European Strategy for Particle Physics

PARALLEL 8 / **DARK MATTER AND DARK SECTOR**

Overview and Methodology of Working Group

Yohei Ema (CERN)

23-27 **JUNE** 2025 **Lido di Venezia**

Submission summary

114 submissions found to be relevant to the Dark Matter and Dark Sector area.

If yes, which benchmark models?
antimatter dark matter coupling, millicharged
light DM, sterile neutrinos (categorization was yes (more in 112)
sexaquark via pbar-He3 annihilation
QCD axion
QCD axion, sub-GeV indirect detection in MeV gap, more general WISPs
QCD axion via FLASH
QCD axion with GRAHAL and MADMAX, WIMPs and sub-GeV with DarkSide, XLZD, TESSERACT
WIMPs with XENONnT,XLZD
WIMPs with XLZD
WIMPs with colliders, indirect with CTAO, dark bosons with antimatter expts???
Heavy DM (CTA) - generic
ULDM, PBH, stochastic bkg
Phase transitions, w/ (heavy) and w/o portal. PBH, stochastic bkg
Light DM
Alps
generic support
Light DM, sterile neutrinos
heavy, ULDM, sub-GeV
heavy, ULDM, sub-GeV
YES (but just mentioned as science case for FCC)

If yes, which benchmark models?
antimatter dark matter coupling, millicharged
YES (but just mentioned as general science case and for FCC)
YES (as national priority, generic)
YES (as national priority, generic)
YES (as national priority, generic)
YES (as consortium priority, generic)
heavy (WIMP),
super-heavy
light DM
YES (as national priority, generic)
super-heavy (exotic compact objects, PBHs), heavy, ULDM
YES (as consortium priority, generic)
no models, focus is complementarity/interplay with cevns
sub-GeV dark matter -- scalar dark matter and heavy neutral leptons via axion-like particle
refers to SBND publications on sensitivity to dark sector particles such as a Higgs-Portal scalar [15], heavy axion-like particles [16, 17] or dark photons that mediate interactions with light dark matter [18, 19]
no models, focus is describing scope of DRDs

If yes, which benchmark models?
antimatter dark matter coupling, millicharged
indirect detection from annihilation in sun
no models, national input
no models, focus is complementarity
no models, focus is compementarity
LDM and ULDM (no models)
ALPs, hidden sector (LDM, ULDM)
LDM (no details)
national input, generic (no models)
LDM (sterile neutrinos)
UDM (ALPs)
categorization was yes (indirect)
collider technology (categorization was yes (?))
LDM (plot with sensitivity to inelastic DM)
Lattice QCD calulations
QCD axion/ALPs
axion/ALP/dark photon
ULDM, WIMPs, sterile neutrino, FIPs, DP, Beamdump
Portals
LDM (BC2)
Portals

If yes, which benchmark models?
antimatter dark matter coupling, millicharged
LDM (inelastic DM)
Portals
Portals
LDM (inelastic DM)
Dark Higgs
Minimal DM, Portals, Alps
Minimal DM, Alps
Alps, UL DM
????
Yes, but superficial discussion.
Alps, light scalars
Light and heavy DM, dark photons
Alps, dark photons (categorization was yes, but superficial)
HNLs, light DM. (categorization was yes, but superficial)
Axion DM
Dark photons, ALPs
Yes, but summary of P5.
Yes, in supplementary material. See 2205.08553. WIMPs, scalar and lepton portal, simplified models.
Same models as 10 TeV COM lepton collider

Relevant mass ranges and benchmark models identified.

Goal of my talk

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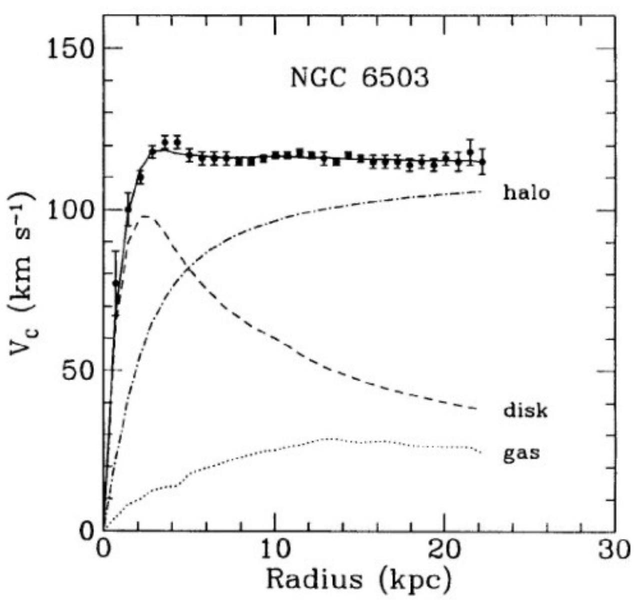
To set up the stage for the subsequent talks.

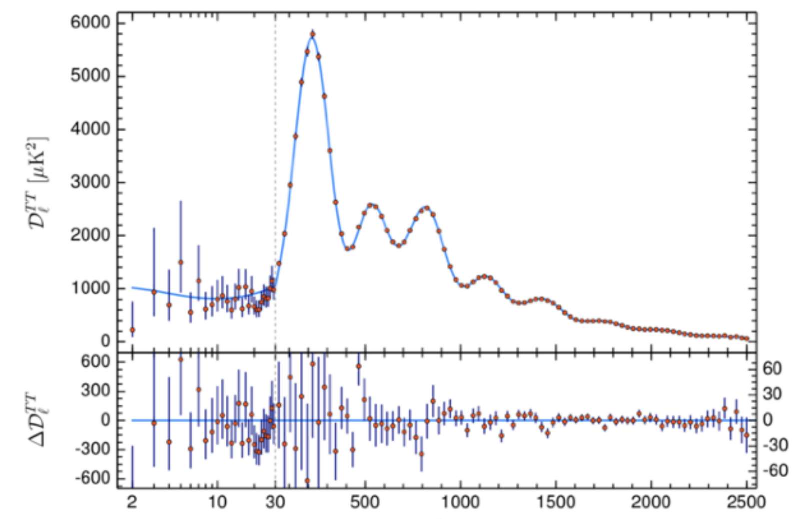
Summarize the basics and define the terminology.

More details, with actual plots, covered later.

Dark matter and dark sector

- Evidence of Dark matter (DM) in different scales:





- We know its energy density, but not its mass and interaction,

$$\boxed{\rho_\chi = m_\chi n_\chi \simeq 0.4\,\mathrm{GeV/cm^3}}$$

though theory-driven representative models exist.

Diverse/complementary efforts to cover diverse mass ranges.

- Unknown new physics needs not be simple = "Dark sector"

Classification

We classify models and methods by mass ranges.

1. Ultralight mass range $m_\chi \lesssim \mathrm{eV}$.

2. Light mass range $\mathrm{keV} \lesssim m_\chi \lesssim \mathrm{GeV}$.

3. Heavy mass range $\mathrm{GeV} \lesssim m_\chi \lesssim 10\,\mathrm{TeV}$.

4. Ultraheavy mass range $\mathrm{TeV} \ll m_\chi$

Ultralight mass range: theory

- Ultralight mass $m_\chi \lesssim$ eV:

$$\text{“Occupation number”} \sim n_\chi \times (m_\chi v)^{-3} \sim \left(\frac{10\,\mathrm{eV}}{m_\chi}\right)^4.$$

Must be a boson, appropriate to think it as ''classical waves''

with frequency $\sim \mathrm{GHz}\left(\frac{10^{-6}\,\mathrm{eV}}{m_\chi}\right).$

- Representative example : QCD axion.

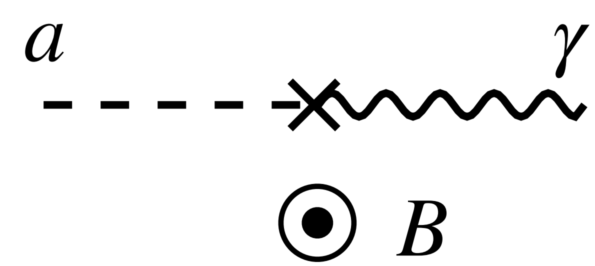
$$\left\{\begin{array}{l}\text{Explain why neutron EDM is small = strong CP problem.}\\[2ex] \text{Naturally light due to Pseudo-Goldstone nature.}\\[2ex] \text{Well-defined relic abundance target.}\end{array}\right.$$

Ultralight mass range: experiment

- Dark matter as a classical wave.

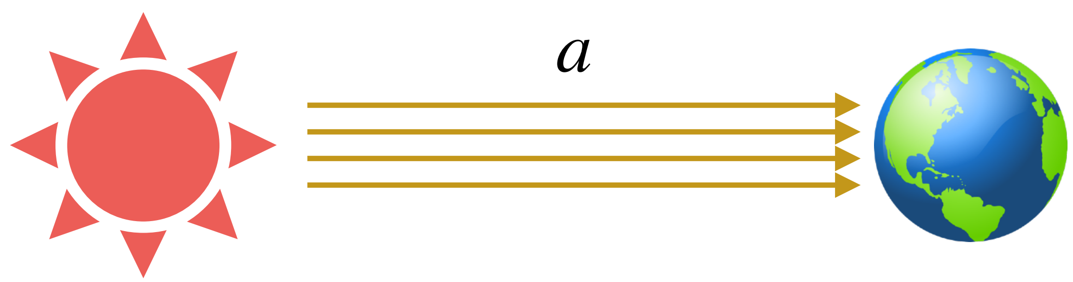
Affect e.g. electromagnetic response.

$$\dot{\vec{E}} - \vec{\nabla} \times \vec{B} = g_{a\gamma\gamma} \underbrace{\left(\dot{a}\vec{B} + \vec{\nabla} a \times \vec{E} \right)}_{\text{DM-induced current}}$$



"haloscope"

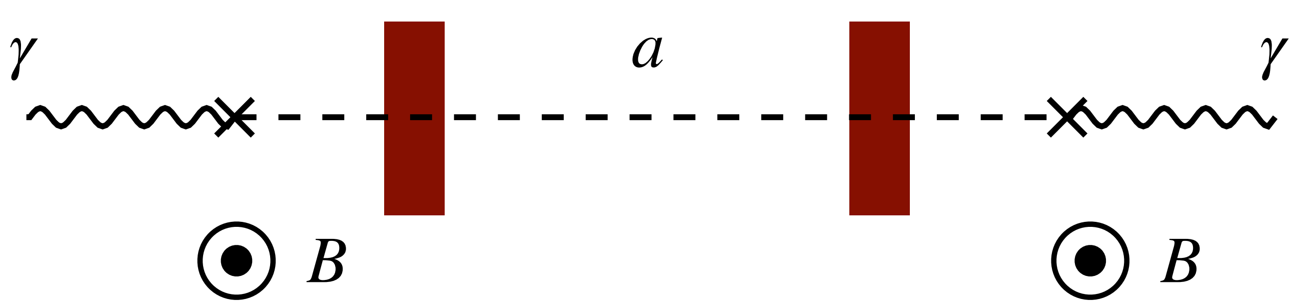
- Astrophysical/cosmological production also important.



"helioscope"

- Can be produced in the laboratory.

e.g. "Light-shining-through-wall"



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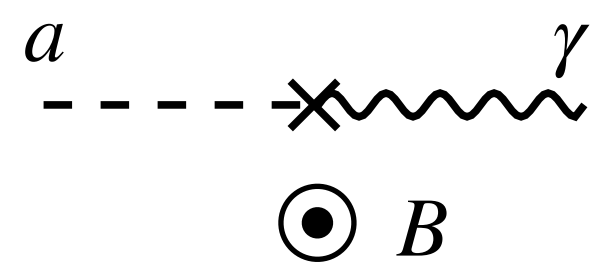
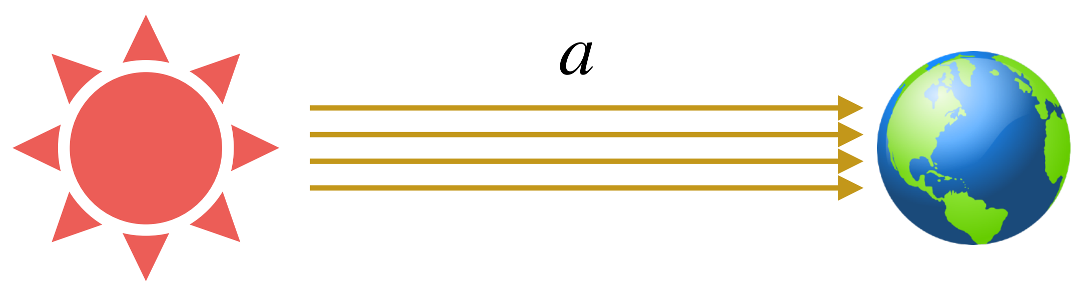


"haloscope"

Covered by Julia Vogel

- Astroph



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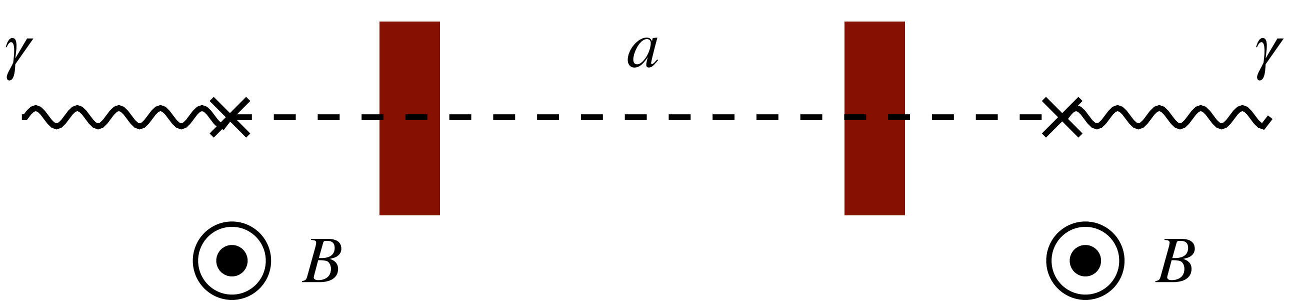

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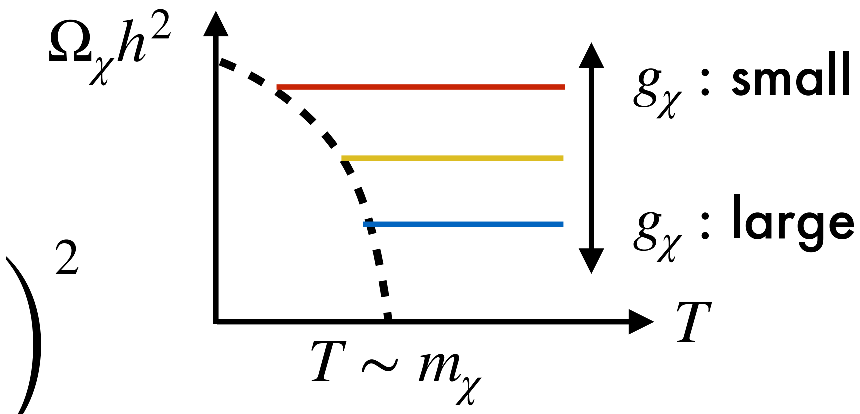
Light mass range: theory

- Cosmological thermal "freeze-out" abundance:

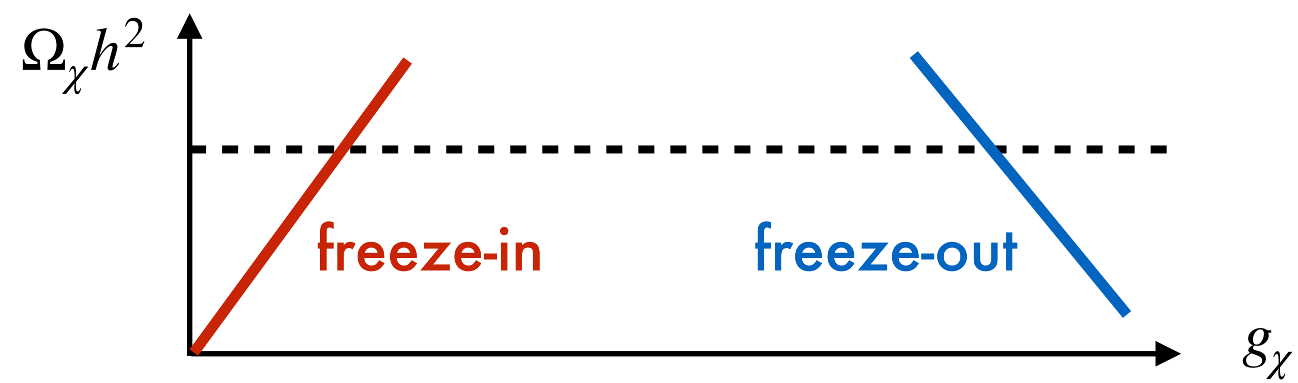


$$\Omega_\chi h^2 \sim \frac{10^{-26}\,\mathrm{cm^3/sec}}{\langle \sigma v \rangle} \sim 0.1 \left(\frac{0.01}{g_\chi^2}\right)^2 \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^2$$

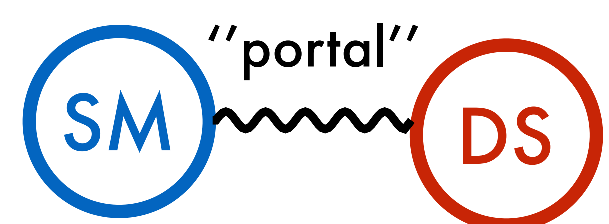
for $\langle \sigma v \rangle = g_\chi^4 / m_\chi^2$.

For $m_\chi \ll 100\,\mathrm{GeV}$, $g_\chi^2 \ll 0.01$: new small coupling.

- Thermal "freeze-in" at tiny g_χ :



- Dark sector can couple to SM via "portals":

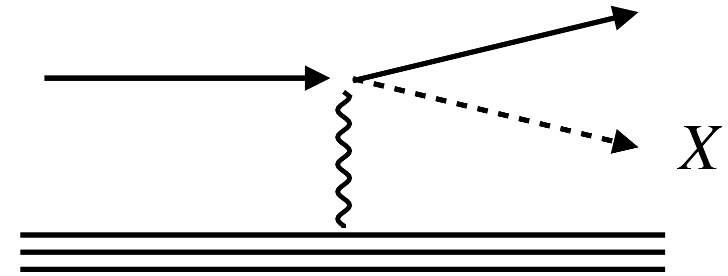


$$\mathscr{L} = \mathscr{O}_{\mathrm{SM}} \times \mathscr{O}_{\mathrm{dark}} = \begin{cases} \epsilon B_{\mu\nu} F'^{\mu\nu} & : \text{dark photon portal,} \\ |H|^2 S, |H|^2 S^2 & : \text{Higgs portal,} \\ L H N_R & : \text{neutrino (HNL) portal,} \\ a F \tilde{F} & : \text{axion-like particle (ALP) portal.} \end{cases}$$

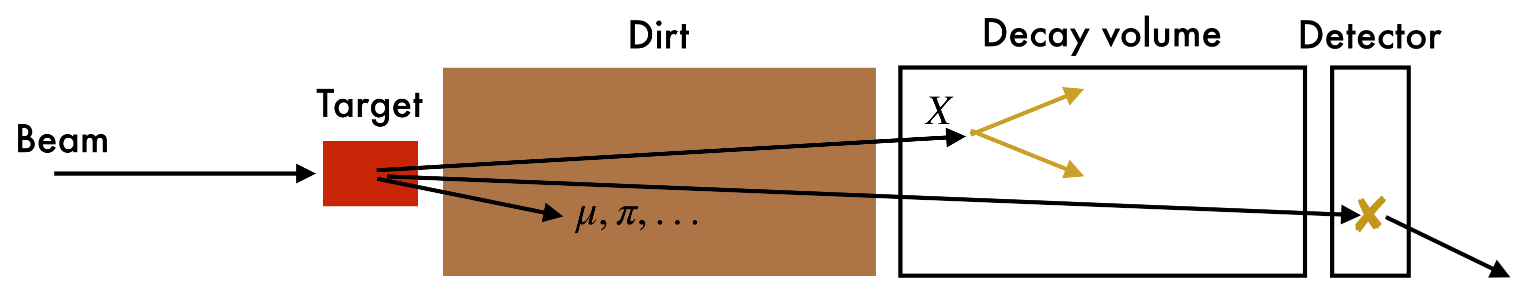
Light mass range: experiment

- Light but weakly coupled. ➡ Precision is crucial.

e.g. Missing energy signals:

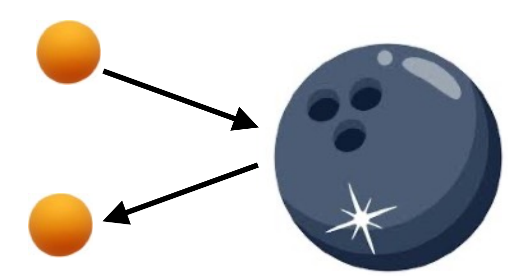


Decay/scattering signals:



- DM direct detection (DD) with lower threshold/lighter target:

$$E_{\text{recoil}} \sim \frac{m_\chi^2}{m_{\text{target}}} v^2 \sim 0.1\,\text{keV} \left(\frac{m_\chi}{1\,\text{GeV}}\right)^2 \left(\frac{10\,\text{GeV}}{m_{\text{target}}}\right)$$



for $m_\chi \ll m_{\text{target}}$.

- Astrophysics/cosmology relevant, especially for $m_\chi \lesssim 10\,\text{MeV}$.

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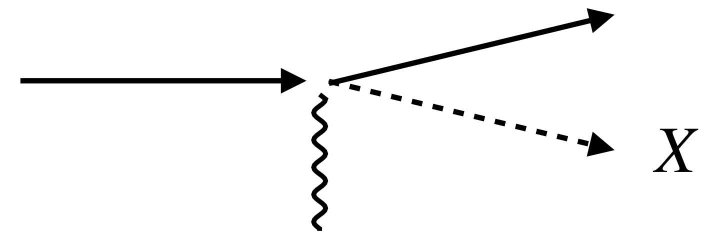

Covered by Maksym Ovchynnikov

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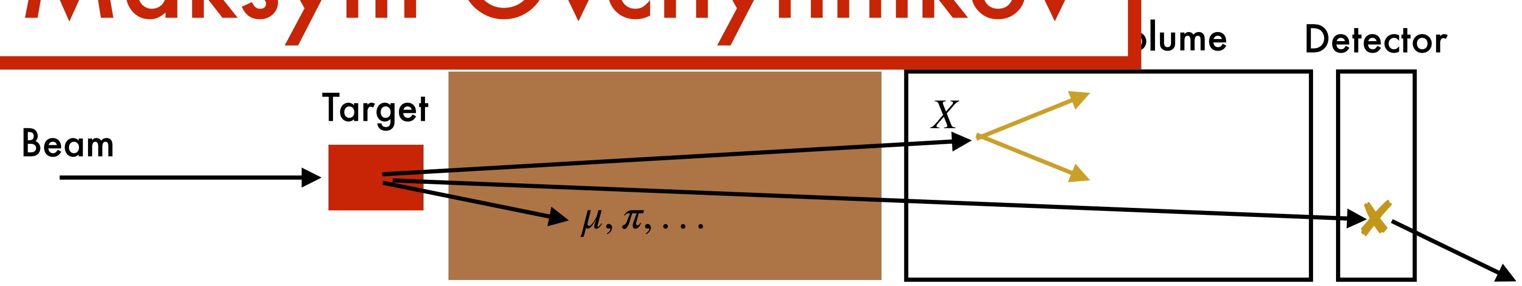

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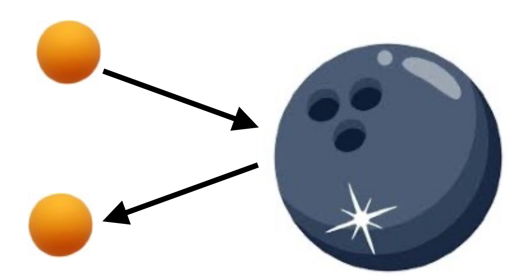

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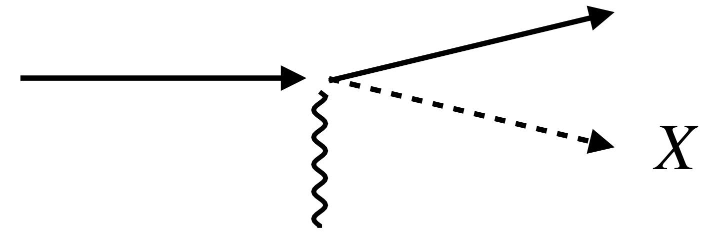

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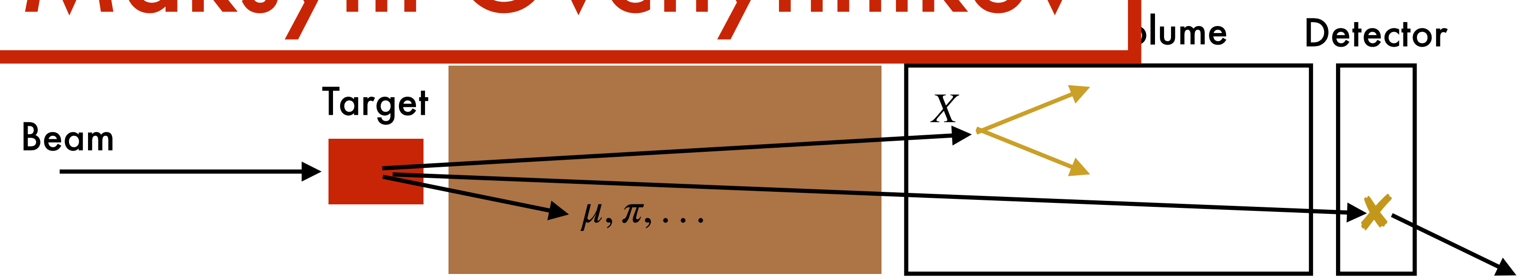

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$$E_{\rm recoil} \sim \frac{m_\chi^2}{m_{\rm target}}$$

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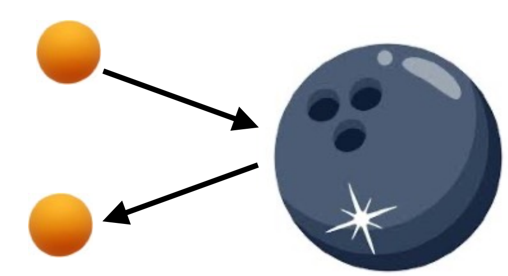

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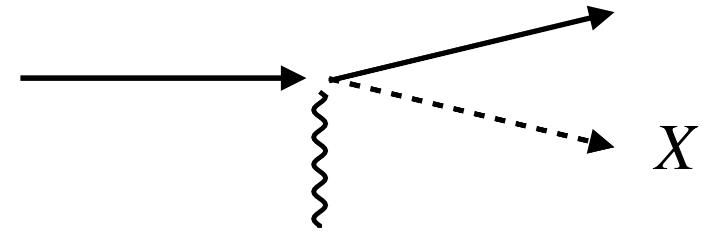

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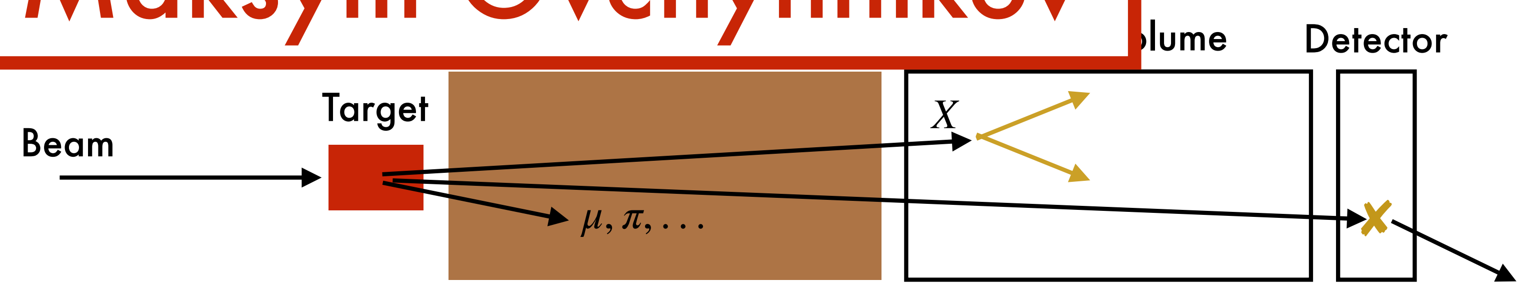

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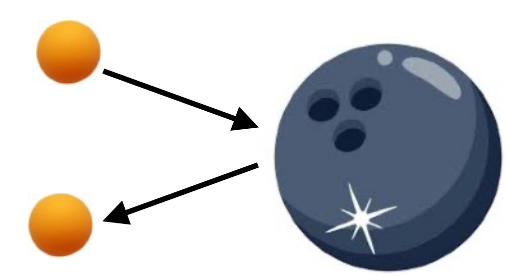

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- Astrophysics/cosmology relevant, especially for $m_\chi \lesssim 10\,\mathrm{MeV}$.

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Heavy mass range: theory

- Thermal relic abundance:

$$\Omega_\chi h^2 \sim \frac{10^{-26}\,\mathrm{cm}^3/\mathrm{sec}}{\langle \sigma v \rangle} \sim 0.1 \left(\frac{0.01}{g_\chi^2}\right)^2 \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^2$$

For $m_\chi \gtrsim 100\,\mathrm{GeV},\ g_\chi^2 \gtrsim 0.01$: sizable coupling.

- May have strong connection to EW physics $g_\chi^2 = g_{\mathrm{SM}}^2,\ \ m_\chi \sim m_{\mathrm{EW}}$.

Weakly interacting massive particles (WIMPs): Higgsino, Wino, ...

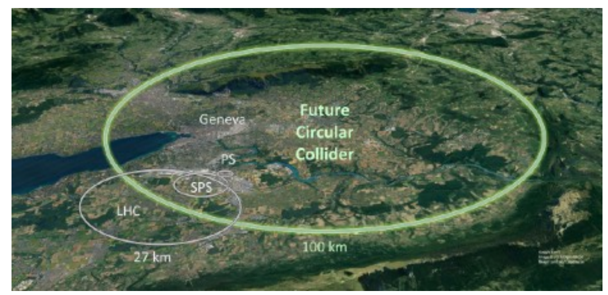
- Even if not, natural to have “portals” to EW physics.

$|H|^2 S, |H|^2 S^2$: Higgs portal, Z'-portal, ...

Heavy mass range: experiment

- Sizable coupling but heavier.

  ➡ High energy colliders crucial.



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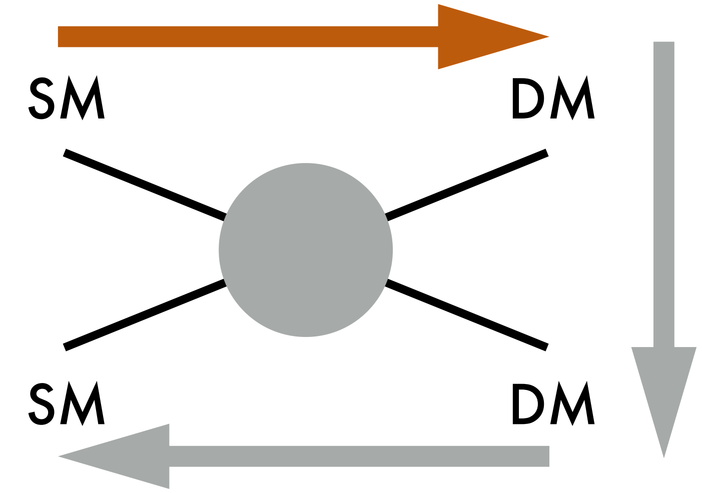
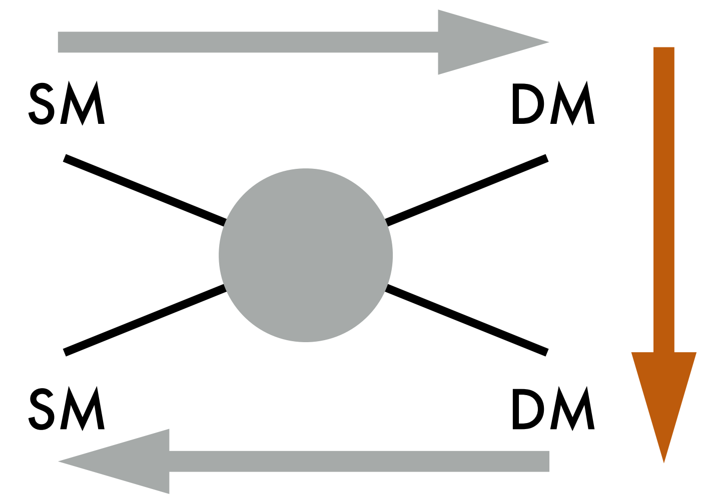
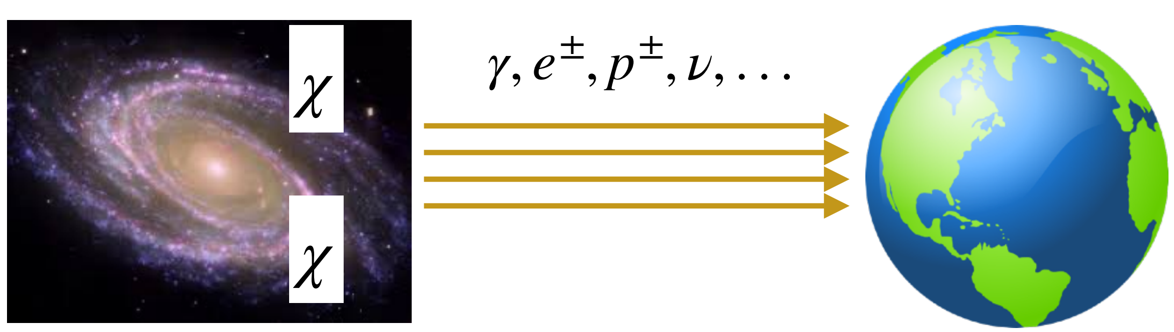


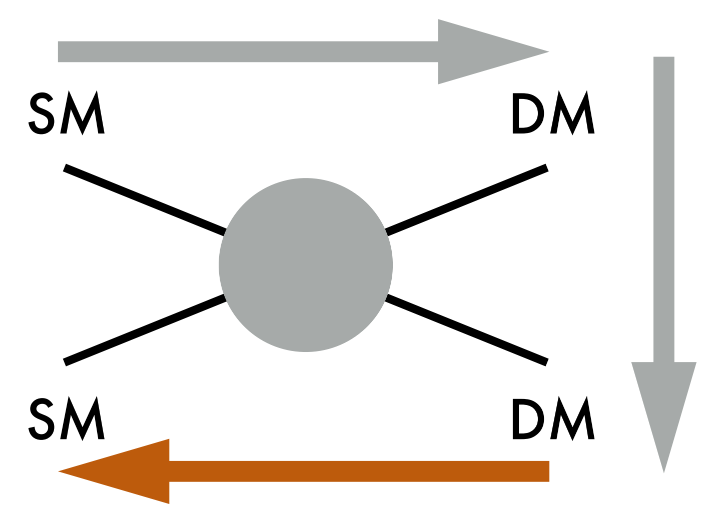
- DM direct detection most sensitive here.

$$E_{\text{recoil}} \sim m_{\text{target}} v^2 \sim 10\,\text{keV} \left(\frac{m_{\text{target}}}{10\,\text{GeV}} \right) \quad \text{for } m_\chi \gtrsim m_{\text{target}}\,.$$



- Indirect detection provides another strong probe.





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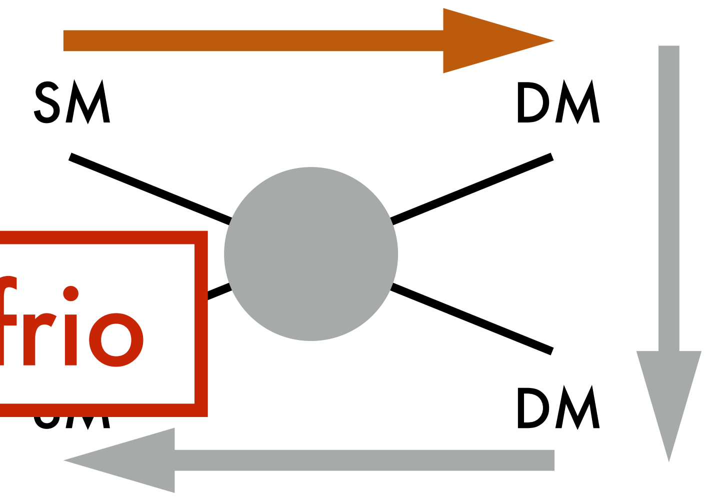

High energy colliders crucial.

Covered by Monica D'Onofrio

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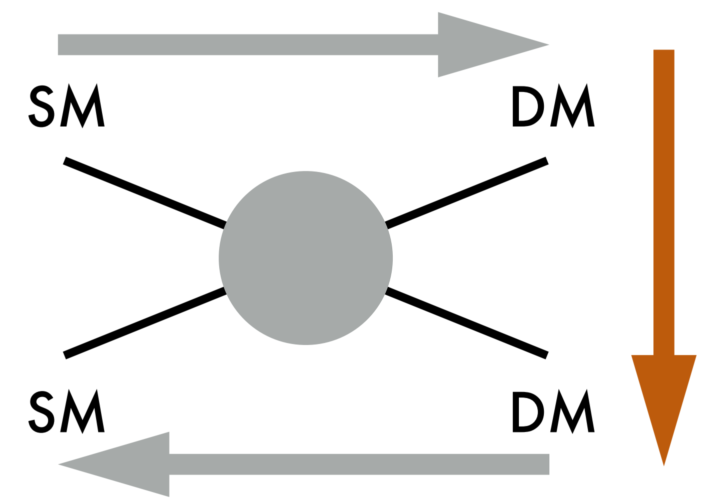

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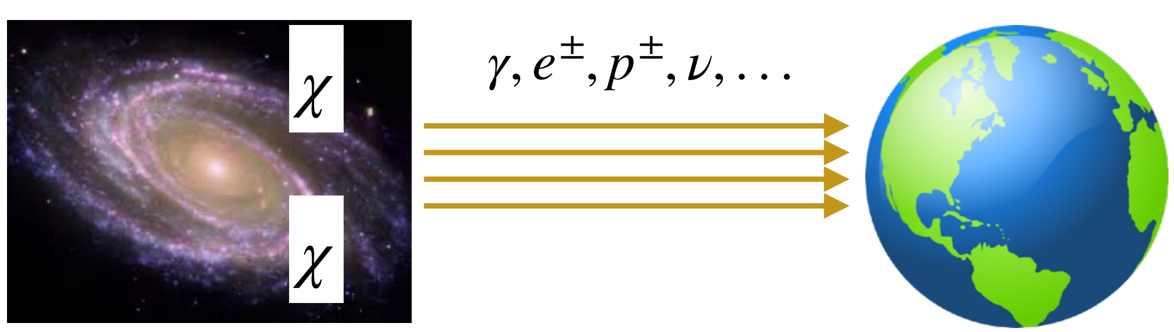

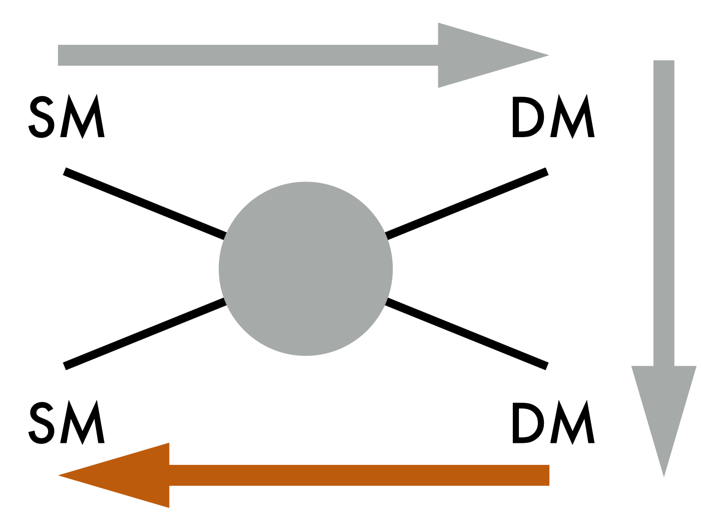

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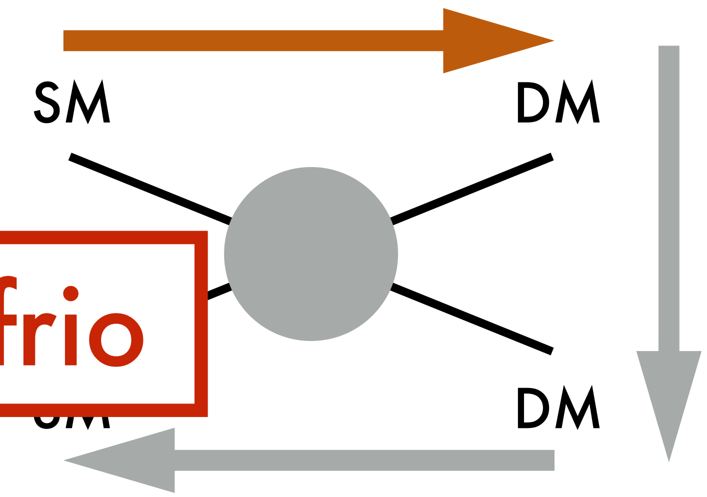

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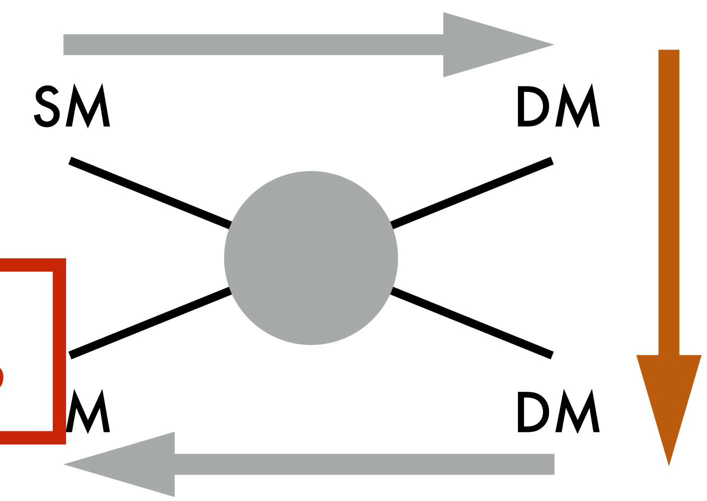

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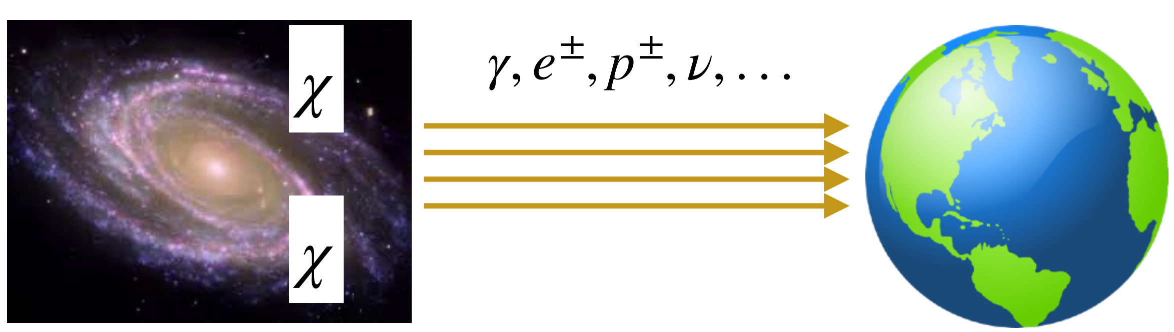

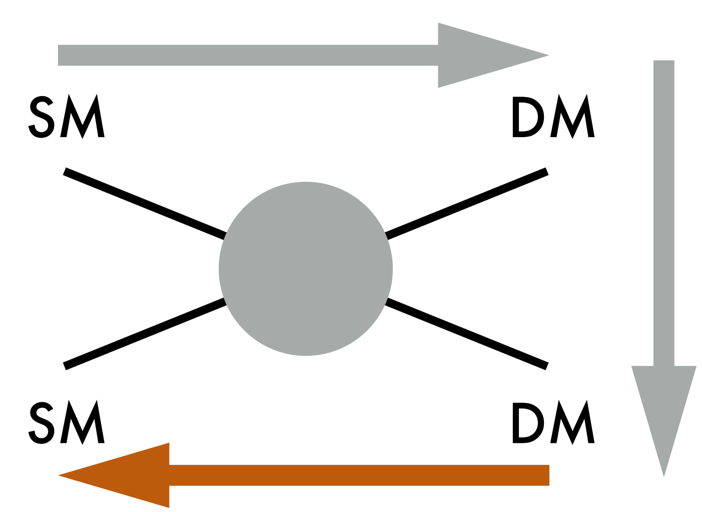

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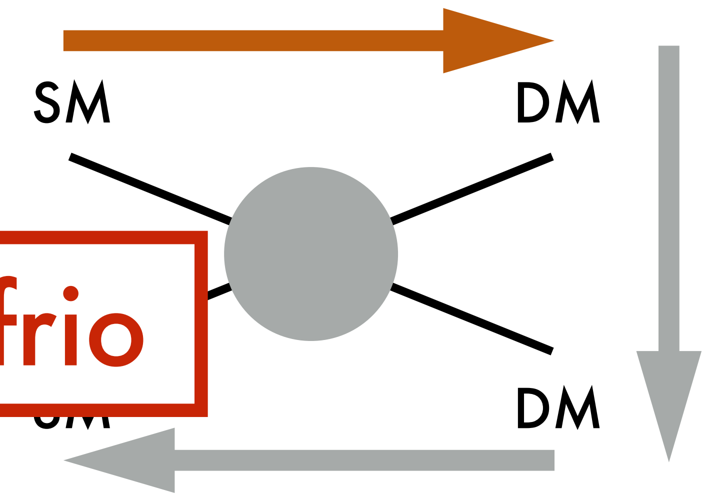

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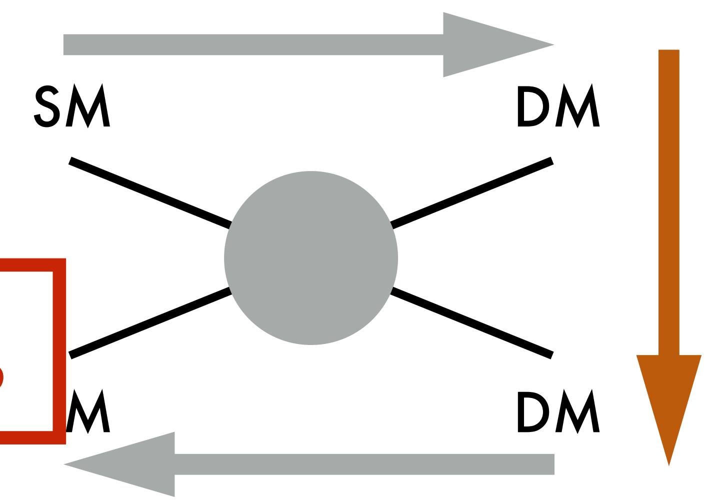

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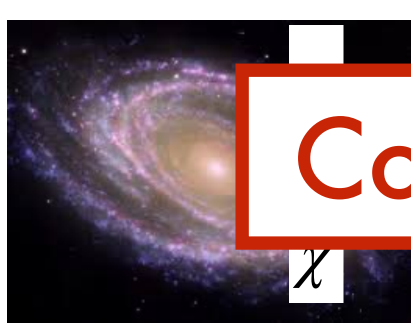

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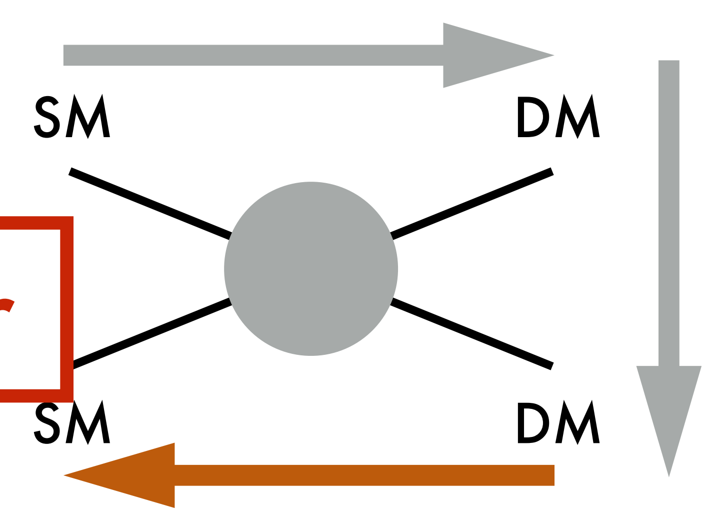


Ultraheavy mass range

- Simple (perturbative) thermal production does not work

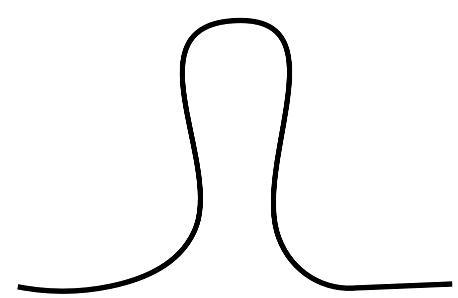
$$\Omega_\chi h^2 \sim \frac{10^{-26}\,\mathrm{cm}^3/\mathrm{sec}}{\langle \sigma v \rangle} \sim 0.1 \left(\frac{1}{g_\chi^2} \right)^2 \left(\frac{m_\chi}{10\,\mathrm{TeV}} \right)^2$$

Coupling becomes non-perturbative for $m_\chi \gg 1\,\mathrm{TeV}$.

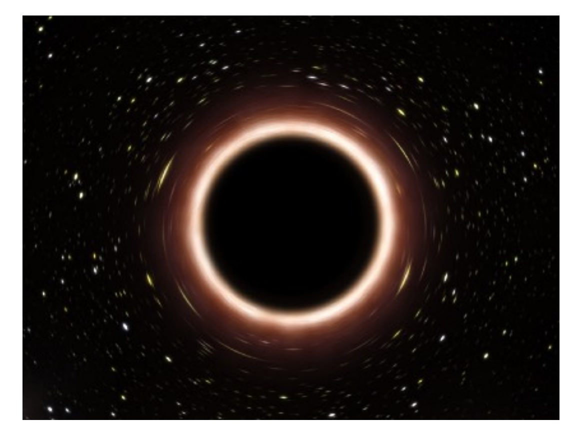
- Can be composite and/or non-thermally produced.

<u>e.g.</u>

Primordial Black Hole (PBH) :



$$\frac{\delta\rho}{\rho} \gtrsim 1$$



- DM direct detection, astrophysics, ..., can probe these models.

Summary

- Diverse techniques necessary to cover diverse mass range.

- Classified according to mass ranges.

  1. Ultralight mass range $m_\chi \lesssim \mathrm{eV}$.
  2. Light mass range $\mathrm{keV} \lesssim m_\chi \lesssim \mathrm{GeV}$.
  3. Heavy mass range $\mathrm{GeV} \lesssim m_\chi \lesssim 10\,\mathrm{TeV}$.
  4. Ultraheavy mass range $\mathrm{TeV} \ll m_\chi$

- More details on each mass range to be covered in the following.