Feebly Interacting Particles from cosmic rays showers

Luc Darmé
IP2I – CNRS

22/06/2022

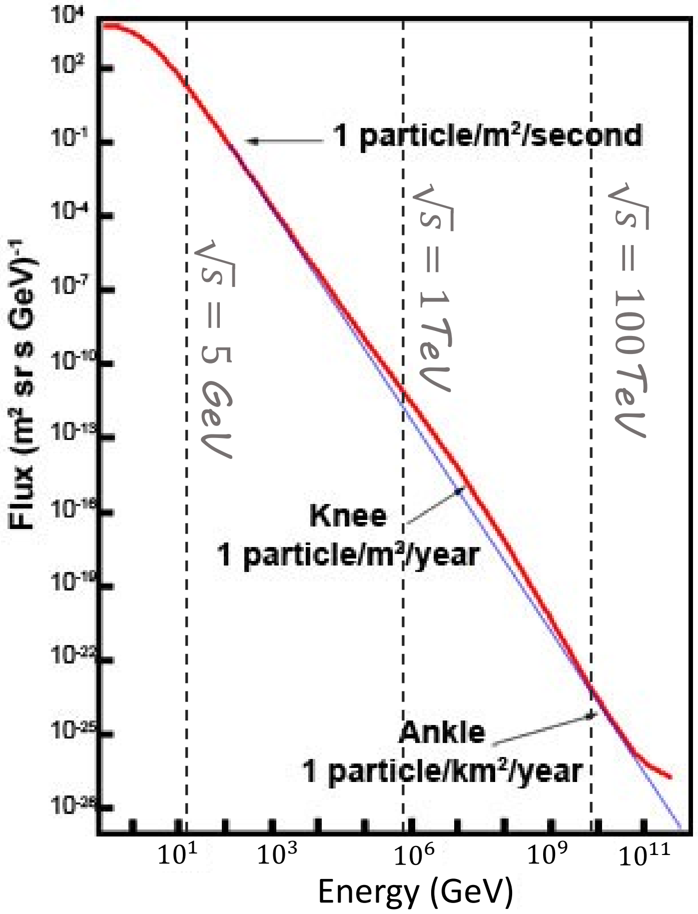
Based on 2205.09773

This work has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101028626

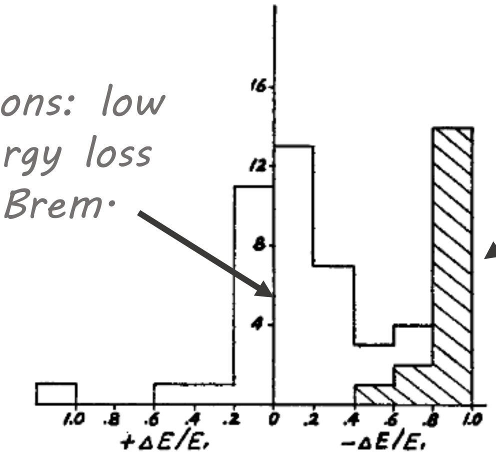
The atmospheric collider

- Cosmic rays (CR) constantly impinge on the higher atmosphere
- Flux extending to extremely large energies, but …
  - →Sharp fall of the flux at larger energies
  - →Can only be used as a “beam dump”

$$s = 2\,E\,m_p$$



Muons: low energy loss by Brem.



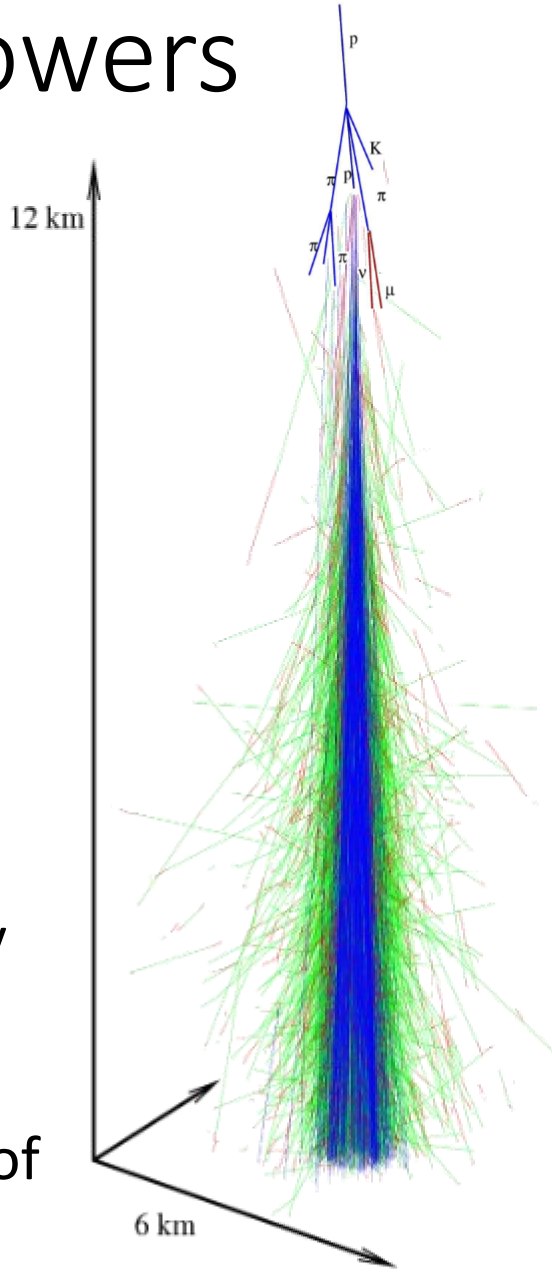
Electrons: large energy loss by Brem.

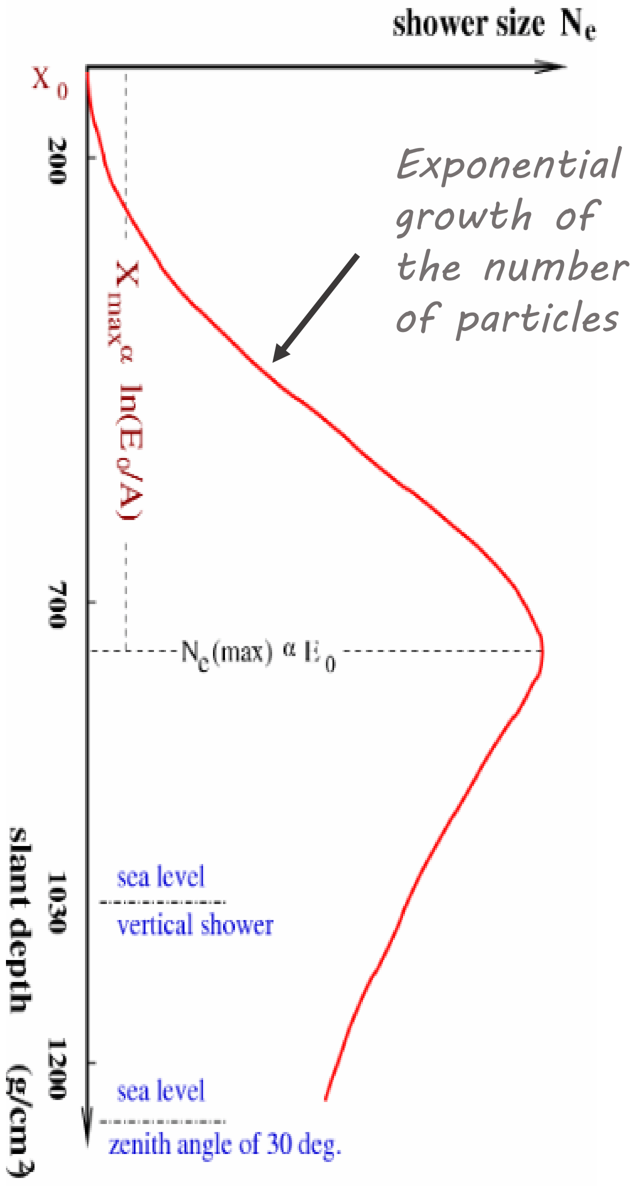
Figure 2: Distribution of fractional losses in 1 cm of platinum.

- CR are well suited to study light new physics *Cf Yongsoo Jho’s talk this morning!*
- Muons have been discovered in this way
  - →Anderson and Neddermeyer 1936

Atmospheric particle showers

- Initial pN interaction creates mostly hadrons final states
- $\pi^0, \eta \to \gamma\gamma$ decays generates of electromagnetic sub-showers
  - → Typically ½ of the total initial energy goes into the e^+, e^-, γ
- Particle showers "convert energy to statistics" : $N^{max} \propto \frac{E_{ini}}{0.6\ GeV} Z_{mat}$
  - → High energy protons convert to many light mesons and a very large number of $e^{\pm}$
  - → Serve as initial states for production of light new physics





Exponential growth of the number of particles

Adapted from R. Engel 2005

Model of Feebly Interacting Particles

- FIPs= “new light and (quasi)-neutral particles which interact with the SM via suppressed new interactions”
- We consider a light vector FIP V^μ

Kinetic mixing: dark photon-like

New gauge interaction: e.g. $L_\mu - L_\tau$ gauge boson

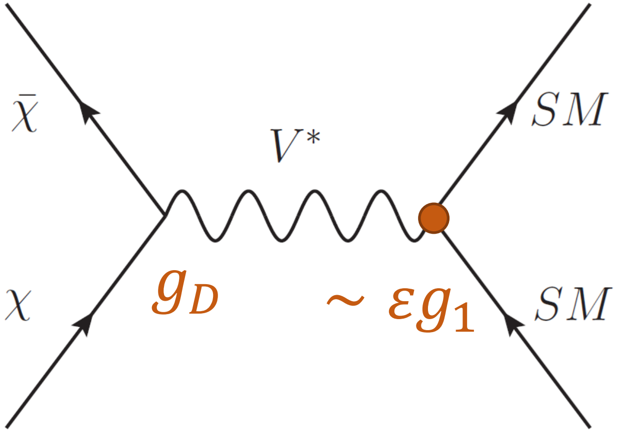
$$\mathcal{L} \supset -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} M_V^2 V_\mu V^\mu + \frac{\epsilon}{2} V_{\mu\nu} \boxed{F^{\mu\nu}} + \sum_{\ell=e,\mu,\tau} V_\mu \boxed{\bar{\ell}\,(g_{V\ell} + \gamma^5 g_{A\ell})\ell} \quad \text{+quarks...}$$

- This constructions are often used in models of thermal sub-GeV dark matters

$$\mathcal{L} \supset -g_D \mathcal{J}_D^\mu V_\mu \longrightarrow$$

Contains FIP/dark sector interaction, can be large!

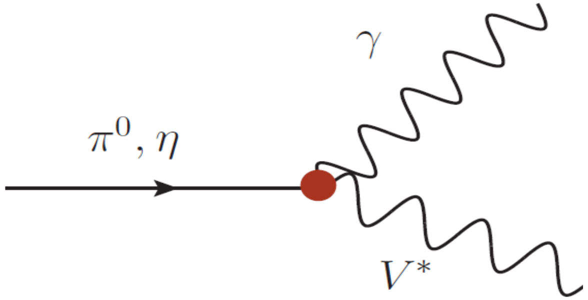
- The dark photon will decay to dark matter particles



Dark photon production from CR

- Production occurs through both hadrons- and EM-driven processes
  → Only the hadronic processes included so far

Light neutral mesons decays

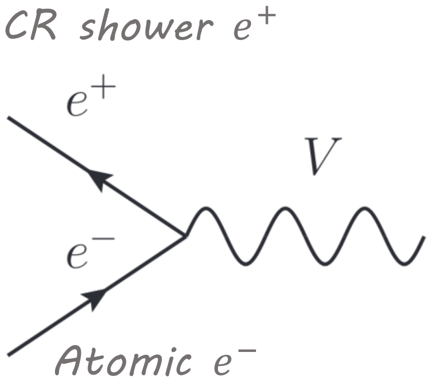


→ Decent number of π^0 progenitors available

→ Strong enhancement from long life-time

$BR_{\pi^0 \to V\gamma} \propto \varepsilon^2$, no α_{em} suppression

Resonant production



with $E_{res} = M_V^2/2m_e$

→ Cross-section extremely large at resonance

→ Fixed positron energy required (up to largish V width)

$$\sigma_{res} \sim \frac{2\alpha_{em}\pi^2}{m_e}\varepsilon^2\,\delta(E_+ - E_{res})$$

- As the shower develops, the secondary e^+ "scans" over various energy
  → helps reaching the resonant energy condition.

Describing FIPs production in a CR shower

pN

- Hadronic shower
- EM sub-showers

- For mesons, we need the distributions in energy: $f_M(E_M)$

- For $\gamma, e^+/e^-$ descriptions of EM showers, differential track lengths $T_{\gamma,e^\pm}(E)$: ("Distance travelled in the atmosphere by all $\gamma, e^\pm$ at energy E")

$$\mathcal{N}_{\rm FIP} \sim \frac{\mathcal{N}_A \rho_{\rm tar}}{A_{\rm tar}} \times T_{e^\pm,\gamma} \times \sigma_{\rm FIP}$$

$T_{\gamma,e^\pm}(E)$, $f_M(E_M)$ can be be typically obtained via:

- Empirical distributions of light mesons (BMTP, Sanford-Wang, Burman-Smith)
- Primary hadrons (Pythia8, EPOS@LHC, QGS JETII) + Analytical EM shower description, track length (Tsai, Rossi-Greisen/Lipari)
- Full MC: GEANT4 , FLUKA (include secondaries), KORSIKA

Bonesini et al., hep-ph/0101163
Sanford, Wang 1967

Burman, Smith 1989

Tsai, 1986
Rossi, Griesen 1941
Lipari, 0809.0190

Bierlich et al.
Pierog 2013
Ostapchenko 2007

The shower (1): getting the mesons right

- Critical to have an accurate description of the light mesons distributions

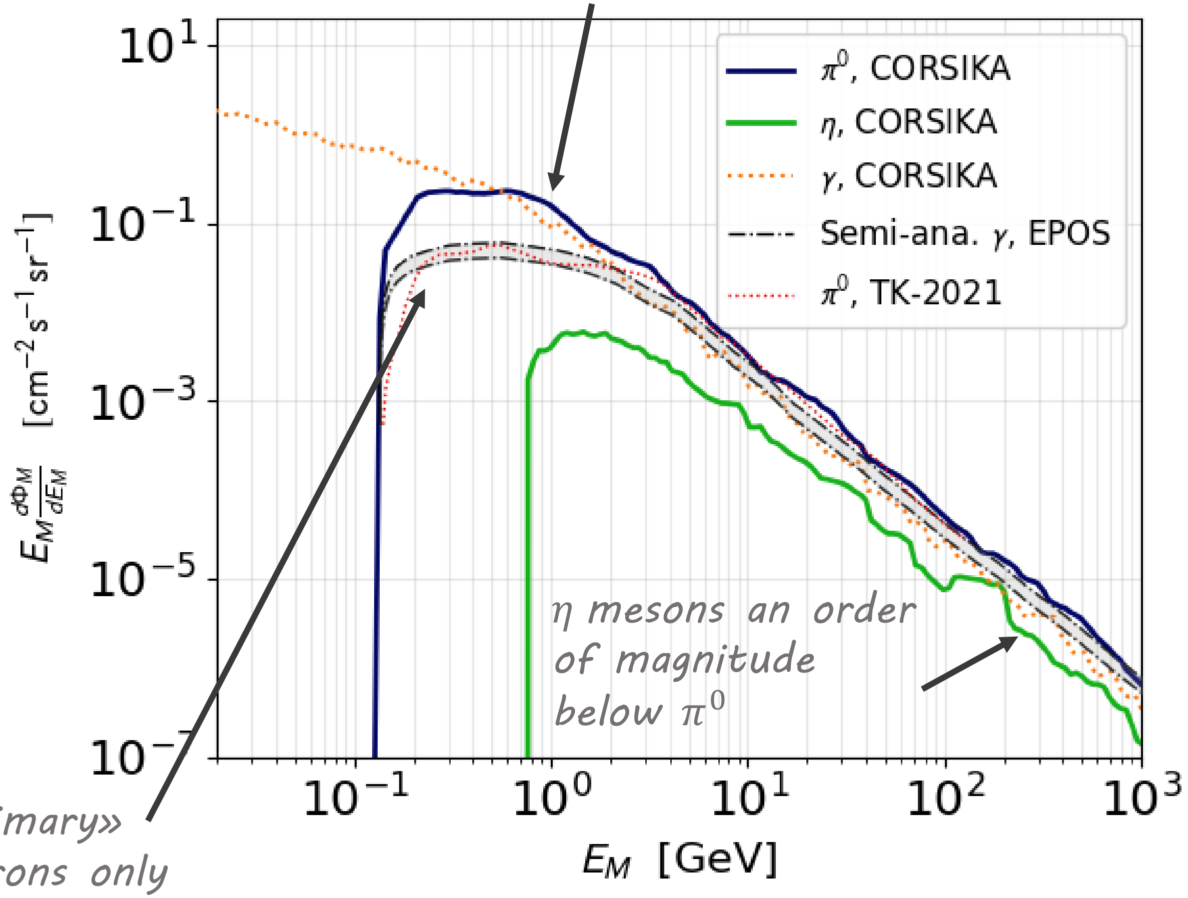
  → light mesons decays serves as EM-showers precursors

  $$\pi^0 \to \gamma\gamma$$

  → direct source of FIP

  $$\pi^0 \to V\gamma$$

- For cross-checks, we do both
  - → Primary interaction only in EPOS
  - → Full shower development in CORSIKA
- Then integrate with the proton CR flux



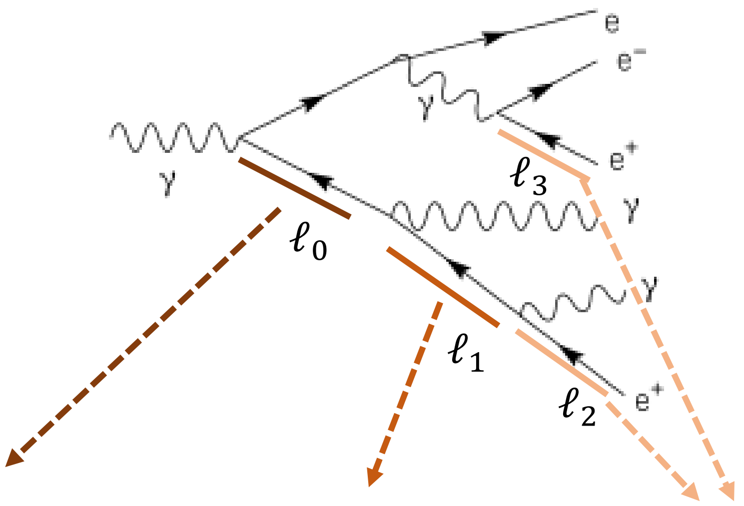
«Secondary» hadrons dominates at low energies !

«Primary» hadrons only

η mesons an order of magnitude below π^0

The SM (2): track lengths in EM showers

- In order to estimate the number of FIPs produced, we need the total distance travelled by positrons of a given energy



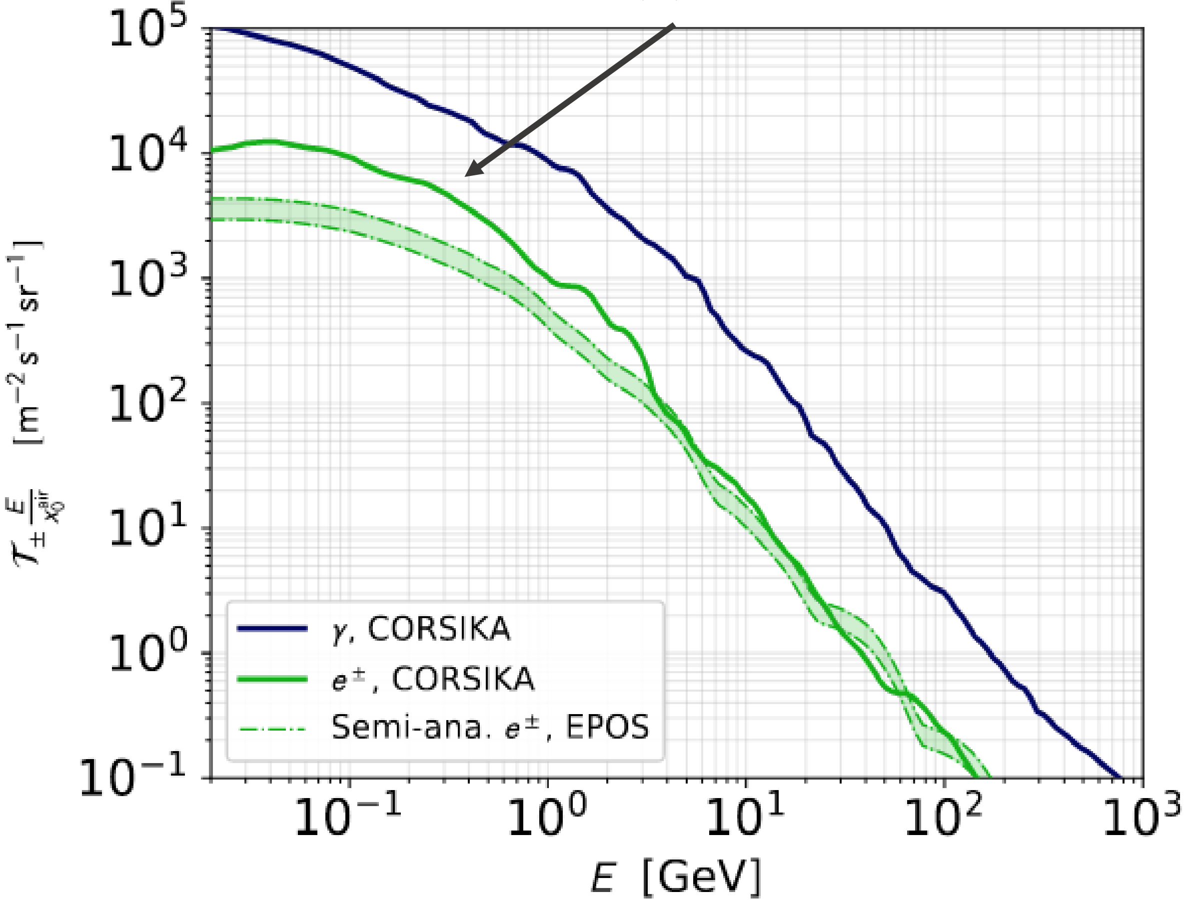
$T_+(E_0) \rightarrow T_+(E_0) + \ell_0$

$T_+(E_1) \rightarrow T_+(E_1) + \ell_1$

$T_+(E_2) \rightarrow T_+(E_2) + \ell_2 + \ell_3$

In practice: make an histogram…

Again secondary production critical



- The atmospheric density as the shower developed must be accounted for (include overburden)

Dark photon distributions

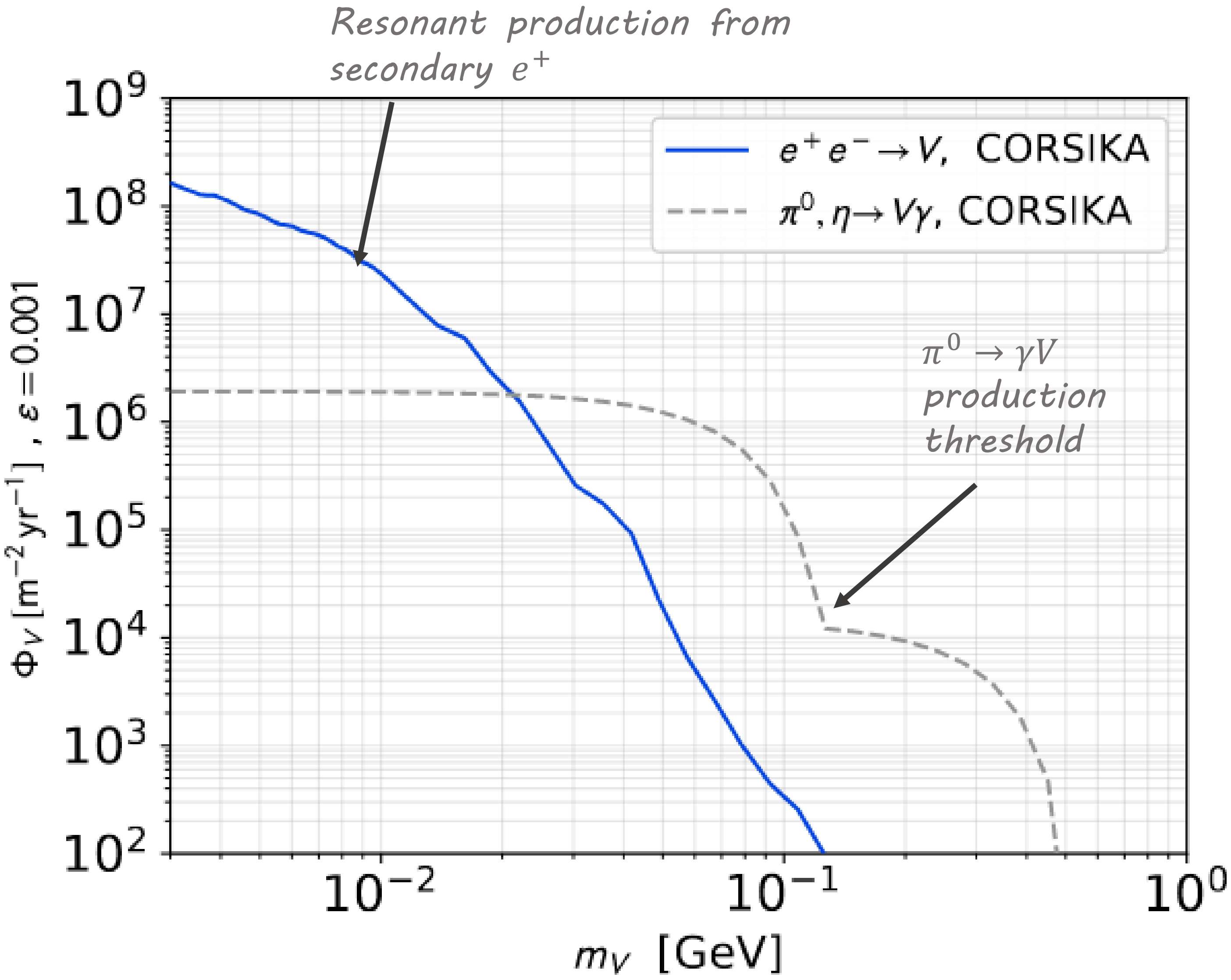
- Resonant process dominates below ~20 MeV

  → Orders of magnitude enhancement in prod. rates

  →Typical kinetic energy is lower than for the meson decays

- Huge rates, but in a very noisy environment + fast dark photon decays

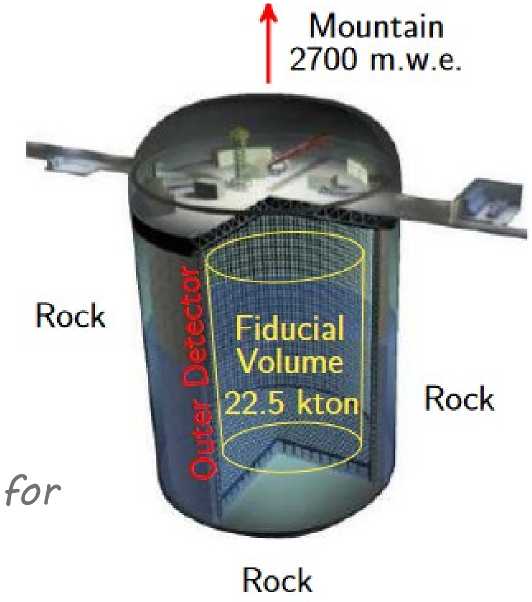
  →We will rely on $V \rightarrow \chi\chi$ followed by a DM detection in shielded underground detectors



Experimental strategy: neutrinos ktons

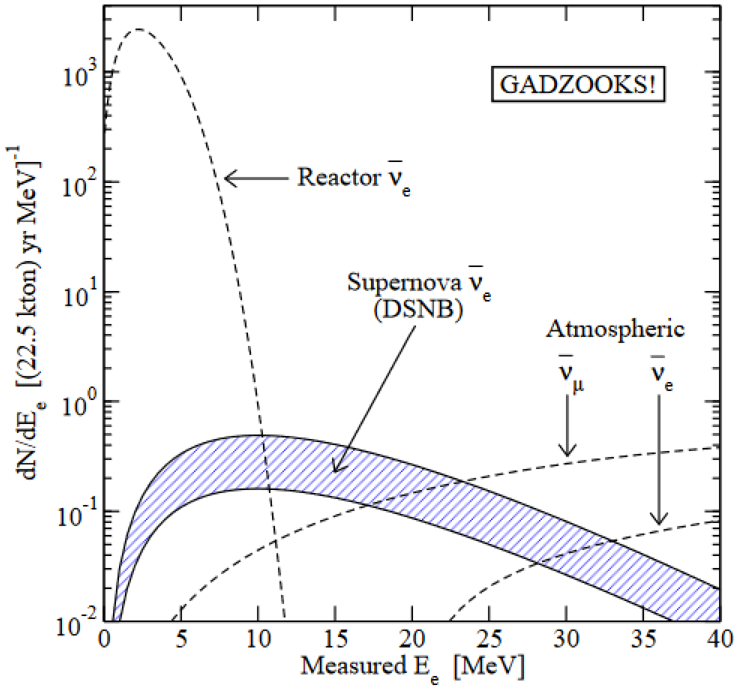
- Since the production process is ubiquous, use the biggest low background detector available: kilotons neutrinos detectors
- The signal is DM-electrons scattering process:

$$\chi e \to \chi e$$



Here SK, could work for DUNE, JUNO ...

Beacom and Vagins – hep-ph/0309300



The resonant spectrum dominate at low masses

$$E_\chi \sim \frac{M_V^2}{4m_e} \sim O(10s)\ \text{MeV}$$

→Looks like supernova neutrinos !

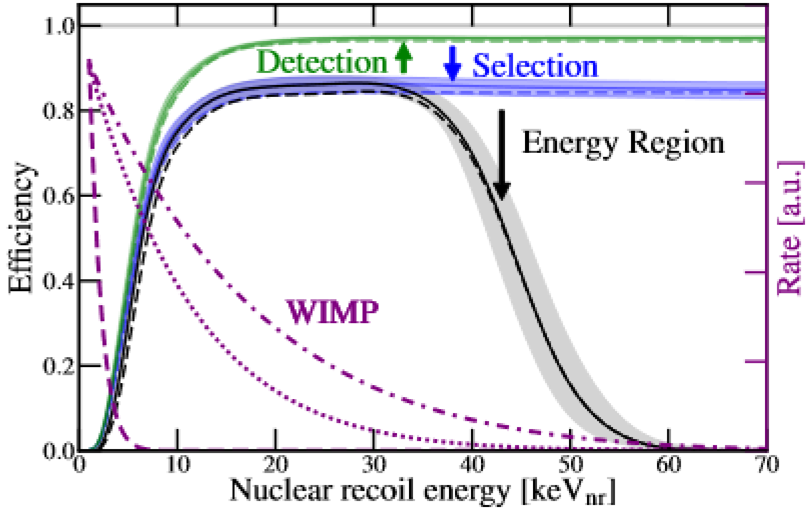
- We can re-interpret to a good extent existing SK constrain in the [16,88] MeV range

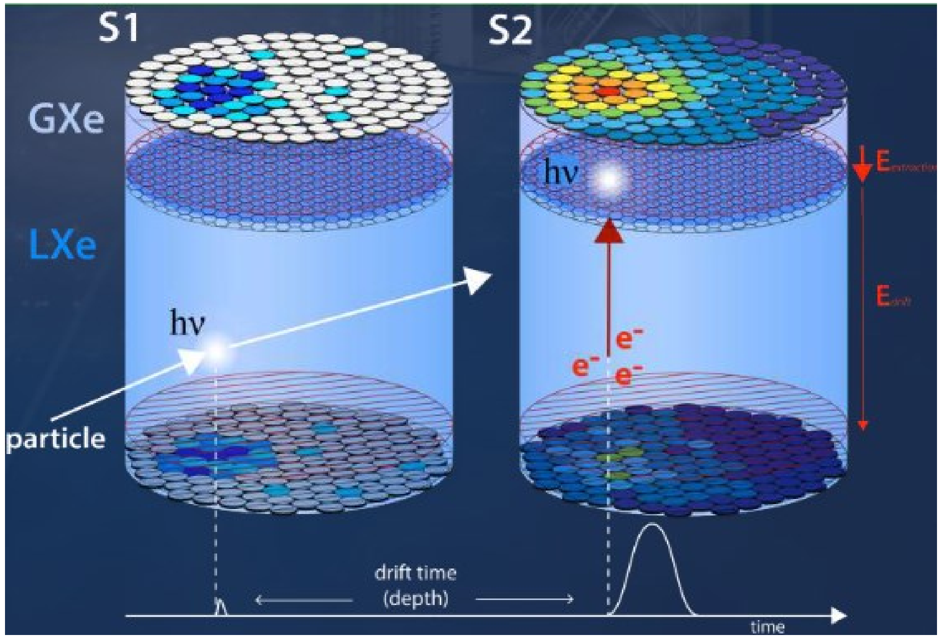
Experimental strategy: “heavy” DM detectors

- The DM is relativistic !
  - →Allow high-energy electrons signal / coherent scattering even from sub-GeV DM
  - → We also study DM-nucleus scattering: $\chi N \to \chi N$ with coherent enhancement

$$\frac{d\sigma^{cr}}{dE_r} = Z^2 F^2_{\text{Helm}}(Q)\,\frac{4\pi\varepsilon^2\alpha_{\text{em}}\alpha_D\tilde{f}_{f,s}M_A}{(E^2-m_\chi^2)(m_V^2+Q^2)}\ ,$$

XENON collaboration - 1805.12562





Here Xenon1T, but also PandaX, DarkLight…

- The recoil energy is corresponds to a non-relativistic, heavy DM one
  - → Use existing WIMP search

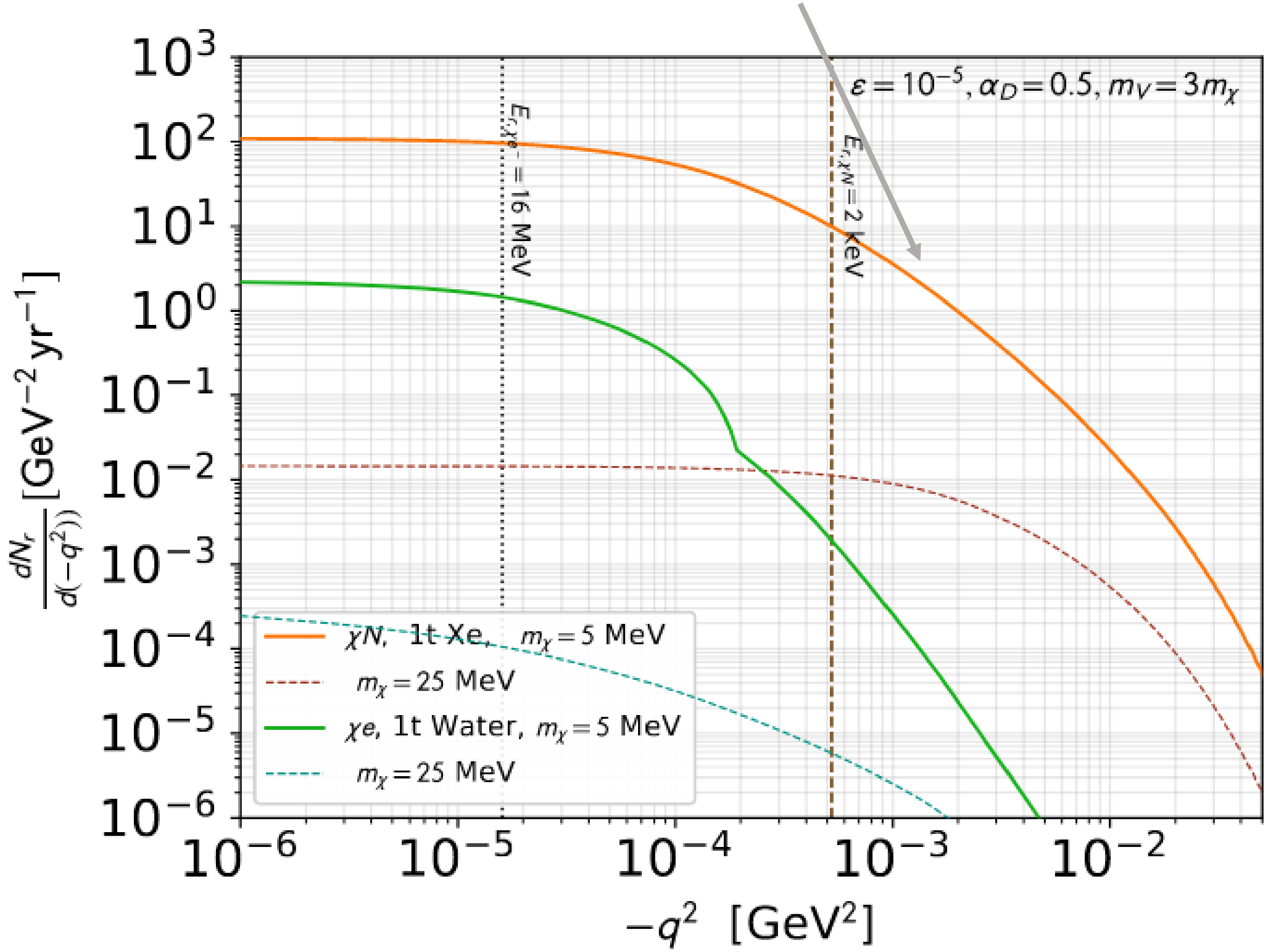
$Q^2 = 2\,m_{Xe}E_r \sim m_V^2 \ \Rightarrow E_r$ ten of keV

Result: events spectrum

- The coherent scattering CS larger than the incoherent electron process

  → But is applicable to much smaller detectors

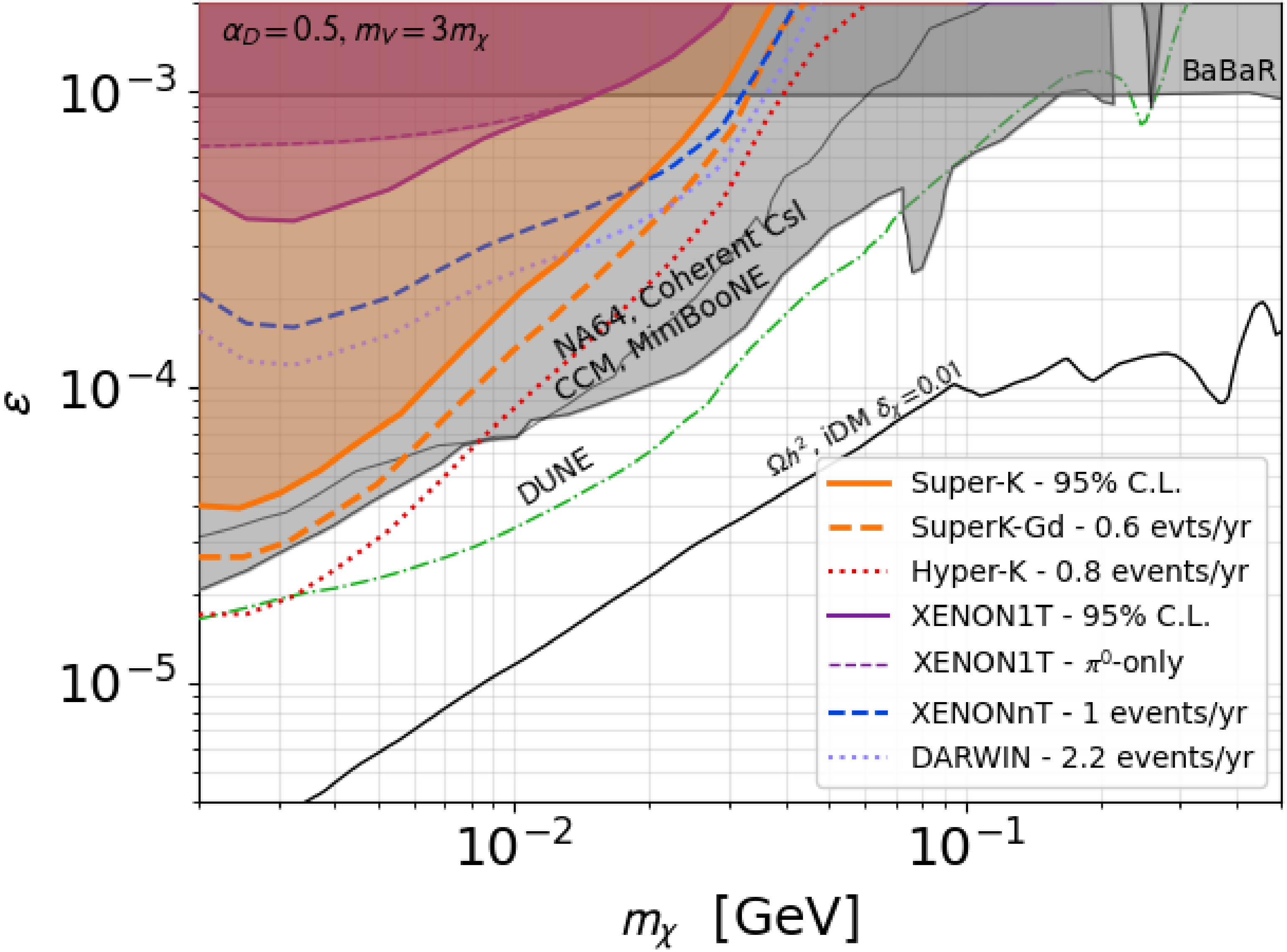
- The higher DM energy allows for signals in XENON even for (tens of) MeV-scale DM



We are a bit short for the WIMP search for MeV DM

Dark photons constraints

- Pure dark photon candidate + light DM
- Strong limits from missing energy searches
  - →$e^- Z \rightarrow e^- V$ at NA64
  - →$e^- e^+ \rightarrow \gamma V$ at BaBar
- Beam neutrino experiments can look for the same signatures (smaller volume as SK, but larger fluxes)
- DM experiments subdominant



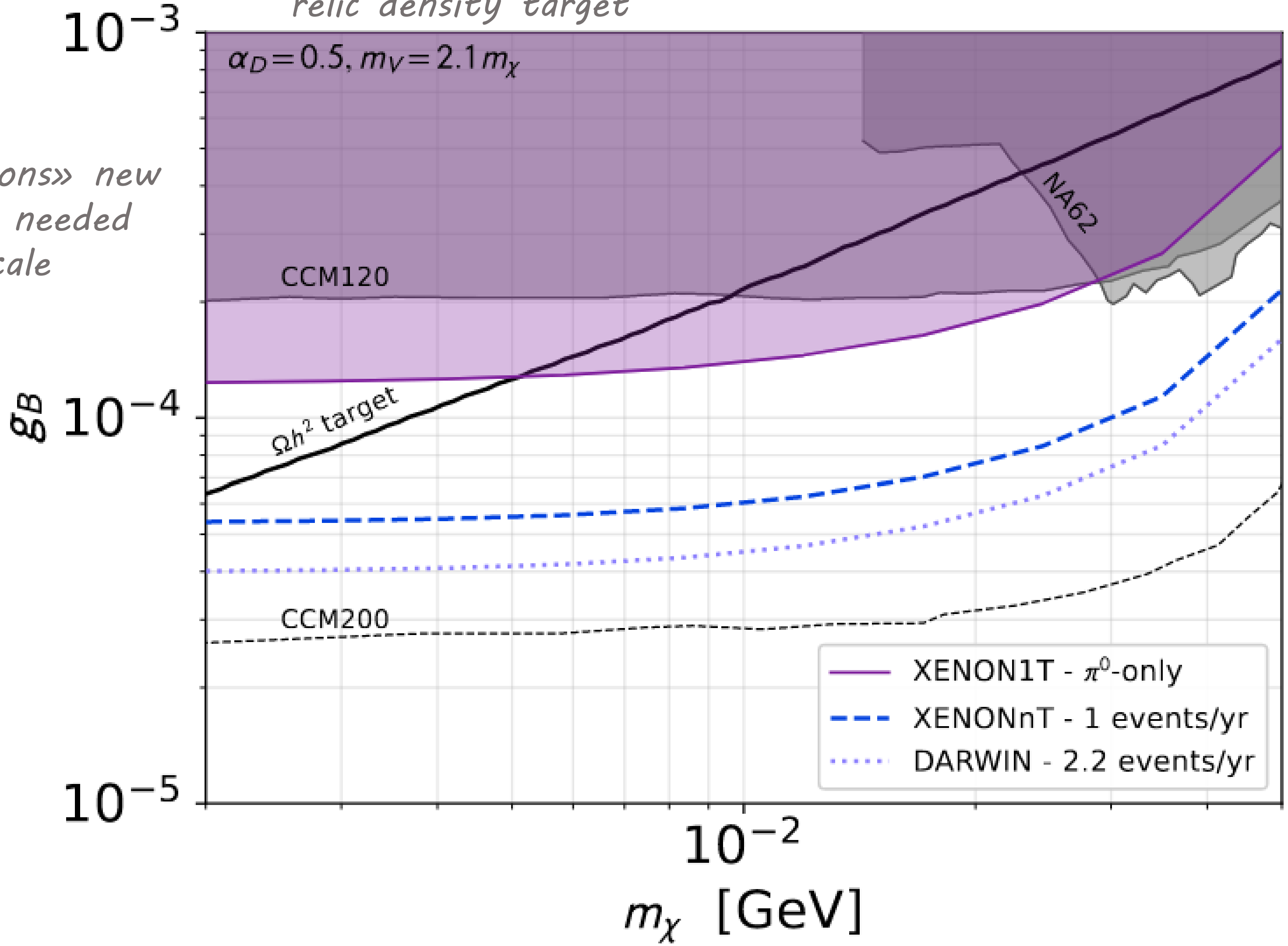
Baryon number example

- Assume now a « baryon » new gauge group
  - →In absence of lepton couplings, neutrinos/DM experiments become the dominant limits.
  - →CCM120 searched for light DM scattering specifically

- Current WIMP search at XENON1T gives the best limit in this parameter space

«Anomalons» new fermions needed at UV scale

Radiatively-generated kinetic mixing assumed for the relic density target



$$g_{B,X1t} = \varepsilon_{X1t} \times \sqrt{4\pi\alpha_{\rm em} Z_{\rm Xe}/A_{\rm Xe}}$$

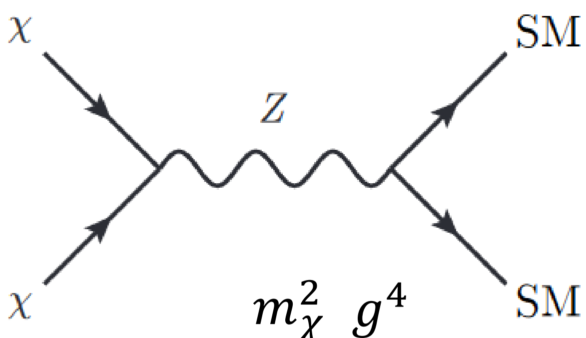
Conclusions

- We presented a full simulation of light mesons and their subsequent showers from cosmic rays in the upper atmosphere
- The dominant FIP production channel at low mass is by far driven by the shower EM component
  - →Resonant production $e^+e^- \to V$ drives the production rates
- Neutrino "telescopes" (aka kilotons far neutrinos detectors) can give limits competitive with the near detectors using atmosphere DM production
- The sub-dominant flux of relativistic dark matter can be observed in standard direct detection experiments, giving them access to sub-GeV dark matter candidates.
- Using also the e^- flux for EM showers.

Back-up :FIPs et simulations

Couplings to a dark sector

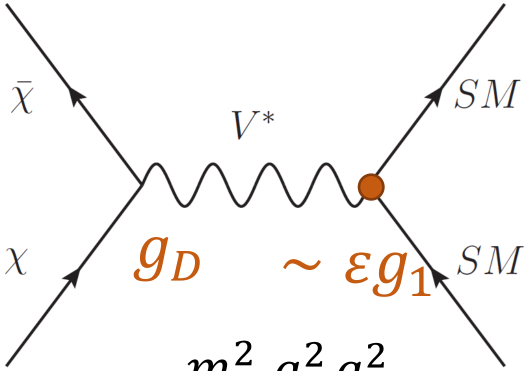
- Interest in FIPs also driven by building models of thermal sub-GeV DM



$$\sigma v \sim \frac{m_\chi^2}{m_Z^4}\frac{g^4}{32\pi}$$

$$\sigma v \sim 4 \cdot 10^{-9}\ \mathrm{GeV}^{-2}$$

$(ie\ \ 2 \cdot 10^{-26} cm^3/s)$



$$\sigma v \sim \frac{m_\chi^2}{m_V^4}\frac{g_D^2 g^2}{32\pi}\varepsilon^2$$

Below the GeV,
at $m_\chi < m_V$,
need $\varepsilon < 10^{-3}$

- Most FIP models can be embedded in a light dark matter setup (of course with various level of complexity …)

  → Altogether an extremely rich literature of new “mechanisms” to obtain the relic density
  (Forbidden DM, Secluded DM, Selfish DM, Cannibal DM, etc …)

Building light inelastic dark matter (1)

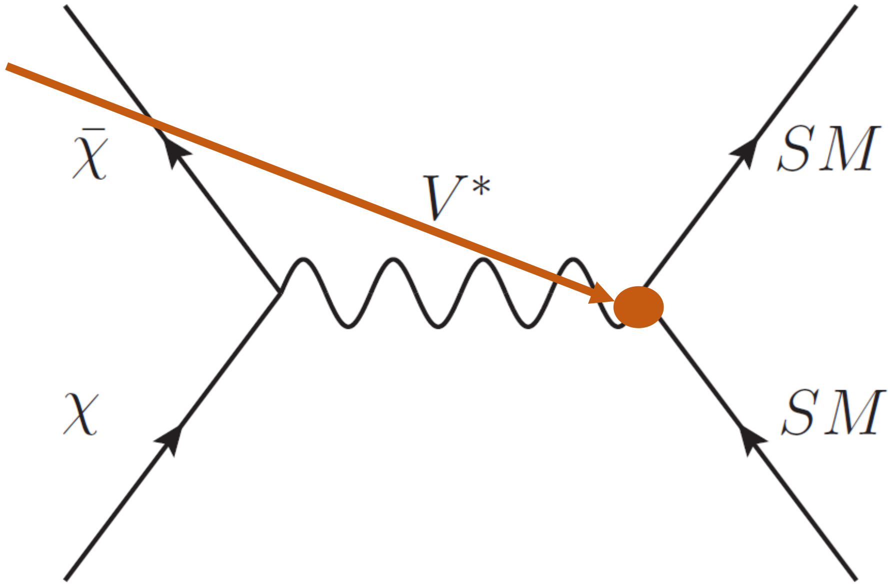
- We first construct the Lagrangian for the dark photon mediator:
- → rely on “kinetic mixing” term

Kinetic mixing term

$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \boxed{\frac{1}{2}\frac{\varepsilon}{\cos\theta_w}B_{\mu\nu}F'^{\mu\nu}}$$

$$\boxed{+(D^\mu S)^*(D_\mu S) + \mu_S^2|S|^2 - \frac{\lambda_S}{2}|S|^4}$$

Dark Higgs potential



- After “dark” U(1) symmetry is broken, a massive light dark photon and a correspondingly light dark Higgs S.

Inelastic dark matter (2)

$$\mathcal{L}^{\mathrm{DM}}_{pDF} = \bar{\chi}\left(i\not{D} - m_\chi\right)\chi + y_{SL} S \bar{\chi}^c P_L \chi + y_{SR} S \bar{\chi}^c P_R \chi \; + \; \text{h.c.}$$

- Introduce a Dirac fermion dark matter

  $\chi = (\chi_L, \bar{\chi}_R)$
- The dark Higgs VEV splits both states, leading to a fermionic mass matrix:

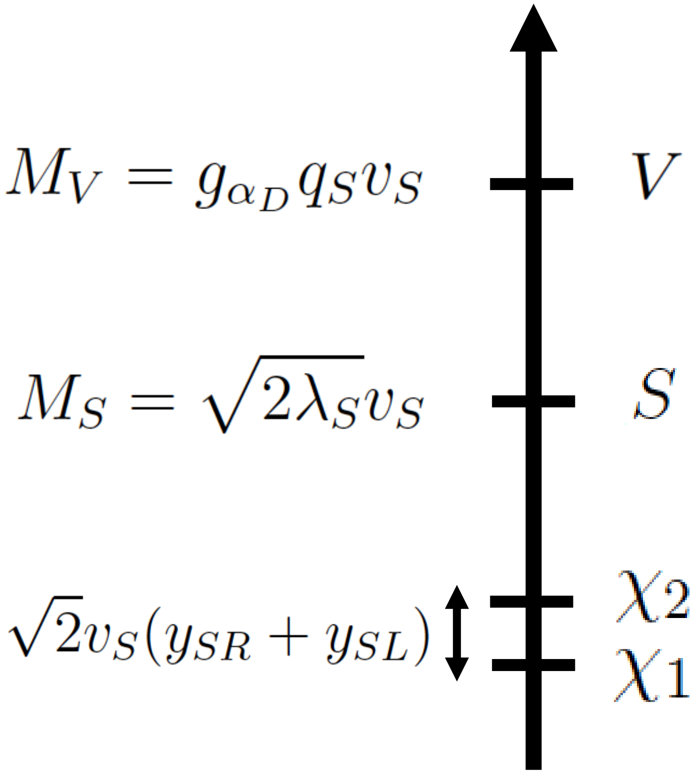
$$M_\chi = \begin{pmatrix} \sqrt{2} v_S y_{SL} & m_\chi \\ m_\chi & \sqrt{2} v_S y_{SR} \; . \end{pmatrix}$$

- After diagonalization we get two Majorana fermions

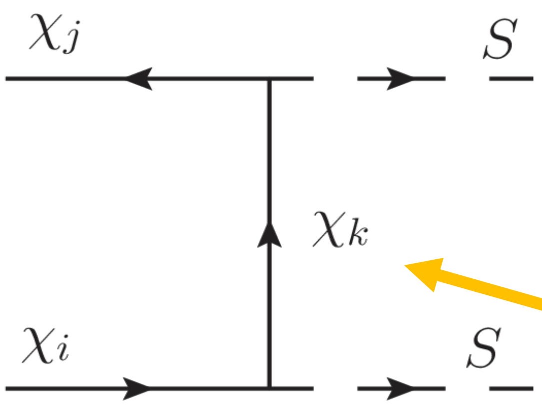
  → Lightest χ_1 state is DM

  → In the limit $y_{SL} \simeq y_{SR}$, the dark photon only interacts via

$$\mathcal{L} = \left(i g_D \bar{\chi}_2 \gamma^\mu \chi_1 + e\varepsilon \mathcal{J}^\mu_{\mathrm{em}}\right) V_\mu$$

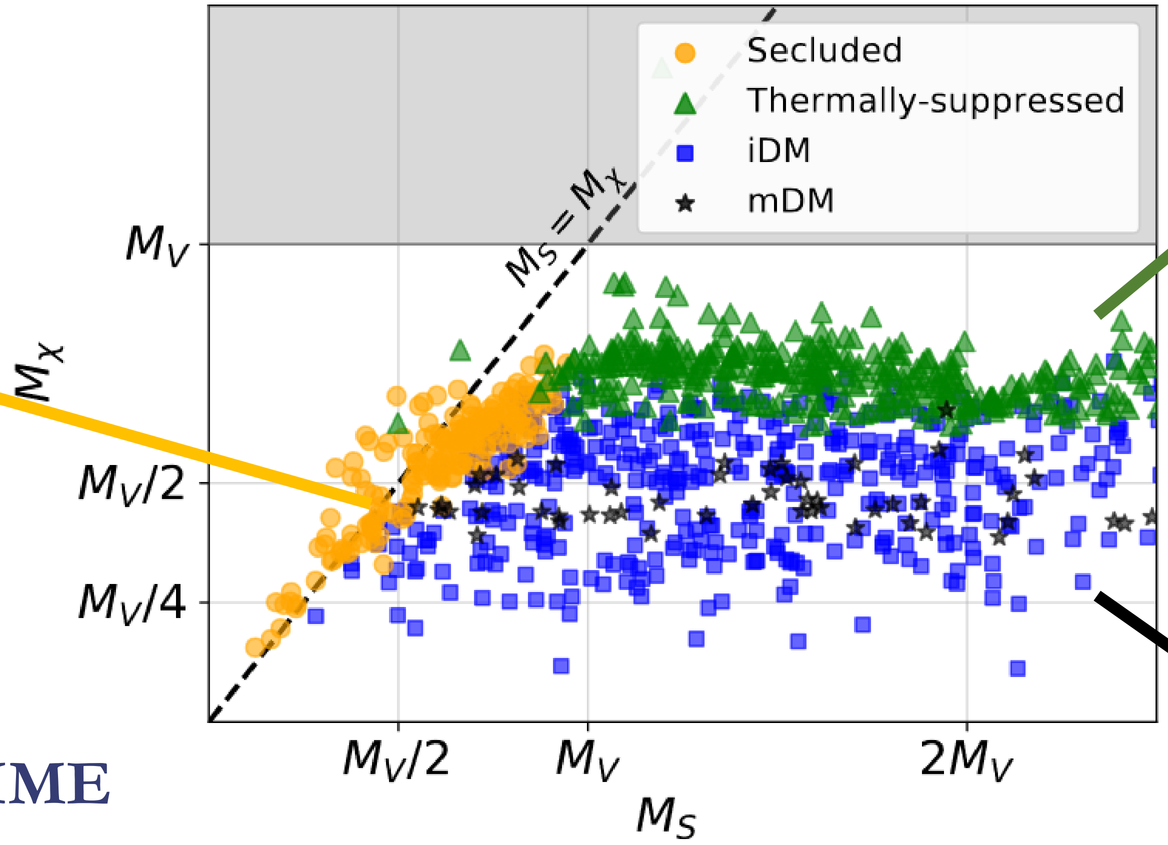


Typical regimes with correct relic density

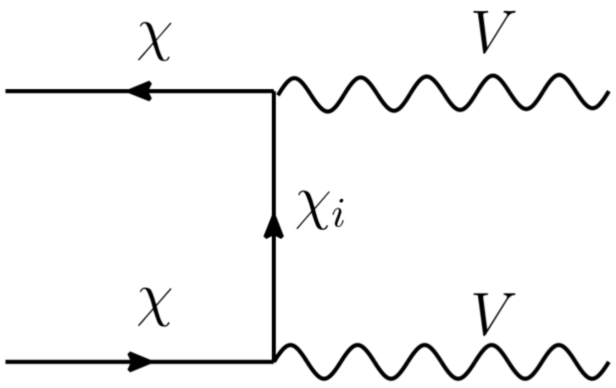


$$M_\chi \gtrsim M_S$$

SECLUDED REGIME

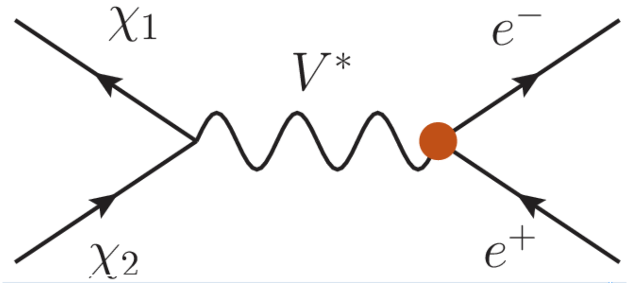


FORBIDDEN REGIME



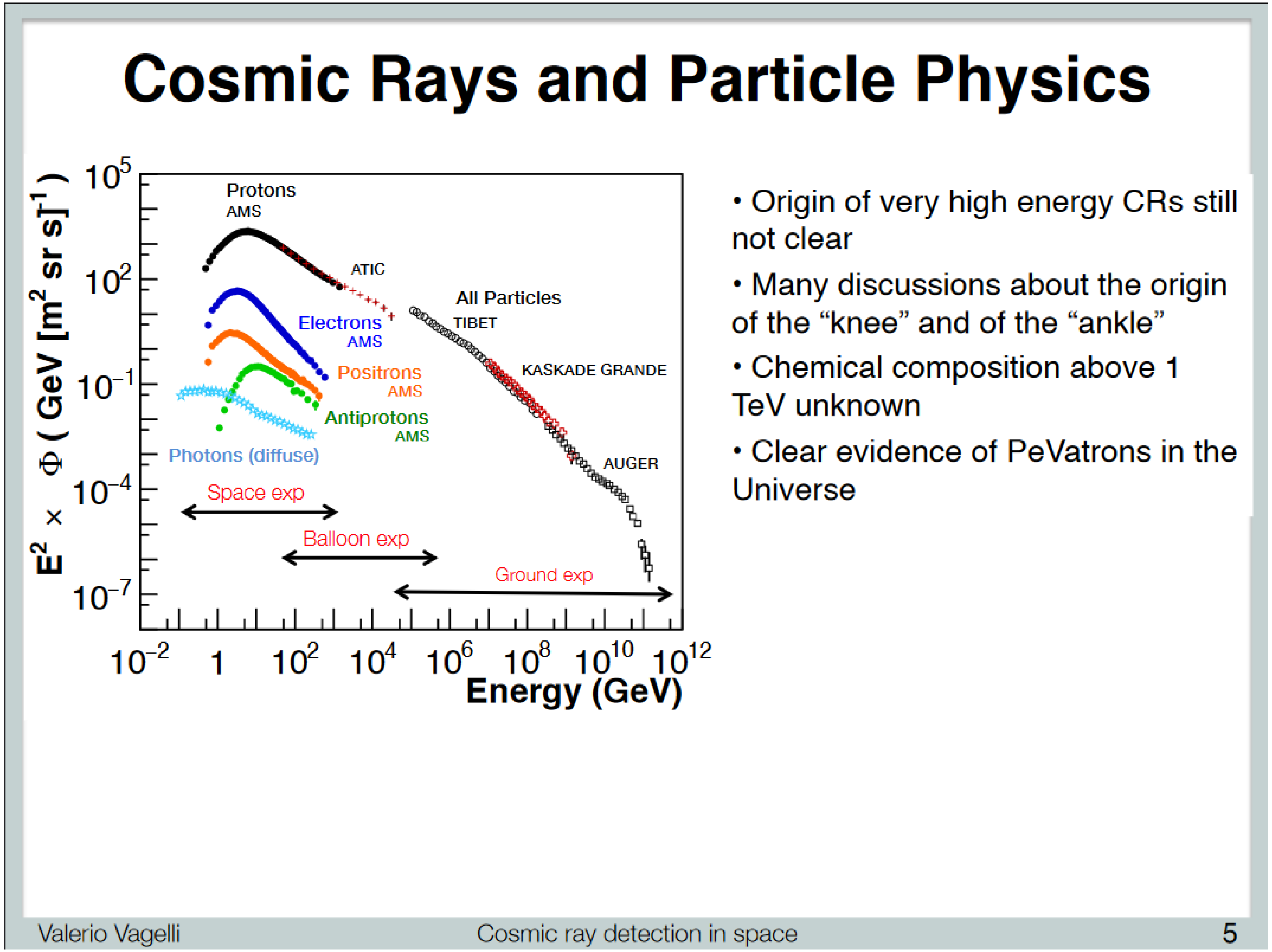
$$M_\chi \lesssim M_V \lesssim M_S$$

iDM/mDM REGIME



All cosmic rays

- Protons strongly dominates the fluxes above the GeV



Cosmic Rays and Particle Physics

- Origin of very high energy CRs still not clear
- Many discussions about the origin of the “knee” and of the “ankle”
- Chemical composition above 1 TeV unknown
- Clear evidence of PeVatrons in the Universe

Valerio Vagelli Cosmic ray detection in space 5