Hunting for dark matter with its high-energy fluxes

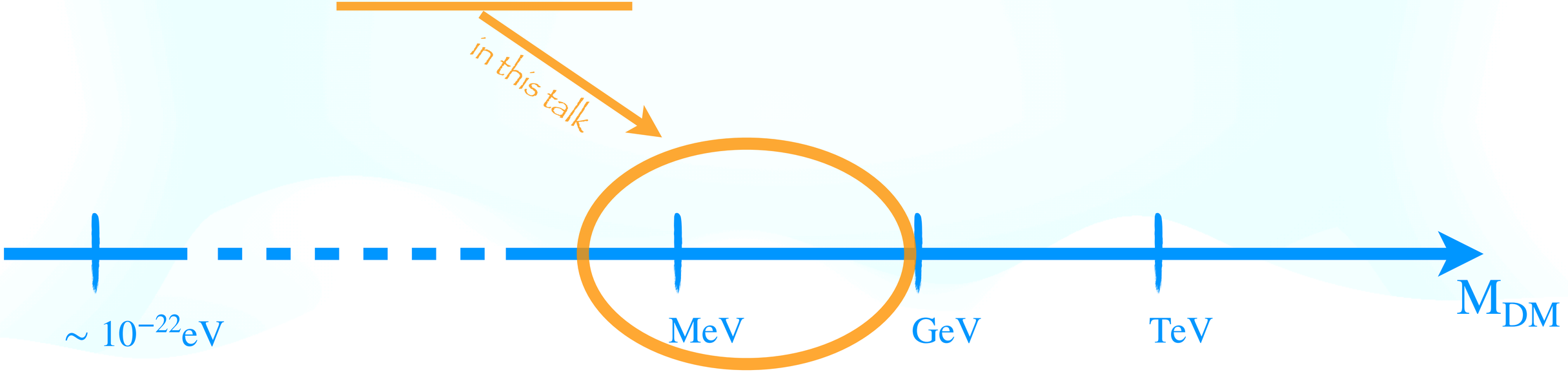
Filippo Sala
U. Bologna

Bo-Fi-Pi Meeting, Florence 15 Mar 2024

Dark Matter 2010's

Dark Matter ~~2010~~'s 2020's

Sub-GeV Dark Matter



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Cosmo histories motivate it/exist

Could be required to solve `anomalies' in data

We can look for it "easily"

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Cosmo histories that predict sub-GeV

Thermal freeze-out at small coupling

SIMP

Hochberg+ 1402.5143

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ELDERs

Kuflik+ 1512.04545

Forbidden DM

D'Agnolo Ruderman 1505.07107

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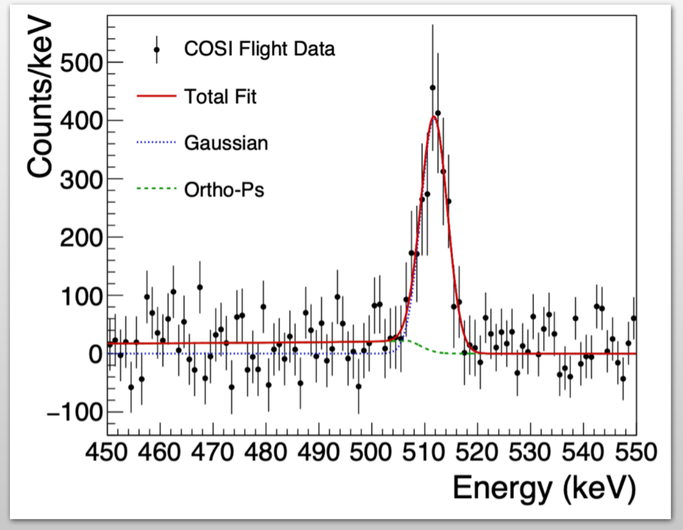
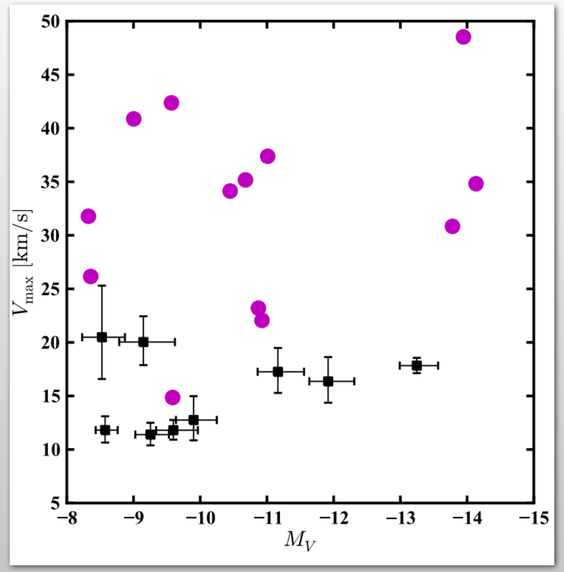
'Anomalies' in data

Galactic photon line @ 511 keV?



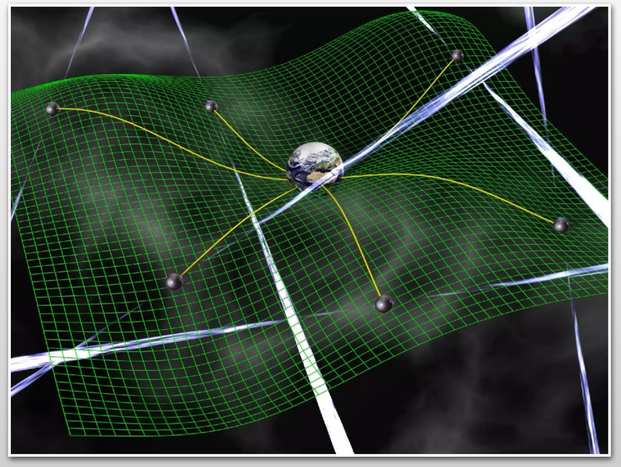
Ema FS Sato 2007.08440

Small scale troubles of DM?



Boylan-Kolchin 1103.0007, Tulin Yu 1705.02358,…

Gravity Waves at PTAs?



Nanograv 2104.13930, …

Bringmann+ 2306.09411, …

…

An example: 511 keV line

COSI balloon 1912.00110

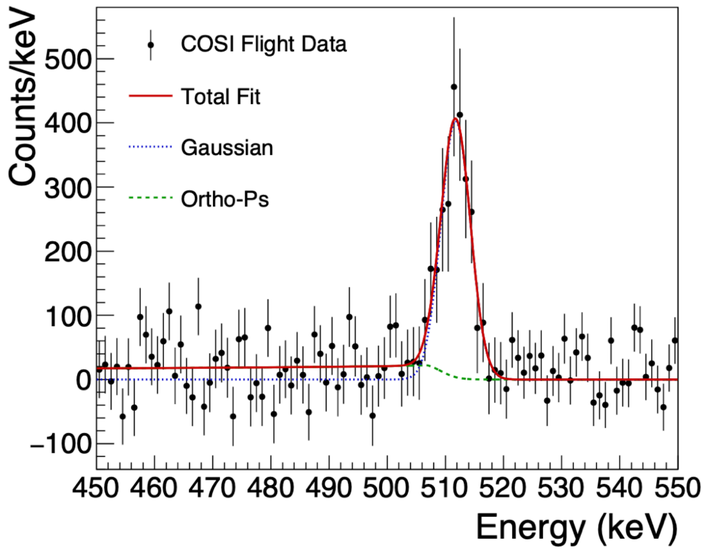


Figure 10. Positron annihilation spectrum from the 2016 COSI flight from a 16° source region around the GC. The spectrum is fit with a single Gaussian component to describe the 511 keV line and the theoretical o-Ps continuum spectrum. The total number of counts in the 511 keV line is 2560±300 cts. The detection significance is 7.2σ detection.

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where are the e^+ from??

Line observed since the 70's (INTEGRAL,...)

Origin: $e^+ e^-$ annihilations & bound states

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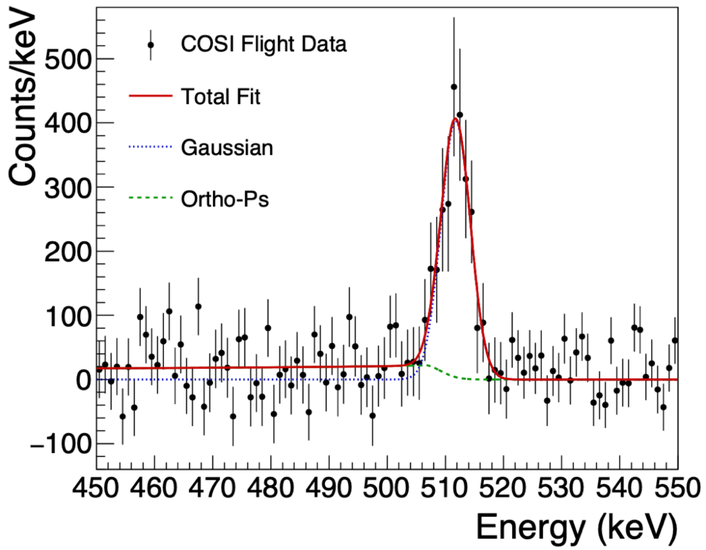

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Low-mass X-ray binaries?

Bartels Calore Storm Weniger 1803.04370

Neutron Star Mergers?

Fuller Kusenko Radice Takhistov 1811.00133

From dark matter annihilations?

First explored in Bohem+ astro-ph/0309686

Yes if:

$$\langle \sigma v \rangle_{511} \simeq 5 \cdot 10^{-31} \left(\frac{M_{\rm DM}}{3\,{\rm MeV}} \right)^2 \frac{{\rm cm}^3}{\rm sec}$$

Vincent+ 1201.0997 (NFW DM profile)

DM mass $\lesssim 3$ MeV

Beacom Yuksel astro-ph/0512411

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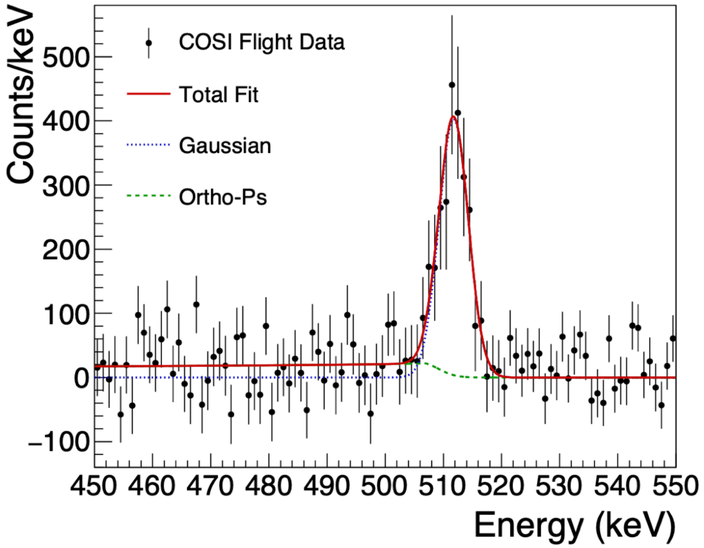

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→ Equilibrium with SM in Early Uni

DM mass $\lesssim 3$ MeV

Beacom Yuksel astro-ph/0512411

→ Excluded by BBN + CMB

Wilkinson Vincent Boehm McCabe 1602.01114

Sub-GeV DM can explain the 511 keV line

Ema FS Sato 2007.08440

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Escudero 1812.05605, Sabti+ 1910.01649
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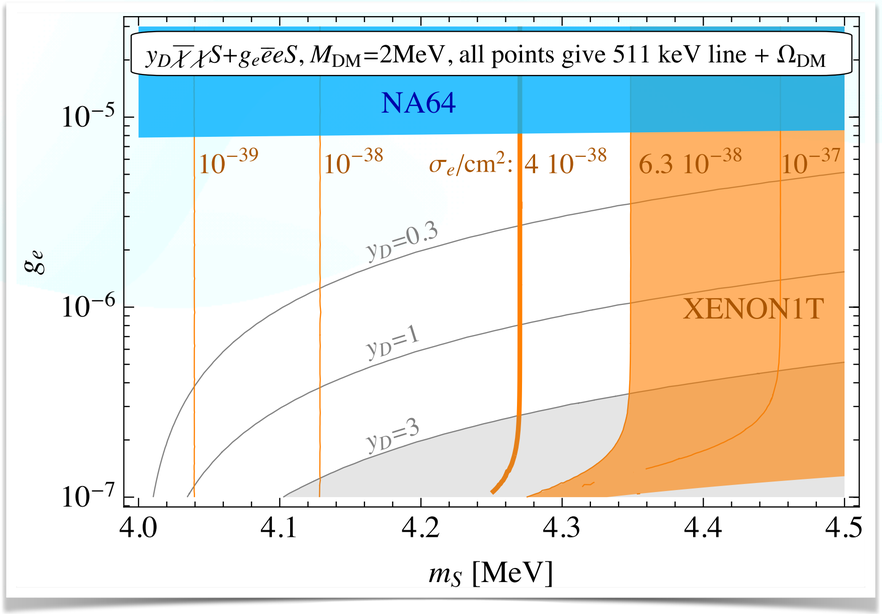

We made it work with thermal DM!

Rich pheno: Direct DM detection

Accelerators

Small-scale astro structures

...

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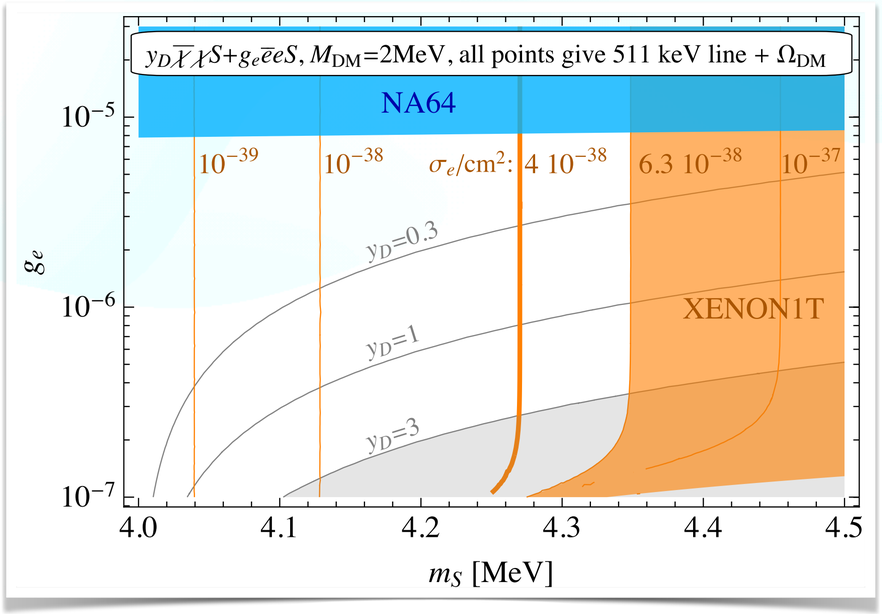

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Stay tuned: our new analysis lowers $\langle\sigma v\rangle_{511}$ and allows for $M_{\rm DM} \gtrsim 10$ MeV

Balaji DeLaTorre Fairbairn FS Silk, in progress

More DM models will work!

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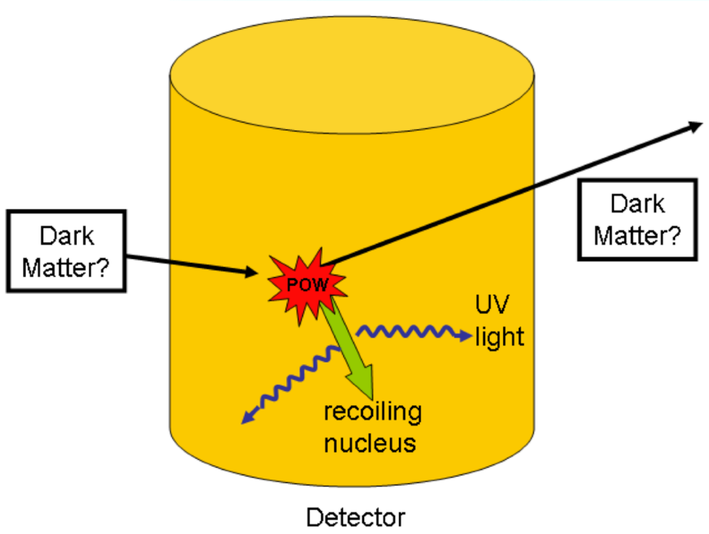
Direct Detection of Sub-GeV Dark Matter ?



Challenge

$$E_{\rm NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \lesssim 190\ {\rm eV} \times \left(\frac{m_\chi}{500\ {\rm MeV}}\right)^2 \left(\frac{16\ {\rm GeV}}{m_N}\right)$$

... ...

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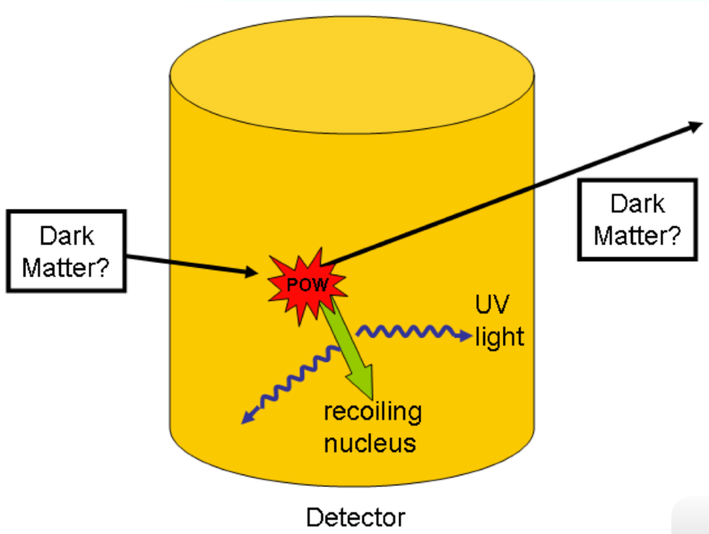

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Solutions 1: lower m_N

NEWS-G
e.g. SciPost Phys. Proc. 12 (2023) 024

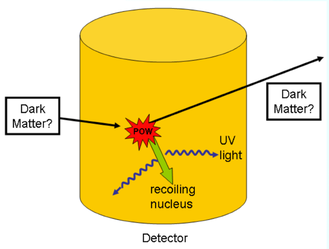
...

Solutions 2: lower the thresholds

PHONON(S) & similar beasts
Campbell-Deem+ 2205.02250 …

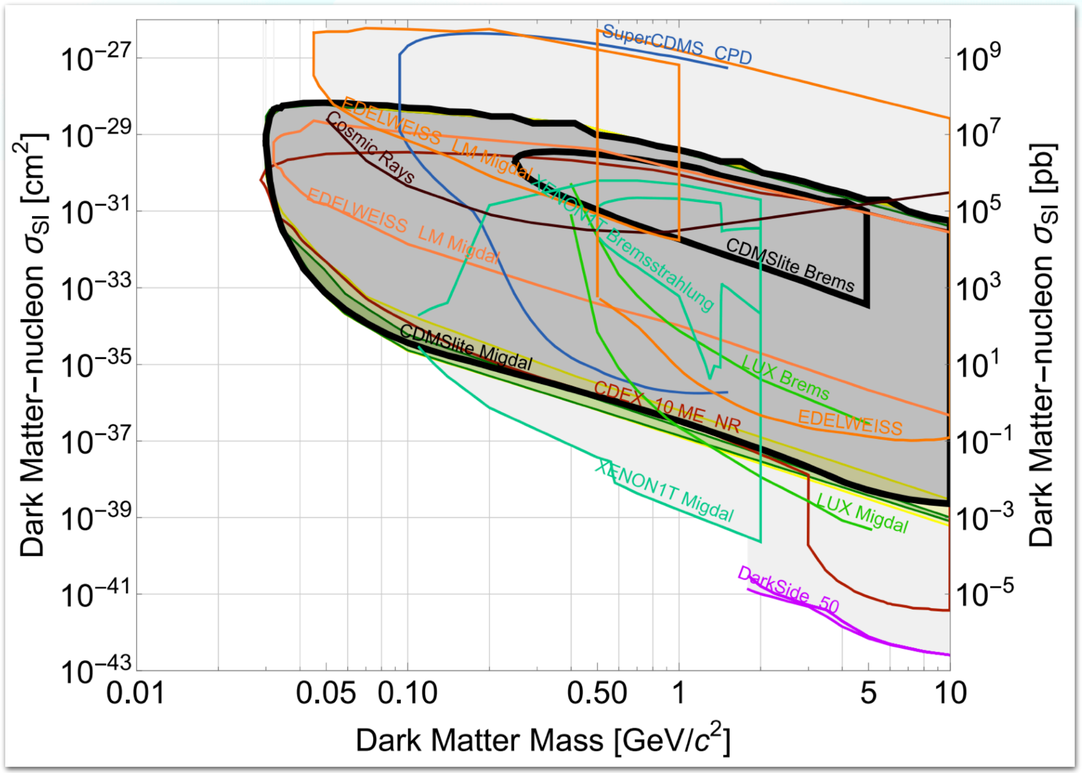
MIGDAL SuperCDMS 2302.09115 …

...

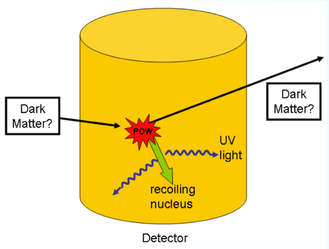


Direct Detection of Sub-GeV DM: Status

Promising, but not cutting deep yet



SuperCDMS 2302.09115



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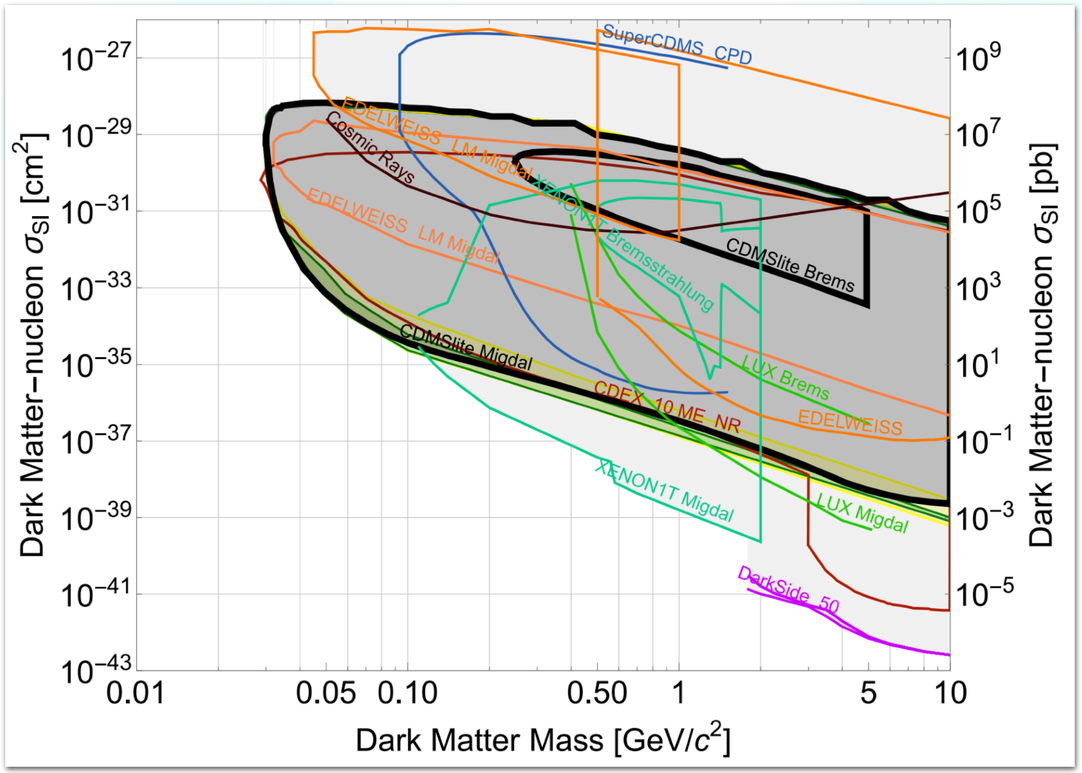
New exp. techniques: better understanding needed



SuperCDMS 2302.09115

MIGDAL effect widely used SuperCDMS, XENON, PandaX,…

BUT: was never observed in the Standard Model

When tried in liquid Xenon
SM signal not found
while ~100 events were predicted!

Xu+ 2307.12952, PRD 2024

Same prediction that go into DM searches...

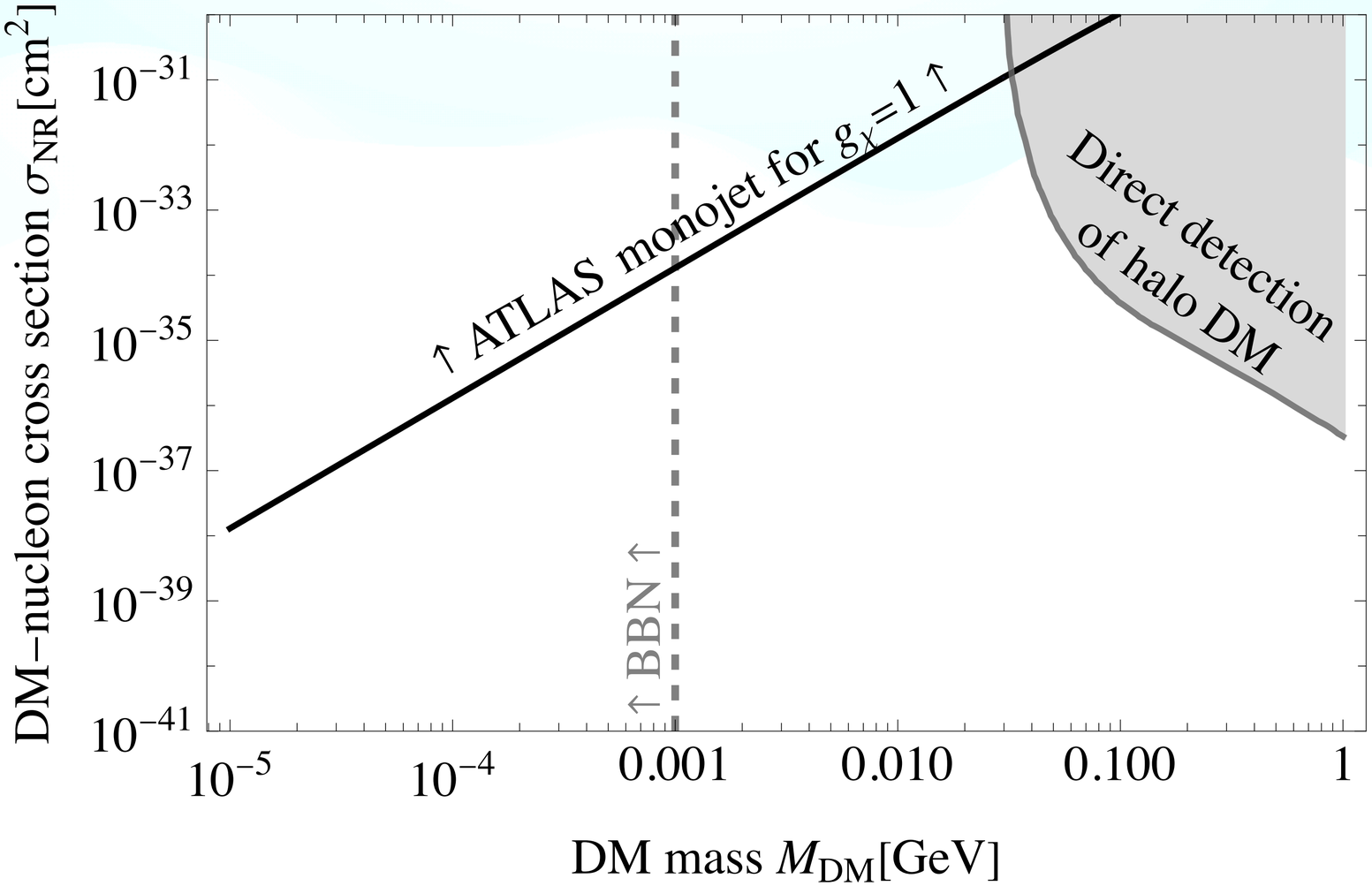
on Detection of sub-GeV dark matter

This Talk: from this ...

Lowering thresholds, current limits

$\mathscr{L} \supset g_\chi \phi \bar{\chi}\chi + g_q \phi \bar{q} q$

$m_\phi = 1$ GeV



This Talk: … to this with 2 ideas

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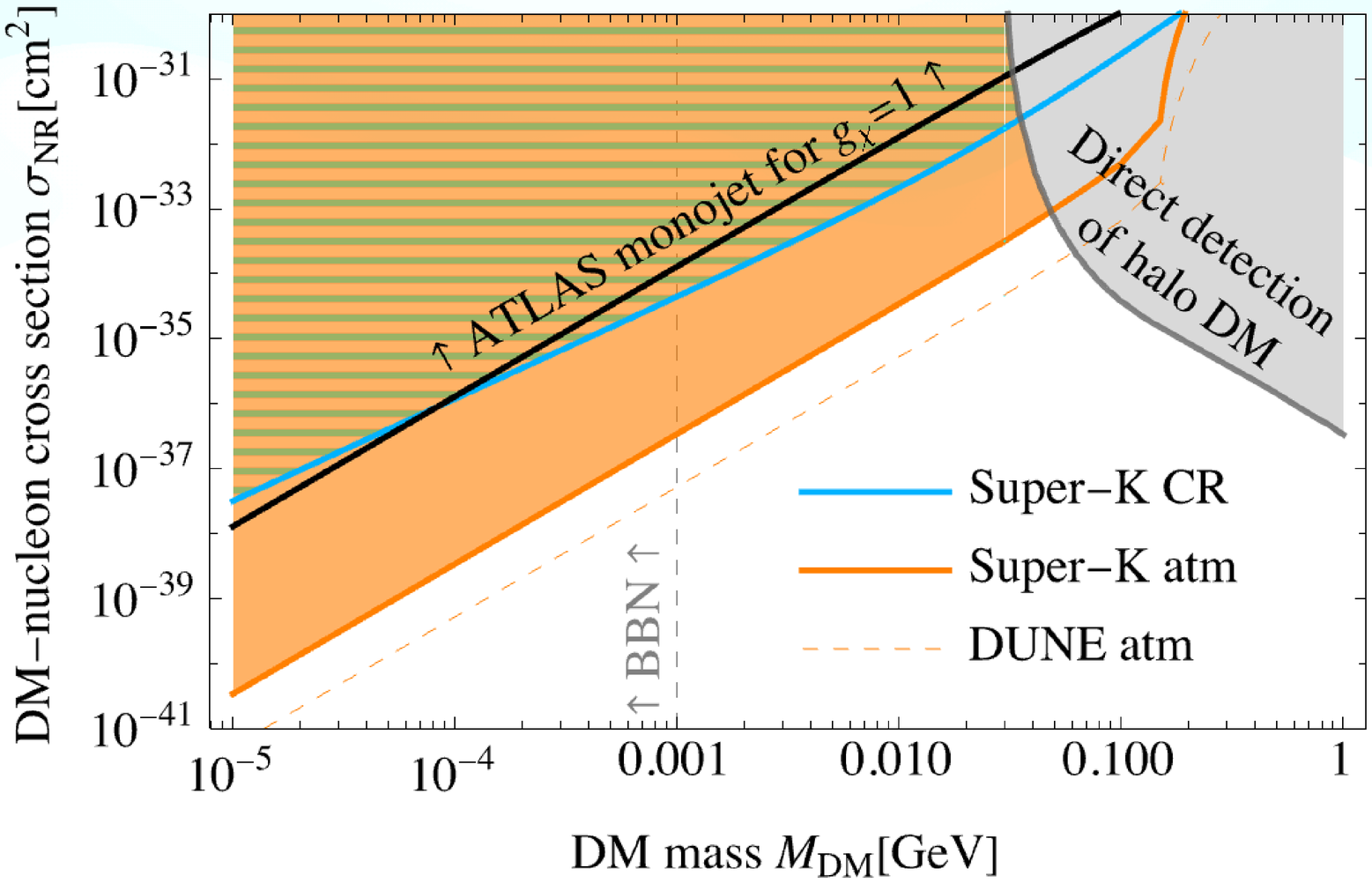

New Idea for Direct Detection

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Ema FS Sato 1811.00520

High-velocity DM component unavoidably generated by **Cosmic-ray scatterings**

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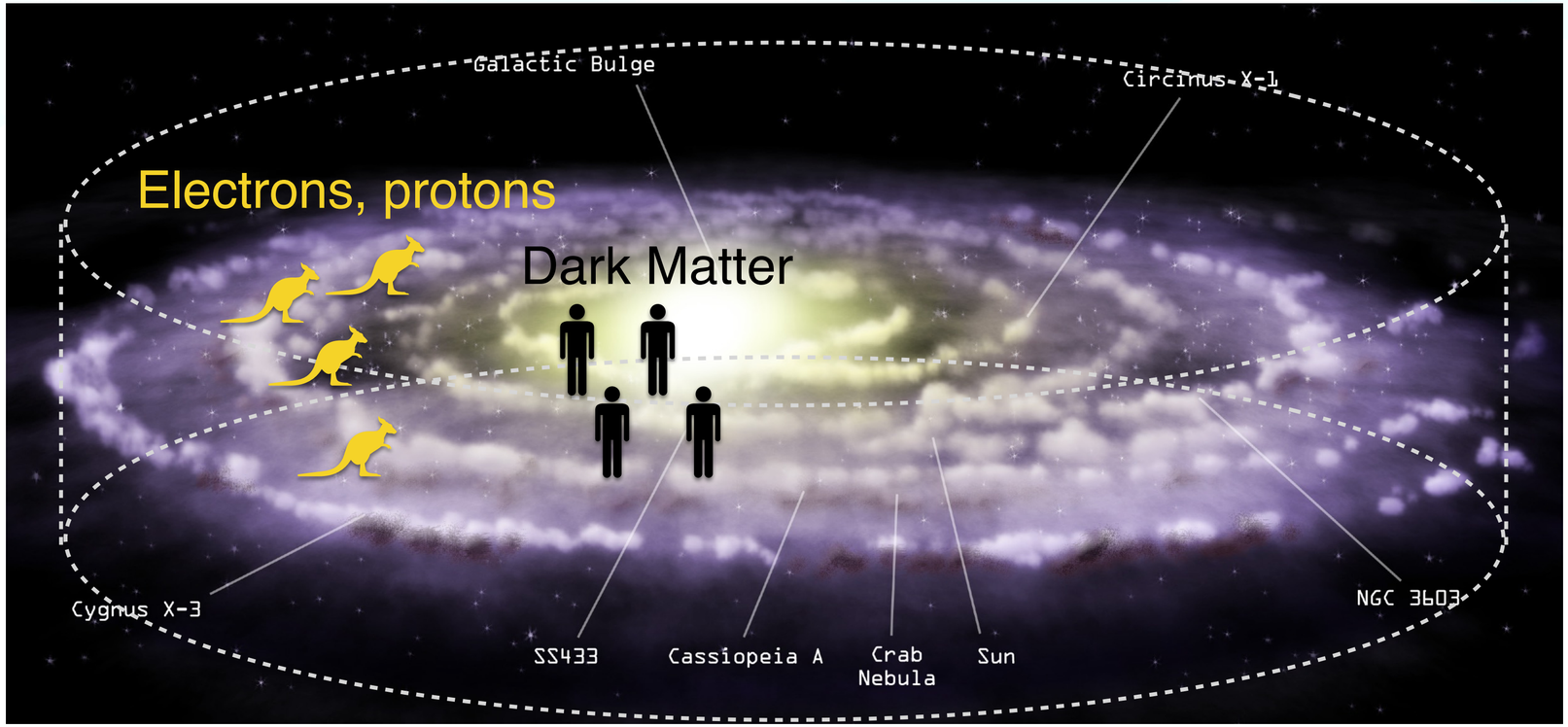

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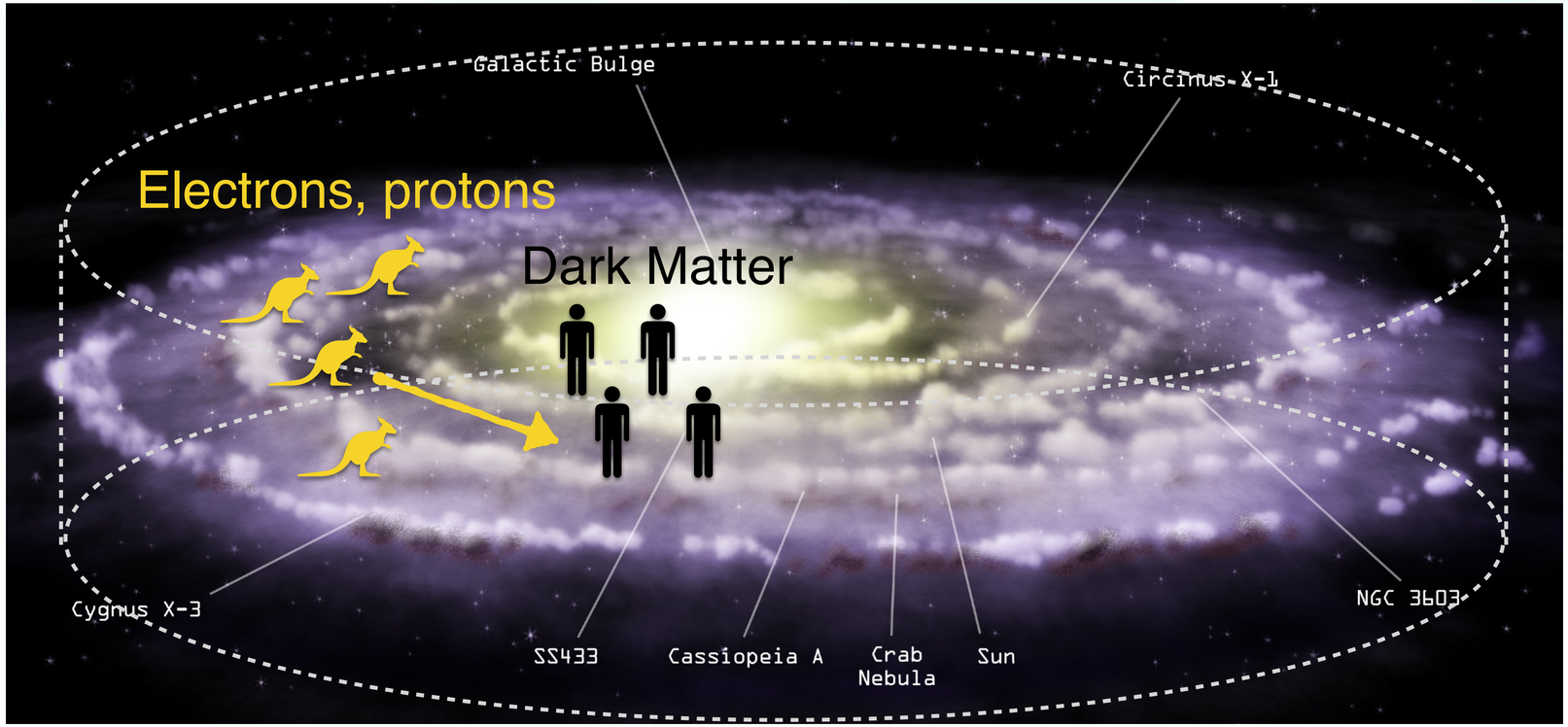

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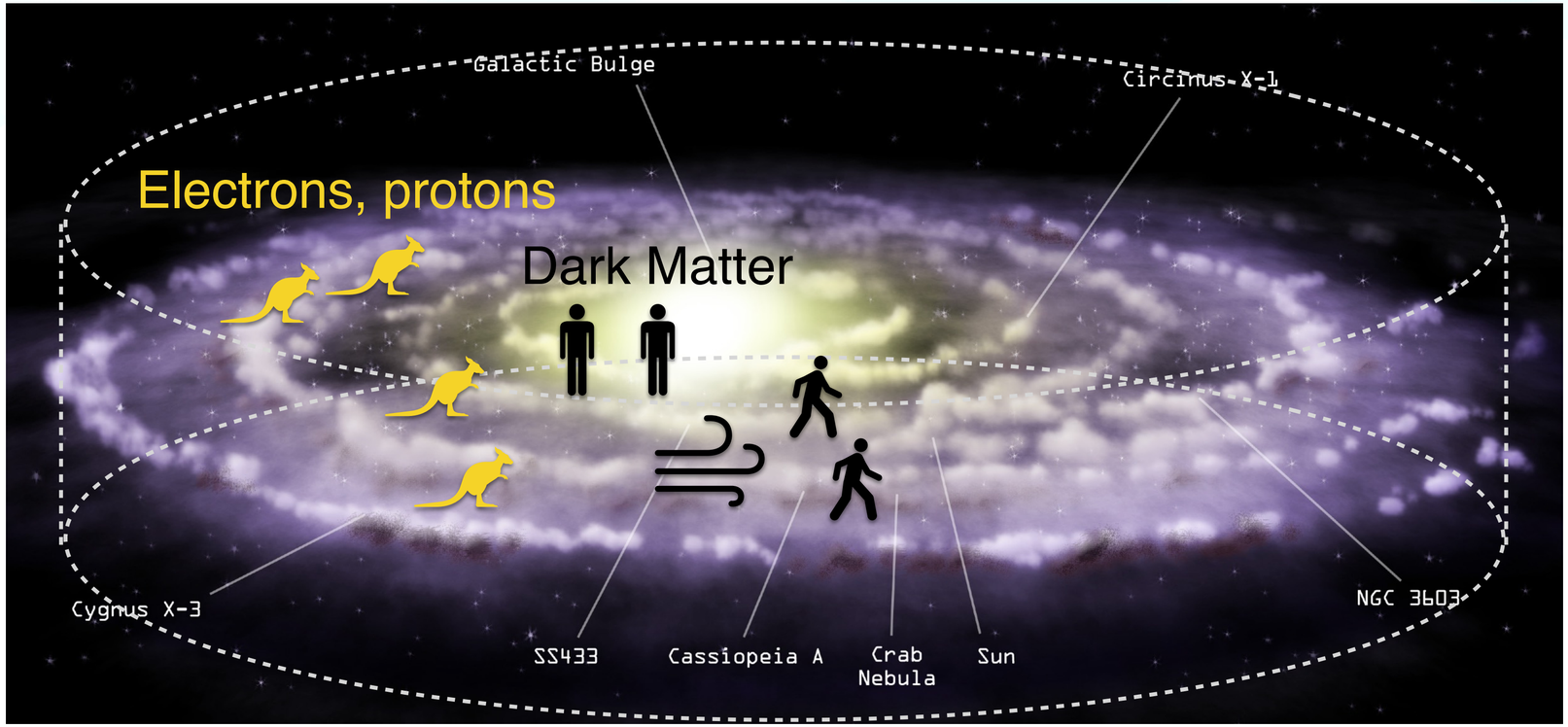

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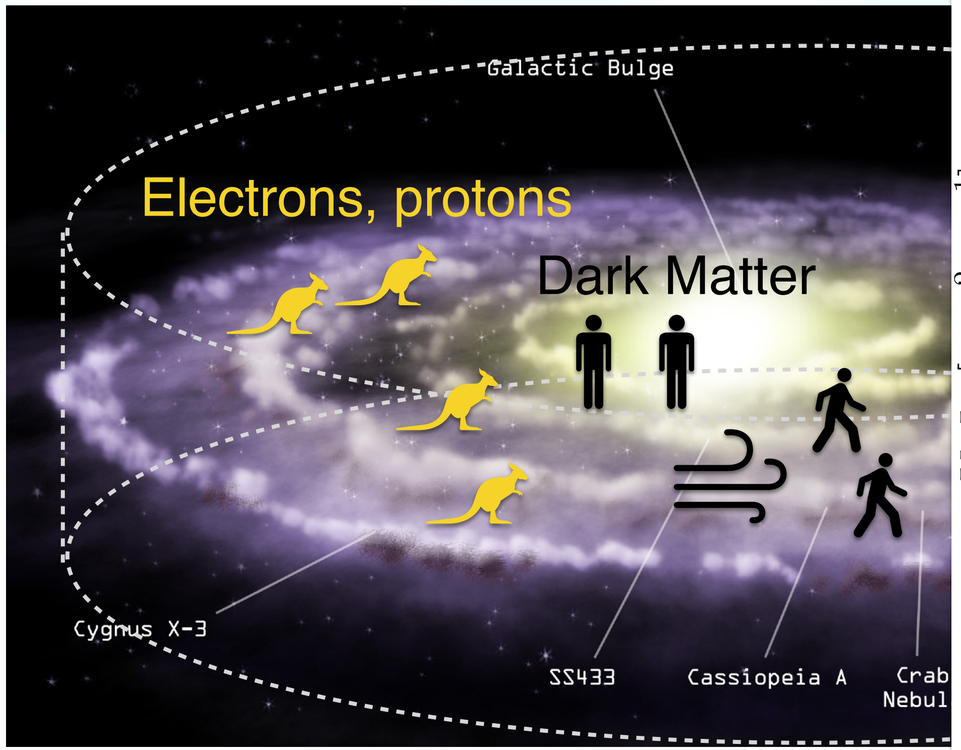

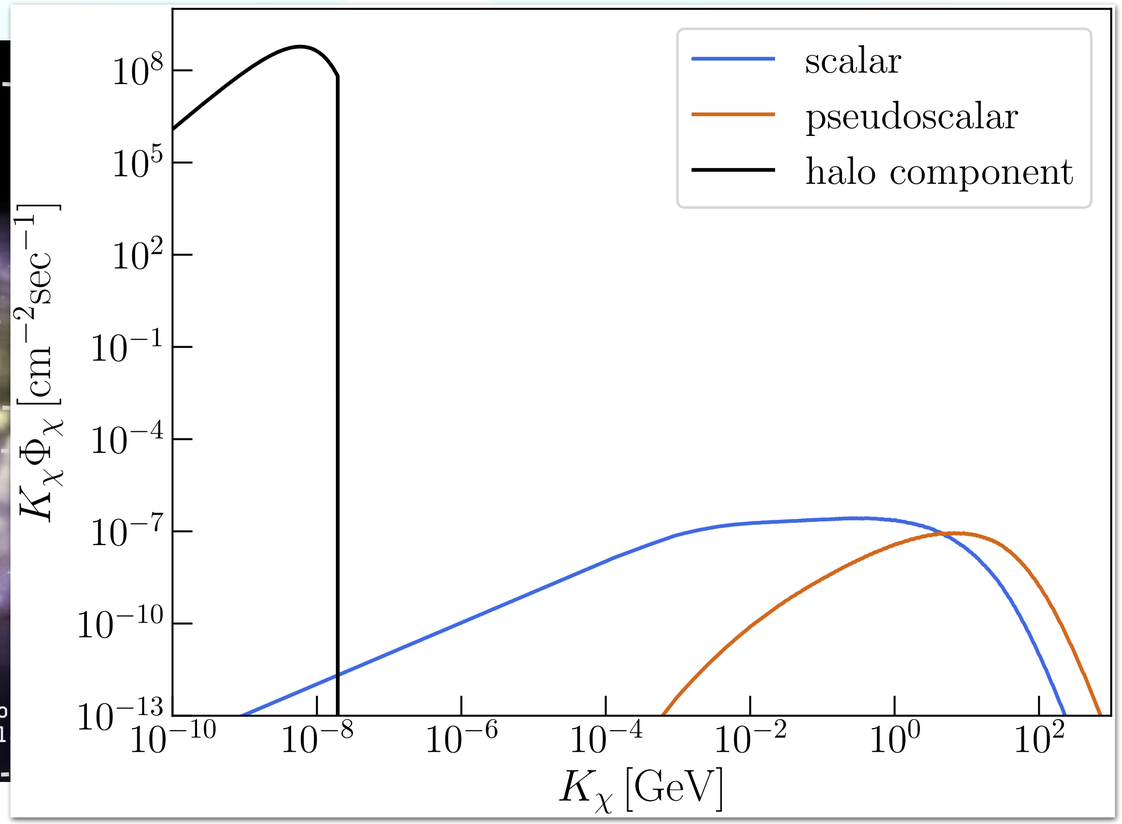

$$M_{\mathrm{DM}} = 10 \text{ MeV}, \quad M_{\mathrm{mediator}} = \mathrm{GeV}, \quad g_\chi g_u = g_\chi g_d = 0.1$$

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Also by **Solar Upscattering**

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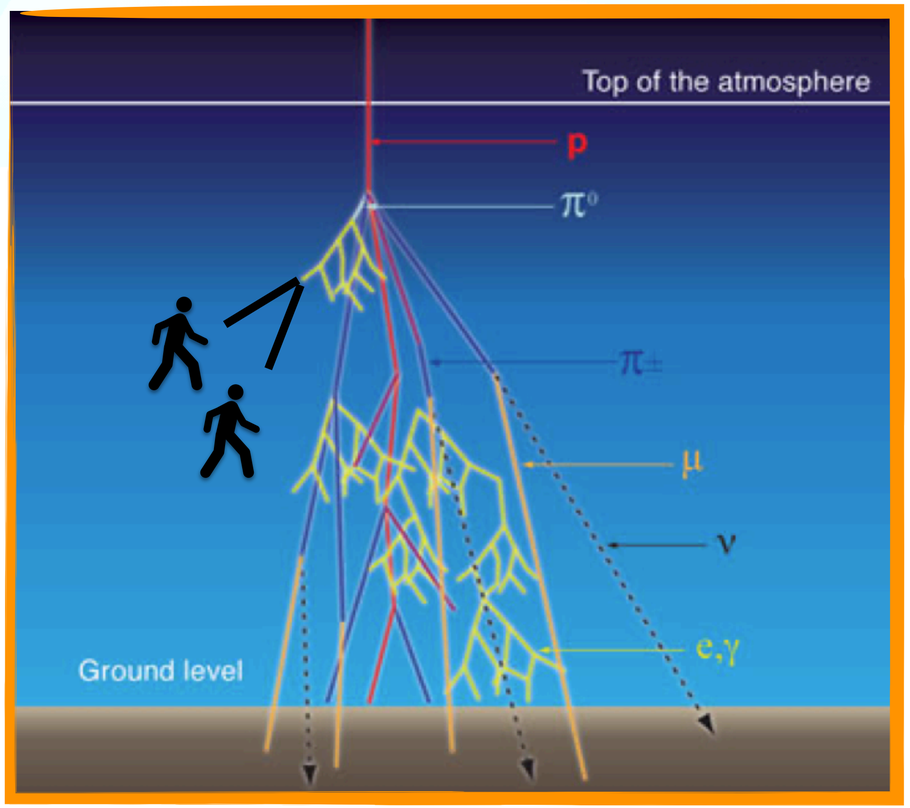

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Also by **Atmospheric Showers**

Alvey+ 1905.05776 , …

Pascoli FS Xotta in progress

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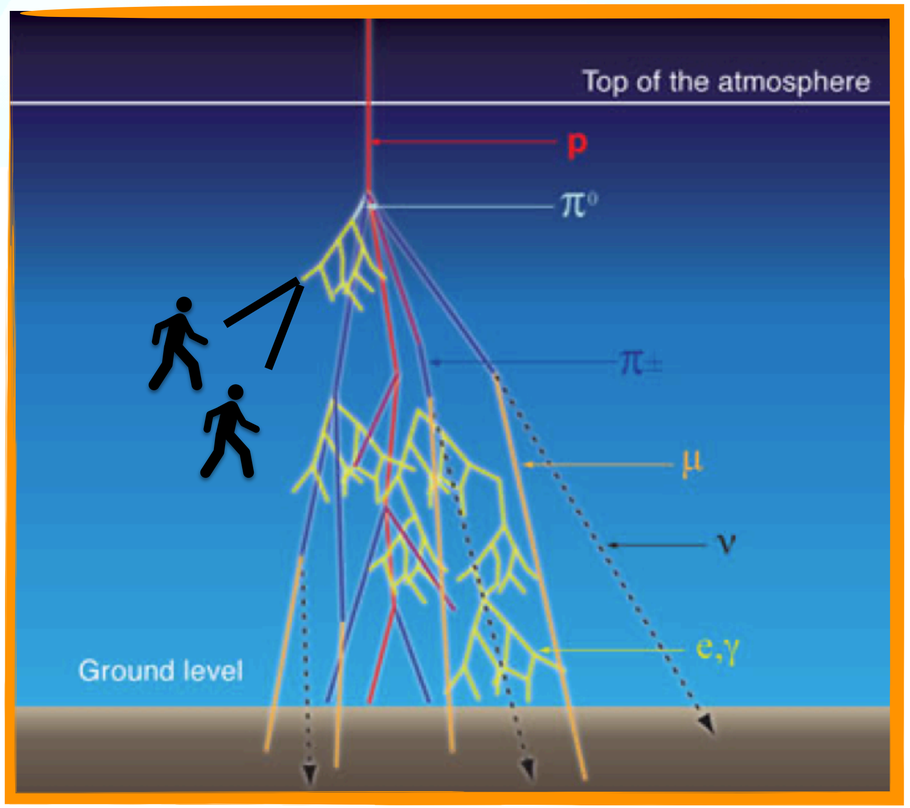

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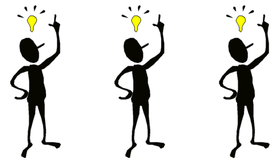
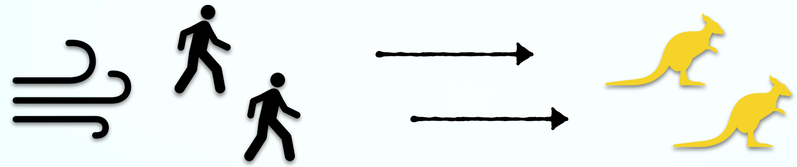
Also by **Blazars**

Wang Granelli Ullio 2111.13644, …

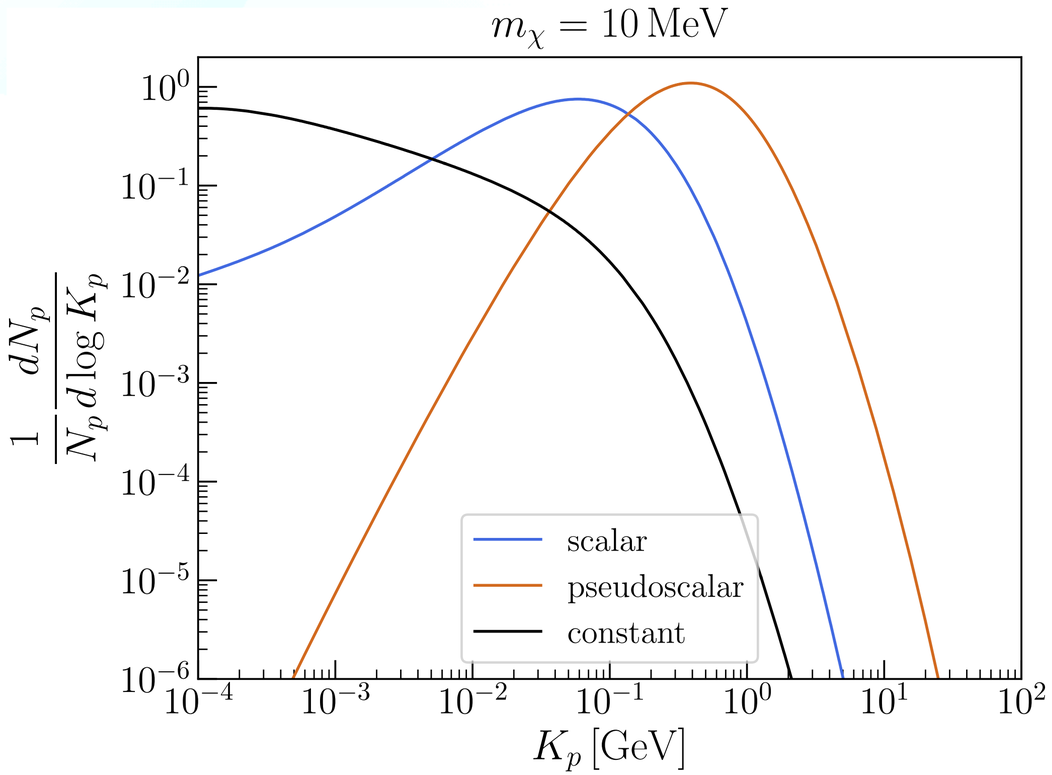
Also by **…**



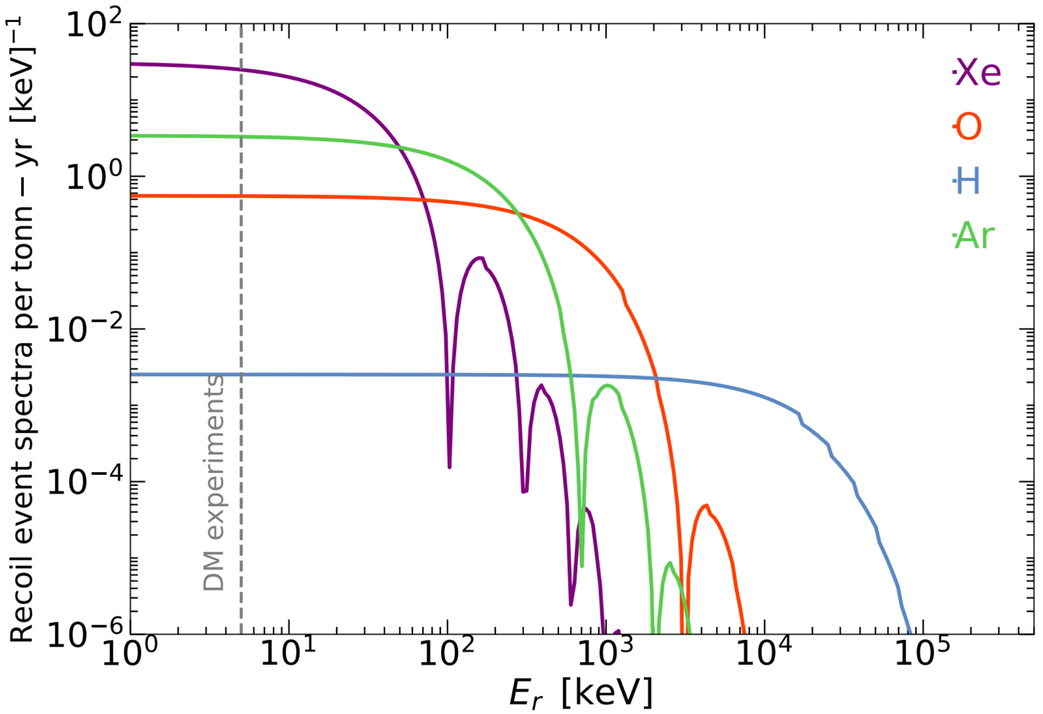
Recoil Spectra from fast Sub-GeV DM



From **Cosmic Rays**, Ema FS Sato 2011.01939



From **Atmosphere**, Arguelles+ 2203.12630



New Idea 2: use Neutrino Detectors

Recoil Energies > 10 MeV ⟶ go to biggest existing detectors!

Ema FS Sato 1811.00520 CR-upscattered DM, electrons

Ema FS Sato 2011.01939 CR-upscattered DM, nucleons

Pascoli FS Xotta in progress Atmospheric DM, nucleons

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CR-DM vs nucleons at Neutrino Experiments

Protons with $p_p > 1.07\ \mathrm{GeV}$ emit Cherenkov light, already used for $\nu's$ in Super-K 0901.1645

We repurposed it!

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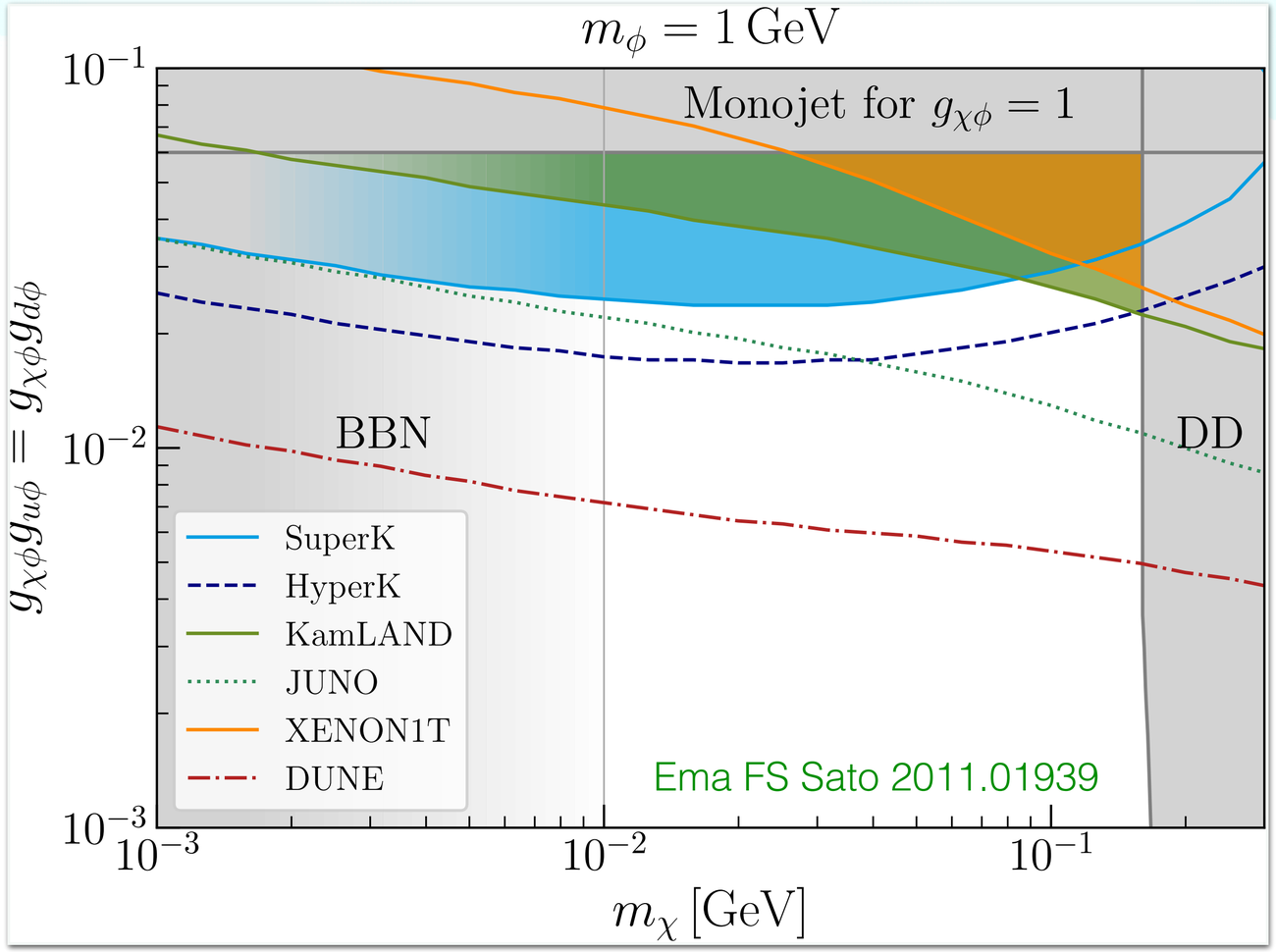

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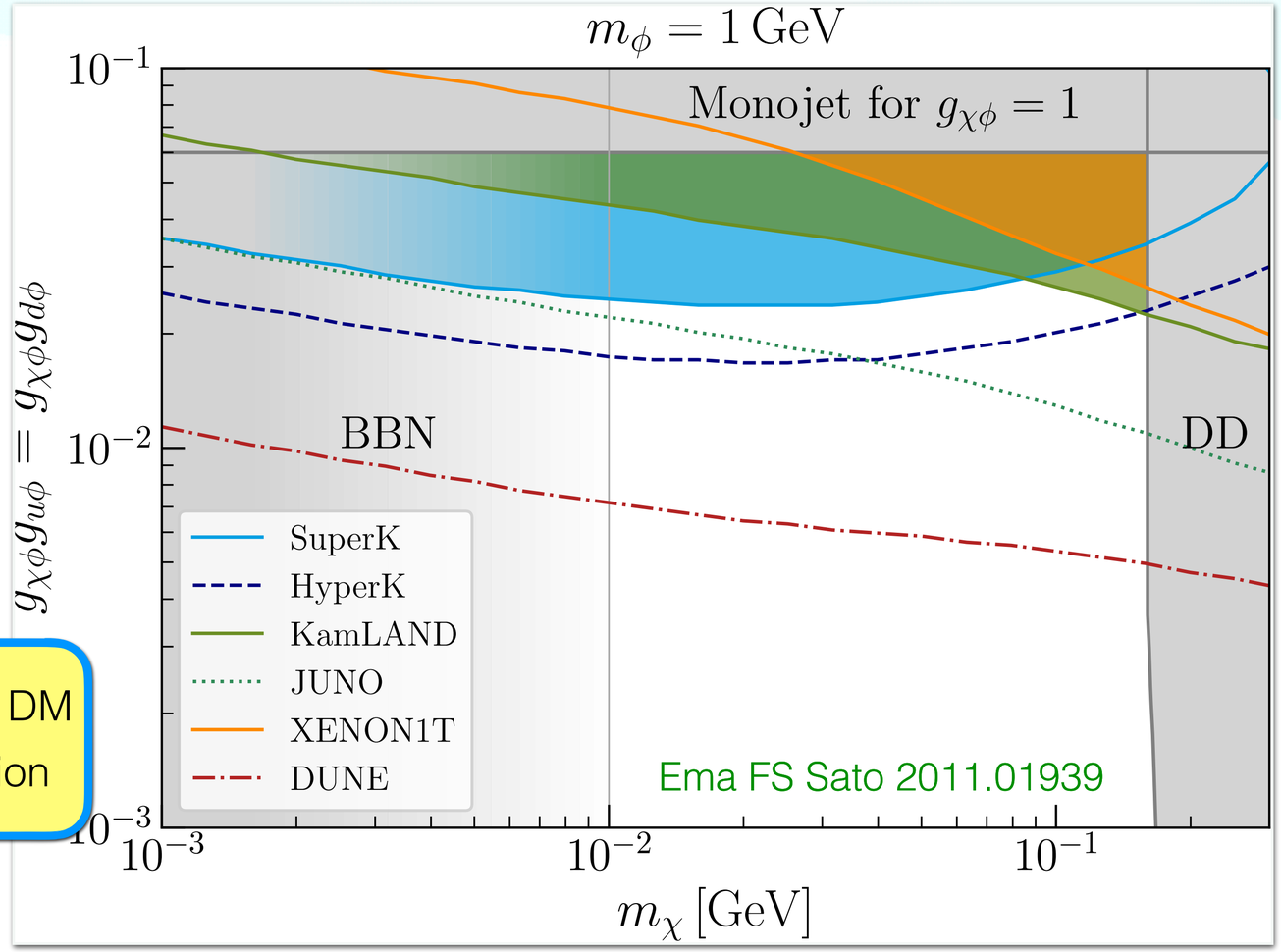

These ideas test also inelastic DM unlike `standard' direct detection

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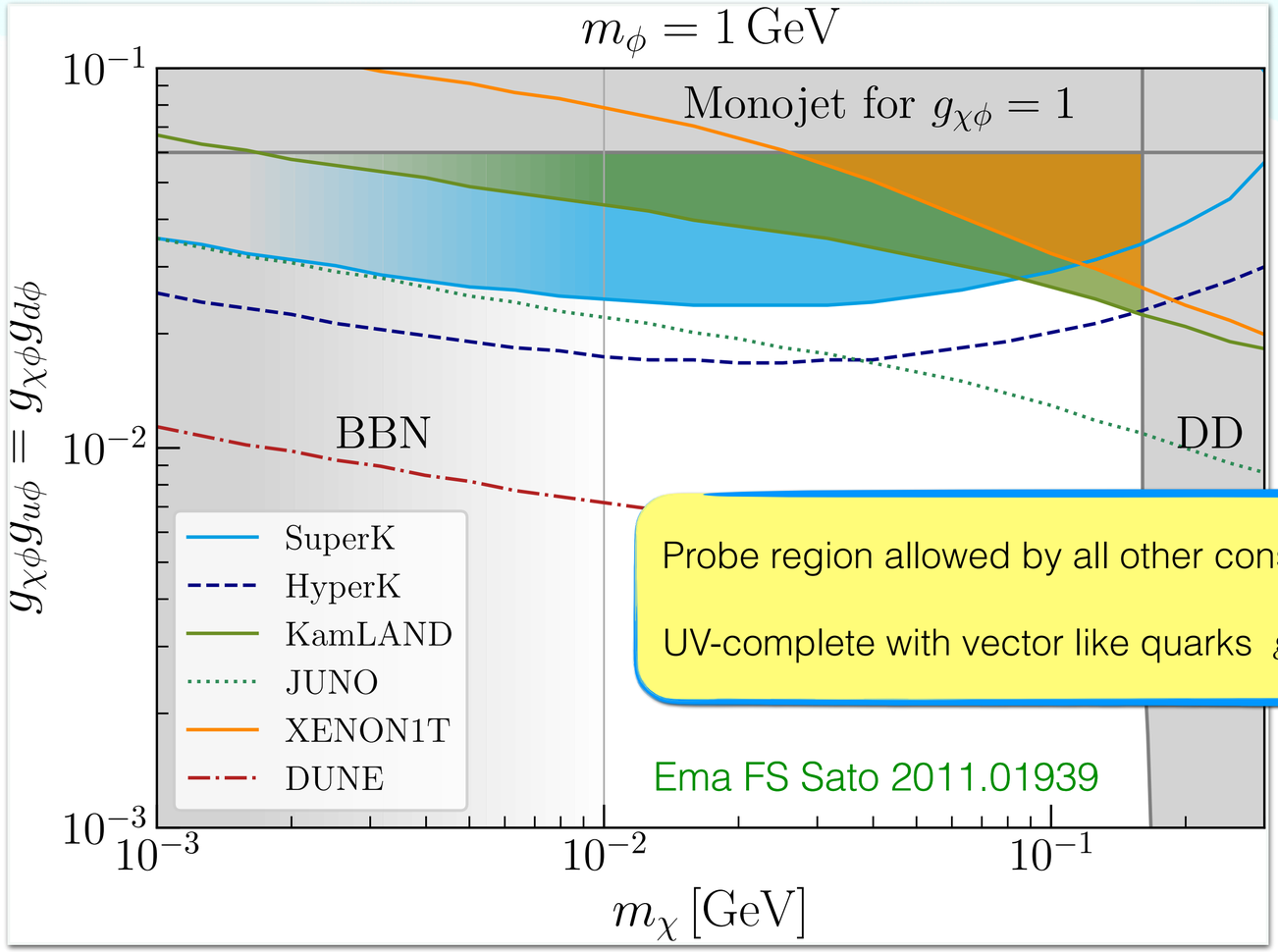


Ema FS Sato 2011.01939

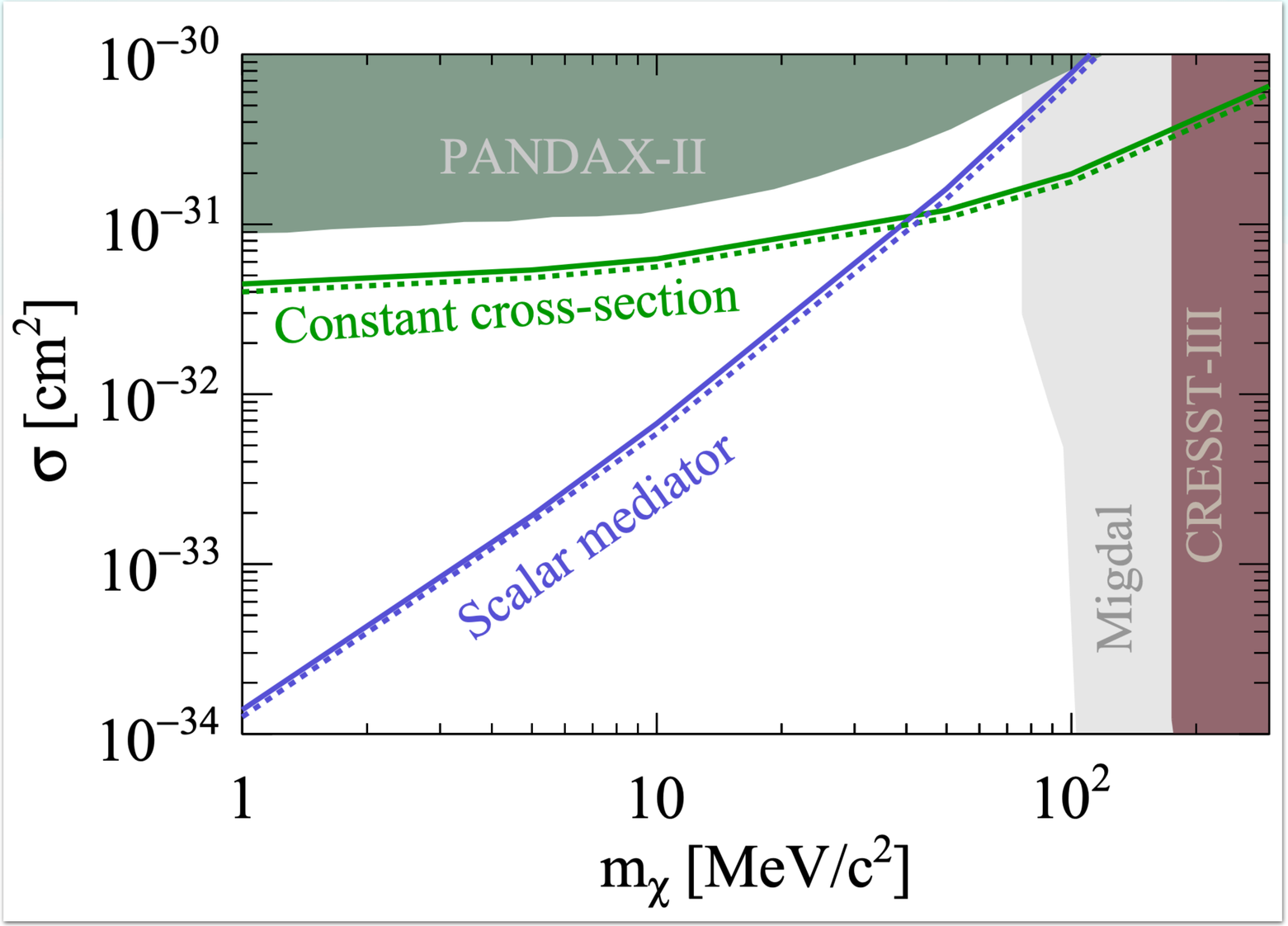
Probe region allowed by all other constraints!

UV-complete with vector like quarks $g_q \sim g_Q \frac{v}{M_Q} \lesssim 0.1$ is OK!

Experimentalist from Super-K, DUNE…

Super-K then did the search!

Super-K 2209.14968



$$\sigma_{\rm NR} = C\,\frac{g^2_{\chi\phi} g^2_{u\phi}}{\pi}\,\frac{\mu^2_{\chi p}}{m^4_\phi}$$

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Neutrino Detectors & Atmospheric DM

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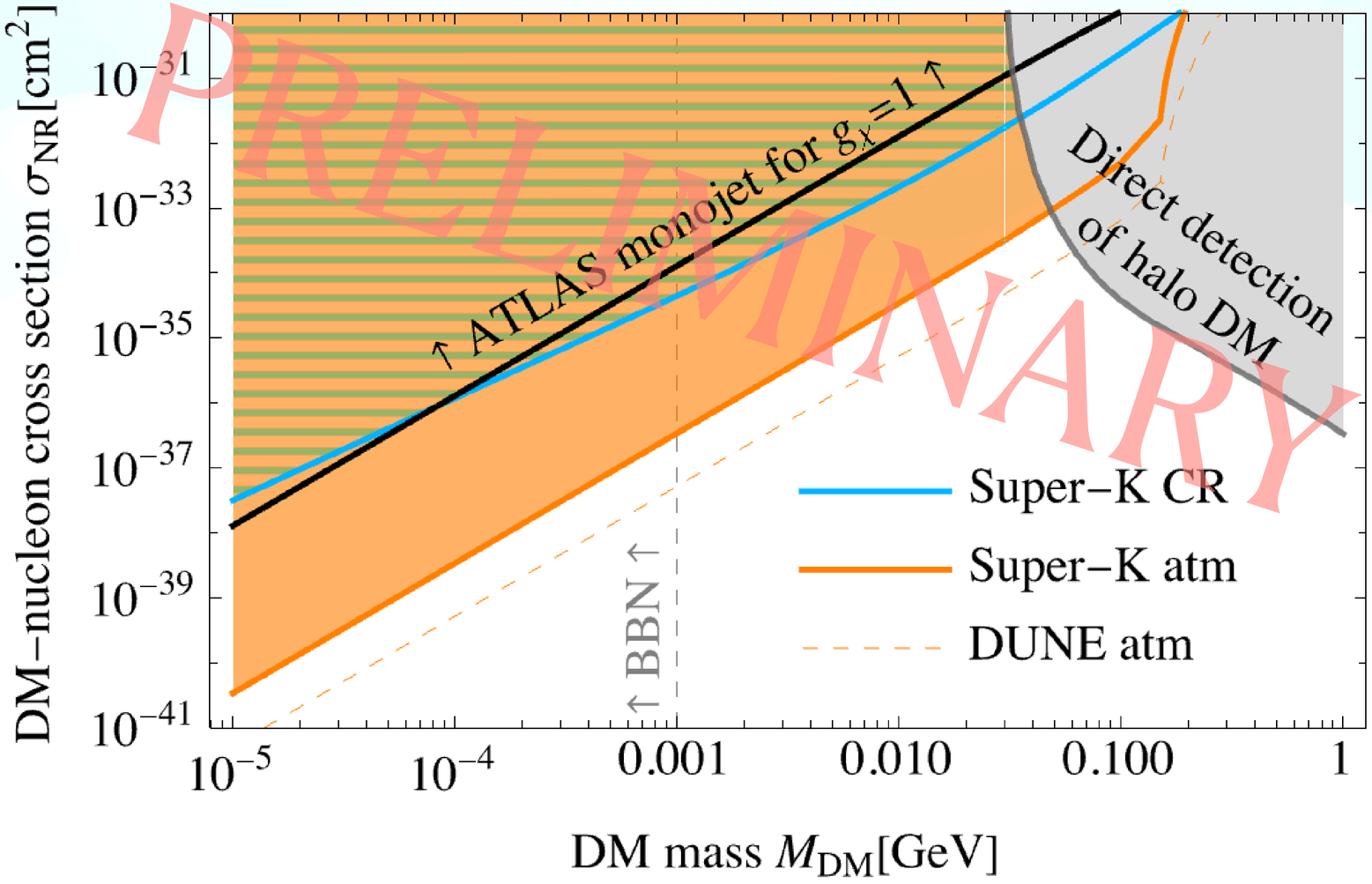

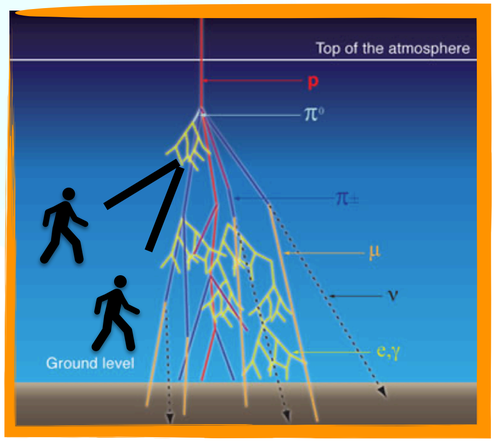

Here only DM from eta mesons

From Dark Matter

To

Relic Neutrino Background

Upscatter the Relic Neutrino Background?

RNB 2024: never observed, capture on tritium (PTOLEMY) does not work without tech. breakthrough

e.g. PTOLEMY 2203.11228

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$\sigma(\mathrm{CR} - \nu_{\mathrm{relic}}) \propto E_{\mathrm{CR}}$ → Relic neutrinos are most upscattered by **Ultra-High-Energy CR!**

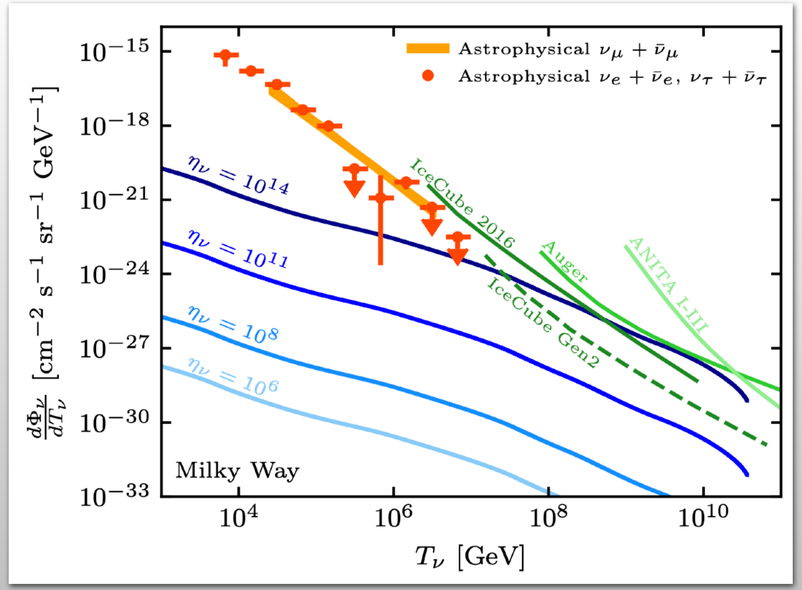
Ciscar-Monsalvatje Herrera Shoemaker 2402.00985

used only UHECR on Earth and TXS

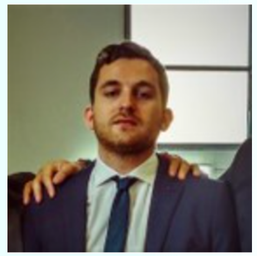
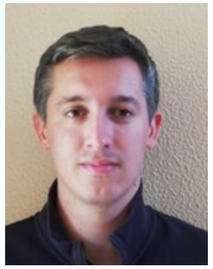
assumed they are protons

To be seen, it needs overdensity

$\eta_\nu \sim 10^{12}$ wrt ΛCDM



Relic Neutrino Background?

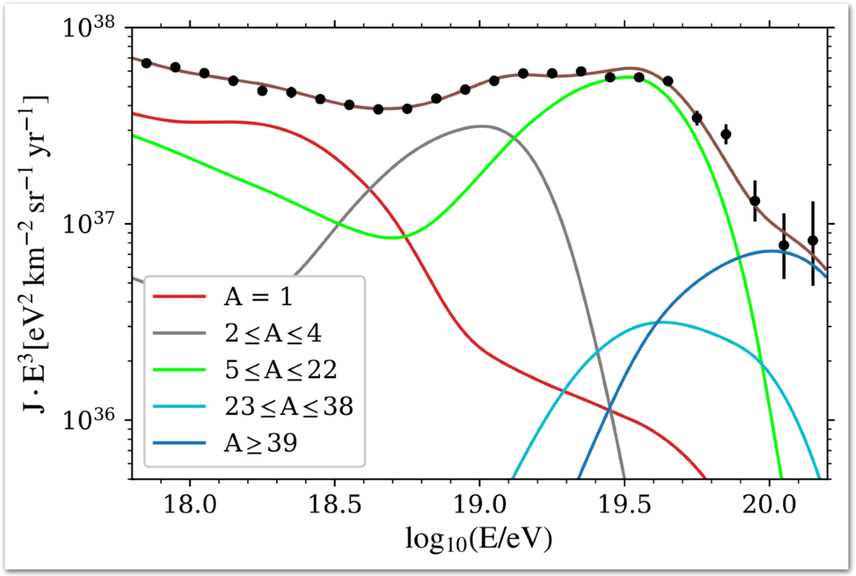
De Marchi Granelli Nava FS in progress

Use UHECR in their **accelerators and reservoirs**

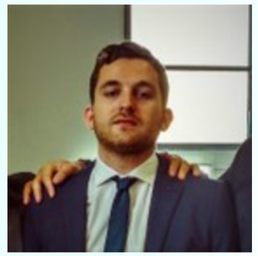
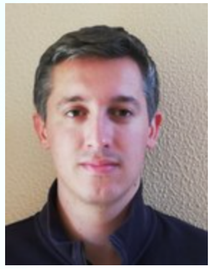
e.g. as modeled in Fang Murase 1704.00015

Use actual **composition** of UHECRs

Auger JCAP05 (2023) 024



Relic Neutrino Background?

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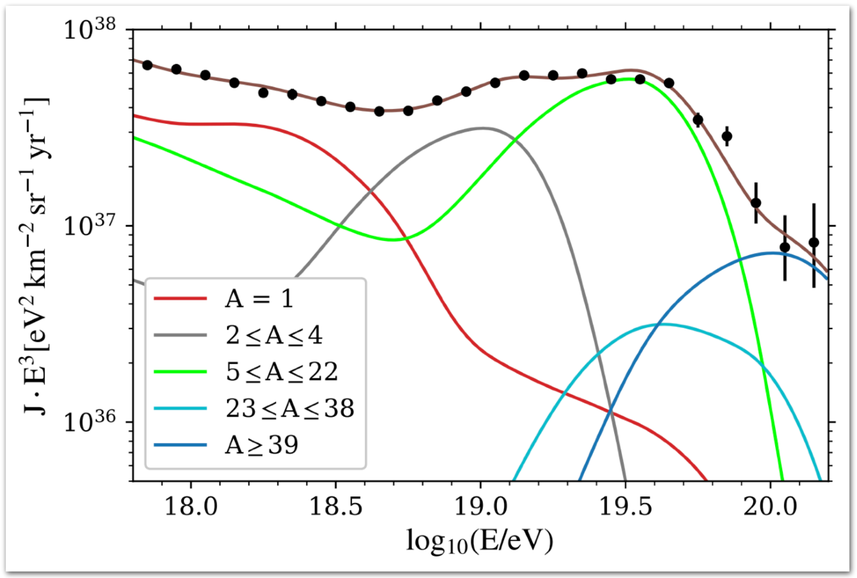
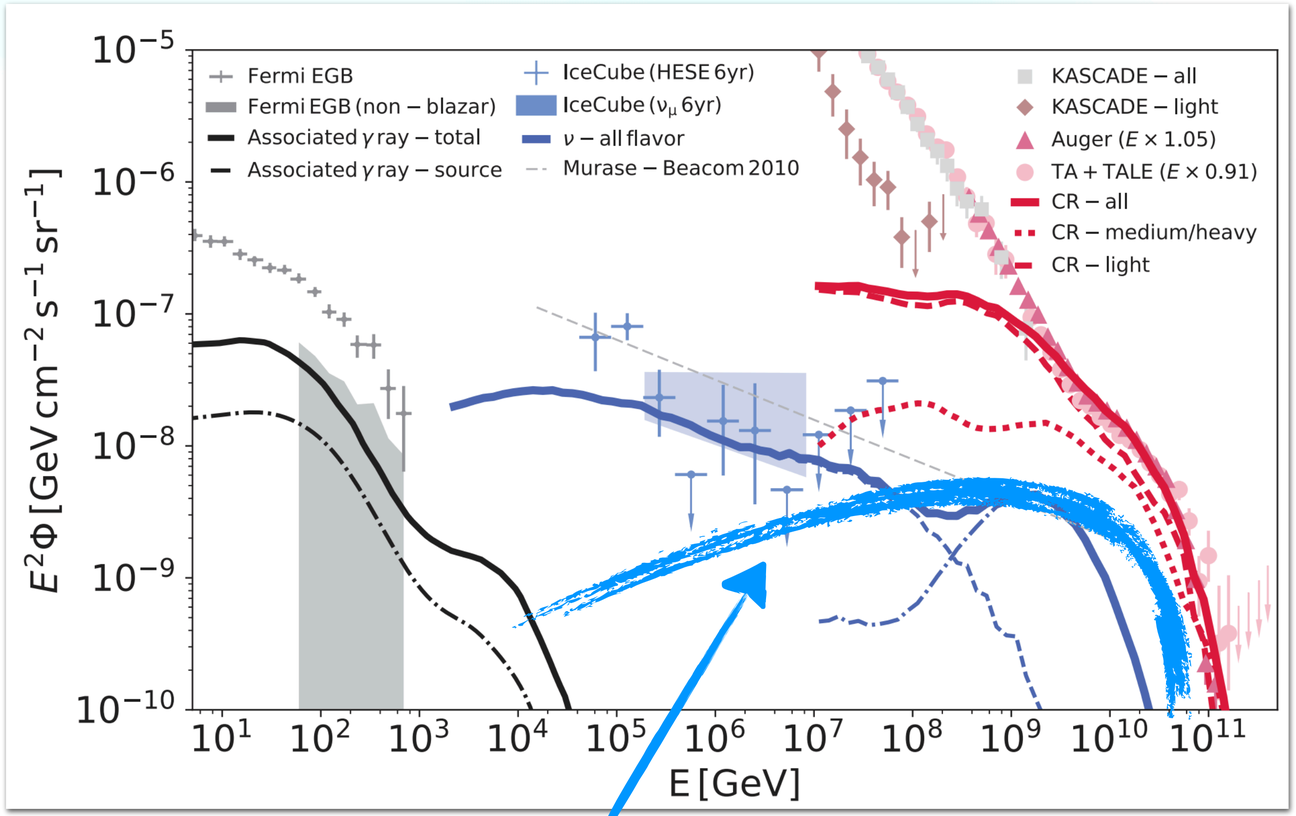


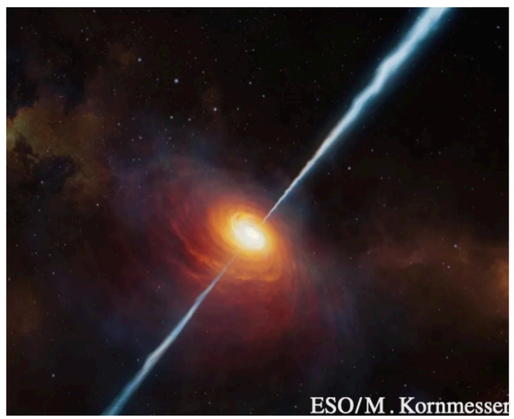


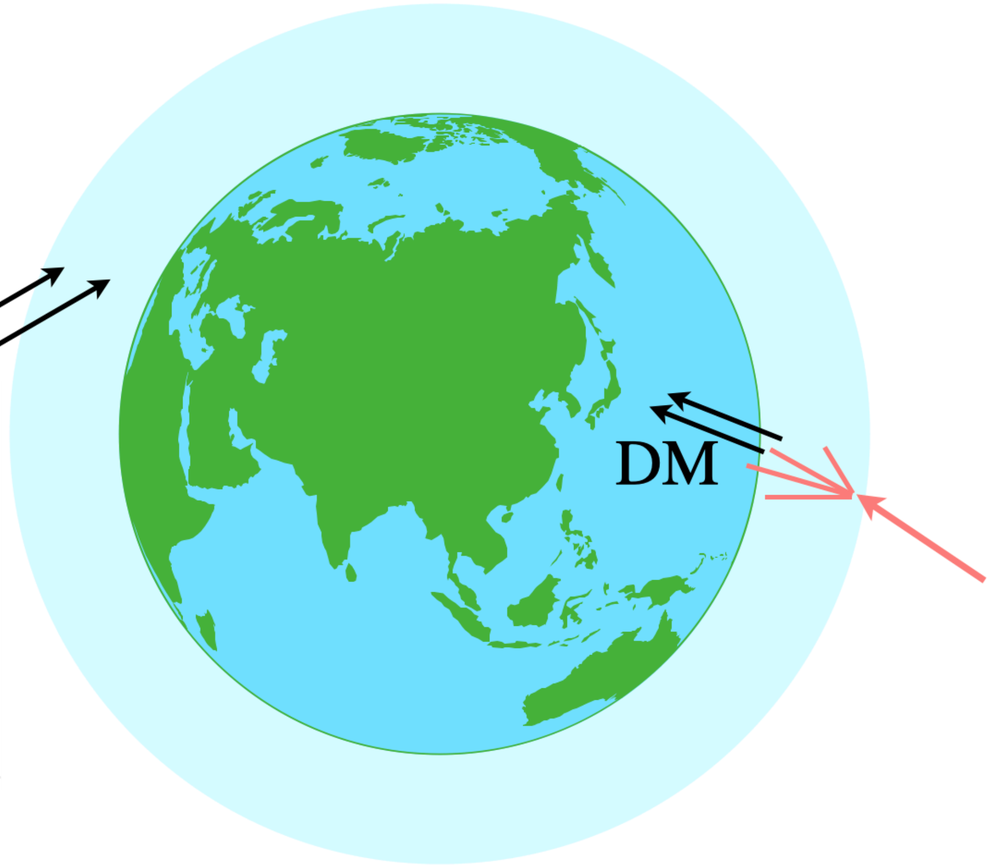
$\eta_\nu \sim 10^8$

Summary: Fast DM + Neutrino Detectors ≈

. . .

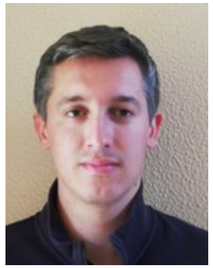
Outlook: Other sources + other detectors (KM3Net, IceCube,..)





De Marchi Granelli Nava FS in progress





Come to Bologna!

Invisibles24 Workshop

1-5 July

https://agenda.infn.it/event/39073/

Invisibles24 School 24-28 June

https://agenda.infn.it/event/39074/

The list of topics and confirmed lecturers will include:

- Dark sectors in the lab and in the sky (**Maxim Pospelov**)
- Astrophysical and cosmological aspects of gravitational waves (**Chiara Caprini**)
- Dark energy and inflation (speaker TBC)
- Effective field theories (**Aneesh Manohar**)
- Soft skills: Writing and Speaking to different audiences (**Patricia Palomino-Manjón**)

The school also features hands-on and tutorial sessions, where students will further discuss the topics covered in the lectures within an informal environment, and a poster session.

Registration Fee: We are working to make the fee as low as possible. We can now guarantee it will be lower than 300 euros. More details on this will be made available here soon.

Confirmed invited speakers and topics (more to be announced)

Martin Bauer (Relic neutrino background)
Simone Blasi (News on domain walls)
Mark Chen (Overview of neutrino experiments: what is new after Neutrino2024?)
Marco Cirelli (Dark matter indirect detection)
Enrique Fernandez-Martinez (BSM with lab neutrinos)
Katherine Freese (Pulsar Timing Arrays)
Belen Gavela (New tests of ALP-fermion interactions)
Edward Hardy (Axion cosmology)
Anson Hook (Reflections on the matter/dark matter coincidence)
Bradley Kavanagh (Black holes inspirals: lessons for dark matter)
Belina von Krosigk (Direct detection of sub-GeV dark matter: experimental status)
Alexander Kusenko (Primordial black holes)
Laura Lopez-Honorez (Cosmological probes of dark matter's energy injections)
Fabio Maltoni (Particle pheno and quantum)
Jorge Martin Camalich (BSM&flavour: life after the anomalies?)
Clara Murgui (Atomic sensors for BSM)
Stephen Parke (Neutrino mass ordering)
Serguey Petcov (Status and prospects of neutrino physics)
Alberto Ramos (The strong CP problem in the quantum rotor)
Marco Regis (Axions in radio)
Nuria Rius (News on leptogenesis)
Marco Selvi (Recent results in dark matter direct detection)
Javi Serra (BSM at finite density)
Geraldine Servant (News on electroweak baryogenesis)
Carlos Tamarit (Is the strong CP problem real?)
Sebastian Trojanowski (Long-lived particles at accelerators)
Jessica Turner (Gravitational waves from GUT and HEP)
Miguel Vanvlasselaer (News on bubbles wall dynamics)
Gwen de Wasseige (IceCube and KM3NeT results - high and low energy frontiers)
Susanne Westhoff (Axion-like particles at colliders)
Sam Witte (Axions clouds around pulsars)

Back up

More on: DM-nucleon scatterings

Cross Sections

$$\mathscr{L} \supset g_\chi\, a\, \bar{\chi} i\gamma_5 \chi + g_q\, a\, \bar{q} i\gamma_5 q$$

$$\frac{d\sigma_a}{dK_f} = \frac{1}{K_{\max}} \frac{g_{\chi a}^2 g_{Na}^2}{16\pi s} \frac{t^2}{\left(m_a^2 - t\right)^2} F_a^2(-t)$$

$$F_a(q^2) = G_a^{u+d}(q^2)$$

PCAC relation

$$G_a^q(-t) = G_A(-t) + \frac{t}{4m_N^2} G_P^q(-t) - 2\epsilon_q G_G(-t)$$

$$g_{Na} = g_a \frac{2m_N}{m_u + m_d} h_{u+d}$$

$$g_{ua} = g_{da} = g_a$$

$$h_q = \frac{\langle N | m_q \bar{q} i\gamma_5 q | N \rangle}{m_N}$$

$$h_{u+d} = 0.45$$

$$\mathscr{L} \supset g_\chi S \bar{\chi}\chi + g_q S \bar{q} q$$

$$\frac{d\sigma_\phi}{dK_f} = \frac{1}{K_{\max}} \frac{g_{\chi\phi}^2 g_{N\phi}^2}{16\pi s} \frac{\left(-t + 4m_\chi^2\right)\left(-t + 4m_A^2\right)}{\left(m_\phi^2 - t\right)^2} n_A^2\, F_A^2(-t)$$

$$F_{\rm He}(q^2) = \frac{1}{\left(1 + q^2/\Lambda_{\rm He}^2\right)^2}, \quad \Lambda_{\rm He} = 410\,\text{MeV}$$

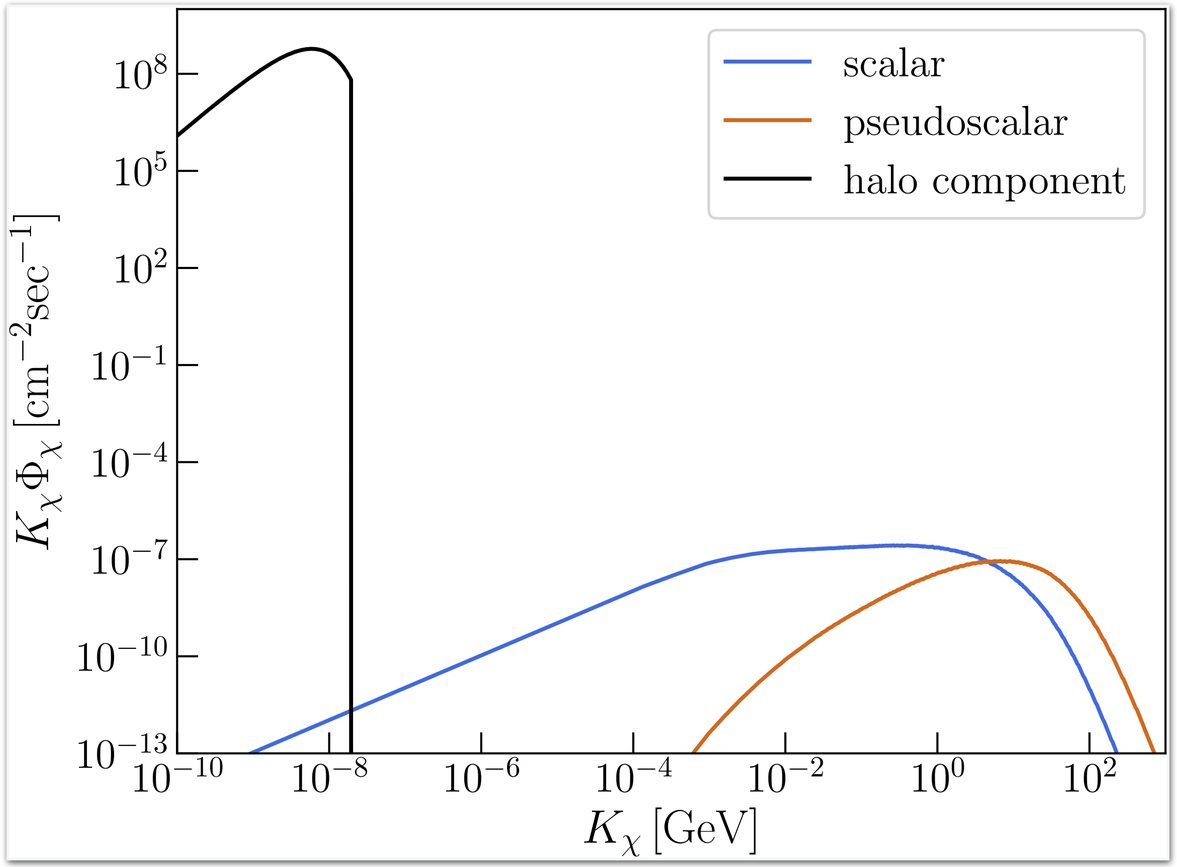
$$g_{N\phi} = g_\phi \left(\frac{m_N}{m_u} f_u^N + \frac{m_N}{m_d} f_d^N \right)$$

$$g_{u\phi} = g_{d\phi} = g_\phi$$

$$f_q^N = \frac{\langle N | m_q \bar{q} q | N \rangle}{m_N}$$

$$f_u^N = 1.99 \times 10^{-2}, \quad f_d^N = 4.31 \times 10^{-2},$$

Flux of Accelerated DM Component



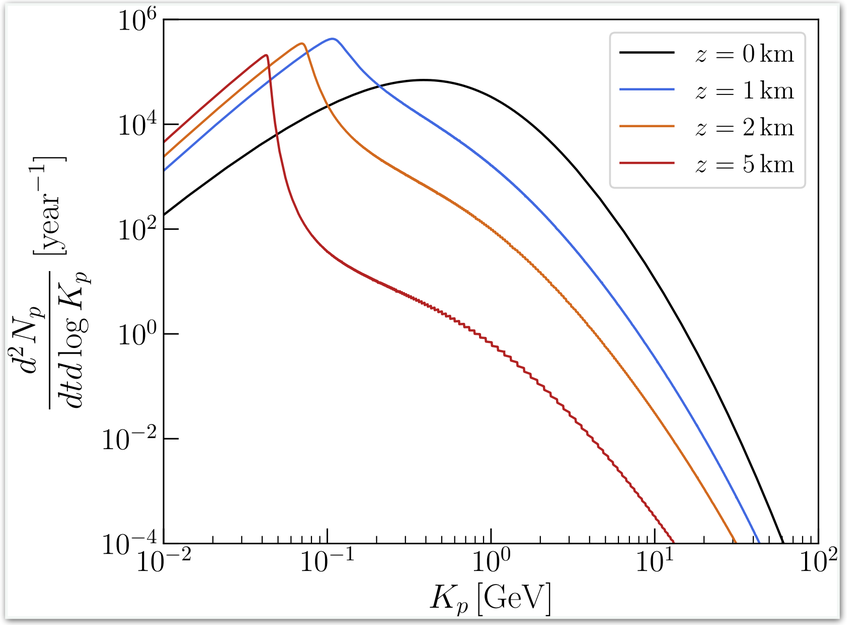
$M_{\mathrm{DM}} = 10\ \mathrm{MeV}, \quad M_{\mathrm{mediator}} = \mathrm{GeV}, \quad g_\chi g_u = g_\chi g_d = 0.1$

Earth Attenuation

$$\frac{d\bar{K}_\chi(z)}{dz} = -\sum_T n_T \int dK_T \, K_T \frac{d\sigma}{dK_T}$$

$$\bar{\Phi}_\chi(z) d\bar{K}_\chi(z) = \Phi_\chi dK_\chi$$

$$\mathscr{L} \supset g_\chi \, a \, \bar{\chi} i\gamma_5 \chi + g_q \, a \, \bar{q} i\gamma_5 q$$



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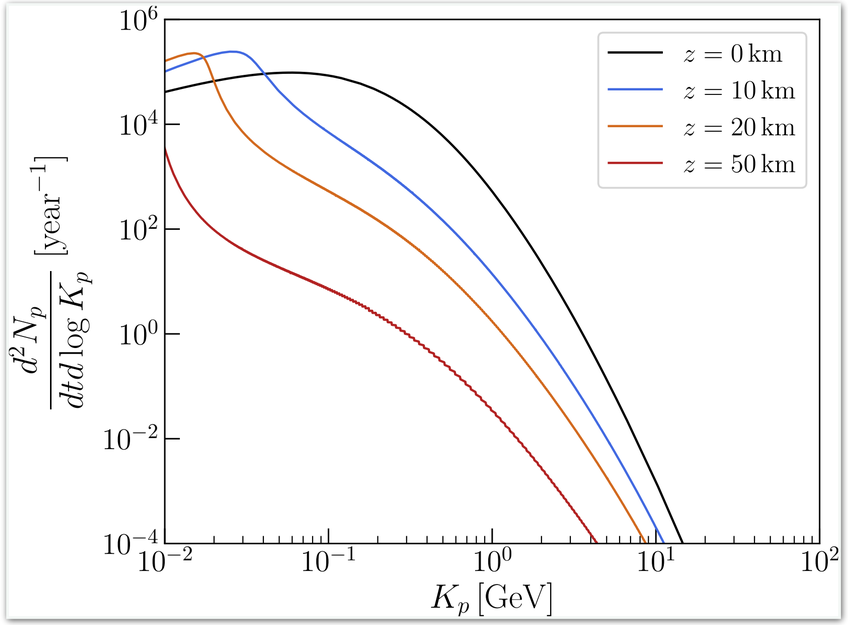

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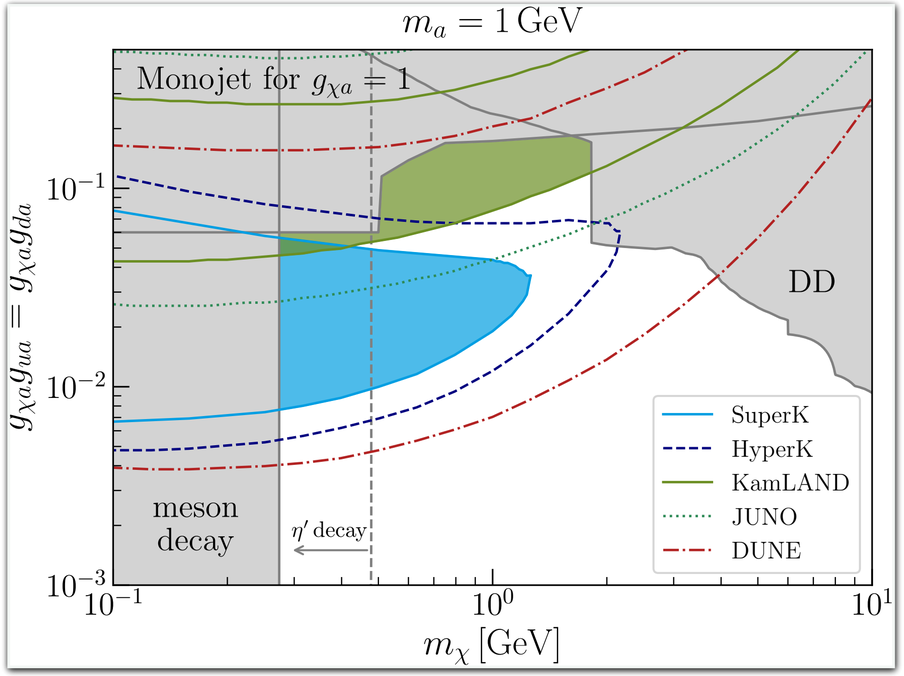
Limits for other values of parameters

$$\mathscr{L} \supset g_\chi\, a\, \bar{\chi} i\gamma_5 \chi + g_q\, a\, \bar{q} i\gamma_5 q$$



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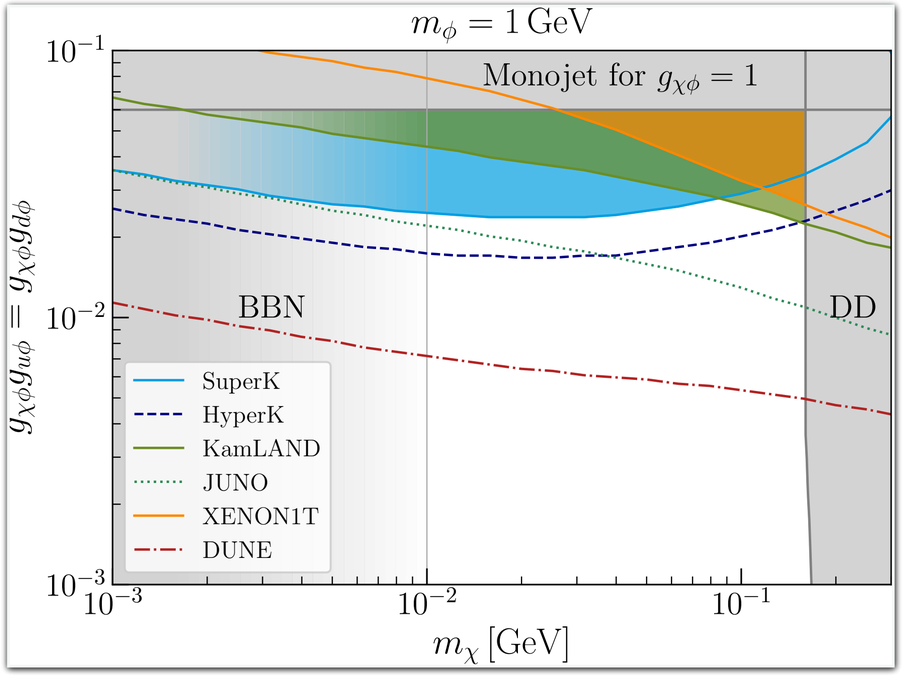

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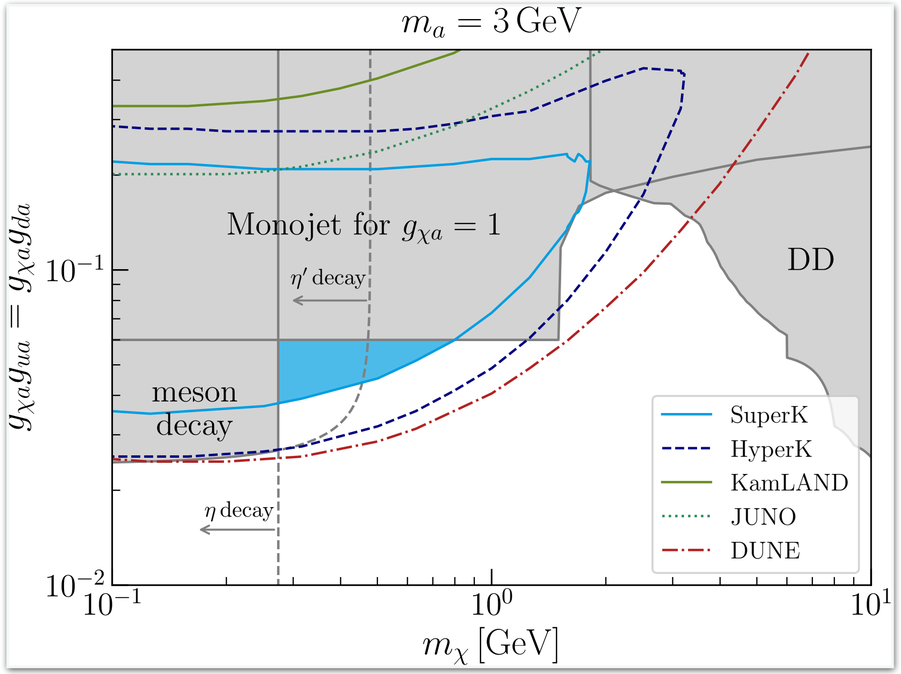

$$\mathscr{L} \supset g_\chi S \bar{\chi}\chi + g_q S \bar{q} q$$