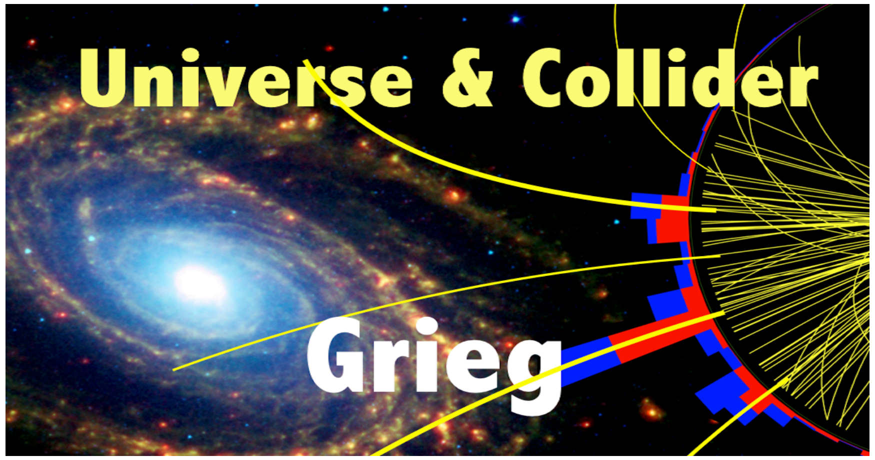
(sub-)GeV dark matter
- asymmetric dark matter -

Ayuki Kamada (University of Warsaw)



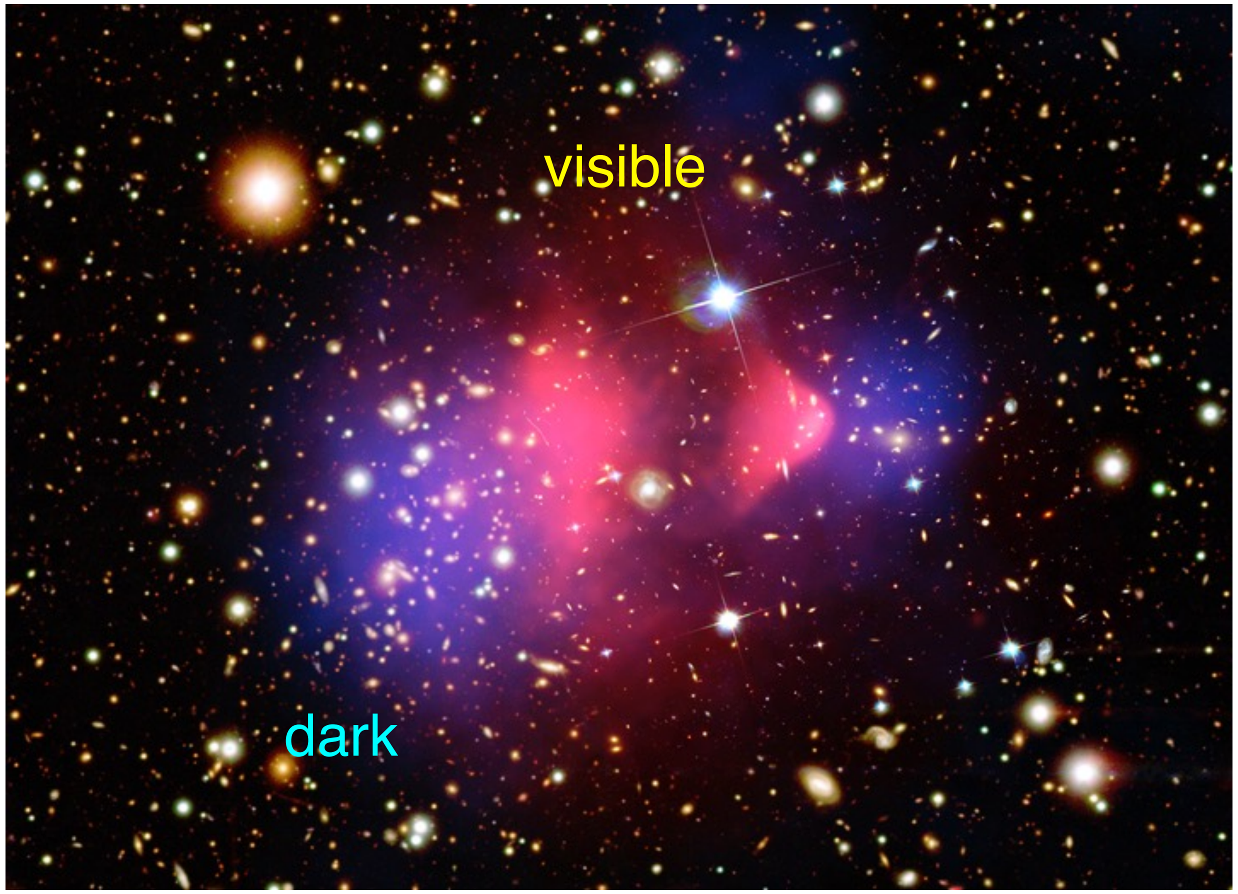
Feb. 21, 2025 @ PAiP-2025

Dark matter

Dark matter

Sebastian's talk

- evident from cosmological observations
    - cosmic microwave background (CMB)…
- essential to form galaxies in the Universe
- one of the biggest mysteries
    - astronomy, cosmology, particle physics…



bullet cluster

WIMP dark matter

Attractive features

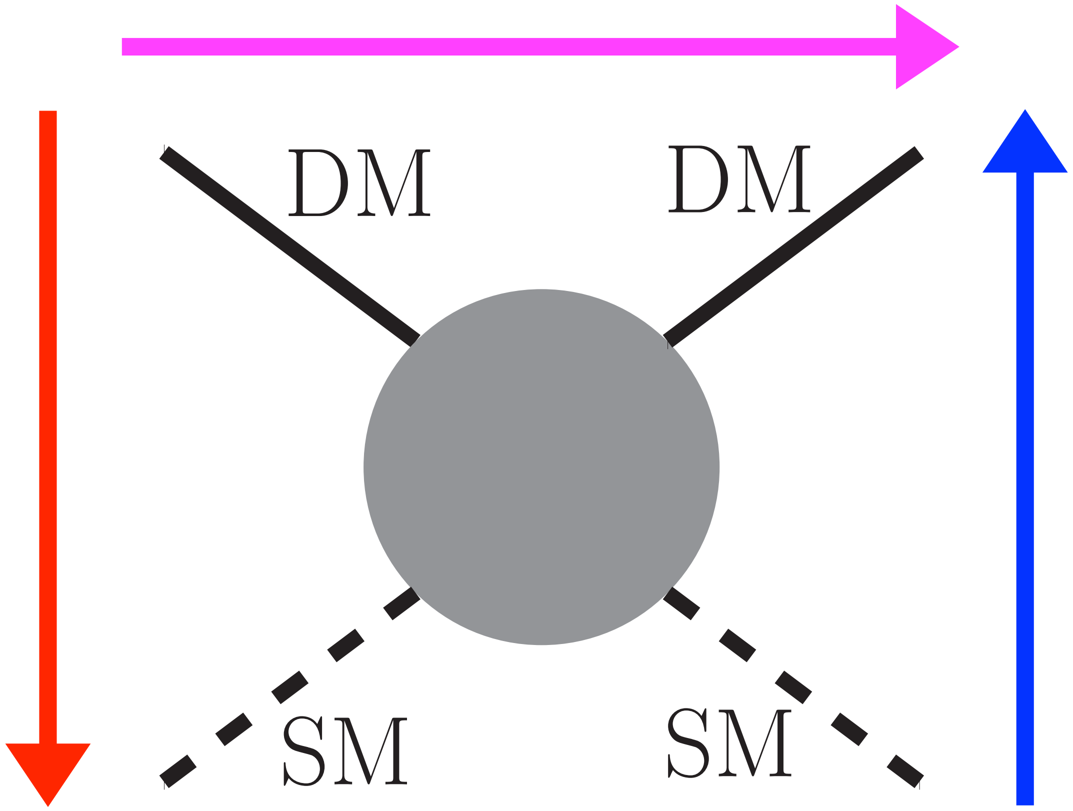
- thermal freeze-out (annihilation in the early Universe)

$$\Omega h^2 = 0.1 \times \frac{3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

- weak-scale annihilation cross section $\langle \sigma_{\mathrm{ann}} v \rangle \simeq 1\,\mathrm{pb} \times c$

- well motivated by hierarchy problem and TeV-scale new physics

- various search strategies
    - direct detection
    - indirect detection
    - collider



Let's be open-minded

- no convincing signals yet (we should wait, but…)
- neither postulated solutions to the hierarchy problem

Contents

General introduction to asymmetric dark matter (ADM)

- concept and motivation
- relation to baryon asymmetry of the Universe (BAU)
- prediction of dark matter mass: O(1) GeV

Dark baryon ADM with dark photon

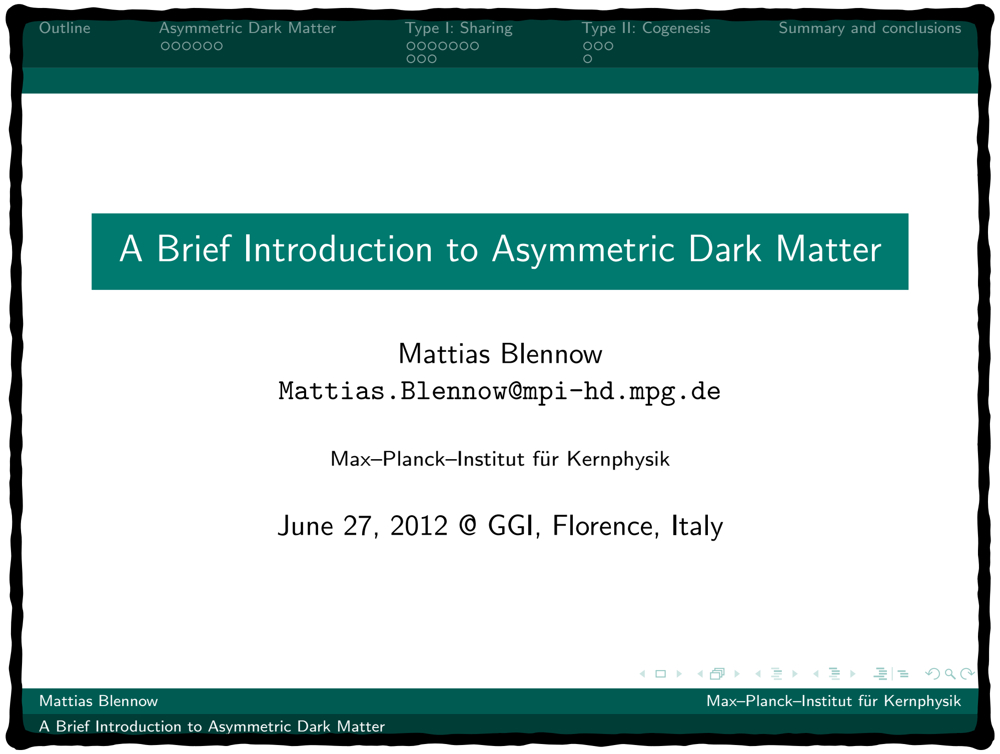
- why dark baryon and dark photon?
- experimental and cosmological signatures

Decaying ADM

- multi-messanger (e^+, γ, ν)
- uncertainty in propagation model

Contents

General introduction to ADM



Outline | Asymmetric Dark Matter | Type I: Sharing | Type II: Cogenesis | Summary and conclusions

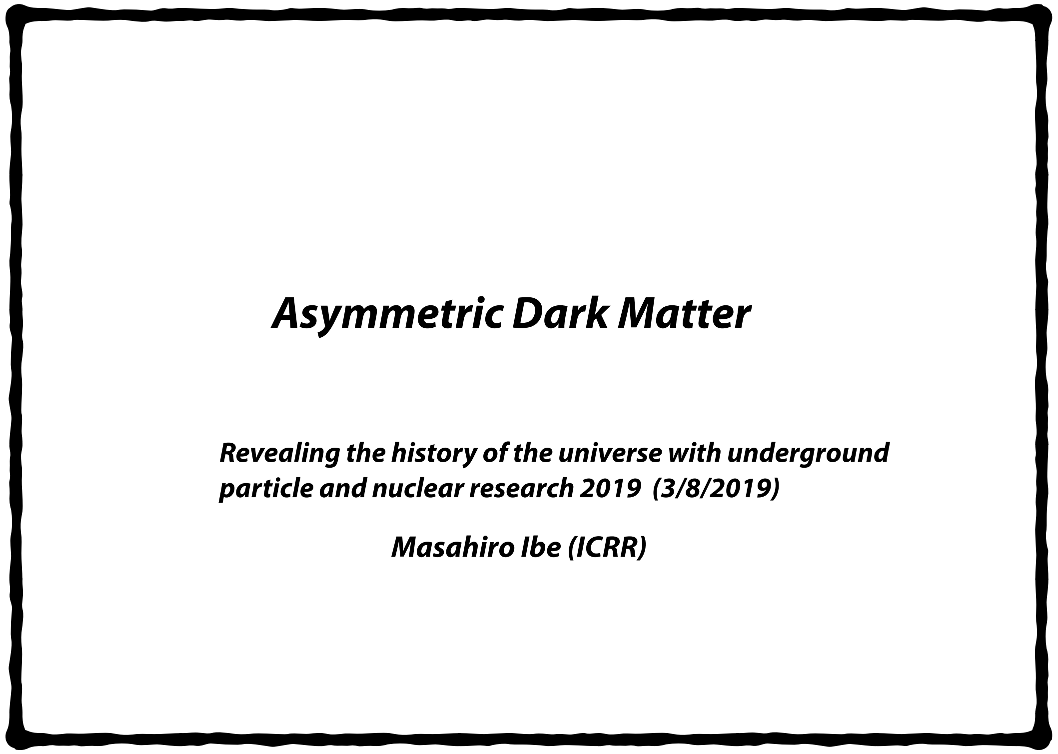
A Brief Introduction to Asymmetric Dark Matter

Mattias Blennow
`Mattias.Blennow@mpi-hd.mpg.de`

Max–Planck–Institut für Kernphysik

June 27, 2012 @ GGI, Florence, Italy

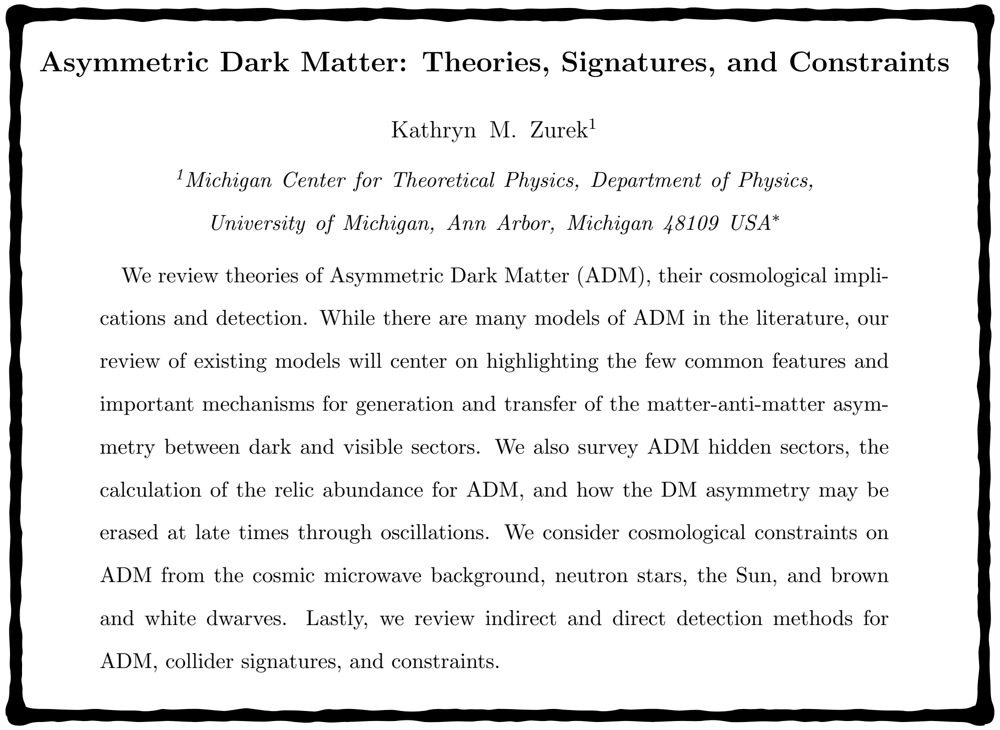
Mattias Blennow | Max–Planck–Institut für Kernphysik
A Brief Introduction to Asymmetric Dark Matter



Asymmetric Dark Matter

Revealing the history of the universe with underground particle and nuclear research 2019 (3/8/2019)

Masahiro Ibe (ICRR)

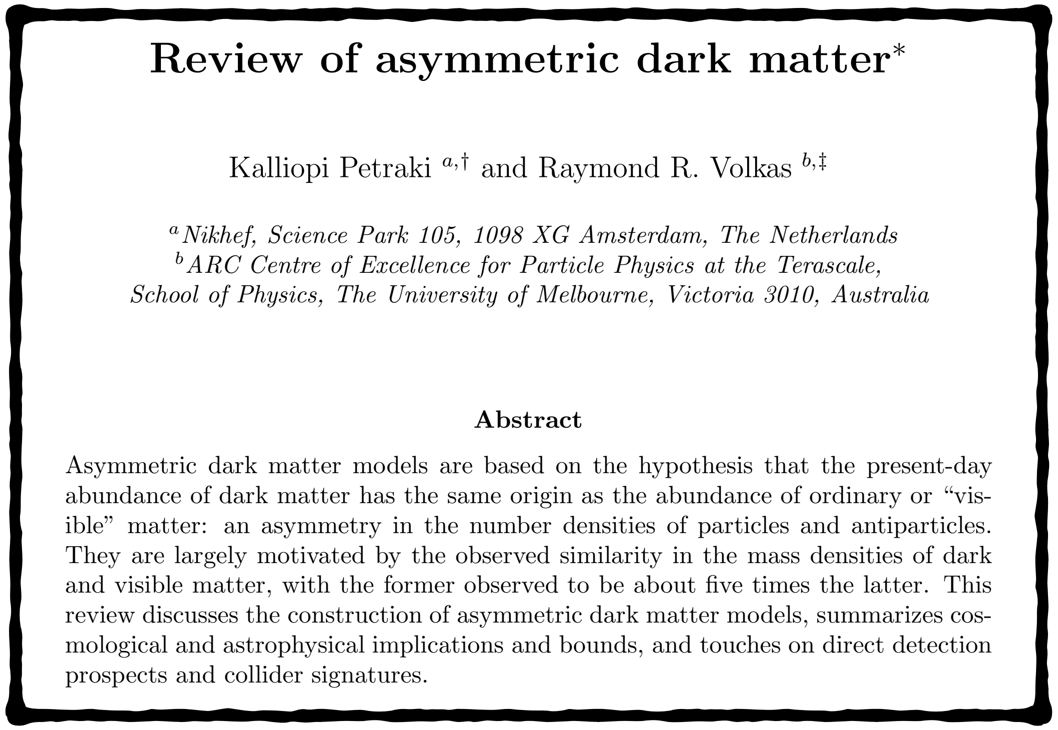


Asymmetric Dark Matter: Theories, Signatures, and Constraints

Kathryn M. Zurek[1]

[1]*Michigan Center for Theoretical Physics, Department of Physics,*
*University of Michigan, Ann Arbor, Michigan 48109 USA**

We review theories of Asymmetric Dark Matter (ADM), their cosmological implications and detection. While there are many models of ADM in the literature, our review of existing models will center on highlighting the few common features and important mechanisms for generation and transfer of the matter-anti-matter asymmetry between dark and visible sectors. We also survey ADM hidden sectors, the calculation of the relic abundance for ADM, and how the DM asymmetry may be erased at late times through oscillations. We consider cosmological constraints on ADM from the cosmic microwave background, neutron stars, the Sun, and brown and white dwarves. Lastly, we review indirect and direct detection methods for ADM, collider signatures, and constraints.



Review of asymmetric dark matter*

Kalliopi Petraki [a,†] and Raymond R. Volkas [b,‡]

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[b]*ARC Centre of Excellence for Particle Physics at the Terascale,*
School of Physics, The University of Melbourne, Victoria 3010, Australia

Abstract

Asymmetric dark matter models are based on the hypothesis that the present-day abundance of dark matter has the same origin as the abundance of ordinary or "visible" matter: an asymmetry in the number densities of particles and antiparticles. They are largely motivated by the observed similarity in the mass densities of dark and visible matter, with the former observed to be about five times the latter. This review discusses the construction of asymmetric dark matter models, summarizes cosmological and astrophysical implications and bounds, and touches on direct detection prospects and collider signatures.

Coincidence problems

Cosmic energy budget

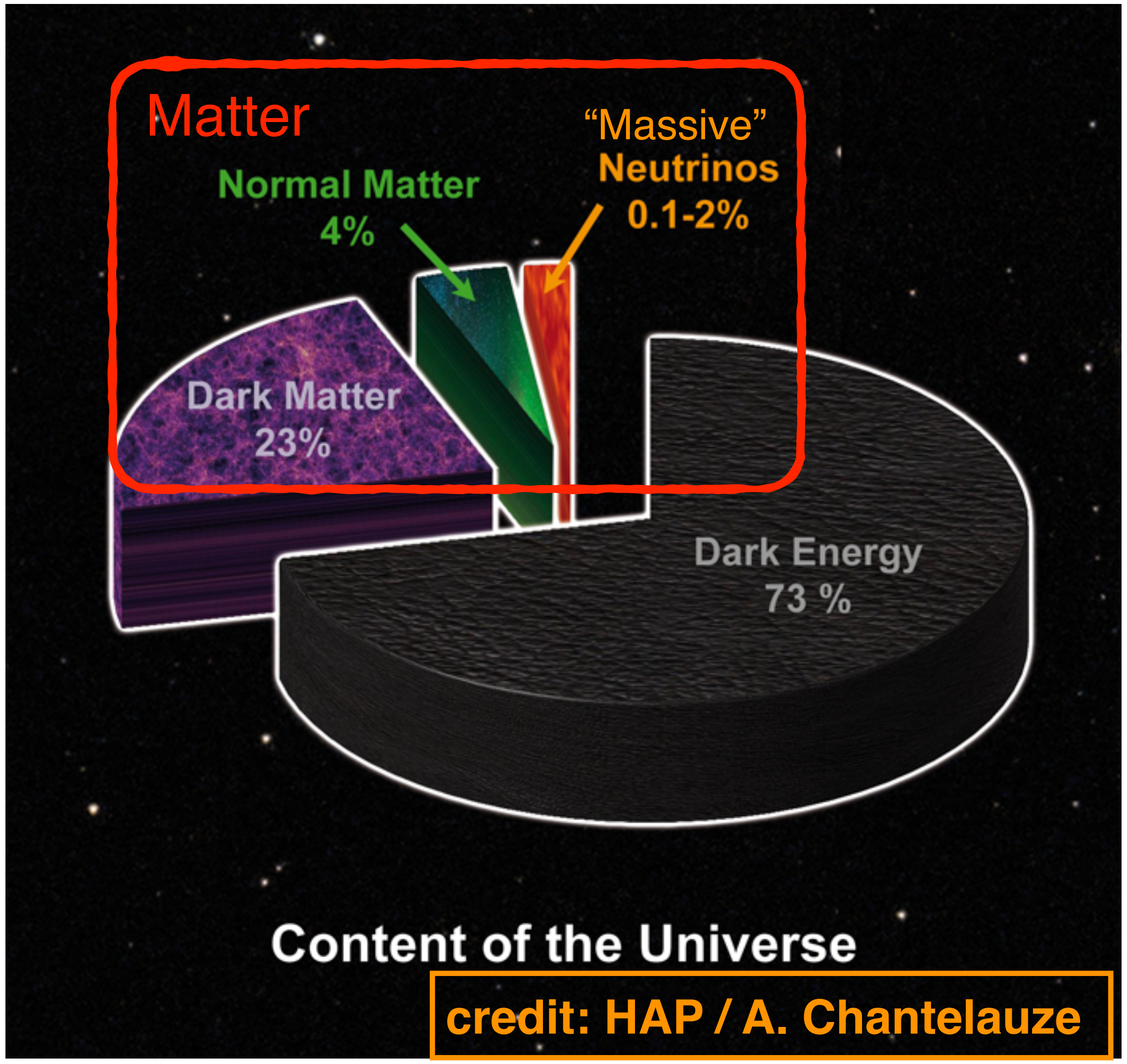
- most famous (notorious) coincidence

  dark energy : matter = 7 : 3

- matter coincidence

  DM : baryons : neutrinos
  = 5 : 1 : 0.03-0.5

  $$\Omega_{\rm DM}h^2 = 5\Omega_B h^2$$



credit: HAP / A. Chantelauze

- focus on DM : baryons

  - this ratio does not change for the age of the Universe

  - the other ratios change with time and
    they are problems of timing: "why now?"

WIMP DM : baryons

Baryon abundance

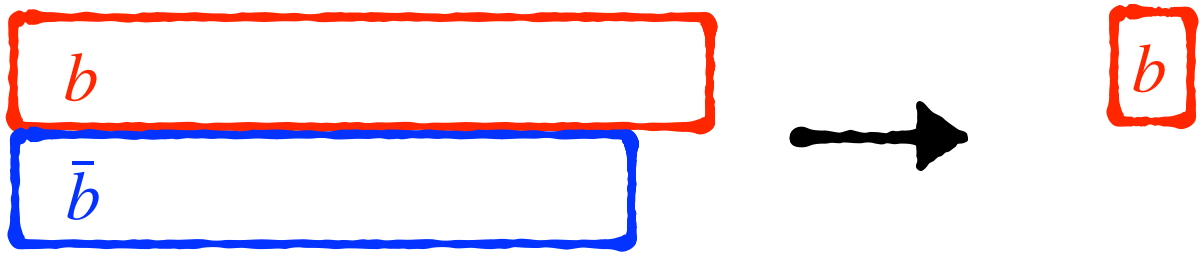
- too small via thermal freeze-out like WIMPs

$$\Omega_{\rm WIMP}h^2 = 0.1\times\frac{3\times10^{-26}\,{\rm cm^3/s}}{\langle\sigma_{\rm ann}v\rangle}$$

strong $p\bar{p} \to \pi\pi\ldots$

- ~~weak~~-scale annihilation cross section $\langle\sigma_{\rm ann}v\rangle \simeq \underset{1\,{\rm b}}{\cancel{1\,{\rm pb}}}\times c$

- determined by the primordial baryon asymmetry $\eta_B = \dfrac{n_b - n_{\bar{b}}}{n_\gamma} = 6\times10^{-10}$



$m_b \simeq 1\,{\rm GeV}$

$\Omega_B h^2 \propto m_b\eta_B$

Coincidence

$$\Omega_{\rm WIMP}h^2 \simeq 30\frac{G_N^{1/2}c^{1/2}\hbar^{3/2}}{\langle\sigma_{\rm ann}v\rangle m_b\eta_B}\Omega_B h^2$$

- combination of many (seemingly) unrelated quantities

- miraculous to get O(1)

Asymmetric DM

ADM abundance

- determined by the primordial dark asymmetry $b \to \chi$ $\quad \bar{b} \to \bar{\chi}$

$$\Omega_D h^2 \propto m_\chi \eta_D$$

- efficient annihilation into light particles

$\langle \sigma_{\rm ann} v \rangle > 1\,{\rm pb} \times c$ - larger than weak-scale

Coincidence

$$\Omega_D h^2 = \boxed{\frac{m_\chi}{m_b}}\boxed{\frac{\eta_D}{\eta_B}}\Omega_B h^2$$

- combination of the ratio of same-dimension quantities

- problem is not solved but less miraculous

One more step: common origin of asymmetries

- unlikely to have $\frac{\eta_D}{\eta_B}$ as a complicated combination of quantities

Common origin of asymmetries

Mechanisms

- transfer (sharing)

  - generate baryon asymmetry and/or dark asymmetry somehow (baryogenesis and/or darkogenesis)

  - transfer one asymmetry to another (equilibrated) through some operator $\mathcal{O}_B\mathcal{O}_D$

  $\mathcal{O}_B = udd, LH, \dots$

  - baryon-number charged (or B-L charged because of weak sphaleron)

  $\mathcal{O}_D = \chi, \chi^2, \dots$

  - dark matter-number charged

  - often end up with $\eta_D \sim \eta_B$

  → $m_\chi \sim 5\,\mathrm{GeV}$

- co-genesis

  - generate baryon asymmetry and dark asymmetry simultaneously

  - transfer is not necessarily → $\dfrac{\eta_D}{\eta_B}$ is free

  $m_\chi \sim 1\,\mathrm{MeV}\text{-}10\,\mathrm{TeV}$

  $1\,\mathrm{MeV}$ - BBN (additional radiation)

  $10\,\mathrm{TeV}$ - Unitarity $\langle\sigma_{\mathrm{ann}}v\rangle > 1\,\mathrm{pb}\times c$

Contents

Masahiro Ibe, AK, Shin Kobayashi, and Wakutaka Nakano, JHEP, 2018
Masahiro Ibe, AK, Shin Kobayashi, Takumi Kuwahara, and Wakutaka Nakano, JHEP, 2019 & PRD, 2019
AK, Hee Jung Kim, and Takumi Kuwahara, JHEP, 2020
AK and Takumi Kuwahara, JHEP, 2022

Dark baryon ADM with dark photon

- why dark baryon and dark photon?
- experimental and cosmological signatures

■ 研究紹介

ダークセクターの物理: 非対称ダークマターの観点から

基礎科学研究院 純粋物理理論研究団
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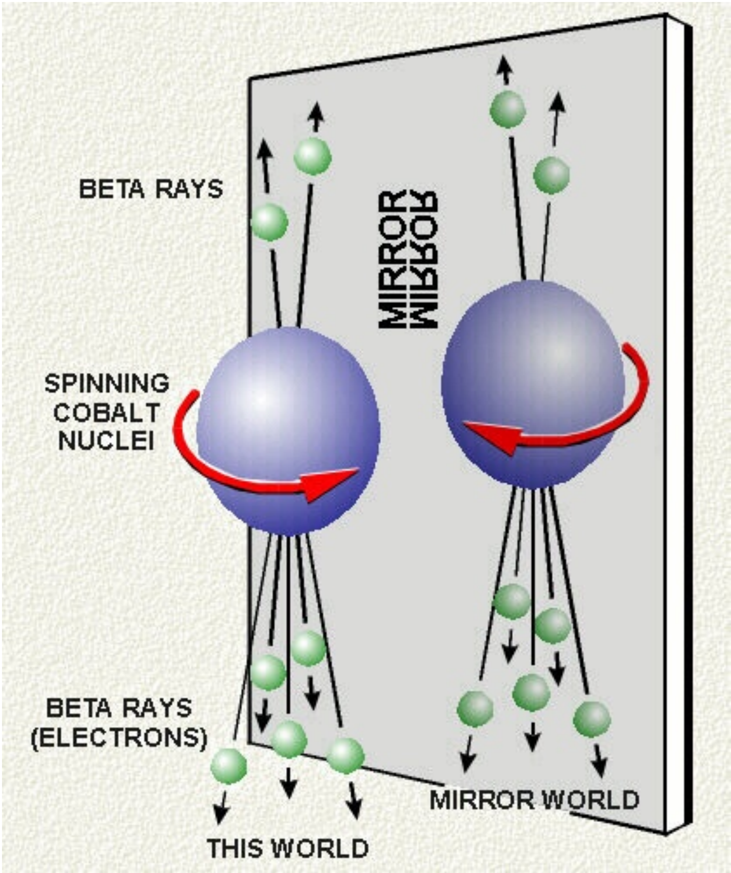
2020年 (令和2年) 10月30日

Mirror matter

Parity violation in weak interaction

- established by Wu experiment (1956)
- people could hardly accept that such a fundamental symmetry is not respected
- P may also involve a change of particle species (matter parity)

  matter ↔ mirror matter

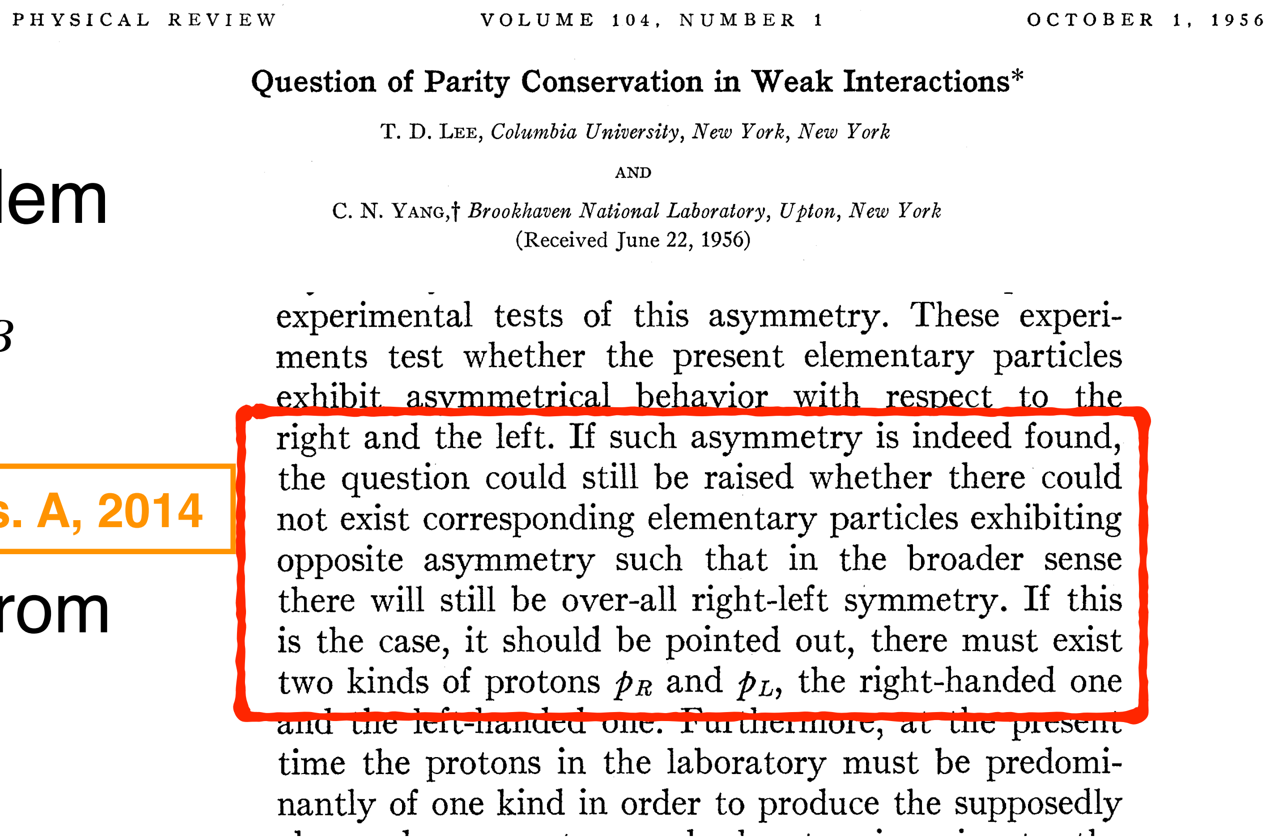


Mirror baryon as ADM

- ideal solution to coincidence problem

$$\Omega_{B'}h^2 = \Omega_B h^2 \quad m_{b'} = m_b \quad \eta_{B'} = \eta_B$$

- unfortunately, not viable as it is
  - $\Omega_D h^2 = 5\Omega_B h^2$ **Foot, Int. J. Mod. Phys. A, 2014**
  - no structure formation (pressure from dark electron and dark photon)
  - dark radiation



PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

experimental tests of this asymmetry. These experiments test whether the present elementary particles exhibit asymmetrical behavior with respect to the right and the left. If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry. If this is the case, it should be pointed out, there must exist two kinds of protons p_R and p_L, the right-handed one and the left-handed one. Furthermore, at the present time the protons in the laboratory must be predominantly of one kind in order to produce the supposedly

Mirror-inspired model

Copy of strong dynamics and electrodynamics

- high energy/temperature

Ibe, AK, Kobayashi, and Nakano, JHEP, 2018

  - dark quarks $u'(2/3)$ $\bar{u}'(-2/3)$ $d'(-1/3)$ $\bar{d}'(1/3)$ $\times N_g$
  - dark gluons g' and dark photon γ'

N_g - generations

  - no leptons or weak interaction
  - charged Higgs (not present in SM) to break electrodynamics
    - Higgsless chiral model $u'(1)$ $\bar{u}'(-a)$ $d'(-1)$ $\bar{d}'(a)$ $s'(0)$ $\bar{s}'(0)$
- low energy/temperature

Ibe, Kobayashi, and Watanabe, JHEP, 2021

  - dark nucleons p' $\bar{p}'$ n' $\bar{n}'$ and pions $\pi'^{\pm}$ π'^{0}
  - massive dark photon γ' assumed to be the lightest particle
- kinetic mixing between photon and dark photon $\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$
  - charged particles feebly couple to dark photon $\epsilon e j_{\mathrm{e}}^{\mu} A'_{\mu}$
    - dark charged particles do not couple to photon (if so, photon is massive)

Transfer mechanism

Transfer operator

Ibe, AK, Kobayashi, and Nakano, JHEP, 2018

$$\frac{1}{M_*^3} L H \bar{u}' \bar{d}' \bar{d}'$$

- B-L ↔ B’
  - B-L-B’ conserved
  - more dark anti-nucleon than dark nucleon

Fukuda, Matsumoto, and Mukhopadhyay, PRD, 2015

- $\Omega_D h^2 = 5\Omega_B h^2 \rightarrow \quad m_{b'} = 8.5\,\mathrm{GeV}/N_{g'} \qquad \Lambda_{\mathrm{QCD}'} \simeq 10\Lambda_{\mathrm{QCD}}/N_{g'}$

Signature

- decaying ADM (discussed next)

Other signatures in the model

- dark radiation
- self-interacting dark matter
- low-threshold direct detection

Wada-san’s talk

- long-lived particle search in colliders

Contents

Based on
Saikat Das, AK, Takumi Kuwahara, Kohta Murase, and Deheng Song,
arXiv: 2412.15641

Decaying ADM

- multi-messanger (e^+, γ, ν)
- uncertainty in propagation model

Decaying ADM

Transfer operator

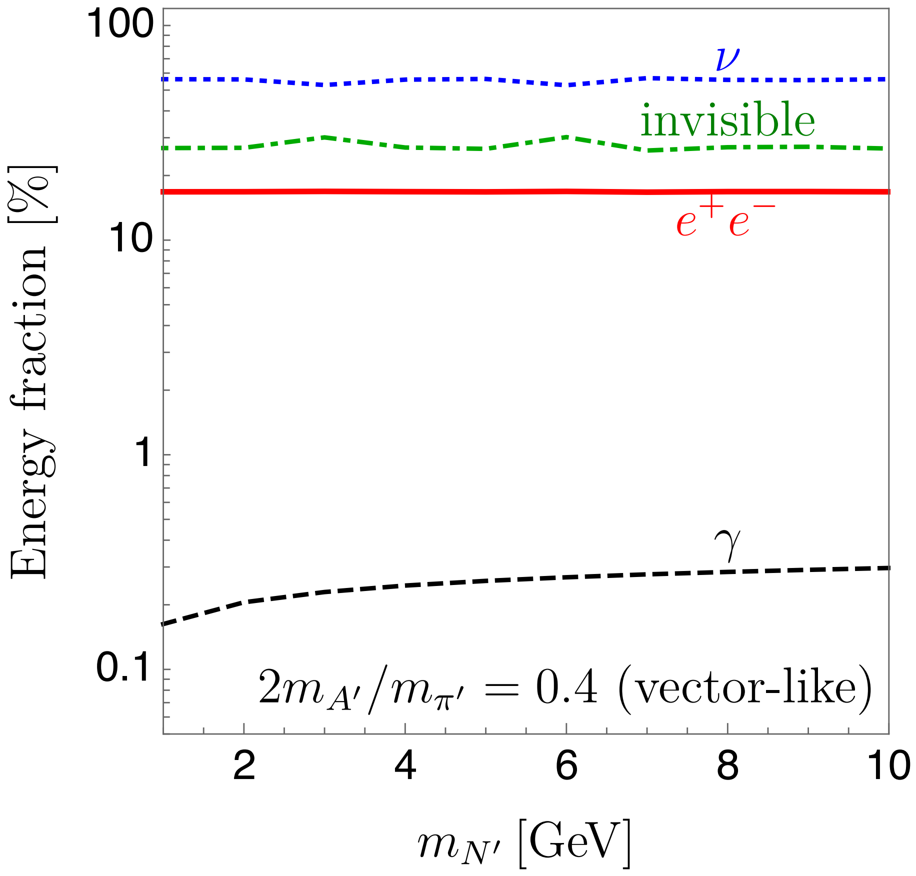
Das, AK, Kuwahara, Murase and Song, arXiv: 2412.15641

$$\frac{1}{M_*^3} L H \bar{u}' \bar{d}' \bar{d}'$$

- dark anti-neutron decay

$$\bar{n}' \to \pi'^0 + \bar{\nu} \qquad \Gamma \propto \frac{m_{b'}^5}{M_*^6}$$

- monochromatic anti-neutrino
  - smoking-gun signal
  - super-(hyper-)Kamiokande (low threshold)



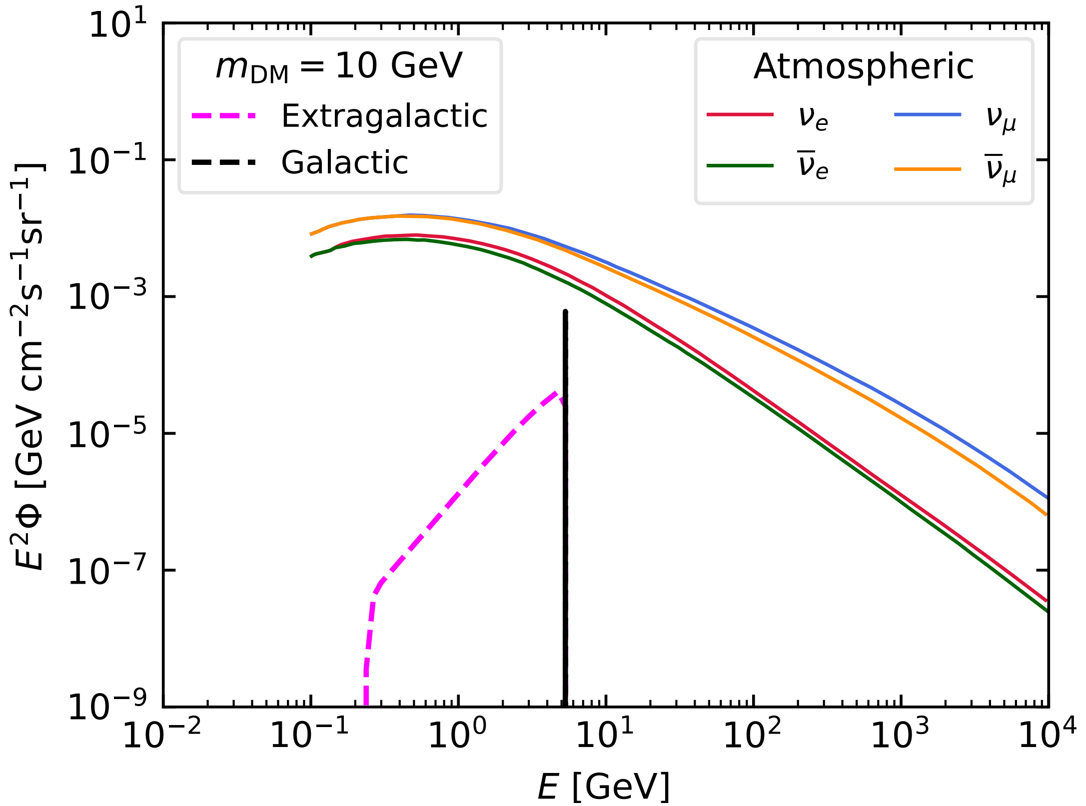
- cascade decay of $\pi'^0 \to 2\gamma' \to 2e^+2e^-$
  - solar modulation and reacceleration are crucial for sub-GeV electron+positron
  - sub-GeV gamma-ray data is also important (final state radiation and inverse compton scattering)

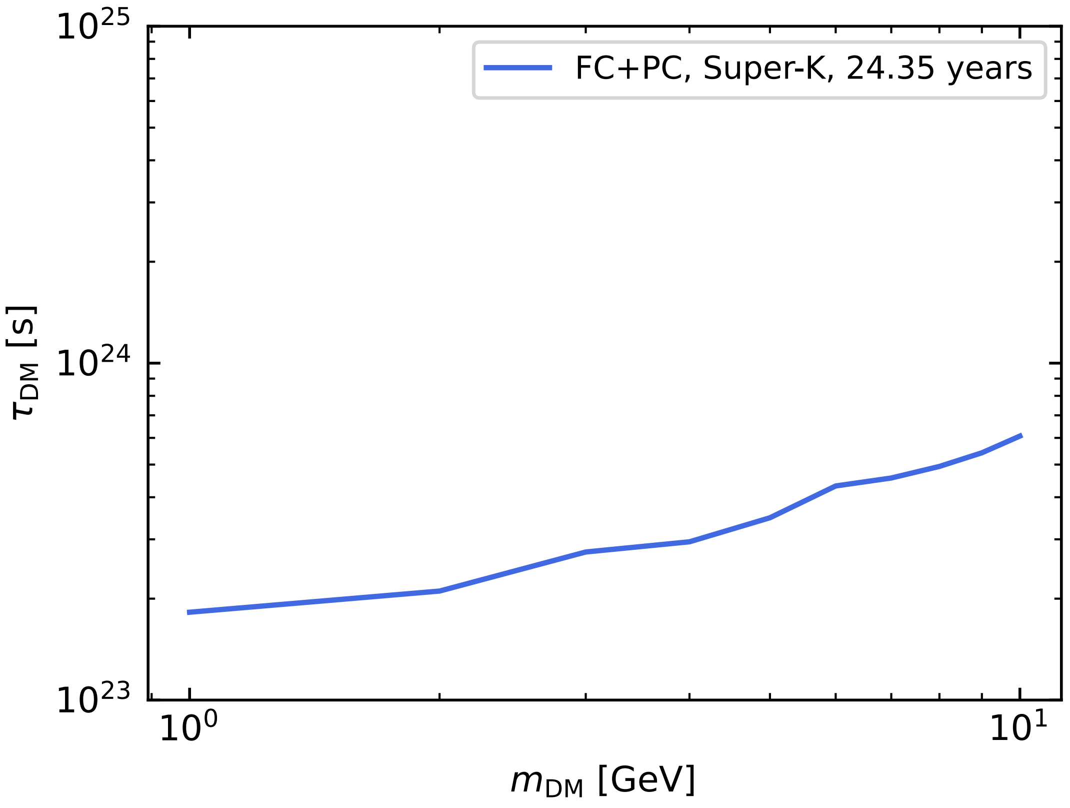
Monochromatic anti-neutrino

Super-(hyper-)Kamiokande

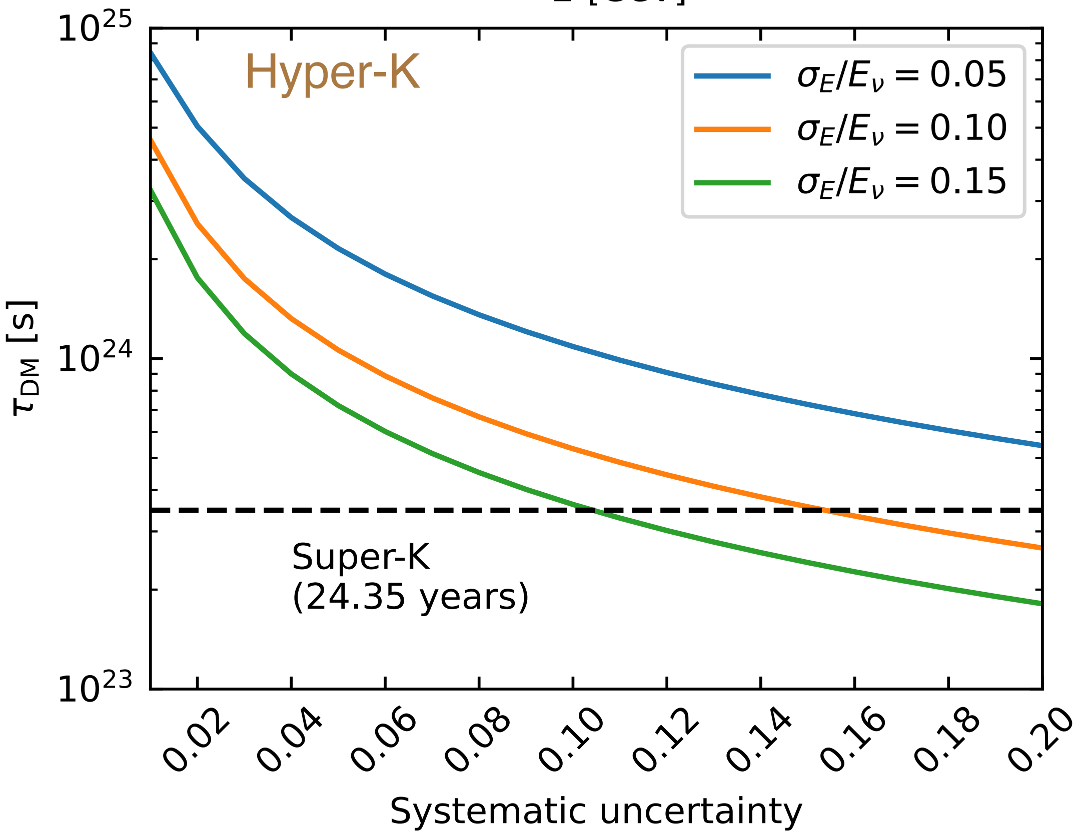
Das, AK, Kuwahara, Murase and Song, arXiv: 2412.15641

- atmospheric neutrino backgrounds
    - details are not available
- conservative approach: detectability of a line on top of expected background with 0.15 uncertainty within $0.25 m_{\rm DM} < E < m_{\rm DM}$





w/o Gd



Electron/positron

Das, AK, Kuwahara, Murase and Song, arXiv: 2412.15641

AMS-02

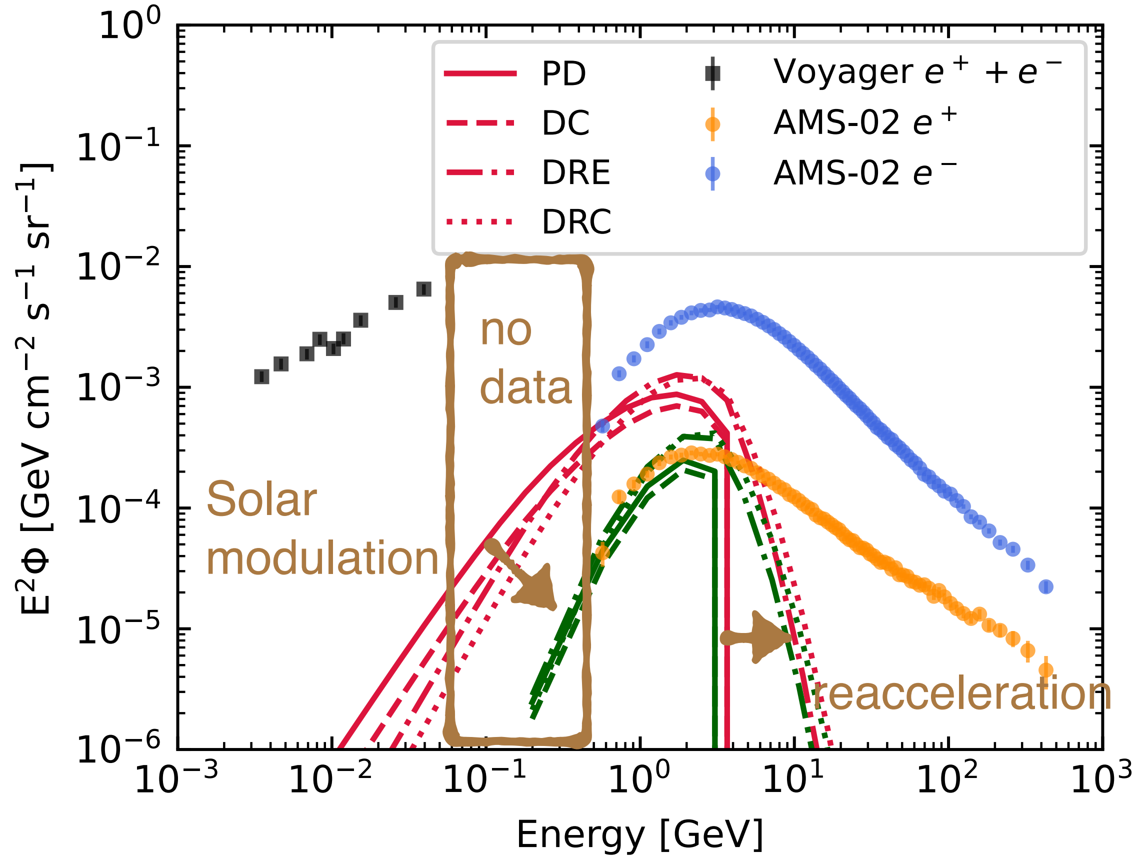
- data points above 0.5 GeV
    - Solar modulation below 5 GeV

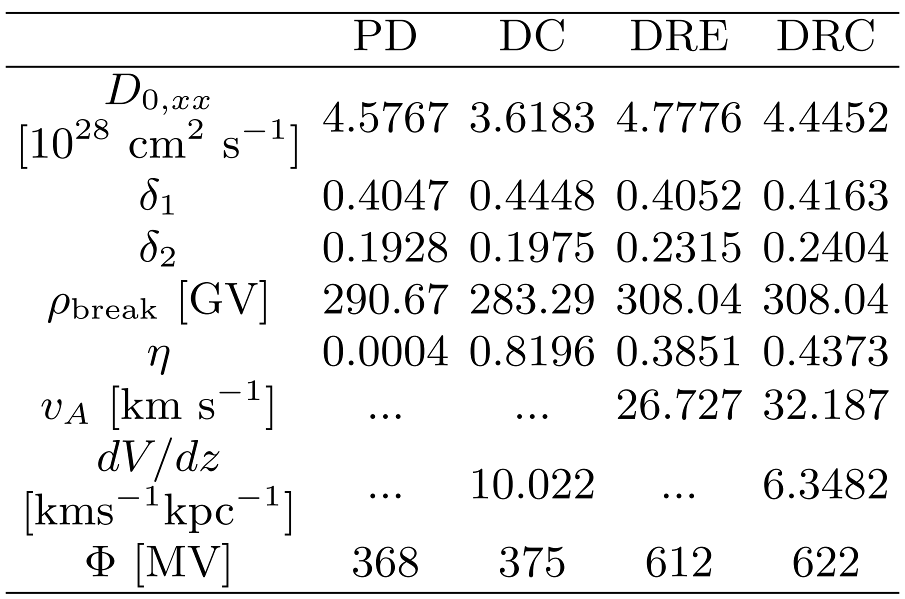
Voyager

- out of heliosphere
    - no Solar modulation
- data points below 0.1 GeV

Reacceleration

- interaction with Galactic plasma (MHD)
- its existence and role is uncertain
    - both with and without reacceleration, one can explain AMS02 and Voyager data





	PD	DC	DRE	DRC
$D_{0,xx}$ $[10^{28}\ \mathrm{cm}^2\ \mathrm{s}^{-1}]$	4.5767	3.6183	4.7776	4.4452
δ_1	0.4047	0.4448	0.4052	0.4163
δ_2	0.1928	0.1975	0.2315	0.2404
ρ_{break} [GV]	290.67	283.29	308.04	308.04
η	0.0004	0.8196	0.3851	0.4373
v_A [km s^{-1}]	...	...	26.727	32.187
dV/dz [kms^{-1}kpc^{-1}]	...	10.022	...	6.3482
Φ [MV]	368	375	612	622

Silver and Orlando, arXiv:2401.06242

- PD: pure diffusion   - DC: diffusion with convection

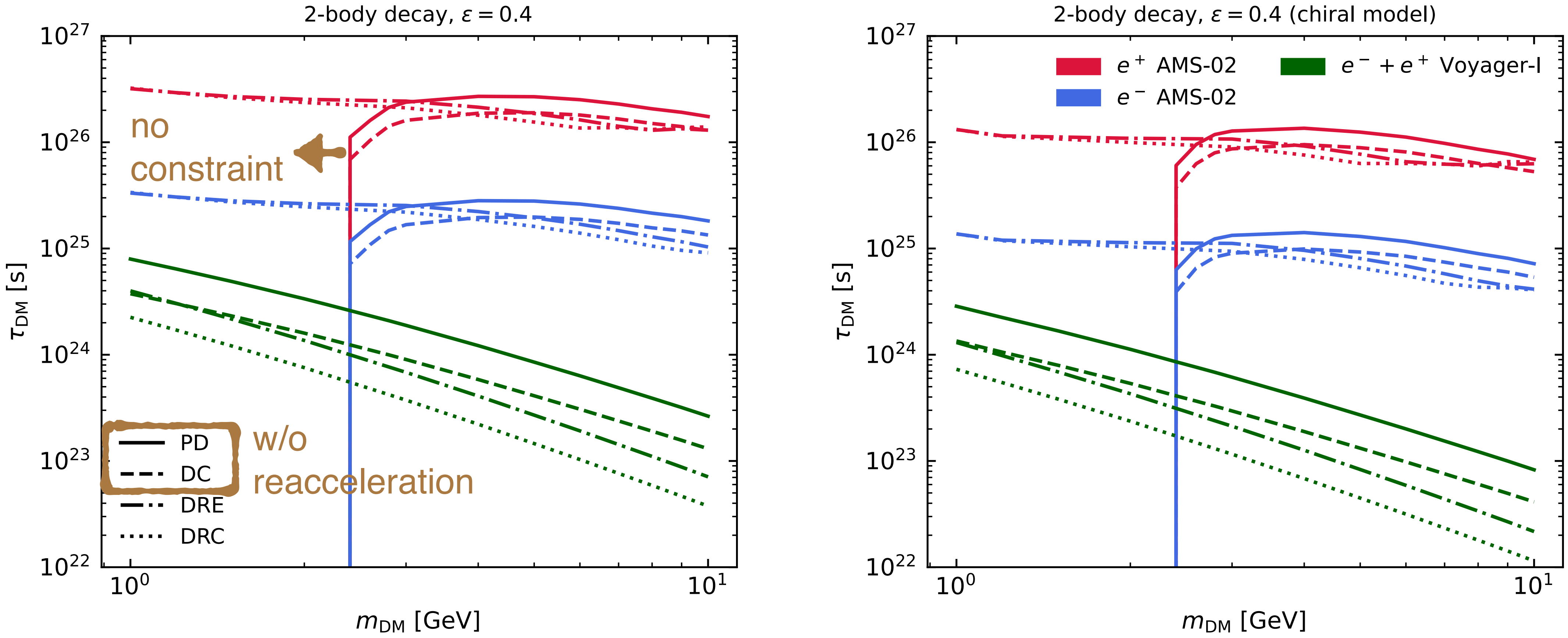
- DRE: diffusion with reacceleration   - DRC: diffusion with reacceleration and convection

Electron/positron

Electron positron constraints

Das, AK, Kuwahara, Murase and Song, arXiv: 2412.15641

- without reacceleration, DM signal falls in the data gap, for $m_{\rm DM} < 2\,{\rm GeV}$



Gamma ray

Fermi, EGRET, COMPTEL and SMM

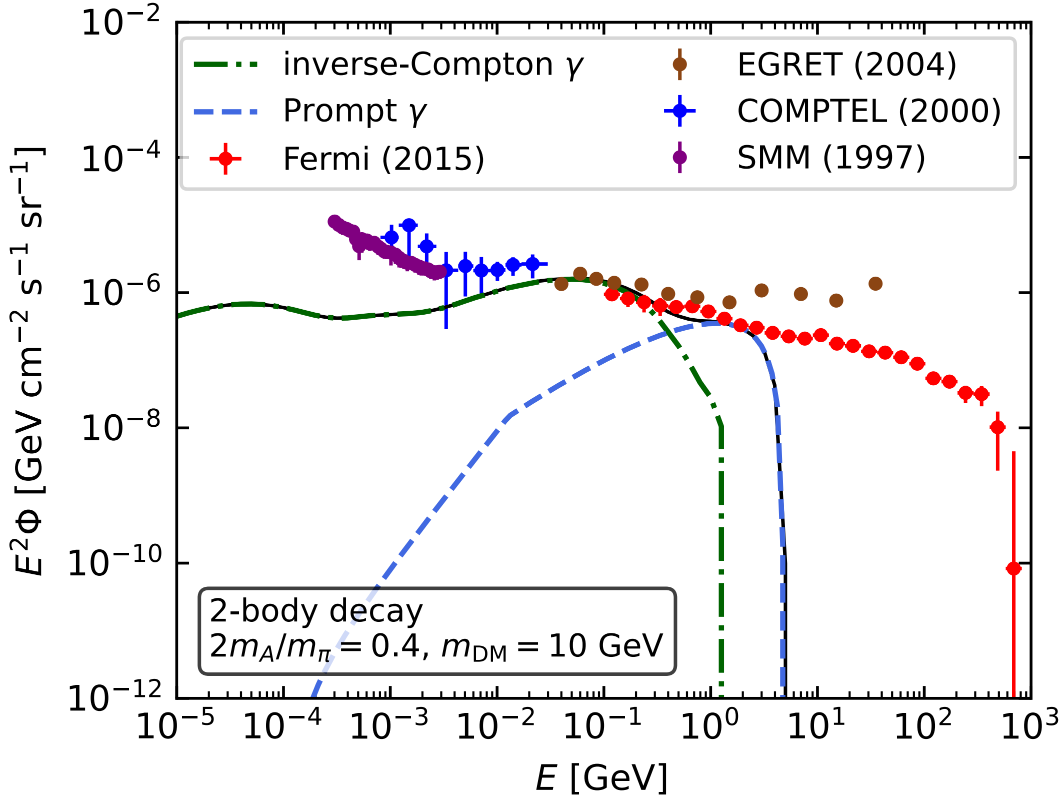
Das, AK, Kuwahara, Murase and Song, arXiv: 2412.15641

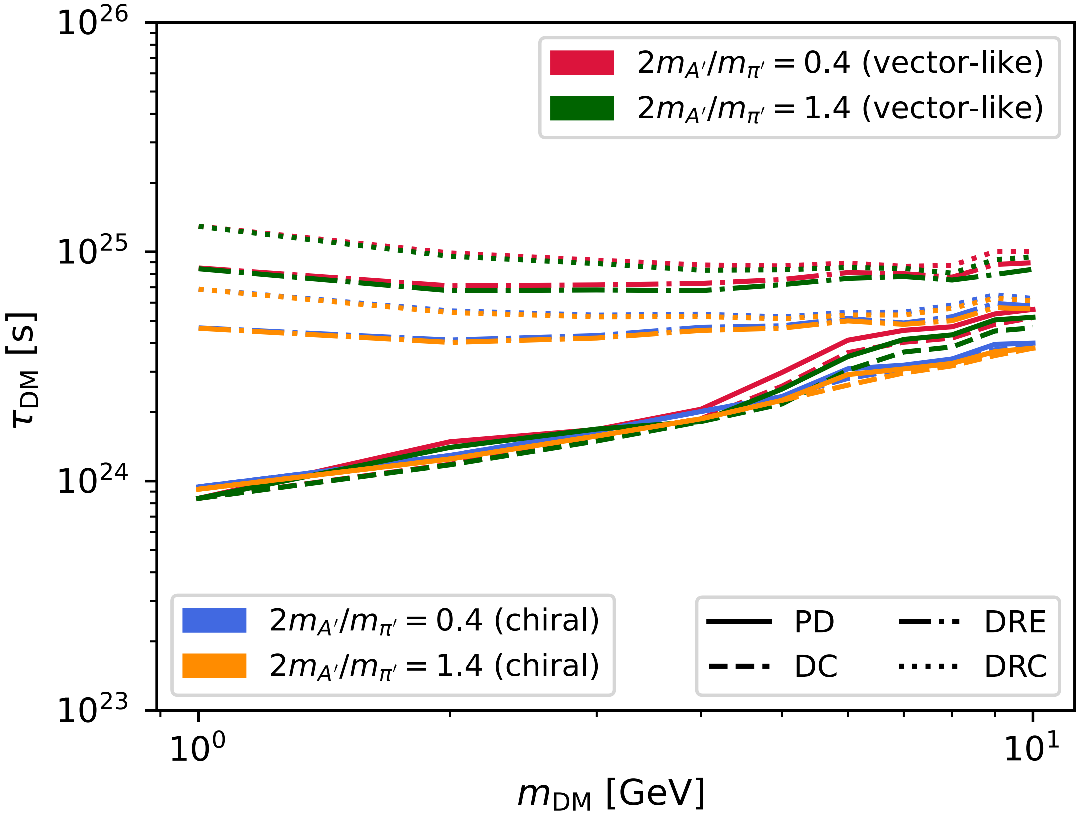
- diffuse background

- DM signal is dominated by secondary gamma from inverse-Compton scattering

- energetic gamma ray is more severely constrained

- yield depends on high-energy electron/positron and thus if reacceleration exists





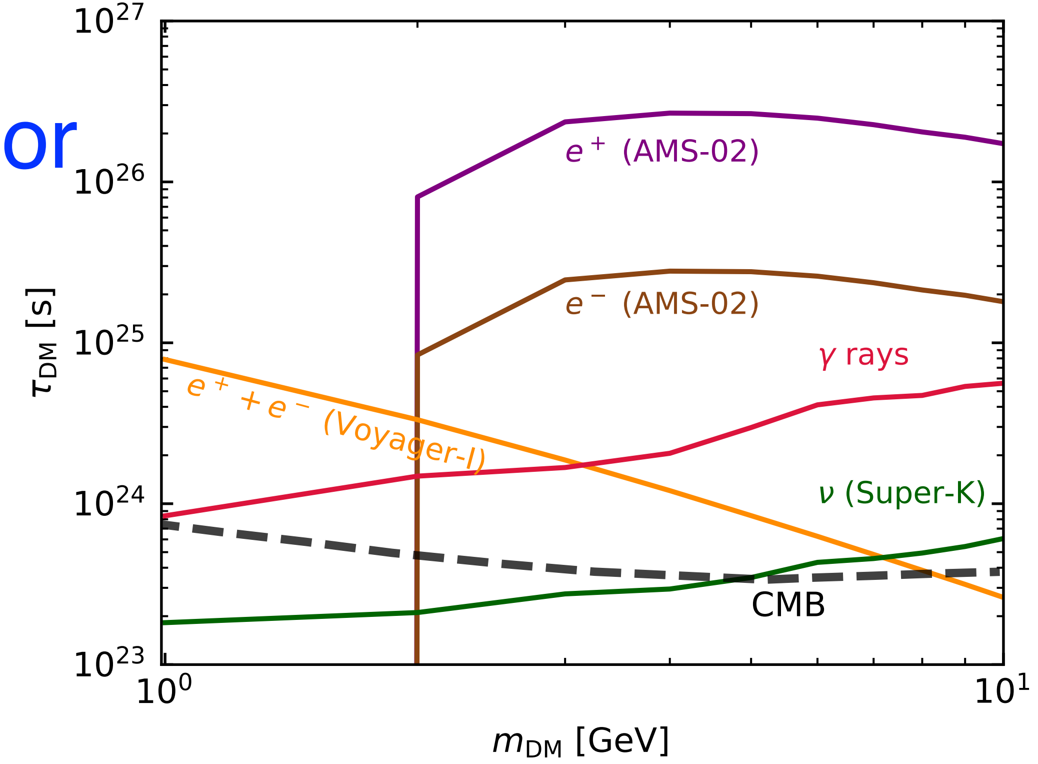
Summary

Asymmetric DM

- interesting alternative to WIMP DM
- motivated by the coincidence of DM : baryons
  - simplify the problem by dark asymmetry
  - full solution? a clue from mirror matter
  - (sub-)GeV-scale mass
- various experimental and cosmological signatures

Decaying ADM through transfer operator

- monochromatic anti-neutrino as a smoking-gun signal
- electromagnetic energy injection provides more stringent constraints



Thank you

Mirror-inspired model

Why dark strong dynamics?

- dark baryon number   D = B’
  - accidental conservation like baryon number
    - conserved at low energy but violated at high energy
    - if not conserved at low energy, baryon decays very quickly
    - if not violated at high energy, no generation of baryon asymmetry
- dark mesons
  - dark baryons efficiently annihilate into dark mesons $p'\bar{p}' \to \pi'\pi'\ldots$
  - fate of pions?

Why dark electrodynamics?

- massive dark photon
  - dark mesons annihilate or decay into dark photons $\pi'^{+}\pi'^{-} \to \gamma'\gamma'$ $\pi'^{0} \to \gamma'\gamma'$
  - eventually decay into SM particles $\gamma' \to e^{+}e^{-}$
    - massless leads to too much dark radiation

Generation and transfer of asymmetry

$$U(1)_{B-L+B'} \to (-1)^{3(B-L+B')}$$

Right-handed neutrinos $\overline{N}$ w/ soft breaking mass M_R

- thermal leptogenesis → $B-L$ asymmetry $T \sim M_R > 10^9\,\mathrm{GeV}$

  Fukugita and Yanagida, PLB, 1986

- see-saw mechanism → active neutrino mass $y_N L H \overline{N} \xrightarrow{\overline{N}} \frac{y_N^2}{M_R} LHLH$
- generation of the portal operator $y_N^2 \sim 10^{-5} \left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)\left(\frac{M_R}{10^9\,\mathrm{GeV}}\right)$

Scalar down quark H'_C w/ mass $M_{H'_C}$

$H'^{\dagger}_C \bar{u}' \bar{d}'$ $H'_C \bar{d}' \overline{N}$

$\xrightarrow{H'_C} \frac{1}{M^2_{H'_C}} \bar{u}' \bar{d}' \bar{d}' \overline{N}$ $y_N L H \overline{N}$

$\xrightarrow{\overline{N}} \frac{y_N}{M^2_{H_C} M_R} \bar{u}' \bar{d}' \bar{d}' L H$

	$SU(3)_D$	$U(1)_D$	$U(1)_{B-L+B'}$
H'_C	$\mathbf{3}$	$-1/3$	$-2/3$

$U(1)_{B-L+B'}$

✗ $H'_C u' d'$ $H'^{\dagger}_C d' \overline{N}$

$\to \frac{1}{M_*^3} u' d' d' L H$

✳ decoupling after leptogenesis $M_{H_C} \sim M_R$

Transfer mechanism

Signatures

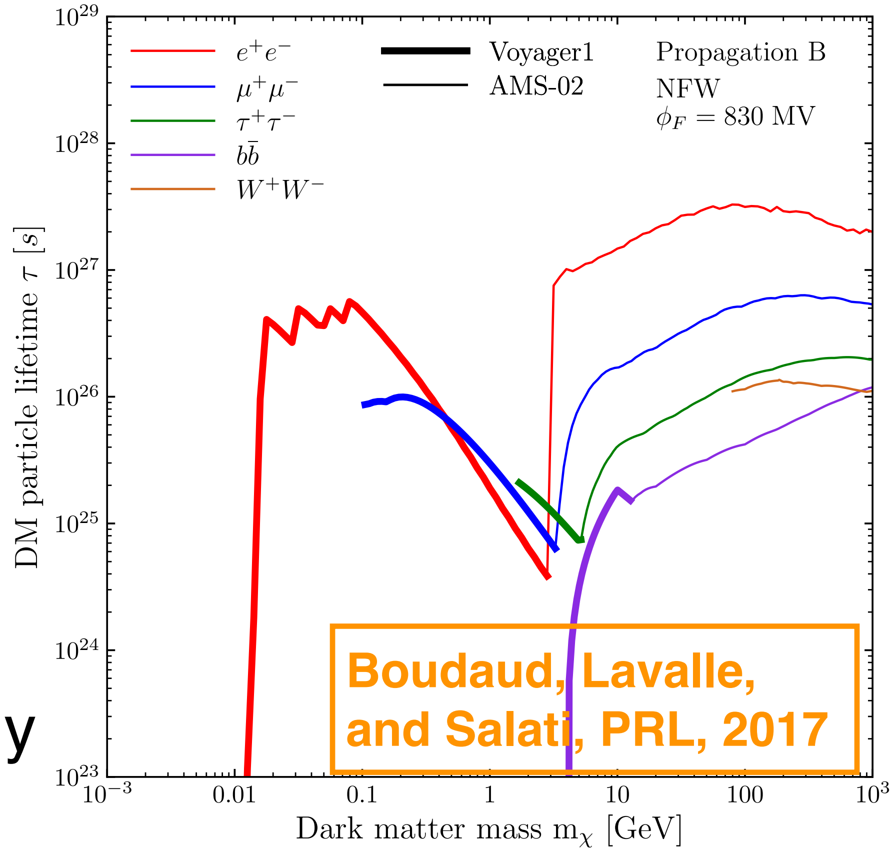
- dark anti-neutron decay into anti-neutrino

$$\bar{n}' \to \pi'^0 + \bar{\nu}$$

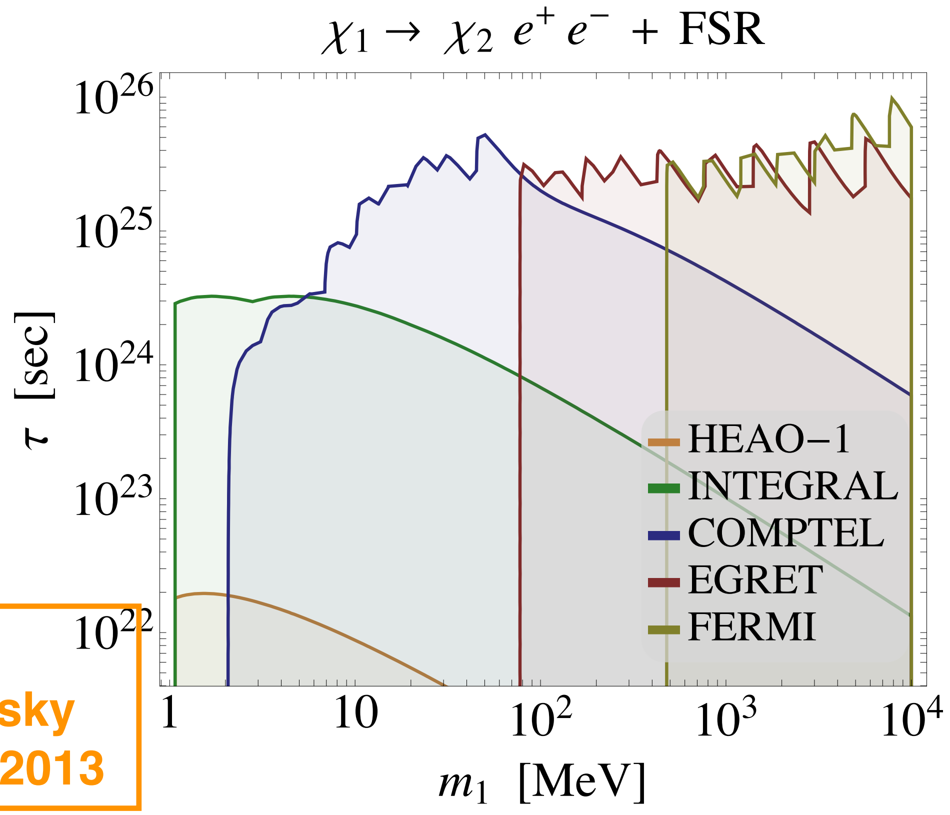
  - cascade decay of $\pi'^0 \to 2\gamma' \to 2e^+2e^-$
    - Voyager data is crucial for sub-GeV electron+positron (modulation free)
    - though re-analysis is needed, conservatively

$$\tau \gtrsim 10^{25}\,\mathrm{sec} \rightarrow M_* > 10^{8.8}\,\mathrm{GeV}$$

    - MeV gamma-ray data is also important (final state radiation)



Boudaud, Lavalle, and Salati, PRL, 2017



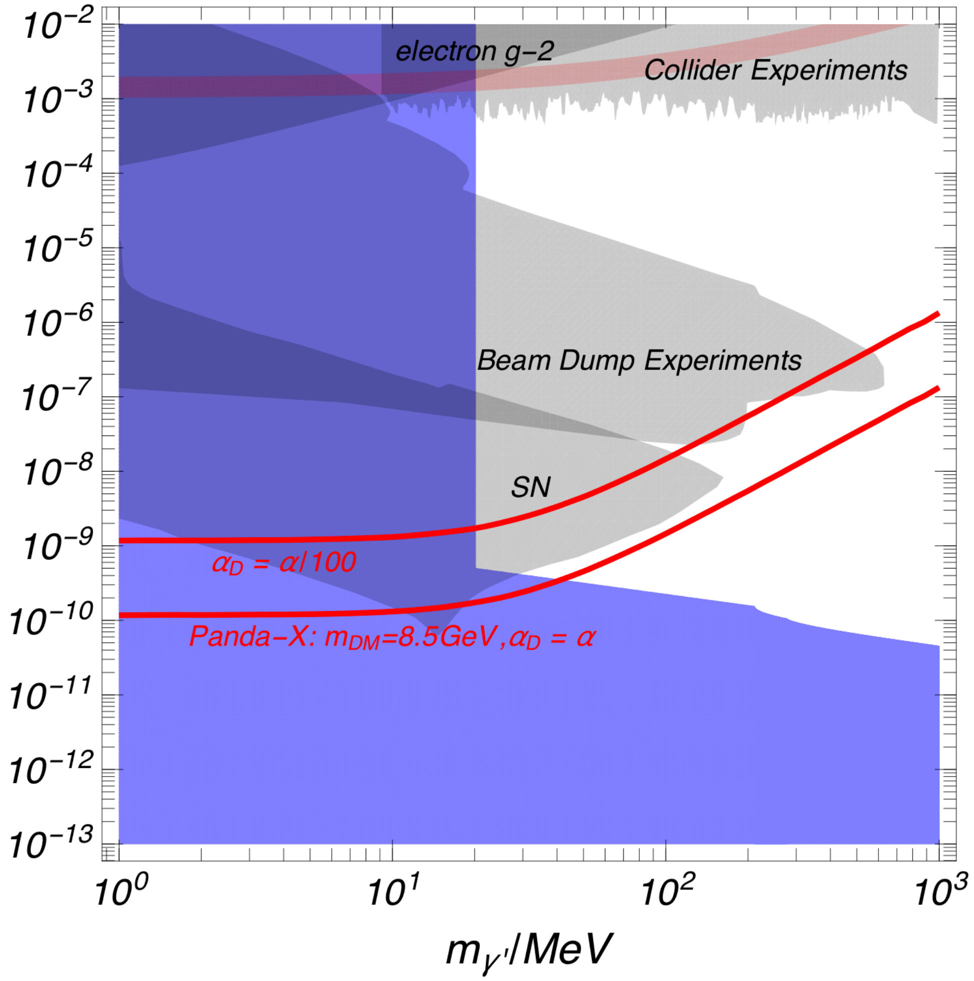
Essig, Kuflik, Mcdermott, Volansky and Zurek, JHEP, 2013

Massive dark photon

Cosmological bounds

- coupling to electron + positron but not neutrinos
  - neutrinos decouple from electron + positron $T \sim 2\,\mathrm{MeV}$
  - decay after that changes temperature ratios between photon and neutrinos
    - negative ΔN_{eff}
- should decay before neutrino decoupling $\Gamma_{A' \to \mathrm{SM}} \propto \epsilon^2 m_{A'}$ $\epsilon e j_{\mathrm{e}}^{\mu} A'_{\mu}$
  - lower bound on ϵ
- thermal abundance should be negligible around decoupling
  - lower bound on $m_{A'}$

Ibe, AK, Kobayashi, and Nakano, JHEP, 2018



Massive dark photon

Direct detection

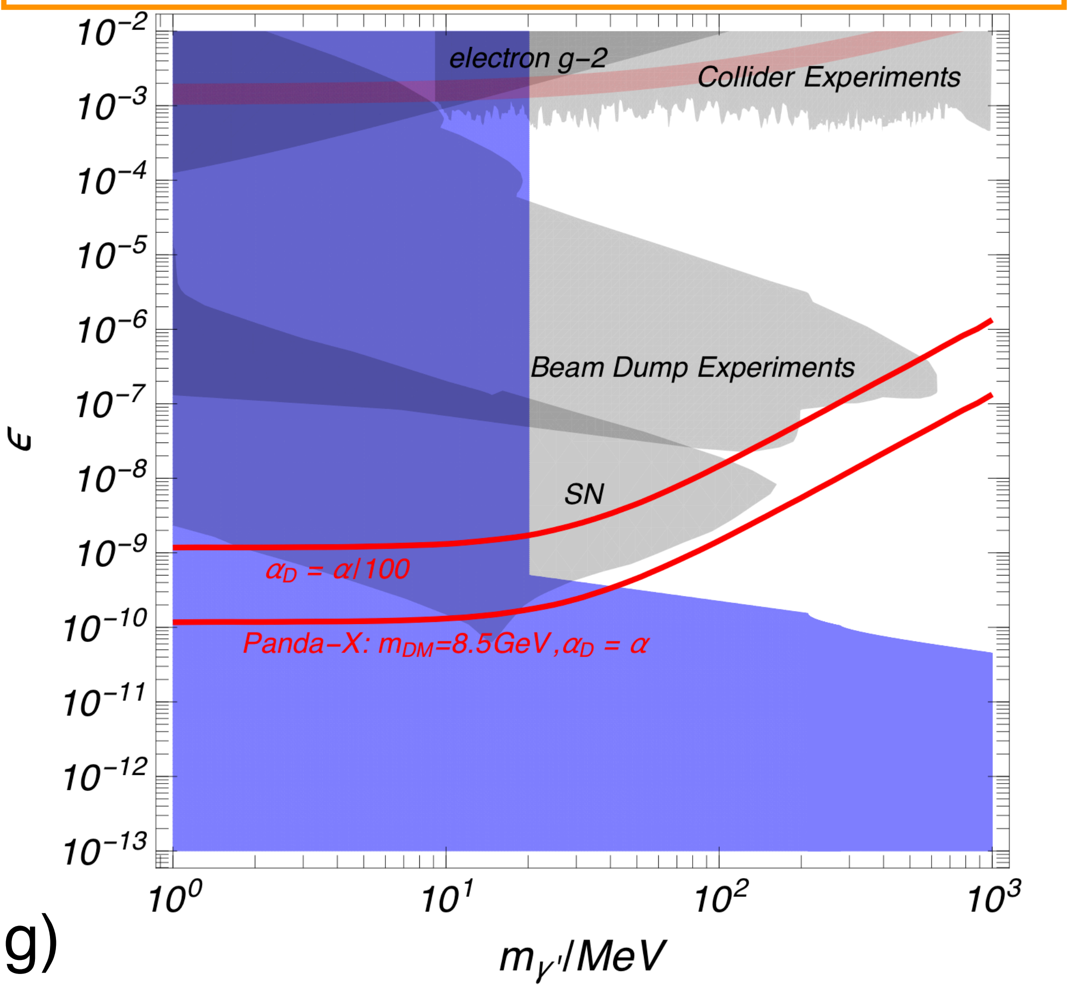
- dark proton - proton scattering through dark photon

  $\sigma \propto \epsilon^2 \alpha \alpha'$ $\epsilon e j_e^\mu A'_\mu$

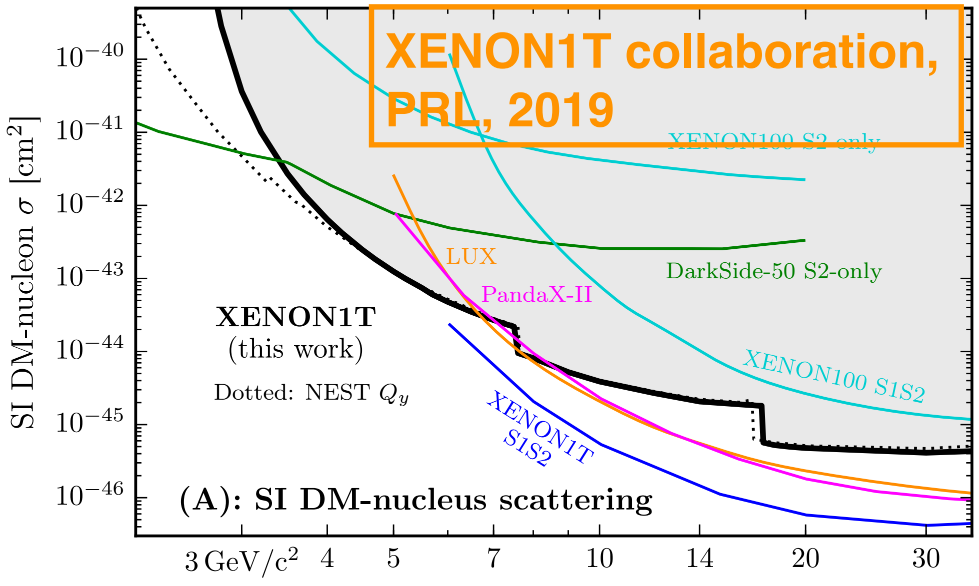
- already largely explored
  - dark proton makes up a sizable portion of present DM
    - dark neutron is darkly neutral
    - dark proton : dark neutron = 1 : 1 (fig)
  - DM mass is around 10 GeV
    - $m_{b'} = 8.5\,\mathrm{GeV}/N_{g'}$ $\sigma \lesssim 10^{-45}$
    - $N_{g'} = 1$ (fig) → $N_{g'} = 8$ $\to 10^{-39}\,\mathrm{cm}^2/\mathrm{g}$
  - large enough dark fine structure constant
    - $\alpha' = \alpha$ (fig)

$$\alpha' > 10^{-4}\alpha \frac{m_{\pi'}}{100\,\mathrm{MeV}} \quad \text{for} \quad \pi'^+\pi'^- \to \gamma'\gamma'$$

Ibe, AK, Kobayashi, and Nakano, JHEP, 2018



XENON1T collaboration, PRL, 2019



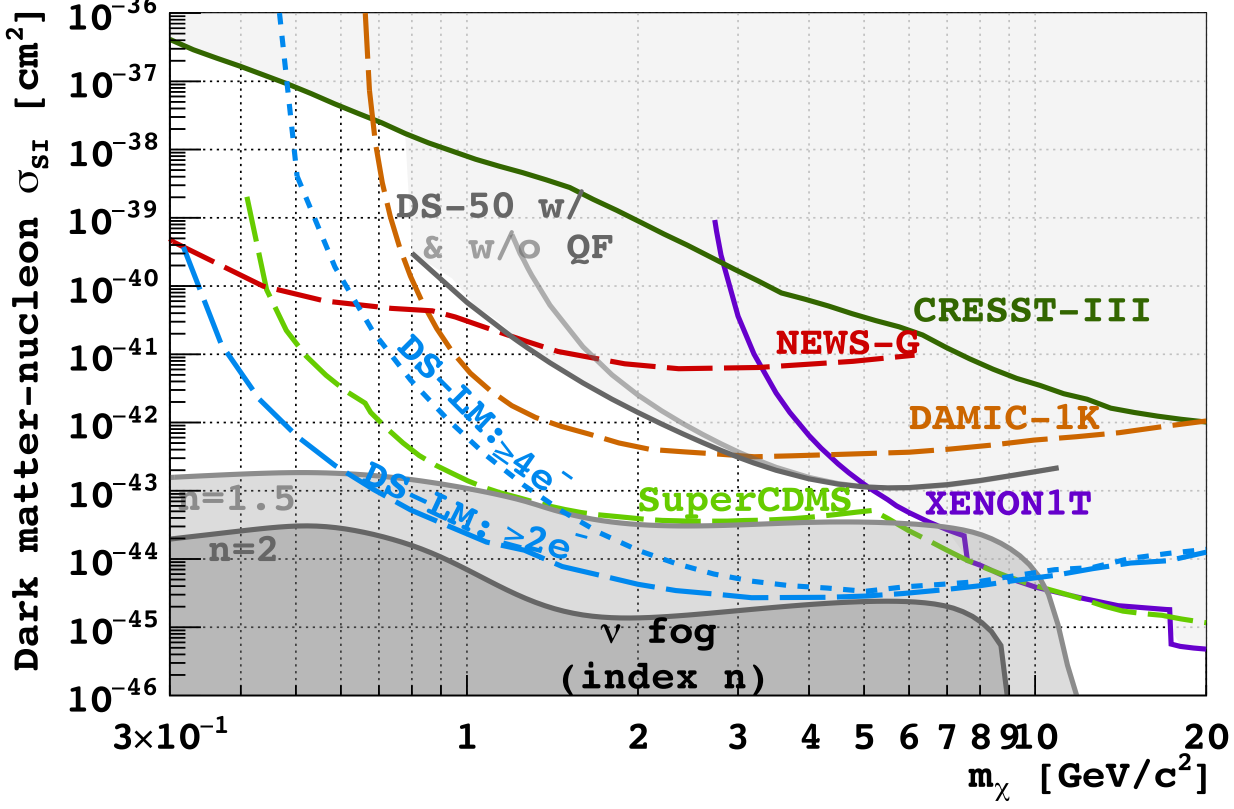
- low recoil energy

Low-mass direct detection

DarkSide

- Liquid Argon: 50 → 20k [kg]
    - new detector (DarkSide-LowMass) is in R&D
    - ADM is in this very mass range
- Japanese dark-matter community in Warsaw
    - Masayuki Wada (AstroCeNT)
    - Masato Kimura (AstroCeNT → J-PARC; Muon g-2/EDM)

DarkSide collaboration, arXiv:2207.11966



“友がみな われよりえらく 見ゆる日よ
花を買ひ来て 妻としたしむ” 石川啄木

Dark hadrons

Self-interacting DM

AK, Kim and Kuwahara, JHEP, 2020

$$\sigma/m \sim \frac{4\pi}{m_{\pi'}^2 m_{b'}} \simeq 0.3\,\mathrm{cm}^2/\mathrm{g}\left(\frac{100\,\mathrm{MeV}}{m_{\pi'}}\right)^2\left(\frac{1\,\mathrm{GeV}}{m_{b'}}\right)$$

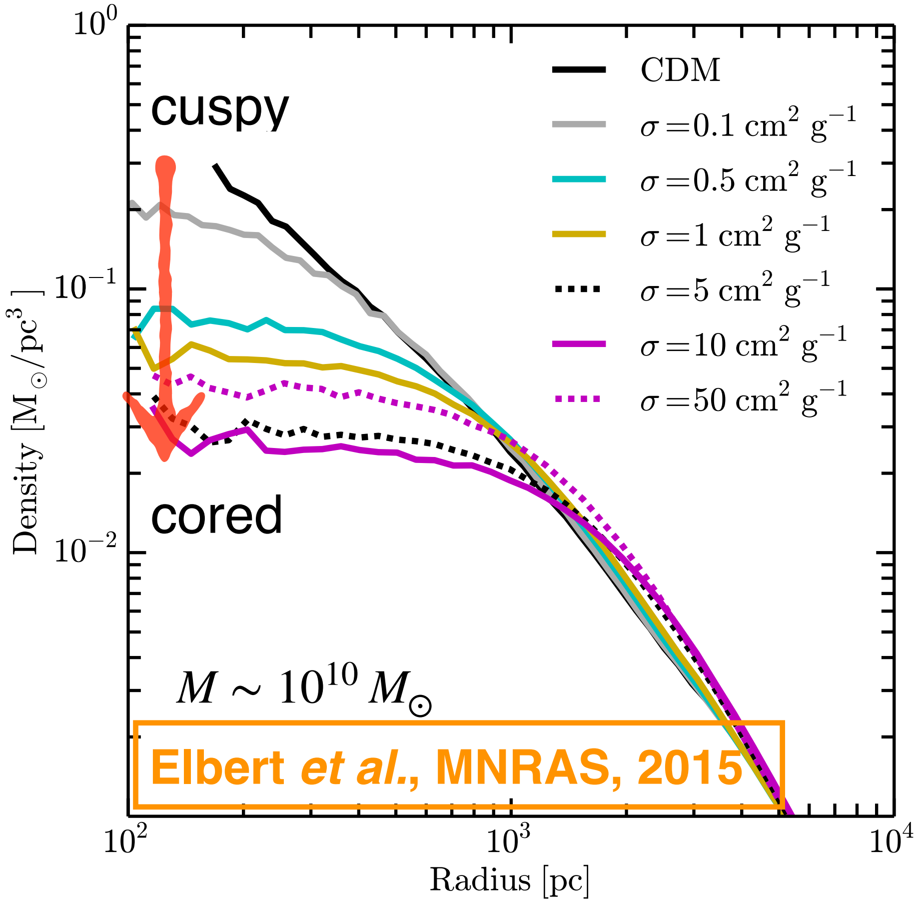
- dark matter density profile inside a halo turns from cuspy to cored

- good for some galaxies but not for others

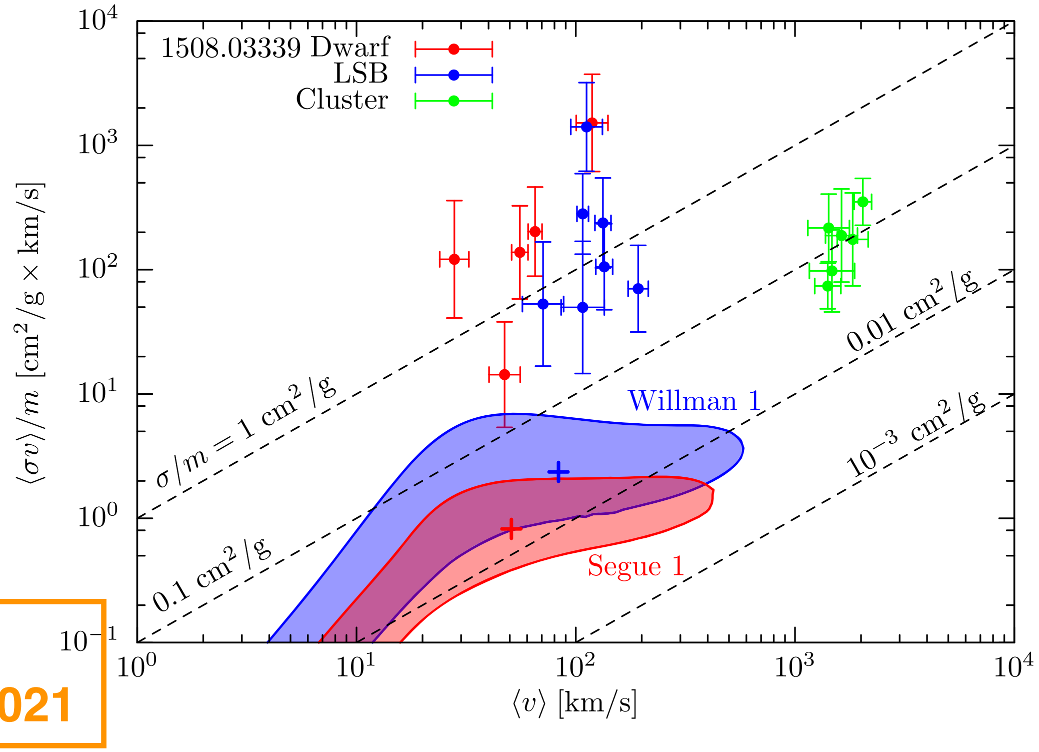
- upper bound on σ/m

  → lower bounds on $m_{\pi'}$ and $m_{b'}$

- keep in mind that the above estimate is conservative
  - scattering length ~ effective range ~ 1 / pion mass
    - but scattering length ~ 10 times effective range for nucleons



Elbert *et al.*, MNRAS, 2015



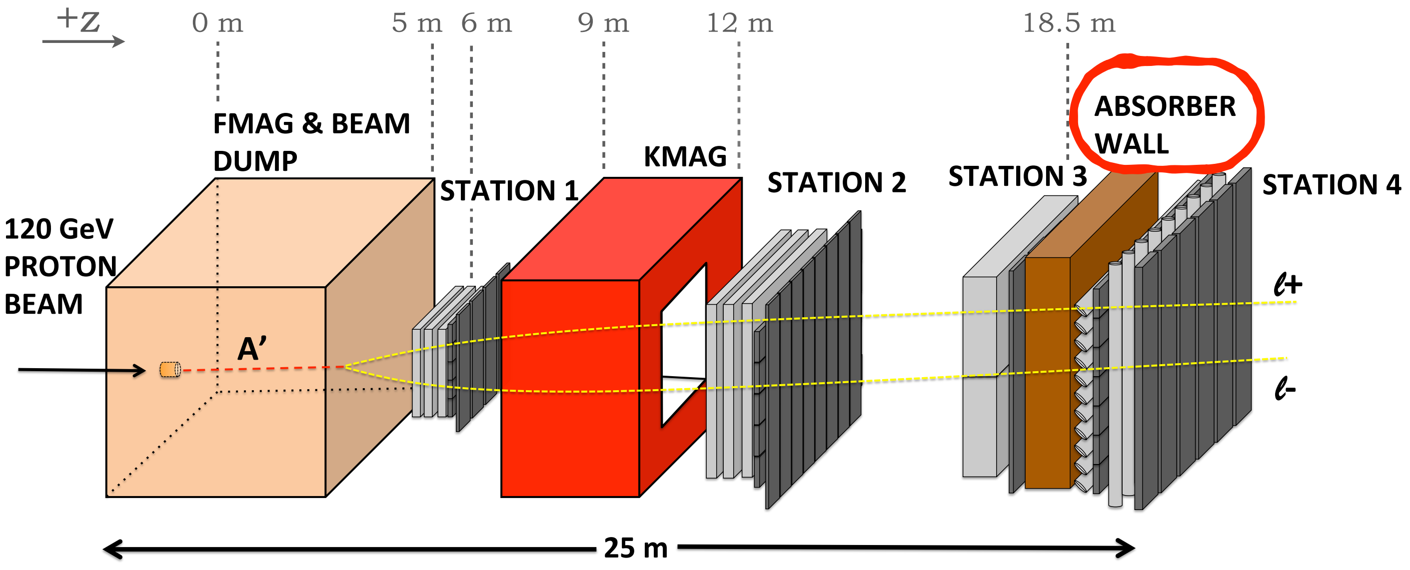
Hayashi, Ibe, Kobayashi, Nakayama, and Shirai, PRD, 2021

Intensity frontier

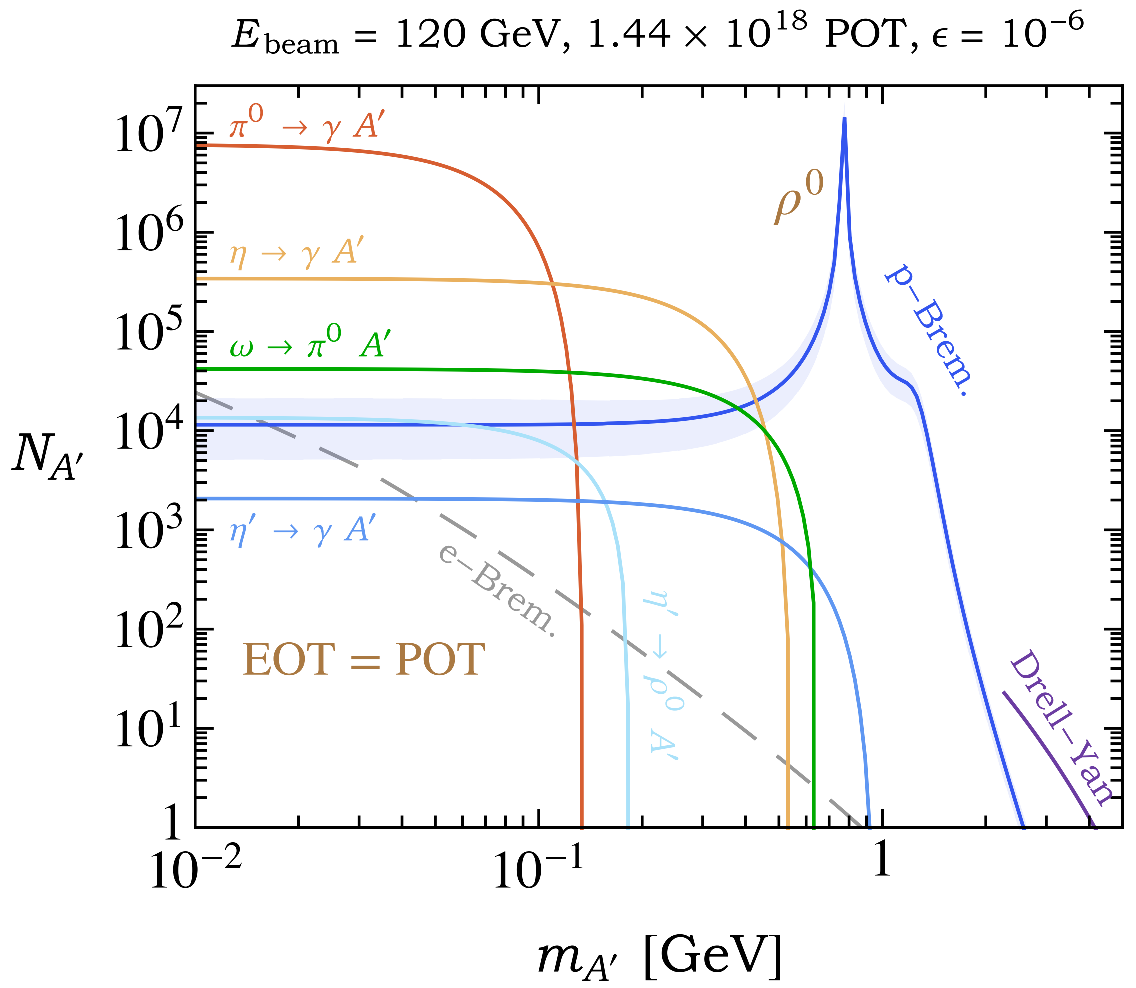
Fixed target experiment

Berlin, Gori, Schuster, and Toro, PRD, 2018

- SeaQuest@Fermilab
  - proton beam at iron target
  - place ECAL (di-electrons) in front of absorber wall (DarkQuest)
  - forward direction $\theta_{\rm det} = 0.05$
- proton on target $\sim 10^{20}$ (phase II; 2026+) $\mathscr{L} \sim 2\,{\rm zb}^{-1}$
  - more dark photons production by proton bremsstrahlung and meson decay compared to electron bremsstrahlung



- anti-q pdf of nucleus through Drell-Yan production of di-muons


$E_{\rm beam} = 120$ GeV, 1.44×10^{18} POT, $\epsilon = 10^{-6}$

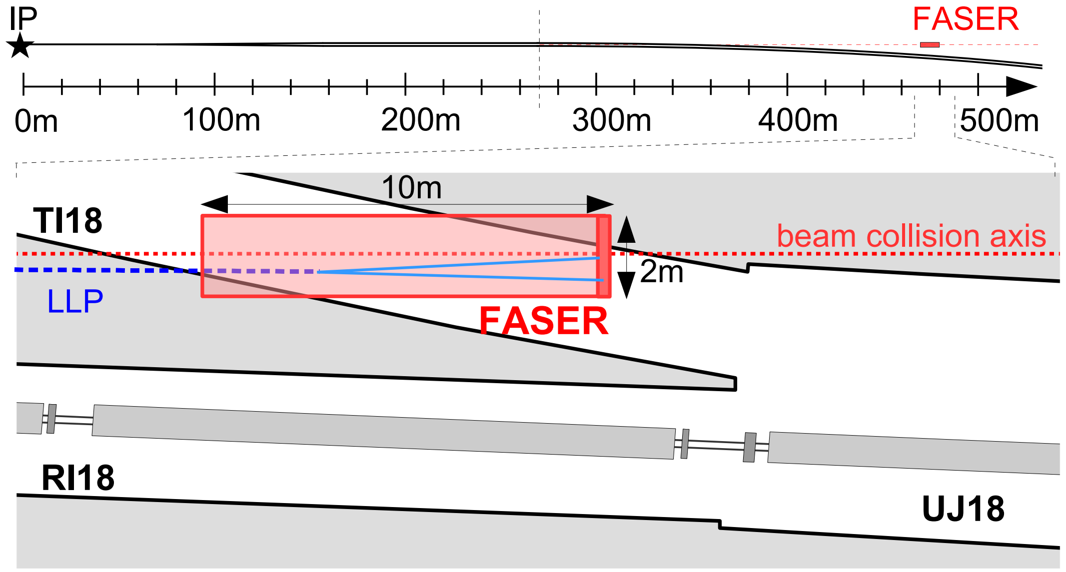
Lifetime frontier

LHC lifetime frontier

- HL-LHC (2027+) $\mathscr{L} = 3\,\mathrm{ab}^{-1}$
  - intensity frontier as well as high-energy frontier

Berlin and Kling, PRD, 2019

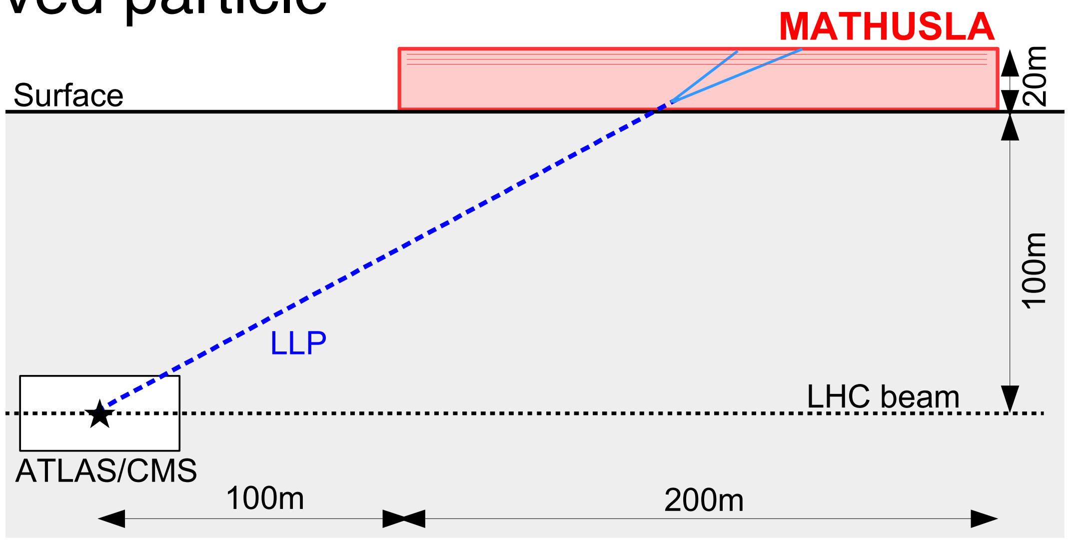
- FASER(2)
  - forward direction $\theta_{\mathrm{det}} = 2 \times 10^{-3}$
  - more boosted and thus shorter lifetime particles come



$$p_{\mathrm{geo}} \sim p_T / \theta_{\mathrm{det}}$$

- typical transverse momentum is determined by the production process of long-lived particle

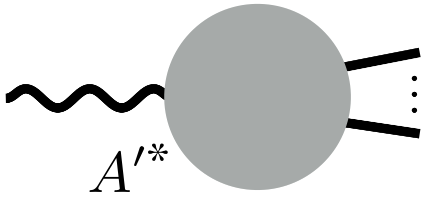
- MATHUSLA (CODEX-b)
  - off-axis $\theta_{\mathrm{det}} = 0.5$
  - less boosted and thus longer lifetime particles come



Production

Virtual dark photon

- produced number of dark hadrons



dark hadrons

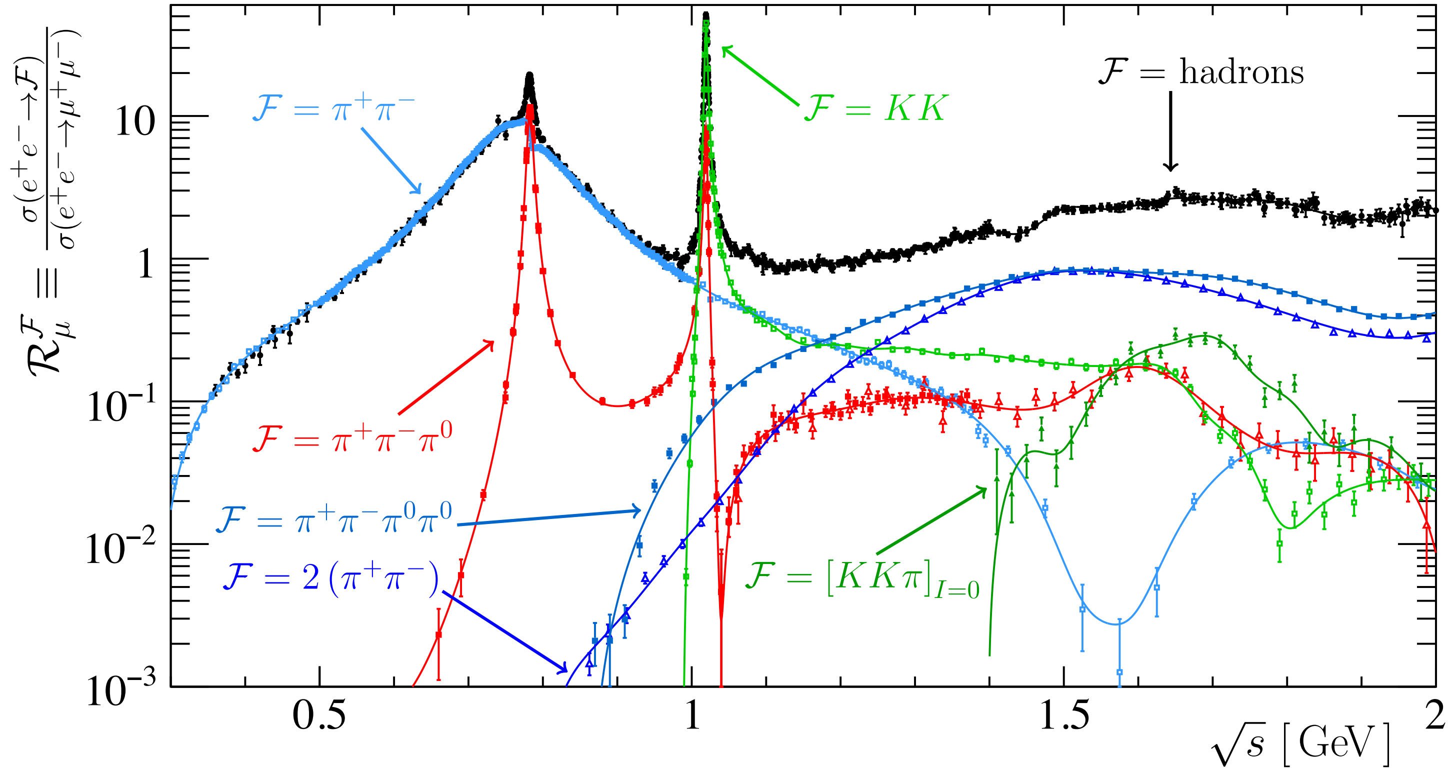
$$N \simeq \int dm_{A'}^{*2} \frac{1}{\pi} \frac{m_{A'}^{*} \Gamma_{A'}(m_{A'} = m_{A'}^{*})}{m_{A'}^{*4}} N_{A'} \Big|_{m_{A'} = m_{A'}^{*}}$$

$\Gamma_{A'}(A' \to \text{hadrons})$

- injection of energy into dark QCD sector through dark QED current

- SM analog
  - below dynamical scale, charged pion production is dominant, but neutral pion production (our interest) is suppressed
    - vector meson dominance
  - above dynamical scale, quarks + hadronization

Ilten, Soreq, Williams, and Xue, JHEP, 2018

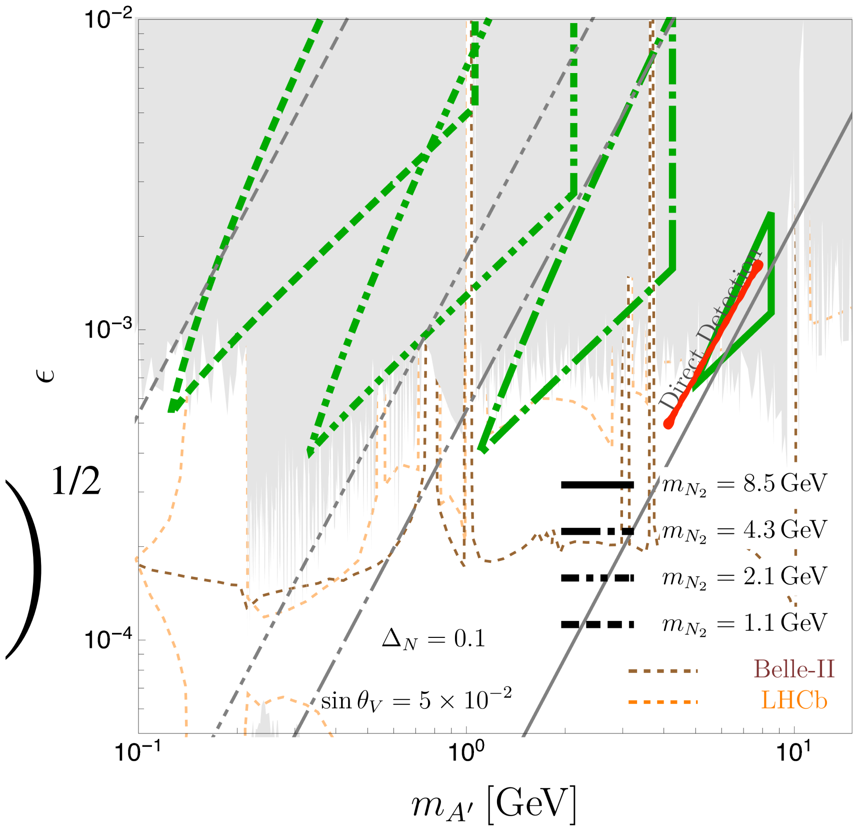


Sensitivities

Direct detection of dark baryons

- because of dark QED breaking, neutron-like state scatters with SM proton through dark photon exchange

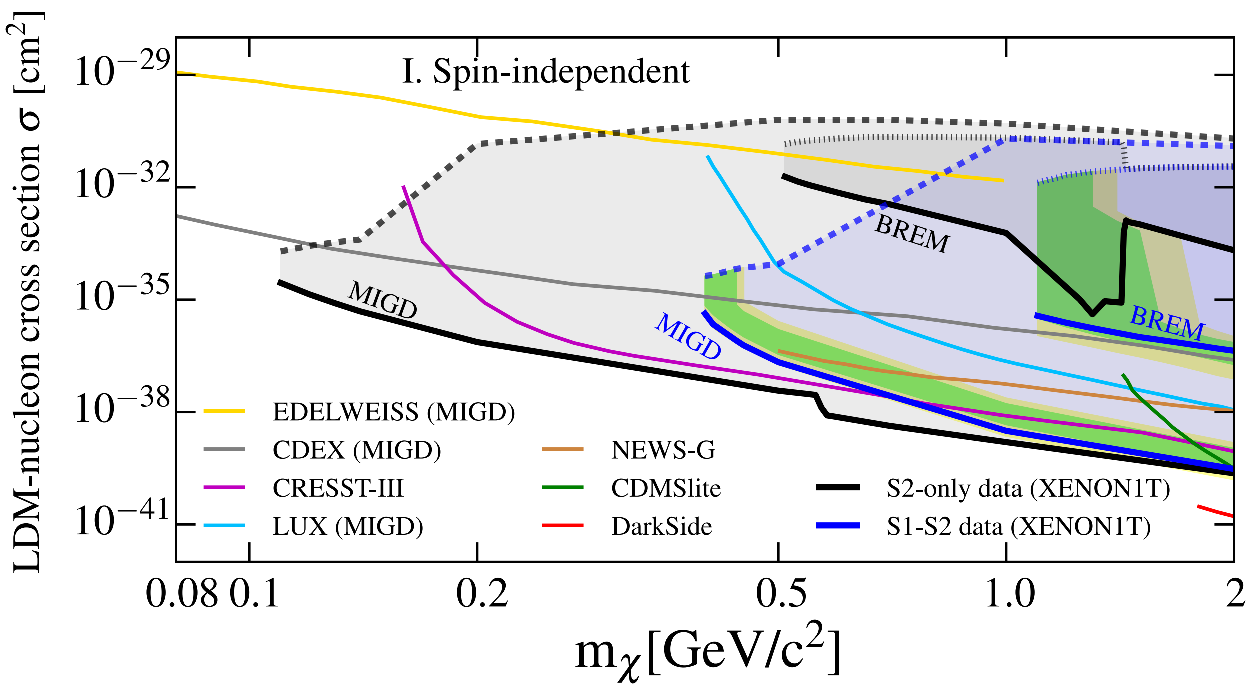
$$\epsilon \sin^2\theta_V \leq 1.4\times 10^{-7}\left(\frac{m_{A'}}{1\,\mathrm{GeV}}\right)^2\left(\frac{\alpha'}{1/137}\right)^{-1/2}\left(\frac{\sigma^{\mathrm{bound}}}{6\times 10^{-45}\,\mathrm{cm}^2}\right)^{1/2}$$

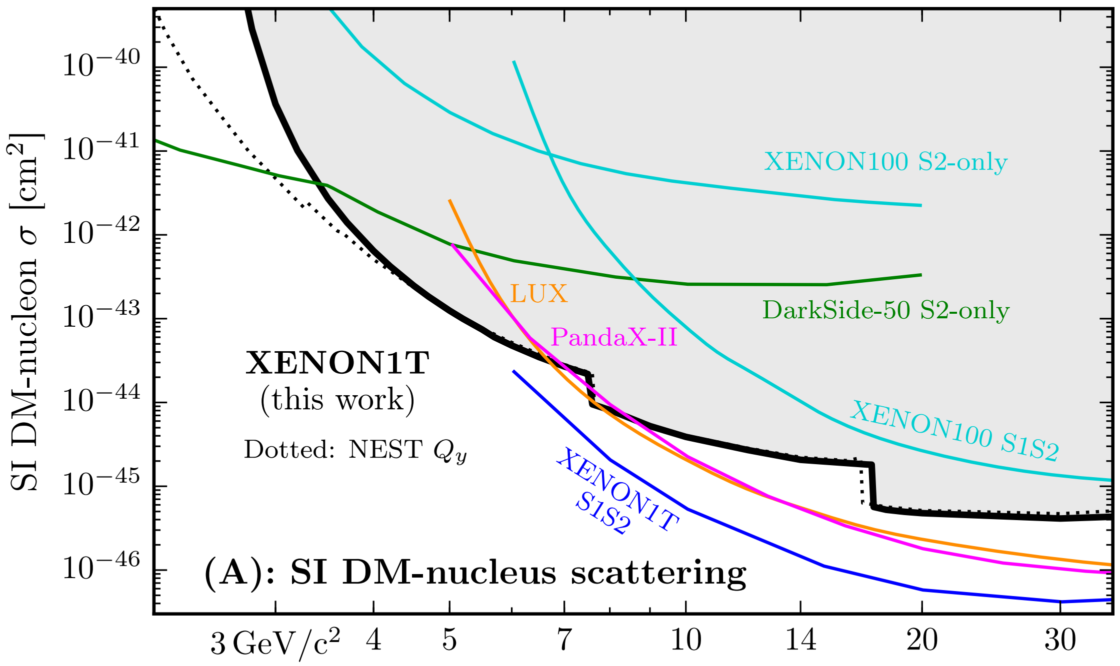


- GeV-scale dark matter

- because of low recoil energy, more dedicated analysis (e.g., "S2[ionization]-only", Migdal effect) is required

XENON1T collaboration, PRL, 2019 & 2019

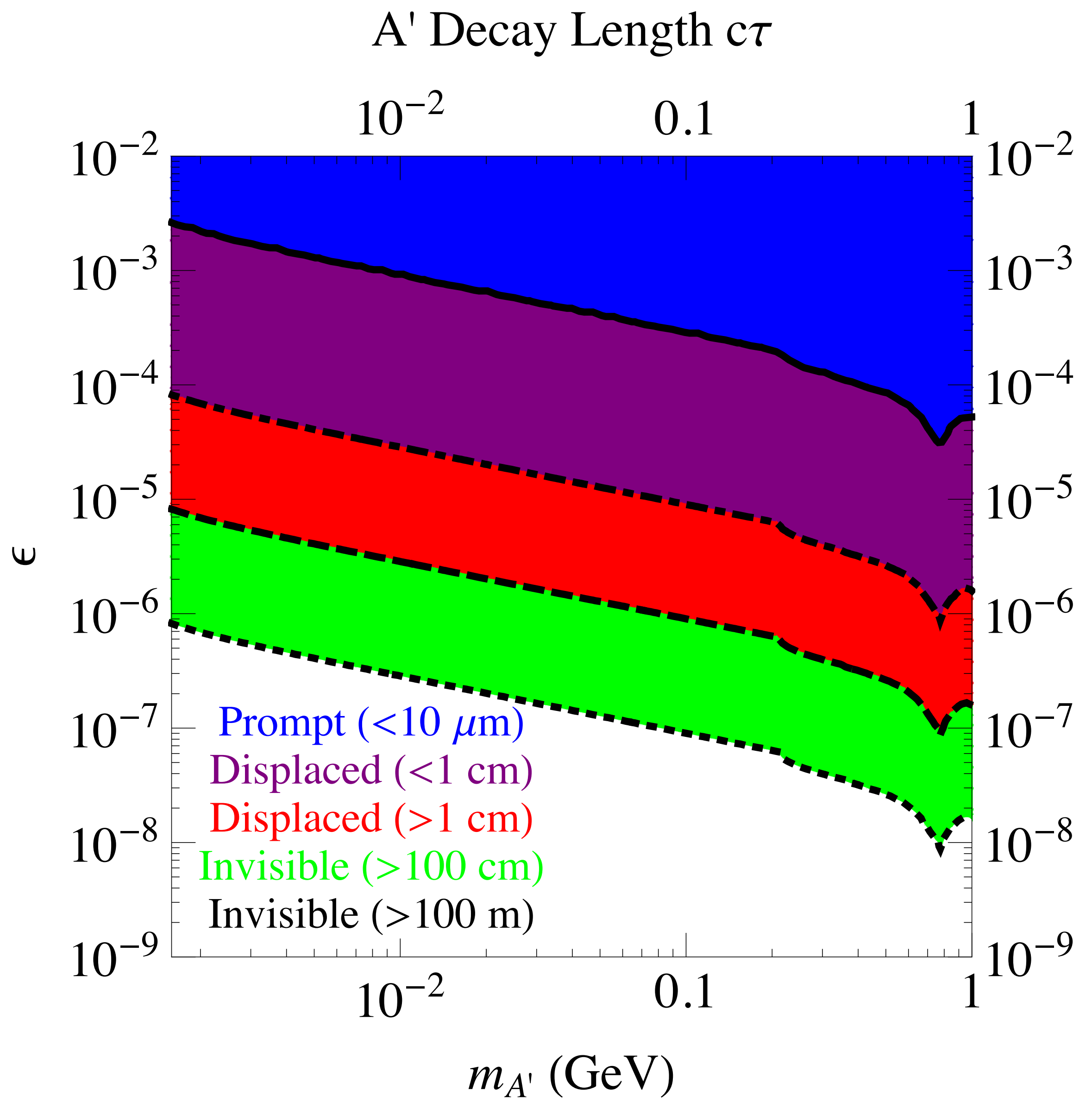




Decay length

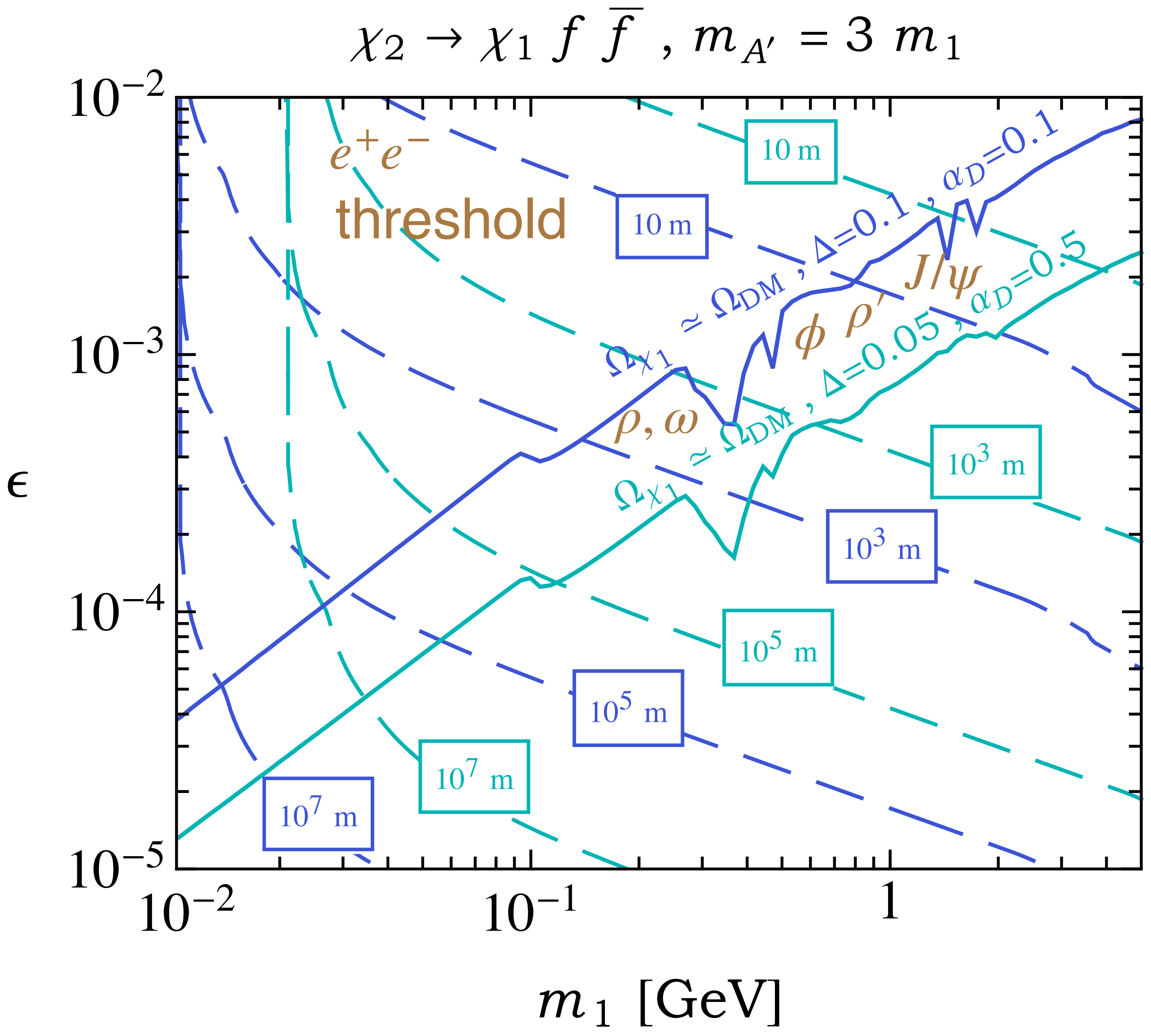
Dark photon portal

- minimal model



Essig, Harnik, Kaplan, and Toro, PRD, 2010

- inelastic dark matter model



Berlin, Gori, Schuster, and Toro, PRD, 2018

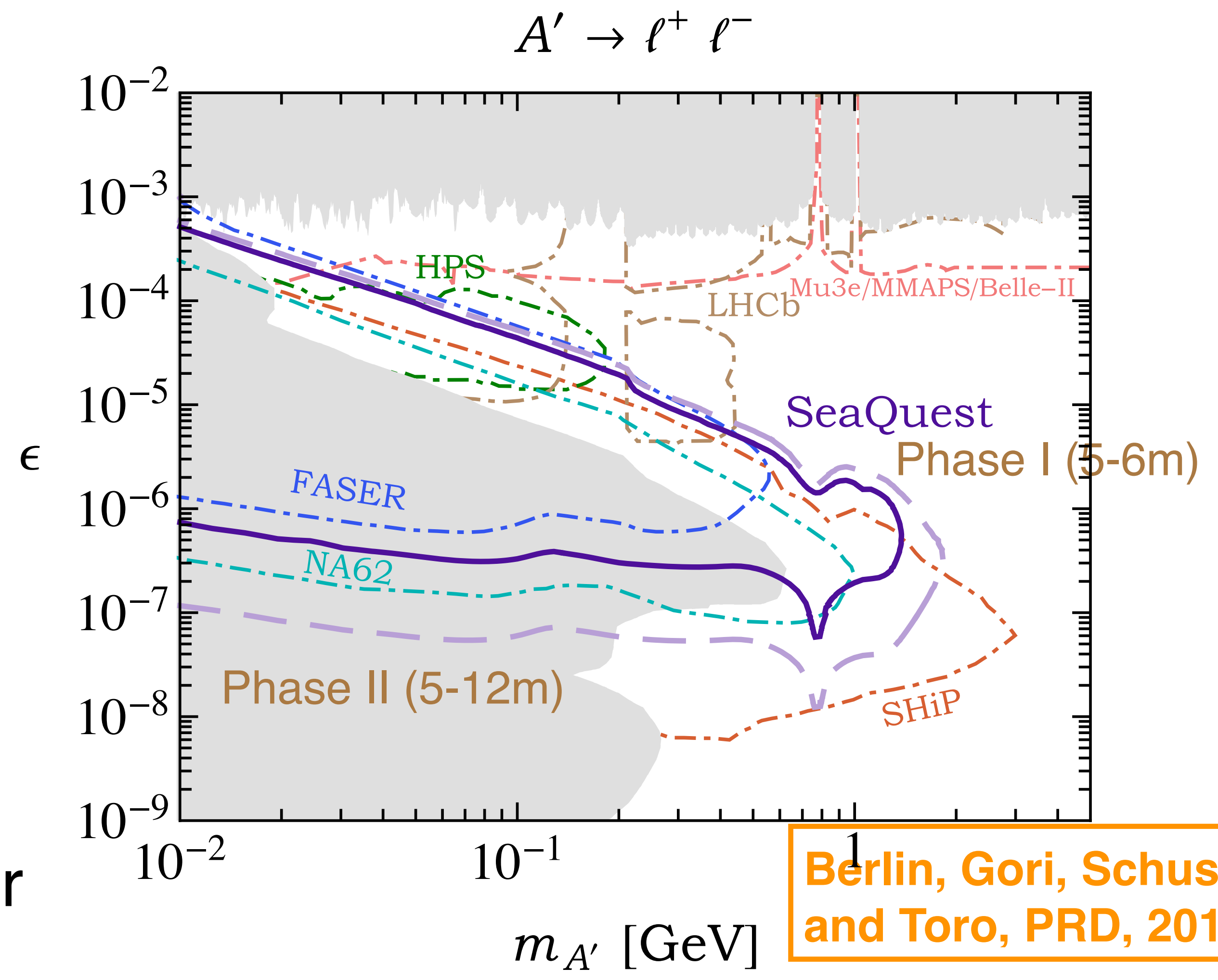
Massive dark photon

Experimental searches

- prompt decay search
  - resonance in invariant mass (LHCb, Belle-II…)

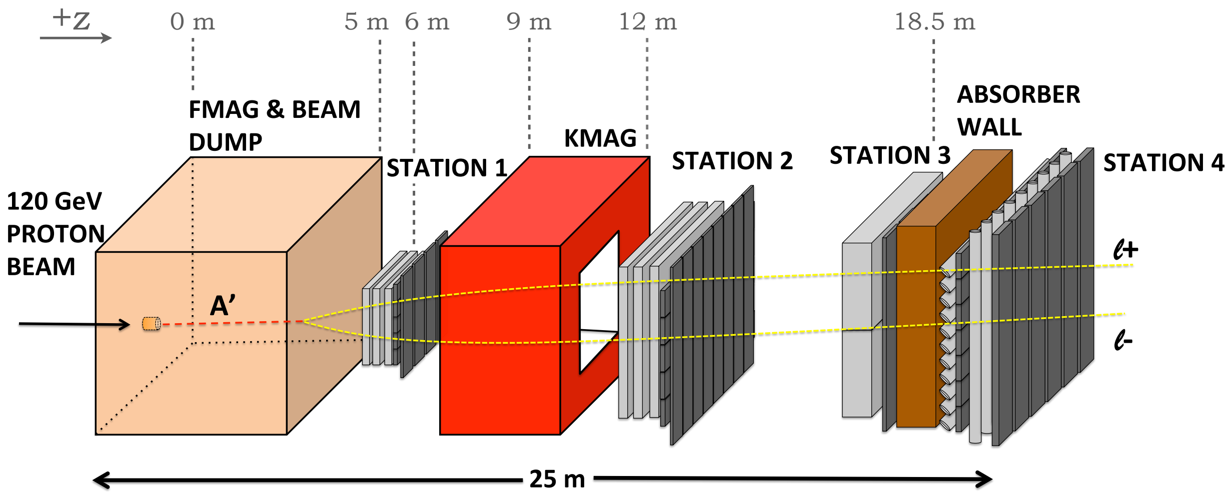
$$\gamma' \to e^+e^- \quad \mu^+\mu^-$$

- long-lived particle (LLP) search
  - displaced vertex (LHCb…)
  - decay in a detector located far from production points



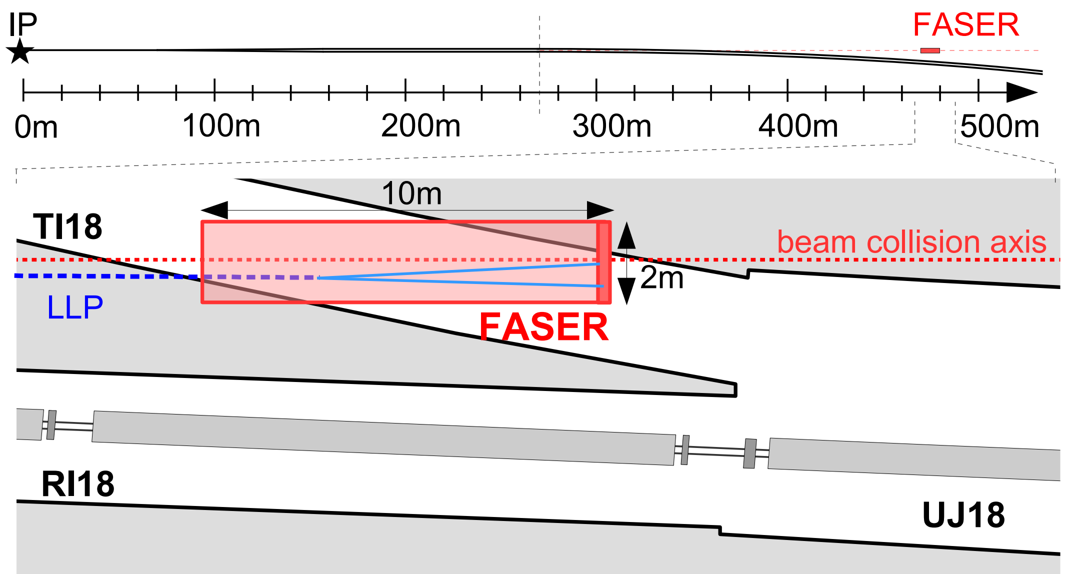
Berlin, Gori, Schuster, and Toro, PRD, 2018

- SeaQuest @ Fermilab



- FASER @ LHC

Berlin and Kling, PRD, 2019

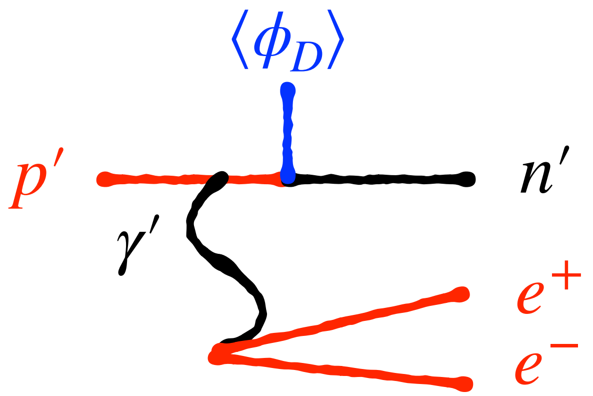


Dark hadrons

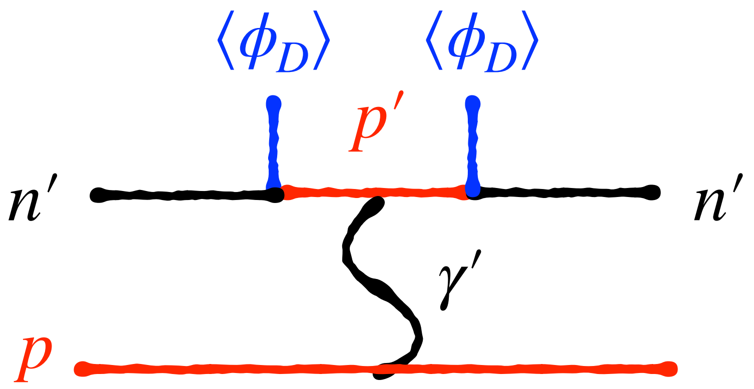
AK and Kuwahara, JHEP, 2022

Transition

$p' \to n' + e^+e^-$



- through charge breaking

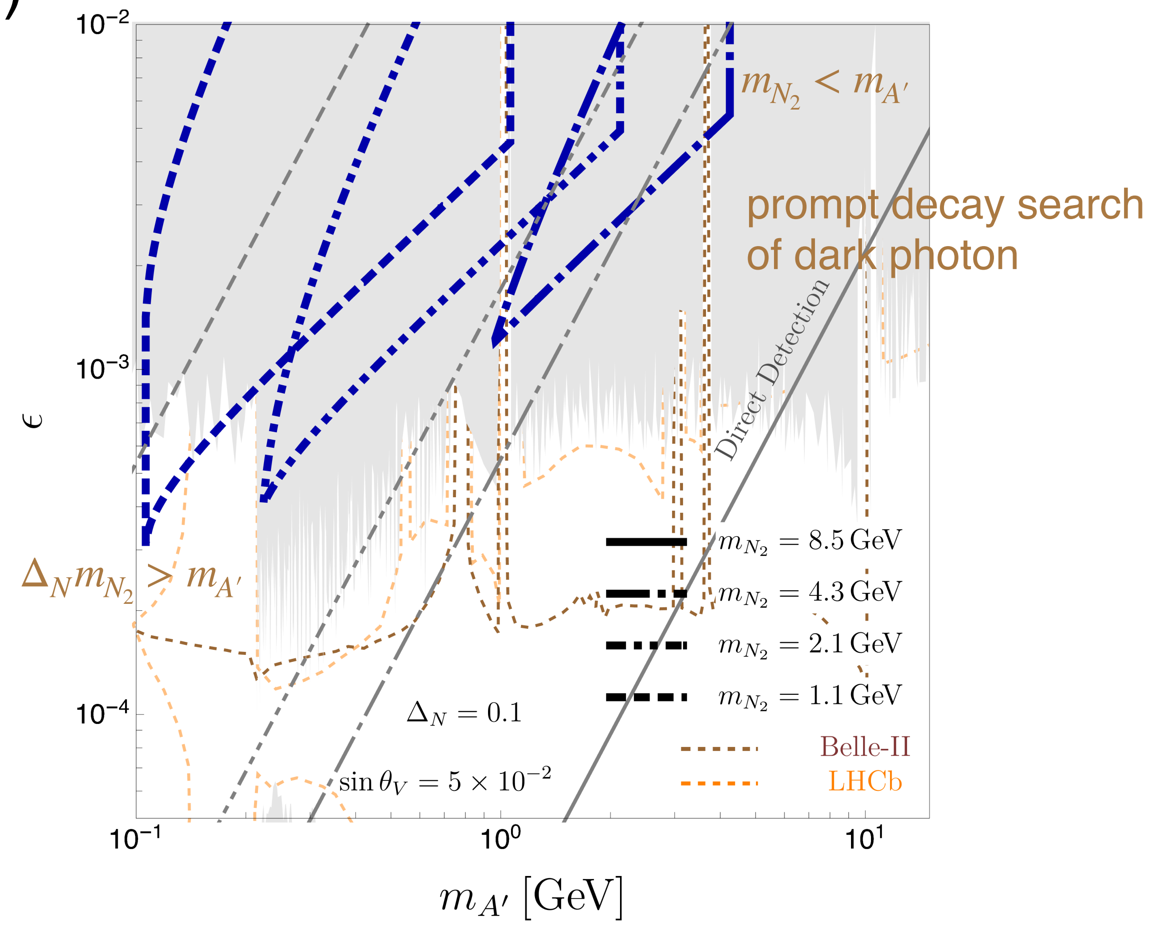


- direct detection constraints are weakened
  - only dark neutron makes up DM
  - not disappear (charge breaking)

LLP search

- sensitivity is comparable with direct detection and prompt decay search of dark photon

- FASER



Dark hadrons

Decay

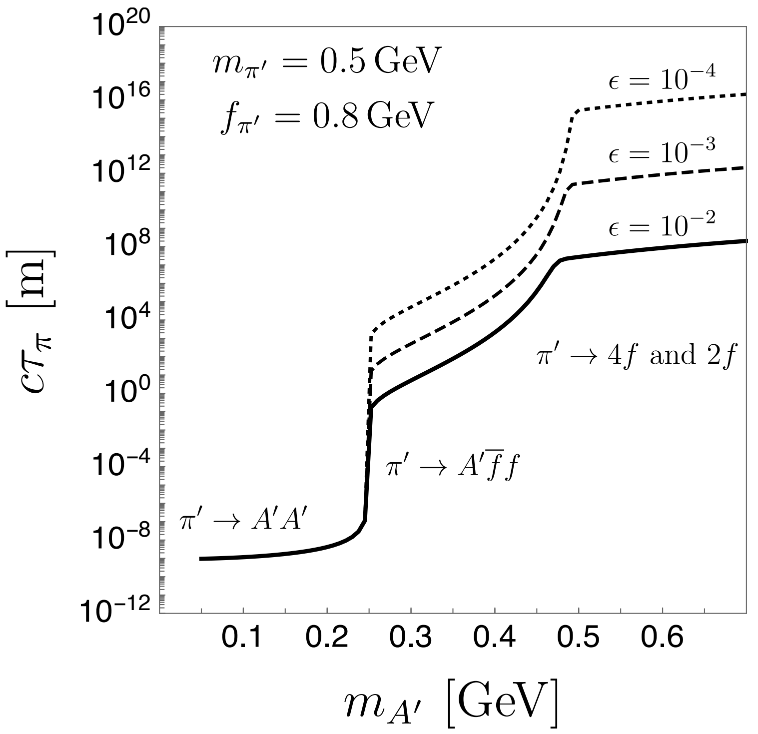
$$\pi'^0 \to \gamma' + e^+e^-$$

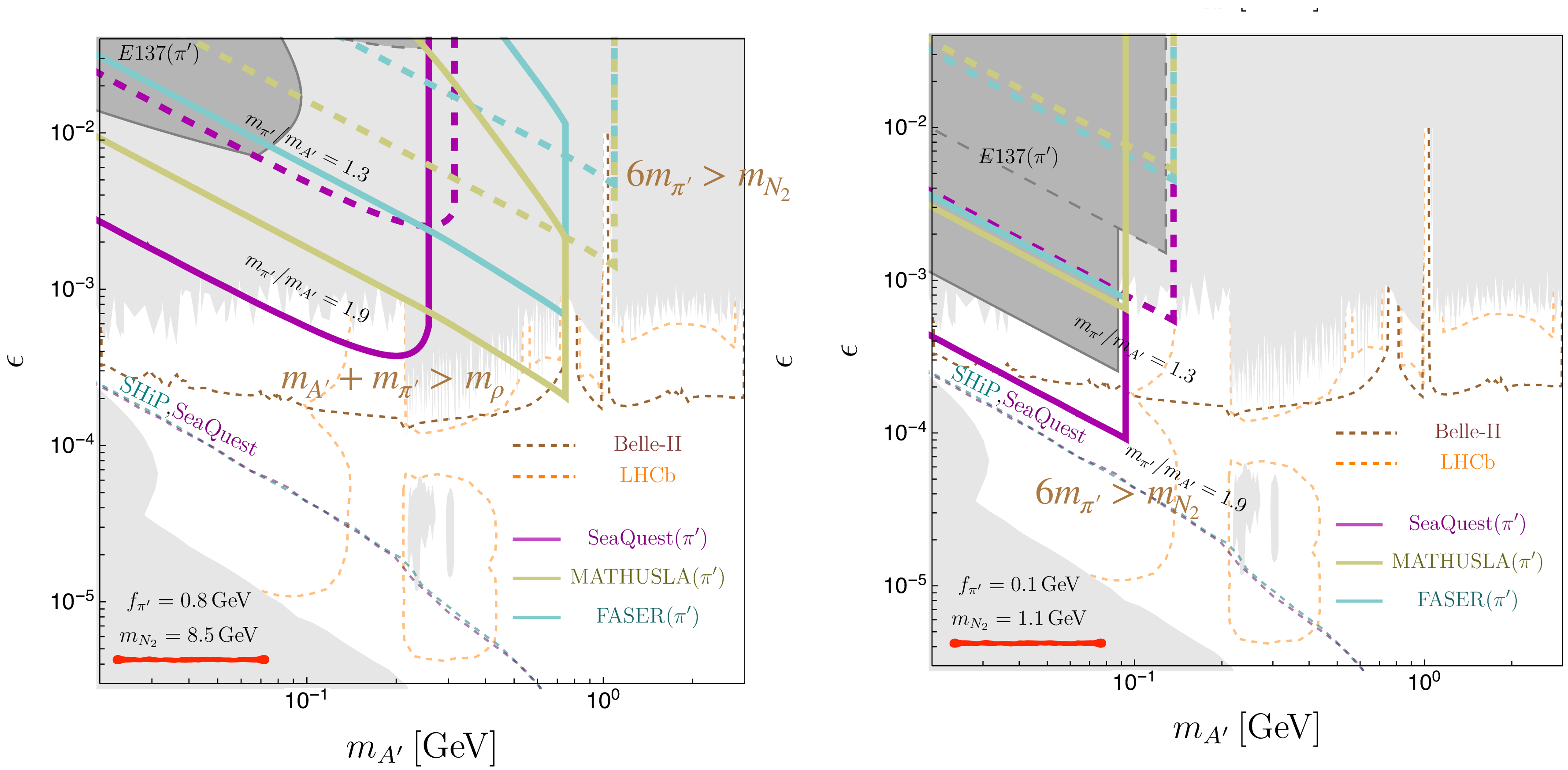
- assume $m_{\gamma'} < m_{\pi'} < 2m_{\gamma'}$
  - otherwise short-lived (no ϵ dependence)

LLP searches

- sensitivity is comparable with direct detection and prompt decay search of dark photon

AK and Kuwahara, JHEP, 2022





- enhanced production for $\Lambda_{\mathrm{QCD}'} < m_\rho$
  - copious production through hadronization

Data points

Overview

- cores in various-size halos

- MW satellite (Draco)

$M_{\text{infall}} \sim 10^9\, M_\odot$

- galaxy cluster (Abell 2744)

$M \sim 10^{14}\, M_\odot$

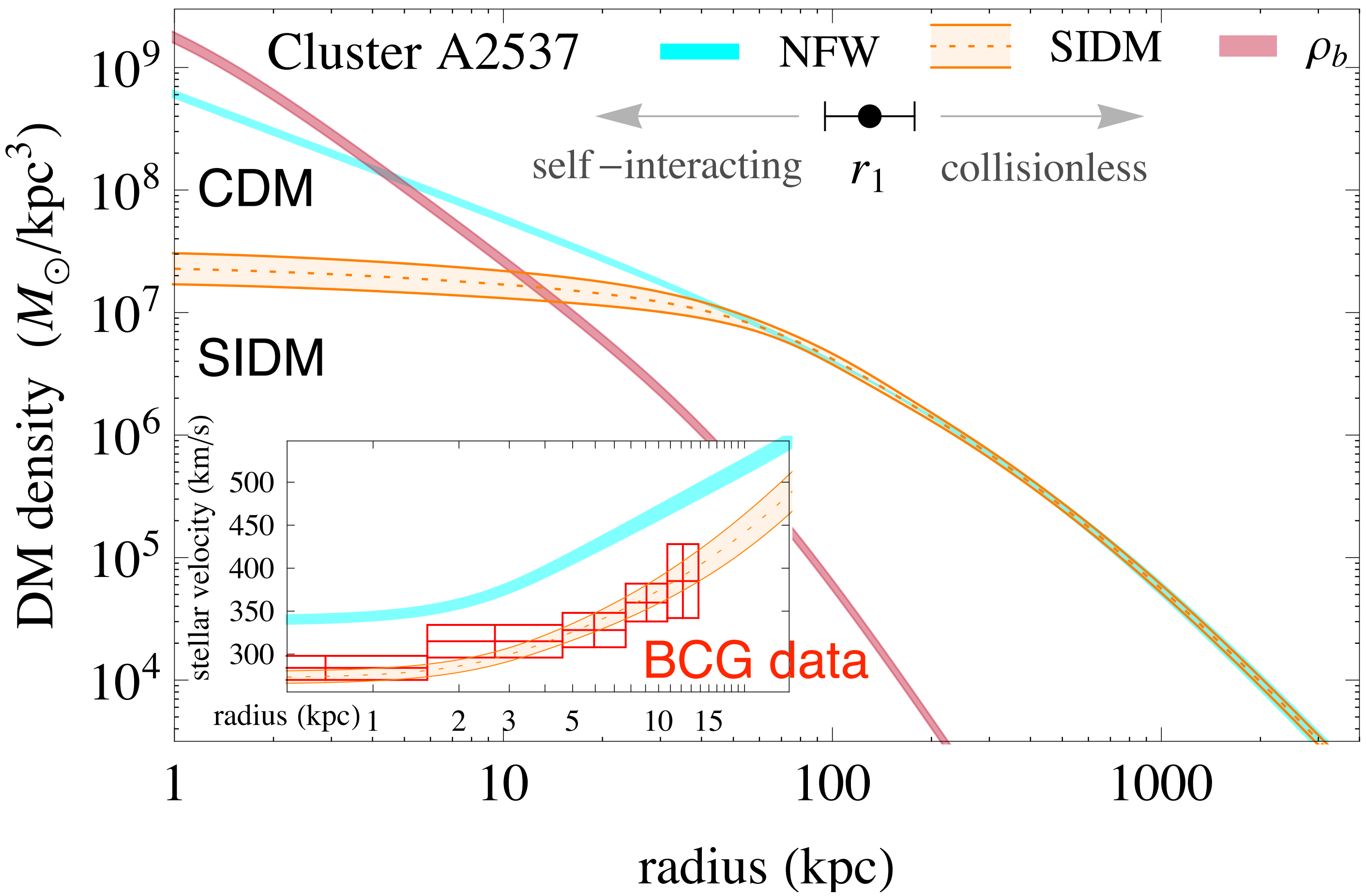
- dwarf spiral galaxy (IC 2574) $M \sim 10^{11}\, M_\odot$

Data points

Galaxy clusters

- mass distribution in the outer region is determined by strong/weak gravitational lensing

- stellar kinematics in the central region (brightest cluster galaxies) prefer cored SIDM profile



$$\sigma_{\mathrm{self}}/m \sim 0.1\,\mathrm{cm}^2/\mathrm{g}$$

$$\langle v_{\mathrm{rel}} \rangle \sim 10^3\,\mathrm{km/s}$$

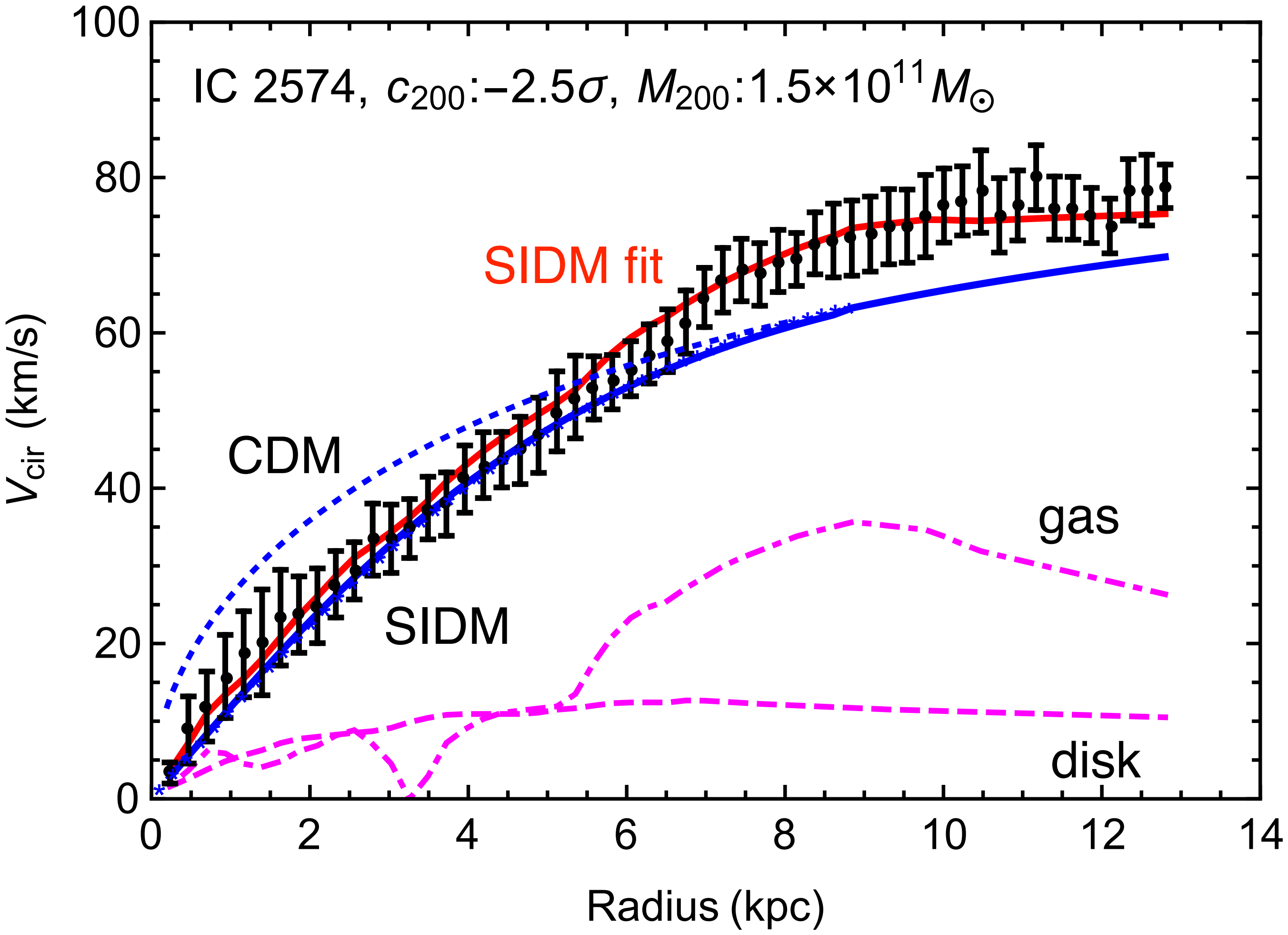
Kaplinghat, Tulin, and Yu, PRL, 2016

Data points

Dwarf spiral galaxies

- mass distribution is broadly determined by rotation curves

- rotation velocity in central region (of some galaxies) prefer cored SIDM profile



$$\sigma_{\rm self}/m \sim 1\,{\rm cm}^2/{\rm g}$$

$$\langle v_{\rm rel}\rangle \sim 10^2\,{\rm km/s}$$

AK, Kaplinghat, Pace, and Yu, PRL, 2017

Diversity in dwarf spiral galaxies

Rotation curves

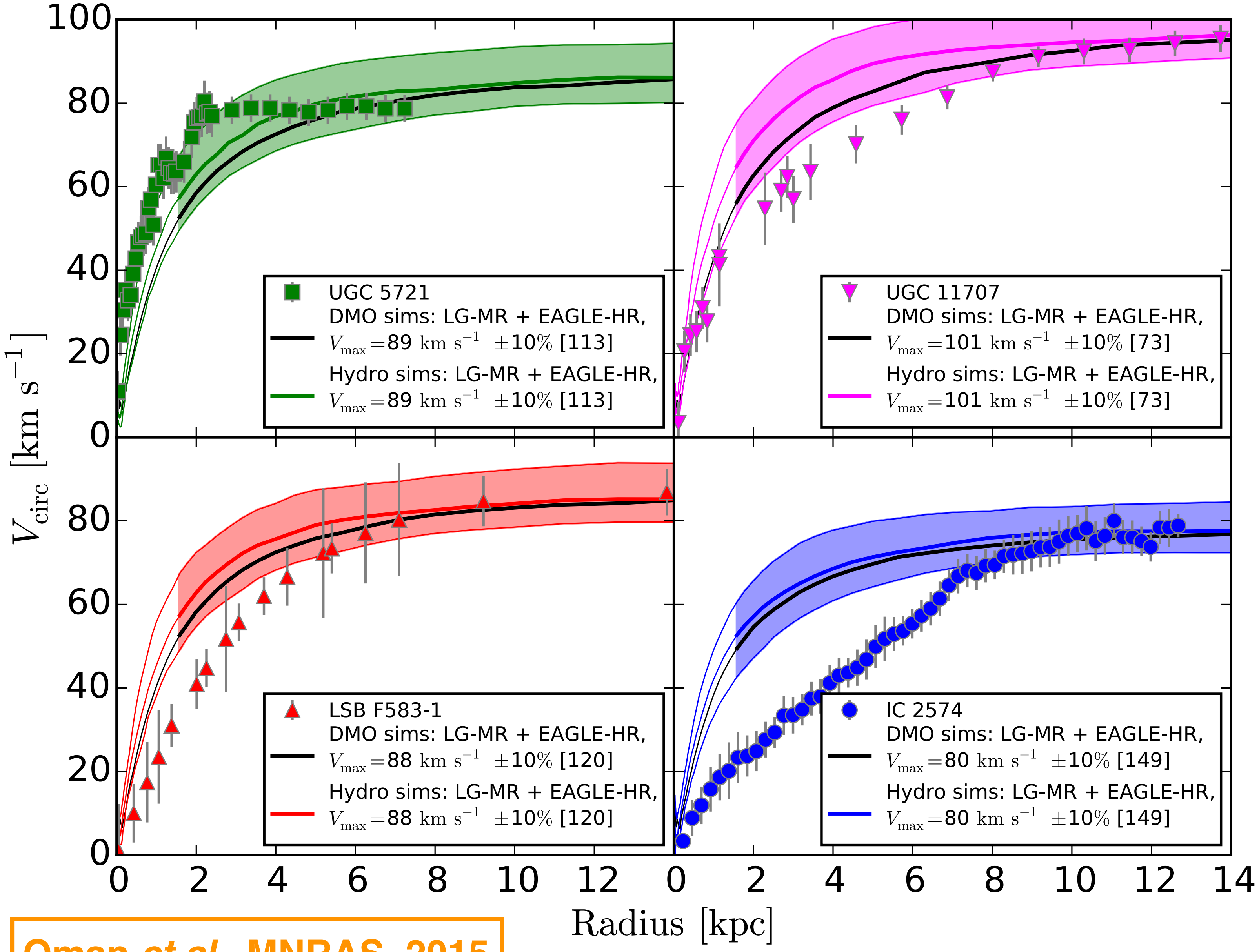
- simulation: inner circular velocity is almost uniquely determined by outer circular velocity

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

- ρ_s and r_s are not independent (concentration-mass relation)

↕

- observation: diverse inner circular velocity

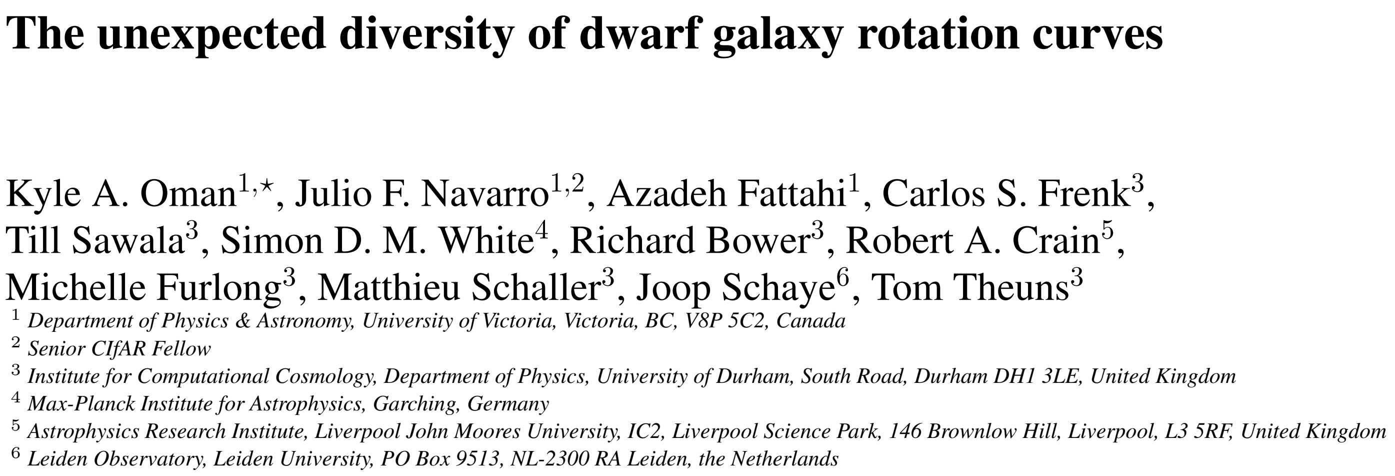


Oman *et al.*, MNRAS, 2015

Can SIDM explain it?

Naively, no

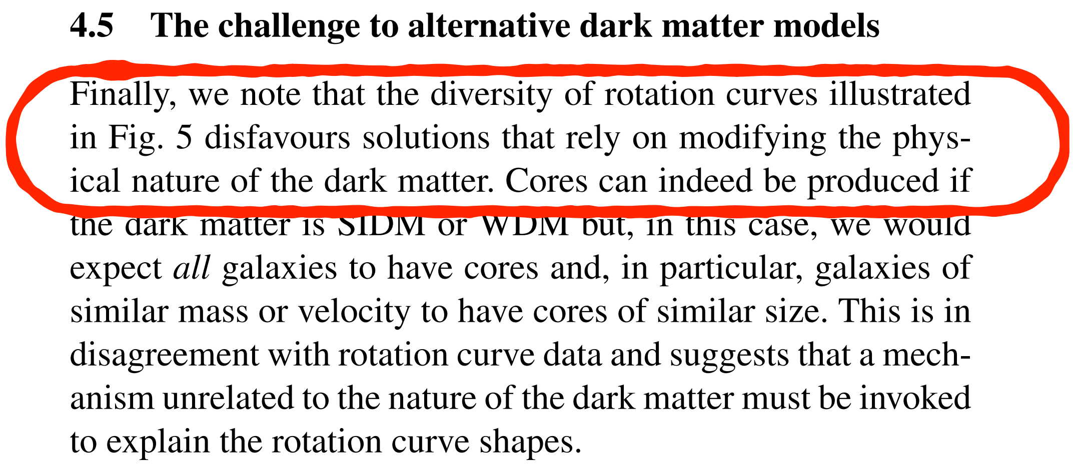
- SIDM has a universal impact



The unexpected diversity of dwarf galaxy rotation curves

Kyle A. Oman[1,⋆], Julio F. Navarro[1,2], Azadeh Fattahi[1], Carlos S. Frenk[3], Till Sawala[3], Simon D. M. White[4], Richard Bower[3], Robert A. Crain[5], Michelle Furlong[3], Matthieu Schaller[3], Joop Schaye[6], Tom Theuns[3]

[1] *Department of Physics & Astronomy, University of Victoria, Victoria, BC, V8P 5C2, Canada*
[2] *Senior CIfAR Fellow*
[3] *Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, United Kingdom*
[4] *Max-Planck Institute for Astrophysics, Garching, Germany*
[5] *Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, 146 Brownlow Hill, Liverpool, L3 5RF, United Kingdom*
[6] *Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands*



4.5 The challenge to alternative dark matter models

Finally, we note that the diversity of rotation curves illustrated in Fig. 5 disfavours solutions that rely on modifying the physical nature of the dark matter. Cores can indeed be produced if the dark matter is SIDM or WDM but, in this case, we would expect *all* galaxies to have cores and, in particular, galaxies of similar mass or velocity to have cores of similar size. This is in disagreement with rotation curve data and suggests that a mechanism unrelated to the nature of the dark matter must be invoked to explain the rotation curve shapes.

Really? But galactic disks show diversity

- different disk sizes in different halos
- SIDM profile is exponentially sensitive to baryon distribution

$$\rho_{\rm DM}(\vec{x}) = \rho^0_{\rm DM}\exp(-\phi(\vec{x})/\sigma^2)$$

$$\Delta\phi = 4\pi G(\rho_{\rm DM} + \boxed{\rho_{\rm baryon}})$$

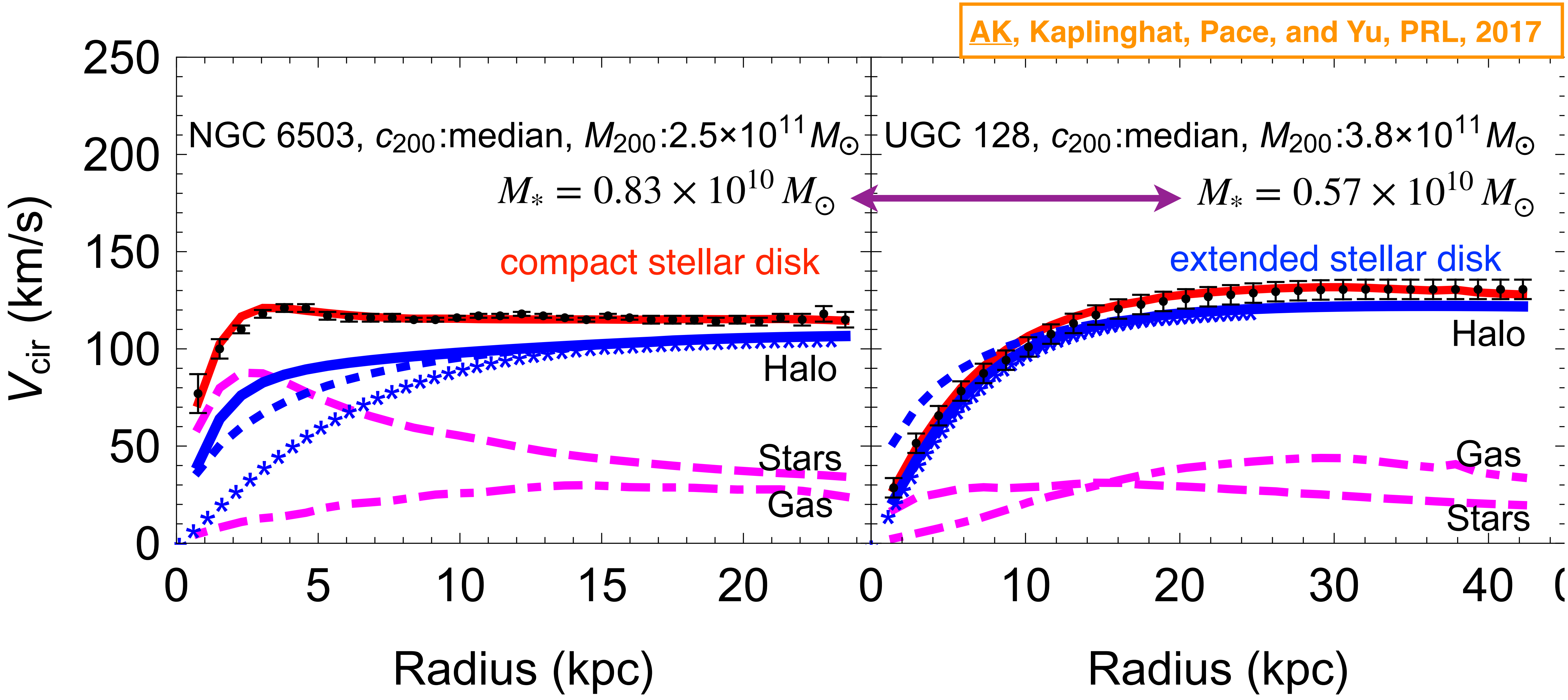
- iso-thermal region forms through self-interaction

SIDM explanation

SIDM reproduces diversity (unlike a naive expectation)

- compact disk→ redistribute SIDM significantly
- extended disk→ unchange SIDM distribution

$\sigma/m = 3\,\mathrm{cm}^2/\mathrm{g}$



AK, Kaplinghat, Pace, and Yu, PRL, 2017

Diversity in MW satellites

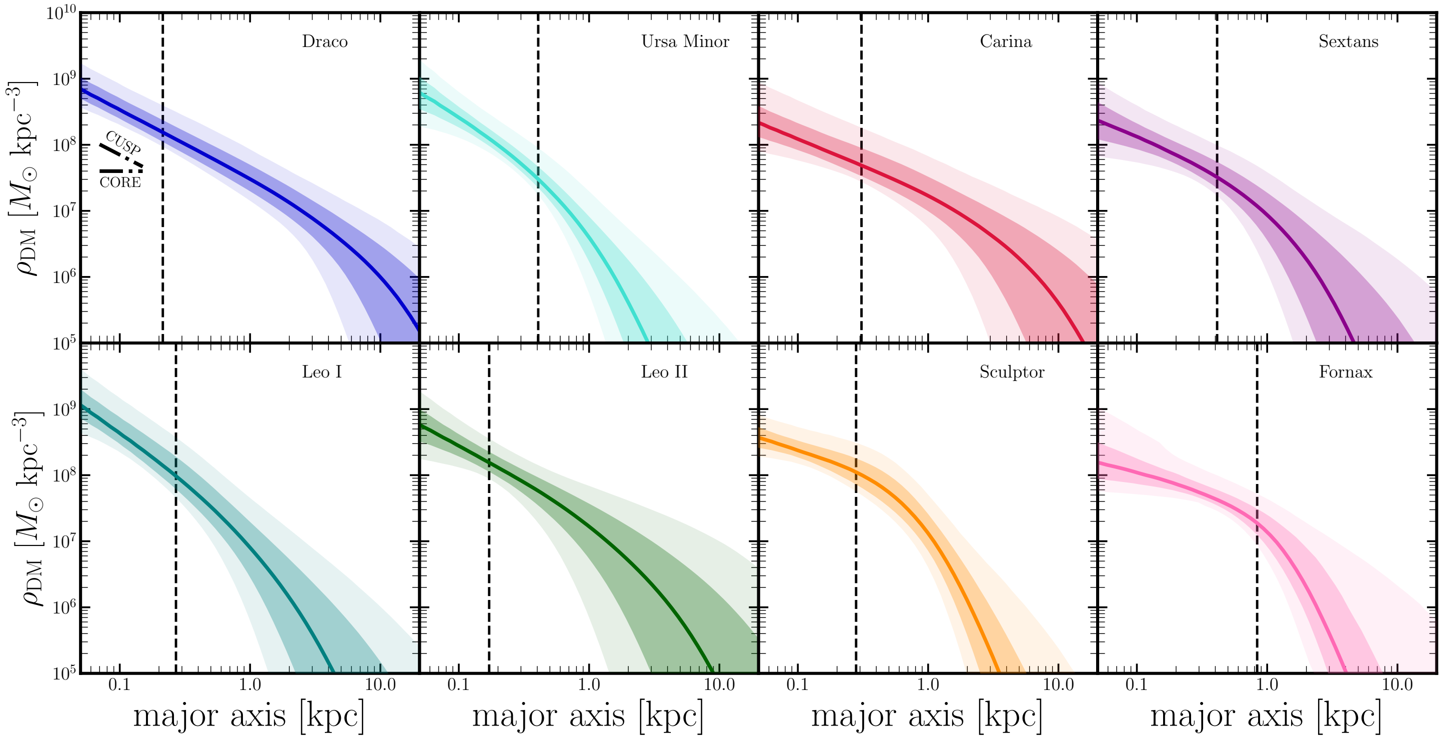
MW satellites (classical)

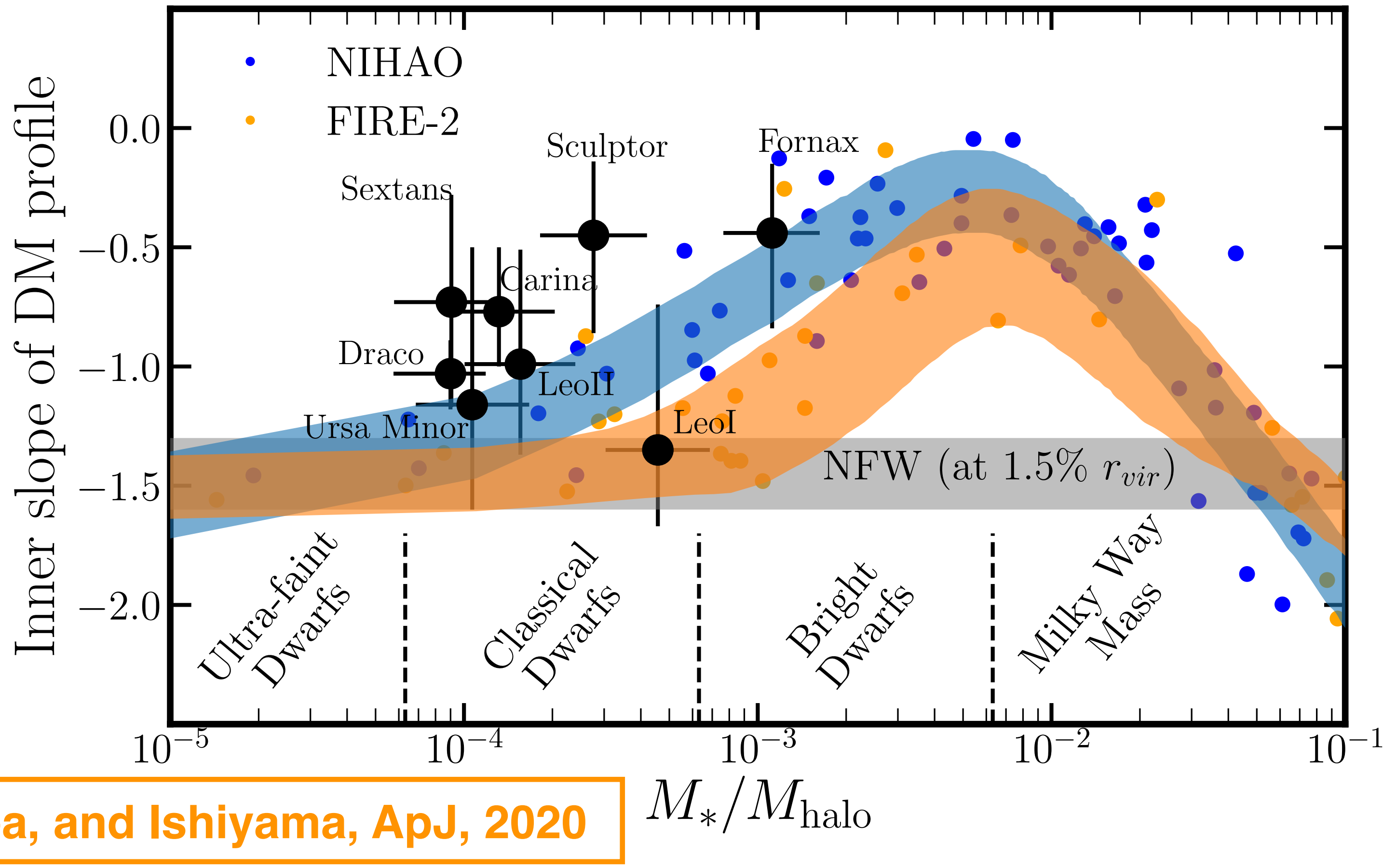
- mass distribution is determined by line-of-sight velocity dispersion (LOSVD) profile

- shows diversity in inner slope and density, though uncertainty is still large

SIDM again? Naively, no

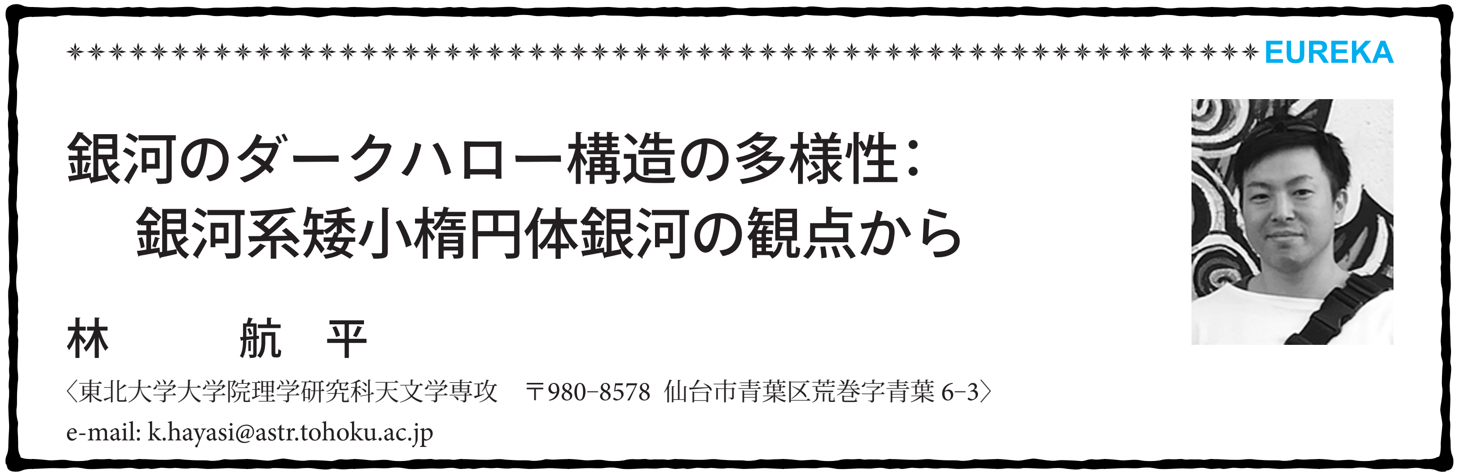
- satellite galaxies have only negligible amount of baryons





Hayashi, Chiba, and Ishiyama, ApJ, 2020

Diversity in MW satellites

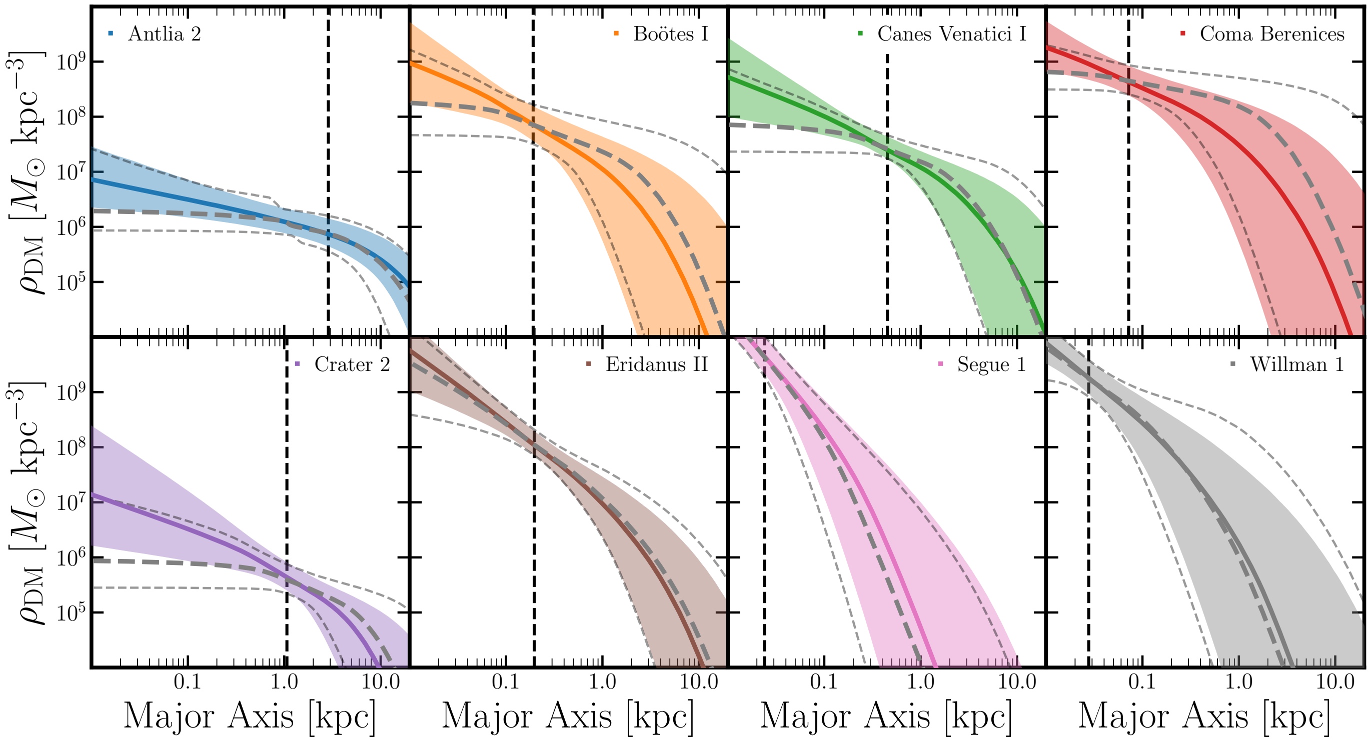


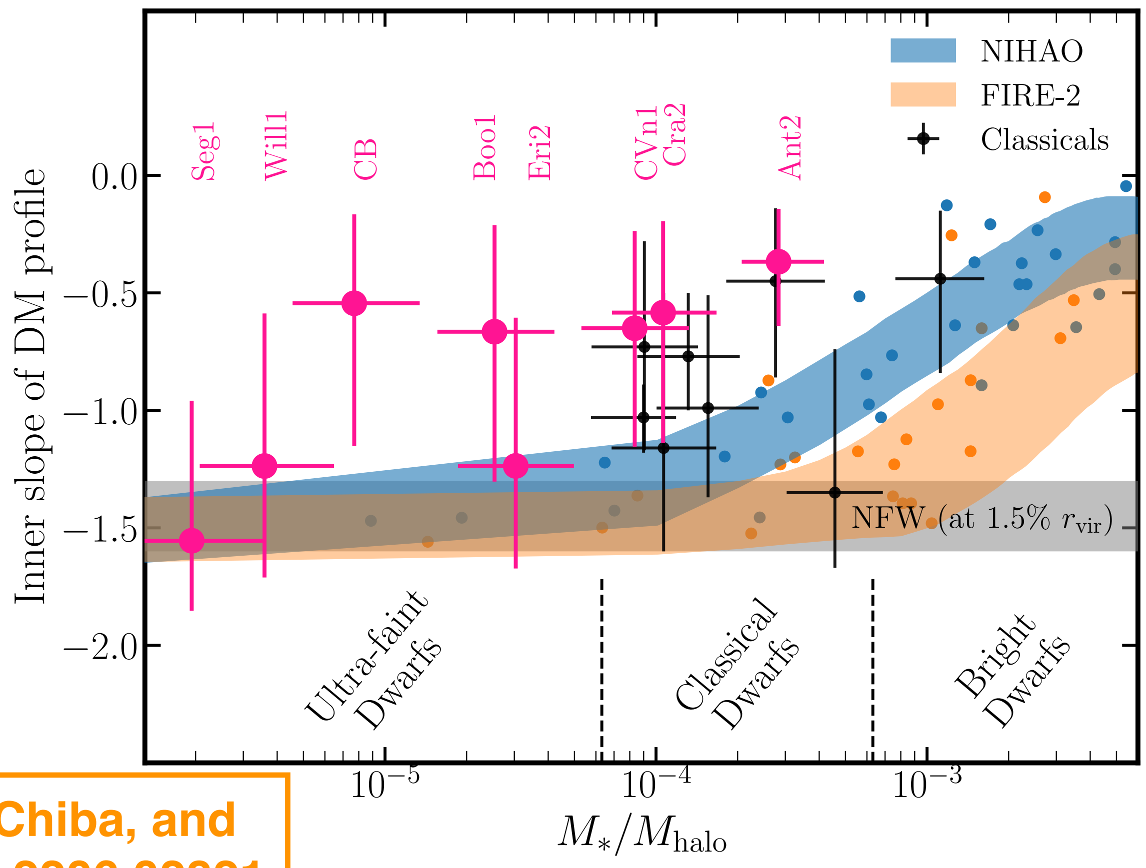
EUREKA

銀河のダークハロー構造の多様性：
銀河系矮小楕円体銀河の観点から

林　航平
〈東北大学大学院理学研究科天文学専攻　〒980–8578 仙台市青葉区荒巻字青葉 6–3〉
e-mail: k.hayasi@astr.tohoku.ac.jp

MW satellites (ultra-faint)



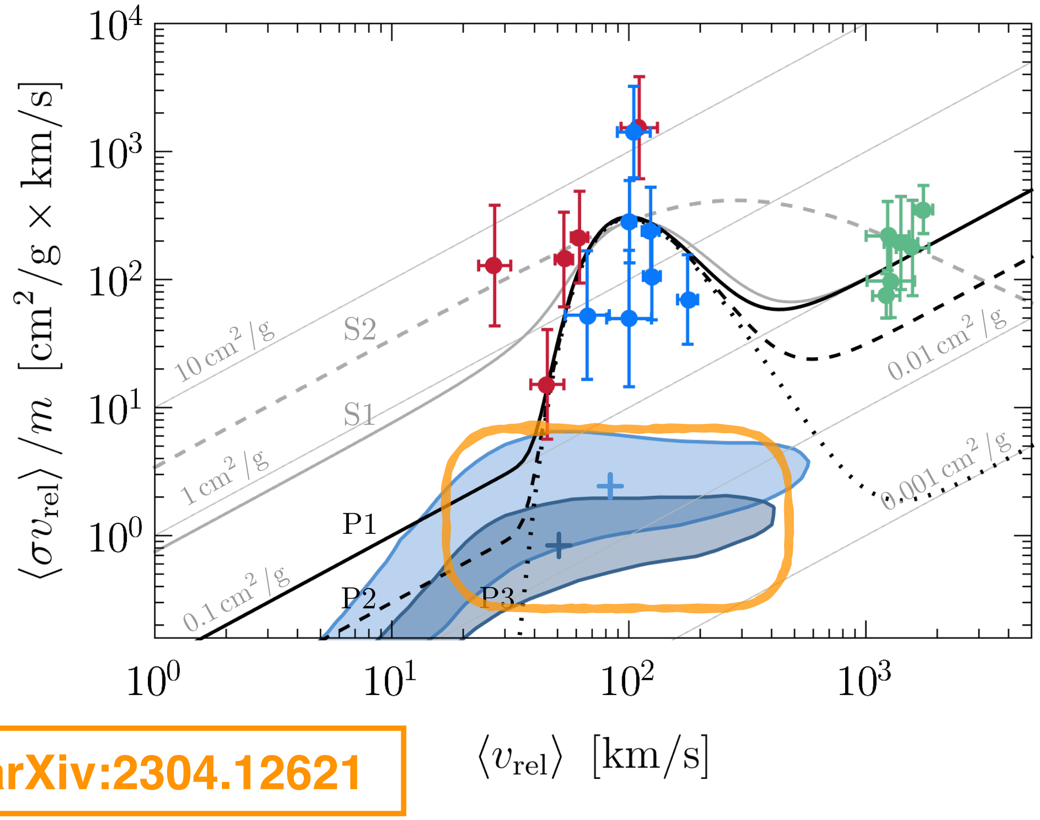


Hayashi, Hirai, Chiba, and Ishiyama, arXiv:2206.02821

Two possibilities on the table

Resonant SIDM

Chu, Garcia-Cely, and Murayama, PRL, 2019



- explain only cuspy profile by taking a small cross section at low velocity

$$\sigma/m < 0.1\,\mathrm{cm}^2/\mathrm{g} \quad \langle v_{\rm rel} \rangle \sim 30\,\mathrm{km/s}$$

- leave cored profile for stellar feedbacks

Hayashi *et al.*, PRD, 2021

AK and Kim, arXiv:2304.12621

Strong SIDM

- explain diversity by taking a further large cross section at low velocity

$$\sigma/m \sim 40\,\mathrm{cm}^2/\mathrm{g}$$

- gravothermal collapse is sensitive to initial profiles and orbits in MW

Correa, MNRAS, 2021

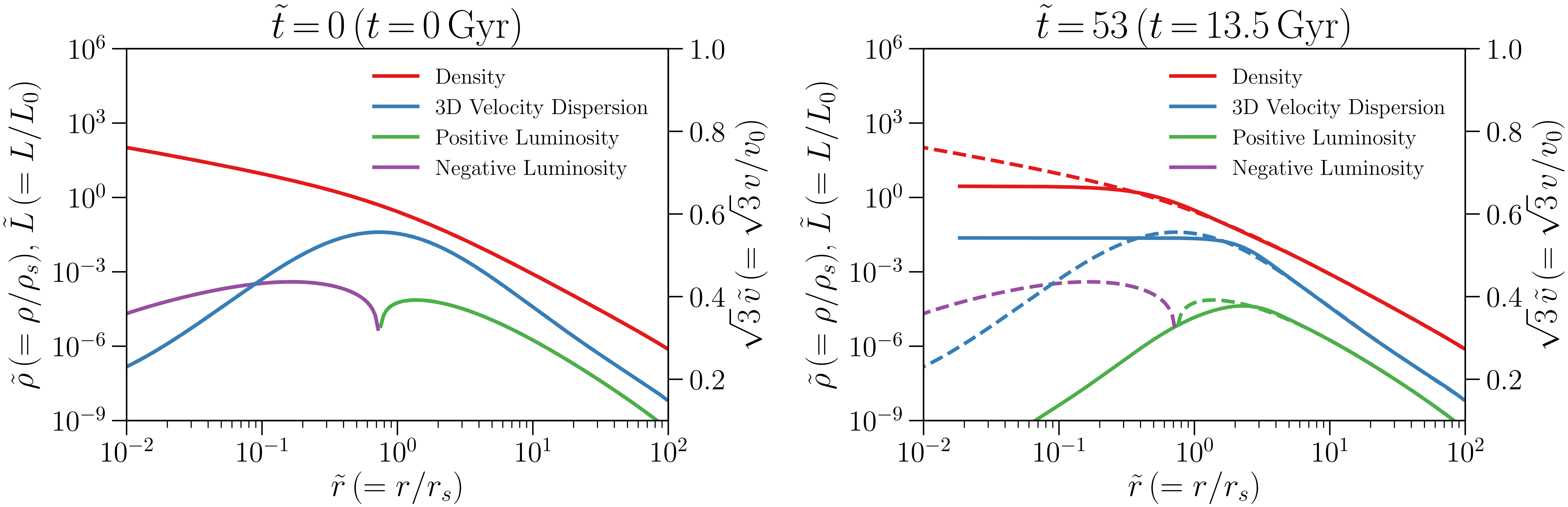
AK, Kim and Kuwahara, JHEP, 2020

Strong SIDM

Gravothermal collapse

- SIDM halo evolution: core expansion → core collapse

- core expansion lasts till the temperature profile gets flat (thermalization)



Nishikawa, Boddy, and Kaplinghat, PRD, 2020

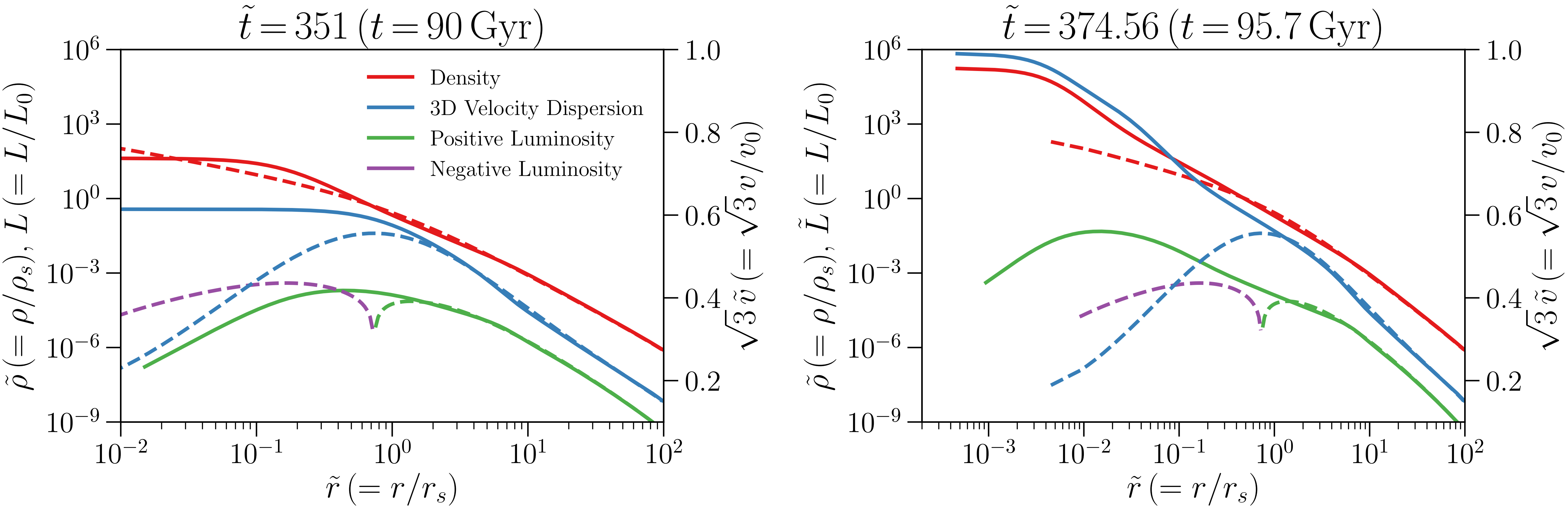
Strong SIDM

Gravothermal collapse

- SIDM halo evolution: core expansion
→ core collapse

- core contraction proceeds by
depositing heat to the outer region

- heat deposit → lower energy but higher
temperature (negative heat capacity)

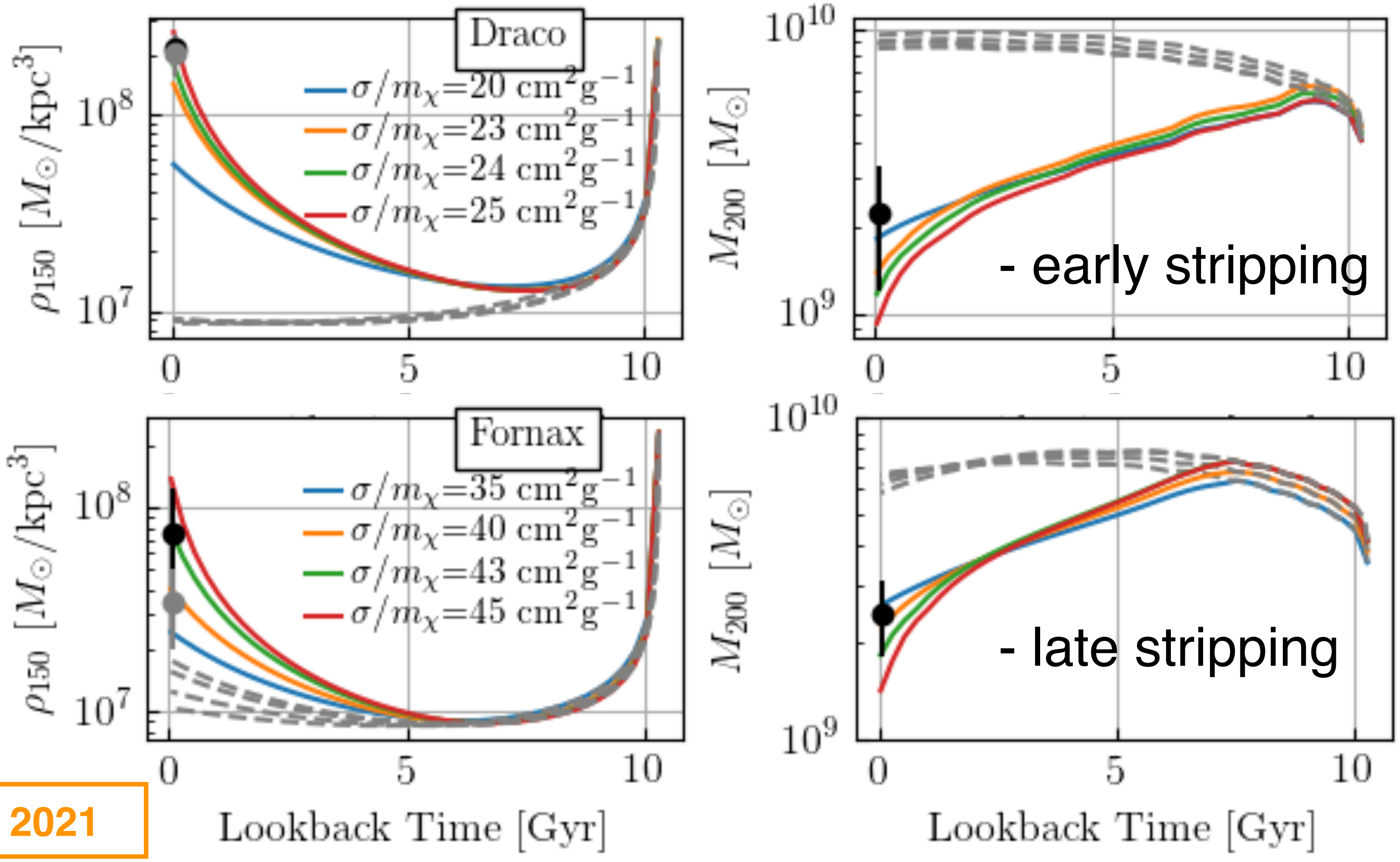


Nishikawa, Boddy, and Kaplinghat, PRD, 2020

Strong SIDM

Gravothermal collapse

- very sensitive to initial profiles and orbits in MW
  - tidal stripping: different orbits in MW → different “initial” profiles
  - tidal stripping accelerates gravothermal collapse



- early stripping

- late stripping

Correa, MNRAS, 2021