Revisiting Supernova 1987A Constraints on Dark Photons

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Collaboration with Rouven Essig and Samuel McDermott

Jae Hyeok Chang

C.N. Yang Institute for Theoretical Physics, Stony Brook

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DARK PHOTON MODEL

- $SU(3)_c \times SU(2)_L \times U(1)_Y$

- $SU(3)_c \times SU(2)_L \times U(1)_Y \times \boldsymbol{U(1)'}$

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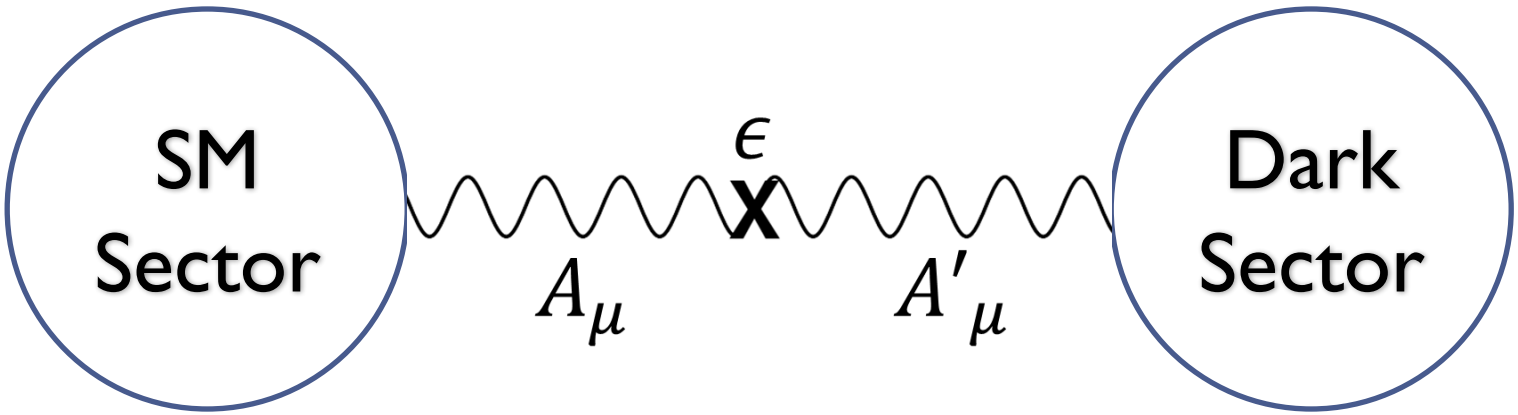
- A'_μ : Dark Photon
- $F'_{\mu\nu}$: Gauge Invariant itself
- $\mathcal{L} \supset \frac{\epsilon_Y}{2} B_{\mu\nu} F'^{\mu\nu}$: Kinetic Mixing
- In low energies, $\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$



- SM sector and dark sector are connected
- Called the vector portal

Various constraints on this model

- Terrestrial experiments
  - Beam dump experiments
  - Colliders experiments
  - (g-2) experiments
- Cosmology
  - Relic abundance
  - CMB
- Astrophysics
  - Supernova1987A
  - Red giants and the sun

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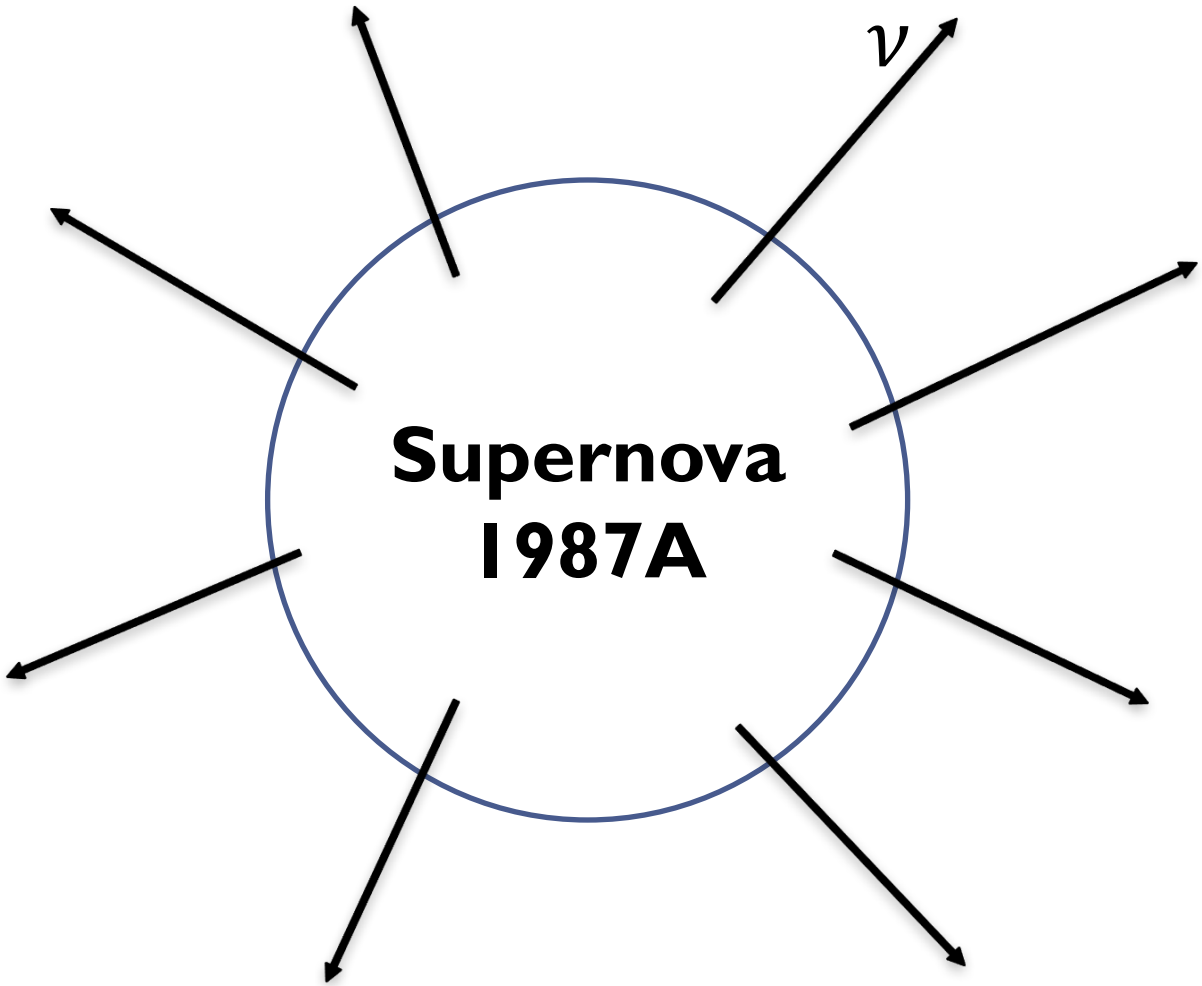
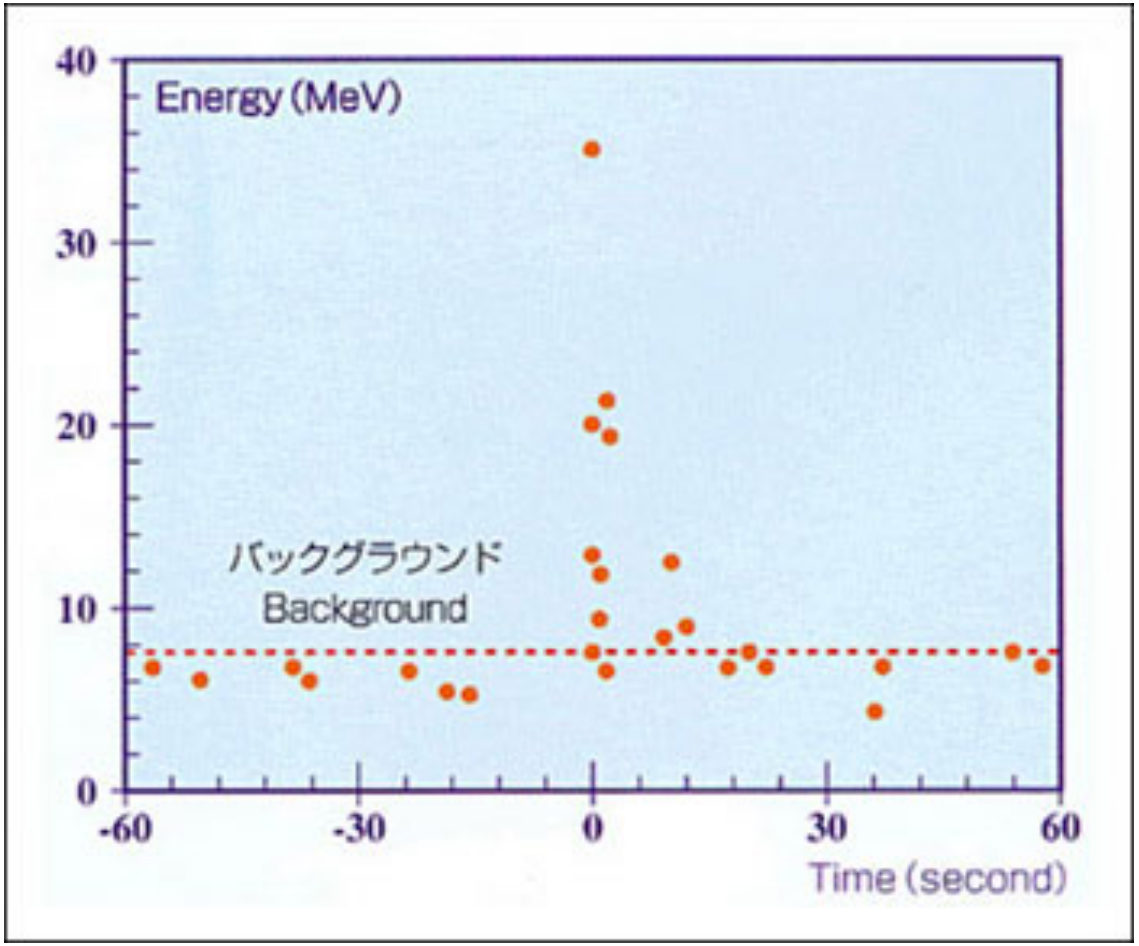
CONSTRAINTS FROM SUPERNOVA 1987A

Supernova 1987A

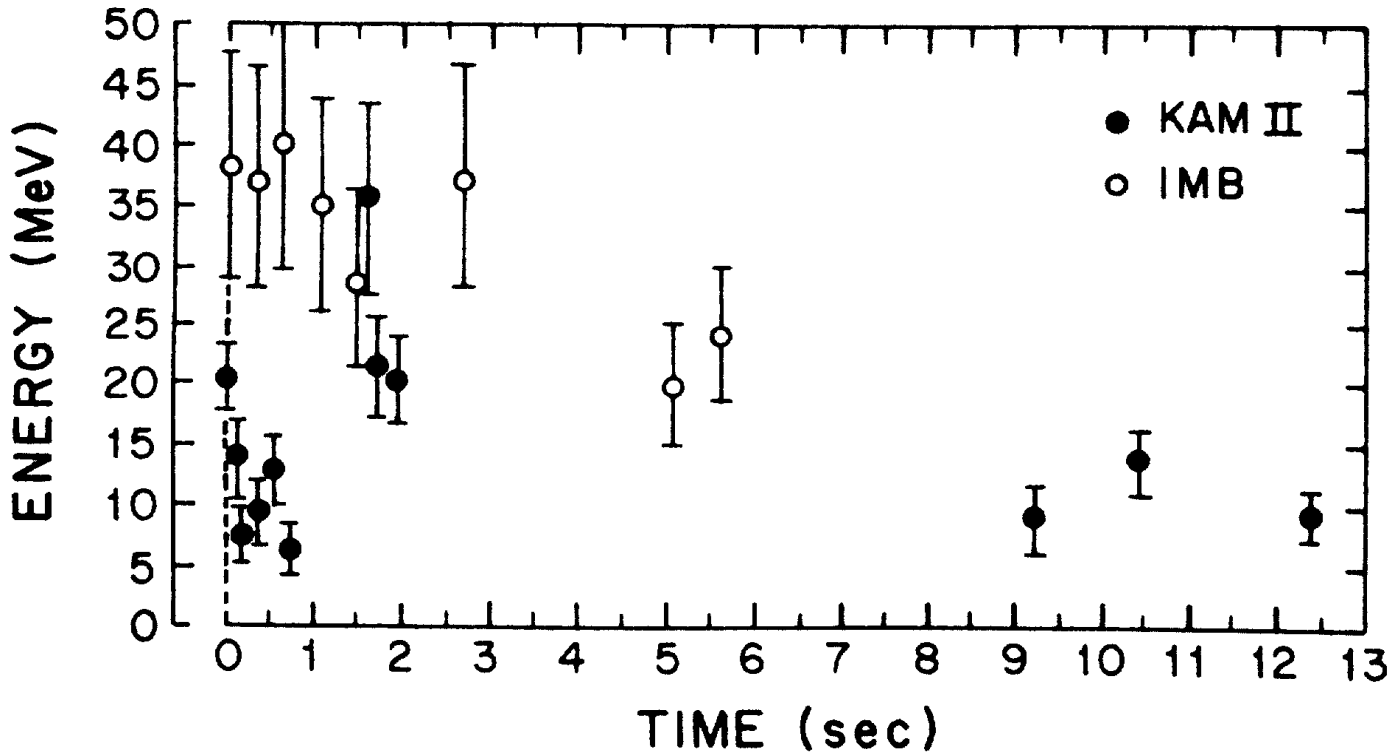


- 99% of energy is carried by neutrinos

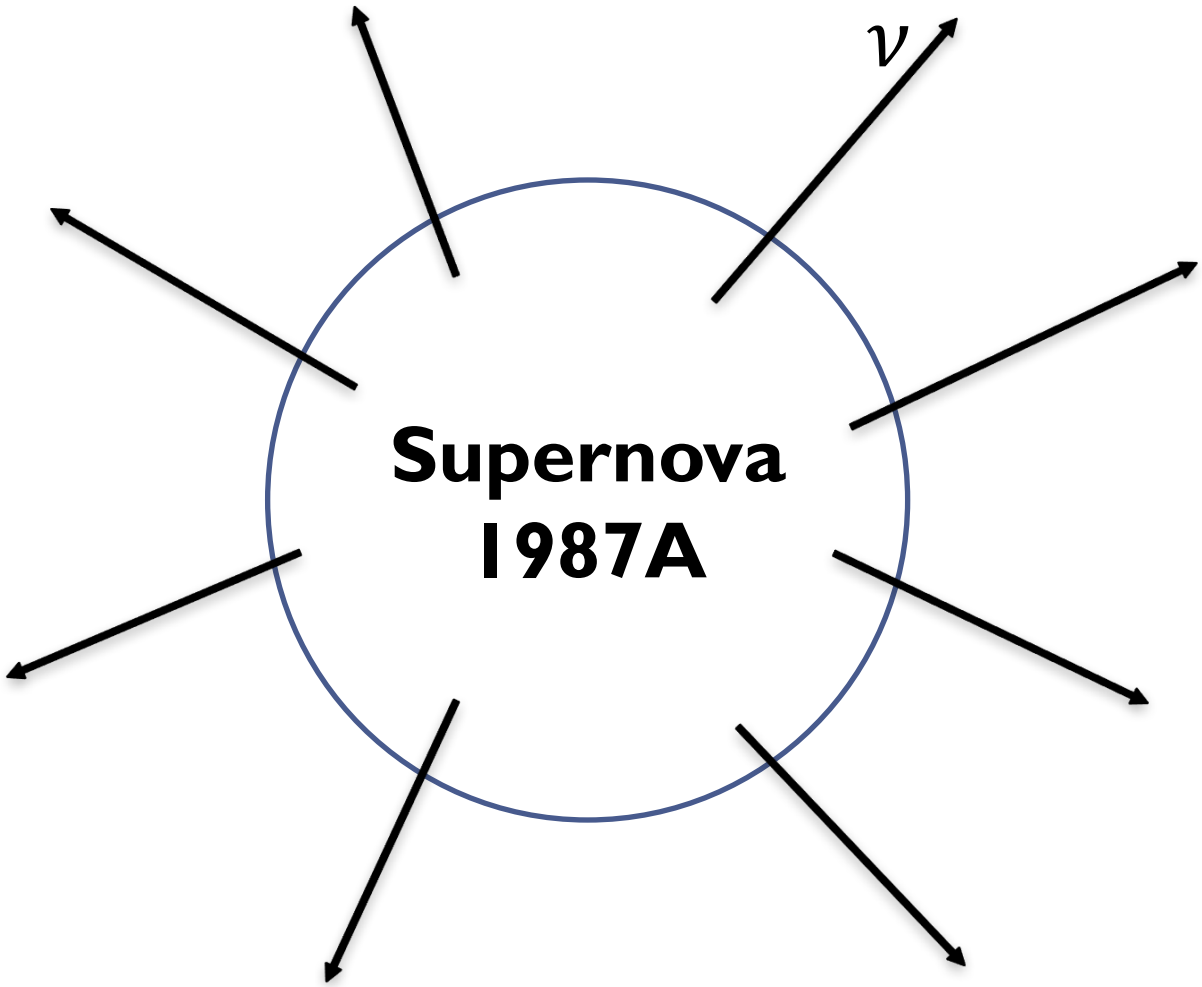


- Kamiokande II, IMB, and Baksan detected the neutrinos at the same time

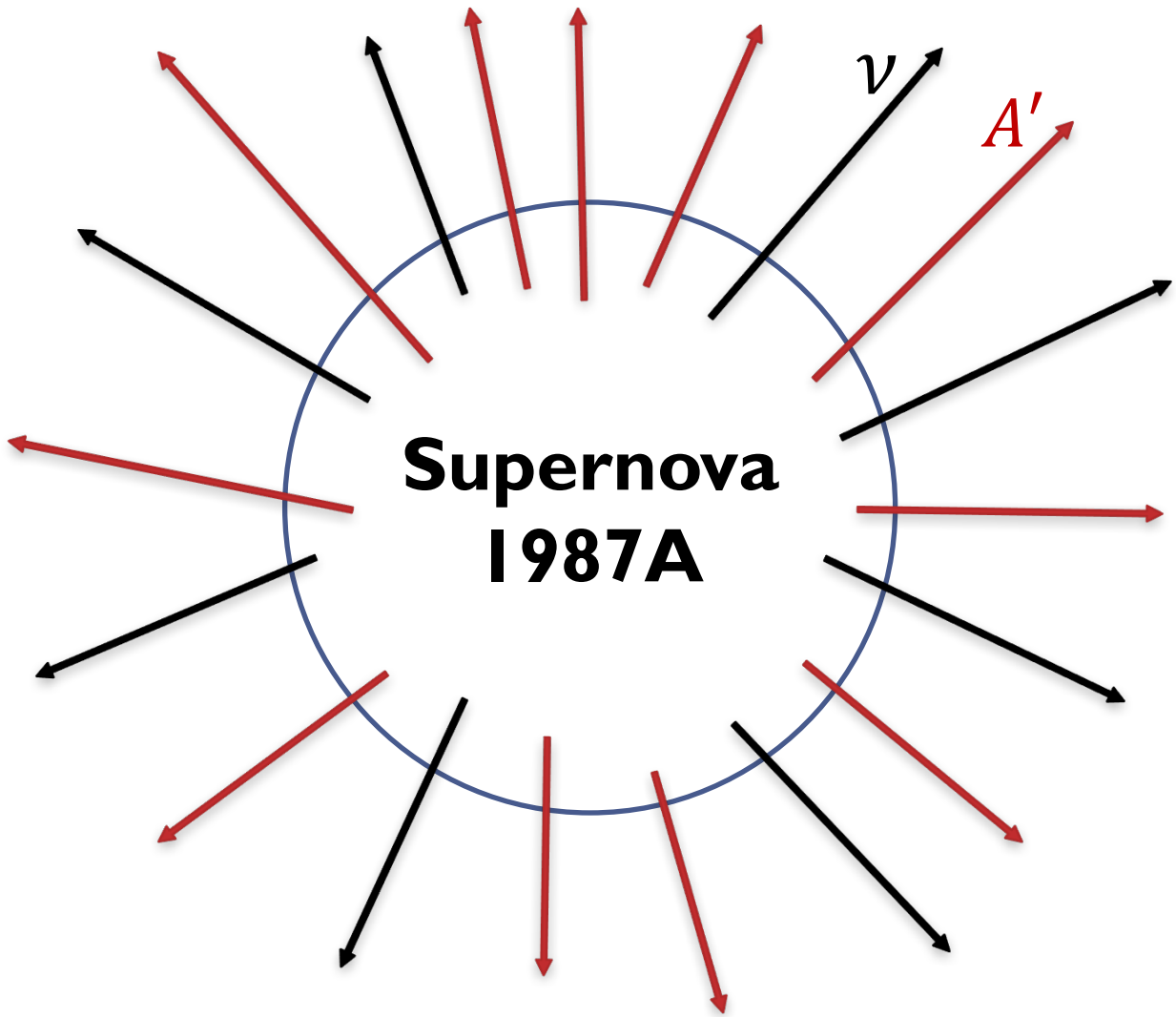
Hirata et al,1988



- Cooling time : ~13 seconds
- Consistent with the SM prediction



- If a new particle exists

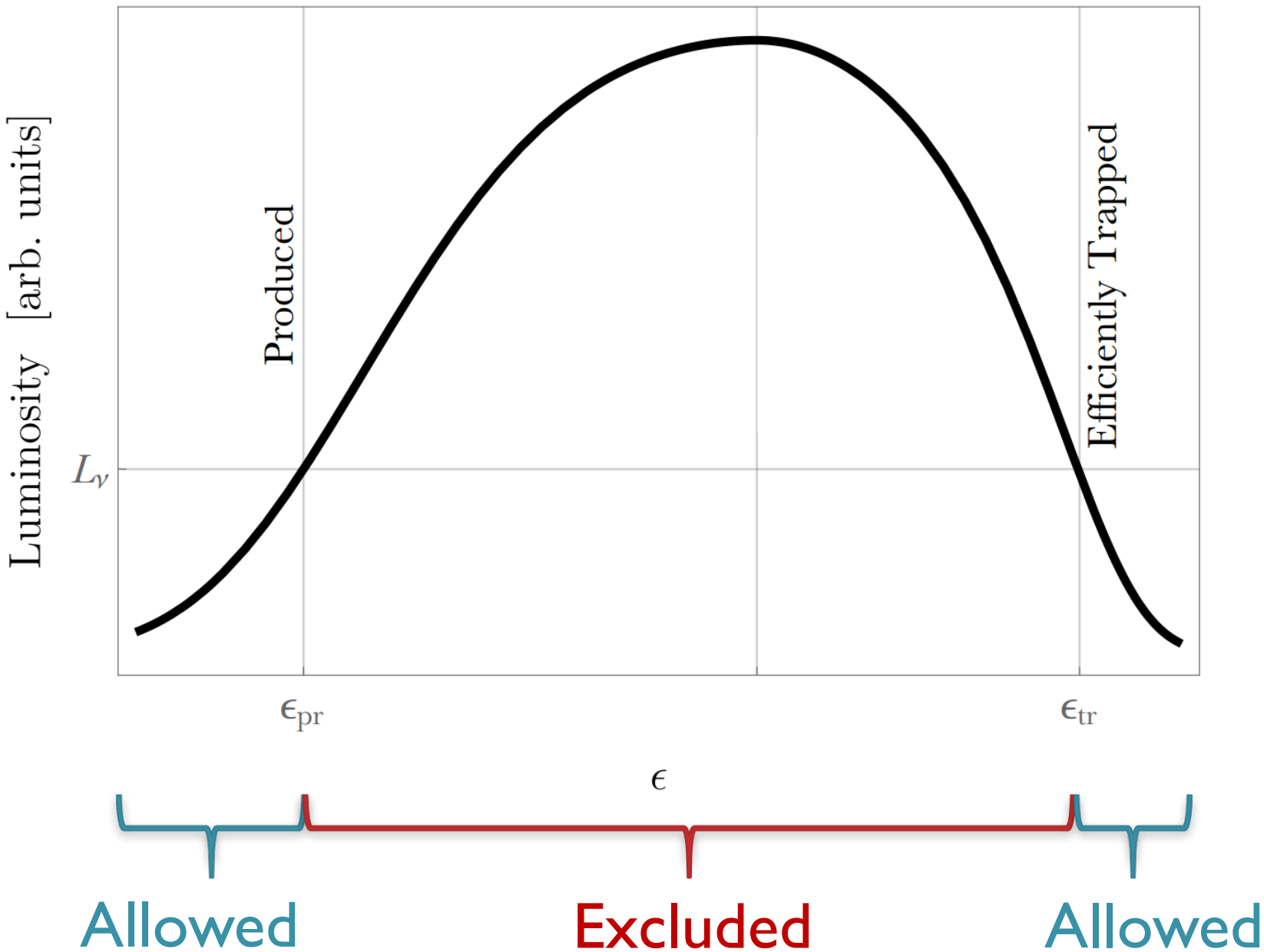


- Supernova cools faster

Raffelt Criterion

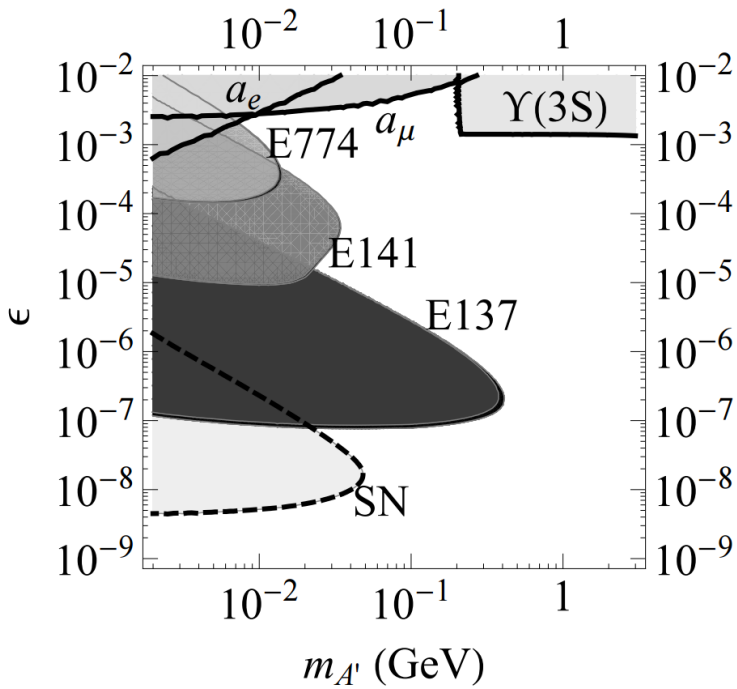
- Energy loss through new particles must be less than energy loss through neutrinos

- $L_{\mathrm{new}} < L_{\nu}$

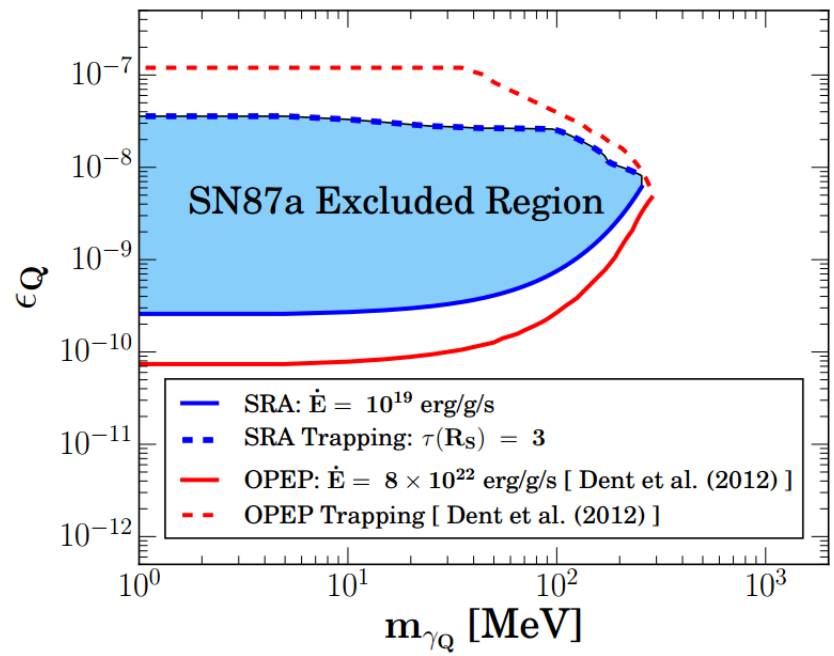

Luminosity [arb. units]
L_ν
Produced
Efficiently Trapped
ϵ_{pr}
ϵ_{tr}
ϵ
Allowed
Excluded
Allowed

Previous Works

- Bjorken et al, 2009



- Dent et al, 2012
- Rrapaj and Reddy, 2015



Didn't consider the Thermal Effects

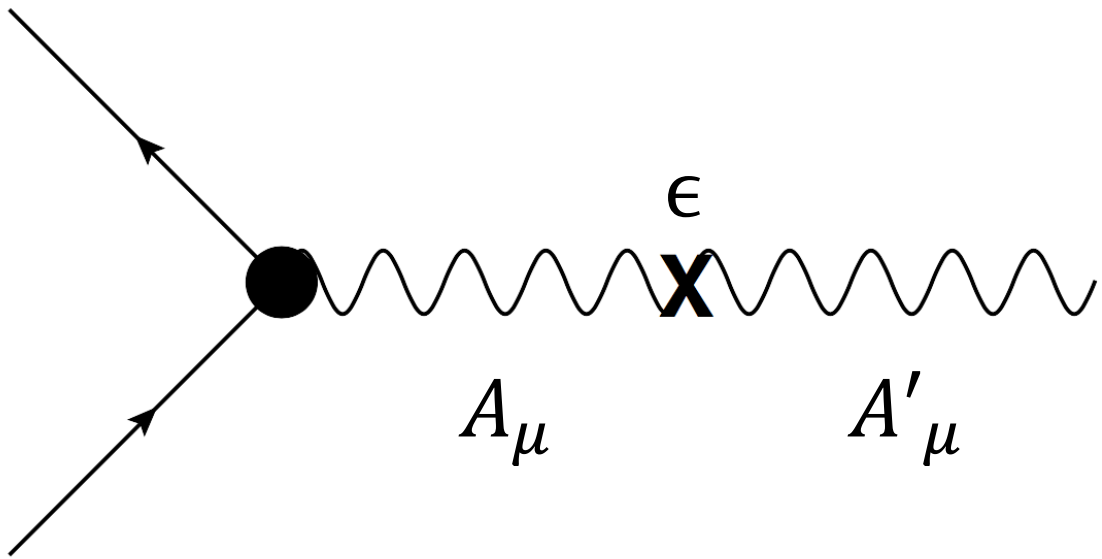
THERMAL EFFECTS ON DARK PHOTON

In Thermal Plasma

- Photon gets plasma mass
- Photon can be absorbed and produced
- Photon propagator changes
- Need Thermal Field Theory

- $\Pi^{\mu\nu} = \Pi^{\mu\nu}_{\text{vac}} + \Pi^{\mu\nu}_{\text{mat}}$
- $\Pi^{\mu\nu}_{\text{vac}}$ is the vacuum part
- $\Pi^{\mu\nu}_{\text{mat}}$ describes thermal plasma effects

- $\mathfrak{Re}\Pi_{\mathrm{mat}}$: Plasma mass of photon
- $\mathfrak{Im}\Pi_{\mathrm{mat}}$: Photon absorption and production
- In SN, Π_{mat} dominates



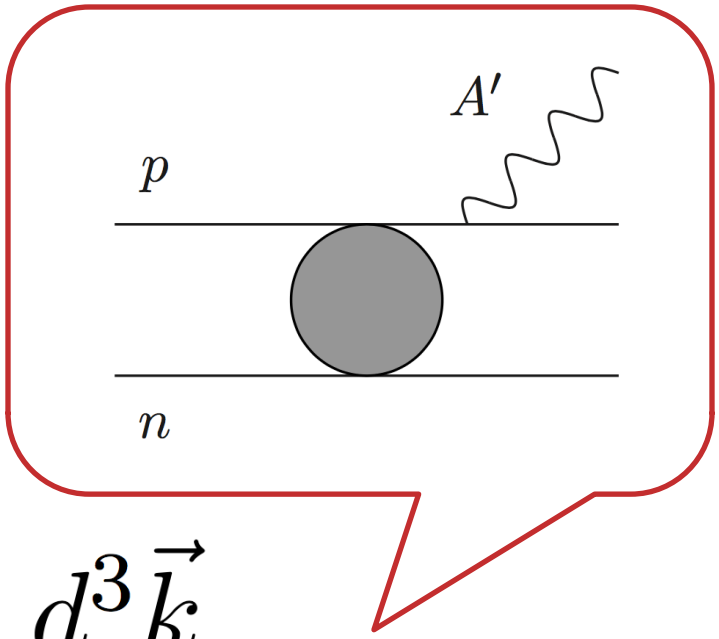
- In thermal plasma,

$$\epsilon_{\mathrm{m}}^2 \equiv \frac{m'^4}{(m'^2 - \Re\mathrm{e}\Pi)^2 + (\Im\mathrm{m}\Pi)^2}\epsilon^2$$

Redondo, 2008 & An et al, 2013

RESULTS

$$L_{A'} = \int dV \int \frac{d^3\vec{k}}{(2\pi)^3} \Gamma_{\text{prod}} e^{-\tau}$$



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Odds of escaping

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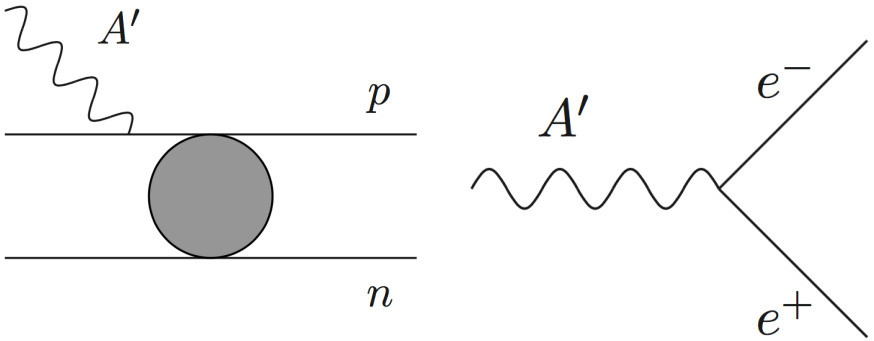
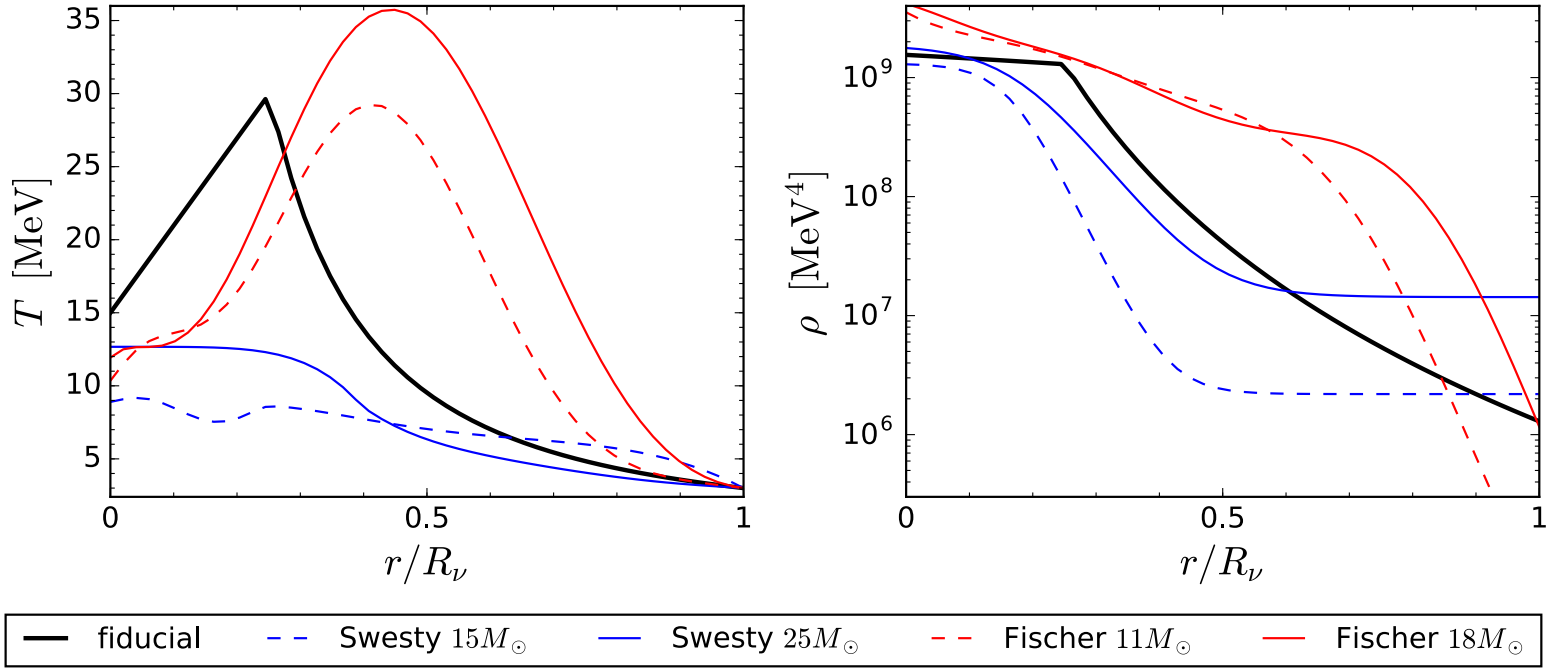
τ : Optical depth

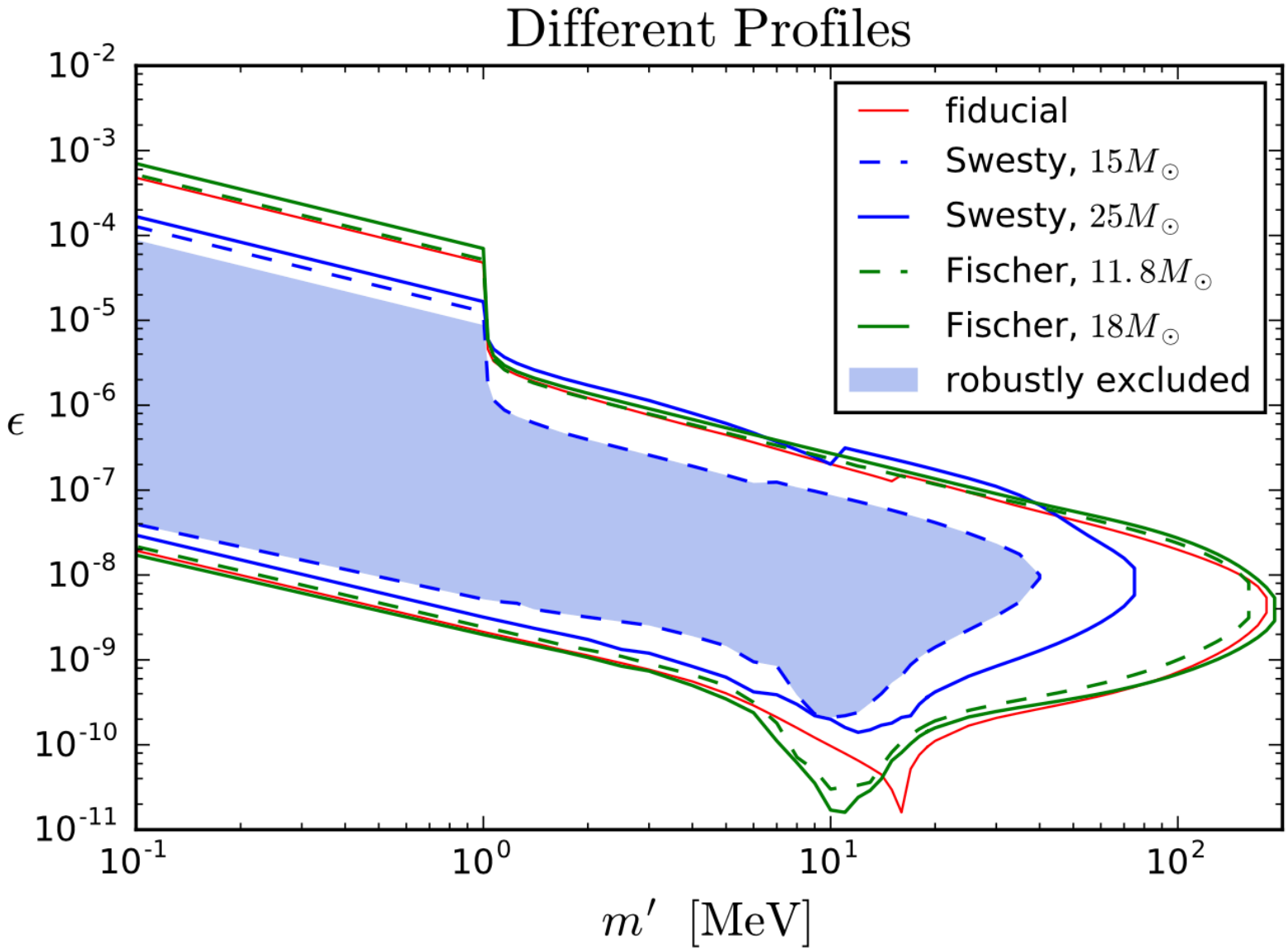


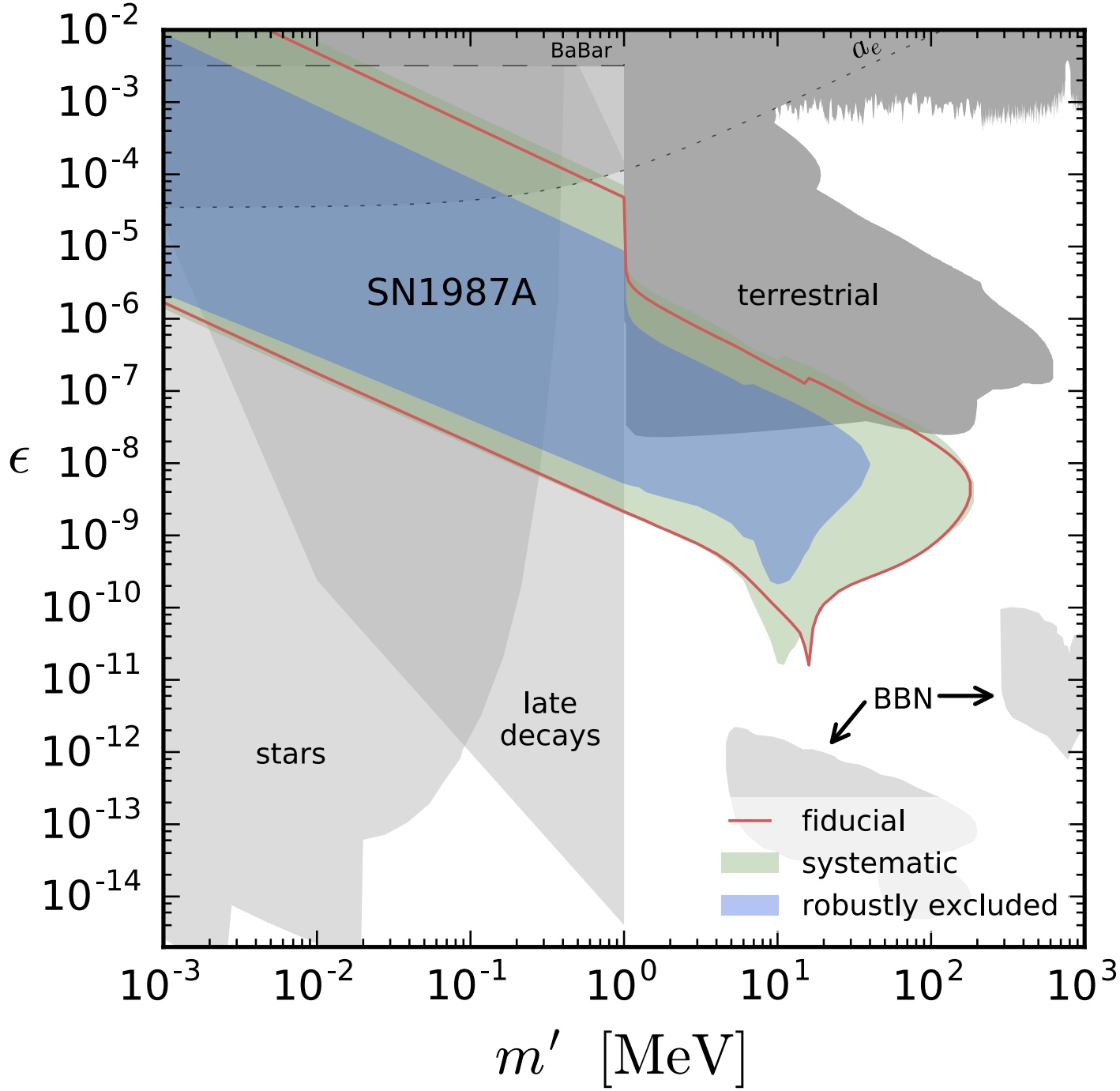
Rule out if $L_{A'} > L_\nu$

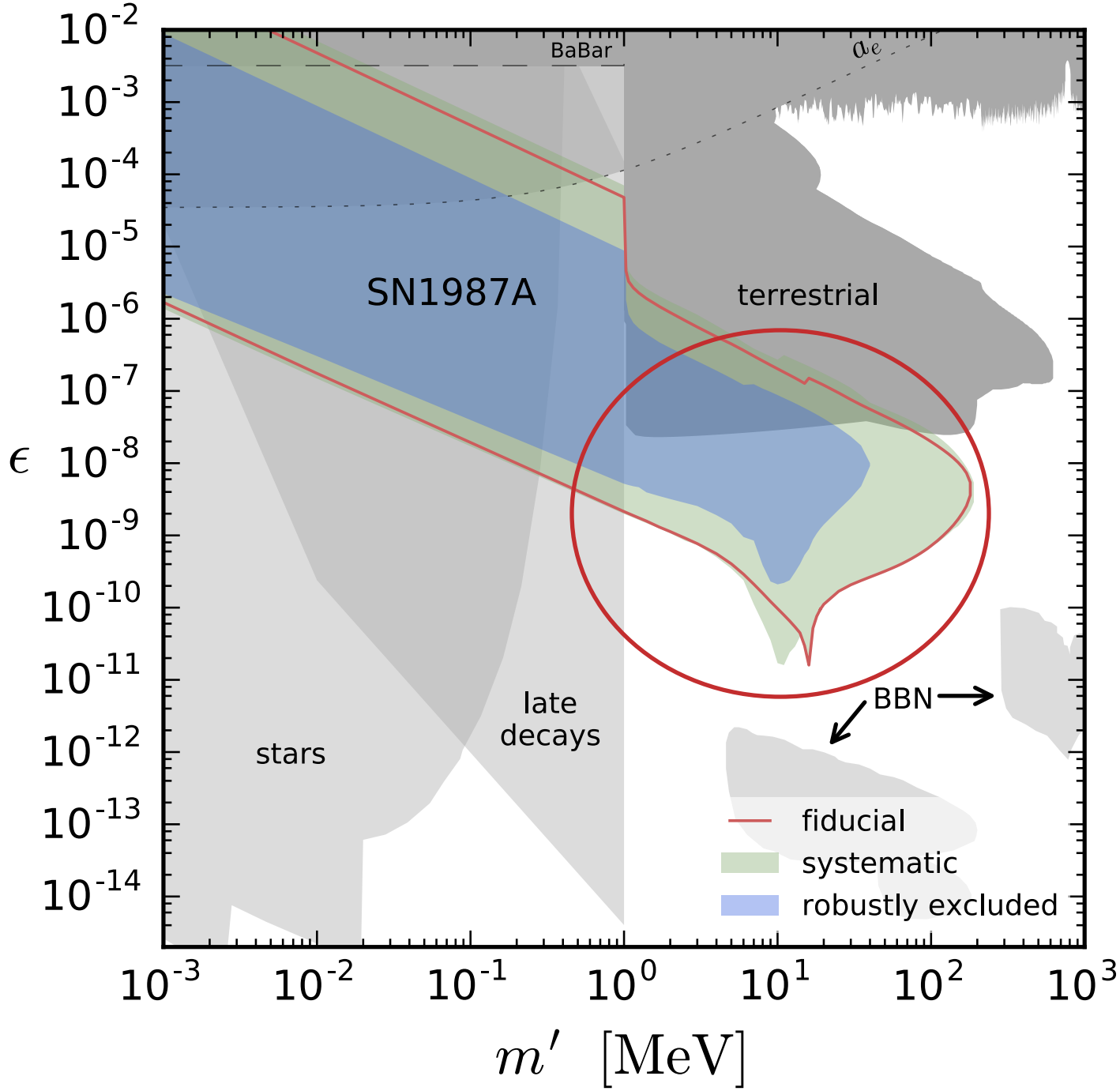
$$L_{A'} = \int dV \int \frac{d^3\vec{k}}{(2\pi)^3} \Gamma_{\rm prod} e^{-\tau}$$

Temperature and Density Profiles




Different Profiles
fiducial
Swesty, $15M_\odot$
Swesty, $25M_\odot$
Fischer, $11.8M_\odot$
Fischer, $18M_\odot$
robustly excluded
ϵ
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-1}
10^{0}
10^{1}
10^{2}
m' [MeV]


BaBar
a_e
SN1987A
terrestrial
stars
late
decays
BBN
fiducial
systematic
robustly excluded
ϵ
m' [MeV]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}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10^{-11}
10^{-12}
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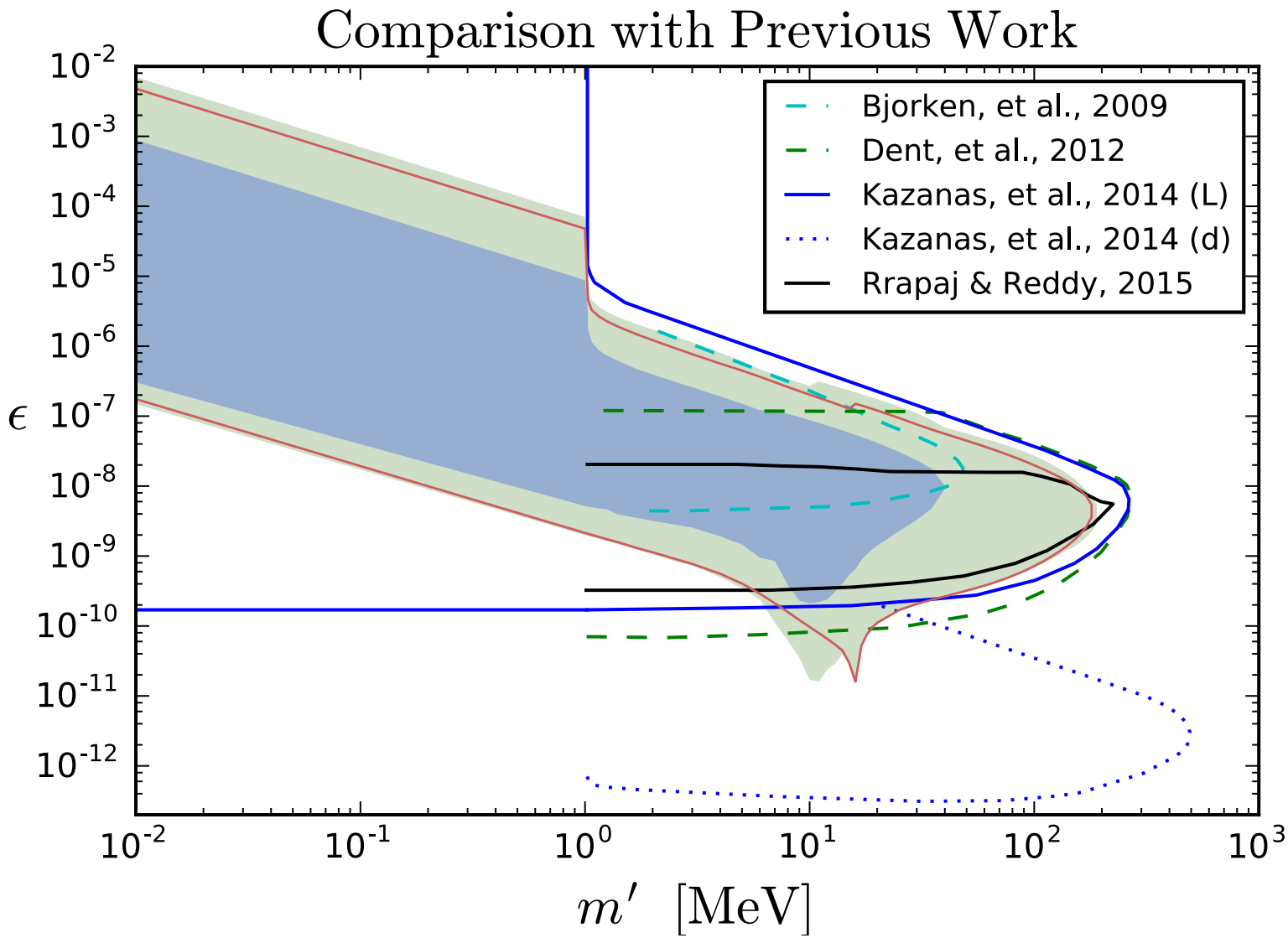
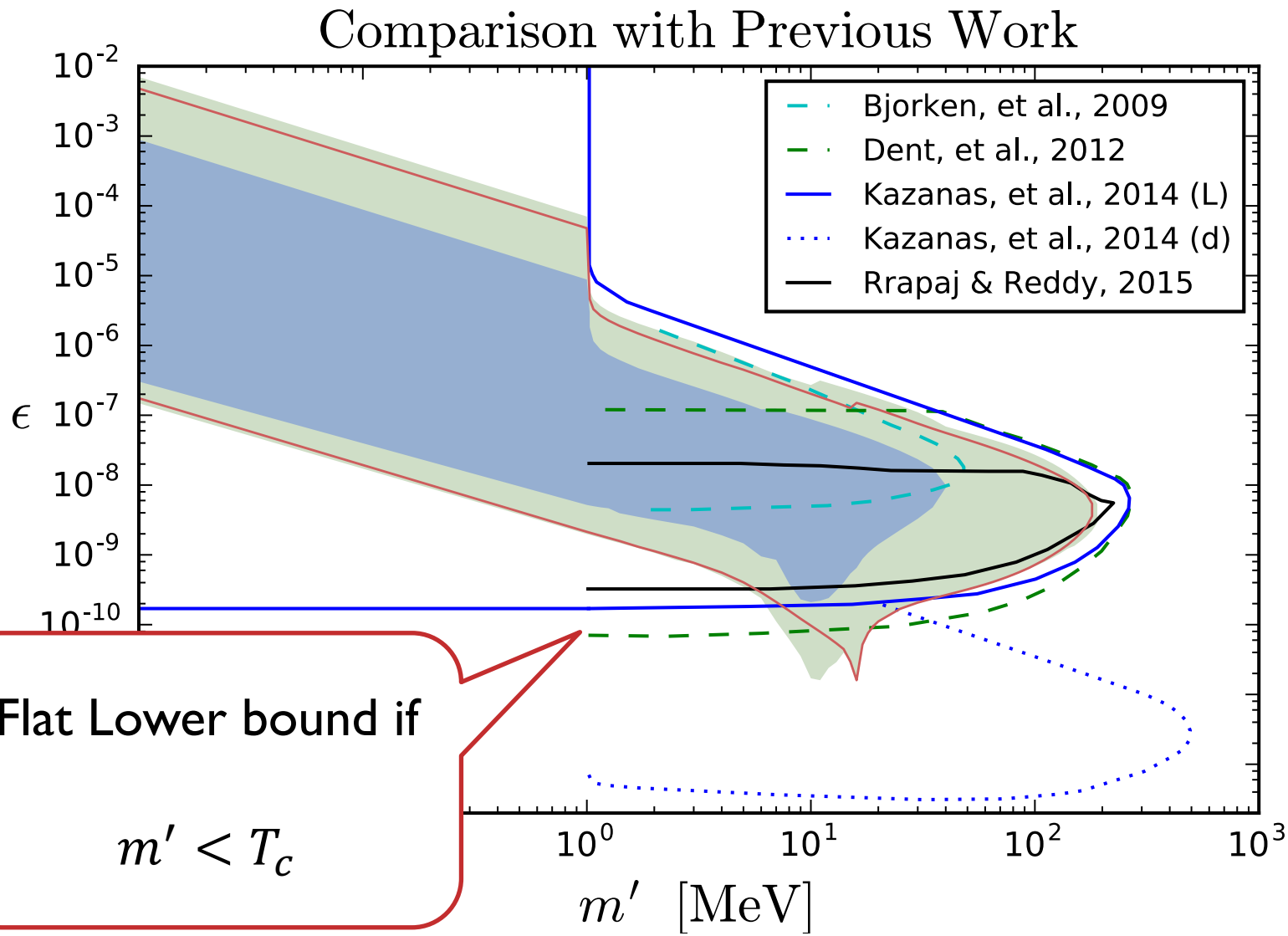
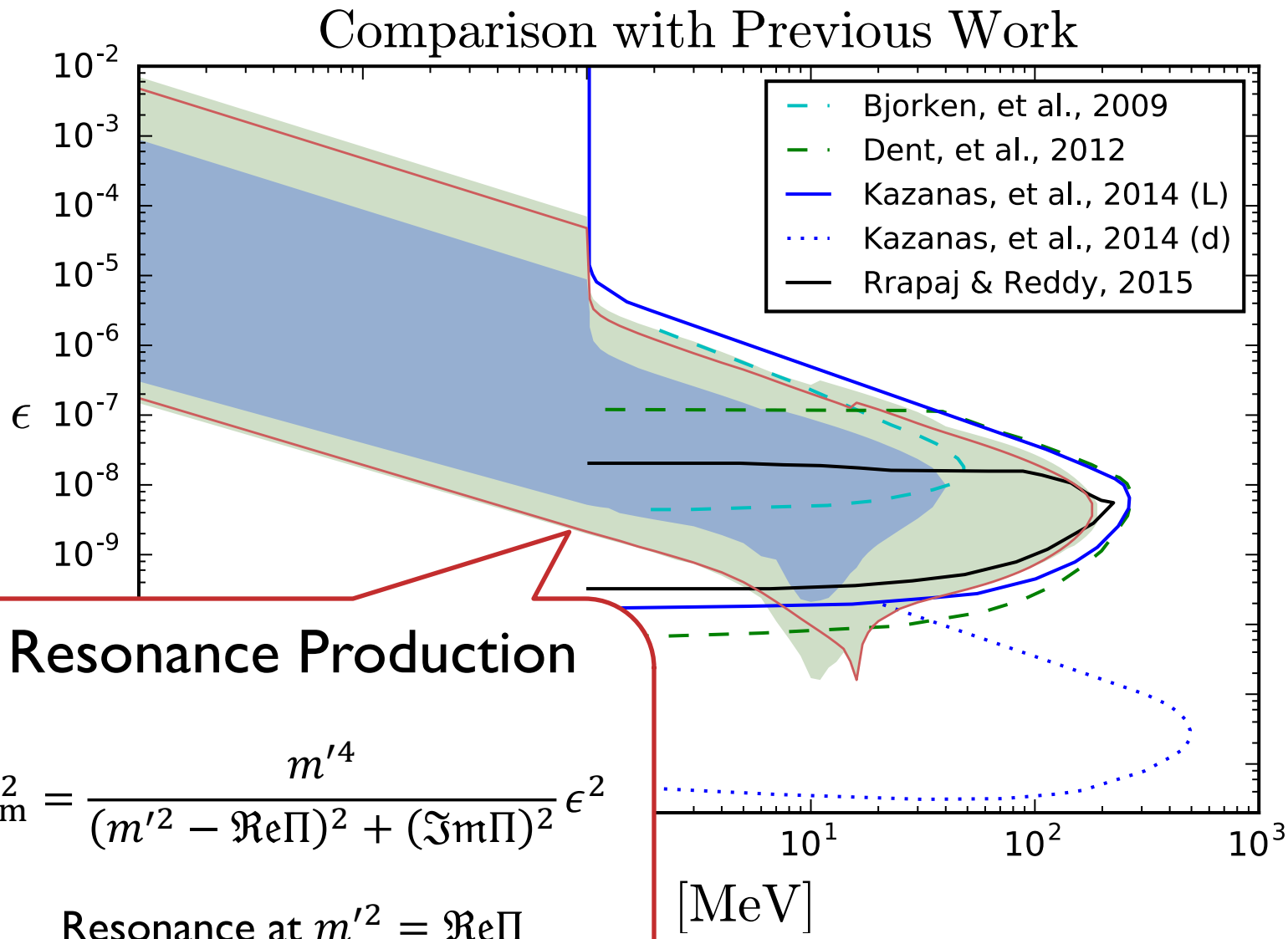
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}


Comparison with Previous Work
Bjorken, et al., 2009
Dent, et al., 2012
Kazanas, et al., 2014 (L)
Kazanas, et al., 2014 (d)
Rrapaj & Reddy, 2015
ϵ
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
m' [MeV]



Flat Lower bound if

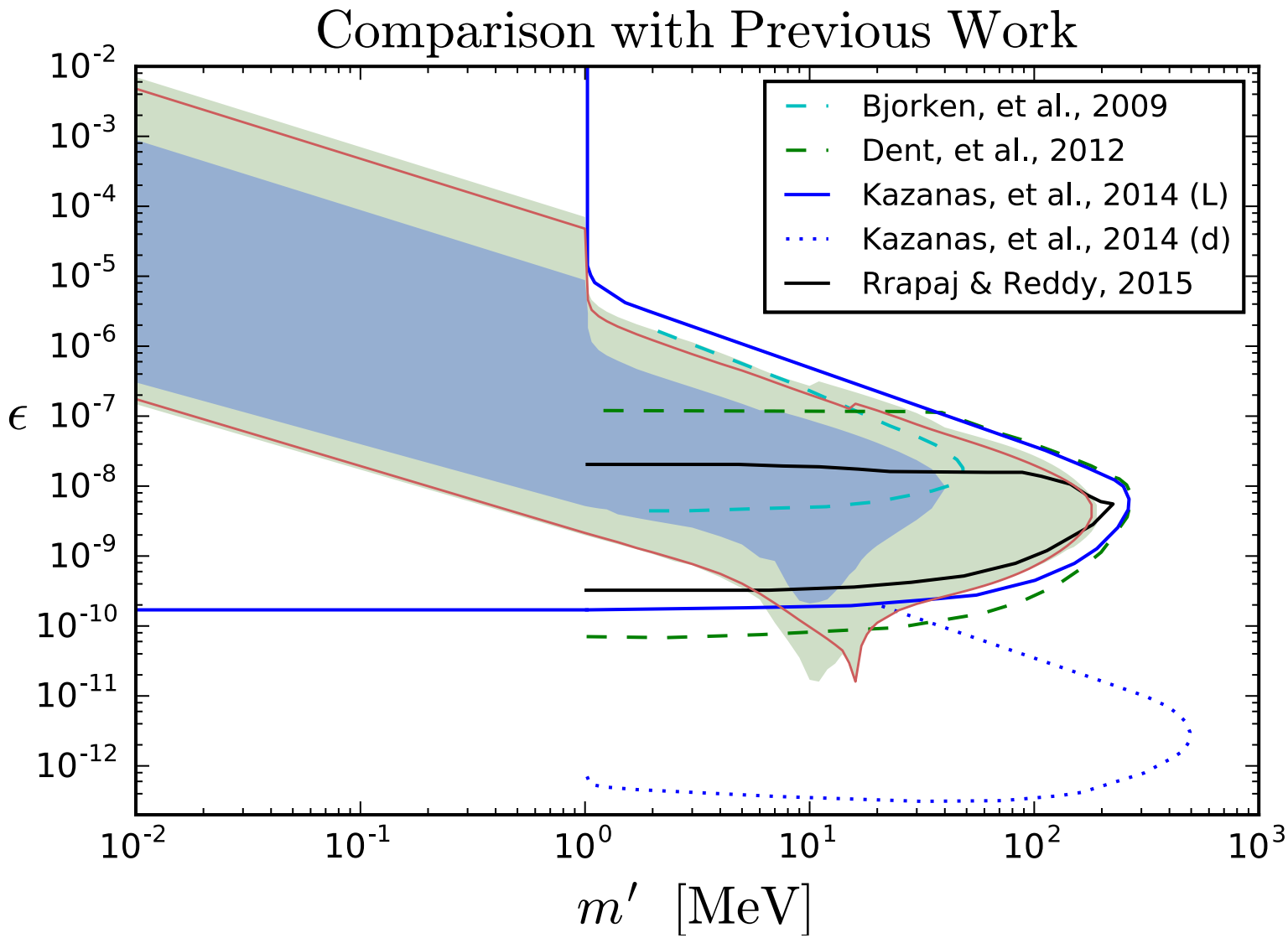
$m' < T_c$



Resonance Production

$$\epsilon_{\mathrm{m}}^2 = \frac{m'^4}{(m'^2 - \Re\mathrm{e}\Pi)^2 + (\Im\mathrm{m}\Pi)^2}\epsilon^2$$

Resonance at $m'^2 = \Re\mathrm{e}\Pi$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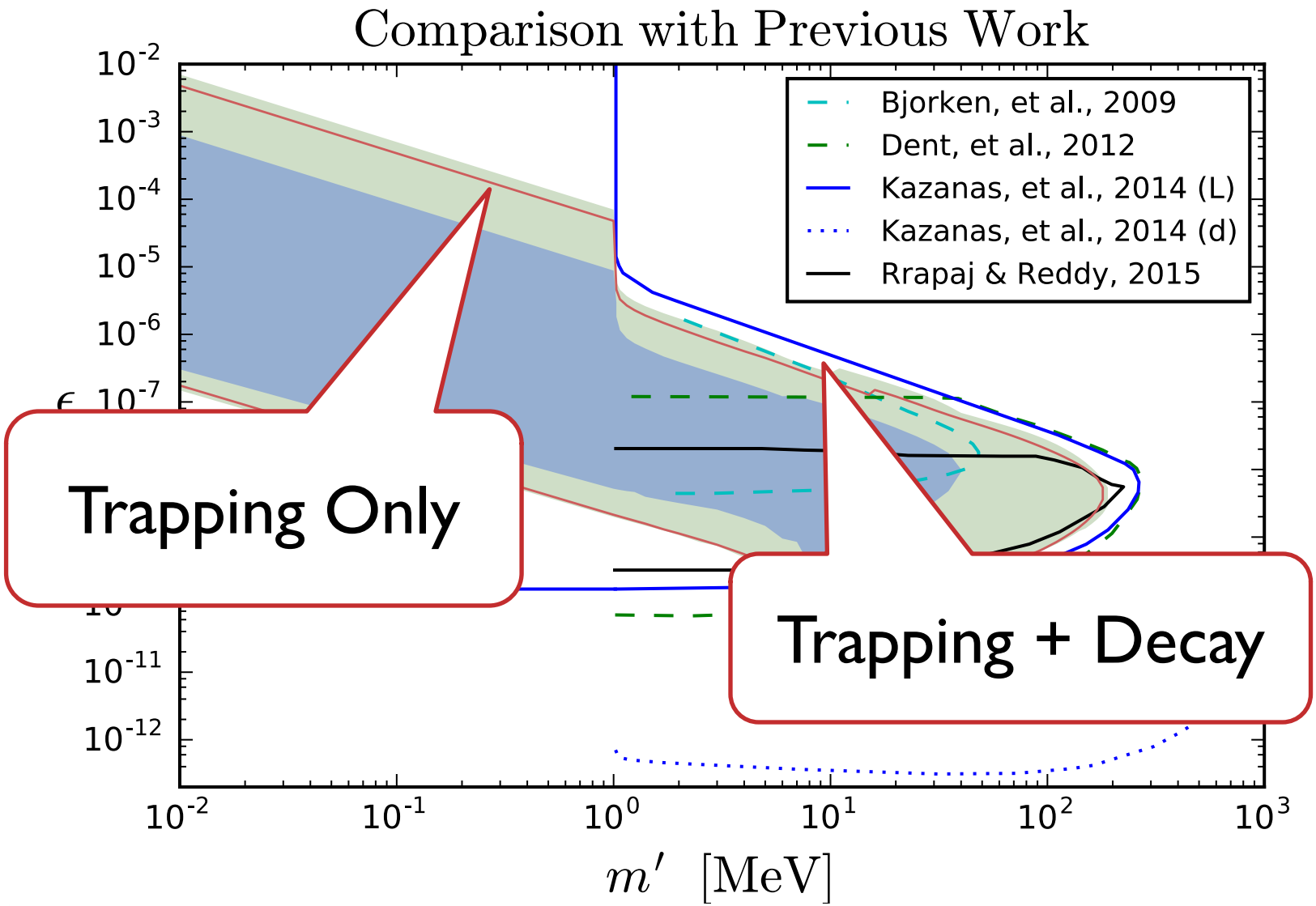
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
m' [MeV]


Comparison with Previous Work
Bjorken, et al., 2009
Dent, et al., 2012
Kazanas, et al., 2014 (L)
Kazanas, et al., 2014 (d)
Rrapaj & Reddy, 2015
Trapping Only
Trapping + Decay
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-11}
10^{-12}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
m' [MeV]

CONCLUSION

Conclusion

- Supernova1987A can give constraints on dark photons
- We calculated the constraints with the thermal effects
- The new results have a different shape compared to the previous works

Work in Progress

- Particles charged under $U(1)'$
- Dark matter candidate
- Can calculate constraints similarly

THANK YOU