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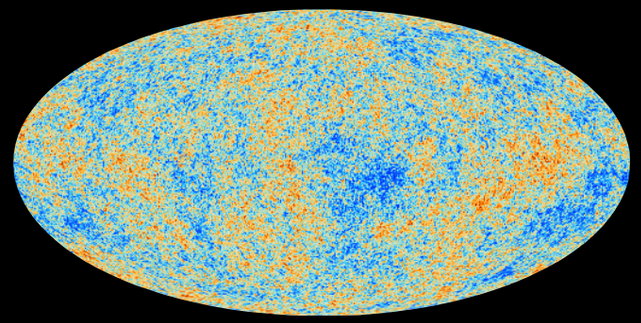
XIX Recontres du Vietnam
Theory Meets Experiment: Particle Astrophysics and Cosmology, Quy Nhon, Vietnam
Jan. 10 2023

Light dark matter constraints from neutron stars and supernova neutrinos

CS Chen & YHL, 1804.03409
GL Lin & YHL, 2004.05312
GL Lin & YHL, 2102.11151
YHL, WH Wu, MR Wu & HT Wong, 2206.06864
YHL, TH Tsai, CW Chiang, GL Lin, HT Wong & MW Wu, *in preparation*

Dark matter is *ubiquitous* in the Universe!



More ancient

Larger space

Universe

CMB

Structure formation

Local Group

MW

Galaxy clusters

local

Gravitational lensings

Dwarf spheroidals

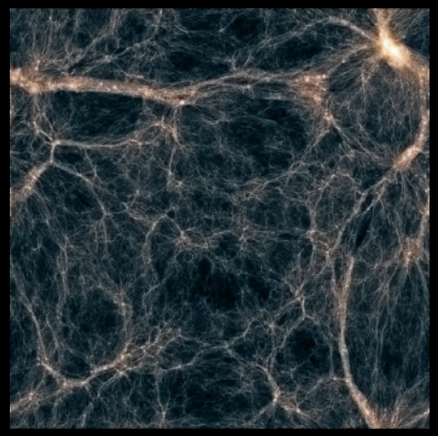
~ 1 kpc

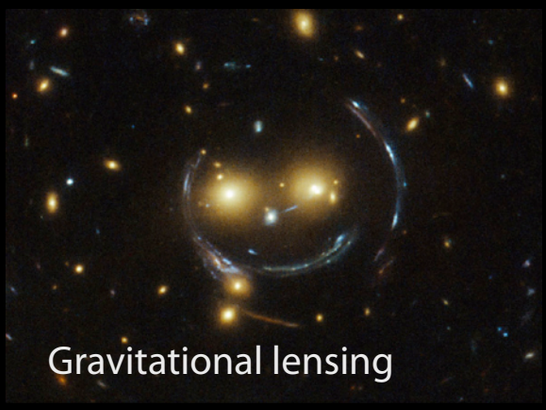
Rotation curves

~ 100 kpc

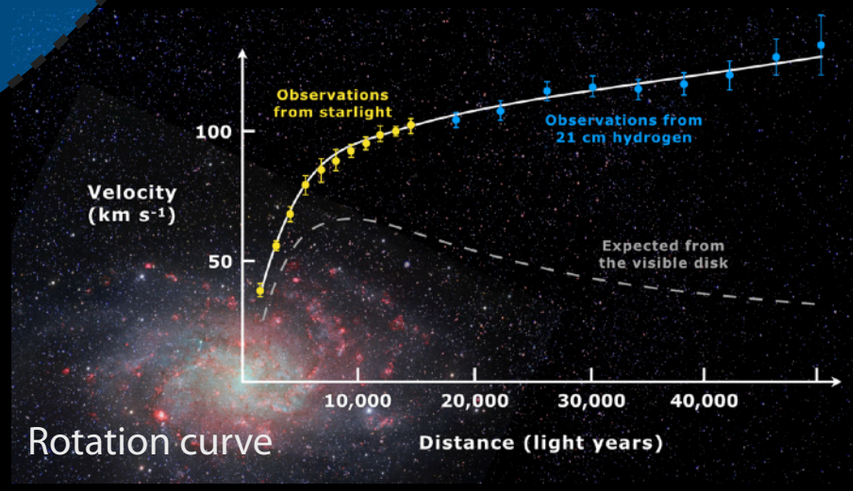
~ Mpc

~ Gpc





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

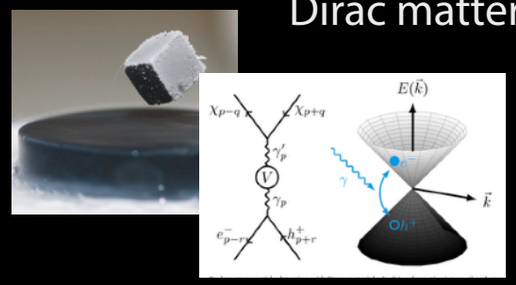
electron recoils

nucleus recoils

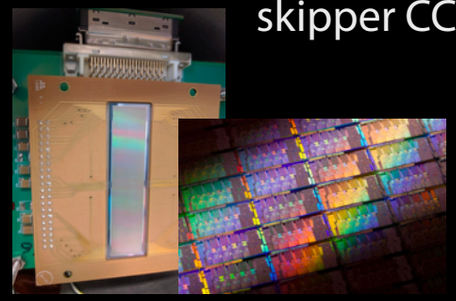
Dark matter direct search

not-to-scale

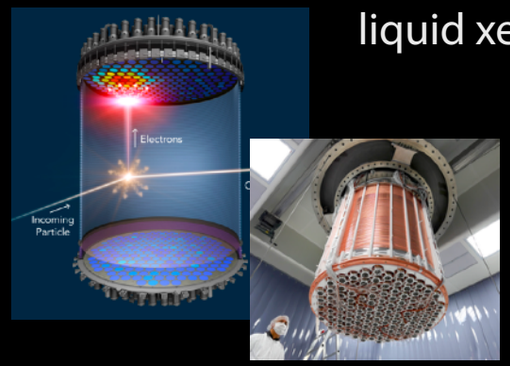
superconductor/graphene
Dirac matter…



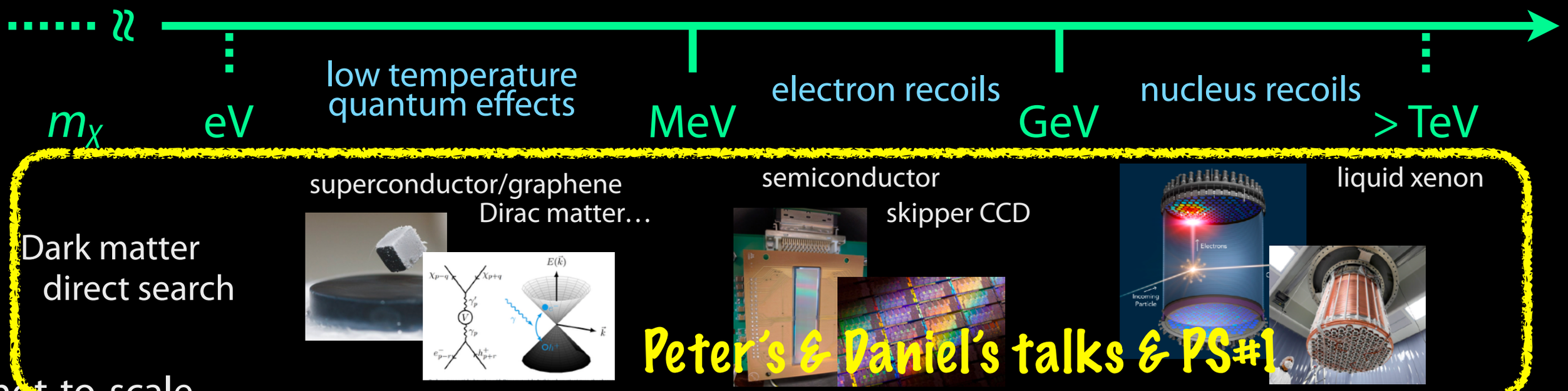
semiconductor
skipper CCD



liquid xenon

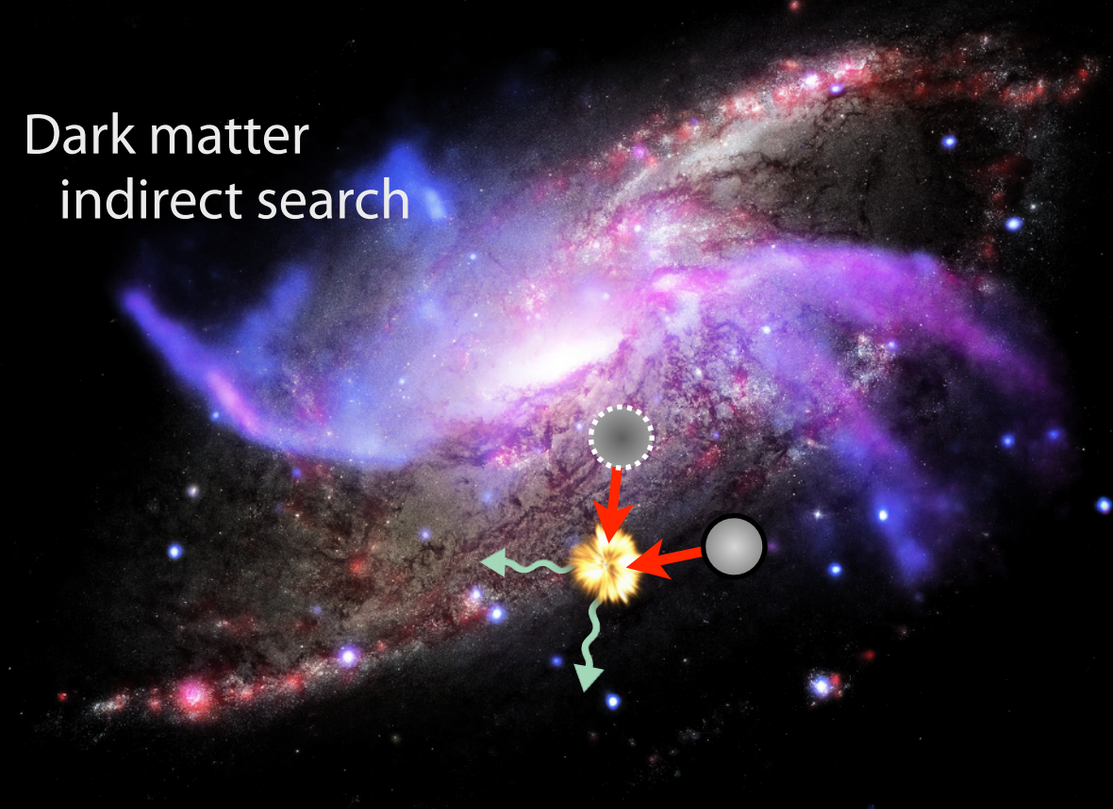


The DM probes: m_χ & σ



The DM probes: m_χ & σ

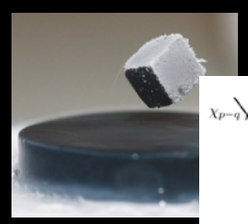
Dark matter
indirect search

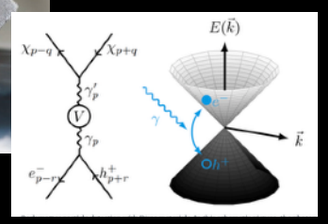


m_χ ..... ≈ eV — low temperature quantum effects — MeV — electron recoils — GeV — nucleus recoils — > TeV

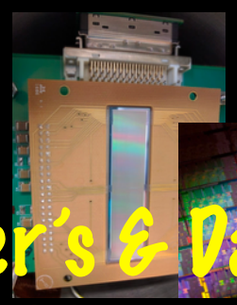
Dark matter
direct search

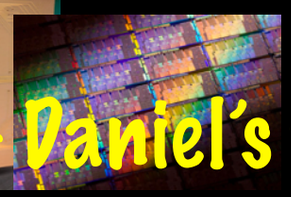
superconductor/graphene
Dirac matter…



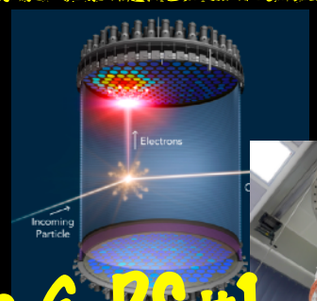


semiconductor
skipper CCD





liquid xenon

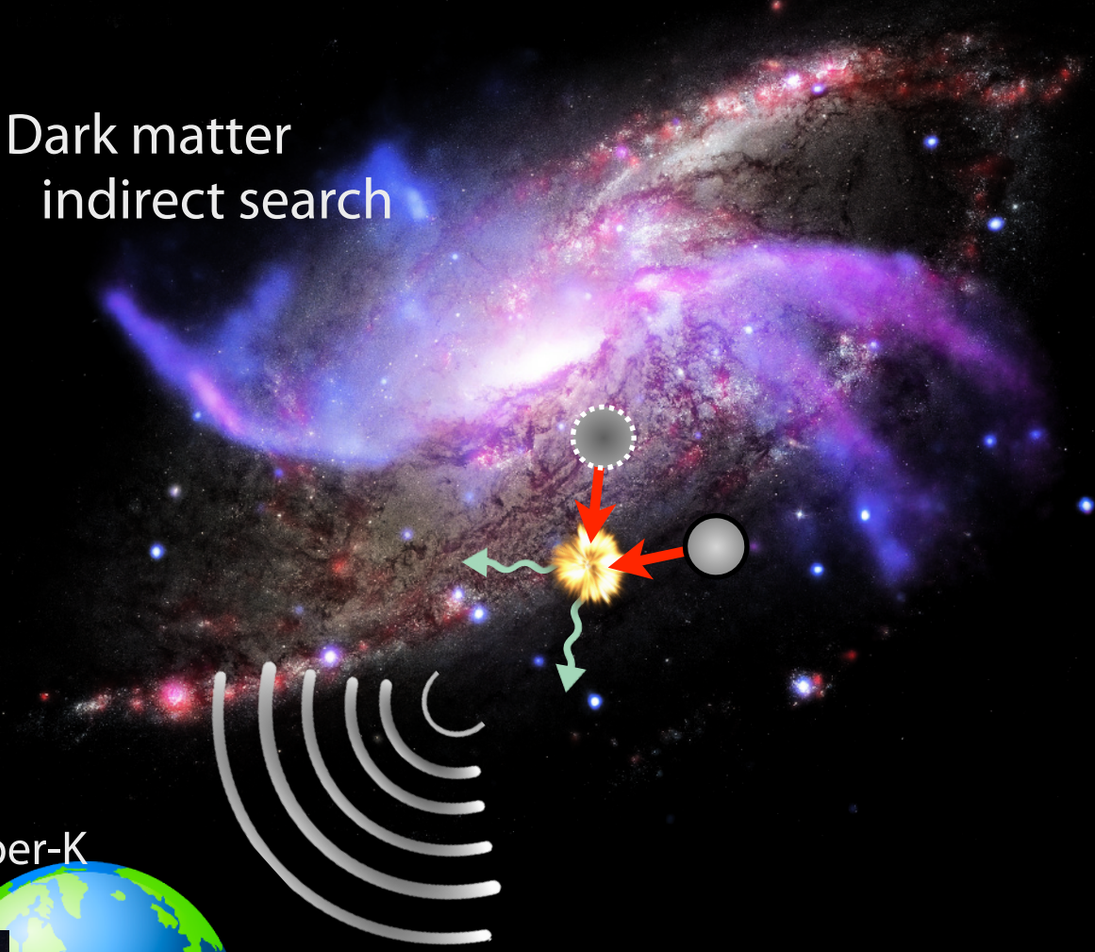


Peter's & Daniel's talks & PS#1

not-to-scale

The DM probes: m_χ & σ

Dark matter
indirect search

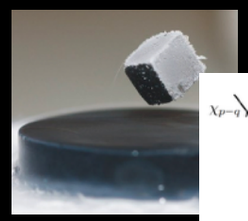


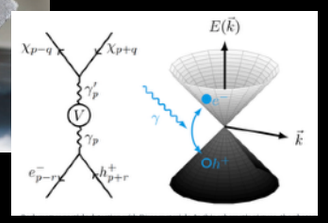
Super-K

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

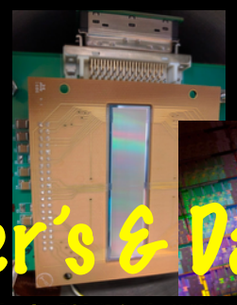
Dark matter
direct search

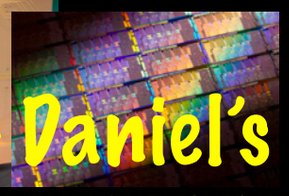
superconductor/graphene
Dirac matter…



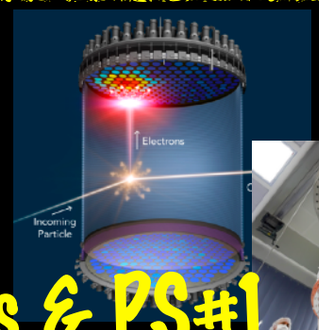


semiconductor
skipper CCD





liquid xenon



Peter's & Daniel's talks & PS#1

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

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

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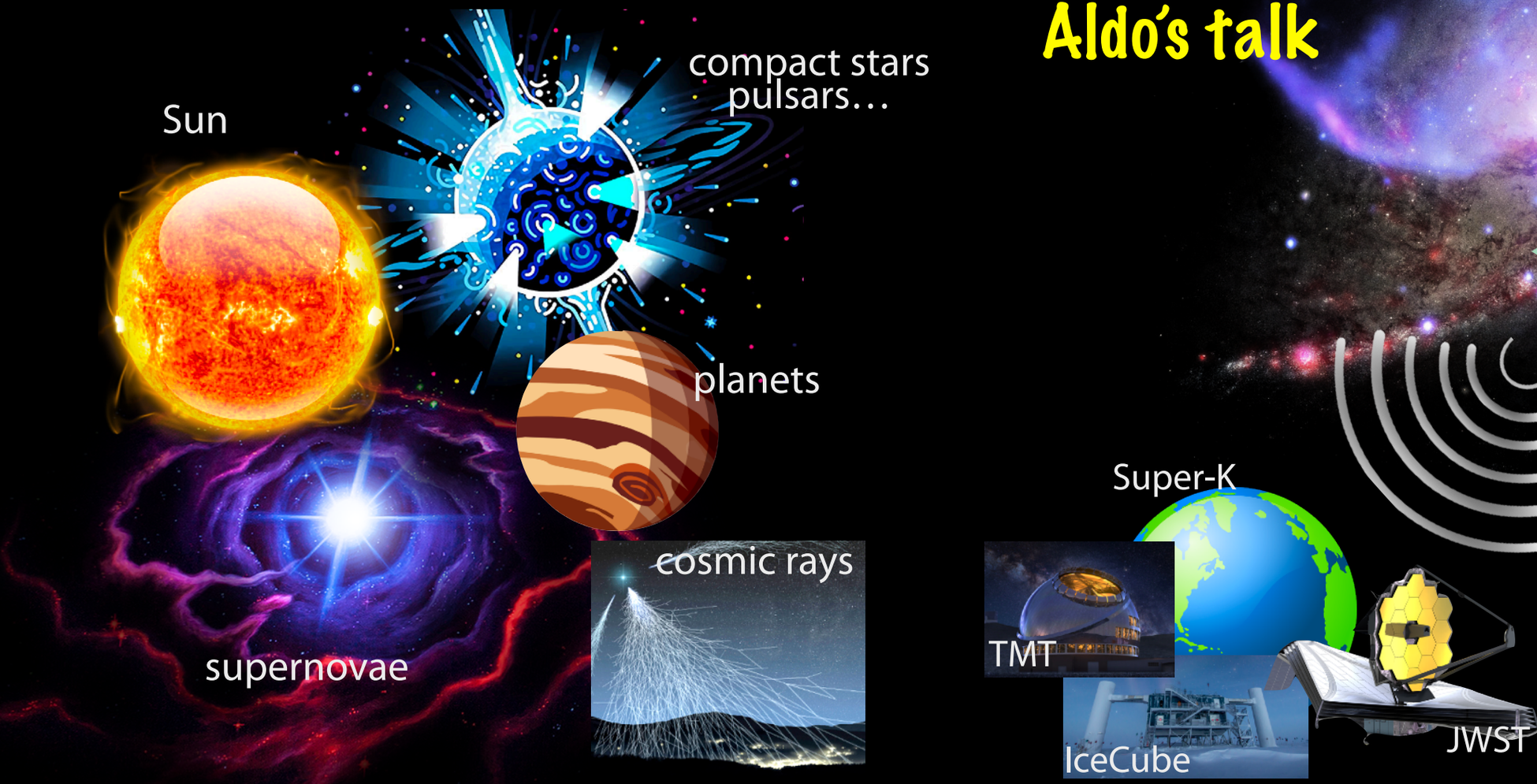
Aldo's talk



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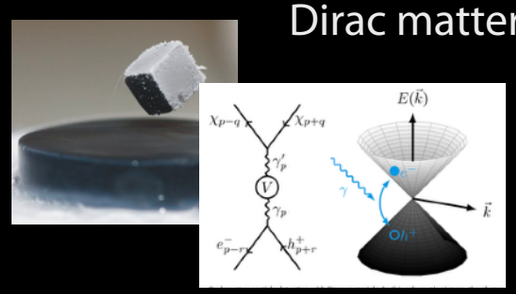

semiconductor
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Peter's & Daniel's talks & PS#1

not-to-scale

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*

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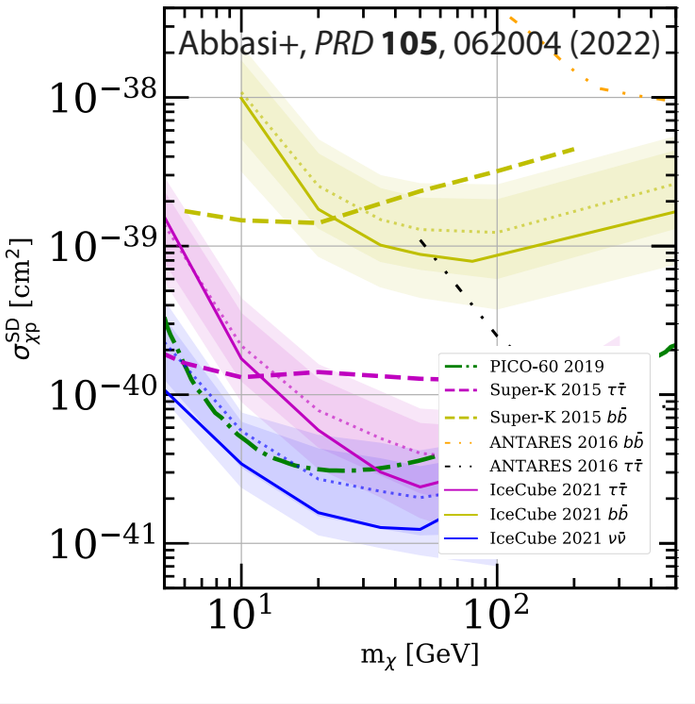
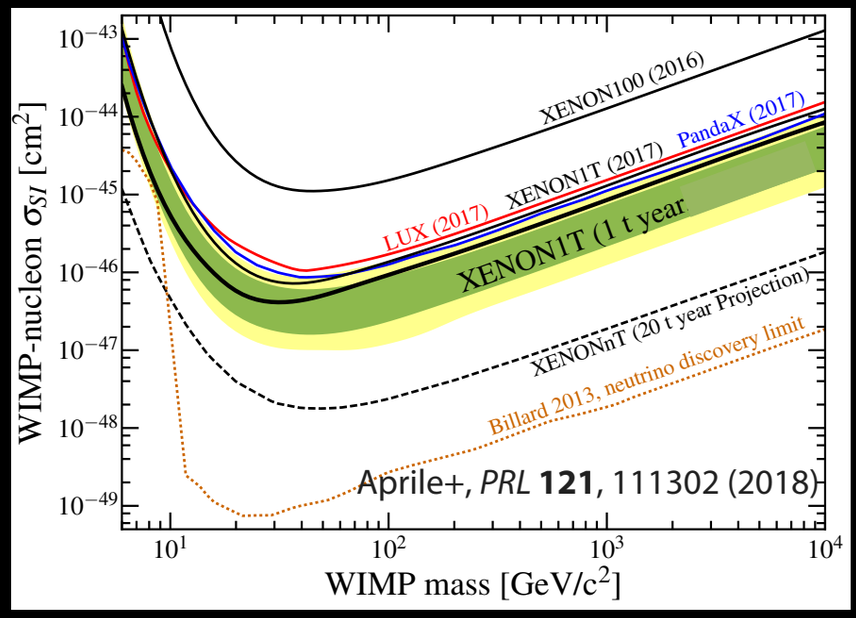
Spin-dependent $\sigma_{\chi p}$

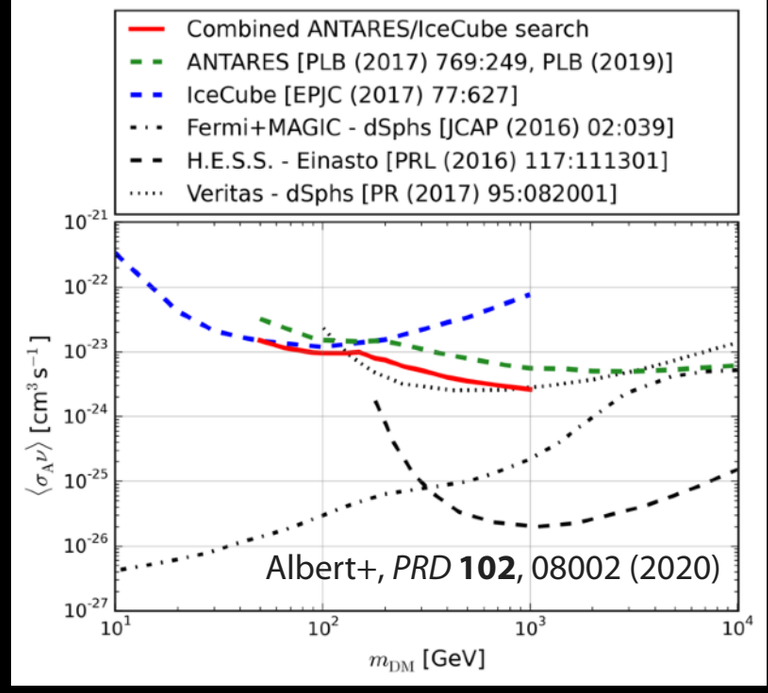


Spin-independent $\sigma_{\chi n}$



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

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

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

Current constraints

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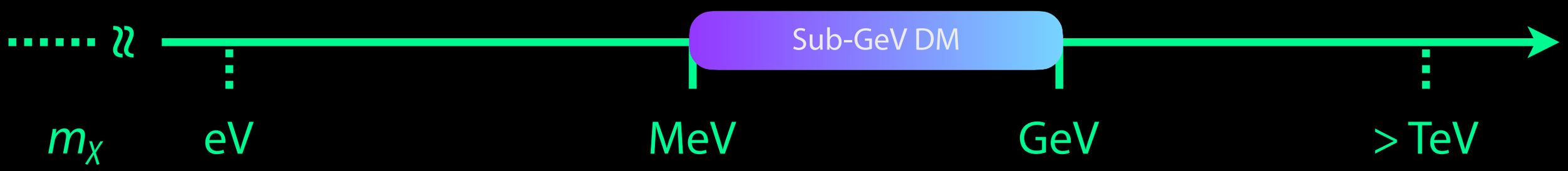

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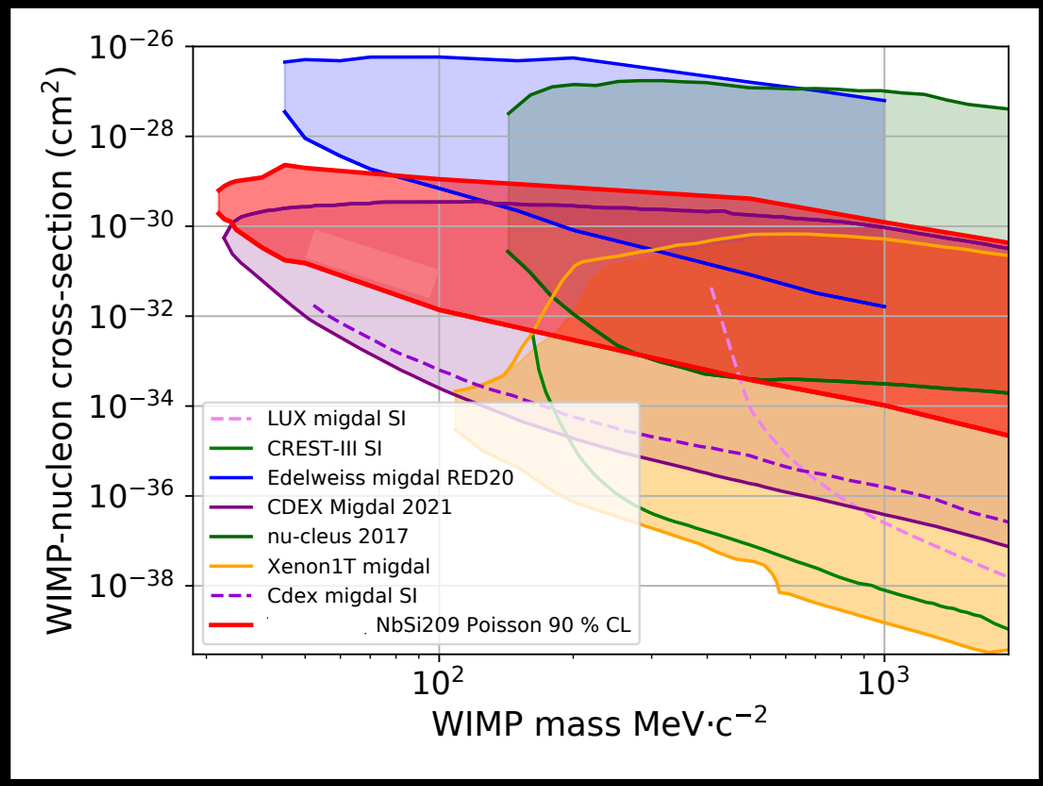
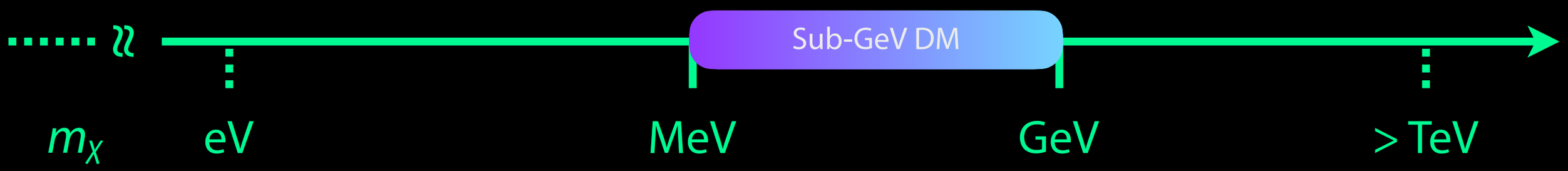
… *for comprehensive reviews*

Lattaud (EDELWEISS), 2211.04176





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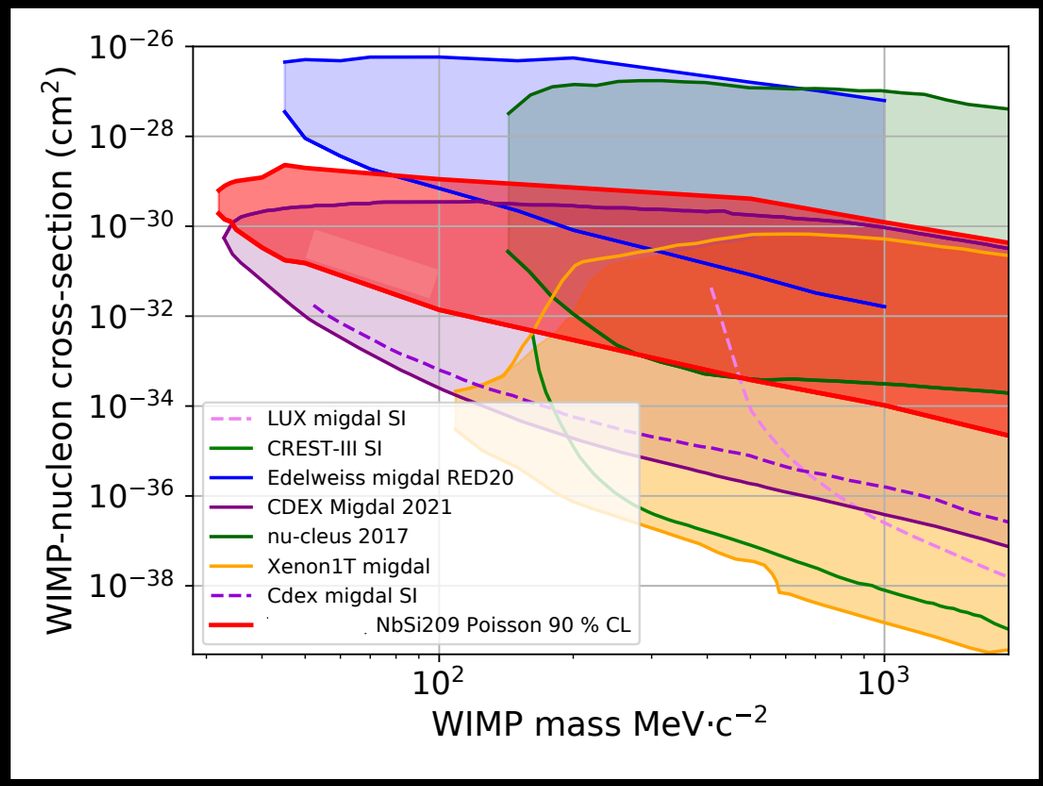

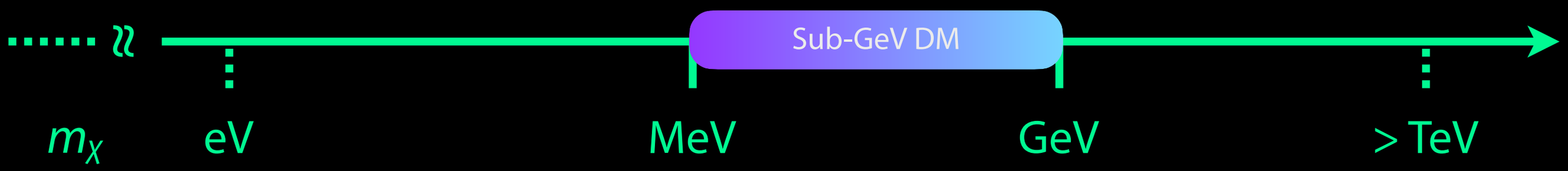

- The constraints decreases as m_χ goes lighter: $\mathcal{O}(10^{-38} - 10^{-26})\,\mathrm{cm}^2$

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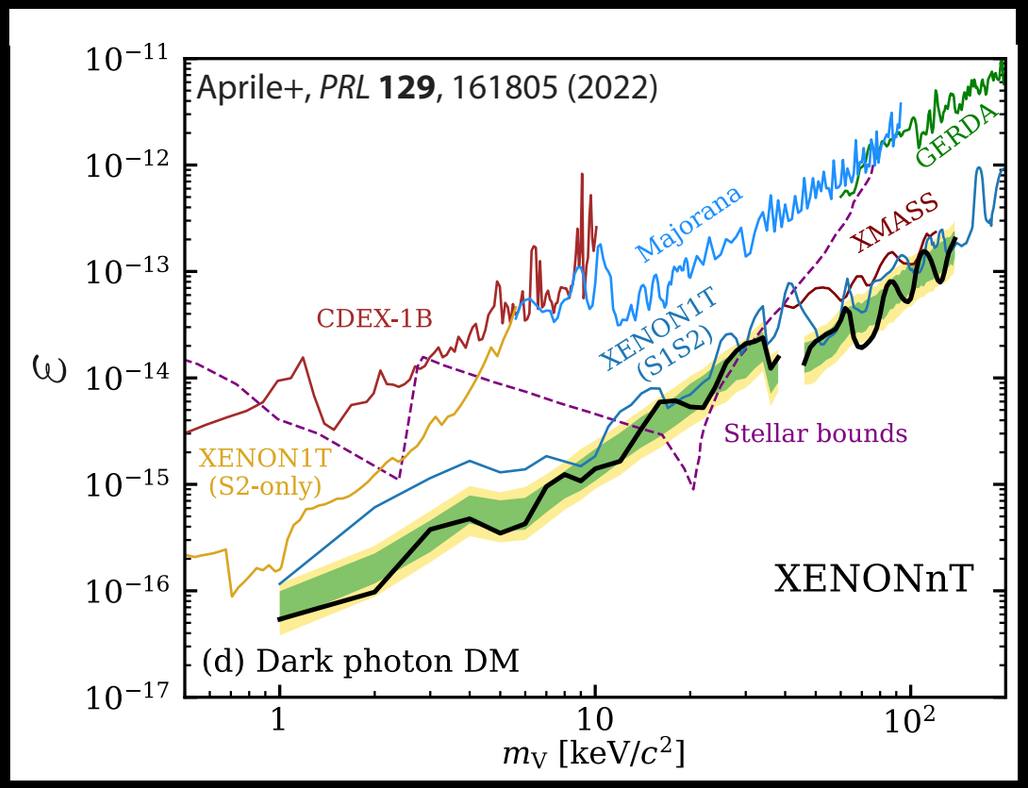

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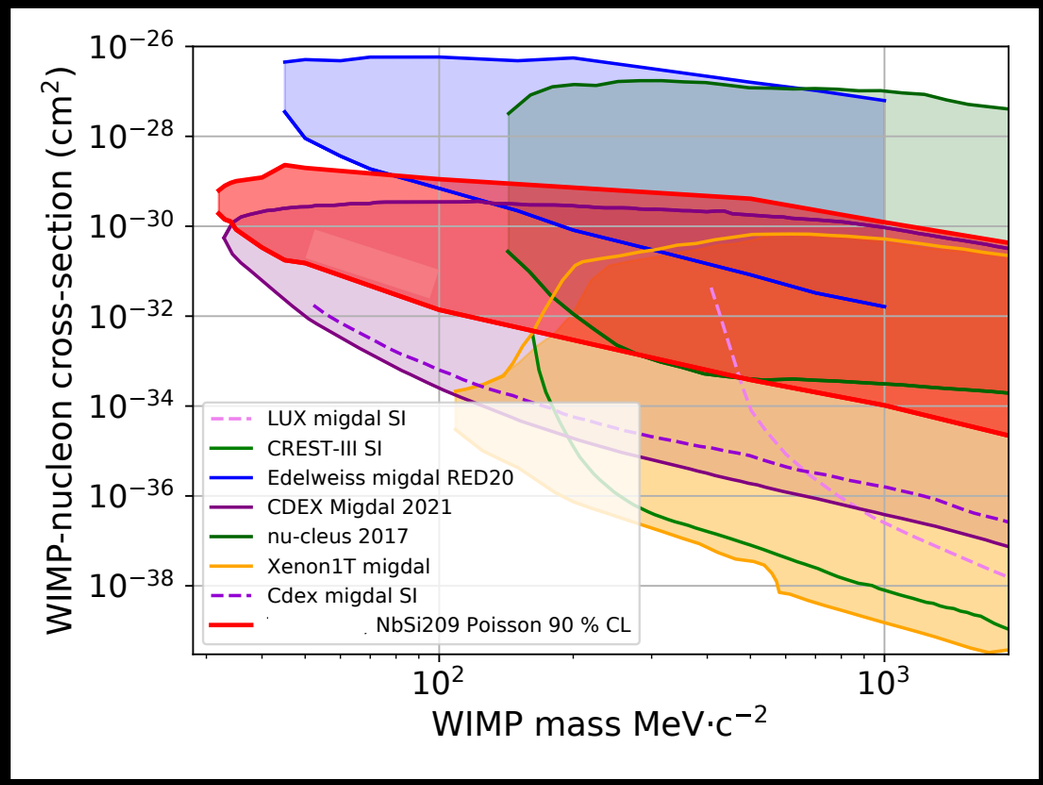

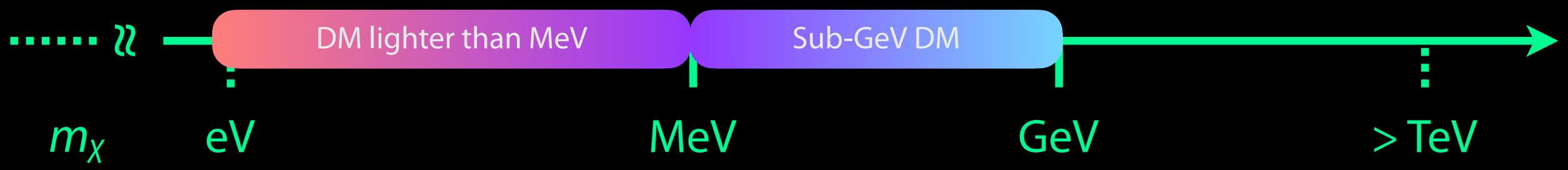

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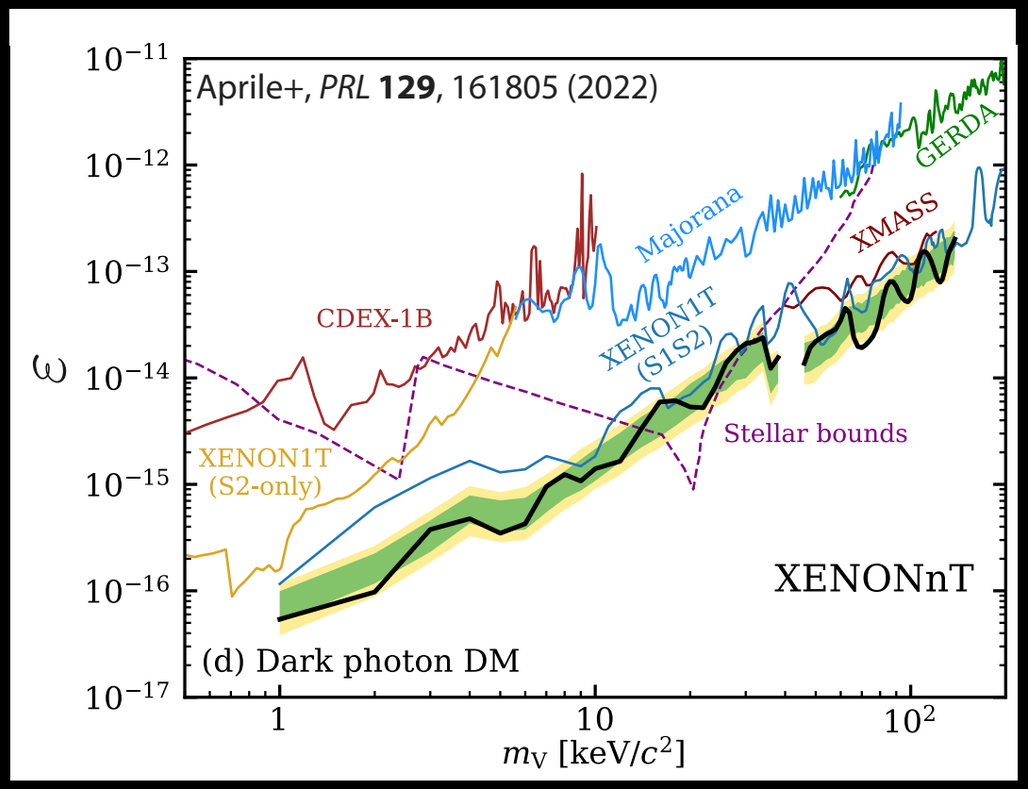

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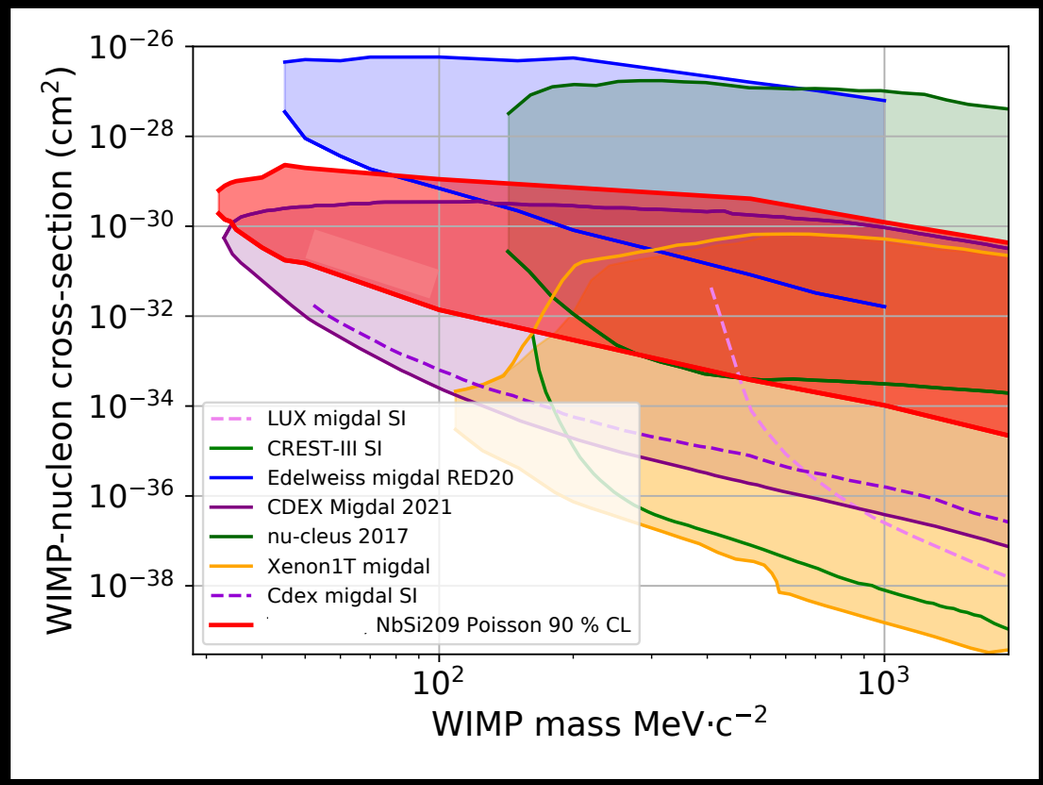
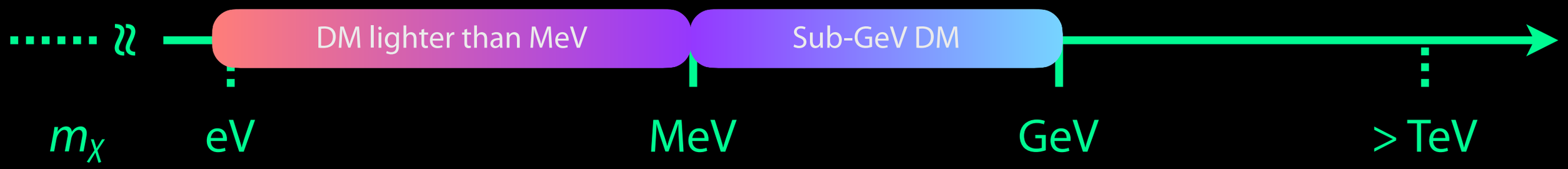




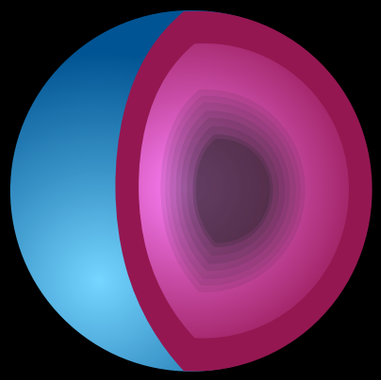
- The constraints decreases as m_χ goes lighter: $\mathcal{O}(10^{-38} - 10^{-26})\,\mathrm{cm}^2$
- Left panel assumes DM is massive dark photon V_μ and can kinetically mix with SM $U(1)$ field A_μ

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

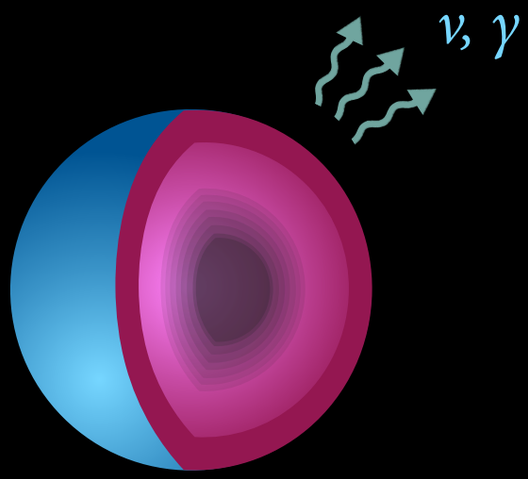
Holdom, *PLB* **166**, 196 (1986)
An+, *PLB* **747**, 331 (2014)

How compact star probes DM?

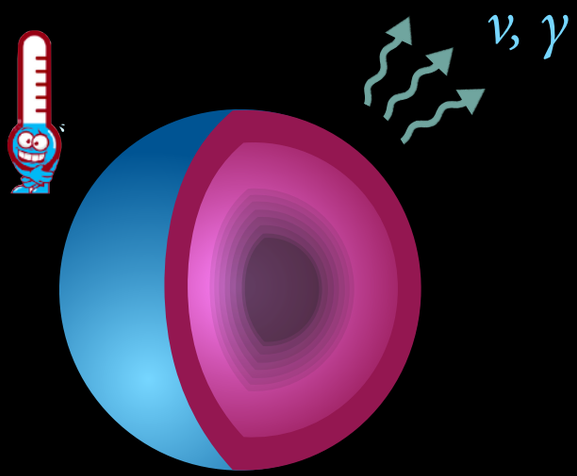
Probing DM with NS

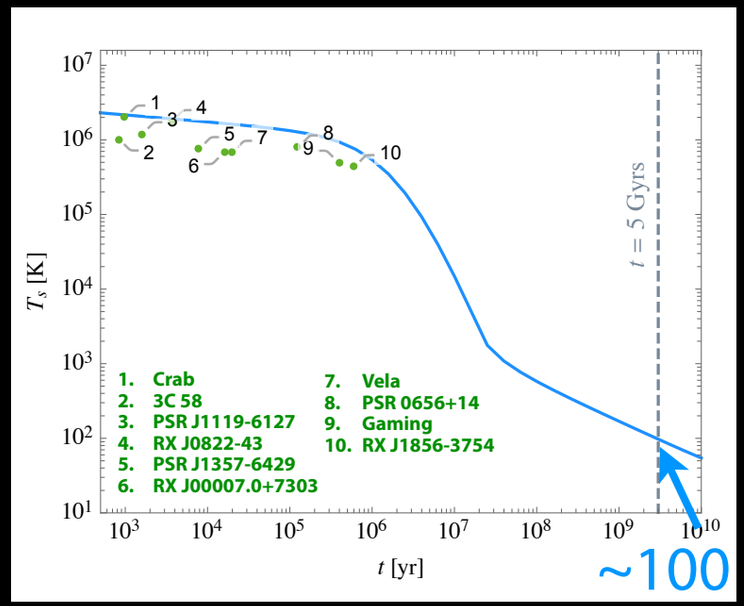


Probing DM with NS



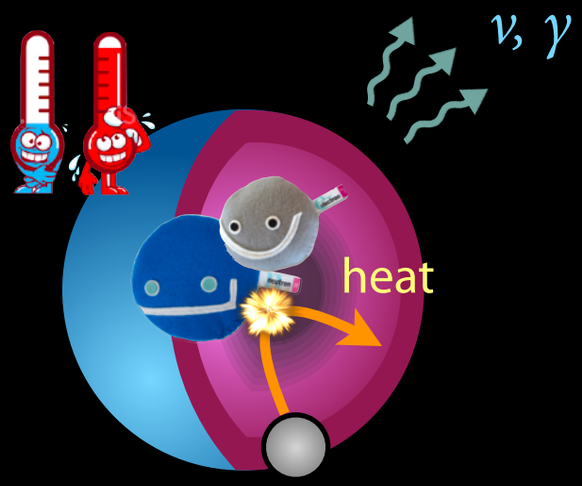
Probing DM with NS



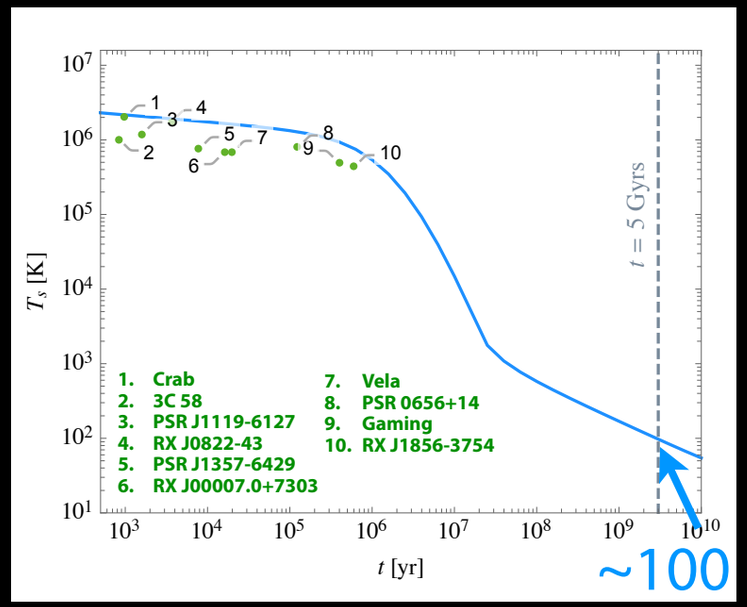


Probing DM with NS

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



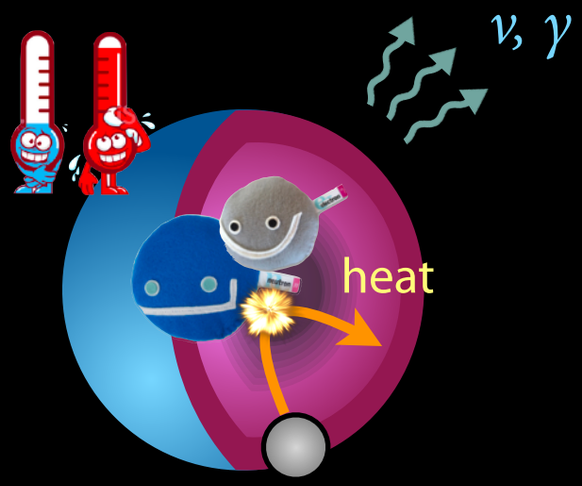
kinetic heating



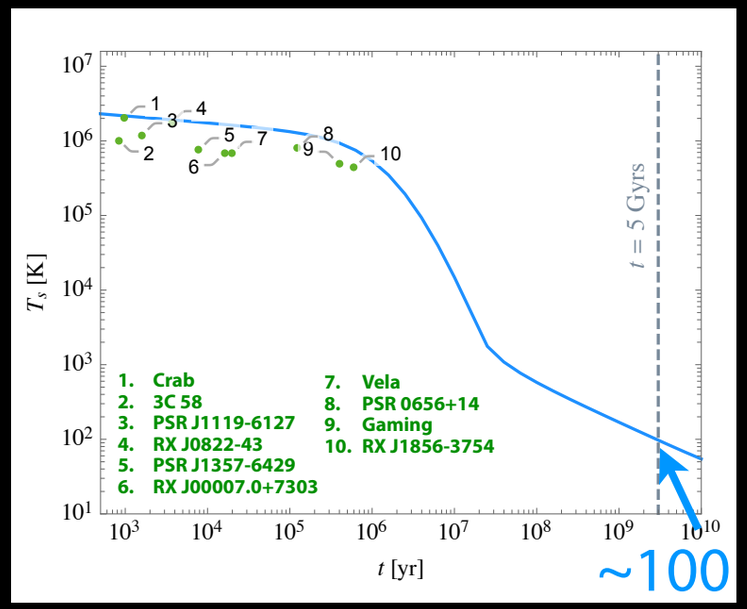
~100 K

Probing DM with NS: The DM heating effect

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



kinetic heating



~100 K

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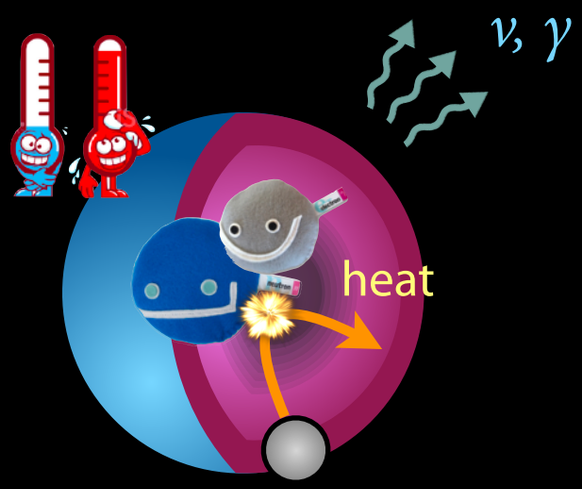

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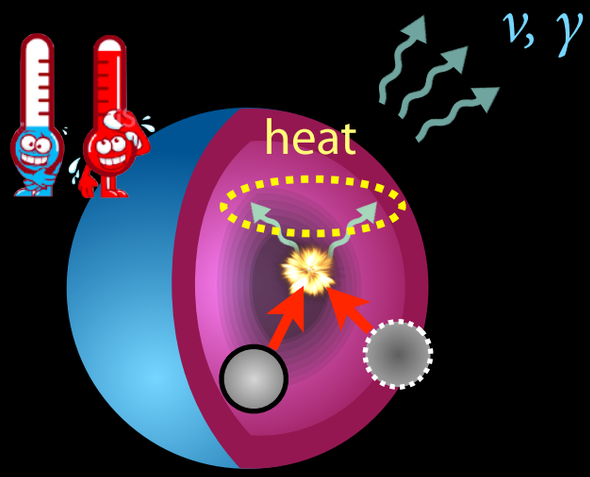
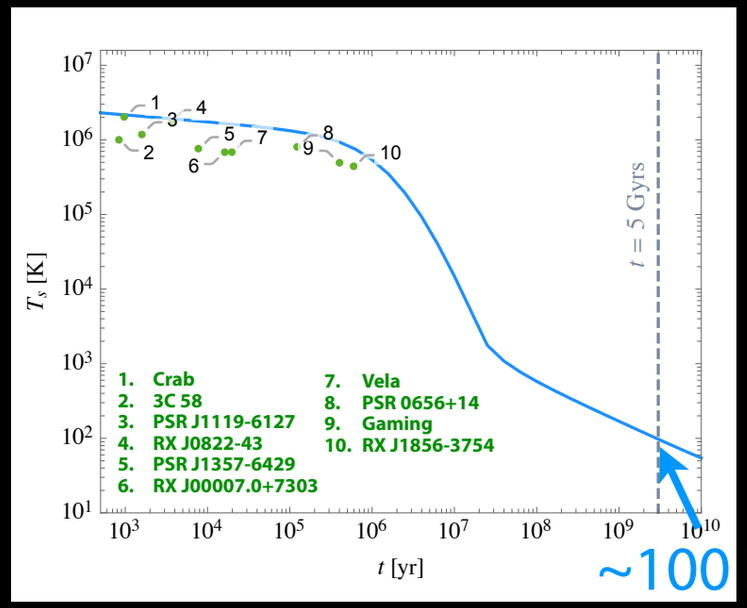


annihilation heating



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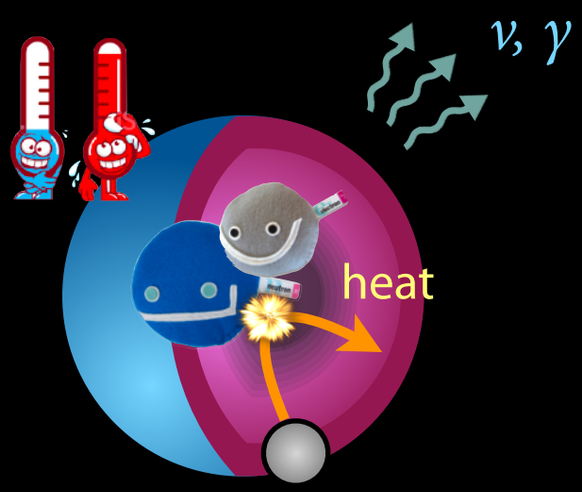

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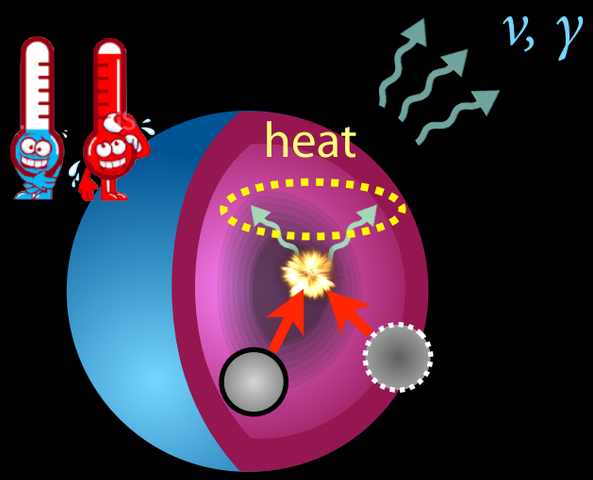

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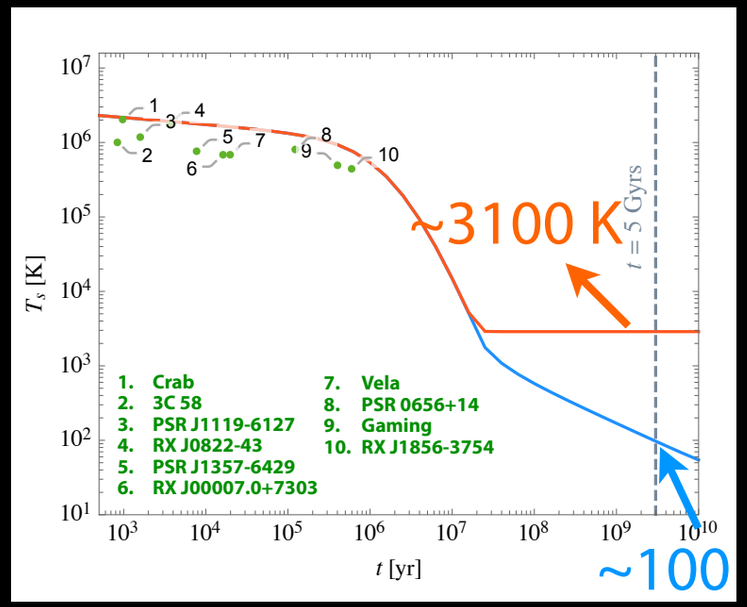

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Page+, *ApJS* **155,** 623 (2004)
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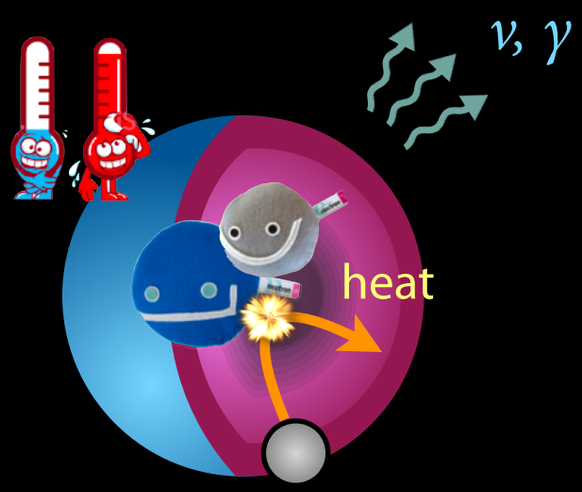

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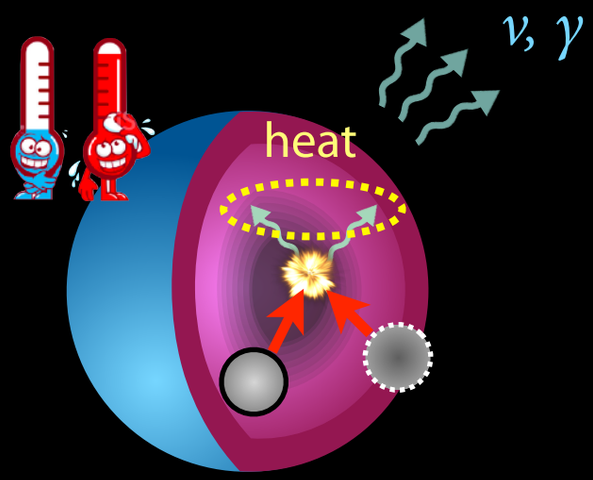

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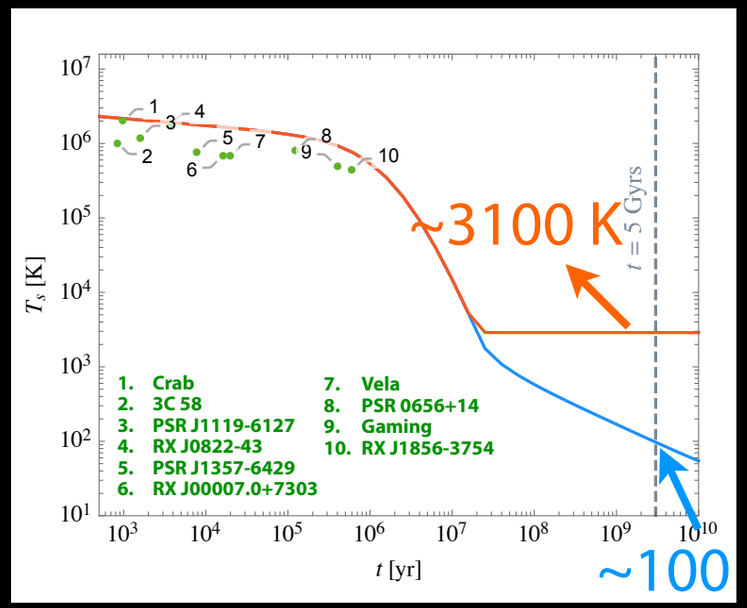

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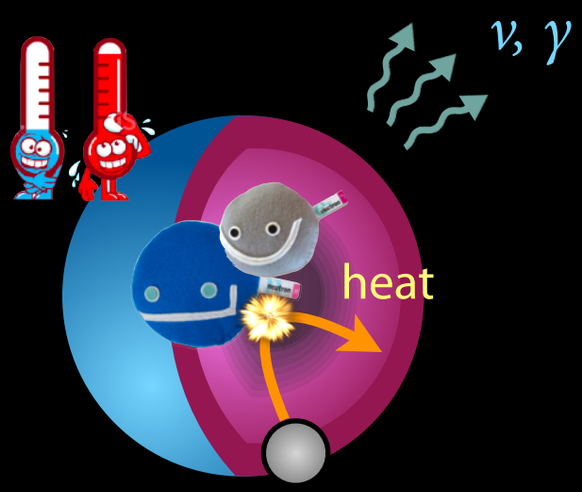

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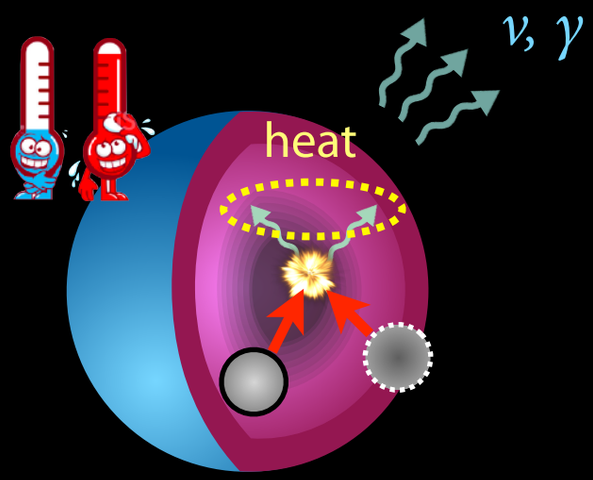

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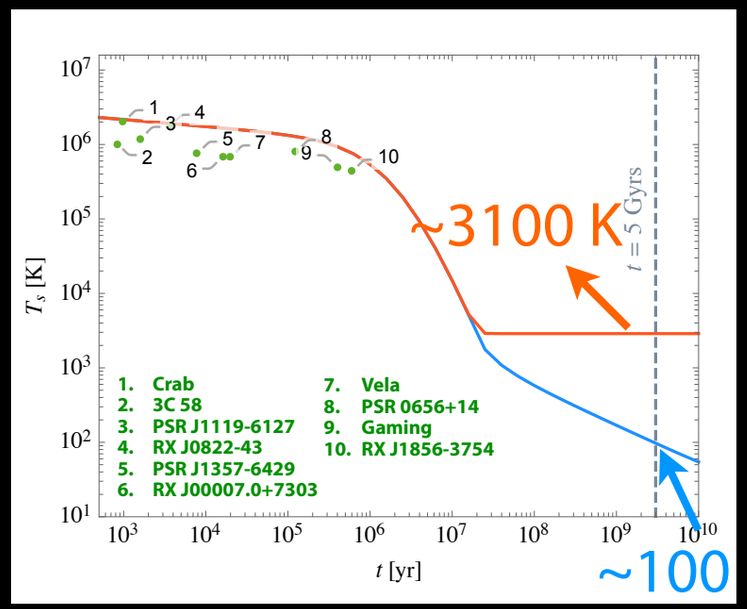

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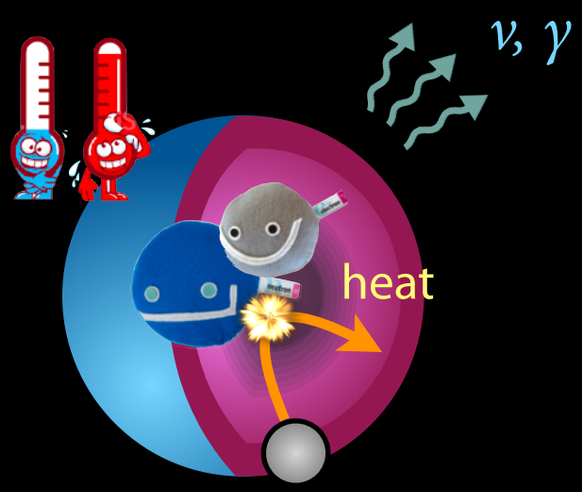

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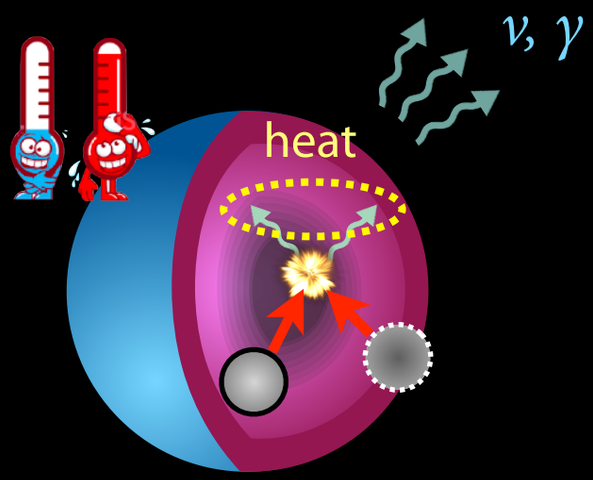

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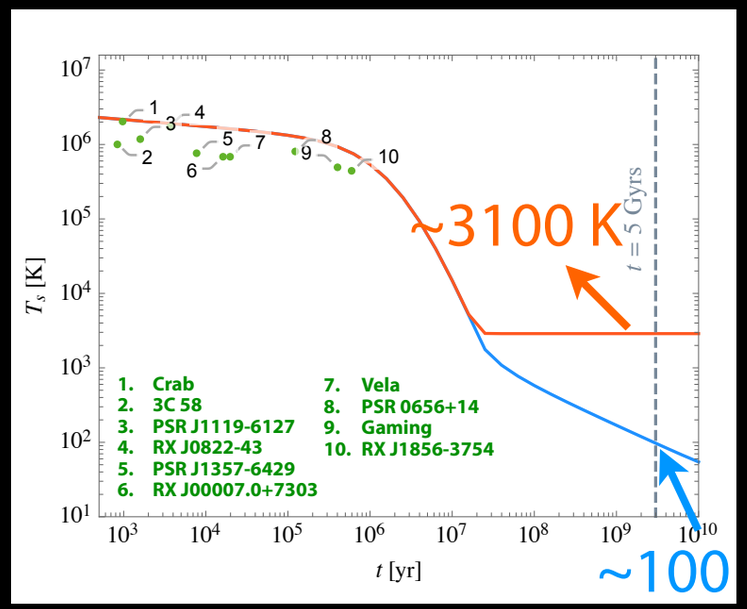

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- The temperature difference between the prediction of the standard cooling mechanism and observation can be used to constrain DM and BSM physics

Lin+, *PRD* **104**, 063021 (2021)

Resulting temperature and sensitivity

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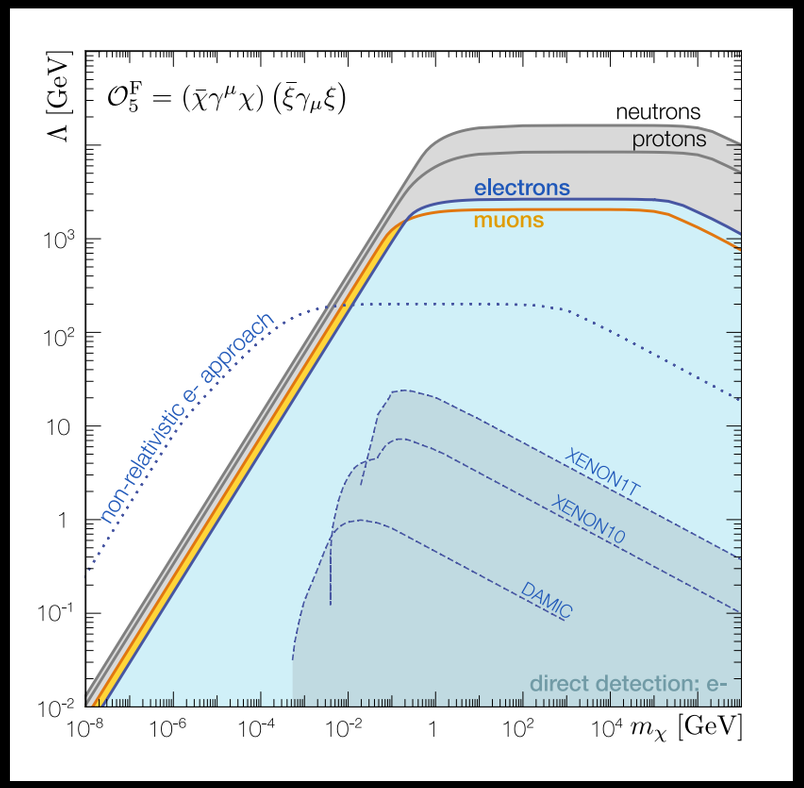
Joglekar+, *PRD* **102**, 123002 (2020)



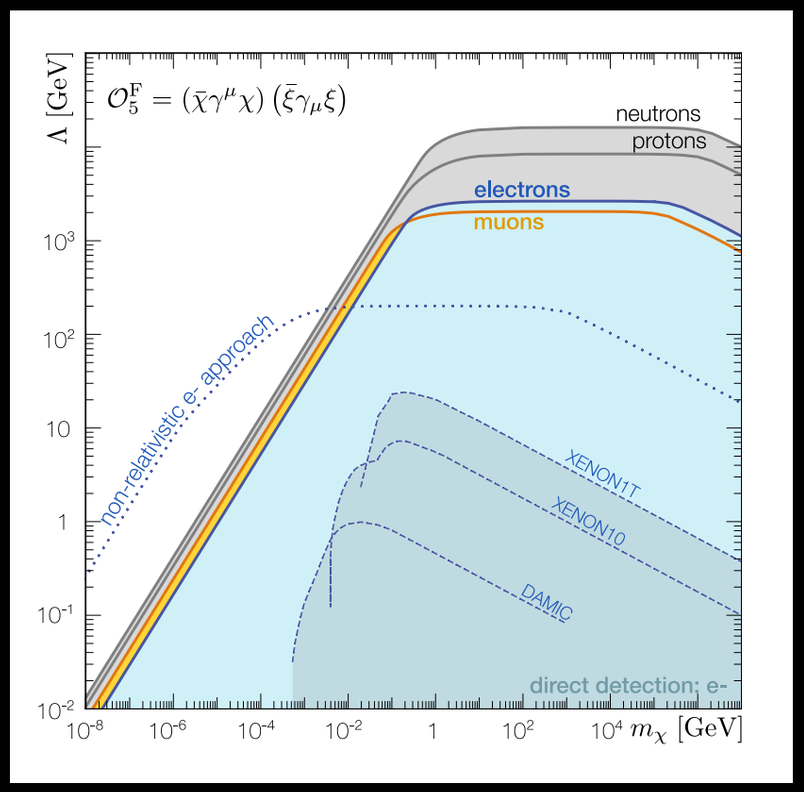
Pure kinetic heating

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

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

Resulting temperature and sensitivity

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



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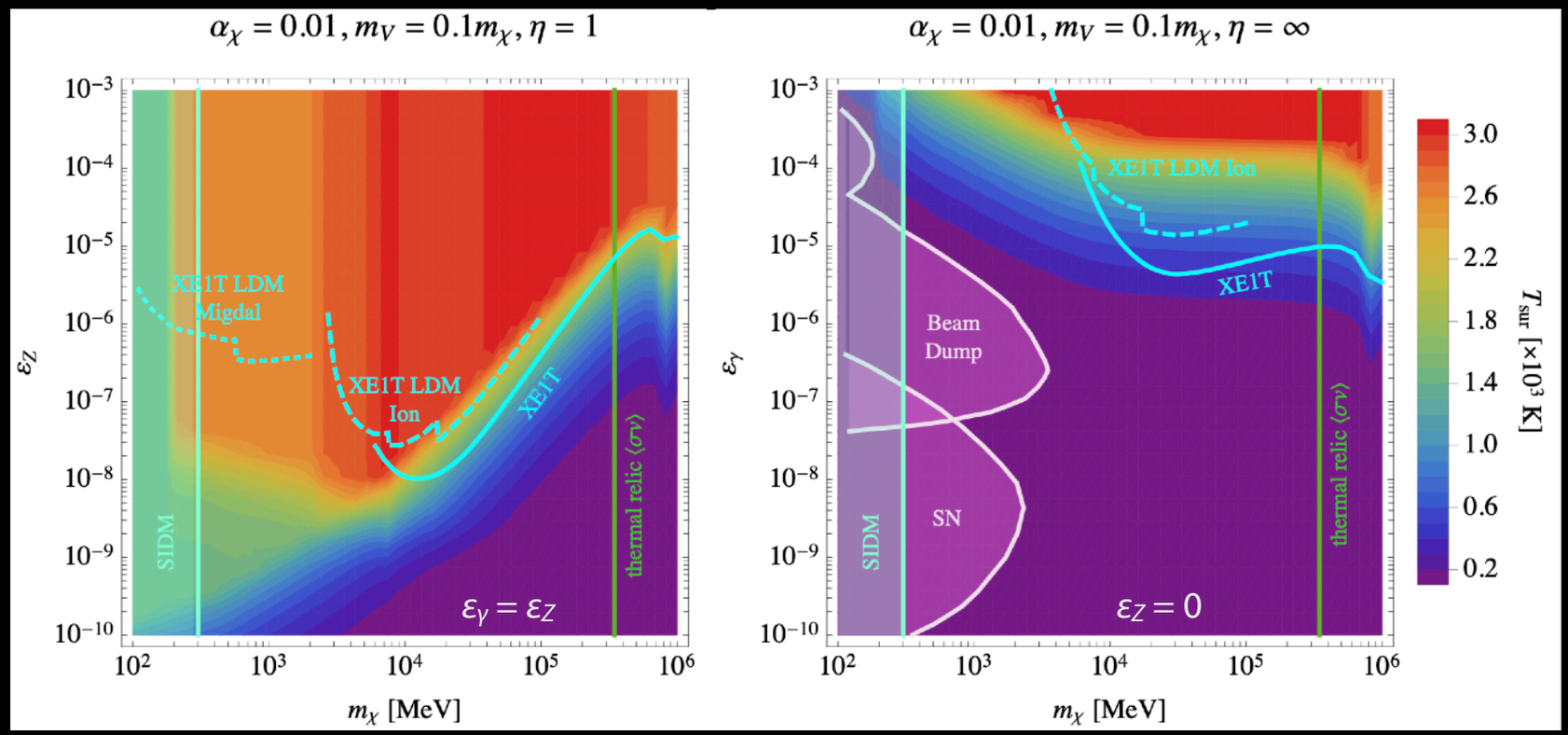

Kinetic + annihilation heating

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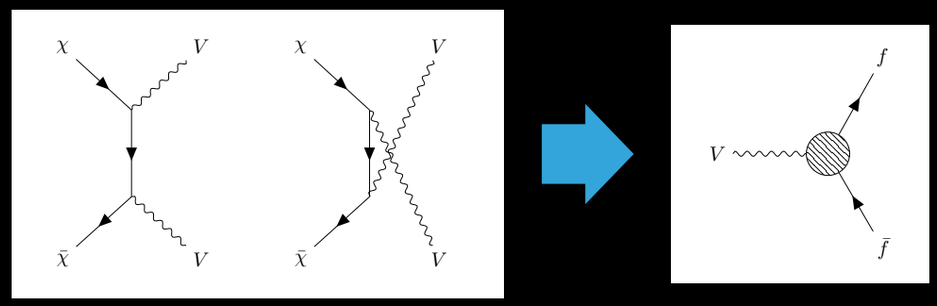
- The neutron to proton yields in NS is about 100, an ideal place for testing asymmetry couplings of DM to EM (ε_γ) & NC (ε_Z) interactions

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



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…for ADM reviews

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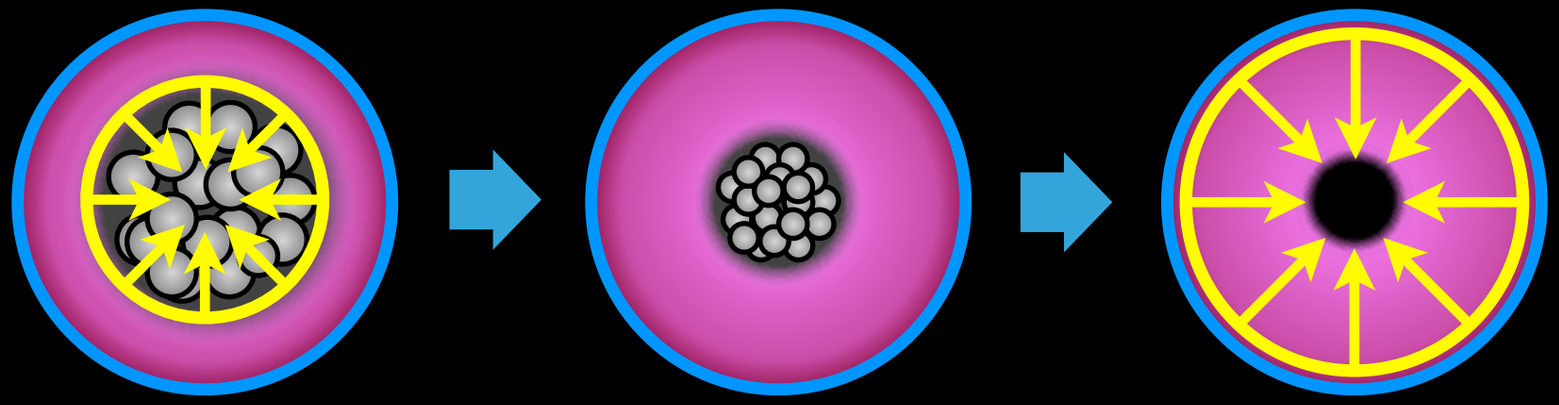

- Asymmetric DM: No annihilation to deplete the number of DM captured in the NS then trigger the gravitational instability
- Fermi degeneracy pressure could be overcame by attractive DM self-interaction ➡ Black hole (BH)
- Accretion dominates or evaporation dominates?

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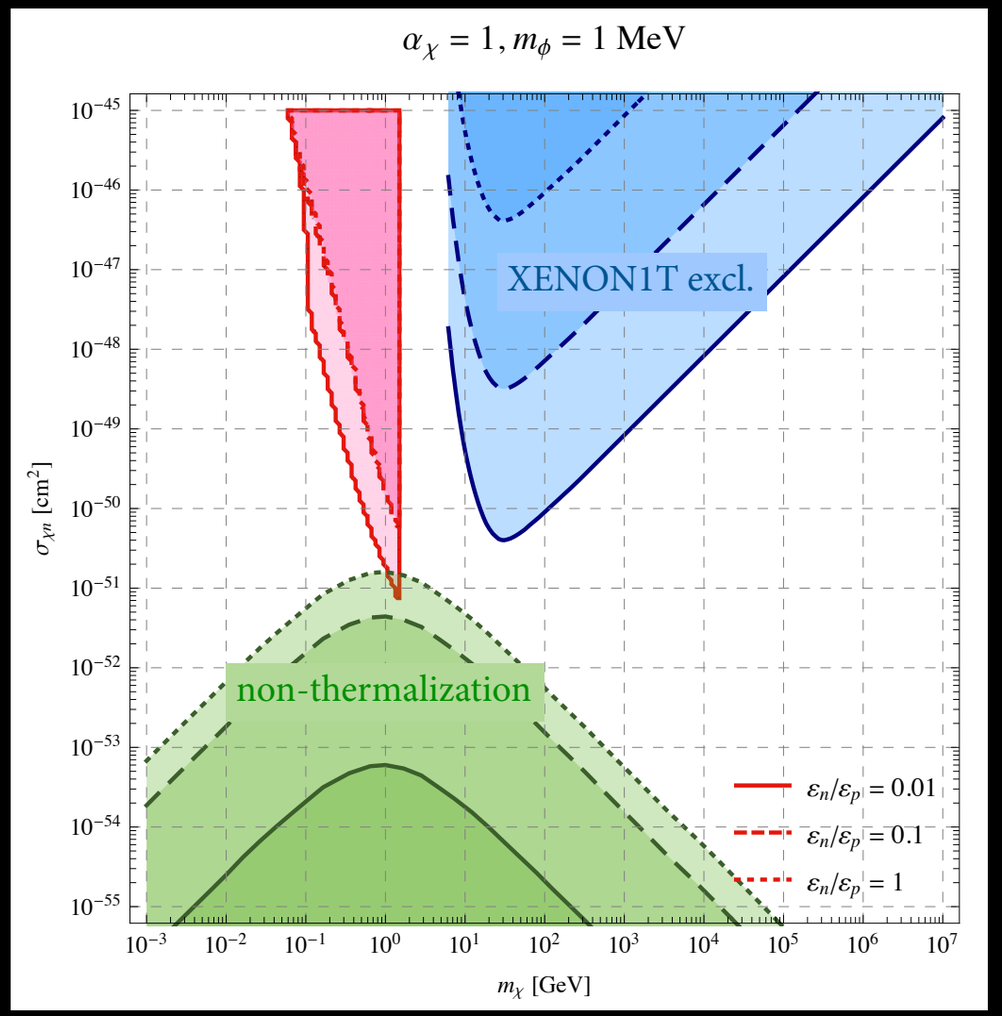

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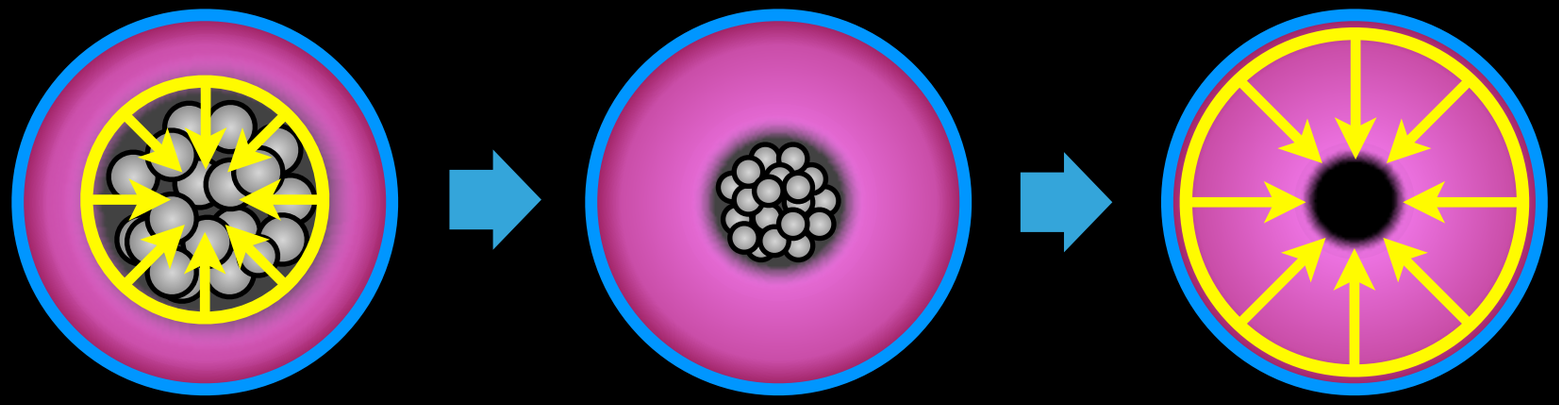

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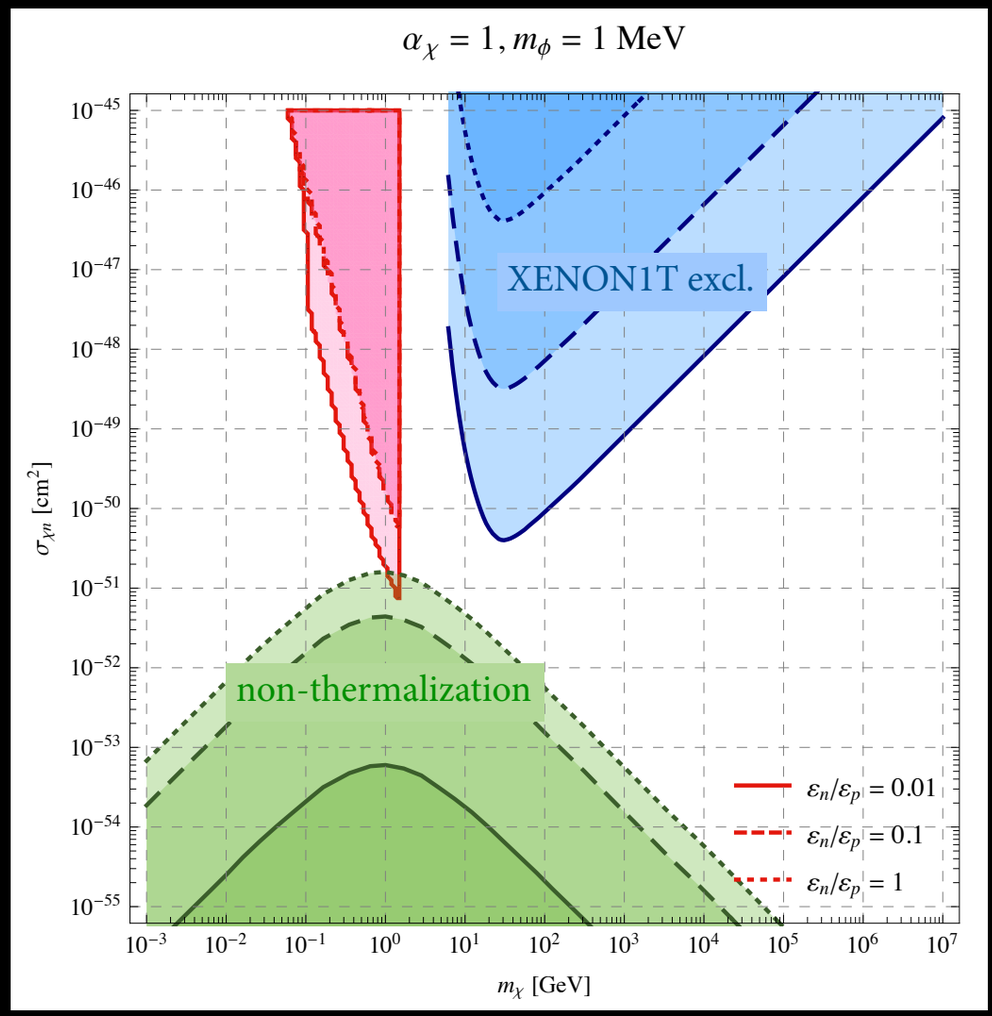

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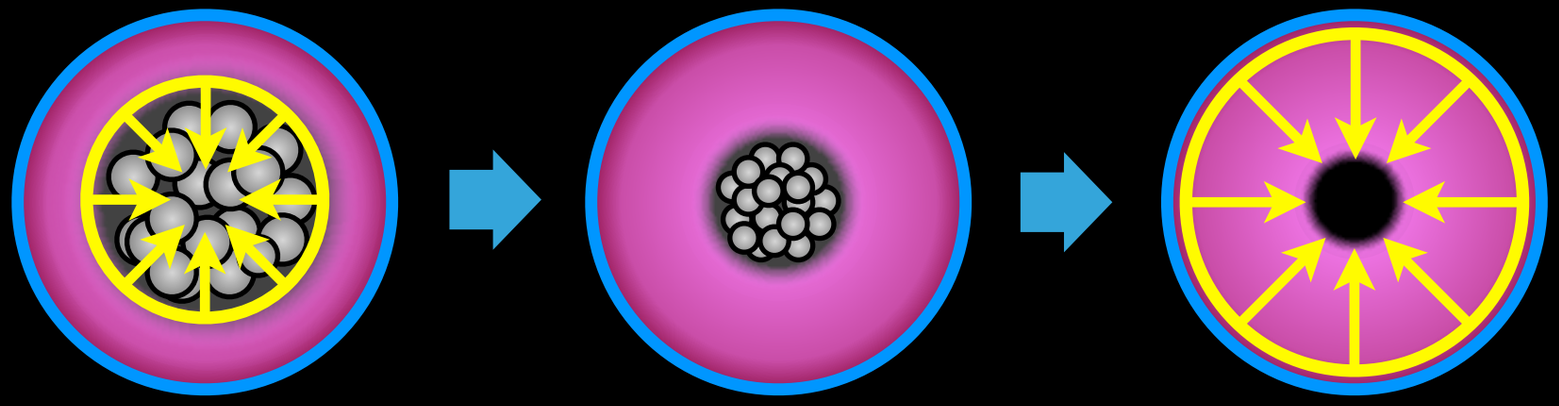

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- Does the DM effective mass in the high density region change due to DM self-interaction
  Gresham+, *PRD* **96**, 096012 (2017)
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- Bosonic DM ➡ Bose-Einstein condensation
  Bell+, *PRD* **87**, 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)
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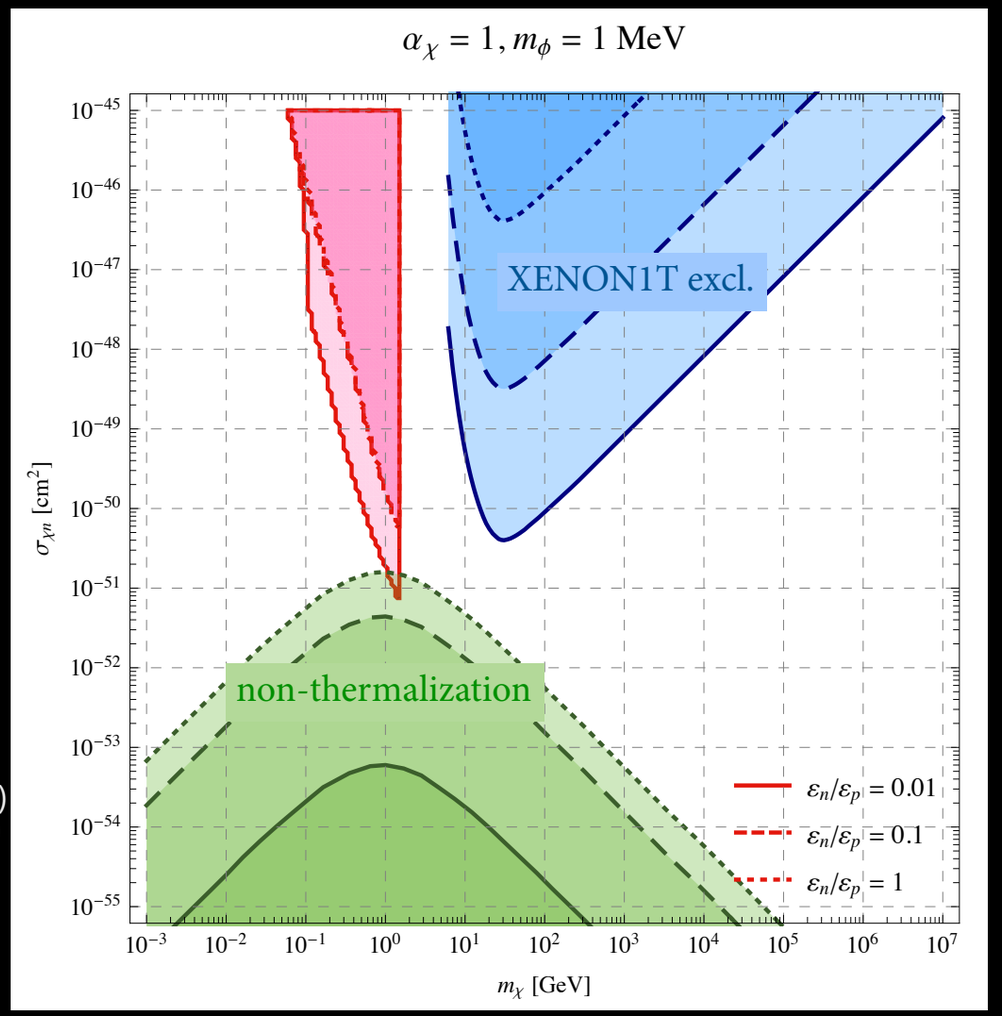

Lighter than MeV: The SNν

The idea behind: Boosted DM (BDM)

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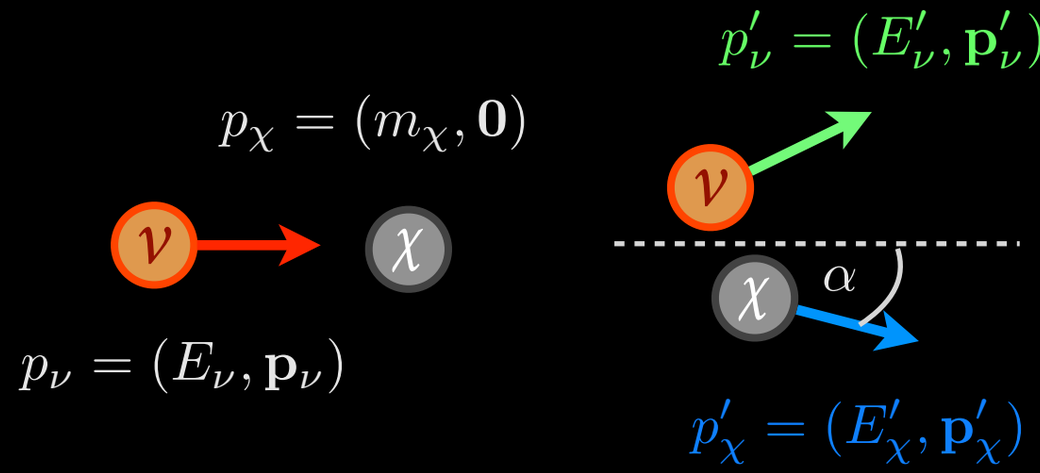

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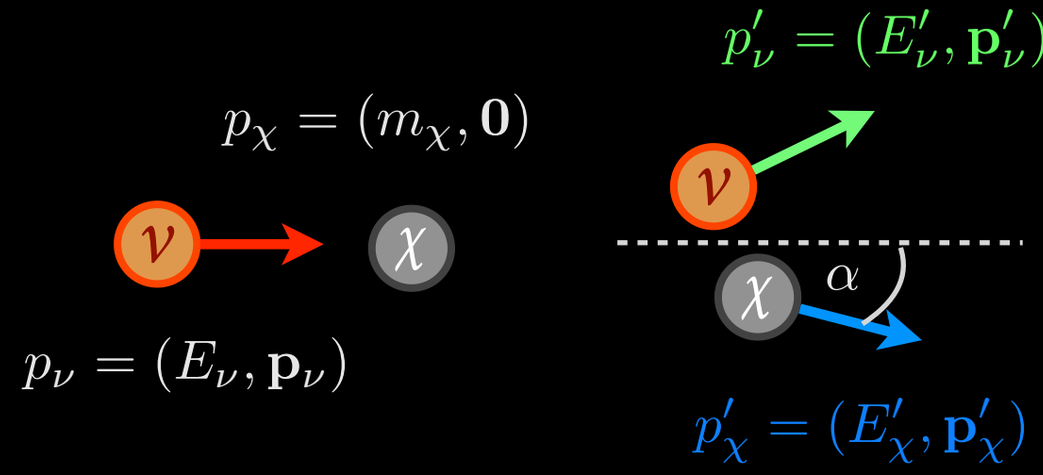

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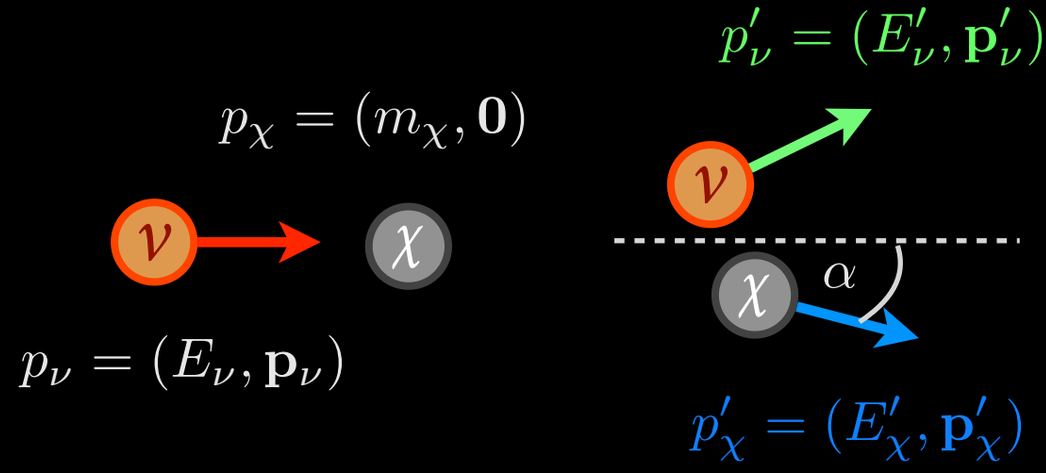

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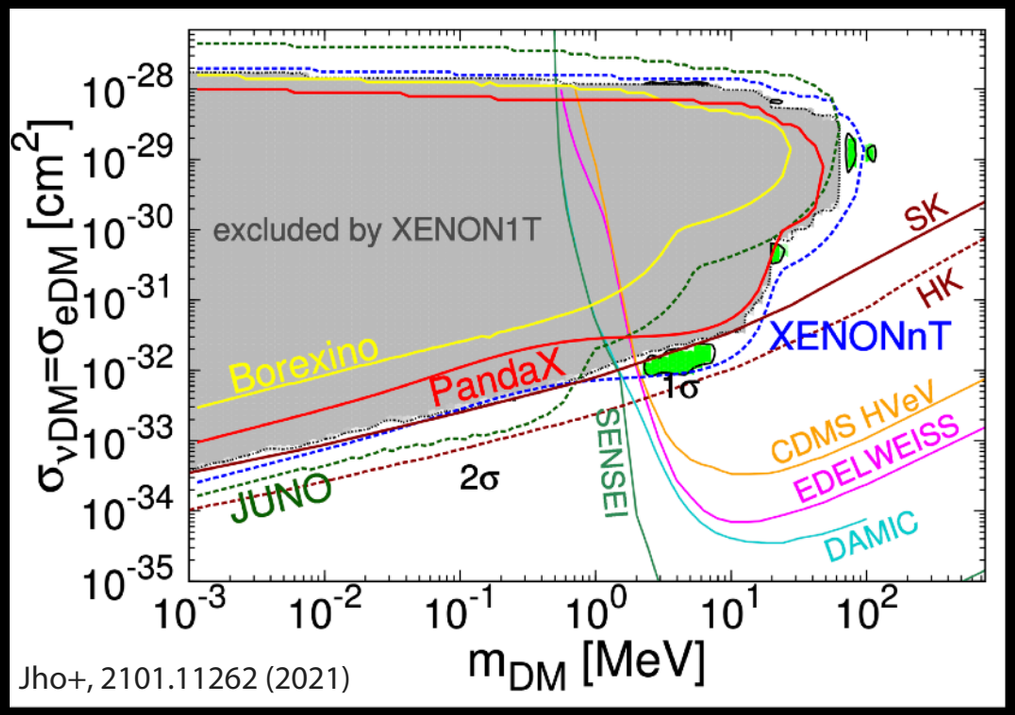
- Current constraints



Cosmic-neutrino BDM

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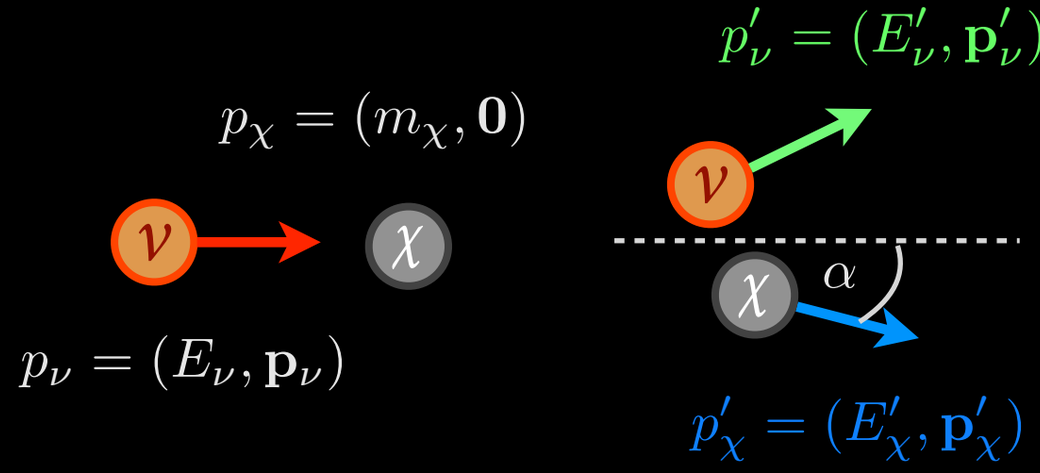

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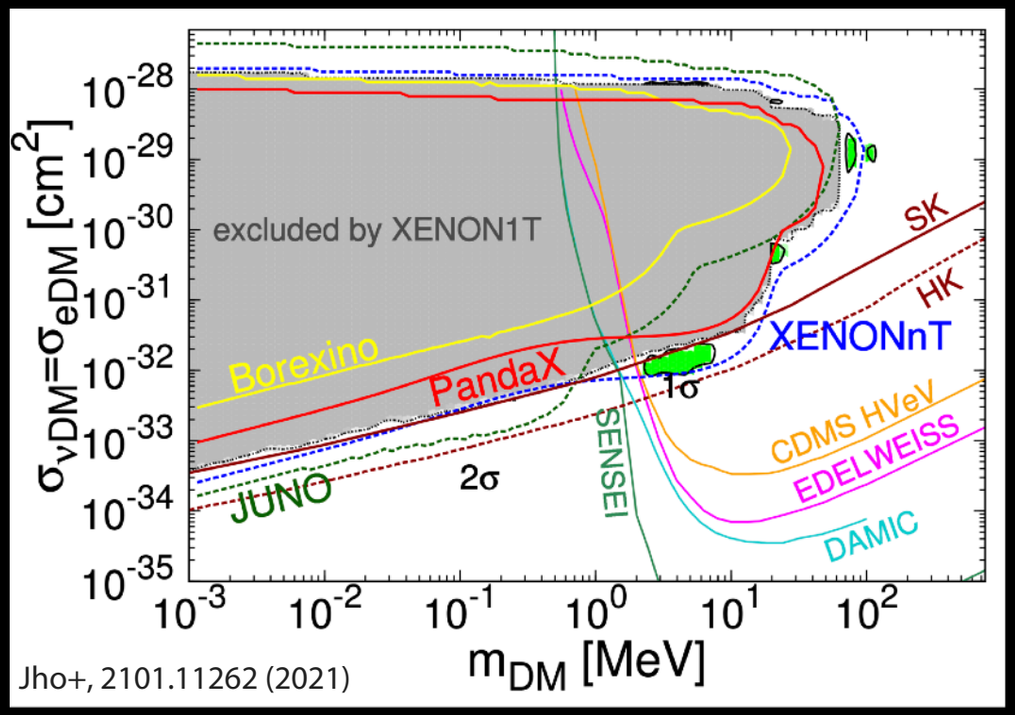

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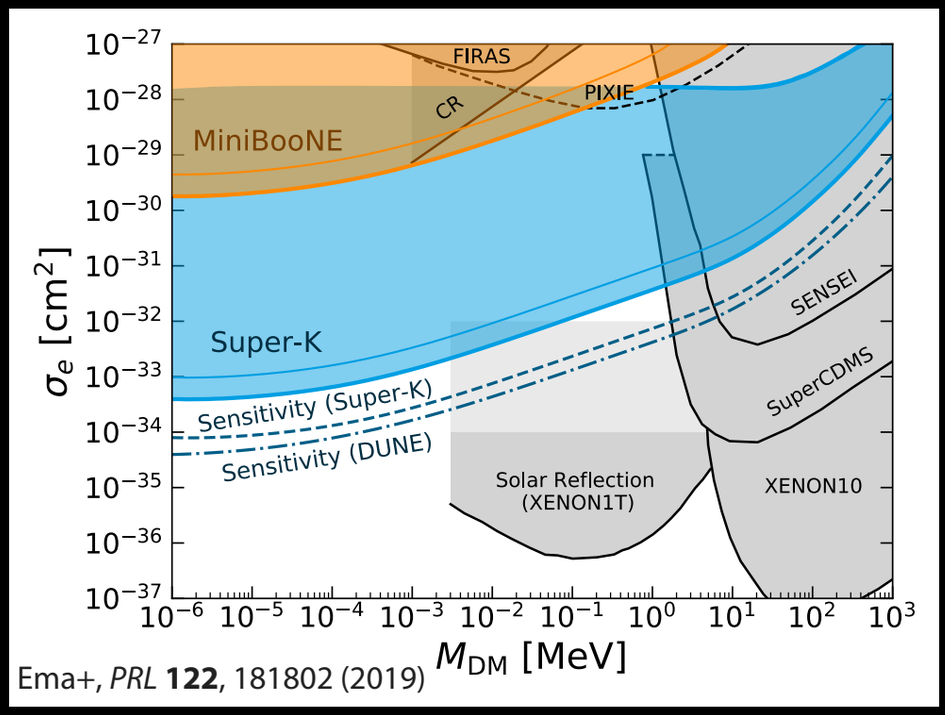
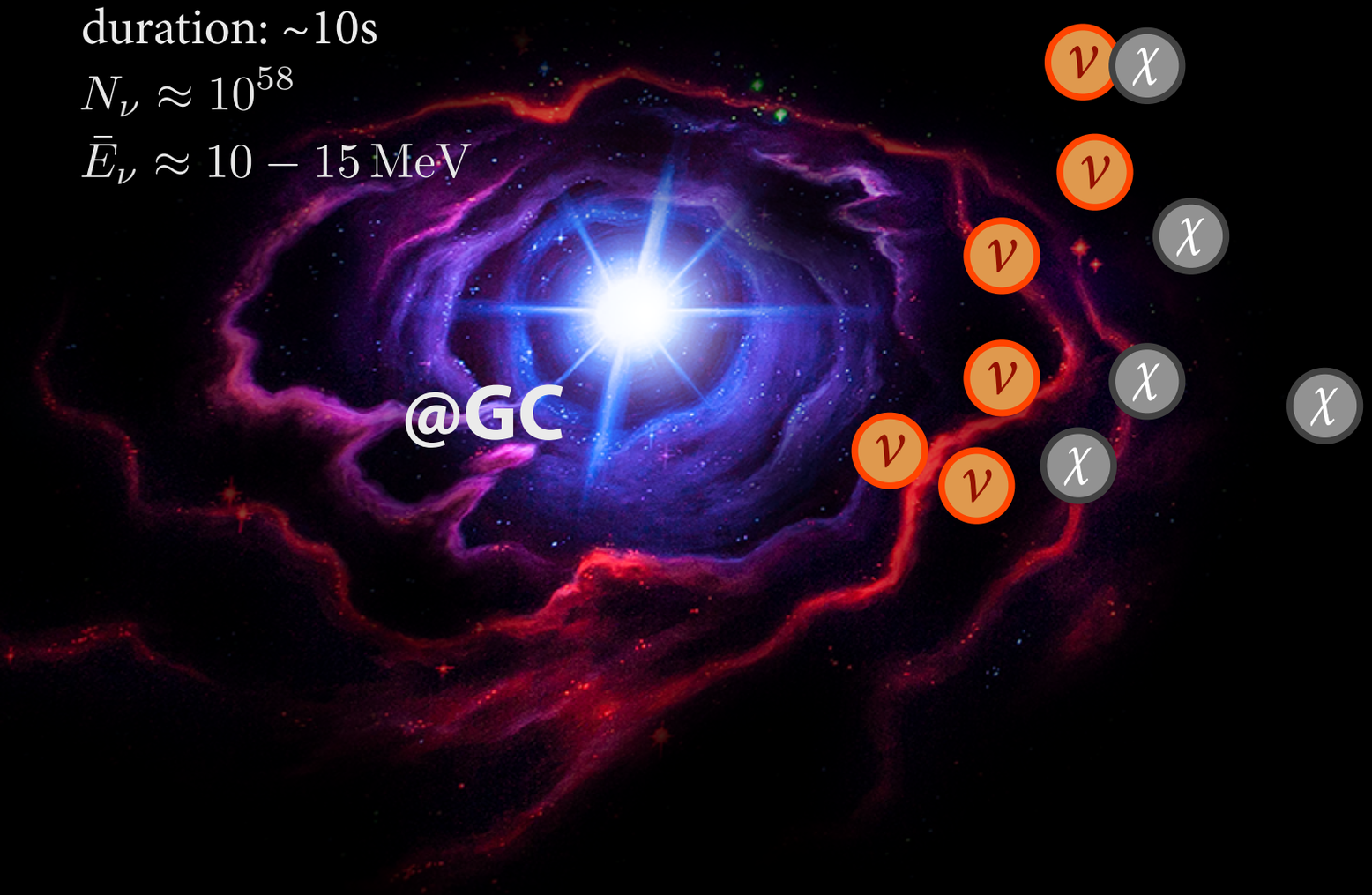


Cosmic-ray BDM

duration: ~10s

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

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



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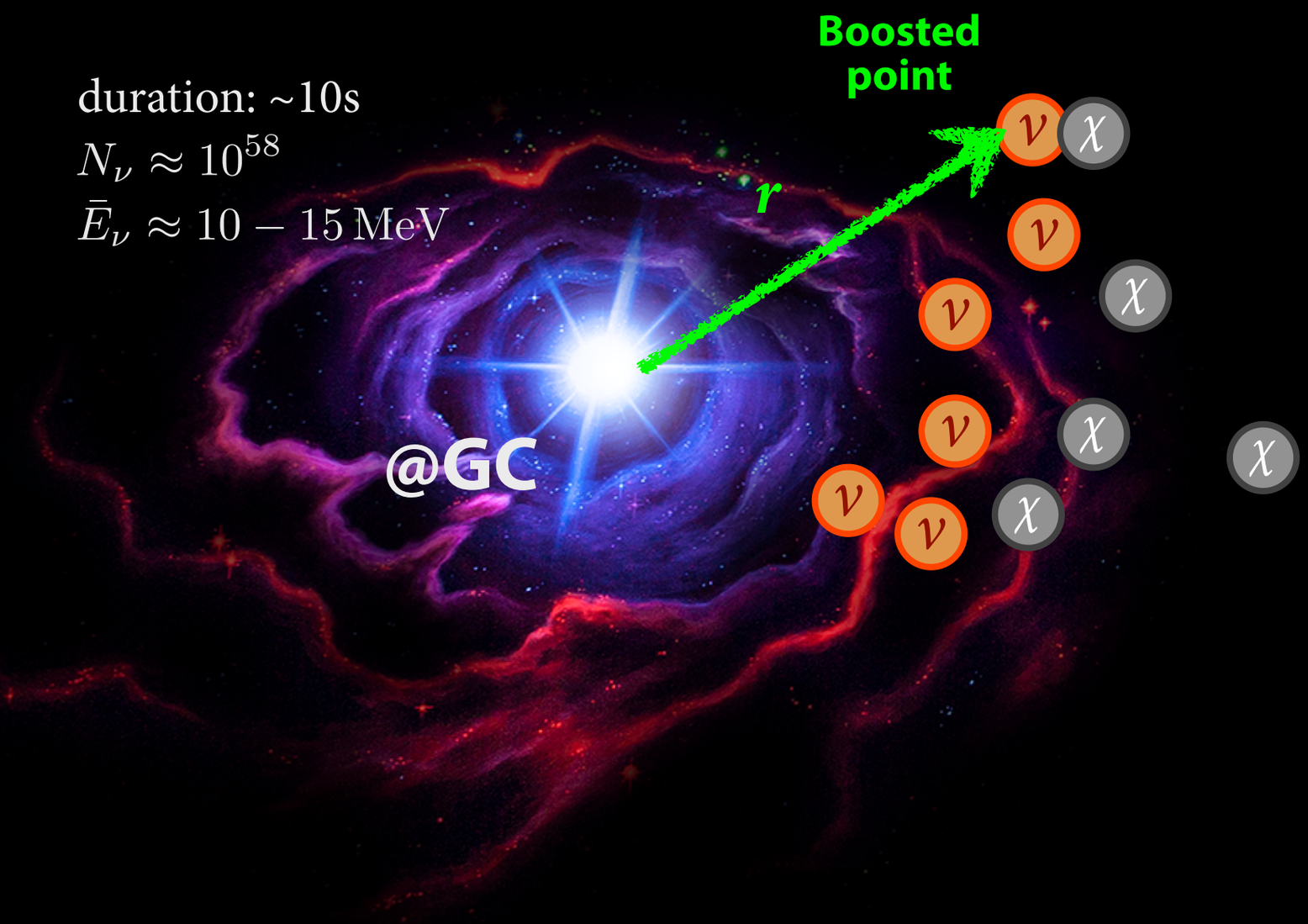

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@GC

Boosted point

r

α

ν_χ

ℓ

Super-K

Time-of-flight

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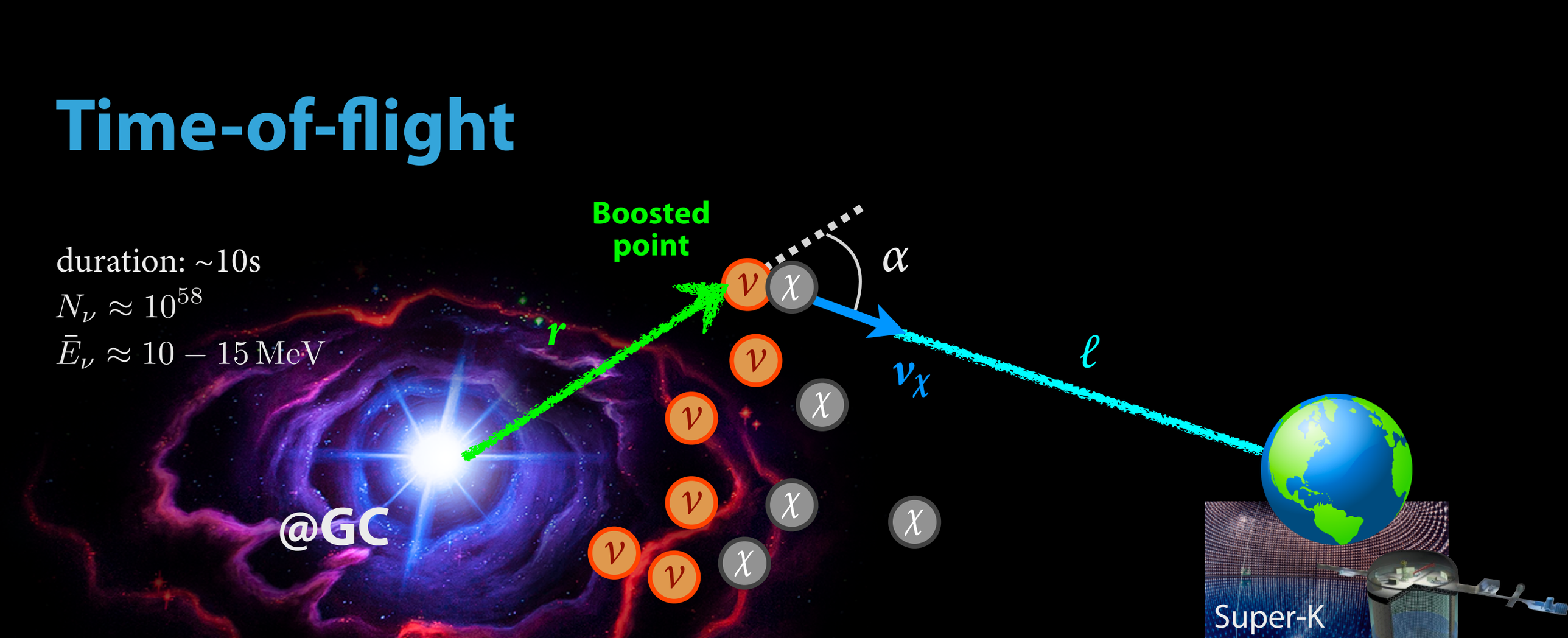

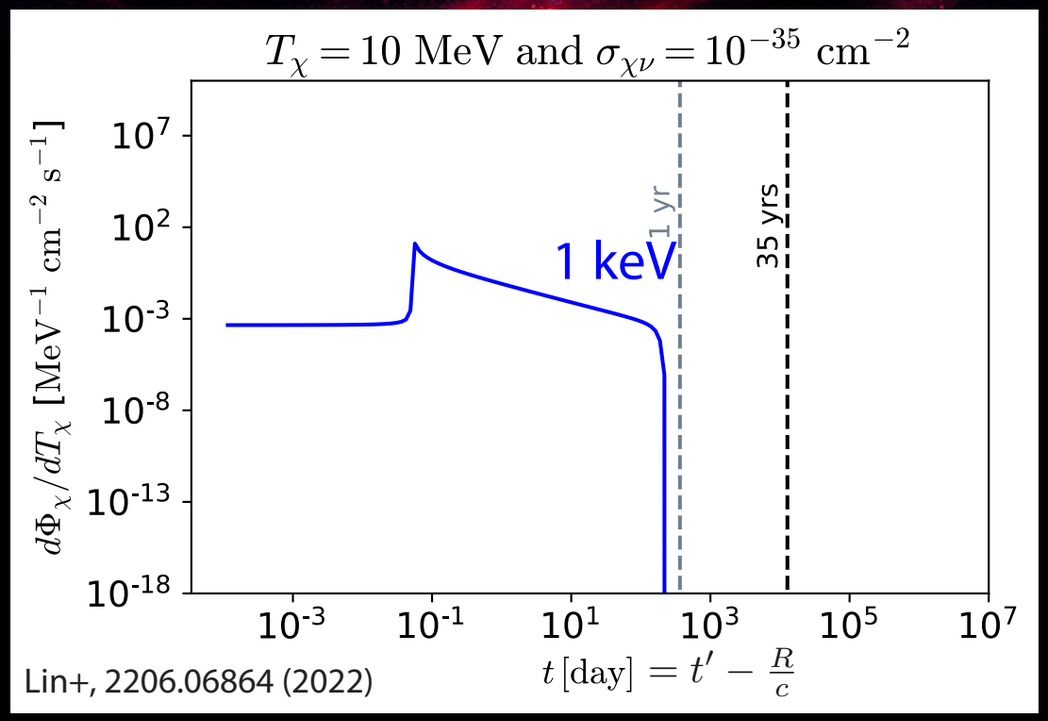

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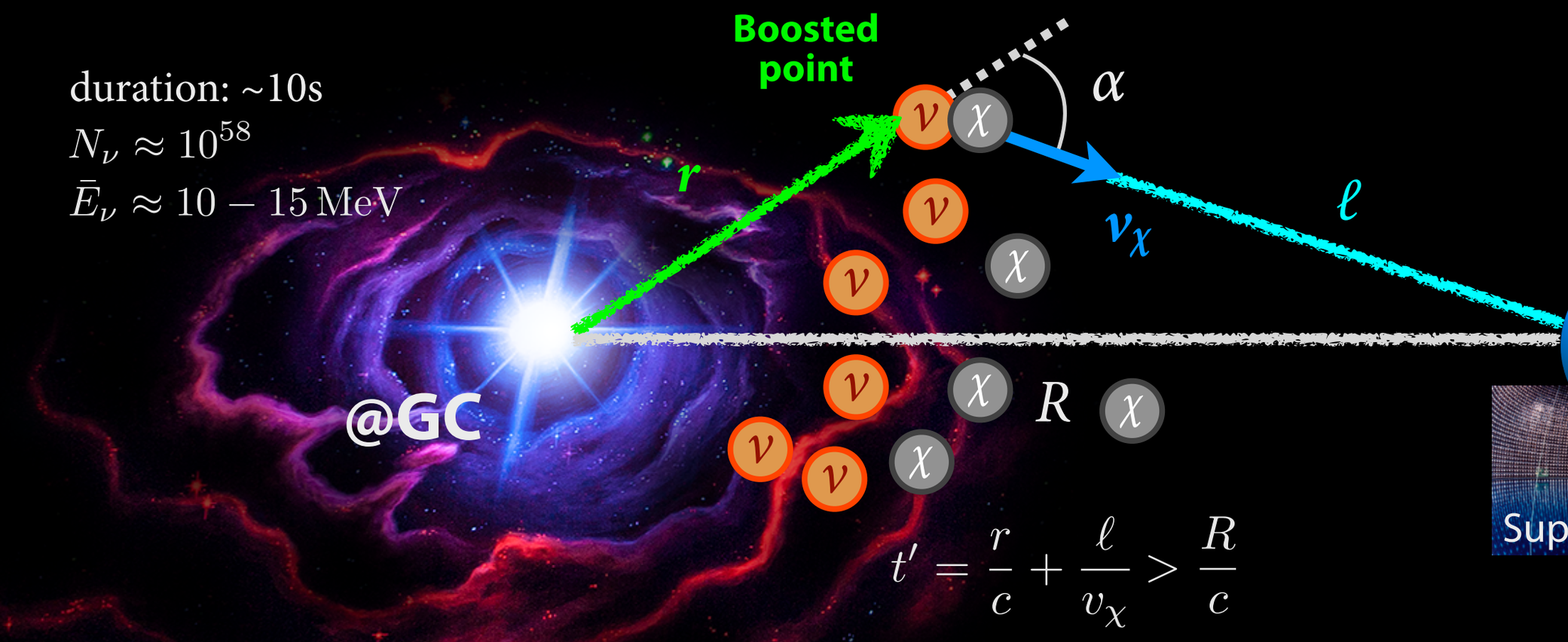
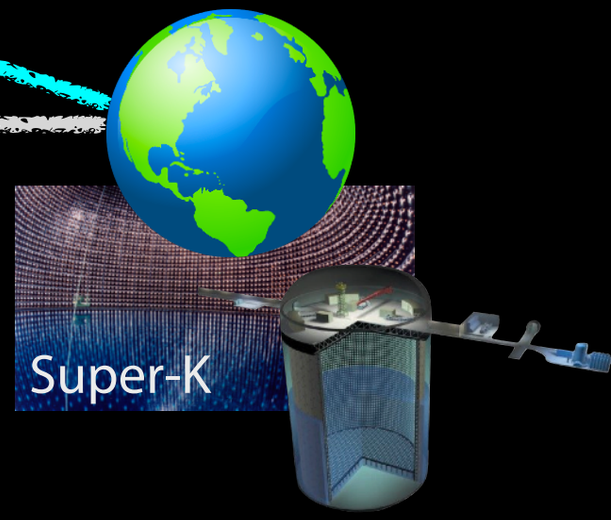
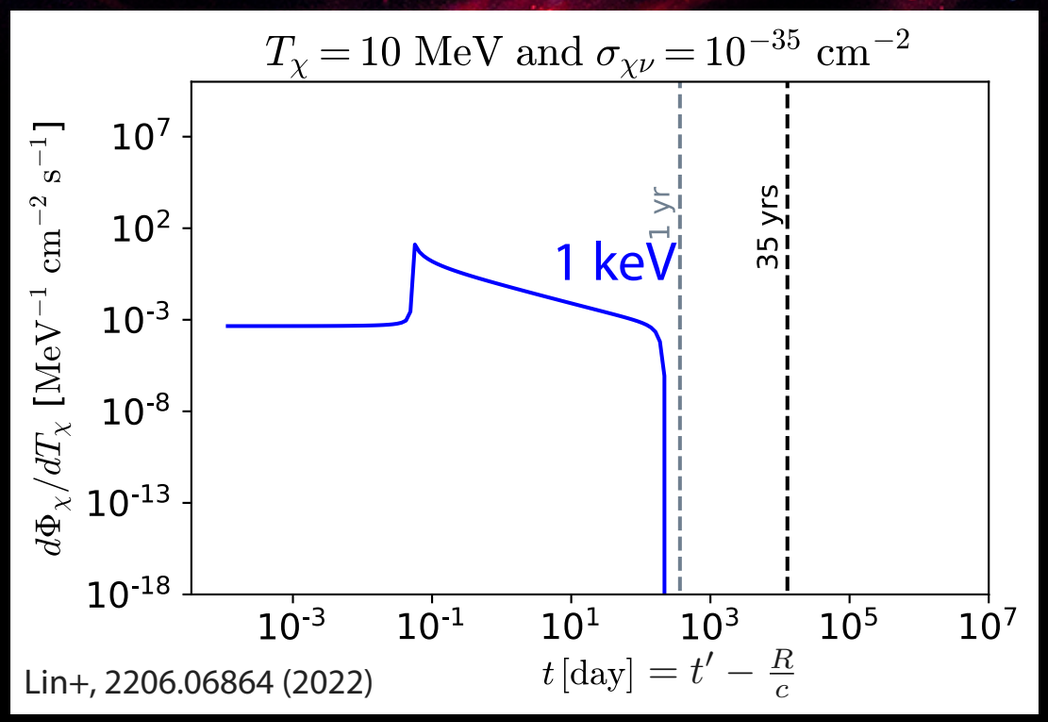




$$t' = \frac{r}{c} + \frac{\ell}{v_\chi} > \frac{R}{c}$$



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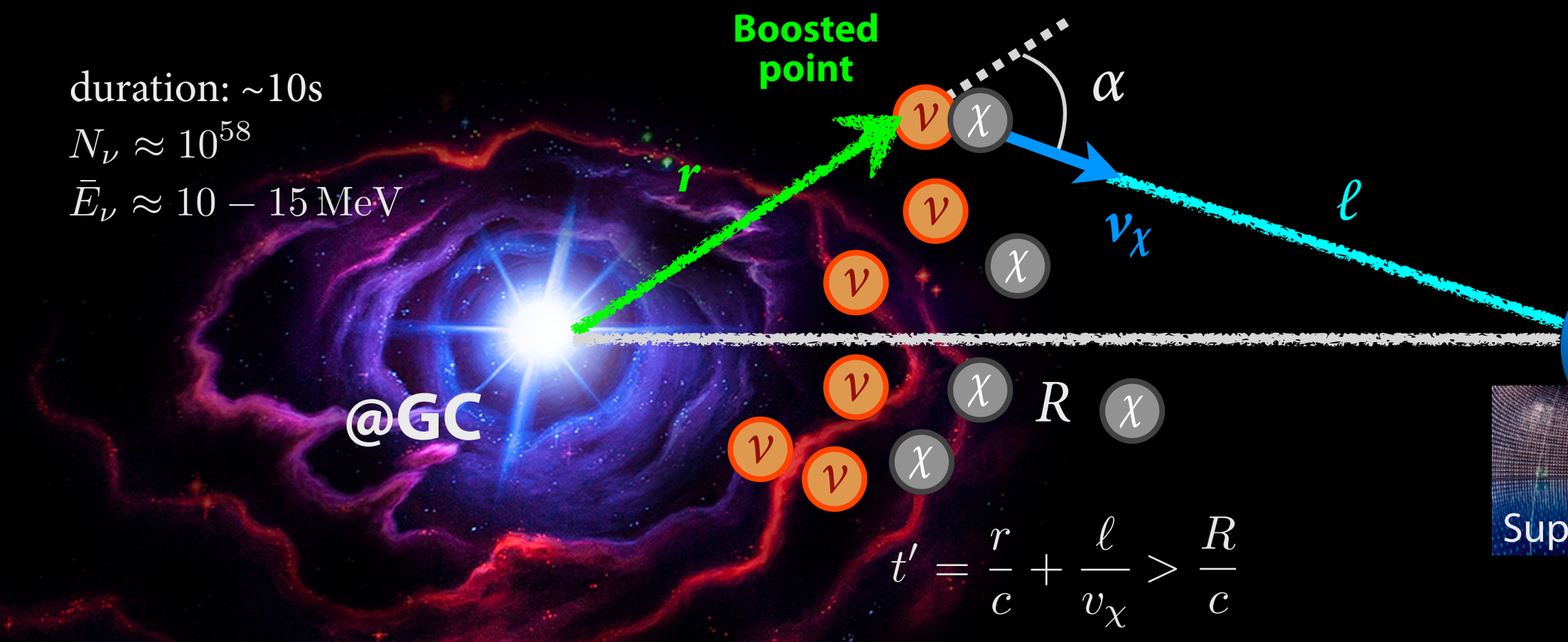
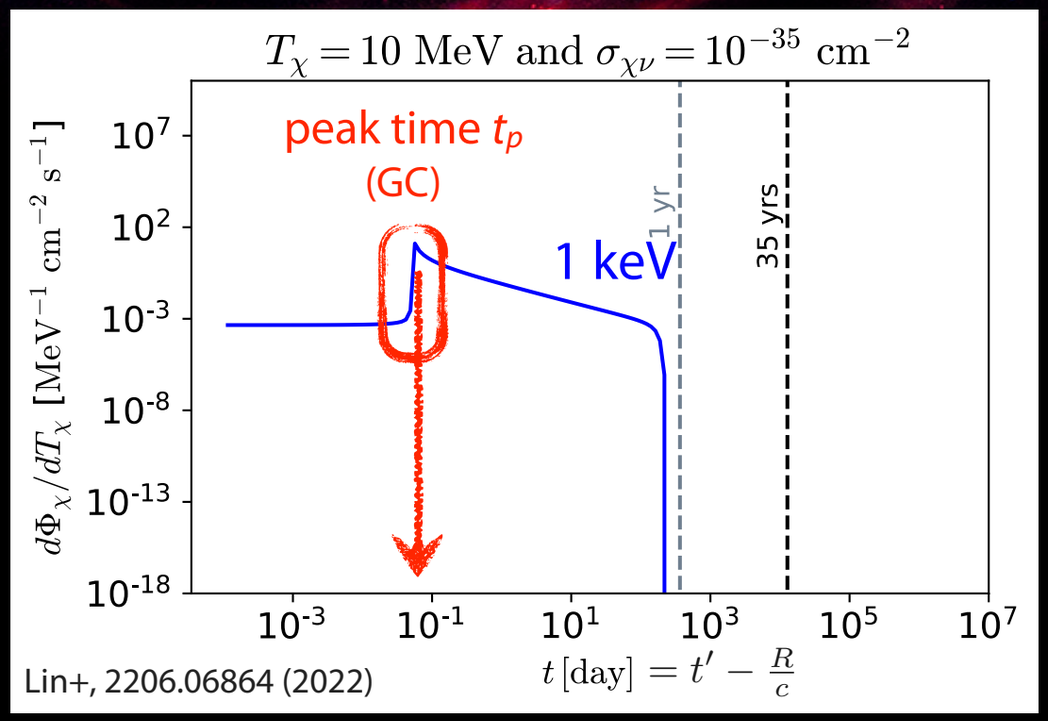
$\bar{E}_\nu \approx 10 - 15\,\mathrm{MeV}$



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



- Peak time $t_p \sim R(1/v_\chi - 1/c)$

Time-of-flight

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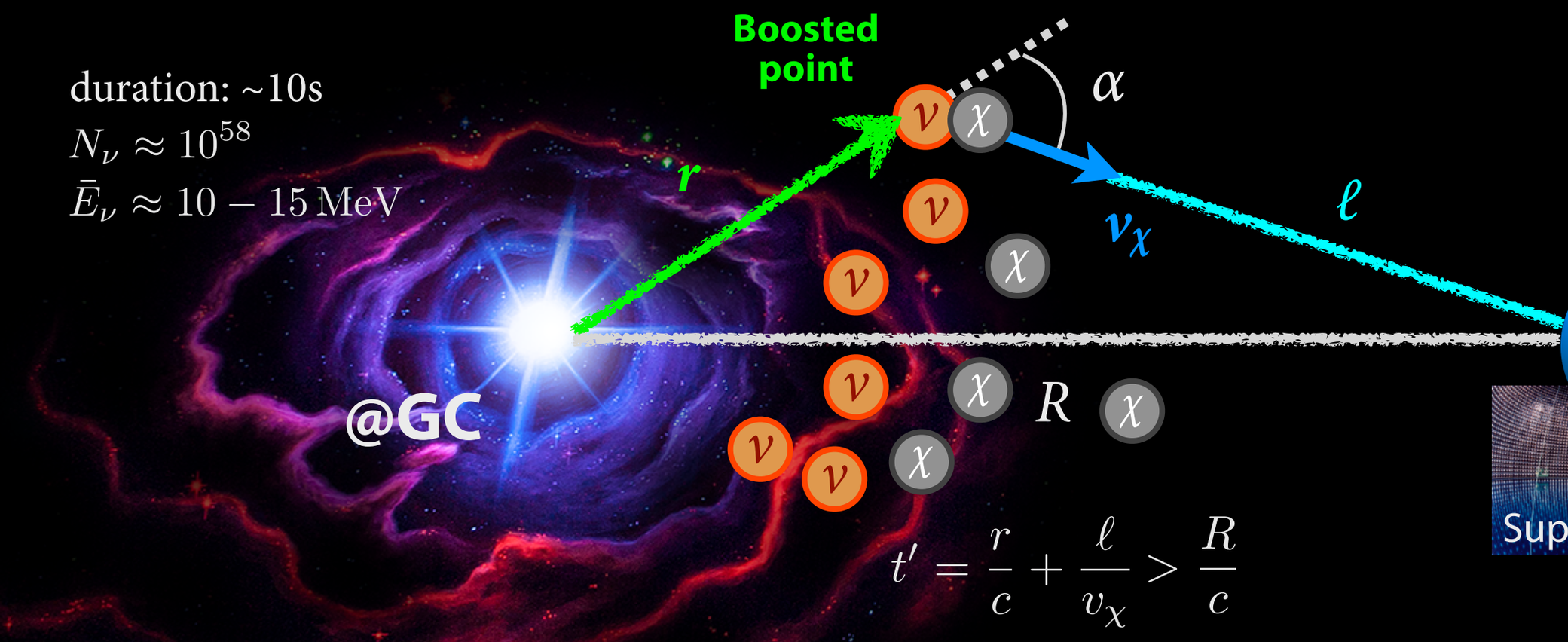

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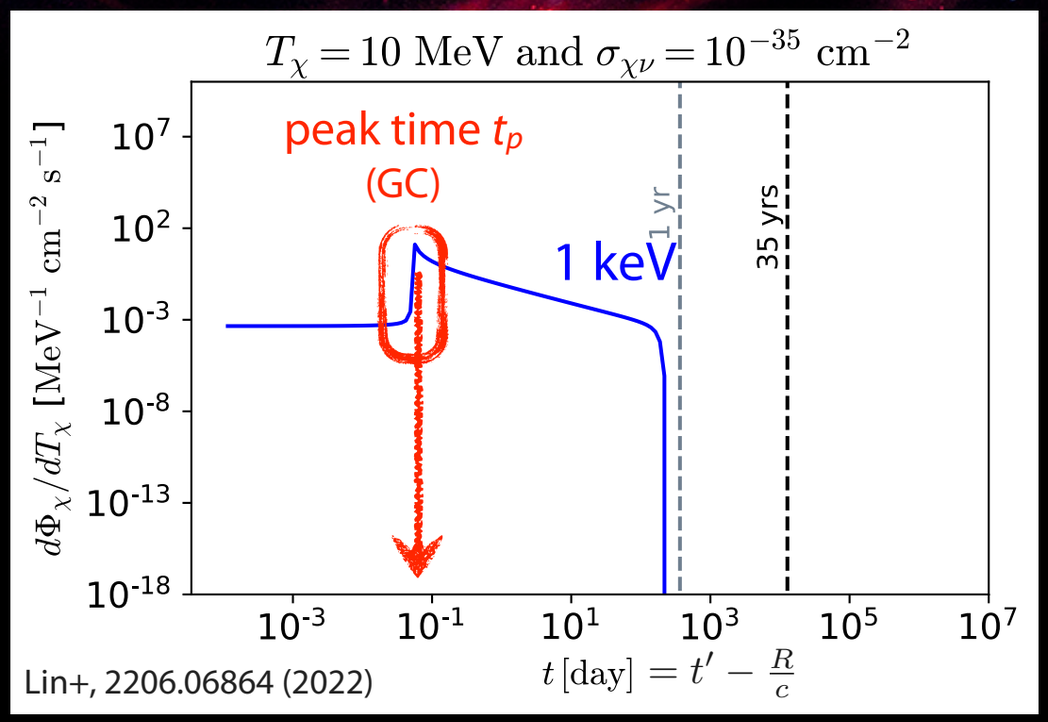

- Peak time $t_p \sim R(1/v_\chi - 1/c)$
- The BDM velocity is determined with

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

Time-of-flight: A direct m_χ measurement

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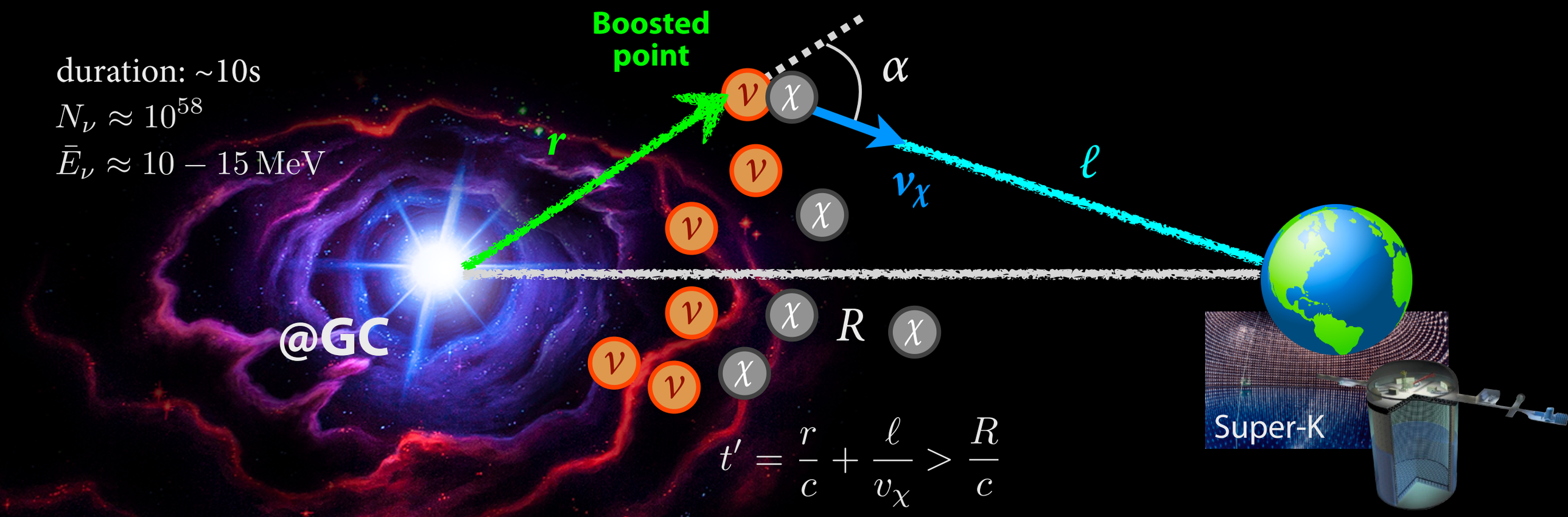

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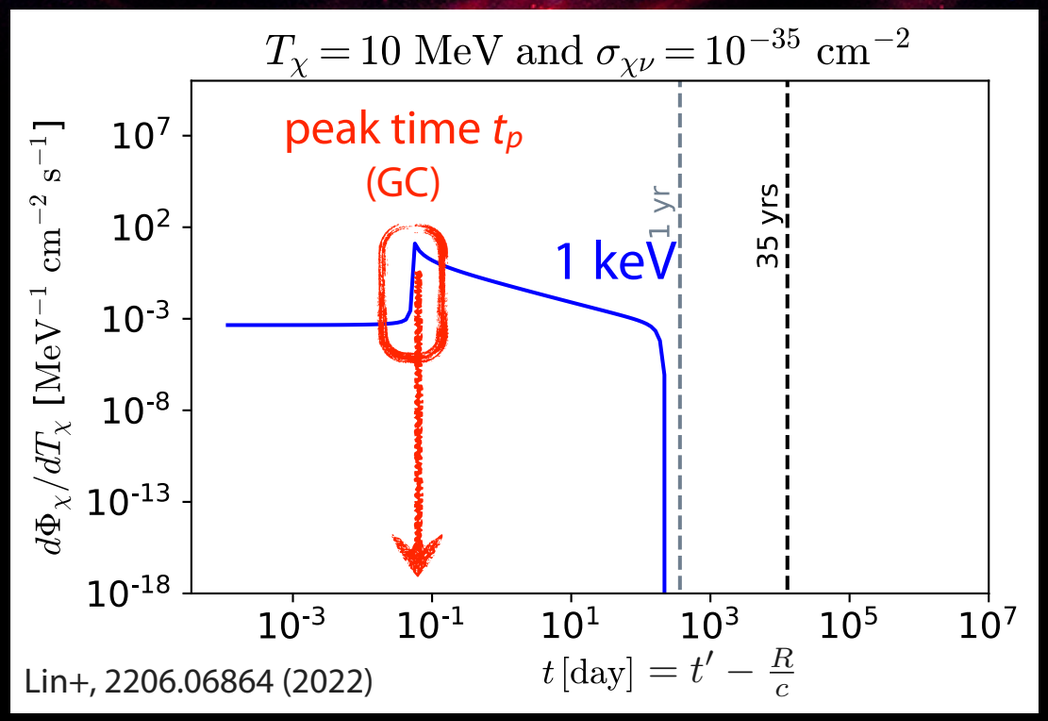

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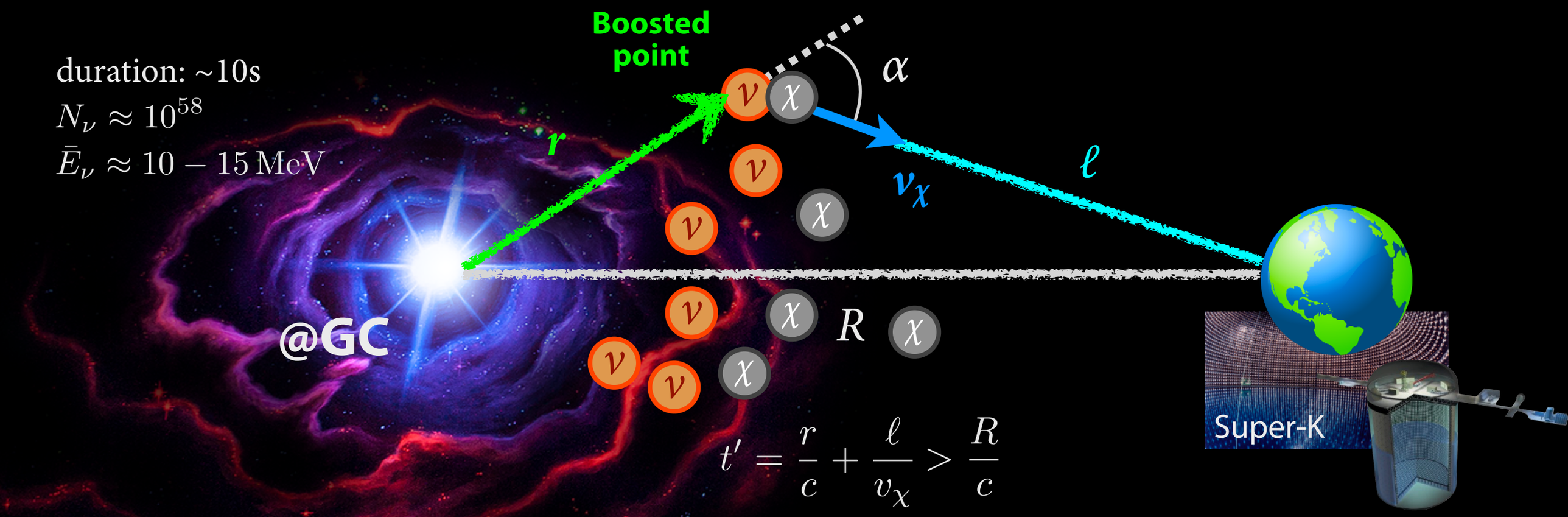

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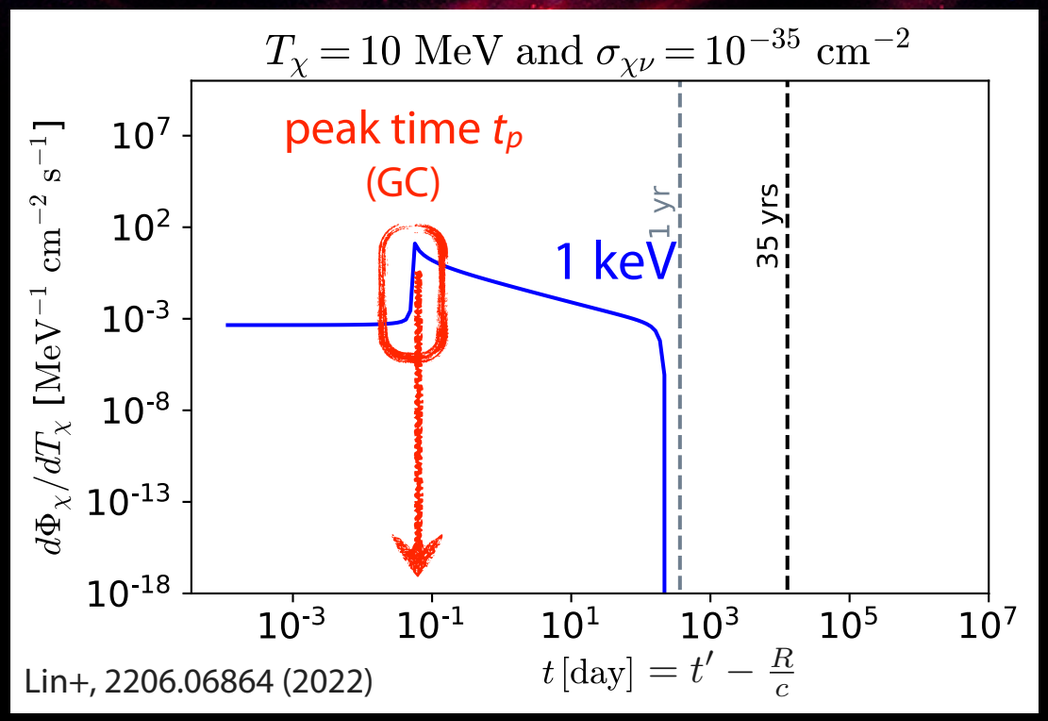

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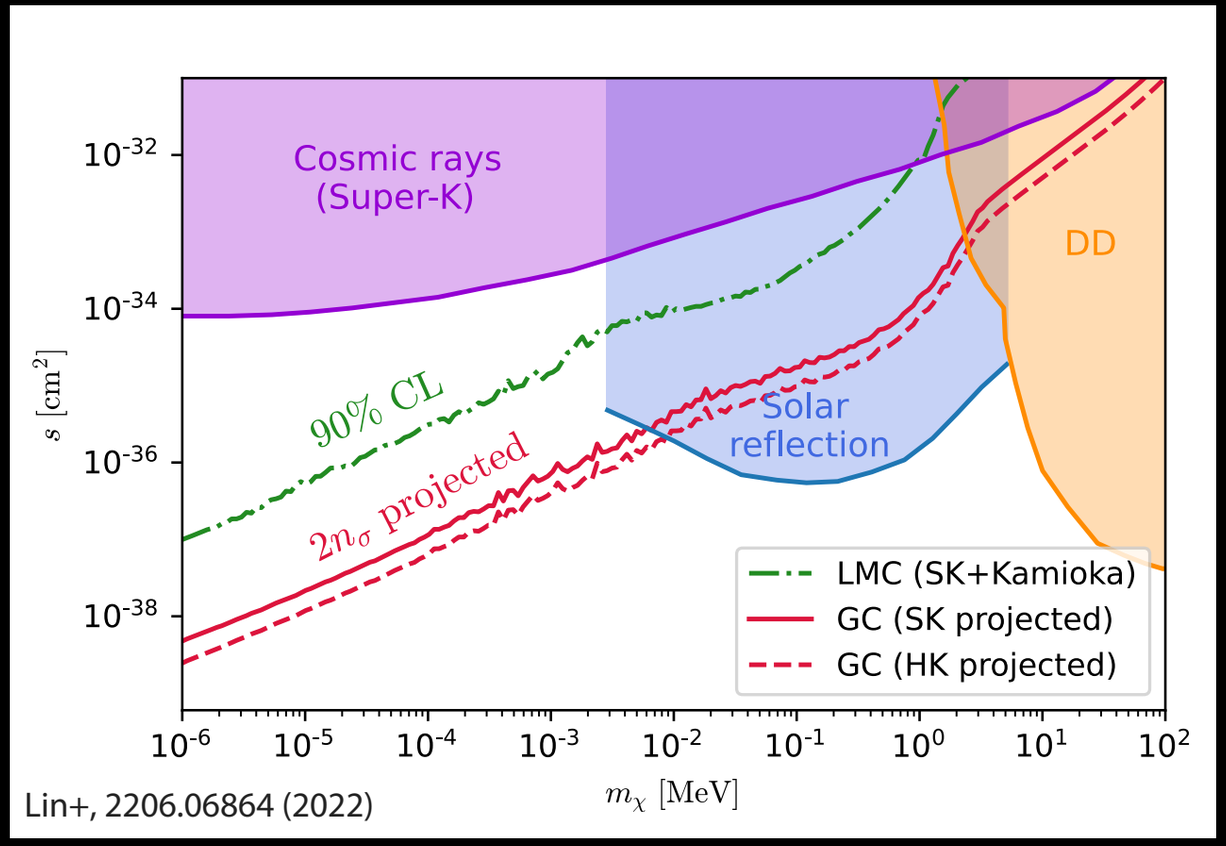
- The position of t_p is **NOT AFFECTED** by $\sigma_{\chi\nu,e}$

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)

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- **Supernova neutrinos**: **boosted DM** and **ToF**
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