Supernova 1987A Constraints on Low-Mass Dark Sectors

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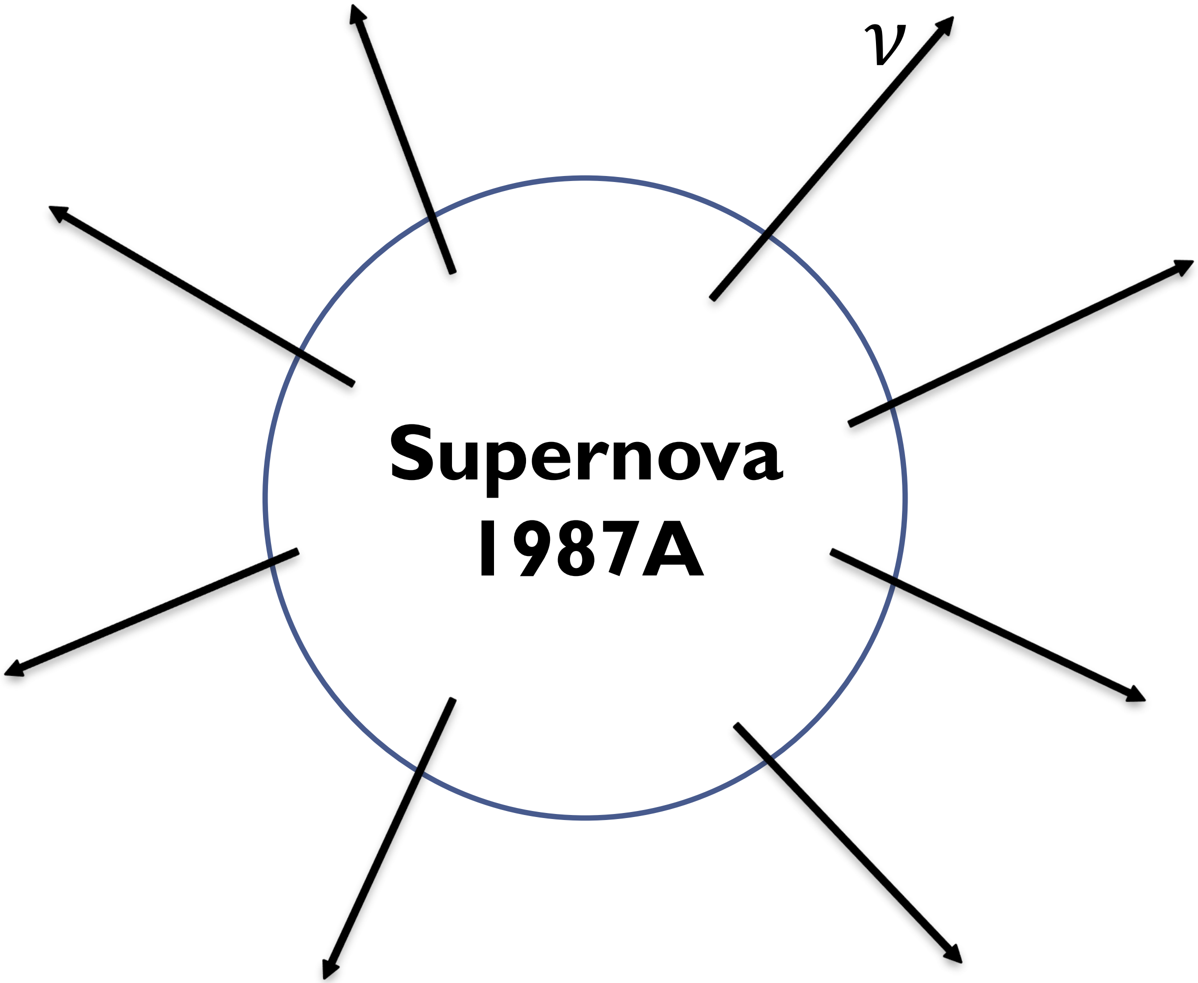
SUPERNOVA 1987A

Supernova 1987A

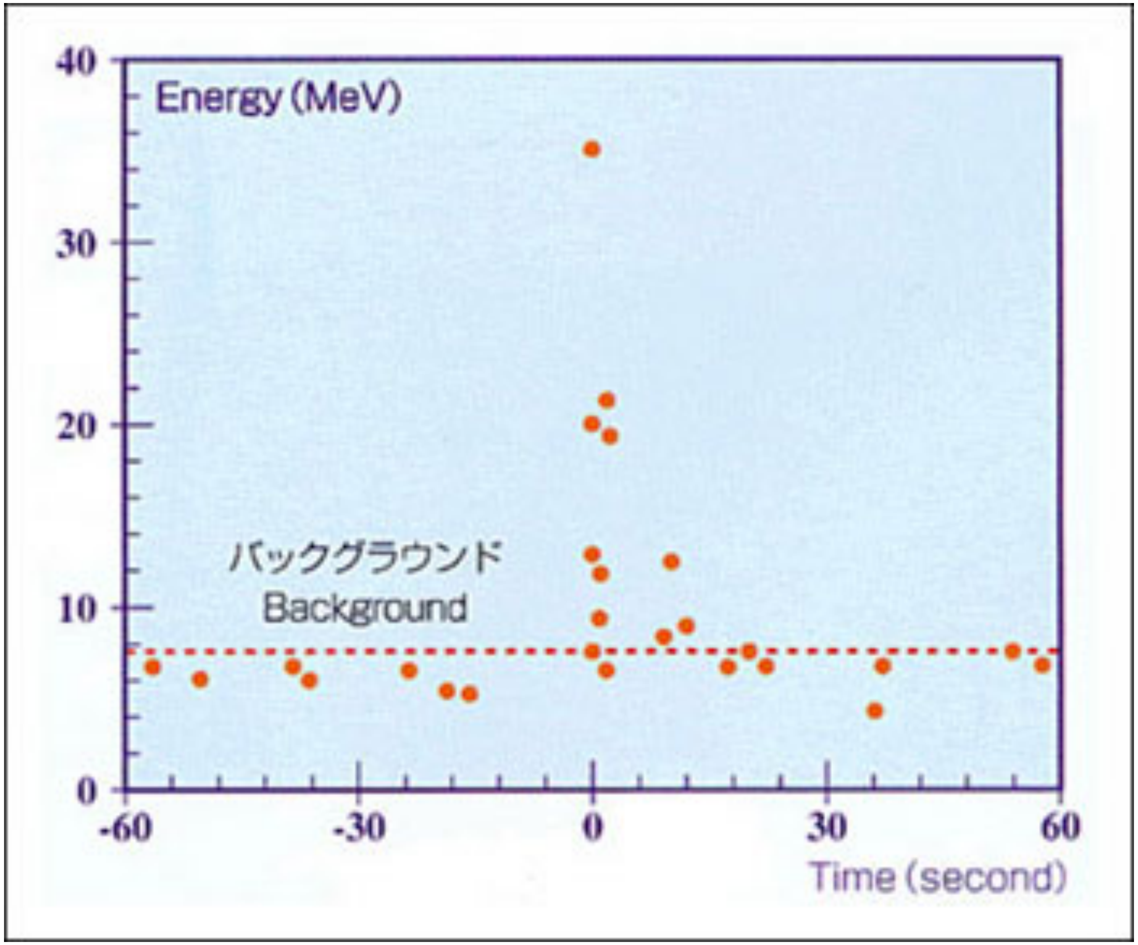
- Type II Supernova observed in 1987
- Closest supernova since Kepler (~50 kpc)
- The only supernova that neutrinos from supernova explosion were detected
- Can be used to constrain new particles

Supernova 1987A



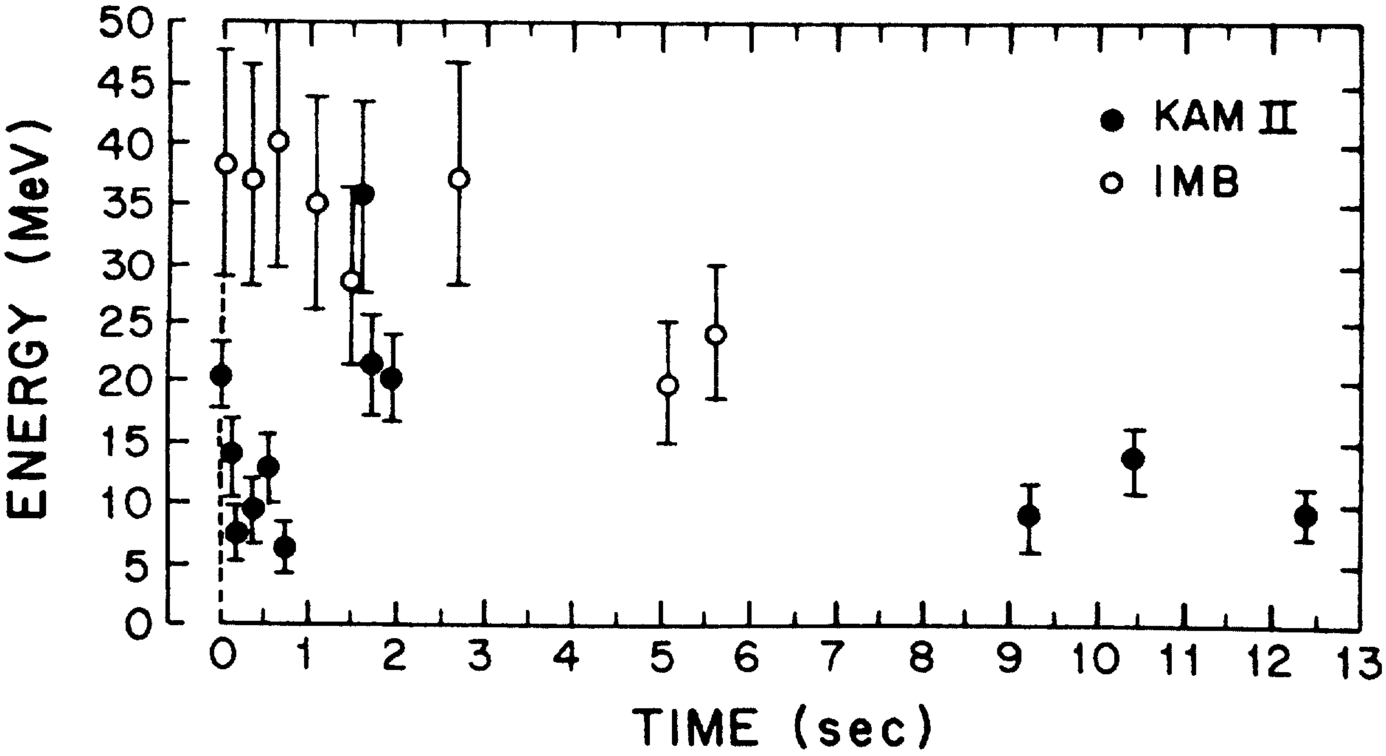
Supernova 1987A

- 99% of energy is carried by neutrinos

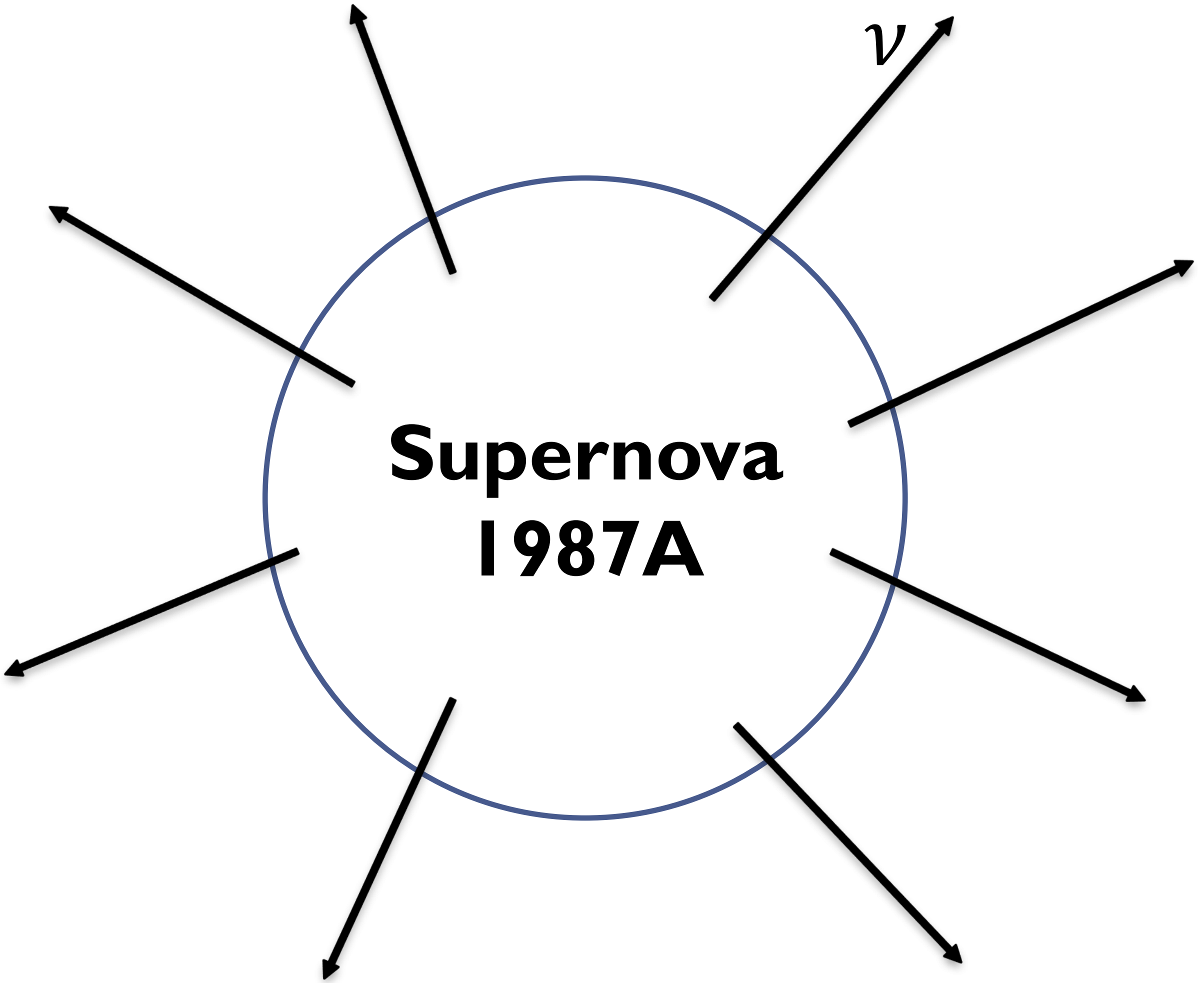


- Kamiokande II, IMB, and Baksan detected the neutrinos at the same time

Hirata et al, 1988

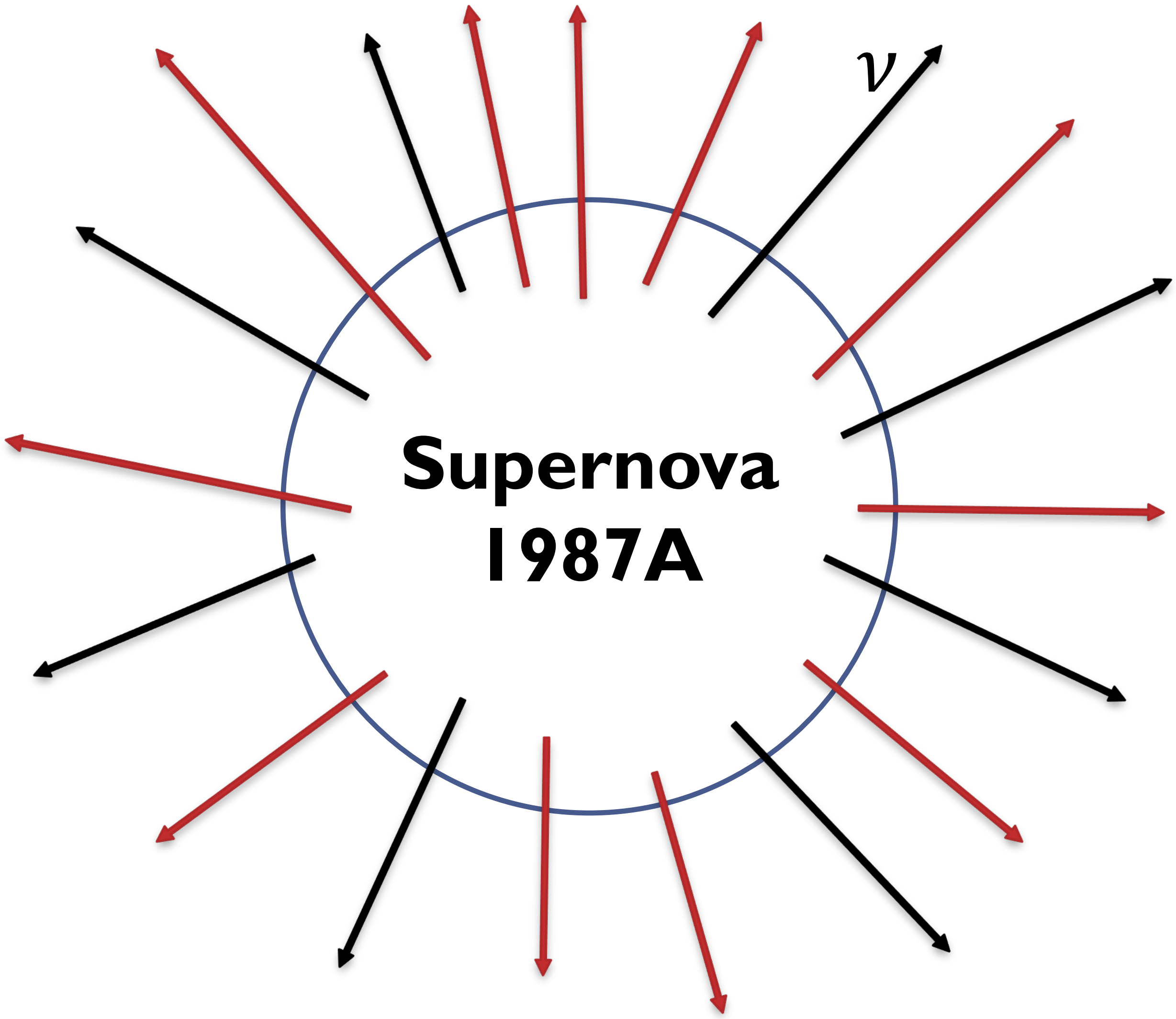


- Cooling time : ~10 seconds
- Consistent with the SM prediction



Supernova 1987A

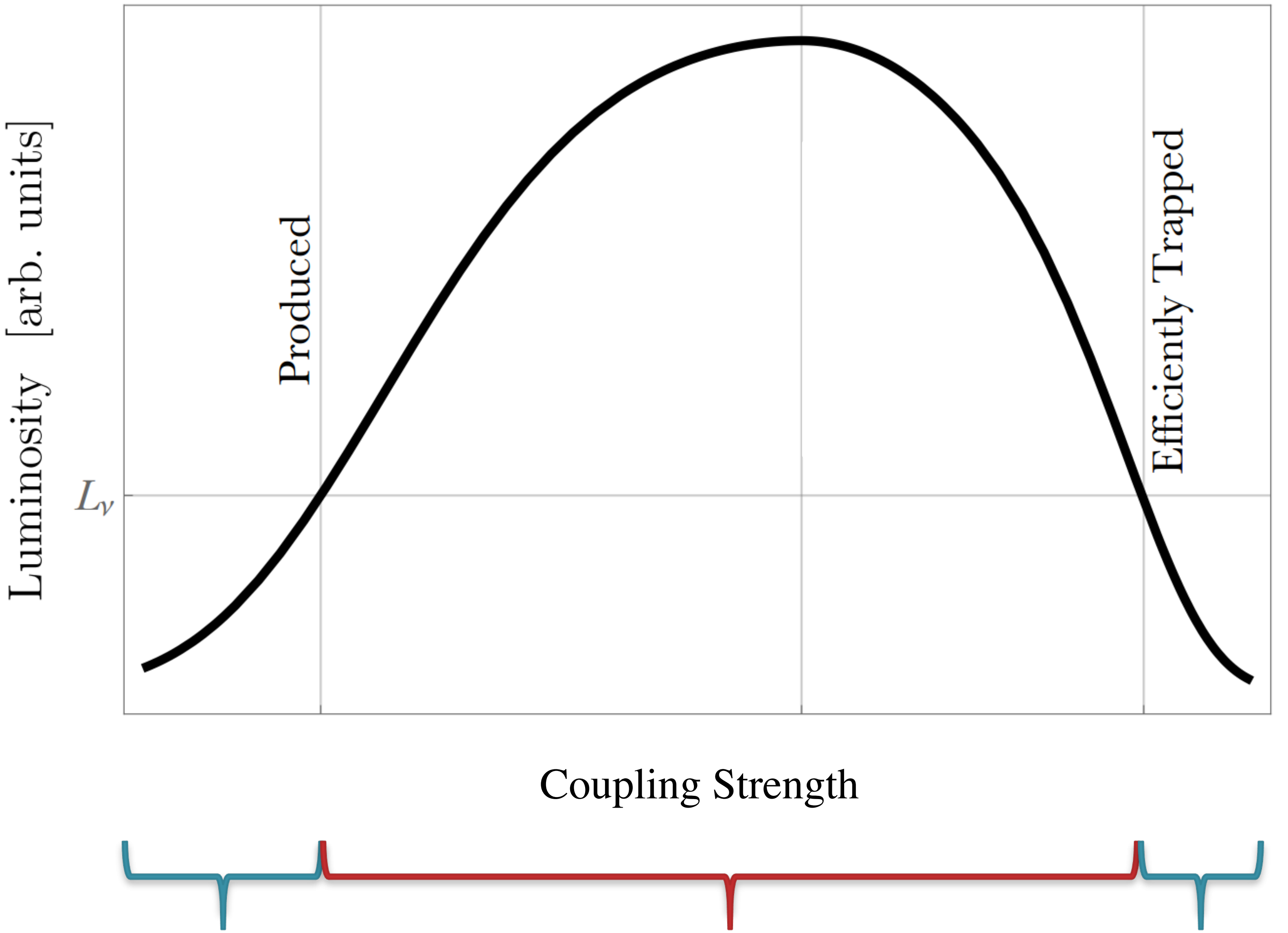
- If a new particle exists



- Supernova cools faster

Raffelt Criterion

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



Allowed

Excluded

Allowed

Supernova Constraints

- **Any type of light novel particles** coupled to the SM can be constrained
- $m \lesssim T_c \approx 30\ MeV$
- The new particle doesn’t need to be relic dark matter
- Provides reasonable lower bounds for experiment searches

Supernova Constraints

- Pure dark photons
- Dark sector fermions
- Inelastic dark matter
- Millicharged particles
- QCD Axions
- Axion-like particles

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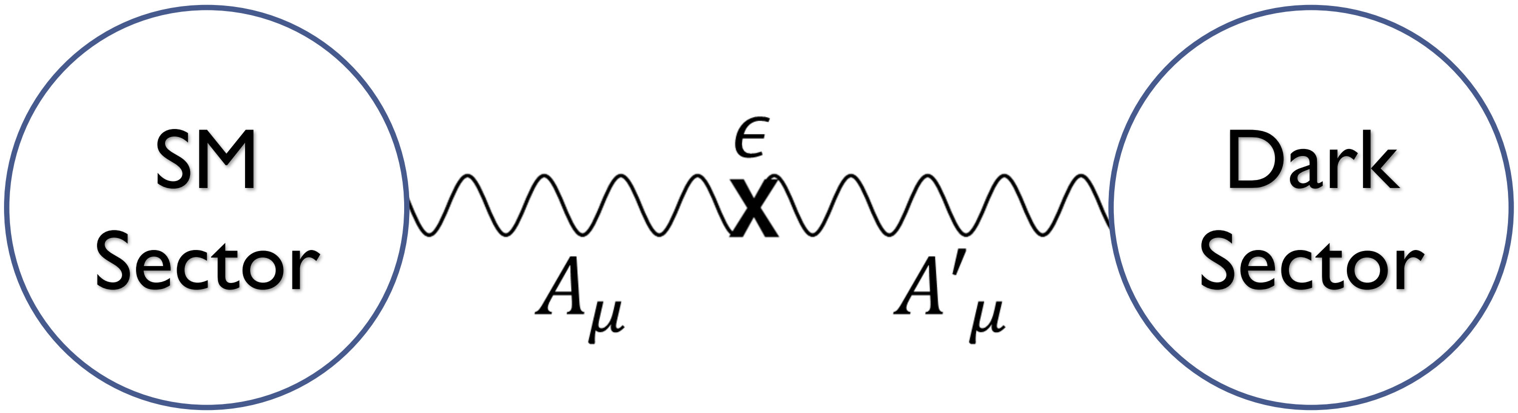
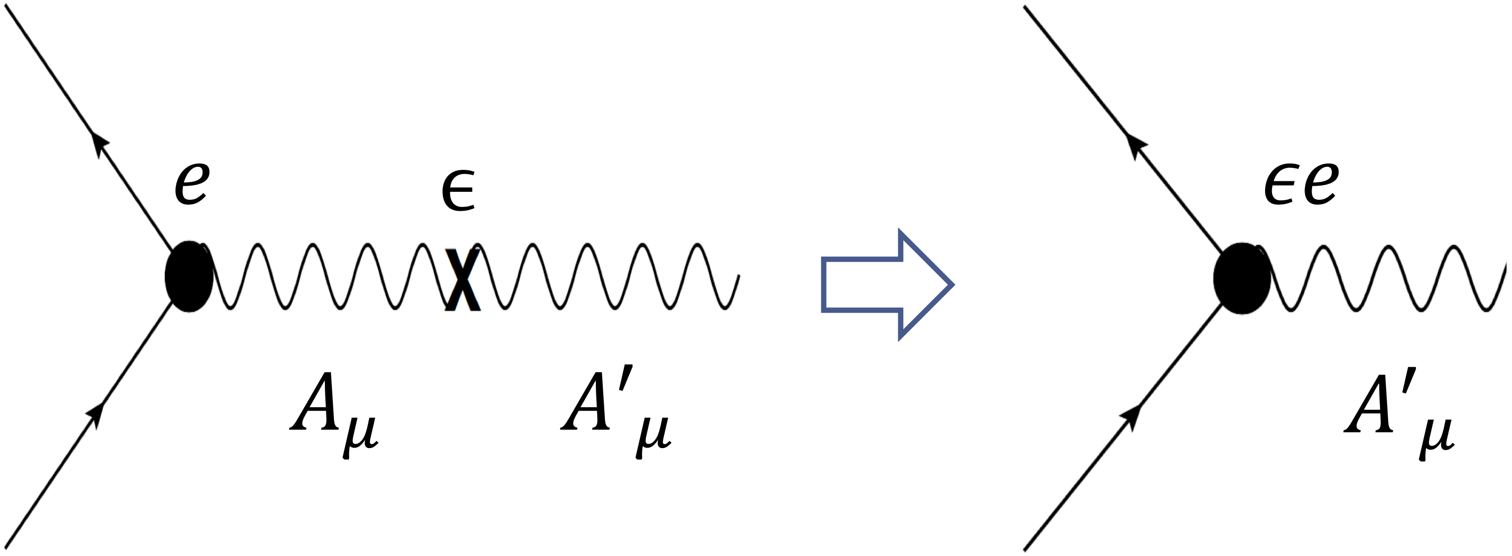
PURE DARK PHOTON



- $SU(3)_c \times SU(2)_L \times U(1)_Y \times \boldsymbol{U(1)'}$
- Dark photon (A') is the gauge boson of $U(1)'$
- In low energies, $\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$

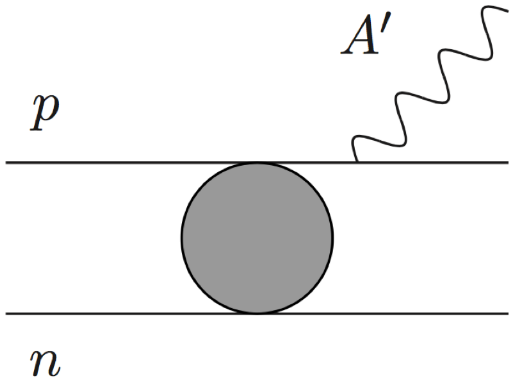


- Dark photon couples to charged SM particles with charge ϵe:

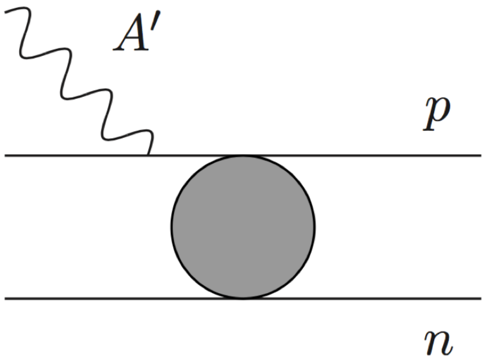
$$\mathcal{M} \propto e \times \frac{1}{q^2} \times \epsilon q^2 = \epsilon e$$

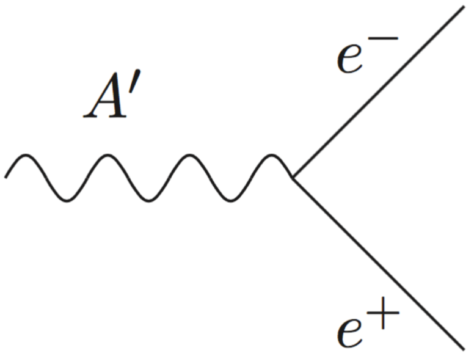
$$\mathcal{L} \supset \epsilon e J^{\mu}_{EM} A'_\mu$$

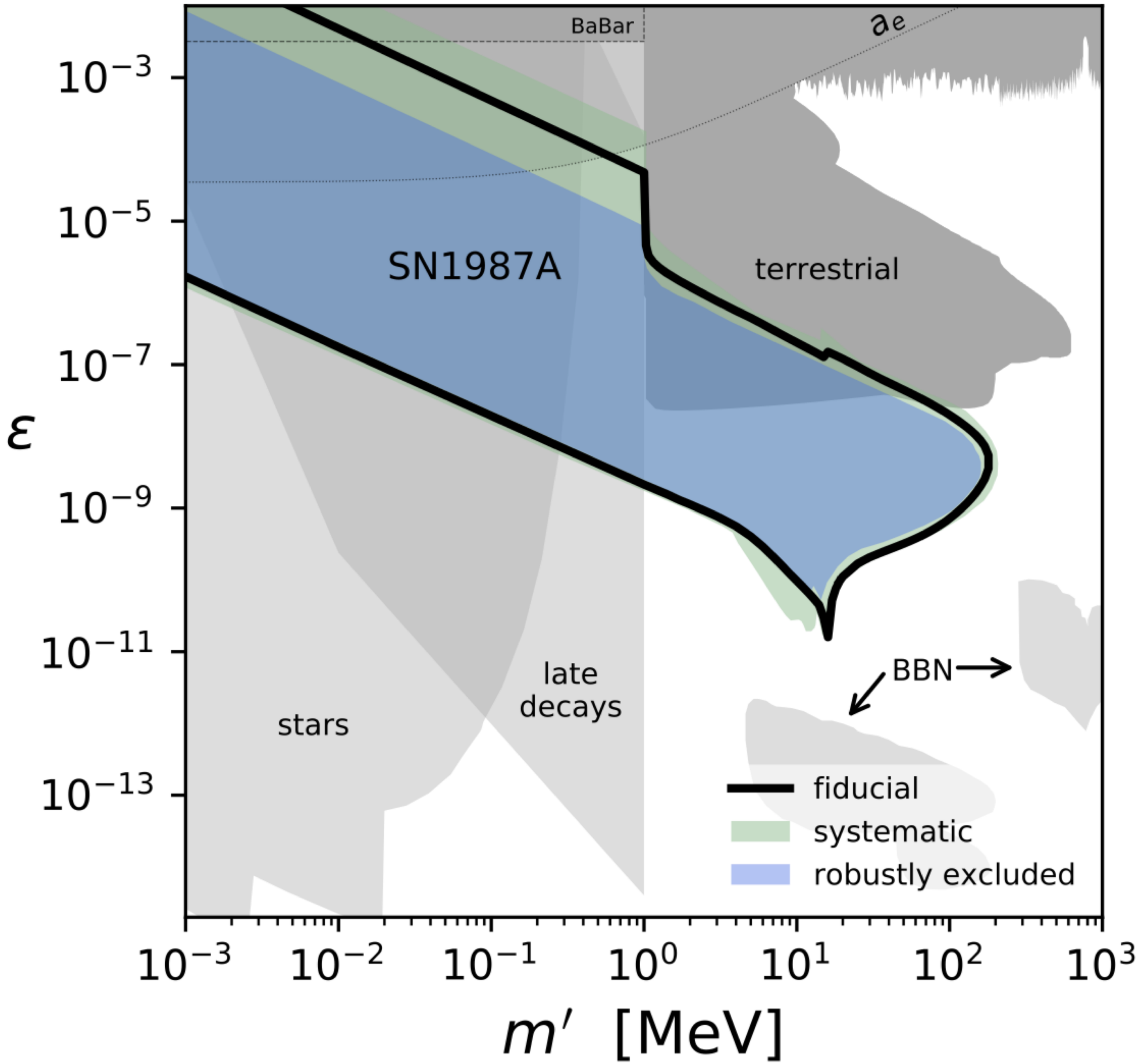
- Dominant production process



- Trapping Process






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

Novelties in this Work(s)

- Varying temperature and density profiles
- Novel treatment for the upper bounds
- Included the thermal effects to the supernova environment for the first time

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Photons in Supernova

- High temperature and high electron density in SN change photon behaviors

- Since dark photon interactions to SM particles are always through photons, must consider these effects

Photons in Supernova

- Photon has a different dispersion relation
  - Photon gets a plasma mass
  - Photon has a longitudinal polarization
- Photon can be produced/absorbed from/into the plasma
- Can be described with polarization tensors

Real Part of Polarization Tensor

- $\omega^2 - k^2 = \mathrm{Re}\Pi$

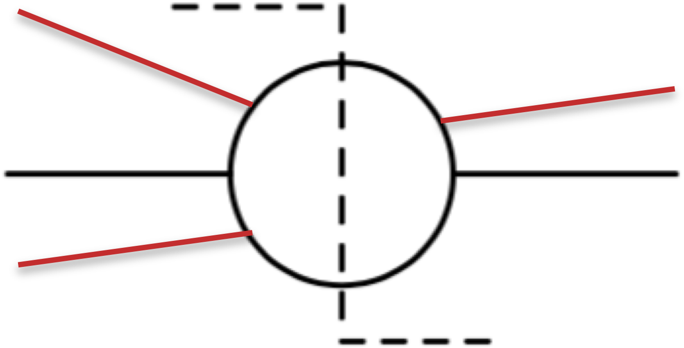
- $\mathrm{Re}\Pi$ acts like a photon mass

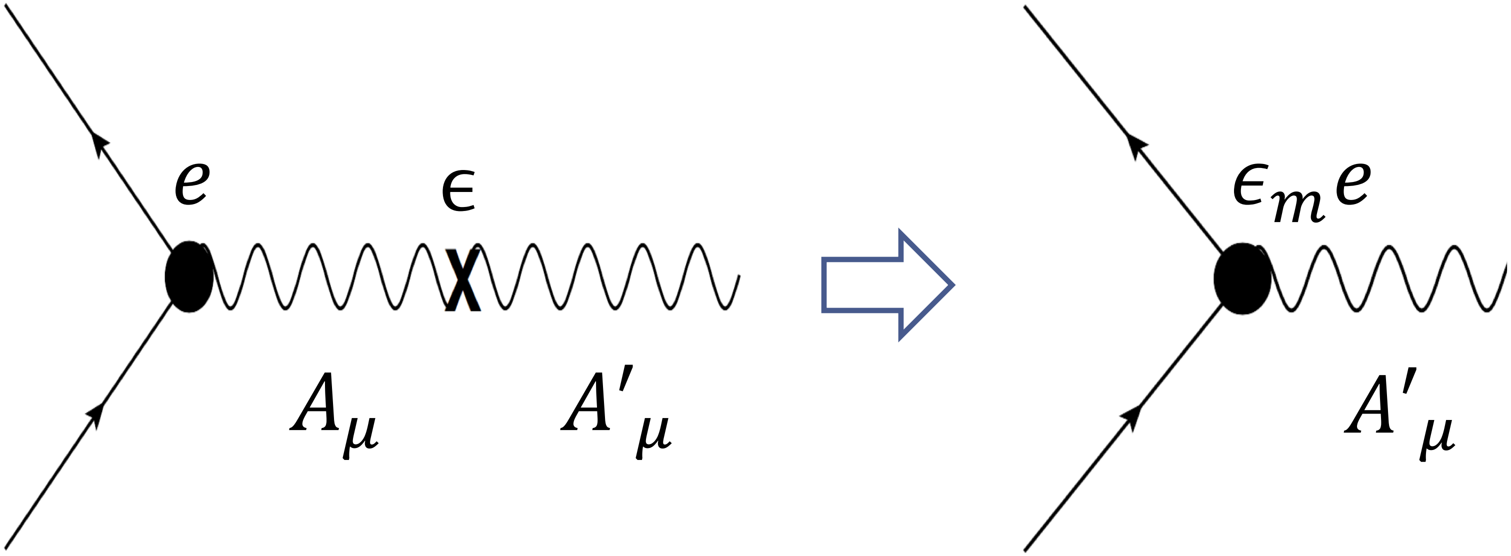
- $\mathrm{Re}\Pi \approx \omega_p^2$
  $\omega_p \sim 15\mathrm{MeV}$ is the plasma frequency

Imaginary Part of Polarization Tensor

- From the optical theorem, but diagrams includes background particles

- $\mathrm{Im}\Pi = \omega\left(\Gamma_{\mathrm{abs}} - \Gamma_{\mathrm{prod}}\right)$





- In supernova,

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

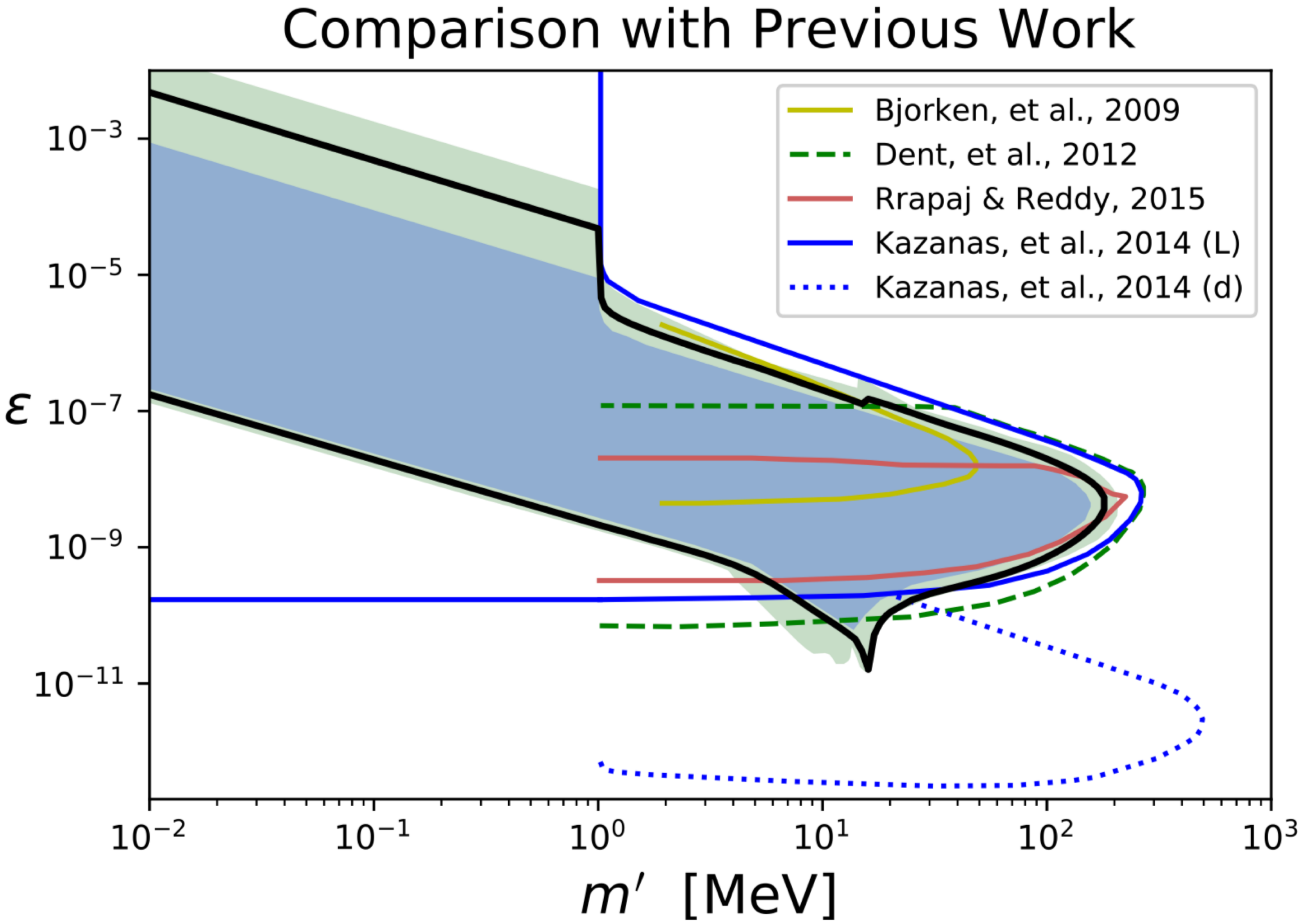
$$\mathcal{L} \supset \epsilon_m e J^{\mu}_{EM} A'_{\mu}, \qquad \epsilon_m \equiv \left|\frac{q^2}{q^2 - \Pi}\right| \epsilon$$

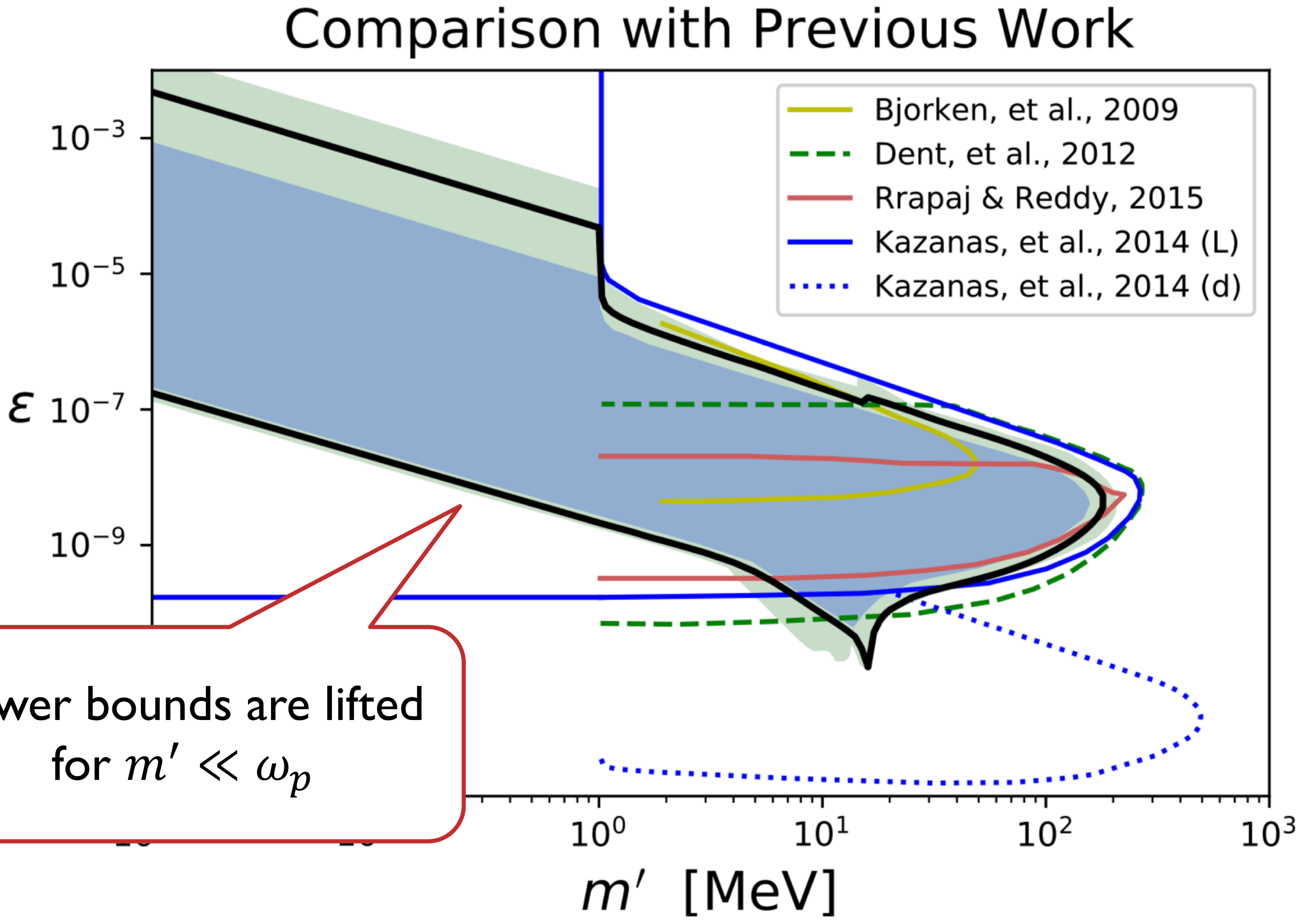
Mixing angle in Supernova

- $\epsilon_m \equiv \left|\frac{q^2}{q^2-\Pi}\right| \epsilon$

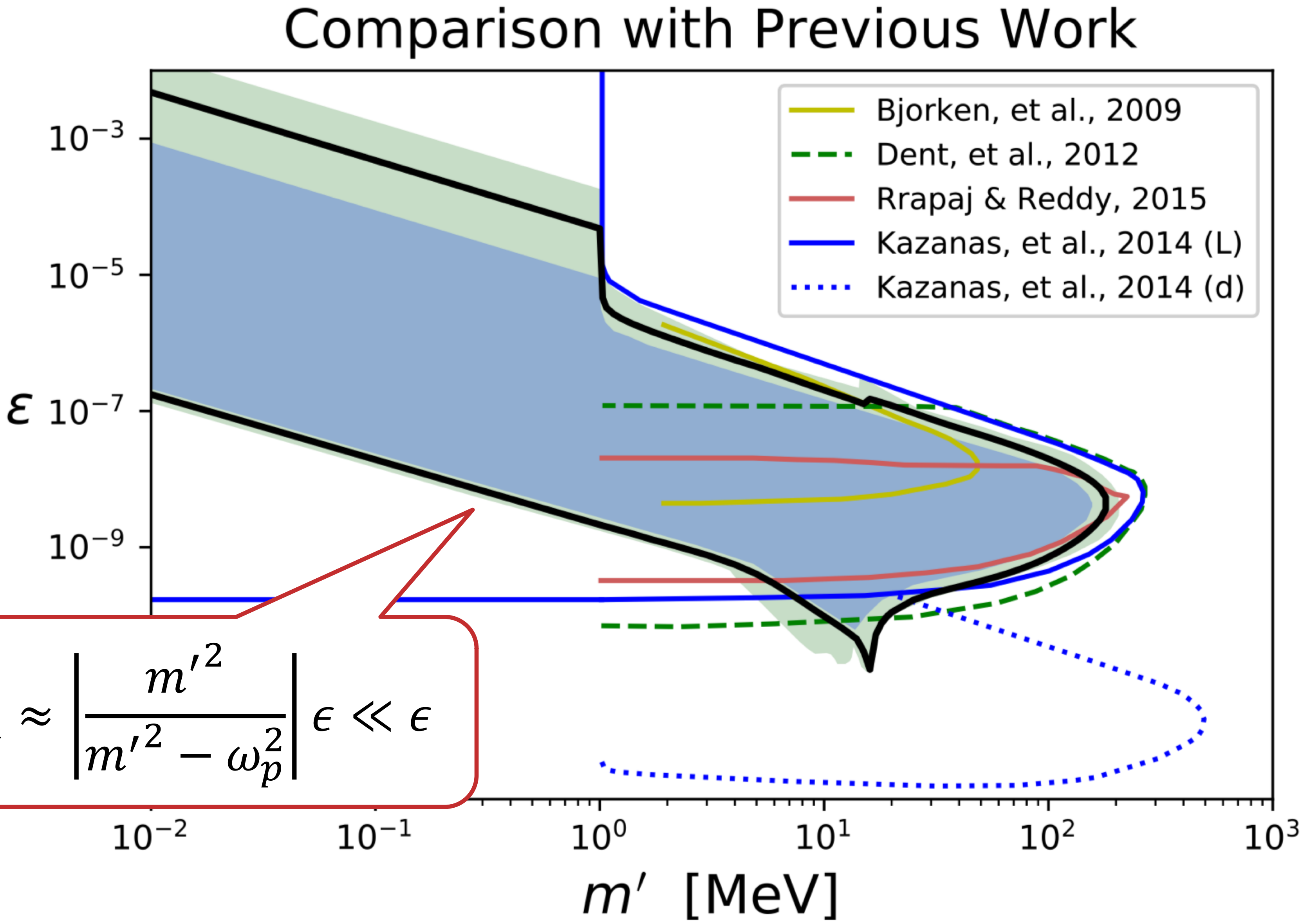
- $\mathrm{Re}\Pi \approx \omega_p^2,\ q^2 = m'^2 \ \rightarrow\ \epsilon_m \approx \left|\frac{m'^2}{m'^2-\omega_p^2}\right| \epsilon$

- $\omega_p \sim 15 MeV$ is the plasma frequency
  - $\epsilon_m \ll \epsilon, \quad m' \ll \omega_p$
  - $\epsilon_m \gg \epsilon, \quad m' \approx \omega_p$
  - $\epsilon_m \approx \epsilon, \quad m' \gg \omega_p$

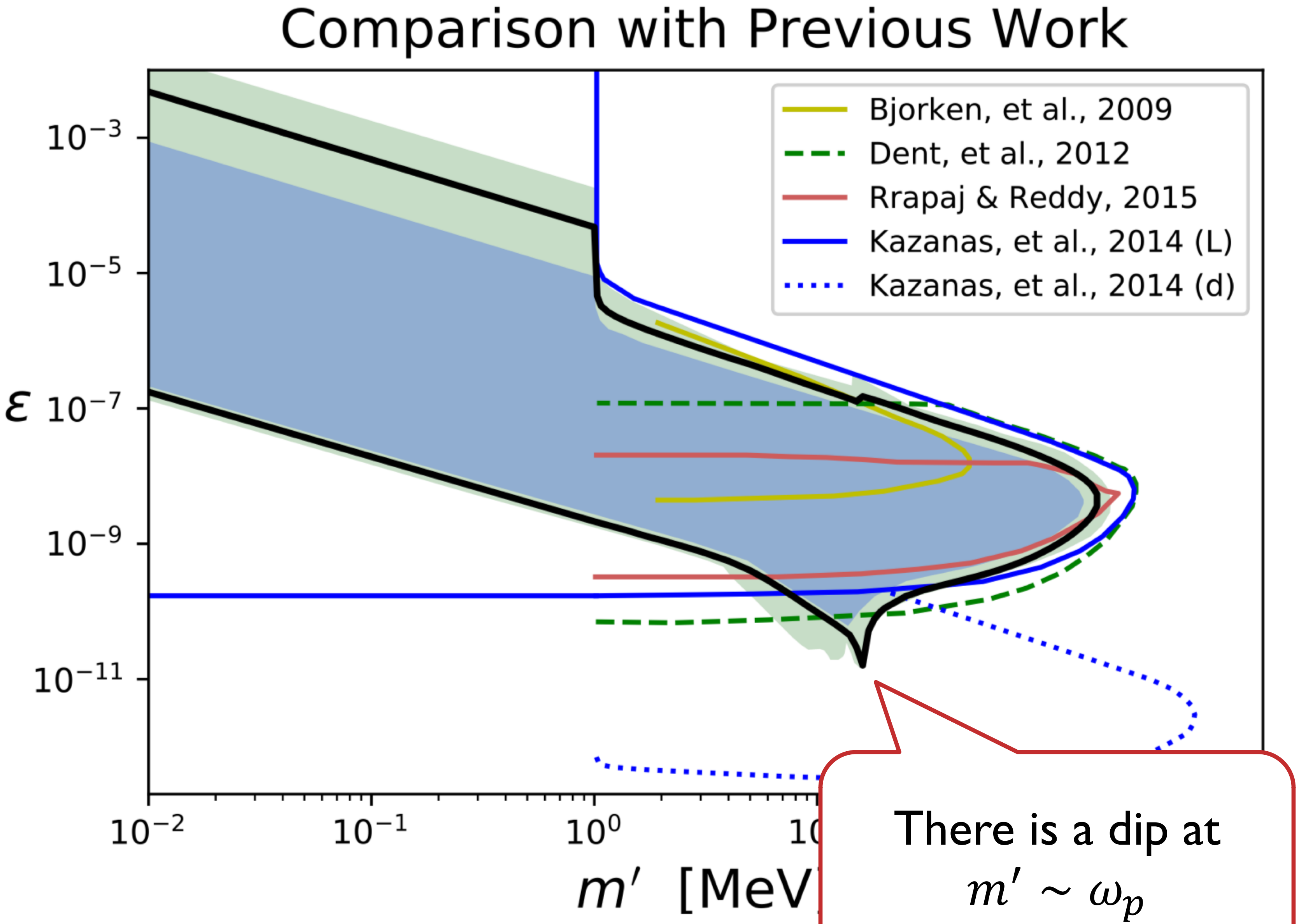

Comparison with Previous Work
Bjorken, et al., 2009
Dent, et al., 2012
Rrapaj & Reddy, 2015
Kazanas, et al., 2014 (L)
Kazanas, et al., 2014 (d)
ε
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
m' [MeV]



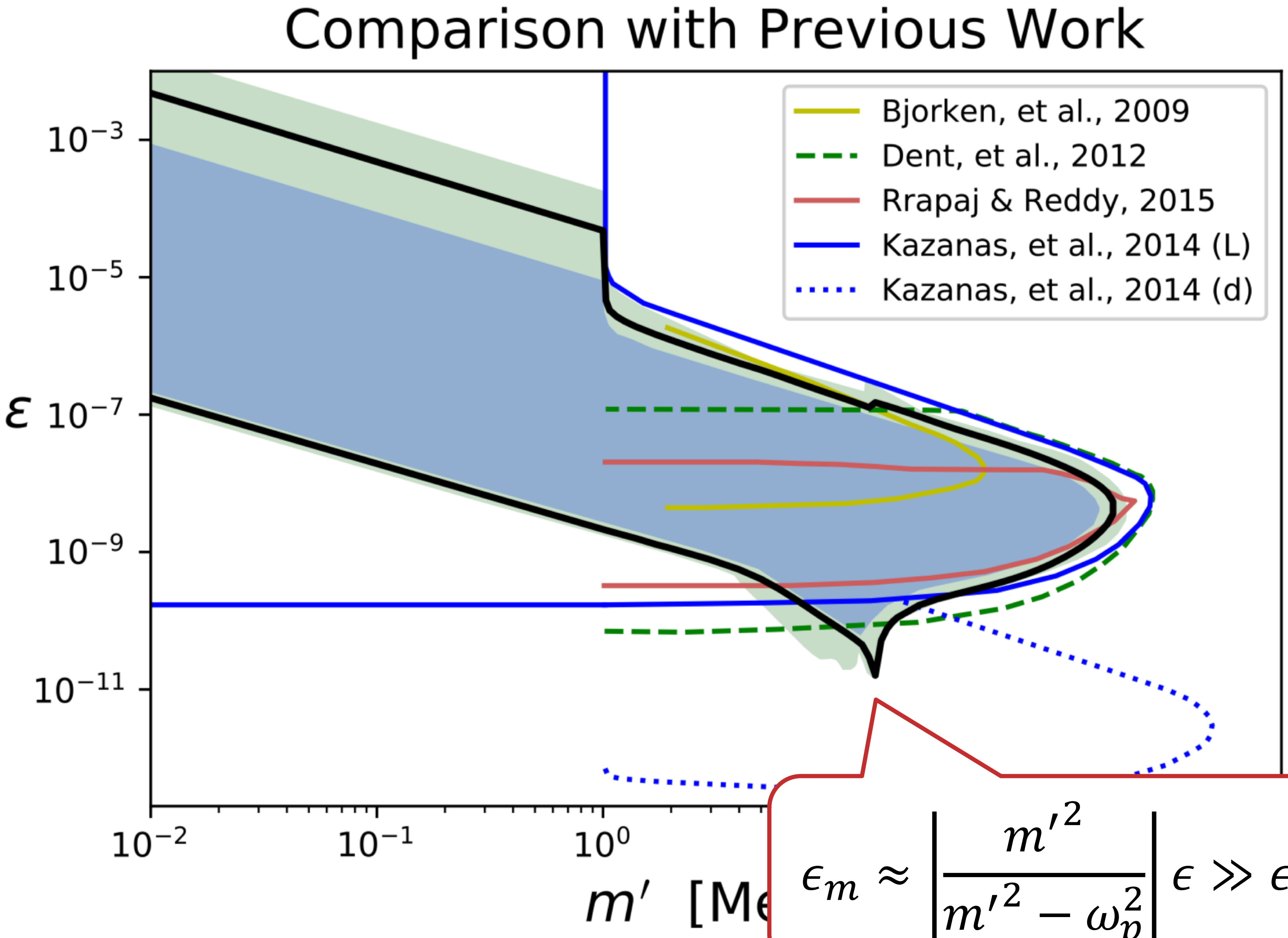
Lower bounds are lifted for $m' \ll \omega_p$



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

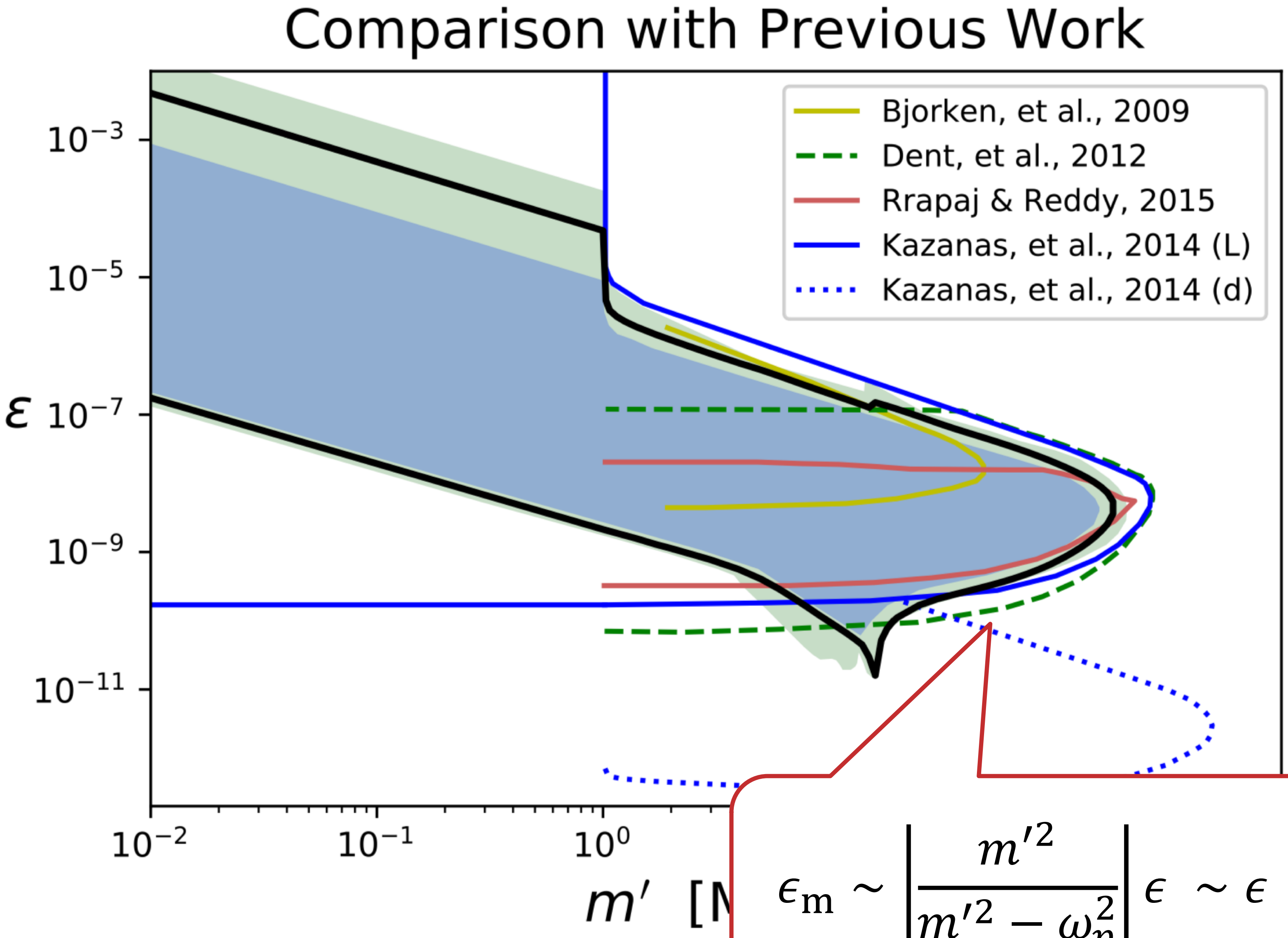


There is a dip at $m' \sim \omega_p$

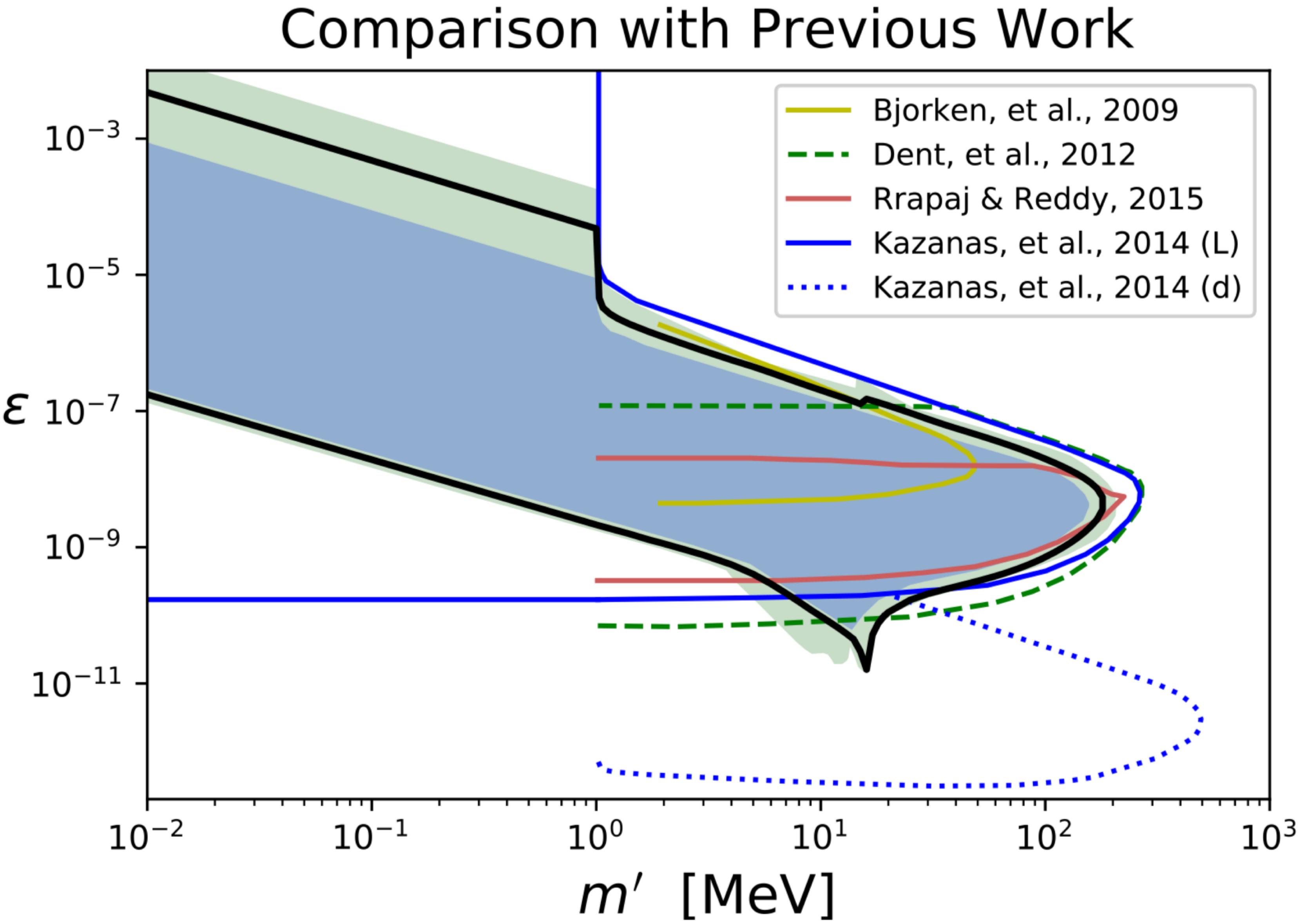


Comparison with Previous Work

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



$$\epsilon_{\mathrm{m}} \sim \left|\frac{m'^2}{m'^2-\omega_p^2}\right|\epsilon \ \sim \epsilon$$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ε
10^{-3}
10^{-5}
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10^{-2}
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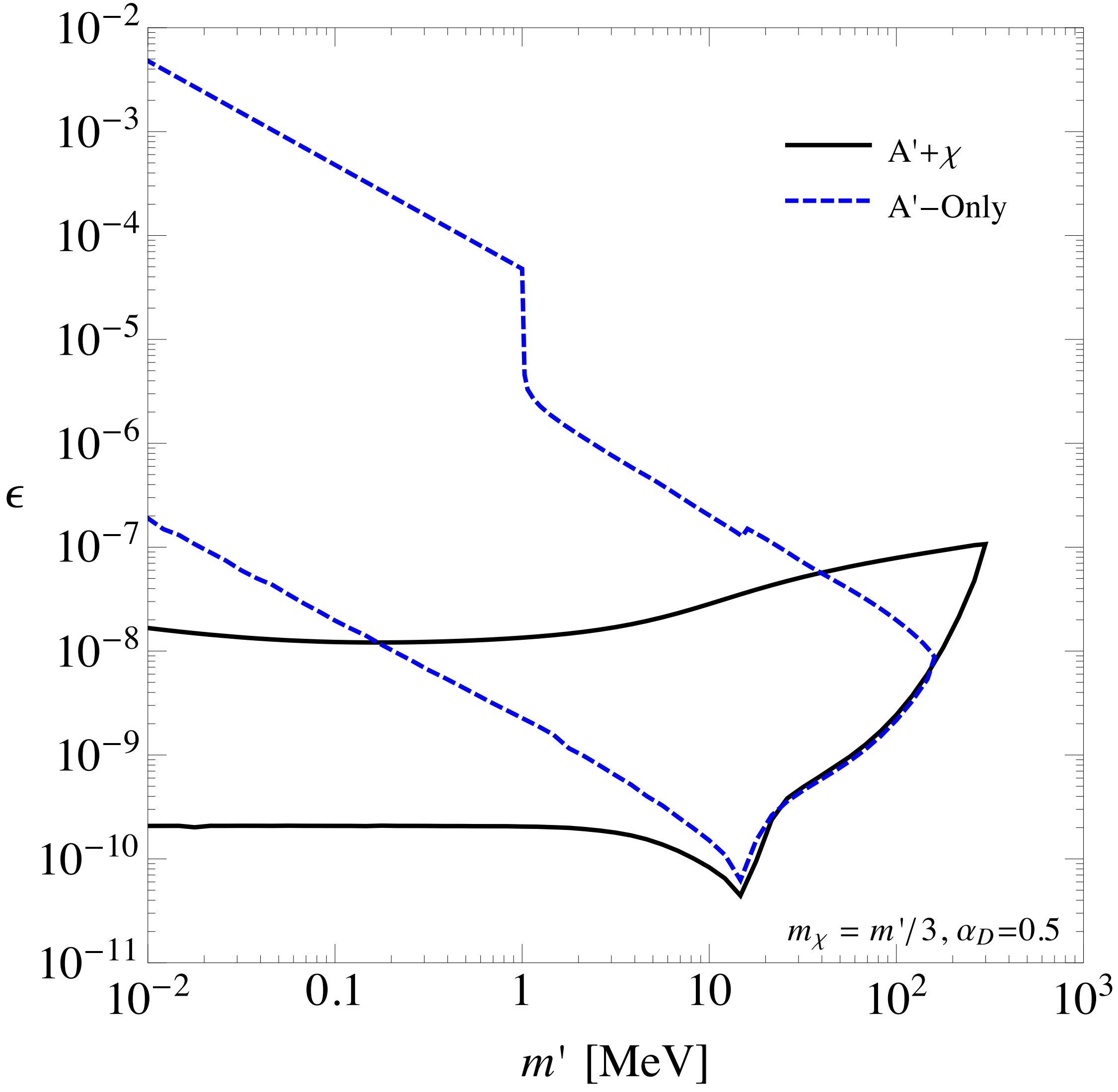
10^{0}
10^{1}
10^{2}
10^{3}
m' [MeV]

DARK SECTOR FERMIONS

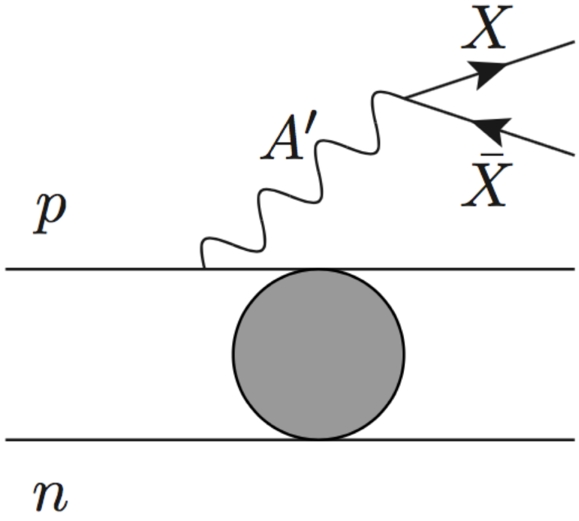
- A Dirac fermion charged under $U(1)'$: χ
- χ is stable → Dark matter candidate
- χ provides a new cooling channel
  → Stronger lower bounds
- Trapping process is totally different
  → Upper bounds changes

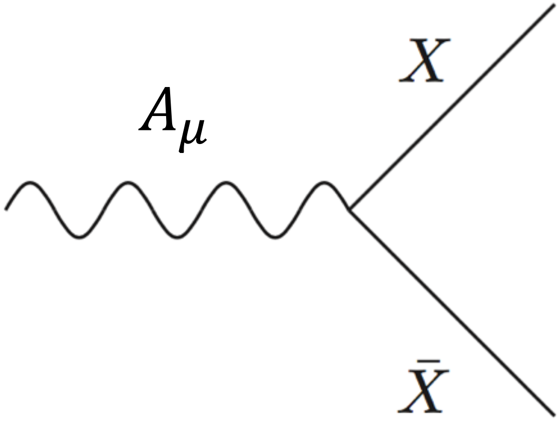
Dark Photon + Dark Matter



Lower Bounds : for Small ϵ

- Dominant production process

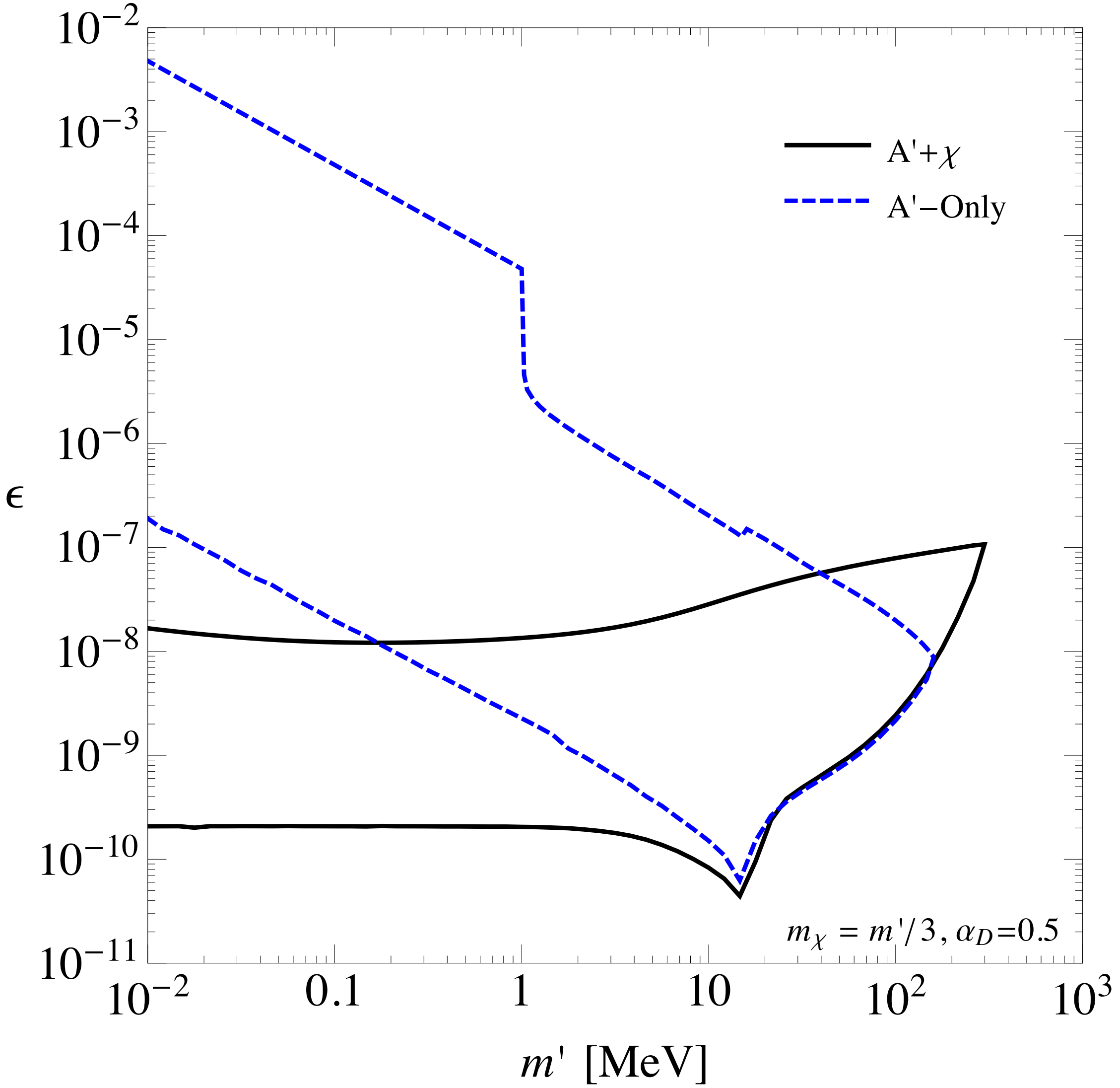




Lower Bounds : for Small ϵ

- New production channel : Photon decay
- $\epsilon_m \equiv \left|\frac{q^2}{q^2 - \Pi}\right| \epsilon \sim \epsilon$
  because $q^2 \neq m'^2$ in general
- Can avoid the thermal suppression at small masses
- Flat lower bounds

Dark Photon + Dark Matter

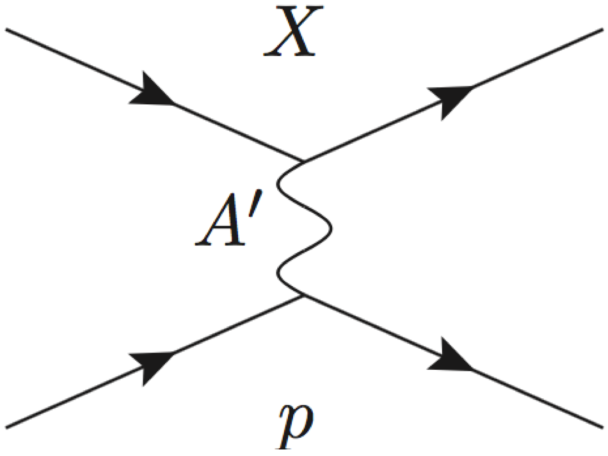


Upper Bounds : for Large ϵ

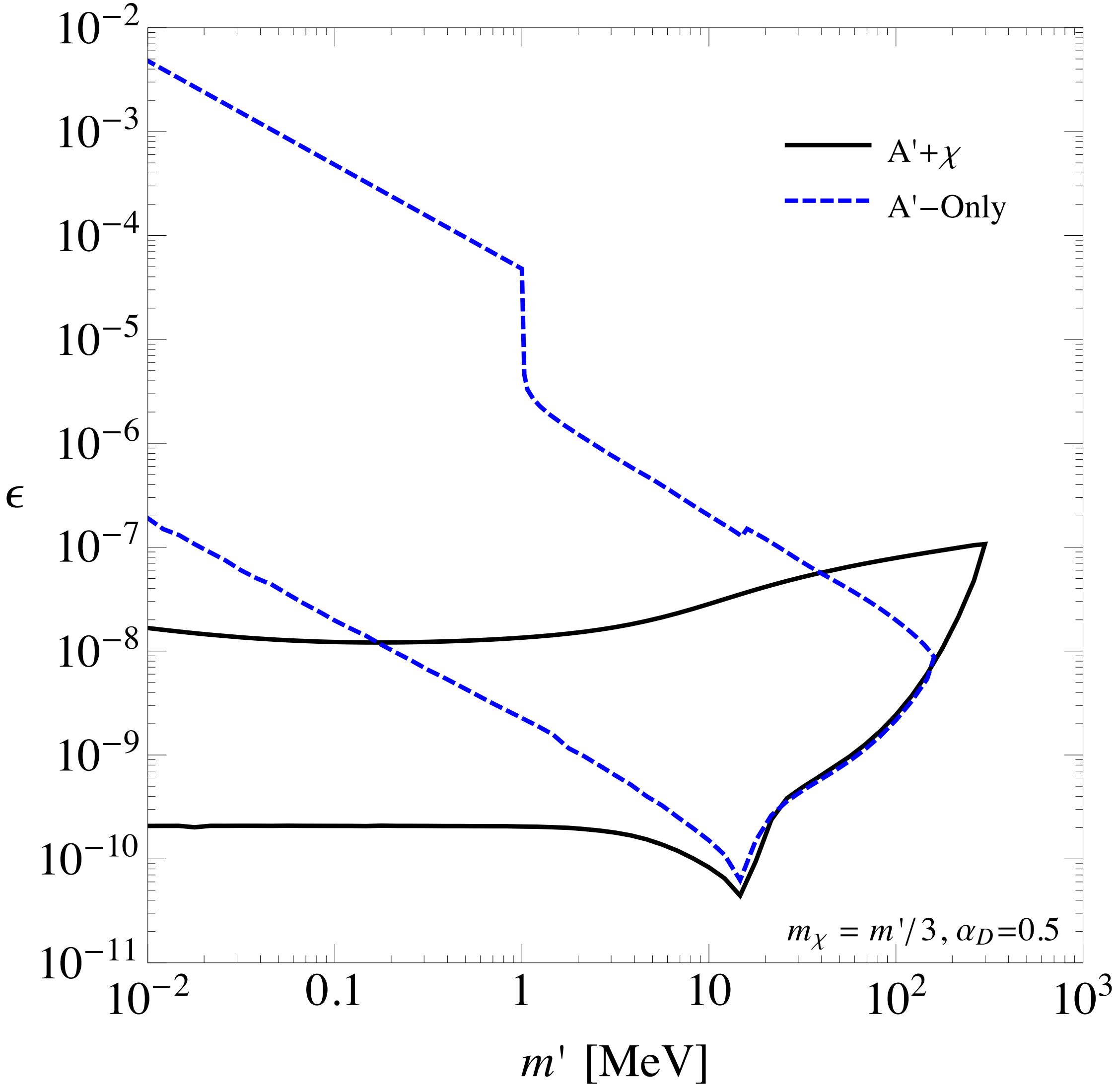
- χ cannot be absorbed into the plasma until it encounter its anti-particle

- Introduced the "Turn-around" criterion

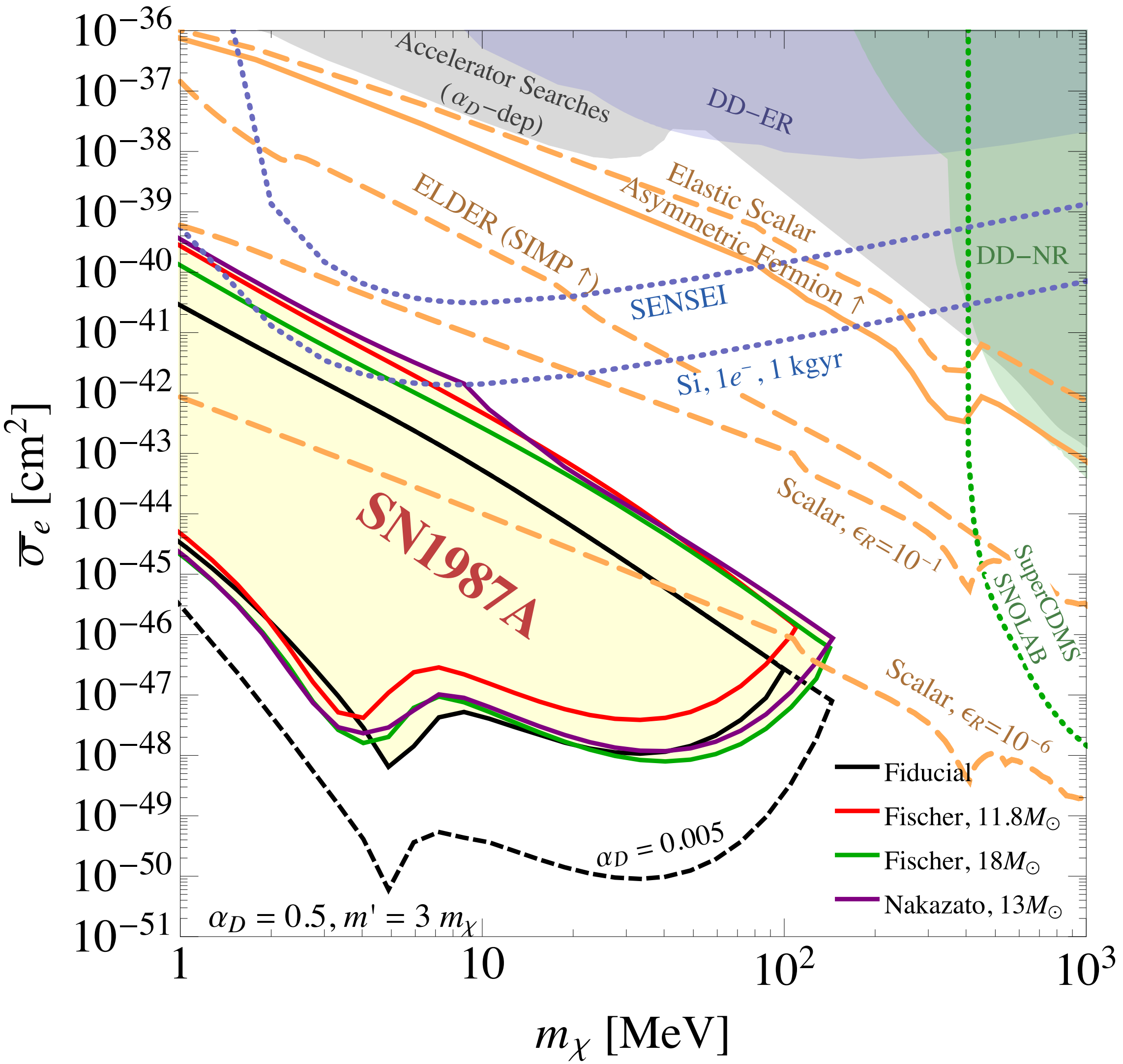
$$\langle \Delta\theta \rangle < \frac{\pi}{2}$$



Dark Photon + Dark Matter

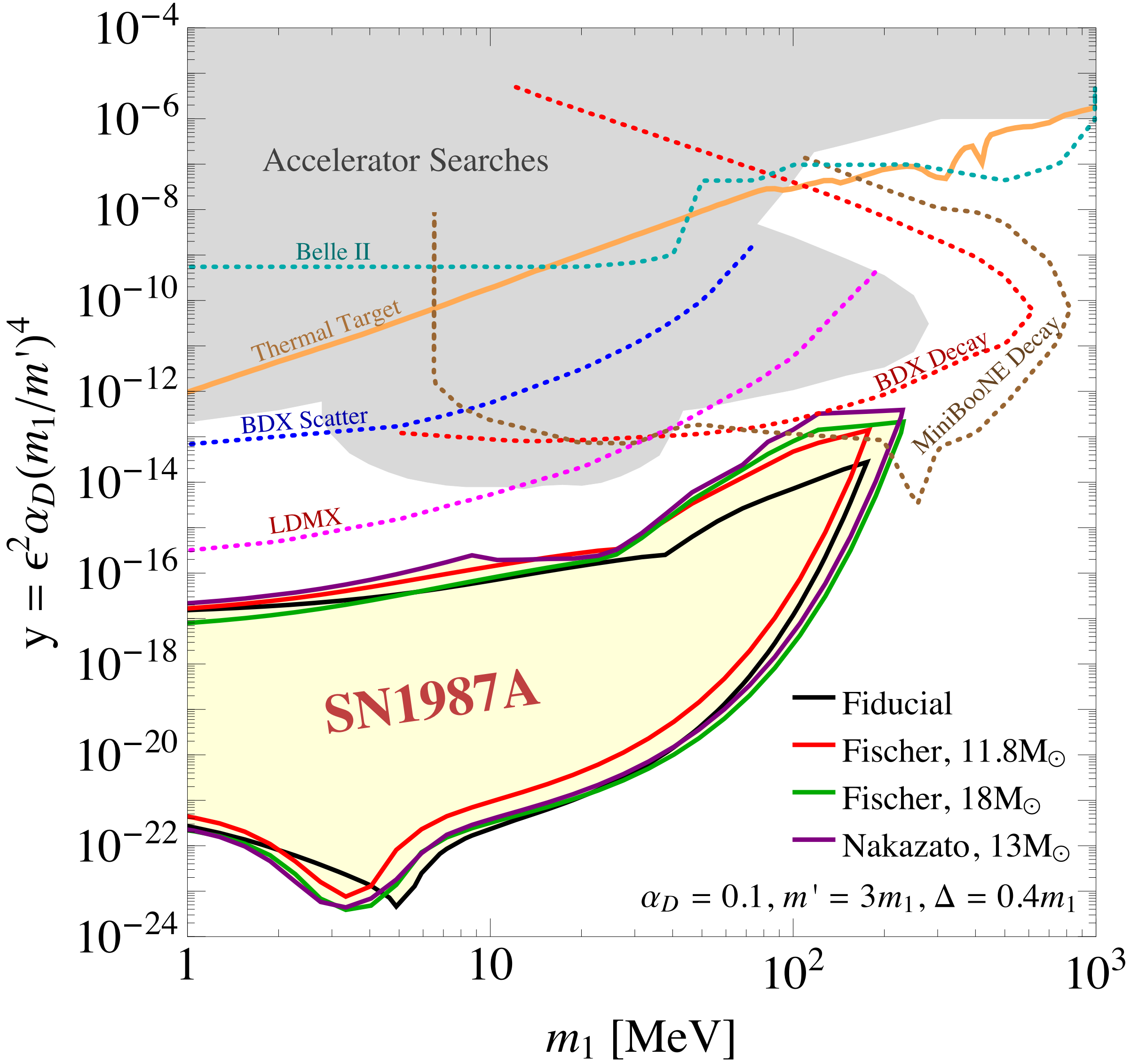


Dark Photon + Dark Matter

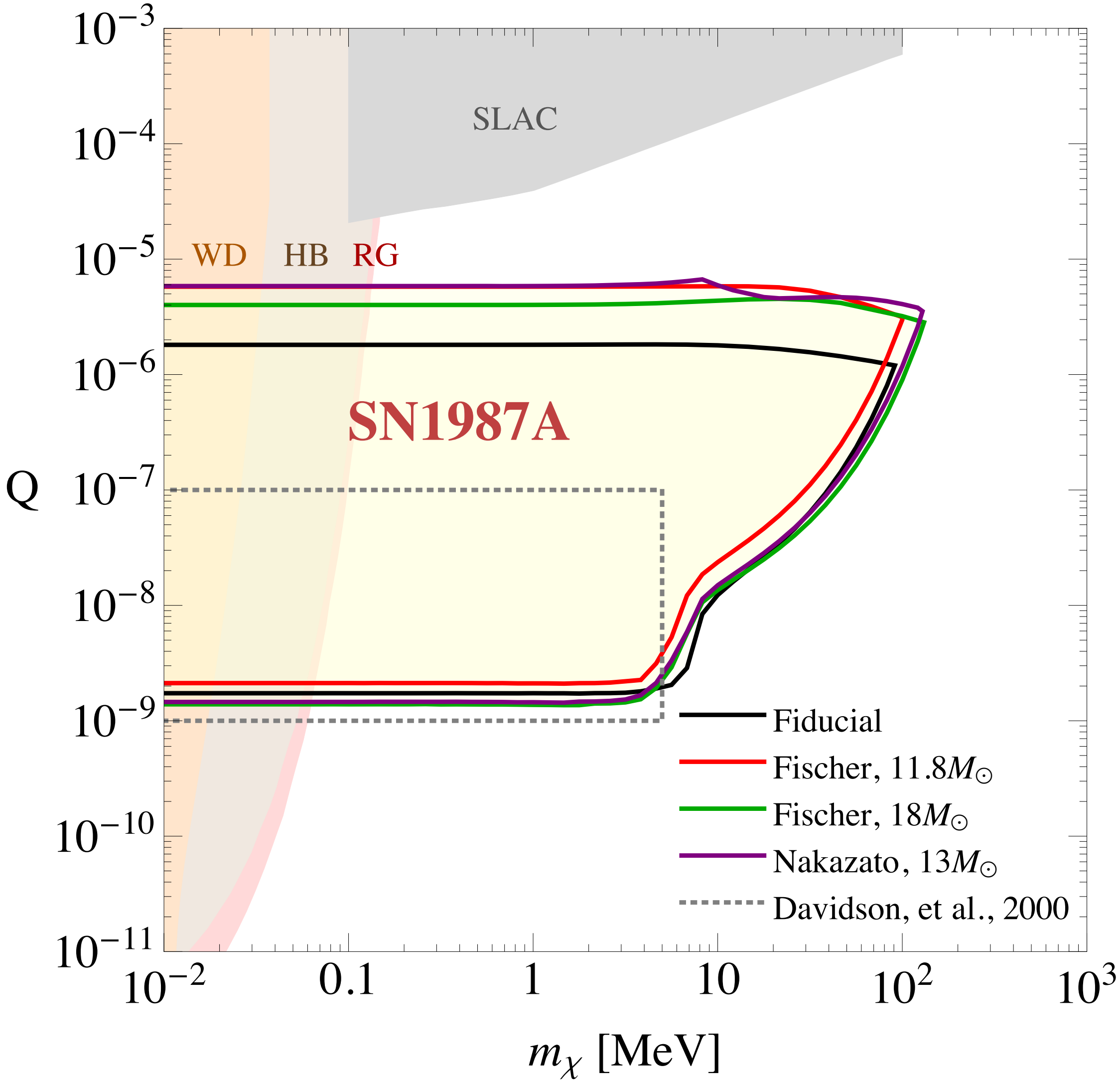


OTHER MODELS

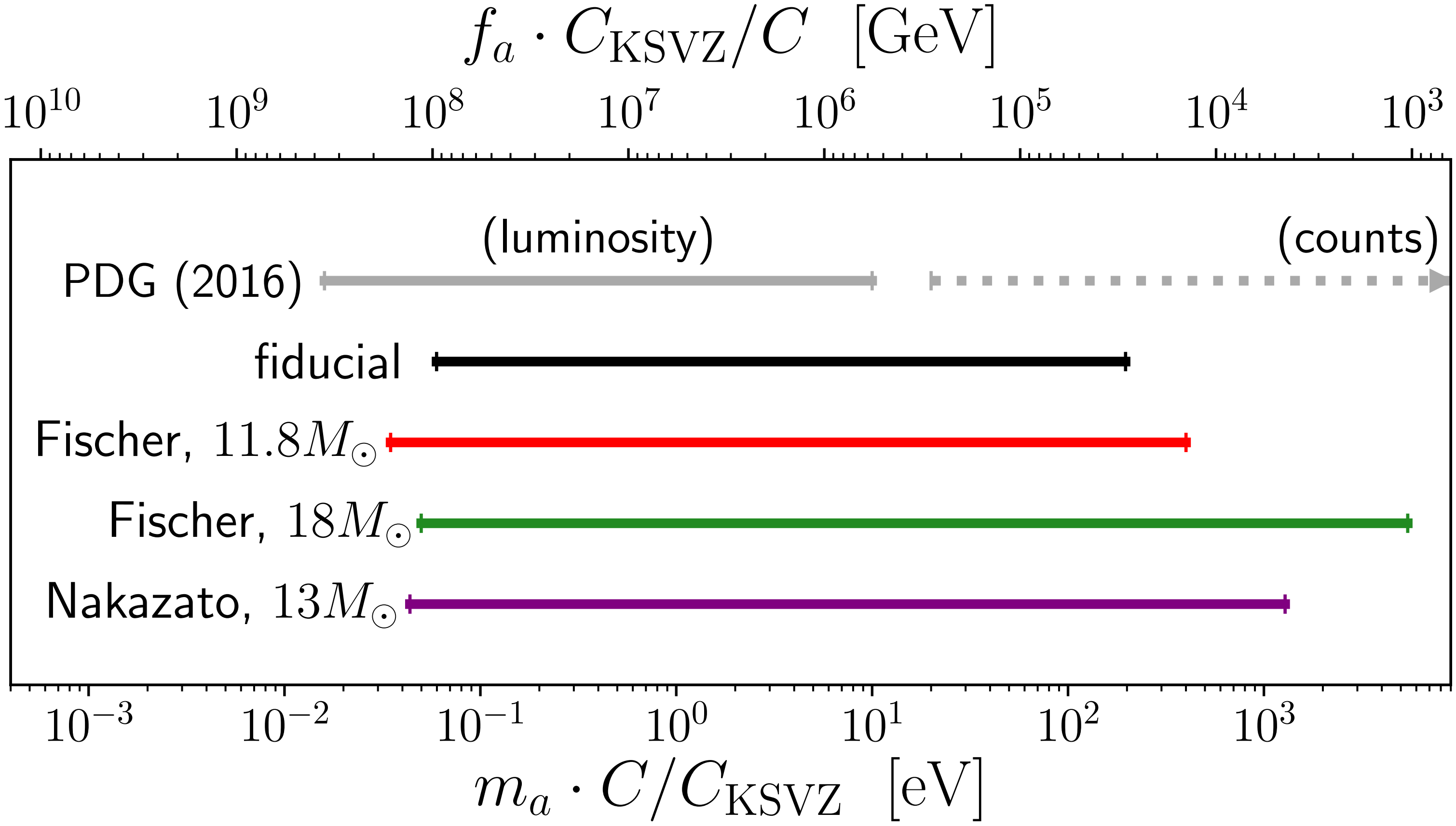
Inelastic Dark Matter



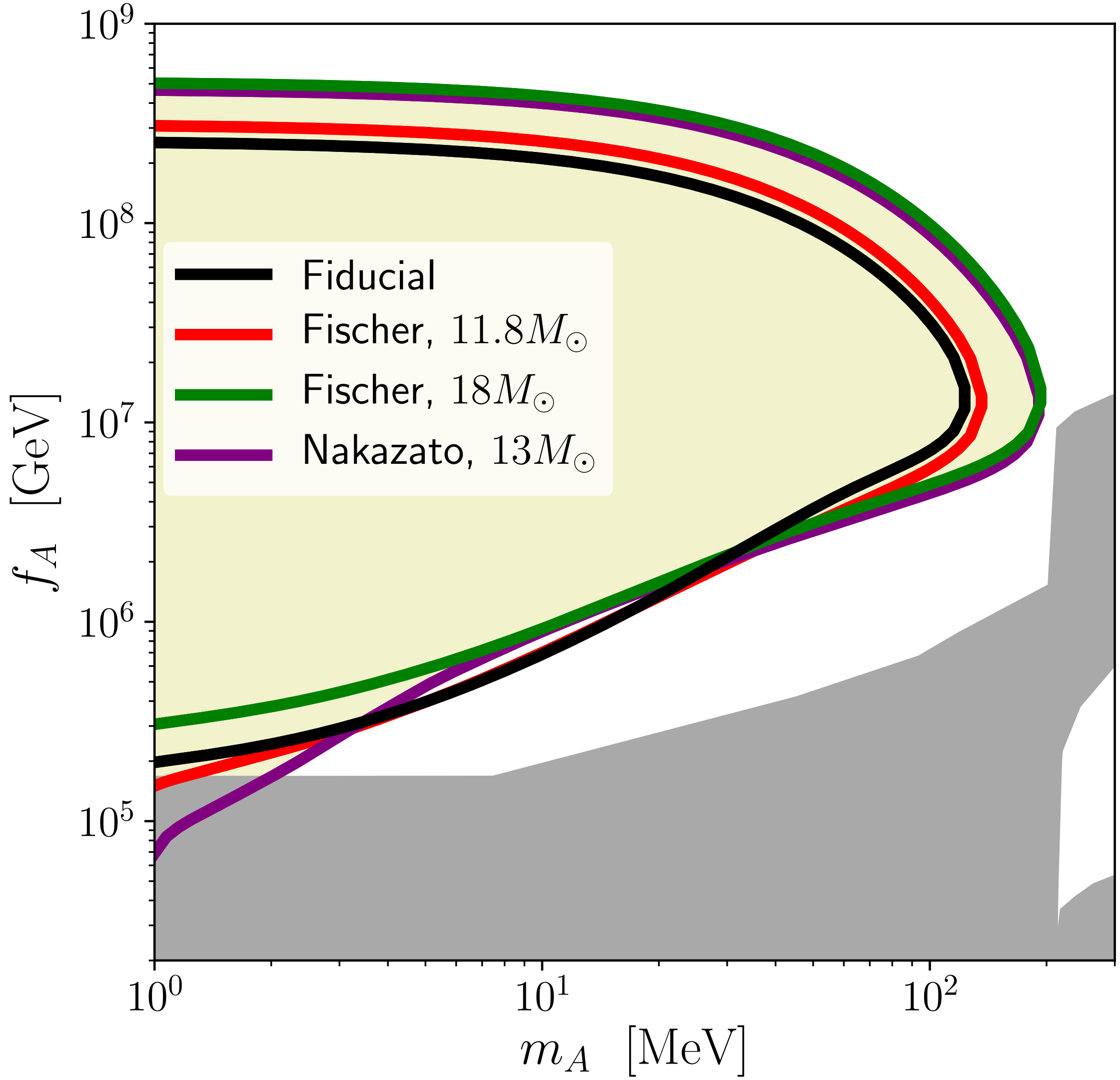
Millicharged Particles



QCD Axions


$f_a \cdot C_{\mathrm{KSVZ}}/C$ [GeV]
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
(luminosity)
(counts)
PDG (2016)
fiducial
Fischer, $11.8M_\odot$
Fischer, $18M_\odot$
Nakazato, $13M_\odot$
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
$m_a \cdot C/C_{\mathrm{KSVZ}}$ [eV]

Axion-like Particles



CONCLUSION

Conclusion

- Supernova1987A can give constraints on low-mass dark sector particles

- We calculated constraints for various models with thermal effects, which provides reasonable lower bounds for experiment searches

THANK YOU

BACK UP

Particle Luminosity

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

$$P = \int dV \int \frac{d^3\vec{k}}{(2\pi)^3} \omega \Gamma_{\mathrm{prod}}$$

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

Particle Luminosity

$$dL = e^{-\tau} dP$$

Odds of escaping

$\tau = \int \Gamma_{abs} dr$ is called the optical depth

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

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

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