

Supernova Constraints

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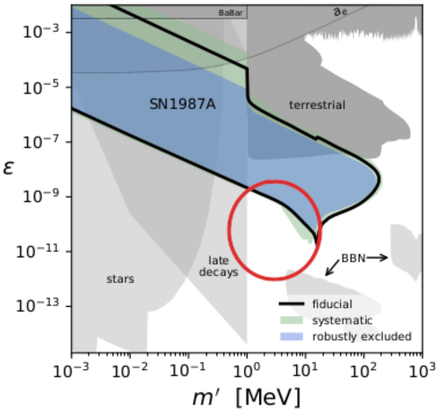
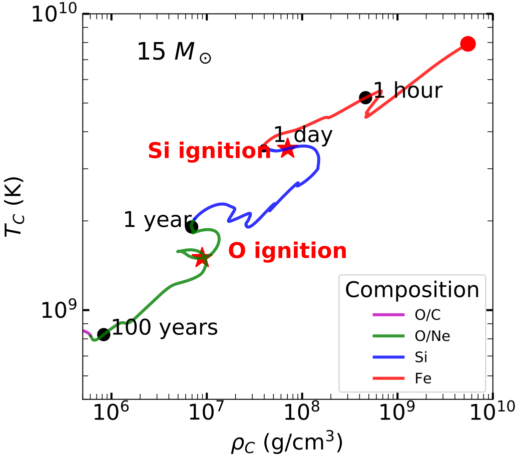
Cooling Constraint



What happens to stellar evolution?

Supernova Progenitors



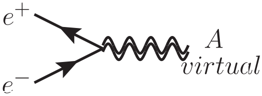
ν cooling important starting from C burning

Pre-supernova neutrinos

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

Dark photons in massive stars

Ermal Rrapaj, Andre Sieverding, and Yong-Zhong Qian Phys. Rev. D 100, 023009(2019)



Pair annihilation

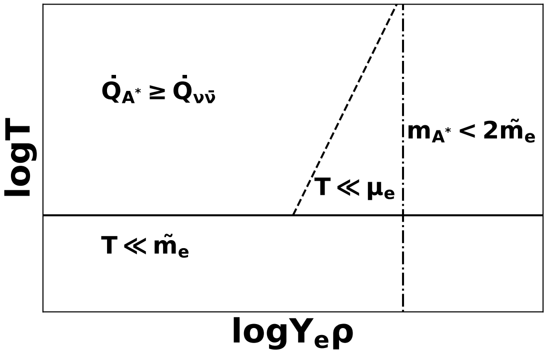
$$\dot{Q}_{A^D} = \int \frac{d^3k}{(2\pi)^3} \omega \Gamma_{A^D\,\mathrm{ems}},$$

$$\Gamma_{A^D\,\mathrm{ems}} = \frac{1}{3}\left(\Gamma^T_{A^D\,\mathrm{ems}} + \Gamma^L_{A^D\,\mathrm{ems}}\right),$$

$$\Gamma_{e^- e^+ \to A^D} = \frac{1}{2\omega}\frac{1}{4\pi}\int d\Omega_\omega \int \frac{d^3p_{e^-}}{2E_{e^-}(2\pi)^3}\int \frac{d^3p_{e^+}}{2E_{e^+}(2\pi)^3}$$
$$|\mathcal{M}_{e^- e^+ \to A^D}|^2 f_{e^-} f_{e^+} (2\pi)^4 \delta^{(4)}(K - P_{e^-} - P_{e^+})$$

Dark photon vs neutrino emission

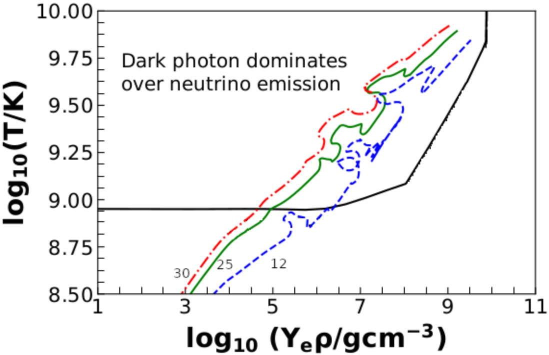
Ermal Rrapaj, Andre Sieverding, and Yong-Zhong Qian Phys. Rev. D 100, 023009(2019)



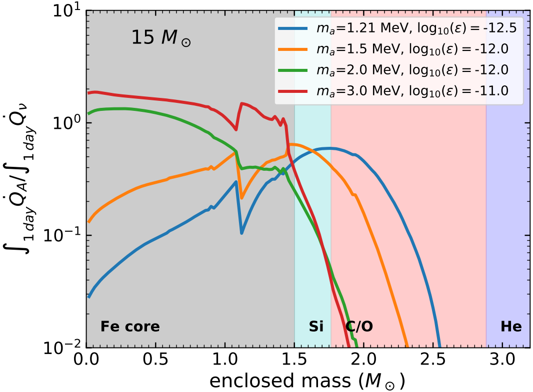
Dark photon and neutrino emission

Ermal Rrapaj, Andre Sieverding, and Yong-Zhong Qian Phys. Rev. D 100, 023009(2019)

$$m_{A^D} = 2\ \text{MeV},\ \epsilon = 10^{-9}$$



Last day of supernova progenitor



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

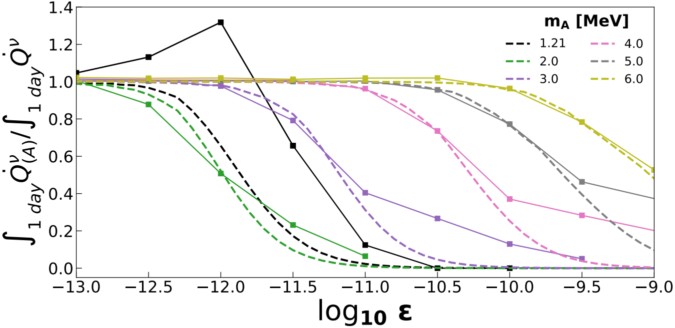
Semi-analytical approximation

'Perturbative' regime

- $\dot{Q}_A \lesssim \dot{Q}_{\nu\bar{\nu}}$
- Speed up core evolution
  - $dt \propto L_{\nu\bar{\nu}}^{-1}$
  - $dt'/dt = L_{\nu\bar{\nu}}/(L_{\nu\bar{\nu}} + L_A)$
- $L'_{\nu\bar{\nu}} < L_{\nu\bar{\nu}}$

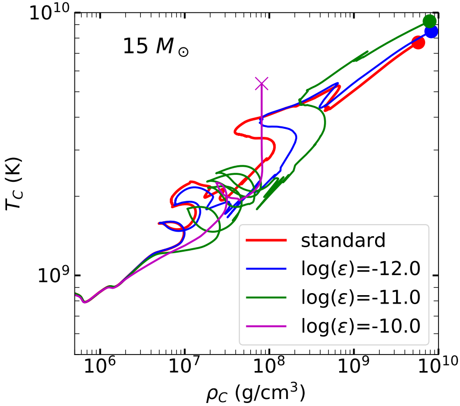
$\nu \Longrightarrow$ the only observable signature of core evolution in the late stages

Last day of supernova progenitor



Numerical simulation (solid) and semi-analytical approximation (dashed)

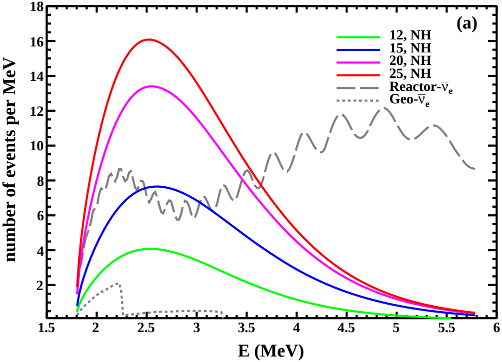
Impact on stellar evolution



- Self-consistent treatment, $m_{A_D} = 2$ MeV
- "x": Thermonuclear runaway during Oxygen burning

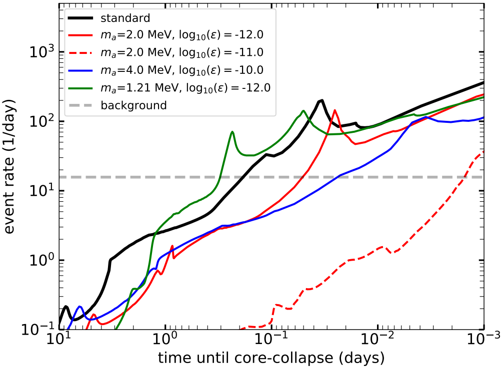
$\overline{\nu}_e$ detection at JUNO: last day count

Gang Guo, Yong-Zhong Qian, Alexander Heger Physics Letters B 796 (2019) 126–130



$e^- e^+ \rightarrow \nu_e \overline{\nu}_e$, 1 kpc, last day

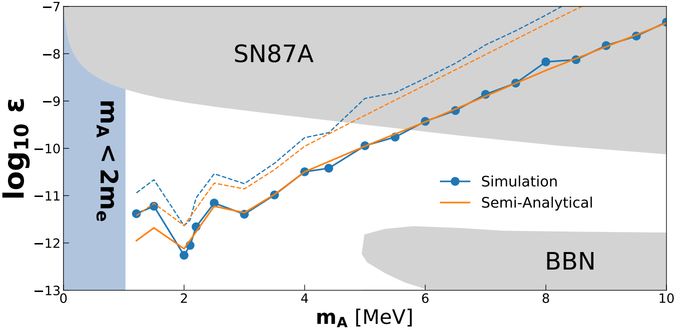
$\overline{\nu}_e$ detection at JUNO: signal time



$e^- e^+ \to \nu_e \overline{\nu}_e$, 15 $M_\odot$, 1 kpc

Future detection and implications

15 $M_\odot$, 600 pc, last day: count 30% above background



Summary

Dark photons in stellar evolution

- Lower mass ($2m_e - 6$ MeV) may play an important role
- Even very low couplings can have dramatic effects
- Semi-analytical treatment for perturbative regime
- Implications for future detections of pre-supernova neutrinos

Thank you!

Institutions

University of Minnesota

University of California, Berkeley

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Collaborators

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