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

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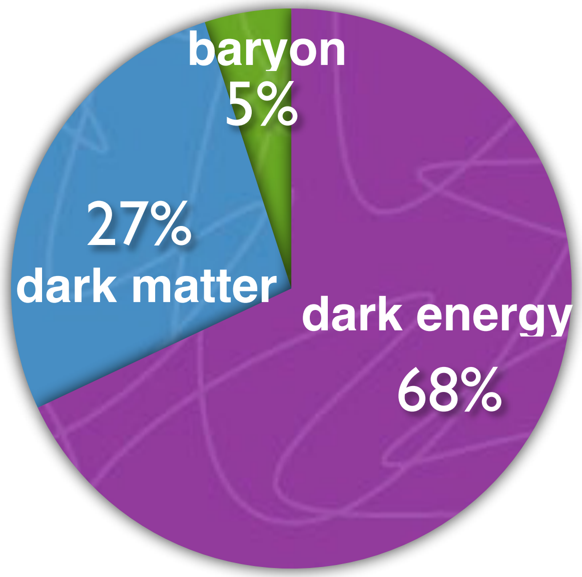
UNIVERSITY OF WARSAW

Mar. 30, 2023 @ B1 Heavy Flavor and Dark Matter Joint Unit Symposium

Dark matter

Dark matter

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



cosmic energy budget

Weakly interacting massive particle (WIMP)

Shirai-san's talk

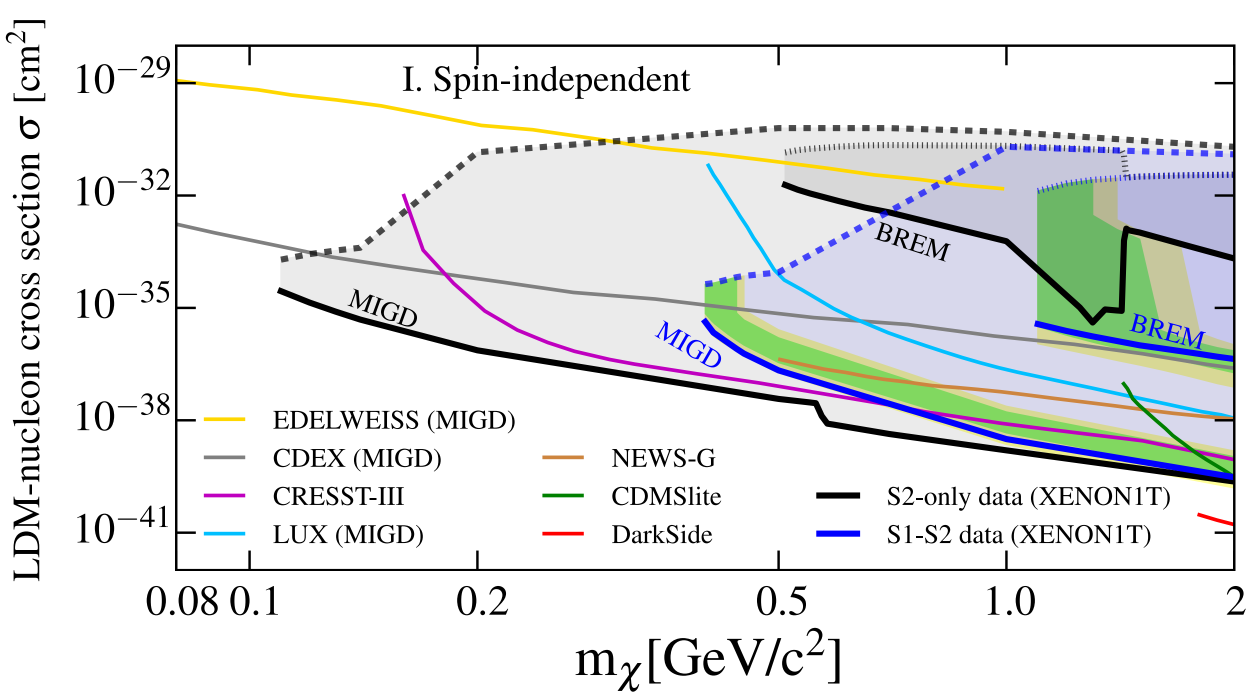
- extensively studied in direct, indirect and collider searches
  - no convincing signal yet
  - neither postulated solutions to the hierarchy problem
- good time to be open-minded

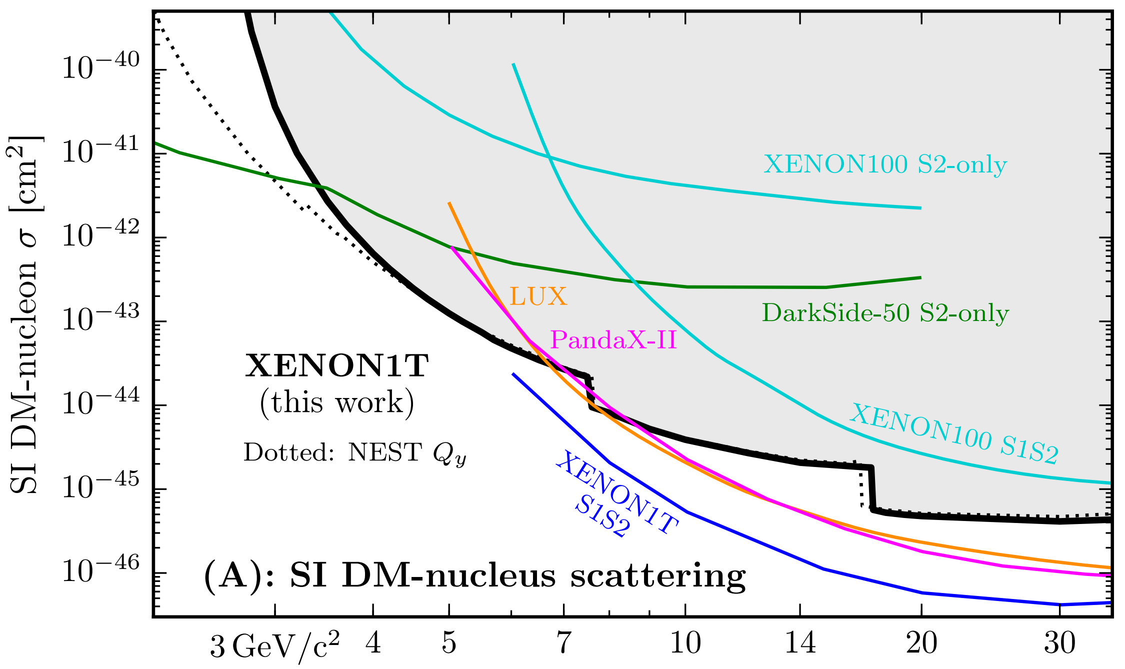
Dark matter

Sub-GeV dark matter

- neutral naturalness
  - twin Higgs
  - dark sector (e.g., mirror sector) accommodates dark matter
- evades conventional direct-detection searches
  - not enough recoil energy
  - new opportunities w/ low-threshold detectors and inelastic channels

XENON1T collaboration, PRL, 2019 & 2019

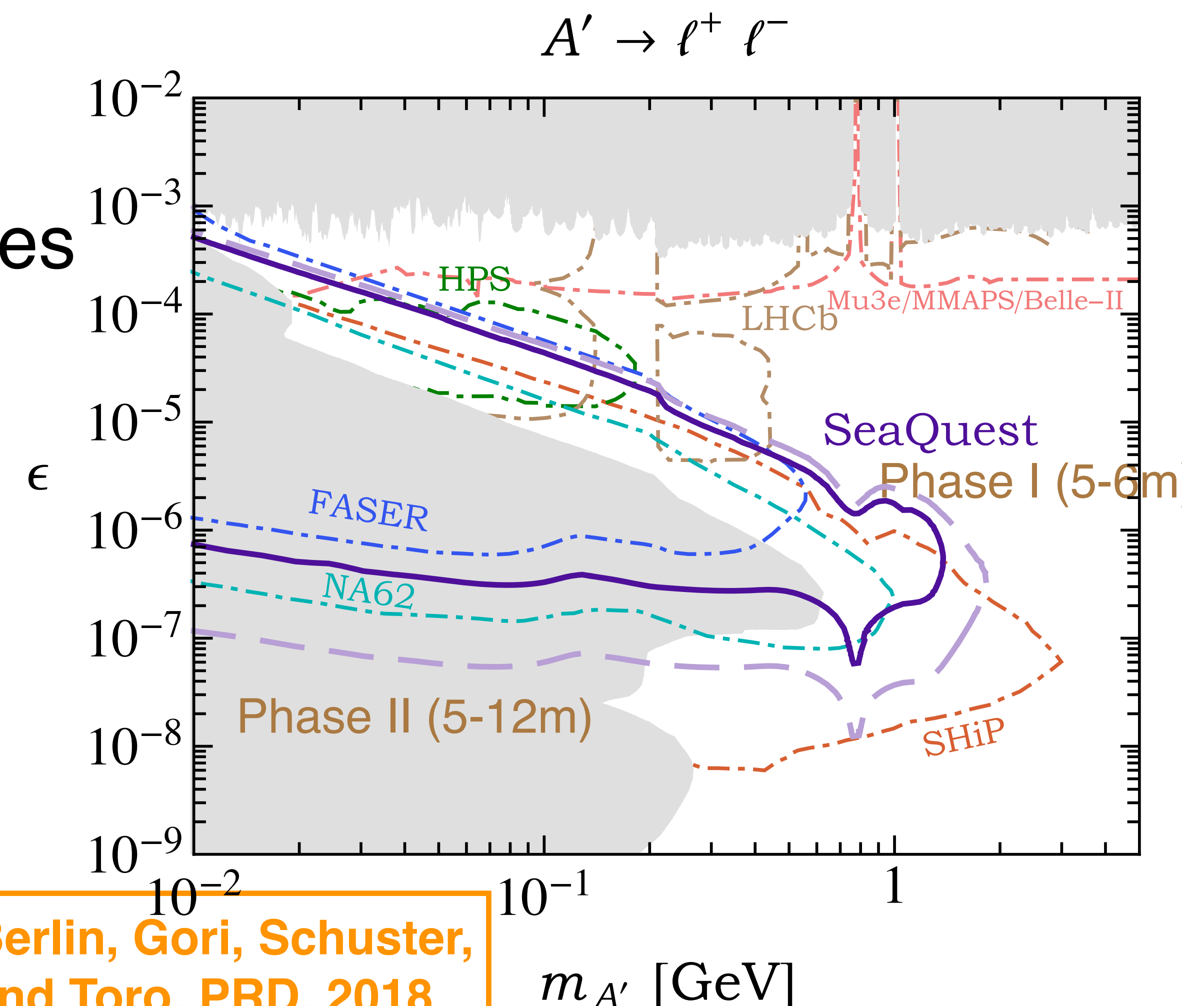




Dark matter

Sub-GeV dark matter

- evades conventional collider searches
  - neutrino backgrounds
  - new opportunities in intensity-frontier experiments (including Belle-II)
  - e.g., dark photon portal $\epsilon e j_{\mathrm{e}}^{\mu} A'_{\mu}$

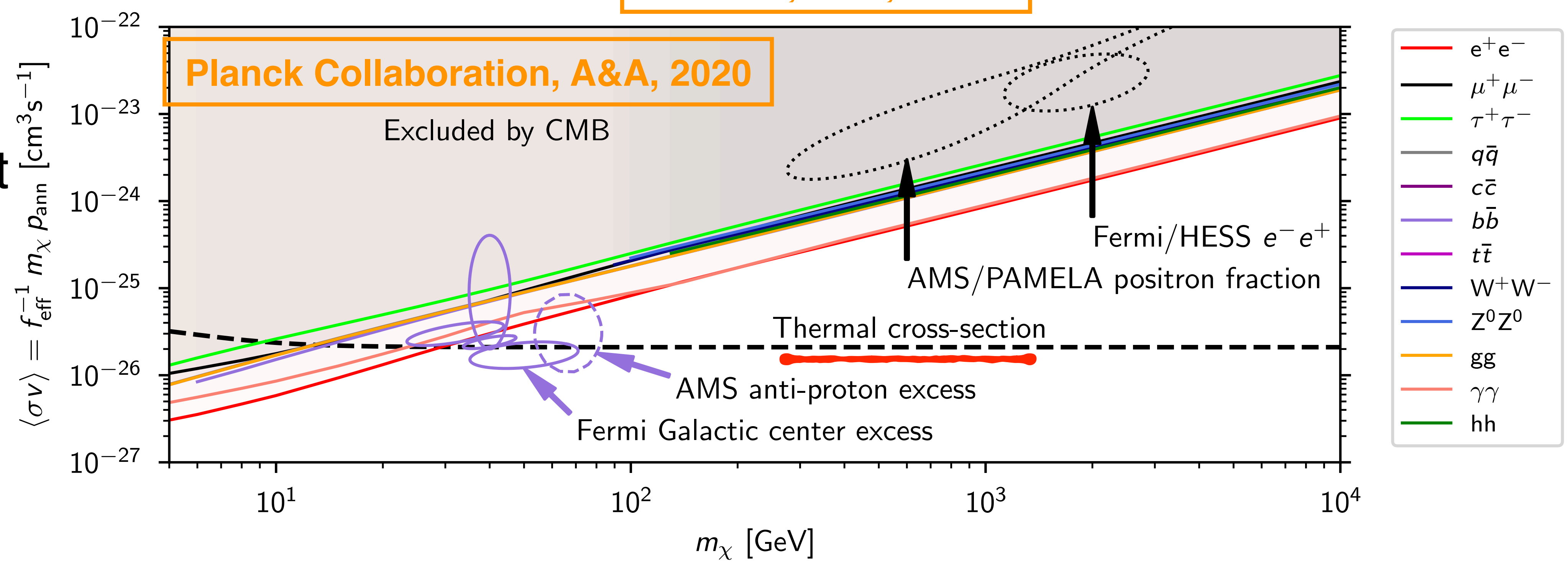


Berlin, Gori, Schuster, and Toro, PRD, 2018

- CMB bounds are relevant
  - s-wave thermal freeze-out

    $m > 10\,\mathrm{GeV}$
  - p-wave is viable

Planck Collaboration, A&A, 2020



Contents

Asymmetric dark matter (ADM)

- no anti-particle (like anti-baryon) at present
    - safe from CMB bounds
- prediction of dark matter mass: O(1) GeV

General introduction to ADM

- concept and motivation
- relation to baryon asymmetry of the Universe (BAU)

Dark baryon ADM with dark photon

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

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

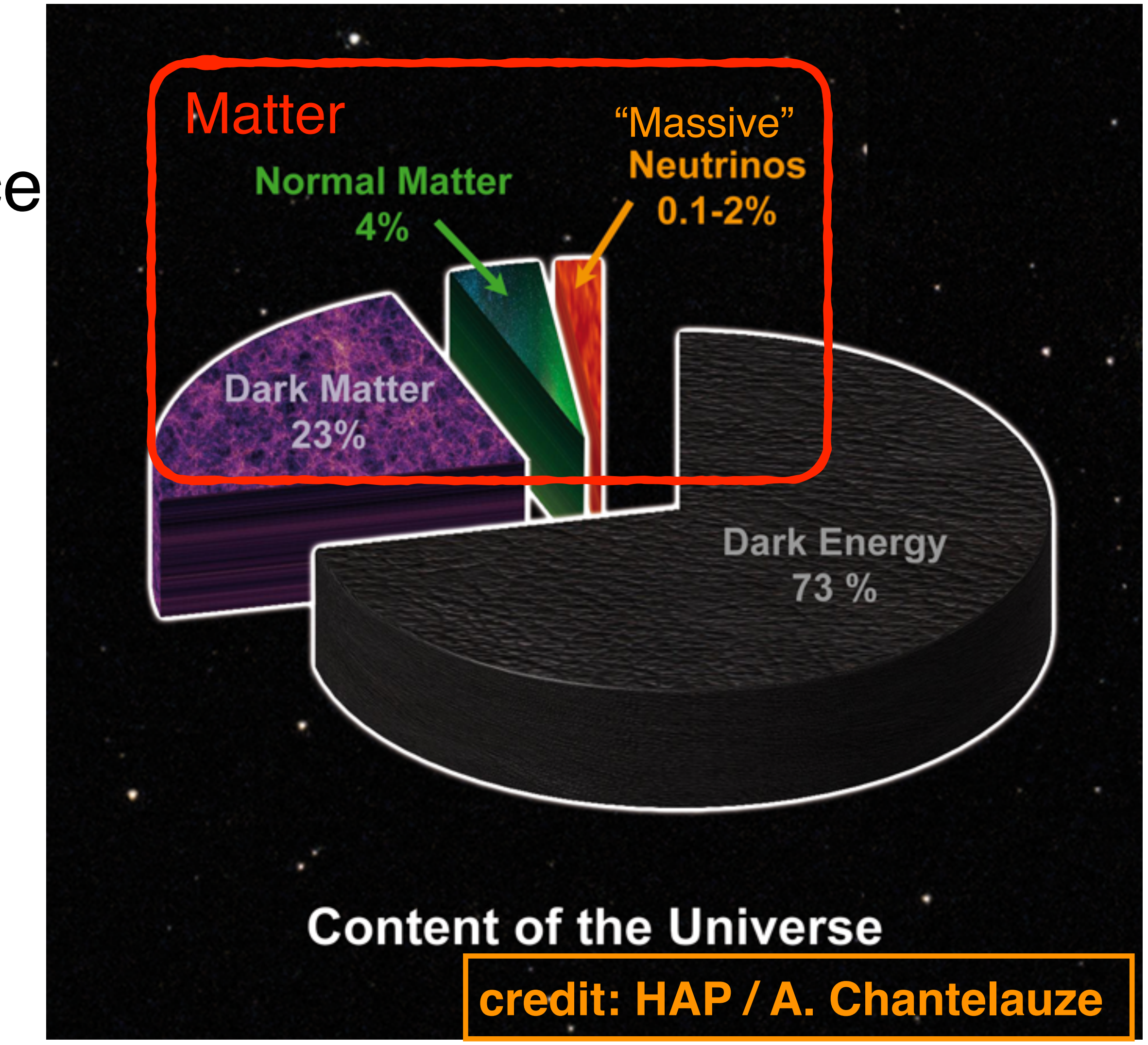
- most famous (notorious) coincidence

dark energy : matter = 7 : 3

- matter coincidence

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

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



- 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

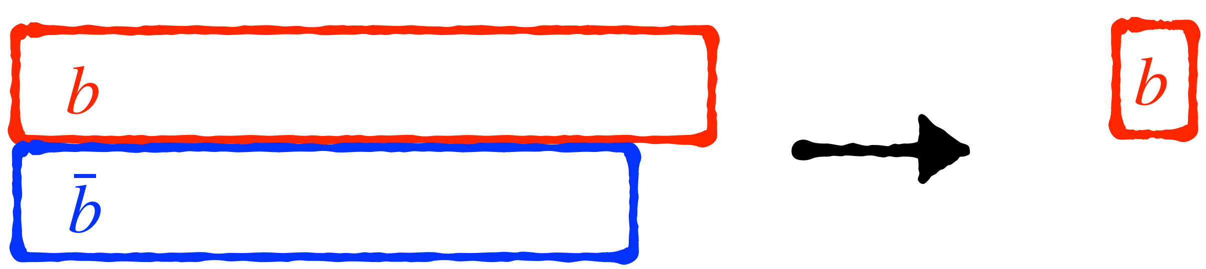
- too small via thermal freeze-out like WIMPs

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

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

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

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



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

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

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 $b \to \chi$ $\bar{b} \to \bar{\chi}$

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

- efficient annihilation into light particles

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

Coincidence

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

- 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 $\mathcal{O}_B \mathcal{O}_D$

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

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

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

    - 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)

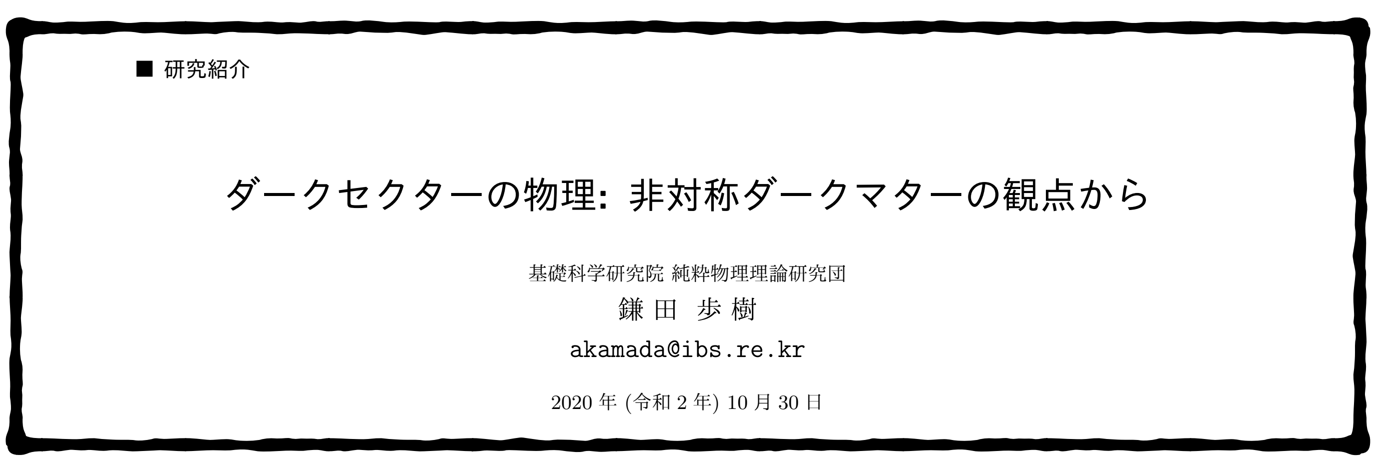
    $10\,\mathrm{TeV}$ - Unitarity $\langle \sigma_{\mathrm{ann}} v \rangle > 1\,\mathrm{pb} \times c$

Contents

Dark baryon ADM with dark photon

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

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


■ 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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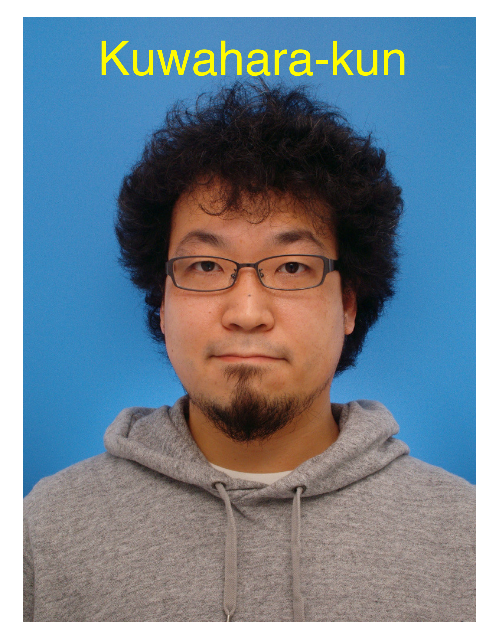
2020 年 (令和 2 年) 10 月 30 日



Mirror matter

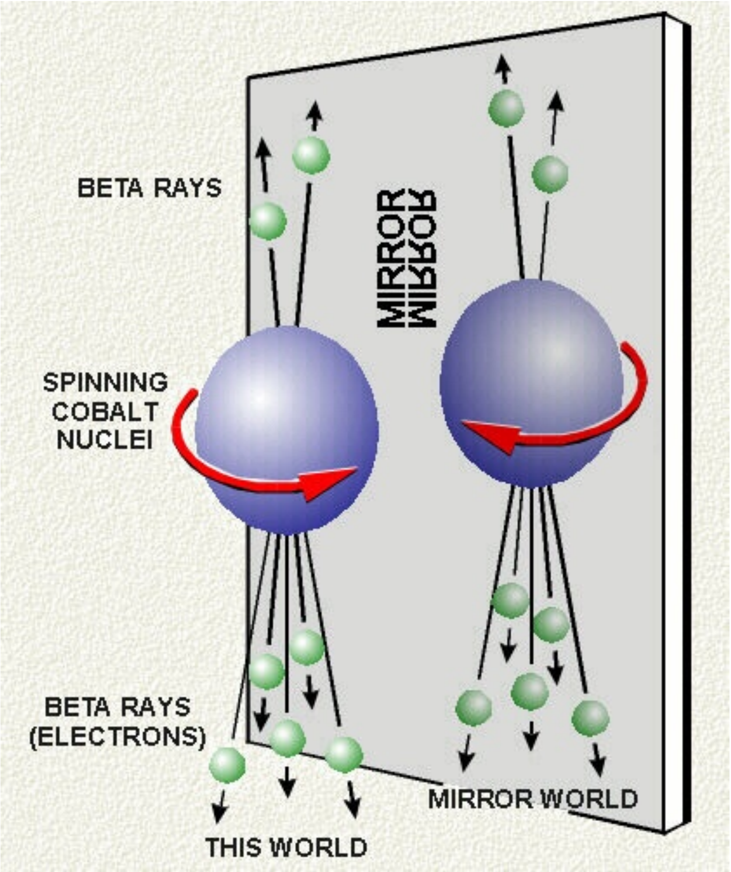
Parity violation in weak interaction

- 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 $u'(2/3)$ $\bar{u}'(-2/3)$ $d'(-1/3)$ $\bar{d}'(1/3)$ $\times N_g$
    - generations
  - dark gluons g' and dark photon γ'
  - no leptons or weak interaction
  - charged Higgs (not present in SM) to break electrodynamics
    - Higgsless version

Ibe, Kobayashi, and Watanabe, JHEP, 2021

- low energy/temperature
  - 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 $\epsilon e j^{\mu}_{\mathrm{e}} A'_{\mu}$
    - dark charged particles do not couple to photon (if so, photon is massive)

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

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

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

Signatures

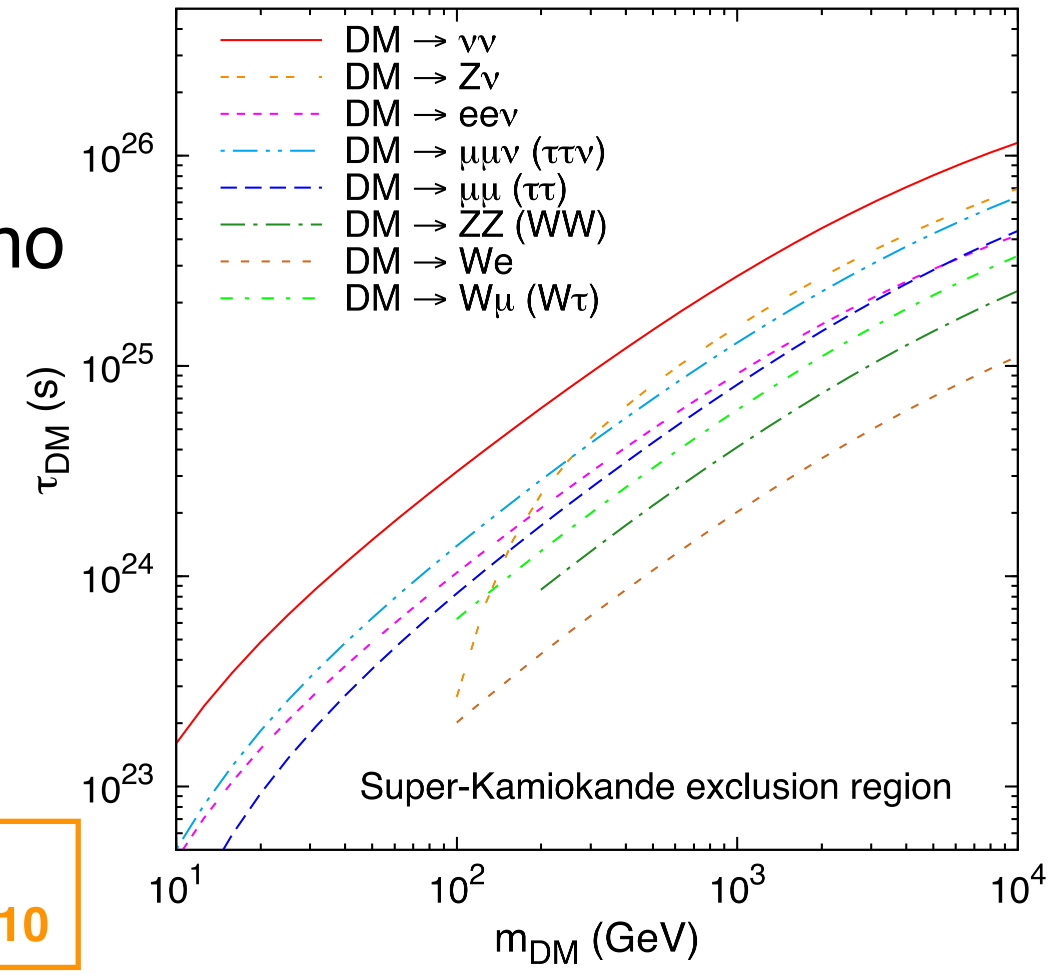
- dark anti-neutron decay into anti-neutrino

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

- monochromatic anti-neutrino
  - super-Kamiokande (low threshold)

$$\tau \gtrsim 10^{23}\,\mathrm{sec} \quad \text{for} \quad m_{b'} \gtrsim 10\,\mathrm{GeV}$$

$$\rightarrow M_* > 10^{8.5}\,\mathrm{GeV}$$



Covi, Grefe, Ibarra, and Tran, JCAP, 2010

Massive dark photon

Direct detection

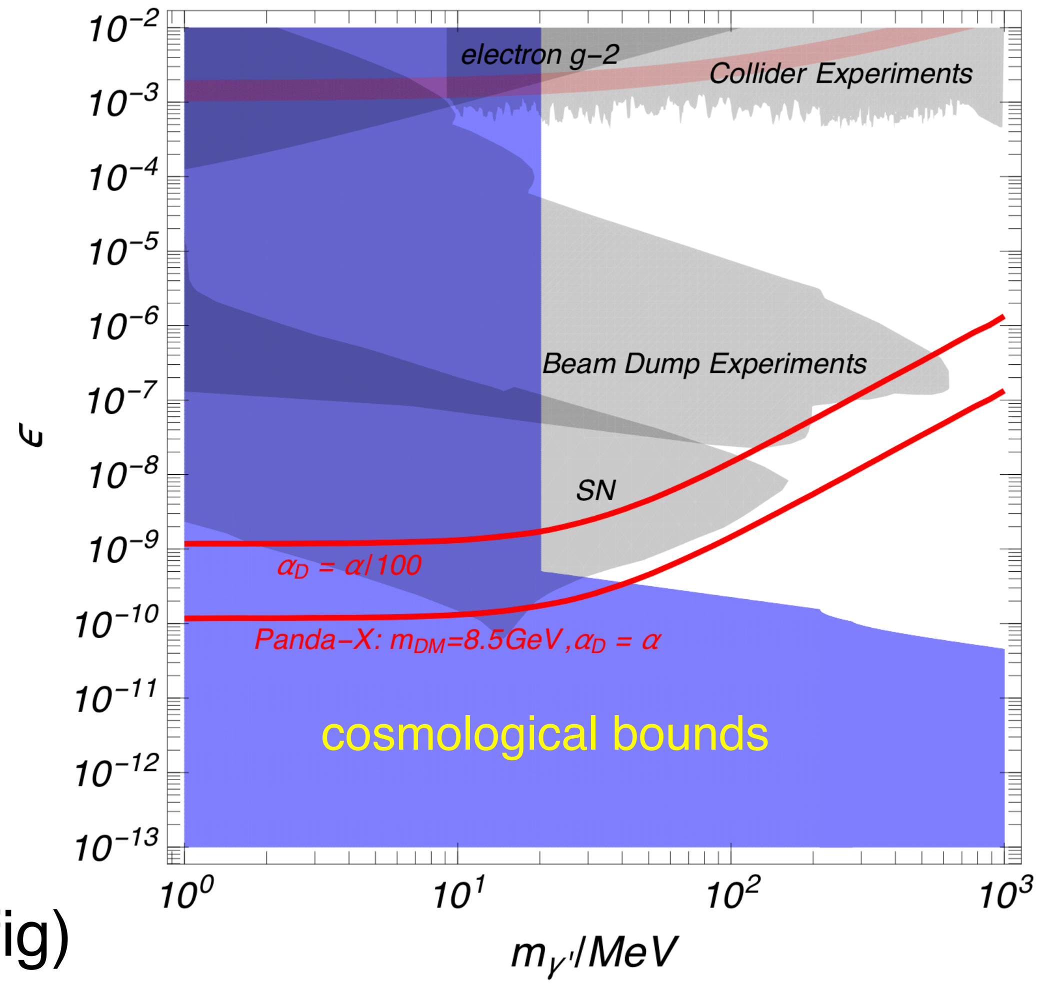
- dark proton - proton scattering through dark photon

$$\sigma \propto \epsilon^2 \alpha \alpha' \qquad \epsilon e j_{\rm e}^{\mu} A'_{\mu}$$

- 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
    - $m_{b'} = 8.5\,\mathrm{GeV}/N_{g'}$
    - $N_{g'} = 1$ (fig) → $N_{g'} = 8$ $\quad \sigma \lesssim 10^{-45} \to 10^{-39}\,\mathrm{cm}^2/\mathrm{g}$
  - 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



- low recoil energy
  - S2(ionization)-only
  - Migdal effect

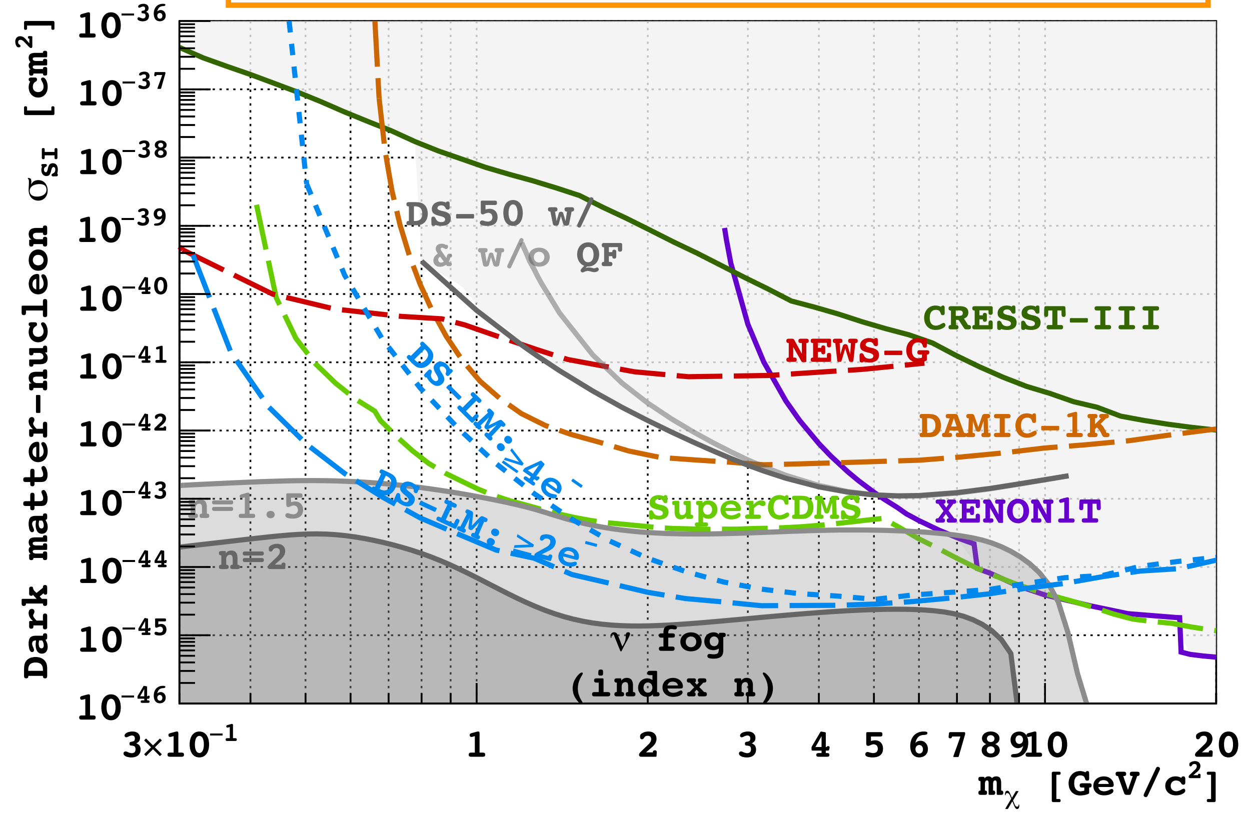
Low-mass direct detection

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)
        - they look for a postdoc; please contact masayuki@camk.edu.pl

“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

DarkSide collaboration, arXiv:2207.11966



Summary

Asymmetric DM

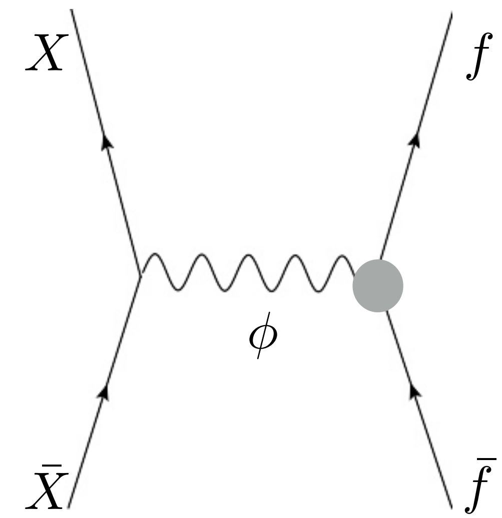
- interesting alternative to WIMP DM
- motivated by the coincidence of DM : baryons
  - simplify the problem by dark asymmetry
  - full solution? a clue from mirror matter
- various experimental and cosmological signatures
  - through transfer operator and light dark states
    - model dependent
  - (sub-)GeV-scale particle searches
    - direct detection, indirect detection, colliders
  - cosmology
    - dark radiation, self-interacting DM

Thank you

Efficient annihilation

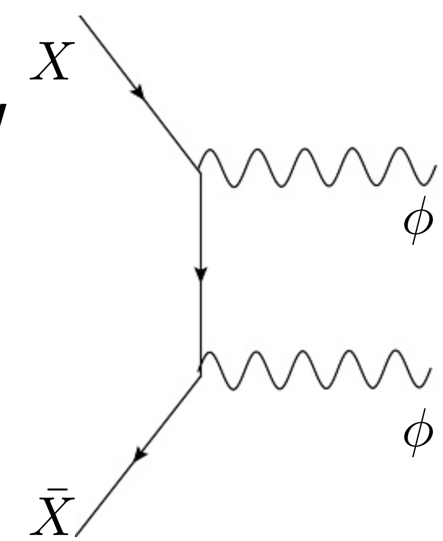
Light final states $\chi\bar{\chi} \to ???$ $\langle \sigma_{\rm ann} v \rangle > 1\,{\rm pb} \times c$

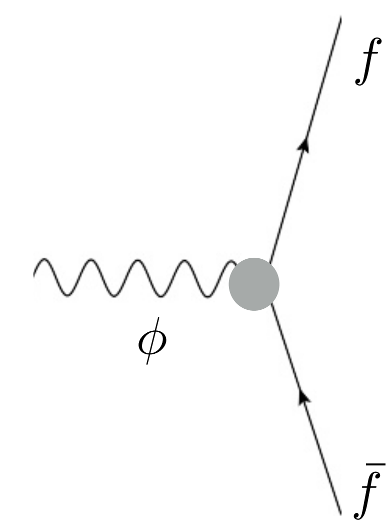
- model-dependent, but tendencies
- SM particles through heavy mediator
    - mediator-SM coupling is bounded from below
    - direct (× indirect) detection $m_\chi > 1\,{\rm GeV}$
    - collider (or fixed-target experiment) searches



- dark light particles
    - mediator-DM coupling is bounded from below
    - long-range force between DM particles
        - self-interacting DM

$$\sigma/m \sim 1\,{\rm cm}^2/{\rm g} \sim 1\,{\rm b/GeV}$$





- mediator-SM coupling can be tiny
- cosmological fate of dark light particles
    - if massive, decay to SM particles
    - if (almost) massless, contributes to dark radiation $\Delta N_{\rm eff}$

Transfer mechanism

Signatures

- dark anti-neutron decay into anti-neutrino

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

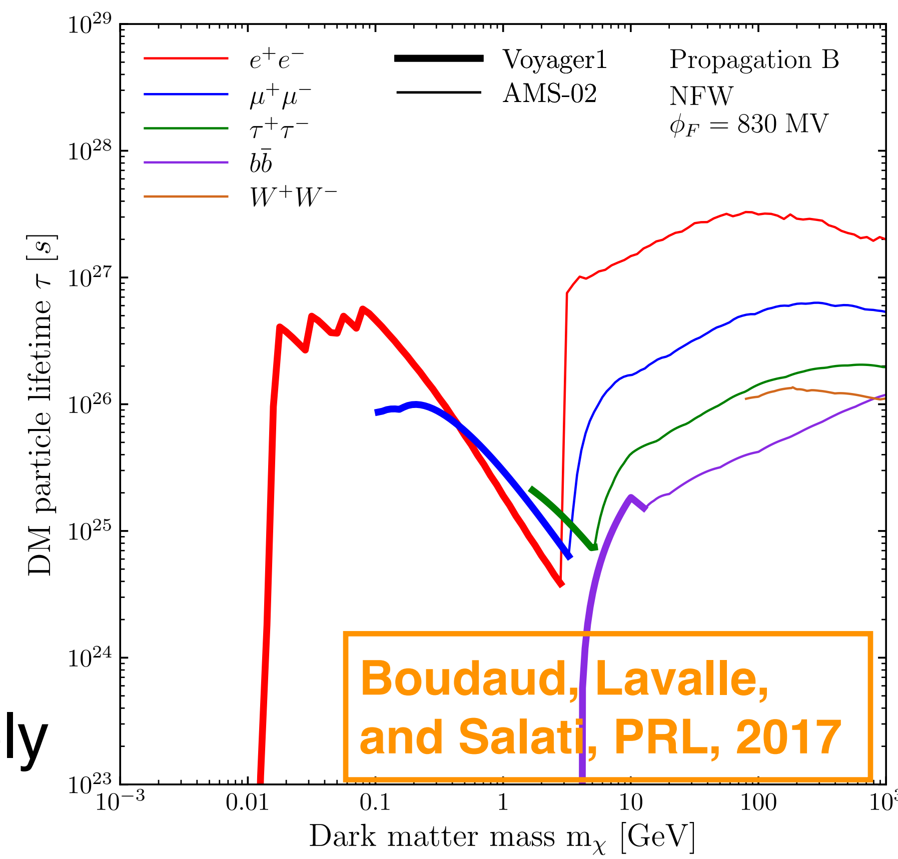
- cascade decay of $\pi'^{0} \rightarrow 2\gamma' \rightarrow 2e^{+}2e^{-}$

  - Voyager data is crucial for sub-GeV electron+positron (modulation free)

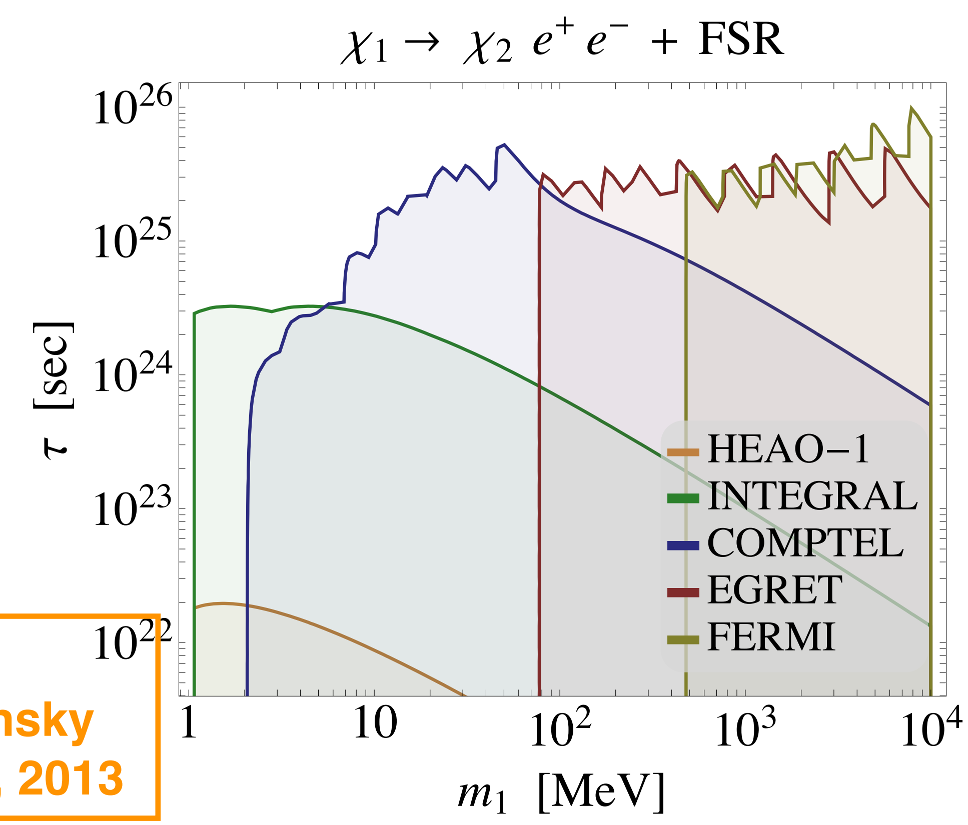
  - though re-analysis is needed, conservatively

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

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



Boudaud, Lavalle, and Salati, PRL, 2017

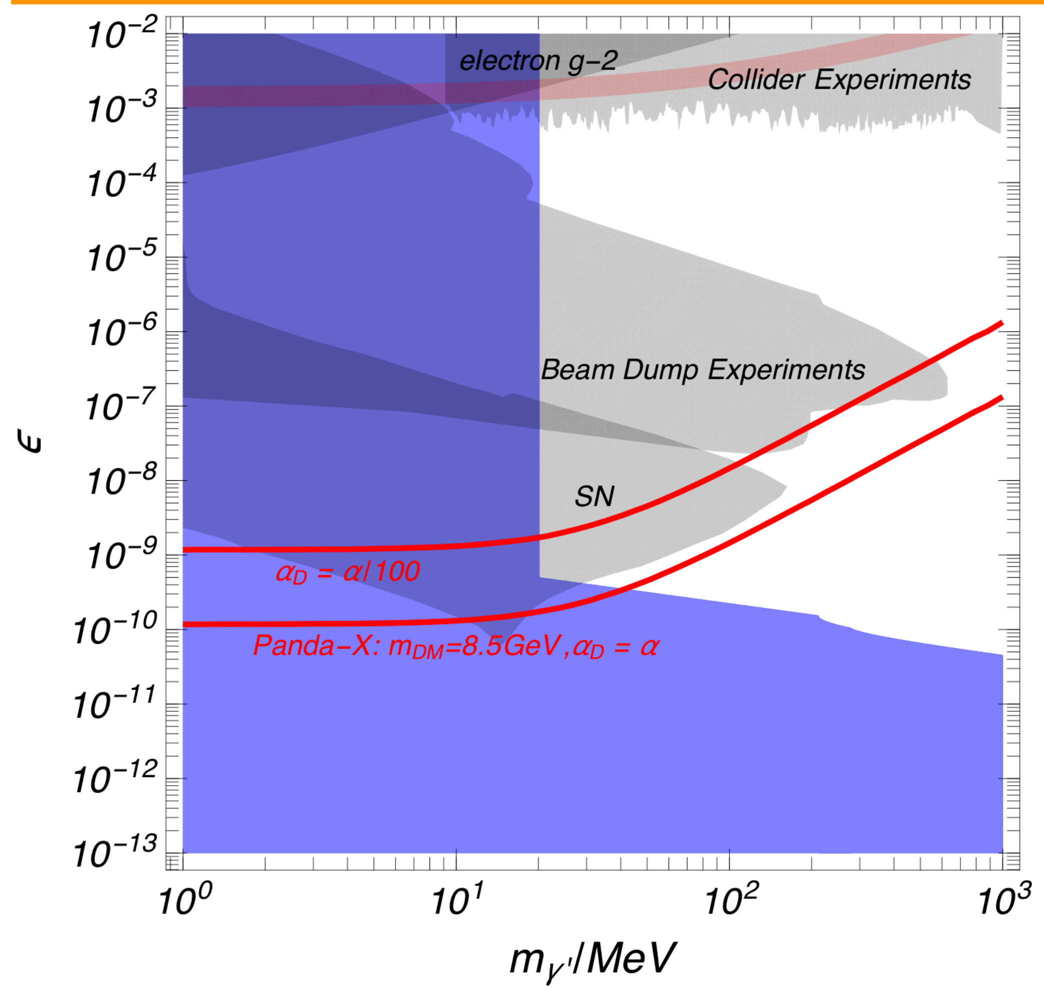


Essig, Kuflik, Mcdermott, Volansky and Zurek, JHEP, 2013

Massive dark photon

Cosmological bounds

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



- 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 $\Delta N_{\rm eff}$
- should decay before neutrino decoupling $\Gamma_{A' \to \mathrm{SM}} \propto \epsilon^2 m_{A'}$ $\epsilon e j_{\rm e}^{\mu} A'_{\mu}$
  - lower bound on ϵ
- thermal abundance should be negligible around decoupling
  - lower bound on $m_{A'}$

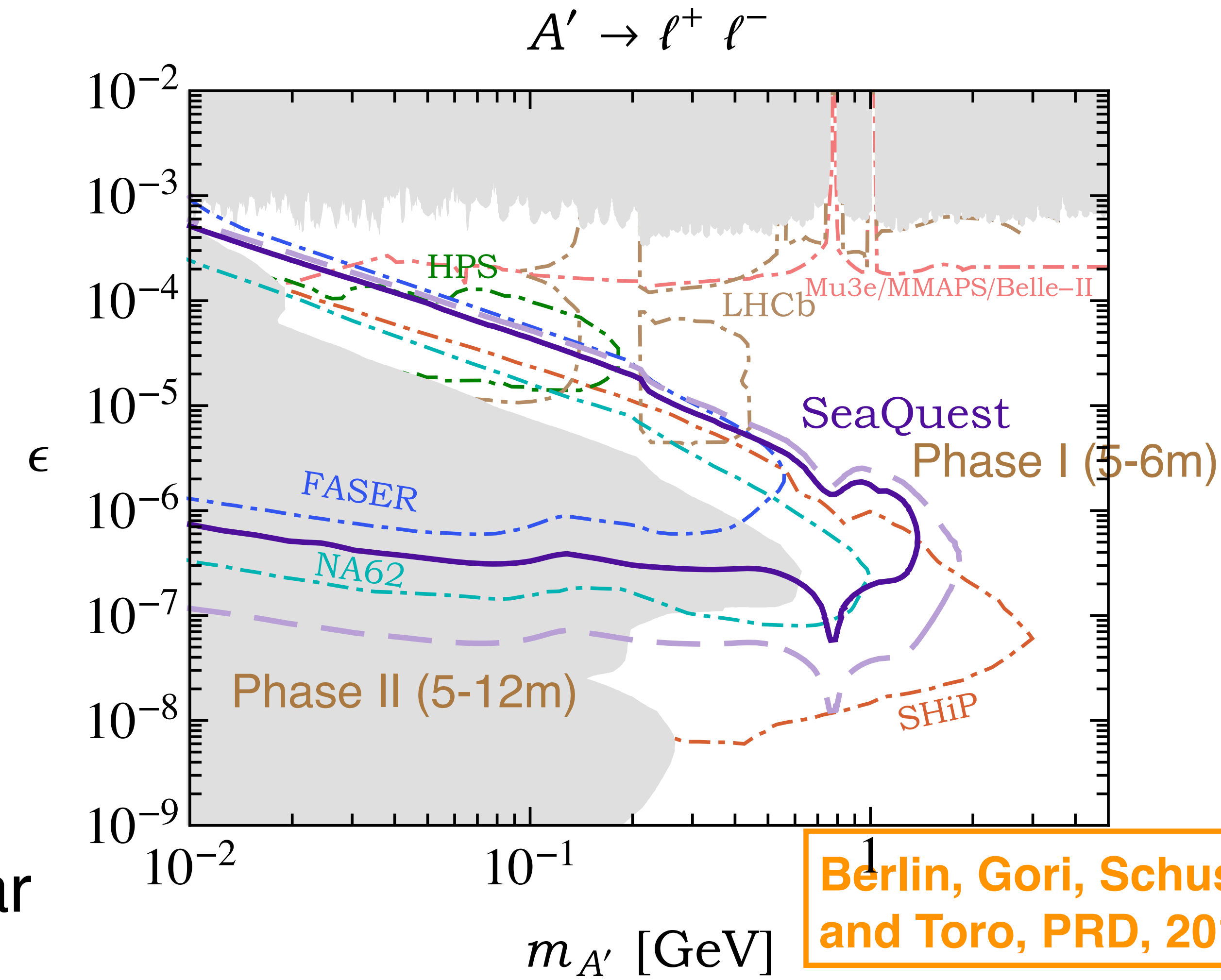
Massive dark photon

Experimental searches

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

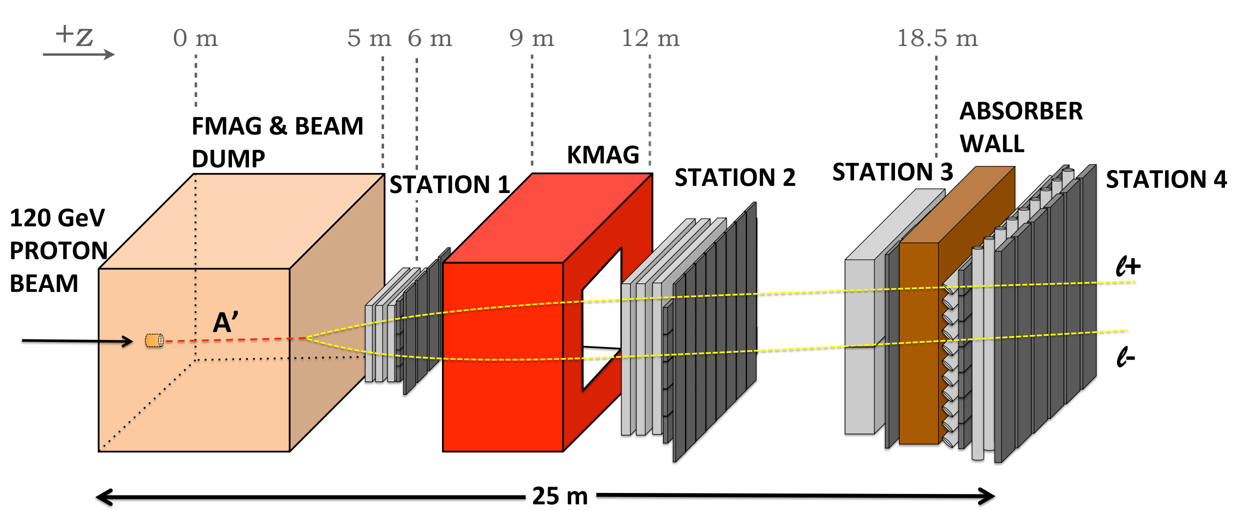
$$\gamma' \to e^+e^- \quad \mu^+\mu^-$$

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



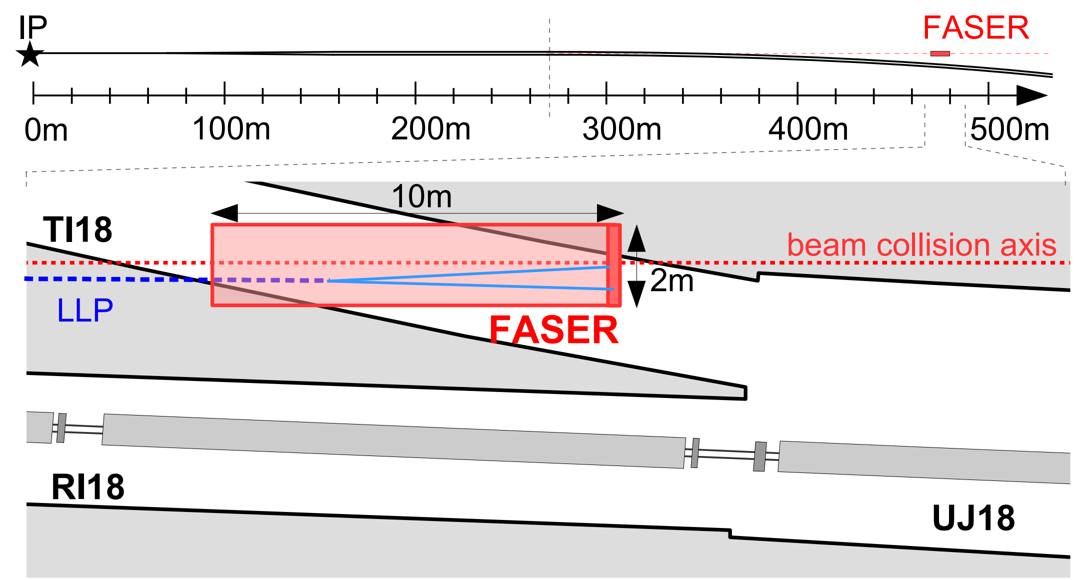
Berlin, Gori, Schuster, and Toro, PRD, 2018

- SeaQuest @ Fermilab



- FASER @ LHC

Berlin and Kling, PRD, 2019

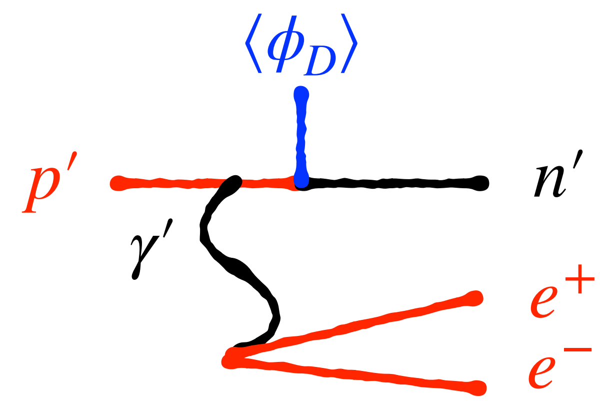


Dark hadrons

[AK and Kuwahara, JHEP, 2022]

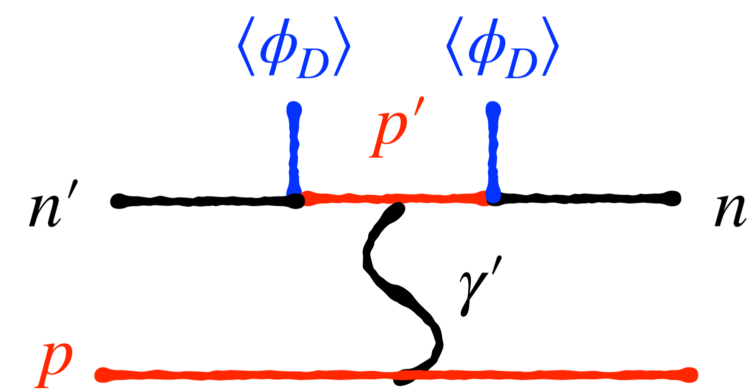
Transition

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



- through charge breaking

- direct detection constraints are weakened



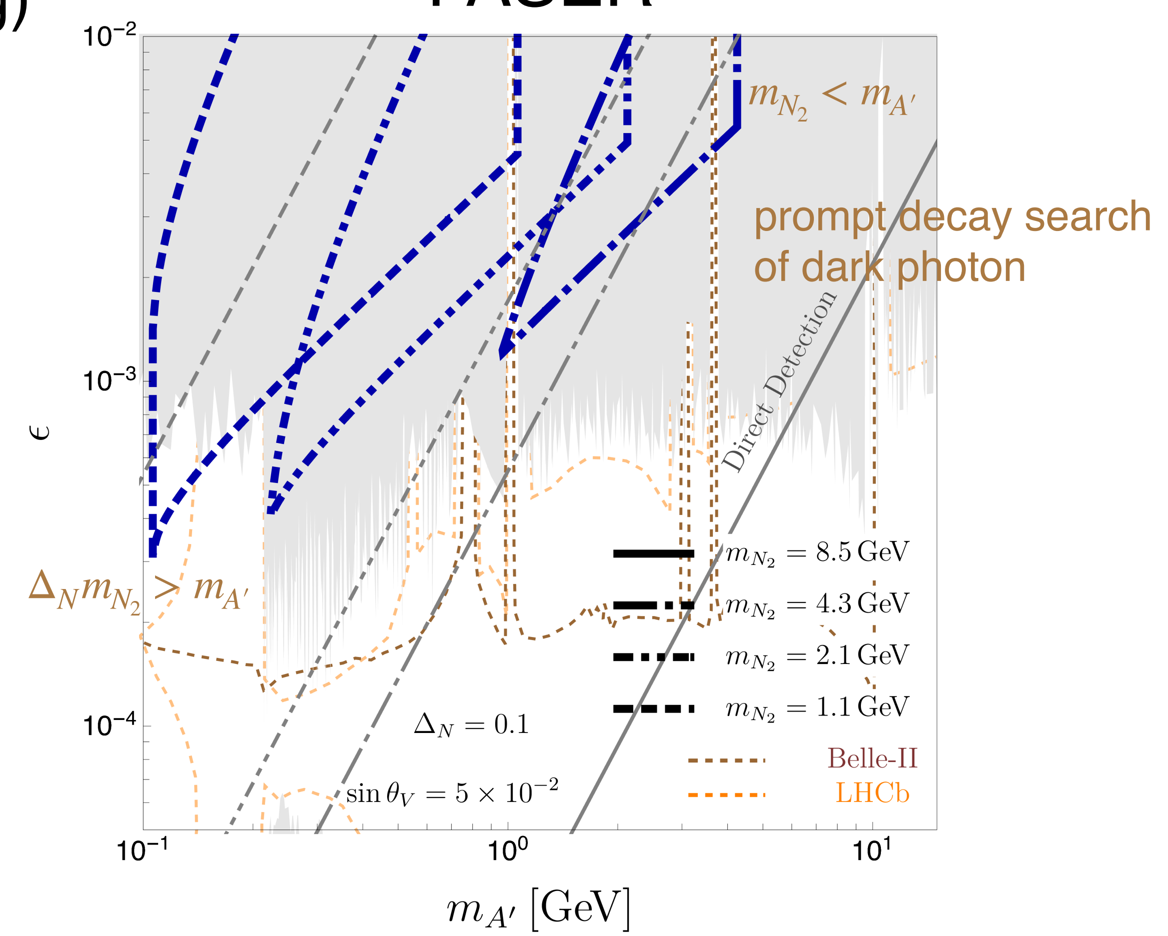
  - only dark neutron makes up DM

  - not disappear (charge breaking)

LLP search

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

- FASER



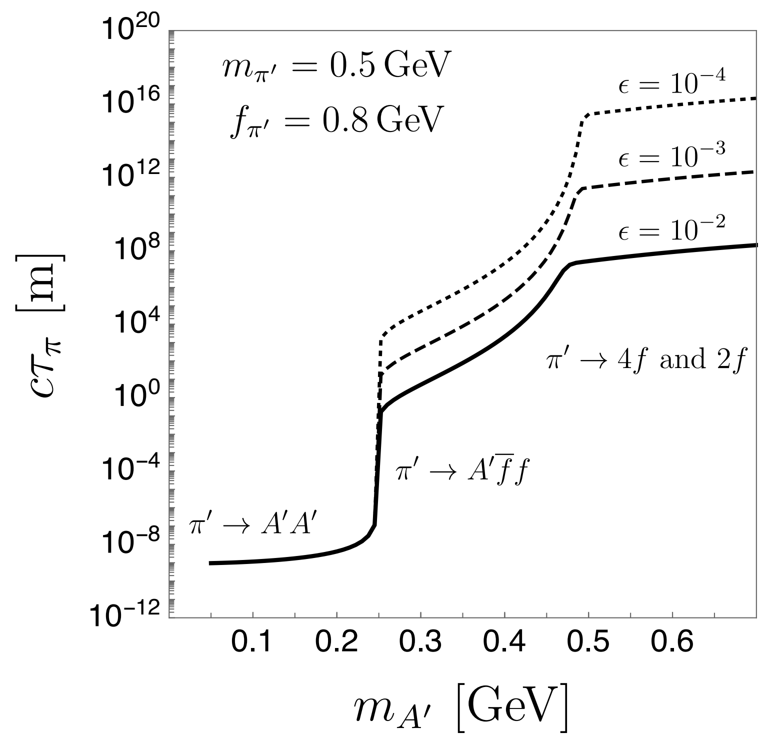
Dark hadrons

Decay

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

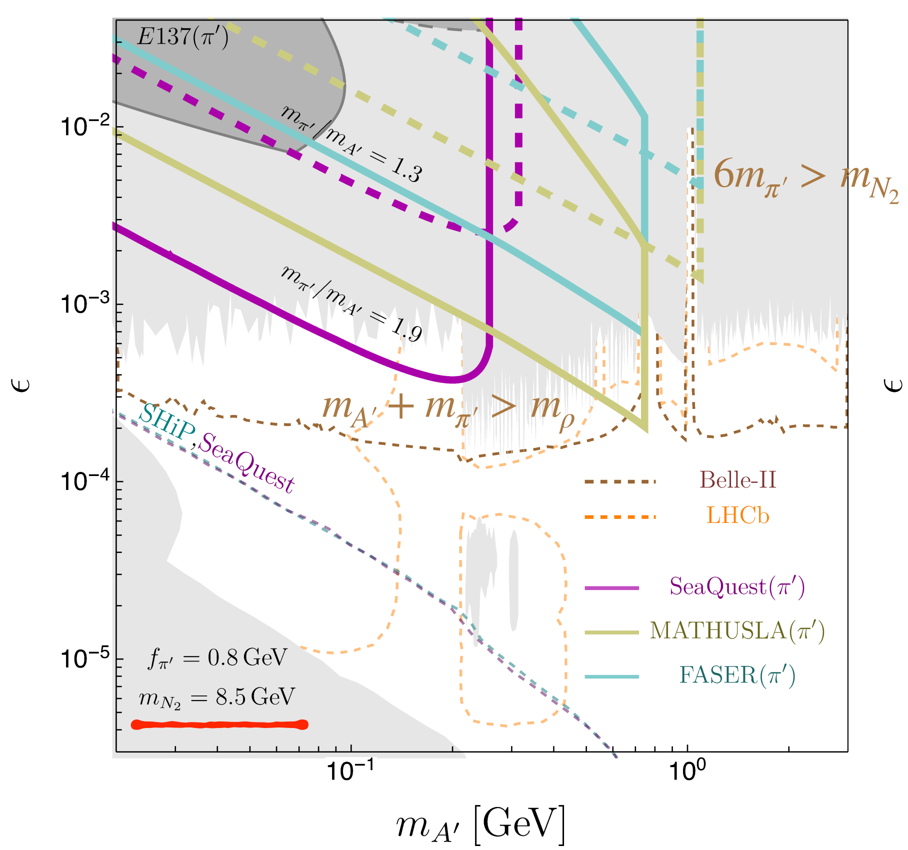
- assume $m_{\gamma'} < m_{\pi'} < 2m_{\gamma'}$
  - otherwise short-lived (no ϵ dependence)

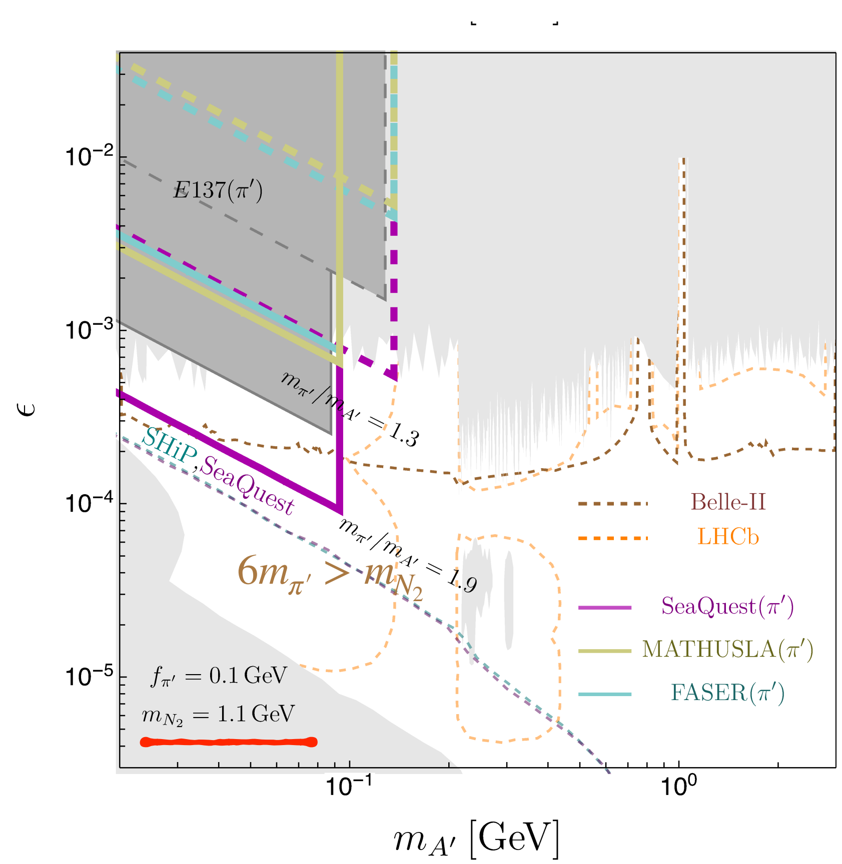
AK and Kuwahara, JHEP, 2022



LLP searches

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





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

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 $y_N L H \overline{N} \overset{\overline{N}}{\to} \frac{y_N^2}{M_R} LHLH$

- 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 $M_{H'_C}$

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

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

$$\overset{H'_C}{\to} \frac{1}{M^2_{H'_C}} \overline{u}' \overline{d}' \overline{d}' \overline{N} \qquad y_N L H \overline{N}$$

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

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

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

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

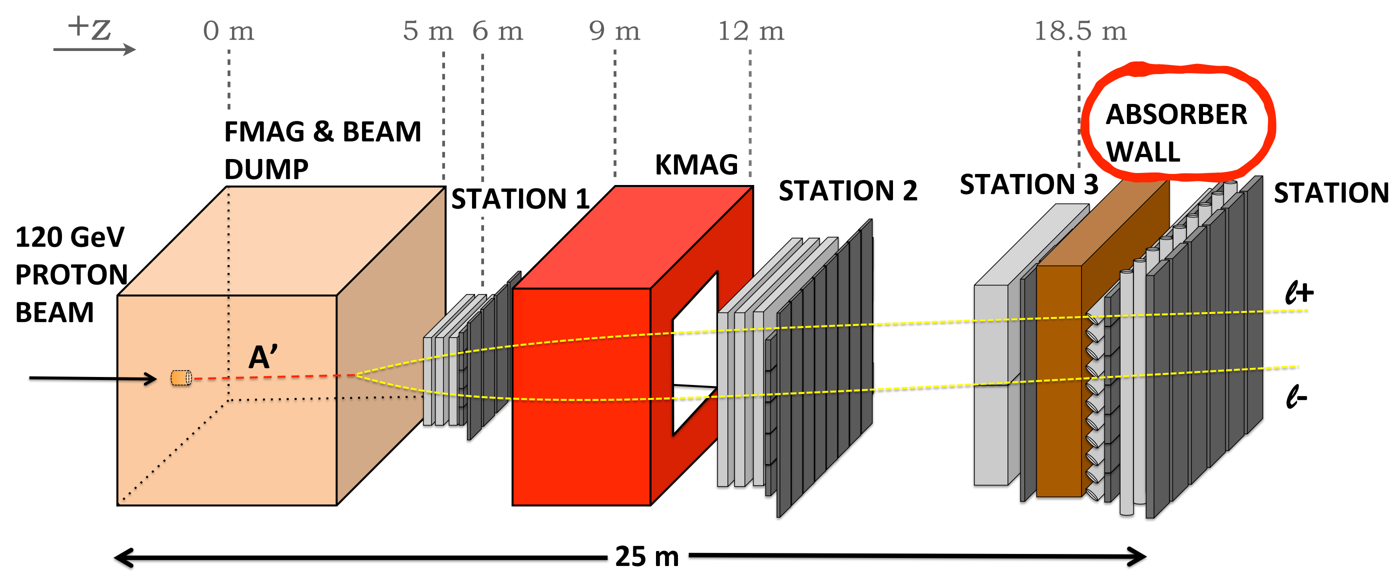
✳ decoupling after leptogenesis $M_{H_C} \sim M_R$

Intensity frontier

Fixed target experiment

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

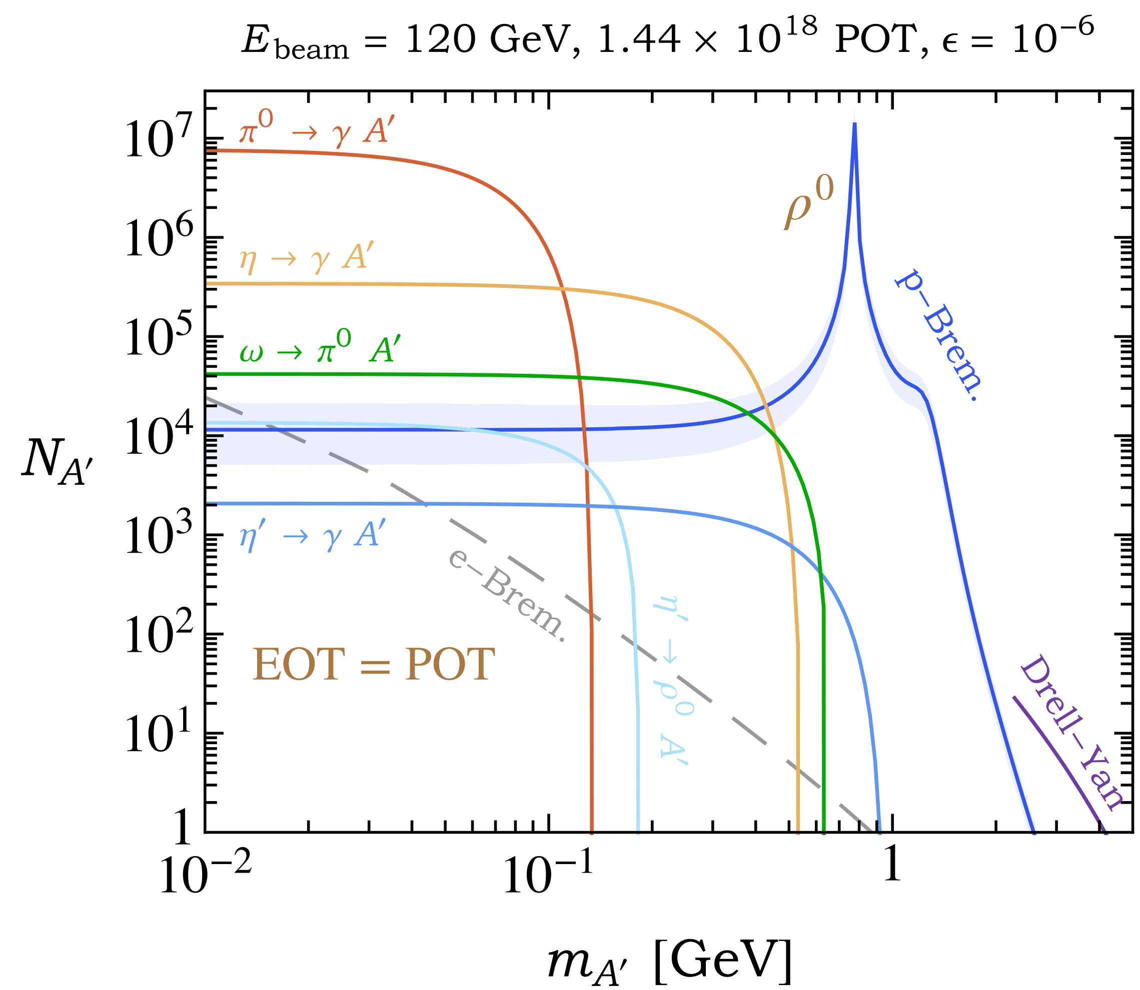
- SeaQuest@Fermilab
  - proton beam at iron target
  - place ECAL (di-electrons) in front of absorber wall (DarkQuest)



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

  - forward direction $\theta_{\rm det} = 0.05$

- proton on target $\sim 10^{20}$ (phase II; 2026+) $\mathscr{L} \sim 2\,{\rm zb}^{-1}$



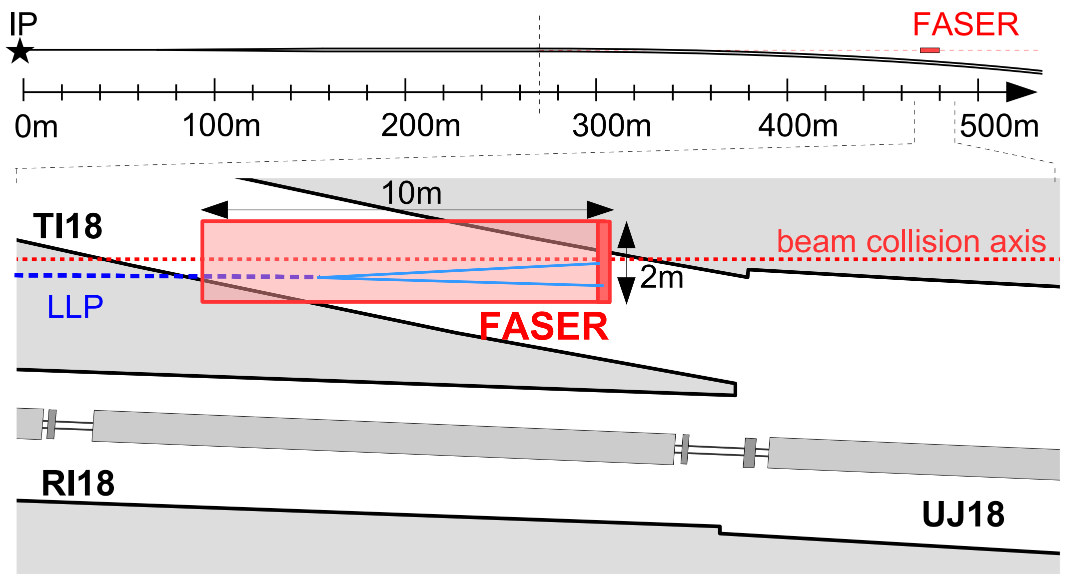
- more dark photons production by proton bremsstrahlung and meson decay compared to electron bremsstrahlung

Lifetime frontier

LHC lifetime frontier

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

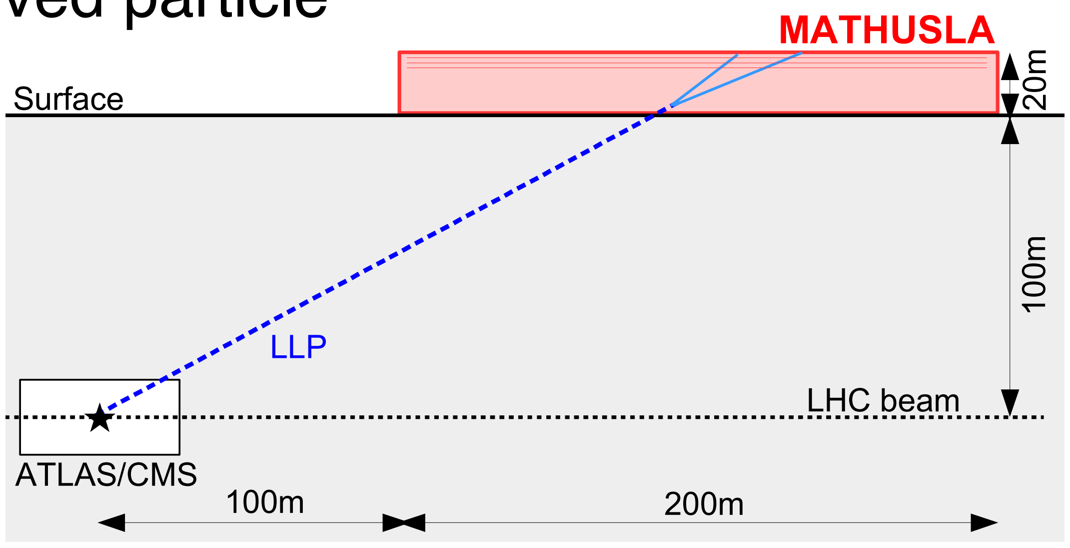
Berlin and Kling, PRD, 2019



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

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

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

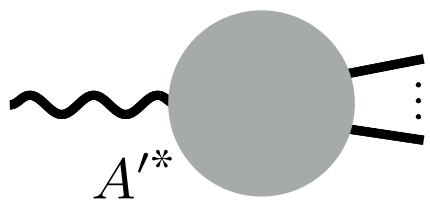


- MATHUSLA (CODEX-b)
  - off-axis $\theta_{\text{det}} = 0.5$
  - less boosted and thus longer lifetime particles come

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

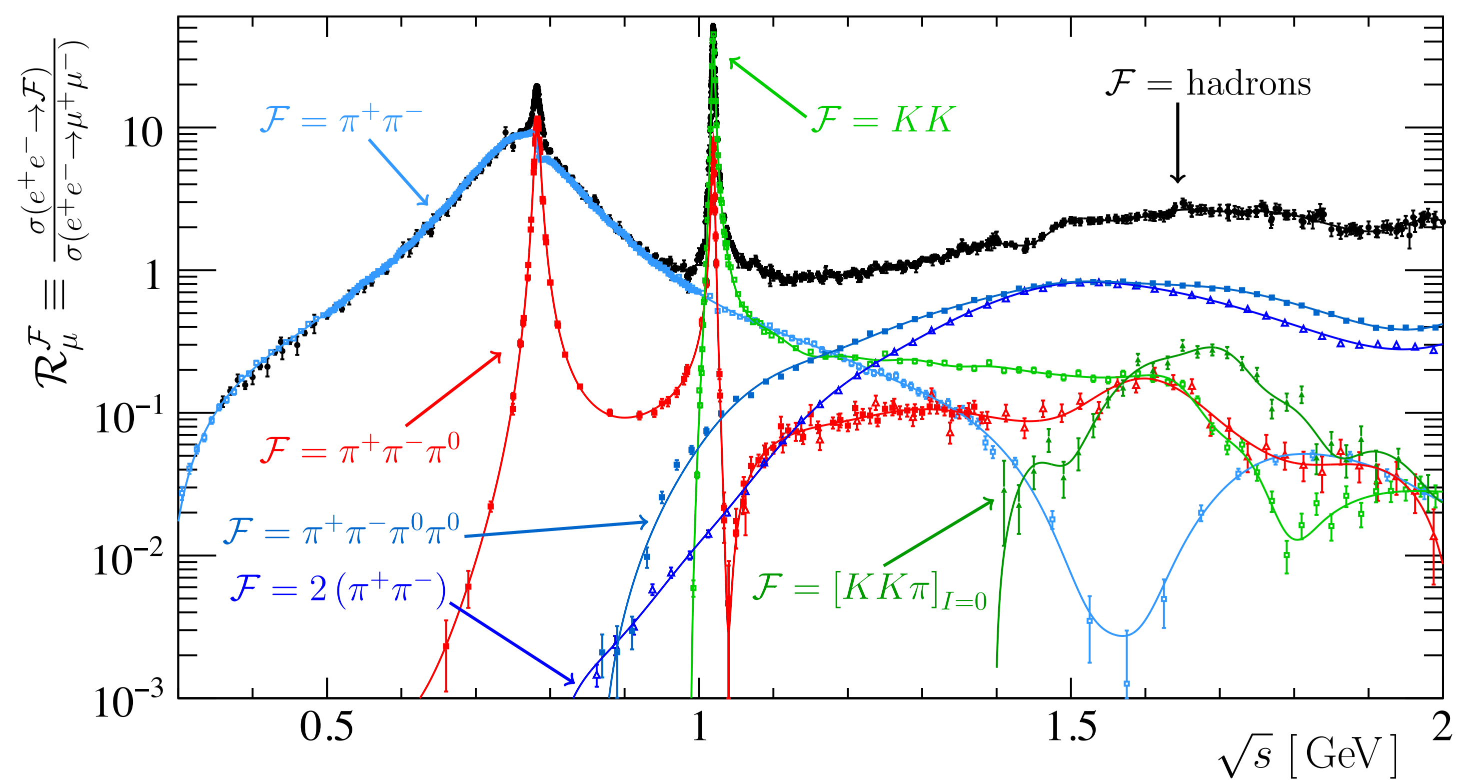
- SM analog

  - 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

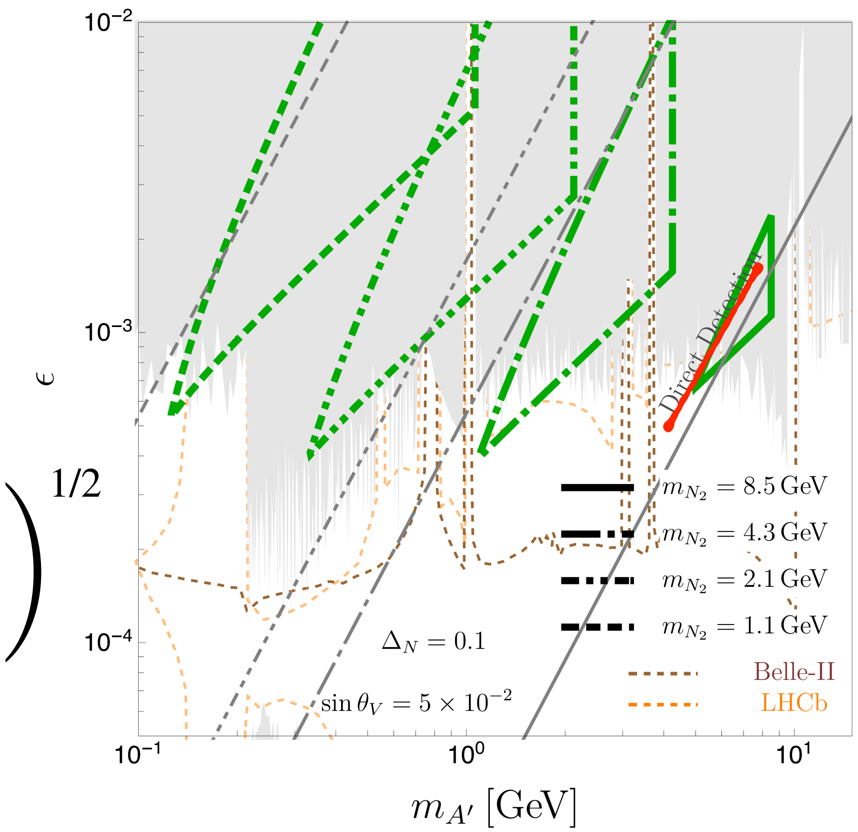


Sensitivities

Direct detection of dark baryons

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

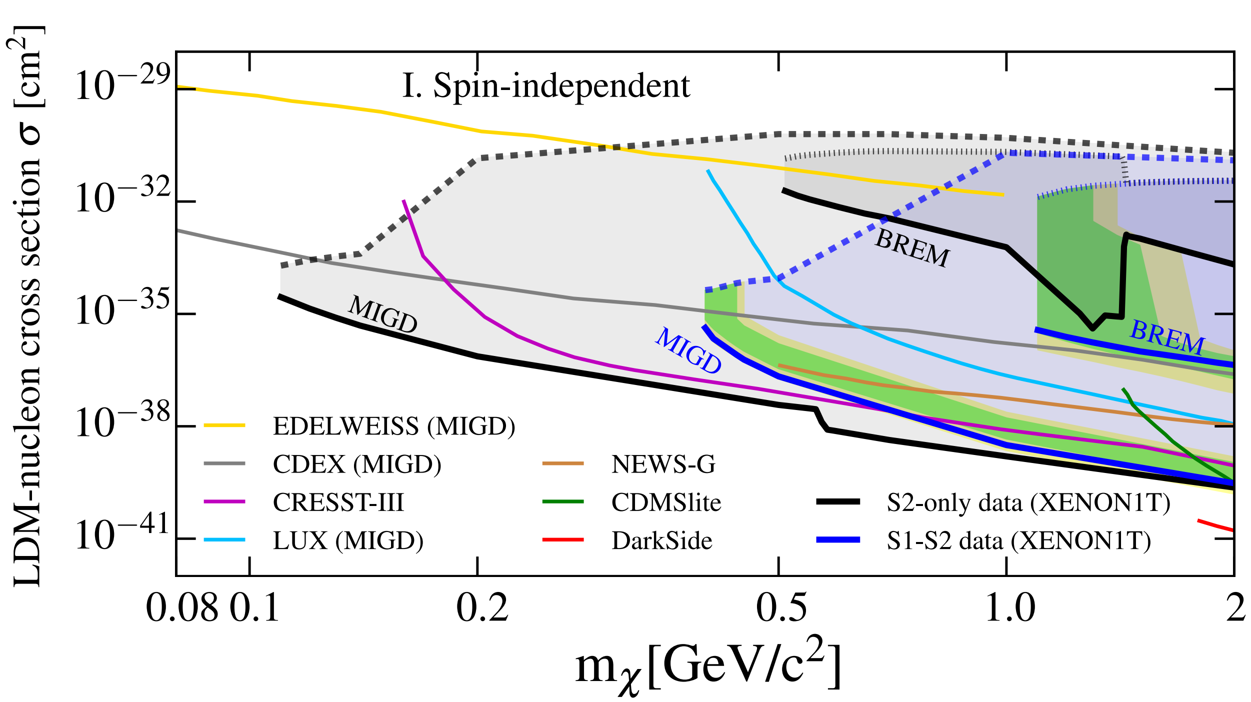
$$\epsilon \sin^2\theta_V \leq 1.4\times10^{-7}\left(\frac{m_{A'}}{1\,\mathrm{GeV}}\right)^2\left(\frac{\alpha'}{1/137}\right)^{-1/2}\left(\frac{\sigma^{\mathrm{bound}}}{6\times10^{-45}\,\mathrm{cm}^2}\right)^{1/2}$$

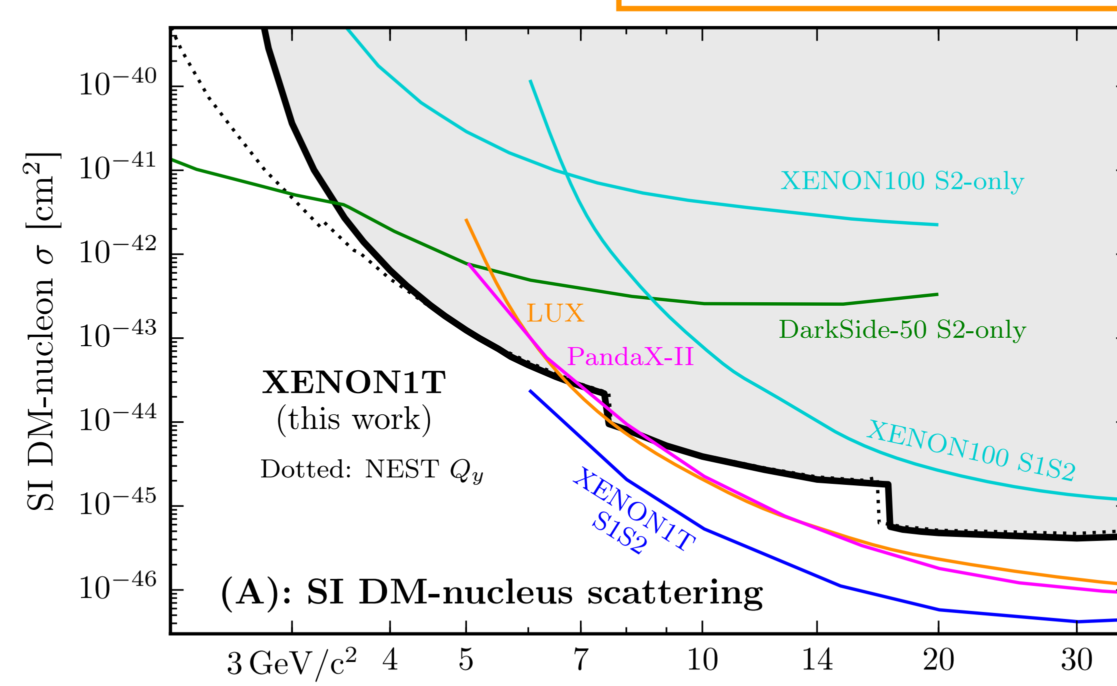


- GeV-scale dark matter

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

XENON1T collaboration, PRL, 2019 & 2019

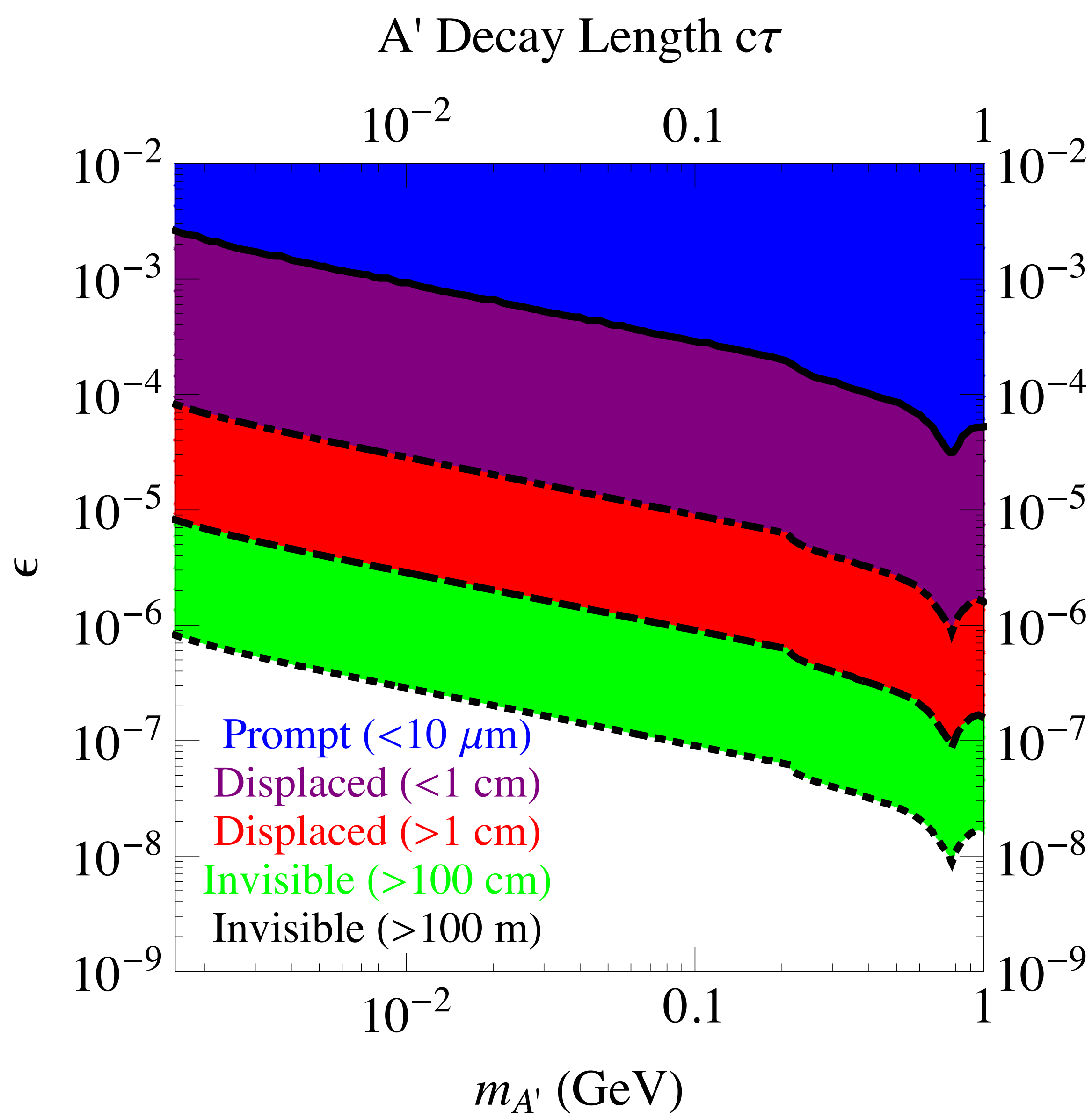




Decay length

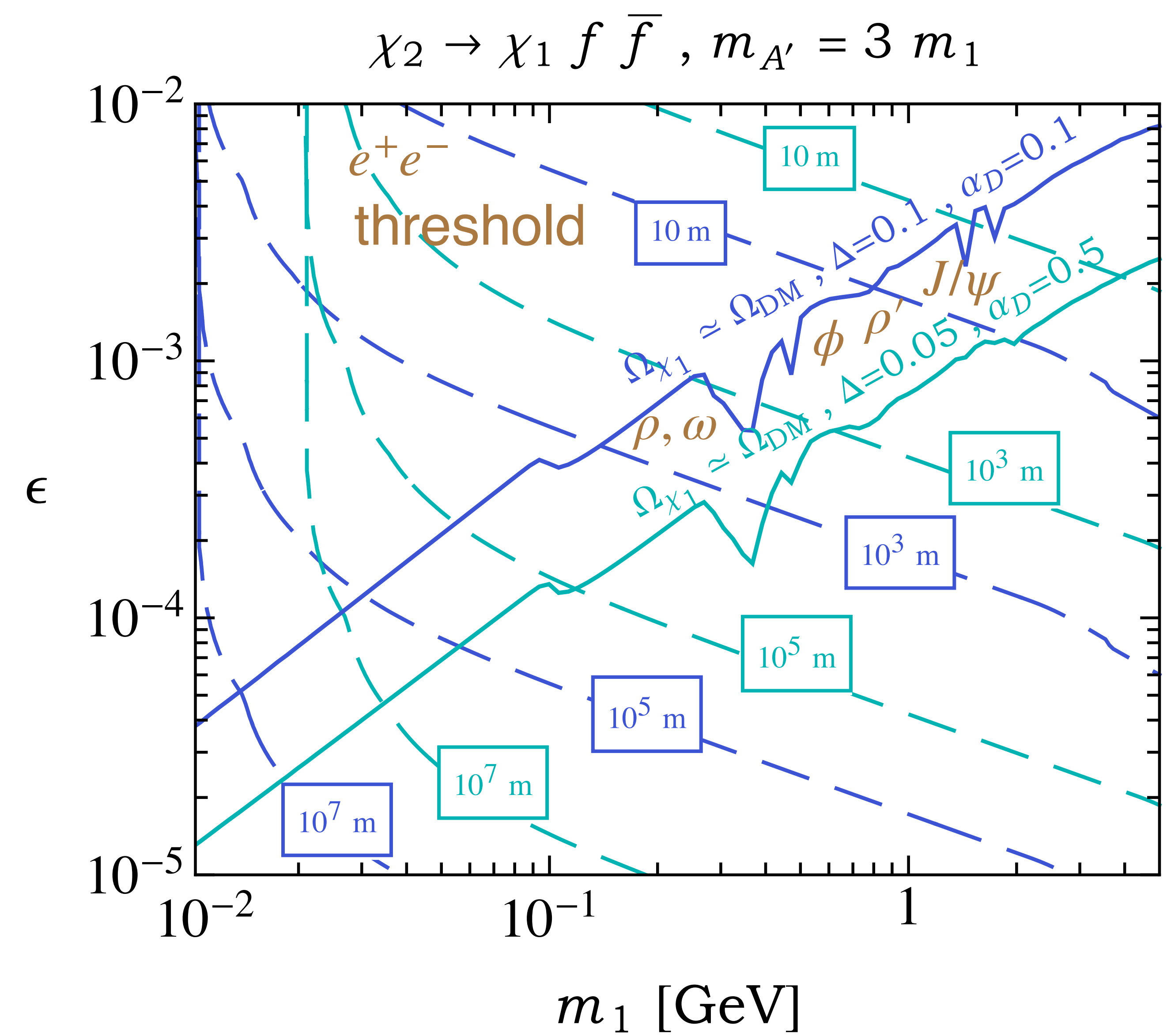
Dark photon portal

- minimal model



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

- inelastic dark matter model



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

Partial-wave analysis

Effective-range theory

- assume that inelastic channel is negligible $\eta_\ell = 1$

$$f_\ell(k) = \frac{1}{k\cot\delta_\ell - ik} \qquad \sigma_\ell = \frac{4\pi}{k^2}(2\ell+1)\sin^2\delta_\ell$$

- effective range theory

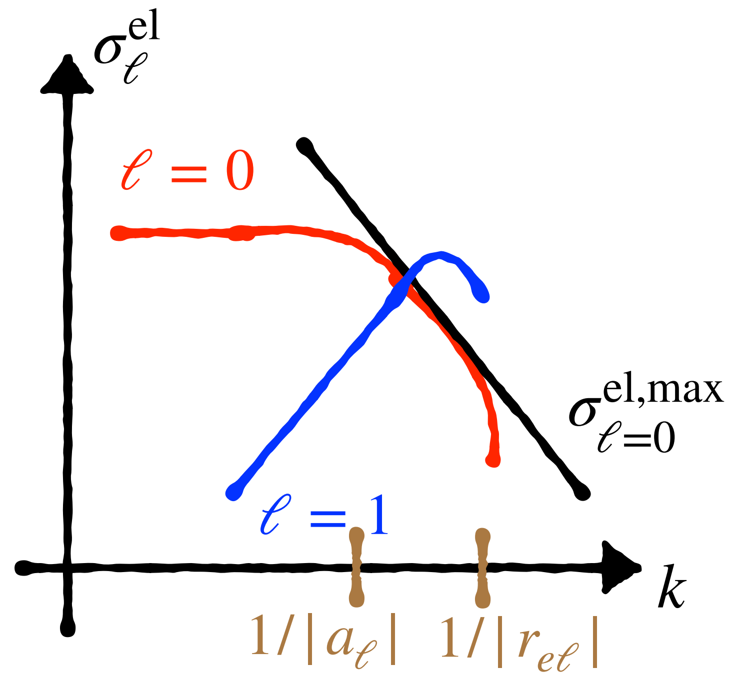
$$k \to 0 \quad k^{2\ell+1}\cot\delta_\ell \to -\frac{1}{a_\ell^{2\ell+1}} + \frac{1}{2r_{e\ell}^{2\ell-1}}k^2$$

- scattering length
- effective range

$$1/|a_\ell| > k \quad \sigma_\ell \simeq 4\pi a_\ell^2(2\ell+1)(ka_\ell)^{4\ell}$$

$$1/|r_{e\ell}| > k > 1/|a_\ell| \quad \sigma_\ell \simeq \frac{4\pi}{k^2}(2\ell+1)$$

- saturate the Unitarity bound



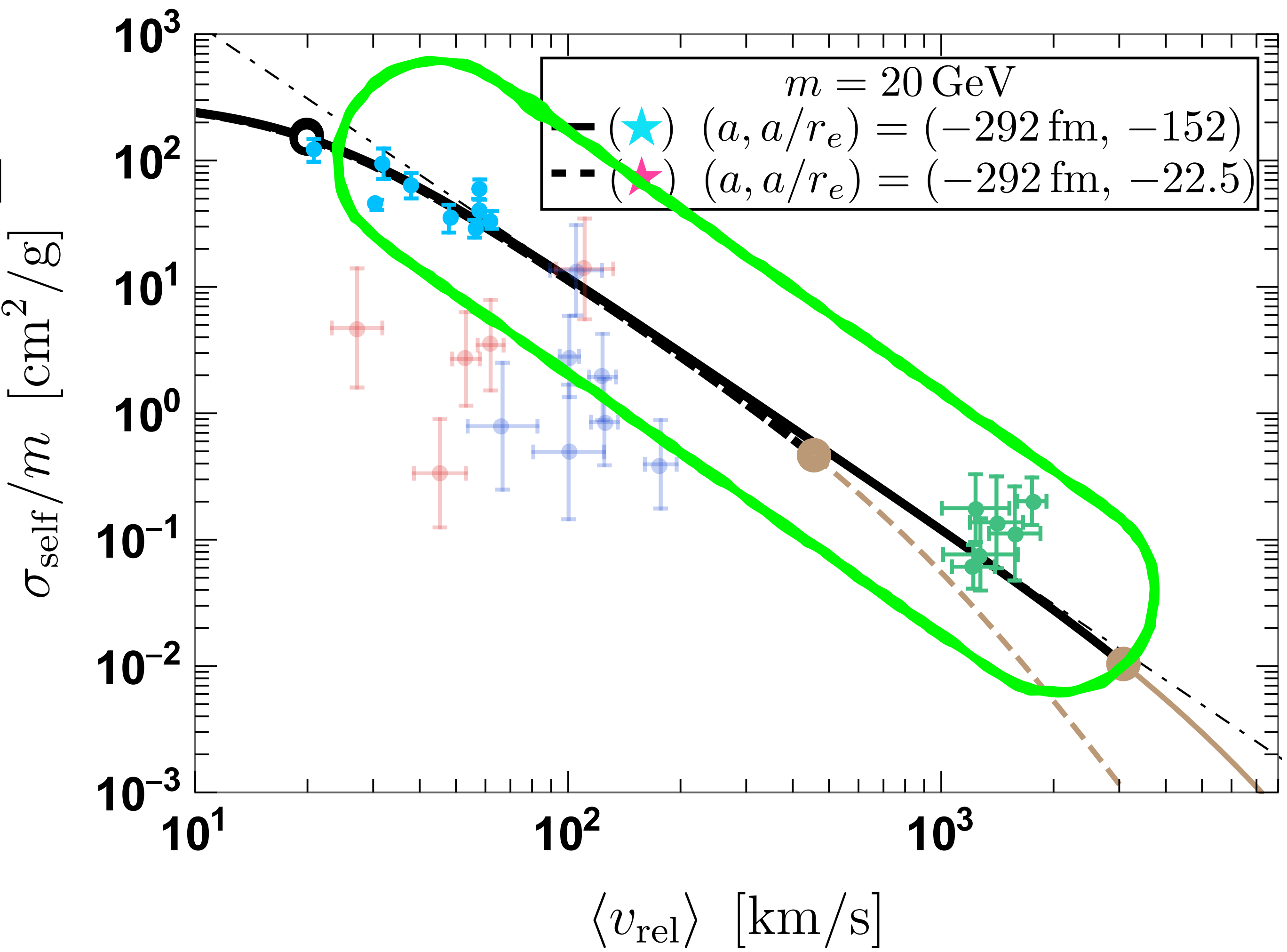
Self-scattering

Maximally self-interacting dark matter

- s -wave Unitarity

$$\sigma^{\text{el}} = \sigma^{\text{el,max}}_{\ell=0} = \frac{16\pi}{m^2 v_{\text{rel}}^2}$$

- suppressed by dark matter mass



AK, Kim, and Kuwahara, JHEP, 2020

- comparison with “data”

  - data points inferred from observed cores in various-size halos

  - $\sigma^{\text{el,max}}_{\ell} \propto 1/v_{\text{rel}}^2$ is in good agreement with data

  - depends solely on DM mass

    $m \simeq 20\,\text{GeV}$

    - cross section suppressed by 8 orders of magnitude for $m \sim 1\,\text{PeV}$

  - large $|a/r_e|$ in effective range theory

Self-scattering

Yukawa (Hulthén) potential $V(r) = -\frac{\alpha e^{-m_\phi r}}{r}$

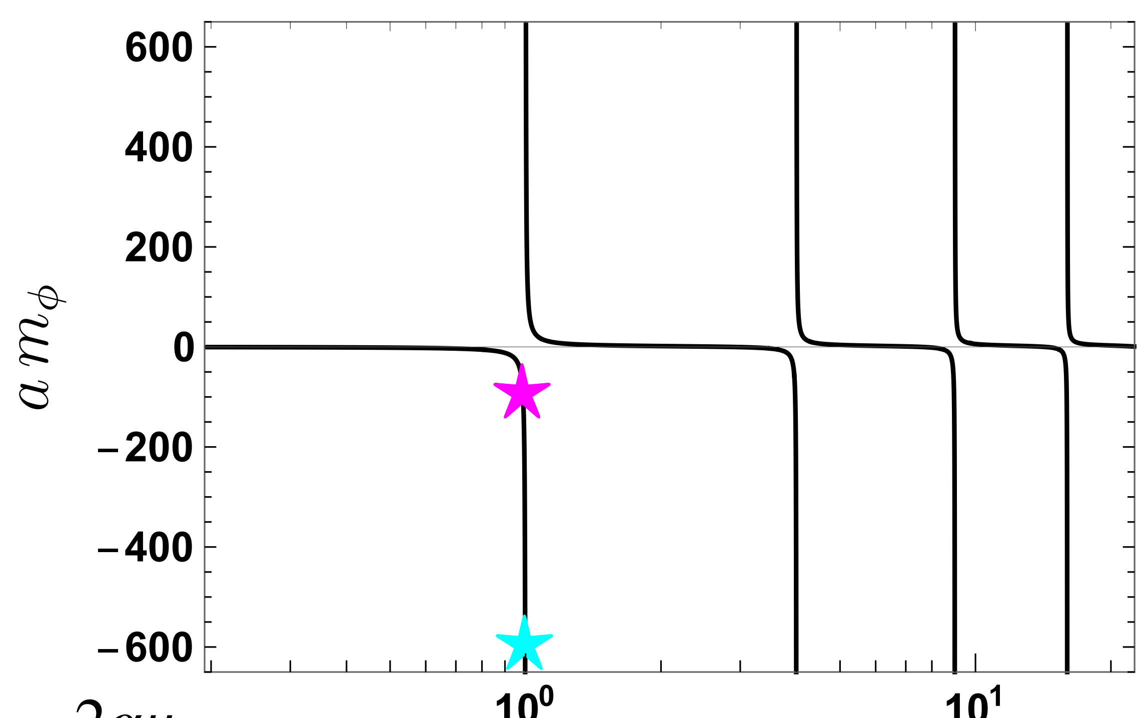
- Hulthén potential approximates Yukawa $V(r) = -\frac{\alpha \delta e^{-\delta r}}{1 - e^{-\delta r}}$ $\delta = \sqrt{2\zeta(3)} m_\phi$
  - analytic expression of the scattering state
- large $|a/r_\mathrm{e}|$ is realized at $\epsilon_\phi \simeq n^2$ $n = 1, 2, \ldots$ for the Yukawa (Hulthén) potential
  - correspond to the almost zero-energy virtual level/bound state $E_b \simeq \frac{1}{ma^2}$

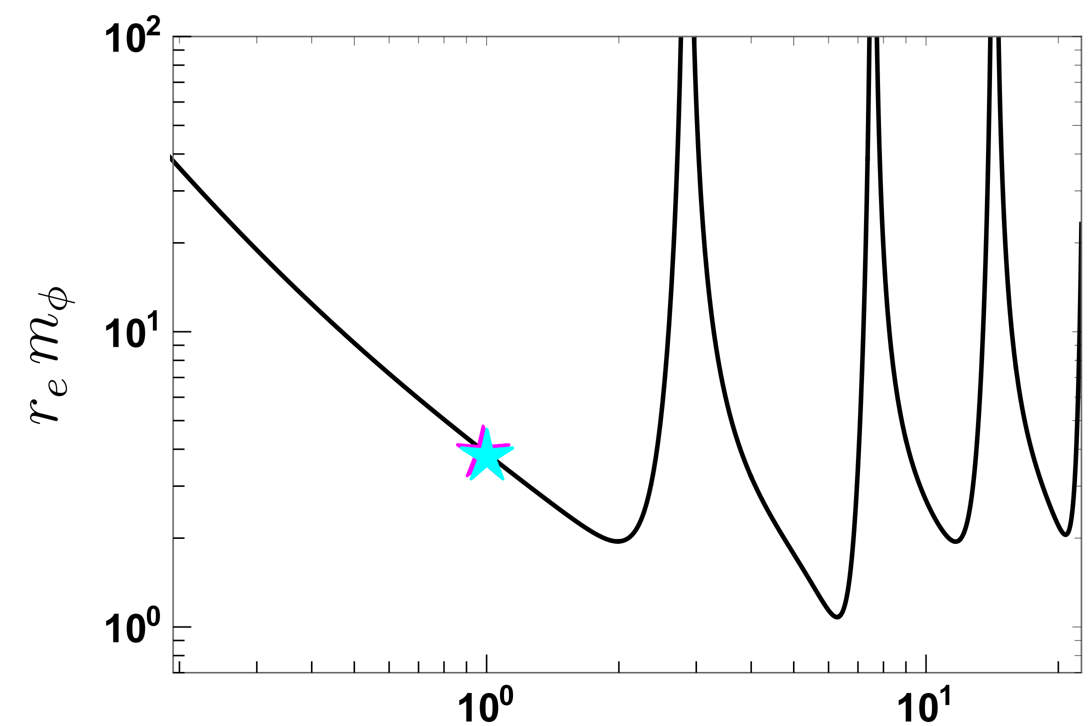
- e.g., neutron-proton

$a_s = -23.7\,\mathrm{fm}$ $r_{es} = 2.76\,\mathrm{fm}$

$a_t = 5.42\,\mathrm{fm}$ $r_{et} = 1.75\,\mathrm{fm}$

- deuteron - pion mass





$\epsilon_\phi = \frac{2\alpha\mu}{\delta}$ $\delta = \sqrt{2\zeta(3)} m_\phi$ ϵ_ϕ

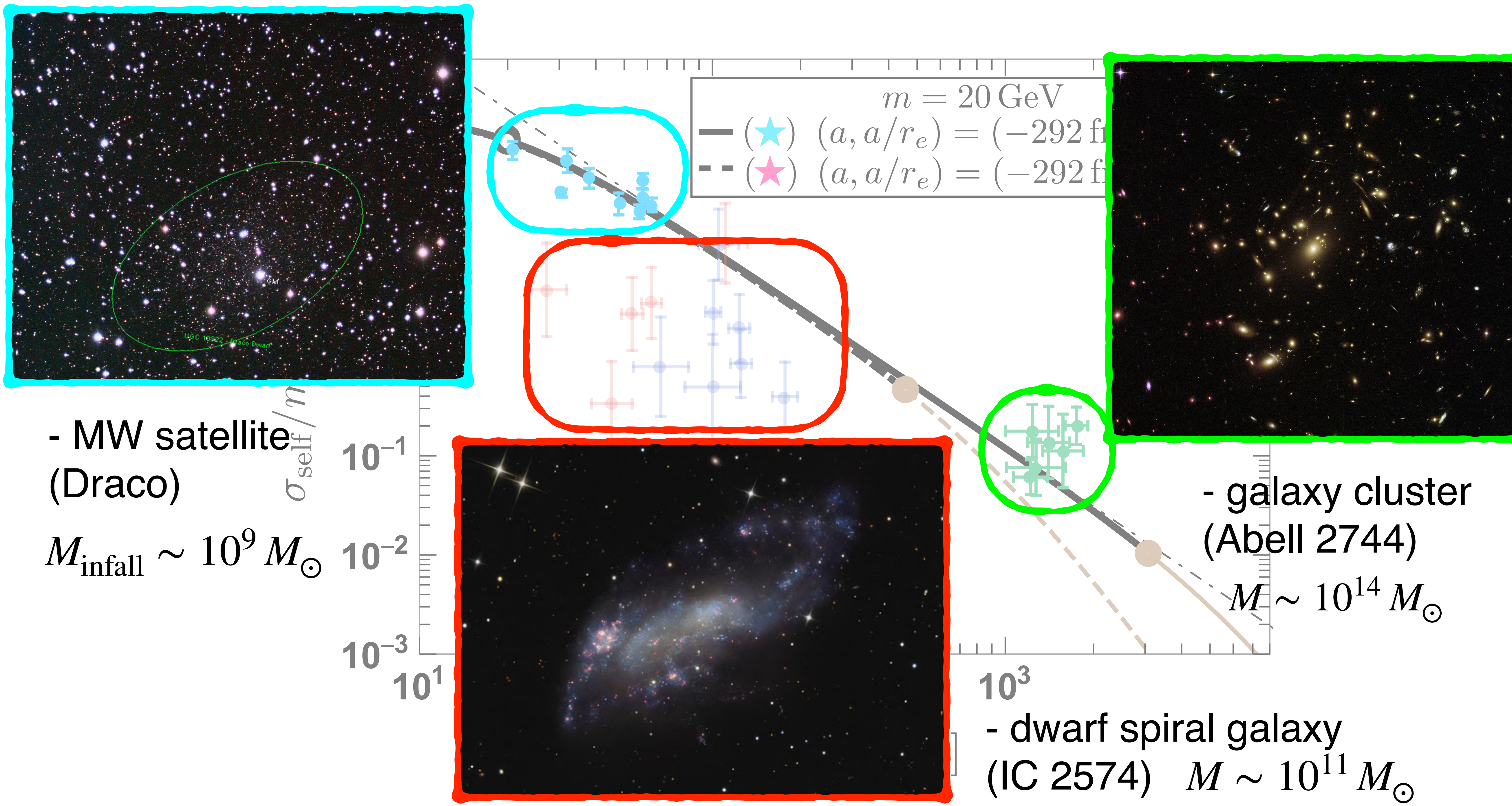
AK, Kim, and Kuwahara, JHEP, 2020

ϵ_ϕ

Data points

Overview

- cores in various-size halos

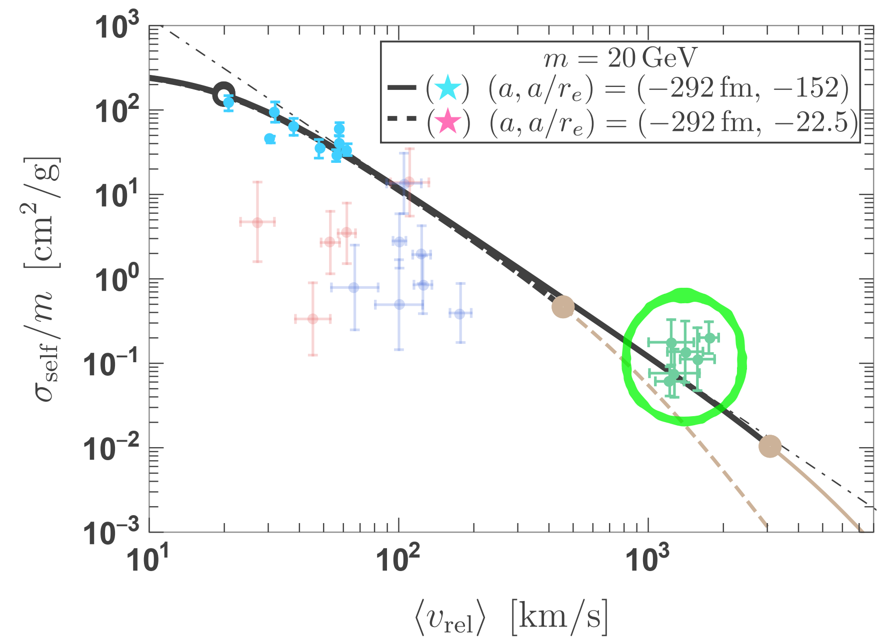


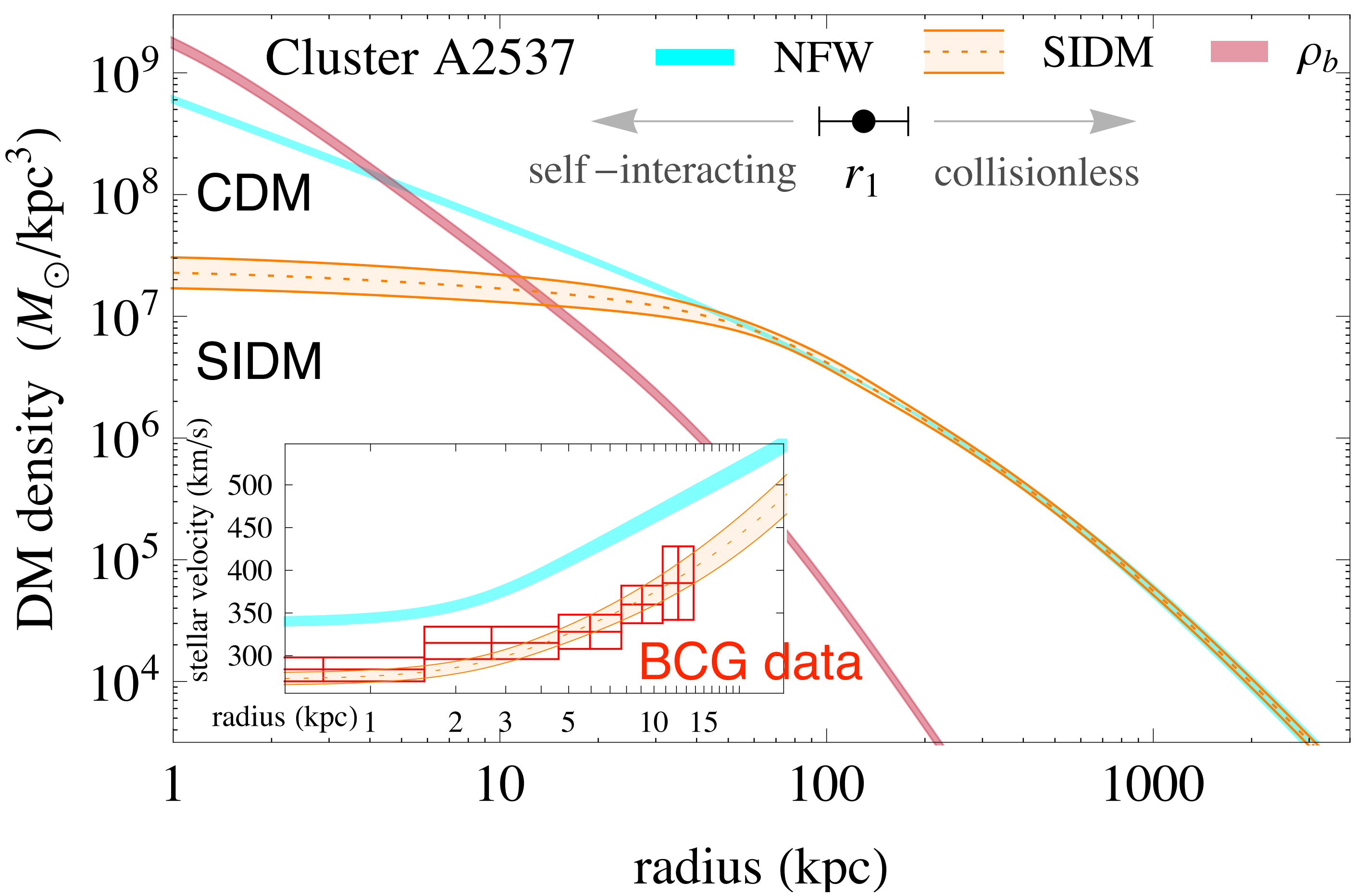
Data points

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





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

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

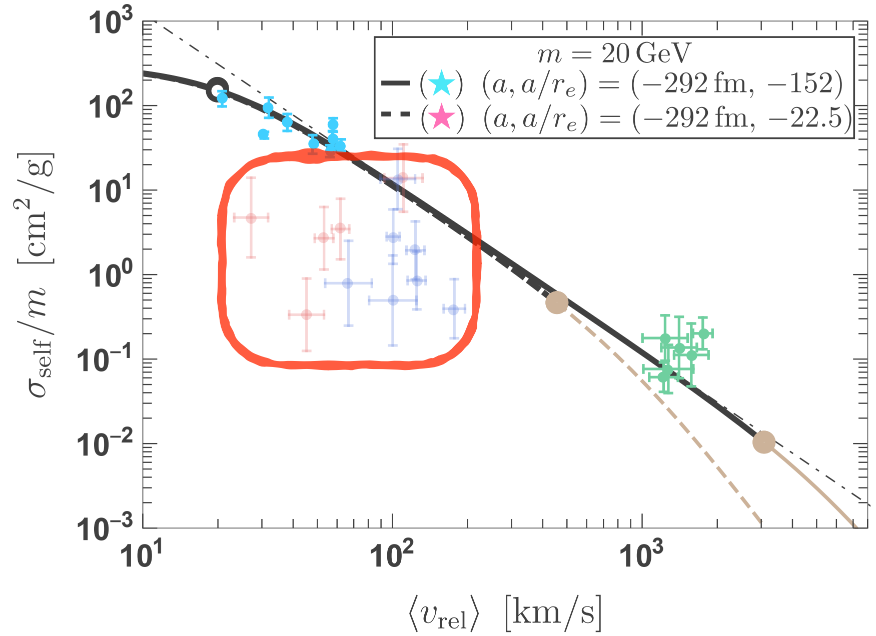
Kaplinghat, Tulin, and Yu, PRL, 2016

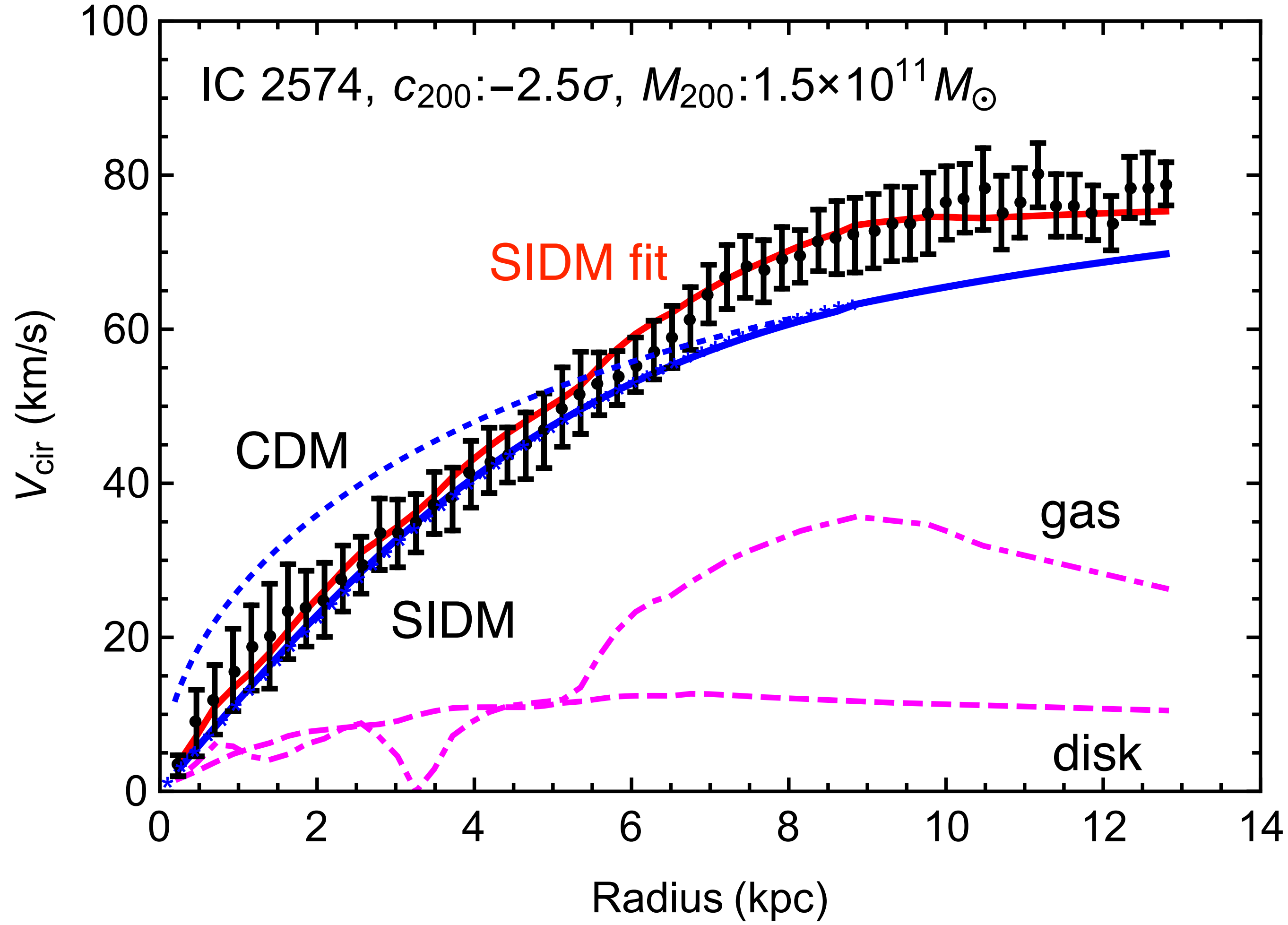
Data points

Dwarf spiral galaxies

- mass distribution is broadly determined by rotation curves

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





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

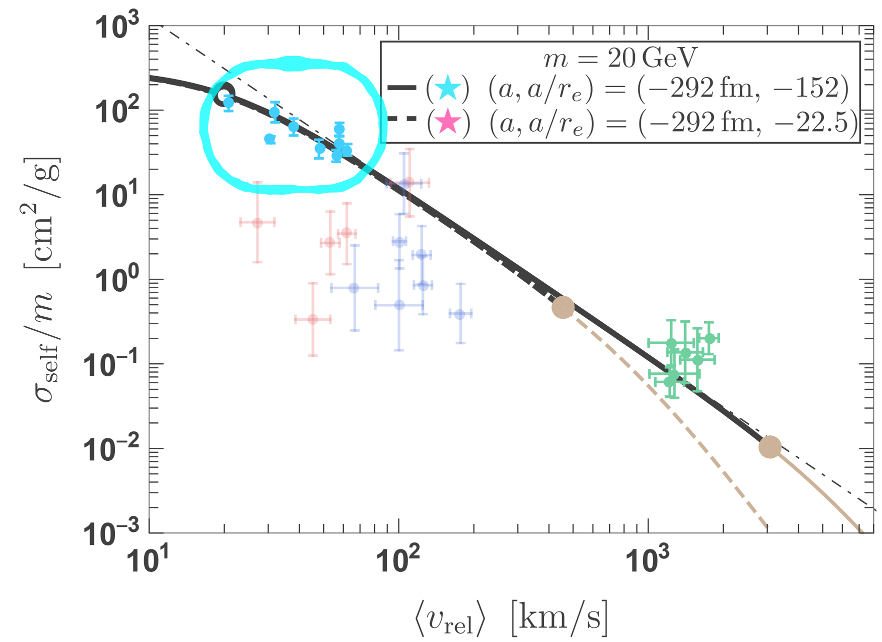
$$\langle v_{\mathrm{rel}} \rangle \sim 10^2\,\mathrm{km/s}$$

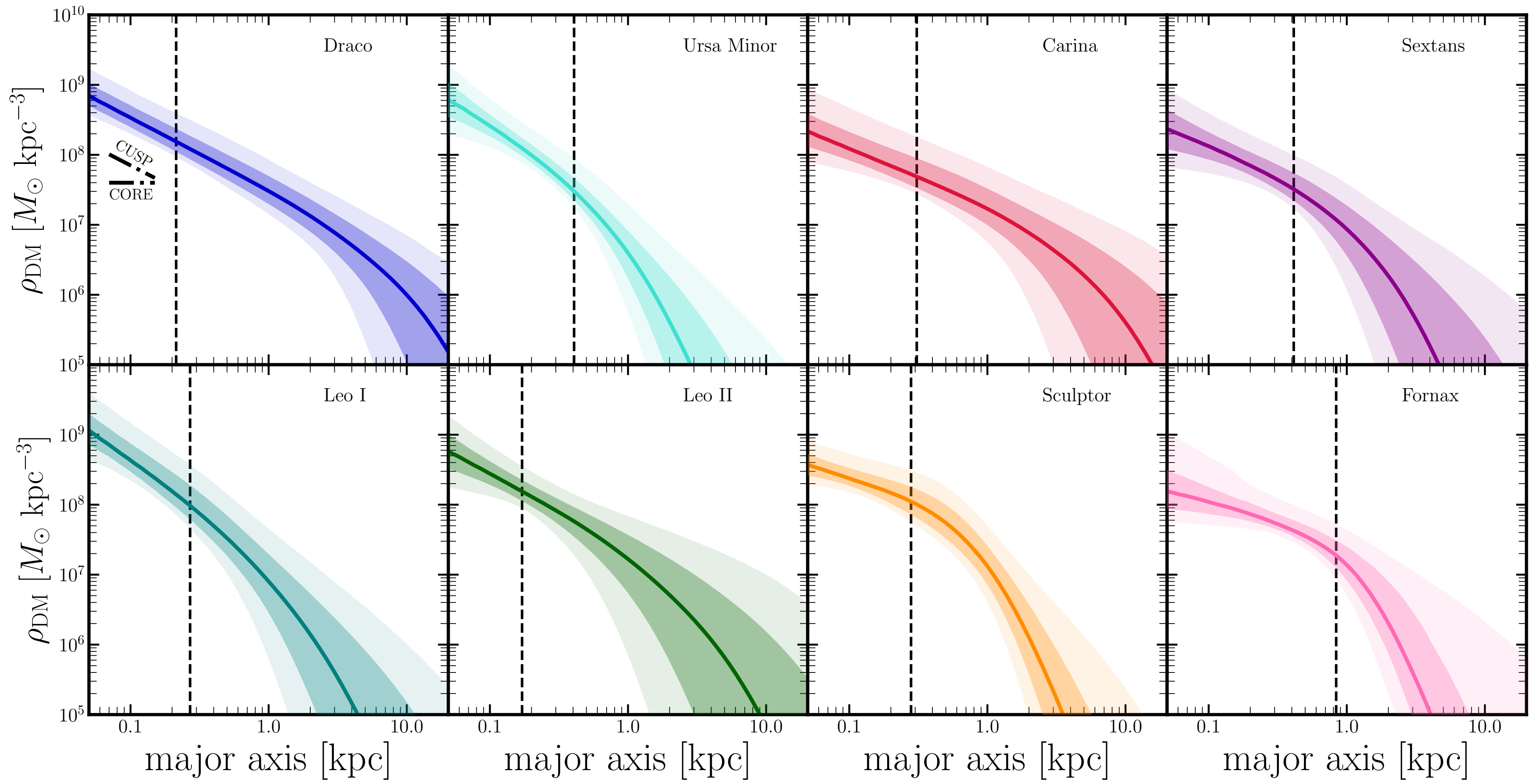
AK, Kaplinghat, Pace, and Yu, PRL, 2017

Data points

MW satellites

- mass distribution is determined by stellar kinematics
- stellar kinematics in the central region (of some satellites) prefer cuspy CDM profile

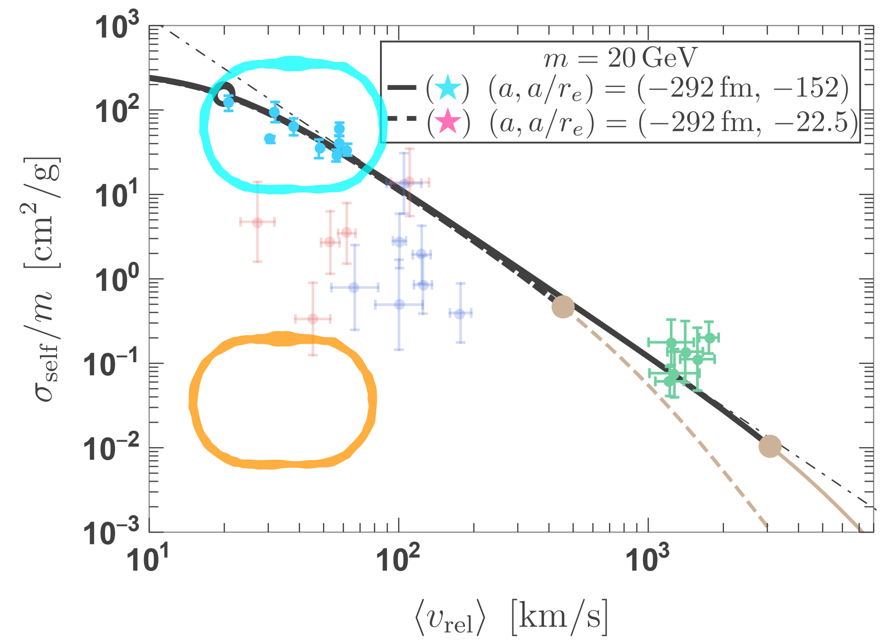




Hayashi, Chiba, and Ishiyama, ApJ, 2020

Data points

MW satellites



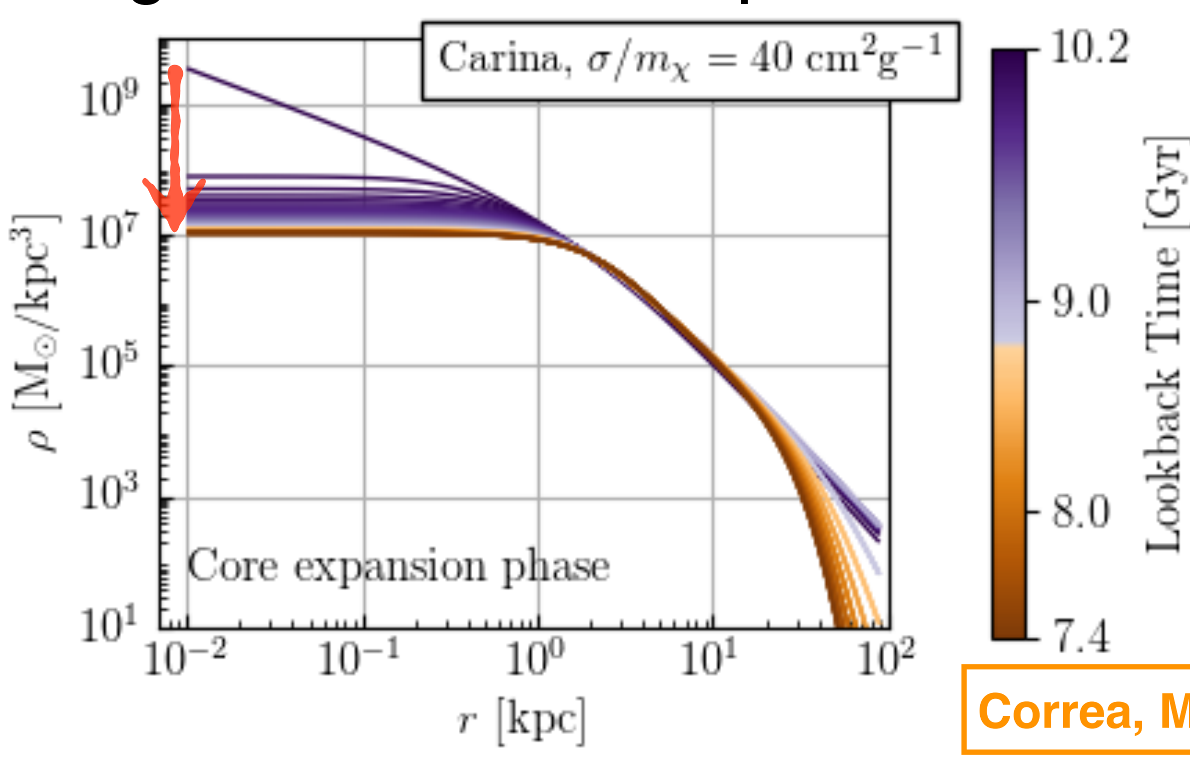
- one possibility is to take as a tiny cross section as $\sigma_{\rm self}/m \simeq 0.01\,\mathrm{cm^2/g}$

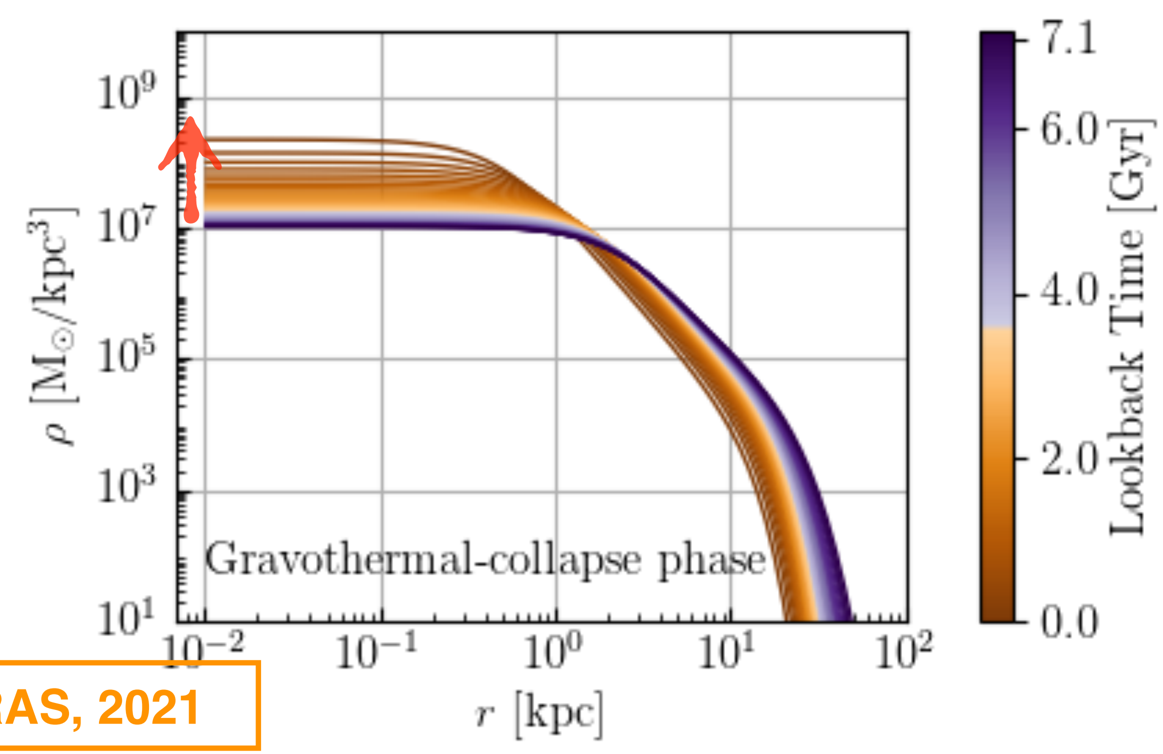
$\langle v_{\rm rel}\rangle \sim 30\,\mathrm{km/s}$

- resonance? **Chu, Garcia-Cely, and Murayama, PRL, 2019**

- another possibility is to take as a large cross section as $\sigma_{\rm self}/m \sim 40\,\mathrm{cm^2/g}$ $\quad \langle v_{\rm rel}\rangle \sim 30\,\mathrm{km/s}$

- gravothermal collapse



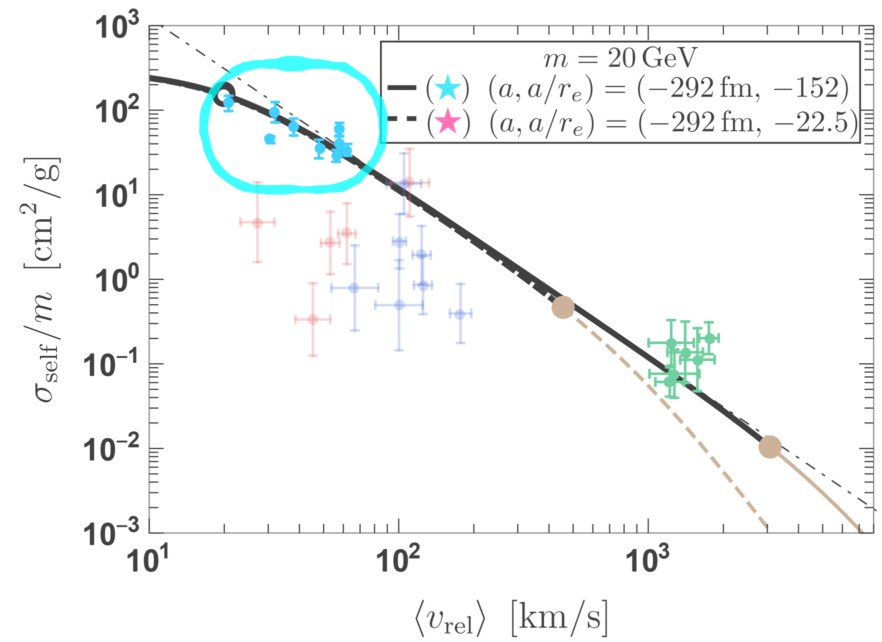


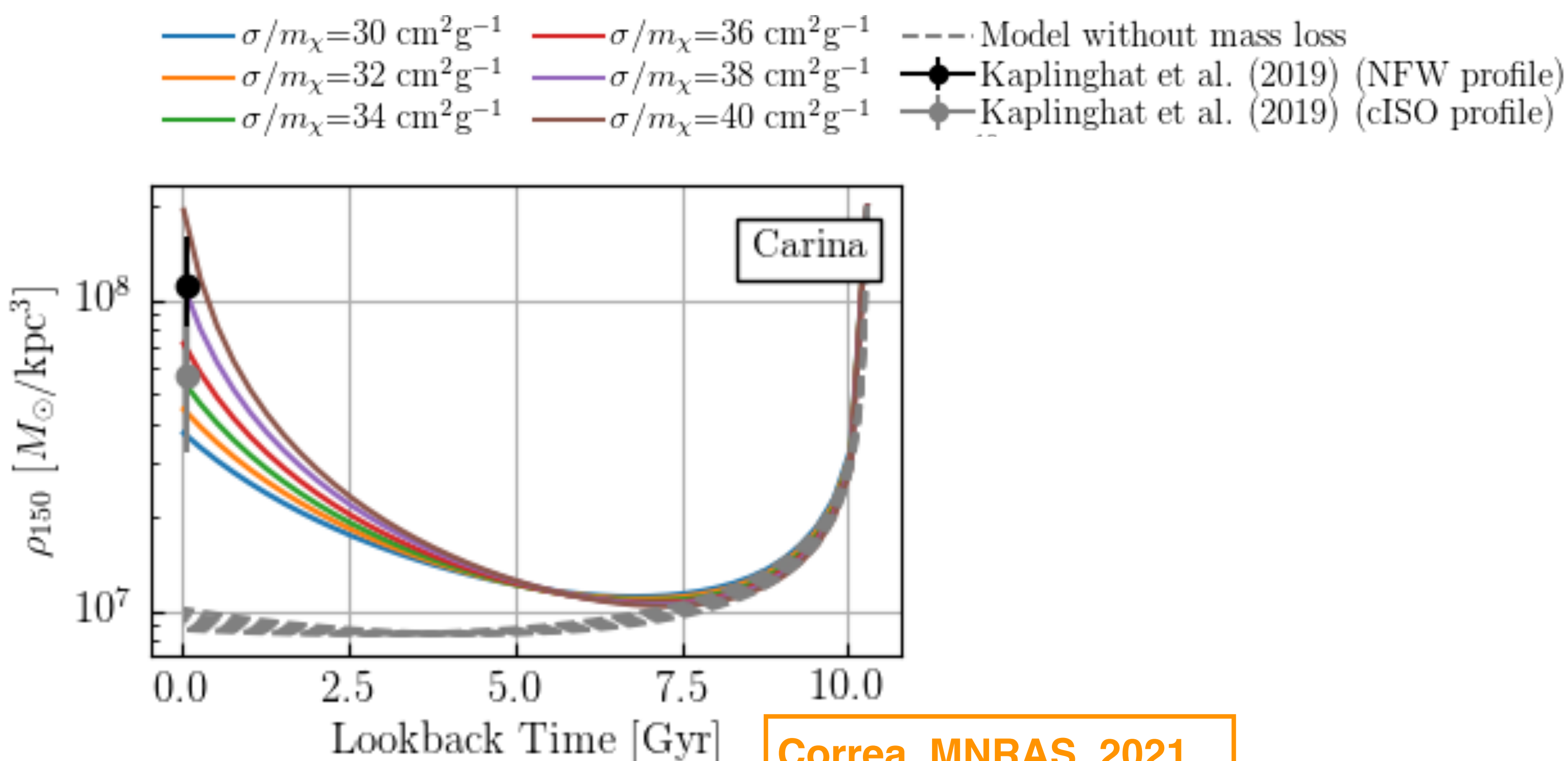
Correa, MNRAS, 2021

Data points

MW satellites

- gravothermal collapse
  - core shrinks and central density gets higher
  - central density at present is very sensitive to the cross section





Correa, MNRAS, 2021

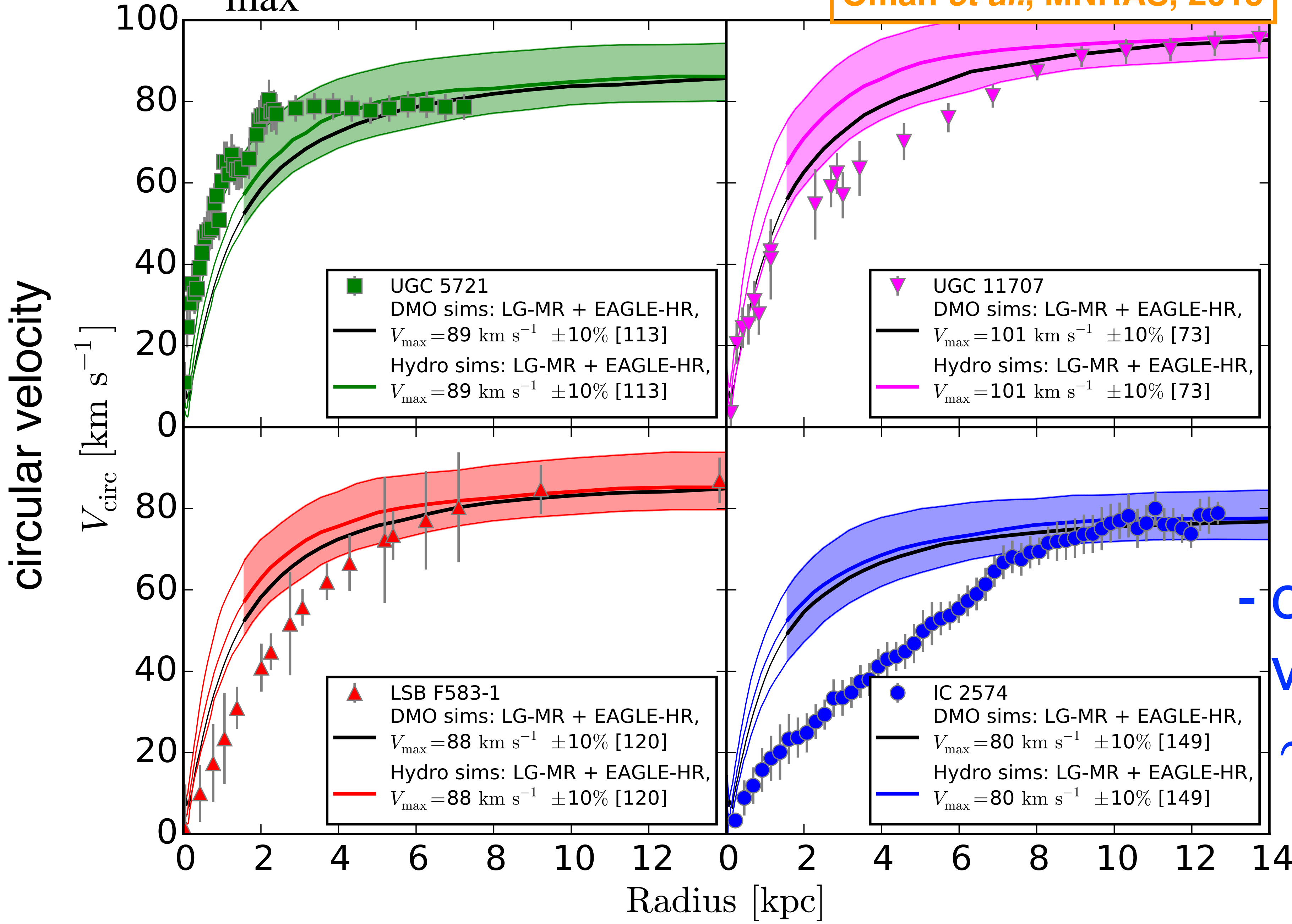
Diversity of inner rotation curves

Collisionless dark matter prediction: inner circular velocity is almost uniquely determined by outer circular velocity

↔ observations show diversity

$V_{\rm max} = 80\text{-}100\,{\rm km/s}$

Oman *et al.*, MNRAS, 2015



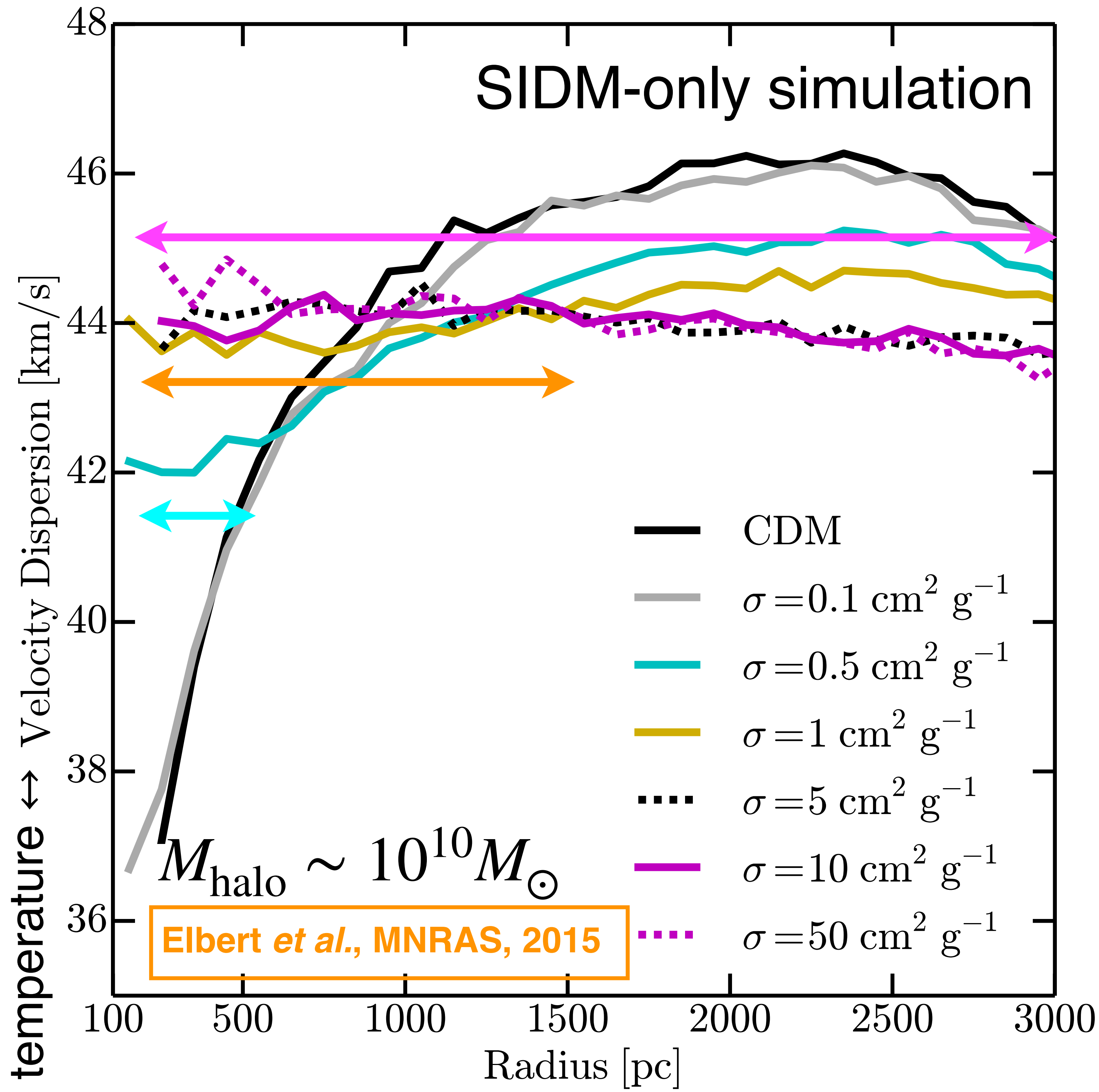
✳ unique prediction is related with the concentration-mass relation

- overpredict the circular velocity by a factor of ~ 2 (~ 4 in mass)

Iso-thermal halo

Self-scattering leads to thermalization of DM halos at $r < r_1$
where self-scattering happens at least one time until now

$$\sigma/m\,\rho(r_1)v(r_1)\,t_{\mathrm{age}} = 1$$



Key observation

Iso-thermal → Boltzmann distribution

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

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

- inner profile is exponentially sensitive to baryon distribution

Baryons form complex objects, which show a large diversity

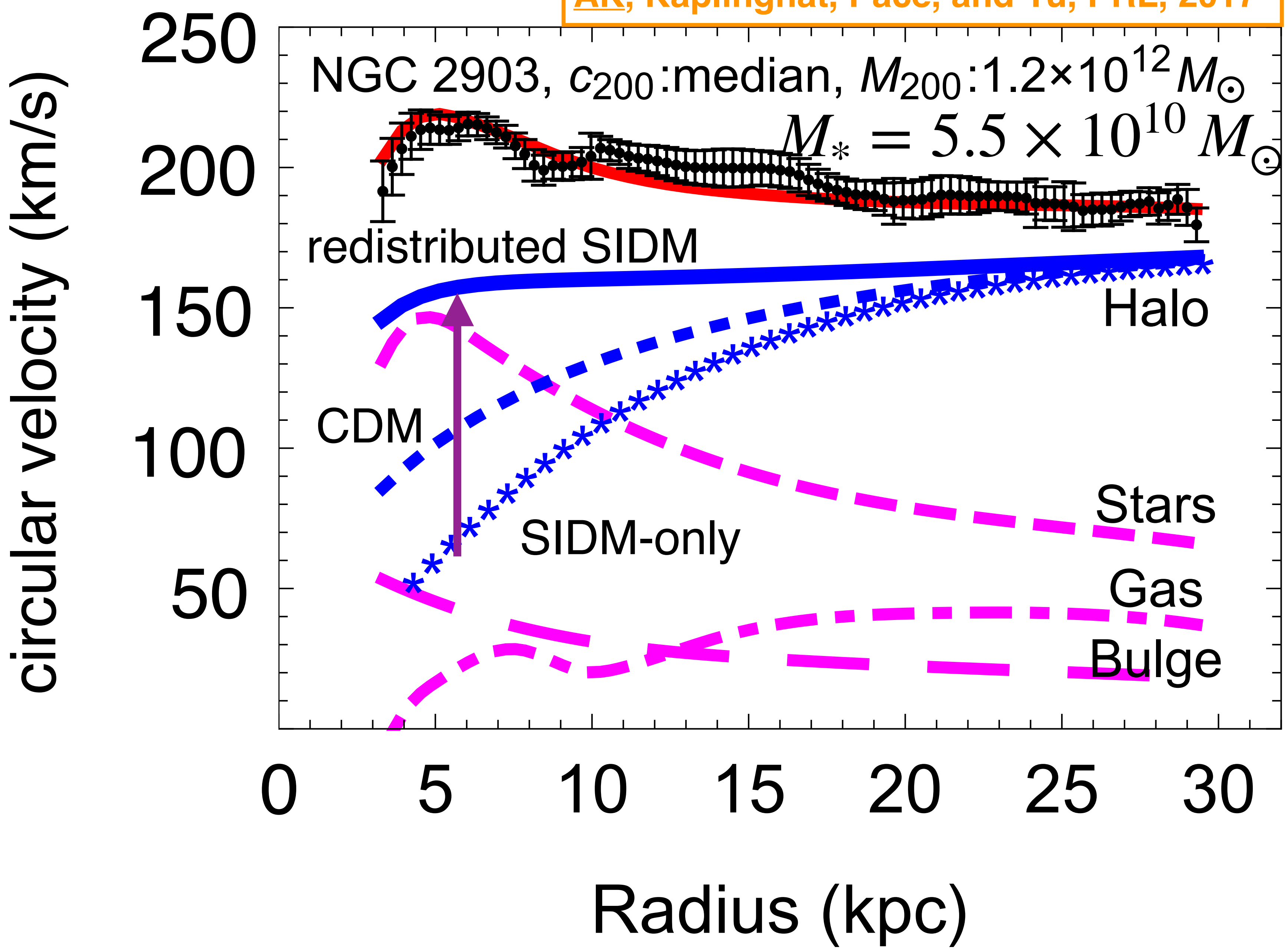
→ SIDM particles, redistributed according to formed baryonic objects, can show a diversity

✳ do not rely on unconstrained subgrid astrophysical processes take into account observed baryon distribution

Impacts in observed galaxies

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

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



- Observed stellar disk makes SIDM inner circular velocity ~ 3 times higher

→ reproducing flat circular velocity at $10\text{-}20\,\mathrm{kpc}$

Diversity in stellar distribution

Similar outer circular velocity and stellar mass, but different stellar distribution

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

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