Direct Detection of Millicharged Particles from Supernovae

Yanou Cui

University of California, Riverside

Arxiv:2606.1131 YC w/Fengyi Li, Xiaolin Qi, Ian M. Shoemaker and Yu-Dai Tsai

Jul 1, CETUP 2026

Outline

- Introduction: millicharged particles (mCPs), our goal
- mCP production in Supernovae (SNe)
- mCP Propagation to Earth: Time Delay
- Terrestrial detection of mCPs from SNe: *A new proposal for mCP discovery!*
- Results: detection prospect
- Conclusion

Theoretical Motivation of mCPs

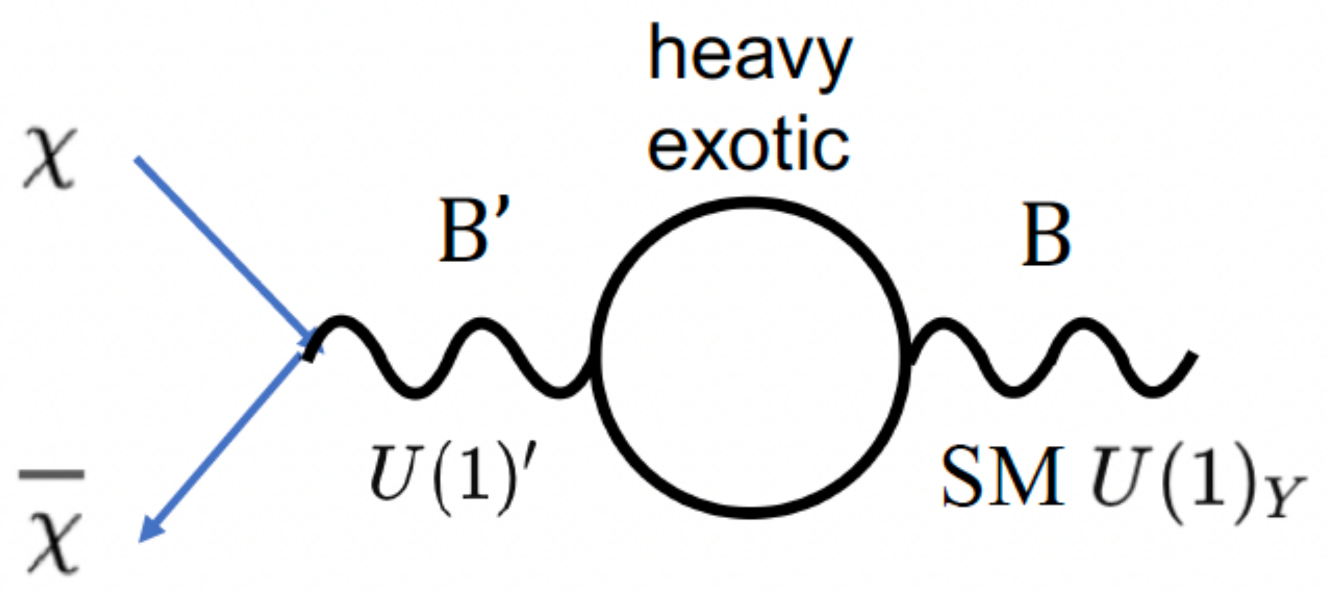
Millicharged particles: BSM particles with small electric charges,

can be dark matter!

"Pure" mCP

- Long standing question: Is electric charge quantized?
- A generic feature of string theory *(Wen, Witten, NPB 1985)*
- A prediction from Grand Unification Theories (GUTs) *(Holdom, PLB 1986)*

Effective mCP: kinetic mixing induced



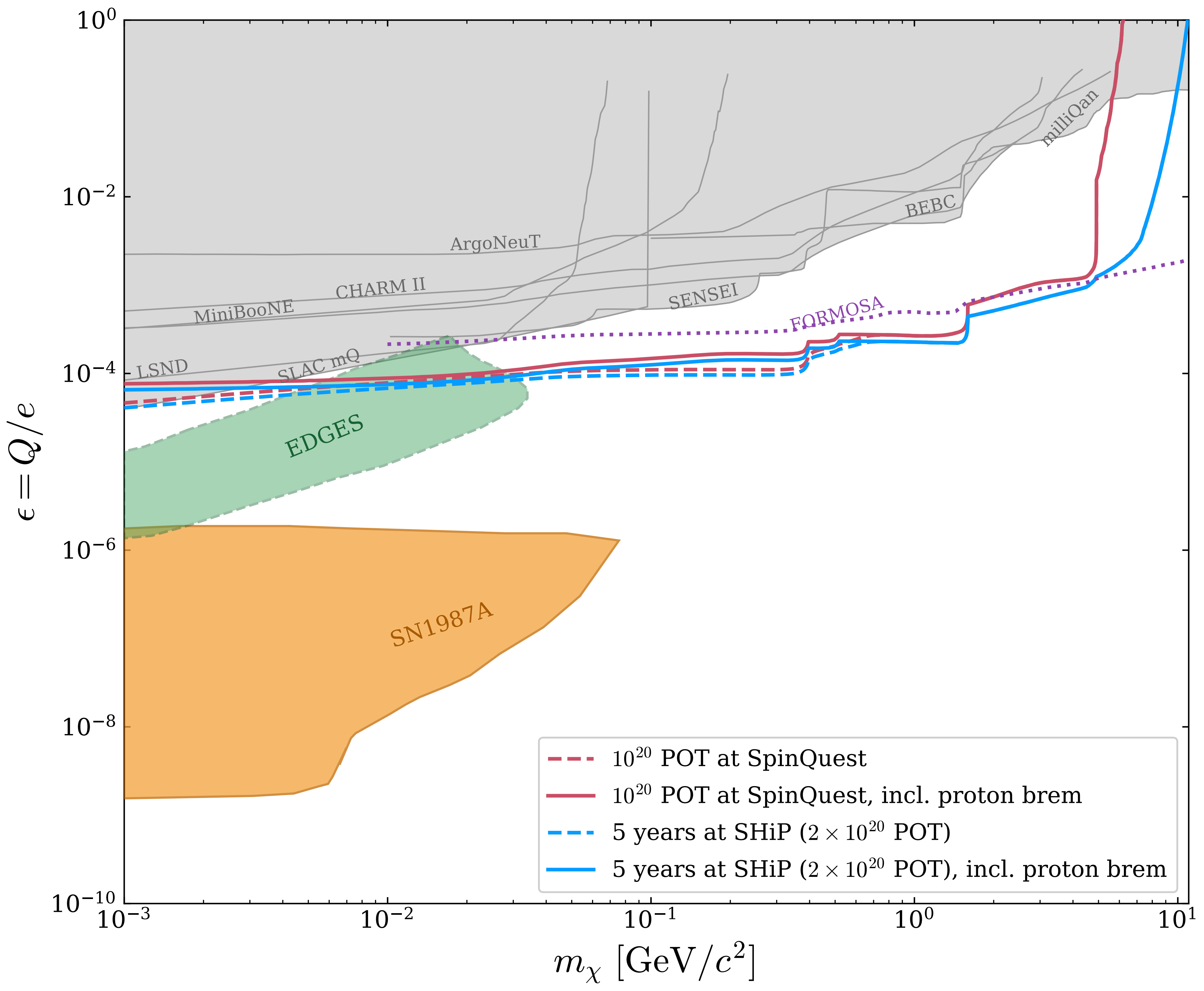
Choose a proper basis: **massless dark photon B' decouple from SM**

$$\mathcal{L}_{\mathrm{MCP}} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\mathrm{MCP}})\chi$$

Existing Searches and Constraints for mCPs

- Laboratory searches: Various experiments at energy + intensity frontiers
  - Electron scattering
  - Ionization
  - Missing energy

- Astrophysical observations:
  - mCP DM: affect 21 cm absorption spectrum (EDGES)
  - Impact on Supernovae dynamics (cooling, LESN)



YC et al. arxiv: 2512.11027

mCP and Core-collapse Supernovae

- **Core-collapse SNe:** Explosive death of a massive star ($M \gtrsim 8M_{\odot}$)

☞ extreme environment: T up to ~ 100 MeV, $\rho \gtrsim 10^{14}\mathrm{g/cm^3}$

☞ efficient production of BSM particles with very weak couplings to SM states, such as mCPs ➡ *Lab in the sky!*

- **Existing studies** on mCP and SNe: impact on SN dynamics ➡ constraints on mCP
  - **SN cooling bound:** Any new energy loss channel to be less efficient than standard neutrino emission, otherwise it would shorten the neutrino burst observed from SN1987A.
  - **Calorimetric bound from Low-energy SN (LESN)**: Any additional energy deposited from the core into the SN mantle does not exceed the observed explosion energy *(Caputo et al. 2022, Li. Et al. 2024)*

mCP and Core-collapse Supernovae

- **Our quest:**

  What about the population of mCPs that can escape the SN core freely and travel to earth? Can we discover them through their EM coupling to the SM?

  ☞ Would the flux of such mCP be significant enough?

  ☞ Are there current/upcoming experiments that can detect such mCPs?

  ☞ Would the signal rate be substantial enough for detection?

  ☞ Can we distinguish the signal from known background such as SN neutrinos?

  ☞ Could this new search expand the sensitivity reach for mCP parameter region beyond existing searches?

mCP and Core-collapse Supernovae

- **Our quest:**

  What about the population of mCPs that can escape the SN core freely and travel to earth? Can we discover them through their EM coupling to the SM?

  ☞ Would the flux of such mCP be significant enough? ✅

  ☞ Are there current/upcoming experiments that can detect such mCPs? ✅

  ☞ Would the signal rate be substantial enough for detection? ✅

  ☞ Can we distinguish the signal from known background such as SN neutrinos? ✅

  ☞ Could this new search expand the sensitivity reach for mCP parameter region beyond existing searches? ✅

mCP and Core-collapse Supernovae

- **Our quest:**

What about the population of mCPs that can escape the SN core freely and travel to earth? Can we discover them through their EM coupling to the SM?

☞ Would the flux of such mCP be significant enough? ✅

☞ Are there current/upcoming experiments that can detect such mCPs? ✅

☞ Would the signal rate be substantial enough for detection? ✅

☞ Can we distinguish the signal from known background such as SN neutrinos? ✅

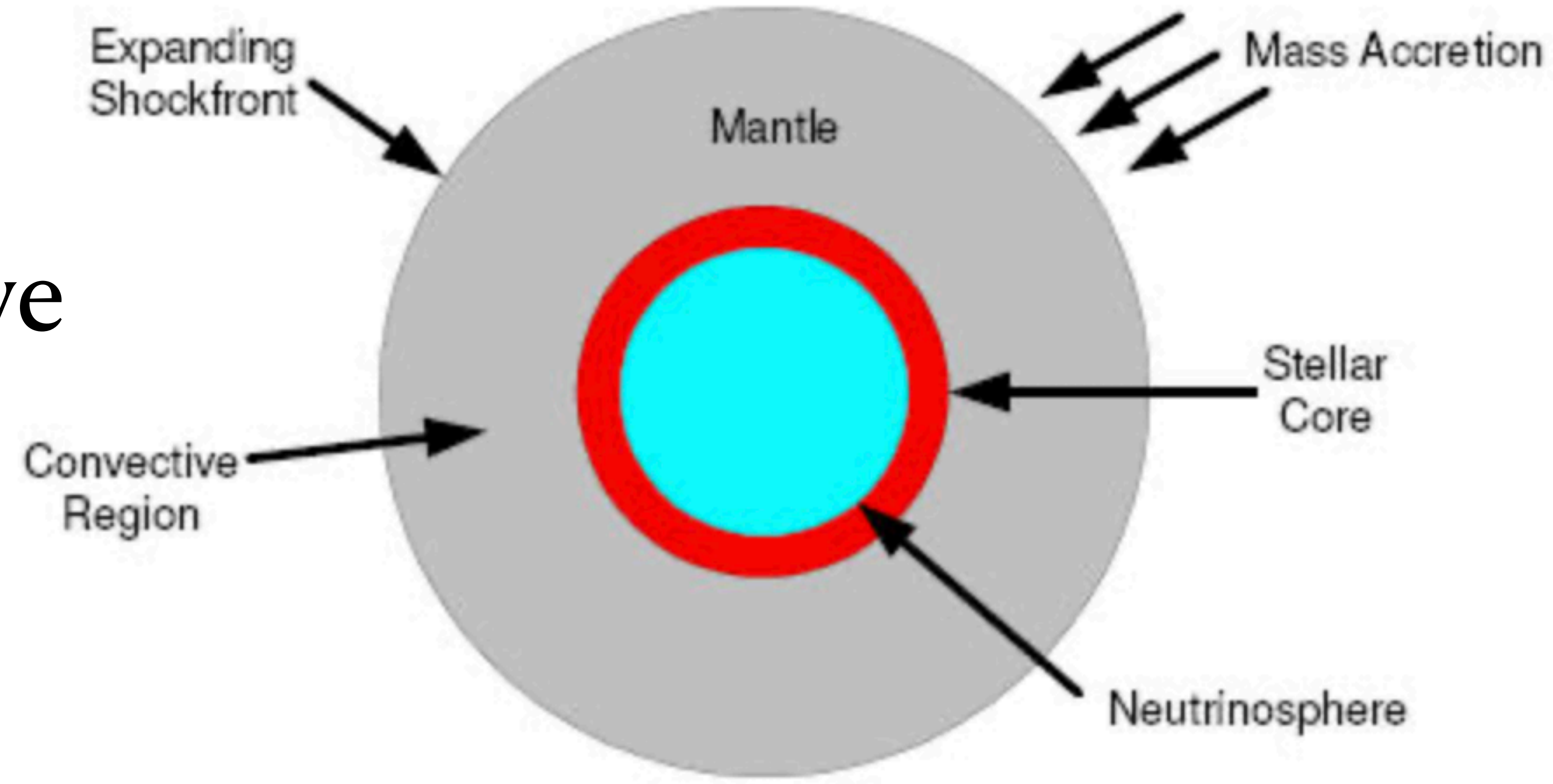
☞ Could this new search expand the sensitivity reach for mCP parameter region beyond existing searches? ✅

★A new proposal for mCP search: terrestrial detection of SN produced mCPs

mCP Production in Supernovae Core

- **Core-collapse SN**: a massive star exhausts nuclear fuel
  → iron core collapses under gravity → a hot, compact
  Proto-neutron star (PNS): core+ mantle; outward shock wave

Figure 1: Theoretical SNe stellar model

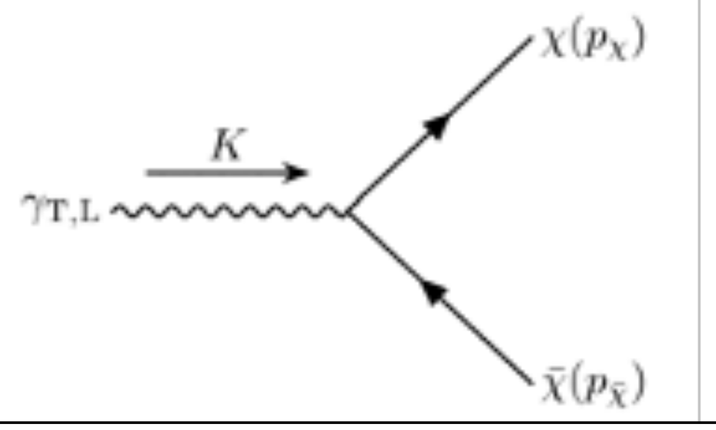
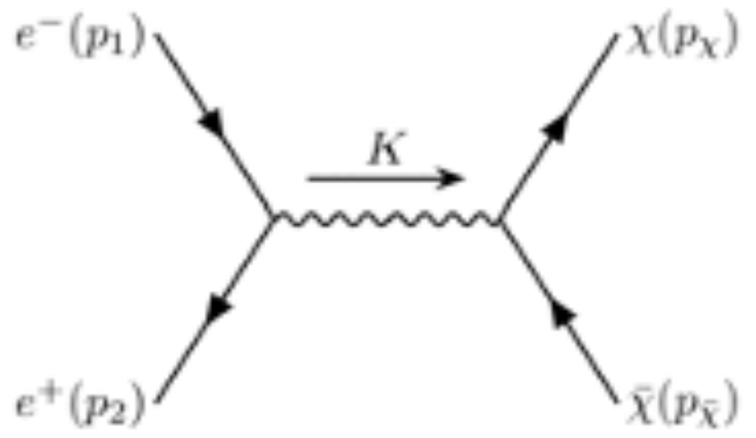
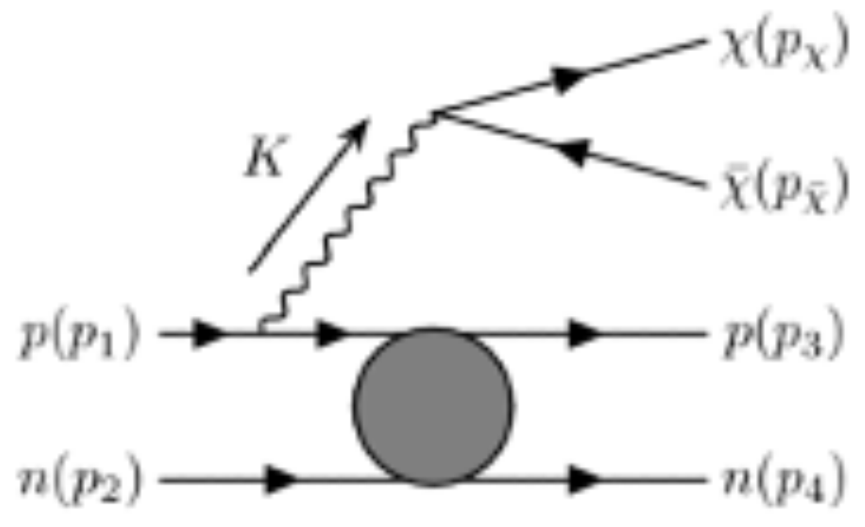


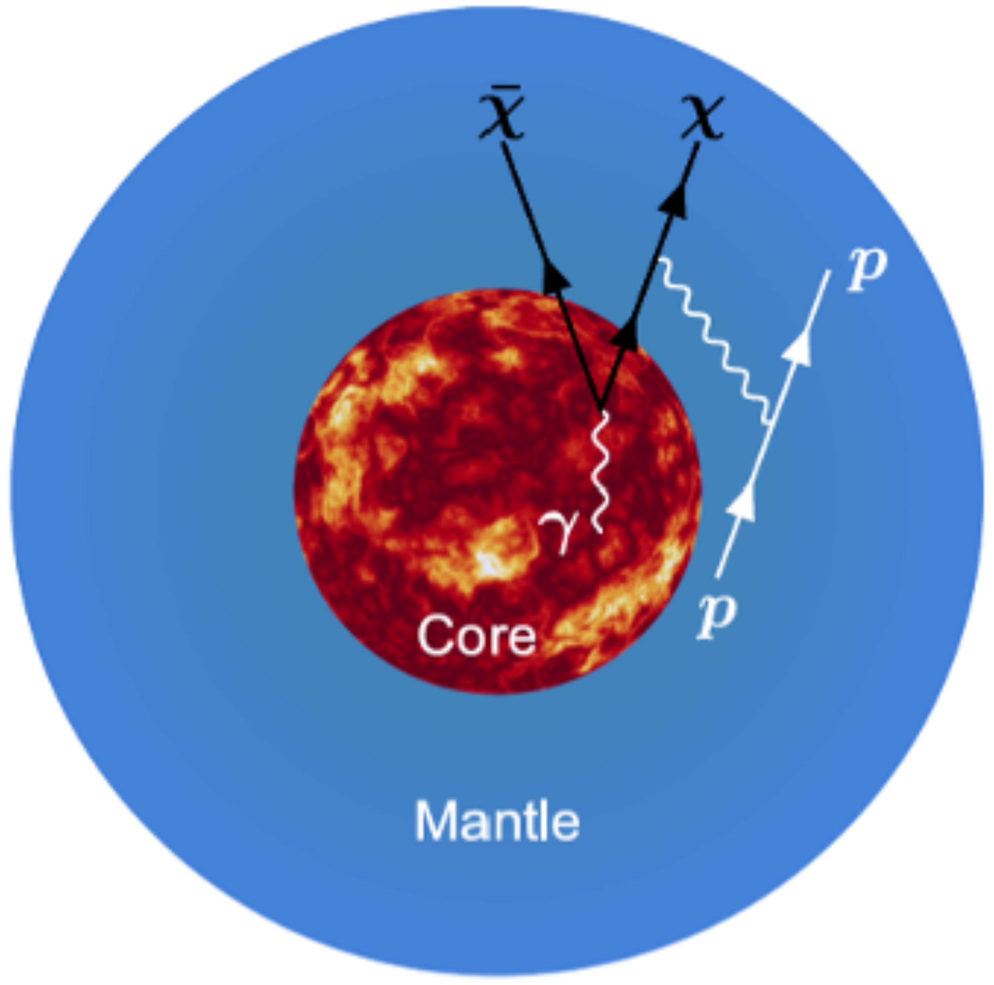
- The condition inside the PNS core defines the production environment of mCPs

- We adopt the *one-zone model* for the SN core *(Caputo, Janka, Raffelt, and E. Vitagliano 2022)*
  Benchmark parameters: $R_c = 12.9\ \text{km}, T_c = 30\ \text{MeV}, \rho_c = 3 \times 10^{14}\text{g/cm}^3, \mu_e = 167\ \text{MeV}$.

- Distance between the SN and Earth: $D = 1\ \text{kpc}$ *(potential next Galactic SN)*,
  $D \simeq 0.17\ \text{kpc}$ *(red giant Betelgeuse, nearby SN progenitor)*; Signal rate $\propto 1/D^2$, strongly suppressed at $D \simeq 50\ \text{kpc}$ (SN1987A)

mCP Production in Supernovae Core

Channel	Process	Feynman diagram
Plasmon decay	$\gamma \to \chi + \bar{\chi}$	
Electron-positron annihilation	$e^+ + e^- \to \chi + \bar{\chi}$	
Proton bremstrahlung	$n + p \to n + p + \chi + \bar{\chi}$	



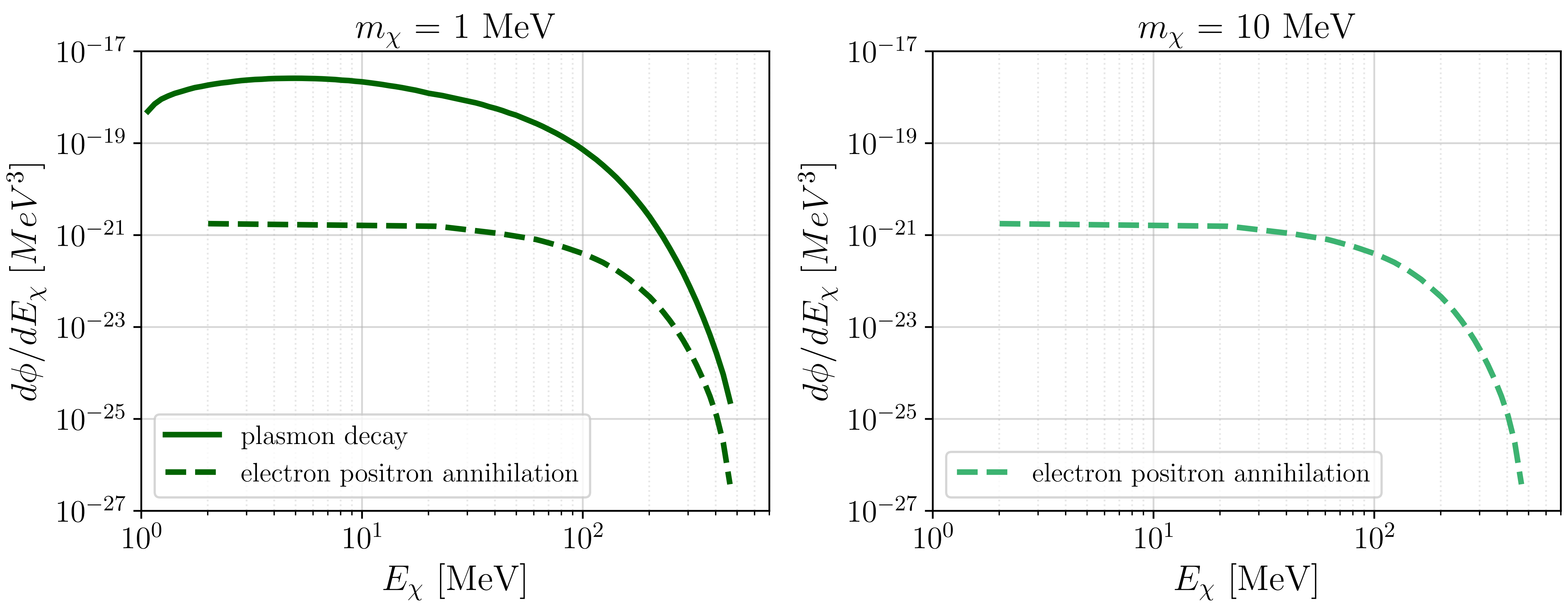
mCP Production in Supernovae Core

- **Plasmon decay** *(photon with an effective mass in the plasma)*:

  dominates at low mass m_χ, due to kinematic threshold ($m_{\text{plasmon}} \sim 12$ MeV)

- e^+e^- **annihilation:** dominates at high mass m_χ
- **Proton bremstrahlung:** potentially important, but notable uncertainties, sensitive to nuclear physics details

  - *Our simplified approach*: focus on plasmon decay and e^+e^- annihilation — conservative, including PB would further enhance mCP signal;
  - *Calculation follows*: *Braaten and Segel 1993, Chu, Kuo, Pradler and Semmelrock 2019,* Li, Liu, Lu and Ye 2024,



mCP Propagation from SN to Earth

mCP Propagation inside the SN

- **Free-streaming in the core**: assumes mCP escape the core without rescattering,

Condition: $\lambda_{\rm mfp} > R_c$ ($\sigma_{\chi e} \sim \varepsilon^2\alpha^2/T_c^2$), met when $\varepsilon \lesssim 10^{-8}$, $m_\chi \lesssim 100$ MeV

☞ Includes the param space of our interest ✅

- **Traversing the mantle:** Coulomb scattering off protons ➡ transfers a fraction of the mCP KE to the shock-heated matter *(the effect used to set the LESN bound)*

— with benchmark $\varepsilon \sim 10^{-9}$, mCP energy loss in the mantle is $< 1\,\%$ of the original mCP energy ☞ safely negligible

mCP Propagation from SN to Earth

Time of Flight (ToF) Delay

- **ToF delay**: a key distinction between SNa mCP and SNa neutrinos.
- A massive particle travels slower than light ☞ an mCP with mass m_χ and energy $\bar{E}_\chi$ arrives at Earth with a ToF delay Δt relative to a massless particle ($m_\nu \ll m_\chi$)

$$\Delta t = \frac{D}{v} - \frac{D}{c} = \frac{D}{c}\left(\frac{1}{\sqrt{1-(m_\chi/\bar{E}_\chi)^2}} - 1\right)$$
$$\simeq 60 \text{ days} \left(\frac{m_\chi}{1 \text{ MeV}}\right)^2 \left(\frac{100 \text{ MeV}}{\bar{E}_\chi}\right)^2 \left(\frac{D}{1 \text{ kpc}}\right)$$

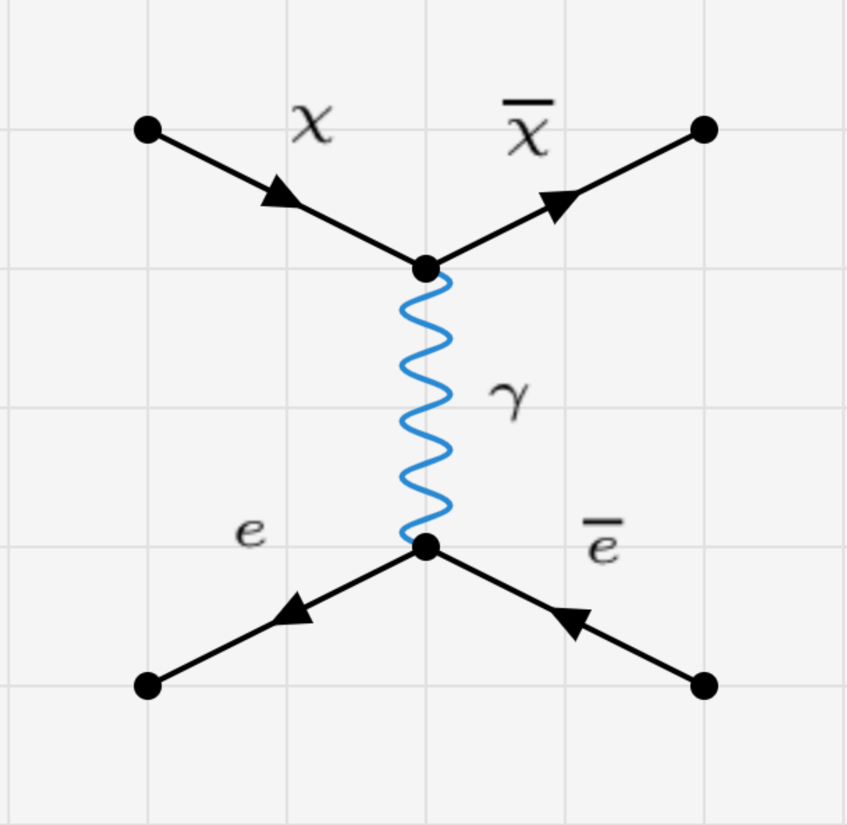
Example: for a SN at $D = 1$ kpc, $m_\chi = 1$ MeV,

Only mCPs with $\bar{E}_\chi \gtrsim 40.5$ MeV arrives within 1 yr after the SN neutrino burst

SNa mCPs arrival to Earth is delayed relative to their neutrinos counterpart (SNa νs)

Terrestrial Detection of SN Produced mCPs

The Signal Events: mCP-electron Scattering



Differential cross section: $$\frac{d\sigma}{dE_e} = \pi\alpha^2\varepsilon^2 \frac{2E_\chi^2 m_e + E_e^2 m_e - E_e\left(m_\chi^2 + m_e(2E_\chi + m_e)\right)}{E_e^2\left(E_\chi^2 - m_\chi^2\right) m_e^2}$$

The differential event number in a detector with N_T target electrons: $$\frac{dN}{dE_e} = \Delta t_{\rm SN} \times N_T \int_{E_{\rm min}^{\rm eff}}^{\infty} dE_\chi \frac{d\phi_\chi}{dE_\chi}\frac{d\sigma}{dE_e}$$

Benchmark: $\Delta t_{\rm SN} = 10\ \rm sec$ $$E_{\rm min}^{\rm eff} = \max\left(E_{\rm min}, \bar{E}_\chi(\Delta t_{\rm obs})\right)$$

Kinematics ➡ $$E_{\rm min} = \left(\frac{E_e}{2} - m_\chi\right)\left(1 \pm \sqrt{1 + \frac{2E_e}{m_e}\frac{(m_e+m_\chi)^2}{(2m_\chi - E_e)^2}}\right)$$

Total number of detected events (within a certain $\Delta t_{\rm obs}$): $$N = \int_{E_{\rm thr}}^{\infty} \frac{dN}{dE_e} dE_e$$

$E_{\rm thr}$: detection threshold, depends on detector

Terrestrial Detection of SN Produced mCPs

Detectors

- Existing/upcoming neutrino or dark matter detectors can be repurposed for searches for mCP from SNe, representative examples:

Detector	Target	Mass	$E_{\rm thr}$	$N_{\rm T}$
XENONnT [46]	LXe	5.9 ton	1 keV	1.5×10^{30}
JUNO [47]	LS	20 kton	0.2 MeV	6.4×10^{33}
DUNE [48]	LAr	40 kton	5 MeV	1.1×10^{34}
Hyper-K [49]	H_2O	30 kton	3.5 MeV	1.0×10^{34}

- Neutrino detectors: larger volume (N_T), dark matter detector: lower threshold ($E_{\rm thr}$)

- We assume 100 % detector efficiency for simplicity, dedicated experimental study worthwhile

Terrestrial Detection of SN Produced mCPs

Background and its Reduction

- **Primary background to the SNa mCP signals**: neutrinos—solar, atmospheric, and SN
  - Neutrino-electron scattering
  - Charged current neutrino-nucleus scattering where the scattered nucleus undetected
- **Background reduction:**
  - Time profile: a key discriminator, $\nu_{\rm atm}$, $\nu_{\rm solar}$ largely time independent; neutrinos from the same SNa burst arrives promptly vs. ToF delay of mCPs ➡ *optimize timing cuts*
  - Directional information: reduce $\nu_{\rm atm}$, $\nu_{\rm solar}$ ➡ *angular cuts*
  - Spectrum of electron recoil energy (in a given time window): mCP and ν differ

☞ For simplicity we adopts the reasonable assumption of zero backgound (detailed study worthwhile for future work)

Results

- **Detection strategy**: SN burst alert by SNEWS *(SuperNova Early Warning System)*-coordinated triggers ➡ start delayed-arrival search following the burst event

- **Discovery criteria**: 10 mCP signal events in one year following a SN burst, assuming 0 bkg. For other choice of criteria, sensitivity curves rescale according to $N \propto \varepsilon^4$

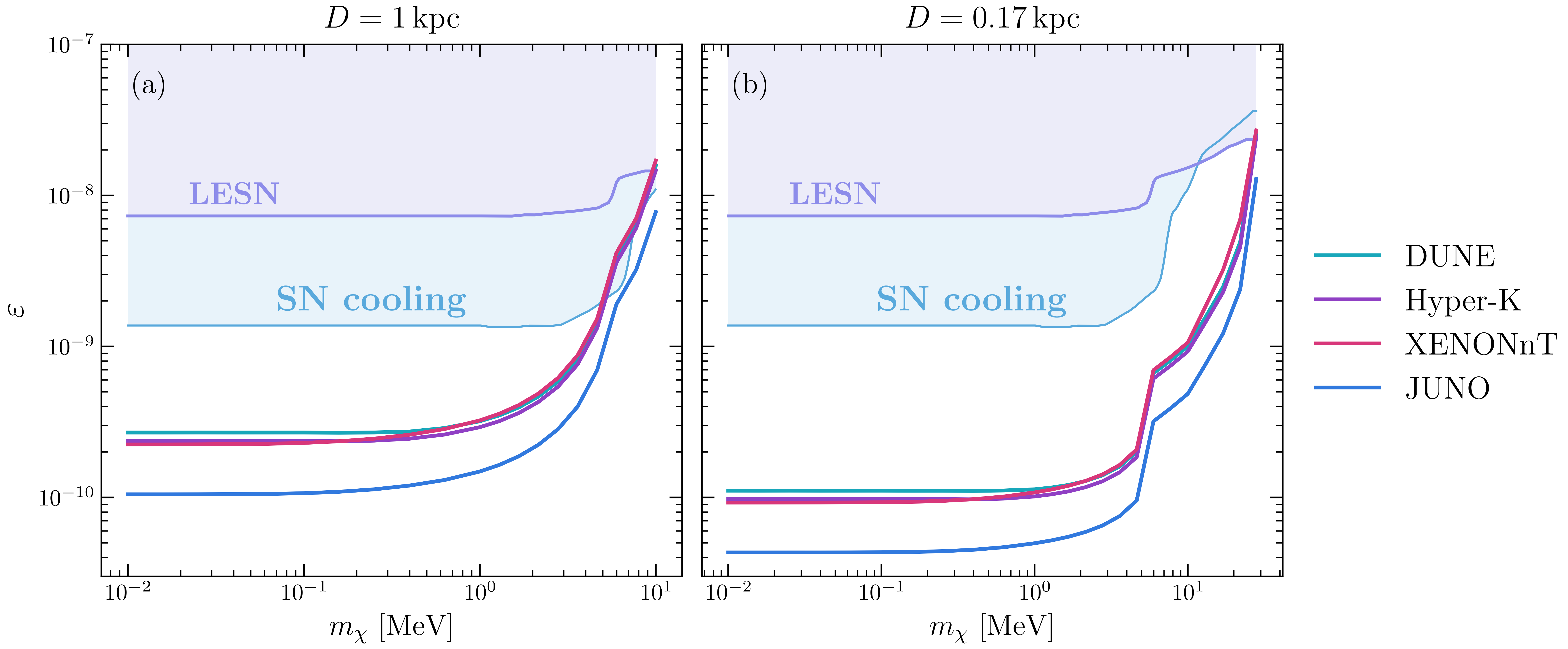
Example: Total event count within the first year after the SNa neutrino burst,

assuming $D = 1$ kpc, $\varepsilon = 10^{-9}$, m_χ in unit of MeV.

Detector	$m_\chi = 0.01$	$m_\chi = 0.1$	$m_\chi = 1$	$m_\chi = 10$
XENONnT	3.9×10^3	3.6×10^3	9.1×10^2	1.2×10^{-4}
JUNO	8.3×10^4	7.7×10^4	2.0×10^4	2.7×10^{-3}
DUNE	1.9×10^3	1.9×10^3	9.6×10^2	1.6×10^{-4}
Hyper-K	3.2×10^3	3.2×10^3	1.4×10^3	2.2×10^{-4}

Results

Sensitivity curves with four benchmark experiments:



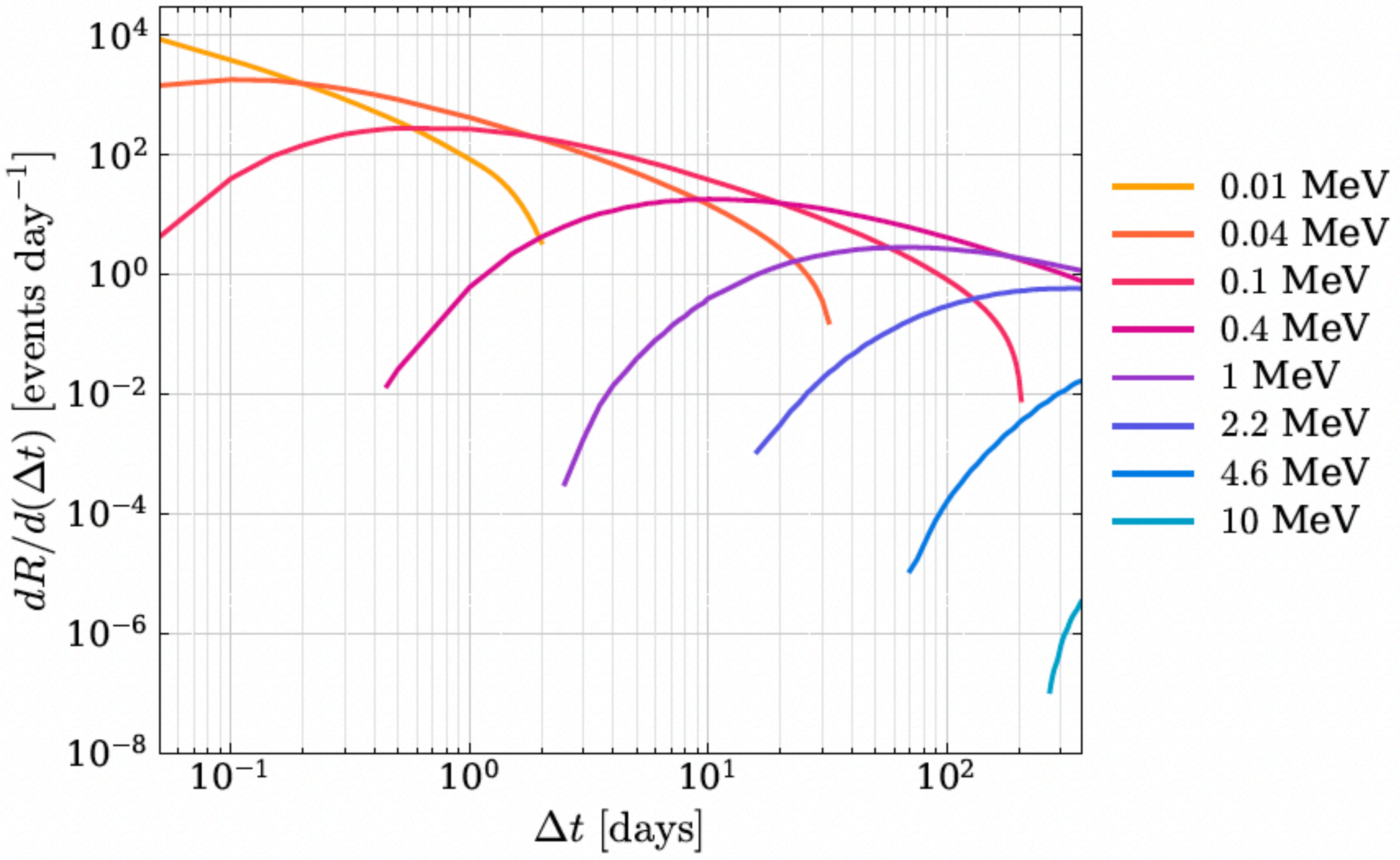
- Compared to SN cooling and LESN bounds , extend the sensitivity reach in ε by up to an order of magnitude! The sharp rise at larger m_χ primarily driven by the ToF cutoff (1 year after burst)

Results

- In light of an excess in signal event counting, additional features to help confirm mCP origin: Time profile and electron recoil spectrum

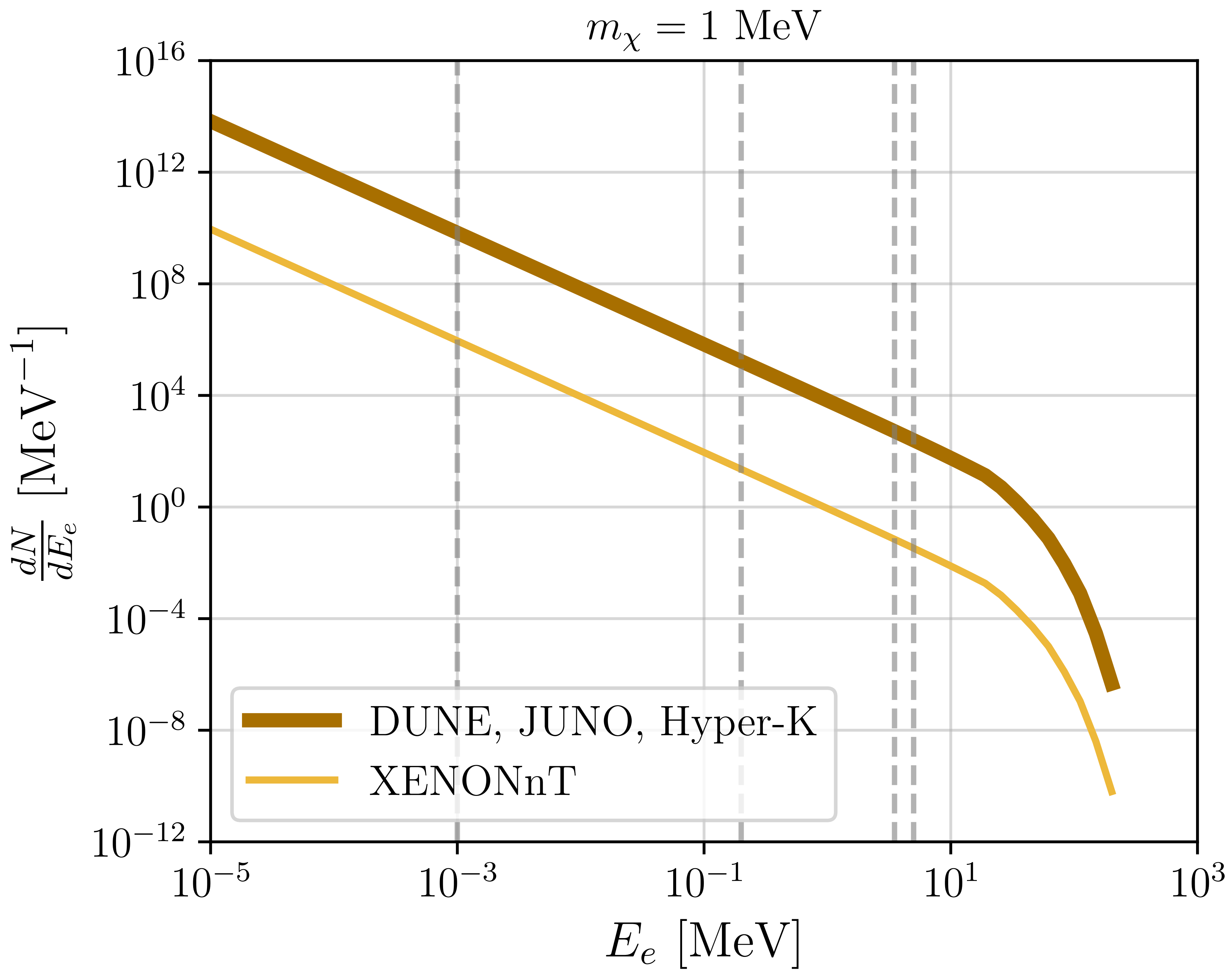
• Time Profile

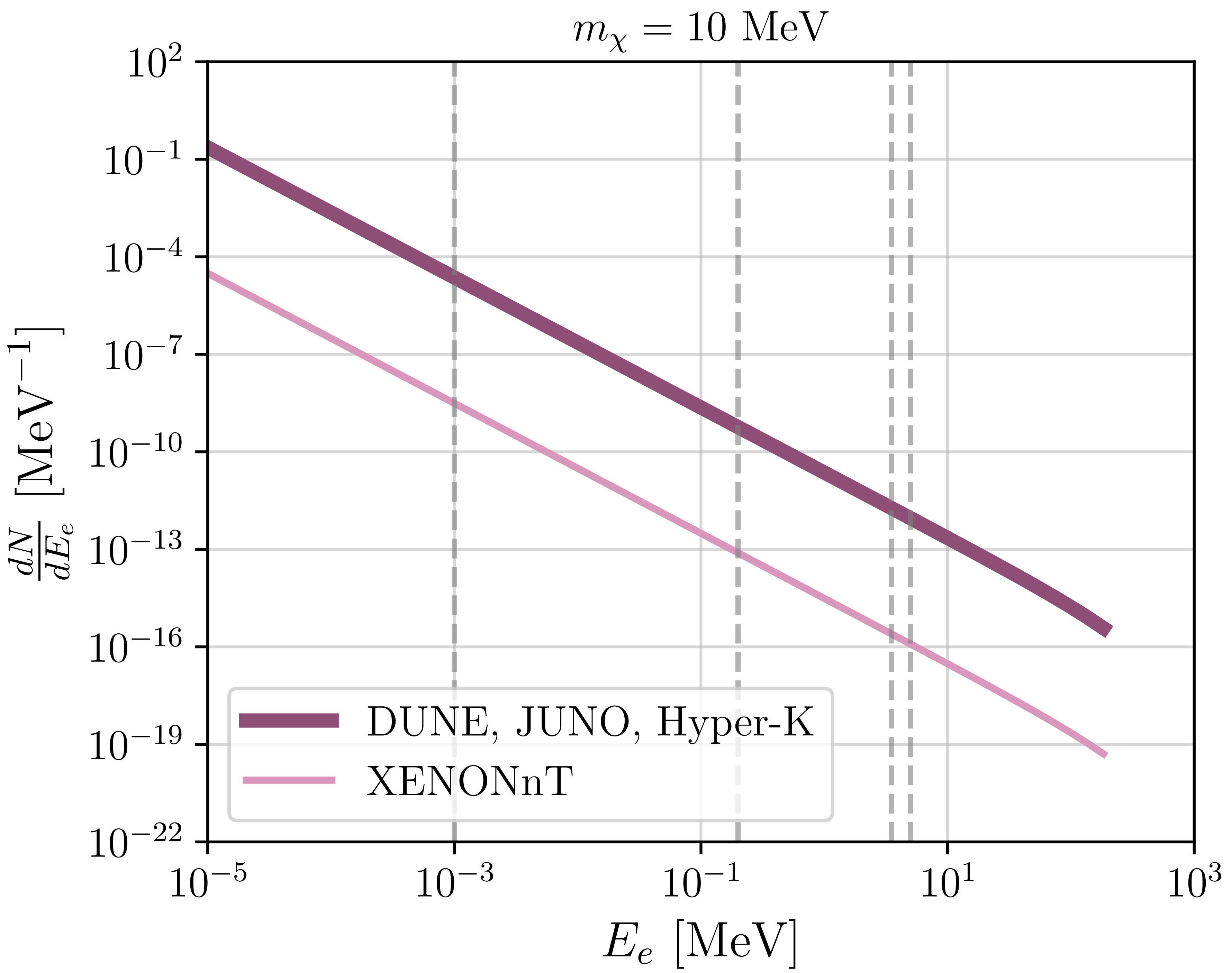
Example: Time profile of the mCP-induced electron recoil event rate at DUNE as a function of ToF delay Δt after a core-collapse SN assuming $D = 1$ kpc, $\varepsilon = 1^{-9}$, for a range of m_χ.



Results

- **Electron recoil spectrum**





Example: The time-integrated electron recoil spectra within the first year after the SN burst. Different experiments are considered for several values of m_χ, assuming $D = 1$ kpc, $\varepsilon = 1^{-9}$.

Conclusion

- **Direct detection of mCPs escaped from SNa:** A new terrestrial probe for astrophysical sourced millicharged particles (mCPs) with promising discovery prospects.
- **No new instrumentation required**, leverage existing experimental infrastructure: neutrino and dark matter detectors, e.g. XENONnT, JUNO, DUNE, Hyper-K.
- **Distinct signals vs. neutrino background**: ToF delay, e^- recoil spectrum, directional info.
- **Complementarity with existing searches/constraints**: improve sensitivity in the mCP param region with small m_χ, small ε; extend below SN1987 cooling and LESN bounds by up to 1 order of magnitude in ε

Next Galactic SNa may be a uniquely sensitive instrument for discovering dark sector particles such as mCPs!

Backup Slides

mCP Propagation from SN to Earth

Galactic Magnetic Field Effects

- mCP carries a small electric charge $Q_\chi = e\varepsilon$ ➡ potentially deflected by $\vec{B}_{\text{Galactic}}$
- To estimate the importance of this effect, estimate the Larmor radius for χ :

$$r_L = \frac{\gamma m_\chi v}{\varepsilon e B} = \frac{E_\chi}{\varepsilon e B}\left[1 - \left(\frac{m_\chi}{E_\chi}\right)^2\right]^{1/2} \simeq 10 \text{ pc}\left(\frac{E_\chi}{10 \text{ MeV}}\right)\left(\frac{10^{-9}}{\varepsilon}\right)\left(\frac{10^{-6} \text{ G}}{B}\right)$$

  - A full treatment of the effect is nontrivial, beyond the scope of the work
  - **Simplified assumption:** magnetic field effect negligible, mCPs propagate along straight trajectories after escaping SN.

Proof of principle: consider UV completion of "effective" mCP associated with a light mass dark photon A', for $10^{-24}\text{eV} \lesssim m_{A'} \lesssim 10^{-11}\text{eV}$, the EM interaction of mCP is long ranged on SN scale, but Yukawa suppressed on scales beyond r_L.