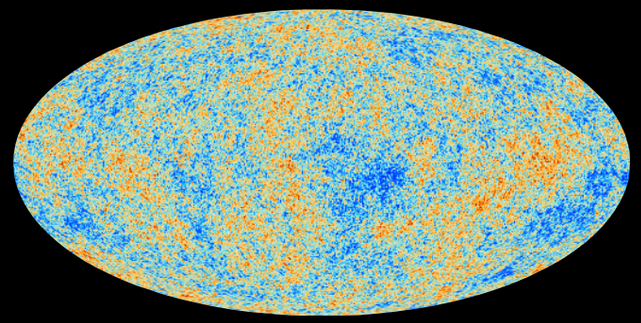
Yen-Hsun Lin (林彥勳)
Physics Division, National Center for Theoretical Sciences, Taiwan
yenhsun@phys.ncku.edu.tw

Annual Theory Meeting on Particle Physics, String Theory, Cosmology and Astrophysics
Dec. 14-16 2022

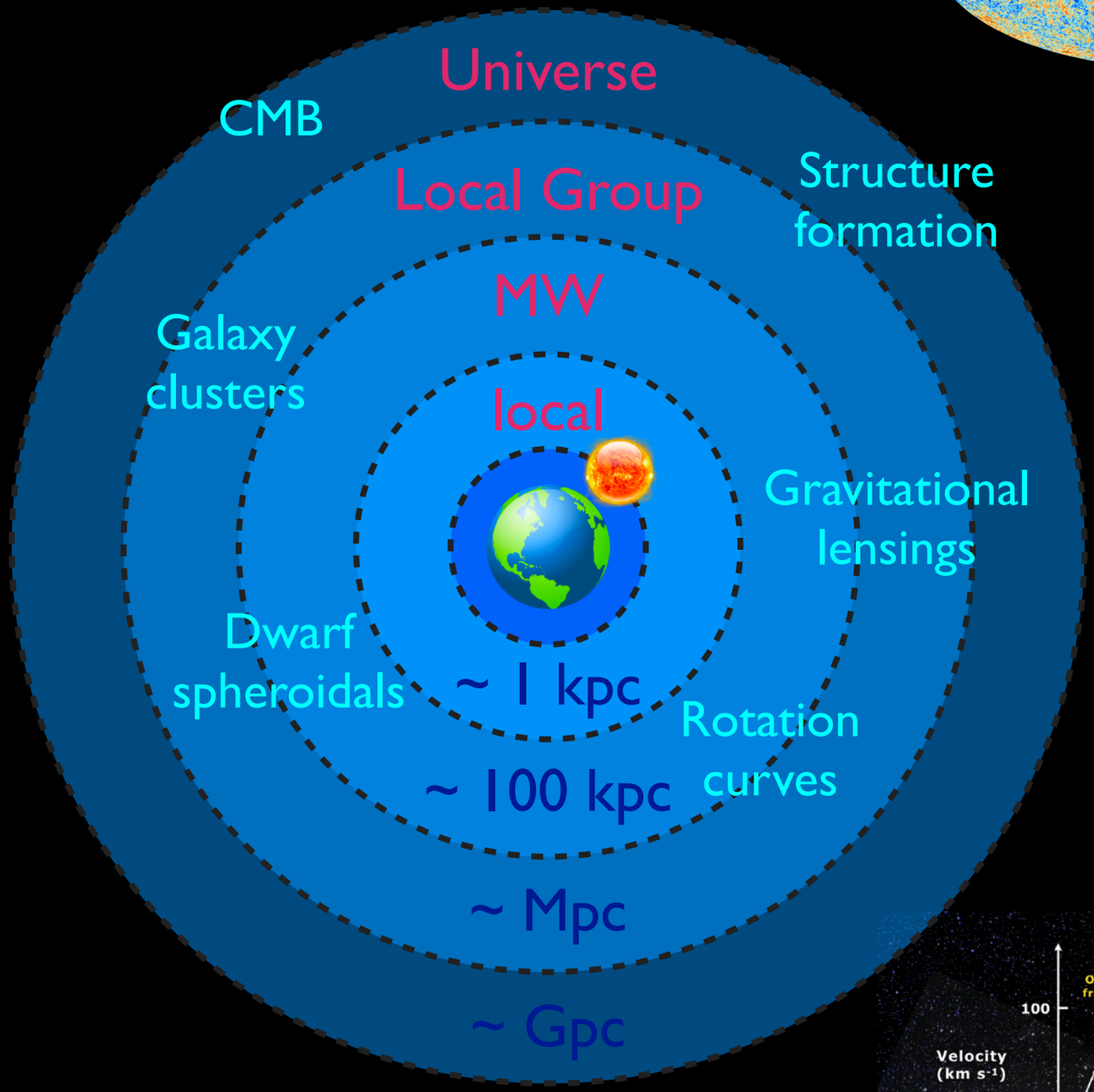
Light dark matter constraints from neutron stars and supernova neutrinos
— *A selected-topics overview*

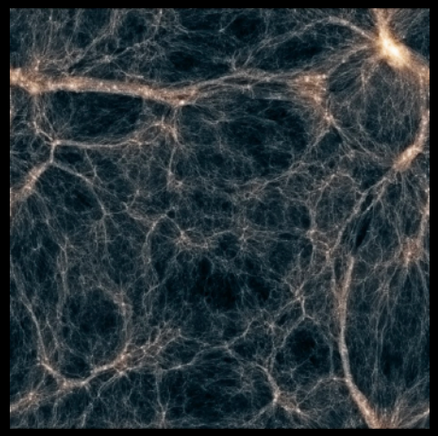
Dark matter is *ubiquitous* in the Universe!

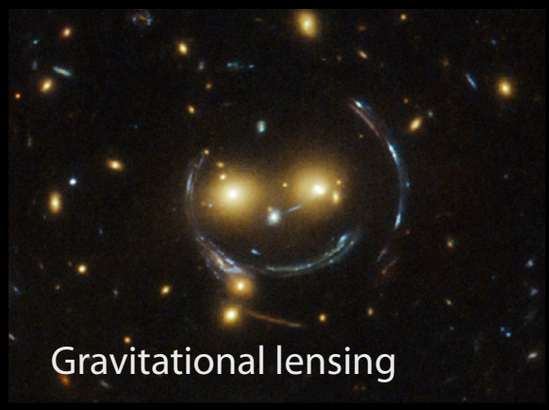


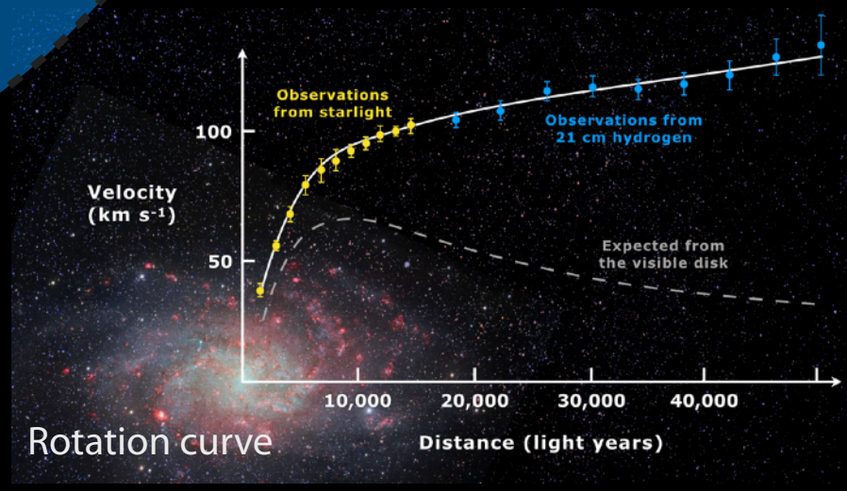
More ancient

Larger space






Gravitational lensing



Rotation curve

$1\,\mathrm{pc} \approx 2.06 \times 10^5\,\mathrm{AU} \approx 3.08 \times 10^{16}\,\mathrm{m}$

What is the essence of DM?

- Dark *matter* ➡ **mass m_χ**
- To *measure* ➡ DM-SM *interaction* ➡ **cross sections $\sigma_{\chi n,p,e\ldots}$, $\langle\sigma v\rangle$**



not-to-scale

The DM probes: m_χ & σ



not-to-scale

The DM probes: m_χ & σ

CDEX Collab.
LUX Collab.
SENSEI Collab.
XENON Collab.
Essig+ (2015)
Hochberg+ (2015)
Hochberg+ (2016)
Geilhufe+ (2019)
Kim+ (2020)
Kahn+ (2020)
Knapen+ (2020)…

m_χ — eV — MeV — GeV — > TeV

low temperature quantum effects

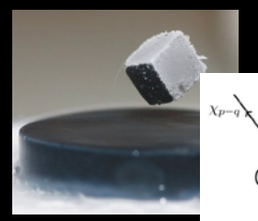
electron recoils

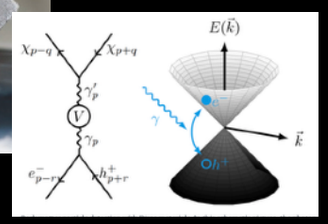
nucleus recoils

Dark matter direct search

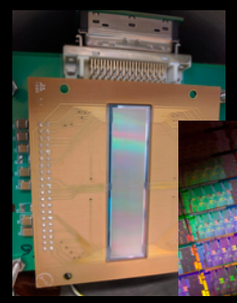
not-to-scale

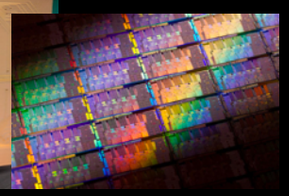
superconductor/graphene Dirac matter…



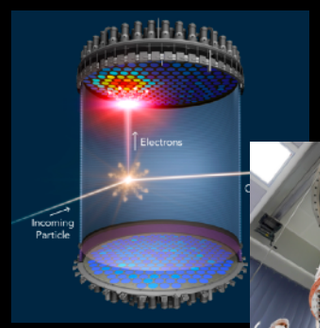


semiconductor skipper CCD



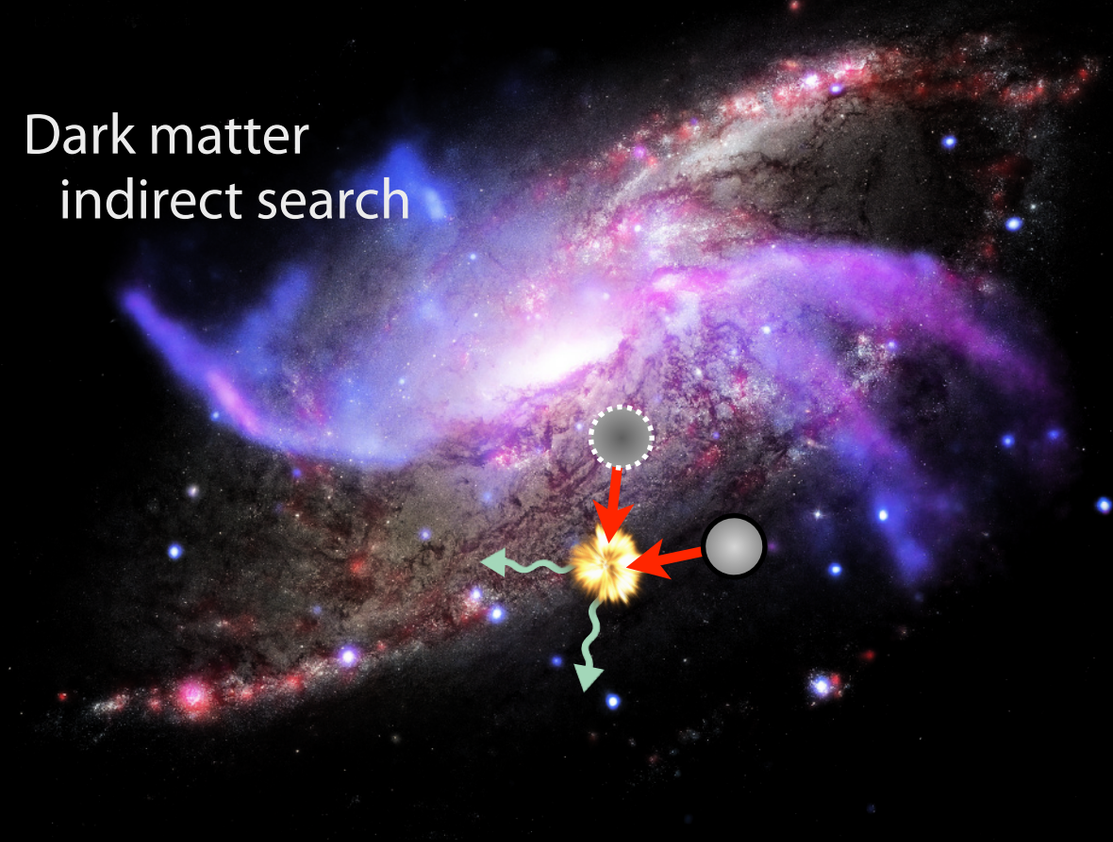


liquid xenon





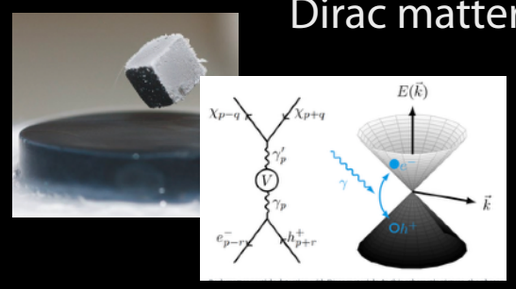
The DM probes: m_χ & σ



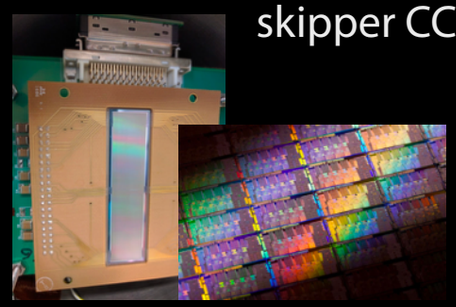


Dark matter
direct search

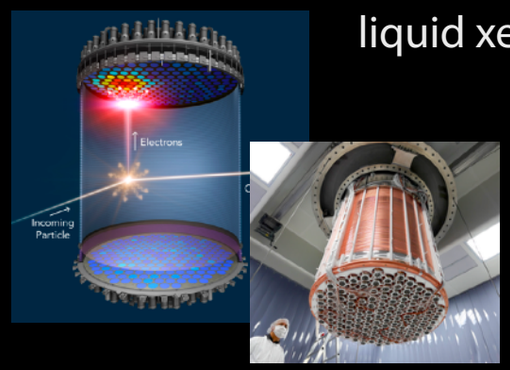
superconductor/graphene
Dirac matter…



semiconductor
skipper CCD



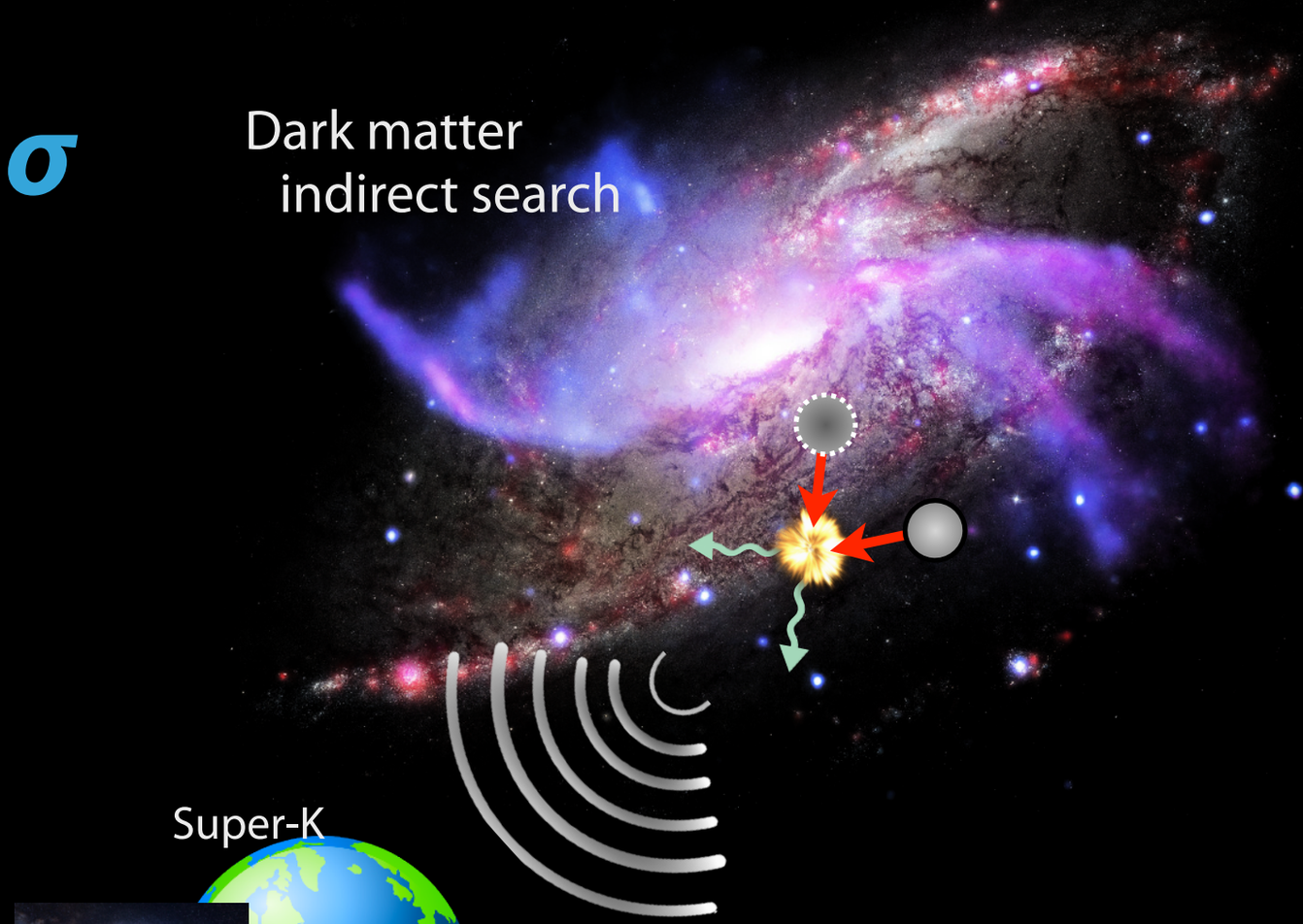
liquid xenon



not-to-scale

The DM probes: m_χ & σ

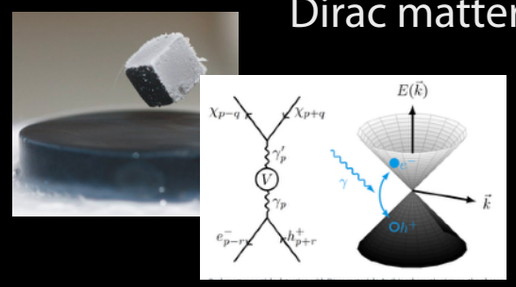
Dark matter
indirect search



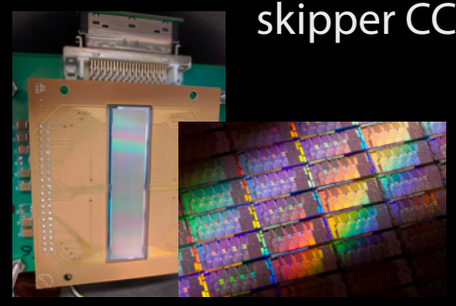
m_χ ····· eV — low temperature quantum effects — MeV — electron recoils — GeV — nucleus recoils — > TeV

Dark matter
direct search

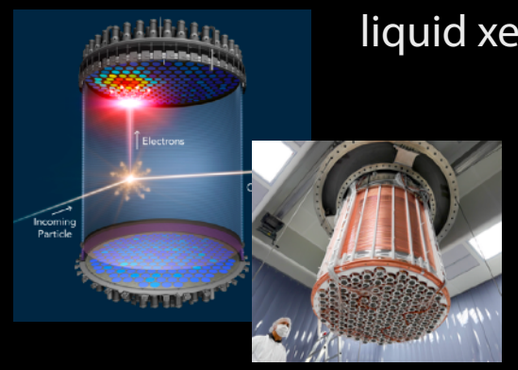
superconductor/graphene
Dirac matter…



semiconductor
skipper CCD



liquid xenon



not-to-scale

The DM probes: m_χ & σ

Dark matter
indirect search

Sun

compact stars
pulsars…

planets

supernovae

cosmic rays

Super-K

TMT

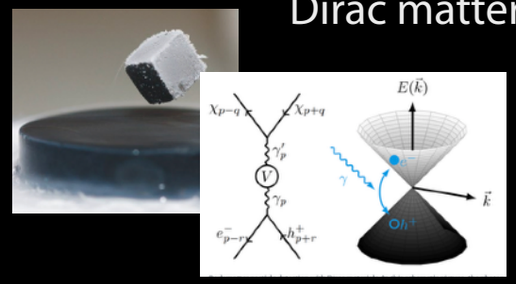
IceCube

JWST

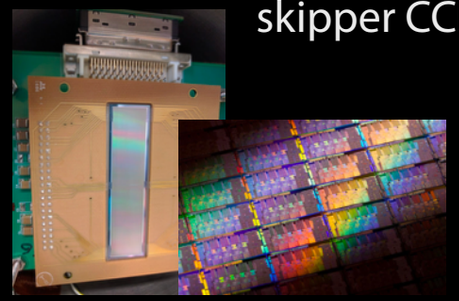
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Dark matter
direct search

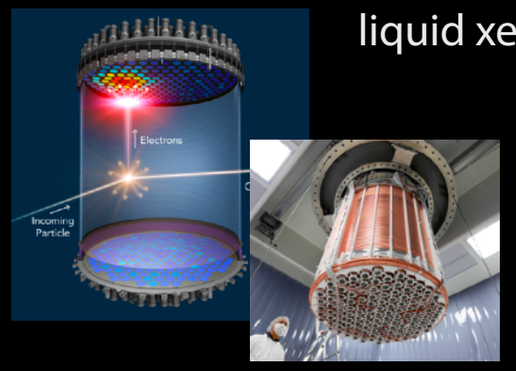
superconductor/graphene
Dirac matter…



semiconductor
skipper CCD



liquid xenon



not-to-scale

Current constraints

See: Jungman+, *PP* **267**, 195 (1996)
Bertone+, *PP* **405**,279 (2005)
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Knapen+, *PRD* **96**, 115021 (2017)
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Cooley+, 2209.07426
… *for comprehensive reviews*



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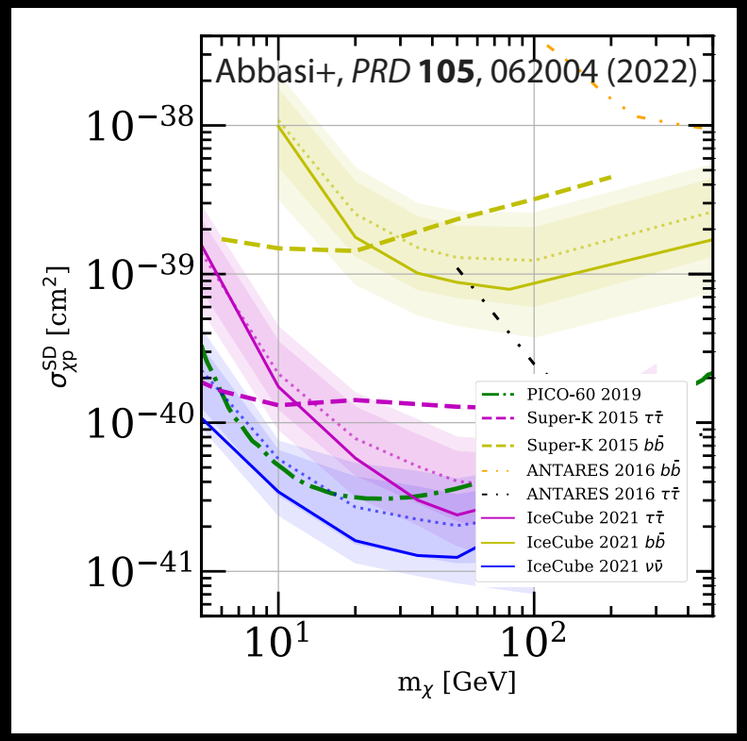
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Spin-dependent $\sigma_{\chi p}$

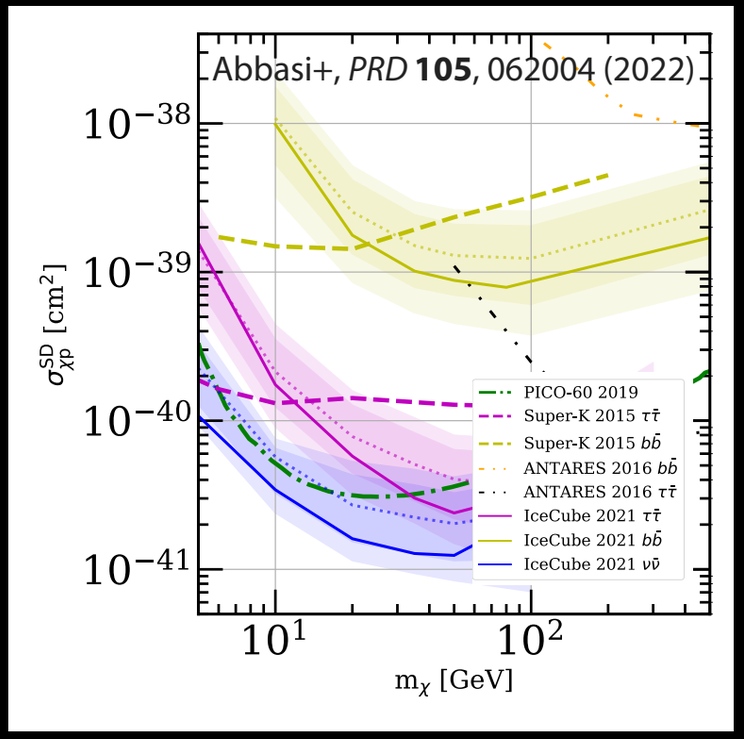




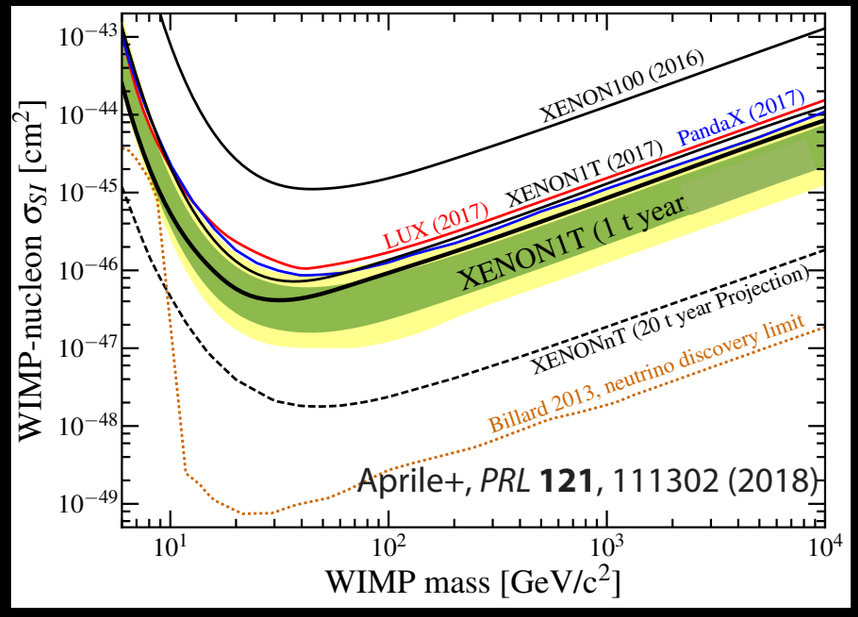
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Spin-dependent $\sigma_{\chi p}$



Spin-independent $\sigma_{\chi n}$



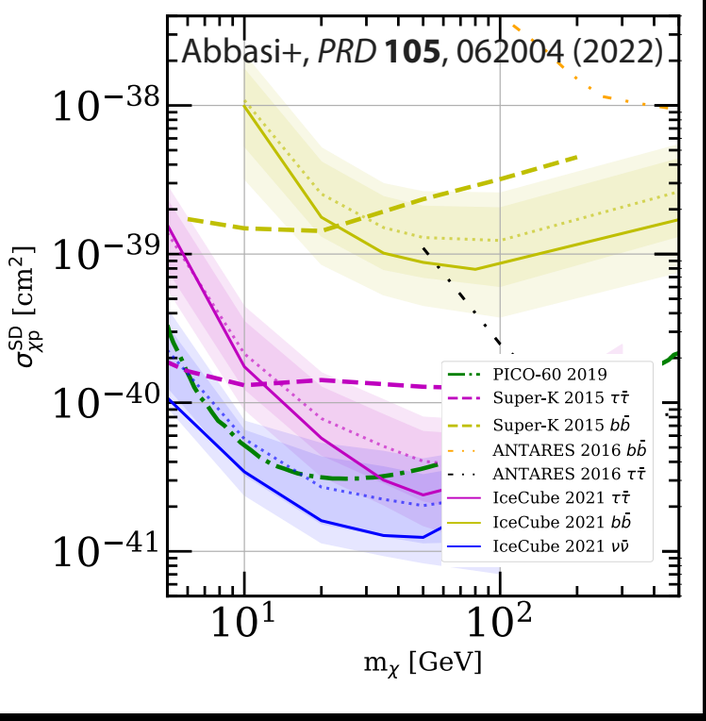
XENON1T constraints on ChEFT and inelastic DM see 2210.07591



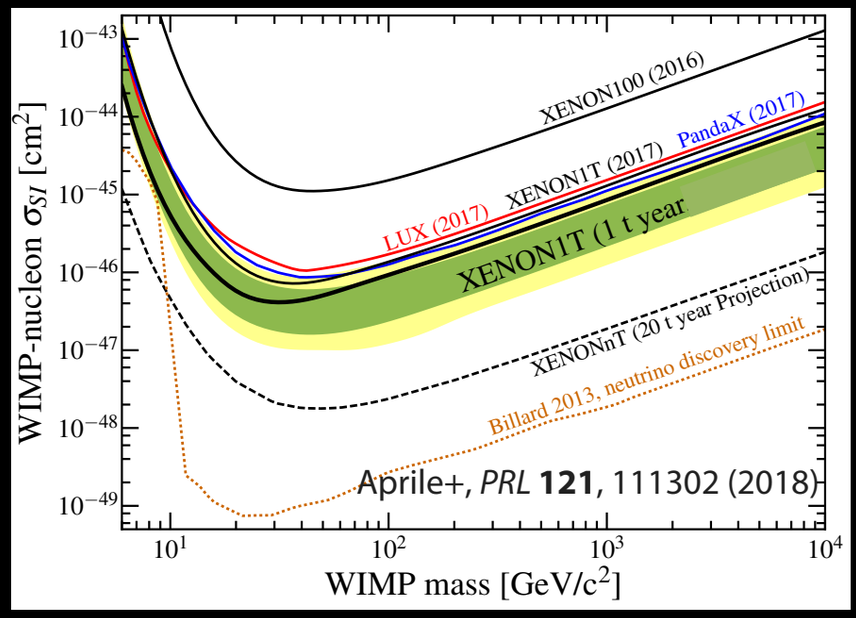
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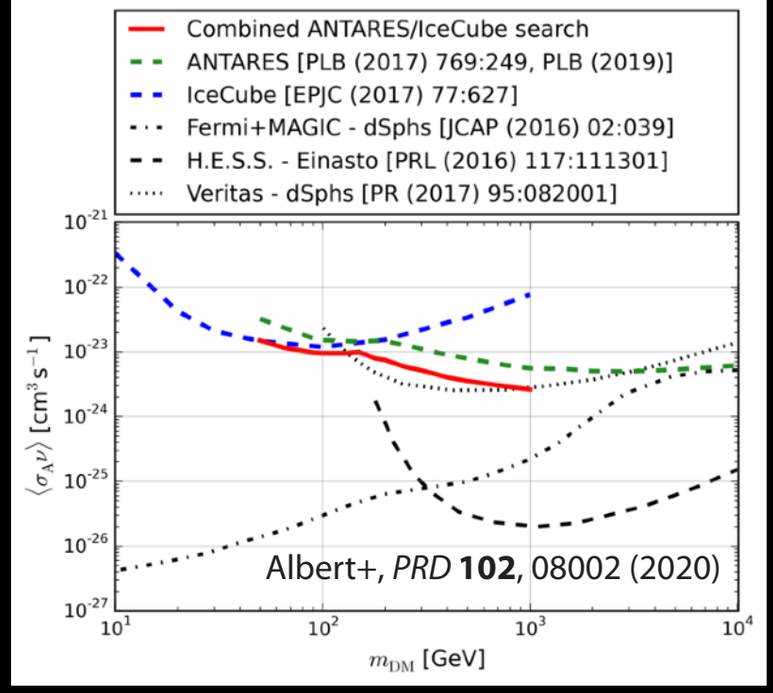


Spin-independent $\sigma_{\chi n}$



XENON1T constraints on ChEFT and inelastic DM see 2210.07591

Annihilation cross section $\langle\sigma v\rangle$

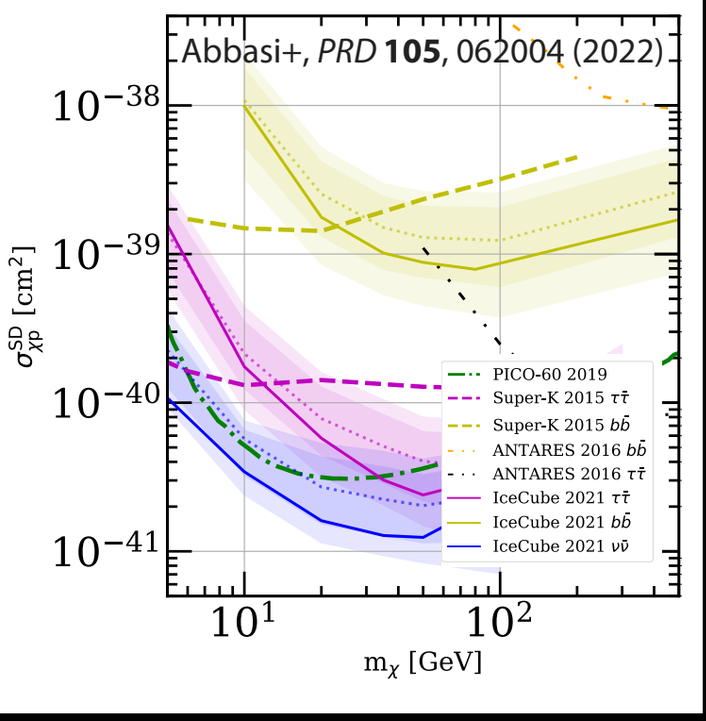




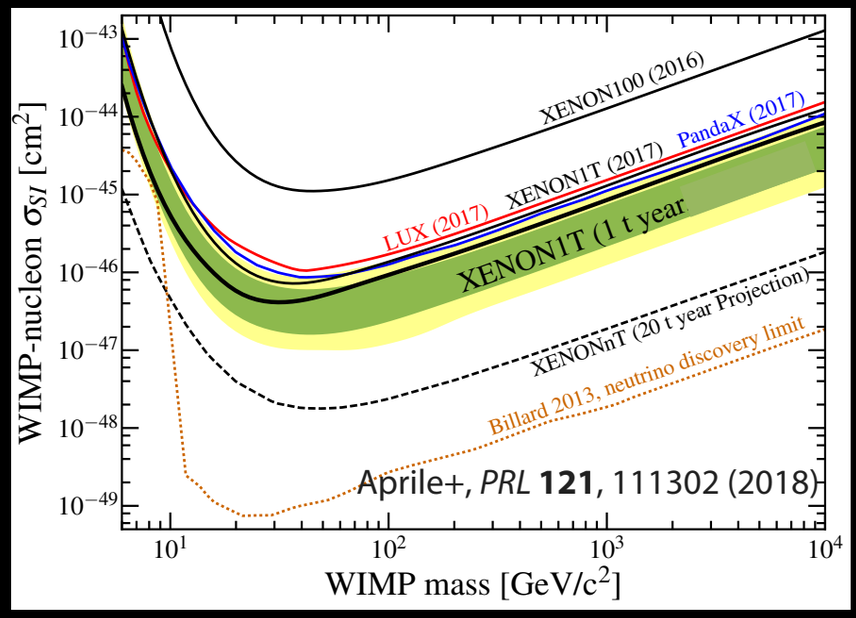
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Spin-dependent $\sigma_{\chi p}$

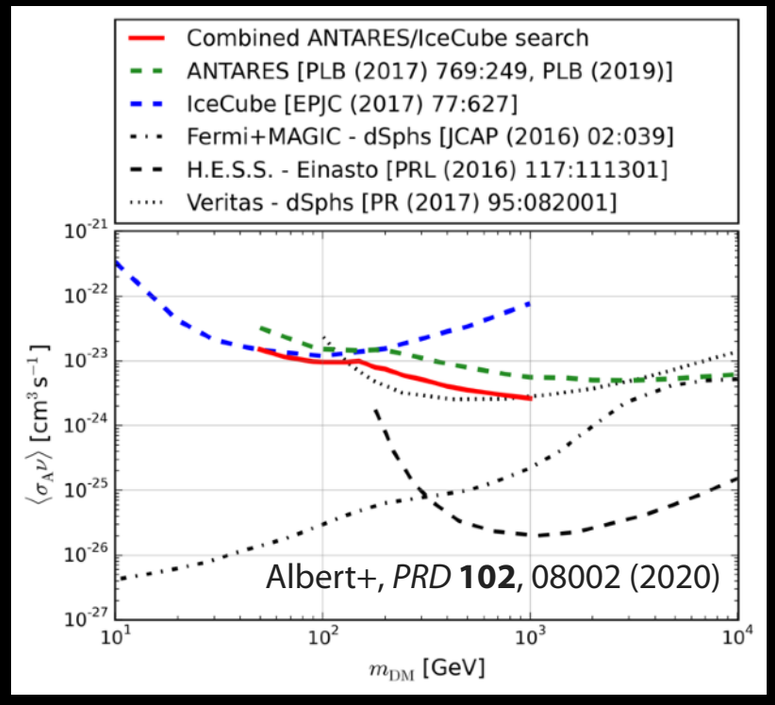


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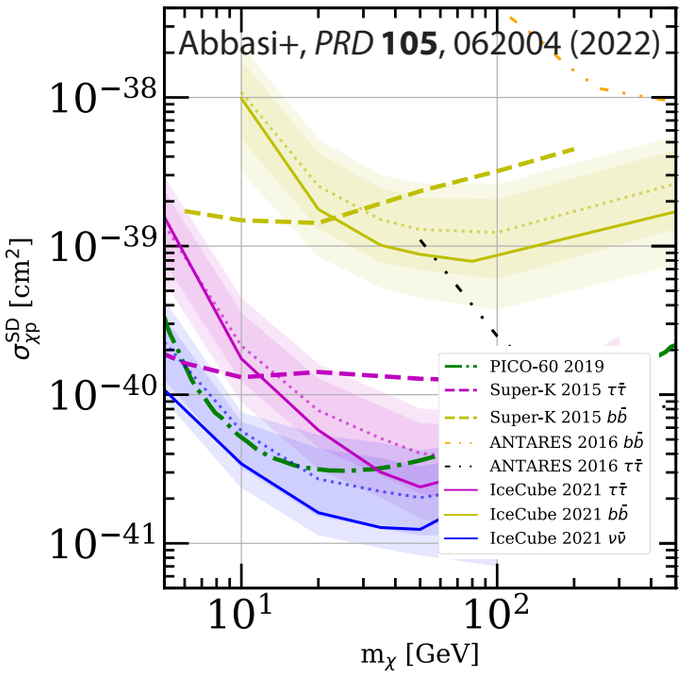
- The constraints are very stringent on various interaction cross section

The stringest limits: $\sigma^{\rm SD}_{\chi p} \sim 10^{-41}\,{\rm cm}^2$ $\sigma^{\rm SI}_{\chi n} \sim 10^{-46}\,{\rm cm}^2$ $\langle\sigma v\rangle \sim 10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}$

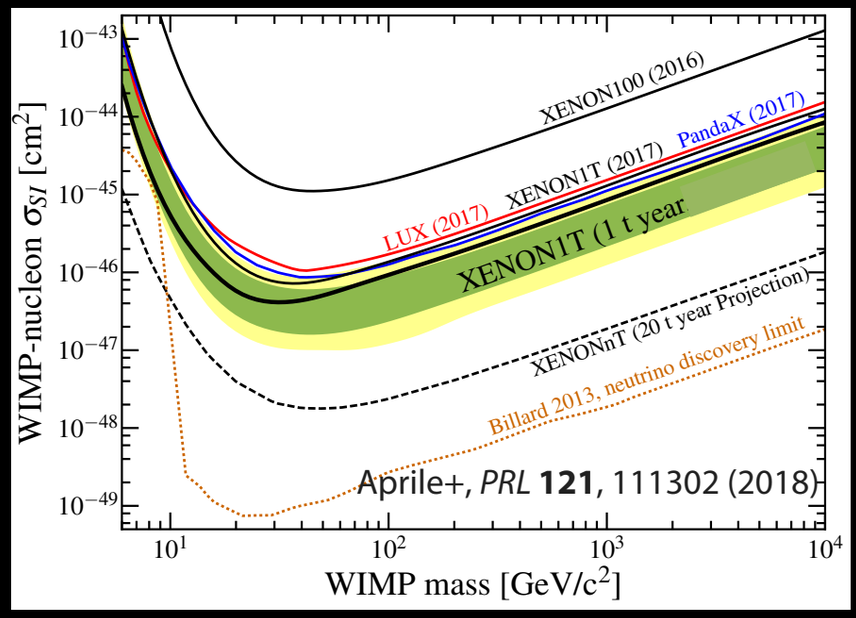
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Spin-dependent $\sigma_{\chi p}$

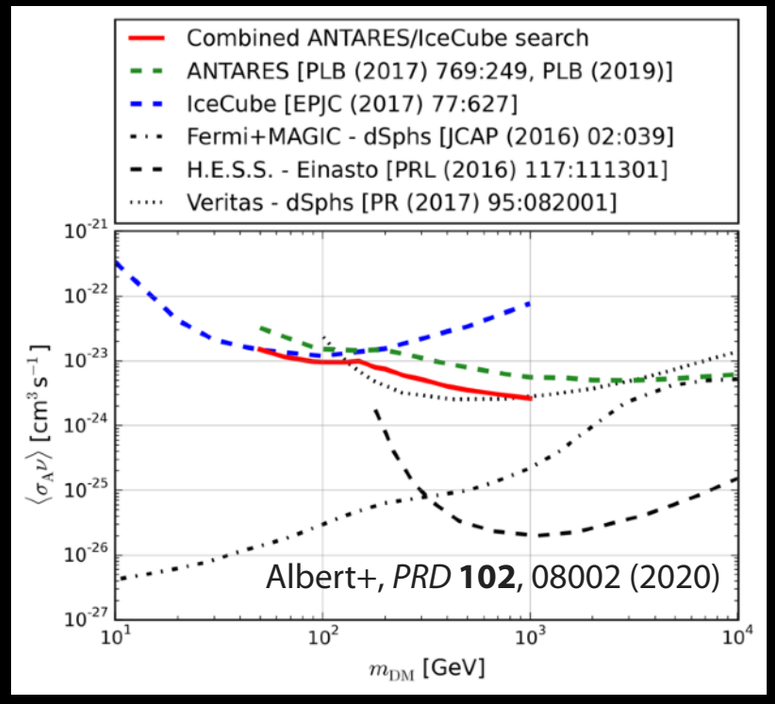


Spin-independent $\sigma_{\chi n}$



XENON1T constraints on ChEFT and inelastic DM see 2210.07591

Annihilation cross section $\langle\sigma v\rangle$





- The constraints are very stringent on various interaction cross section

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- The constraints are in general independent of any particle physics model

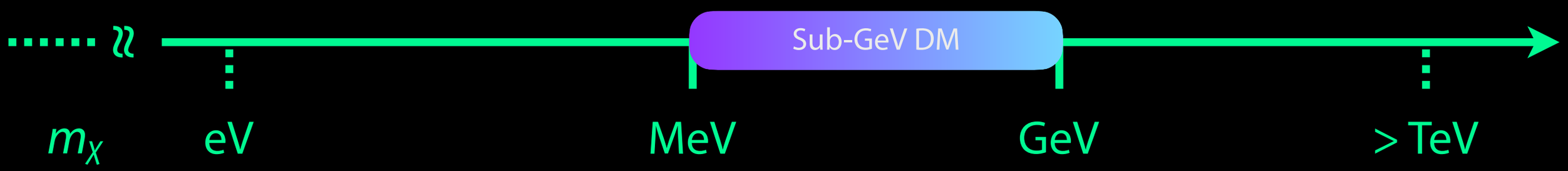
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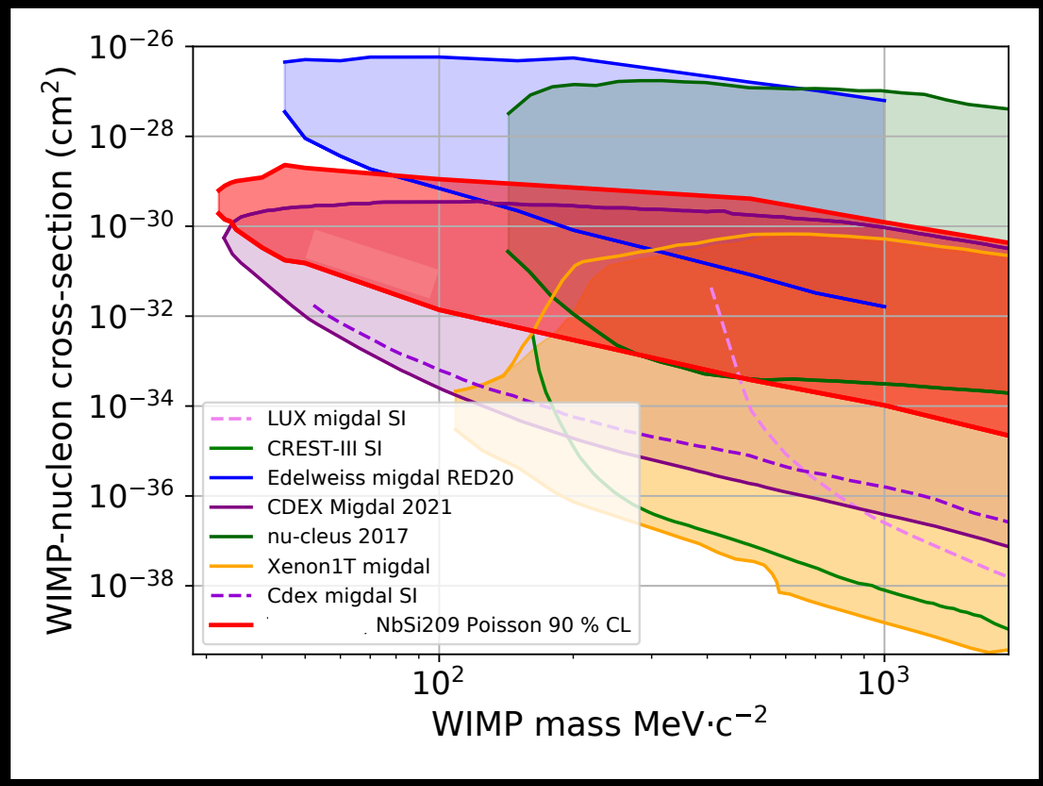
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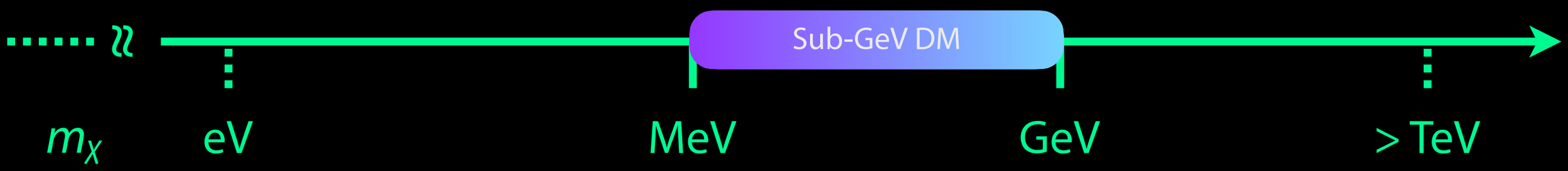


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Lattaud (EDELWEISS), 2211.04176

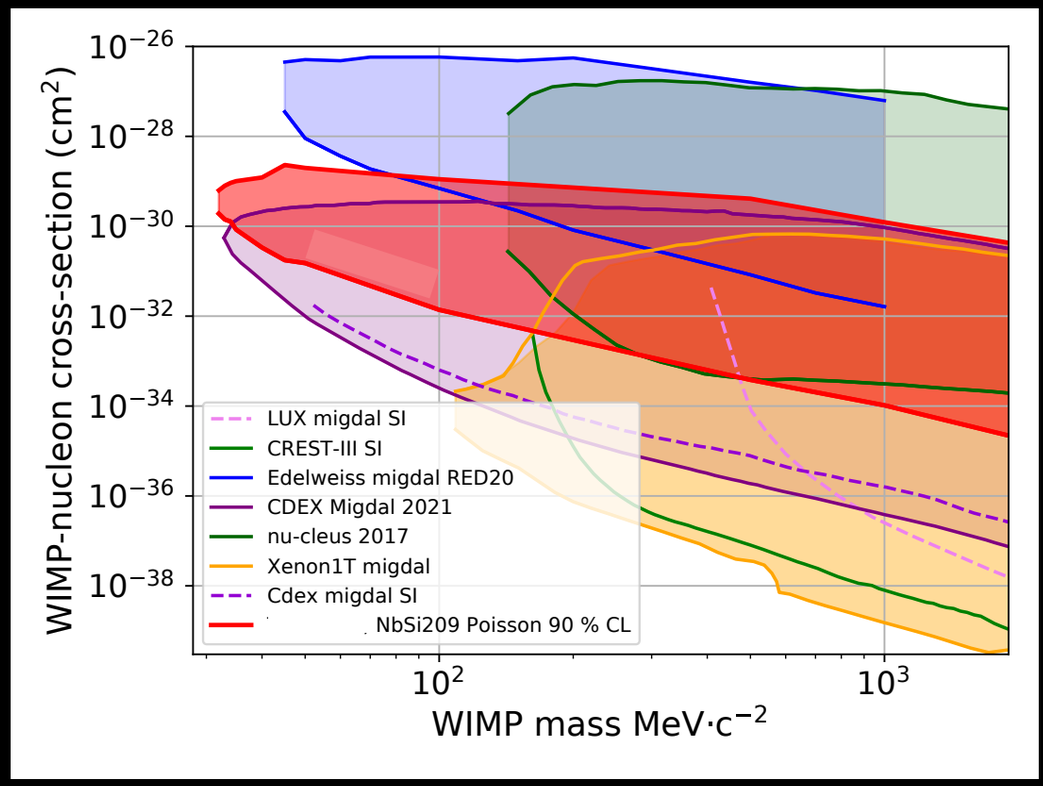


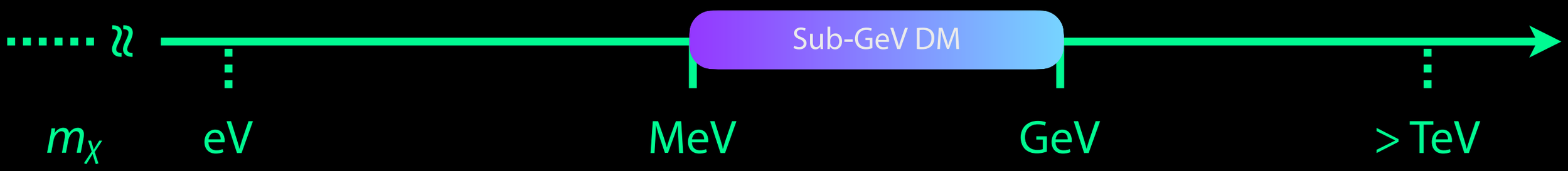


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Lattaud (EDELWEISS), 2211.04176

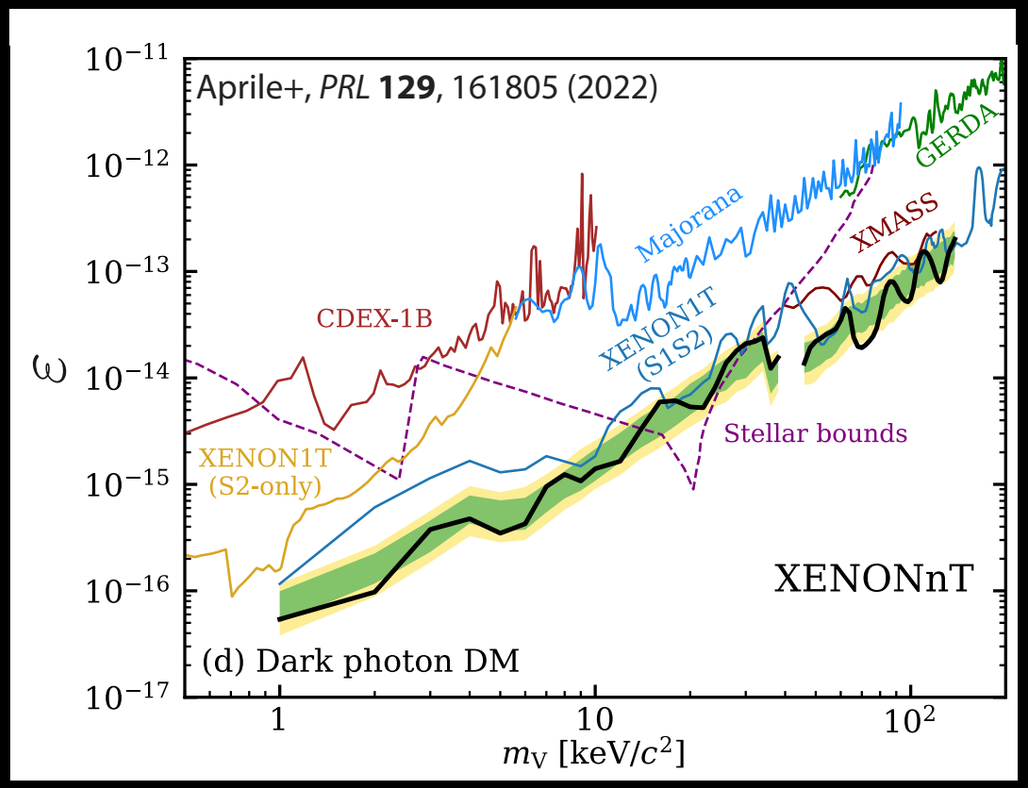




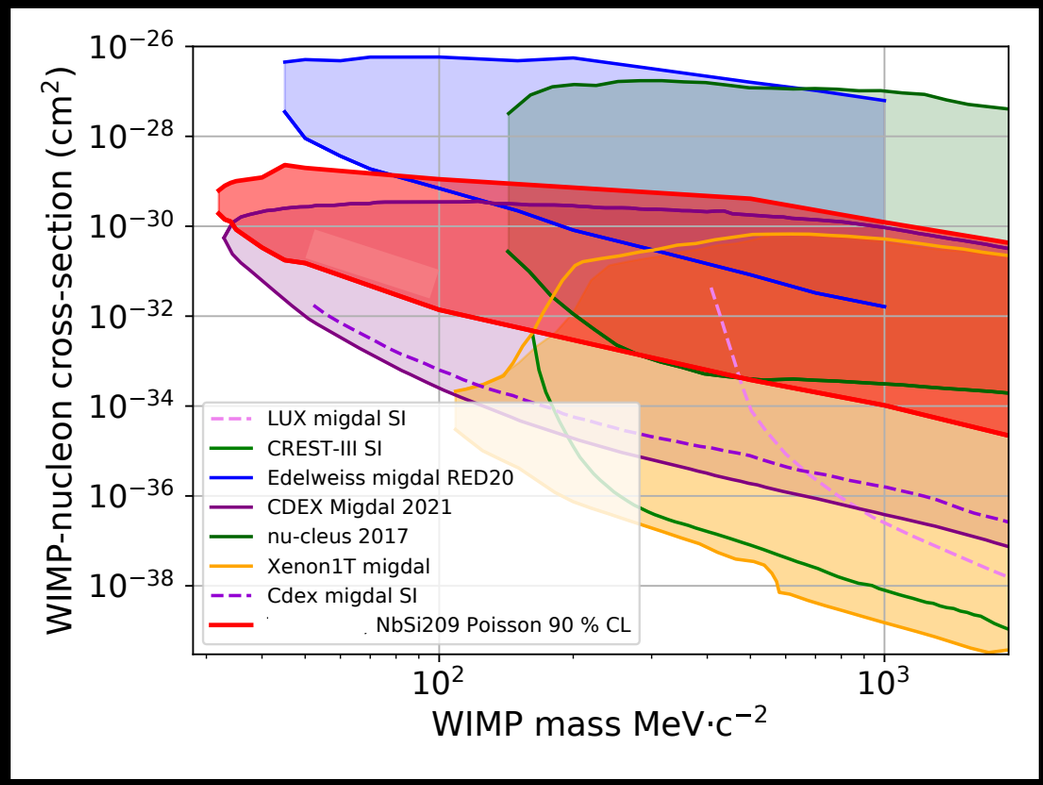
- The constraints decreases as m_χ goes lighter: $\mathcal{O}(10^{-38} - 10^{-26})\,\mathrm{cm}^2$

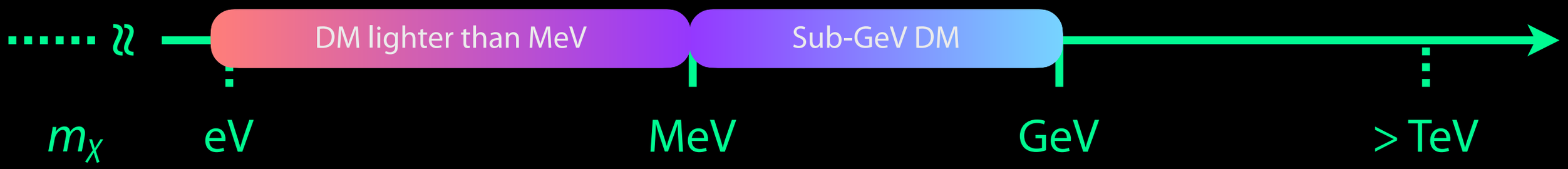
Current constraints

See: Jungman+, *PP* **267**, 195 (1996)
Bertone+, *PP* **405**,279 (2005)
Battaglieri+, 1707,04591
Knapen+, *PRD* **96**, 115021 (2017)
Lin (TASI2018), 1904.07915 (2019)
Essig+, 2203,08297
Billard+, *RPP* **85**, 056201 (2022)
Cooley+, 2209.07426
… *for comprehensive reviews*



Lattaud (EDELWEISS), 2211.04176

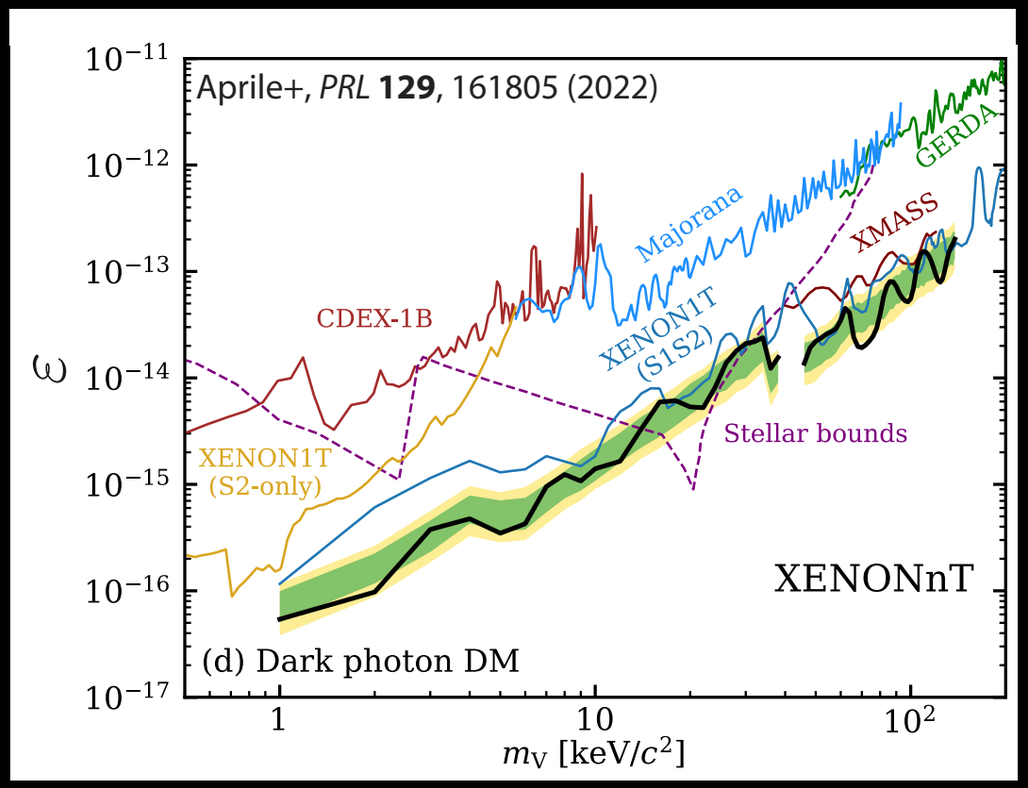




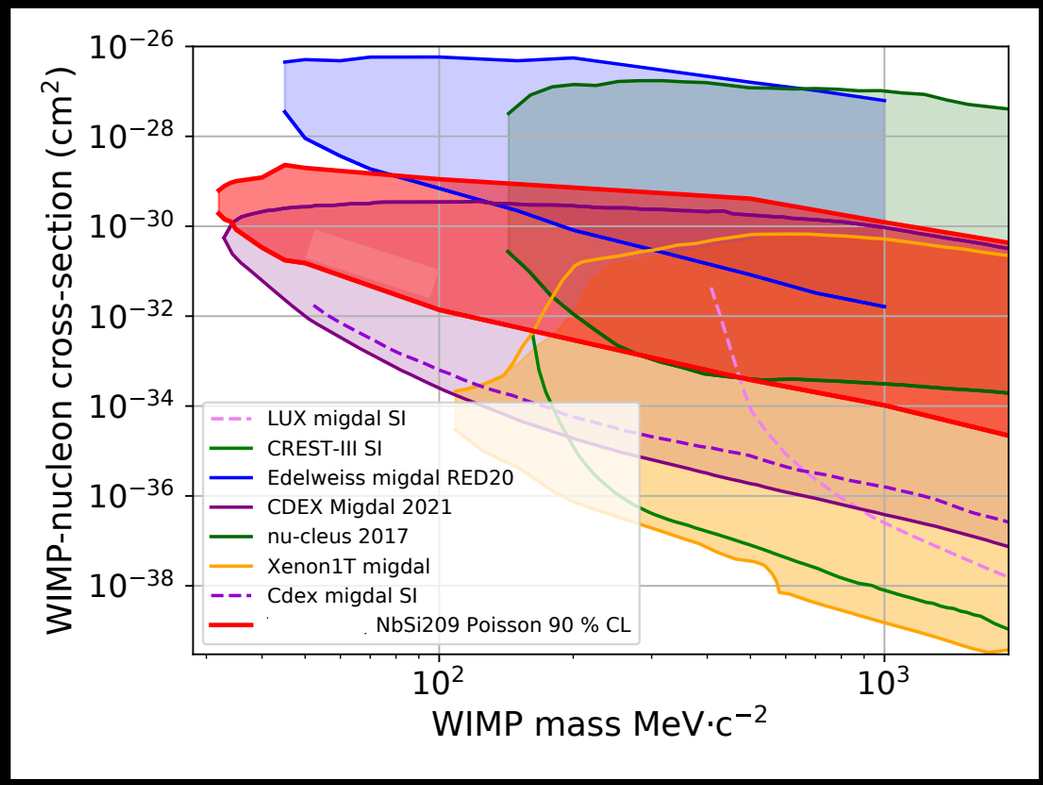
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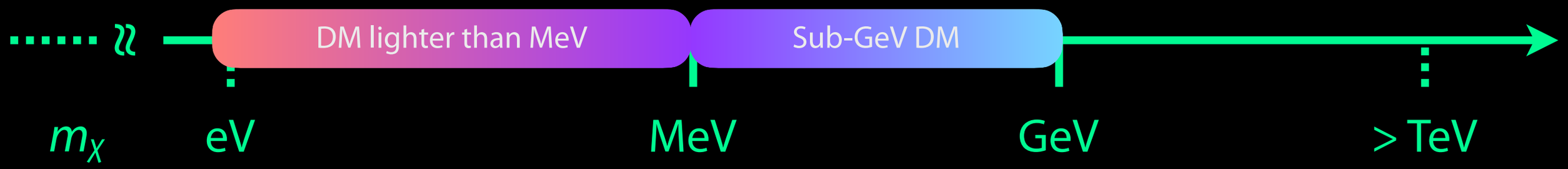
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Lattaud (EDELWEISS), 2211.04176





- The constraints decreases as m_χ goes lighter: $\mathcal{O}(10^{-38} - 10^{-26})\,\mathrm{cm}^2$
- Left panel assumes DM is massive dark photon V_μ and can kinetically mix with SM $U(1)$ field A_μ

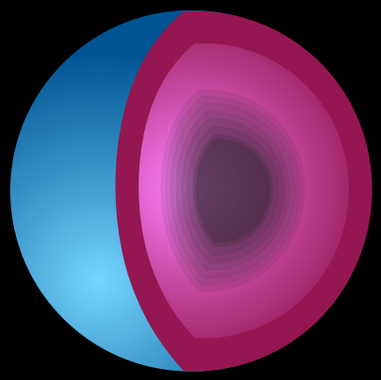
$$\mathcal{L} \supset -\frac{\varepsilon}{2} F_{\mu\nu} V^{\mu\nu} + \frac{m_V^2}{2} V_\mu V^\mu$$

Holdom, *PLB* **166**, 196 (1986)
An+, *PLB* **747**, 331 (2014)

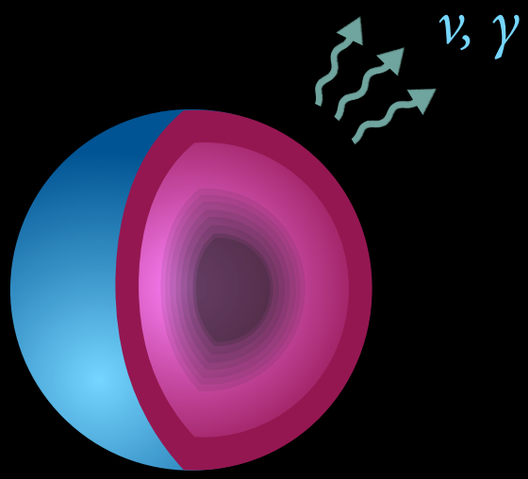


How compact star probes DM?

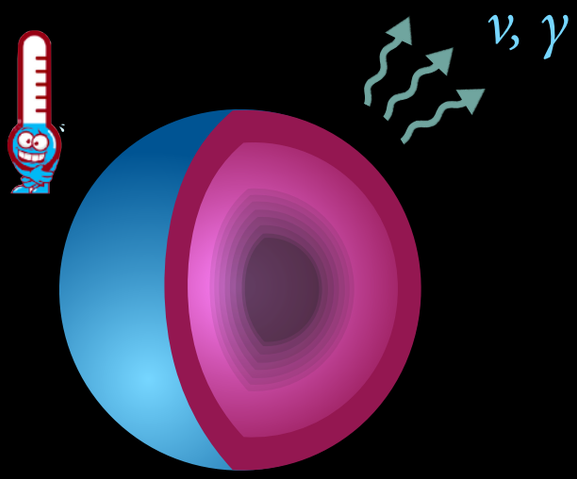
Probing DM with NS

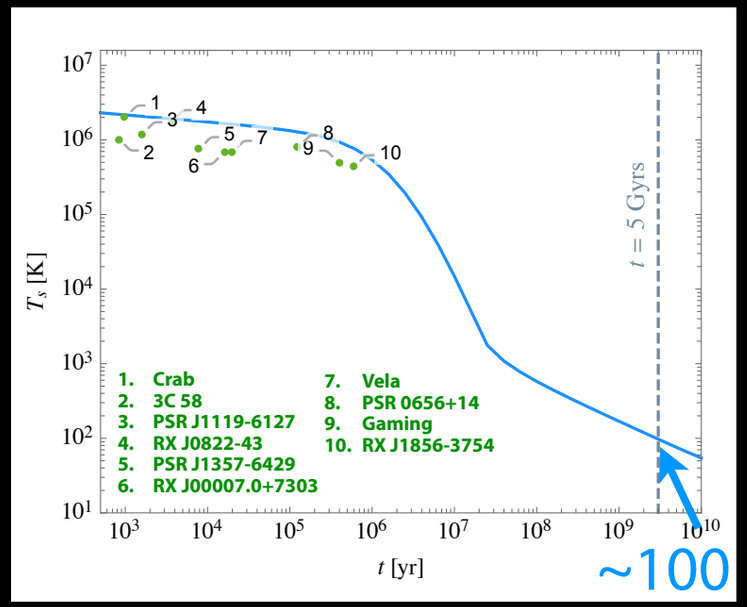


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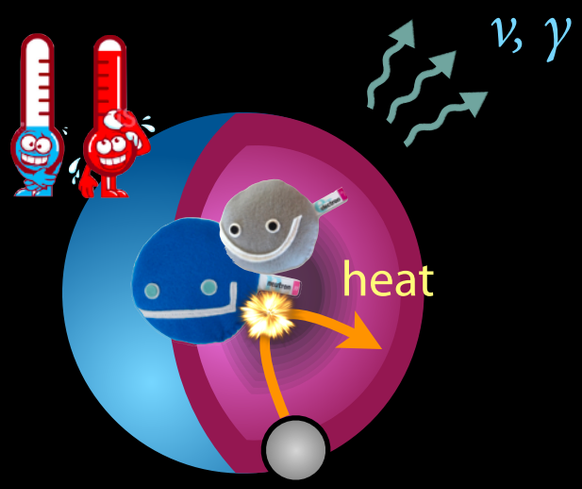
Probing DM with NS



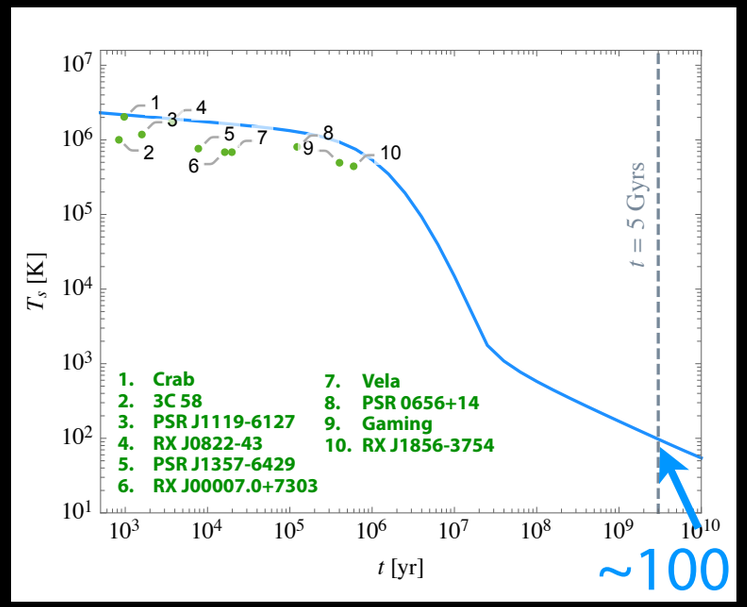


Probing DM with NS

Baryakhtar+, *PRL* **119**, 131801 (2017)



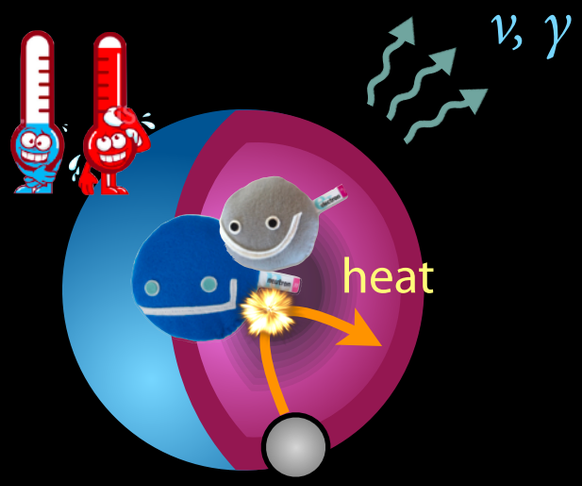
kinetic heating



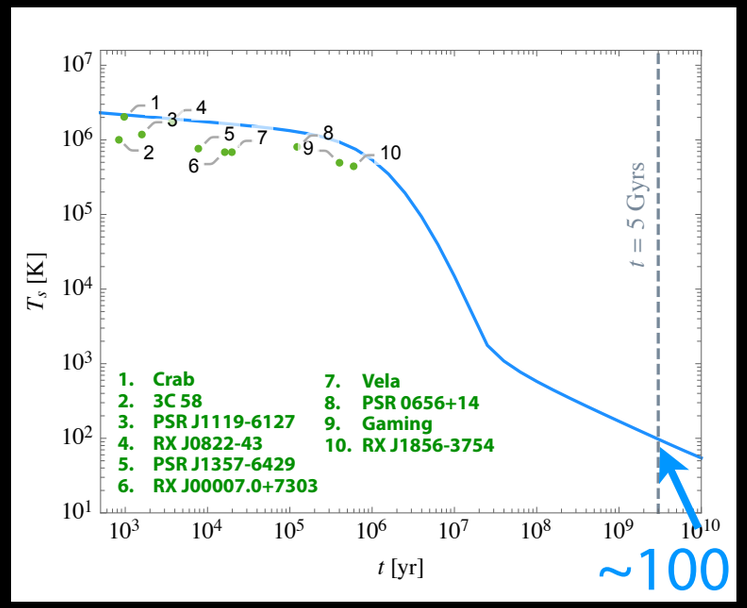
~100 K

Probing DM with NS: The DM heating effect

Baryakhtar+, *PRL* **119**, 131801 (2017)



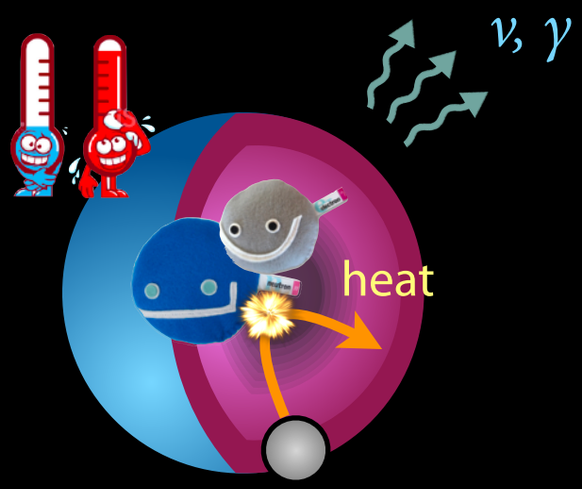
kinetic heating



~100 K

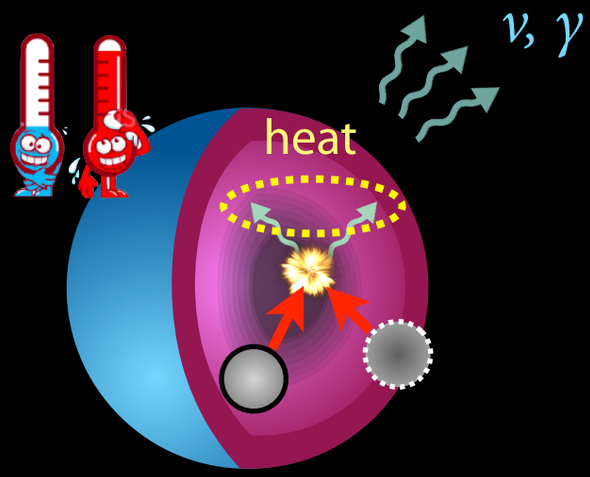
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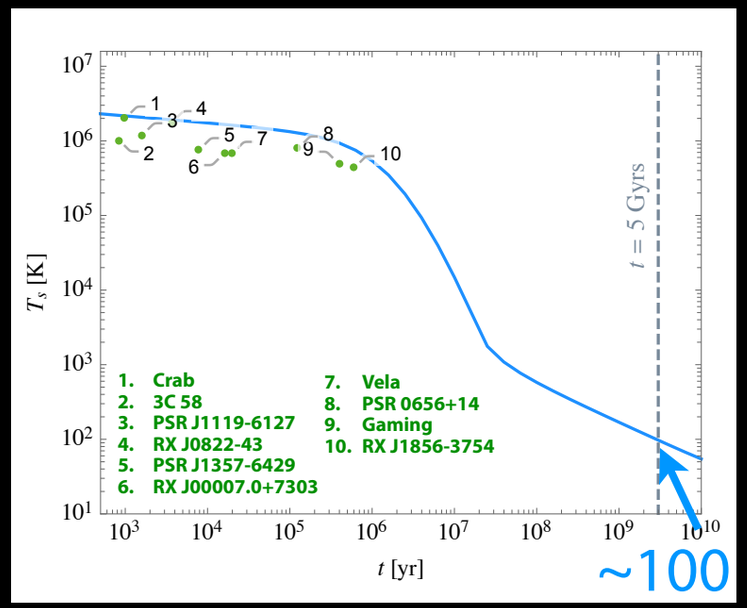


kinetic heating

Kouvaris, *PRD* **77**, 023006 (2008)



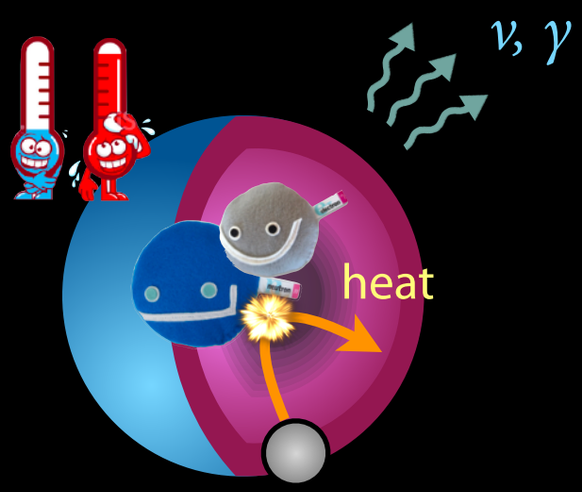
annihilation heating



~100 K

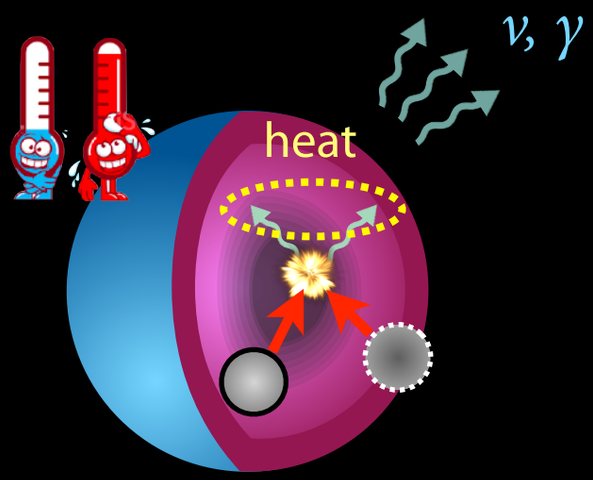
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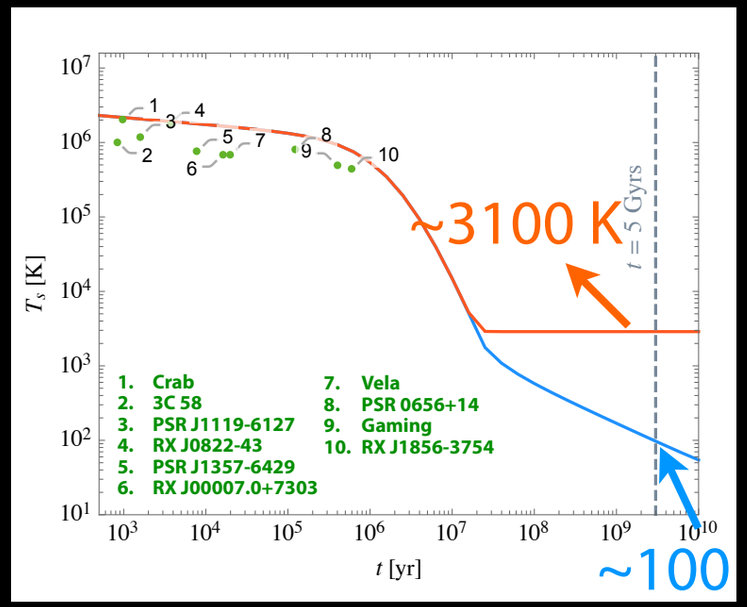


kinetic heating

Kouvaris, *PRD* **77**, 023006 (2008)



annihilation heating



- Energy could be transferred from both effects to NS and affect the cooling process

$$\frac{dT_{\rm int}}{dt} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_\chi}{c_V}$$

$\epsilon_{\nu,\gamma}$: neutrino and photon coolings

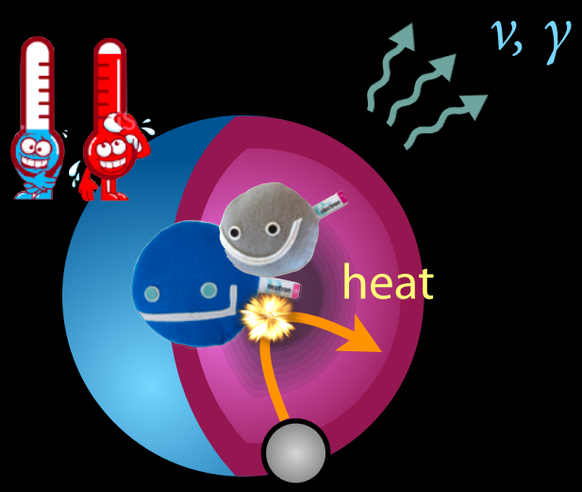
ϵ_χ : DM heating

Page+, *ApJS* **155,** 623 (2004)

Kouvaris, *PRD* **77**, 023006 (2008)

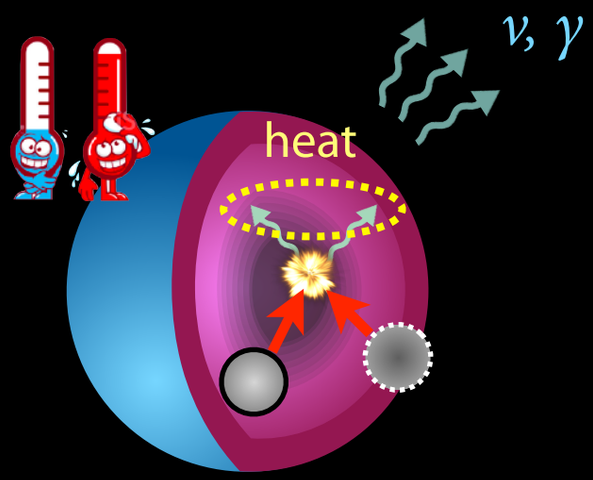
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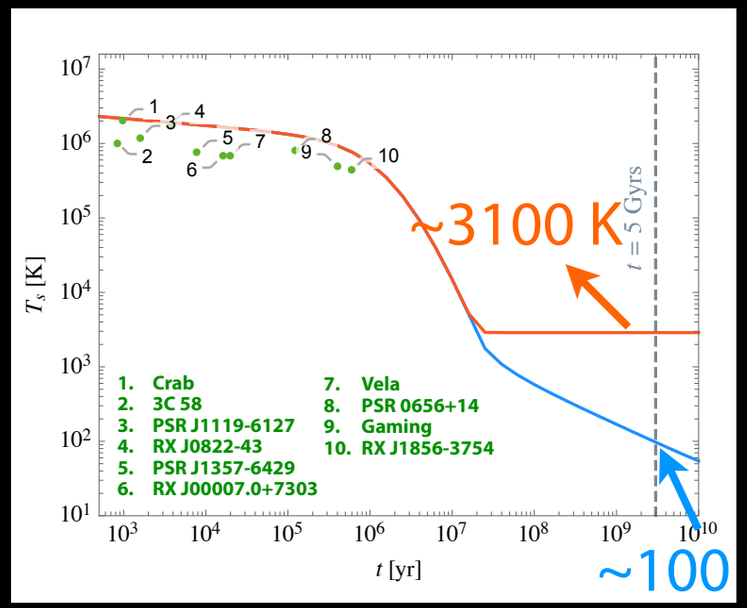


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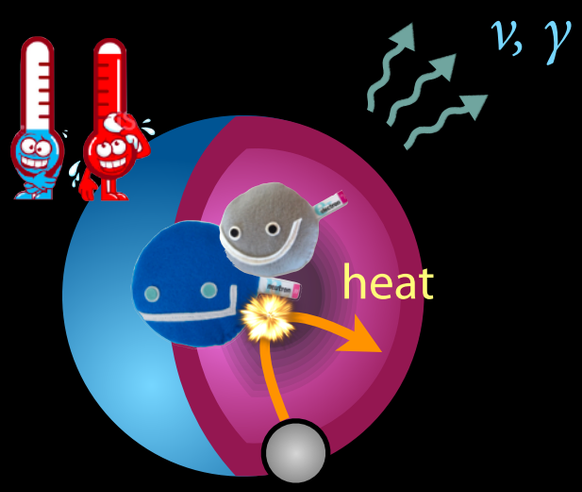
- The temperature of Gyr-old NS could be lifted up to $\mathcal{O}(3000\,{\rm K})$

$$T_{\rm kin} \approx 1750 f^{1/4}\,{\rm K} \qquad \text{or} \qquad T_{\rm kin+ann} \approx 3100 f^{1/4}\,{\rm K}$$

Raj+, *PRD* **97**, 043006 (2018)
Lin+, *JHEP* **08**, 069 (2018)

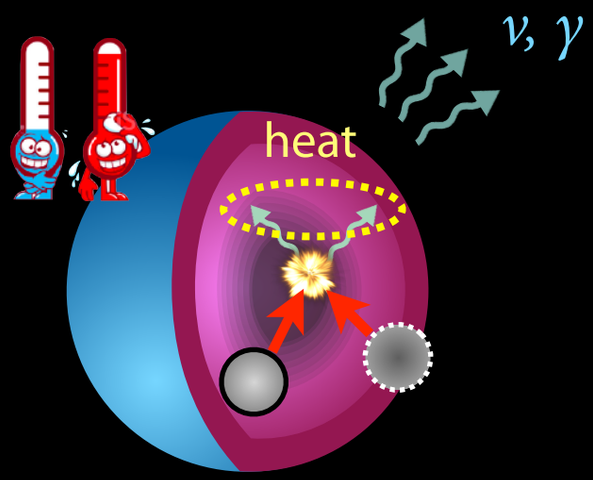
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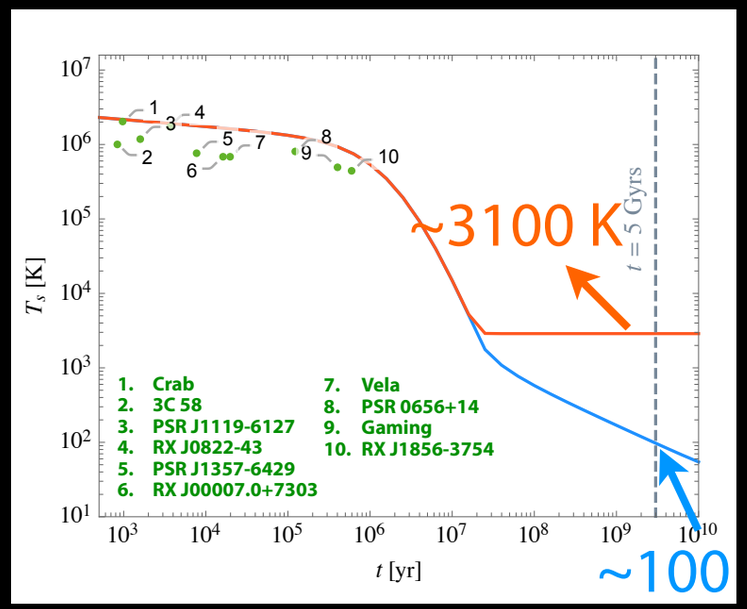


kinetic heating

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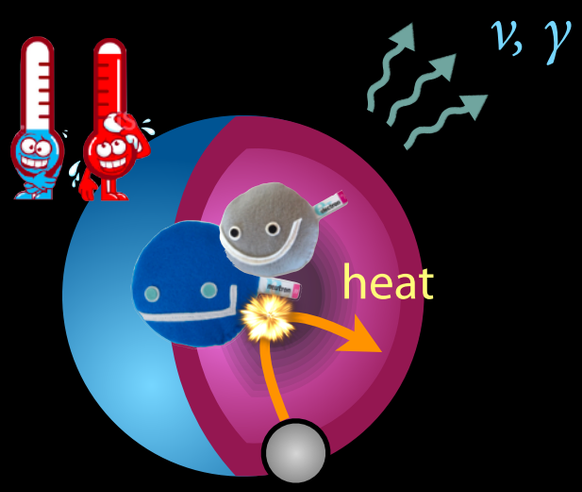
Raj+, *PRD* **97**, 043006 (2018)
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- All model-dependent and kinematic terms are encoded in $0 \leqq f \leqq 1$, eg. cross sections, branching ratios, Pauli blocking effect…etc

Bell+, *JCAP* **09**, 028 (2020)
Bell+, *JCAP* **03**, 086 (2021)

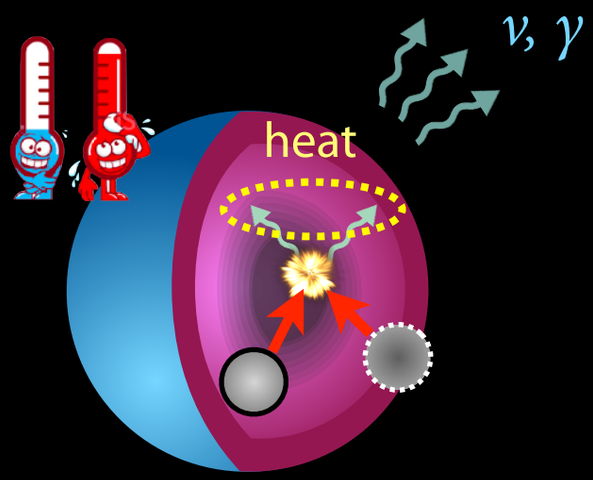
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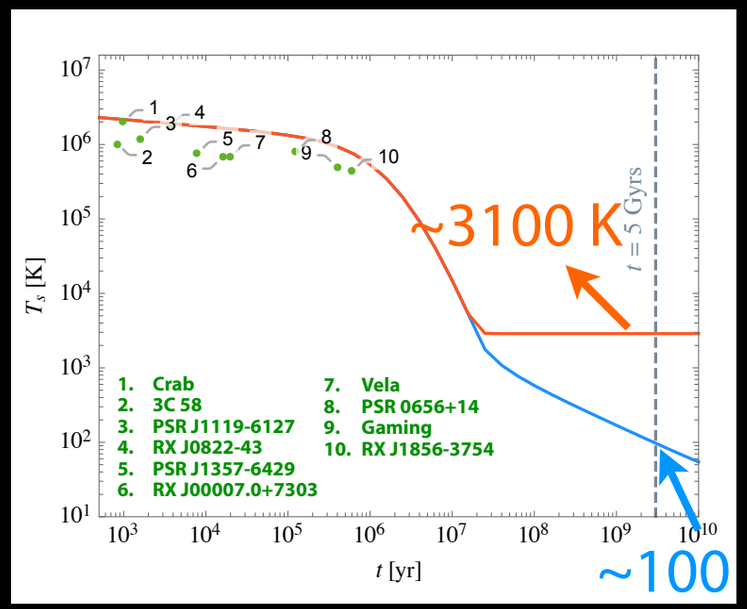


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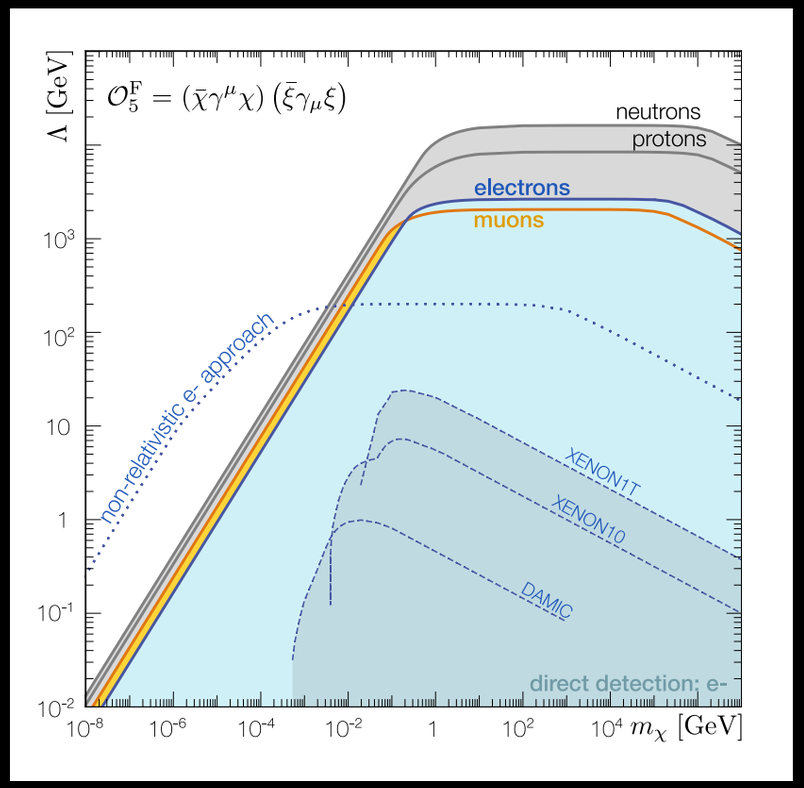
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Bell+, *JCAP* **03**, 086 (2021)
- The temperature difference between the prediction of the standard cooling mechanism and observation can be used to constrain DM and BSM physics Lin+, *PRD* **104**, 063021 (2021)

Resulting temperature and sensitivity

Resulting temperature and sensitivity

Joglekar+, *PRD* **102**, 123002 (2020)



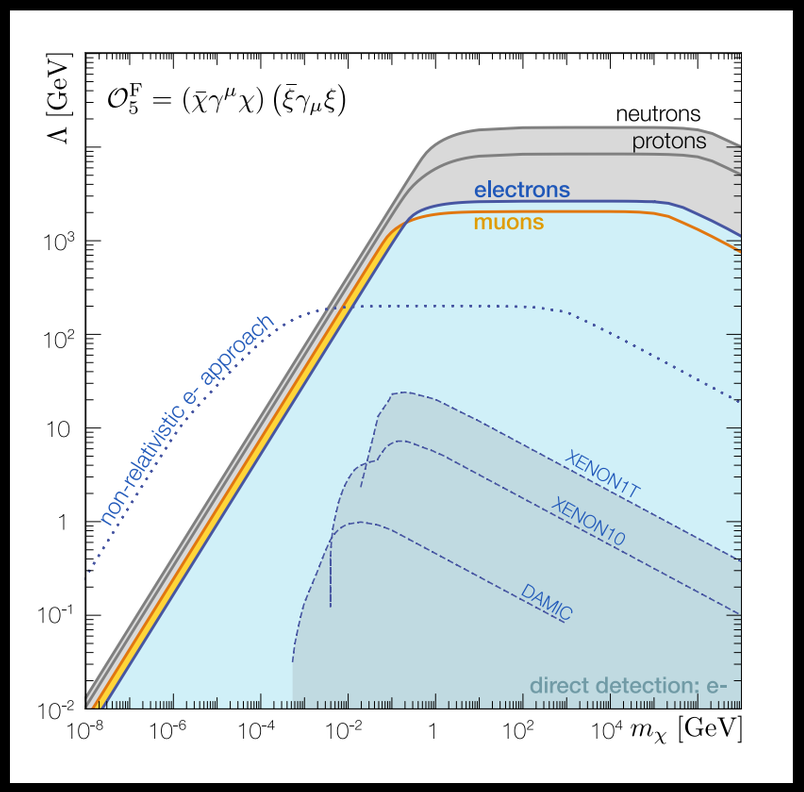
Pure kinetic heating

- NS probes the sensitivity region (left) that is much larger than the direct search for

$$T_s = 1600 f^{1/4}\,\mathrm{K} \text{ for } f = 1$$

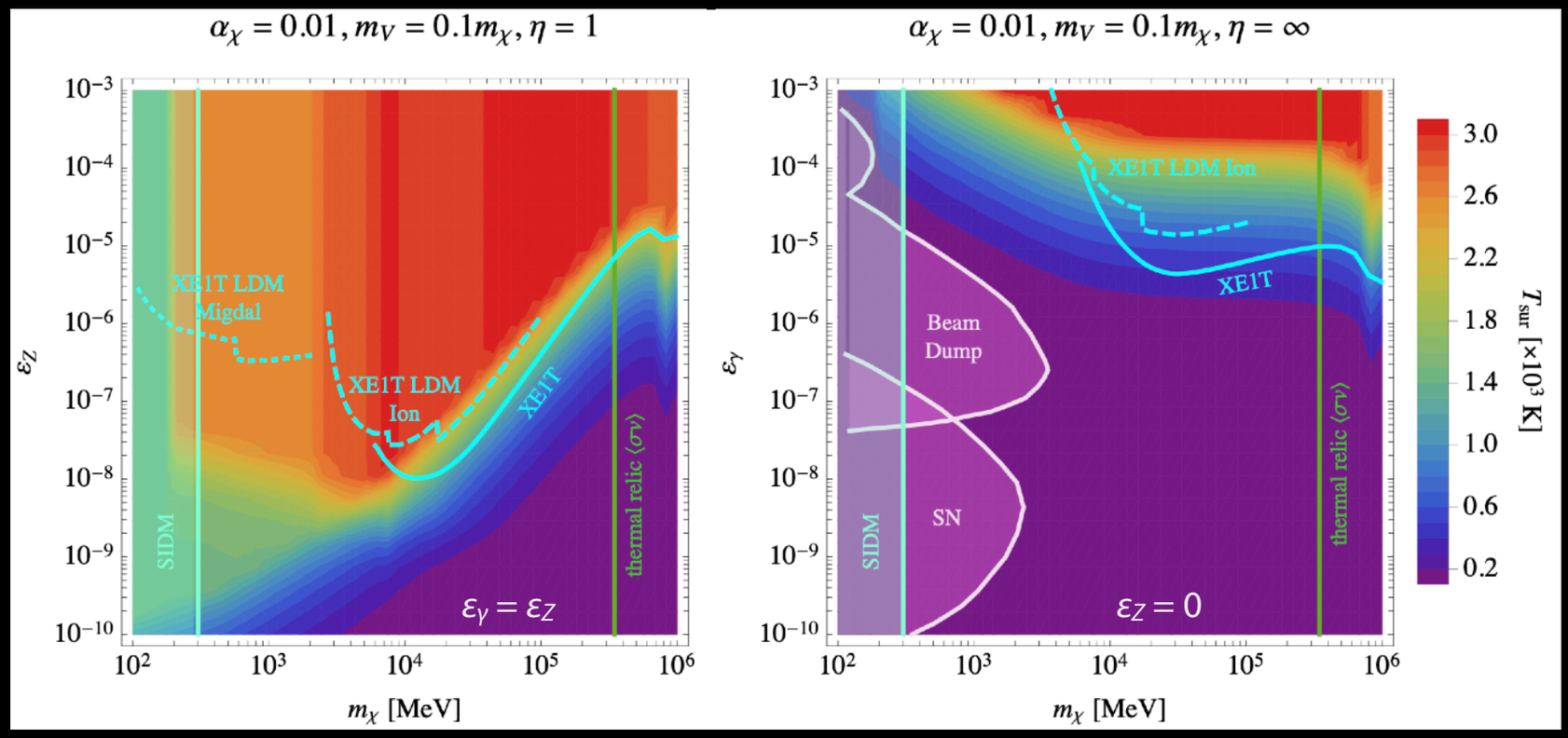
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Joglekar+, *PRD* **102**, 123002 (2020)



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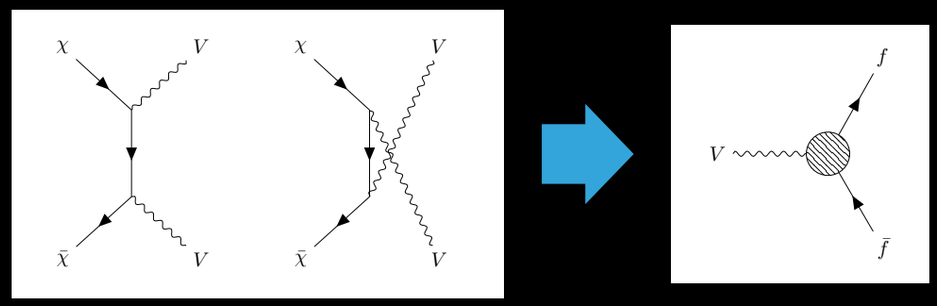
Kinetic + annihilation heating

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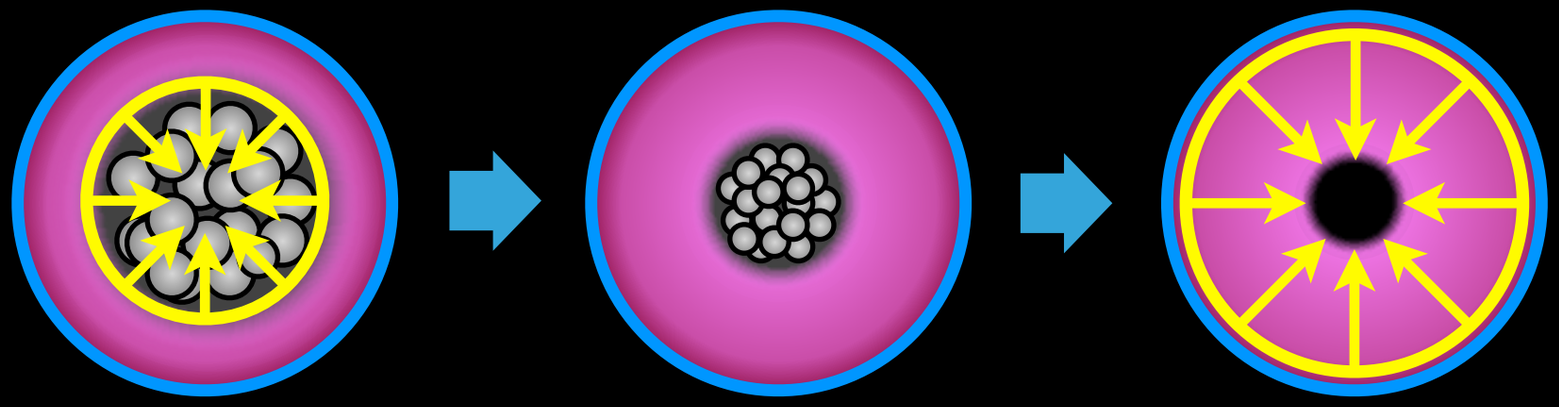
- The neutron to proton yields in NS is about 100, an ideal place for testing asymmetry couplings of DM to EM (ε_γ) & NC (ε_Z) interactions

$$\mathcal{L}_{\rm portal} = \left(\varepsilon_\gamma e J_\mu^{\rm EM} + \tilde{\varepsilon}_Z \frac{g_2}{\cos\theta_W} J_\mu^{\rm NC}\right) V^\mu$$



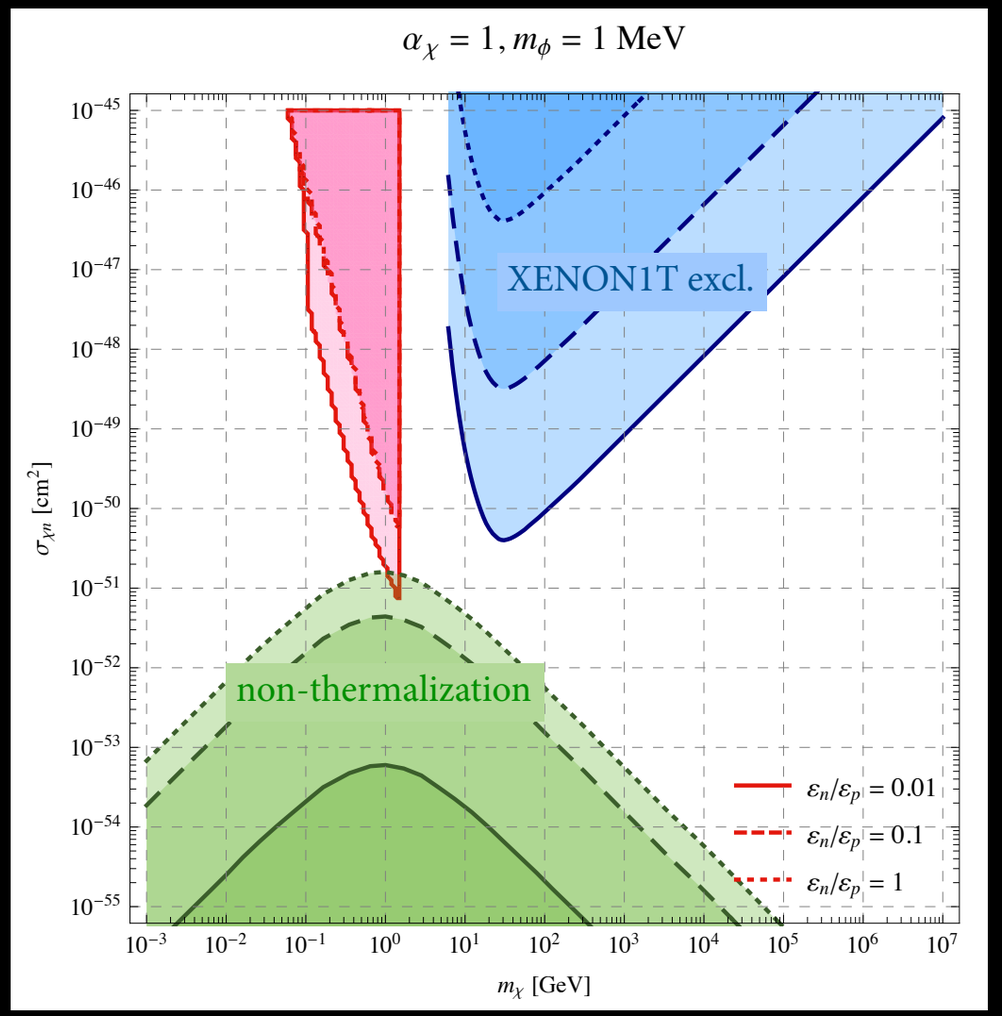
See: Petraki+, *IJMPA* **28**, 1330028 (2013)
Zurek, *PP* **537**, 91 (2014)
…for ADM reviews

Probing DM with NS: The DM collapse



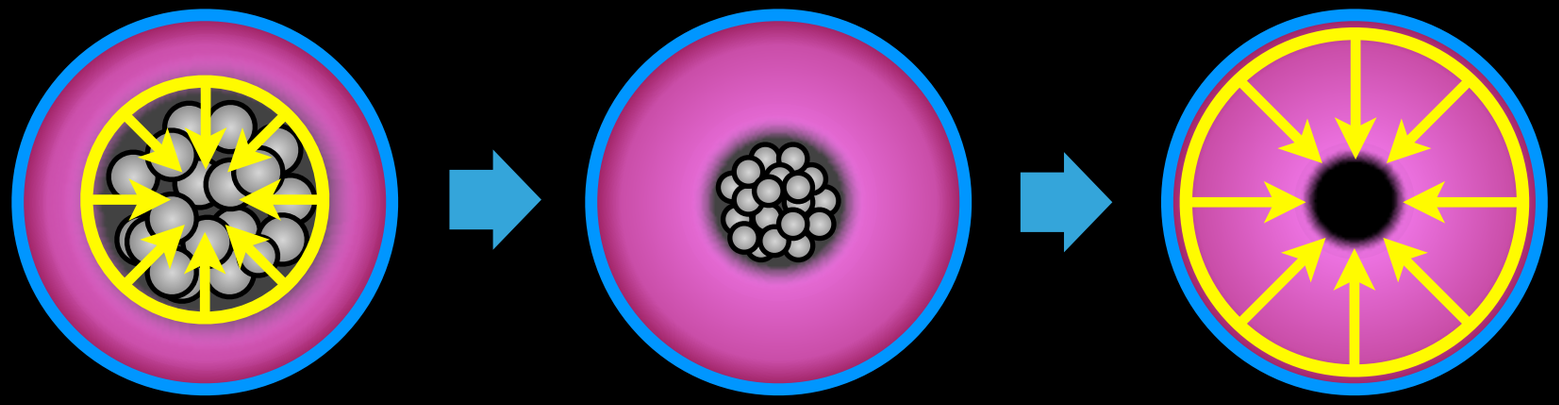
- Asymmetric DM: No annihilation to deplete the number of DM captured in the NS then trigger the gravitational instability
- Fermi degeneracy pressure could be overcame by attractive DM self-interaction ➡ Black hole (BH)
- Accretion dominates or evaporation dominates?

Bramante+, *PRD* **89**, 015010 (2014)
Lin+, *JCAP* **08**, 022 (2020)



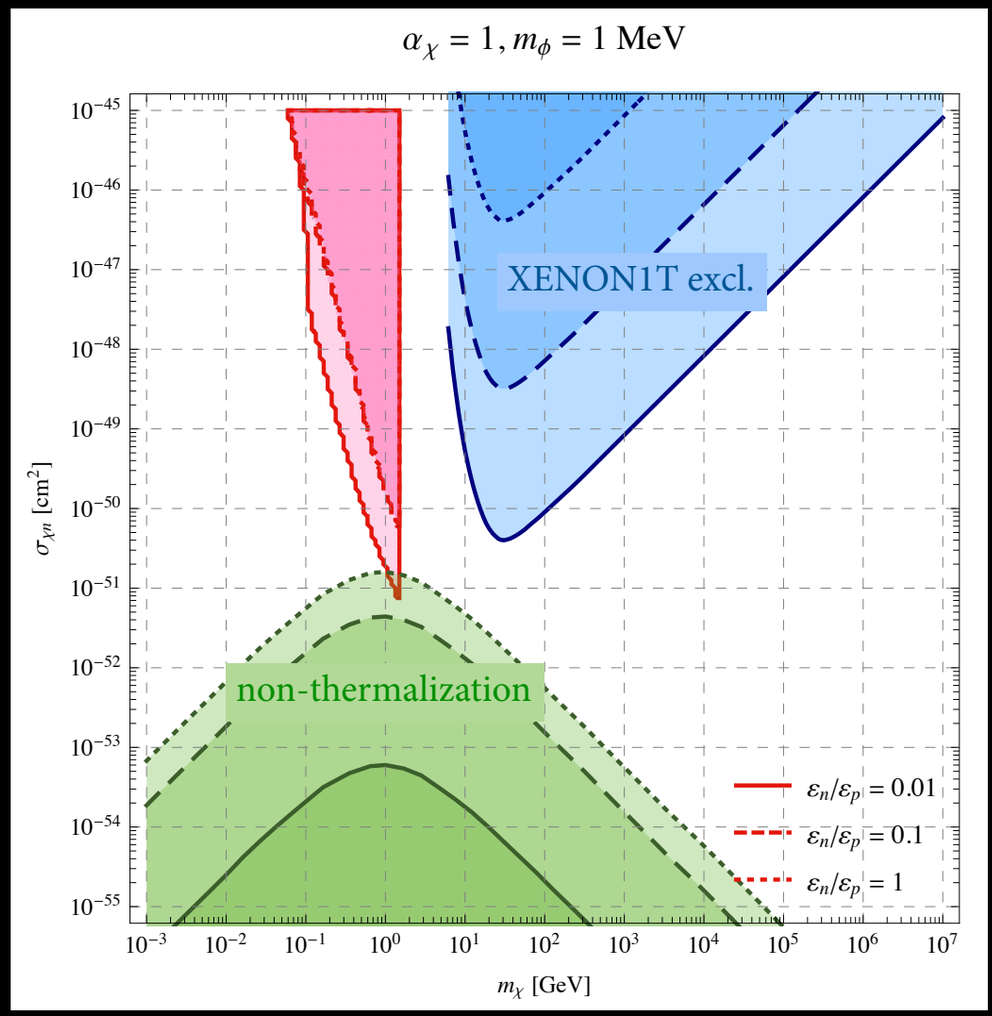
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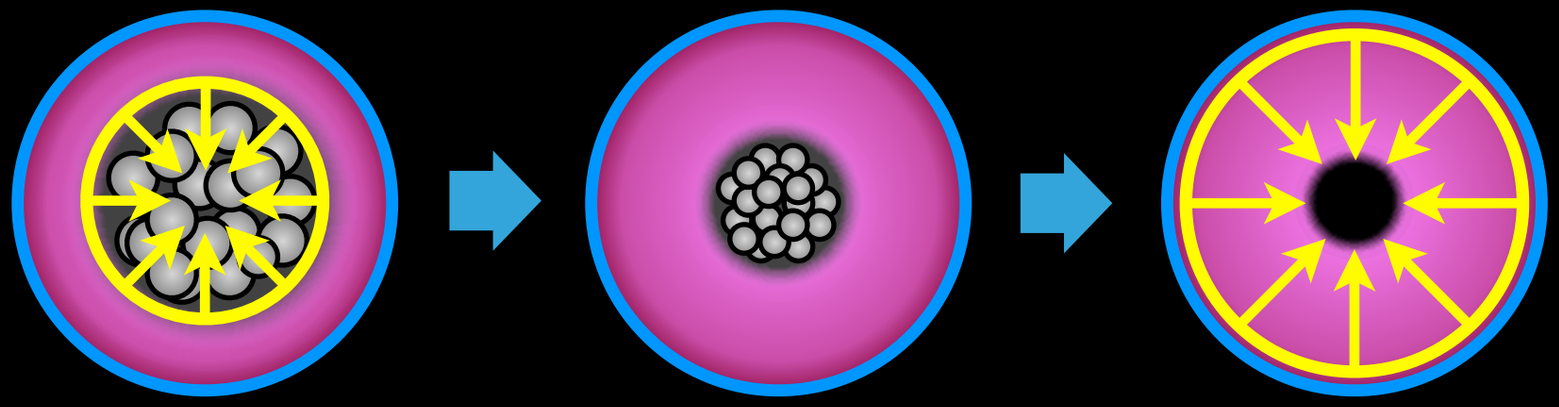
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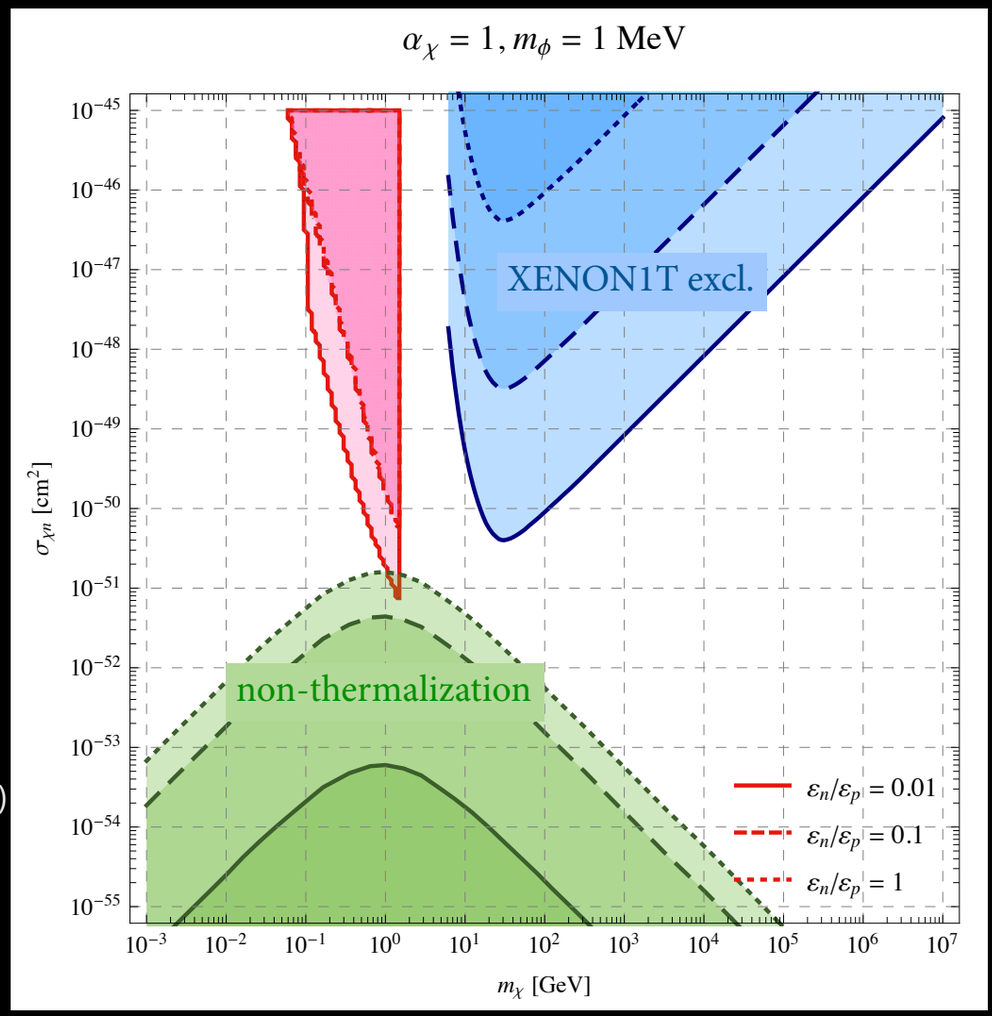
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- Does the DM effective mass in the high density region change due to DM self-interaction
  Gresham+, *PRD* **96**, 096012 (2017)
  Gresham+, *PRD* **99**, 083008 (2019)
- Bosonic DM ➡ Bose-Einstein condensation
  Bell+, *PRD* **87**, 123507 (2013)
  Guver+, *JCAP* **05**, 013 (2014)
  Kouvaris+, *PRD* **92**, 063526 (2015)
- Is such endoparasitic BH in NS observable?
  East+, *PRD* **100**, 124026 (2019)

Bramante+, *PRD* **89**, 015010 (2014)
Lin+, *JCAP* **08**, 022 (2020)



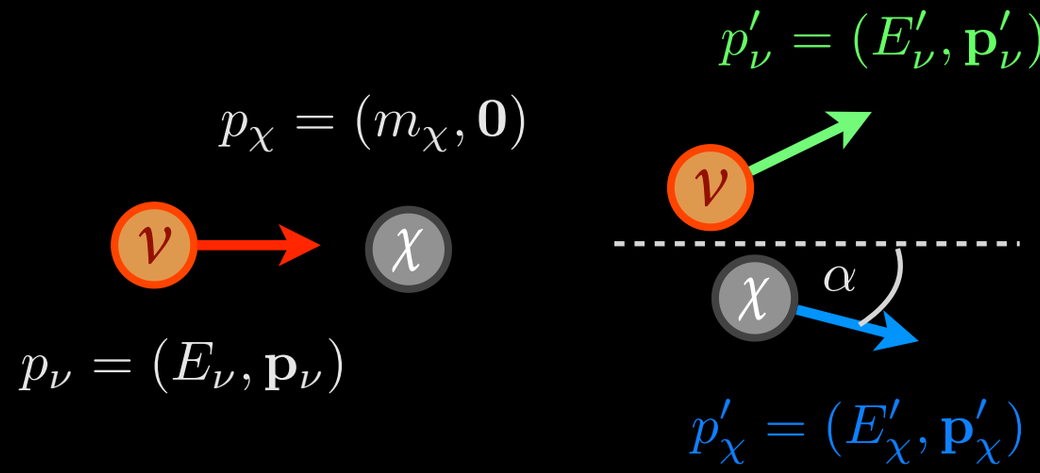


Lighter than MeV: The SNν

The idea behind: Boosted DM (BDM)

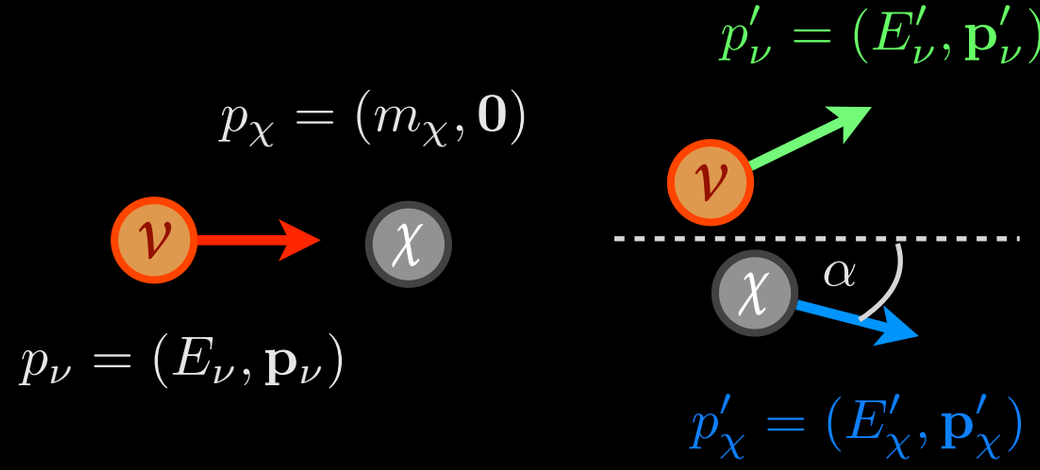
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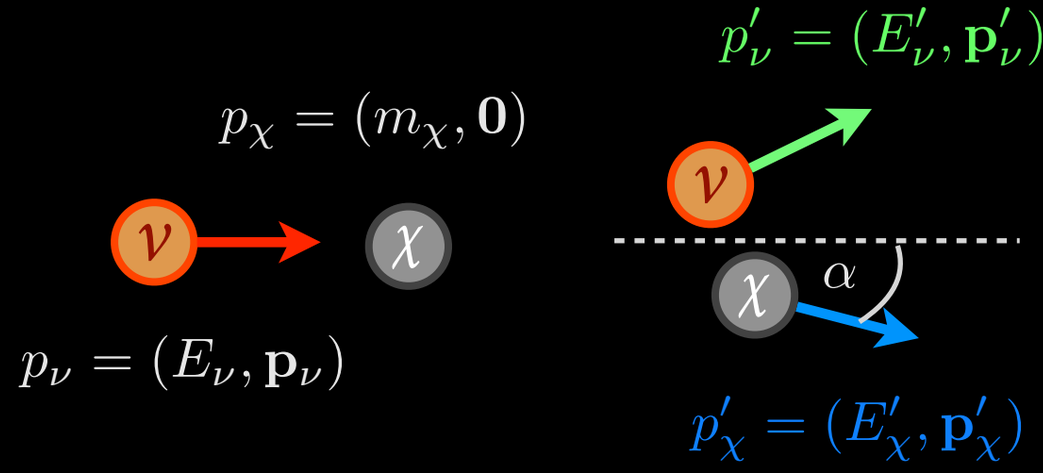
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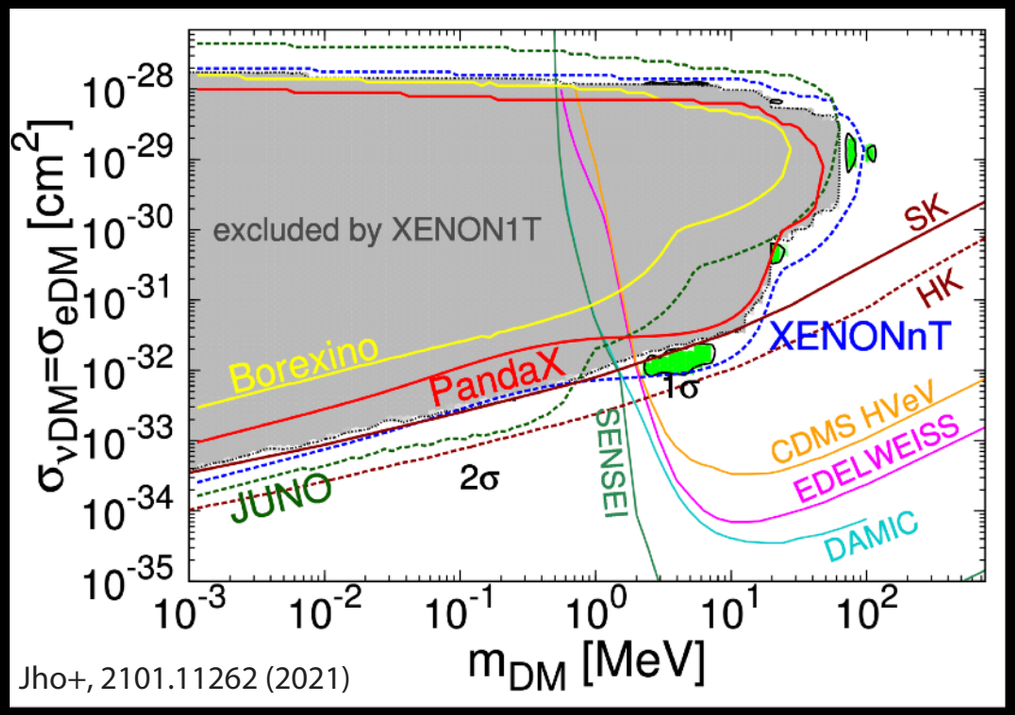
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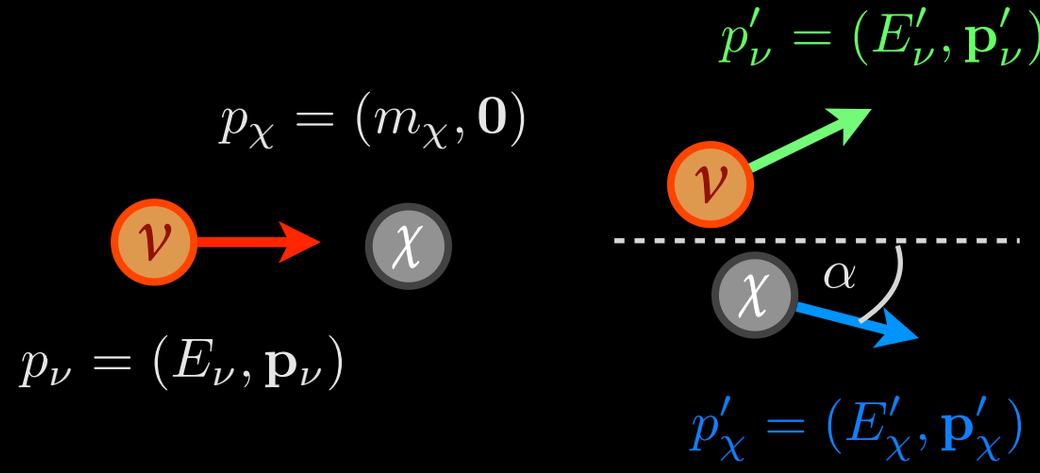
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Cosmic-neutrino BDM

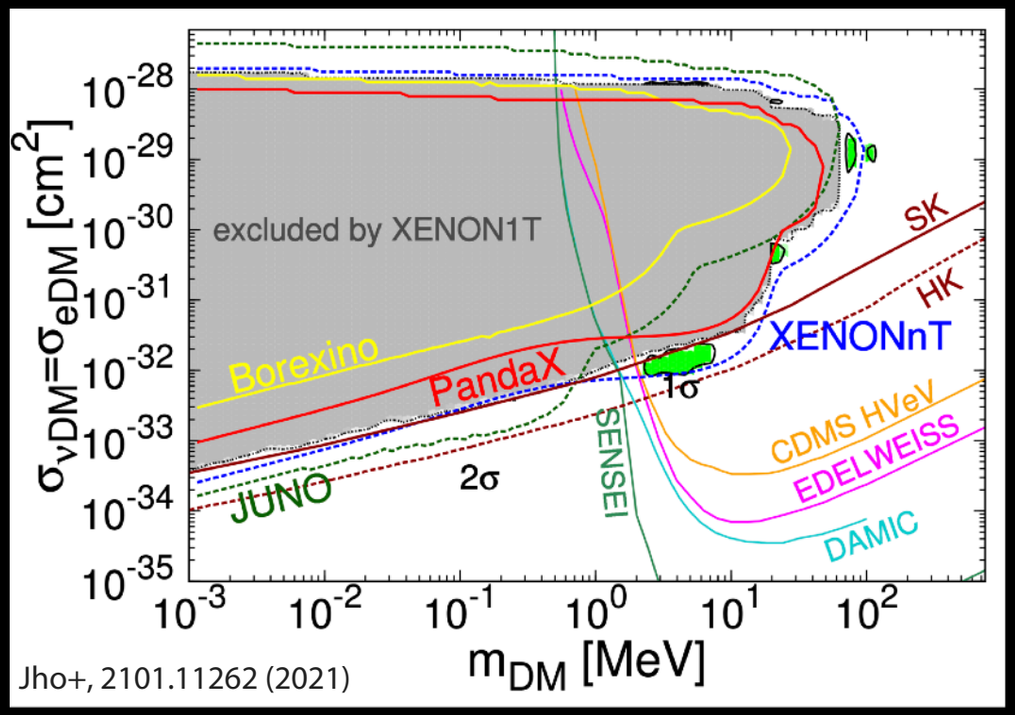
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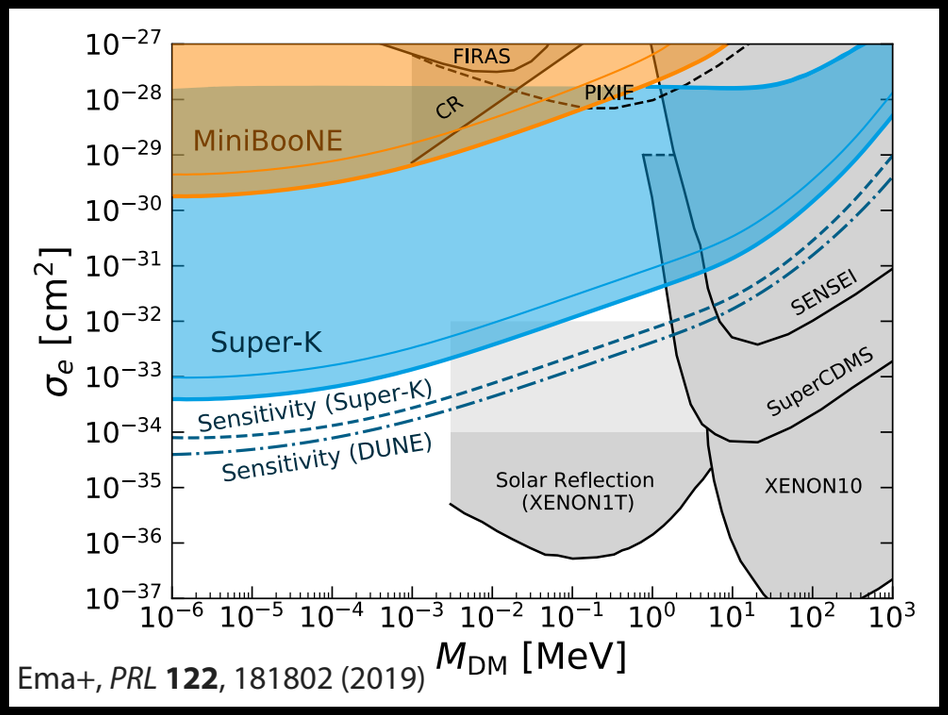


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Cosmic-neutrino BDM

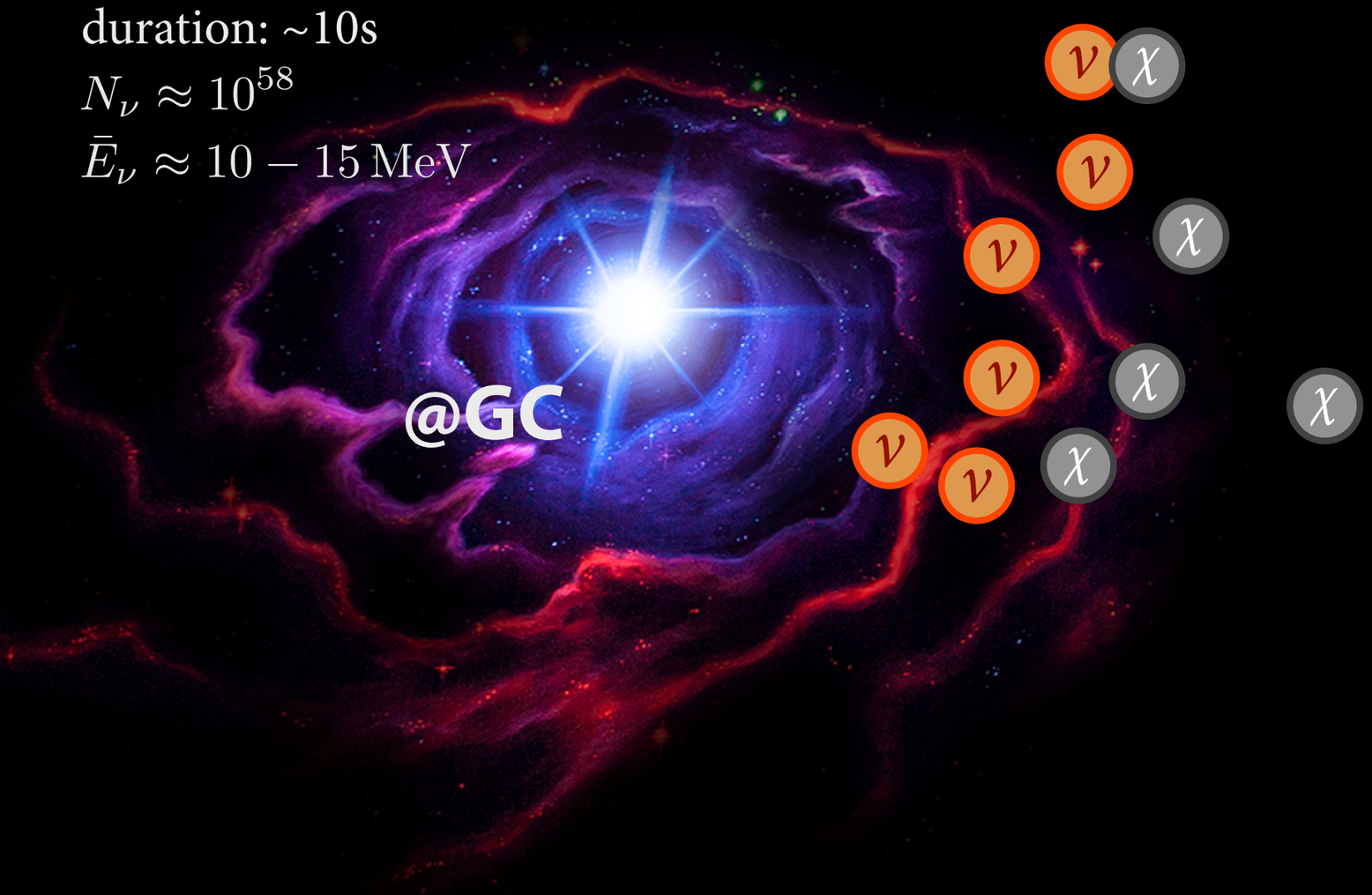


Cosmic-ray BDM

duration: ~10s

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

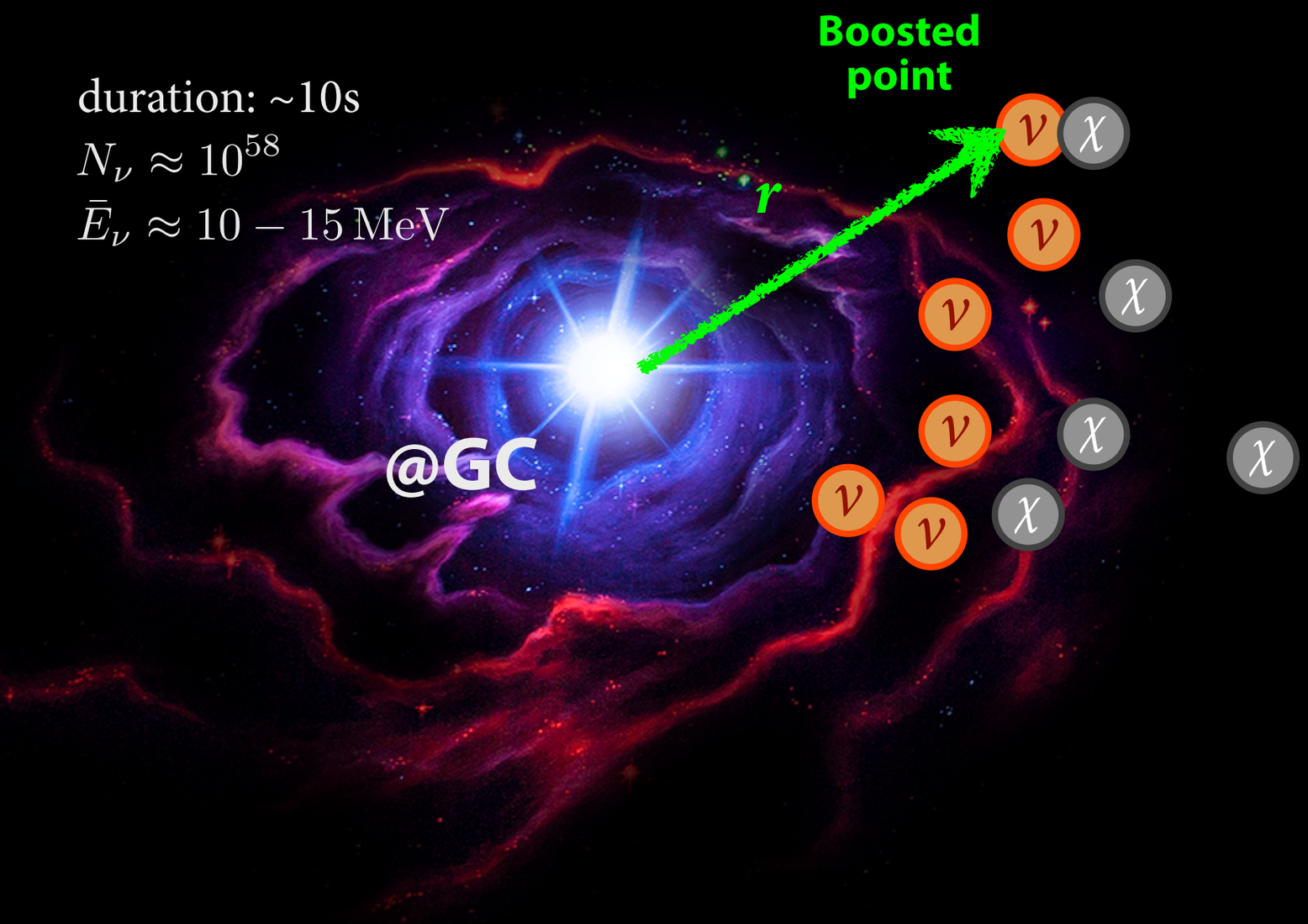
$\bar{E}_\nu \approx 10 - 15\,\mathrm{MeV}$



duration: ~10s

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Boosted point

r

α

ν_χ

ℓ

@GC

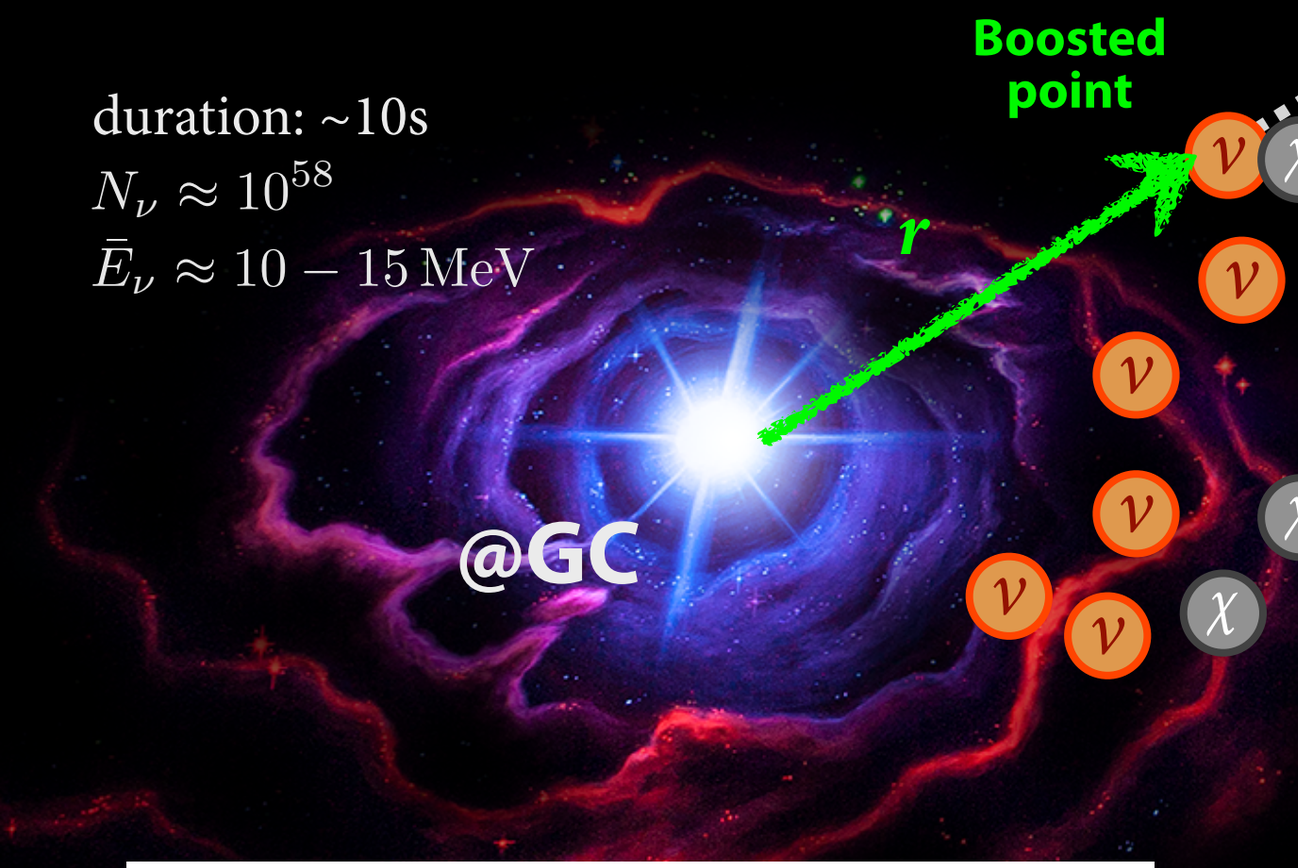
Super-K

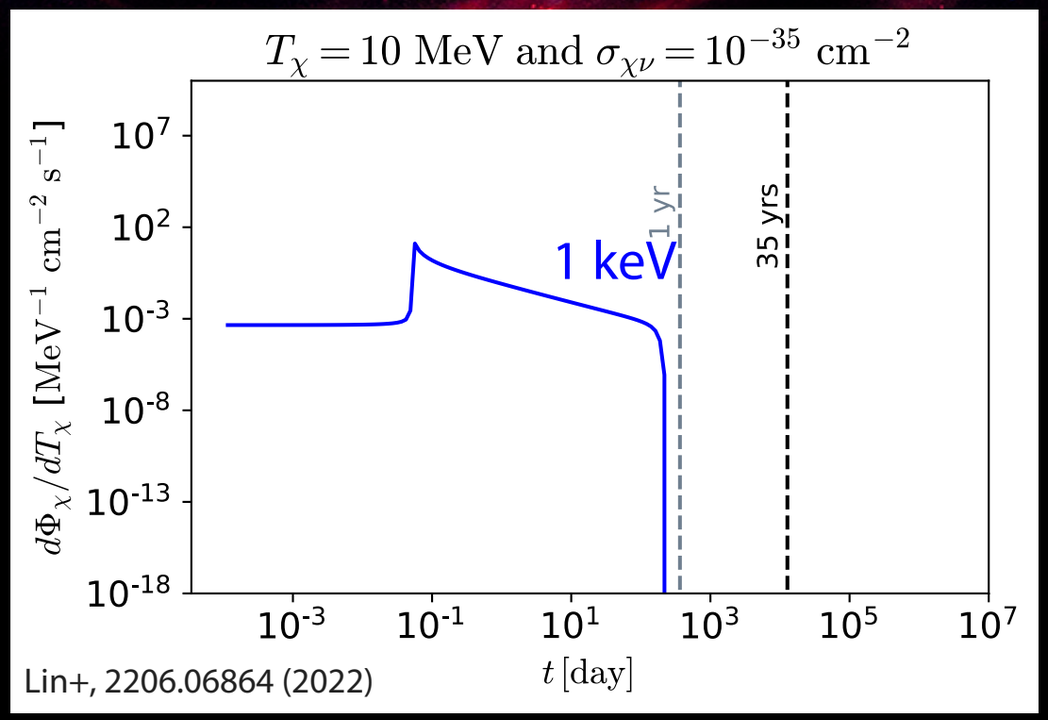
Time-of-flight

duration: ~10s

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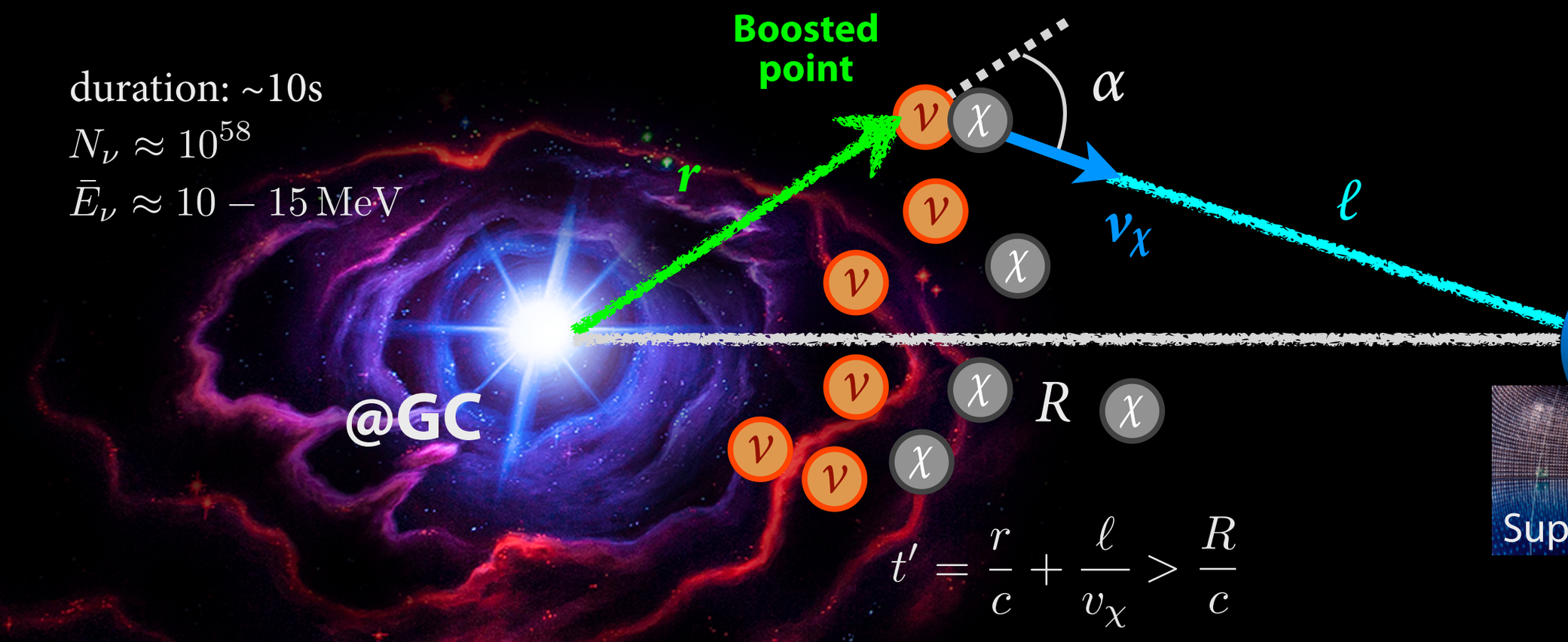


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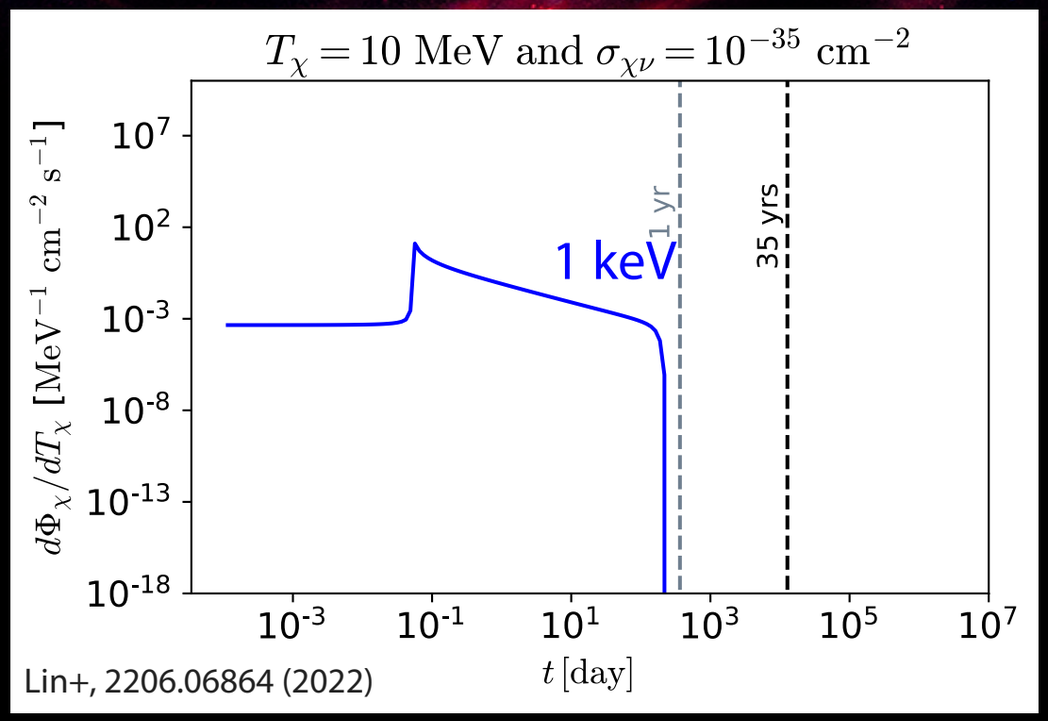
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$$t' = \frac{r}{c} + \frac{\ell}{v_\chi} > \frac{R}{c}$$



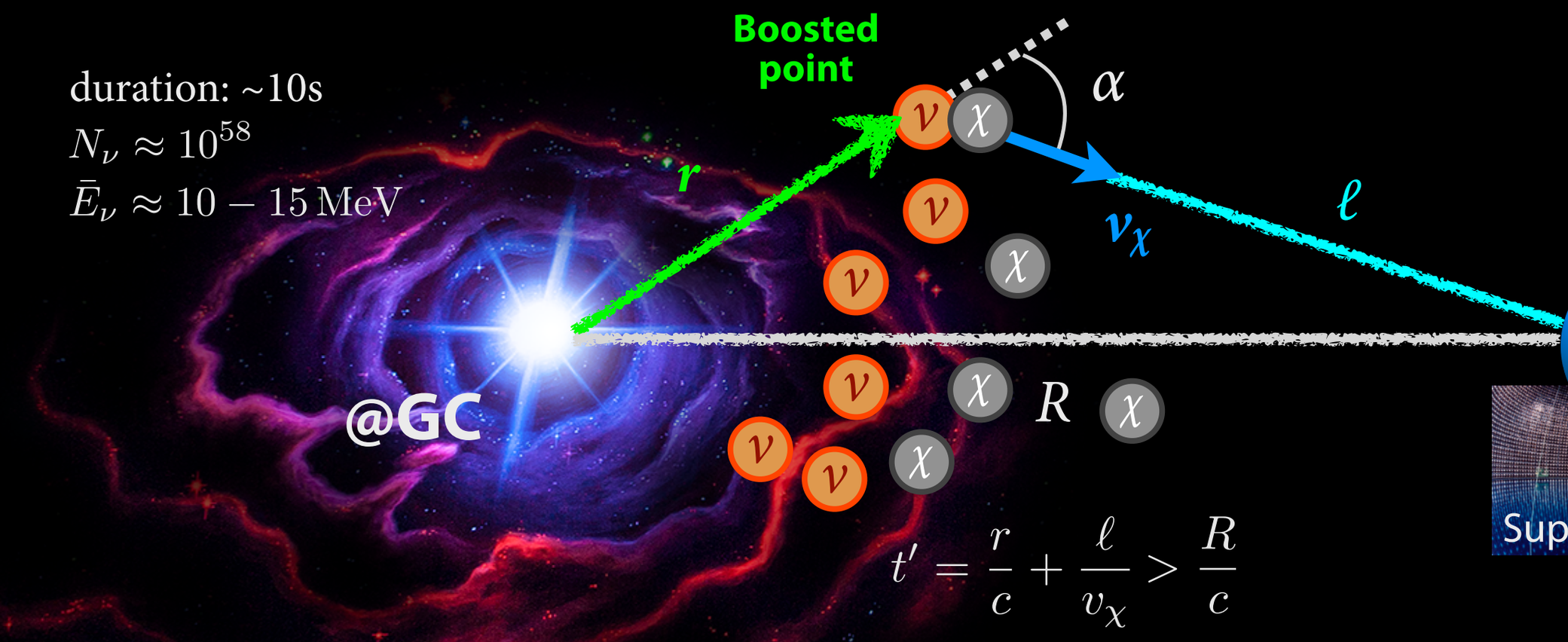
Lin+, 2206.06864 (2022)

Time-of-flight

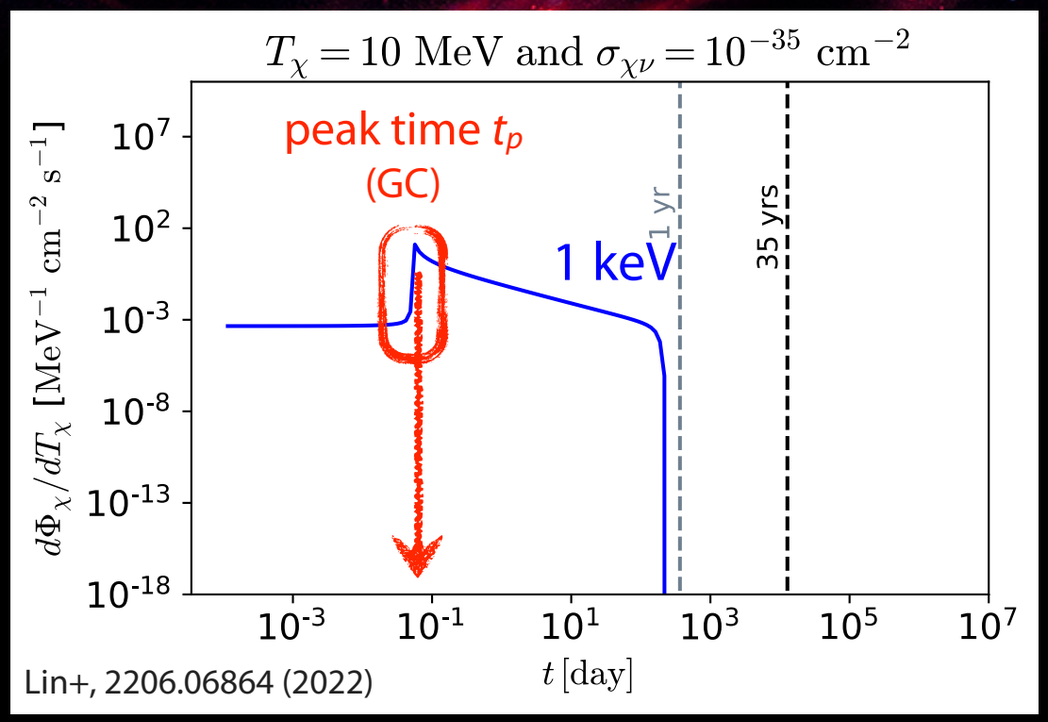
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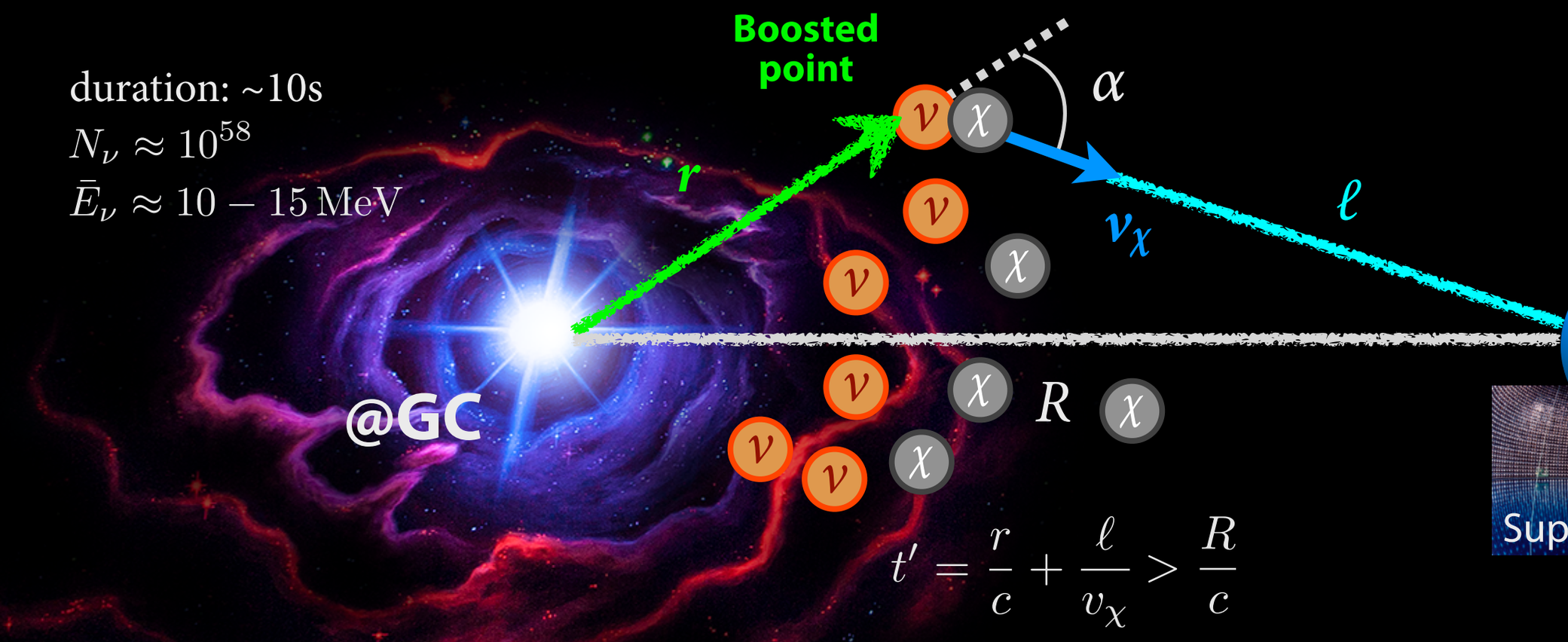
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Time-of-flight

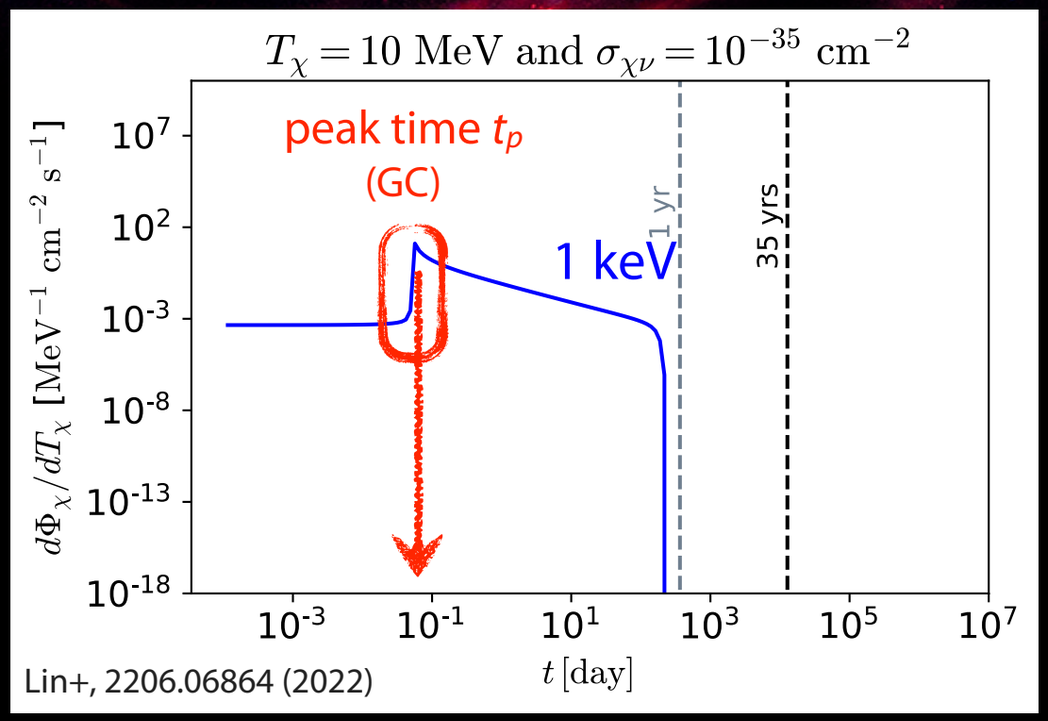
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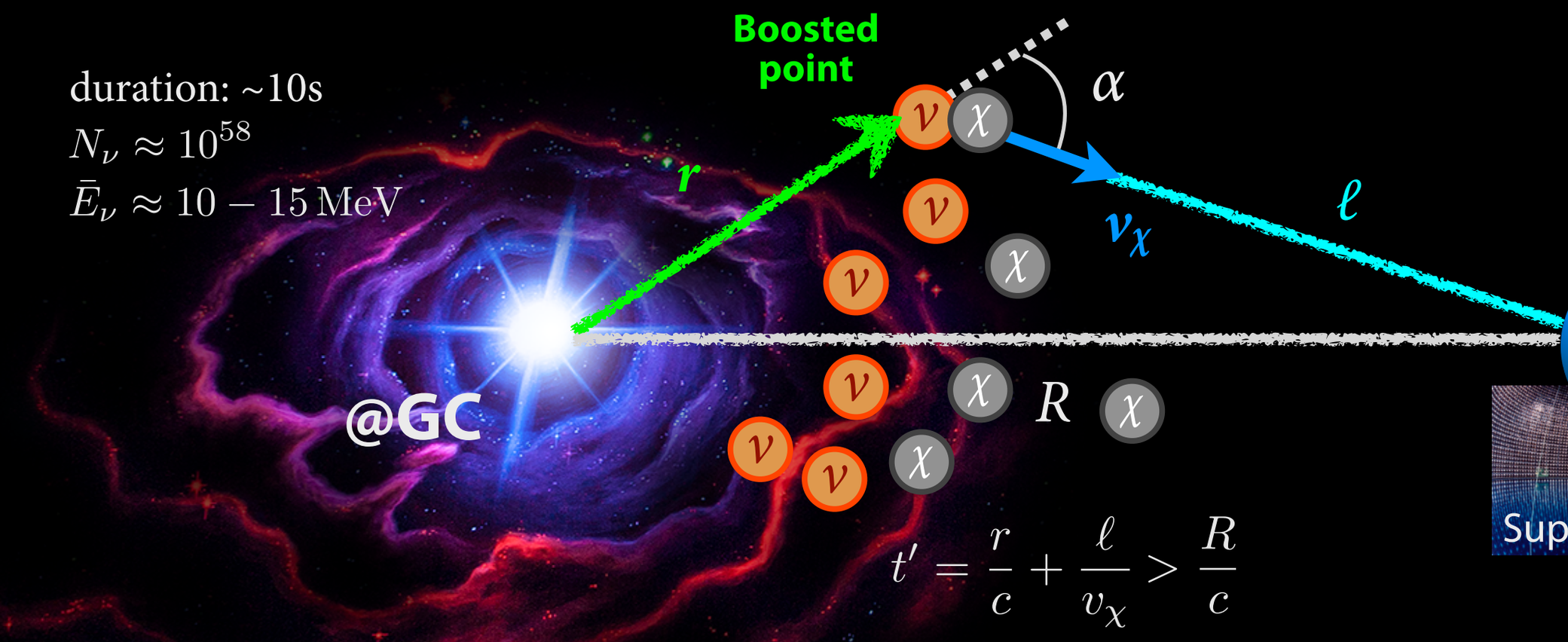
$$v_\chi = \sqrt{T_\chi(2m_\chi + T_\chi)}/(T_\chi + m_\chi)$$

Time-of-flight: A direct m_χ measurement

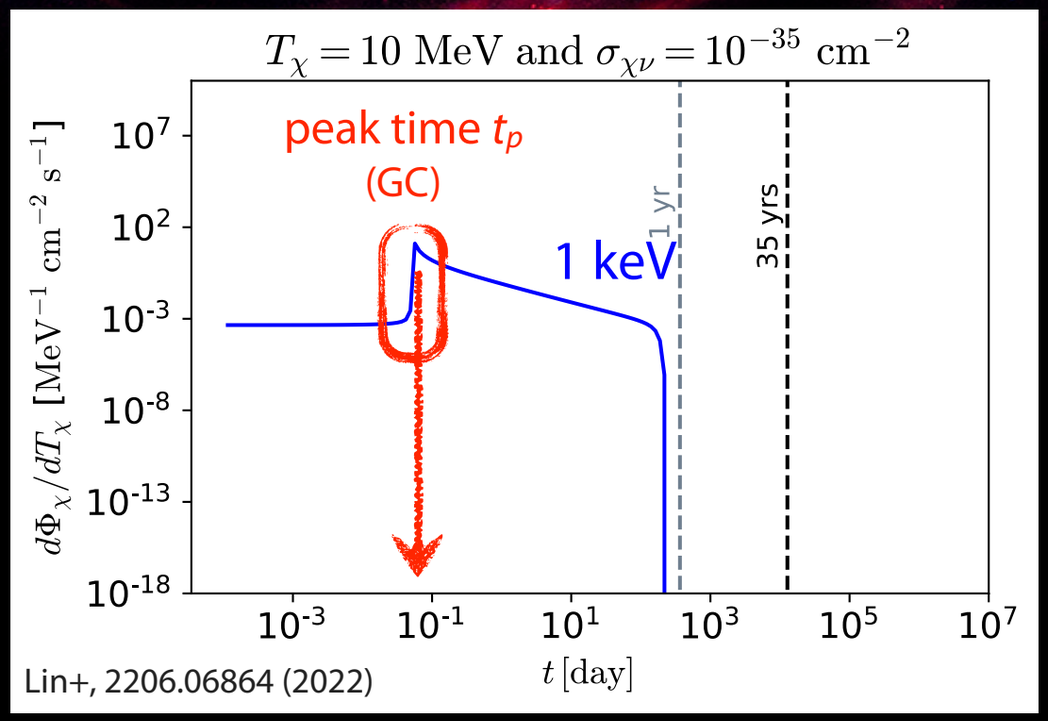
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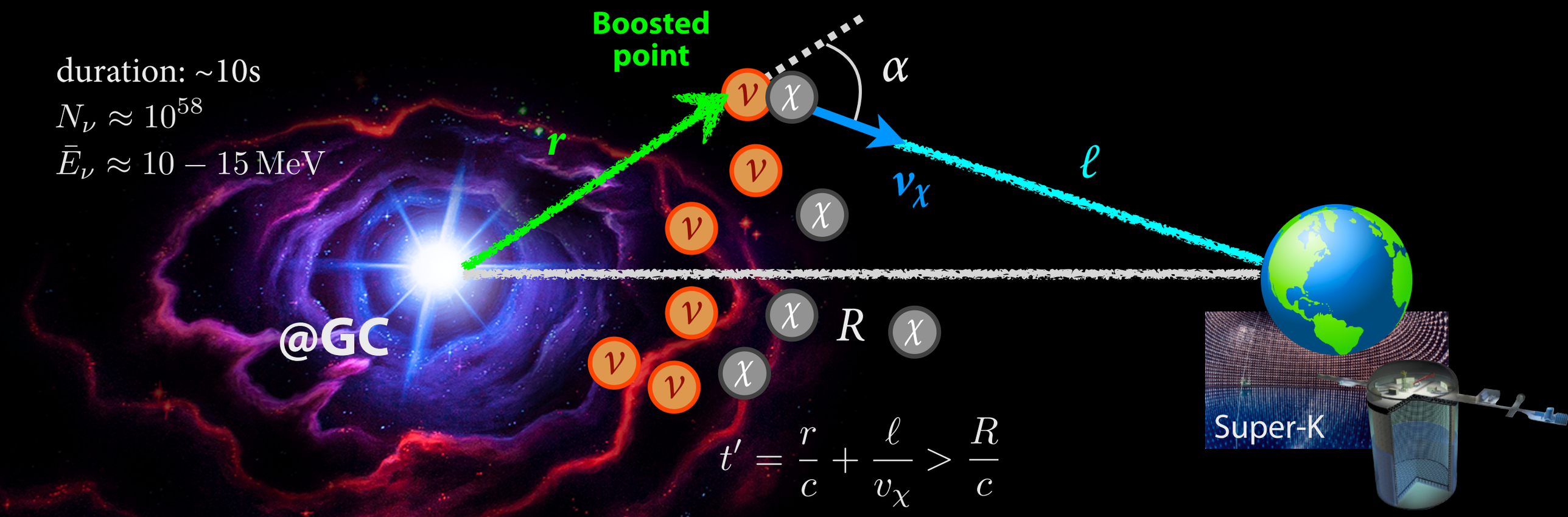
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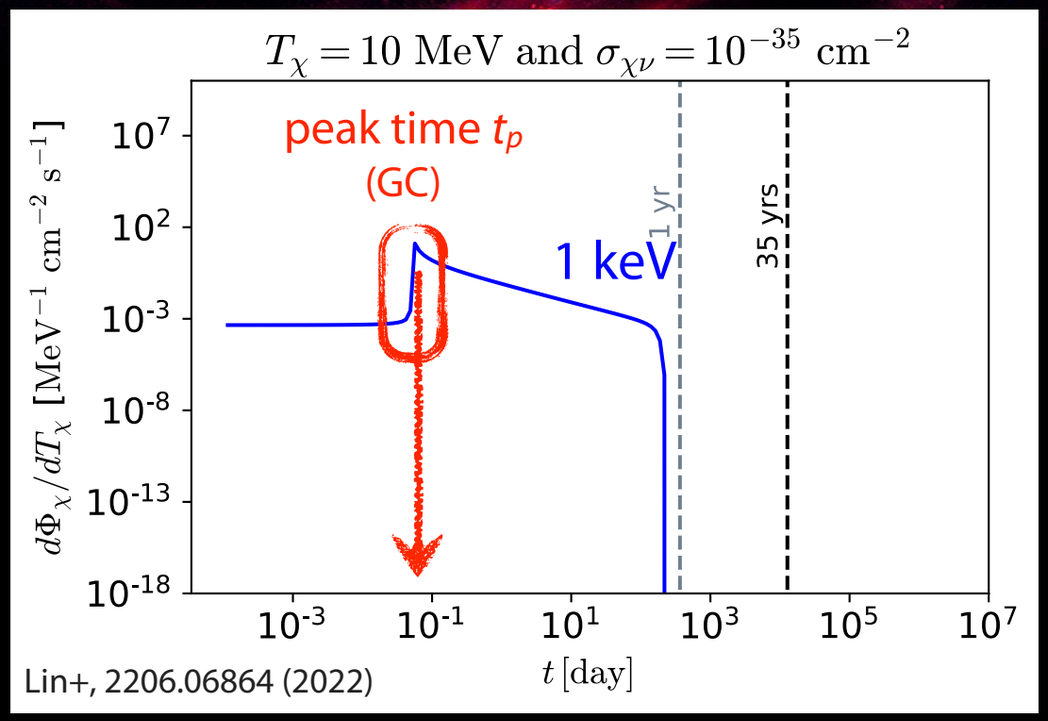
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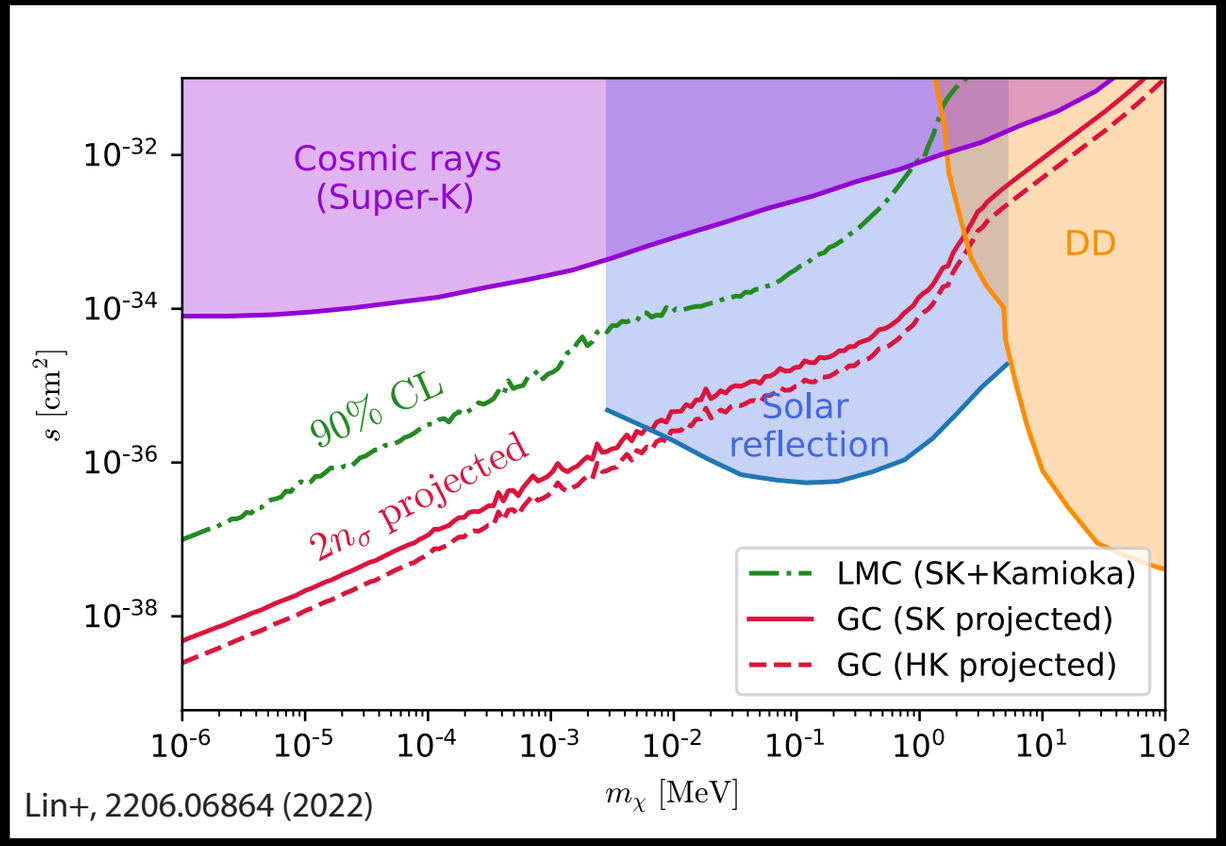
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- Given T_χ and t_p, the DM mass m_χ can be measured directly
- The position of t_p is **NOT AFFECTED** by $\sigma_{\chi\nu,e}$

Constraint and sensitivity

- Constraint from SN1987A (LMC) and projected sensitivity for the next GC SN are placed on $s = \sqrt{\sigma_{\chi\nu}\sigma_{\chi e}}$ as $N_\chi \propto \sigma_{\chi\nu}\sigma_{\chi e}$
- To compare with the existing bounds, we assume $\sigma_{\chi\nu} = \sigma_{\chi e}$
- ToF is not only for direct m_χ measurement, but also for background control
- The background $N_b \sim 526$ events/kton/year Abe+ (SK), *PRD* **94**, 052010 (2016)



Lin+, 2206.06864 (2022)



Summary

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- Selected-topics on LDM probe with NS and supernova neutrinos are presented
- Both are complementary to the current direct searches
- NS: **heating** and **DM collapse**
- **Supernova neutrinos**: **boosted DM** and **ToF**
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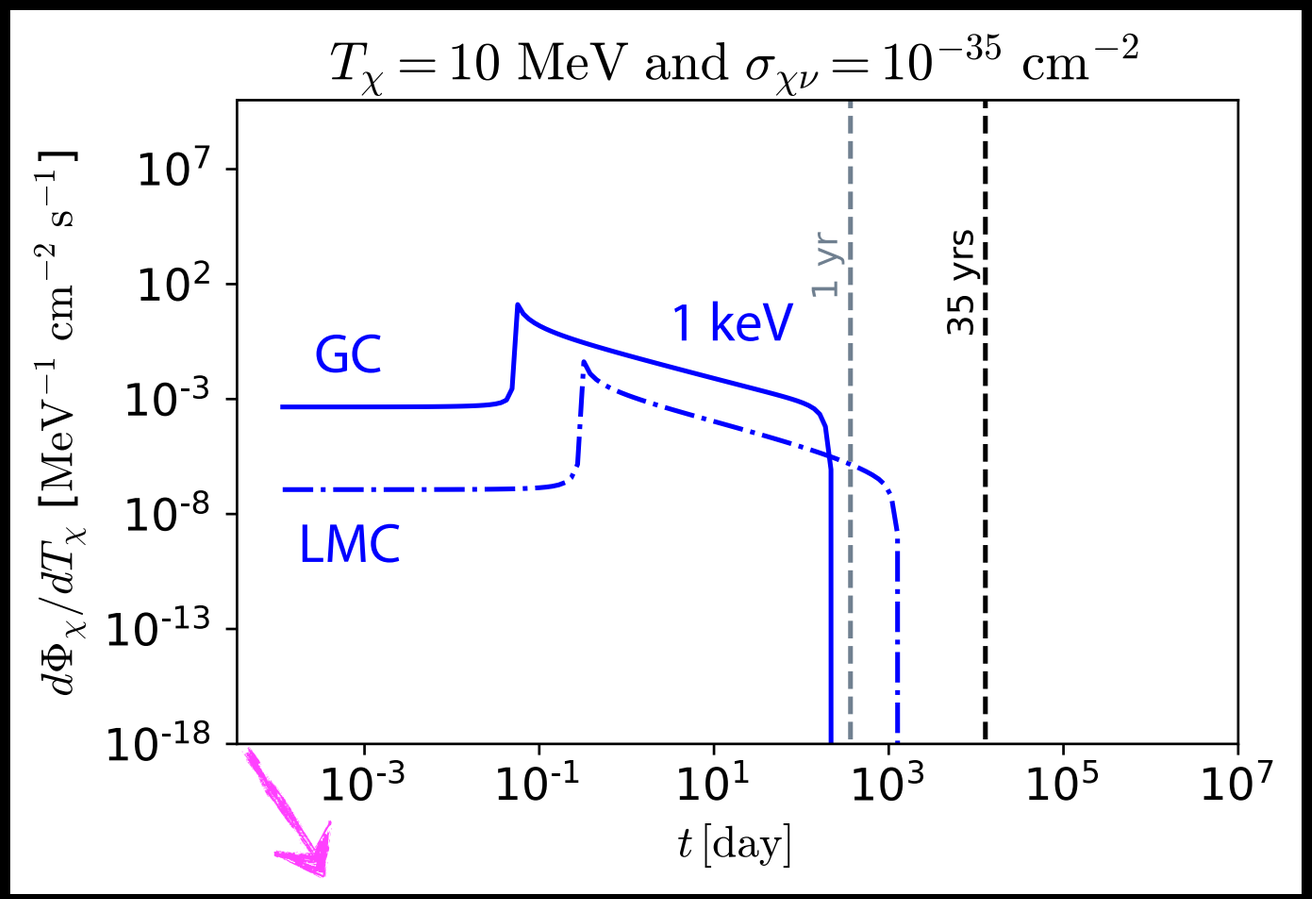
backups

BDM flux in MW & LMC

- DM profile

$$n_\chi(r) = \frac{\rho_s}{m_\chi} \frac{1}{\frac{r}{r_s}(1+\frac{r}{r_s})^n}, \quad (n, \rho_s, r_s) = \begin{cases} (2, 184\,\mathrm{MeV\,cm^{-3}}, 24.4\,\mathrm{kpc}), & \mathrm{MW} \\ (3, 68\,\mathrm{MeV\,cm^{-3}}, 31.9\,\mathrm{kpc}), & \mathrm{LMC\ (SN1987a)} \end{cases}$$

- BDM flux vs. m_χ



t_0 = 10 s: to avoid overlapping with SNν

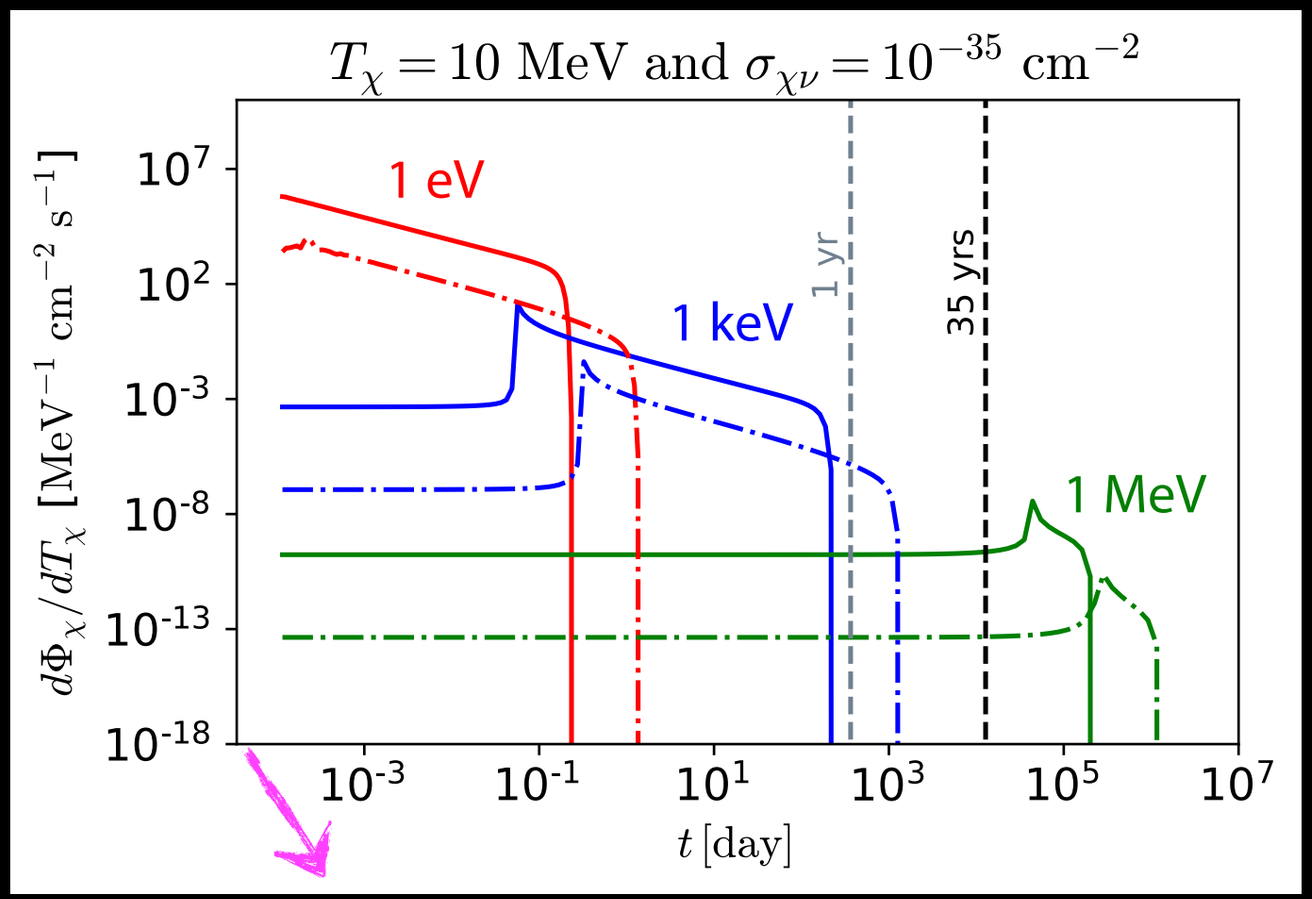
- t_p for LMC is delayed accordingly due to $R_{\mathrm{LMC}} = 50$ kpc > $R_{\mathrm{GC}} = 8.5$ kpc
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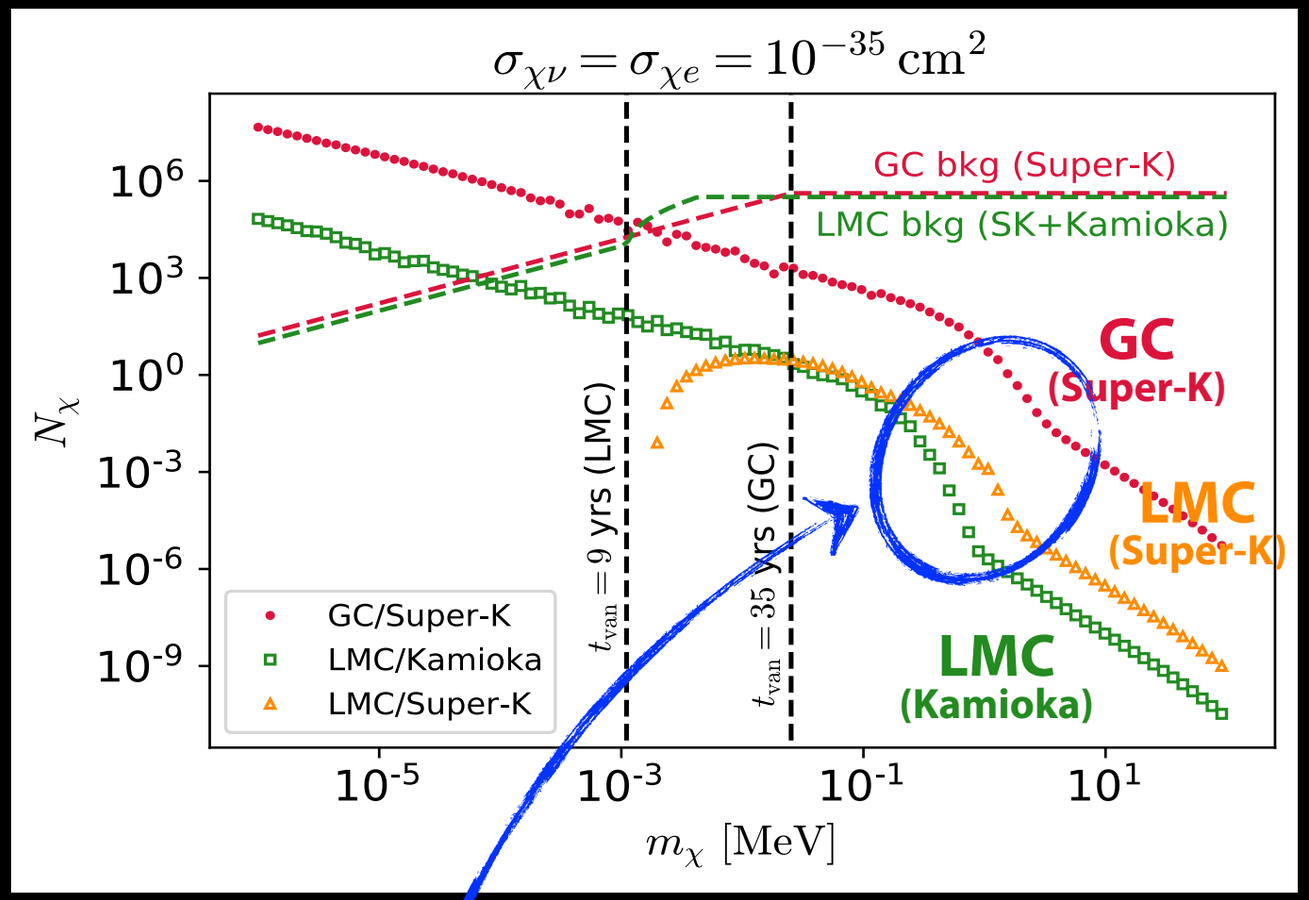
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BDM event and background



- The *rapid decreasing* of N_χ vs. m_χ indicates the tail part cannot be fully incorporated
- The background $N_b \sim 526 M_T t_{\rm exp}$ increases as $t_{\rm van} < t_{\rm cut} = 35$ yrs but saturates when $t_{\rm van} > t_{\rm cut}$

- The BDM event (taking $\sigma_{\chi\nu} = \sigma_{\chi e}$)

$$N_\chi = N_e \sigma_{\chi e} \int_{T_{\rm th}}^{T_{\rm max}} dT_\chi \int_{t_0}^{t_{\rm exp}} dt \frac{d\Phi_\chi}{dT_\chi}$$

- LMC (SN1987a):
  - Kamiokande: 1987-1996
  - Super-K: 1996 - present
- $m_\chi < 1.1$ keV has $t_{\rm van} < 9$ years, which is unobservable to Super-K
- GC case is similar

