Supernova 1987A Constraints on Low-Mass Hidden Sectors

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SUPERNOVA 1987A

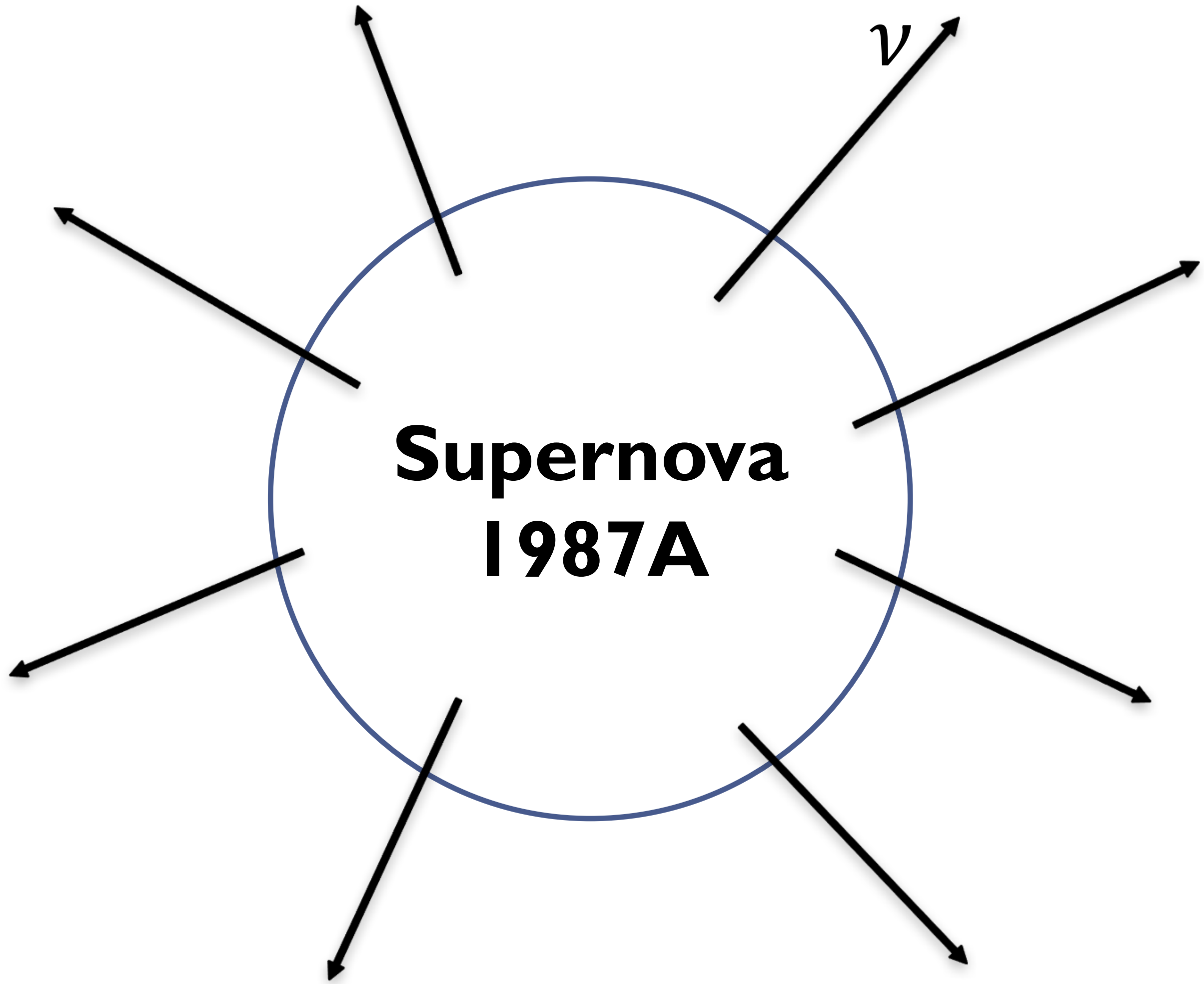
Supernova 1987A

- Closest supernova since Kepler
- The only supernova which neutrinos from supernova explosion were detected
- The neutrino observations were consistent with the theoretical prediction

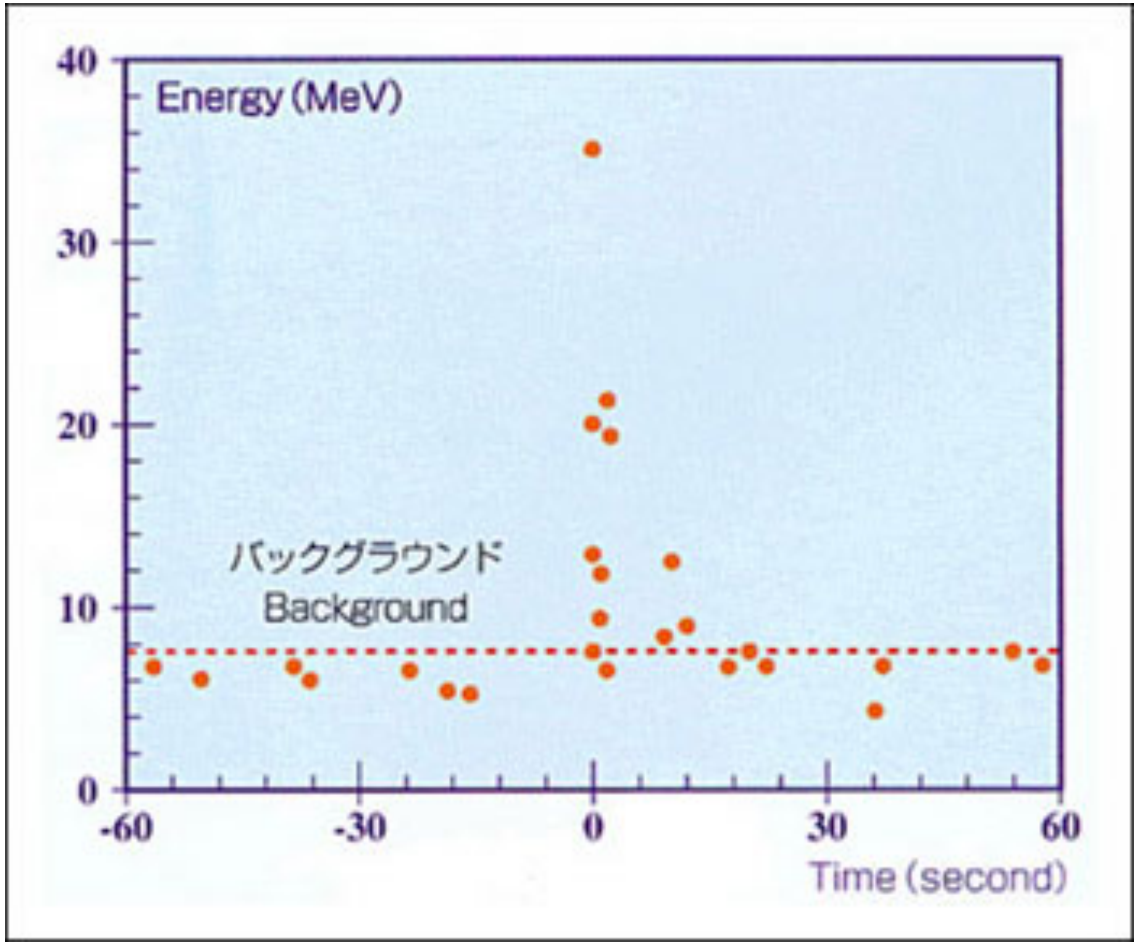
Supernova Constraints

- **Any type of light novel particles** coupled to the SM can be constrained
- $m \lesssim T_c \approx 30\ MeV$
- Used for axions, sterile neutrinos, and dark photons

Supernova 1987A

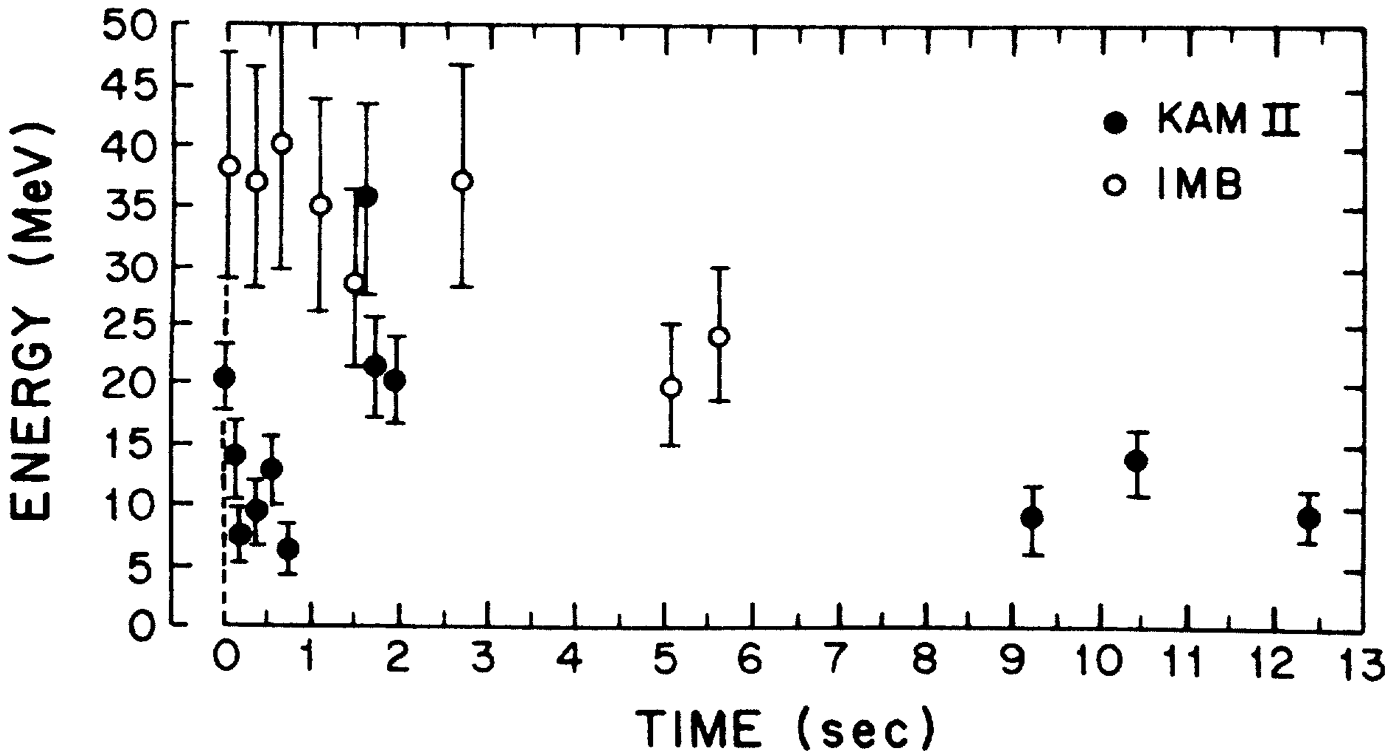


- 99% of energy is carried by neutrinos

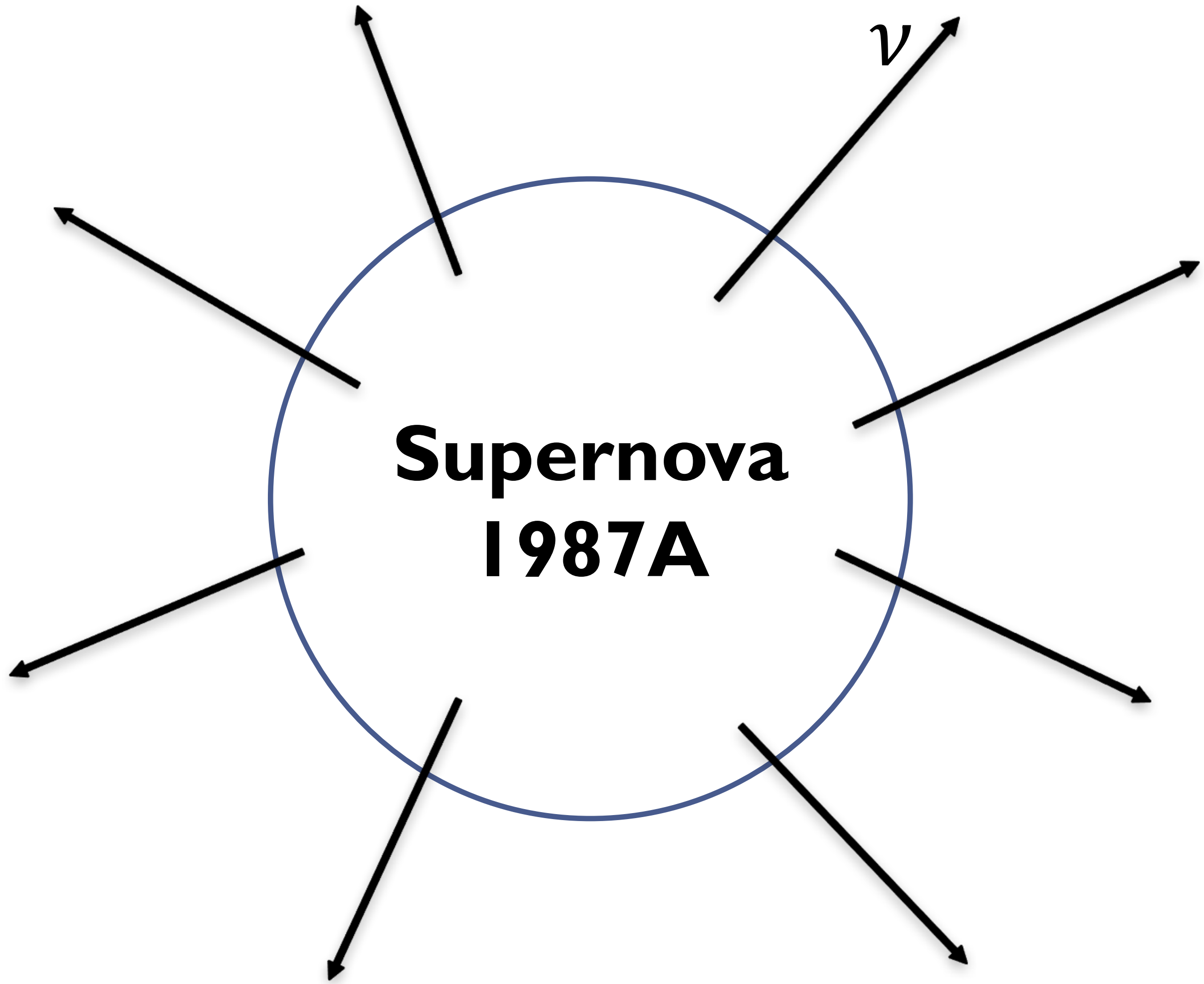


- Kamiokande II, IMB, and Baksan detected the neutrinos at the same time

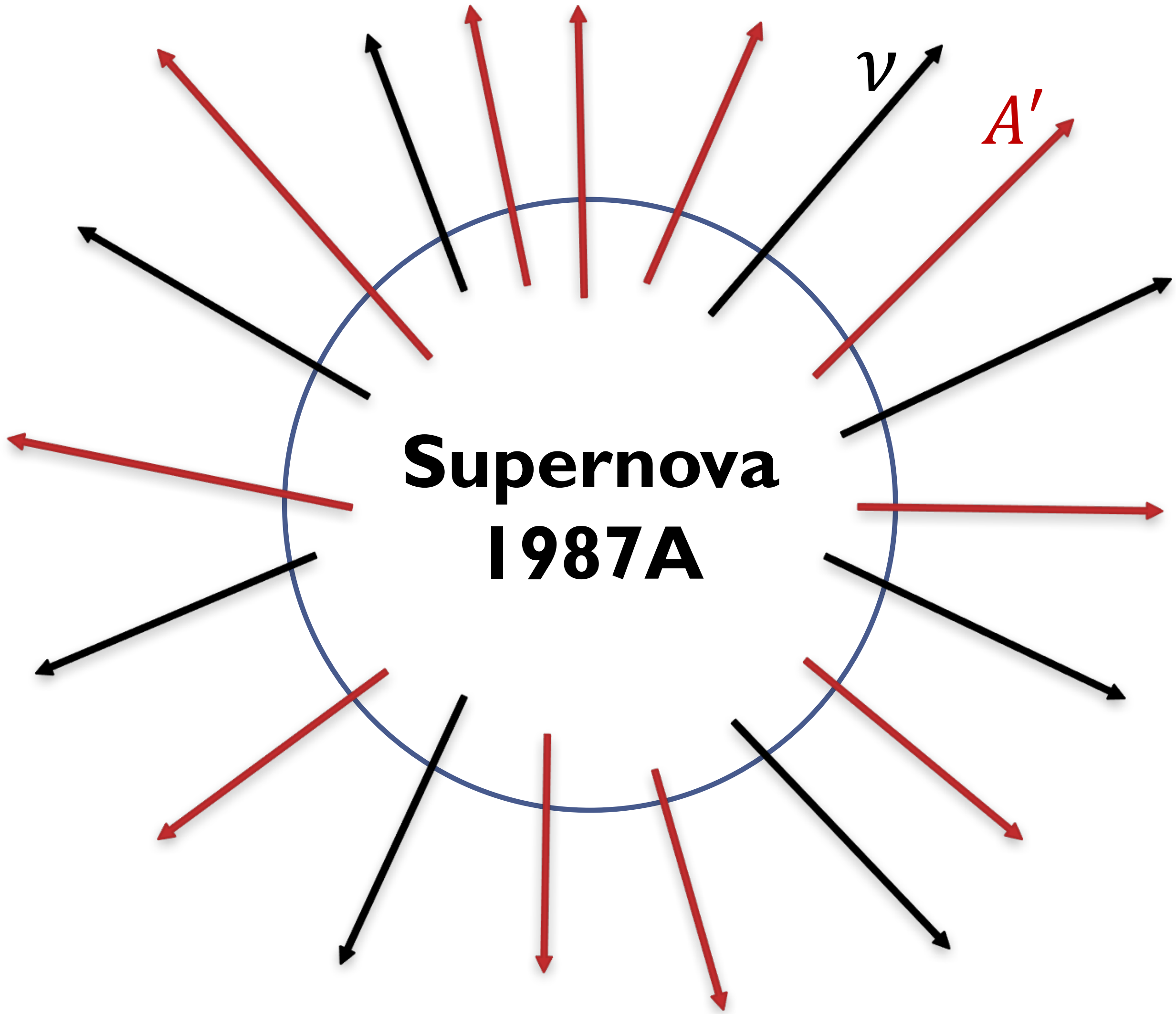
Hirata et al, 1988



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



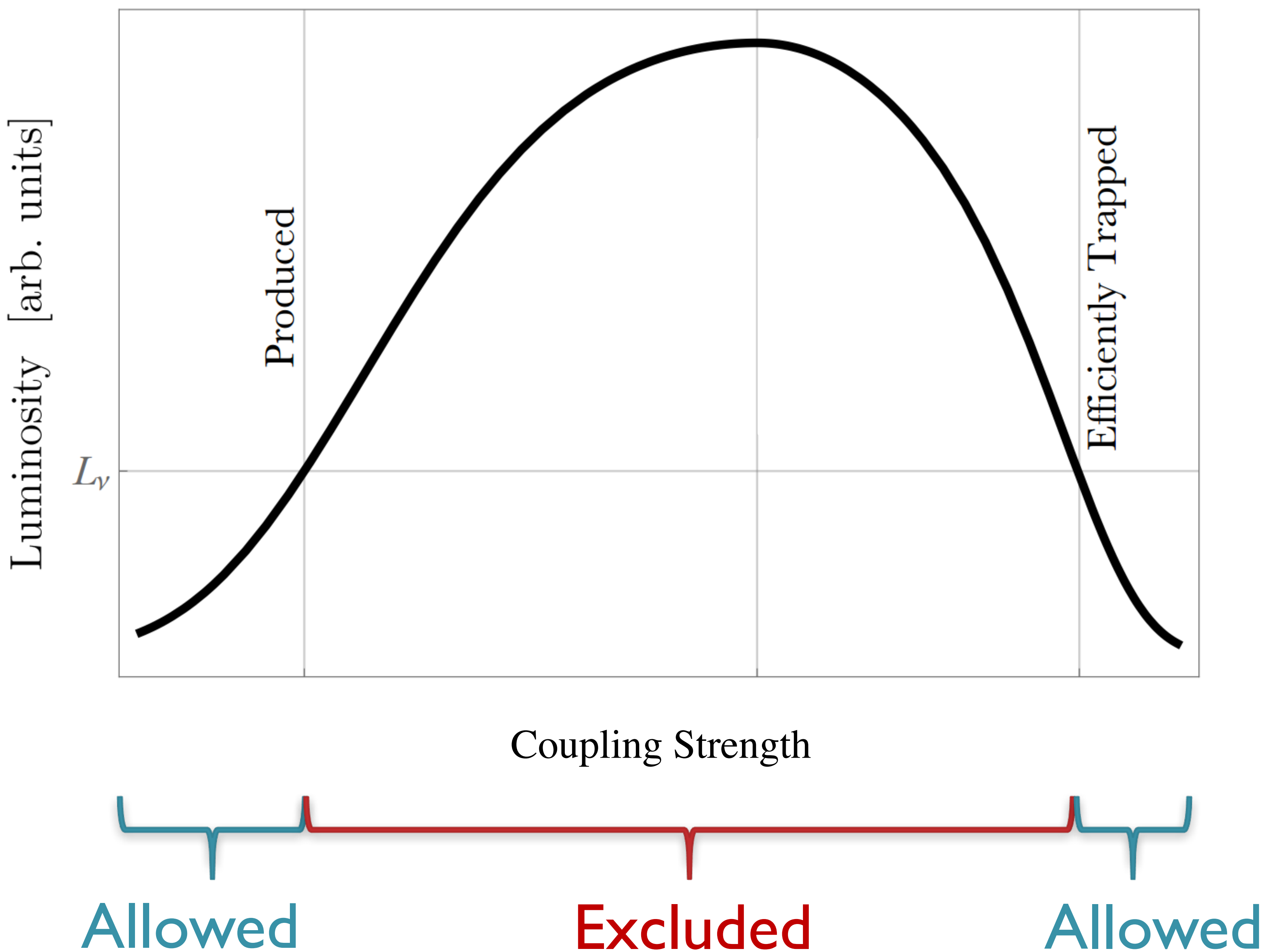
- If a new particle exists



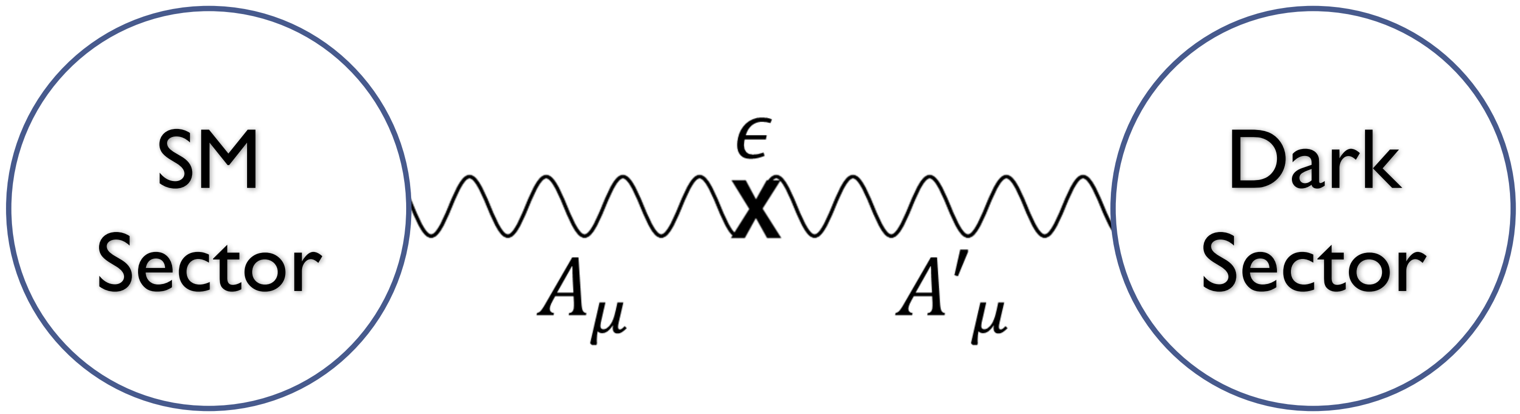
- Supernova cools faster

Raffelt Criterion

- Energy loss through new particles must be less than energy loss through neutrinos
- $L_{\text{new}} < L_\nu$


Luminosity [arb. units]
L_ν
Produced
Efficiently Trapped
Coupling Strength
Allowed
Excluded
Allowed

DARK PHOTON MODEL

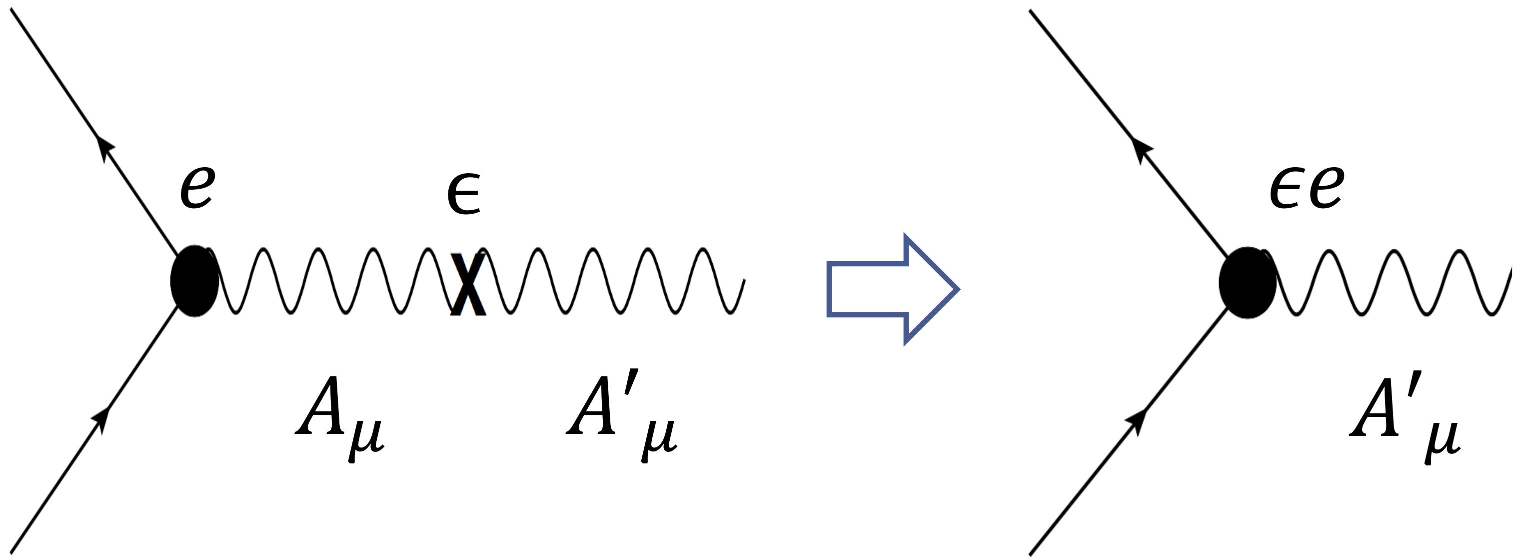


- $SU(3)_c \times SU(2)_L \times U(1)_Y \times \boldsymbol{U(1)'}$
- In low energies, $\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$
- Called the vector portal

Dark Photon in Supernova

- Photon gets plasma mass and has longitudinal polarization
- Photon propagator changes
- Since Dark photon is mixed with photon, these effects must be considered

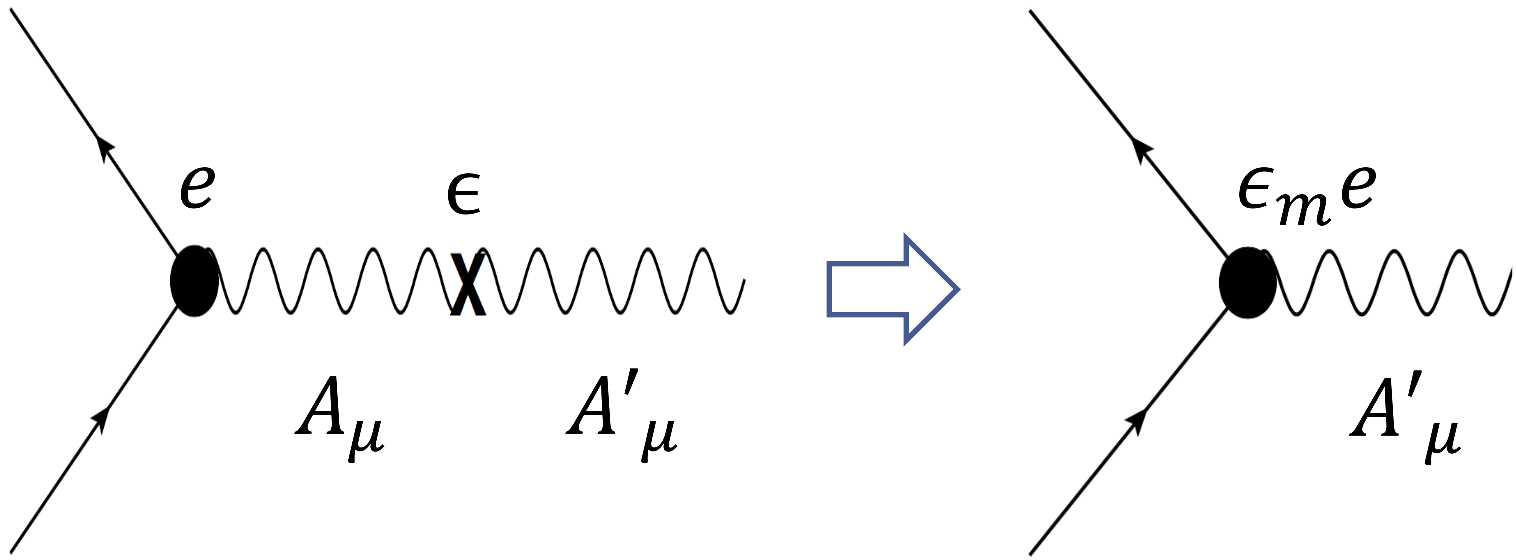
- $\Pi = \Pi_{vac} + \Pi_{mat}$
- Π_{vac} is the vacuum part
- Π_{mat} describes thermal plasma effects
- $\Pi_{mat} \gg \Pi_{vac}$



- In vacuum,

$$\mathcal{M} \propto e \times \frac{1}{q^2} \times \epsilon q^2 = \epsilon e$$

$$\mathcal{L} \supset \epsilon e J^{\mu}_{EM} A'_\mu$$



- In supernova,

$$\mathcal{M} \propto e \times \frac{1}{q^2 - \Pi} \times \epsilon q^2 = e\frac{q^2}{q^2 - \Pi}\epsilon$$

$$\mathcal{L} \supset \epsilon_m e J^{\mu}_{EM} A'_{\mu}, \qquad \epsilon_m \equiv \left|\frac{q^2}{q^2 - \Pi}\right| \epsilon$$

Mixing angle in Supernova

- $\epsilon_m \equiv \left|\frac{q^2}{q^2-\Pi}\right| \epsilon$
- $\Pi \approx \omega_p^2 \quad \rightarrow \quad \epsilon_m \approx \left|\frac{q^2}{q^2-\omega_p^2}\right| \epsilon$
- $\omega_p \sim 15 MeV$ is the plasma frequency
  - $\epsilon_m \ll \epsilon, \quad q^2 \ll \omega_p^2$
  - $\epsilon_m \gg \epsilon, \quad q^2 \approx \omega_p^2$
  - $\epsilon_m \approx \epsilon, \quad q^2 \gg \omega_p^2$

Novelties in this Work

- Included the thermal effects to the supernova environment for the first time
- Varying temperature and density profiles
- Considered various dark photon models

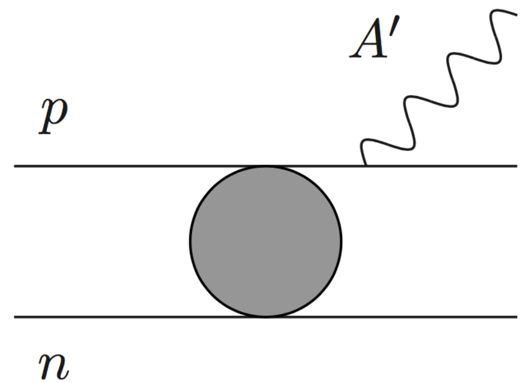
Dark Photon Models

- Pure dark photon
- Dark sector fermion
- Millicharged dark matter
  (Work in progress)

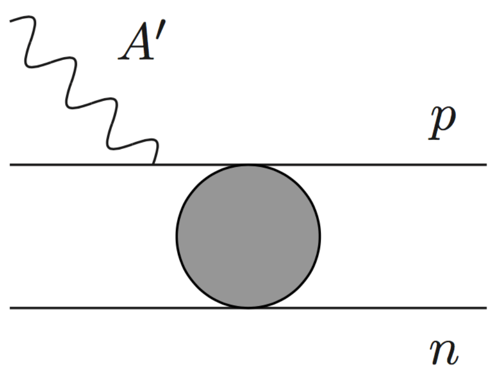
PURE DARK PHOTON

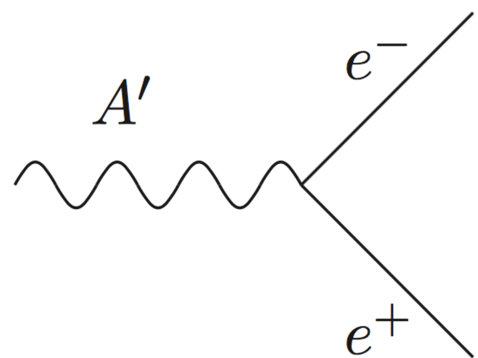
- All other hidden sector particle masses are much heavier than T_c
- Consider A' only
- Dark photons are on-shell, $q^2 = m'^2$

- Dominant production process



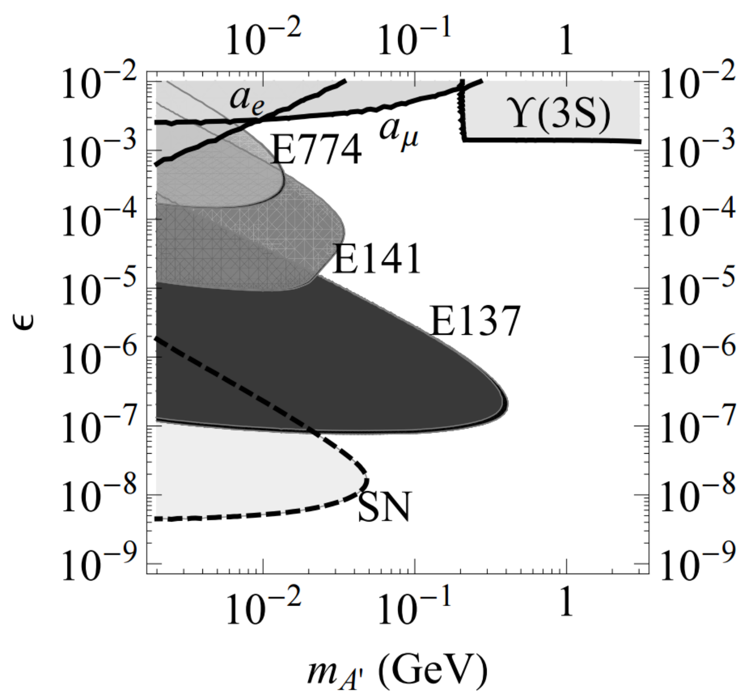
- Trapping Process



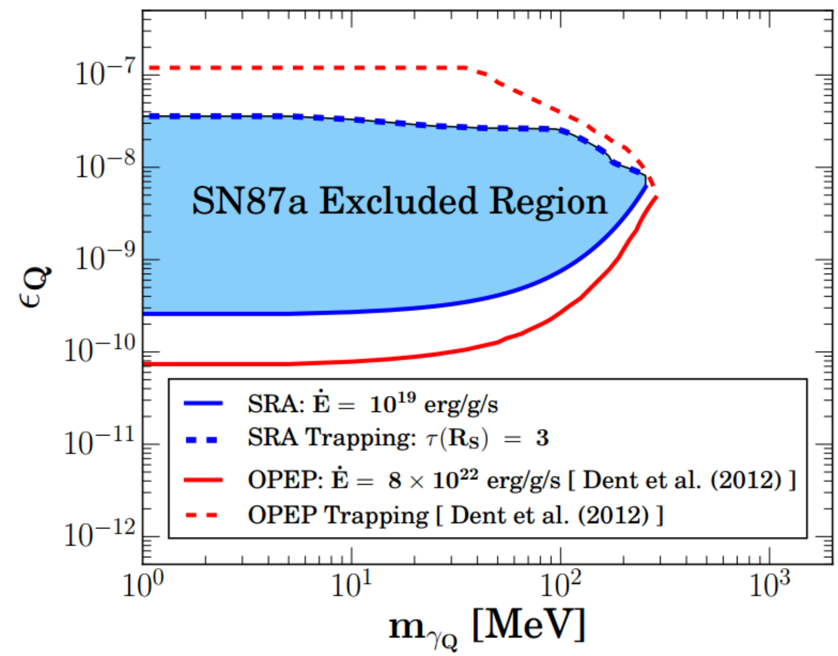


Previous Works

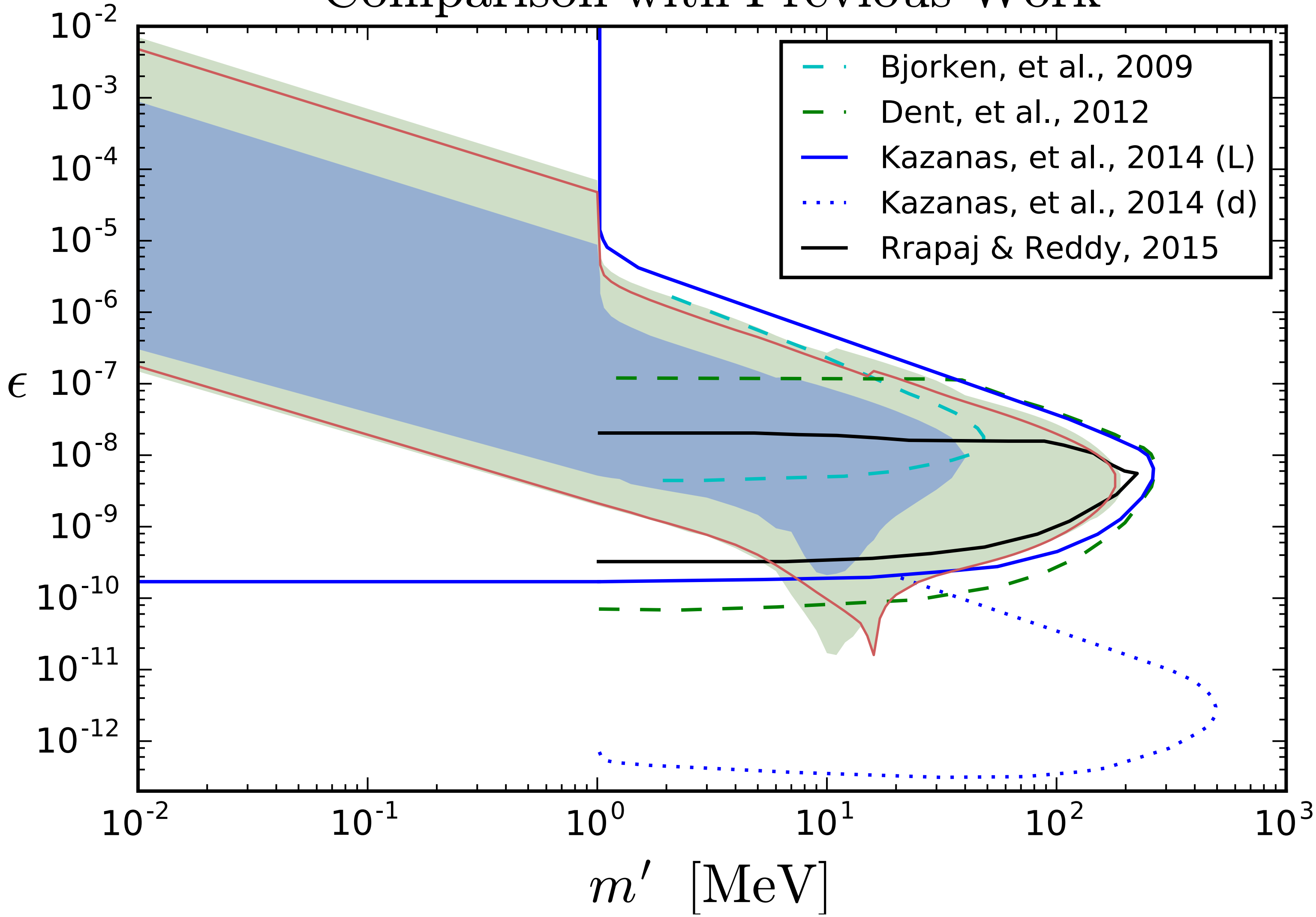
- Bjorken et al, 2009

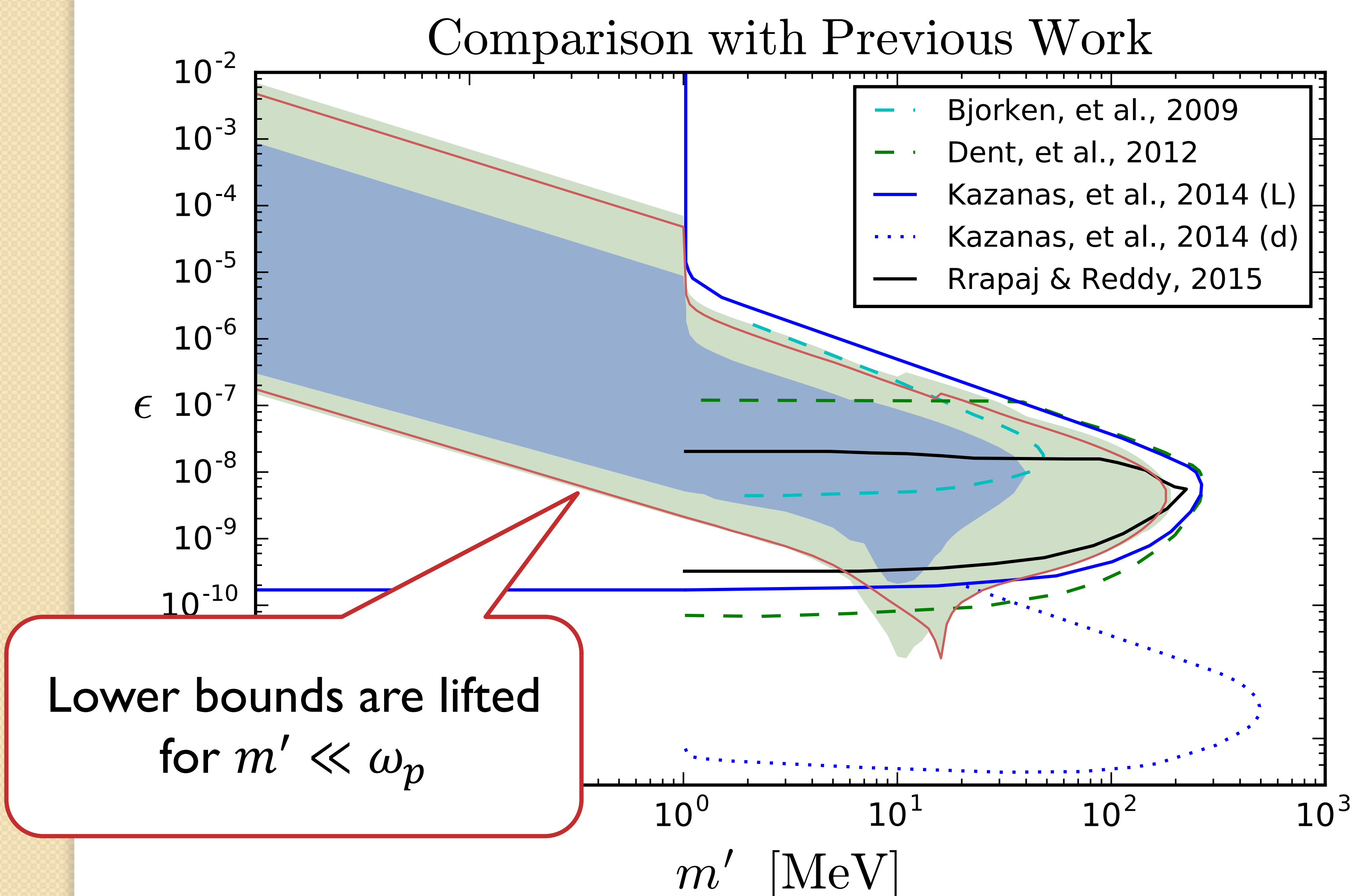


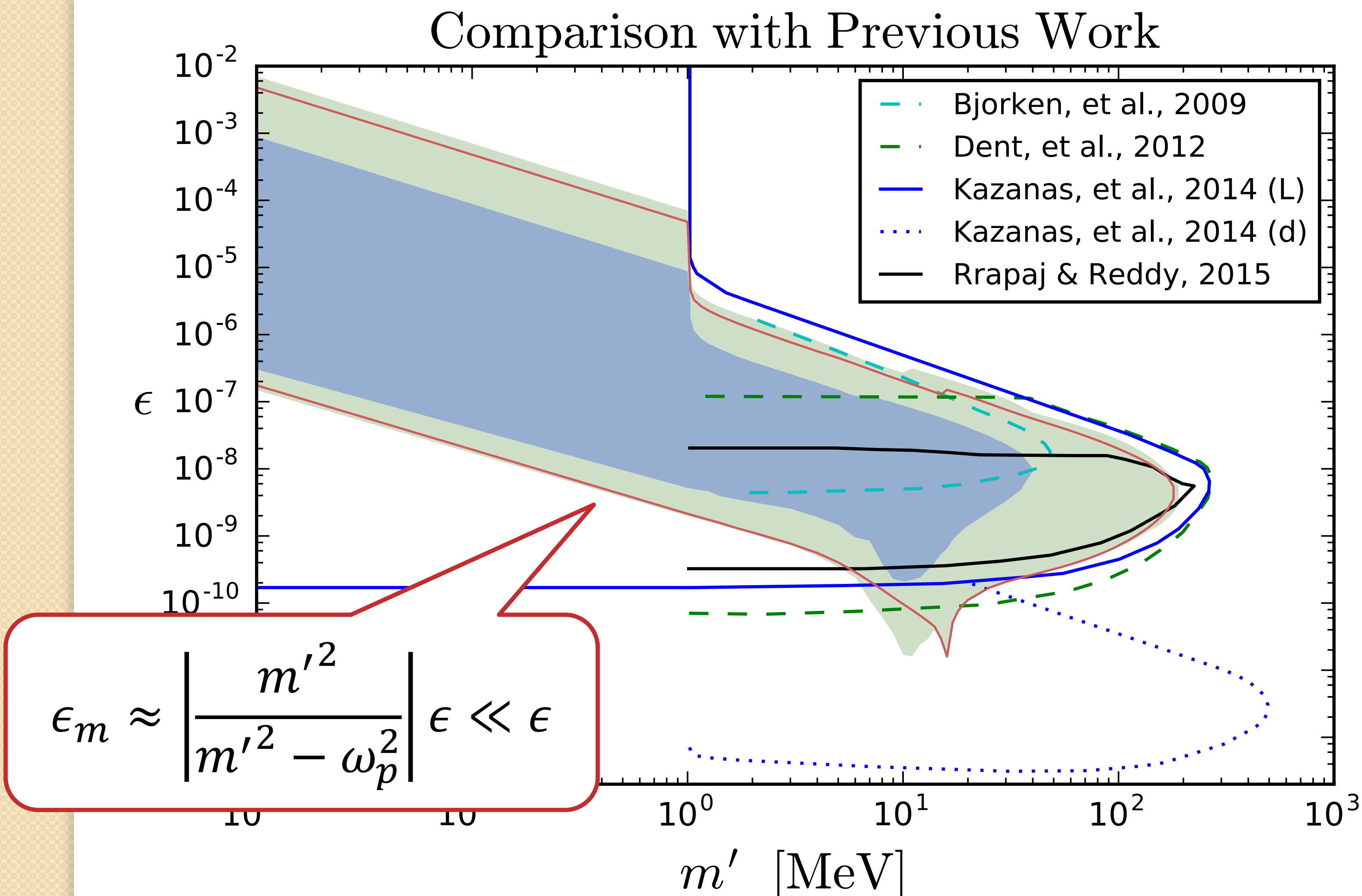
- Dent et al, 2012
- Rrapaj and Reddy, 2015



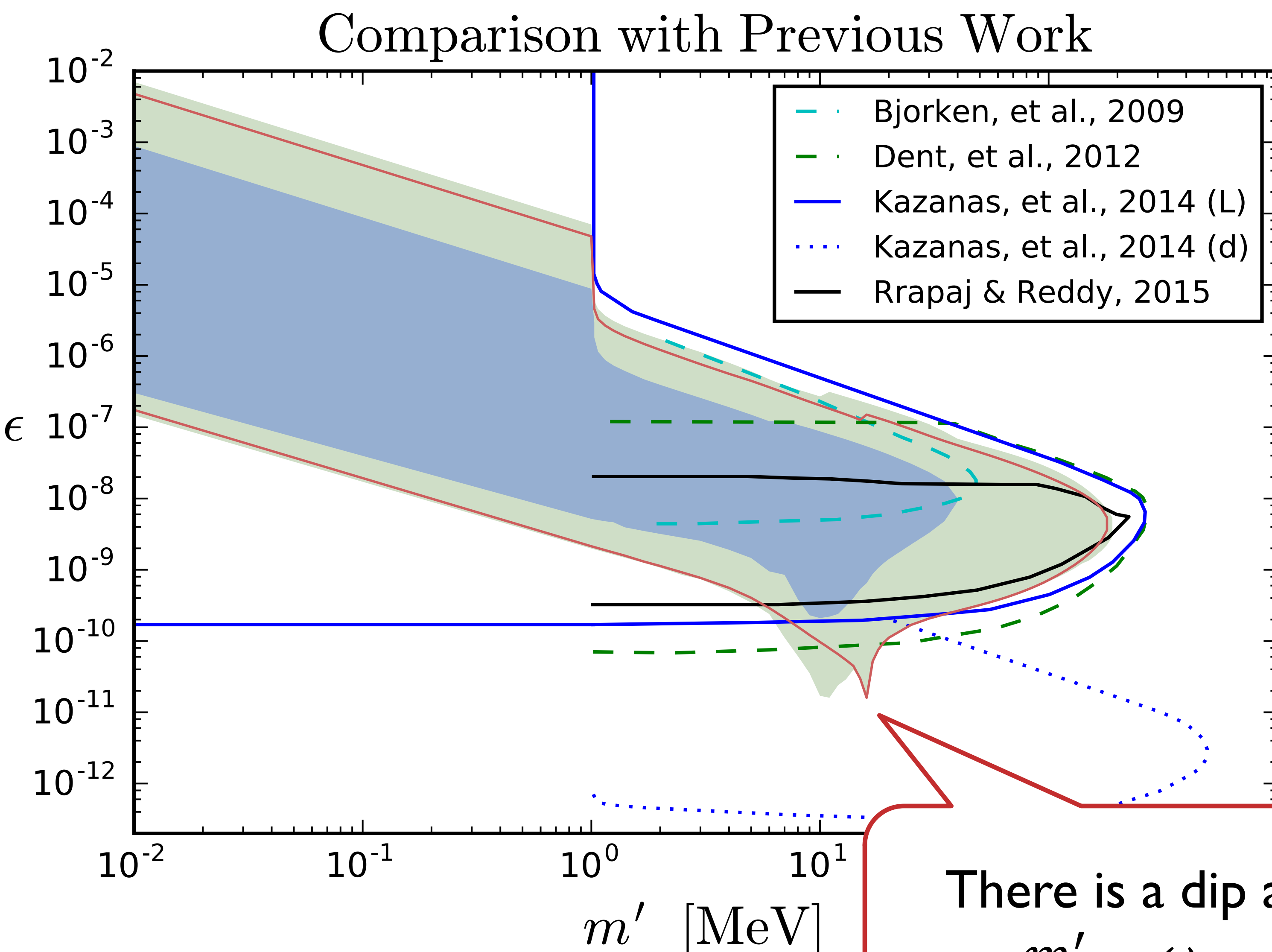
Comparison with Previous Work



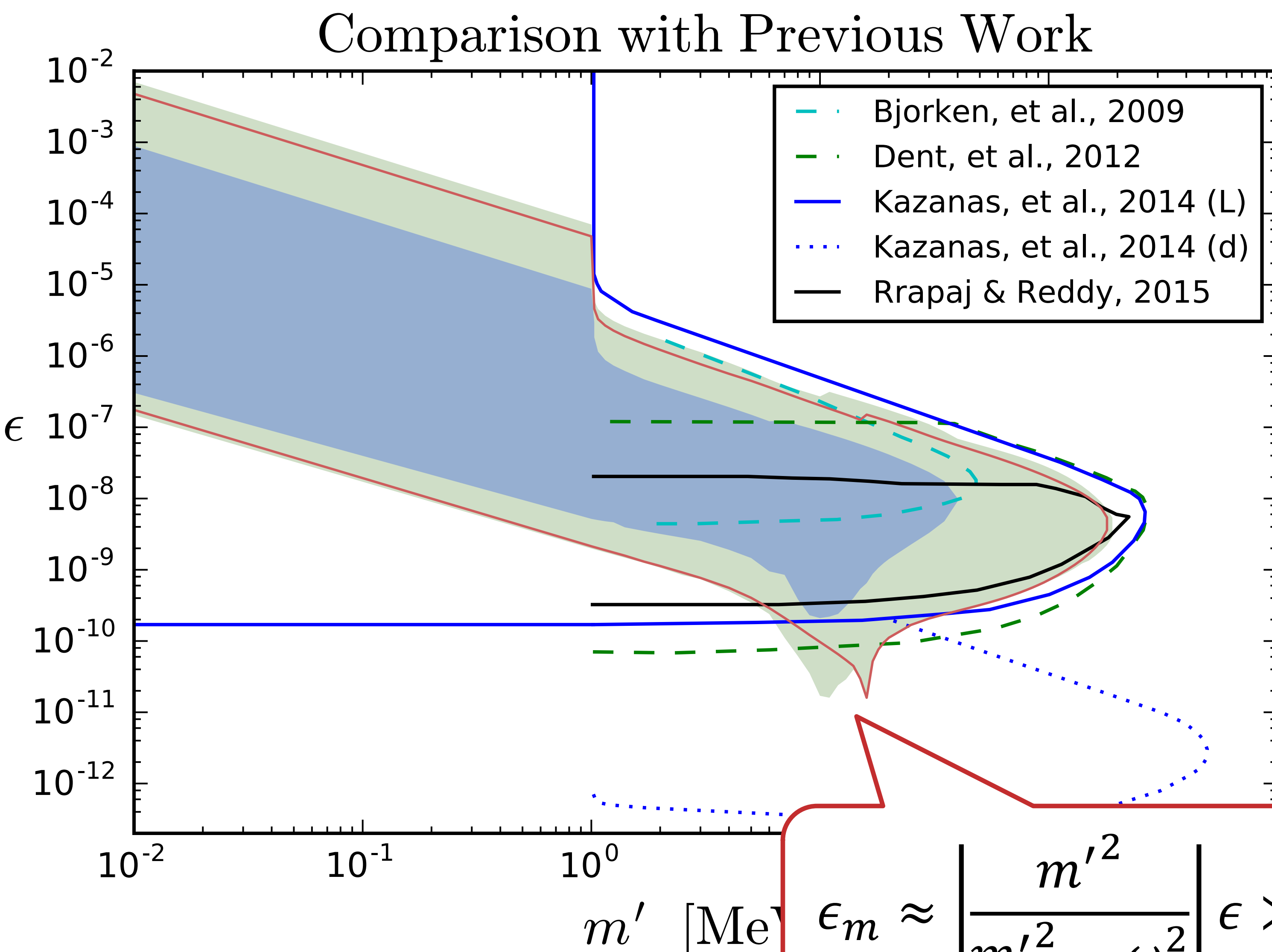

Comparison with Previous Work
Bjorken, et al., 2009
Dent, et al., 2012
Kazanas, et al., 2014 (L)
Kazanas, et al., 2014 (d)
Rrapaj & Reddy, 2015
ϵ
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{0}
10^{1}
10^{2}
10^{3}
m' [MeV]
Lower bounds are lifted for $m' \ll \omega_p$



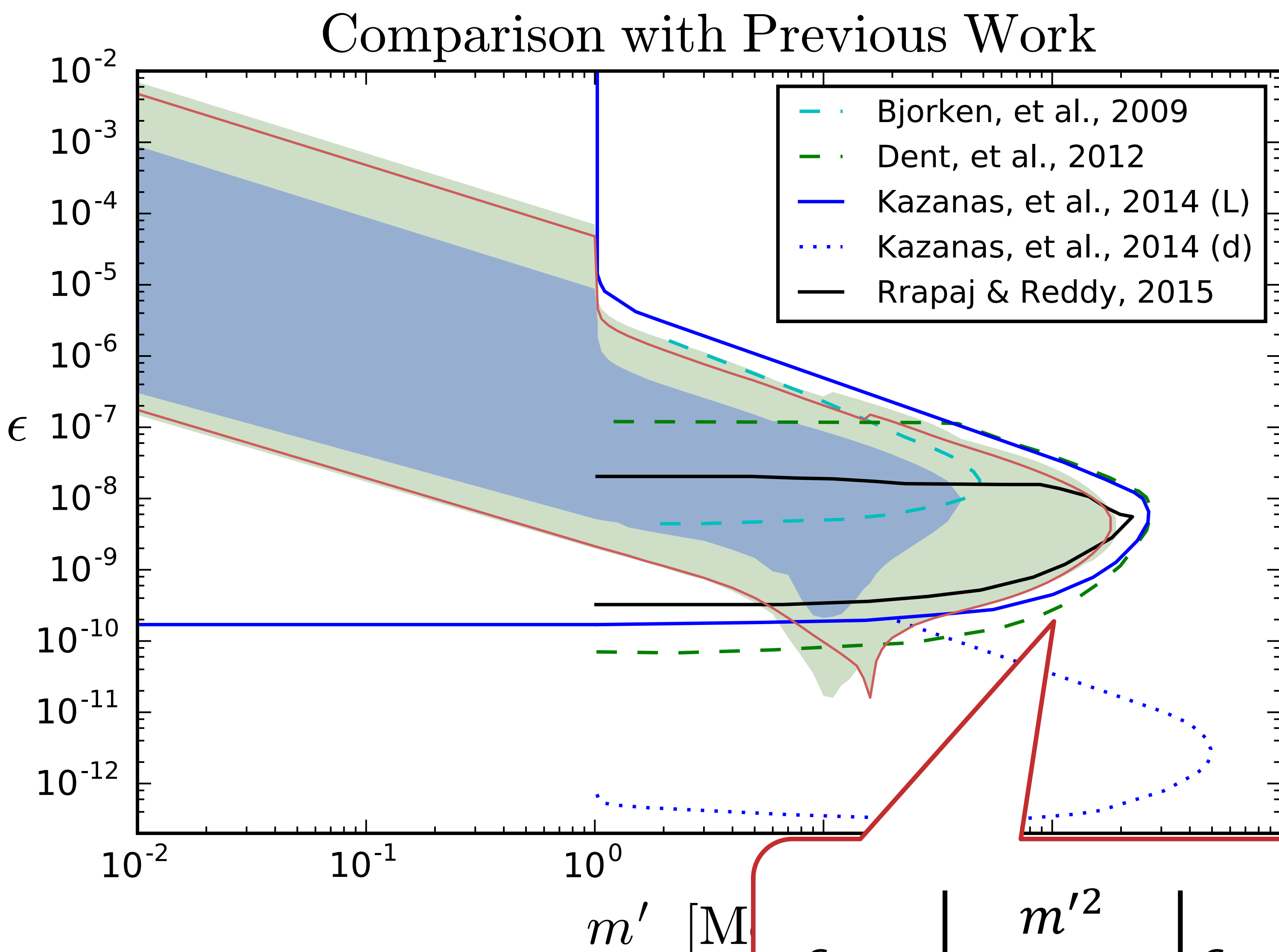
$$\epsilon_m \approx \left|\frac{m'^2}{m'^2 - \omega_p^2}\right| \epsilon \ll \epsilon$$



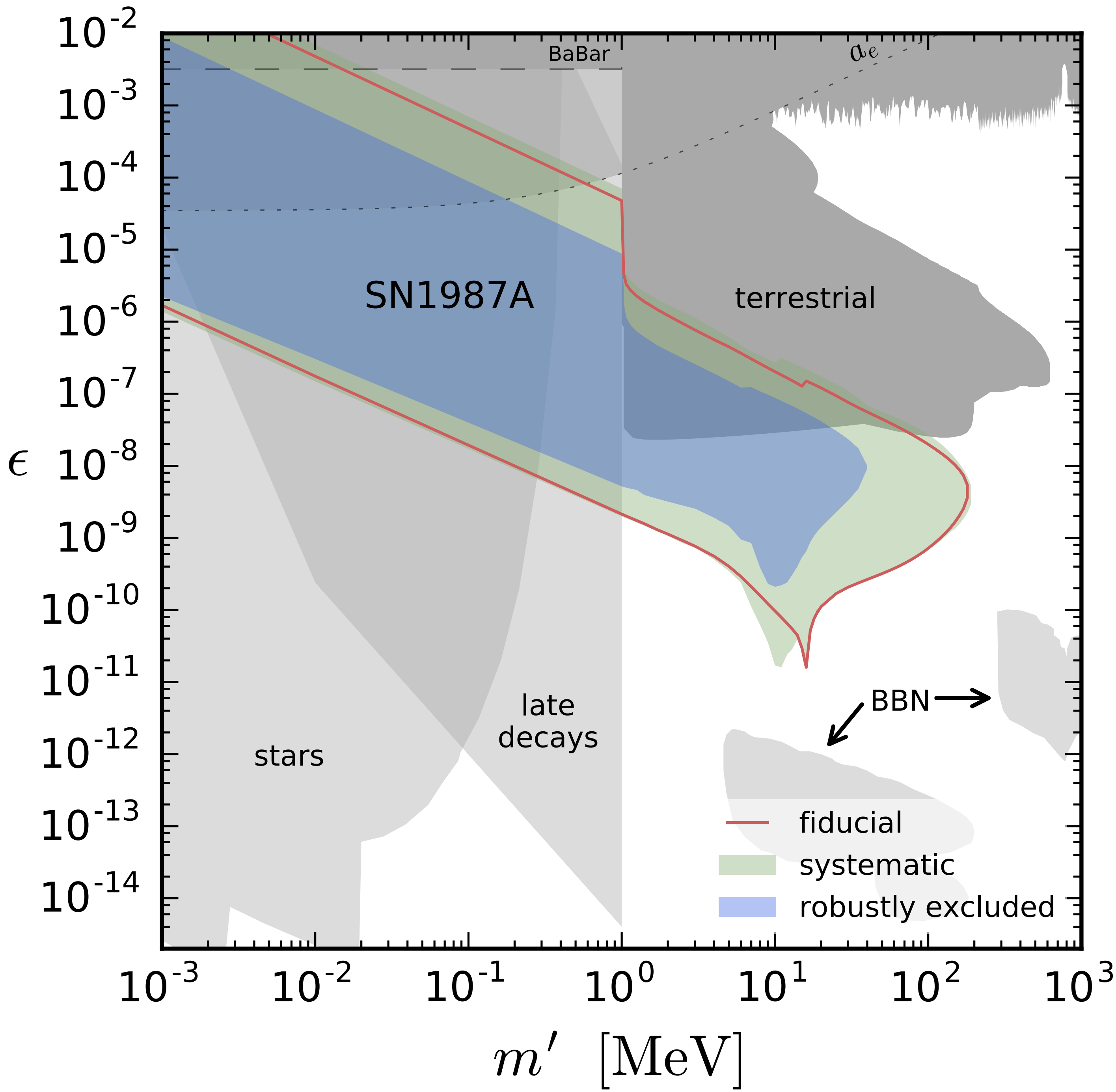
There is a dip at $m' \sim \omega_p$



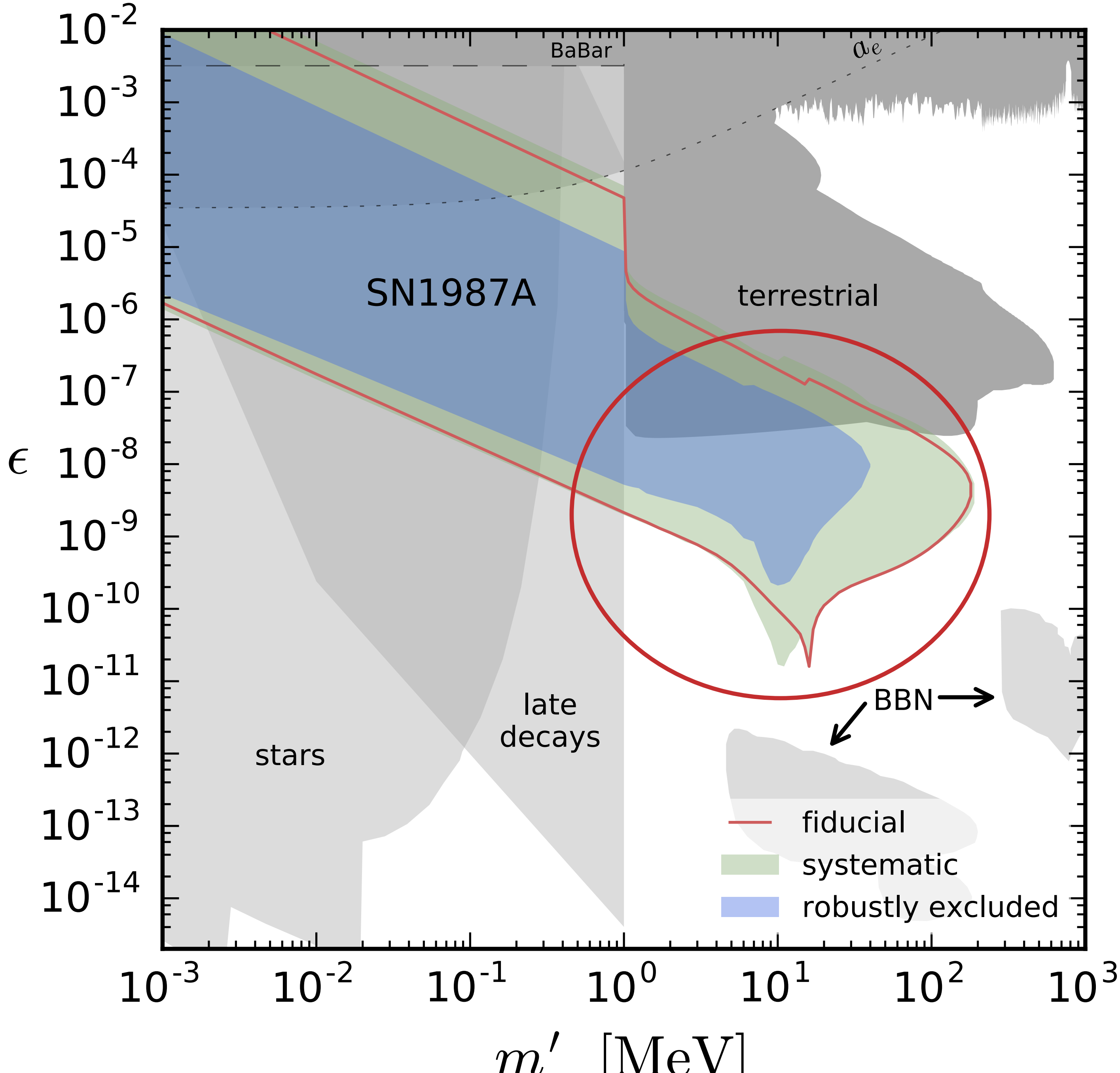
$$\epsilon_m \approx \left|\frac{m'^2}{m'^2 - \omega_p^2}\right| \epsilon \gg \epsilon$$



$$\epsilon_{\mathrm{m}} \sim \left|\frac{m'^2}{m'^2 - \omega_p^2}\right| \epsilon \ \sim \epsilon$$



BaBar
α_e
SN1987A
terrestrial
late decays
stars
BBN
fiducial
systematic
robustly excluded
ϵ
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}
m' [MeV]

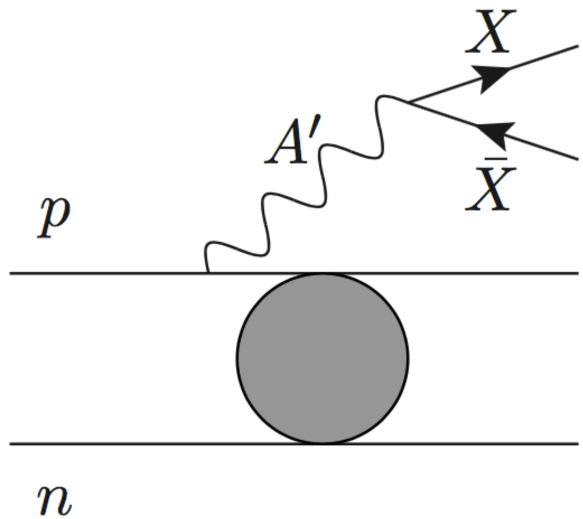


BaBar
α_e
SN1987A
terrestrial
late decays
stars
BBN
fiducial
systematic
robustly excluded
ϵ
m' [MeV]

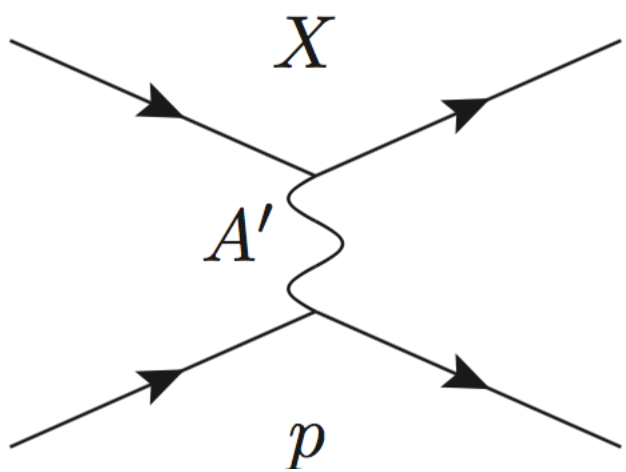
DARK SECTOR FERMIONS

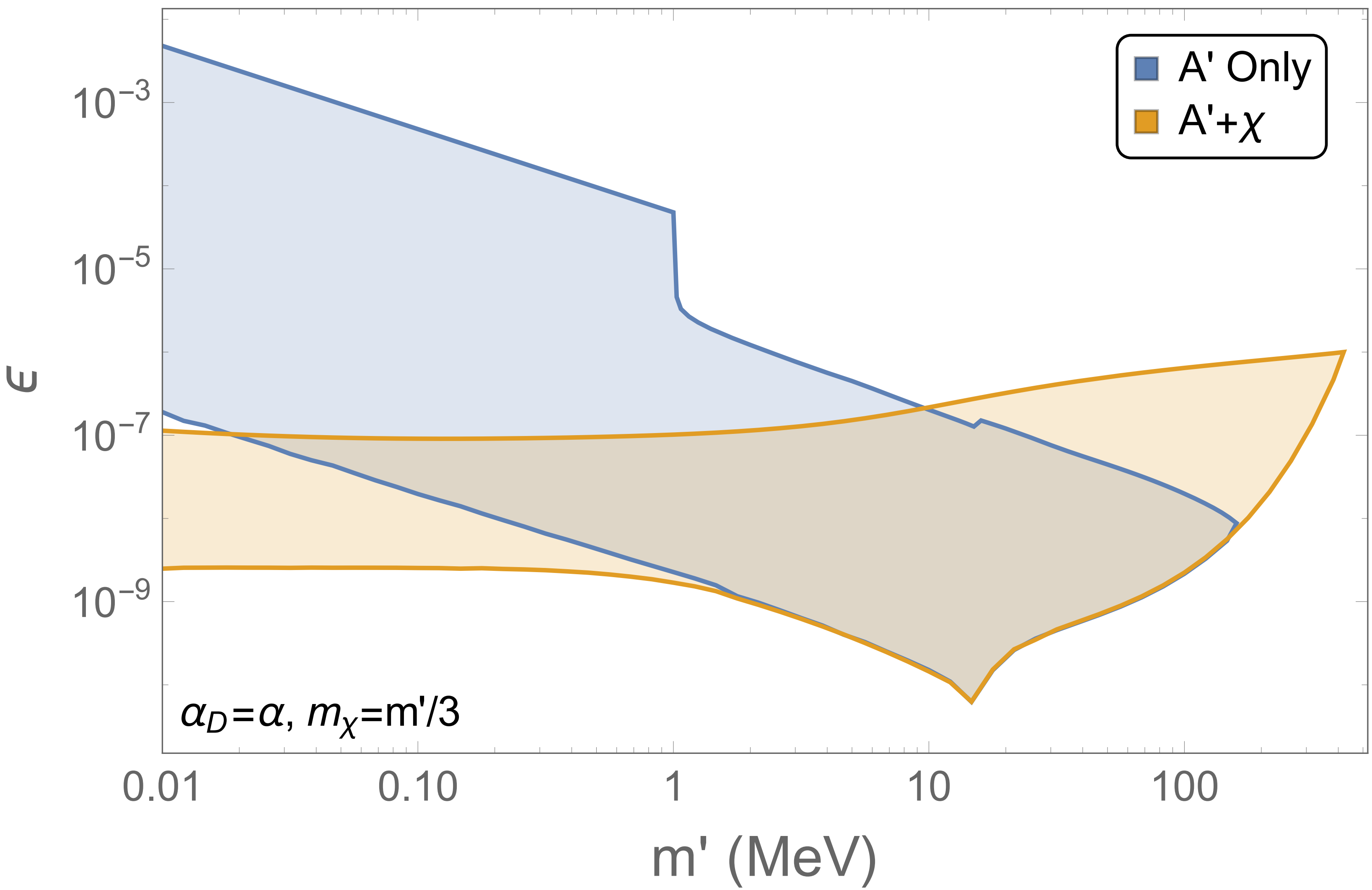
- Fermion charged under $U(1)'$: χ
- Consider $A' + \chi$
- χ is stable → Dark matter candidate
- Dark photon can decay into a χ pair
- Dark photons can be off-shell, $q^2 \neq m'^2$
  - Lower bound becomes stronger
- Cannot be absorbed without $\bar{\chi}$
  - Upper bound changes significantly

- Dominant production process

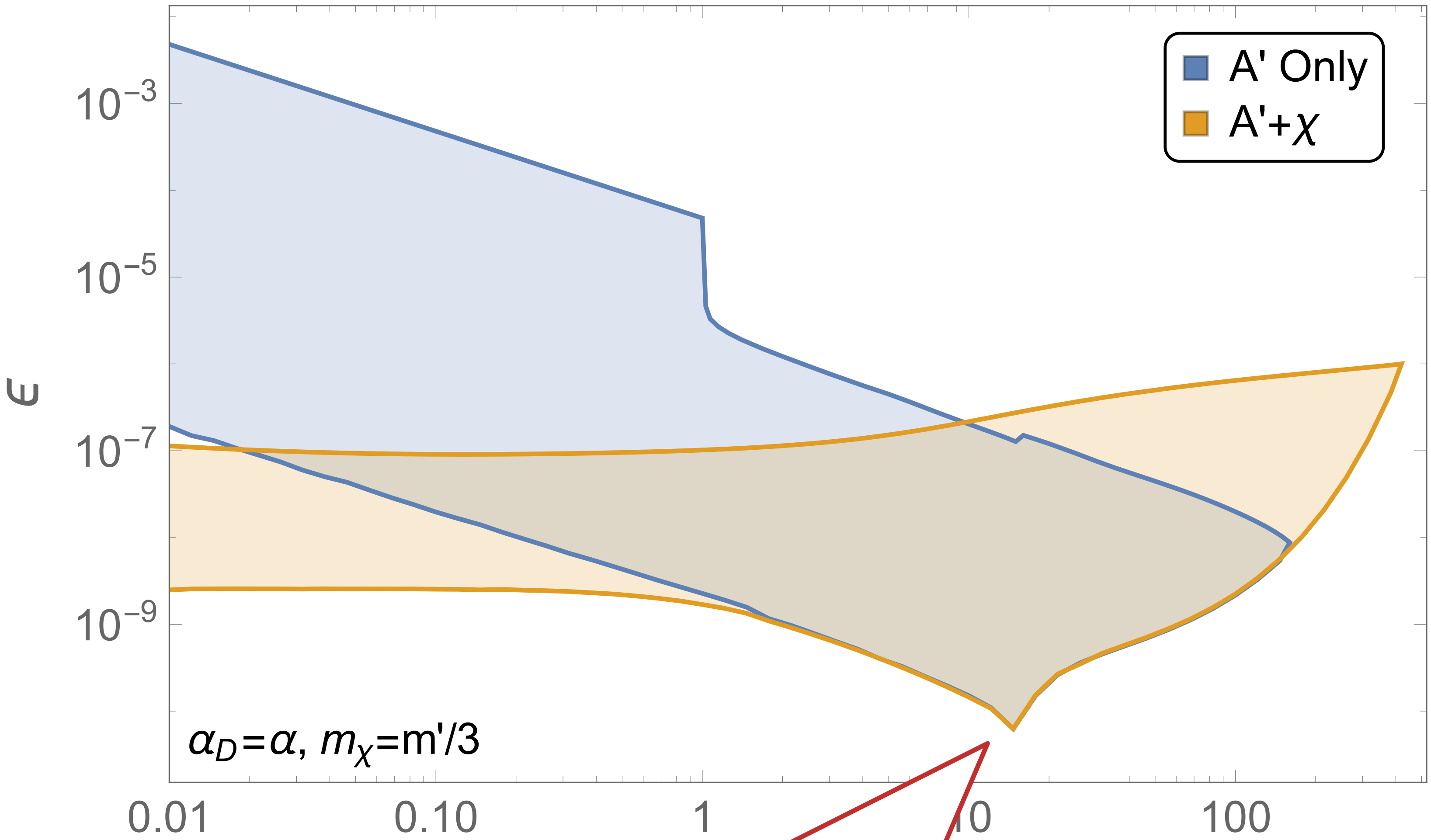


- Trapping Process



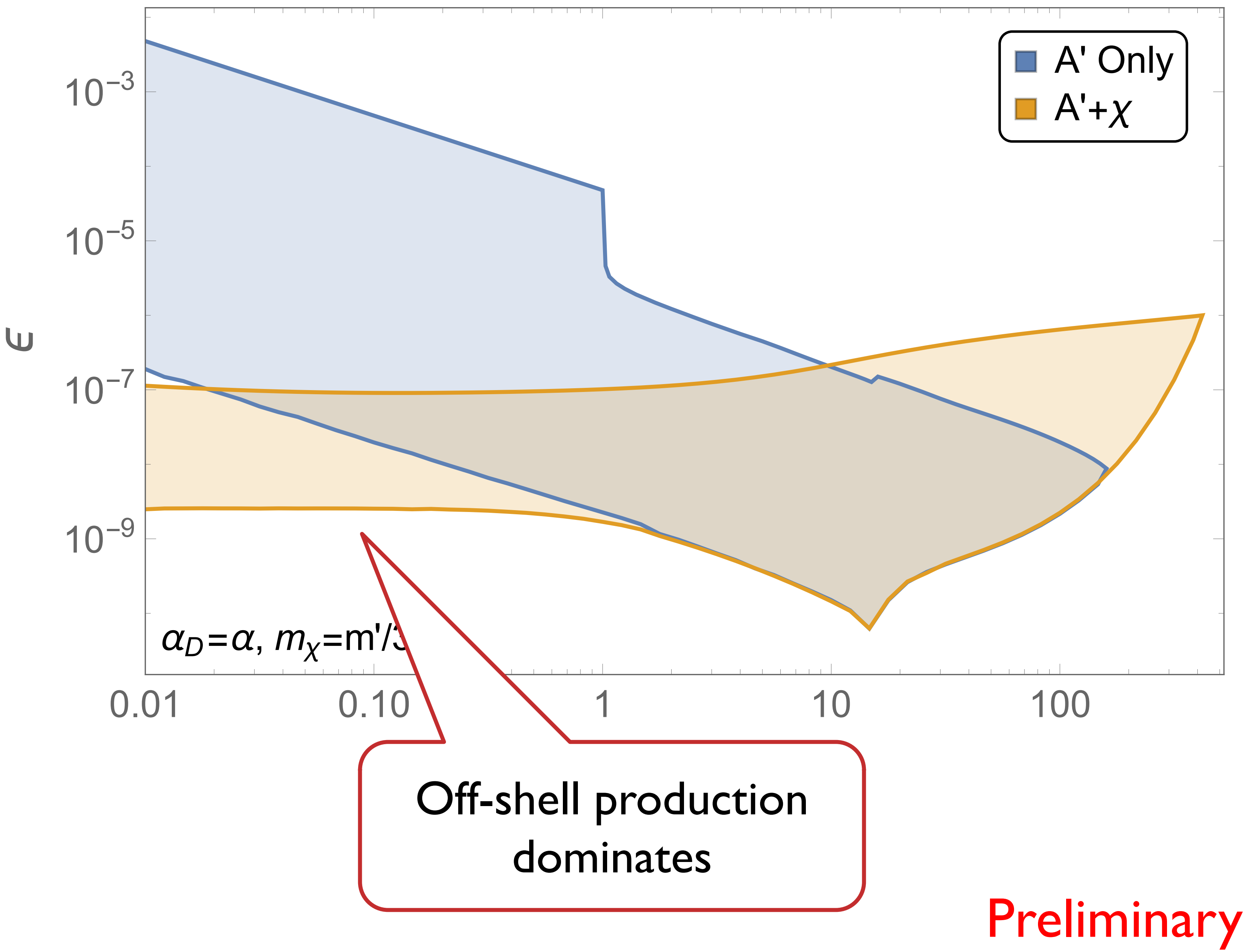


Preliminary

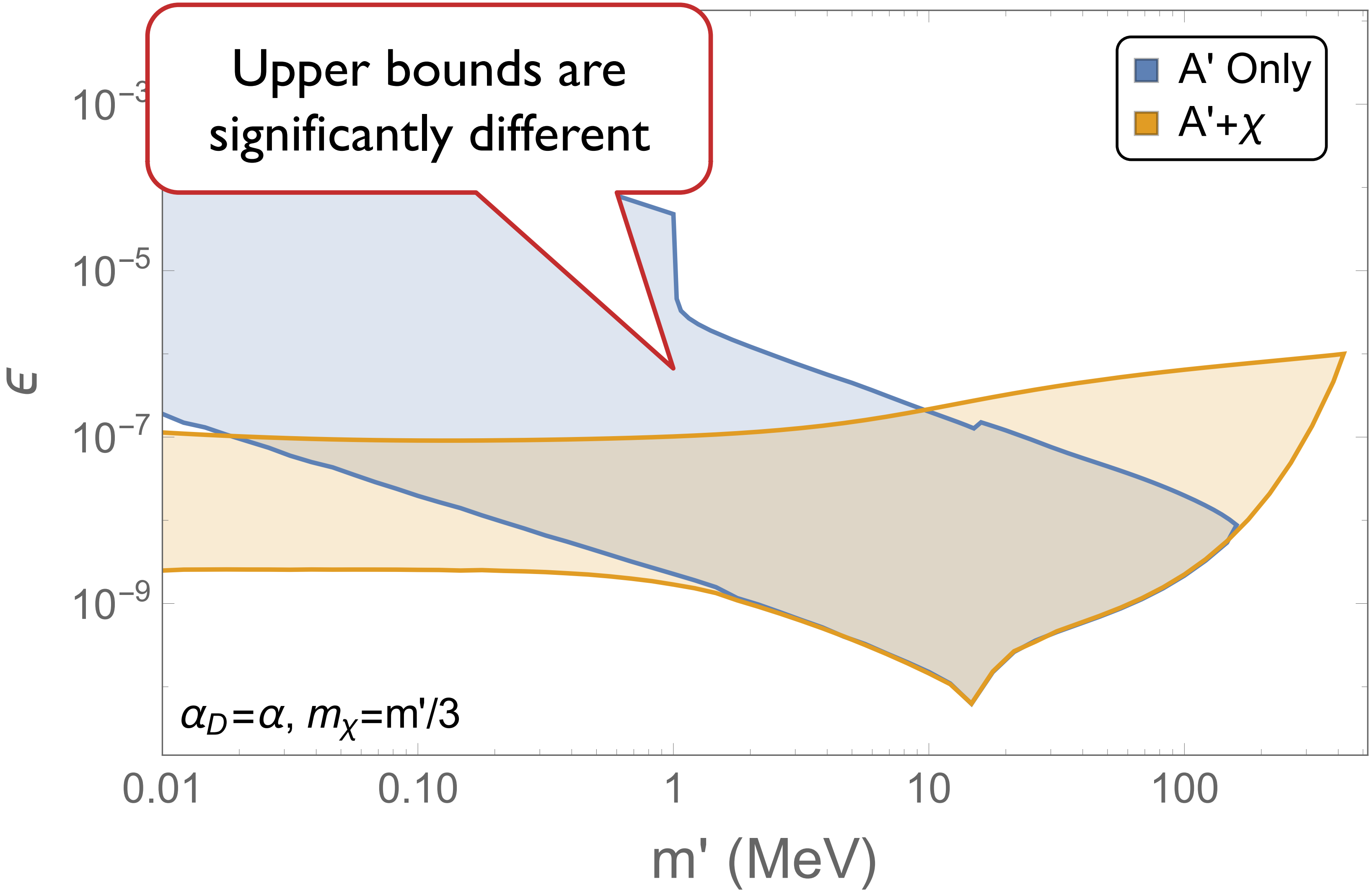


On-shell production:
Two cases have same lower bounds

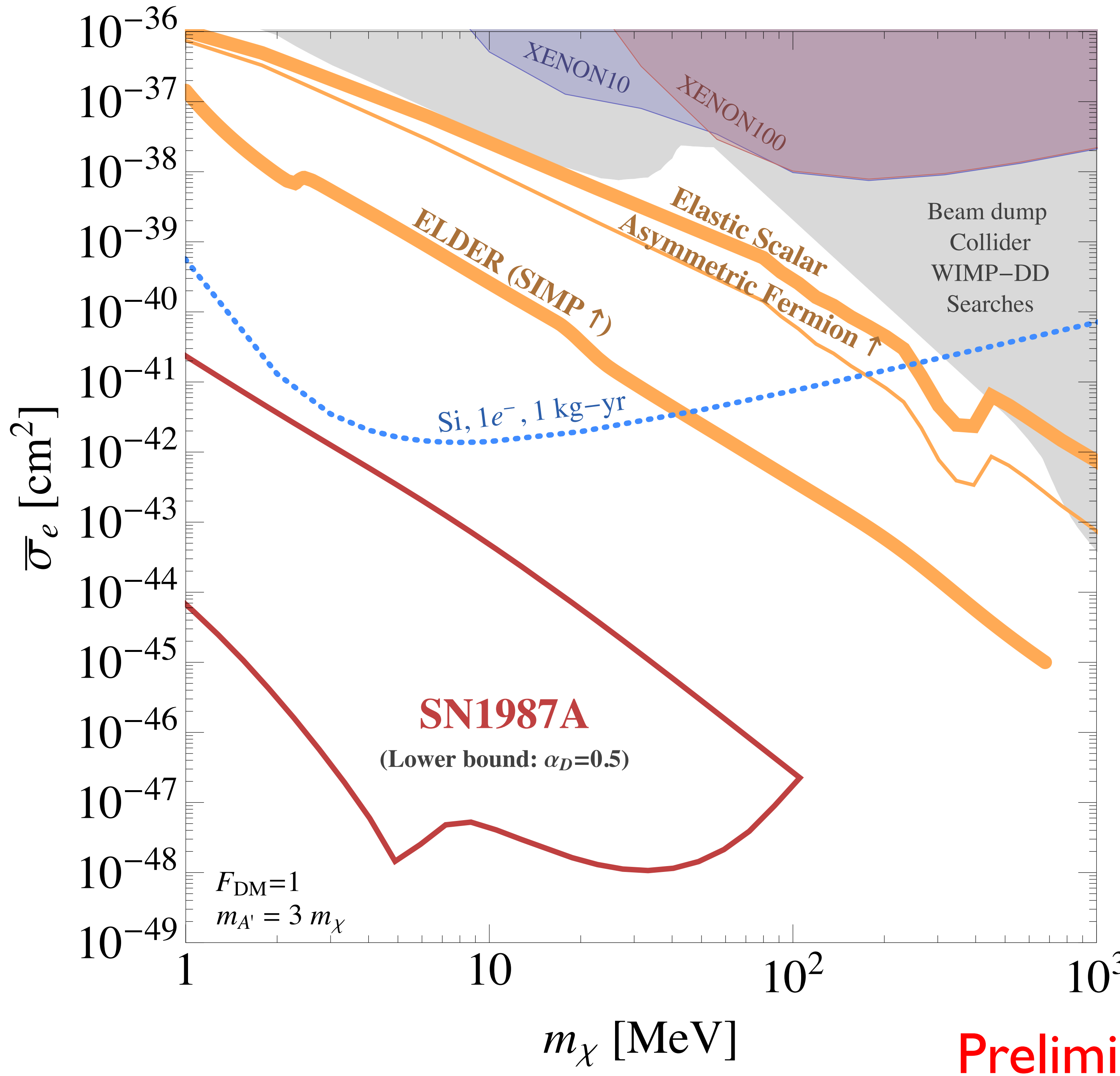
Preliminary



A' Only
A'+χ
ε
10^−3
10^−5
10^−7
10^−9
αD=α, mχ=m'/3
0.01
0.10
1
10
100
Off-shell production dominates
Preliminary



Preliminary



Preliminary

CONCLUSION

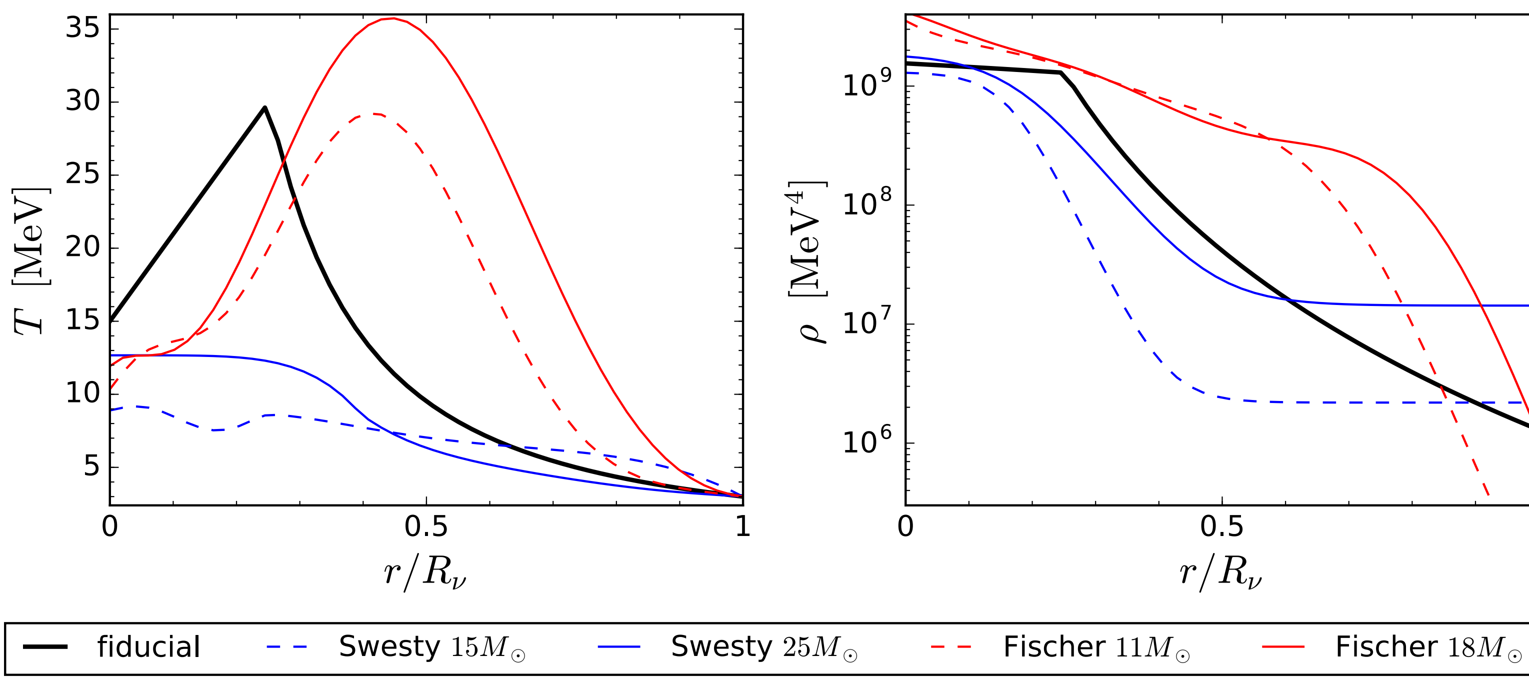
Conclusion

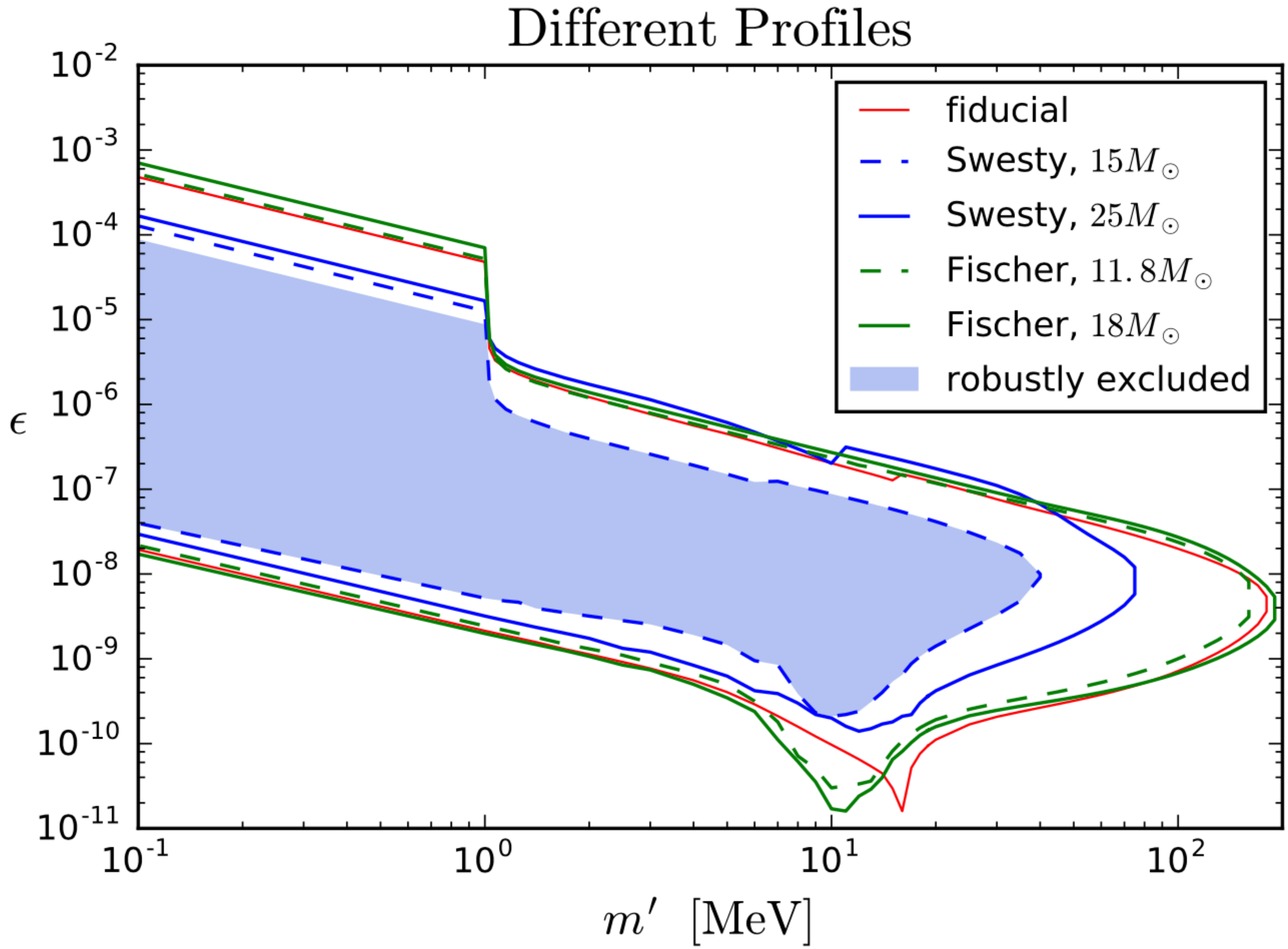
- Supernova1987A can give constraints on low-mass dark sector particles
- For the dark photon models, thermal effects have a crucial role
- We calculated constraints for the pure dark photon and for the dark sector fermions, and constraints for the millicharged DM are in progress

THANK YOU

BACK UP

Temperature and Density Profiles





Different Profiles
fiducial
Swesty, $15M_\odot$
Swesty, $25M_\odot$
Fischer, $11.8M_\odot$
Fischer, $18M_\odot$
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^{-1}
10^{0}
10^{1}
10^{2}

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

$$\tau = \int_r^{r_f} \Gamma_{\text{abs}} dr'$$

$$\omega_p^2 = \frac{4\pi\alpha n_e}{E_F}$$

$$E_F^2 = m_e^2 + (3\pi n_e)^{2/3}$$

$$\bar{\sigma}_e = \frac{16\pi\mu_{\chi e}\epsilon^2\alpha\alpha_D}{(m'^2 + \alpha^2 m_e^2)^2}$$