NDM 2025, Institut Henri Poincaré, Paris, May 5 - 23, 2025

Shimmering Darkness

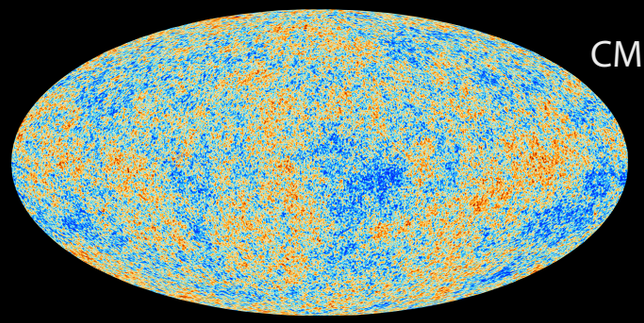
Mapping the distribution of SNν BDM across the sky

Yen-Hsun Lin
Academia Sinica
yenhsun@phys.ncku.edu.tw

snorer
snorer yenhsunlin

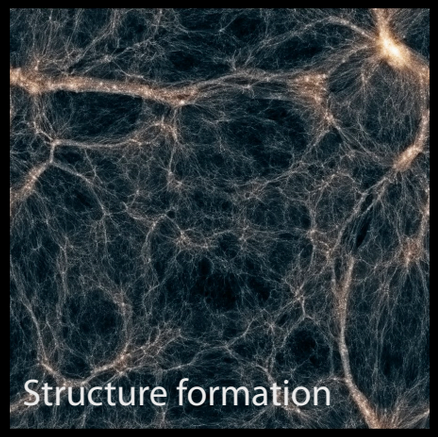
Academia Sinica
Grid-Computing Center

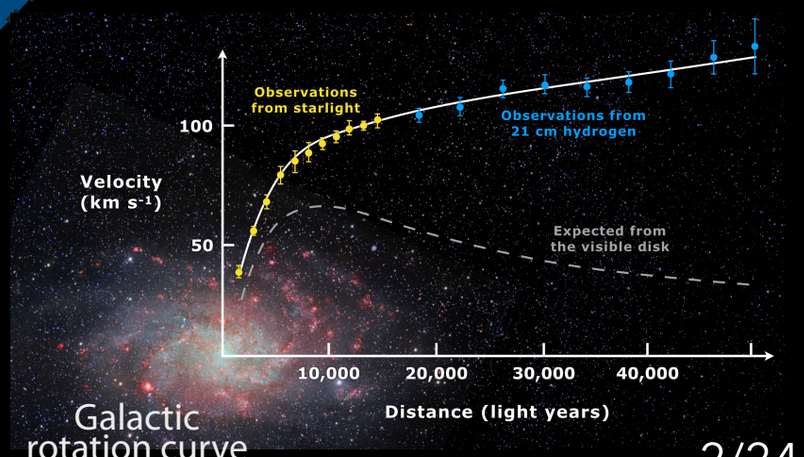
Dark matter is ***ubiquitous*** in the Universe!



More ancient

Larger space



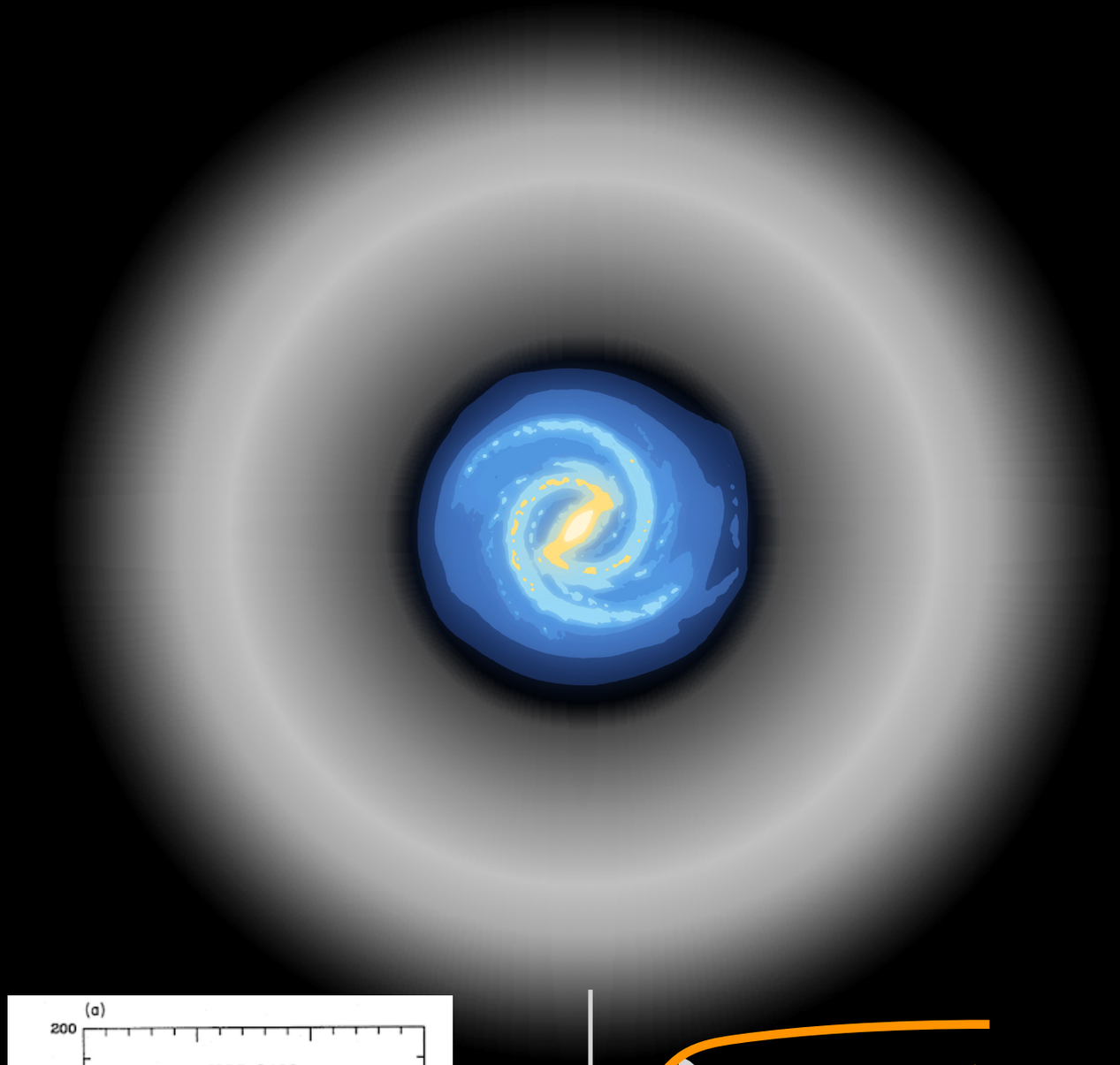


Galactic rotation curve

not-to-scale

Gondolo+ 1999
Ullio+ 2001
Gnedin+2004
Cline+ 2023

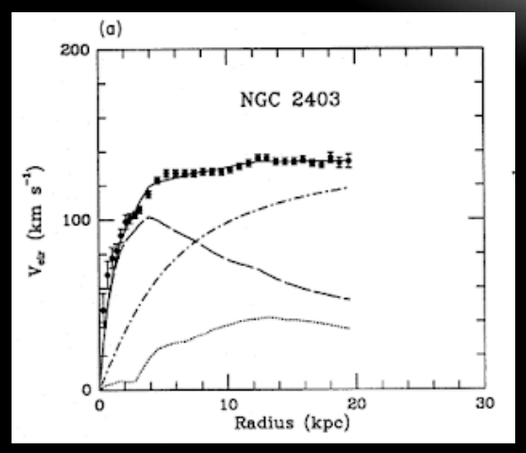
Dark matter halo

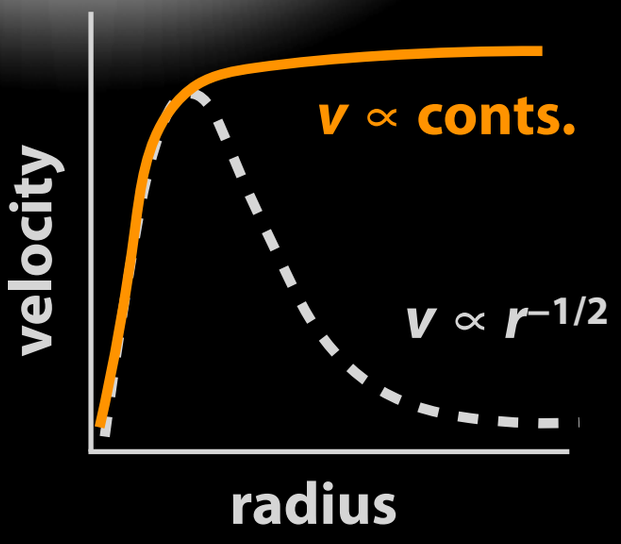


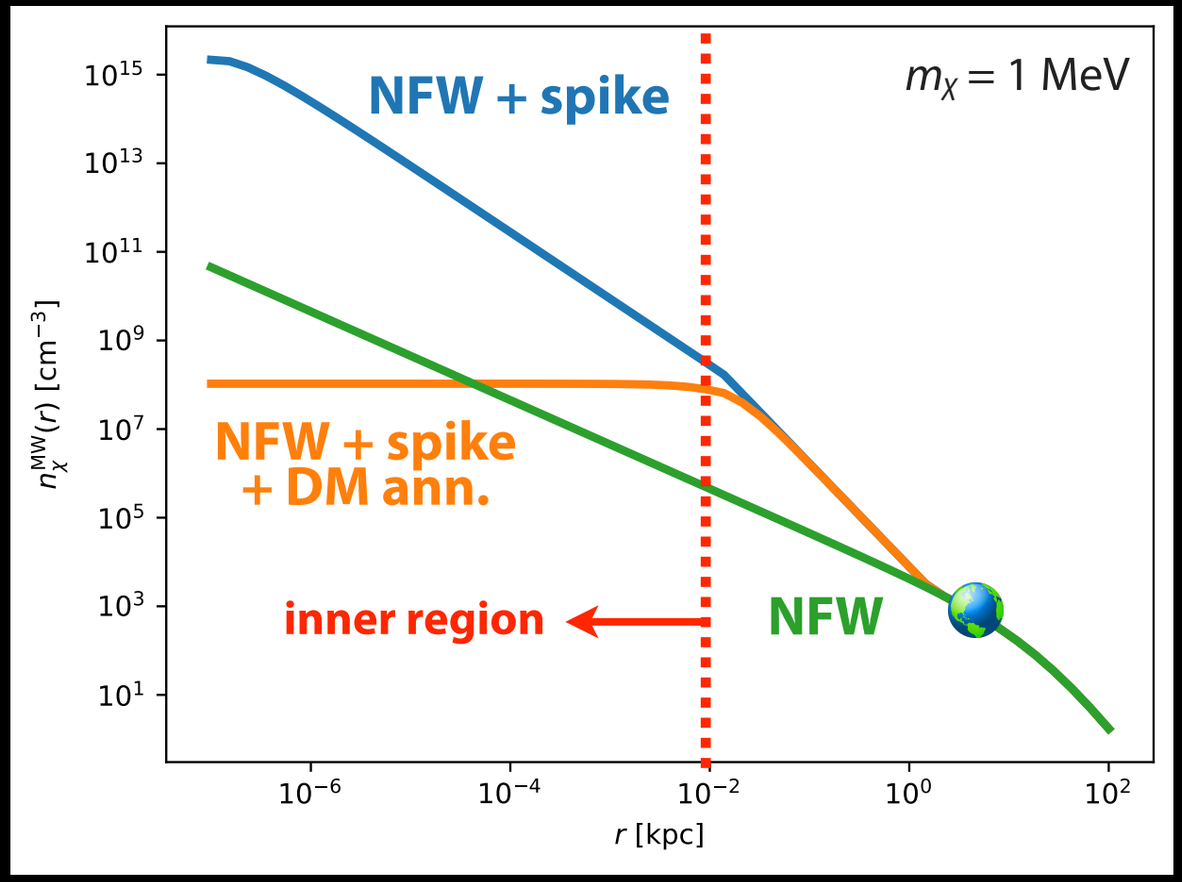
- Dark matter density in our Milky Way is characterized by **Navarro–Frenk–White (NFW) profile**

$$\rho_\chi(r) = \frac{\rho_s}{\frac{r}{r_s}(1+\frac{r}{r_s})^2}$$

with ρ_s = 184 MeV cm^{-3} and r_s = 24.4 kpc



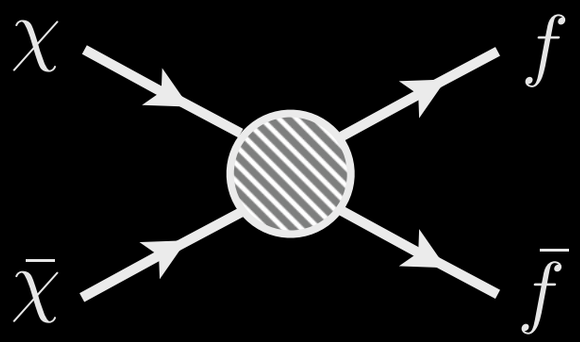




not-to-scale

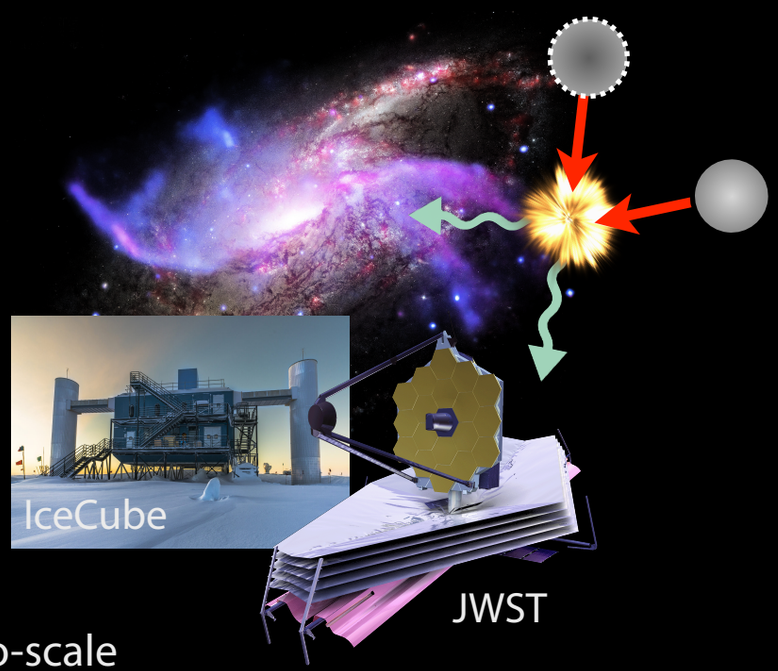
Modern approaches for probing DM

MAKE



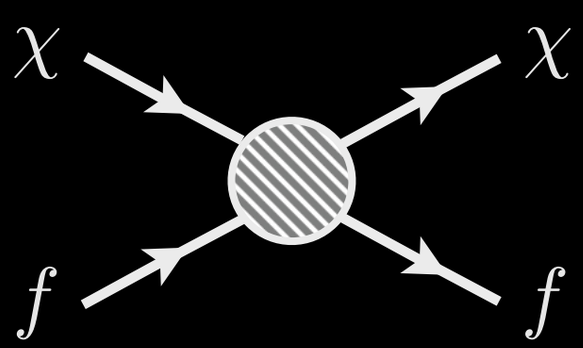
Annihilation signals in deep space

$\langle \sigma v \rangle$



not-to-scale

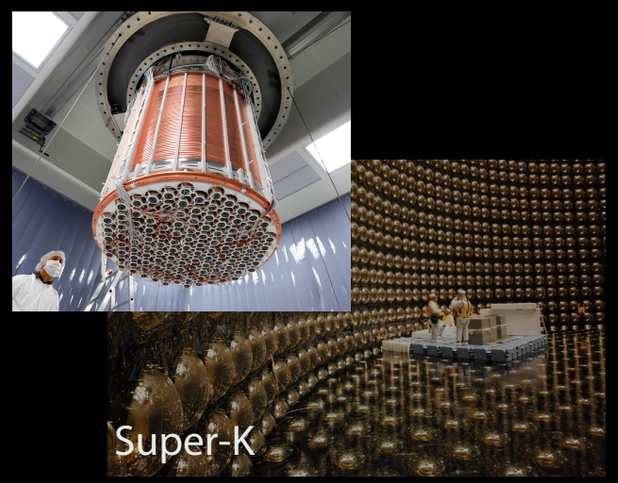
SHAKE



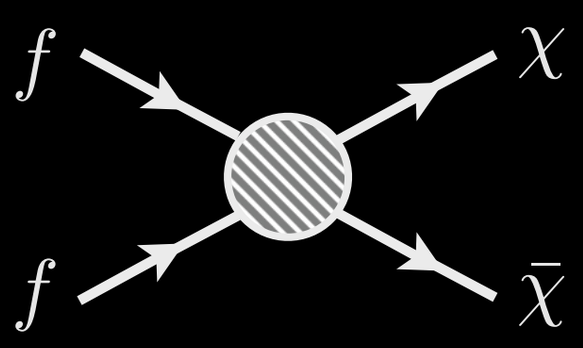
Recoil signals from DM scattering off nucleus and leptons

$\sigma_{\chi f}$

XENON



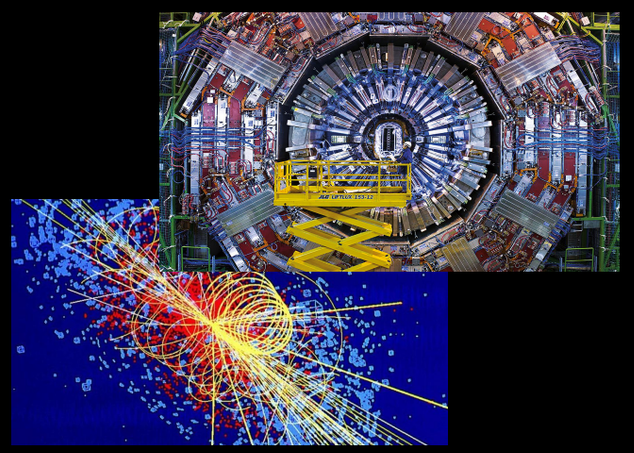
BREAK



Missing momentum

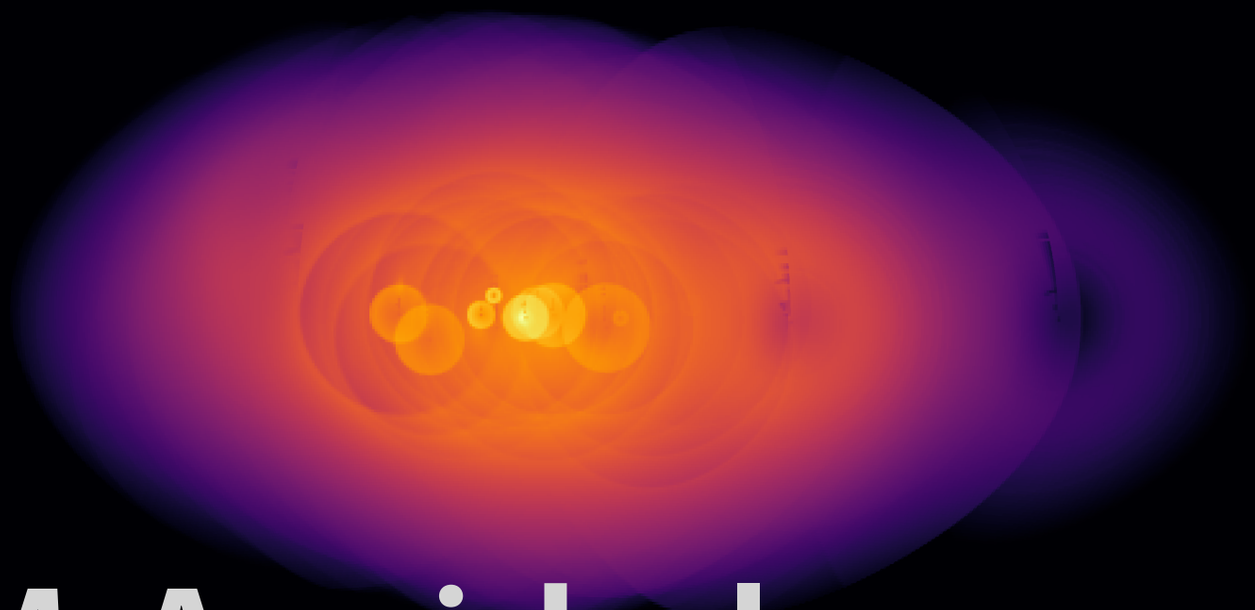
Λ

LHC



Outline

- **Supernova-neutrino-boosted dark matter (SN*ν* BDM)**
  - ▸ Concept introduction
  - ▸ Time-dependent flux and direct DM mass measurement
- **BDM flux from SNe in the past**
  - ▸ In our Milky Way (distribution in both spatial and temporal dimensions)
  - ▸ From all galaxies in the Universe
- **Summary**



SN*ν* BDM: A quick glance

A direct measurement of dark matter mass through time-of-flight signature

YHL+, *PRL* **130**, 111002 (2023) [2206.06864]
YHL+, *PRD* **108**, 083013 (2023) [2307.03522]

Milky Way

GC

χ

α

ν

χ

propagation time

$$t = \frac{\ell}{v_\chi}$$

ℓ

θ

R_e

Super-K

not-to-scale

SNe@GC

BDM flux at Earth

Duration: ~10 s

$N_\nu \approx 10^{58}$

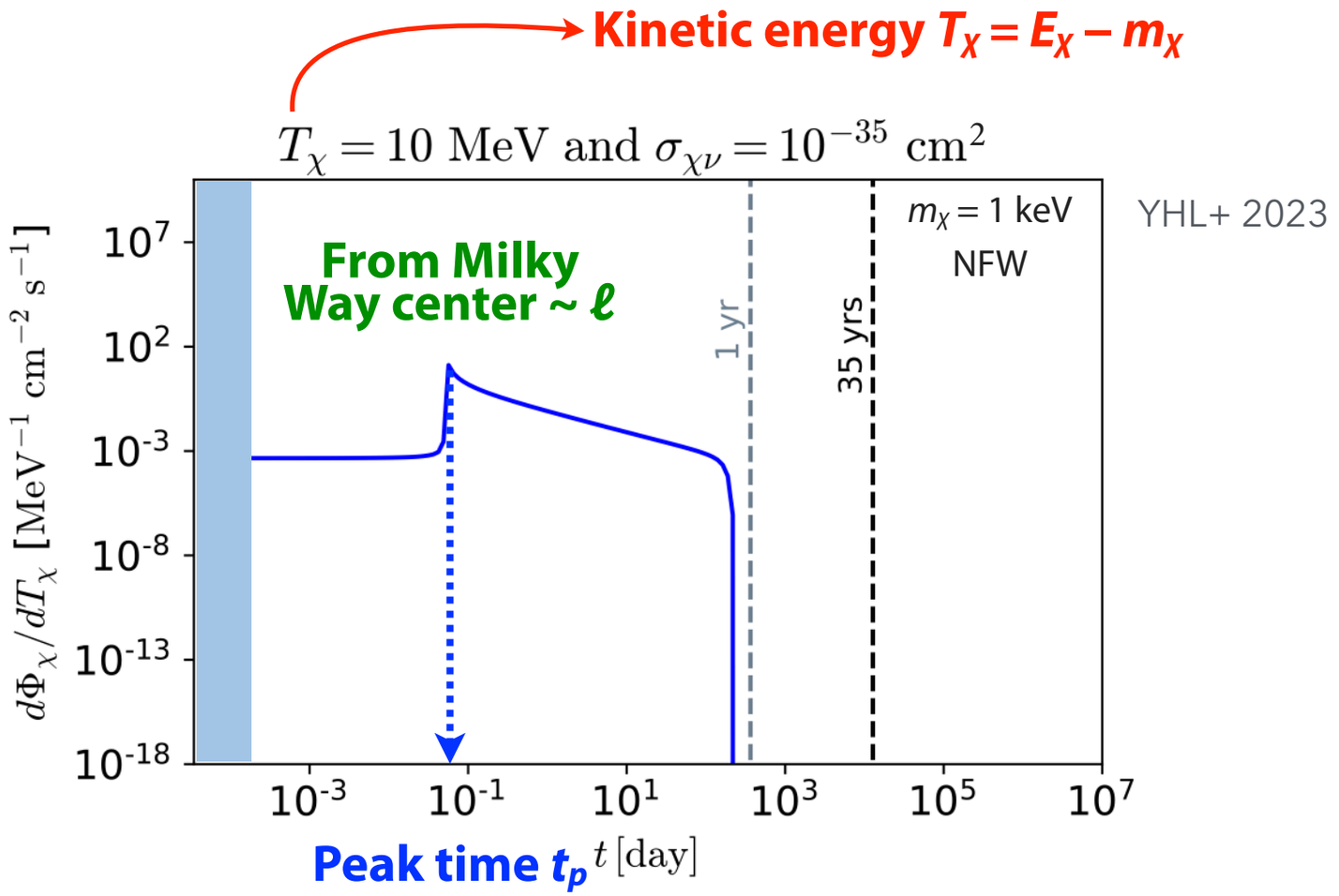
$\bar{E}_\nu \approx 10 - 15$ MeV

$$\frac{d\phi_\nu}{dE_\nu} = \sum_i \frac{L_\nu}{4\pi r^2 \langle E_{\nu_i} \rangle} E_\nu^2 f_{\nu_i}(E_\nu)$$

Duan+ 2006

$$\frac{d\Phi_\chi(T_\chi, t)}{dT_\chi} = 2\pi r \int_0^1 d\cos\theta \mathcal{J}\ j_\chi(r, T_\chi, \alpha)|_{t'=\frac{r}{c}+\frac{\ell}{v_\chi}}$$

Time-dependent flux and DM mass

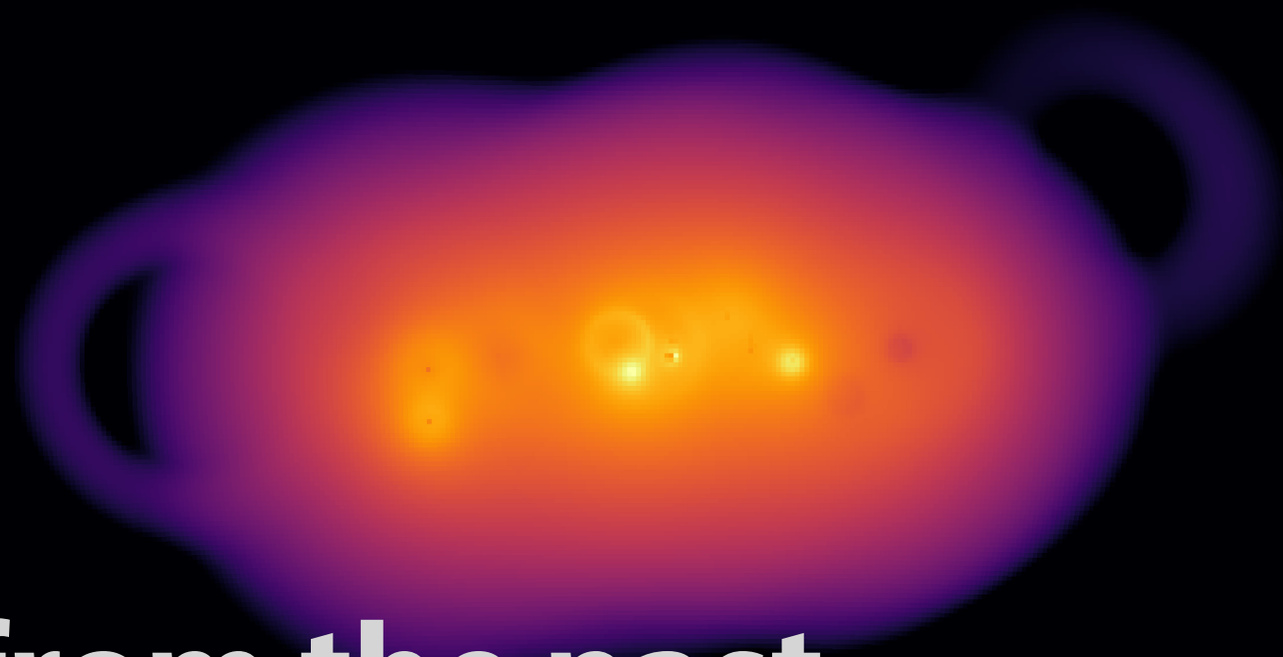


YHL+ 2023

- Three measurable quantities t_p, ℓ and v_χ uniquely determine m_χ

$$t_p \sim \frac{\ell}{v_\chi(T_\chi, m_\chi)} \rightarrow m_\chi \simeq 9.7\ \text{keV} \times \left(\frac{t_p}{10\ \text{days}}\right)^{1/2} \left(\frac{T_\chi}{10\ \text{MeV}}\right)$$

- Precise flux measurement in large underground detectors can be a good complementary probe to the DM direct search



Echoes from the past

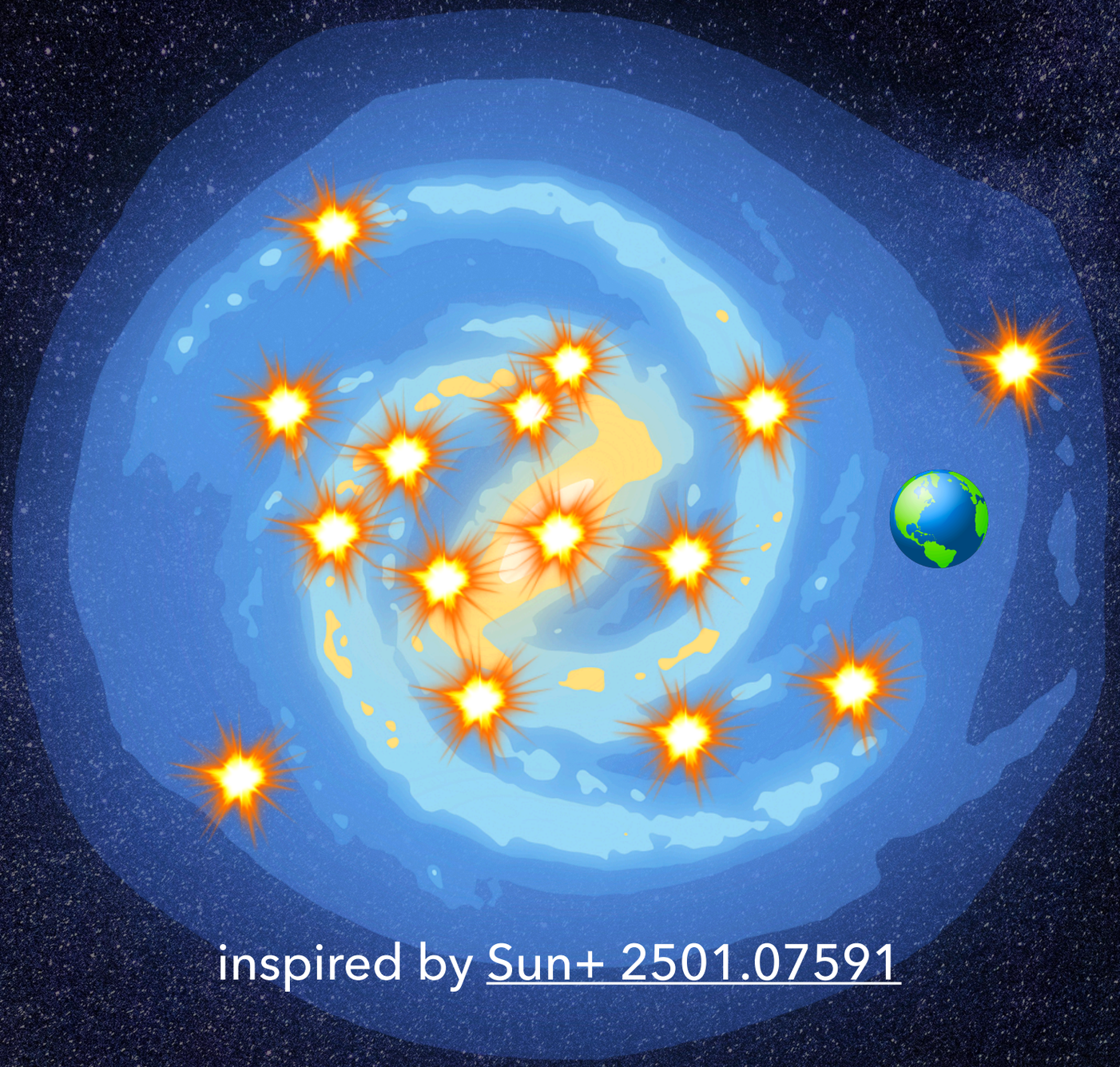
SN*ν* BDM from the past SNe in our Milky Way and all galaxies in the Universe

YHL & MRW, *PRL* **133**, 111004 (2024) [2404.08528]
25xx.xxxxx, *in preparation*

not-to-scale

Where to look?

Diffusive?

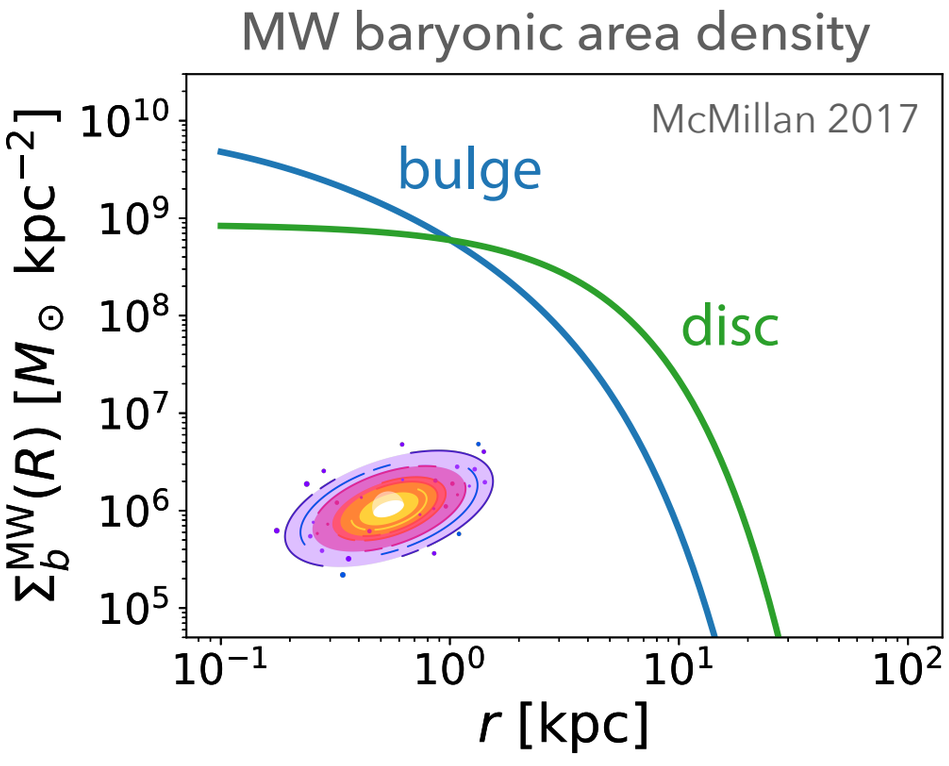


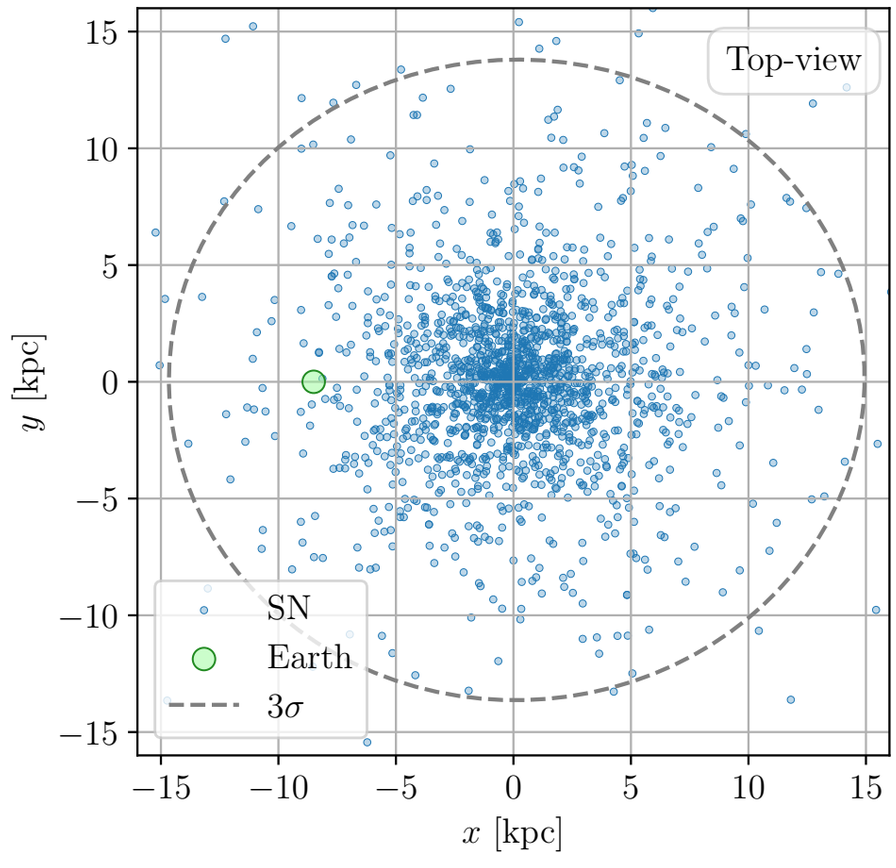
Transient?

inspired by Sun+ 2501.07591

When to look?

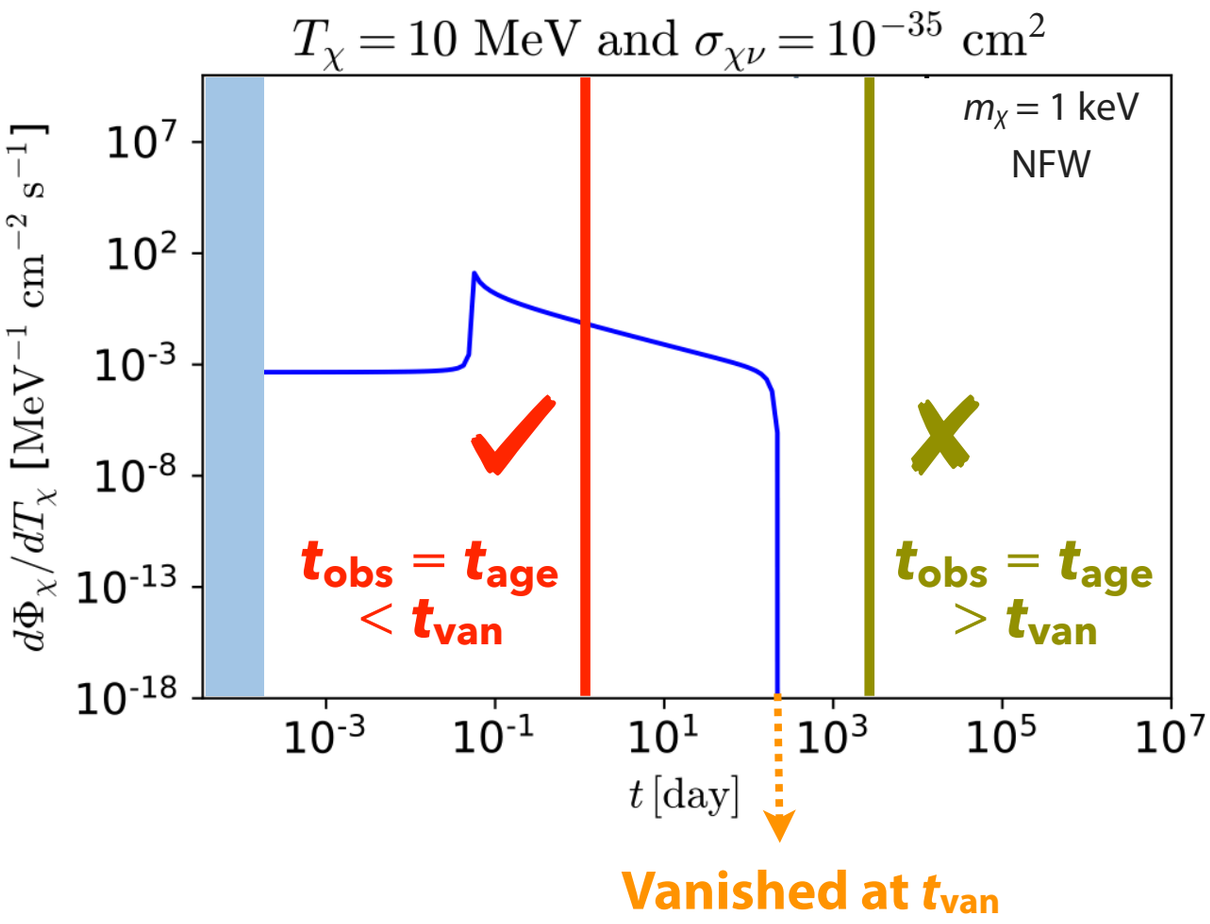
- Core-collapse SN rate $1/\tau$ ~ 1.63/century (τ ~61 yrs) → Mean 1,630 SNe in **100,000 years** Rozwadowska+ 2021
- The SNe spatial distribution over the Milky Way

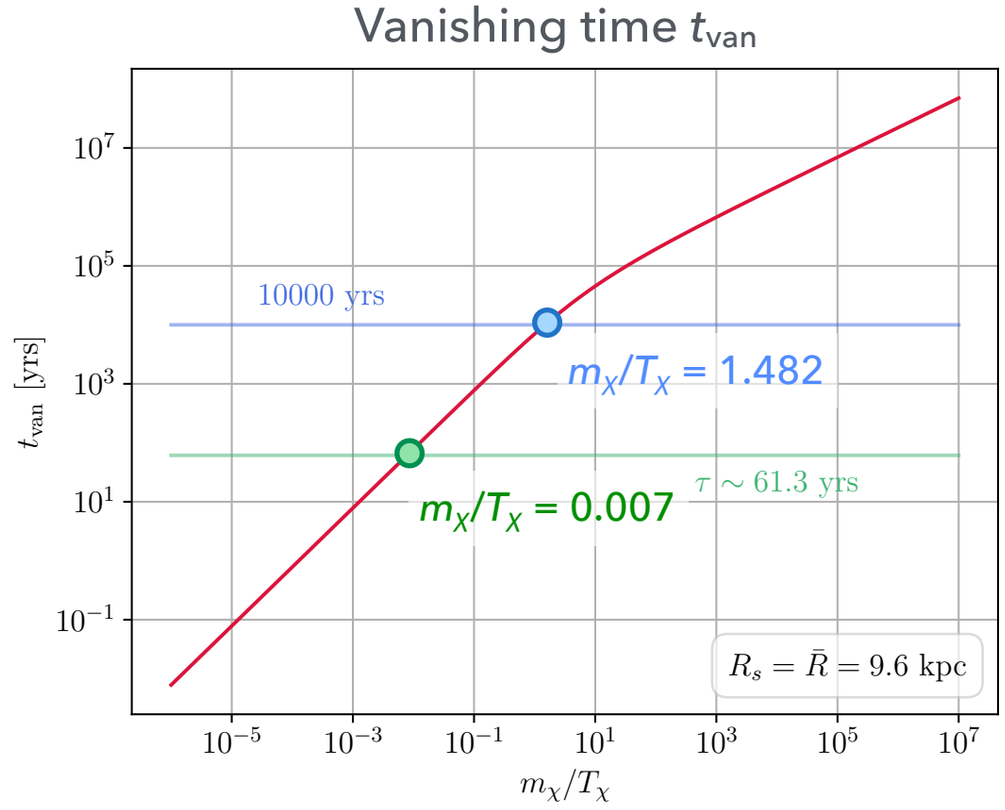




- The SN occurrence follows uniform distribution within **100,000 years**

The vanishing of the flux

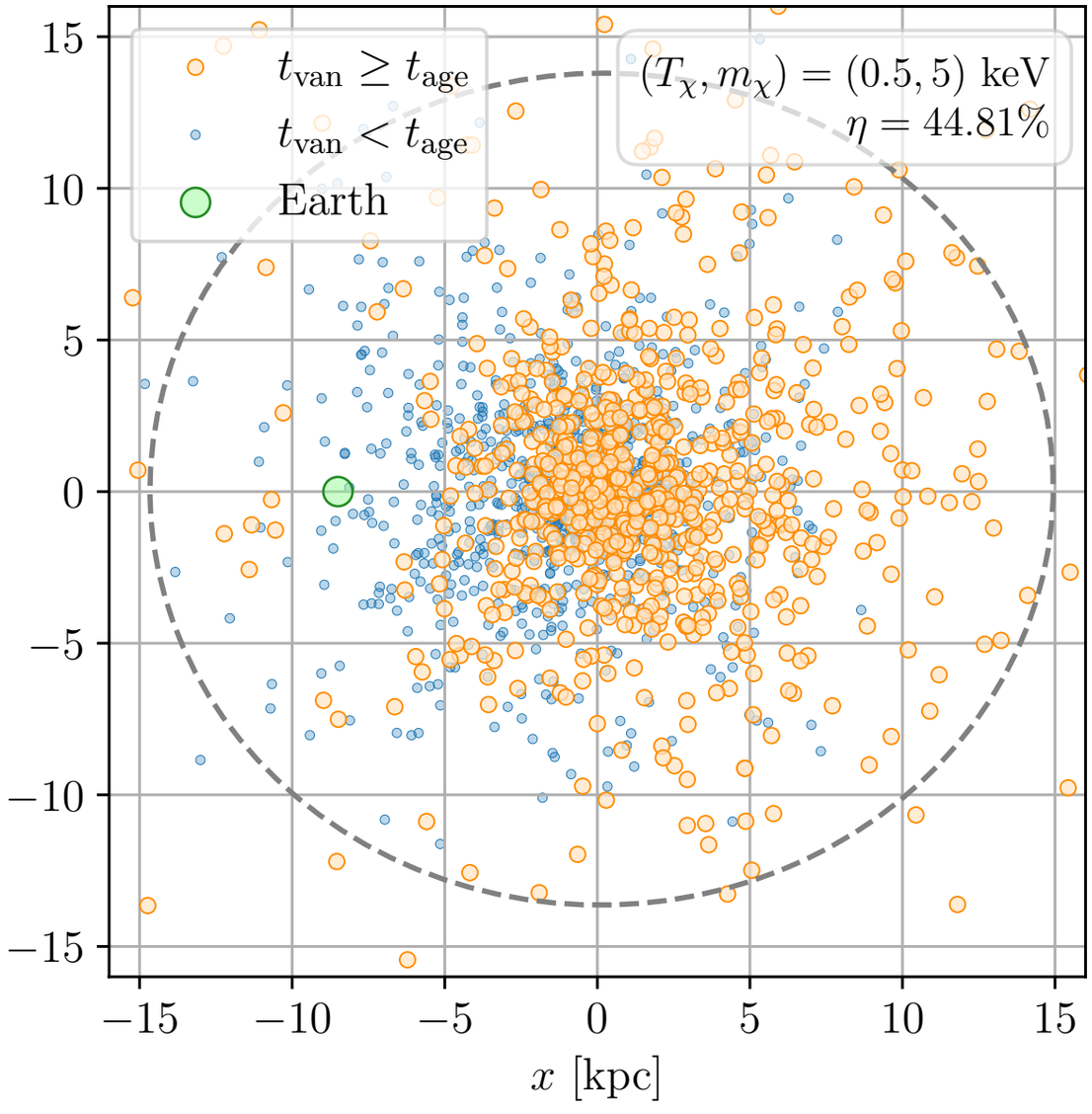




- Non-zero BDM contribution at Earth happens when **$t_{van} > t_{age}$**
- Larger m_χ/T_χ yields longer t_{van}

$$t_{van} \sim \begin{cases} \frac{R_s}{c}\sqrt{\frac{m_\chi}{2T_\chi}} \approx 6.2\times10^5\,\text{yrs}\left(\frac{R_s}{8.5\text{kpc}}\right)\left(\frac{m_\chi/T_\chi}{1000}\right)^{1/2}, & \frac{m_\chi}{T_\chi} \gg 1 \quad \text{(non-rel.)} \\ \frac{R_s}{c}\frac{m_\chi}{4T_\chi} \approx 6.9\,\text{yrs}\left(\frac{R_s}{8.5\text{kpc}}\right)\left(\frac{m_\chi/T_\chi}{0.001}\right), & \frac{m_\chi}{T_\chi} \ll 1 \quad \text{(ultra-rel.)} \end{cases}$$

m_χ = 5 keV
t = 10^5 years, present day (AD 2025)

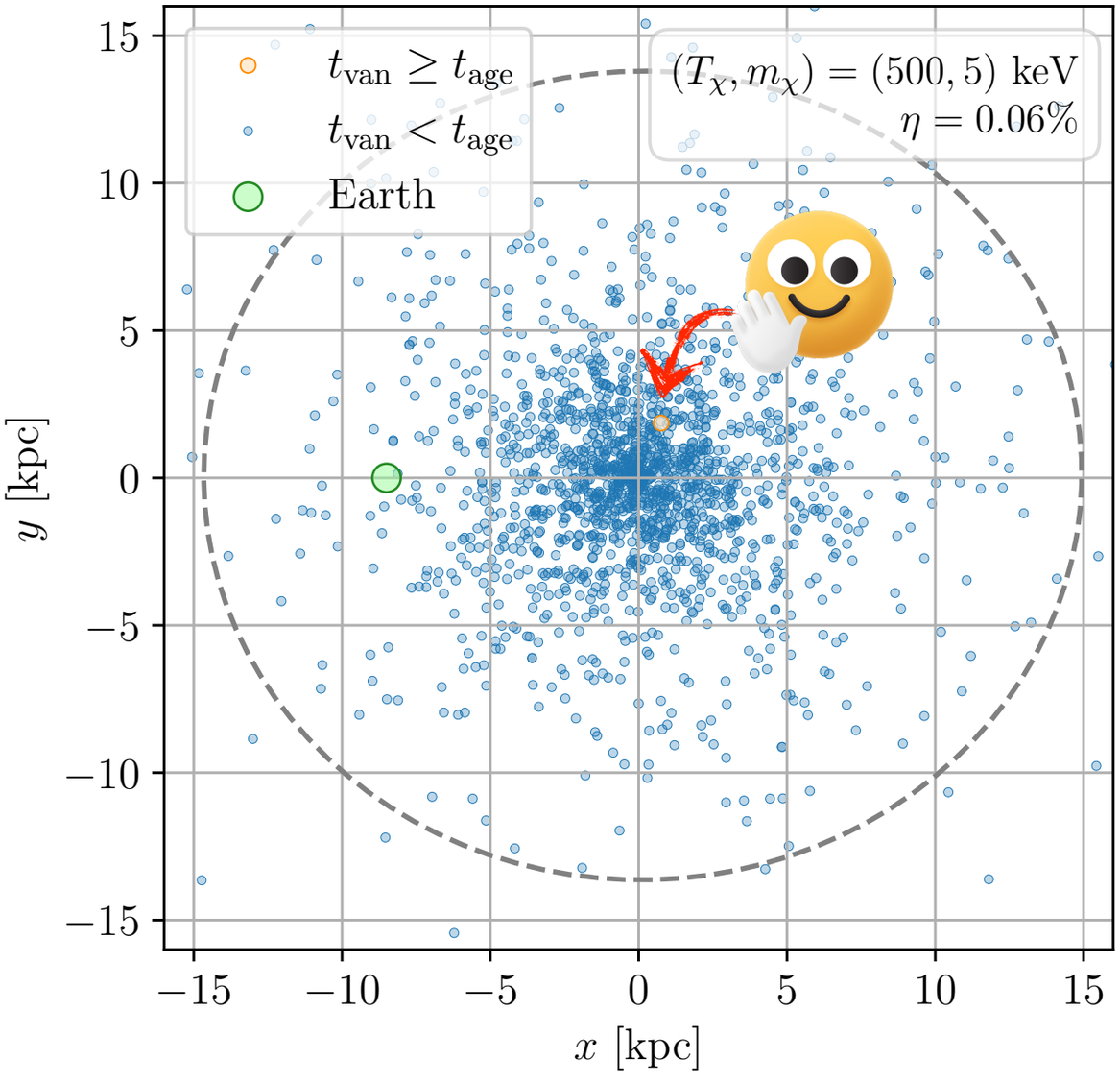


T_X = 0.5 keV

m_X/T_X = 10

Contributed SN rate:

44.81%



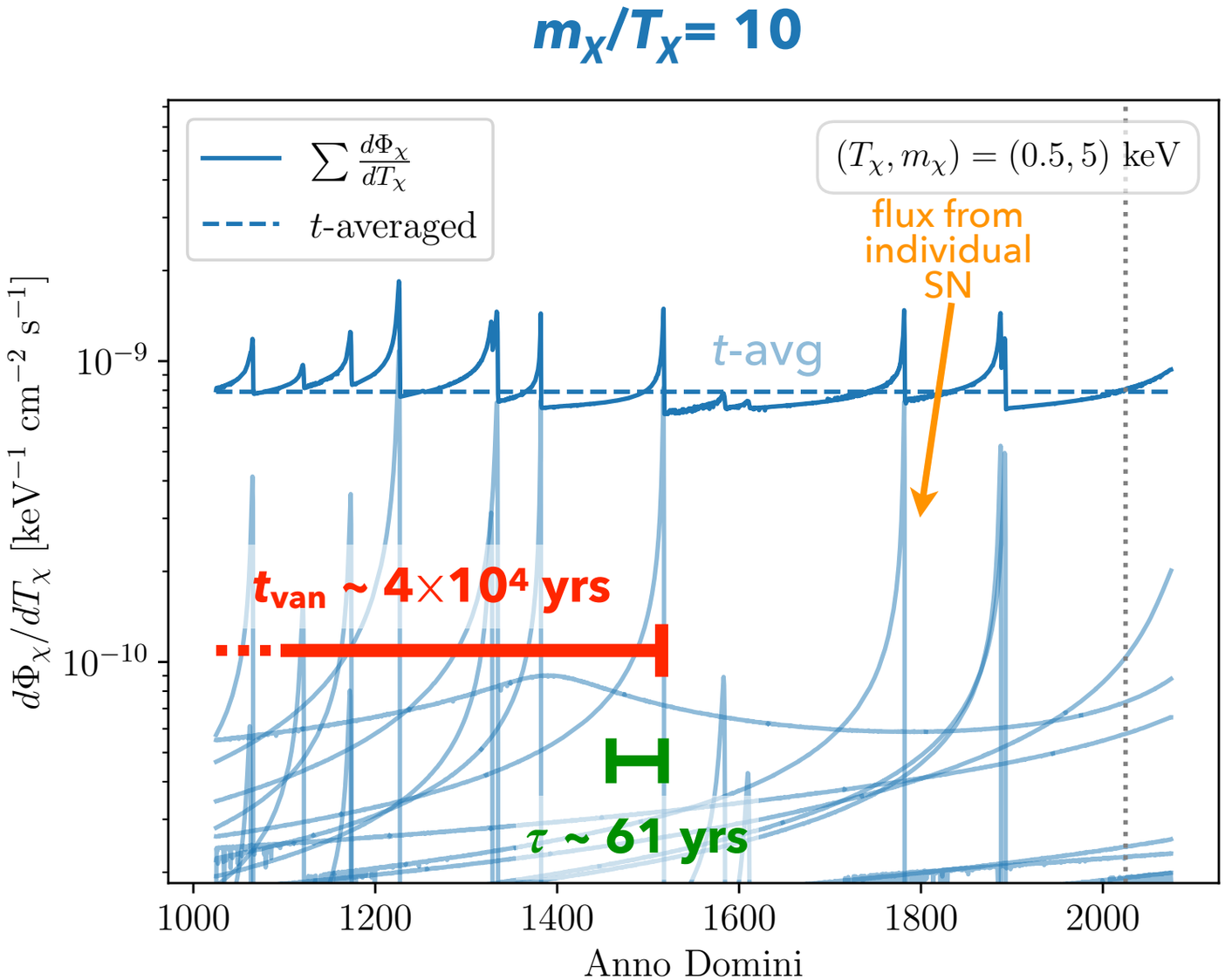
T_X = 500 keV

m_X/T_X = 0.01

Contributed SN rate:

0.06%

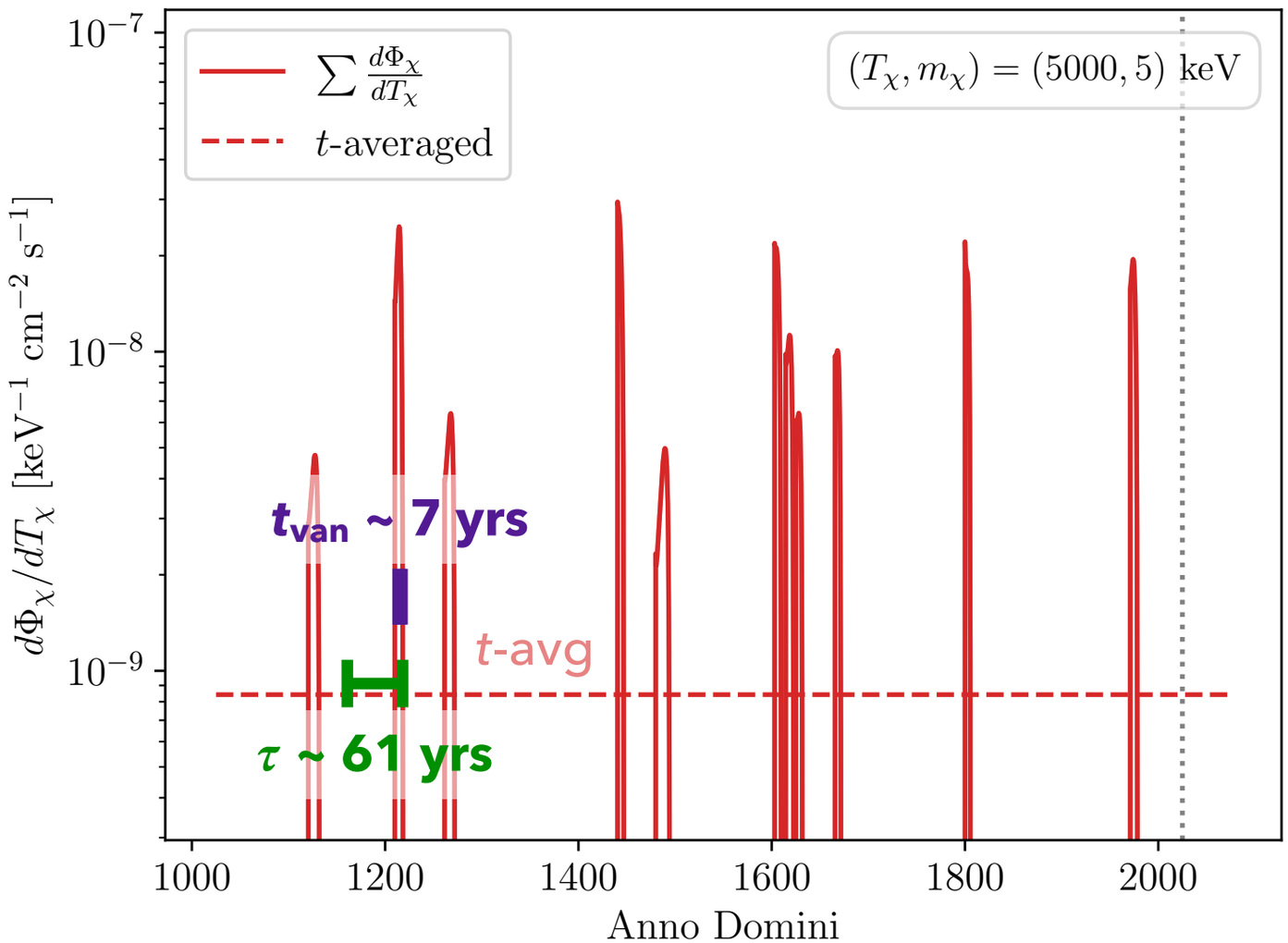
Total BDM flux vs. time



- Fluxes ***overlapped*** → Manifest ***diffuse behavior***
- $t_{van} \gg \tau$ → $m_\chi/T_\chi \gg 0.1$ (non-relativistic) → time-averaged approx. is valid

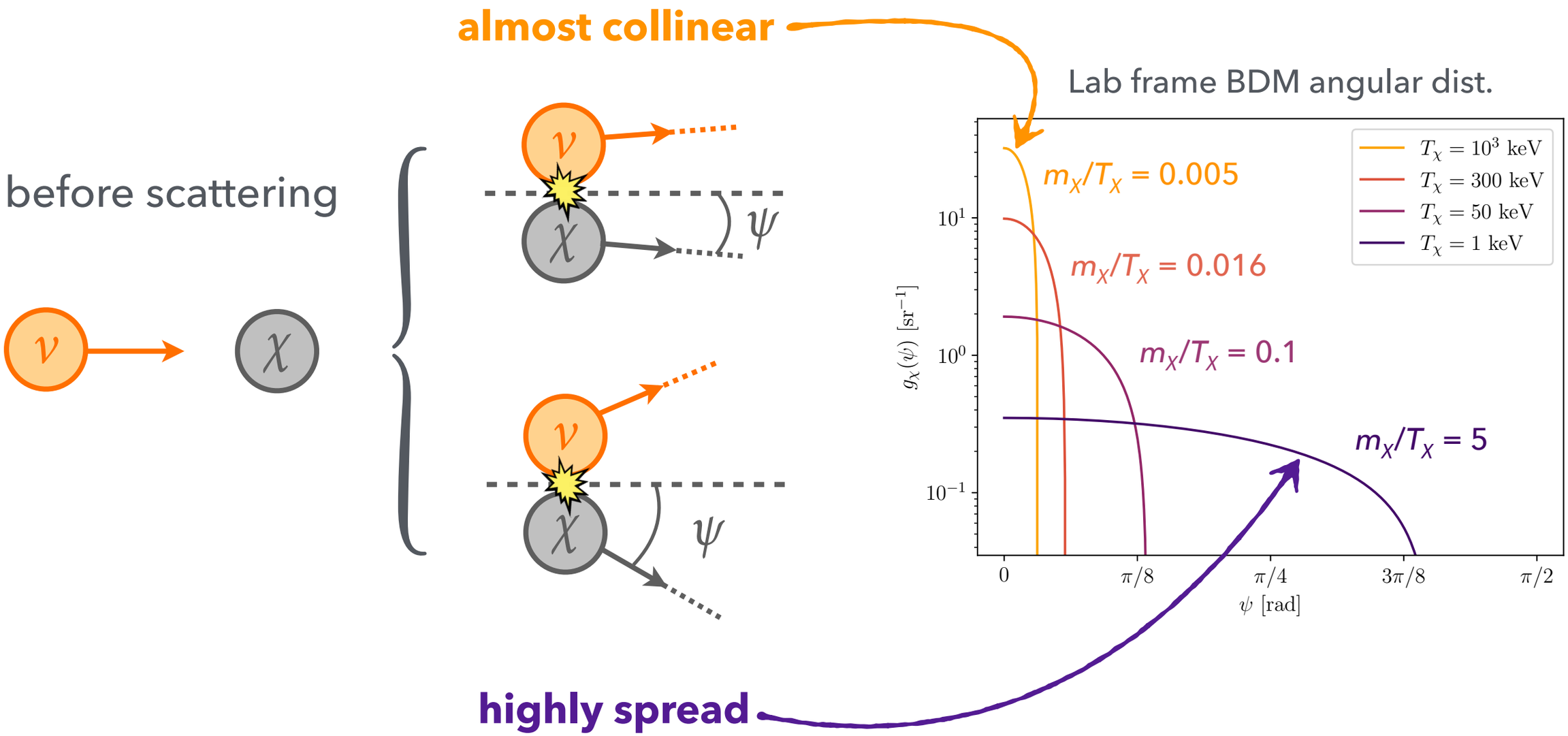
Total BDM flux vs. time

m_χ/T_χ = 0.001

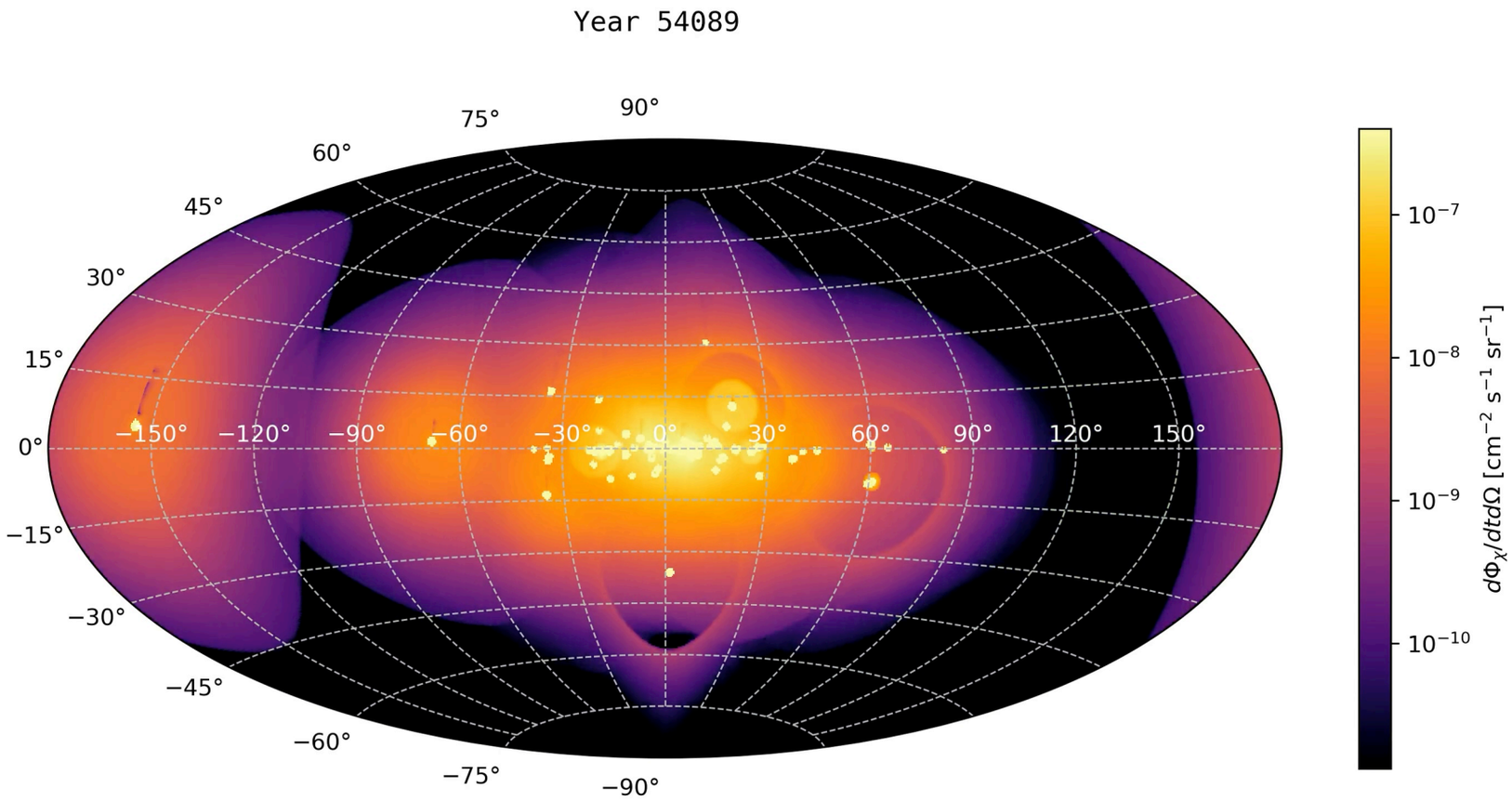


- Fluxes ***did not overlap*** → Manifest ***transient behavior***
- $t_{van} \ll \tau \rightarrow m_\chi/T_\chi \ll 0.1$ (relativistic) → time-averaged approx. breaks down

The spatial distribution

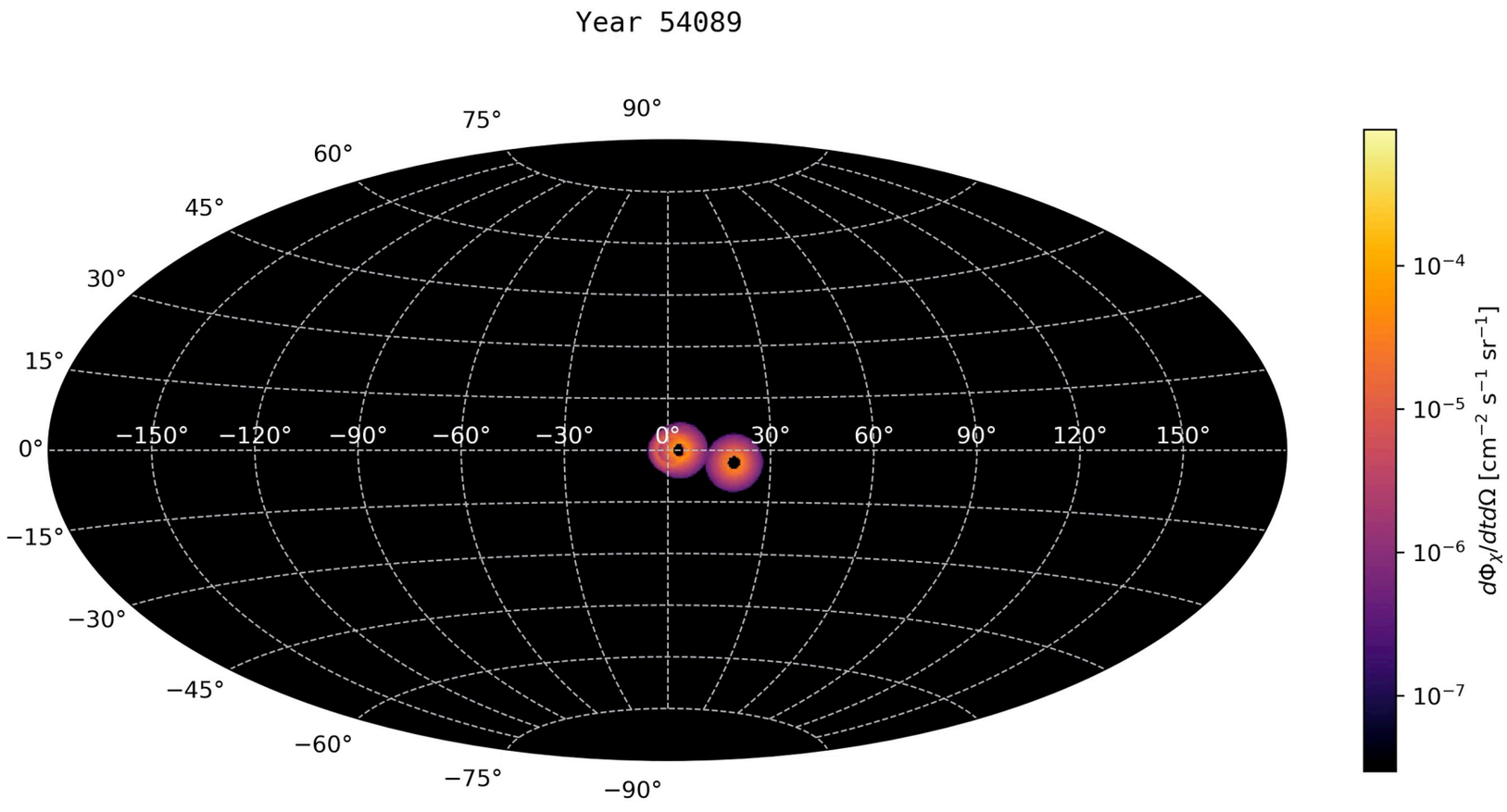


- $m_X/T_X \ll 0.1$ BDM is highly collinear with the incoming neutrino
- $m_X/T_X \gtrsim 0.1$ BDM would be much spread in the space after scattering

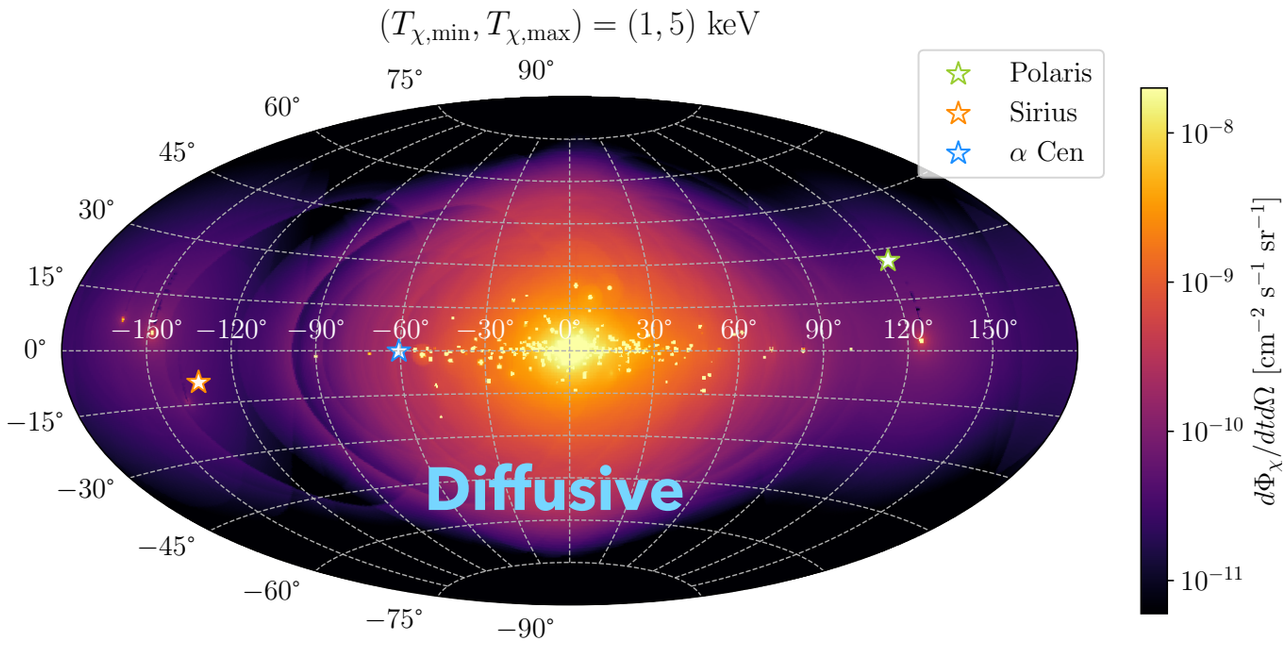


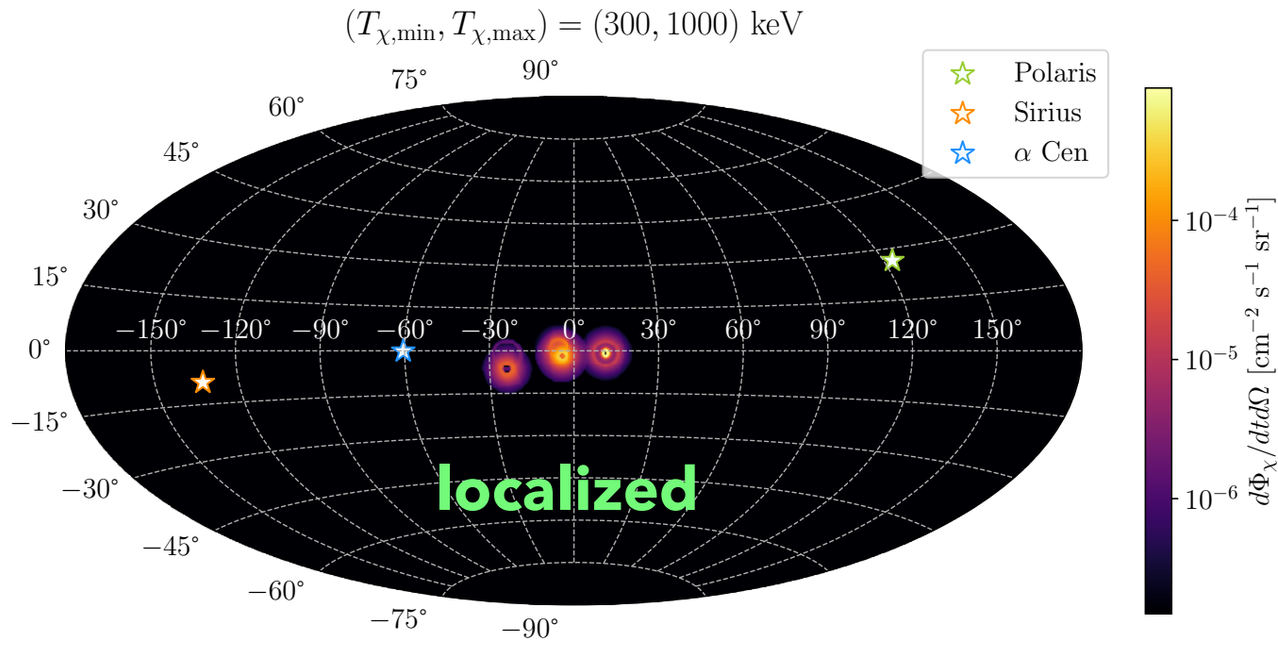
Non-relativistic
$T_\chi \in [1,5]$ keV
$m_\chi/T_\chi \in [0.1,1]$

To animation page



Relativistic
$T_\chi \in [300,1000]$ keV
$m_\chi/T_\chi \in [0.005,0.016]$

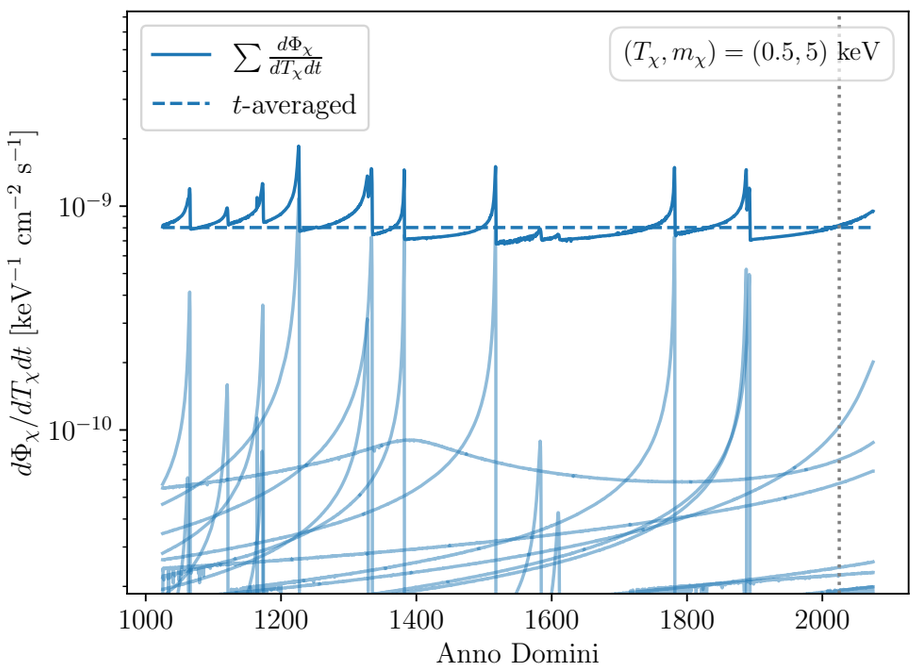




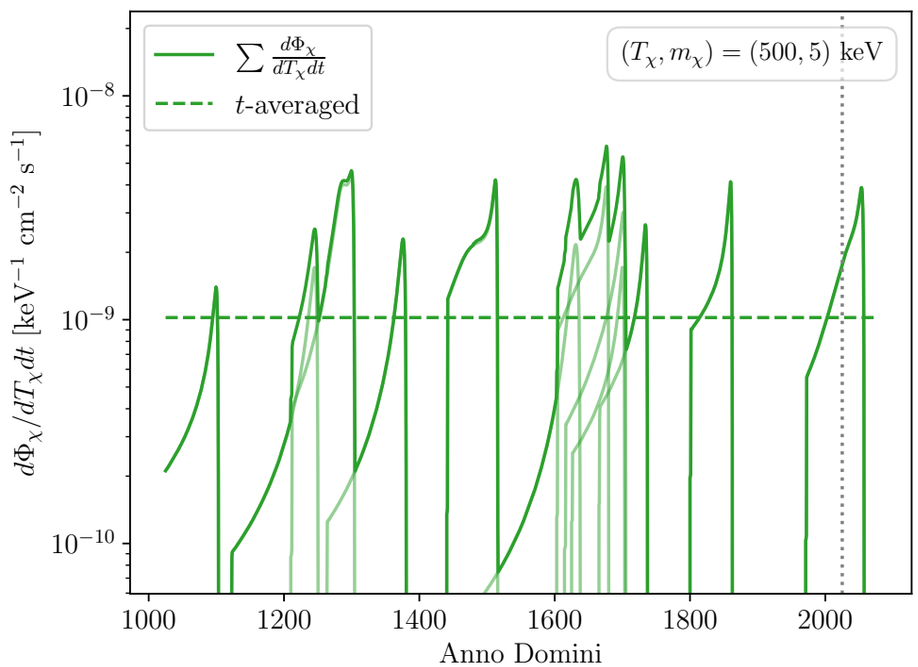
Distribution across the *spatial dimension*

Where **and** ***when*** **to look for the signature**

Distribution across the *temporal dimension*



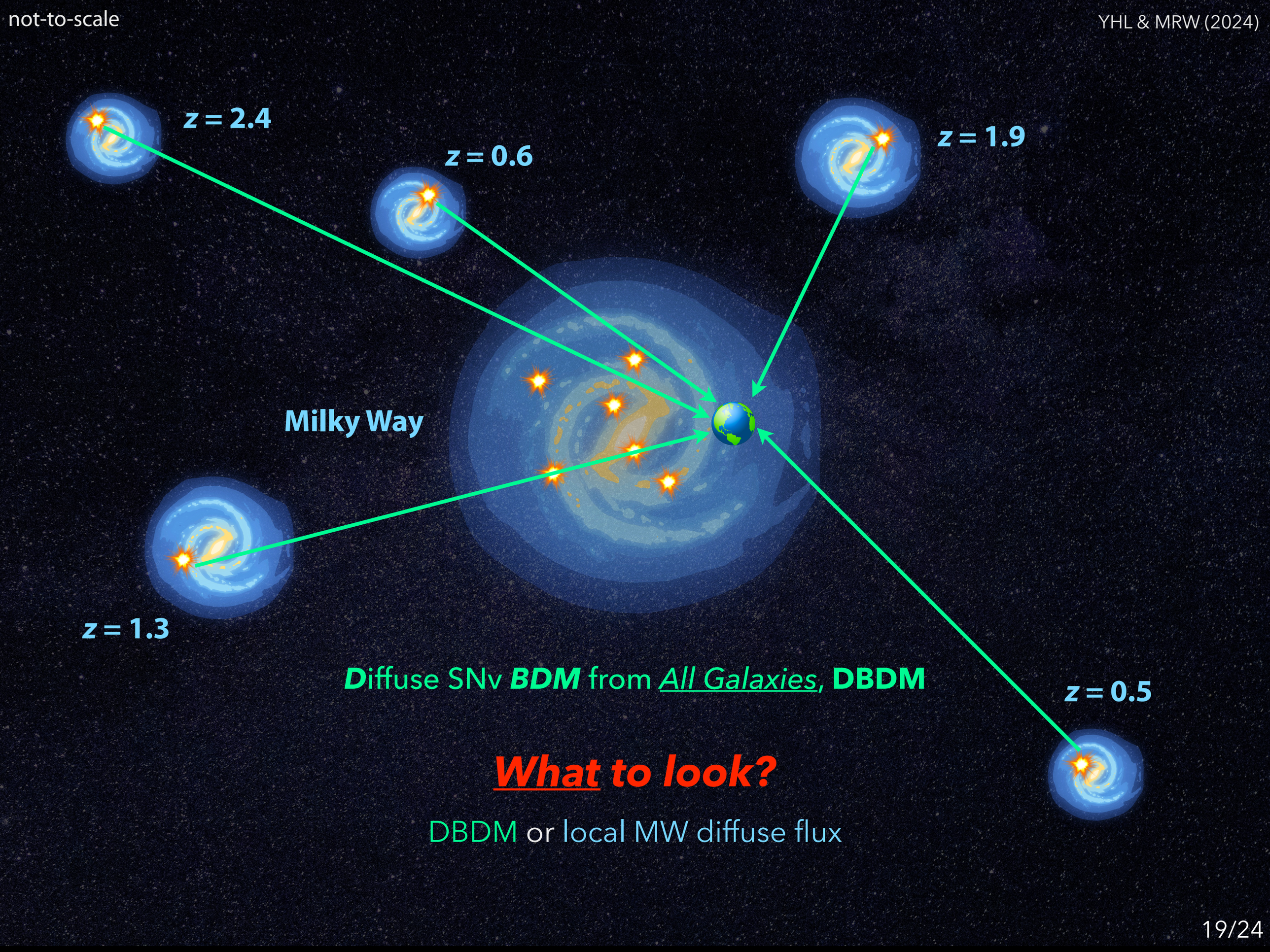
$m_\chi/T_\chi \gtrsim 0.1$



$m_\chi/T_\chi \ll 0.1$

not-to-scale

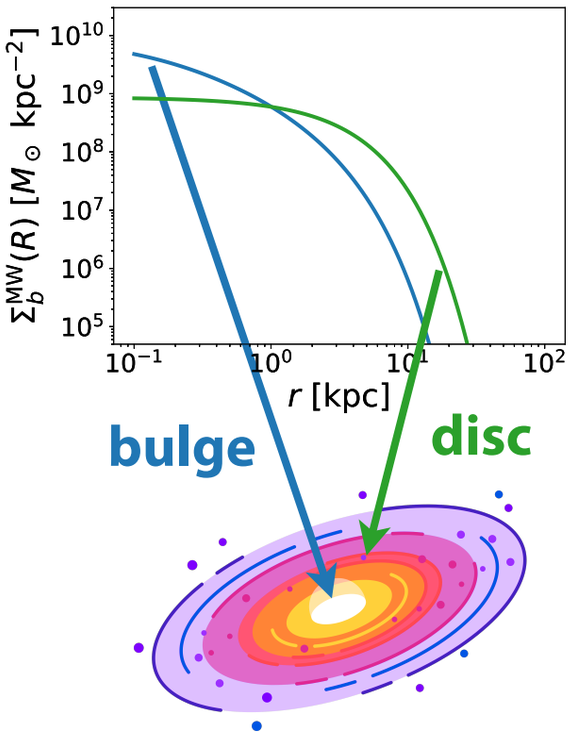
YHL & MRW (2024)



Diffuse SNv ***BDM*** from *All Galaxies*, **DBDM**

What to look?

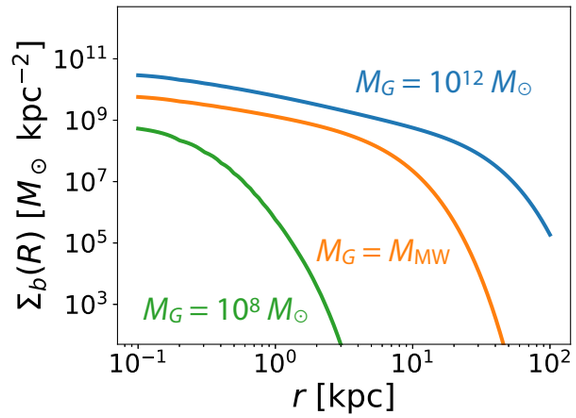
DBDM or local MW diffuse flux

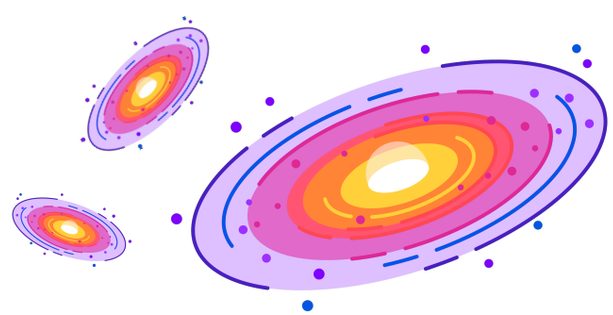


McMillan 2017

$$\rho_b(R,h) = \frac{\rho_{0,b}}{[1+r'(R,h)/r_0]^\alpha} e^{-\frac{r'^2(R,h)}{r_{\rm cut}^2}}$$

$$\rho_d(R,h) = \frac{\Sigma_0}{2h_d} e^{-\frac{|h|}{h_d} - \frac{R}{Rd}}$$



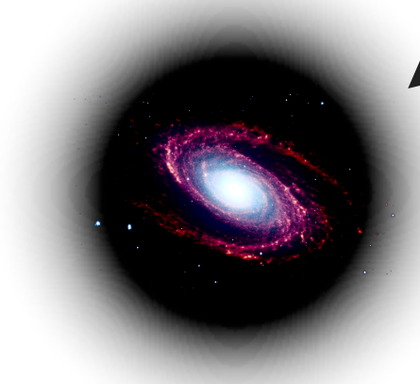


The DBDM flux

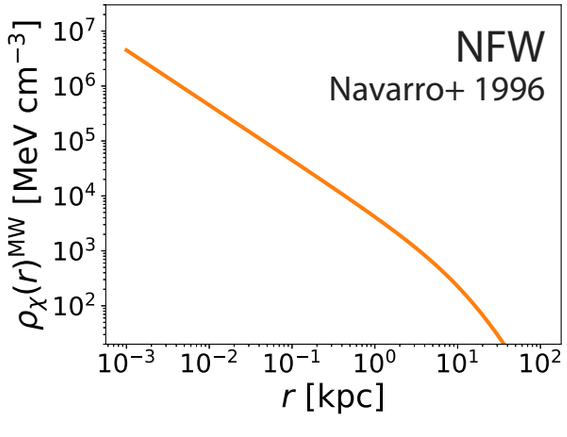
MW

$$\frac{d\Phi_\chi}{dT_\chi} = \frac{v_\chi}{H_0}\int_0^{z_{\rm max}} \frac{dz}{\epsilon(z)} \int dM_G \frac{d\Gamma_{\rm SN}(z)}{dM_G} \frac{d\bar{N}_\chi(M_G)}{dT'_\chi}$$

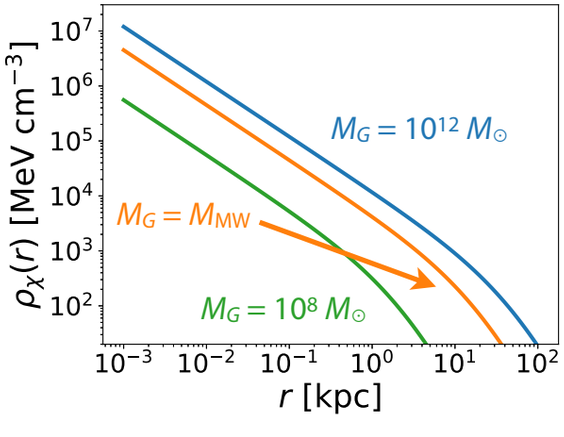
Arbitrary galaxy



$M_{\rm halo} = \eta M_G$
$\eta \sim 20$ - 50
Moster+ 2010
Grielli+ 2020

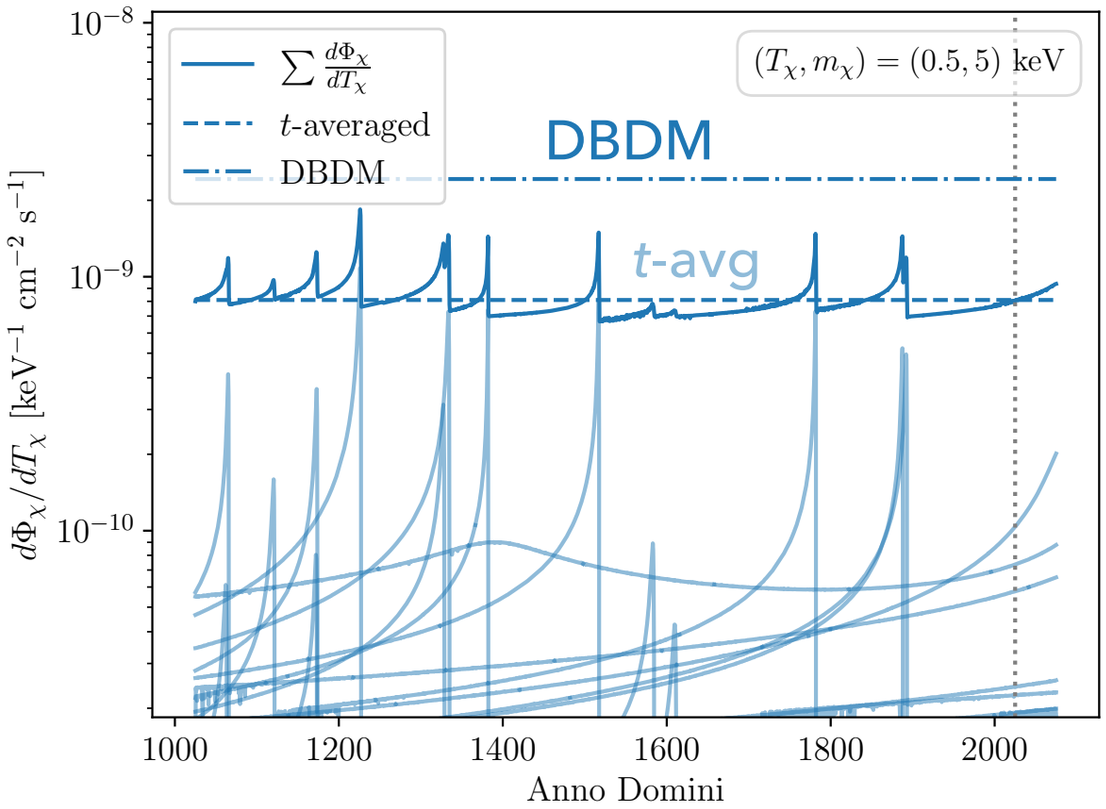


$$\rho_\chi(r) = \frac{\rho_s}{\frac{r}{r_s}(1+\frac{r}{r_s})^n}$$

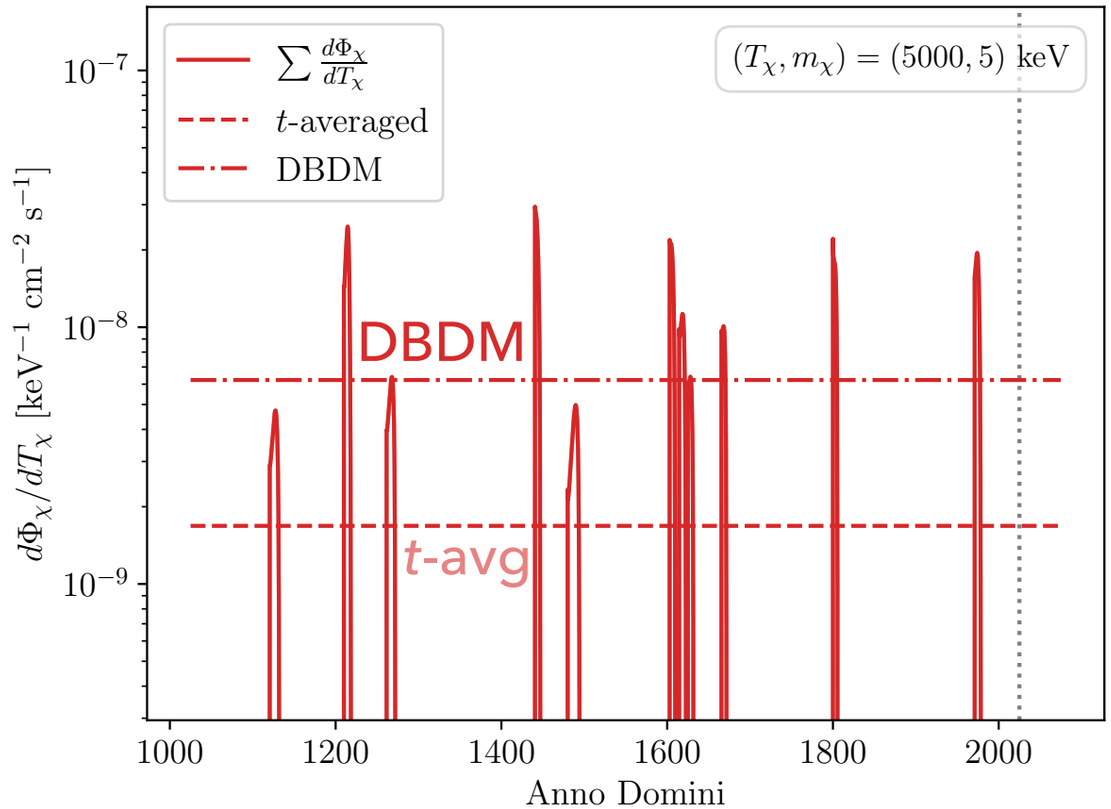


Flux revisited

$m_\chi/T_\chi = 10$

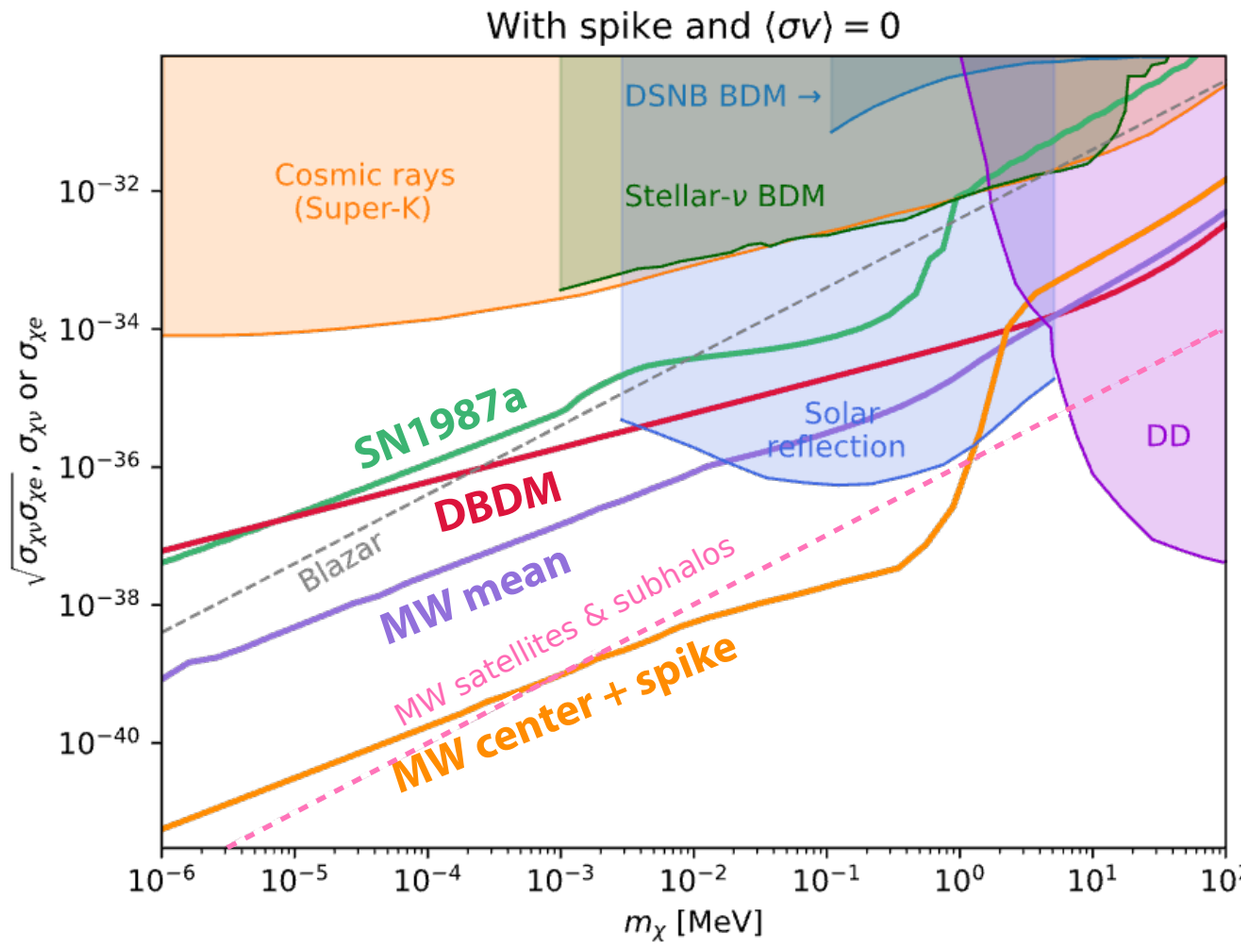


$m_\chi/T_\chi = 0.001$



- DBDM flux > MW t-averaged flux when $m_\chi/T_\chi > 0.1$ (non-relativistic)
- BDM flux from individual SN > DBDM flux when $m_\chi/T_\chi \ll 0.1$ (relativistic)

Constraints & sensitivities



YHL+ 2023
YHL & MRW 2024

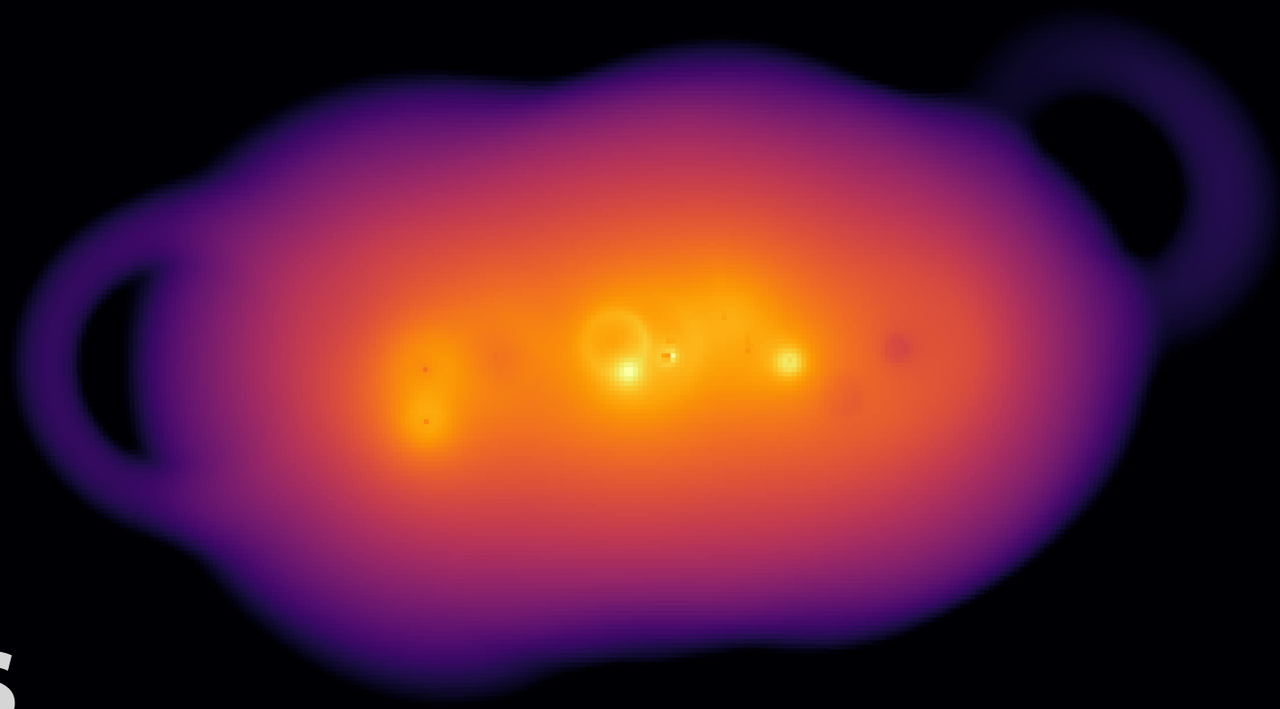
- Assuming energy-independent cross sections and $\sigma_{\chi\nu} = \sigma_{\chi e}$
- SN1987a 90%CL in Kamioka + Super-K
- 2-sigma projected sensitivity in Hyper-K

Summary

- **BDM signature from individual SN (next galactic SN)**
  - ▸ Time-dependent feature can be used to measure DM mass directly

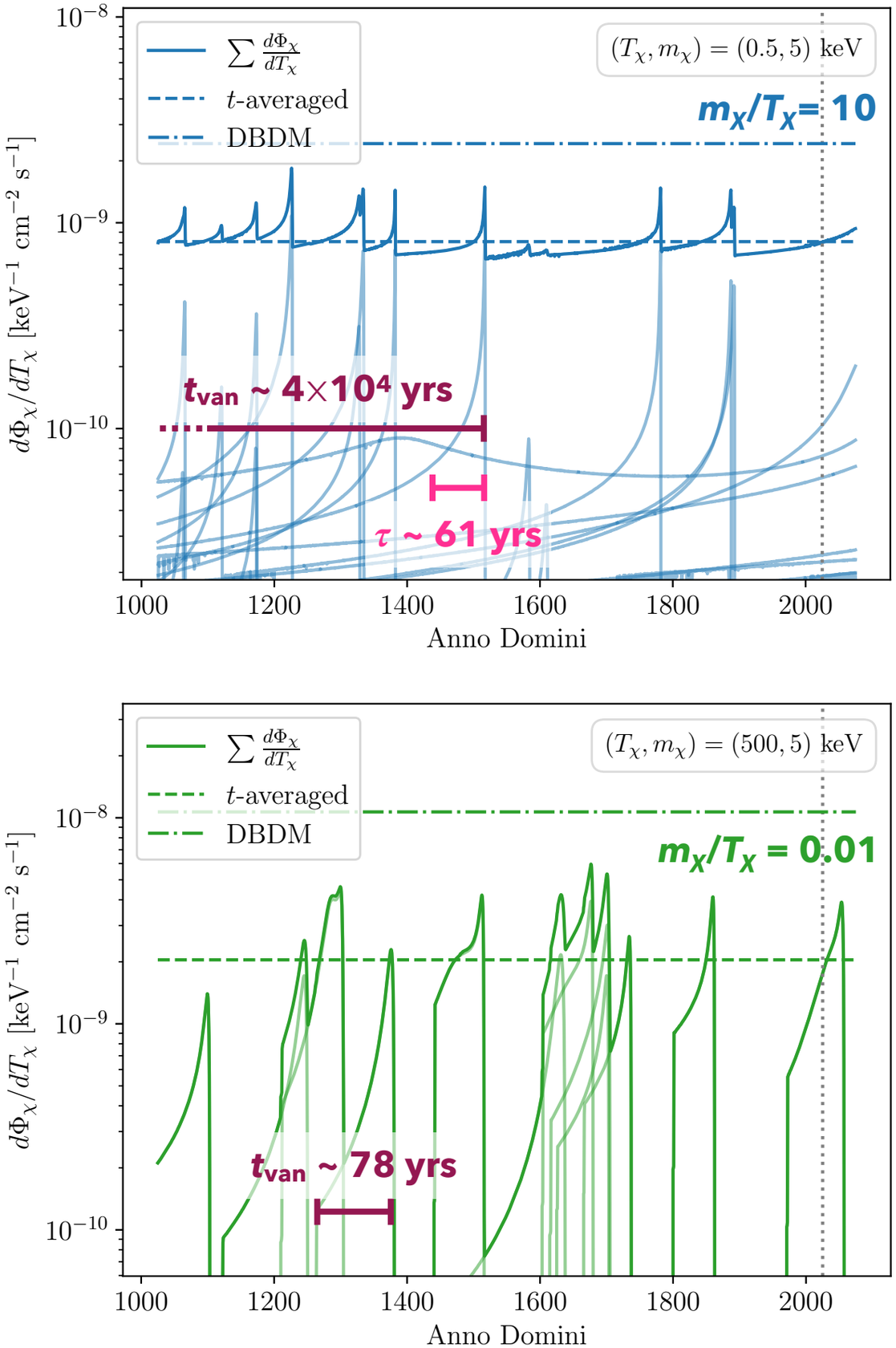
$$m_\chi \simeq 9.7\ \mathrm{keV} \times \left(\frac{t_p}{10\ \mathrm{days}}\right)^{1/2} \left(\frac{T_\chi}{10\ \mathrm{MeV}}\right)$$

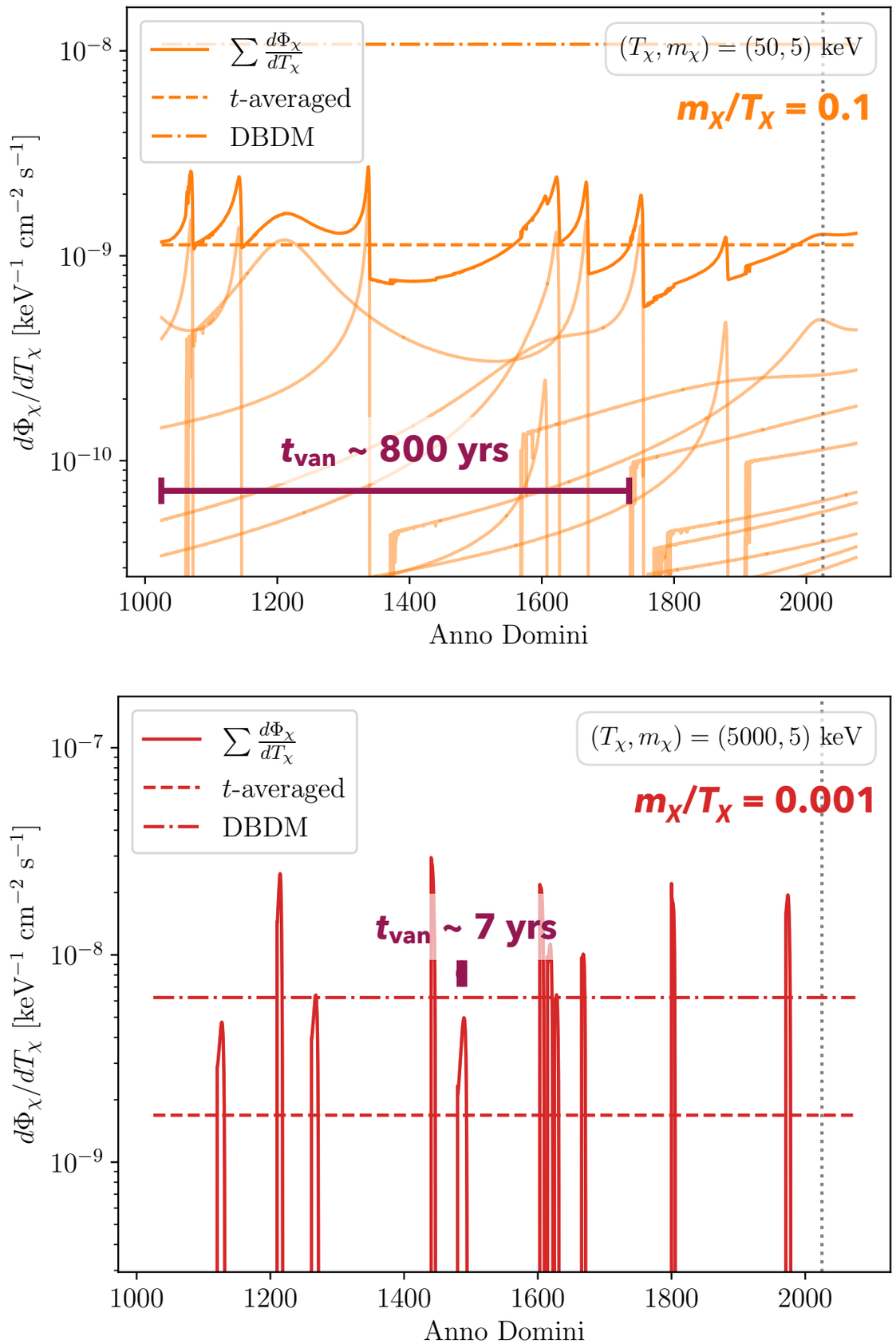
  - ▸ Suppressing the background accumulation → enhancing the sensitivity
- **BDM flux behaves diffusively or not that depends on m_χ/T_χ (t_{van}/τ)**
- **What BDM component is more promising to look for**
  - ▸ Diffuse SNv BDM from all galaxies (DBDM) provides better constraint
  - ▸ Next galactic SN will offer exciting opportunity for BDM search



Backups

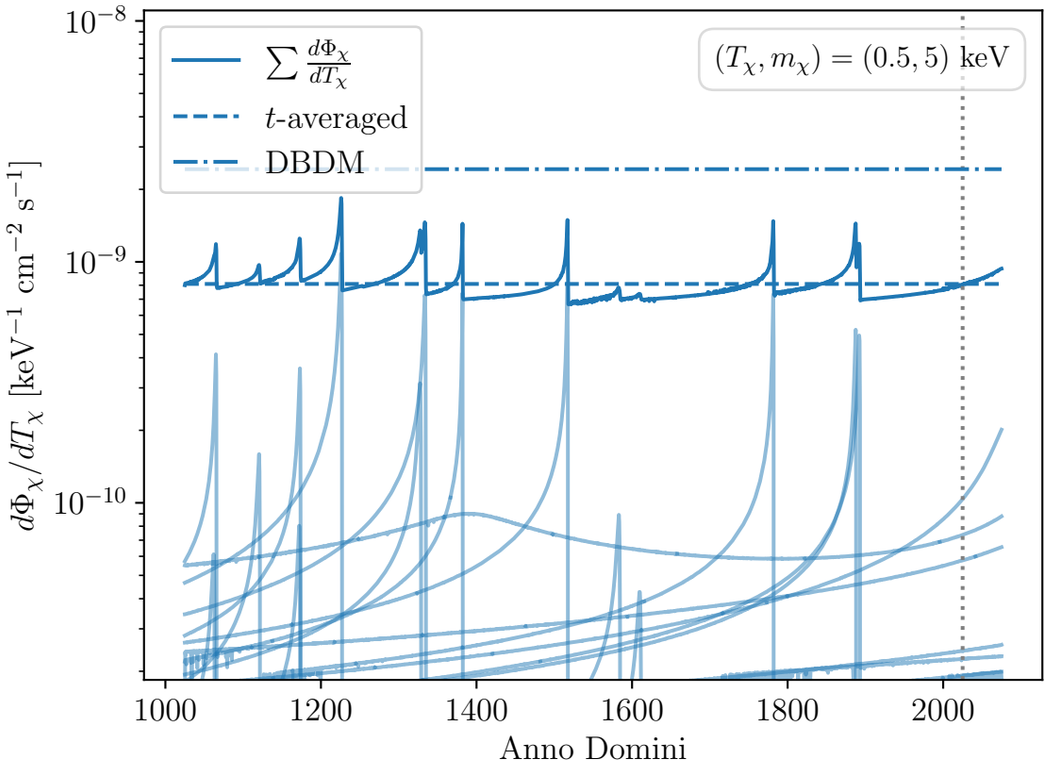
Total BDM flux vs. time



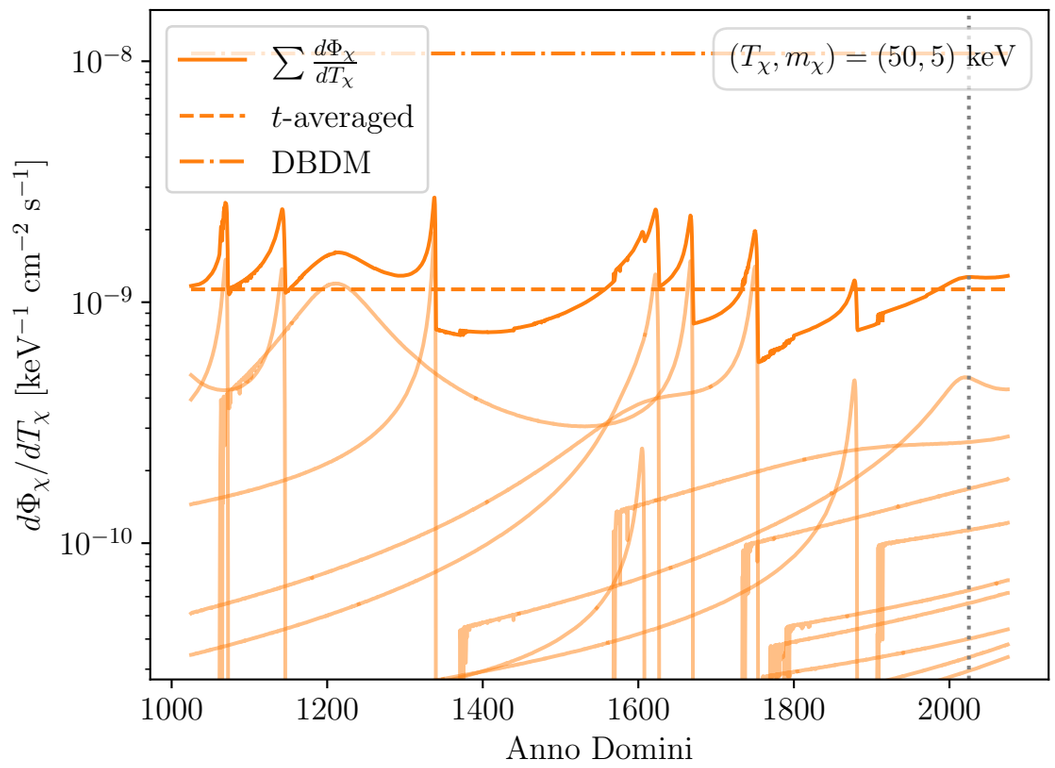


T_χ ~ O(keV)

m_χ/T_χ= 10

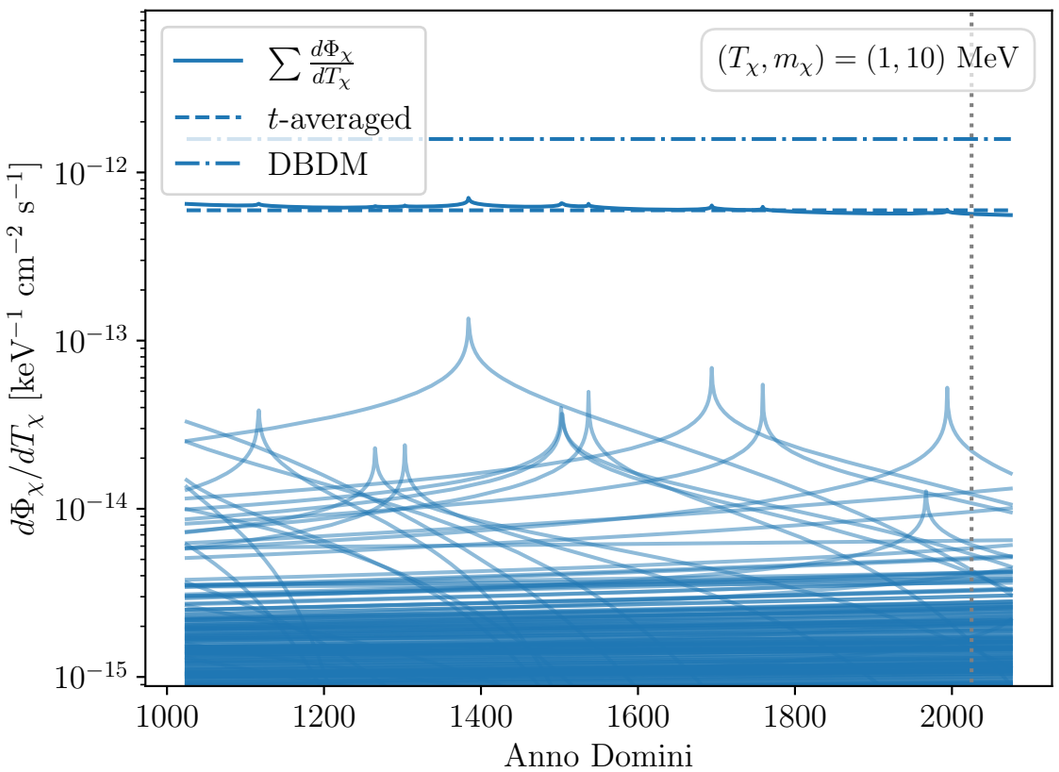


m_χ/T_χ = 0.1

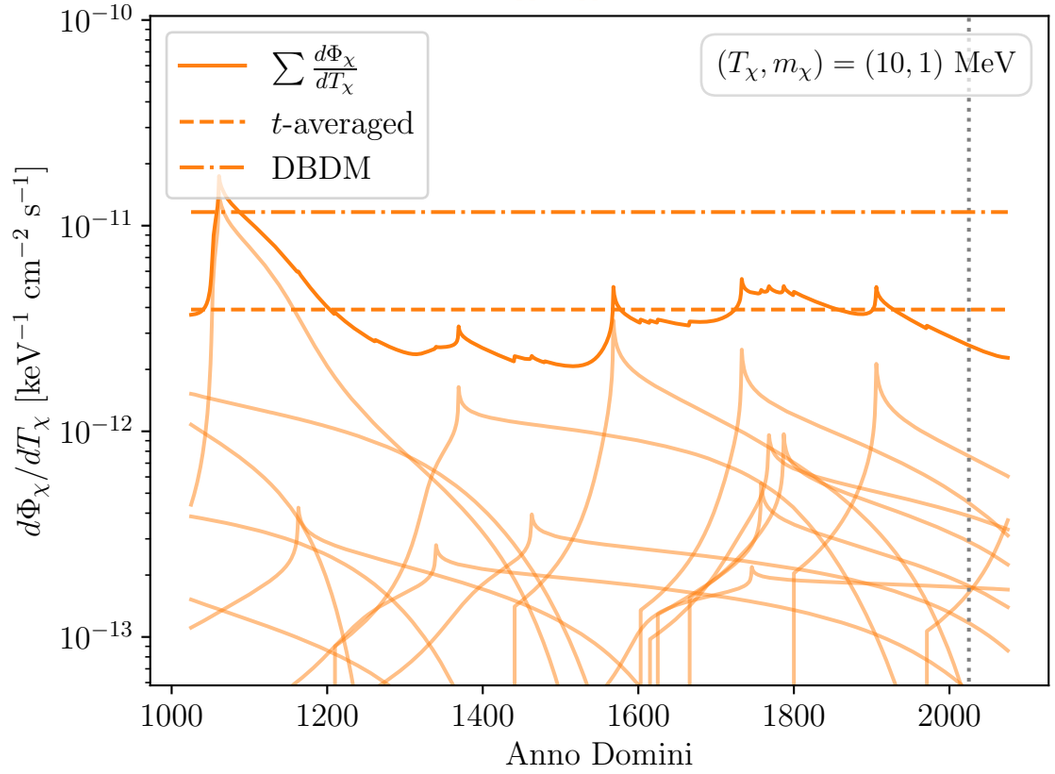


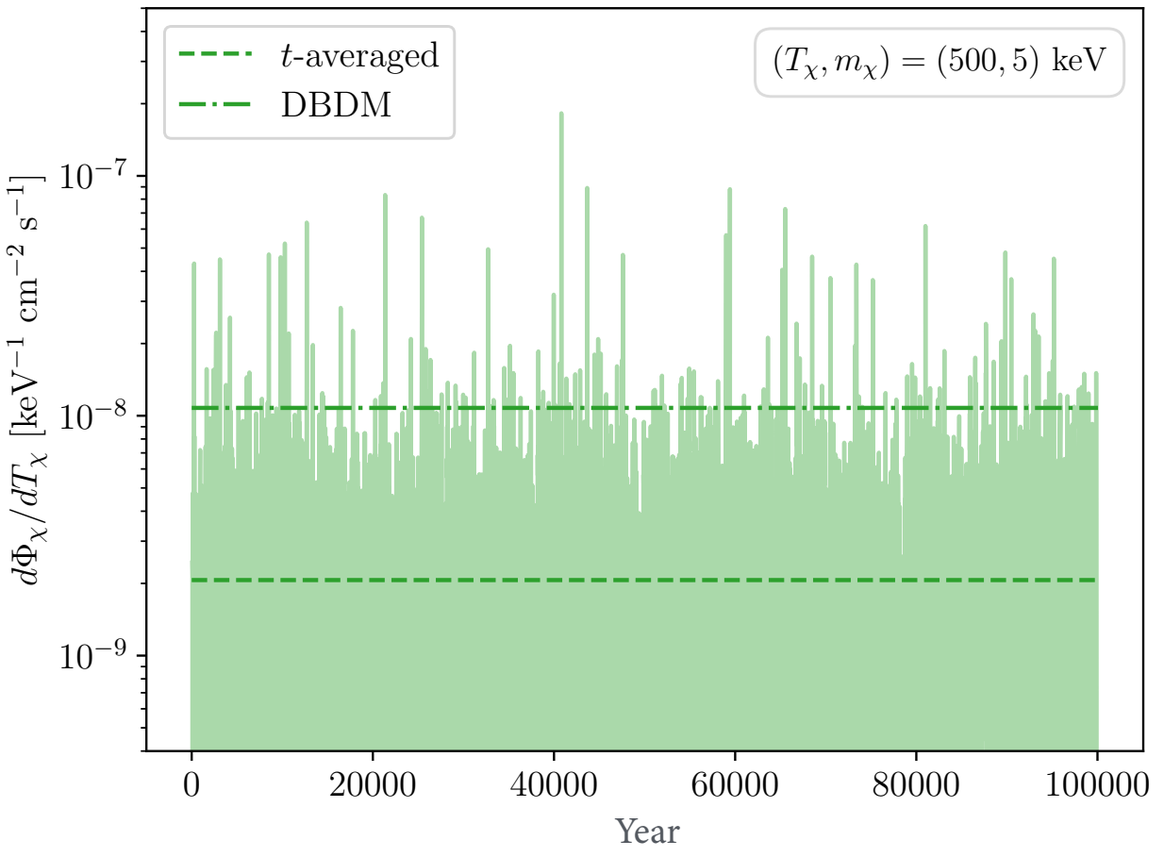
T_χ ~ O(MeV)

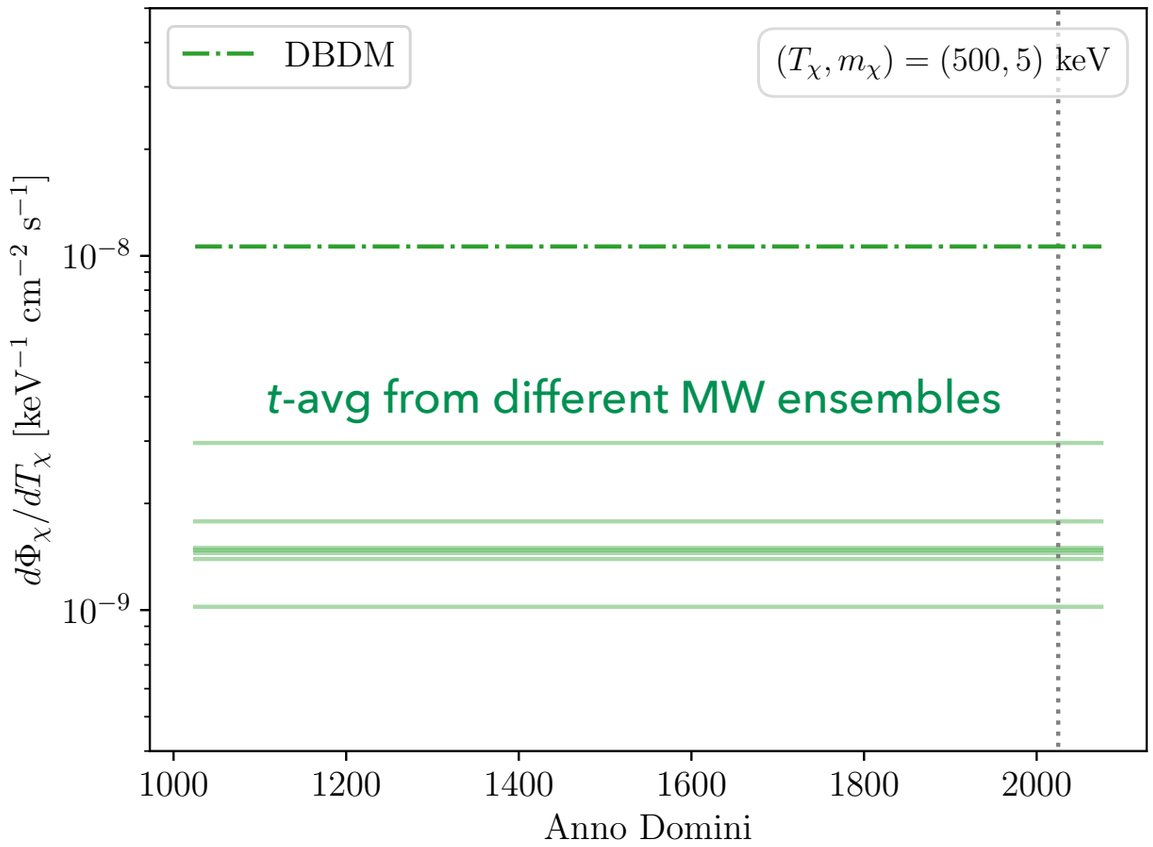
m_χ/T_χ= 10

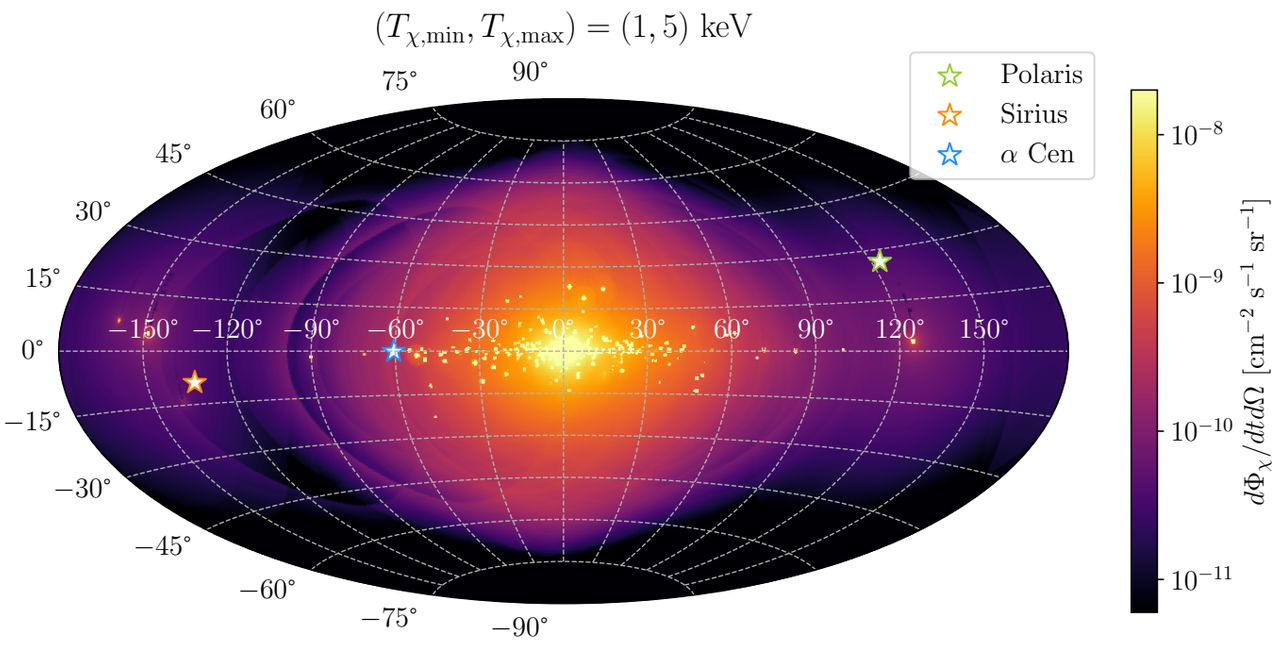


m_χ/T_χ = 0.1

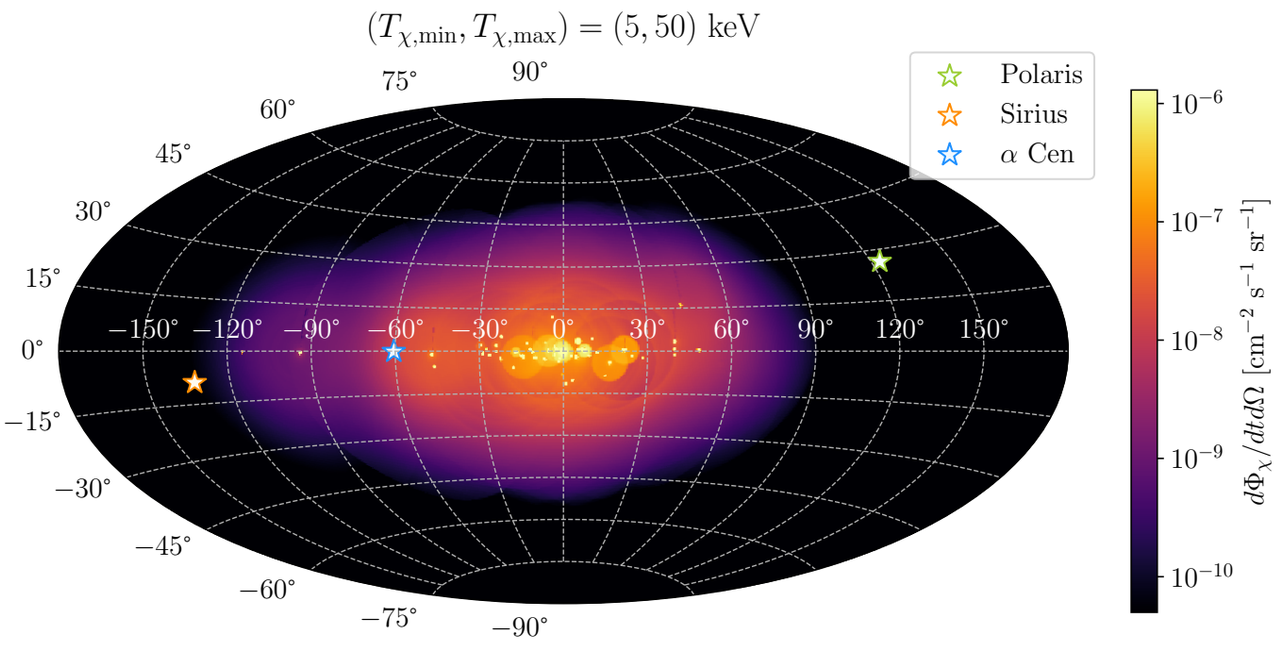



t-averaged
DBDM
$(T_\chi, m_\chi) = (500, 5)$ keV
$d\Phi_\chi/dT_\chi$ [keV^{-1} cm^{-2} s^{-1}]
10^{-7}
10^{-8}
10^{-9}
0
20000
40000
60000
80000
100000
Year


DBDM
$(T_\chi, m_\chi) = (500, 5)$ keV
t-avg from different MW ensembles
$d\Phi_\chi/dT_\chi$ [keV^{-1} cm^{-2} s^{-1}]
10^{-8}
10^{-9}
1000
1200
1400
1600
1800
2000
Anno Domini

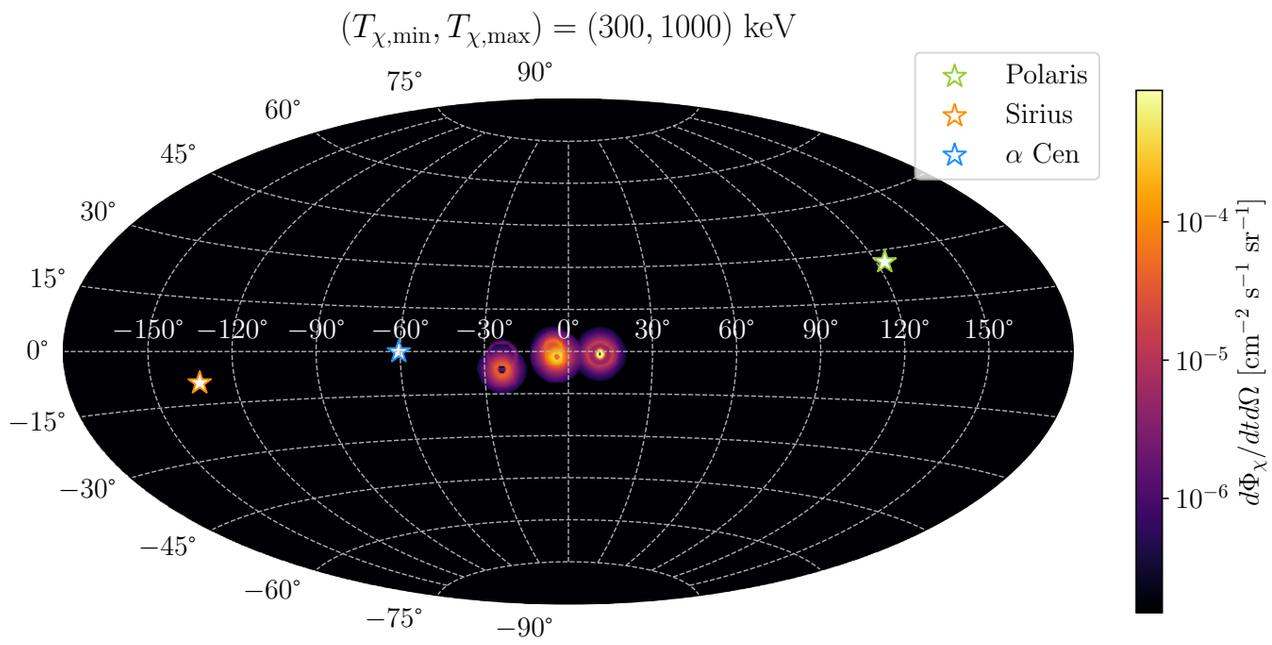


$m_\chi/T_\chi \in [1,5]$

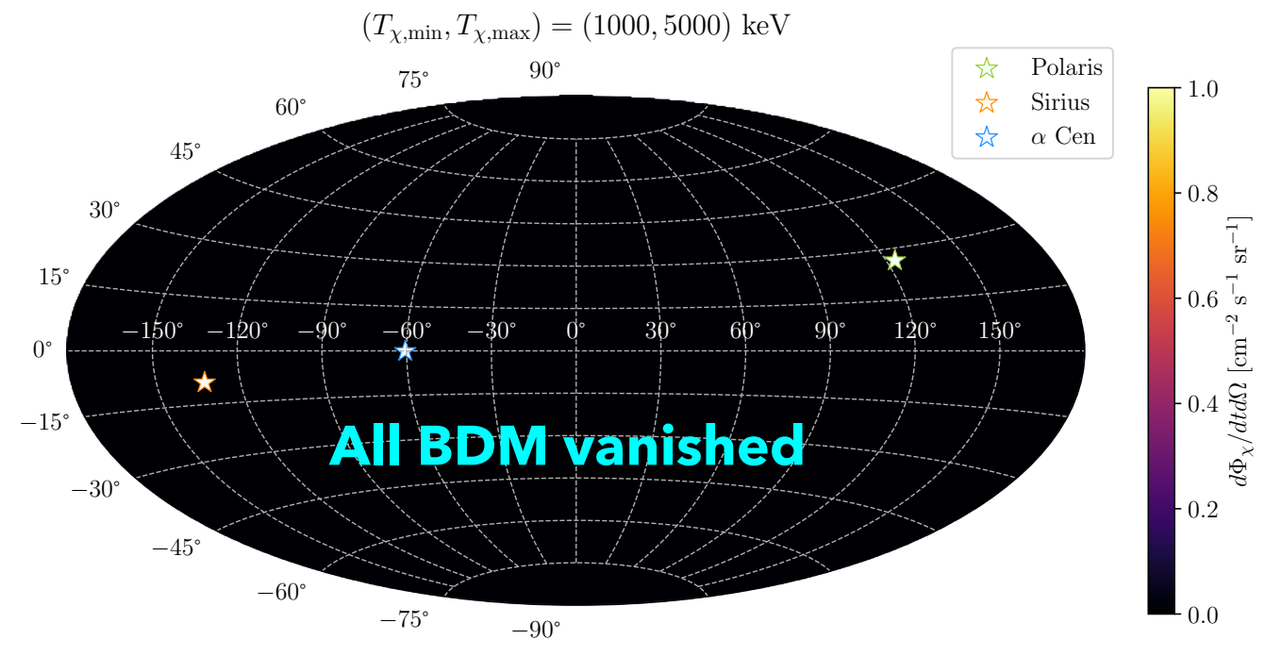


$m_\chi/T_\chi \in [0.1,1]$

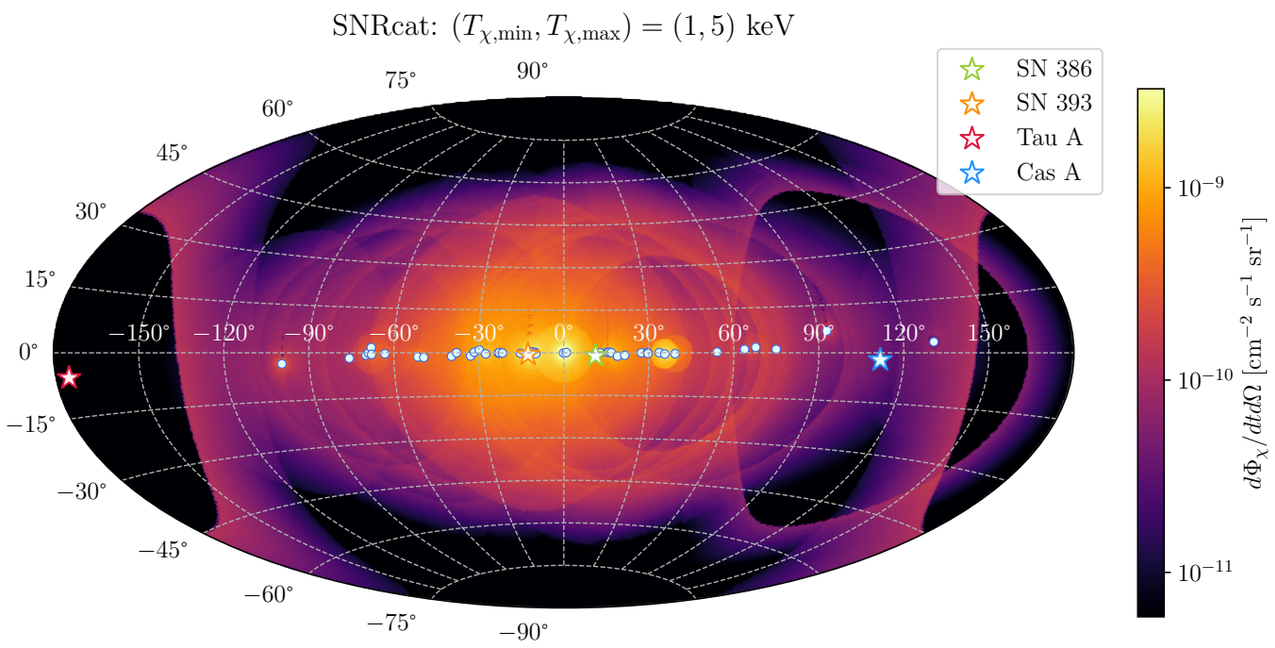
$m_\chi/T_\chi \in [0.005,0.016]$



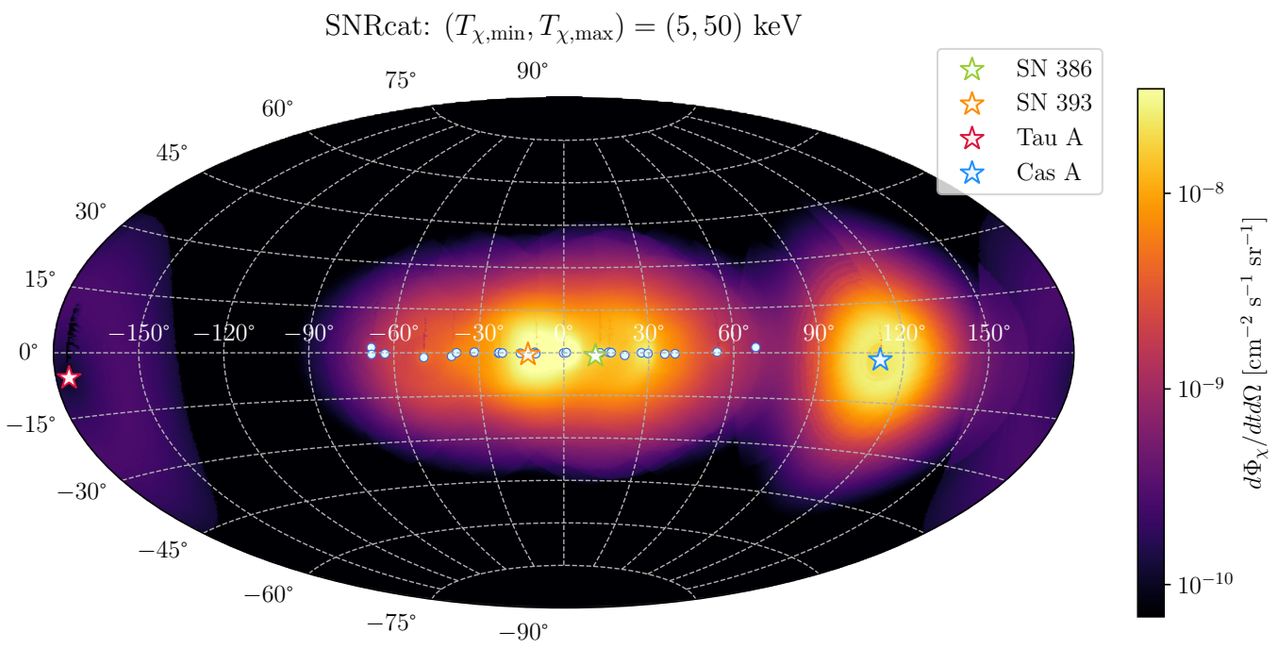
$m_\chi/T_\chi \in [0.005,0.001]$



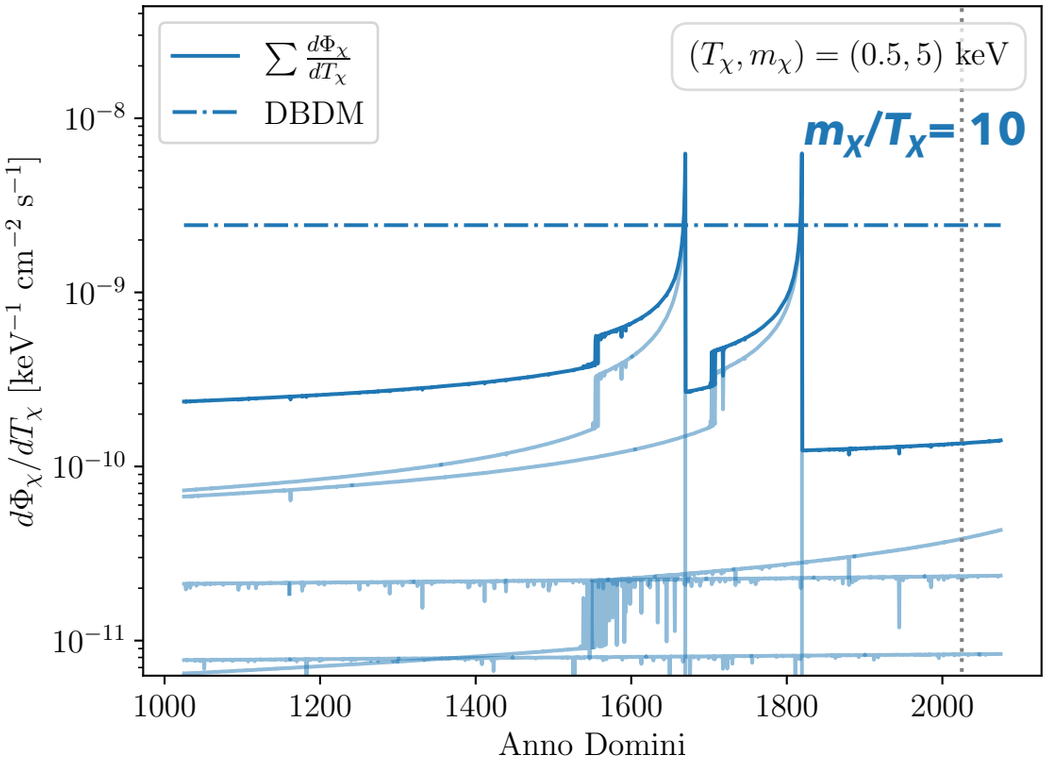
BDM from documented SNRs

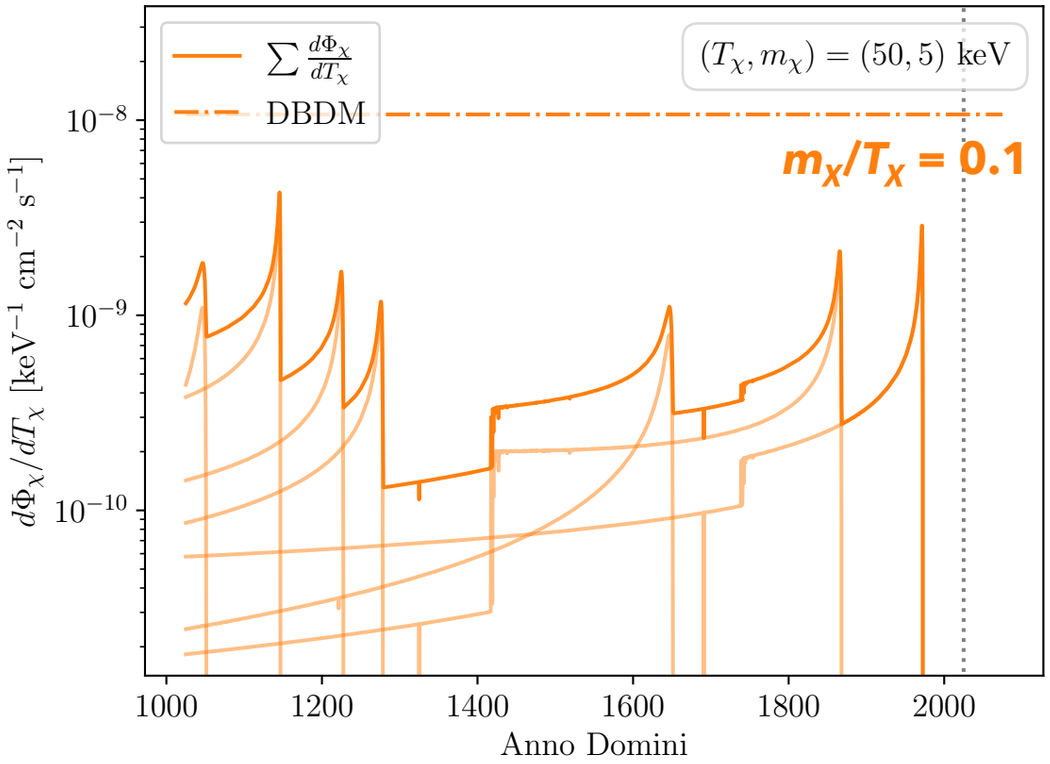


$m_\chi/T_\chi \in [1,5]$



$m_\chi/T_\chi \in [0.1,1]$





SNRcat: `http://snrcat.physics.umanitoba.ca/`