Supernova 1987A Constraints on Low-Mass Hidden Sectors

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SUPERNOVA 1987A

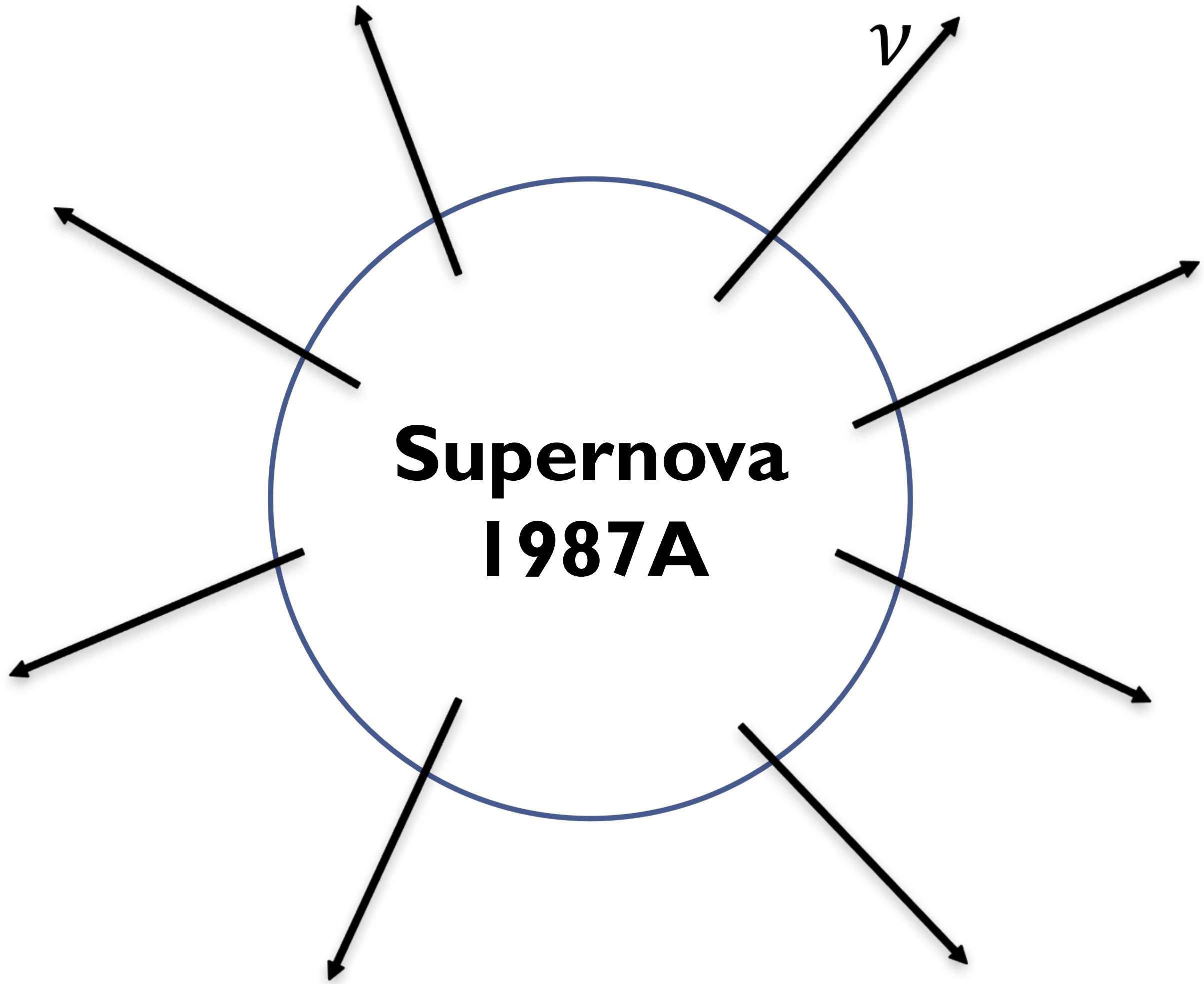
Supernova 1987A

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

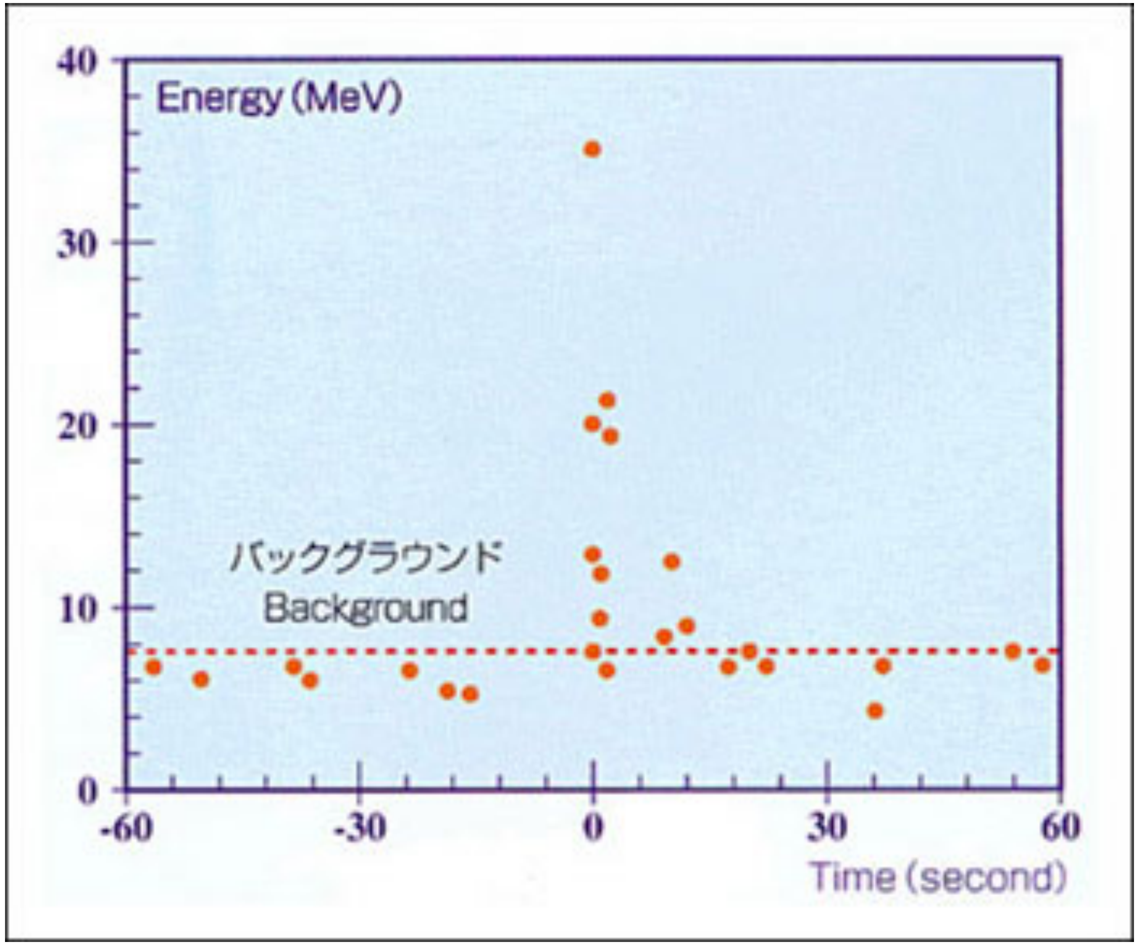
Supernova Constraints

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

Supernova 1987A

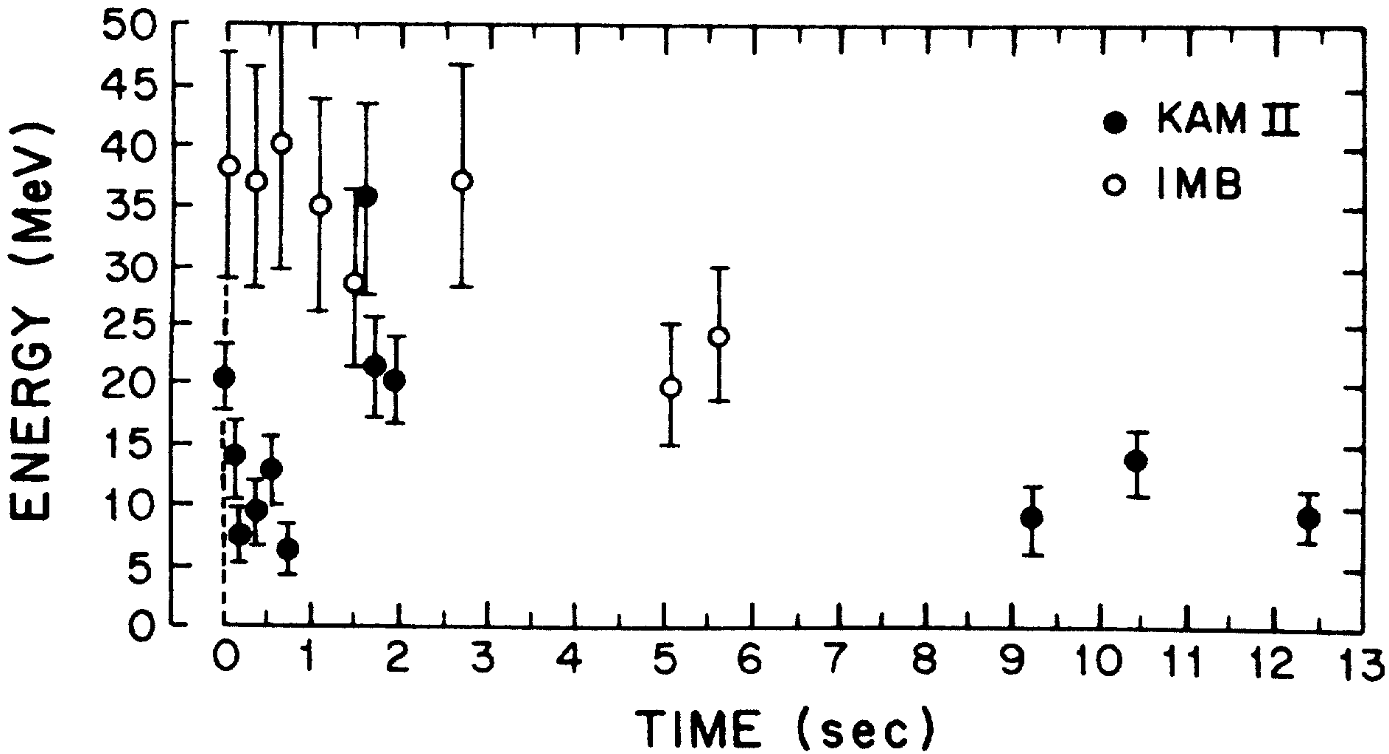


- 99% of energy is carried by neutrinos

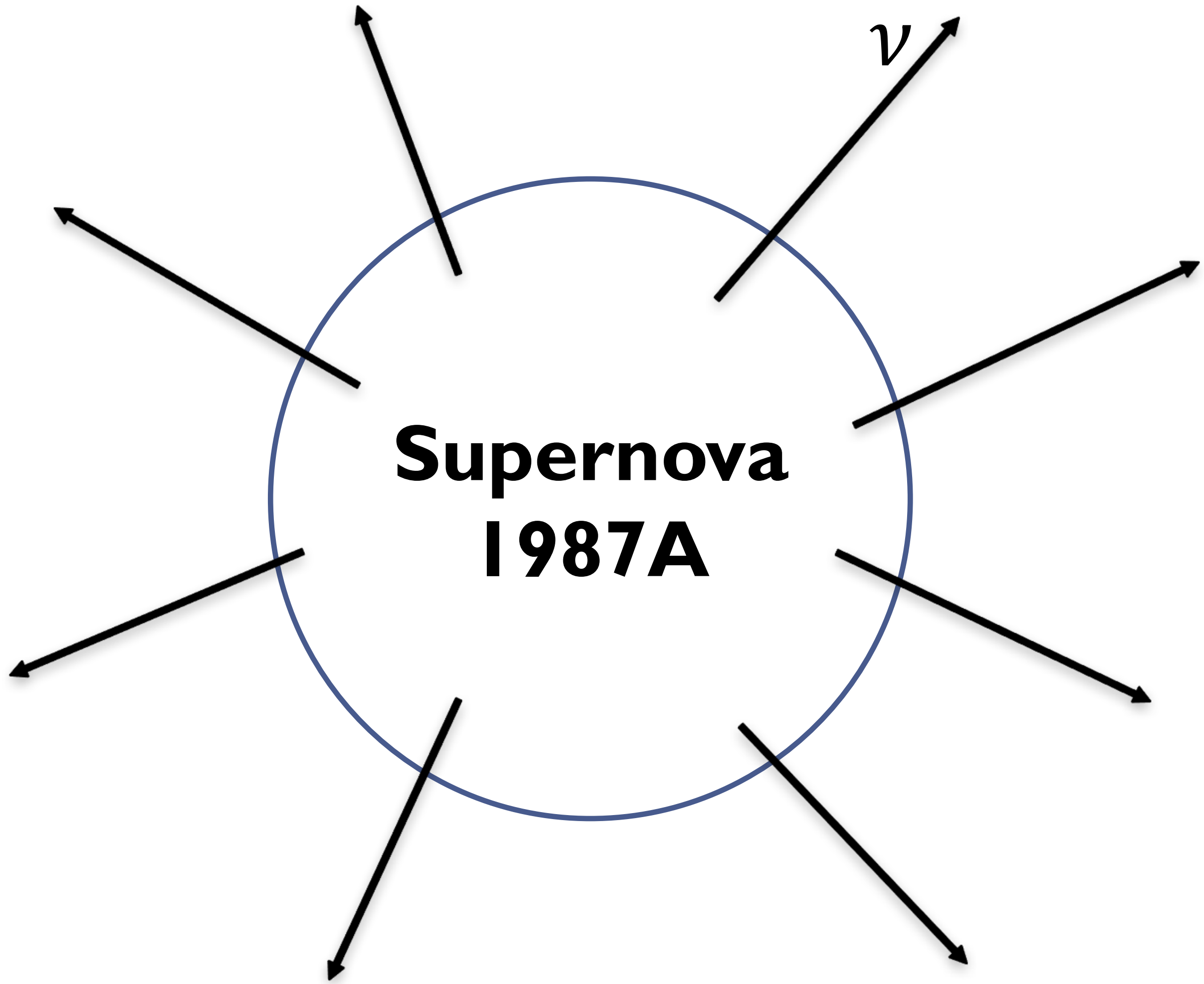


- Kamiokande II, IMB, and Baksan detected the neutrinos at the same time

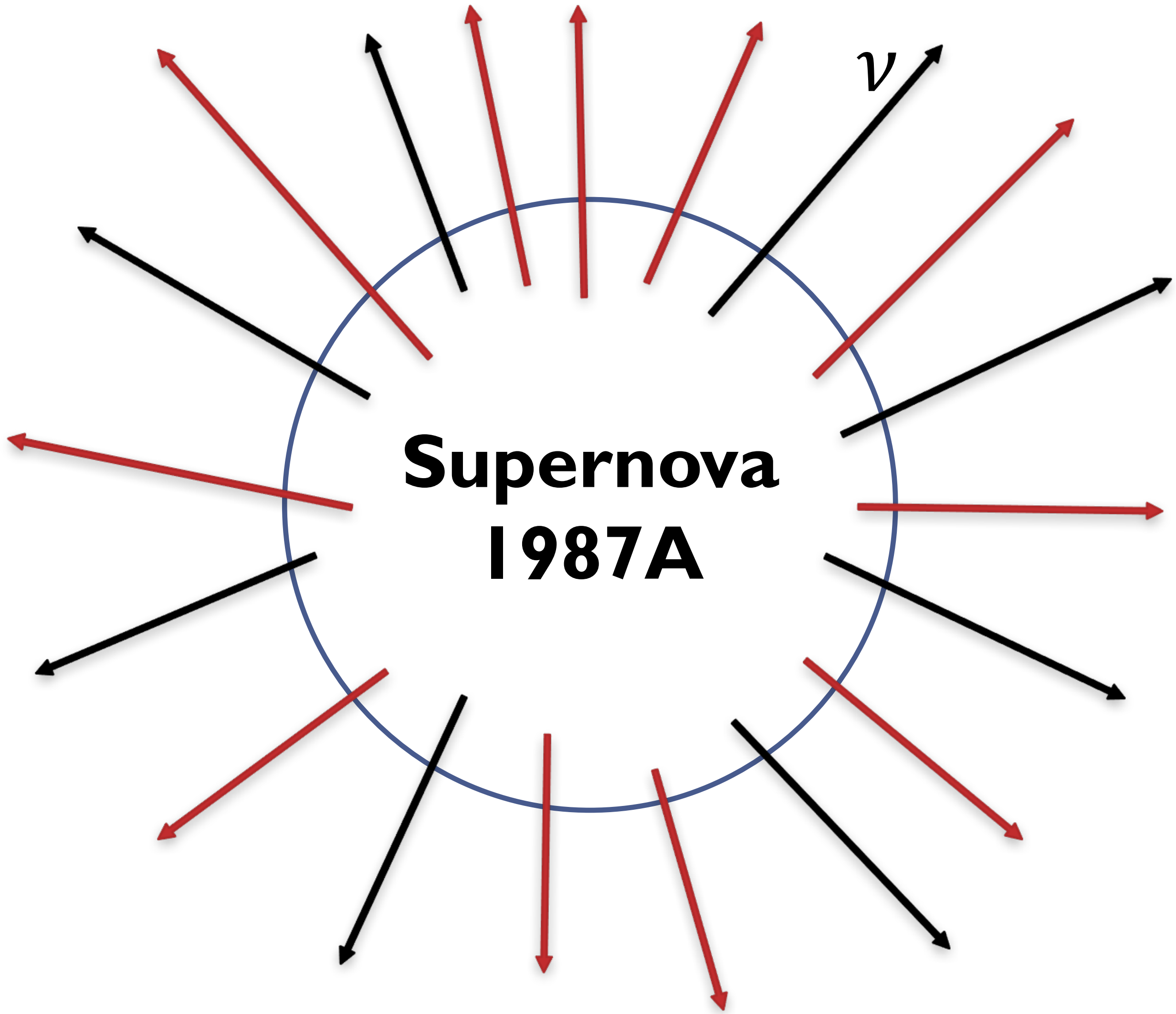
Hirata et al, 1988



- Cooling time : ~10 seconds
- Consistent with the SM prediction



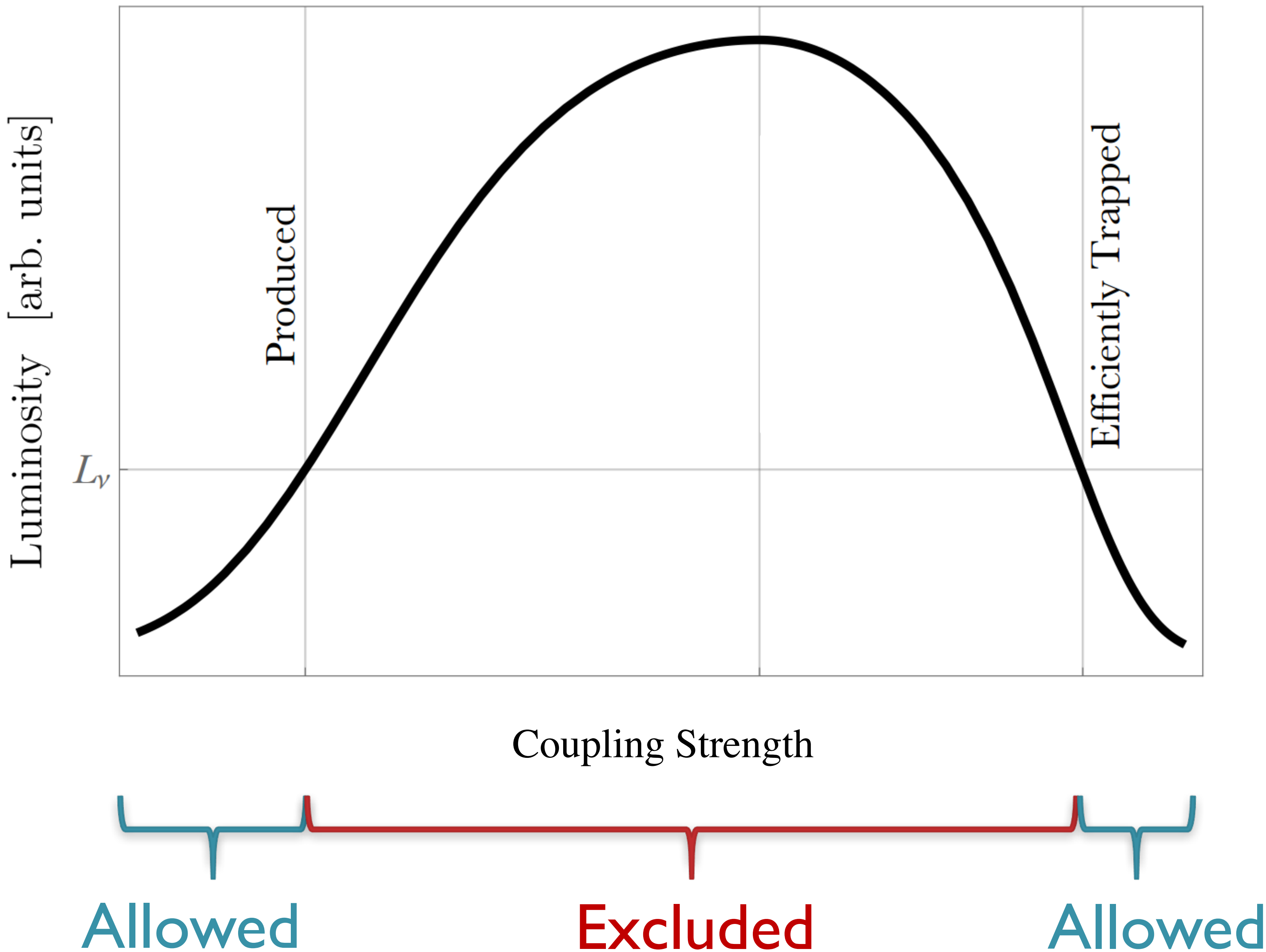
- If a new particle exists



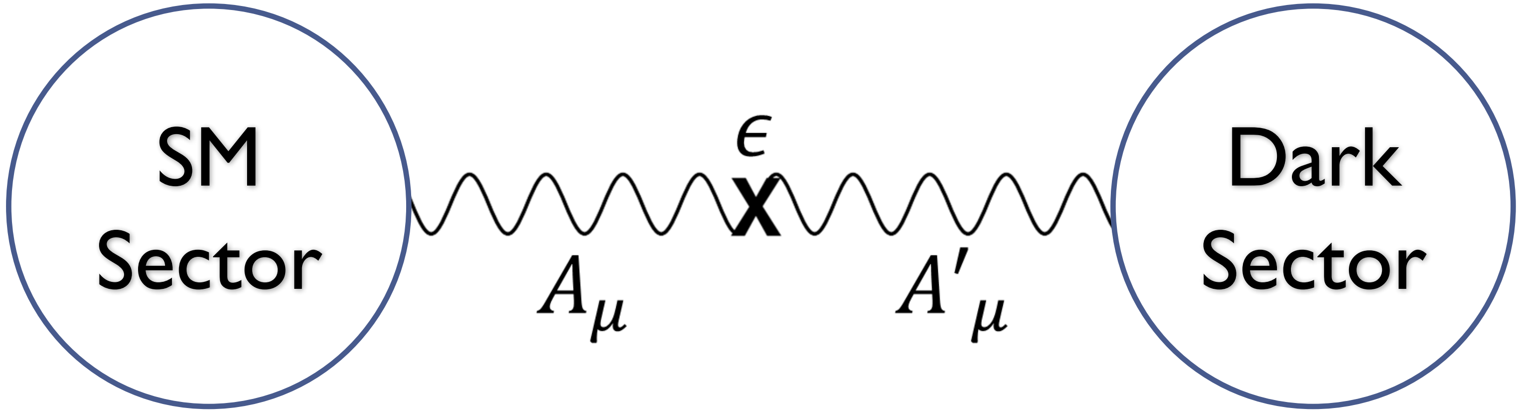
- Supernova cools faster

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

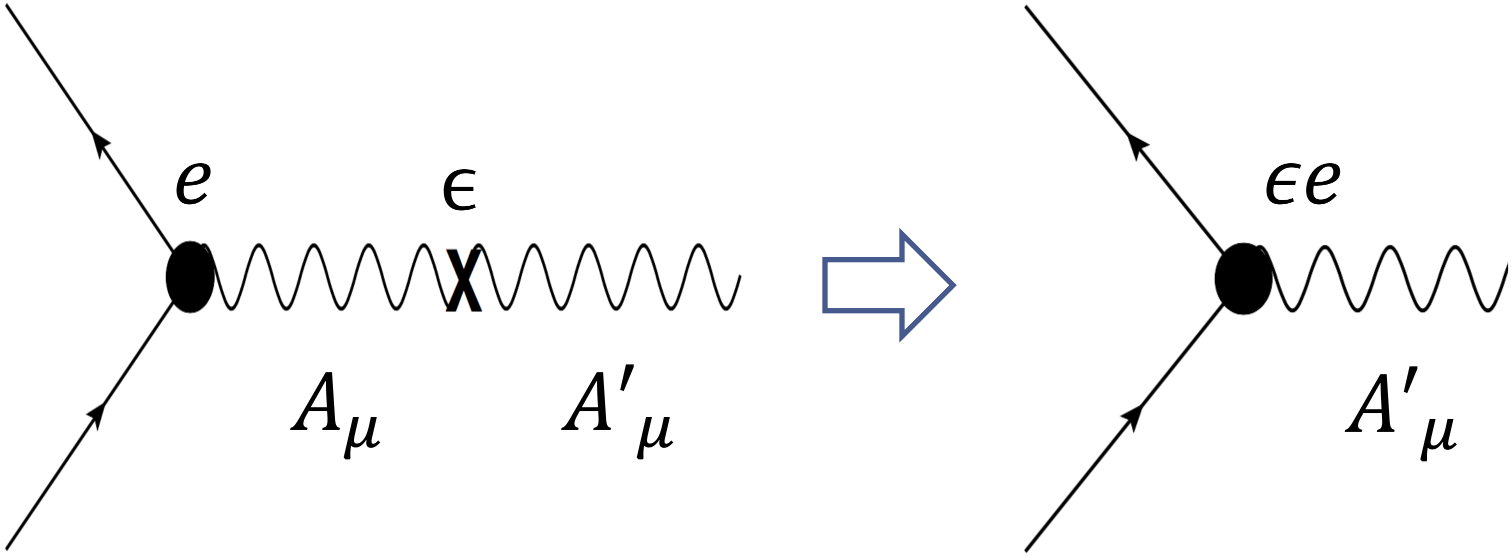


- $SU(3)_c \times SU(2)_L \times U(1)_Y \times \boldsymbol{U(1)'}$
- In low energies, $\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$
- Called the vector portal

Dark Photon in Supernova

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

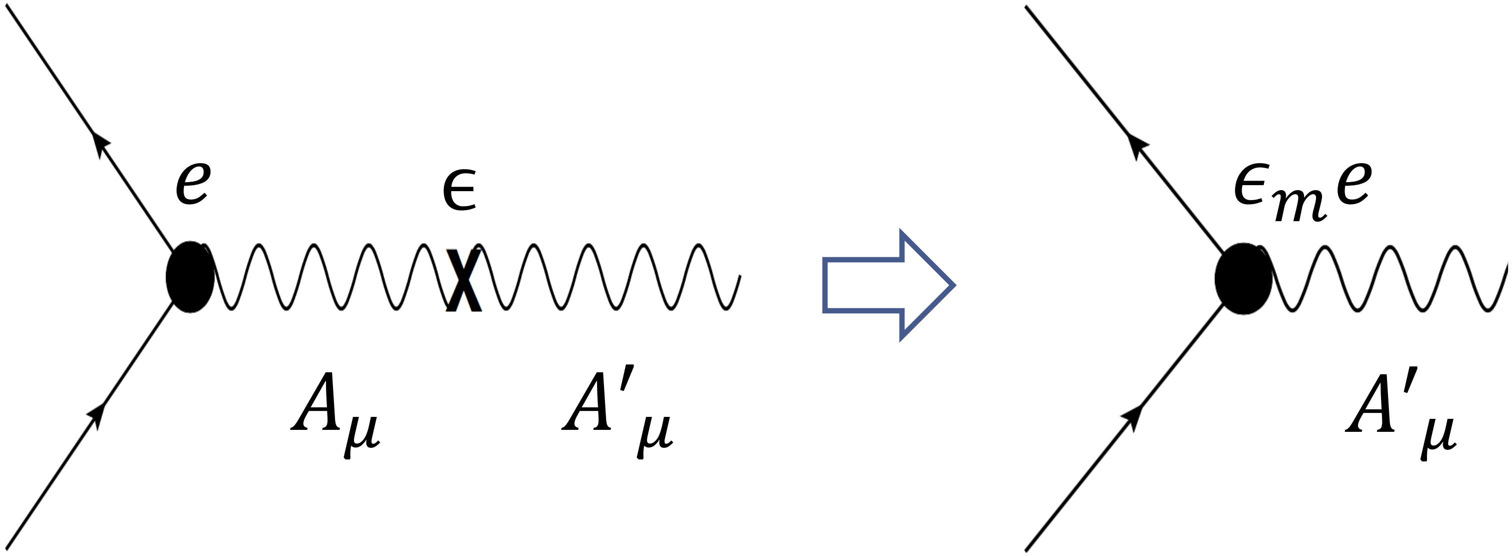
- $\Pi = \Pi_{vac} + \Pi_{mat}$
- Π_{vac} is the vacuum part
- Π_{mat} describes thermal plasma effects
- $\Pi_{mat} \gg \Pi_{vac}$



- 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
- Milli-charged dark matter
- Inelastic dark matter (Work in progress)

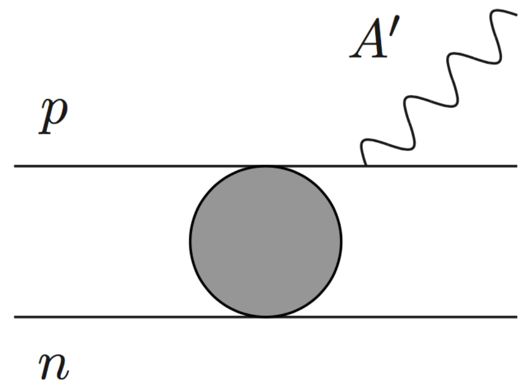
PURE DARK PHOTON

- All other hidden sector particle masses are much heavier than T_c

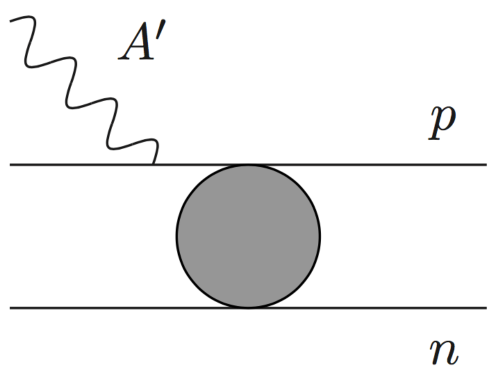
- Consider A' only

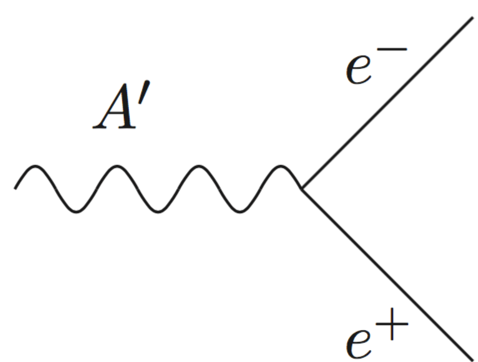
- Dark photons are on-shell, $q^2 = m'^2$

- Dominant production process



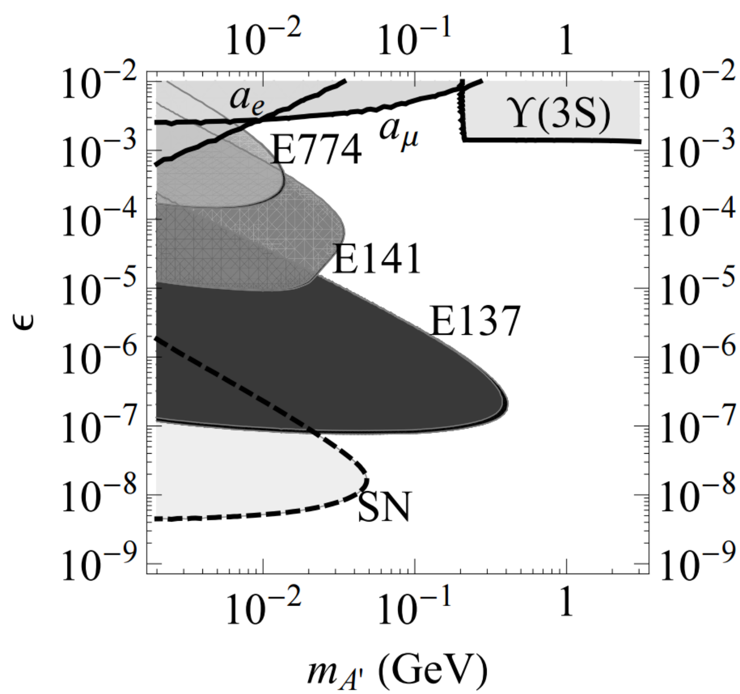
- Trapping Process



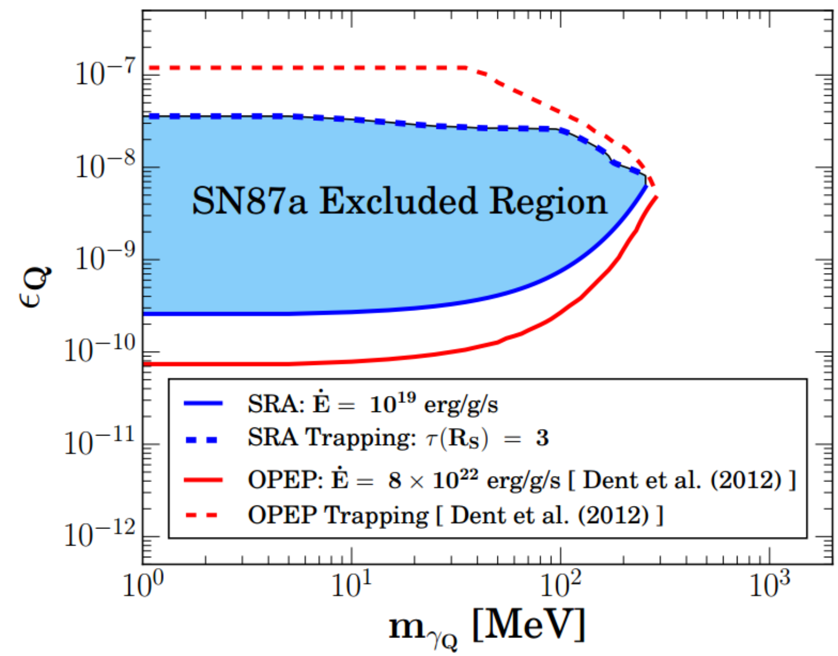


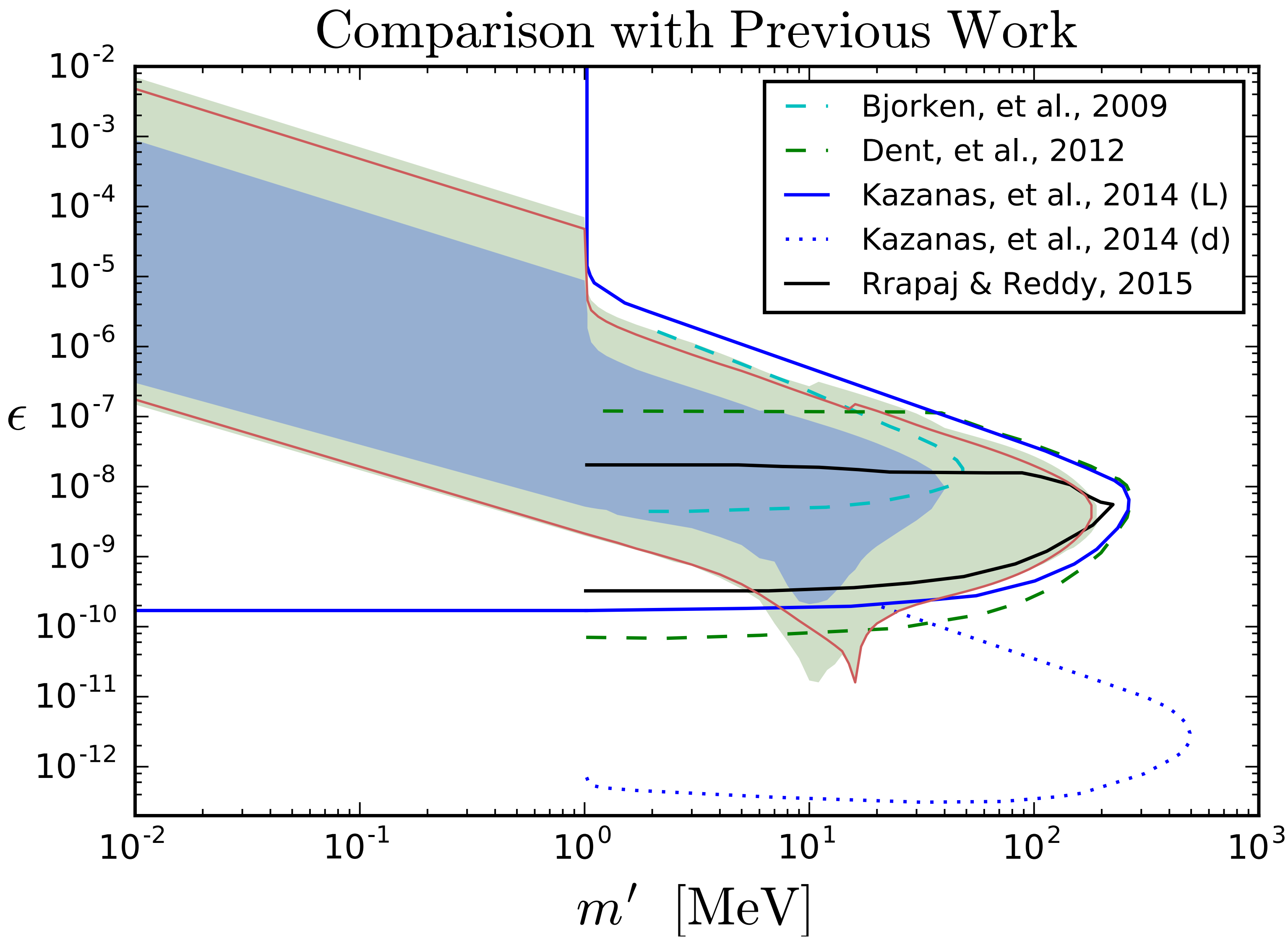
Previous Works

- Bjorken et al, 2009

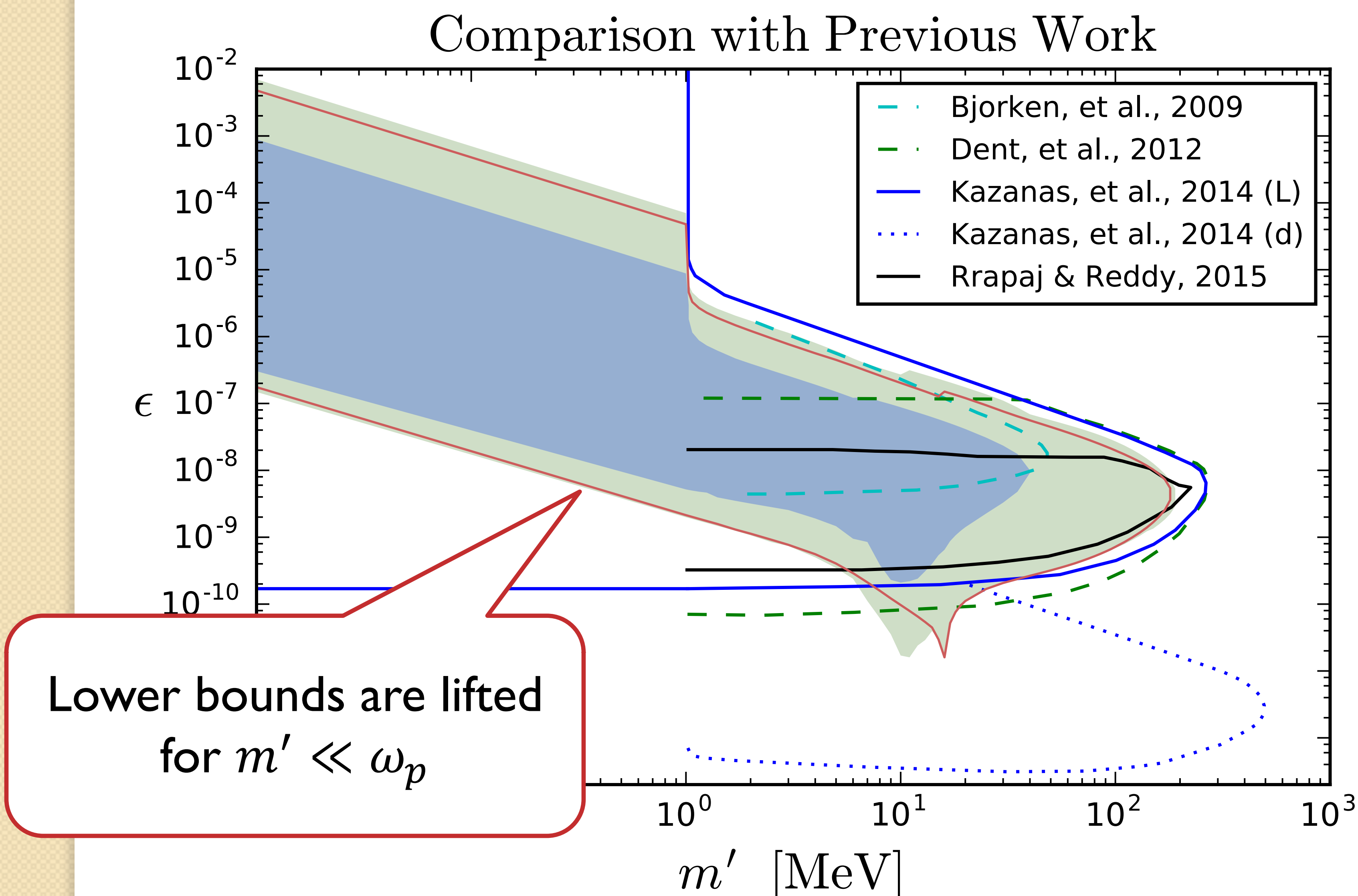


- Dent et al, 2012
- Rrapaj and Reddy, 2015





Comparison with Previous Work
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]



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ϵ
10^{-2}
10^{-3}
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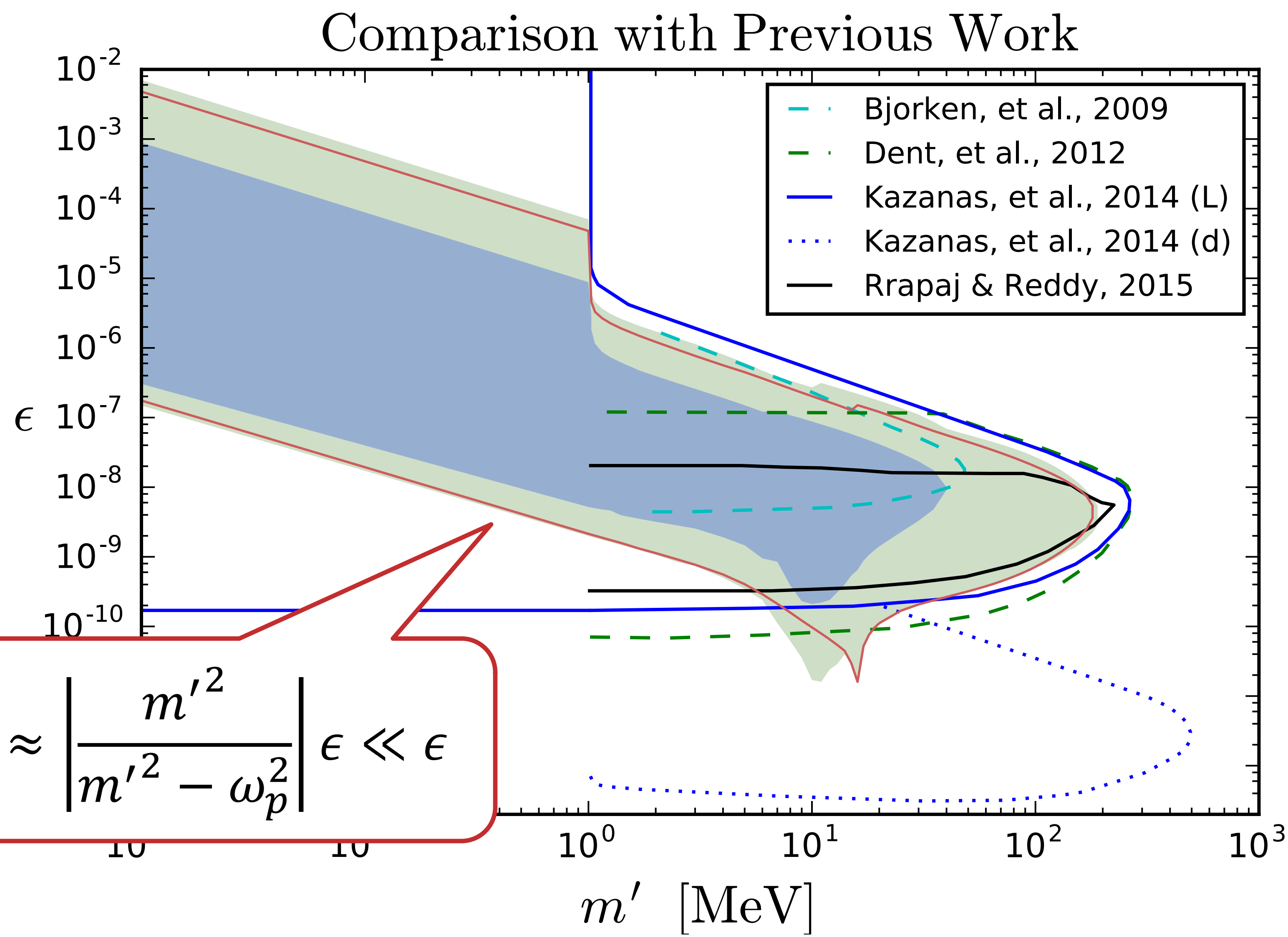
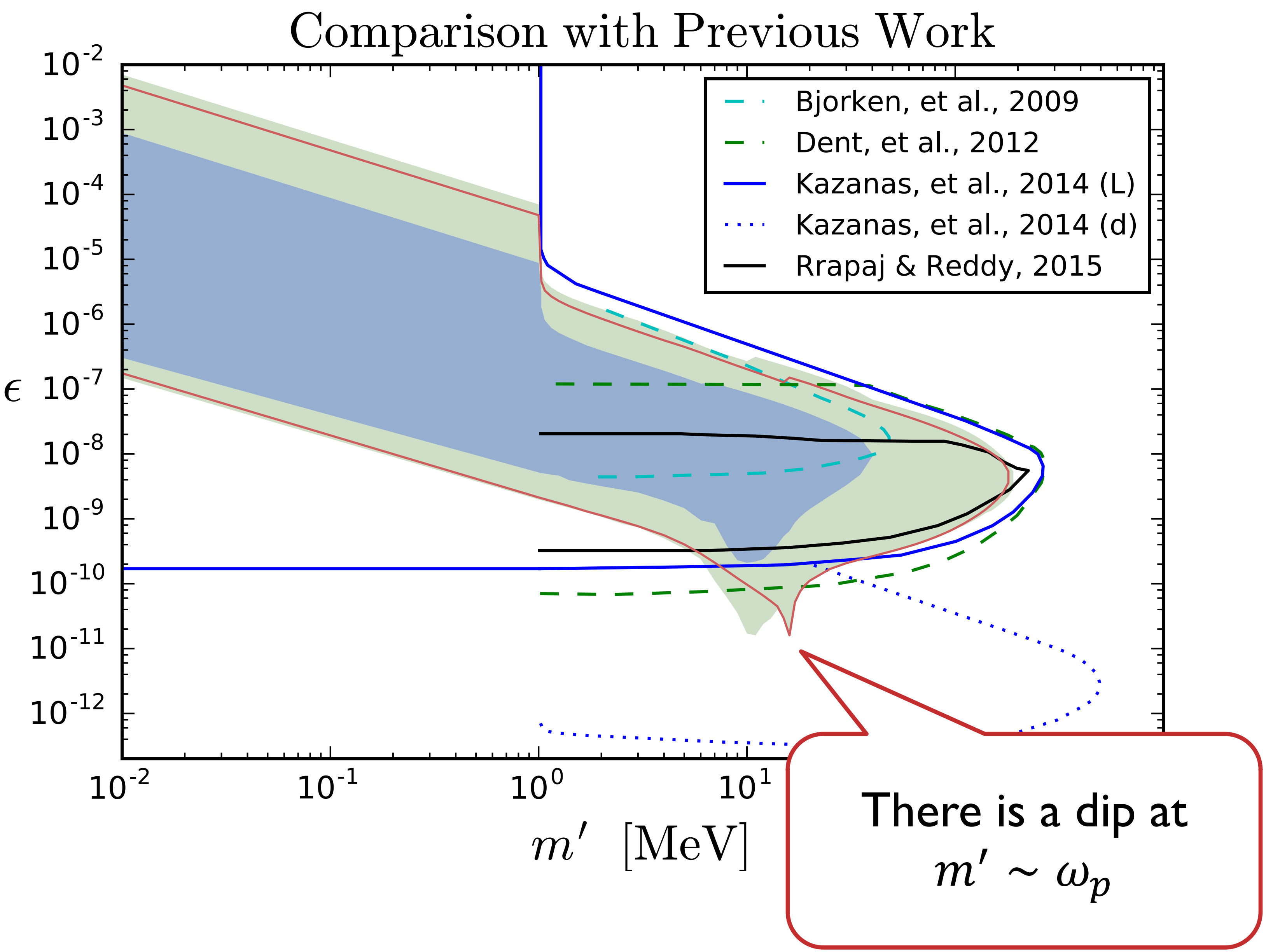
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{0}
10^{1}
10^{2}
10^{3}
m' [MeV]
Lower bounds are lifted for $m' \ll \omega_p$



$$\epsilon_m \approx \left|\frac{m'^2}{m'^2 - \omega_p^2}\right| \epsilon \ll \epsilon$$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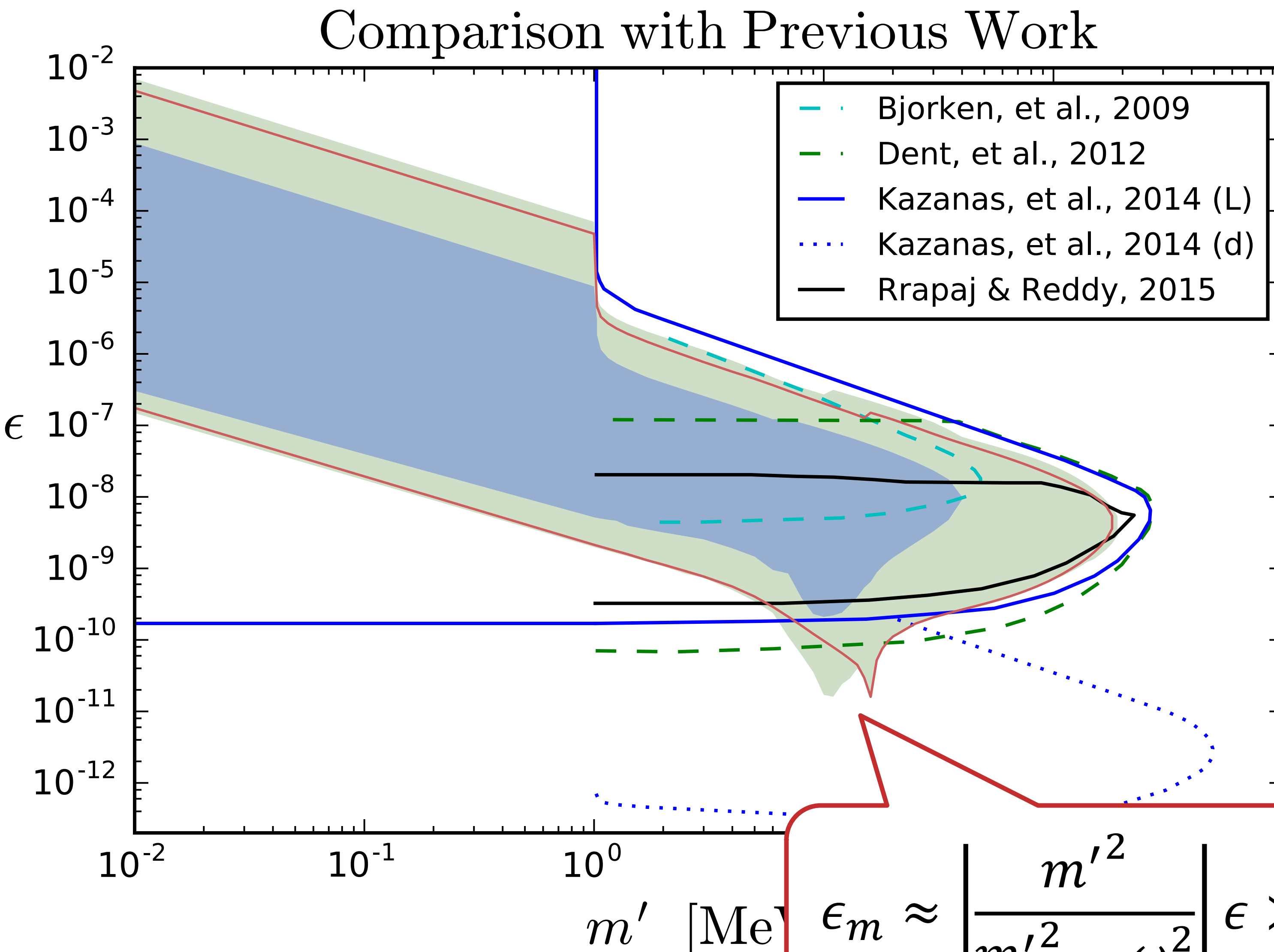
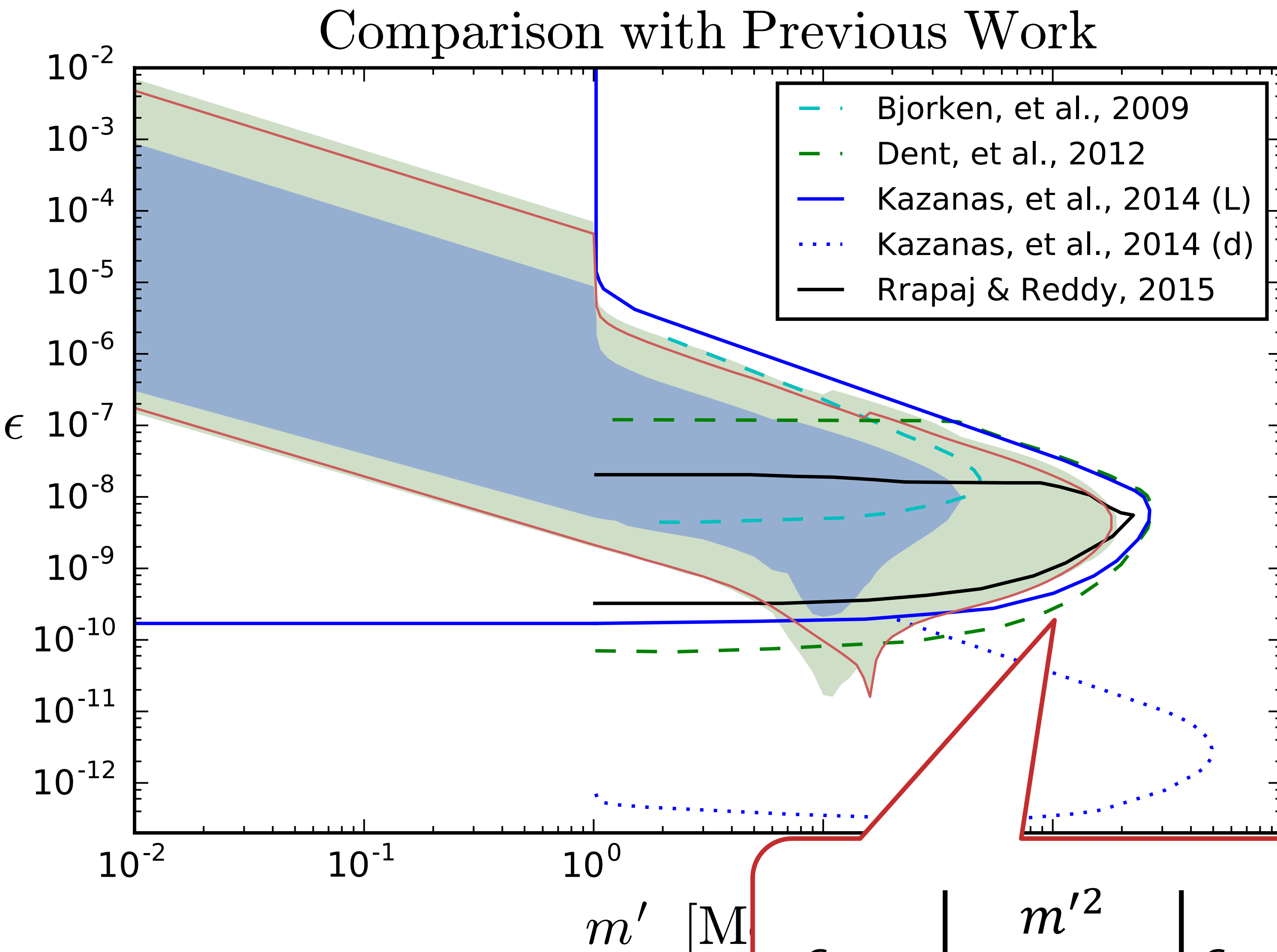
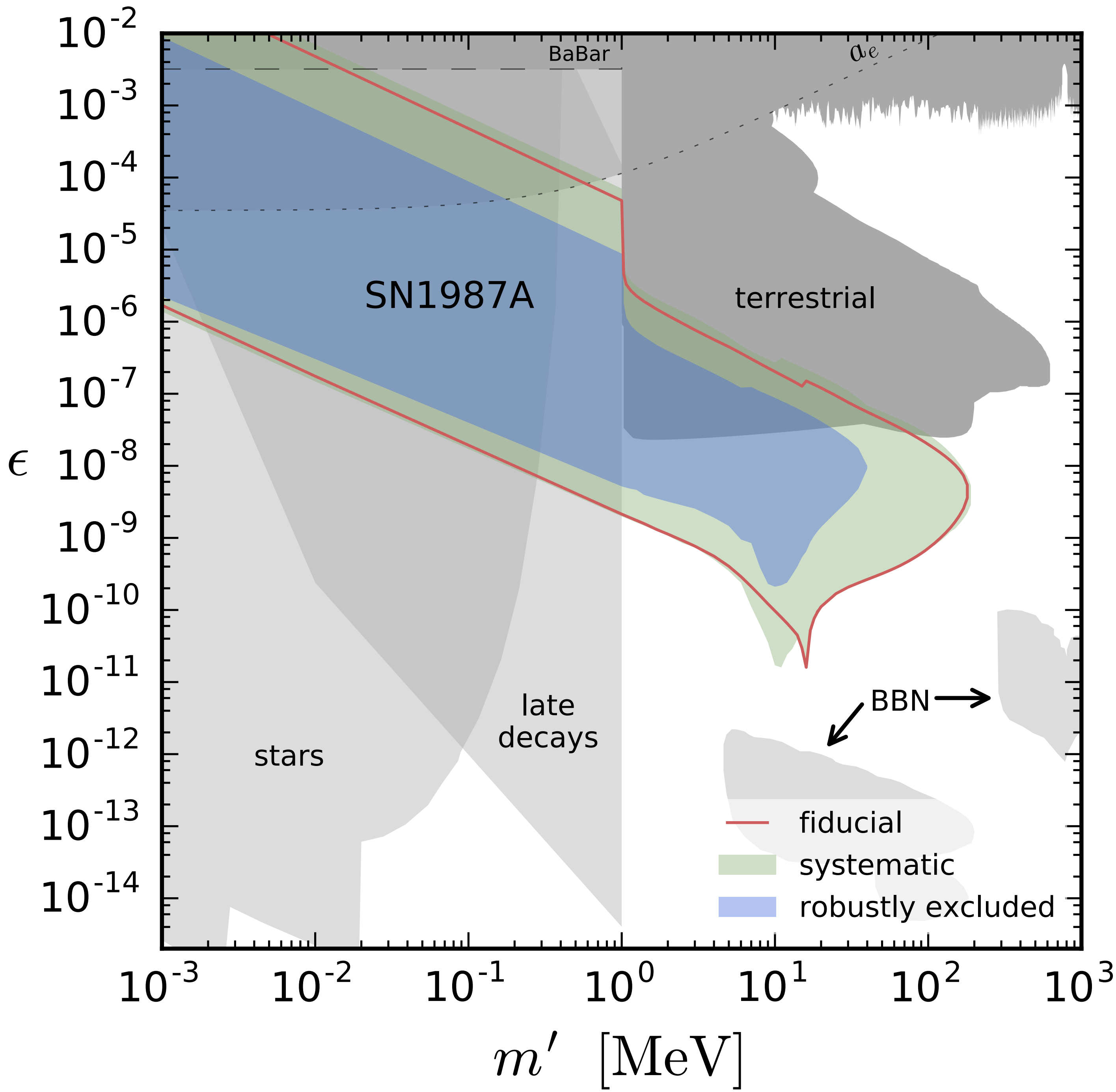
ϵ
10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
10^{-2} 10^{-1} 10^{0} 10^{1}
m' [MeV]
There is a dip at
$m' \sim \omega_p$



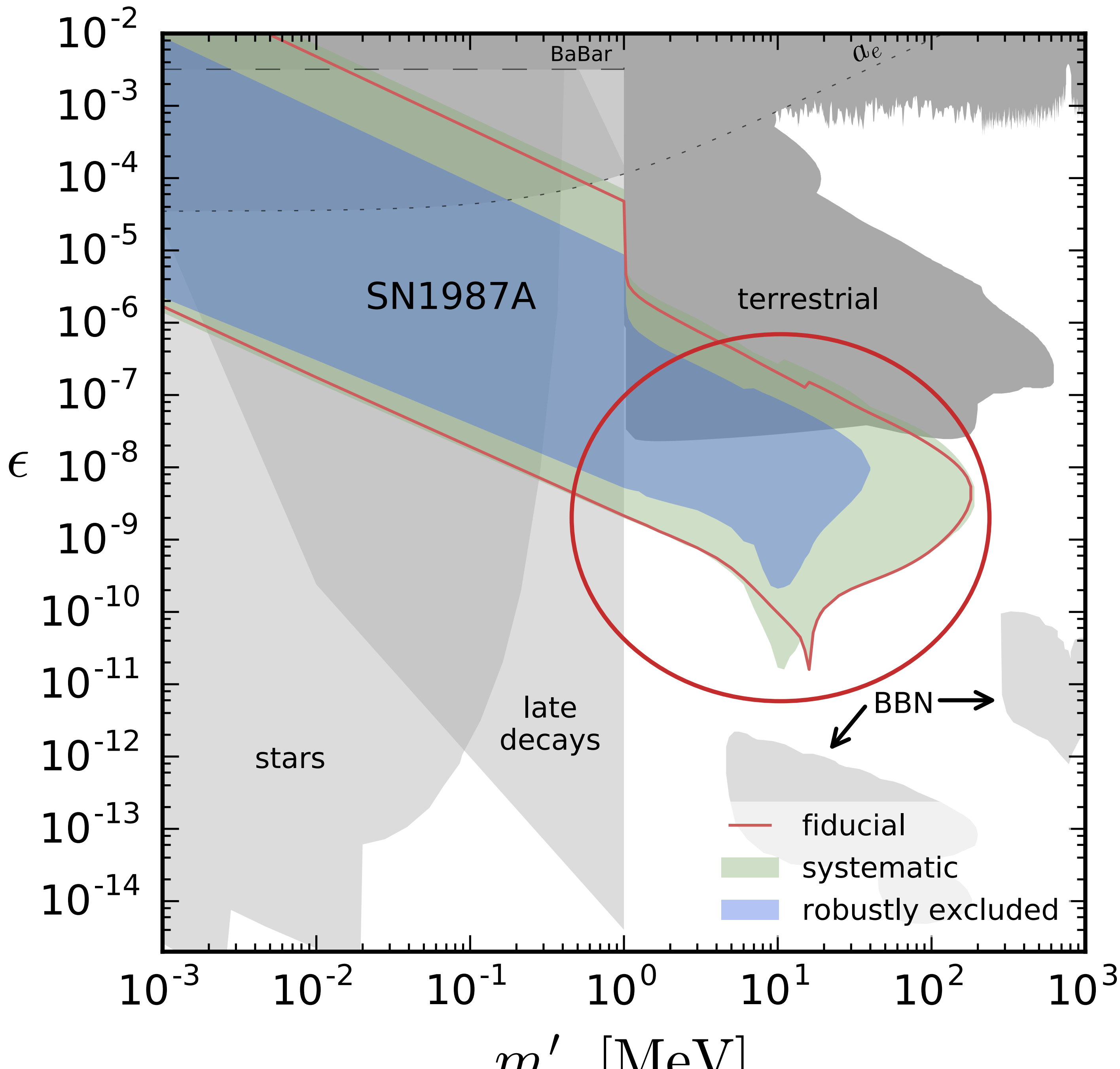
$$\epsilon_m \approx \left|\frac{m'^2}{m'^2 - \omega_p^2}\right| \epsilon \gg \epsilon$$



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



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

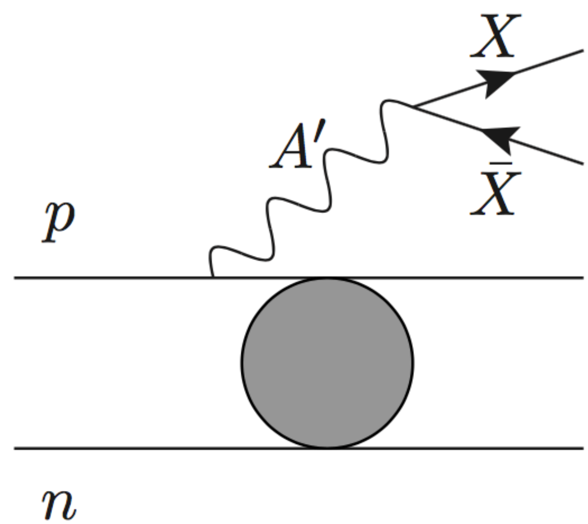


10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
ϵ
BaBar
α_e
SN1987A
terrestrial
BBN
stars
late decays
fiducial
systematic
robustly excluded
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
m' [MeV]

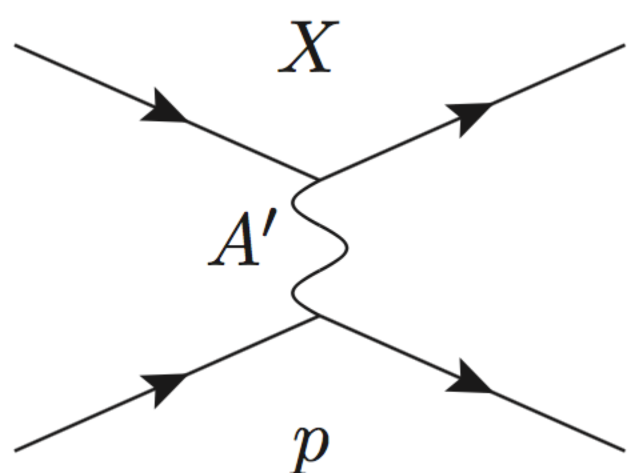
DARK SECTOR FERMIONS

- Fermion charged under $U(1)'$: χ
- χ is stable → Dark matter candidate
- χ can carry more energy to outside of supernova
- Depending on mass hierarchy, dark photon may decay to a $\chi\bar{\chi}$ pair

- Dominant production process

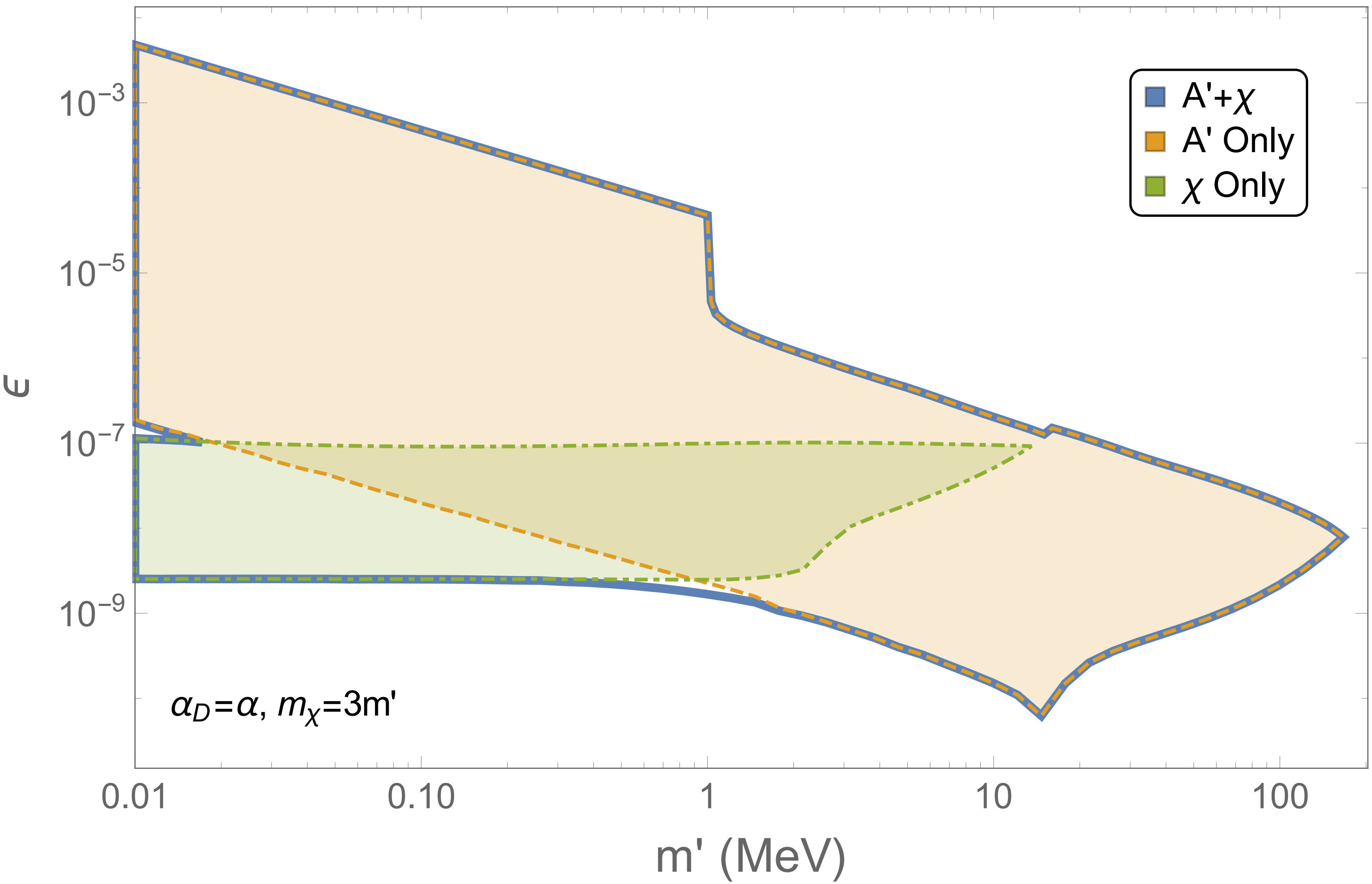


- Trapping Process



Heavy DM

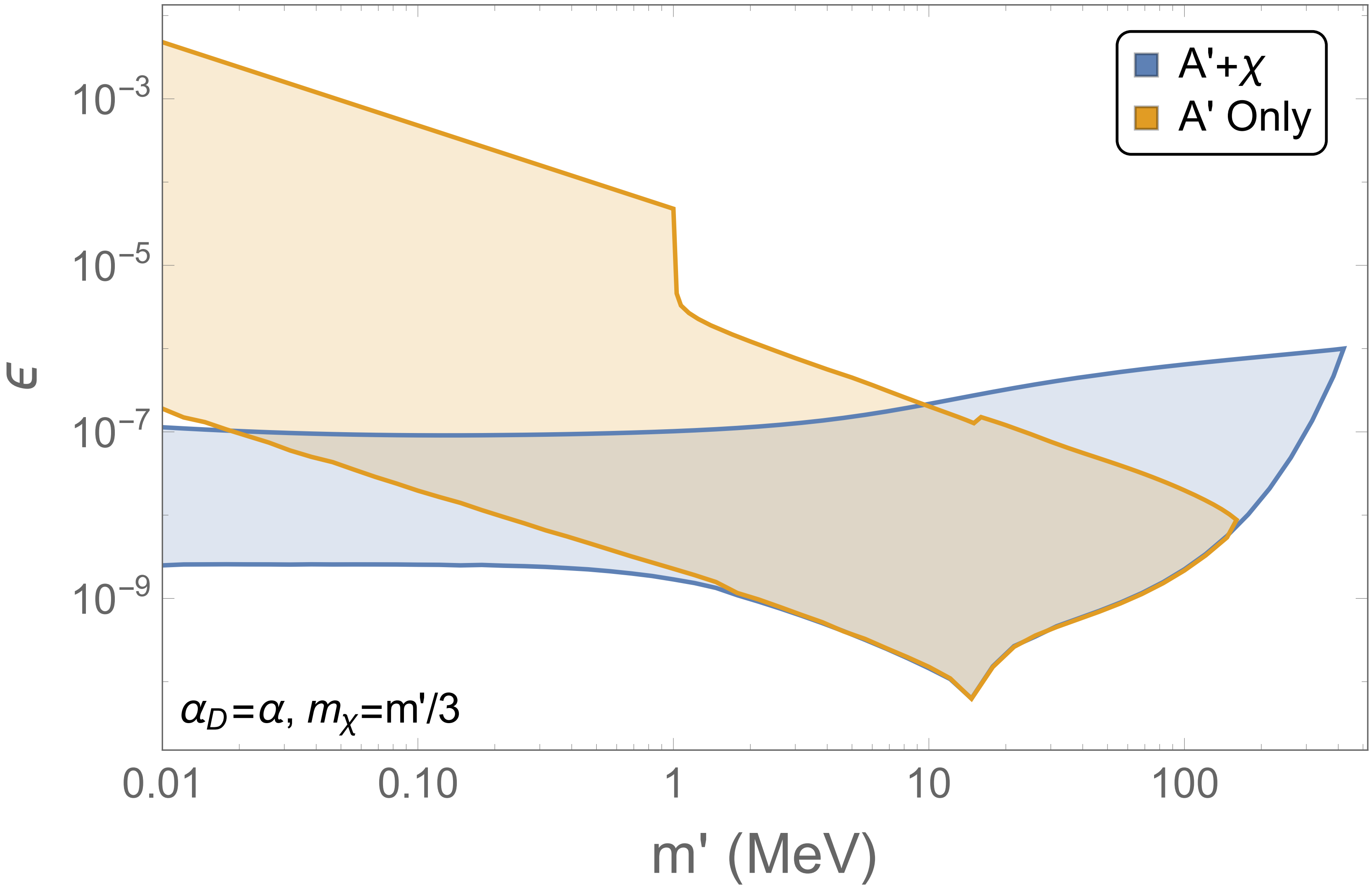
- $m_\chi > \frac{m'}{2}$
- Dark photon cannot decay to $\chi\bar{\chi}$
- χ's are produced through off-shell dark photon
- χ energy flow in addition to dark photon



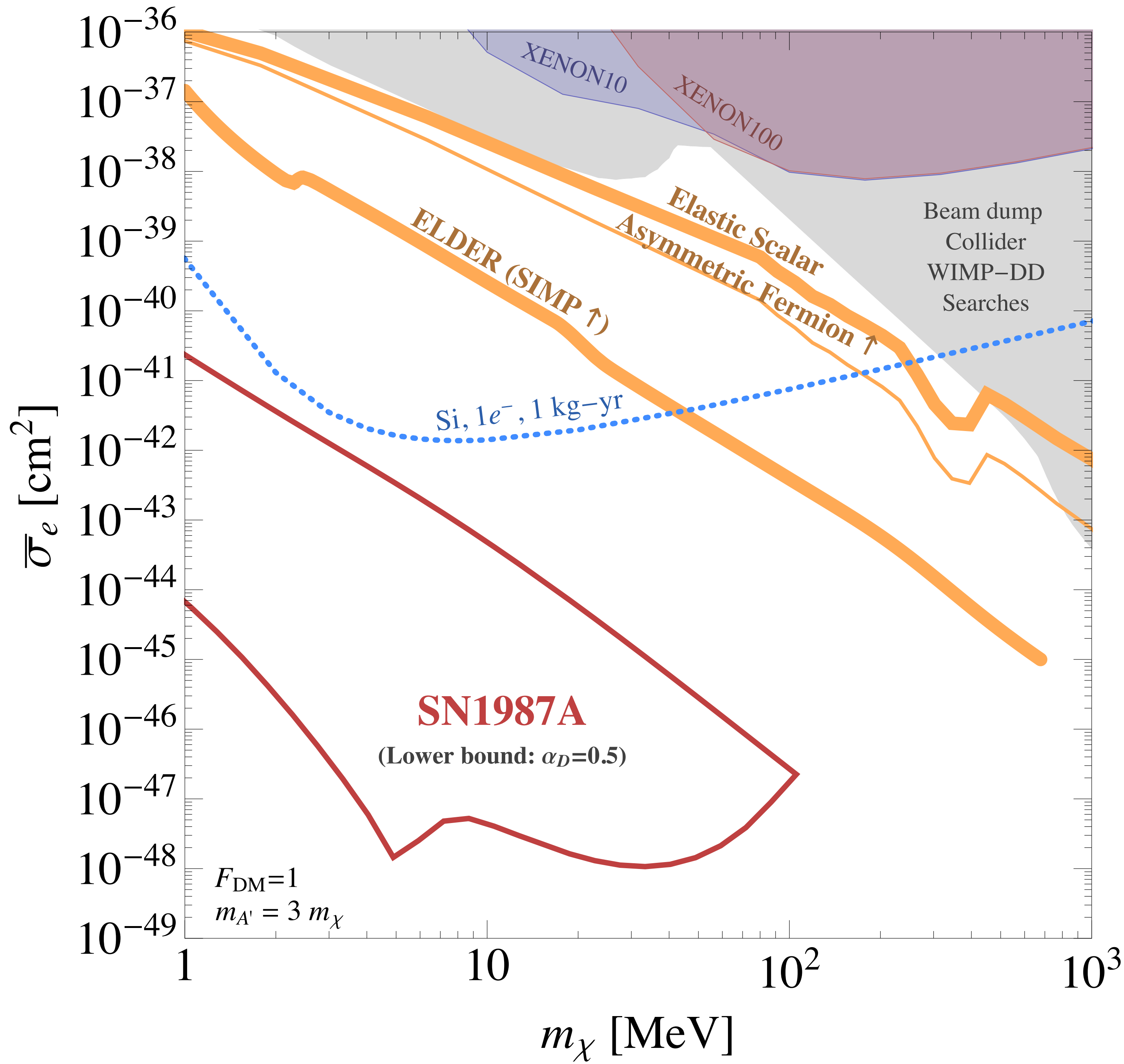
A'+χ
A' Only
χ Only
$\alpha_D=\alpha$, m_χ=3m'
ε
10^{-3}
10^{-5}
10^{-7}
10^{-9}
0.01
0.10
1
10
100
m' (MeV)

Light DM

- $m_\chi < \frac{m'}{2}$
- Dark photons decay to $\chi\bar{\chi}$
- All the novel energy flow is through χ
- The upper bound is determined only from χ particles



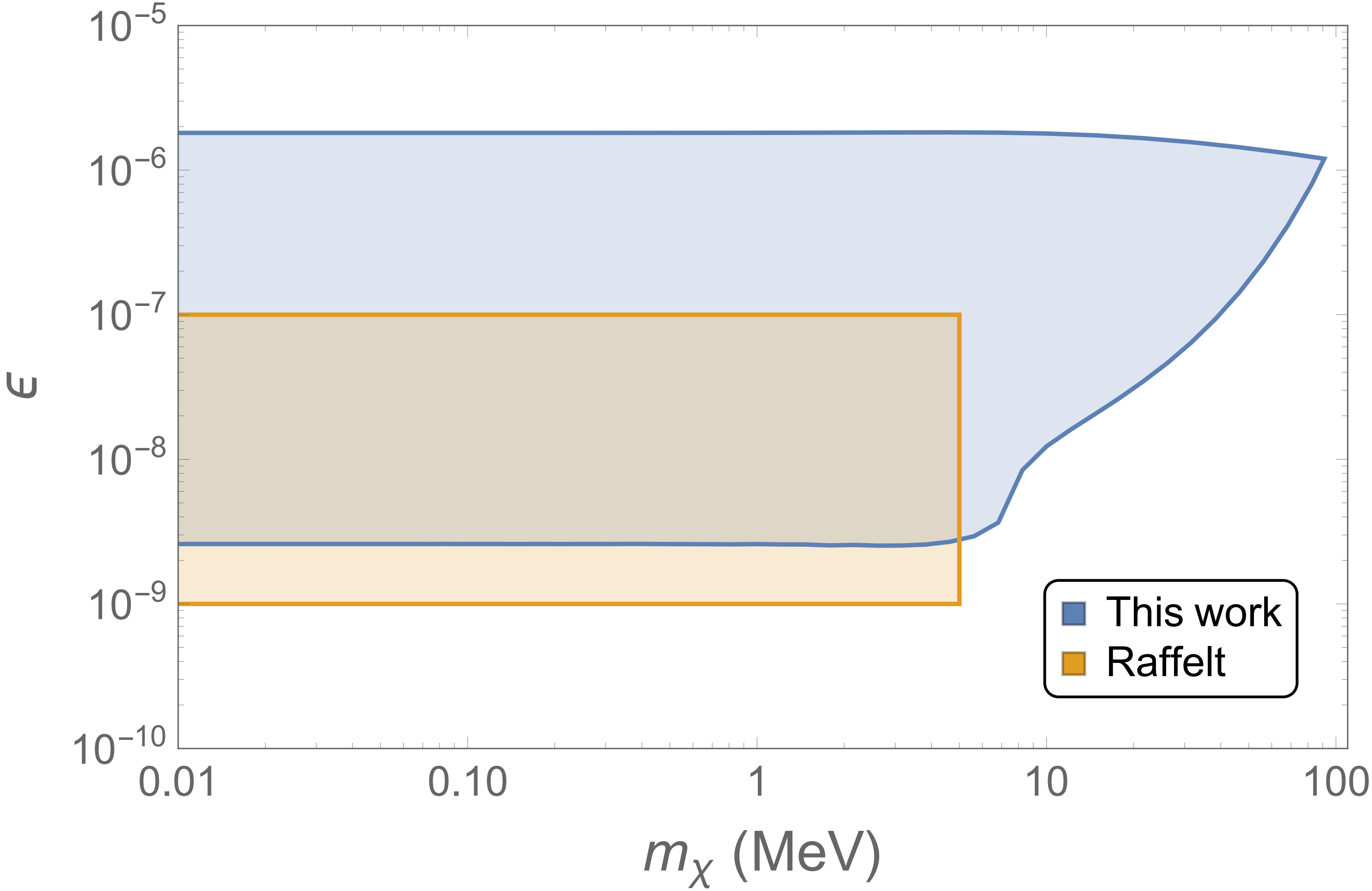
A'+χ
A' Only
10^−3
10^−5
10^−7
10^−9
ϵ
α_D=α, m_χ=m'/3
0.01
0.10
1
10
100
m' (MeV)



XENON10
XENON100
Elastic Scalar
Asymmetric Fermion ↑
ELDER (SIMP ↑)
Beam dump
Collider
WIMP−DD
Searches
Si, 1e⁻, 1 kg−yr
SN1987A
(Lower bound: α_D=0.5)
F_{DM}=1
$m_{A'} = 3\ m_\chi$
$\overline{\sigma}_e$ [cm²]
m_χ [MeV]

Milli-charged DM

- χ has a small electric charge ϵe
- $m' = 0$ case
- No on-shell dark photon production



10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
ϵ
0.01
0.10
1
10
100
m_χ (MeV)
This work
Raffelt

CONCLUSION

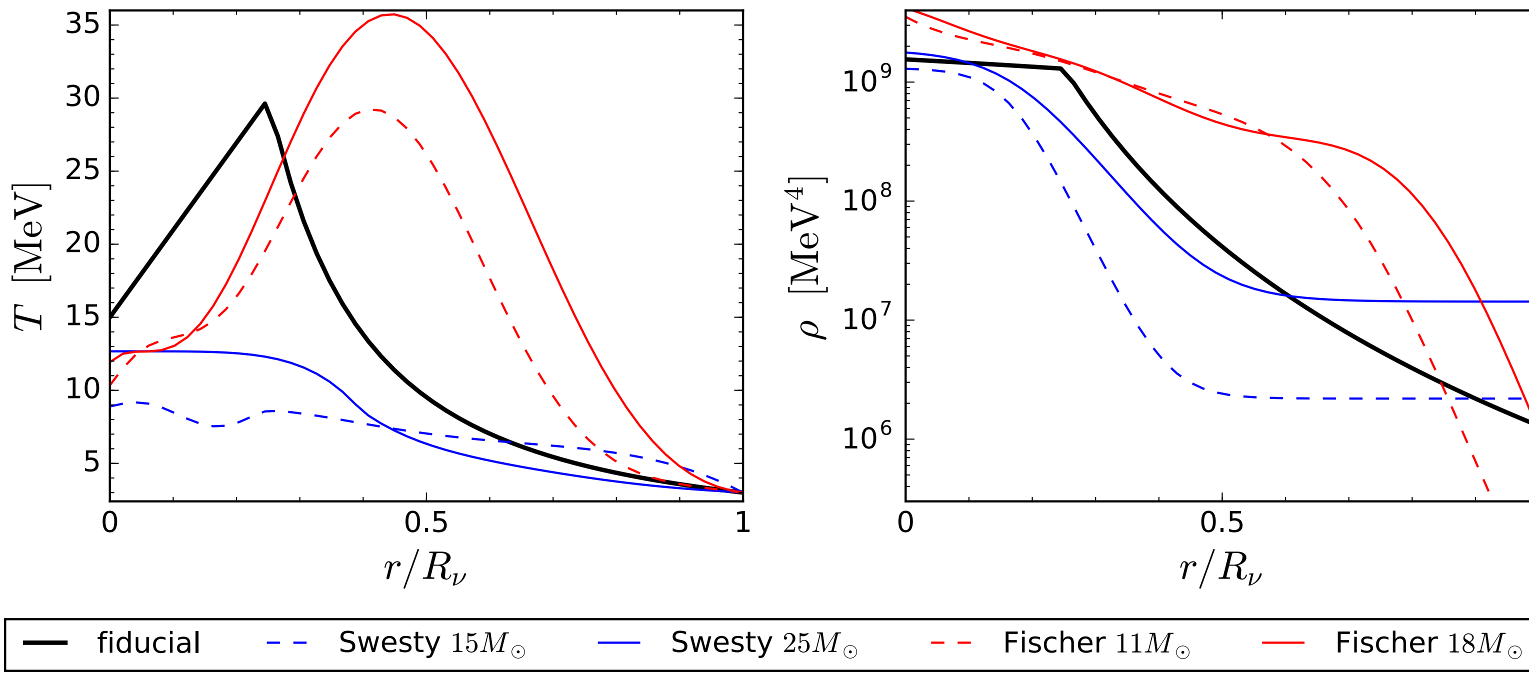
Conclusion

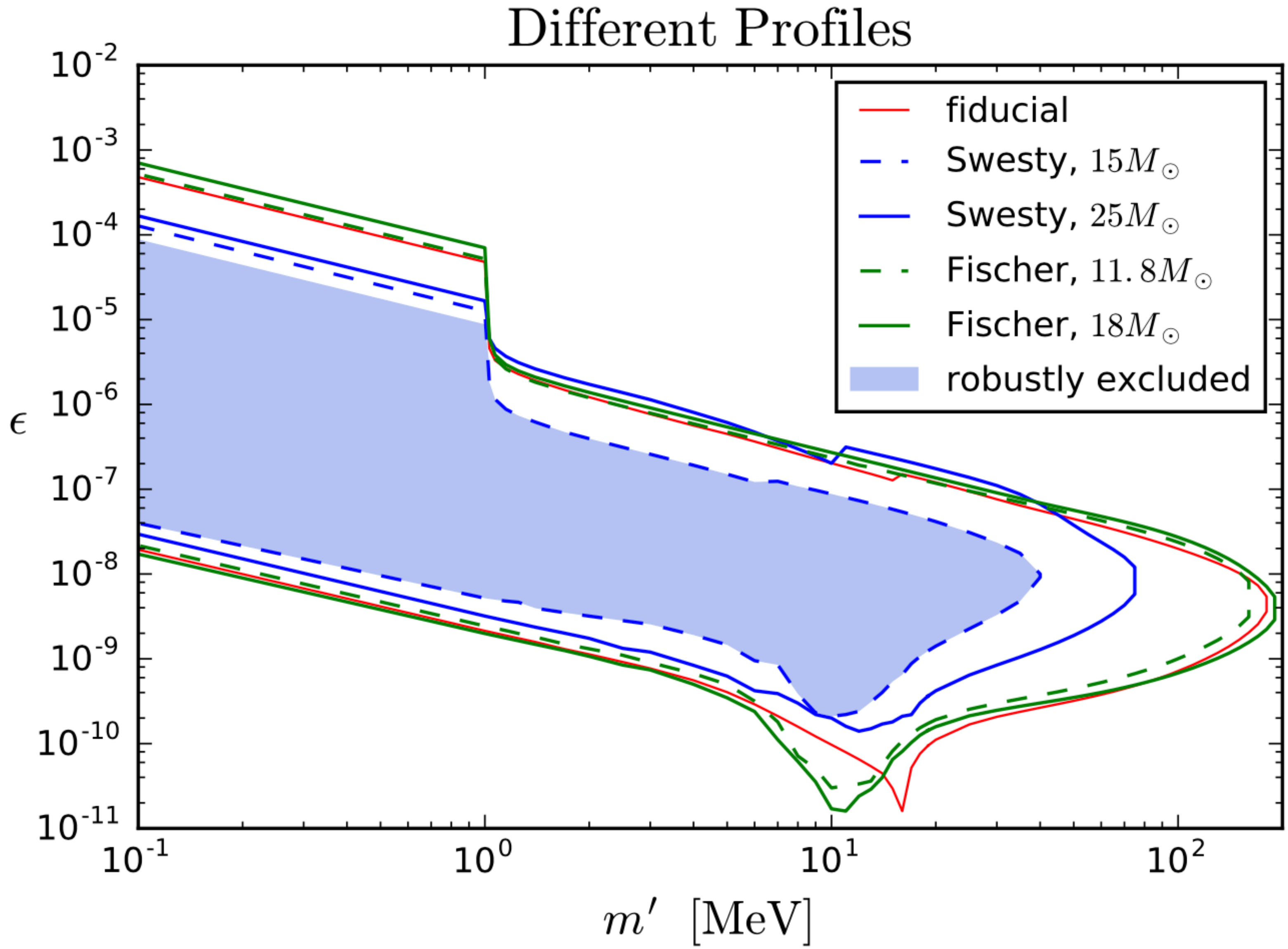
- Supernova1987A can give constraints on low-mass dark sector particles
- For the dark photon models, thermal effects have a crucial role
- We calculated constraints for the pure dark photon, the dark sector fermions, and the milli-charged DM, and constraints for the inelastic DM are in progress

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}

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

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

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

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

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