# Supernova 1987A Constraints on Low-Mass Dark Sectors

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Collaboration with Rouven Essig and Samuel McDermott

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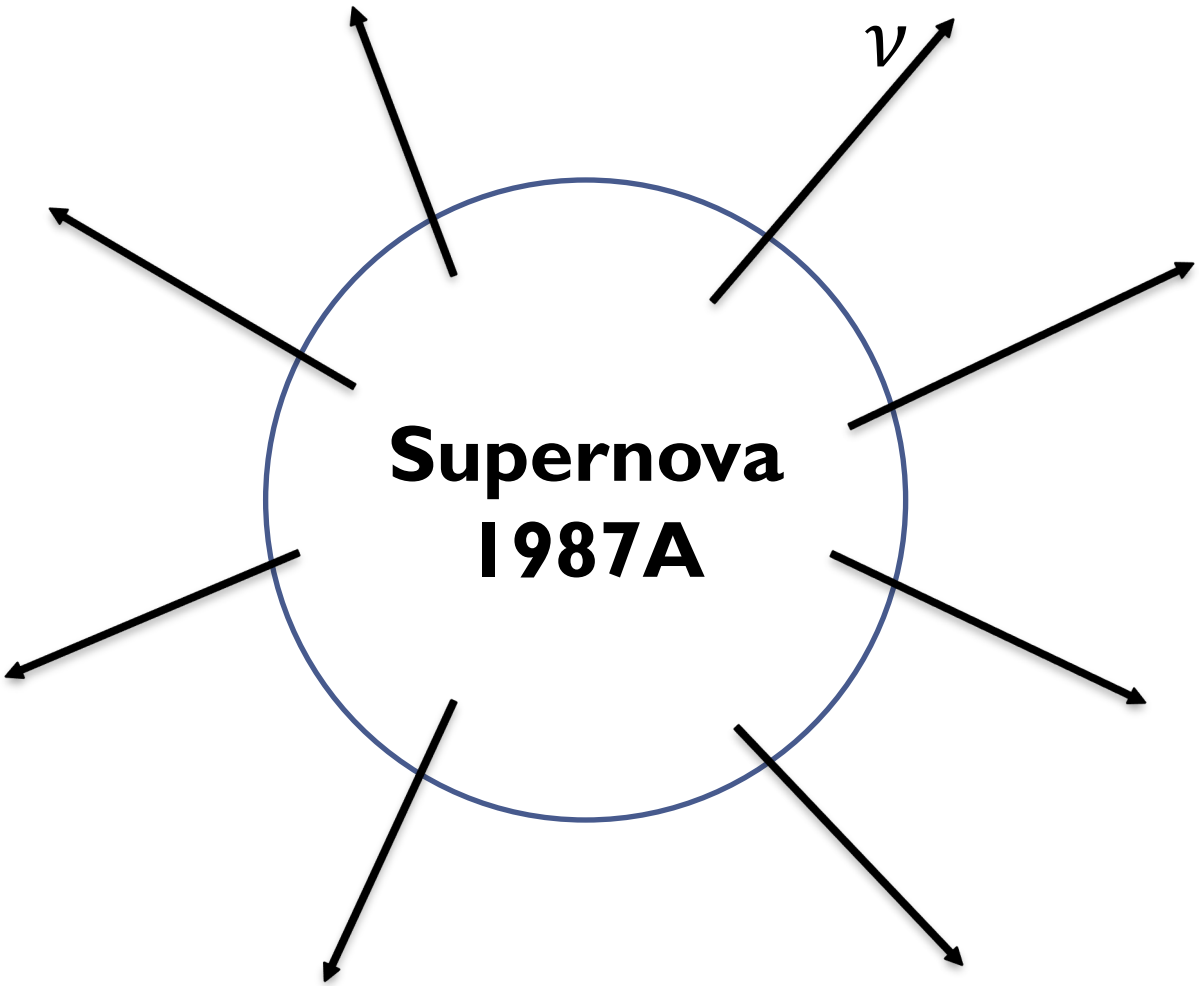
# SUPERNOVA 1987A

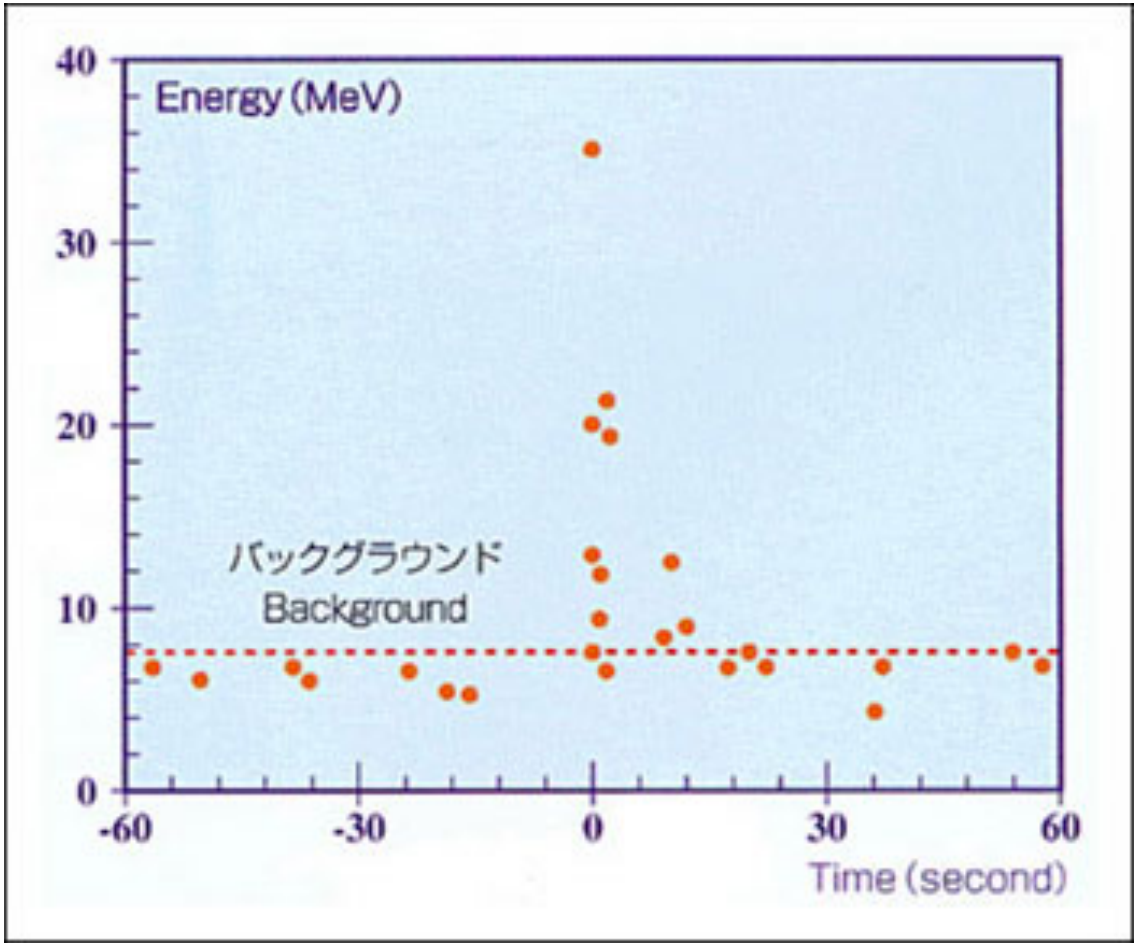
# Supernova 1987A

- 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

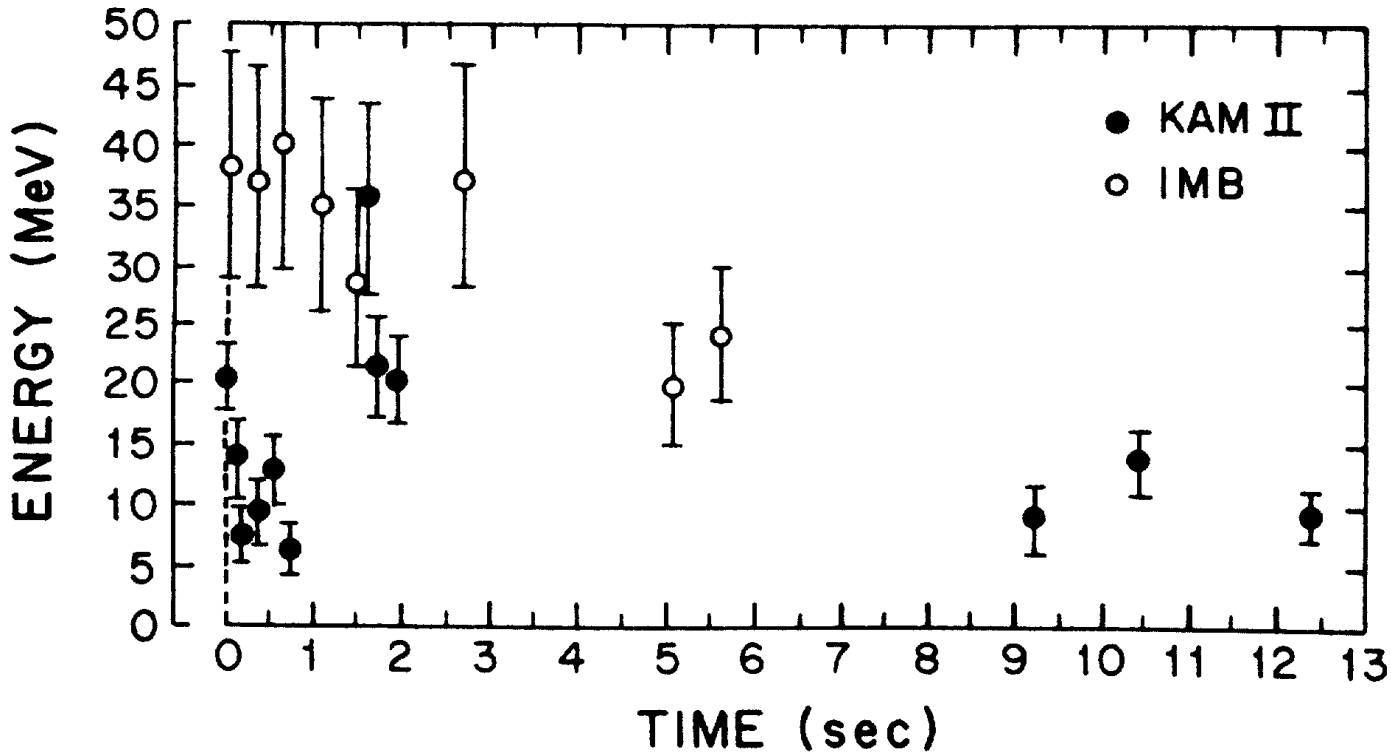



- 99% of energy is carried by neutrinos

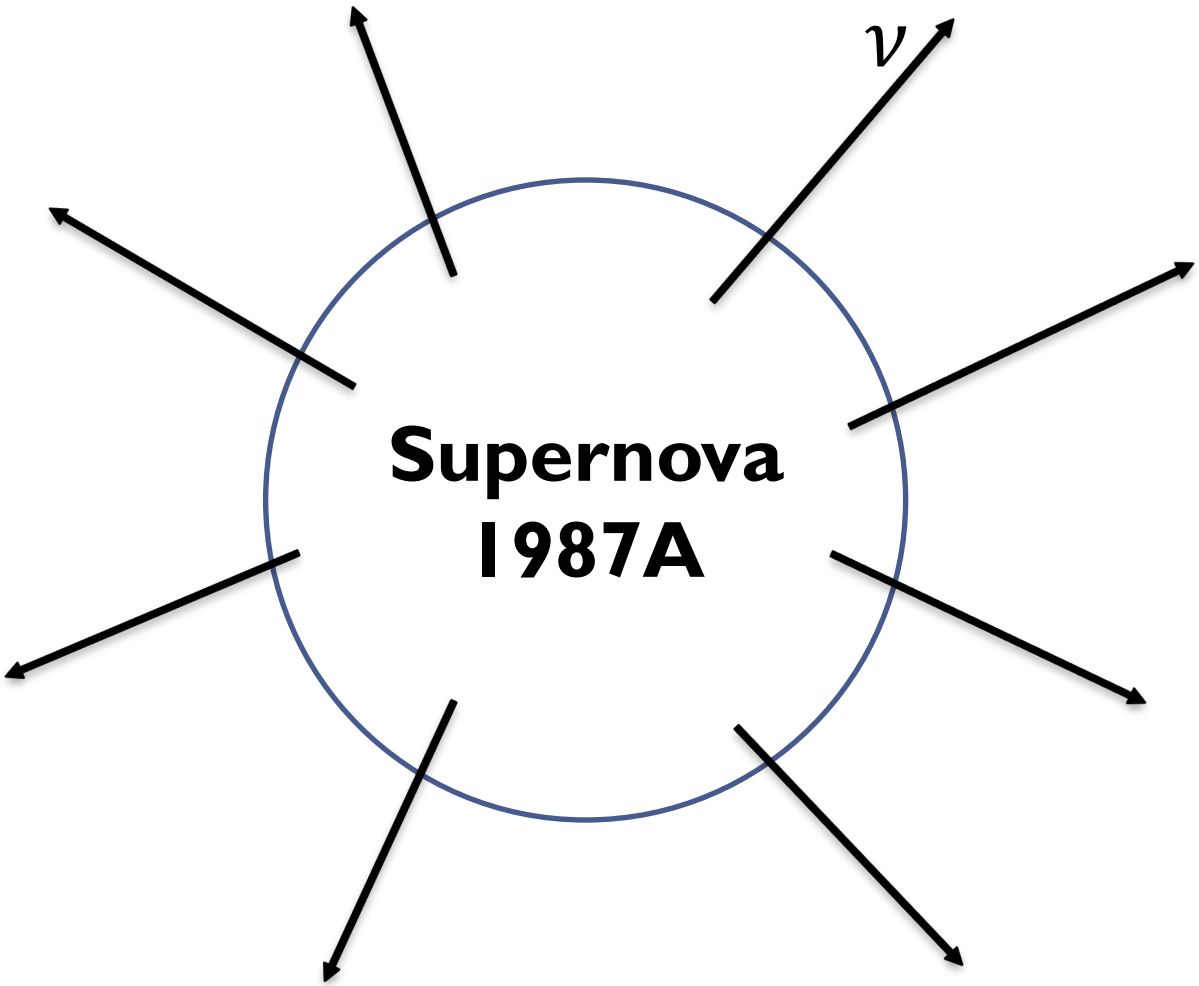



- Kamiokande II, IMB, and Baksan detected the neutrinos at the same time

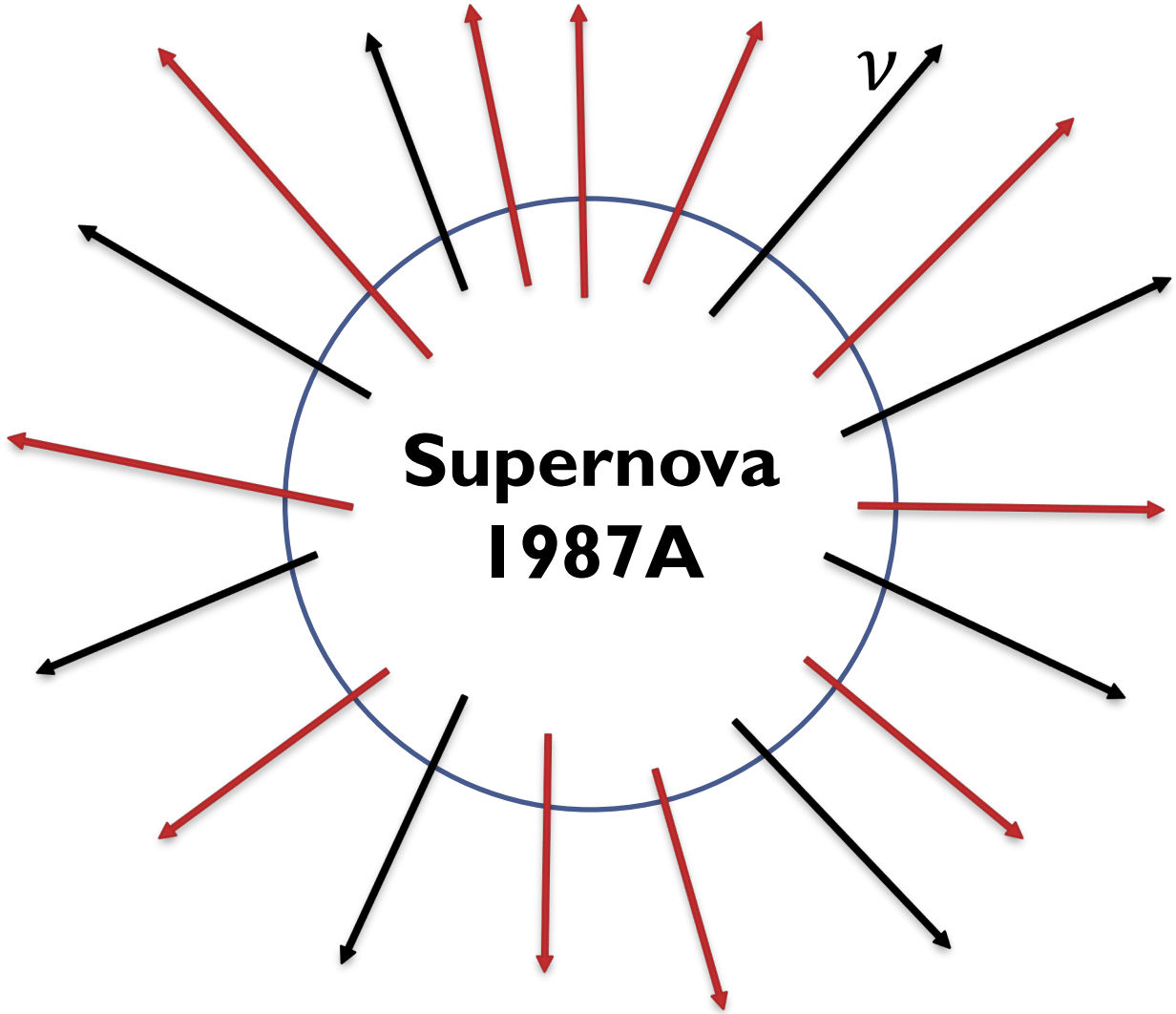
Hirata et al,1988




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




- If a new particle exists

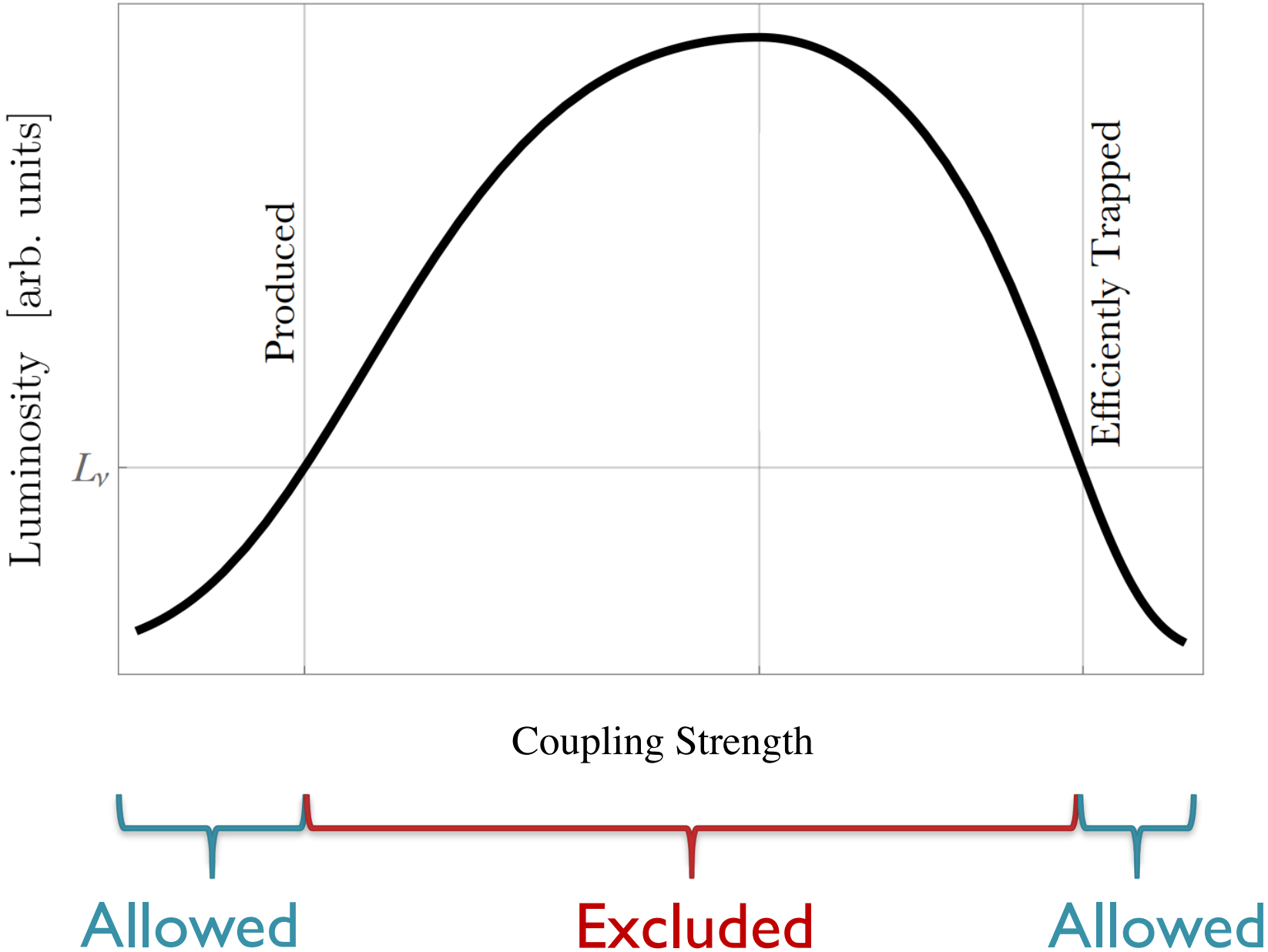



- Supernova cools faster

# Raffelt Criterion

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

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


Luminosity [arb. units]
$L_\nu$
Produced
Efficiently Trapped
Coupling Strength
Allowed
Excluded
Allowed

# Supernova Constraints

- **Any type of light novel particles** coupled to the SM can be constrained
- $m \lesssim T_c \approx 30\ MeV$
- 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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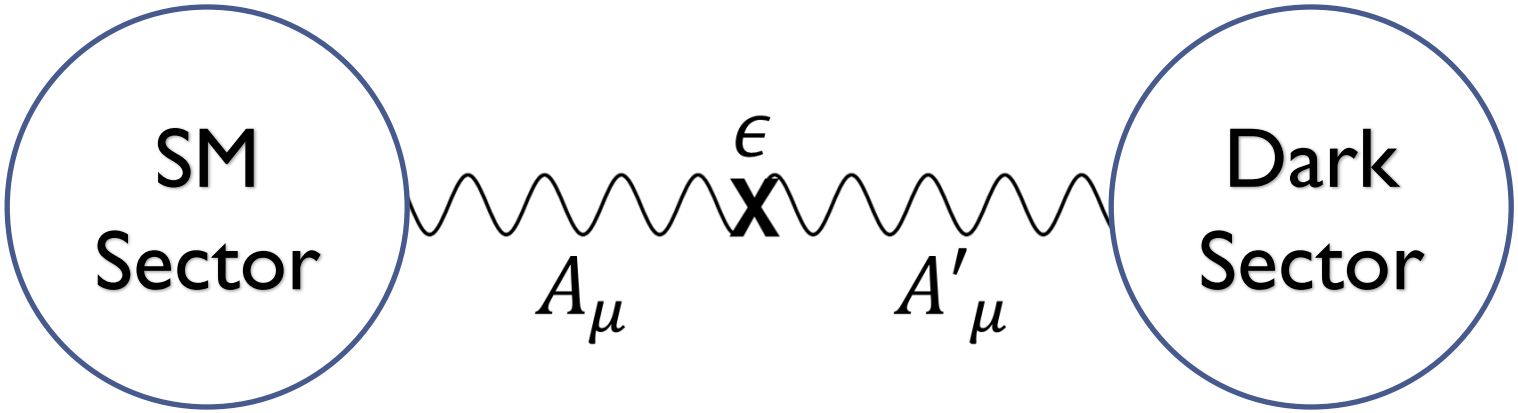
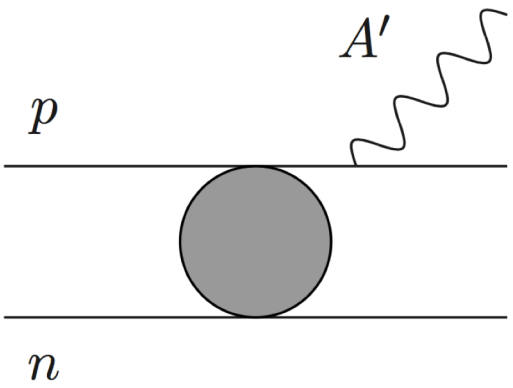
# PURE DARK PHOTON

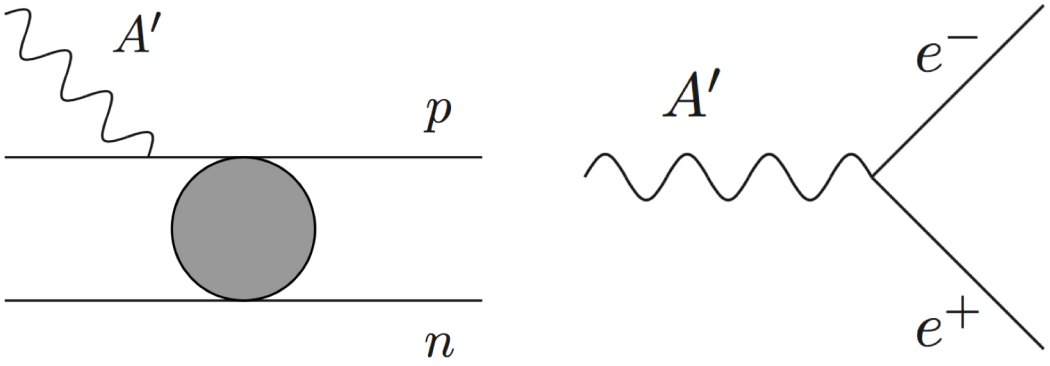


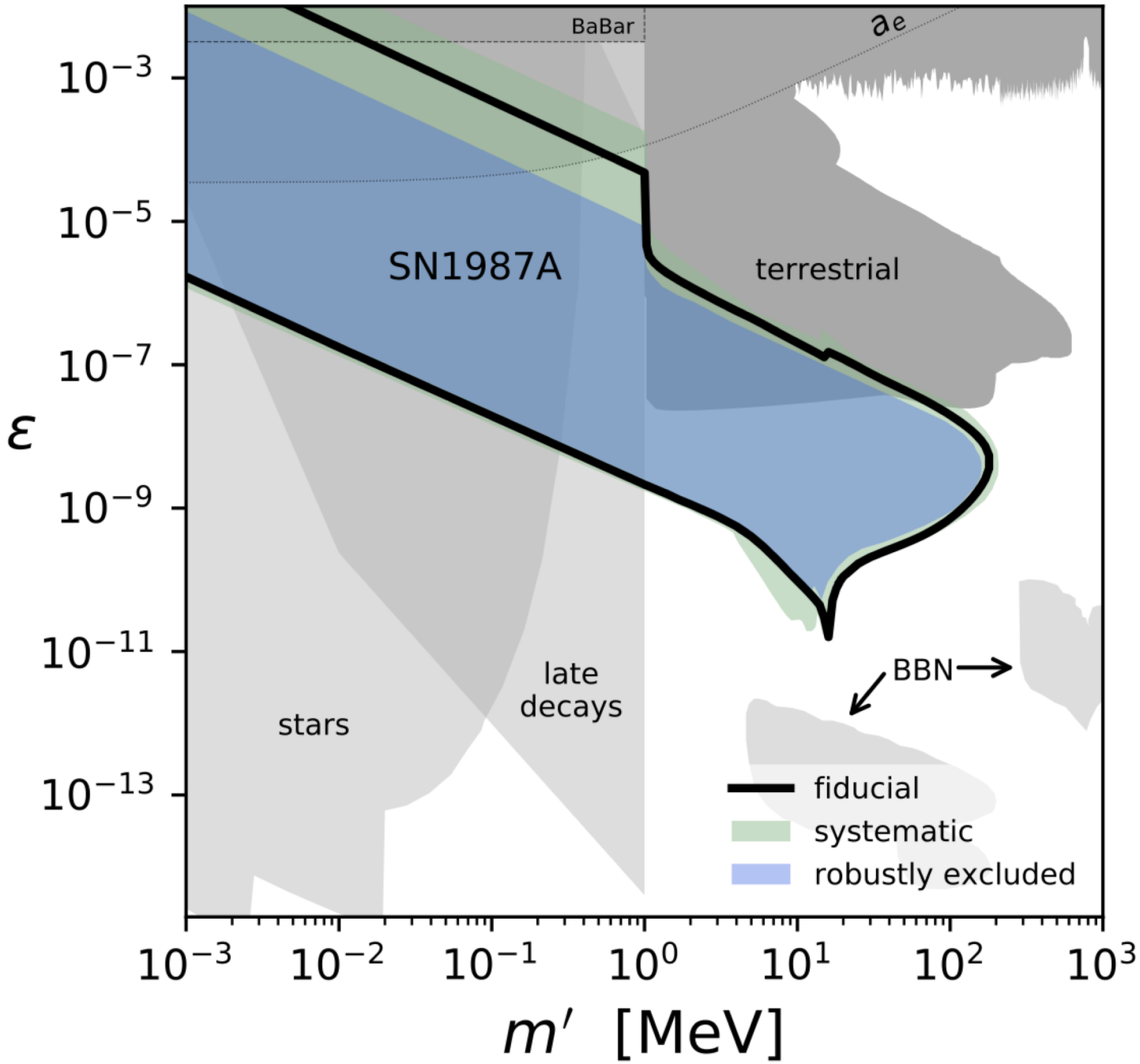

- $SU(3)_c \times SU(2)_L \times U(1)_Y \times \boldsymbol{U(1)'}$
- Dark photon ($A'$) is the gauge boson of $U(1)'$
- In low energies, $\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$

- Dominant production process

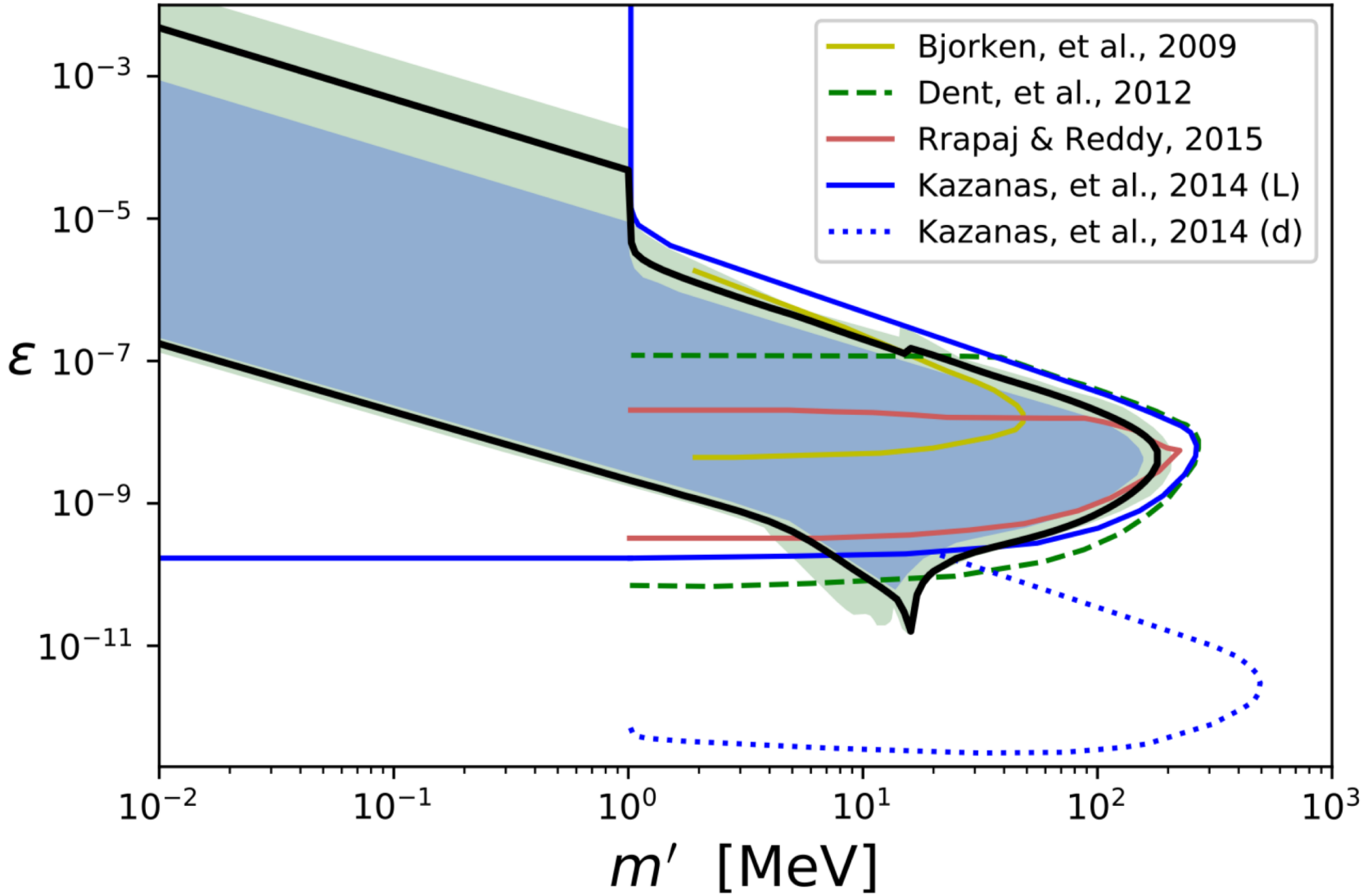



- Trapping Process




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

# Comparison with Previous Work



# 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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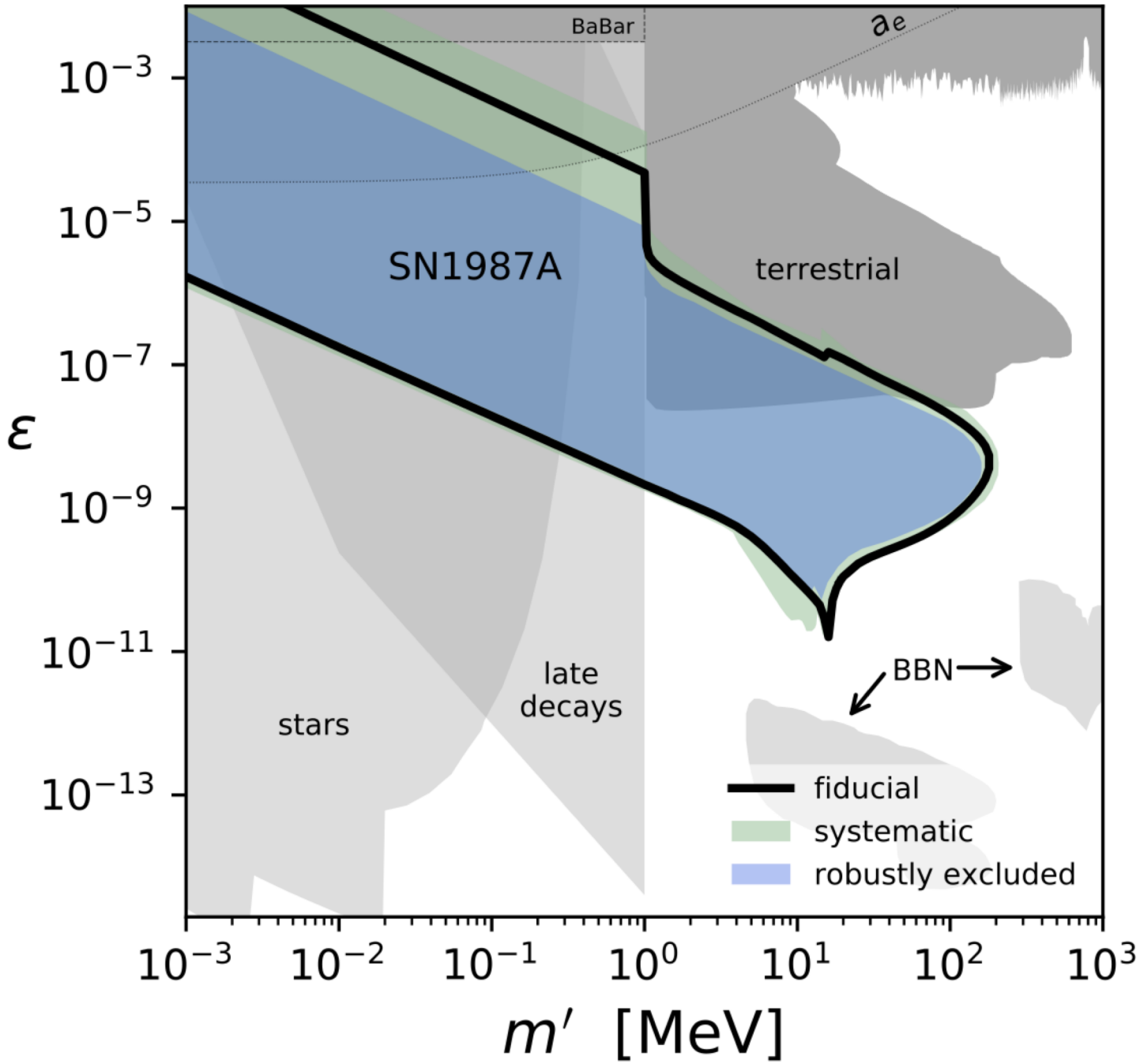
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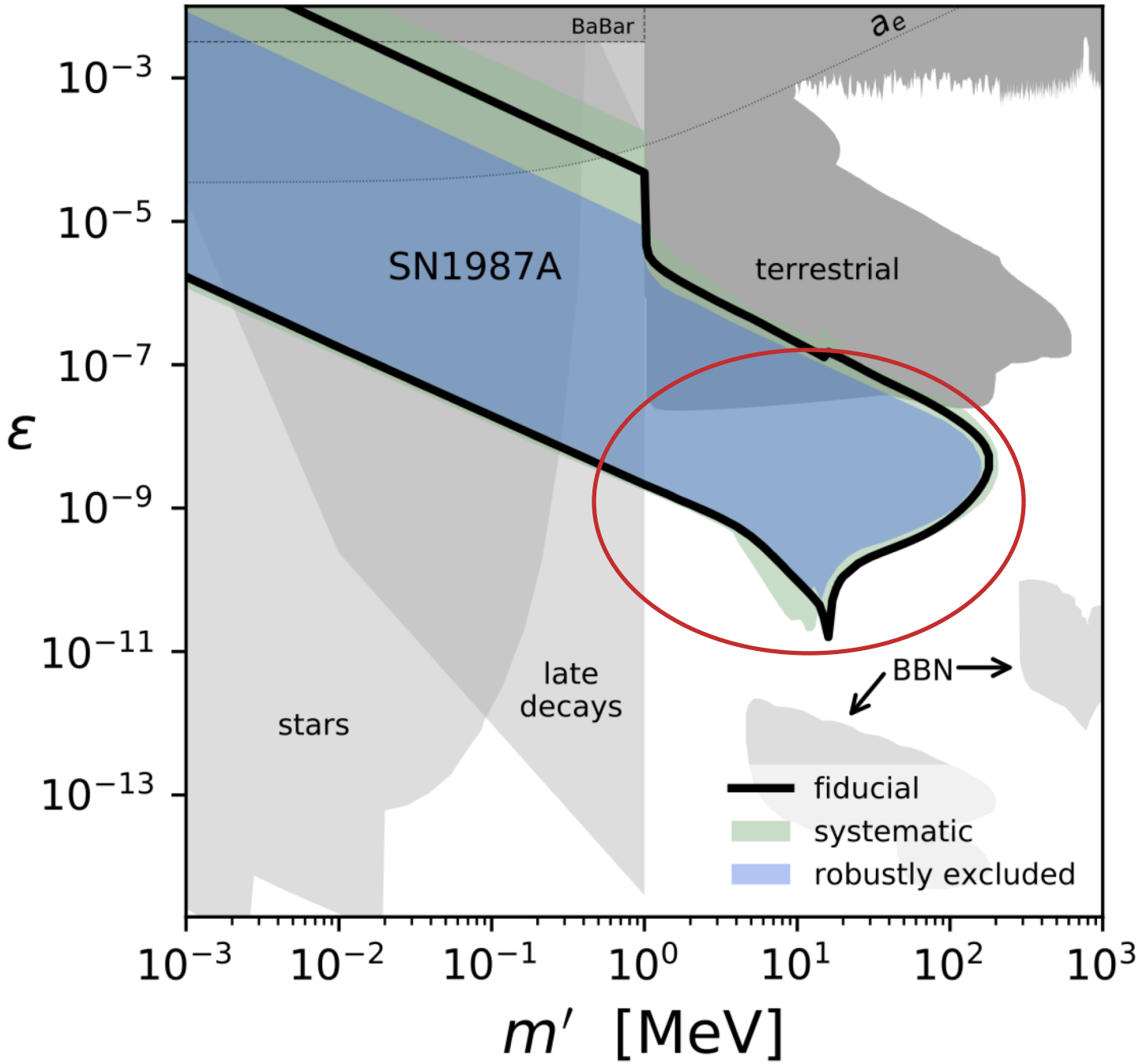
$m'$ [MeV]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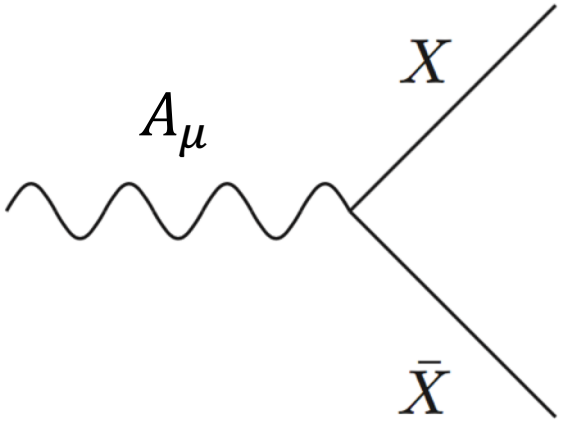
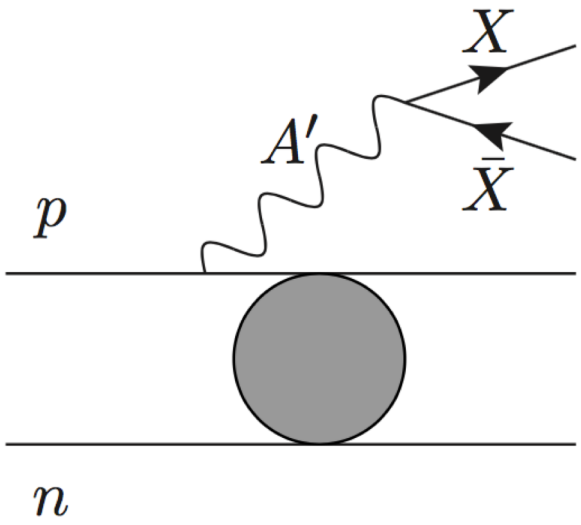
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
$m'$ [MeV]

# DARK SECTOR FERMIONS

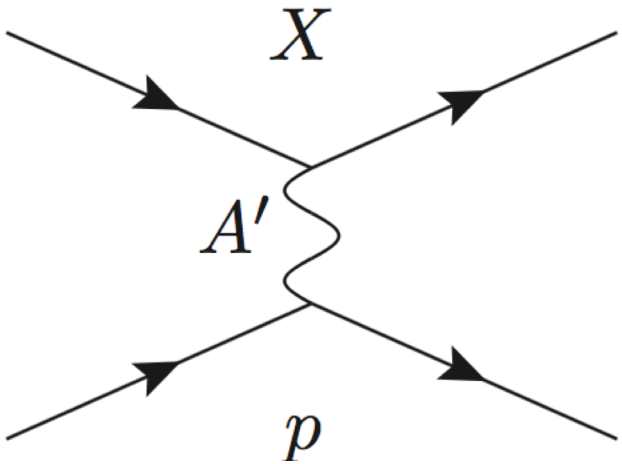
- A Dirac fermion charged under $U(1)'$: $\chi$
- $\chi$ is stable $\rightarrow$ Dark matter candidate
- $\chi$ provides a new cooling channel
  $\rightarrow$ Stronger lower bounds
- Trapping process is totally different
  $\rightarrow$ Upper bounds changes

- Dominant production process



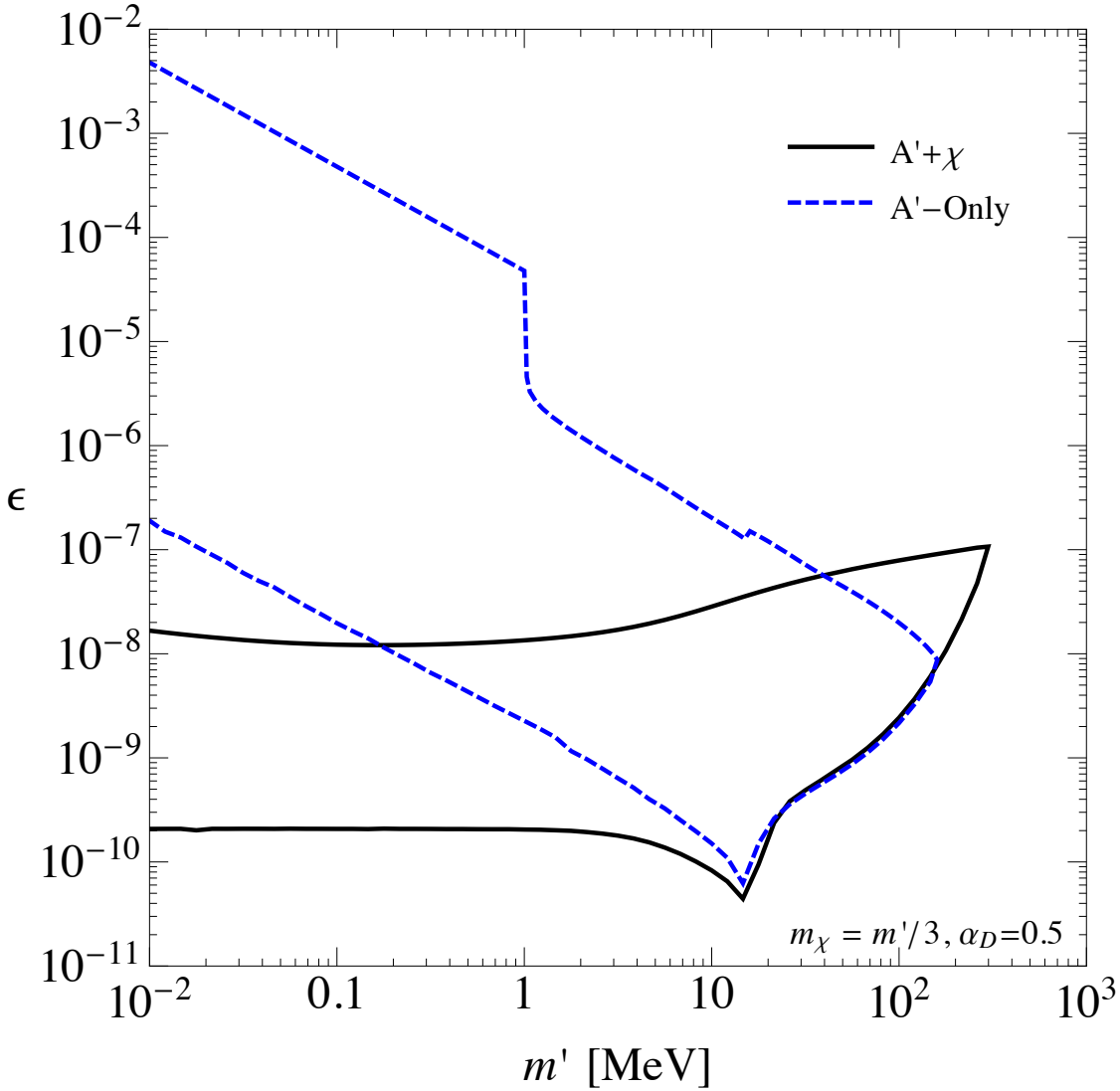

- Trapping Process



# Mass Hierarchy

- Depending on mass hierarchy, dark photon may decay to a $\chi\bar{\chi}$ pair
- This changes phenomenology of $\chi$ production and absorption
- Consider both heavy DM case and light DM case

# Light Dark Matter Case



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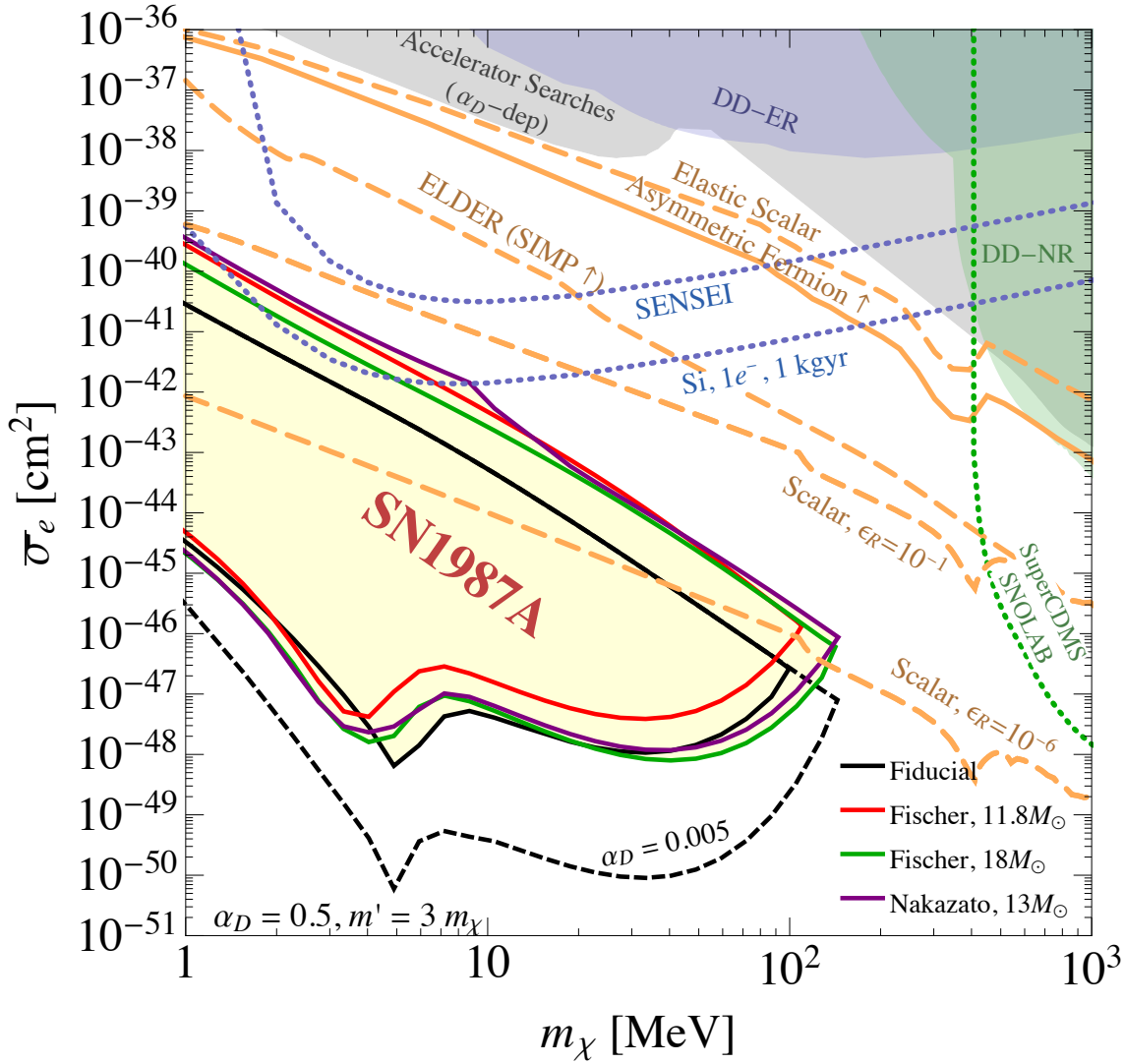
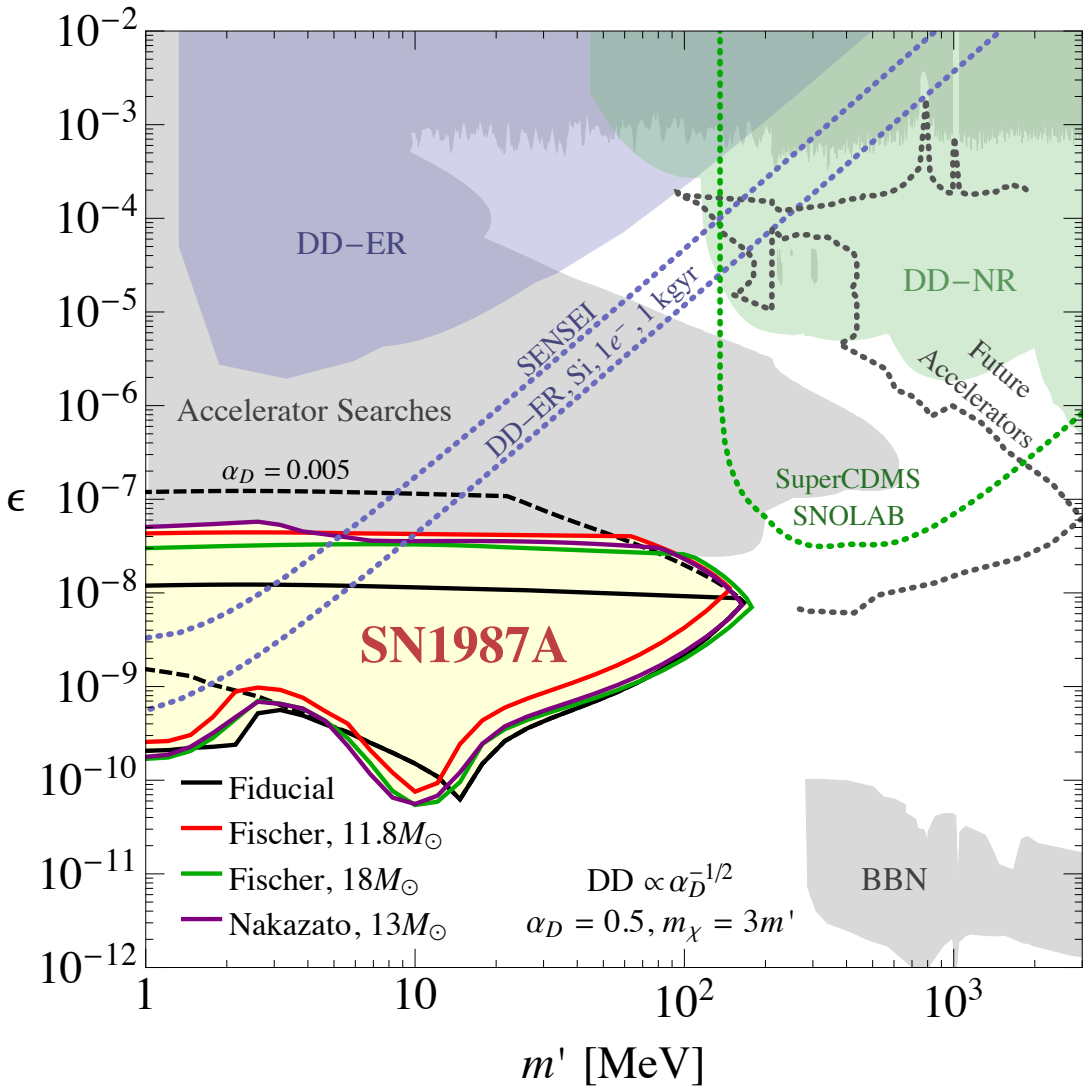
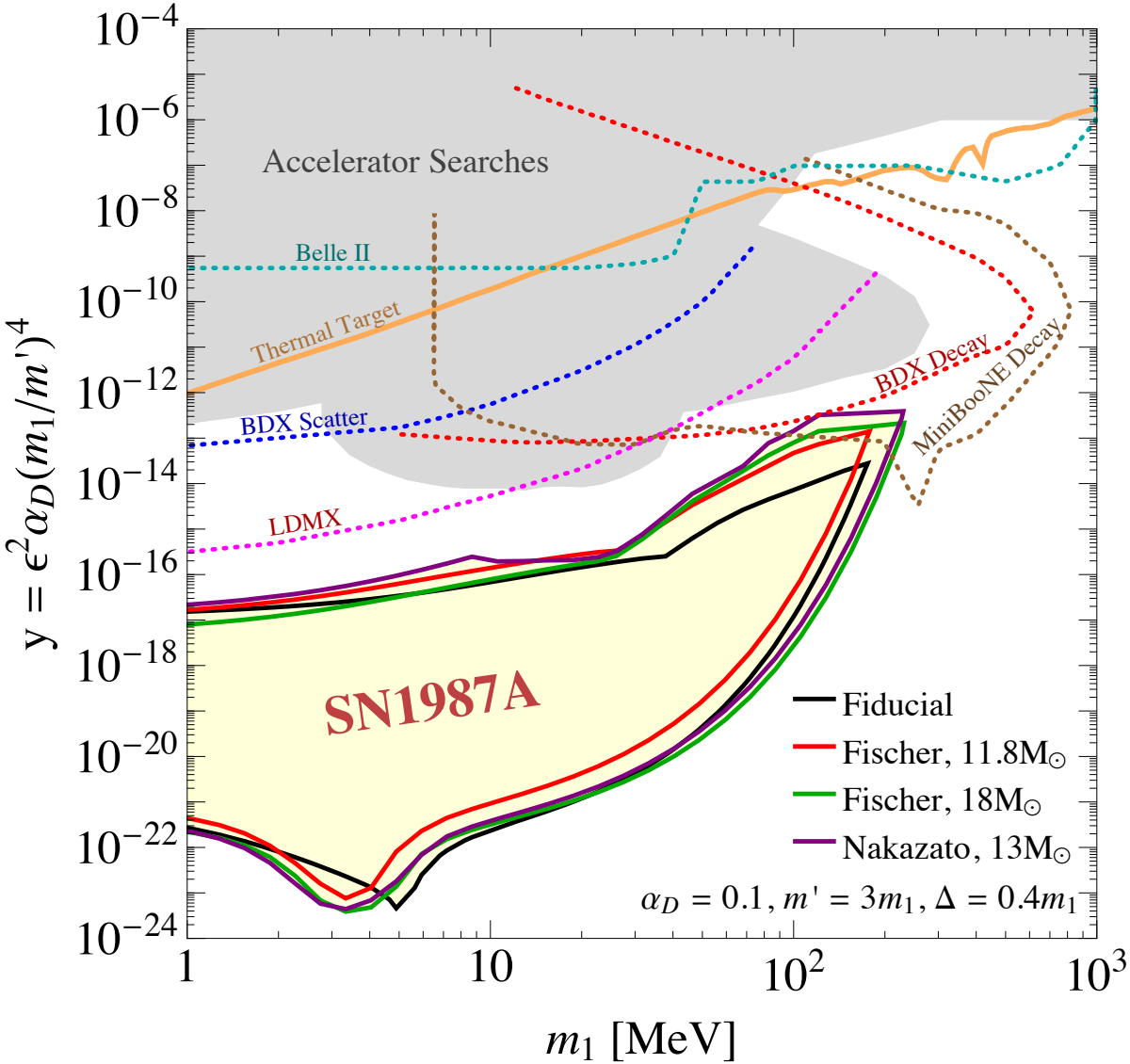


# OTHER MODELS

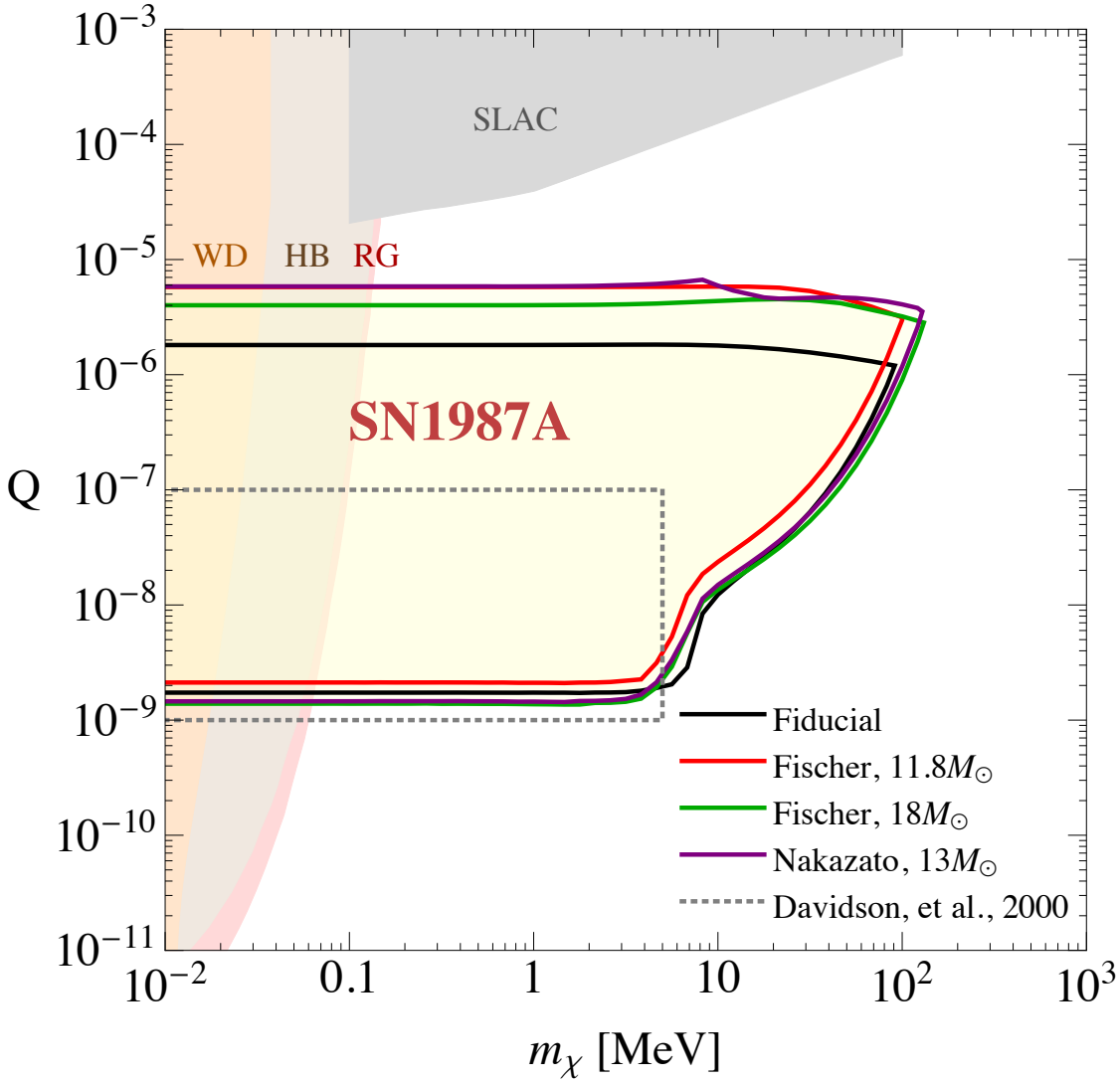
# Heavy Dark Matter Case



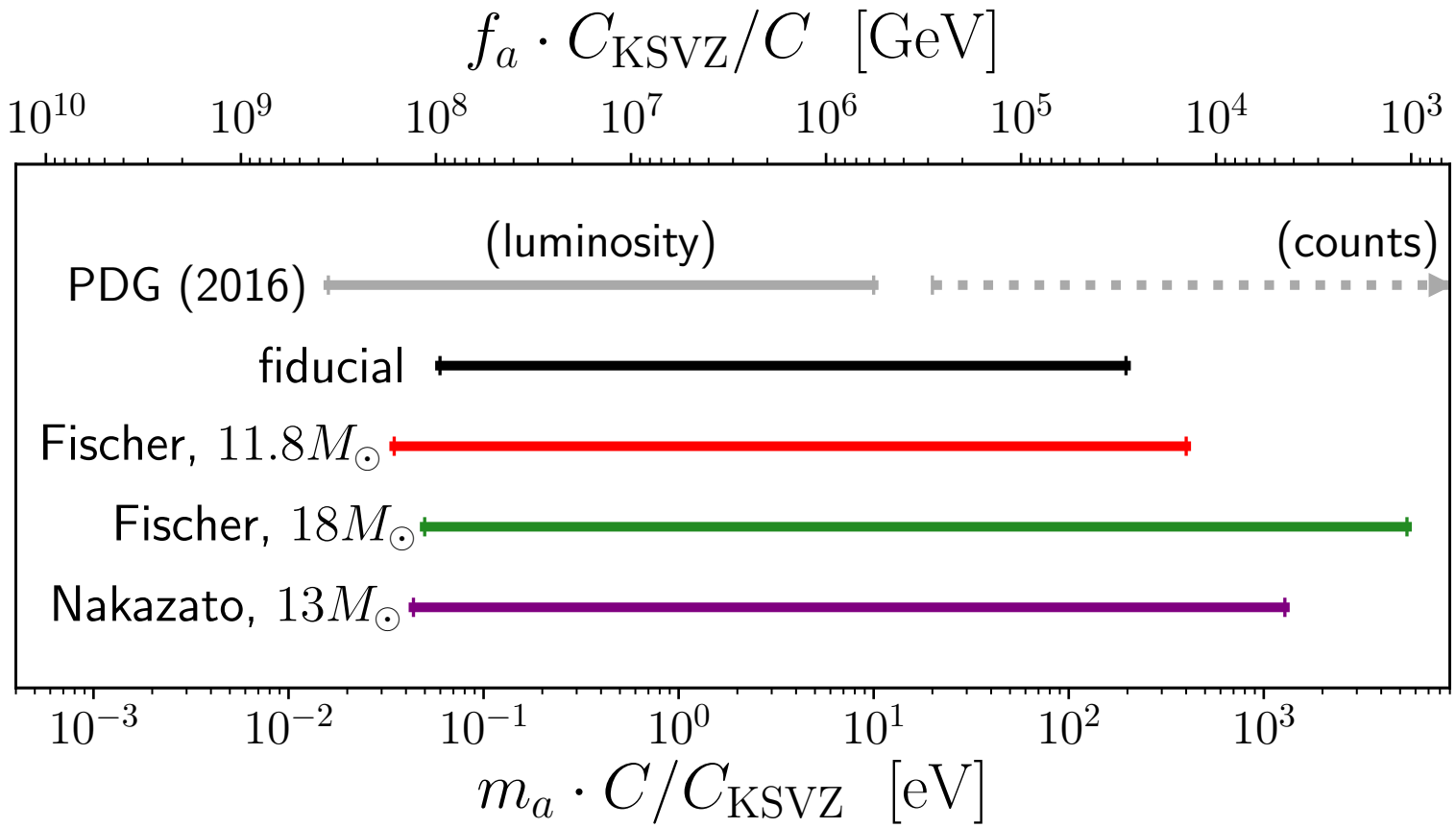
# Inelastic Dark Matter



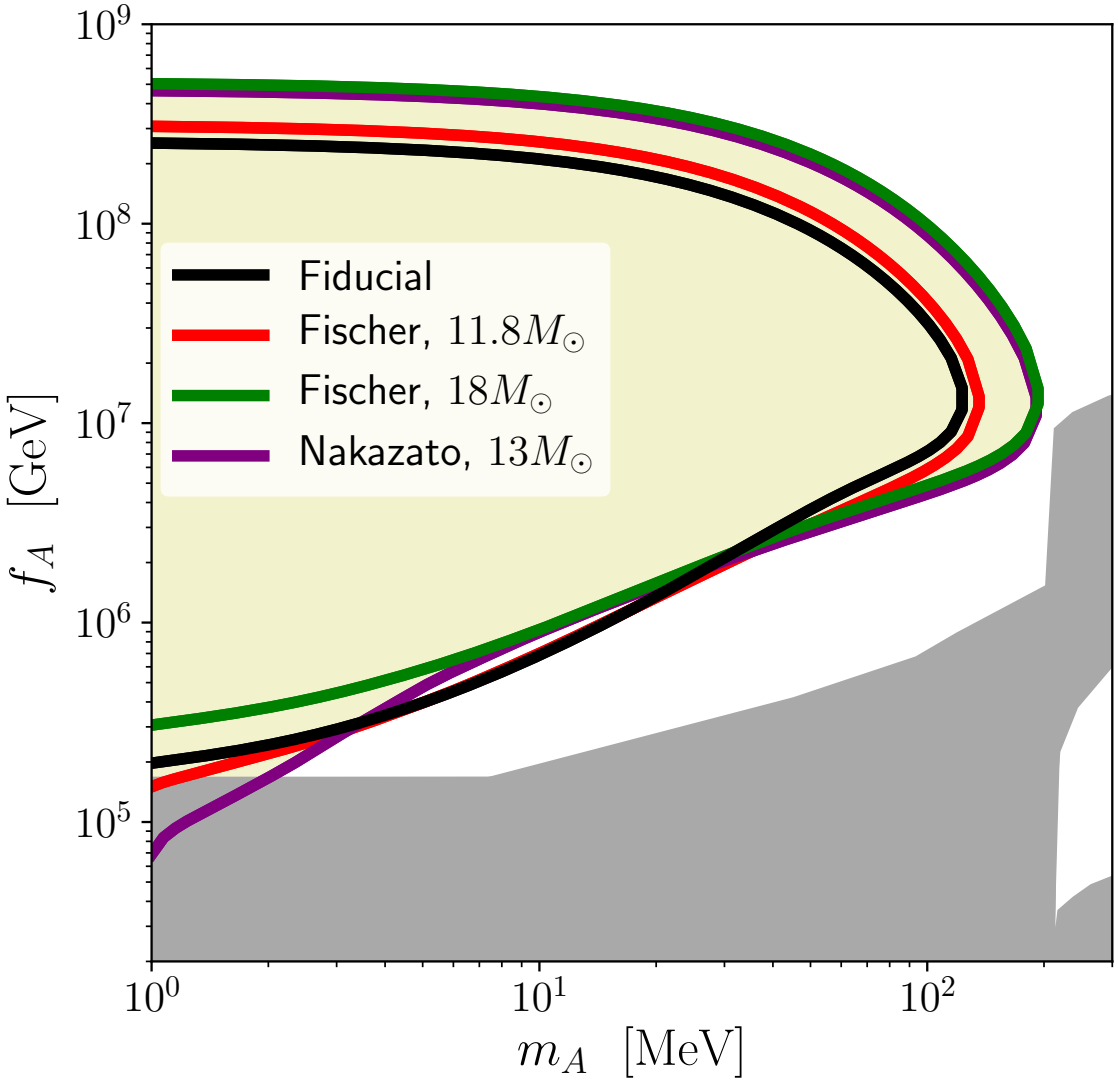
# Millicharged Particles



# 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

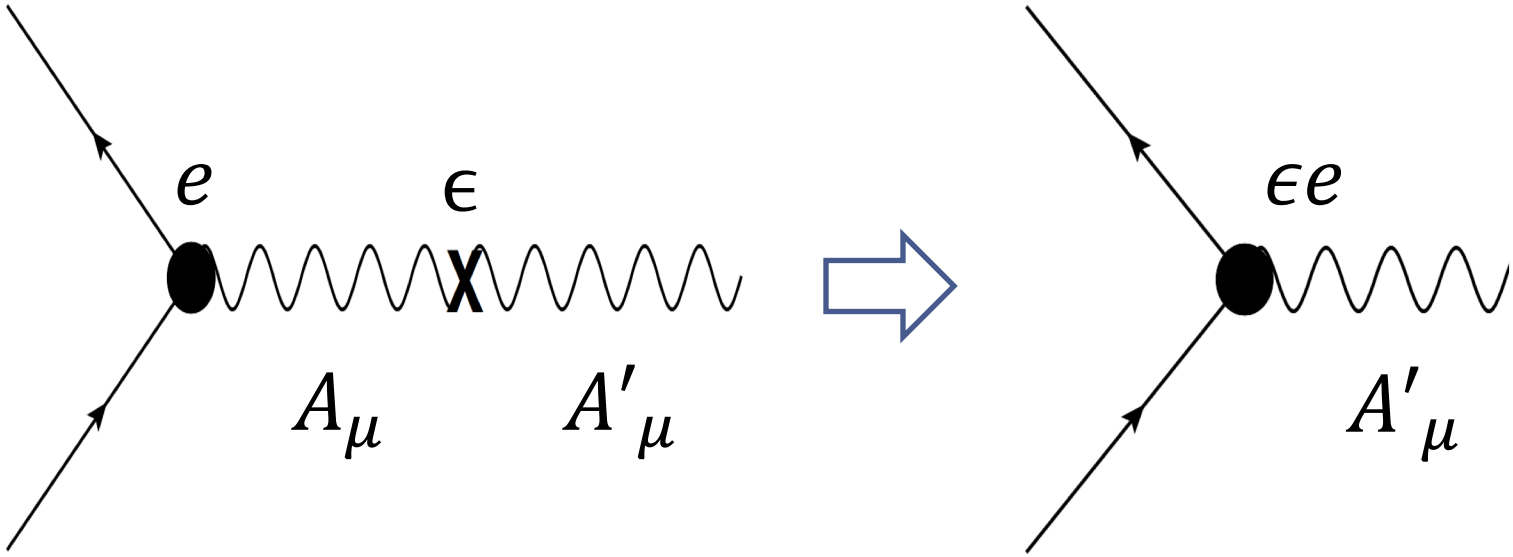
# Conclusion

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

- We calculated constraints for various models, which provides reasonable lower bound for experiment searches

# THANK YOU

# BACK UP




- Dark photon couples to charged SM particles with charge $\epsilon e$:

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

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

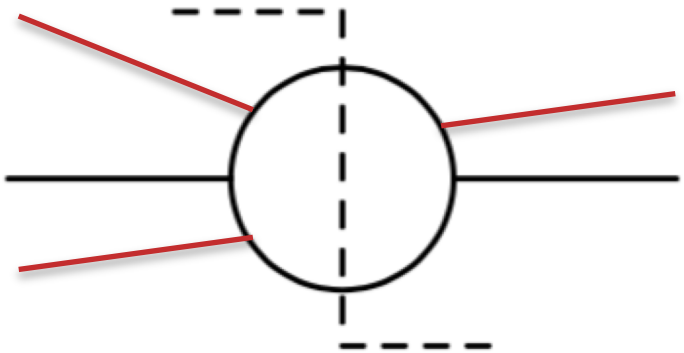
# Real Part of Polarization Tensor

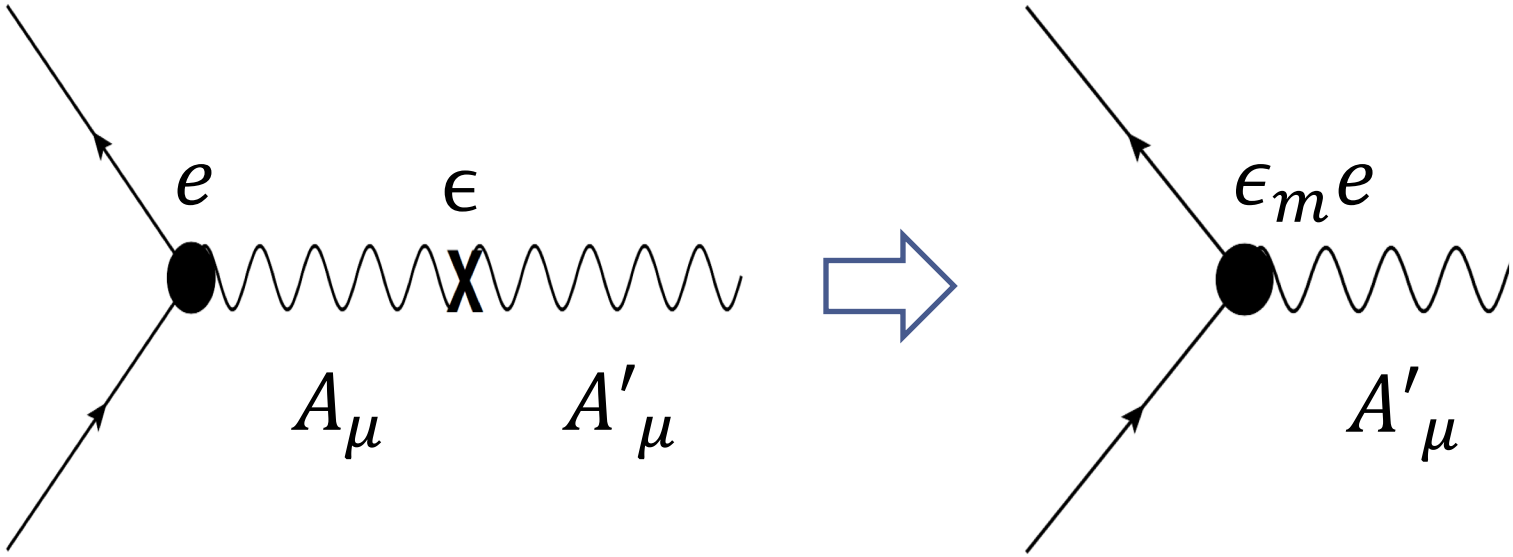
- $\omega^2 - k^2 = \mathrm{Re}\Pi$
- $\mathrm{Re}\Pi$ acts like a photon mass
- $\mathrm{Re}\Pi \approx \omega_p^2$
  $\omega_p \sim 15\mathrm{MeV}$ is the plasma frequency

# 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,

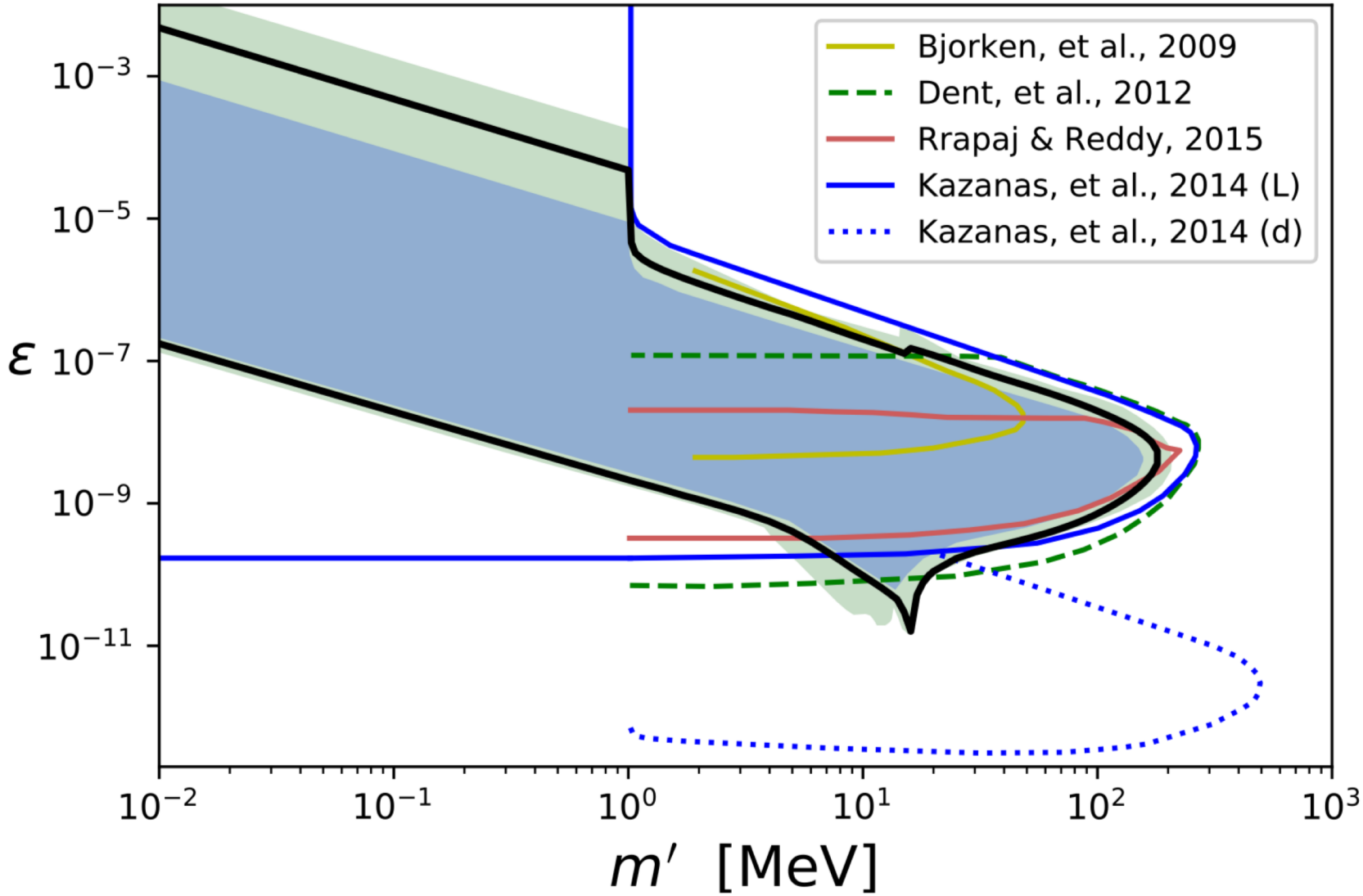
$$\mathcal{M} \propto e \times \frac{1}{q^2 - \Pi} \times \epsilon q^2 = e \frac{q^2}{q^2 - \Pi} \epsilon$$

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

# 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



# Particle Luminosity

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

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

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

# Particle Luminosity

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

Odds of escaping

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

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

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

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