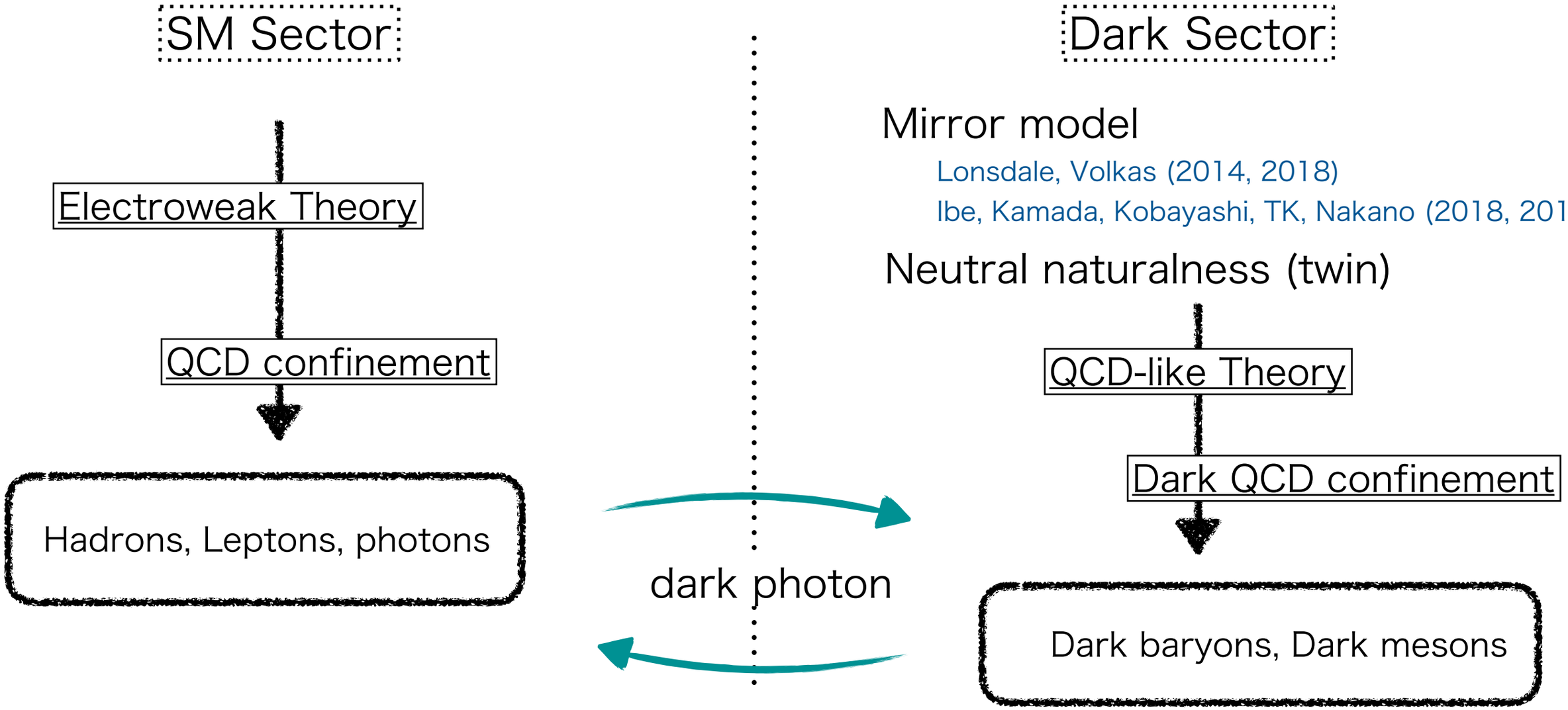
LLP2024
Jul 1, 2024

Confining Dark Sector and Long-lived Particle Searches

Takumi Kuwahara
CHEP, Peking U.

in collaborations with
A. Kamada (2112.01202, JHEP 03 (2022) 176)
S. Yuan (2303.03736, JHEP 06 (2023) 208)

Dark Sector with Confining dynamics

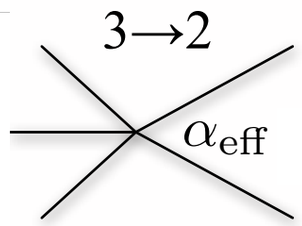


- Similar confinement scale $\Lambda'_{\rm QCD} \sim 1\,{\rm GeV}$ is expected in models with the SM copy
- Dark hadron DM
  - dark pions (ex. SIMP ...) Hochberg, Kuflik, Murayama, Volansky, Wacker (2015)
  - dark baryons (ex. composite asymmetric DM ...)

Ibe, Kamada, Kobayashi, Nakano (2018)

We consider SU(3) $\mathrm{QCD}_{\rm dark} \times \mathrm{QED}_{\rm dark}$

Strongly-interacting Massive Particle Scenario



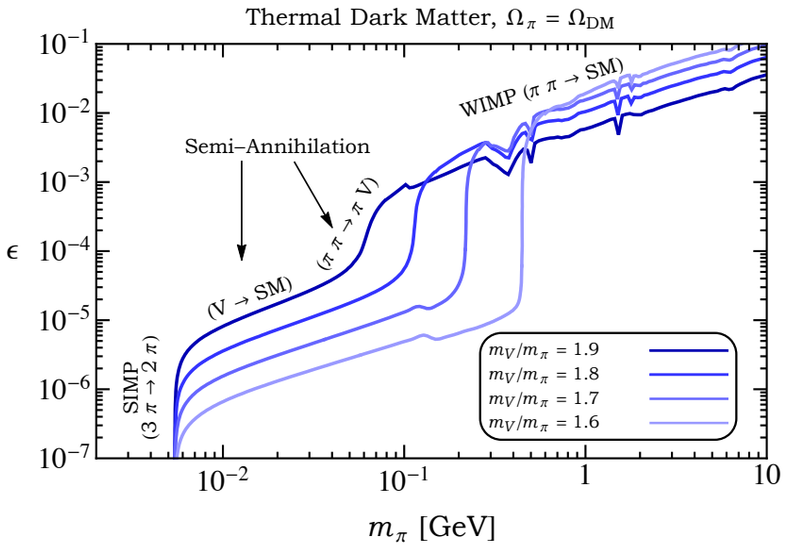
✓ Freeze-out of number-changing process — Hochberg, Kuflik, Volansky, Wacker (2014)

$$\langle \sigma v^2 \rangle = \frac{\alpha_{\rm eff}^3}{m_\chi^5} \qquad \Omega_{\rm DM} h^2 \sim 0.1 \to \alpha_{\rm eff} \simeq 1\,, m_\chi \simeq 100\,{\rm MeV}$$

✓ Safe from astrophysical/cosmological constraints

late-time energy injection to EM channel

✓ Dark photons for kinetic equilibrium



Berlin, Blinov, Gori, Schuster, Toro (2018)

Why compositeness?

- natural number-changing operator (Wess-Zumino-Witten term)
- sub-GeV-scale mass (pNGB/dimensional transmutation)
- stability by flavor symmetry (no chiral anomaly)
  - Dark resonances for large couplings

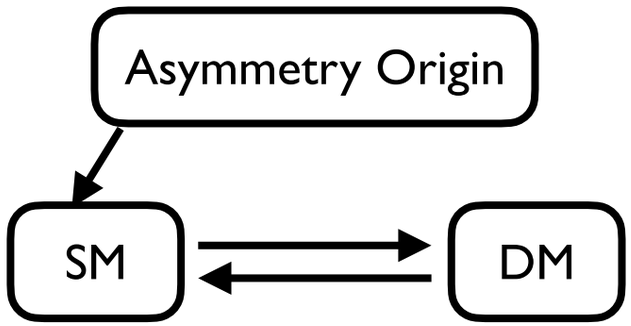
$$m_{\pi'} \simeq \frac{4\pi}{\sqrt{N_C}} f_{\pi'} \simeq m_{V'}$$ vector mesons in QCD-like theory

Asymmetric DM Scenario

✓ particle-antiparticle asymmetries

$$\eta_B \equiv \frac{n_B - \bar{n}_B}{n_\gamma} \quad \text{and} \quad \eta_{\rm DM} \equiv \frac{n_{\rm DM} - \bar{n}_{\rm DM}}{n_\gamma}$$

generated via sharing asymmetry: $\eta_B \sim \eta_{\rm DM}$



$$\frac{\Omega_{\rm DM}}{\Omega_B} = \frac{m_{\rm DM}\,\eta_{\rm DM}}{m_B\,\eta_B} \sim 5 \text{ : DM mass ~ O(1) GeV}$$

✓ Safe from astrophysical/cosmological constraints

no anti-particle -> no late-time energy injection to EM channel

Why compositeness?

- strong depletion of symmetric component
- GeV-scale mass (dimensional transmutation)
- stability by dark baryon number

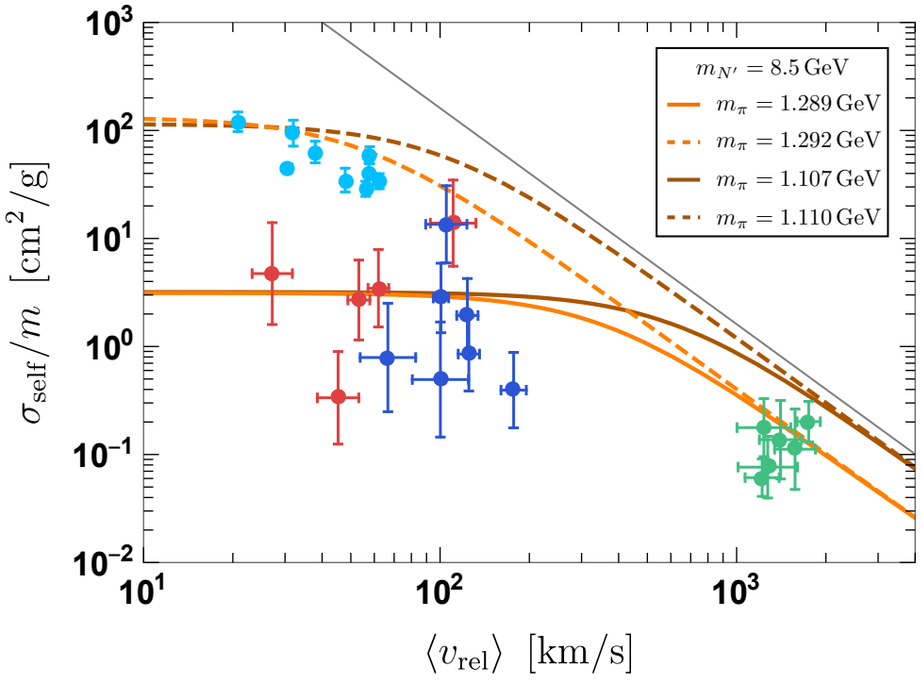
- ✓ Dark photon for releasing dark-sector entropy

  symmetric part of dark nucleons ⇒ dark pions

  dark pions ⇒ dark photon ⇒ SM particles

- ✓ velocity-dependent self-scattering

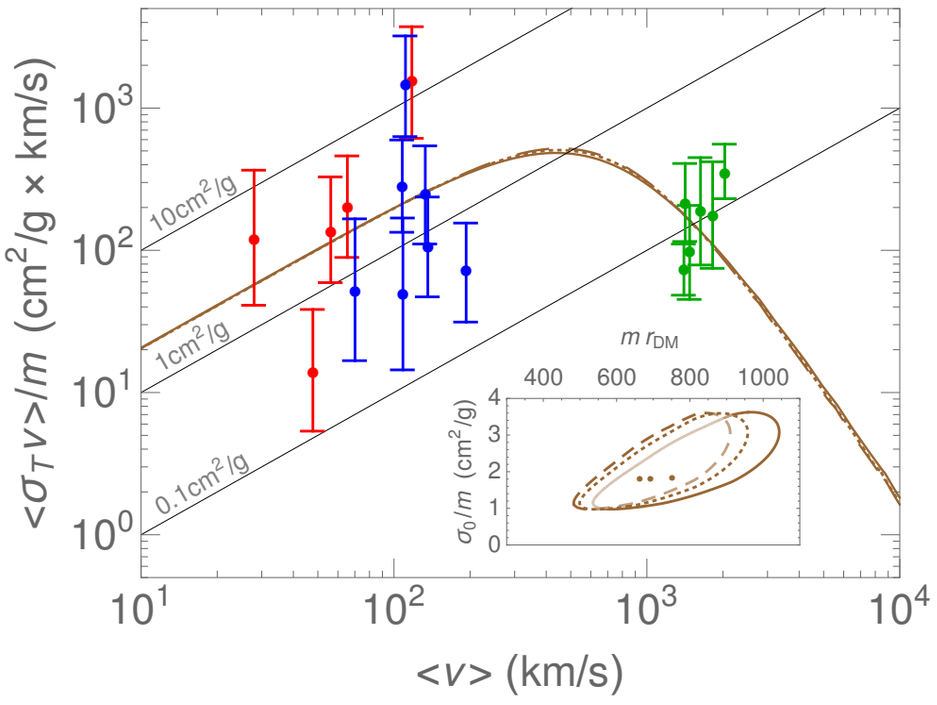
Kamada, Kim, TK (2020)



SM-like Spectrum

$$m_{A'} < m_{\pi'} \ll m_{N'}$$

Chu, Garcia-Cely, Murayama (2019)



Puffy DM $\quad m_{A'} \lesssim m_{\eta'} \simeq m_{V'}$

dark "nucleus" (finite-size DM)

N-N scattering by V': $\sim m_{V'}^{-1}$

<< size of nuclei: $r_{\rm DM} \sim A^{1/3} m_{\eta'}^{-1}$

Long-lived Particle Signals

two kinds of tests for confining dark sector at collider/fixed-target experiments

dark photon decay

visible decay signal ($m_{A'} \lesssim$ dark hadron mass)

- Prompt decay: BaBar, KLOE, LHCb, ...
- LLP @ Fixed-target: E137, CHARM, DarkQuest, νCal, ...
  @ Collider: FASER(2), FACET, ...

invisible decay signal (dark hadron mass $\lesssim m_{A'}$)

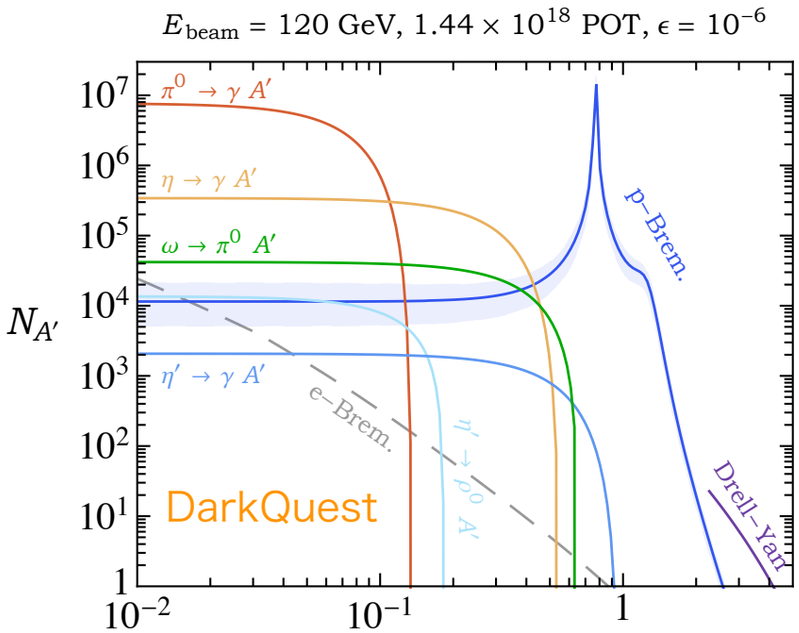
- mono-photon signal (BaBar, Belle-II): $e^+e^- \to \gamma A'$
- missing-energy searches (NA64, LDMX)
  A' →dark hadrons

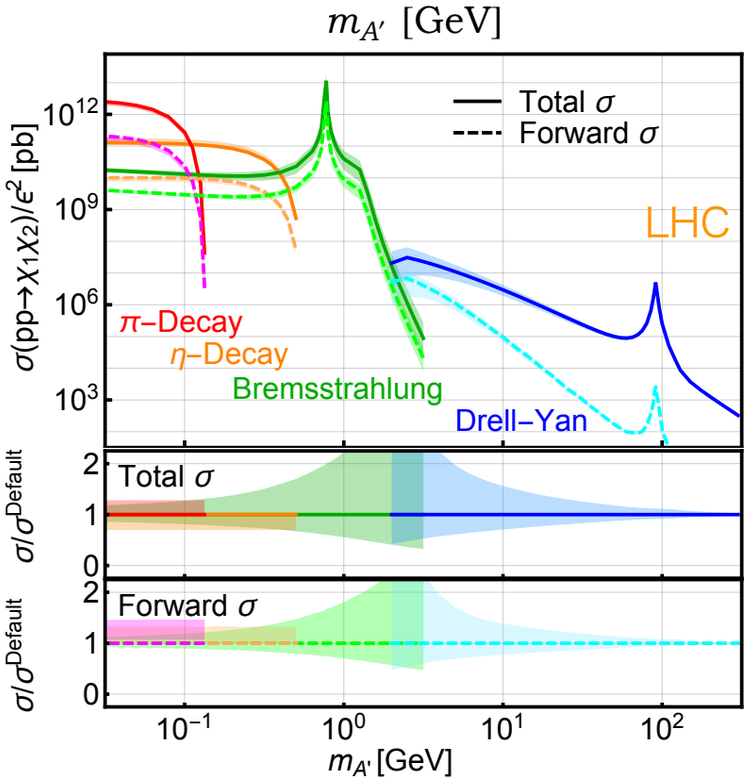
dark hadron processes (with emitting off-shell A')

- dark nucleon transition: $N_2' \to N_1' + e^+e^-$
- dark vector meson decay: $V'^0 \to \ell^+\ell^-$, $V'^{\pm} \to \pi'^{\pm}\ell^+\ell^-$ (when $m_{V'} \lesssim m_{A'}(+m_{\pi'})$)
- dark pion decay: $\pi' \to A' + e^+e^-$

Dark Hadron Production

Berlin, Gori, Schuster, Toro (2018)





Berlin, Kling (2018)

Dark hadrons produced via dark photon portal

On-shell Dark Photon $m_{h'} < m_{A'}$

dark hadrons from prompt decay of A'

$$N_{V'} \simeq N_{A'} \mathrm{Br}(A' \to \text{dark hadrons})$$

Off-shell Dark Photon $m_{A'} < m_{h'}$

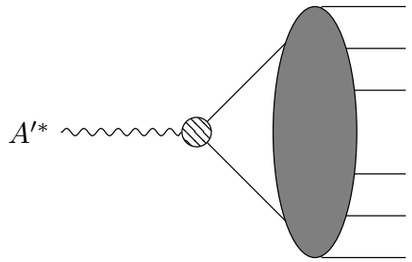
approximate cross section

$$\frac{d\sigma}{dm_{A'}^{*2} dx} = \frac{d\sigma_{A'}(m_{A'}^*)}{dx} \times \frac{1}{\pi} \frac{m_{A'}^* \Gamma_{A'}(A' \to \text{dark hadrons})}{(m_{A'}^{*2} - m_{A'}^2)^2 + (m_{A'}^* \Gamma_{A'})^2}$$

off-shell A' production — A' decay (with $m_{A'}^*$)

Dark Hadronization -off-shell case-

dark hadron production for energy injection $m^*_{A'}$ above $\Lambda'_{\rm QCD}$



$$N_h \simeq \frac{n_h \alpha'}{\pi}\Big(\sum Q_{q'}^2\Big) N_{A'}\Big|_{m^*_{A'}=\Lambda'_{\rm QCD}}$$

hadron multiplicity

SM value @ J/psi threshold

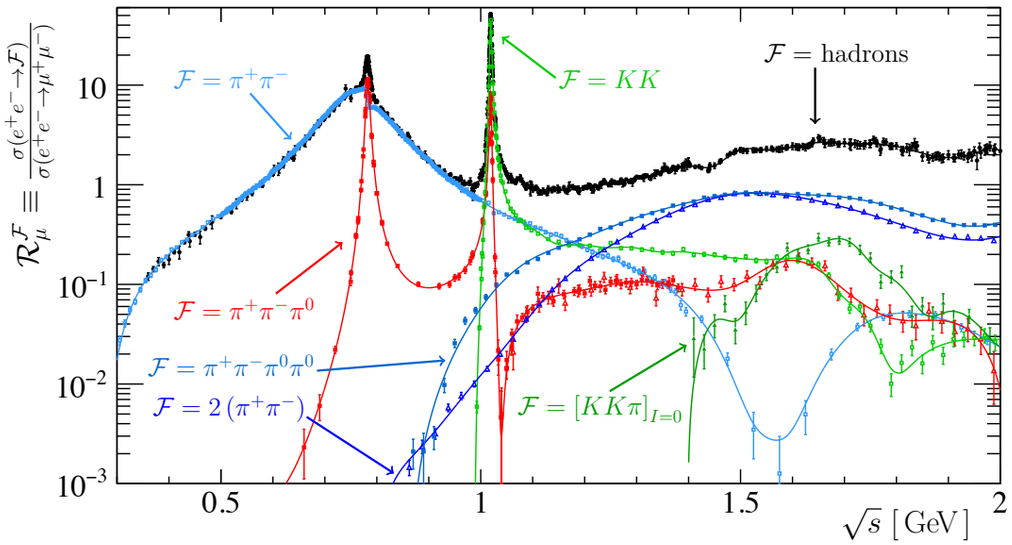
DASP Collab. (1979)

$$n_{N'} \simeq 0.08 \qquad n_{\pi'} \simeq 2.0$$

* neutral pion produced above ω-resonance

No corresponding SM value for ρ @ threshold

$$n_{V'} \simeq 0.01 - 1$$



Ilten, Soreq, Williams, Xue (2018)

PDG data

Dark Pions (ADM) Kamada, TK (2021)

Dark Pion Production

via gauged Wess-Zumino-Witten term

$$\mathcal{L}_{\rm eff.} \supset -\frac{N_C \alpha'}{24\pi f_{\pi'}} \pi' F'^{\mu\nu} \tilde{F}'_{\mu\nu} - \frac{i N_C e'}{12\pi^2 f_{\pi'}^3} \epsilon^{\mu\nu\rho\sigma} A'_\mu \partial_\nu \pi'^+ \partial_\rho \pi'^- \partial_\sigma \pi'$$

subdominant for $m_{A'} \ll f_{\pi'}$

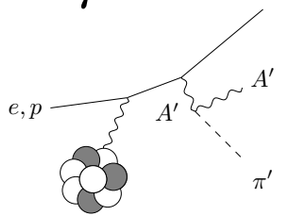
Energy injection $m^*_{A'}$ below $\Lambda'_{\rm QCD}$

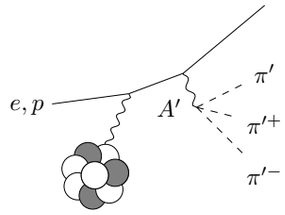
- light meson decay

$$\pi \to \gamma A' \to \gamma \pi'^0 A'$$

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

- bremsstrahlung





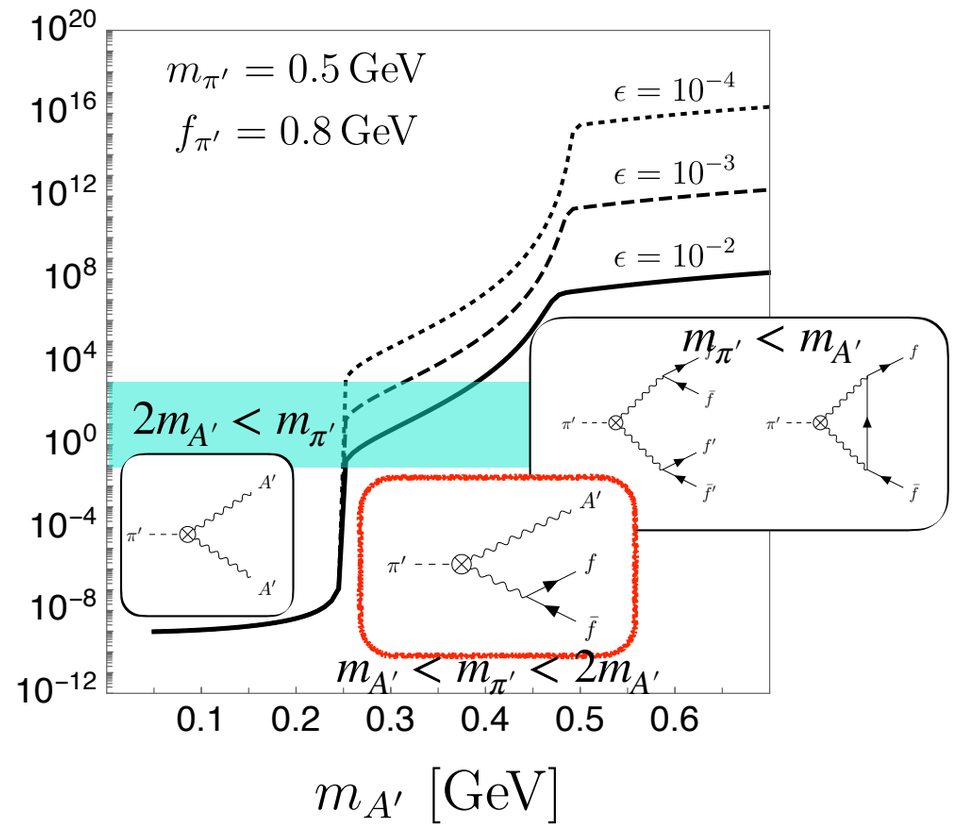
Dark Pion Decay

via gauged Wess-Zumino-Witten term

$$\mathcal{L}_{\rm eff.} \supset -\frac{N_C \alpha'}{24\pi f_{\pi'}} \pi' F'^{\mu\nu} \tilde{F}'_{\mu\nu}$$

- semi-SM decay: ~ O(1) m

$$c\tau_\pi(\pi'^3 \to A' + f\bar{f}) \simeq 0.3\,\mathrm{m} \left(\frac{1.0\ \mathrm{GeV}}{m_{A'}}\right)^3 \left(\frac{f_{\pi'}}{0.8\ \mathrm{GeV}}\right)^2 \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{0.1}{\alpha'}\right)^2$$



Visible Decay Searches for Dark Pions

Kamada, TK (2021)

$$m_{A'} < m_{\pi'} < 2m_{A'}$$

decay constant: $f_{\pi'} \simeq f_\pi \left(\frac{m_{N'}}{m_p} \right)$

visibly-decay dark photon

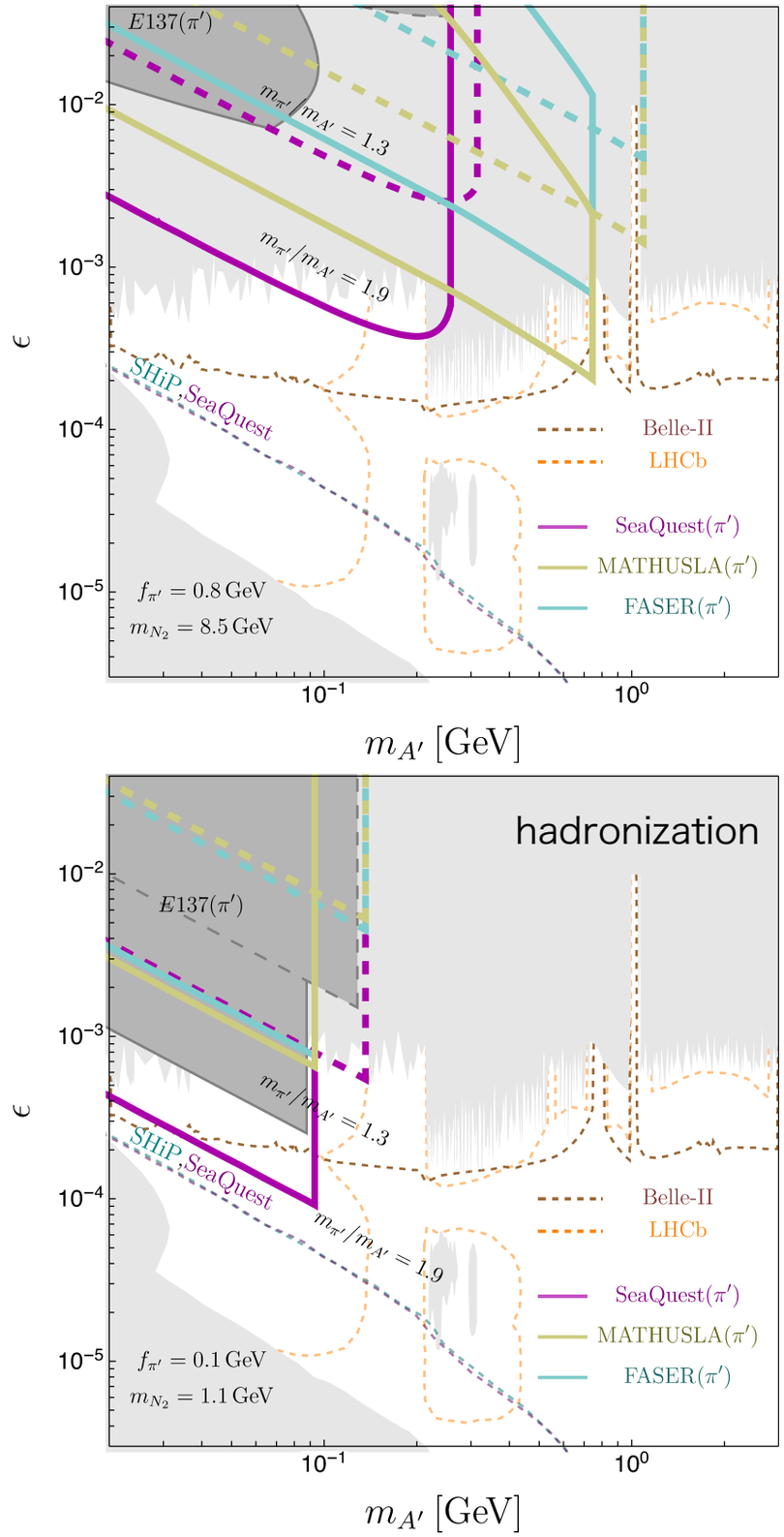
Belle-II, LHC-b (Prompt decay)
SHiP, DarkQuest (Fixed-target)

Existing Constraints:
BaBar/KLOE/LHC-b (Prompt decay)
E137/CHARM/νCal (Fixed-target)

dark pion decay

hadronization
LHC/DarkQuest for $m_{N'} \simeq m_\rho$

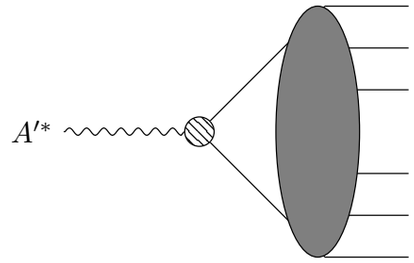
Sharp cuts:
hadronization (LHC) $6m_{\pi'} \simeq m_{N'}$
p bremsstrahlung $m_{\pi'} + m_{A'} \simeq m_\rho$



Dark Nucleon (ADM)

Kamada, TK (2021)

Dark Nucleon Production



hadronization just above nucleon-pair prod. threshold

$$N_{N_1} \simeq \frac{n_{N'}\alpha'}{\pi}\left(\sum Q_{q'}^2\right) N_{A'}\Big|_{m_{A'}^*=\sqrt{10}m_{N'}}$$

hadron multiplicity $n_{N'} \simeq 0.08$

SM value @ J/psi threshold

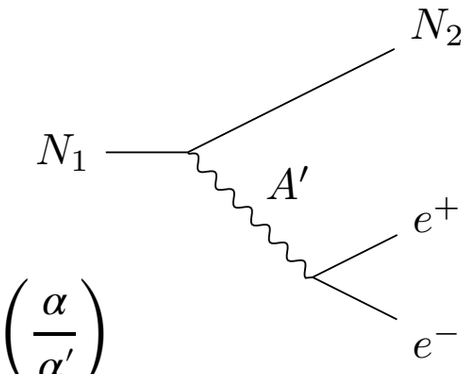
DASP Collab. (1979)

Dark Nucleon Transition

- dark nucleon mixing via $U(1)_D$ breaking

off-shell dark photon when $\Delta_N m_{N_2} < m_{A'}$

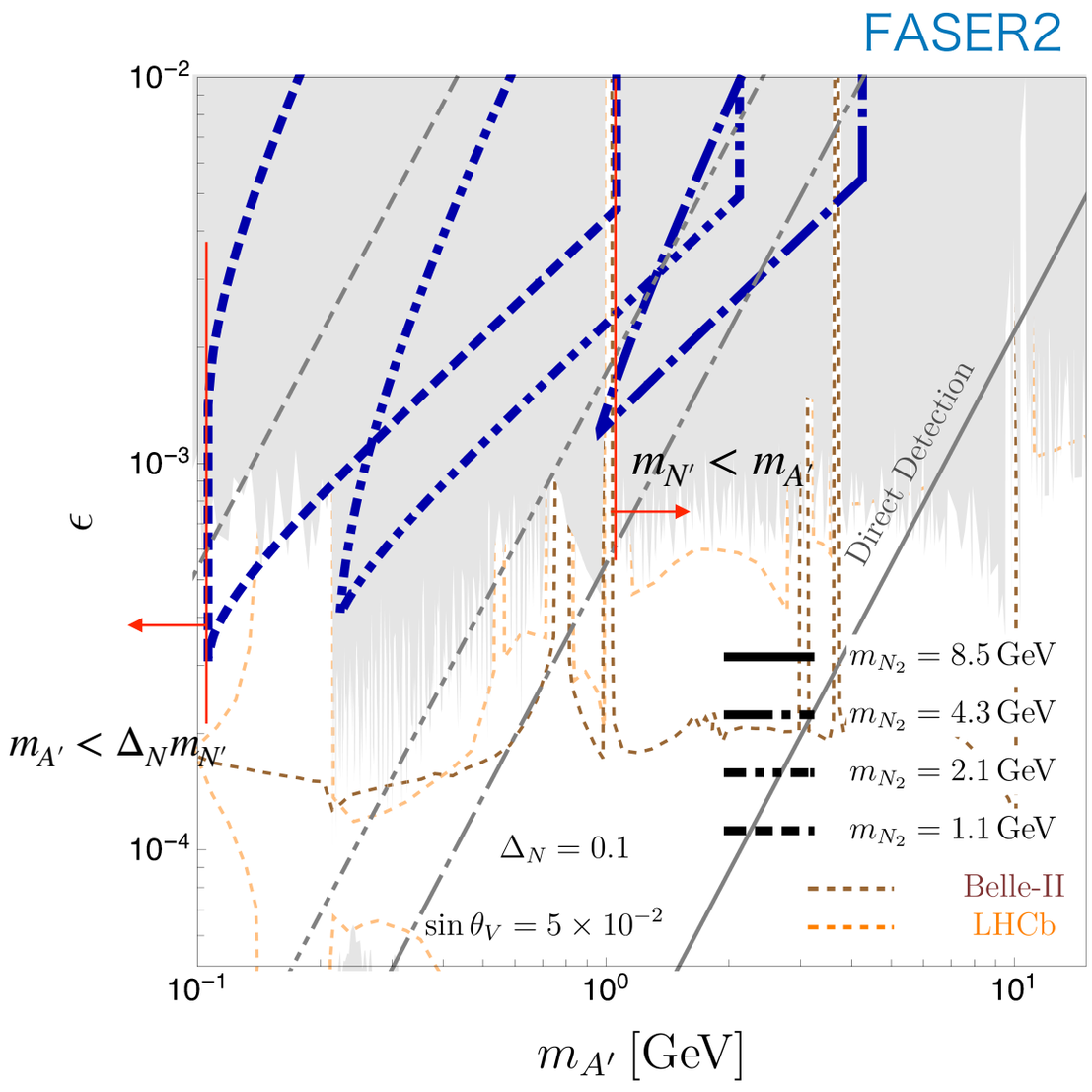
$$\Gamma(N_1 \to N_2 + f\bar{f}) \simeq \frac{\epsilon^2\alpha'\alpha Q_f^2}{15\pi}\sin^2 2\theta_V \frac{m_{N_2}^5 \Delta_N^5}{m_{A'}^4} \qquad m_f = 0 \text{ limit}$$

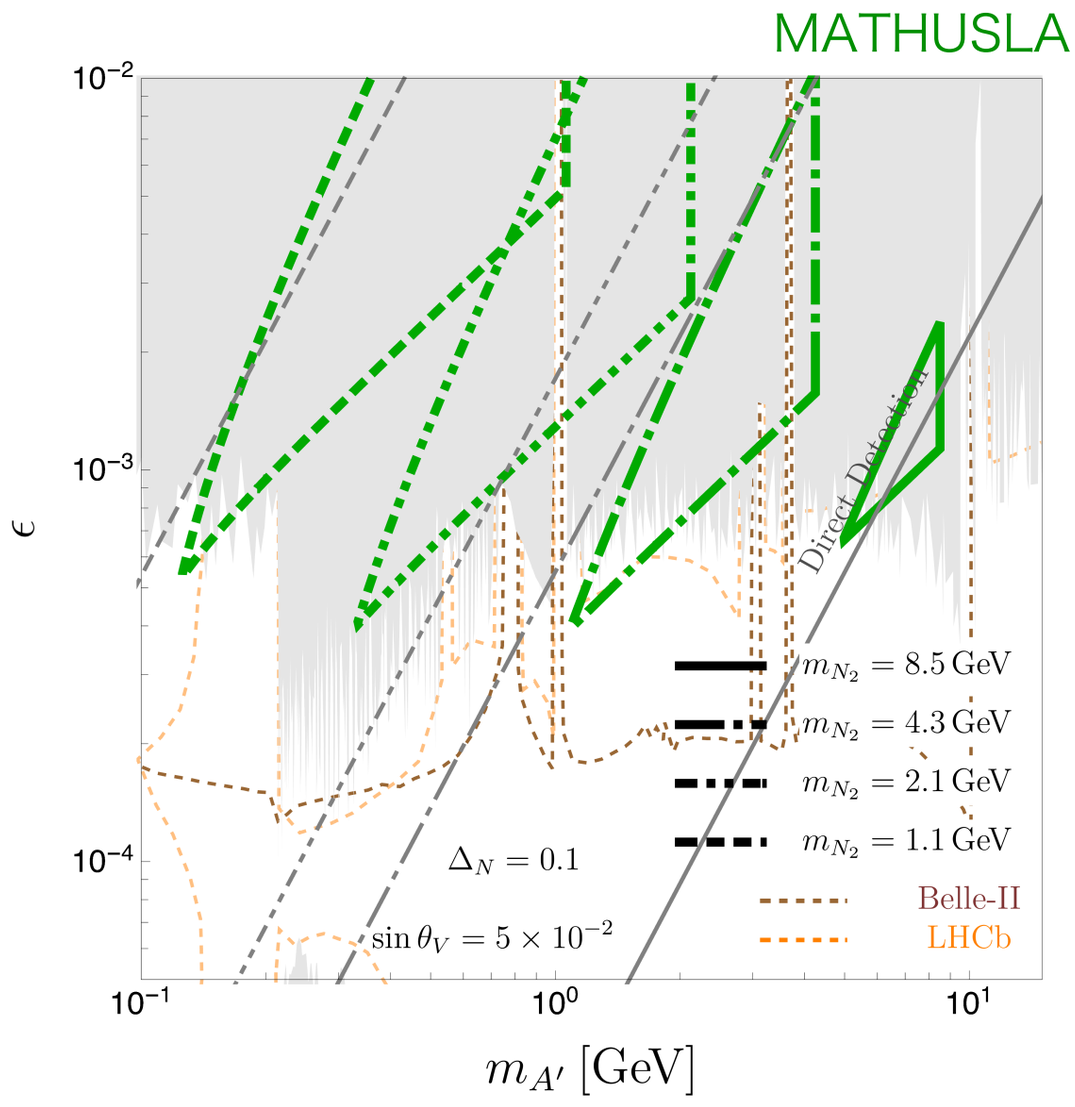


$$c\tau(N_1 \to N_2 + f\bar{f}) \simeq 3\,\mathrm{m}\left(\frac{0.1}{\Delta_N}\right)^5\left(\frac{8.5\ \mathrm{GeV}}{m_{N_2}}\right)^5\left(\frac{m_{A'}}{3\ \mathrm{GeV}}\right)^4\left(\frac{10^{-2}}{\sin 2\theta_V}\right)^2\left(\frac{5\times10^{-3}}{\epsilon}\right)^2\left(\frac{\alpha}{\alpha'}\right)$$

Visible Decay Searches for Dark Nucleons

Kamada, TK (2021)





dark n-like nucleon = DM

DM-SM scattering

- kinetic mixing
- n'-p' mixing / $U(1)_D$ violation

Direct detection

PandaX-II (2018,2021)
DarkSide-50 (2018)
CRESST-III (2019)

Dark Vector Mesons (ADM/SIMP)

TK, Yuan (2023)

Dark V' Production

production through gauged Wess-Zumino-Witten term

$$\mathscr{L}_{\rm WZW} \supset -\frac{3e'g}{8\pi^2 f_{\pi'}}\epsilon^{\mu\nu\rho\sigma}\partial_\mu A'_\nu \mathrm{Tr}\left(\{Q, V'_\rho\}\partial_\sigma \pi'\right)$$

Different charge matrices for different models

$Q_{\rm SIMP} = \mathrm{diag}(1\,, -1\,, -1)\,,$

- no anomalous decay $Q^2 \propto 1$ (stable dark pion)

$Q_{\rm ADM} = \frac{1}{3}\mathrm{diag}(2\,, -1\,, -1)\,,$

- anomalous decay
- alleviate cosmological problems

Dark V' Decay

decay through gauged WZW term (charged V')/kinetic mixing with A' (neutral V')

leaves visible signals for $m_{V'} < m_{\pi'} + m_{A'}$

$$\mathscr{L} \supset -\frac{e'}{g}\mathrm{Tr}(QV'_{\mu\nu})F'^{\mu\nu}$$

$$c\tau(V'^a \to \ell^+\ell^-) \simeq \mathcal{O}(10^{-5})\,[\mathrm{m}]\left(\frac{0.01}{\alpha'}\right)\left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{m_{\pi'}/f_{\pi'}}{3}\right)^2\left(\frac{500\,\mathrm{MeV}}{m_{V'}}\right),$$

$$c\tau(V'^a \to \pi'^b\ell^+\ell^-) \simeq \mathcal{O}(1)\,[\mathrm{m}]\left(\frac{0.01}{\alpha'}\right)\left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{3}{m_{\pi'}/f_{\pi'}}\right)^4\left(\frac{500\,\mathrm{MeV}}{m_{V'}}\right)$$

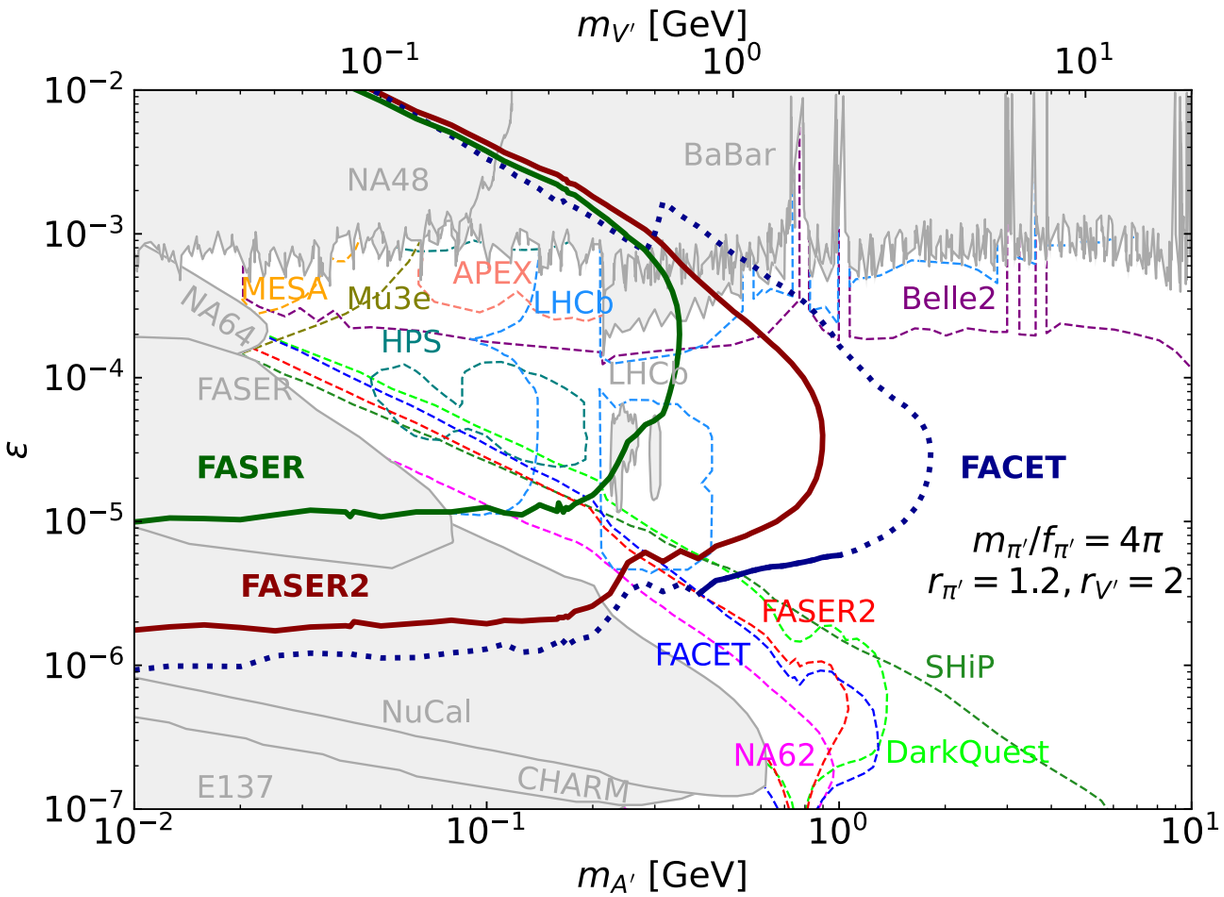
Visible Decay Searches for Dark Vector Mesons

TK, Yuan (2023)

FORESEE package

Kling, Trojanowski (2021)

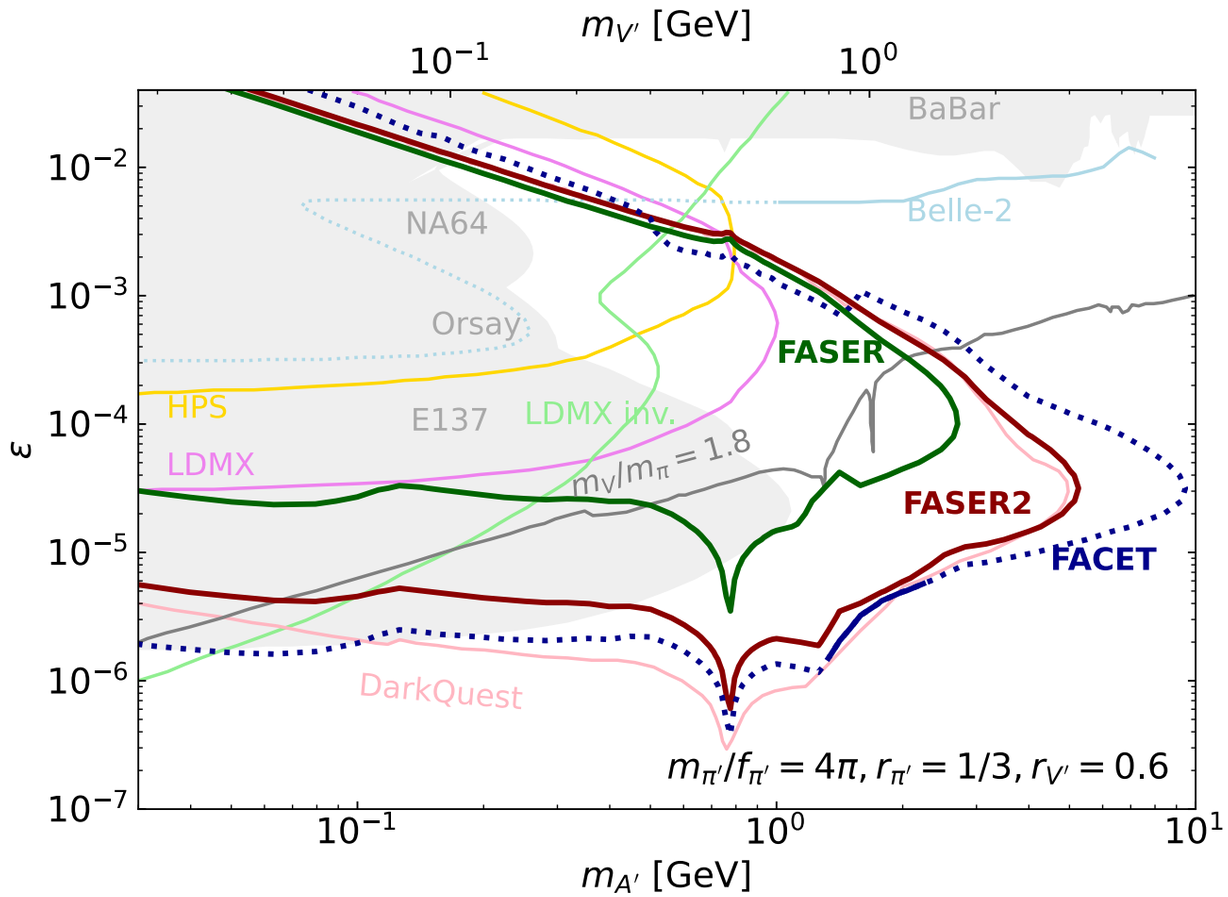
off-shell production (Composite ADM scenario)



(solid/dotted) V' visible decay searches

(dashed) A' visible decay searches

on-shell production (dark-pion DM scenario)



(dark colors) V' visible decay searches

(light colors) A' invisible decay searches

Summary and Discussions

Confining Dark Sector searches with Lifetime frontier

- visible signals from dark hadrons via dark photon
- dark nucleon dark matter/dark pion dark matter
- LHC lifetime frontier (FASER/FACET/MATHUSLA...)
  Fixed-target Experiments (DarkQuest...)

Dark Hadrons with dark photon @ LLP searches

✓ dark hadron processes
- N' transition ($\Delta m_{N'} < m_{A'}$)
- π' decay ($m_{A'} < m_{\pi'} < 2m_{A'}$)
- V' decay ($m_{\pi'} < m_{V'} < 2m_{\pi'}$)

✓ A' decay signals
- visible decay (ADM)/ invisible decay (dark pion DM)

Backup Slides

Asymmetries

If the asymmetry is fully shared b/w dark and visible sectors

$$m_{\rm DM} = \frac{\Omega_{\rm DM}}{\Omega_B} m_B \frac{\eta_B}{\eta_{\rm DM}} \simeq 5{\rm GeV} \frac{\eta_B}{\eta_{\rm DM}}$$

- chemical equilibrium
- conservation of charges (B-L, Q)
- rapid sphaleron & top decoupled before EWSB

$$\frac{\eta_B}{\eta_{\rm SM}} = \frac{30}{97}, \qquad \frac{\eta_{\rm SM}}{\eta_{\rm DM}} = \frac{237}{44 n_{g'}}$$

Weinberg, **Cosmology**
Ibe, Matsumoto, Yanagida (2011)
Fukuda, Matsumoto, Mukhopadhyay (2015)

$n_{g'}$: # of generations, $U', \overline{U}', D', \overline{D}'$

the ADM mass

$$m_{\rm DM} \simeq \frac{8.5}{n_{g'}} {\rm GeV}$$

LLP Constraints/Sensitivities

The number of signals

$$N_{\rm signal} \simeq N_{\rm LLP} \times ({\rm effic.})\,,$$

$$({\rm effic.}) \simeq \frac{1}{N_{\rm event}} \sum_{\rm event} (e^{-\frac{r_{\rm min}}{d}} - e^{-\frac{r_{\rm max}}{d}}) A\,.$$

geometric efficiency

energy threshold

decay length $d = c\tau\beta\gamma$

We formulate approximate sensitivity curves instead of generating events by MC from existing sensitivity curves (A', iDM, ...) Kamada, TK (2021)

Upper bound on decay rate

decay before detector: ($d \ll r_{\rm min}$)

$$\frac{c\tau_{\rm LLP} p_{\rm max} m_{\rm LLP}^{-1}}{r_{\rm min}} \ln \frac{N_{\rm LLP} A}{N_{\rm signal}} \simeq 1$$

$$\frac{d_0}{r_{\rm min}} \ln \frac{N_\chi^0 A_0}{N_{\rm signal}} \simeq 1$$

reference

$$\ln \frac{N_{\rm LLP} A}{N_\chi^0 A_0} + \frac{r_{\rm min}}{d_0} = \frac{r_{\rm min}}{c\tau_{\rm LLP} p_{\rm max} m_{\rm LLP}^{-1}}$$

Lower bound on decay rate

rarely decays inside detector: ($d \gg r_{\rm max}$)

$$\frac{r_{\rm max} - r_{\rm min}}{c\tau_{\rm LLP} p_{\rm min} m_{\rm LLP}^{-1}} \frac{N_{\rm LLP}}{N_{\rm signal}} A \simeq 1$$

$$\frac{r_{\rm max} - r_{\rm min}}{d_0} \frac{N_\chi^0}{N_{\rm signal}} A_0 \simeq 1$$

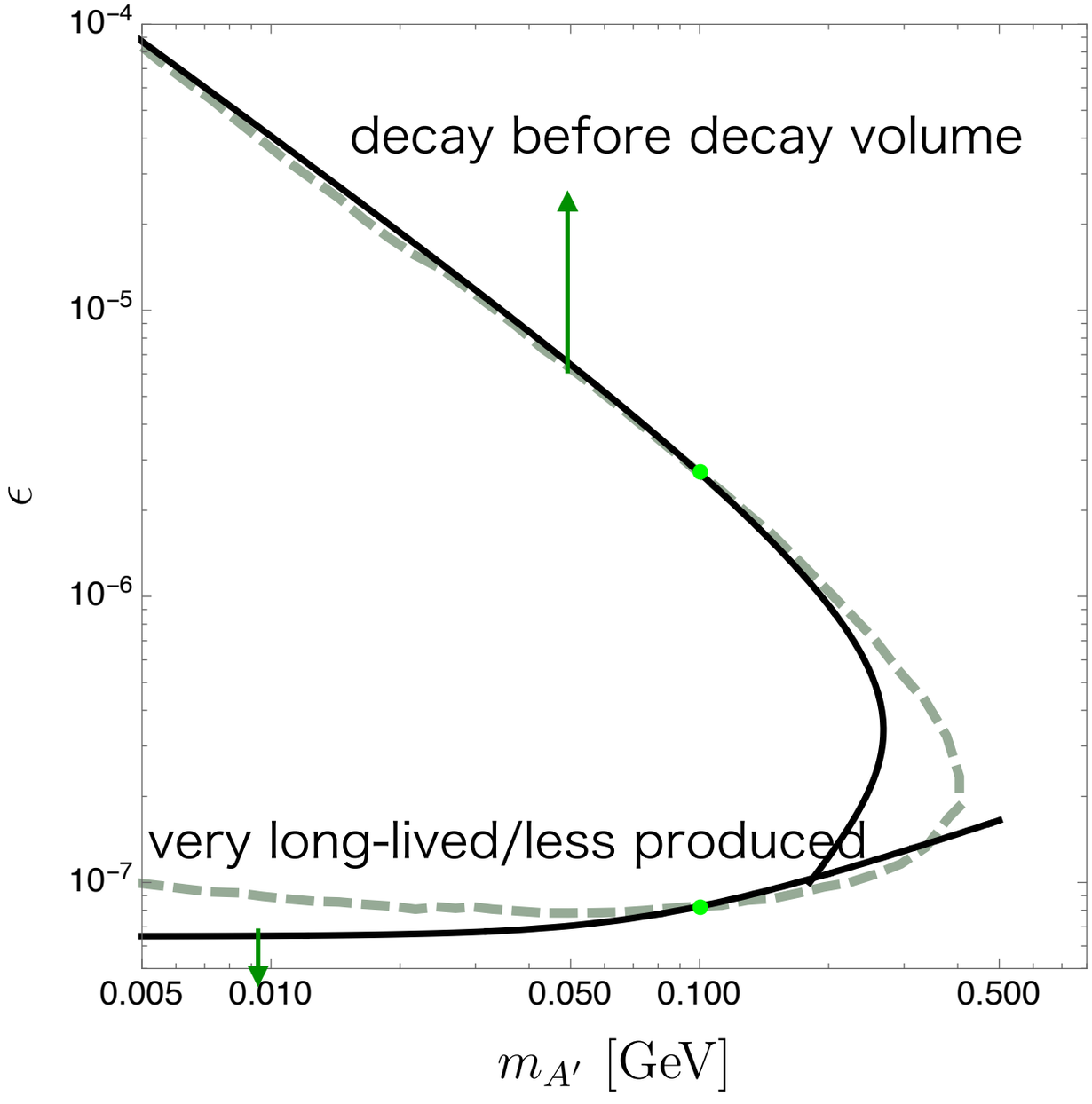
reference

$$\frac{r_{\rm max} - r_{\rm min}}{c\tau_{\rm LLP} p_{N_1:{\rm min}} m_{\rm LLP}^{-1}} \frac{N_{\rm LLP}}{N_\chi^0} \frac{A}{A_0} = \frac{r_{\rm max} - r_{\rm min}}{d_0}$$

Validity of Fitting approx. functions

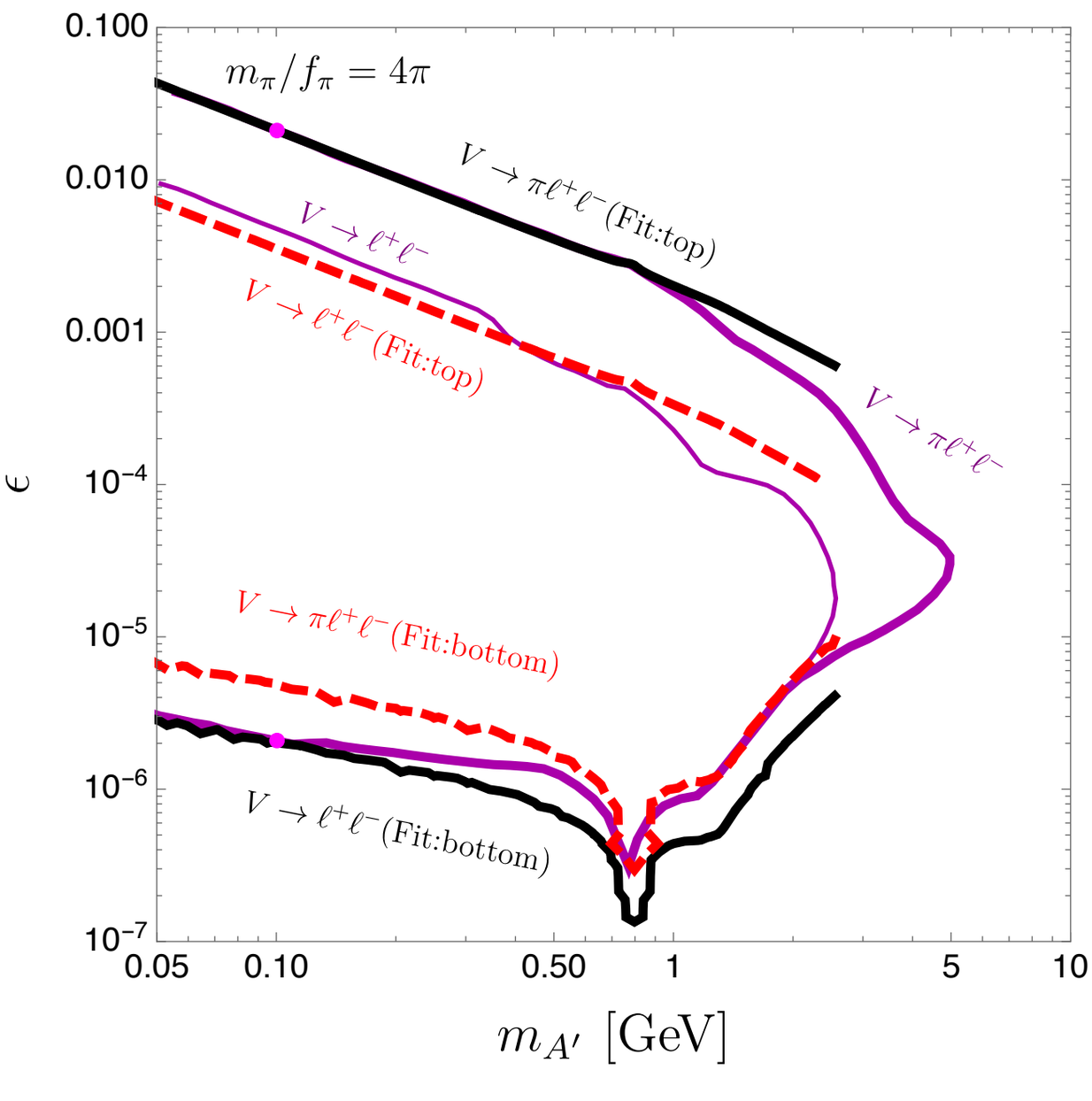
E137 dark photon searches

Bjorken, Essig, Schuster, Toro (2009)



SeaQuest dark rho meson searches

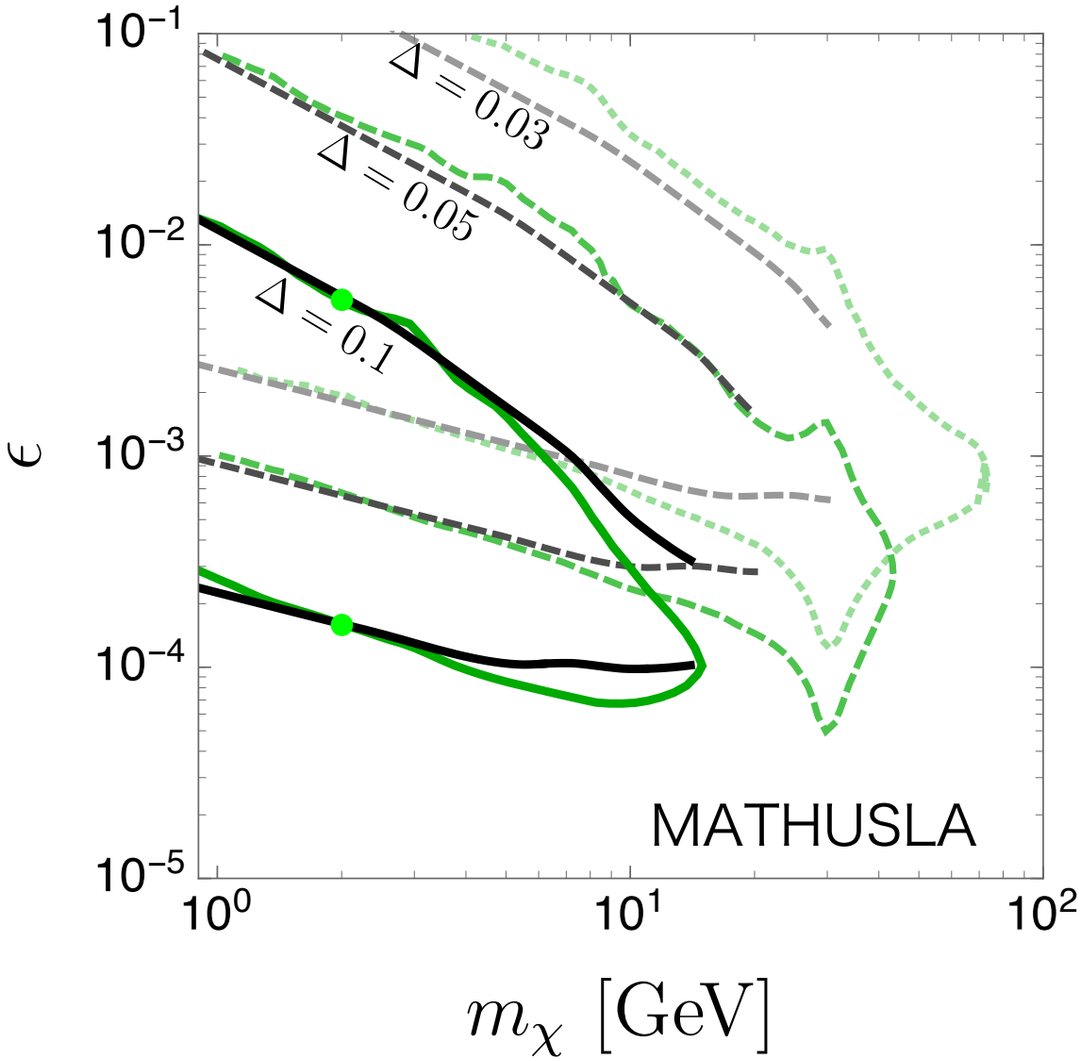
Berlin, Blinov, Gori, Schuster, Toro (2018)

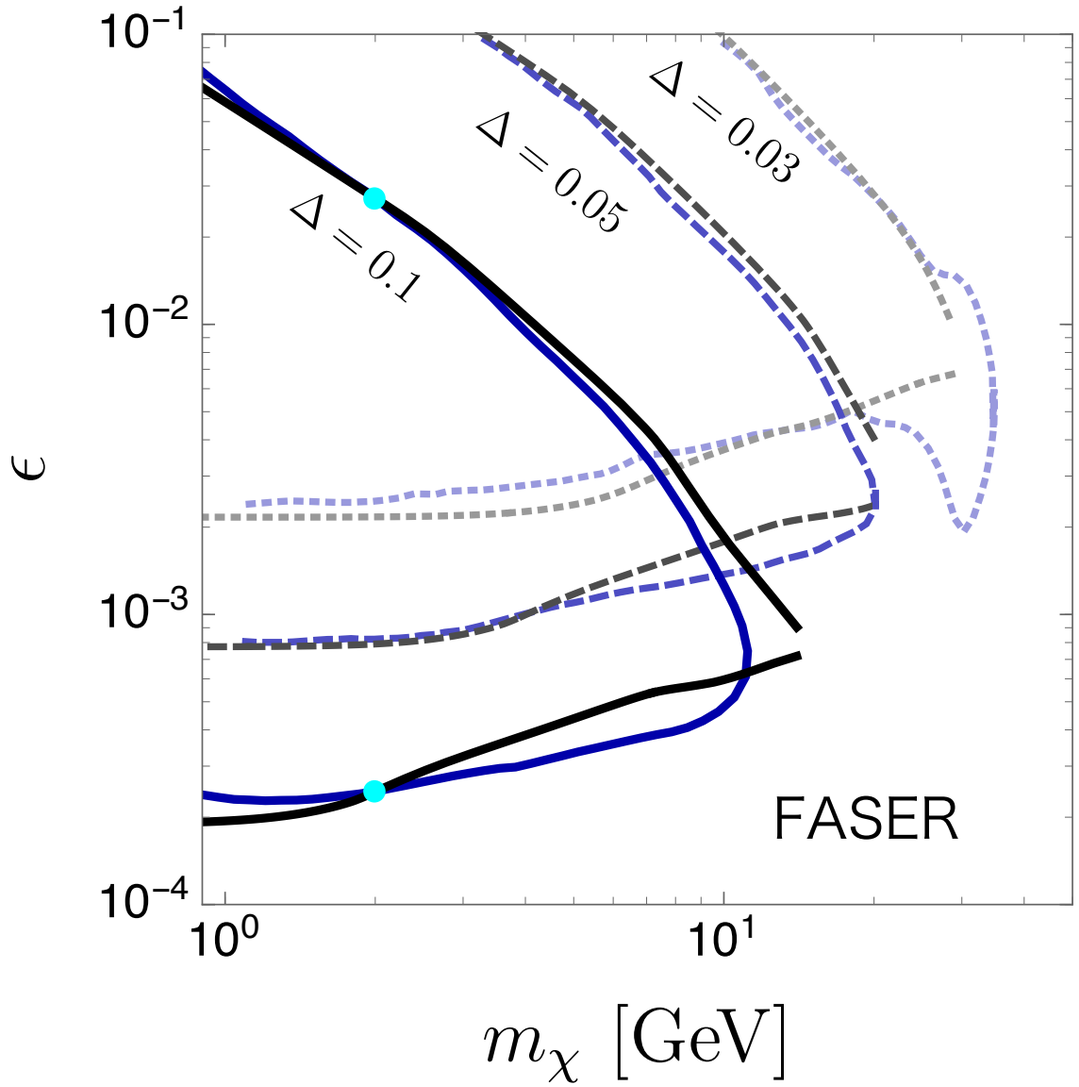


Validity of Fitting approx. functions

iDM searches at LHC frontier

Berlin, Kling (2018)





Intermediate-scale Portal interactions

$\overline{N}_R$ (SM singlet) couples to dark sector

$$\mathcal{L} = \frac{1}{M'^2}\overline{U}'\overline{D}'\overline{D}'\overline{N}_R + y_N L H \overline{N}_R + \frac{1}{2}M_R \overline{N}_R \overline{N}_R + \text{h.c.}$$

$$\to \frac{y_N^2}{M_R^2}(LH)^2 + \text{h.c.}$$ neutrino mass

$$+ \frac{y_N}{M'^2 M_R}\overline{U}'\overline{D}'\overline{D}'(LH) + \text{h.c.}$$ portal interaction

$$+ \frac{1}{2M'^4 M_R}(\overline{U}'\overline{D}'\overline{D}')^2 + \text{h.c.}$$ DM oscillation

- The portal interaction connects two sectors until $T \sim T_D \sim M' \left(M'/M_{\rm Pl}\right)^{\frac{1}{3}}$.
- DM decays through the portal interaction: SK constraint on $\bar{\nu}$ signal

  -> $M' \gtrsim 10^{8.5}$ GeV Fukuda, Matsumoto, Mukhopadhyay (2014)
- Majorana mass for dark neutron: leads DM oscillation

  indirect detection constraint

  Buckley, Profumo (2011)

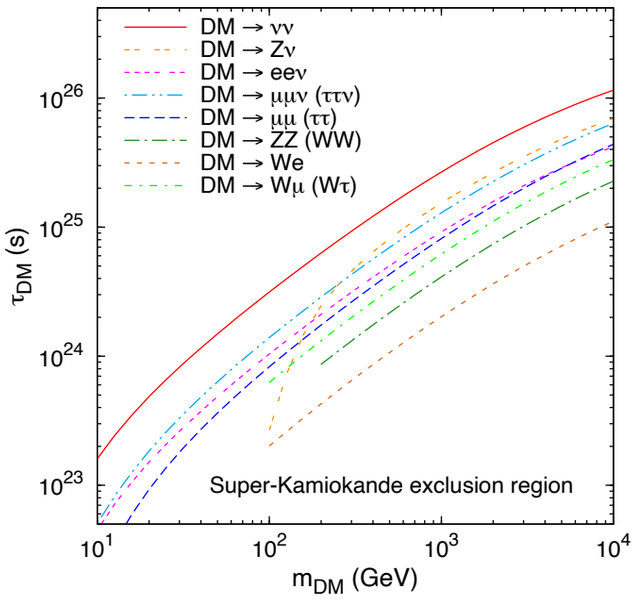
  Ibe, Kobayashi, Nagai, Nakano (2019)

Signals from Intermediate-scale Portal

indirect constraints on M_R

- $\bar{\nu}$ Signal from DM Decay: $n' \to \bar{\nu} + \pi'^0$

Covi, Grefe, Ibarra, Tran (2010)
Feldstein, Fitzpatrick (2010)
Fukuda, Matsumoto, Mukhopadhyay (2014)



$$\frac{y_N}{M'^2 M_R}\overline{U}'\overline{D}'\overline{D}'(LH) + \text{h.c.}$$

$$\tau_{n'} \simeq 10^{17}\text{years}\left(\frac{(M'^2 M_R)^{1/3}}{10^9\ \text{GeV}}\right)^6\left(\frac{10\ \text{GeV}}{m_{n'}}\right)^5$$

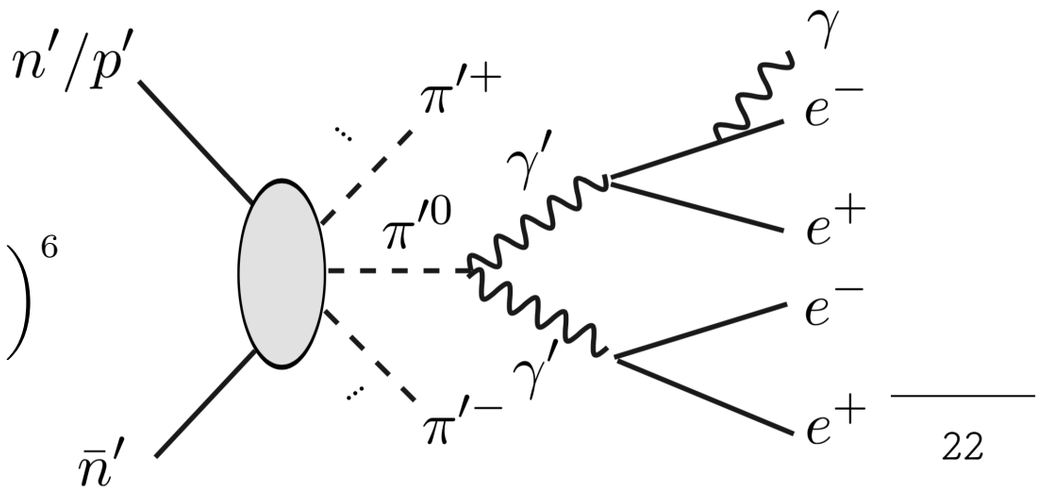
from SK ν-flux measurement: $(M'^2 M_R)^{1/3} \gtrsim 10^{8.5}\ \text{GeV}$

- DM-$\overline{\text{DM}}$ annihilation

Ibe, Kobayashi, Nagai, Nakano (2019)

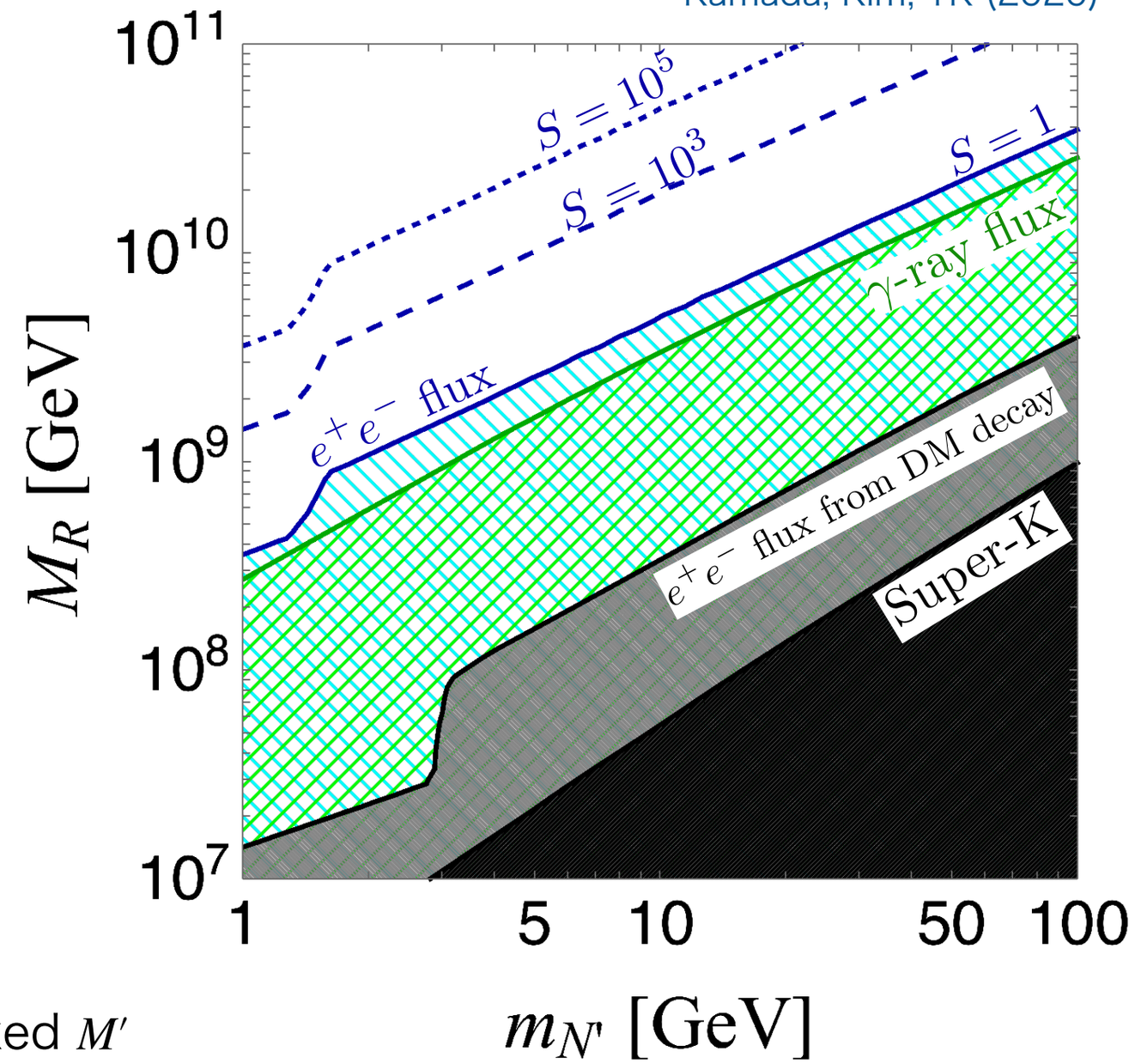
$$\frac{1}{2M'^4 M_R}(\overline{U}'\overline{D}'\overline{D}')^2 + \text{h.c.}$$

$$\tau_{n'\text{-}\overline{n}'} \simeq 10^{14}\text{years}\left(\frac{M_R}{10^9\ \text{GeV}}\right)\left(\frac{M'}{3\times 10^9\ \text{GeV}}\right)^4\left(\frac{10\ \text{GeV}}{m_{n'}}\right)^6$$



Bounds on M_R

Kamada, Kim, TK (2020)



Fixed M'

S : Sommerfeld factor

γ-ray flux from MW's dSphs

Fermi-LAT Collab., PRL (2015)

$\bar{\nu}$-flux measurement (super-K)

e^+-e^- flux (annihilation $\langle\sigma v\rangle$)

$m_{N'} \gtrsim 1.5$ GeV @ AMS-02

$m_{N'} \lesssim 1.5$ GeV @ Voyager-1

Stone, et al, Sience (2013)
AMS Collab., PRL (2014)

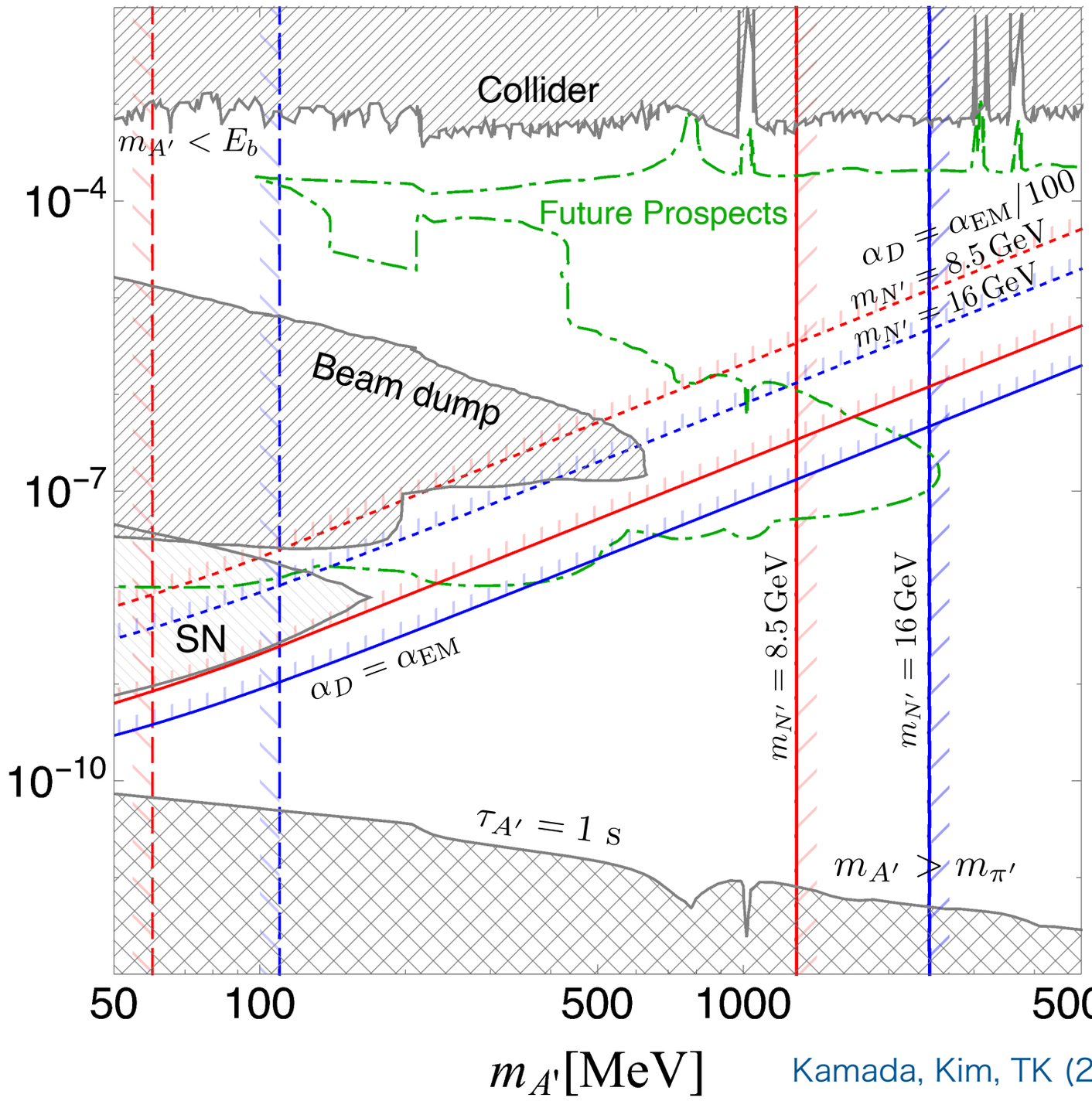
e^+-e^- flux from dark meson ($\tau_{\rm DM}$)

$m_{N'} \gtrsim 3.0$ GeV @ AMS-02

$m_{N'} \lesssim 3.0$ GeV @ Voyager-1

Boudaud, Lavalle, Salati (2016)

Bounds on Dark Photon Parameters



Kamada, Kim, TK (2020)

direct detection experiment

Panda-X (54 ton×day)

$\sigma > 10^{-44}\ \mathrm{cm}^2$ 1802.06912

DM ratio $p' : n' = 1 : 1$

Dark photon:

lightest in dark sector

Collider&Beam-dump

Supernova 1987A

A' recoupling after ν decoupling

reheats only γ, e^+, e^-

- change T_ν/T_γ i.e. N_{eff}

roughly $\tau_{A'} \lesssim 1\,\mathrm{s}$

Velocity dependence

Effective range theory

Scattering cross section

$$k = \mu v_{\rm rel} = \frac{1}{2} m_{\rm DM} v_{\rm rel}$$

$$\sigma = \sum_\ell \sigma_\ell = \sum_\ell \frac{4\pi}{k^2}(2\ell+1)\sin^2\delta_\ell$$

Low-energy ($k^2 \to 0$) expansion of phase shift δ_0

H. A. Bethe (1949)
J. M. Blatt, J. D. Jackson (1949)

S-wave ($\ell = 0$) $\quad k\cot\delta_0 \to -\frac{1}{a} + \frac{r_e}{2}k^2$

See also Chu, Garcia-Cely, Murayama (2019)

characterized by scattering length a and effective range r_e

Cross section

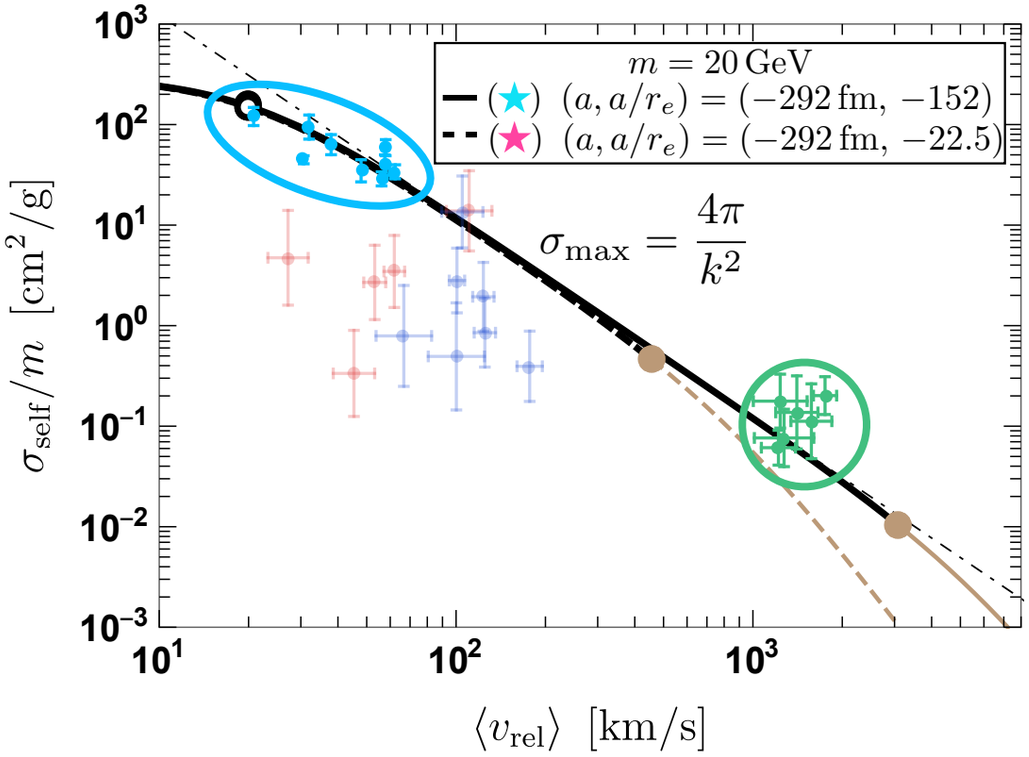
$$\sigma = \frac{4\pi a^2}{1 + k^2(a^2 - a r_e) + \frac{1}{4}a^2 r_e^2 k^4}$$

$|a/r_e| \gg 1$: strong velocity dependence $\quad \sigma_{\rm max} = \frac{4\pi}{k^2}$ $\quad$ for $|a|^{-2} \ll k^2 \ll |r_e|^{-2}$

$k \to 0$: low-energy limit $\quad \sigma = 4\pi a^2$

v dependence of self-scattering

Strong velocity dependence: maximally SIDM



Kamada, Kim, TK (2020)

Galaxy clusters: $v \simeq 10^3\,\mathrm{km/s}$

To form core of galaxy clusters
To avoid the constraints from galaxy lensing

MW's dSph: $v \simeq 30\,\mathrm{km/s}$

Draco (cuspy): $\sigma/m < 0.57\,\mathrm{cm}^2/\mathrm{g}$

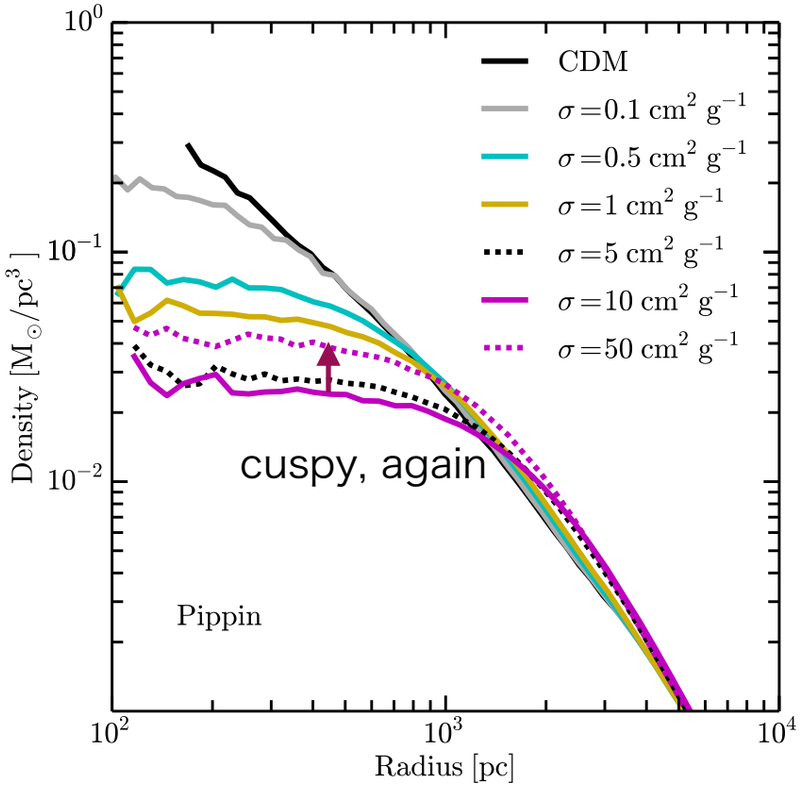
Read, Walker, Steger (2018)

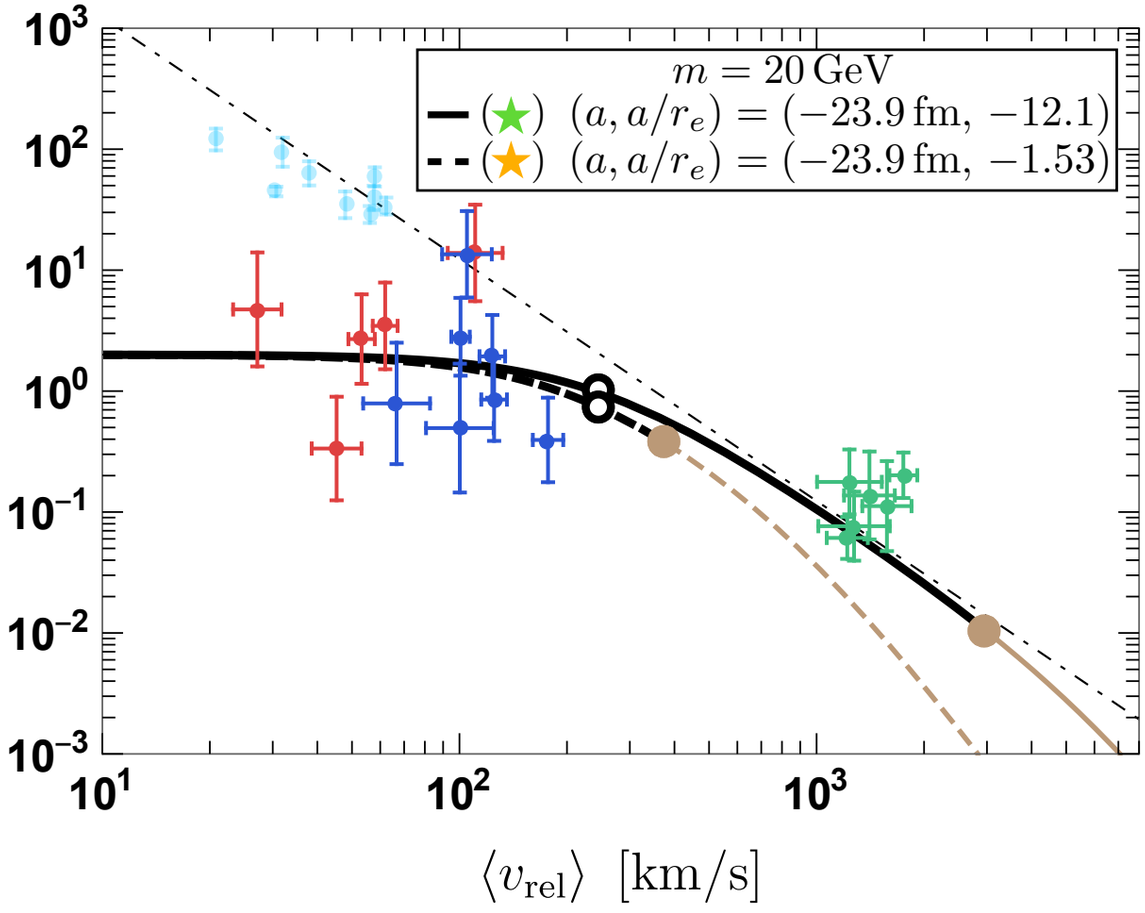
Core formation or Core contraction phase?

MW's dSph (core contraction)

$\sigma/m \simeq 30\text{-}200\,\mathrm{cm}^2/\mathrm{g}$

Correa (2020)





Field dwarf galaxies

Light Surface Brightness Galaxies

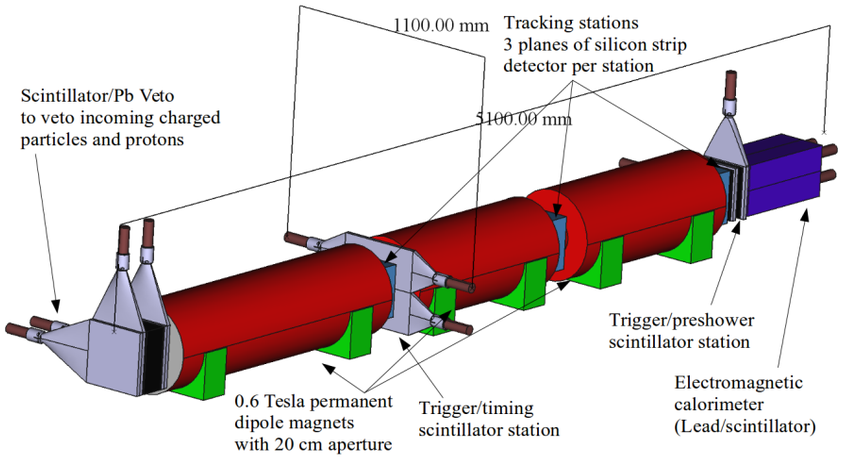
Observed diversity of galaxy rotation curve

Kamada, Kaplinghat, Pace, Yu (2016)

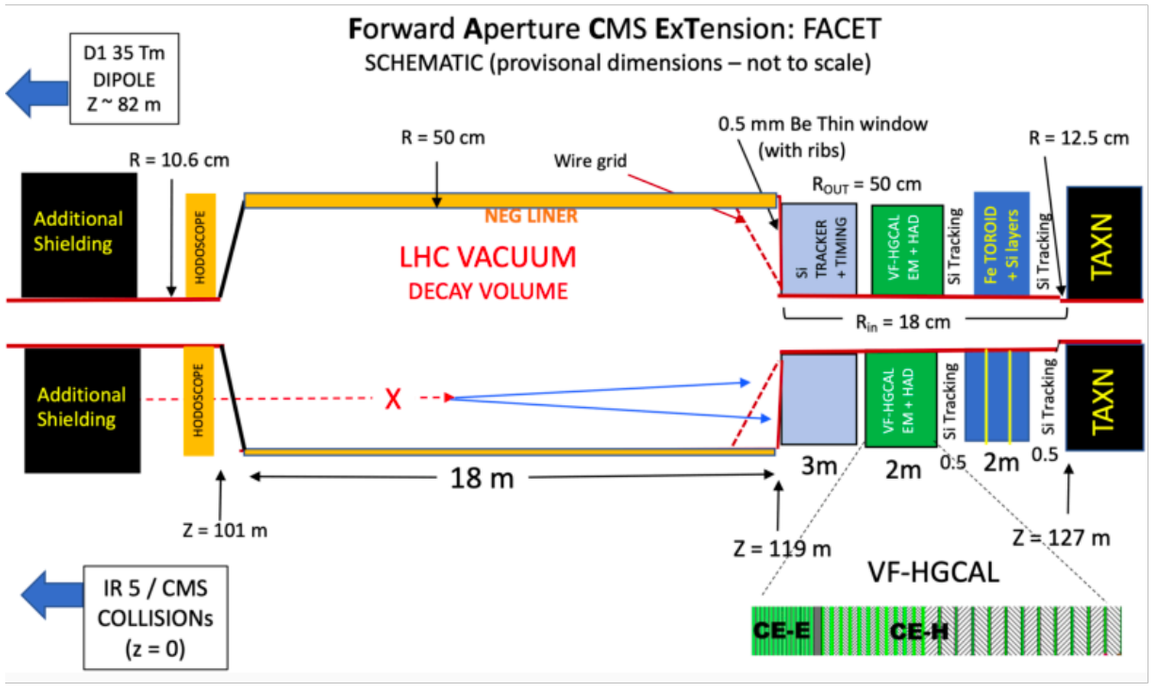
$\sigma/m \simeq 1\,\mathrm{cm}^2/\mathrm{g}$ for $v \simeq 100\,\mathrm{km/s}$

LHC Forward Detector

FASER2



FACET



Detector	Distance	Length	Radius	Threshold	Luminosity
FASER	480 m	1.5 m	10 cm	100 GeV	$150\,\mathrm{fb}^{-1}$
FASER2	480 m	5 m	1 m	100 GeV	$3\,\mathrm{ab}^{-1}$
FACET	120 m	18 m	$0.18\mathrm{m} < R < 0.5\mathrm{m}$	10 GeV	$3\,\mathrm{ab}^{-1}$

minimum E for e^+e^-

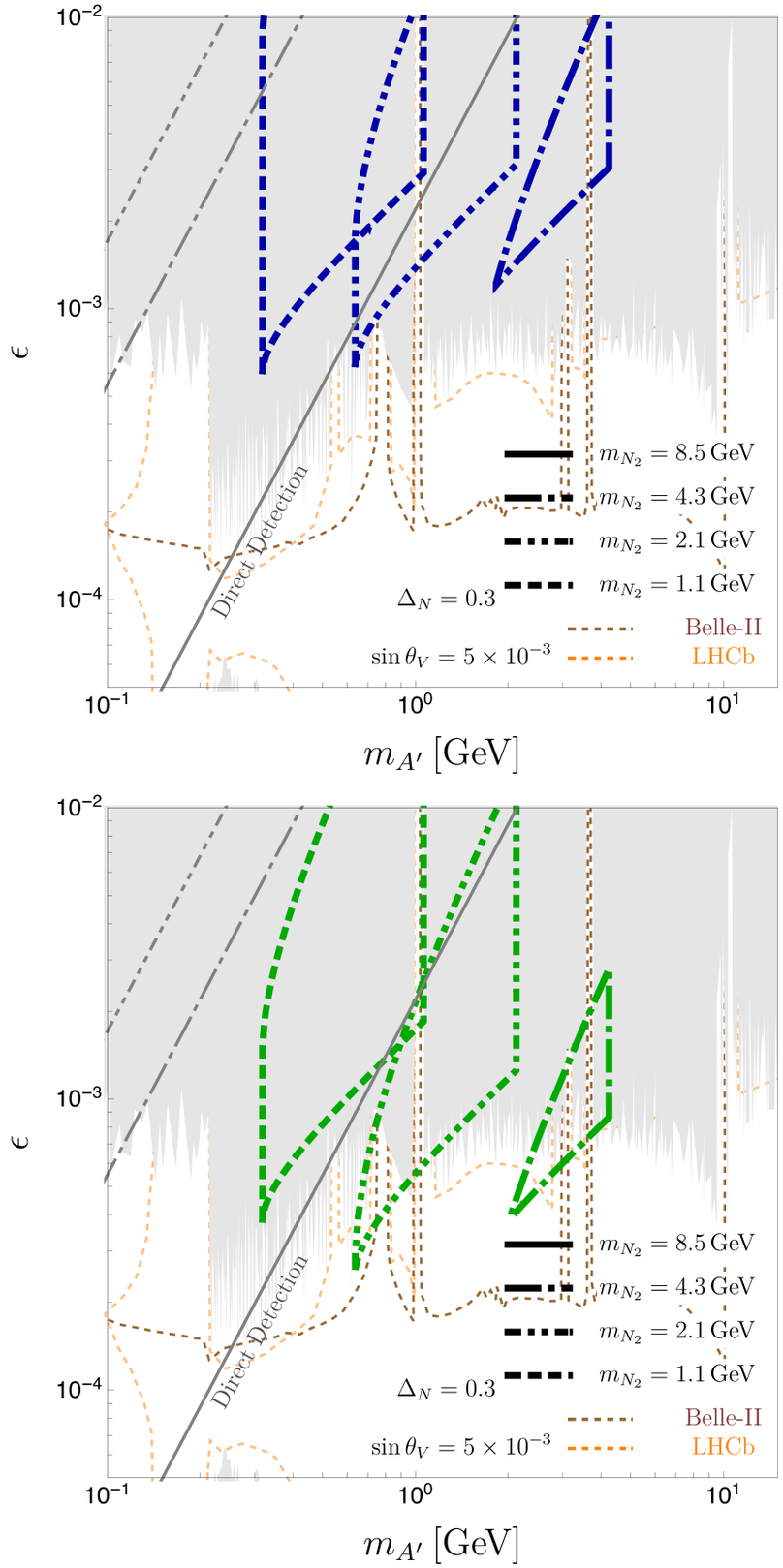
Further investigation might be necessary for FACET

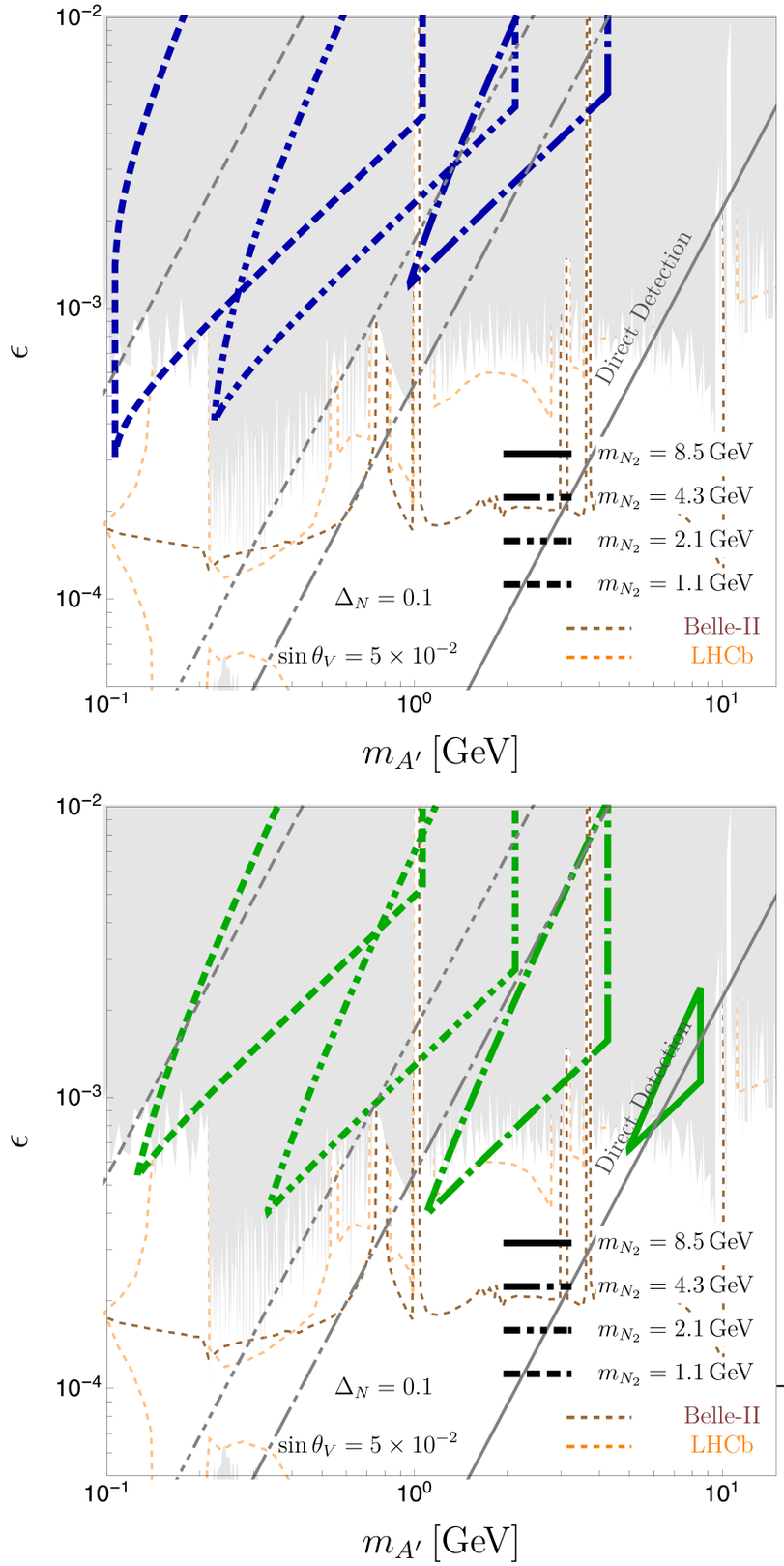
(Bkg events estimation)

FASER case: 0 Bkg is supported by the first run

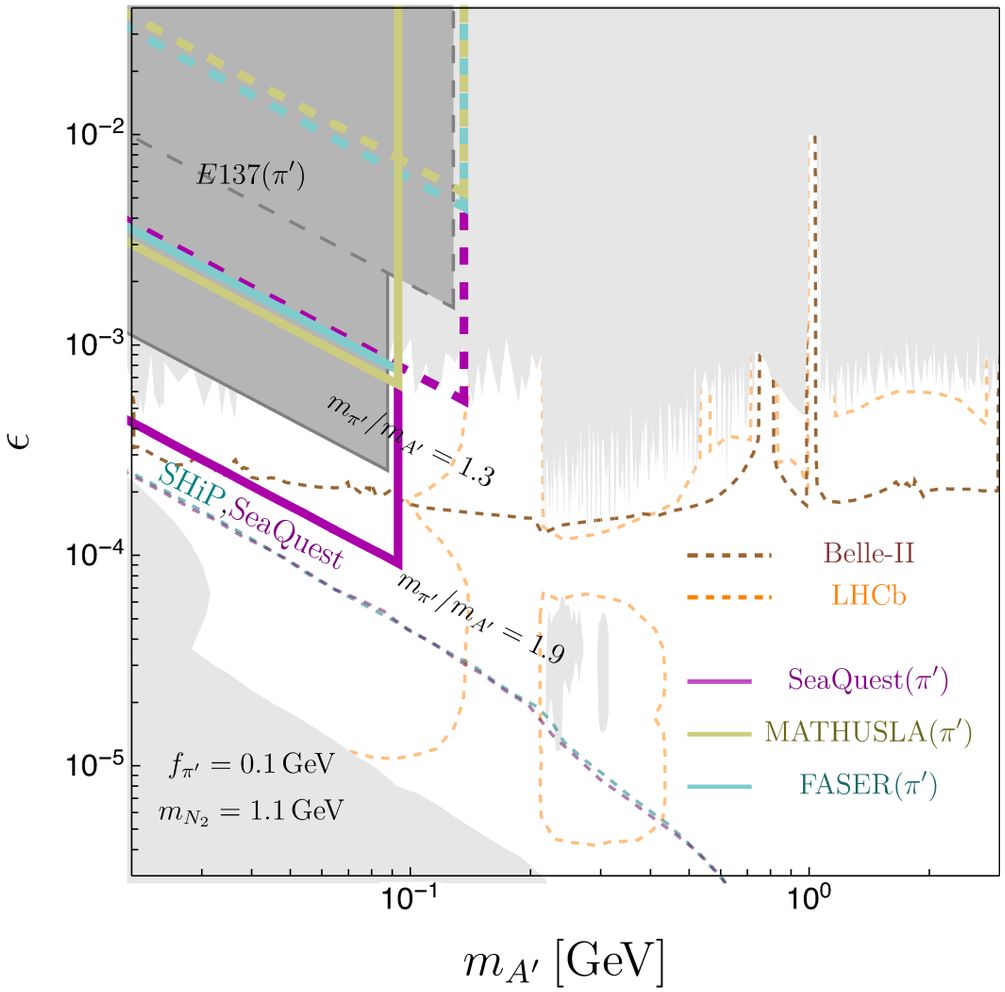
Different Parameter Choices

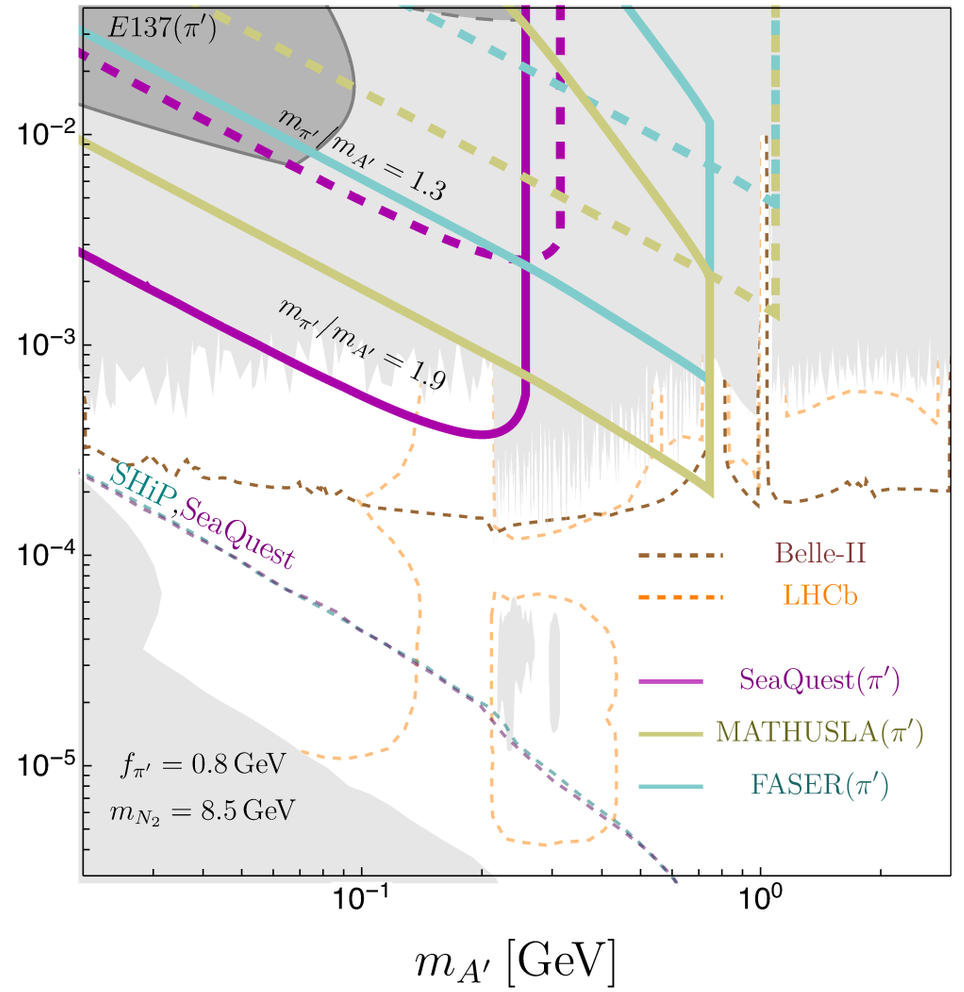
Dark nucleon transition





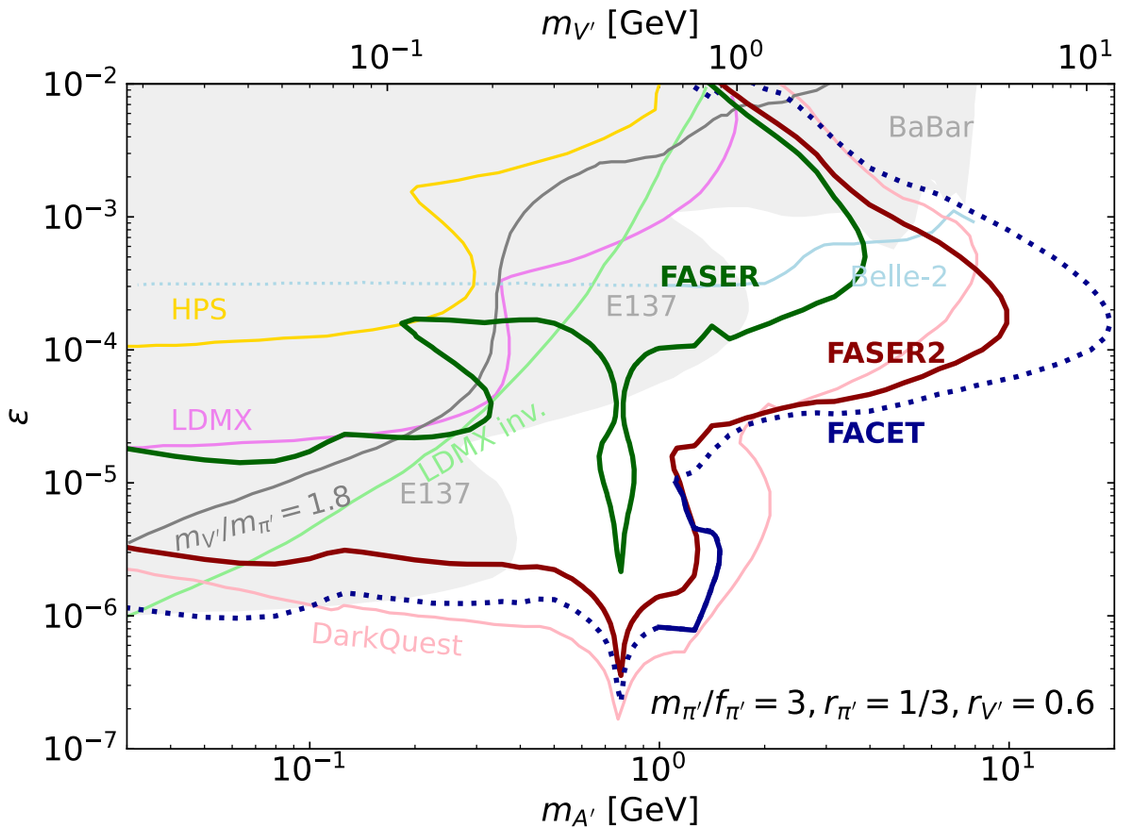
Dark Pion Decay

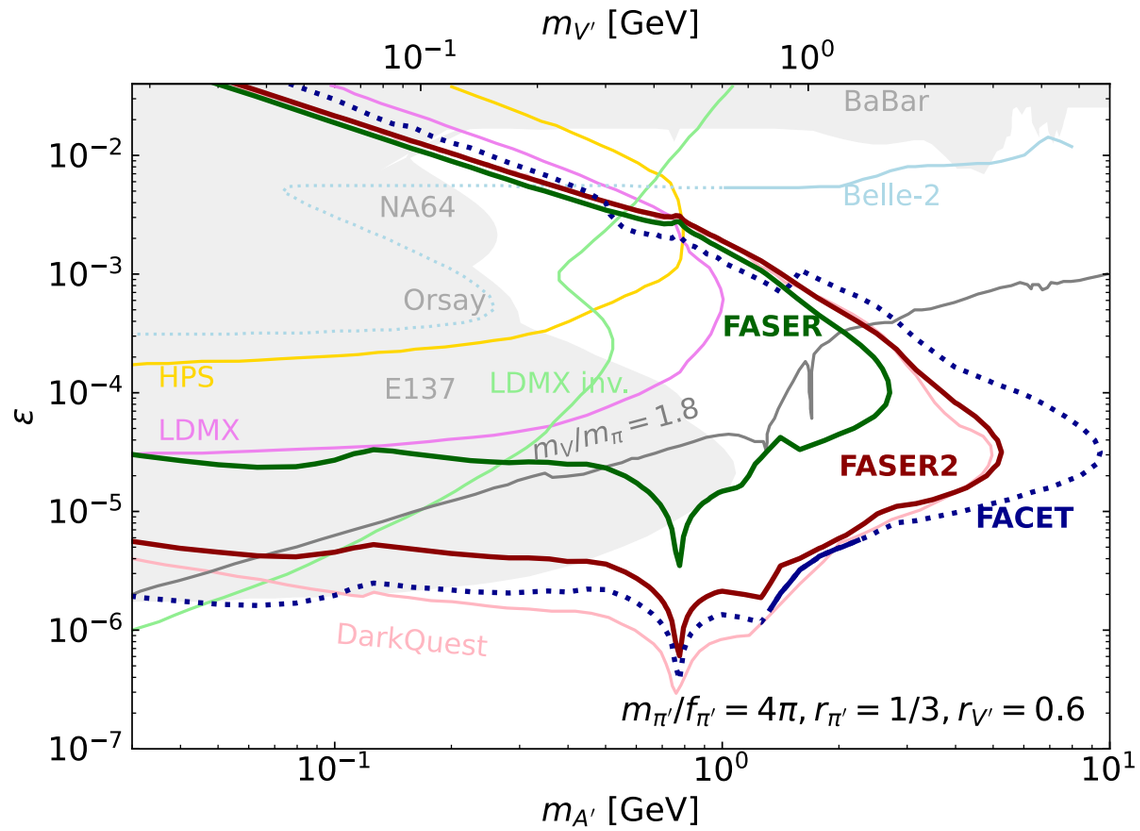




V' Decay

on-shell production (dark-pion DM scenario)

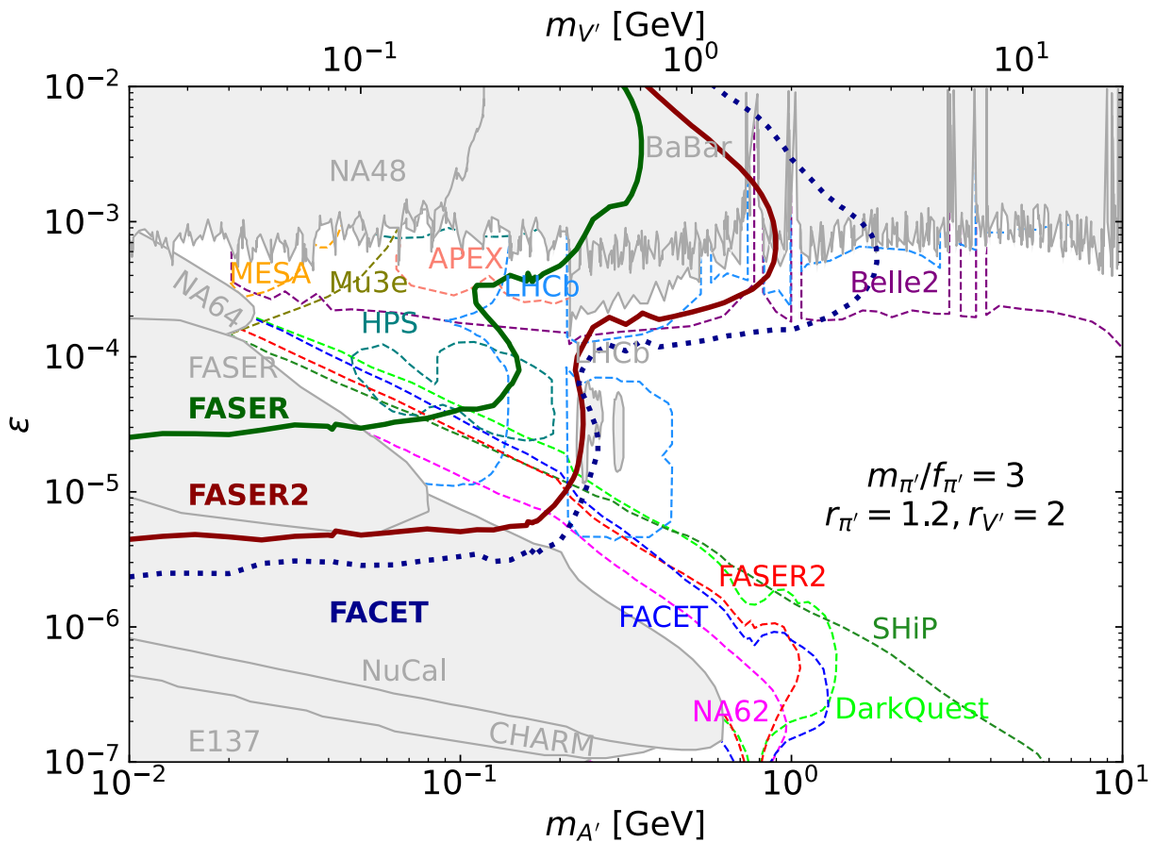


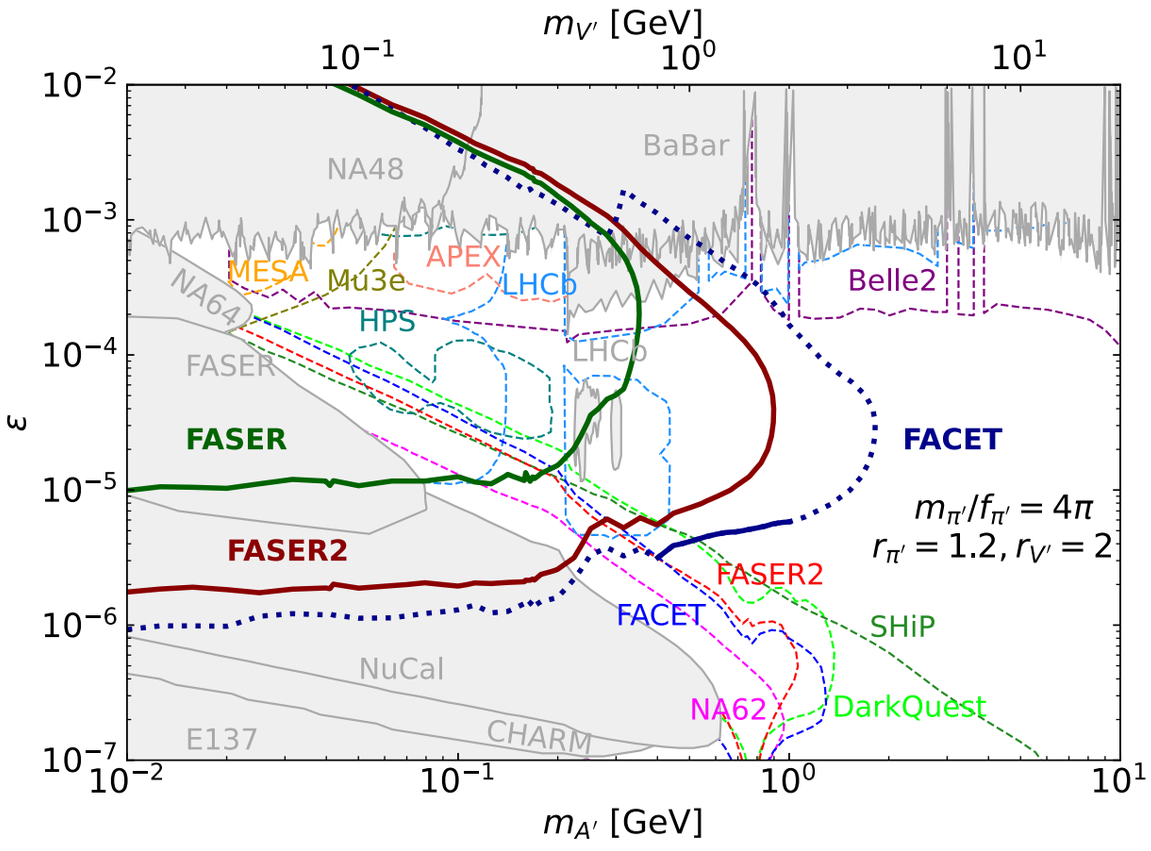


(dark colors) visible decay searches of dark vector mesons
(light colors) invisible decay searches of dark photons

V' Decay

off-shell production (Composite ADM scenario)





(solid/dotted) visible decay searches of dark vector mesons
(dashed) visible decay searches of dark photons