Detecting dark particles from Supernovae

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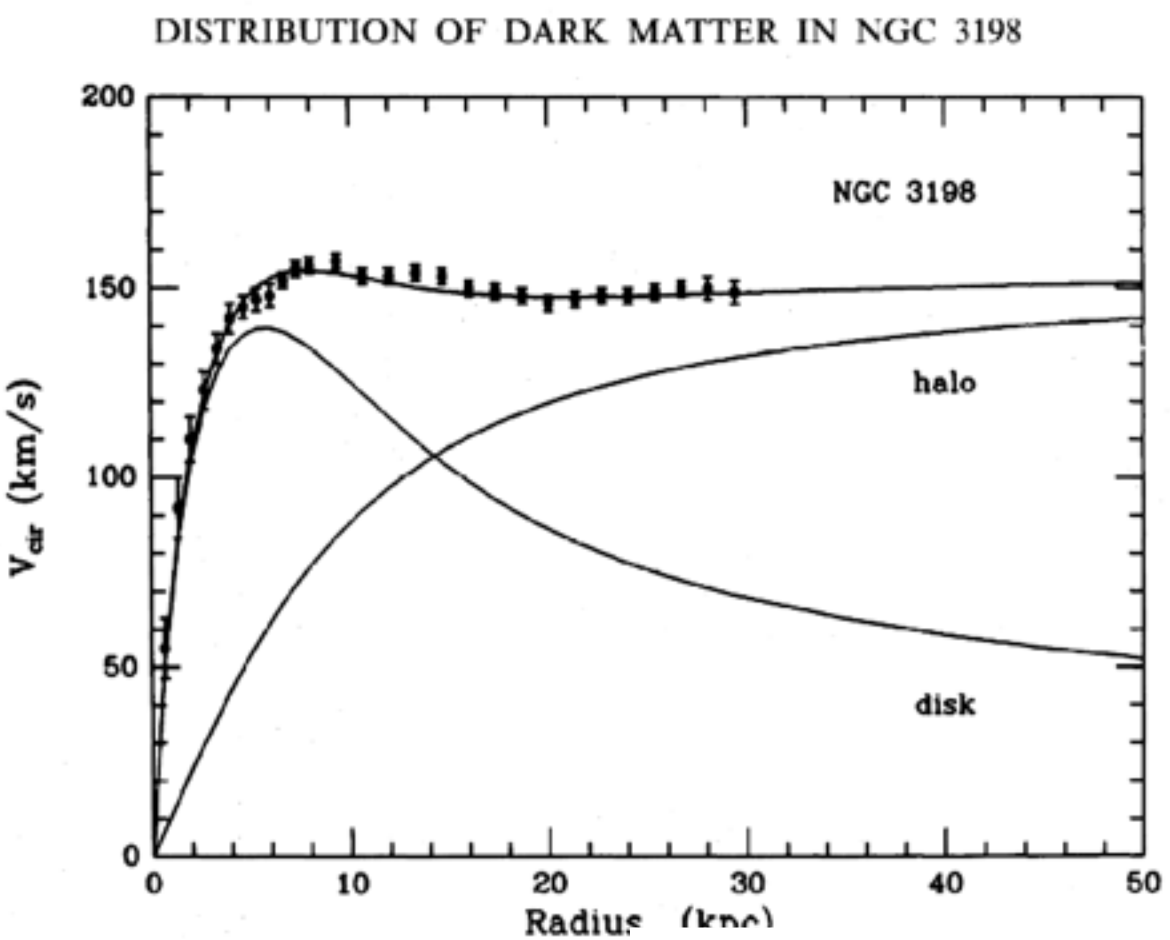
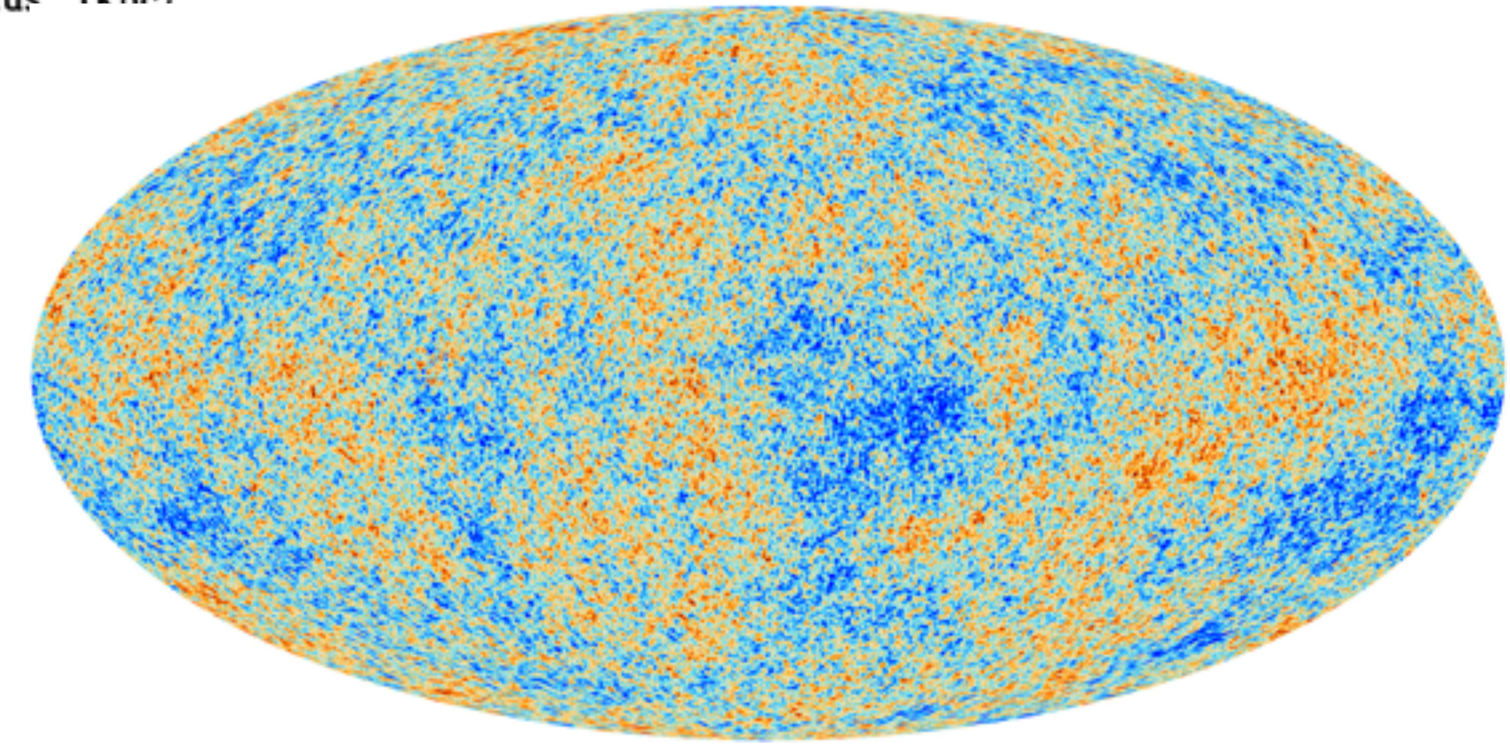
In collaboration with W. deRocco, P. Graham, D. Kasen and S. Rajendran

Dark matter


DISTRIBUTION OF DARK MATTER IN NGC 3198
NGC 3198
halo
disk
V_{cir} (km/s)
200
150
100
50
0
0
10
20
30
40
50
Radius (kpc)



WIMP searches

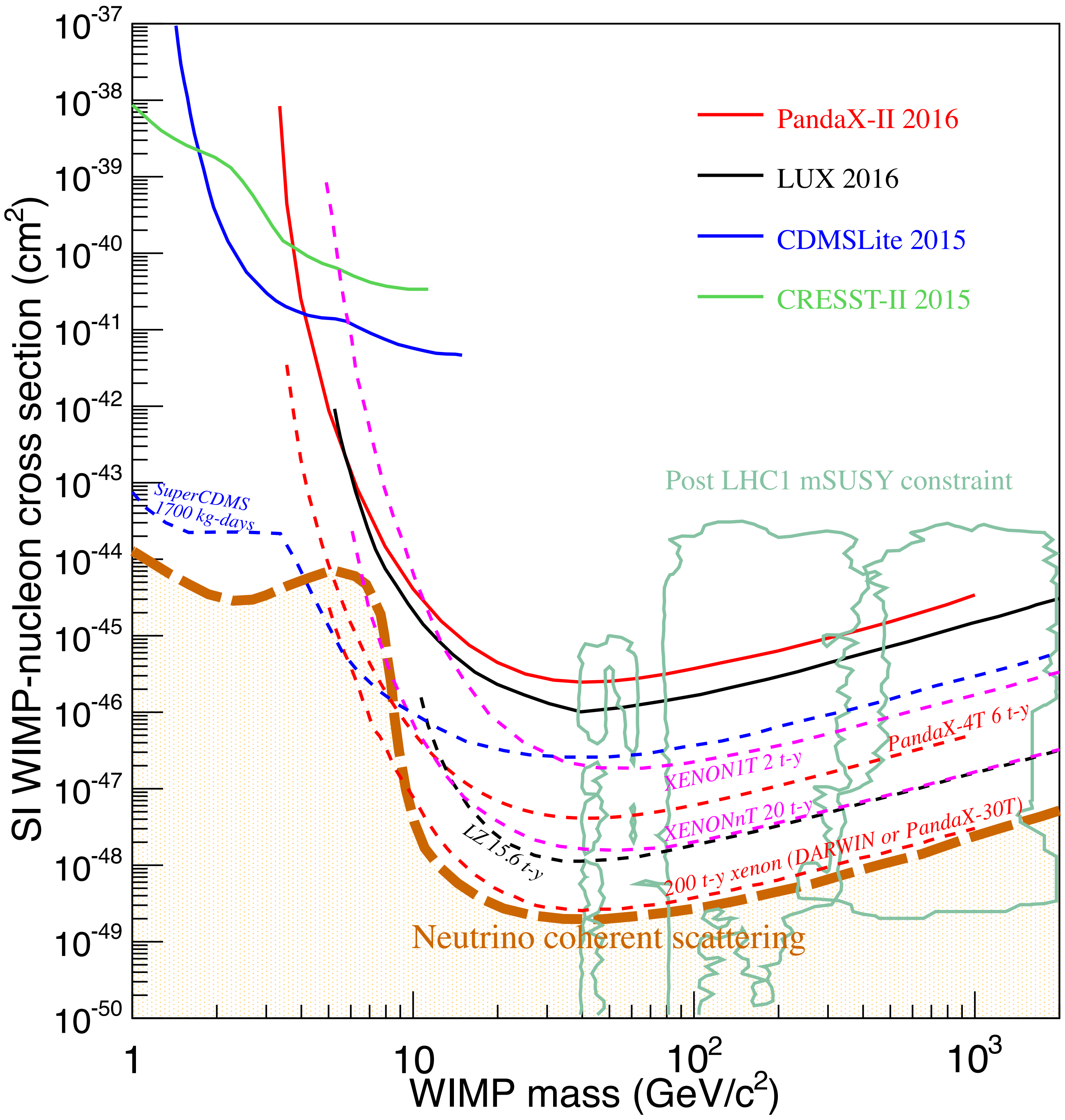


*Figure taken from arxiv:1709.00688

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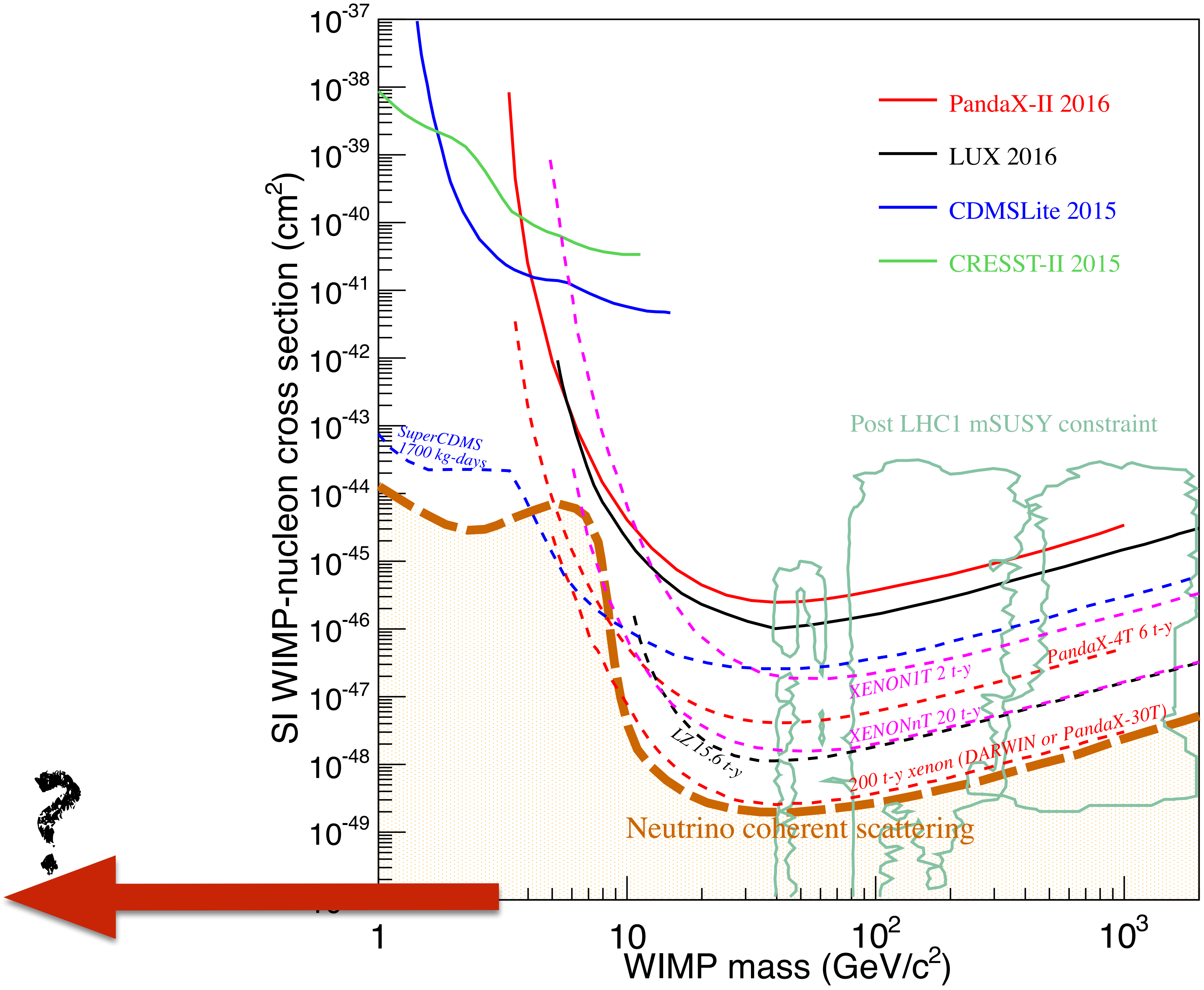

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Challenges for sub-GeV DM

Low kinetic energy: $v \sim 10^{-3}$

$$K \sim 10^{-6} m_\chi < keV$$

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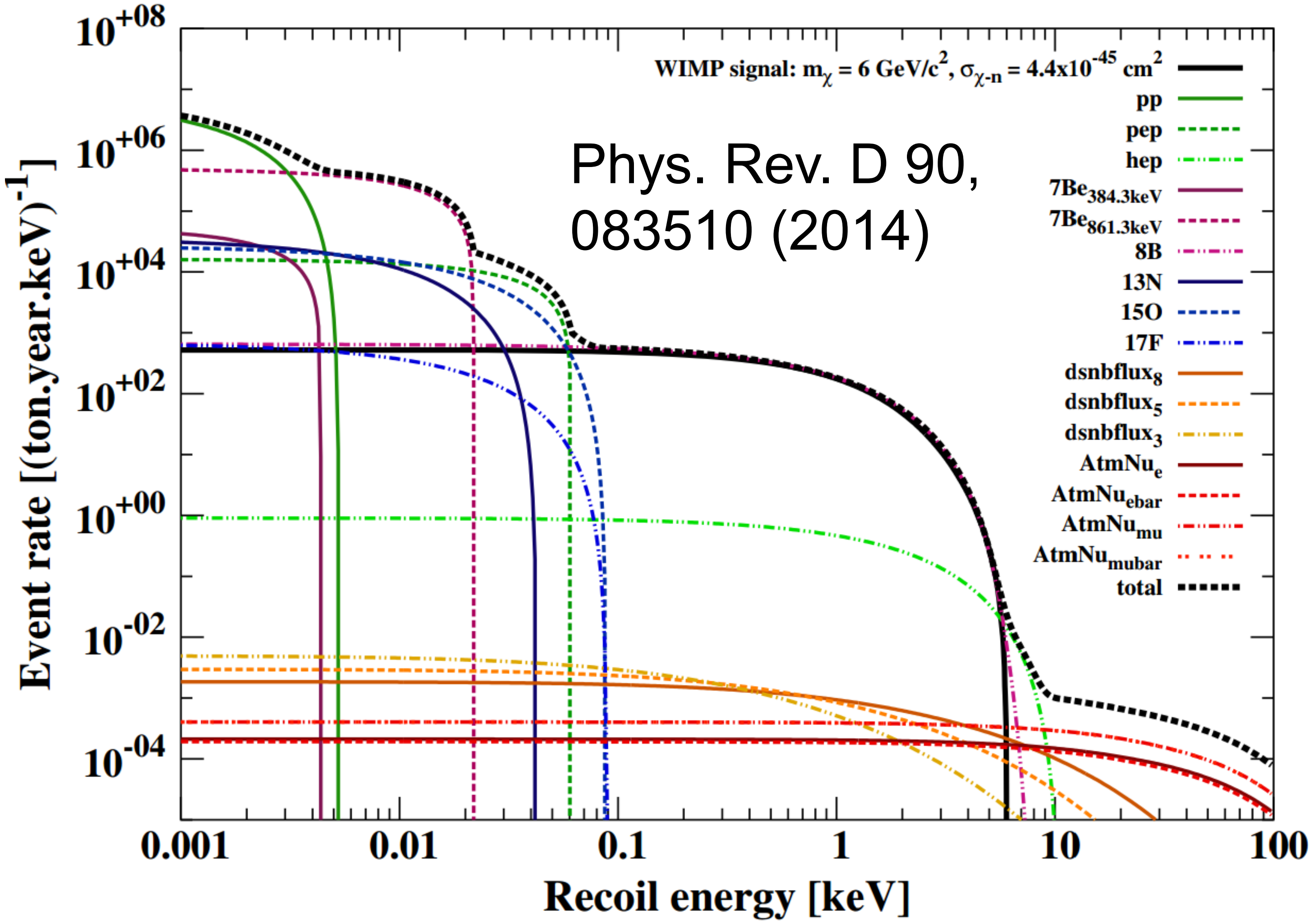
Large background:



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Many strategies

- Search for electron scattering
- Accelerator searches
- New targets

…

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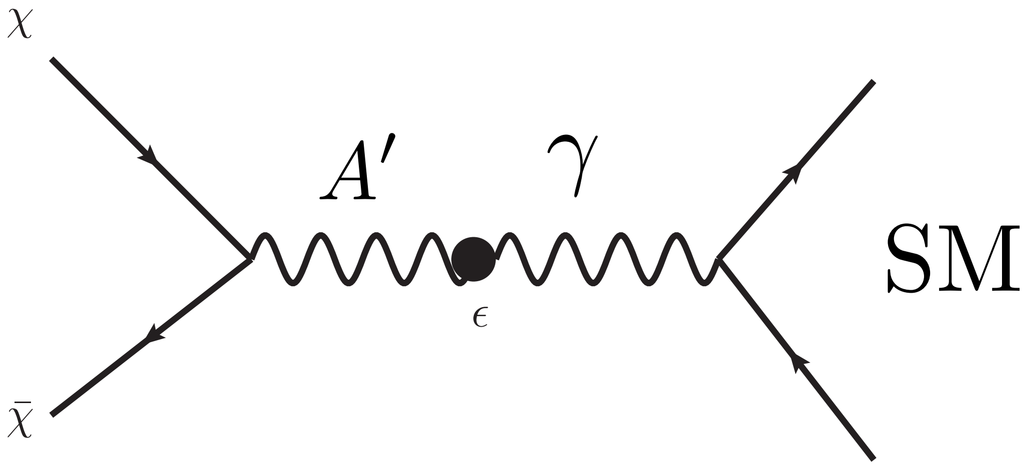
Searching for boosted dark matter from Supernovae

Outline

- Model
- Source: Supernovae
- Computing fluxes and projected sensitivity
- Conclusion and future directions

Dark photon portal

$$\mathcal{L} \supset A'_\mu \bar{\chi}\gamma^\mu \chi + \epsilon F'_{\mu\nu} F^{\mu\nu}$$



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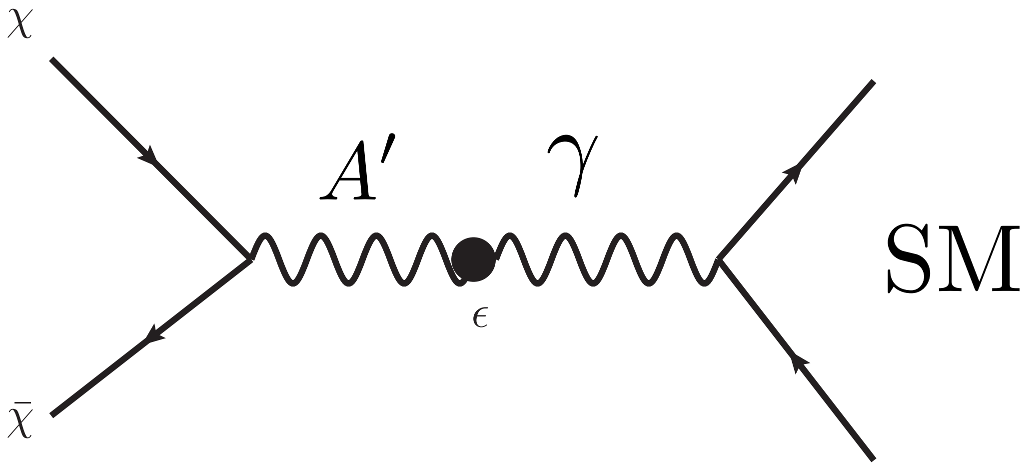

$$m_{A'} \gtrsim 200 \text{ MeV} > m_\chi$$

$$\mathcal{L} \supset \frac{g_d e \epsilon}{m_{A'}^2} \bar{\chi}\gamma_\mu \chi J^\mu_{\text{EM}}$$

Dark photon portal

$$\mathcal{L} \supset \frac{g_d e \epsilon}{m_{A'}^2} \bar{\chi} \gamma_\mu \chi J^\mu_{\rm EM} \qquad \longrightarrow \qquad y = \alpha_d \epsilon^2 \left(\frac{m_\chi}{m_{A'}} \right)^4$$

$$\sigma \sim \frac{\alpha y}{m_\chi^2}$$

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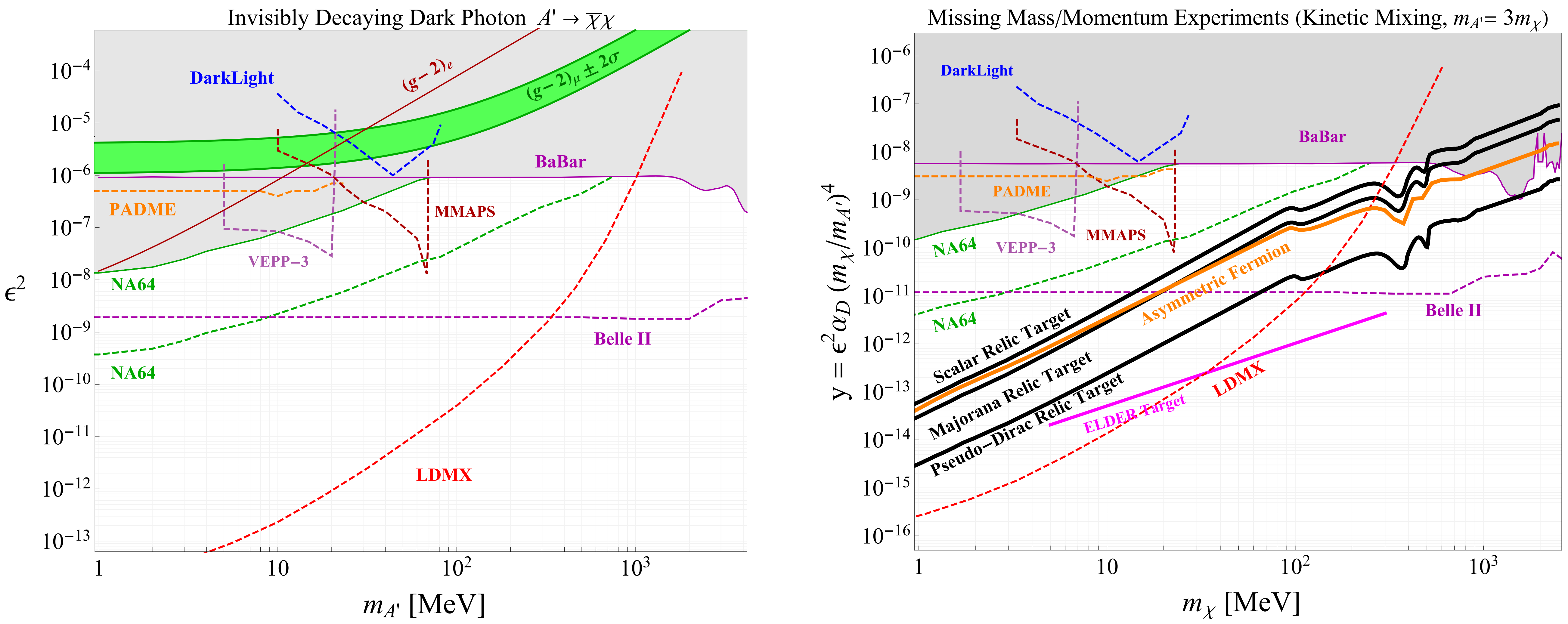

* Figure from US Cosmic Visions Report

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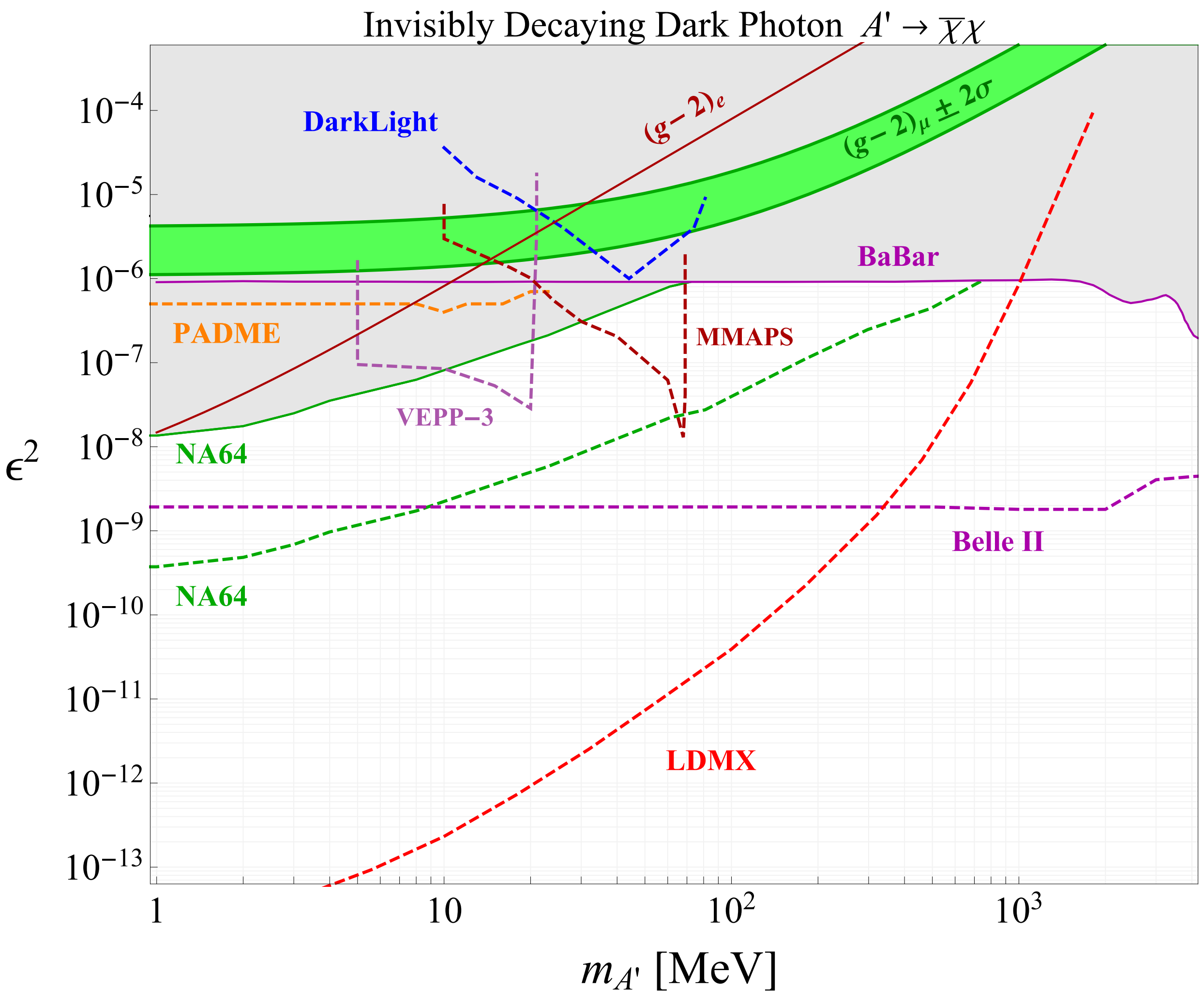

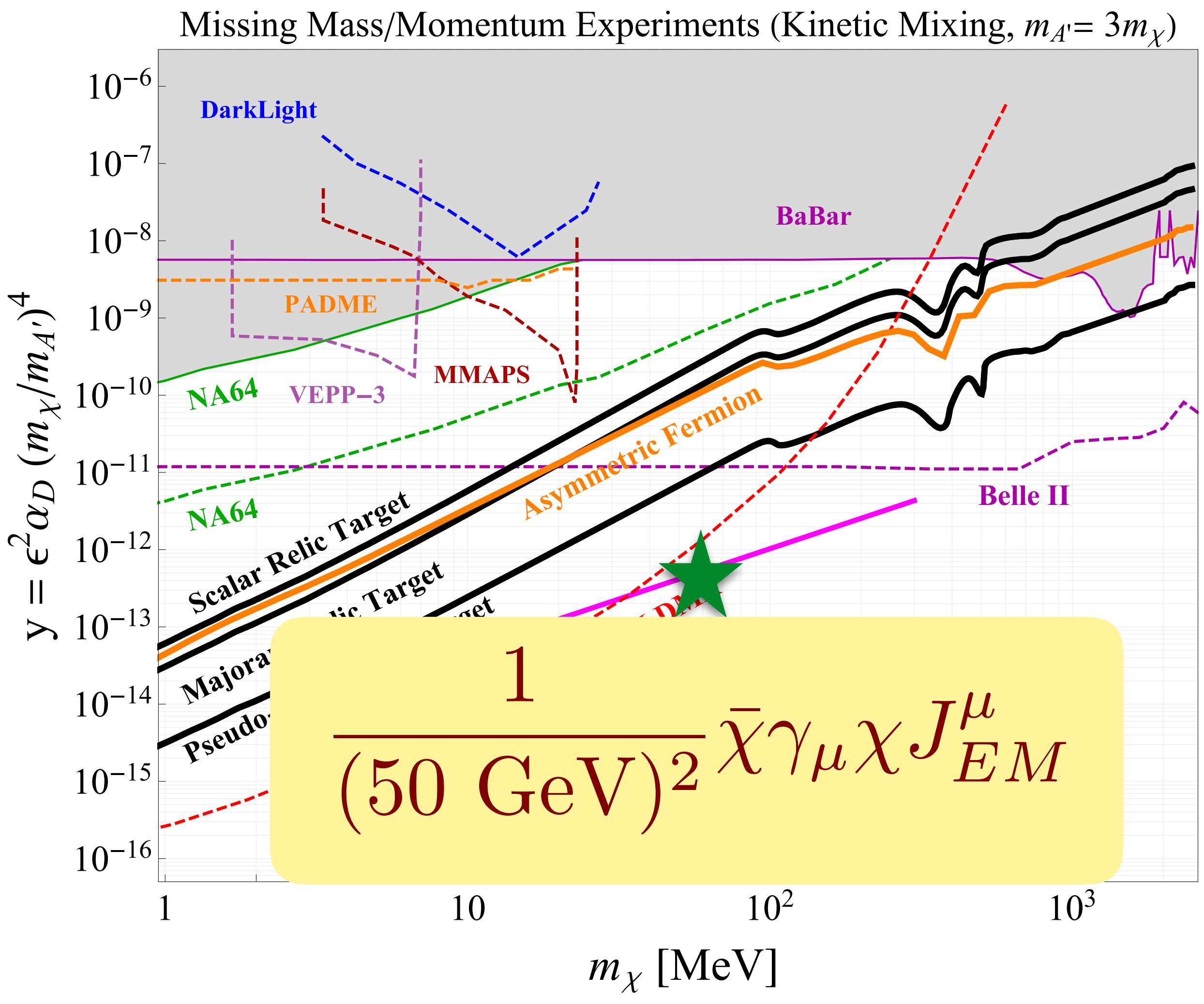

$$\frac{1}{(50\ \text{GeV})^2}\bar{\chi}\gamma_\mu\chi J^\mu_{EM}$$

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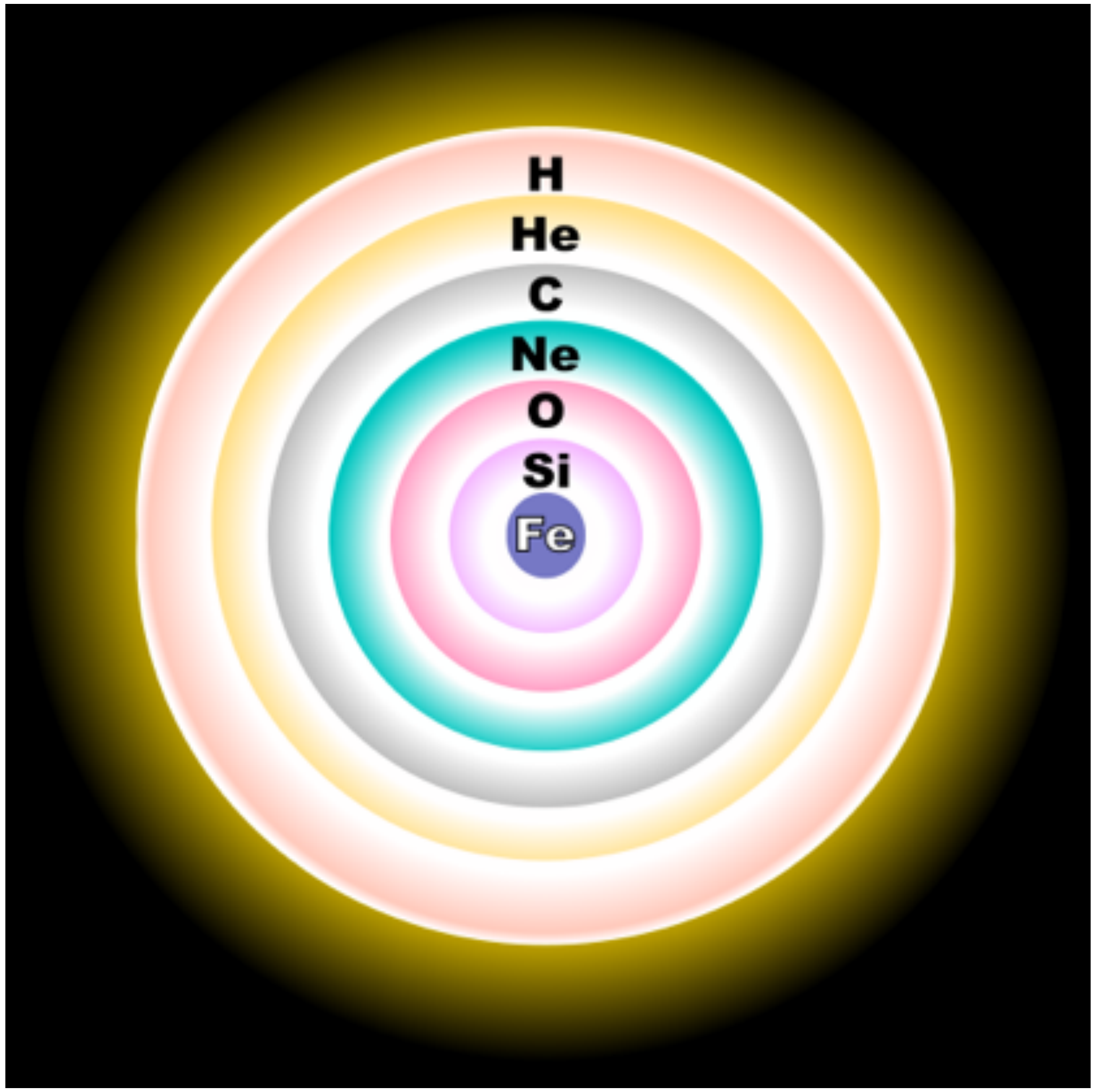
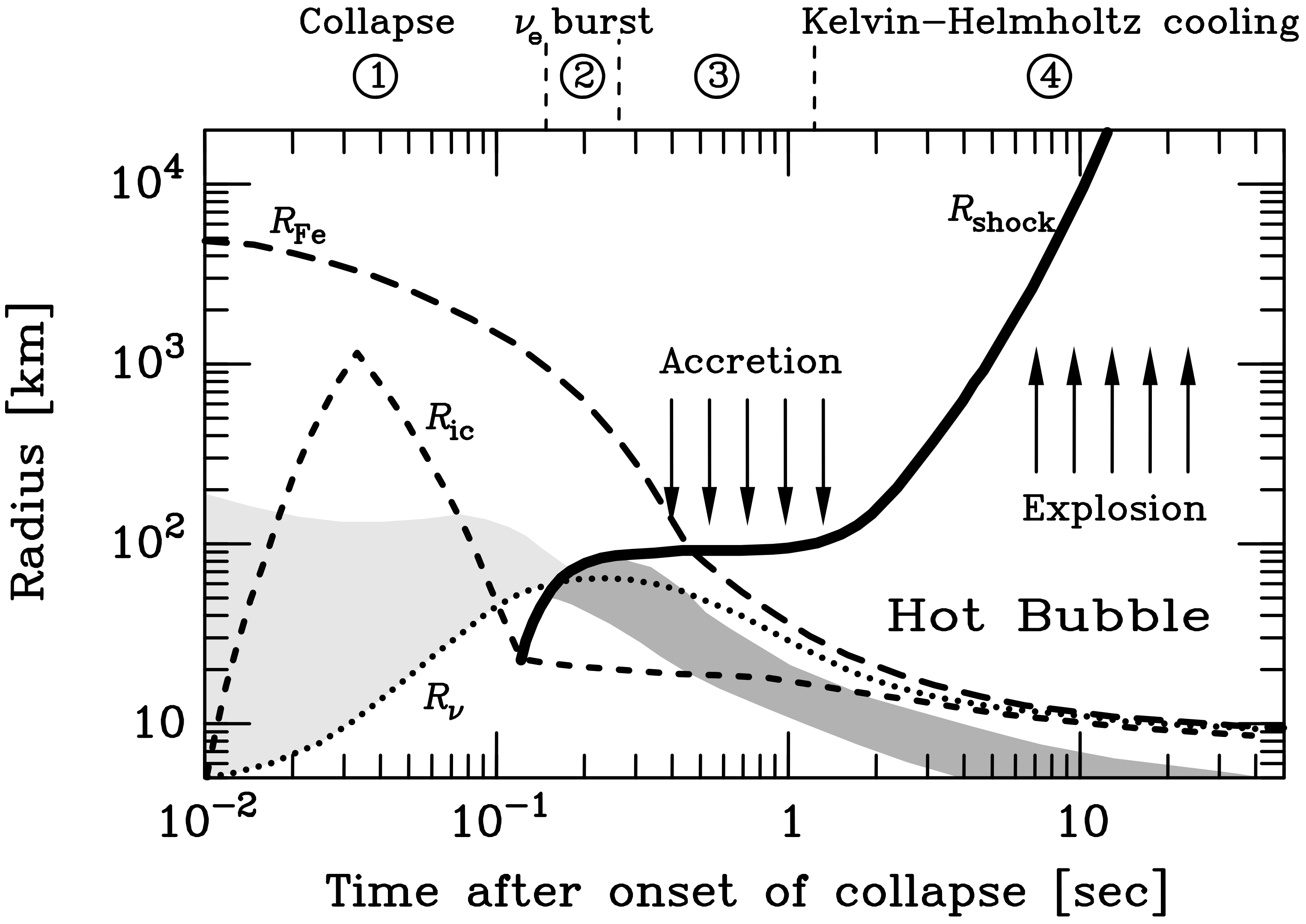
Supernovae

Core-Collapse Supernova



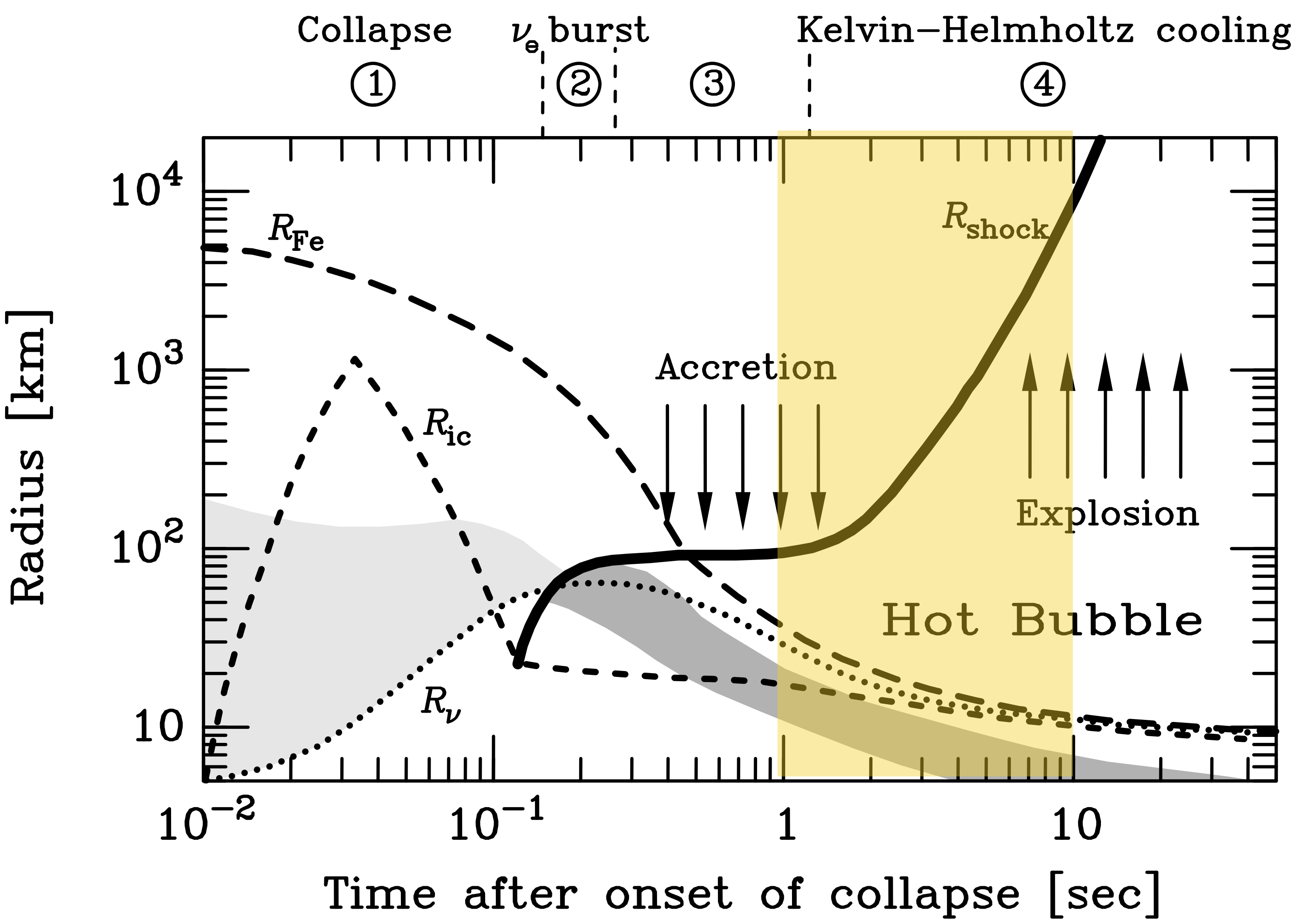
- Very massive stars, $M > 8\ M_{sun}$, become unstable at the end of their life
- Once the iron core reaches the Chandrasekhar limit, $M \sim 1.5\ M_{sun}$, electron degeneracy cannot support the core and it collapses
- Densities are so large neutrinos become trapped and the gravitational binding energy is transferred to a large lepton chemical potential

Core-Collapse Supernova



* Figures from: G. Raffelt, "Stars as Laboratories for Fundamental Physics" , 1996

Core-Collapse Supernova

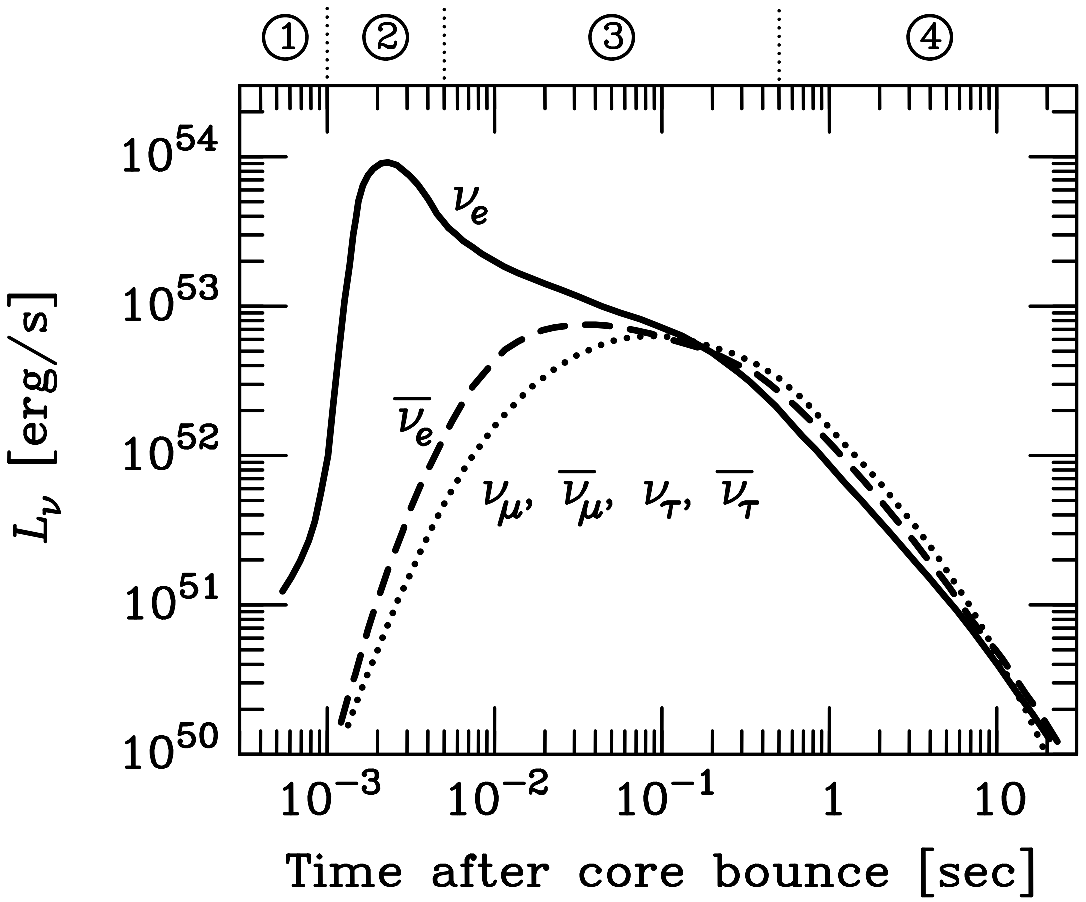


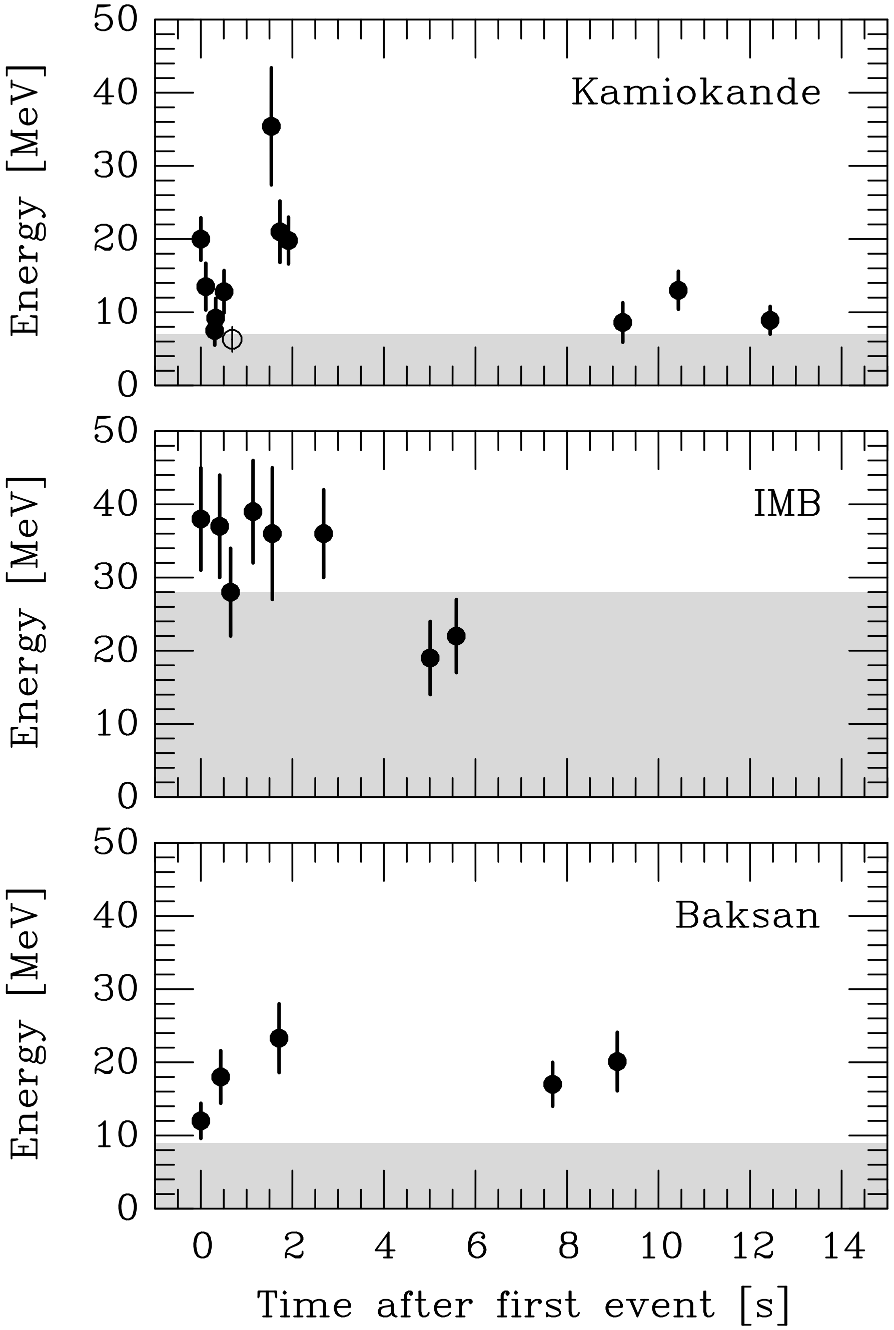
- Inner region is hot and quasi-static from 1 to 10 seconds
- Dark matter flux will be mostly sensitive to what happens at radii < 10^3 km

* Figures from: G. Raffelt, "Stars as Laboratories for Fundamental Physics" , 1996

SN1987a

Detected neutrino signal!





$$d \approx 55 \text{ kpc}$$

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Dark matter flux

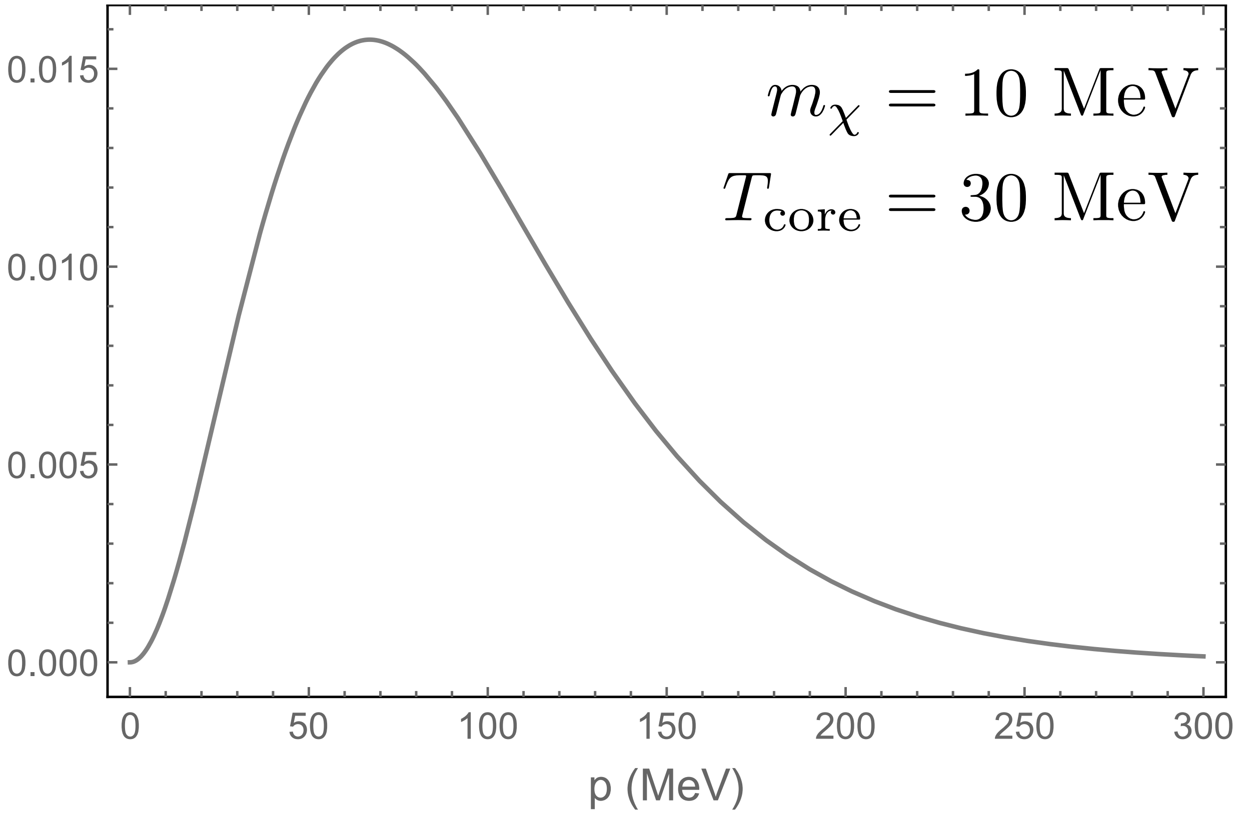
Important effects

Must take into account

- Interactions are large, so dark matter is trapped inside Supernova out to larger radii:
  - Emits as a black-body (surface vs volume)
  - Lower temperature

- Significant velocity spread → signal is significantly spread in time

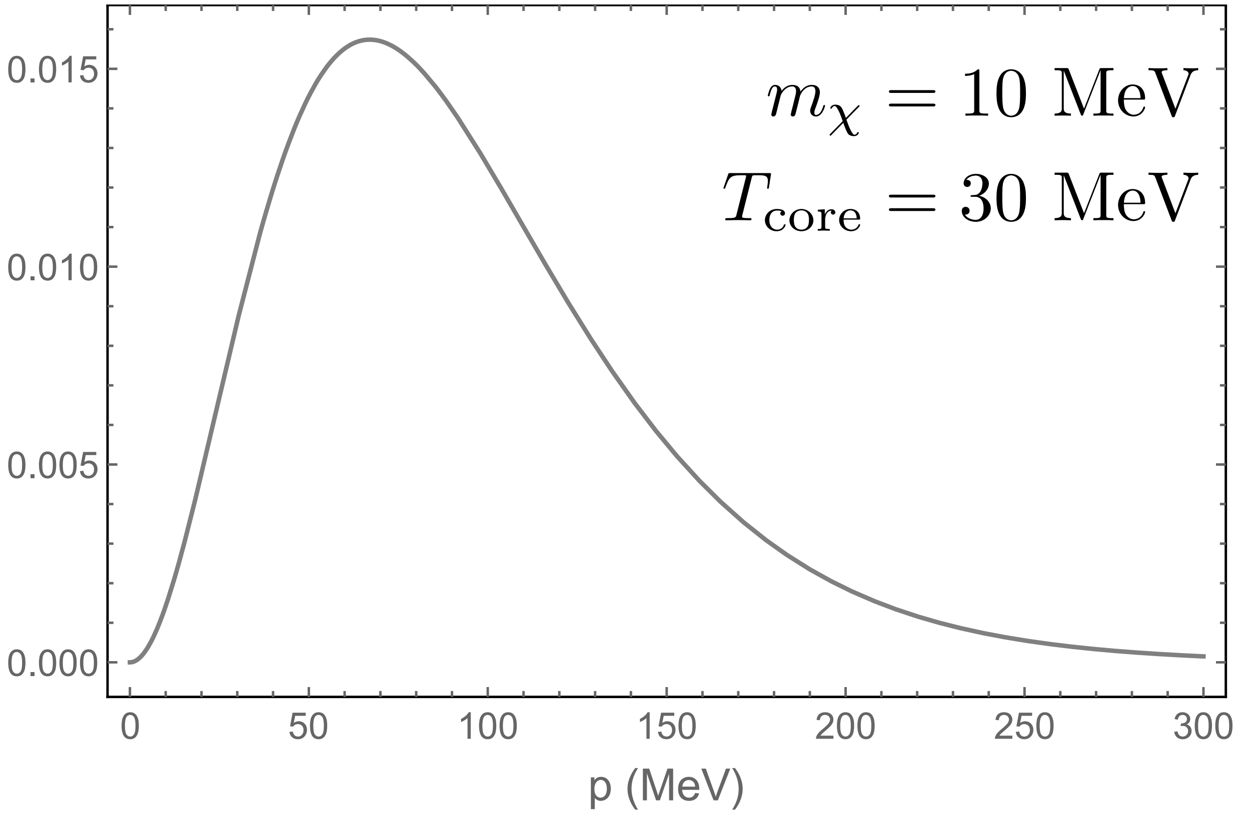
Velocity spread



$$\langle E_\chi \rangle \sim 60 \text{ MeV}$$

$$\langle v_\chi \rangle \sim 0.98$$

Velocity spread



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55 kpc ~ 180000 light years

- Dark matter from SN1987a: still some years to get here
- Signal spread:

$$\frac{\delta v}{v} \sim 1 \longrightarrow \frac{\delta t}{180000\text{yr}} \text{ dilution}$$

Semi-relativistic DM

- Dark matter from SN1987a: still some years to get here
- Signal spread: 10^{-13} dilution

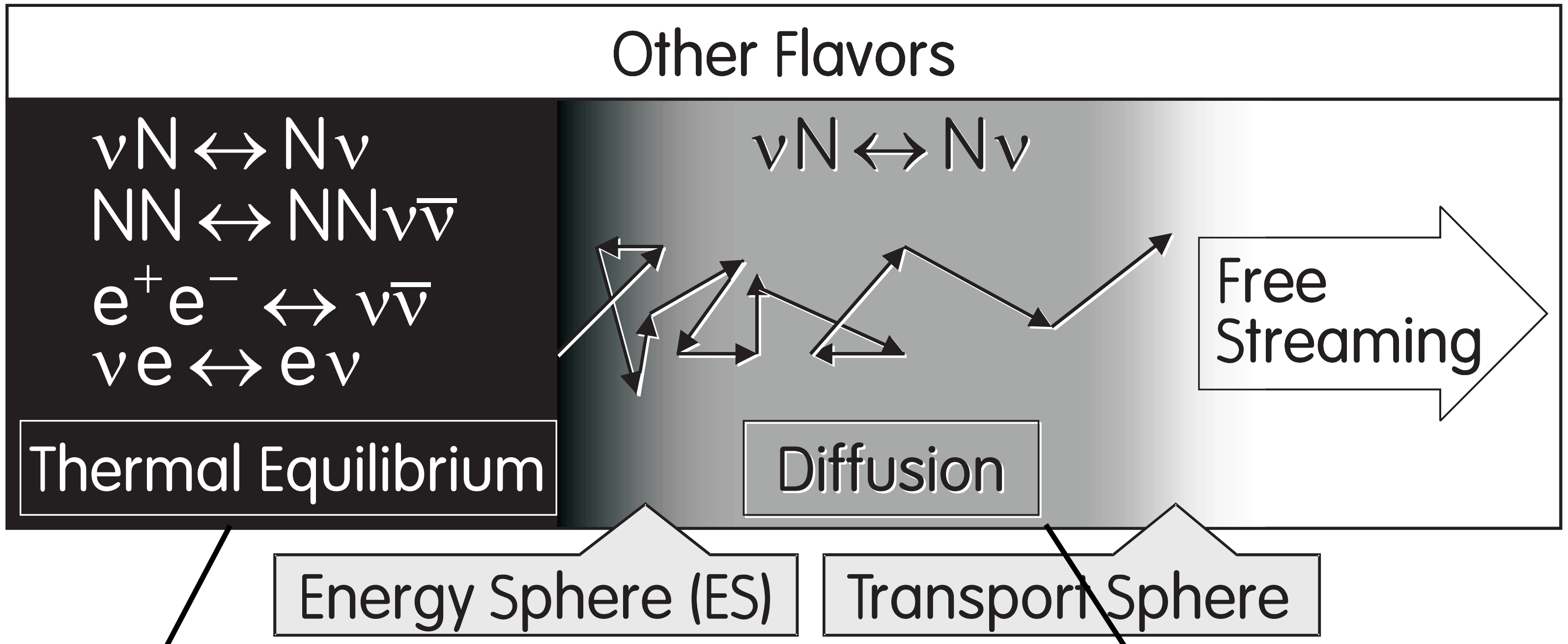
- SN1987a not useful
- Sensitive to older SN (potentially much closer)
- Sensitive to diffuse background of older SN

Effects of large interactions?

- If interactions are large, dark matter can annihilate fast before getting out of Supernova
- It takes time for dark matter to move out since it bounces around scattering with other particles

Understanding Trapped Regime

Useful analogy with neutrino case



Interactions that change neutrino number and/or energy

Interactions that change direction without significant change in energy

Figure taken from: G. Raffelt astro-ph/0105250

Understanding Trapped Regime

- Ultimately described by a Boltzmann equation
- Reasonable results can be obtained using a “freeze-out” calculation.

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<u>Freeze-out in time</u>

Rate ~ 1/timescale

e.g.

$$H \sim n\langle \sigma v \rangle$$

<u>Freeze-out in space</u>

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e.g.

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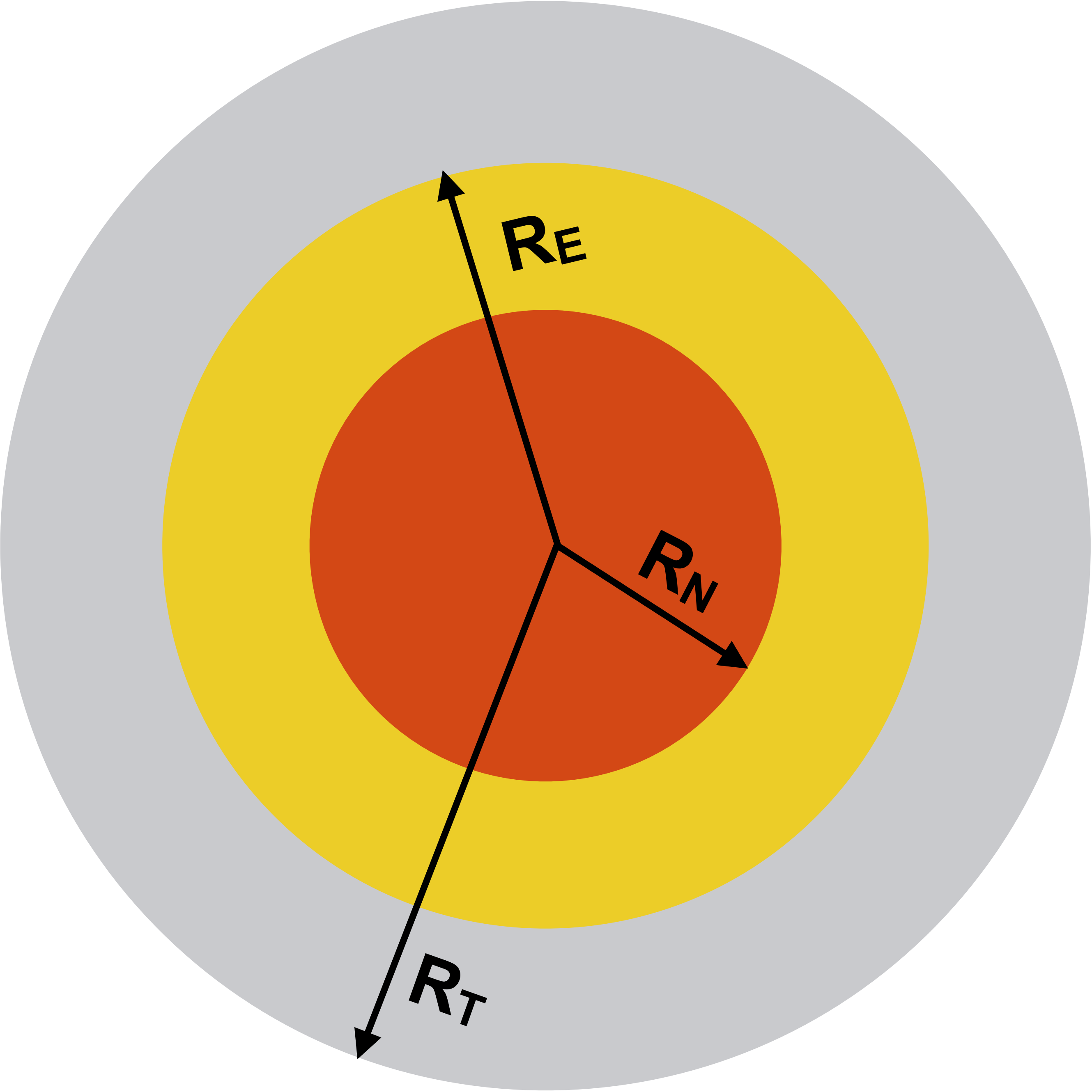
Freeze-out in space

Mean free path ~ typical distance

e.g.

$$\frac{1}{n(r)\langle\sigma\rangle} \sim r$$

Freeze-out Picture



- R_N : Number sphere

$$\bar{\chi}\chi \to e^+e^-$$

- R_E : Energy sphere

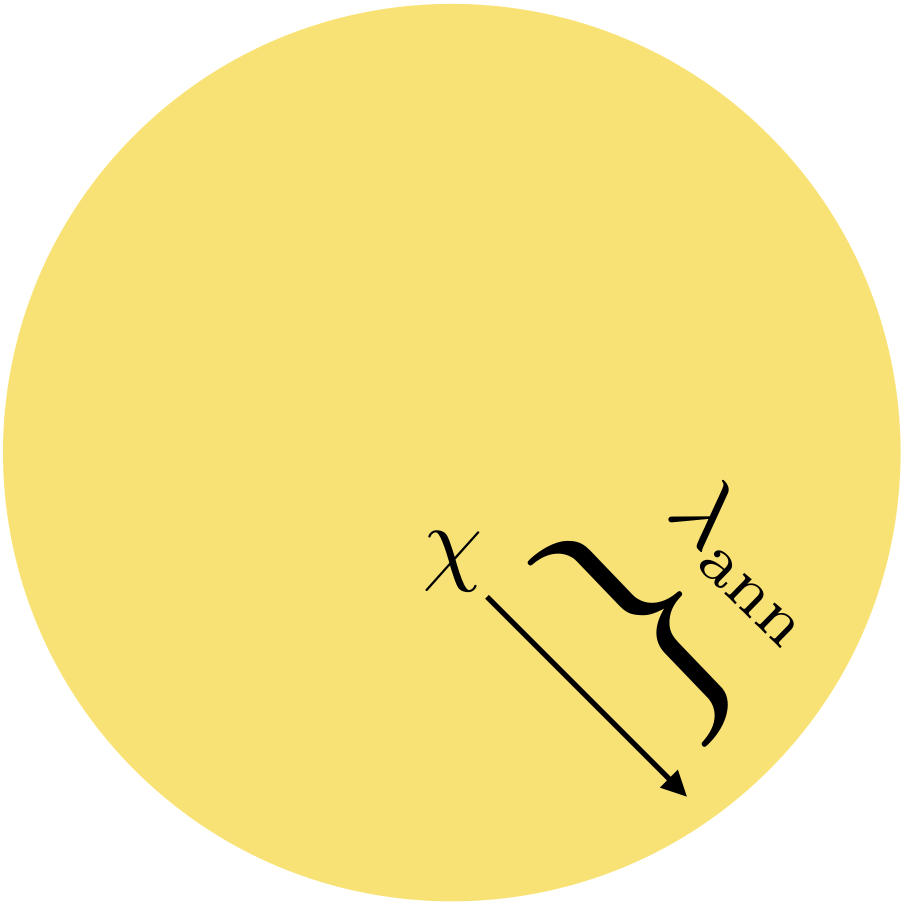
$$\chi e^\pm \to \chi e^\pm$$

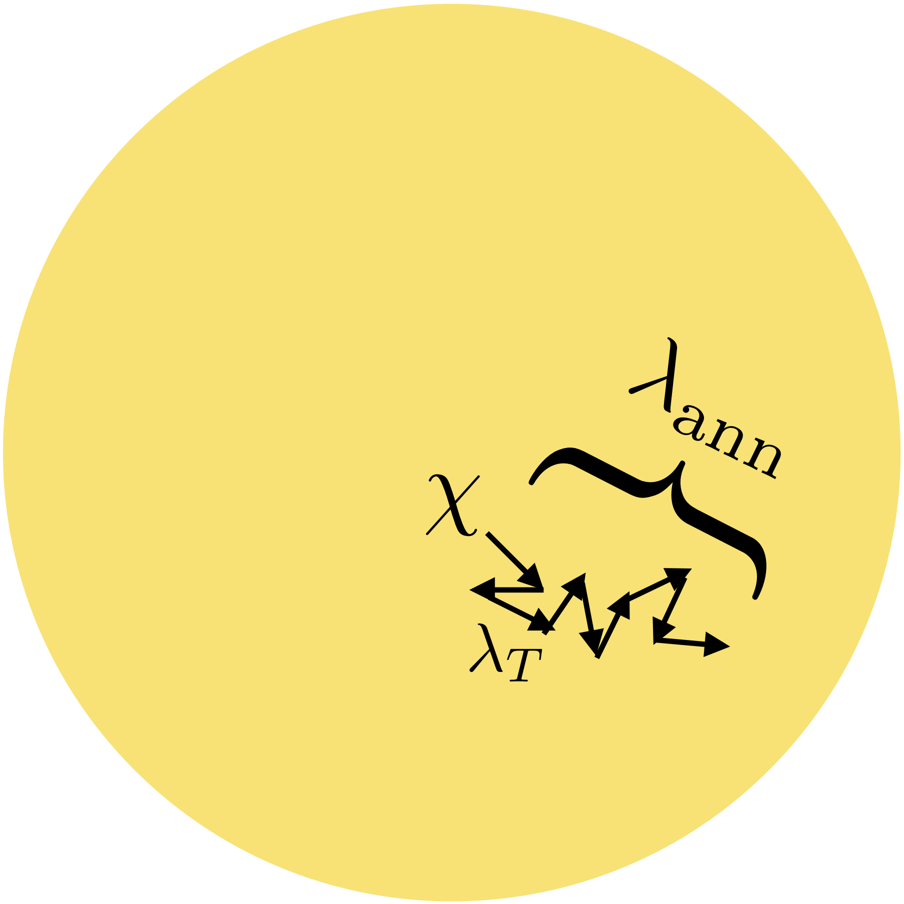
- R_T : Transport sphere

$$\chi p \to \chi p$$

Radial freeze-out

<u>Freeze-out requirement:</u>


No other interactions


Diffusion

It takes $\left(\frac{\lambda_{\rm ann}}{\lambda_T}\right)$ longer to cover $\lambda_{\rm ann}$

Radial freeze-out

Freeze-out requirement:

$$\tau_x = \int_{r_x}^{\infty} \frac{dr}{\lambda_x} = 2/3 \quad \Longrightarrow \quad \tau_{\rm ann} = \int_{r_N}^{\infty} \frac{dr}{\sqrt{\lambda_{\rm ann}\,\lambda_T}} = 2/3$$

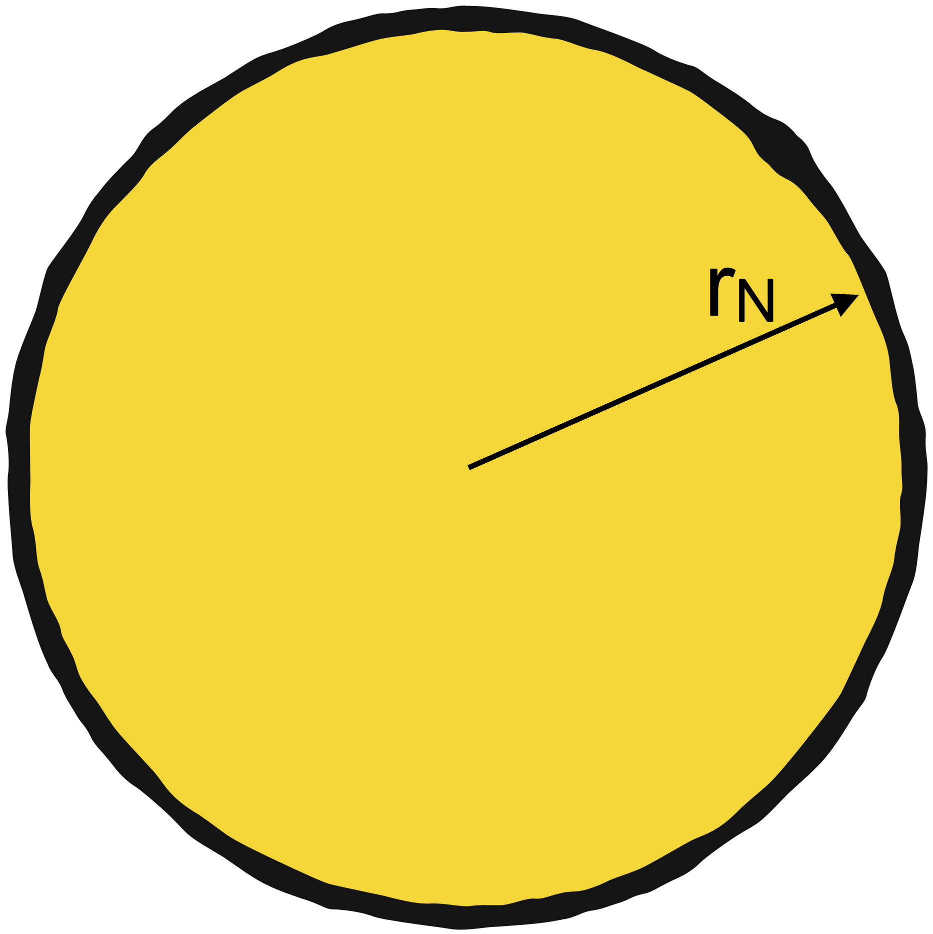
$$\lambda_T \ll \lambda_{\rm ann}$$

Annihilations become effectively more efficient

Freeze-out calculation

Annihilation Sphere:

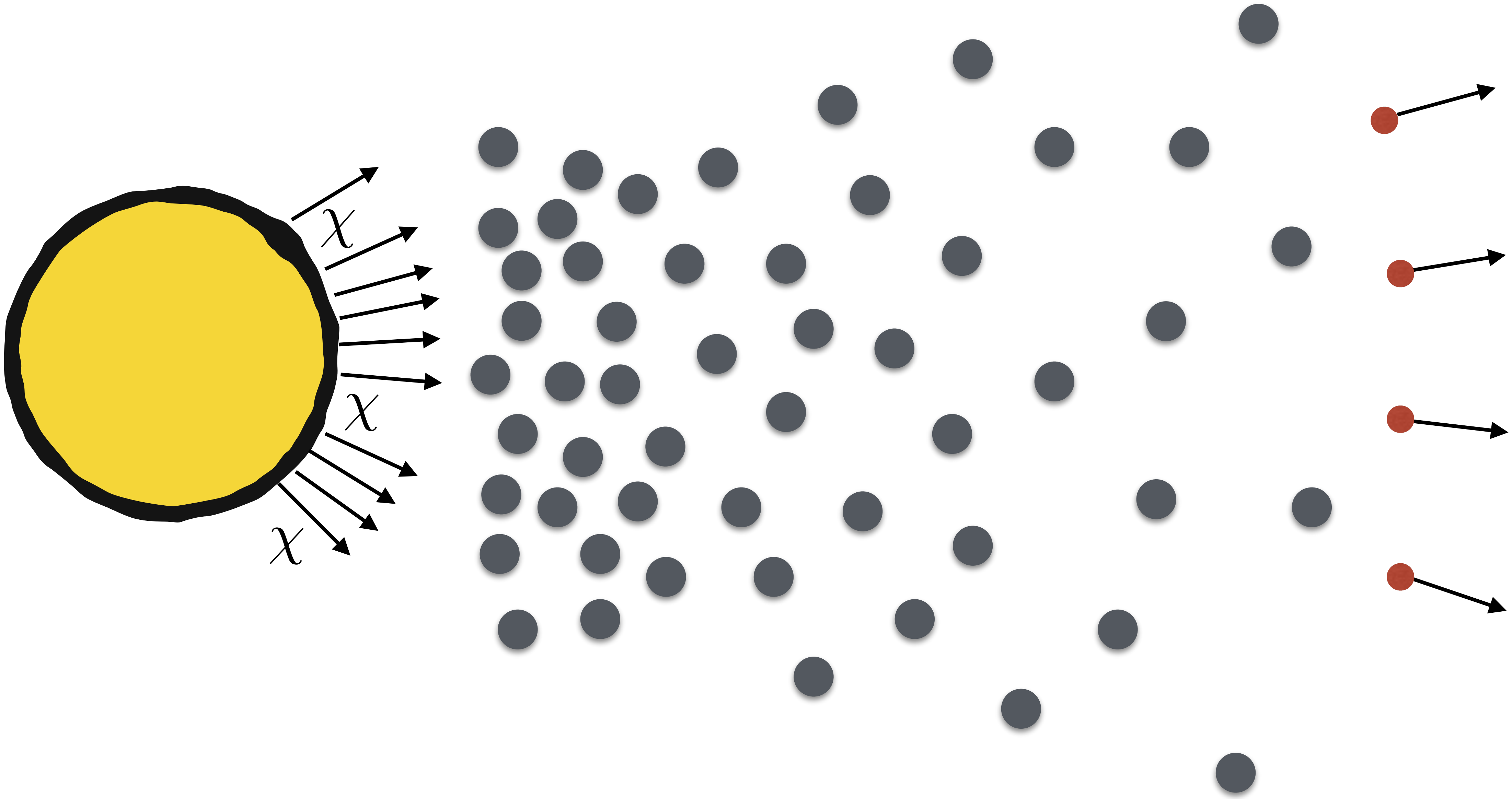
$$\tau_{\rm ann} = \int_{r_N}^{\infty} \frac{dr}{\sqrt{\lambda_{\rm ann}\, \lambda_T}} = 2/3$$



Treat as a perfect black-body

$$\Phi|_{r_N} = \frac{1}{4\pi^2} \int_{m_\chi}^{\infty} dE \, \frac{(E^2 - m_\chi^2)}{e^{E/T(r_N)} + 1}$$

Flux transmission



Flux decreases due to
scattering with protons

Flux transmission

$$\Phi(r \gg r_N) = \frac{\Phi(r_N)}{(1 + \frac{3}{4}s_*)} \left(\frac{r_N}{r}\right)^2$$

$$s_* = \sigma_T \int_{r_N}^{\infty} dr\ n_p(r) \left(\frac{r_N}{r}\right)^2$$

Flux transmission

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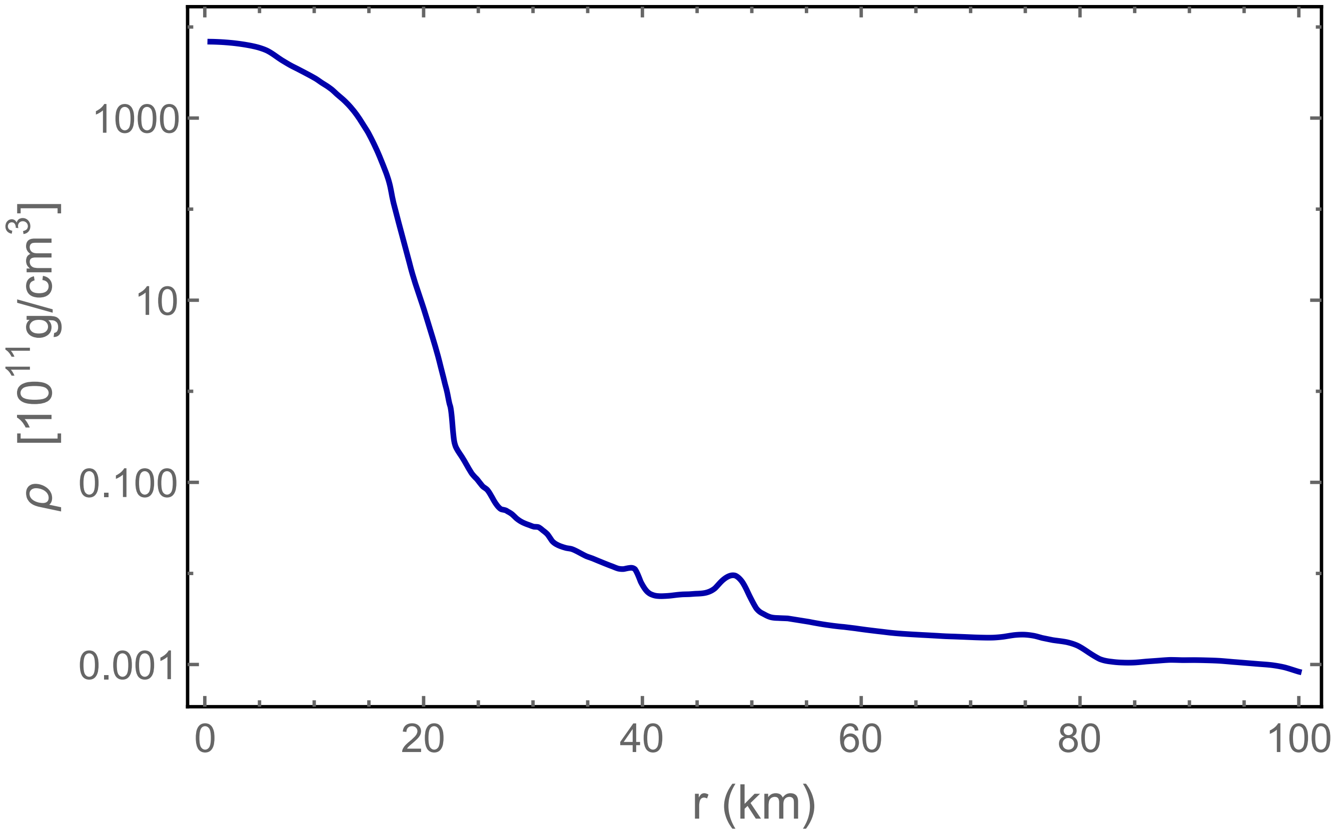
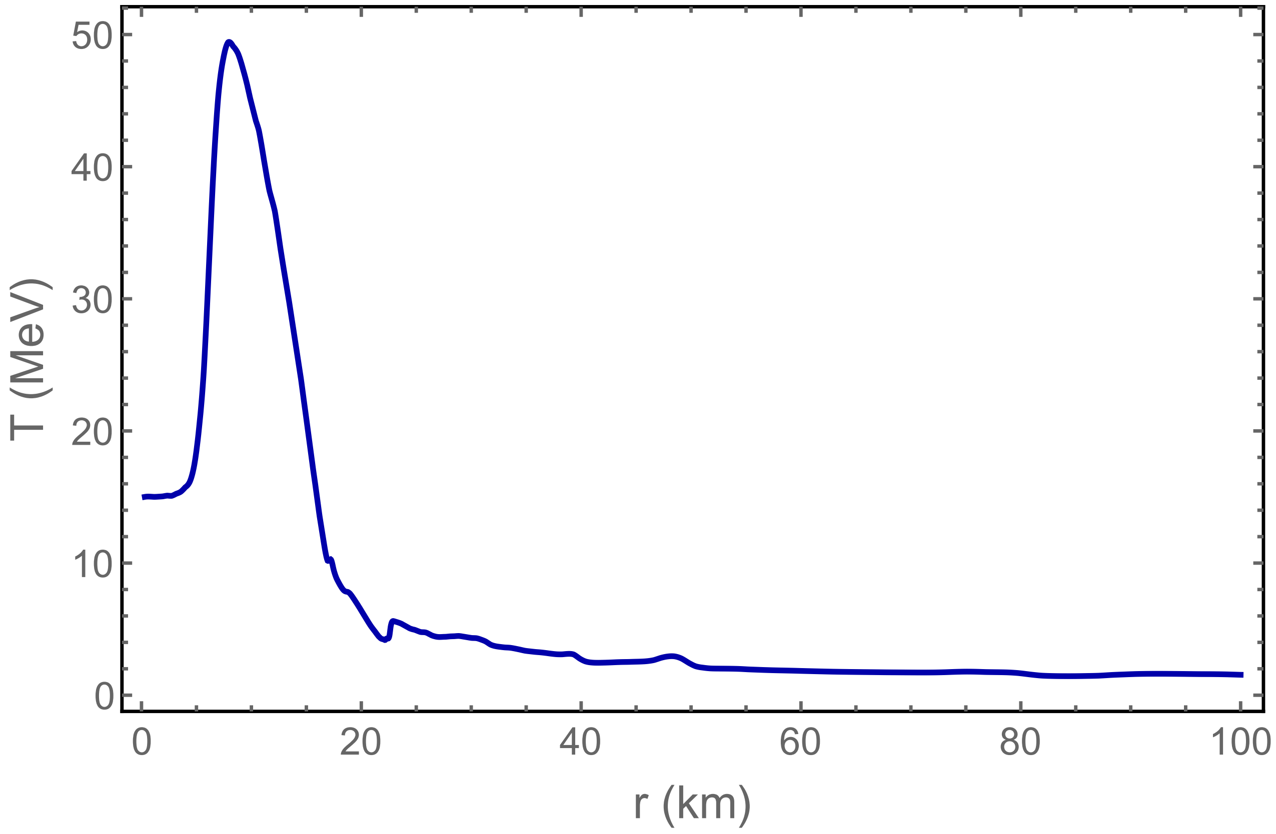
Currently we treat the effect of the energy sphere by assuming it doesn't change the total flux but redistributes momenta according to the temperature in r_E

Computing the flux

Snapshot at 1.5 seconds post bounce





What is the flux on Earth?

- Single Supernova near Earth
- **Diffuse signal from past Supernovae in the galaxy**
- Diffuse signal from extra galactic Supernovae

Diffuse background

- Estimated galactic rate is around 2 Supernovae per century (maybe higher in the past)
- Assuming constant rate across the galactic disk we can translate the diffuse flux in terms of an equivalent single event

$$\Phi_{\rm diff} = 0.038\Phi_{1-sn}(R_{SN})\left(\frac{R_{SN}}{\rm kpc}\right)^2\frac{\Delta t}{50{\rm years}}$$

Detecting DM flux

- Electron targets:

$$\Delta k_e \approx m_e \, v_{\rm DM}$$

$$\sigma_{\chi e} \propto \frac{m_e}{E_\chi}$$

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→

$$E_r \approx \frac{2 p_\chi^2}{m_n}$$

$$p_{\rm min}^{\rm Xe} \approx 17 \text{ MeV}$$

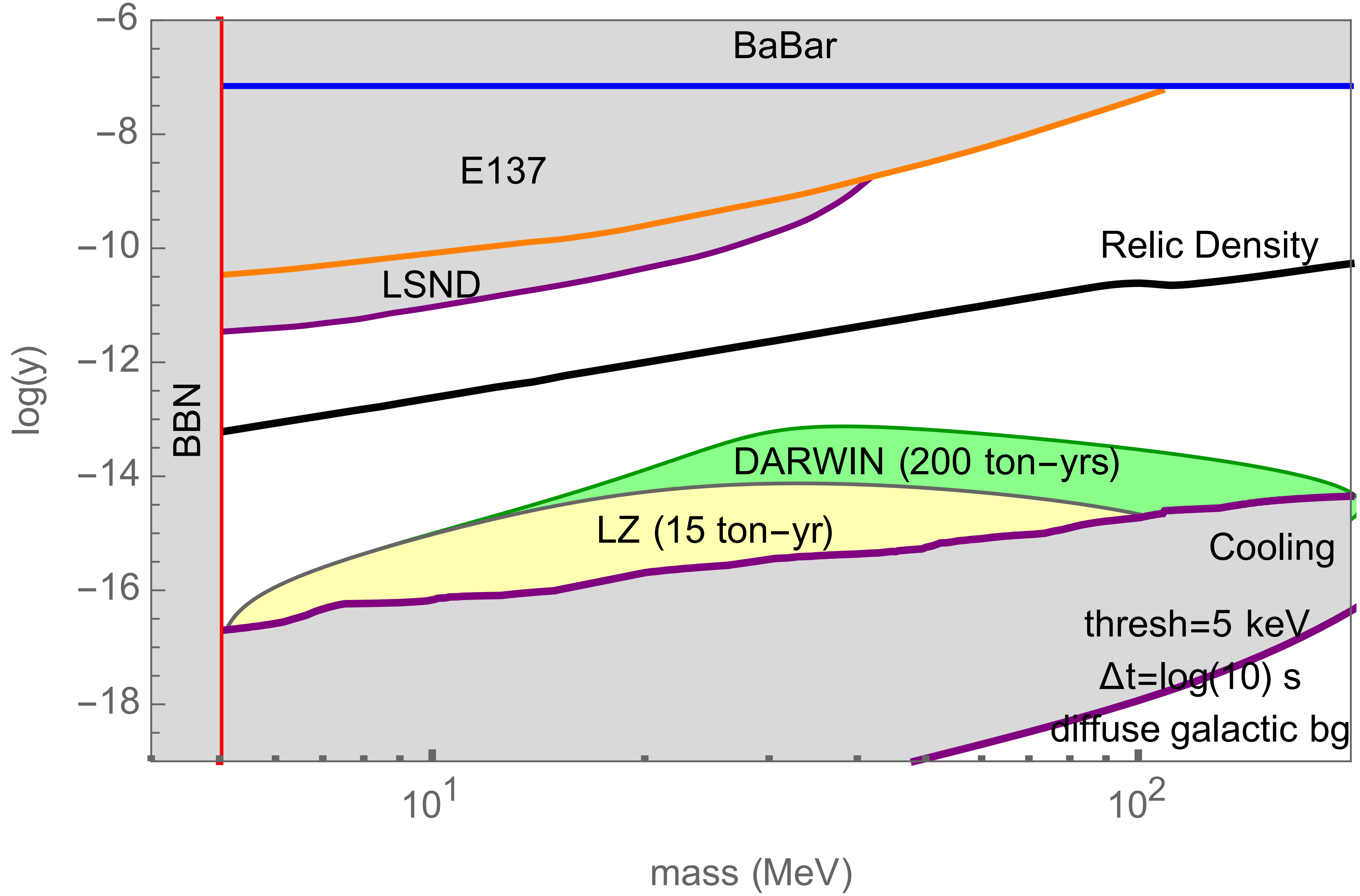
Cooling bounds

- We have observed the neutrinos from SN1987a with spectrum consistent with predictions
- A conservative criteria for when new particles lead to such large deviations that the expected neutrino signal would be significantly changed is:

$$L_\chi \gtrsim 3 \times 10^{52} \mathrm{ergs/s}$$

Preliminary reach plot

Galactic diffuse Supernovae flux



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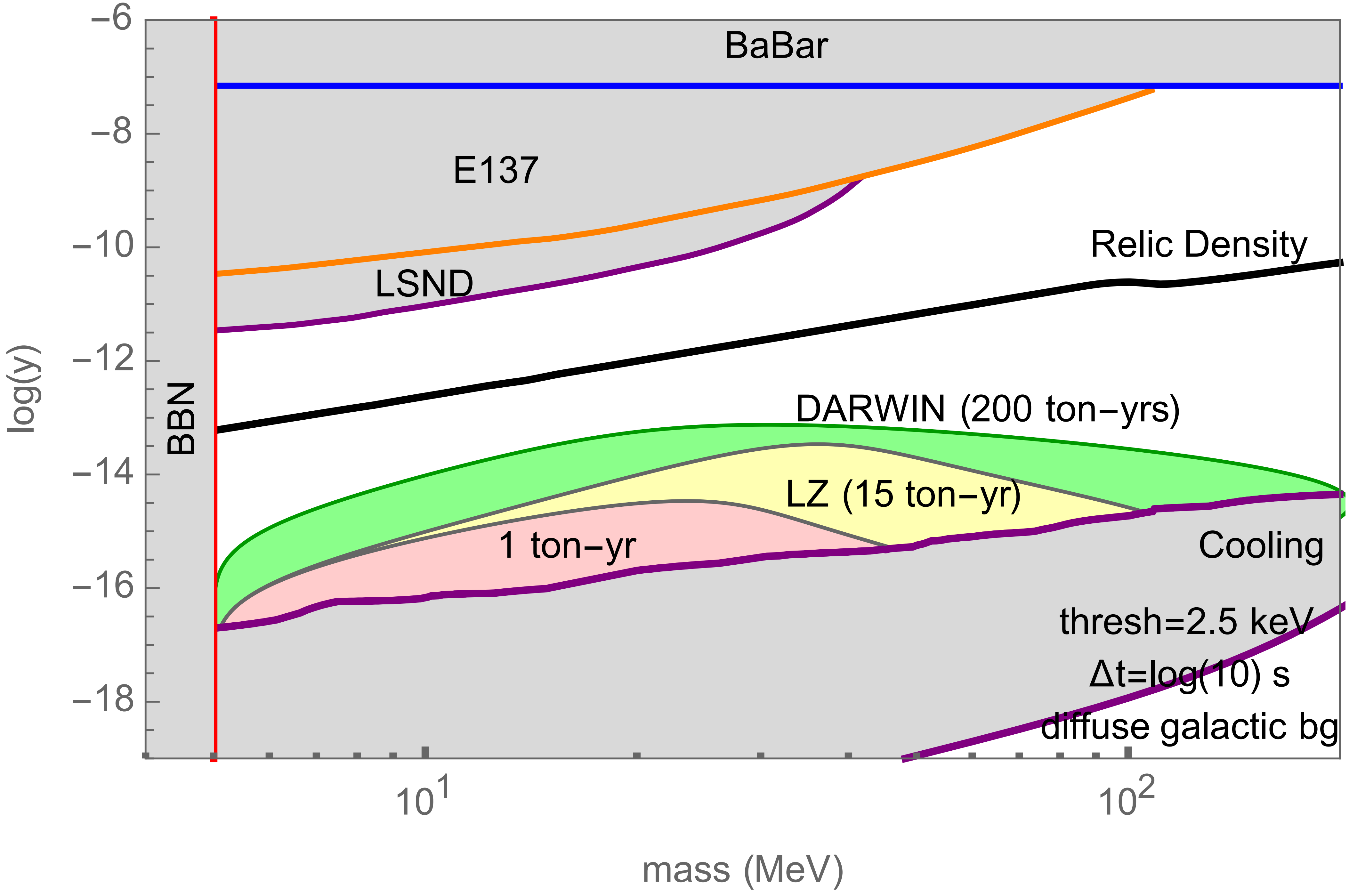

Conclusions

- Supernovae can be a source of boosted dark sector particles. Because of their large velocity, they are more easily detected than the local dark matter population.
- Some regions of parameter space might be probed by Xenon1T and a large region will be tested in future Xe experiments.
- Fluxes could be larger depending on time-scales associated with the Supernova.
- Need to explore profile dependence.
- We explored a minimal heavy dark photon portal scenario. This analysis can be extended to a number of other dark sector scenarios.
- These models might also lead to interesting new features in Supernovae that haven't been explored…