Theoretical Landscape of Dark Matter Searches in Neutrino Experiments

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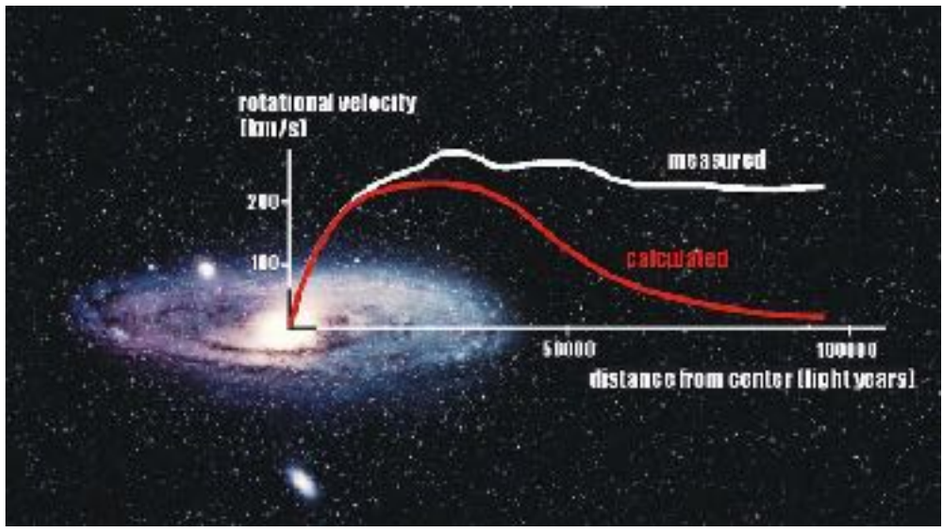
UC Riverside

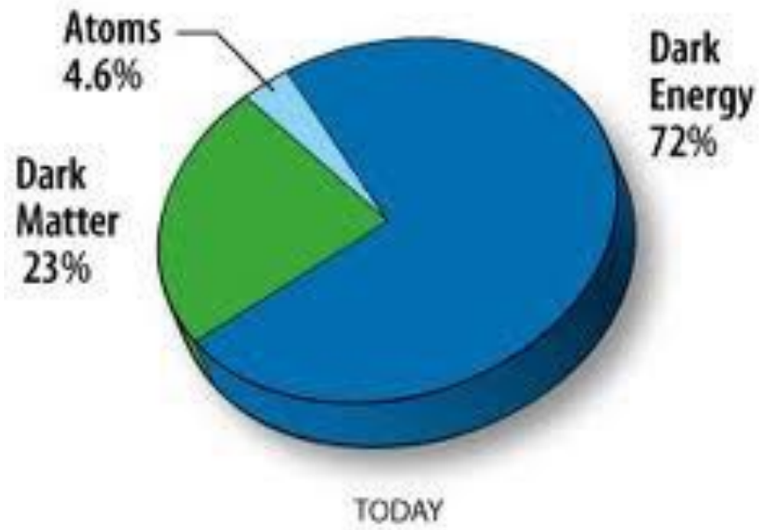
UTA Workshop on
“ New Opportunities at the Next Generation Neutrino Experiments”
Apr 12, 2019

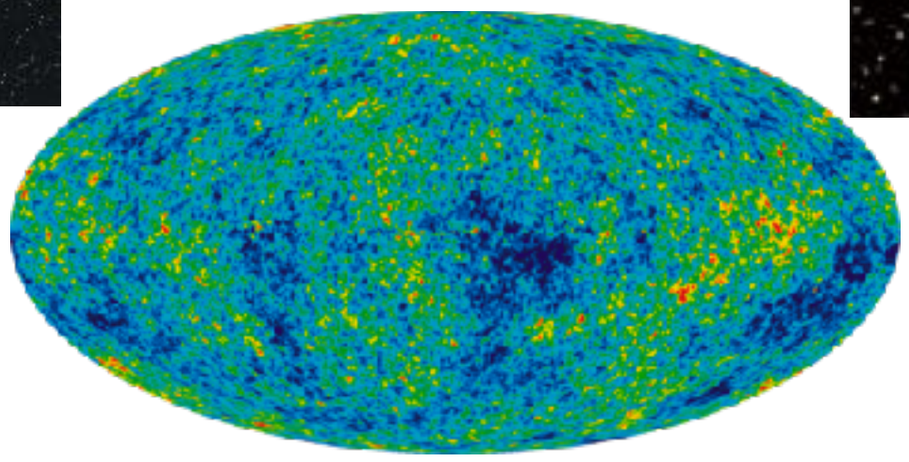
What is Dark Matter ?

- **Dark Matter: 85%** of cosmic matter abundance!

  Cold, non-relativistic

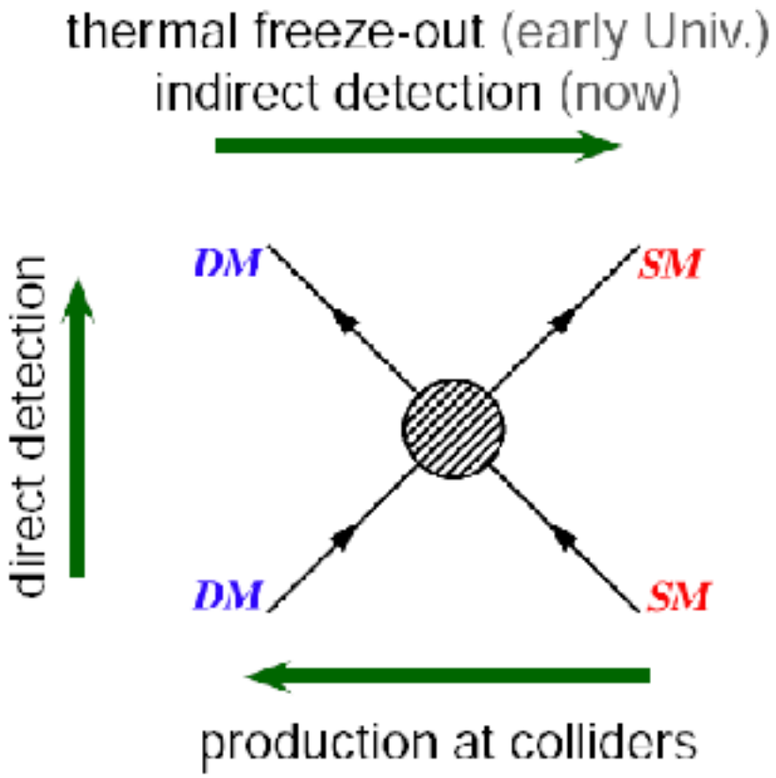


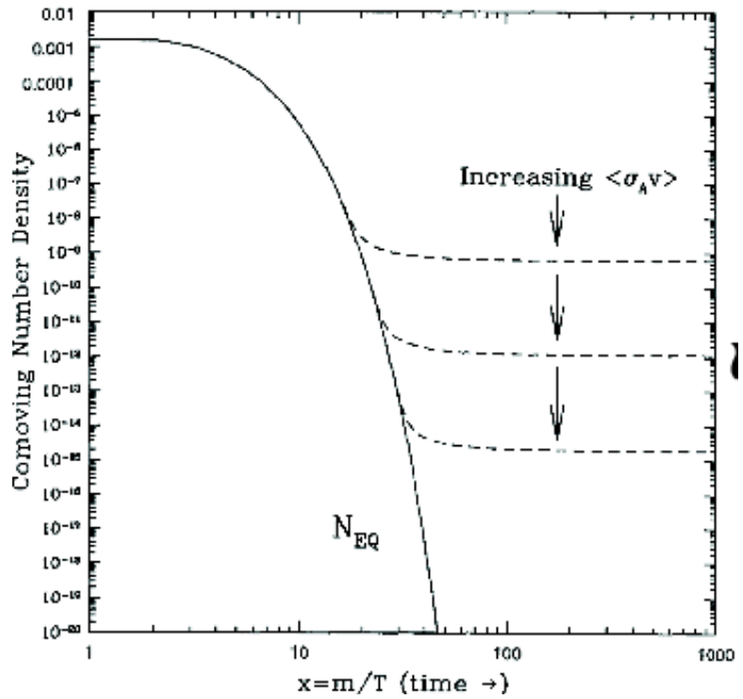




Big mystery! Demand new particle physics beyond the Standard Model !

WIMP DM Paradigm Facing Challenges





- But no convincing signal yet: many years, many experiments…

$$\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1} \sim 0.1 \left(\frac{G_{\rm Fermi}}{G_\chi} \right)^2 \left(\frac{M_{\rm weak}}{m_\chi} \right)^2$$

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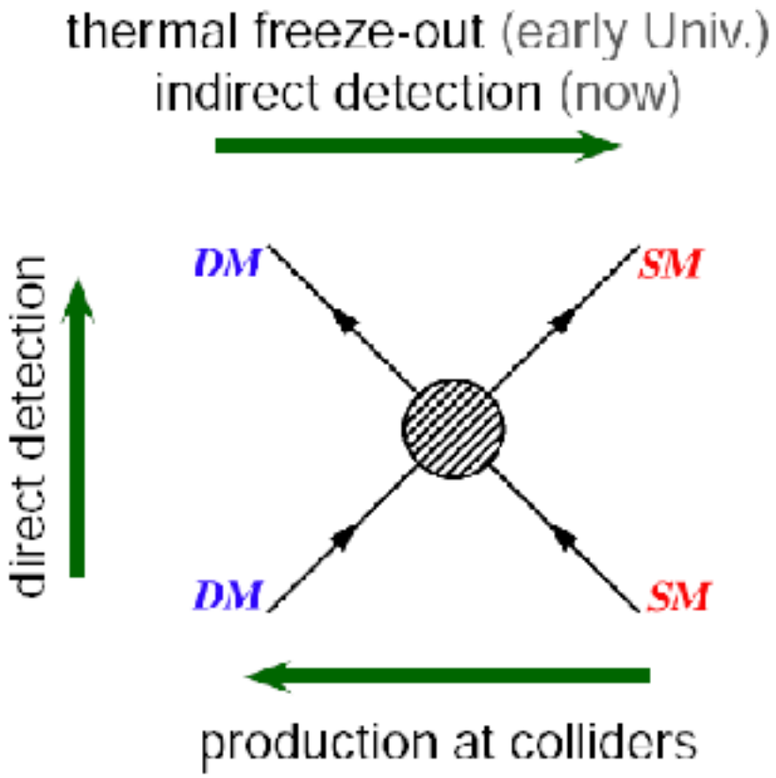

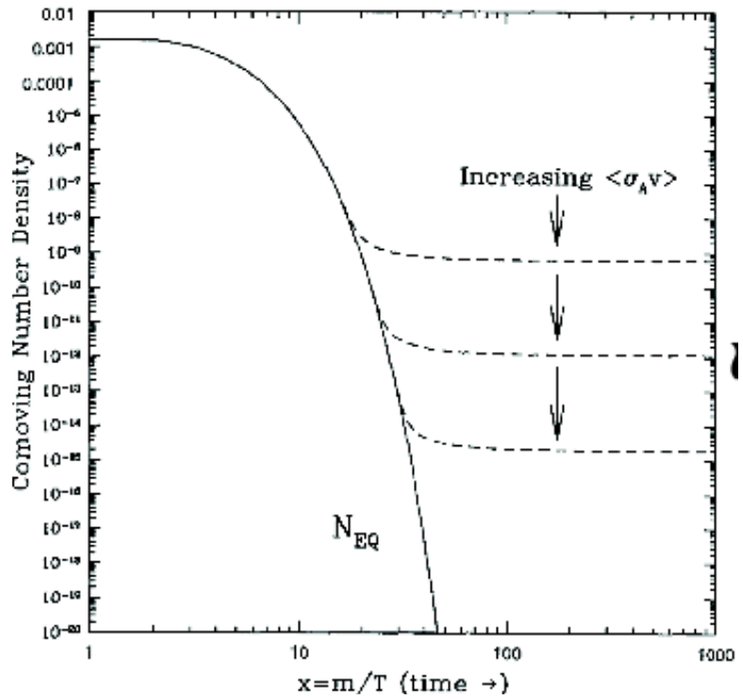

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Time to go beyond the paradigm!

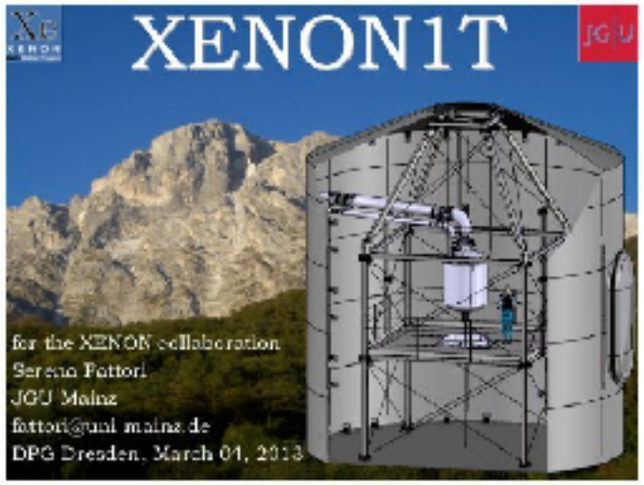
☞ New theories, new experimental probes for DM…

(DM: mass? interaction with SM? self-interaction? how many species? thermal or non-thermal? fundamental particle or composite?…)

Experimental probes for DM

- A Brief Review of the familiar (incomplete list)

- **If DM interacts with SM beyond gravity:**



- Detect cosmic bkg of DM:
  - Direct detection (~10 keV E_{nucl}),
  - Indirect detection
    (DM annihilation to SM in GC/Sun)

- Produce DM at terrestrial accelerator experiments:
  - colliders

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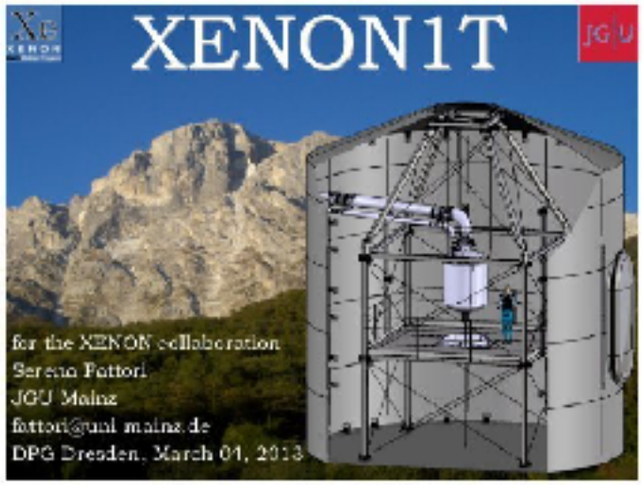

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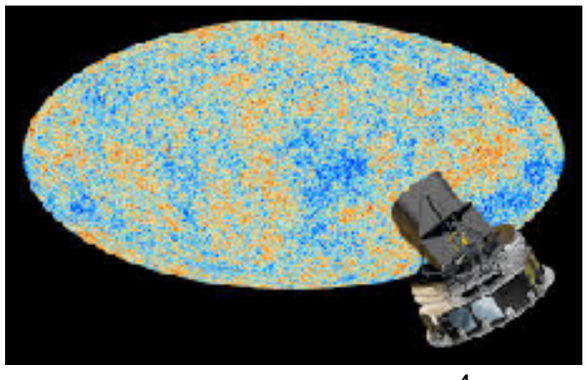
- **If DM only interacts with SM gravitationally:**

- Astro/cosmo probes:
  - CMB, DM halo, GW



Opportunities for DM searches in Neutrino facillities?

(If DM interacts with SM beyond gravity…)

- **Detect cosmic bkg of DM:**

Advantages: large volume, e.g. IceCube, SuperK, DUNE, sensitivity to high *E* scattering events (c.f. direct detection)

Examples: boosted DM (BDM), iBDM, self-destructing DM (+ the vanilla example: WIMP annihilation to ν)

- **Produce DM with terrestrial accelerators:**

Advantages: fixed target+high intensity beam, e.g. MiniBoone, DUNE, NOvA (c.f. LHC)

Examples: low mass DM search (MeV-GeV)

Detect Cosmic Background of Relic DM

Example-1: Boosted DM

JCAP 1410 (2014) 062, **YC** w/Agashe, Necib, Thaler,

JCAP 1502 (2015) , **YC** w/Berger, Zhao;

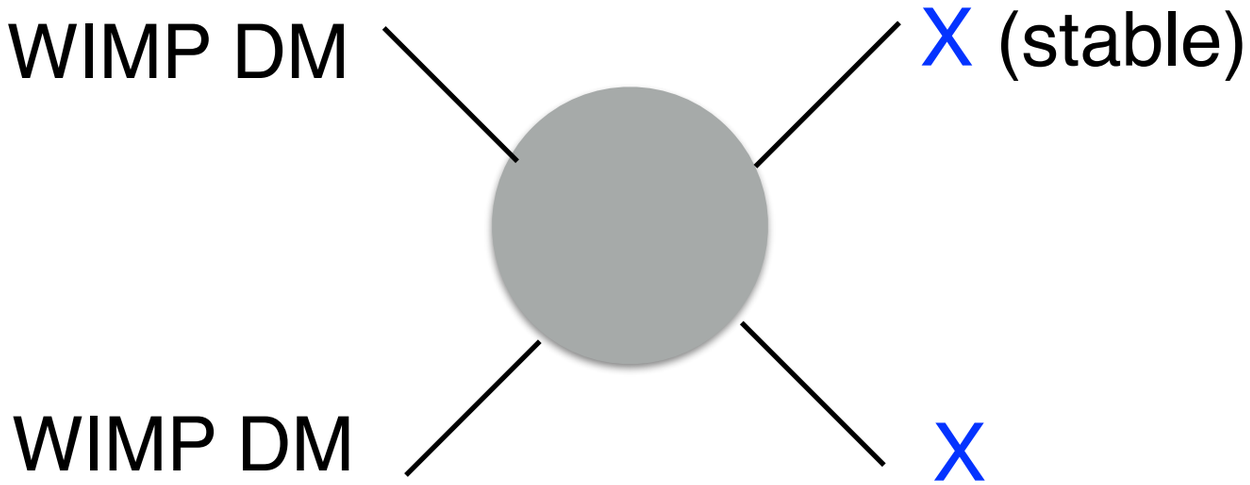
YC *with Berger, Tsai et al. (DUNE TDR+ papers in progress)*

Boosted DM: DM today may not be all cold,

a component of non-thermally produced DM may be (semi-)relativistic, and the smoking-gun signal for DM!

Motivations of Boosted Dark Matter-1

A New Realization of WIMP Miracle



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- Conventional signals absent/suppressed
- Applies to other masses!

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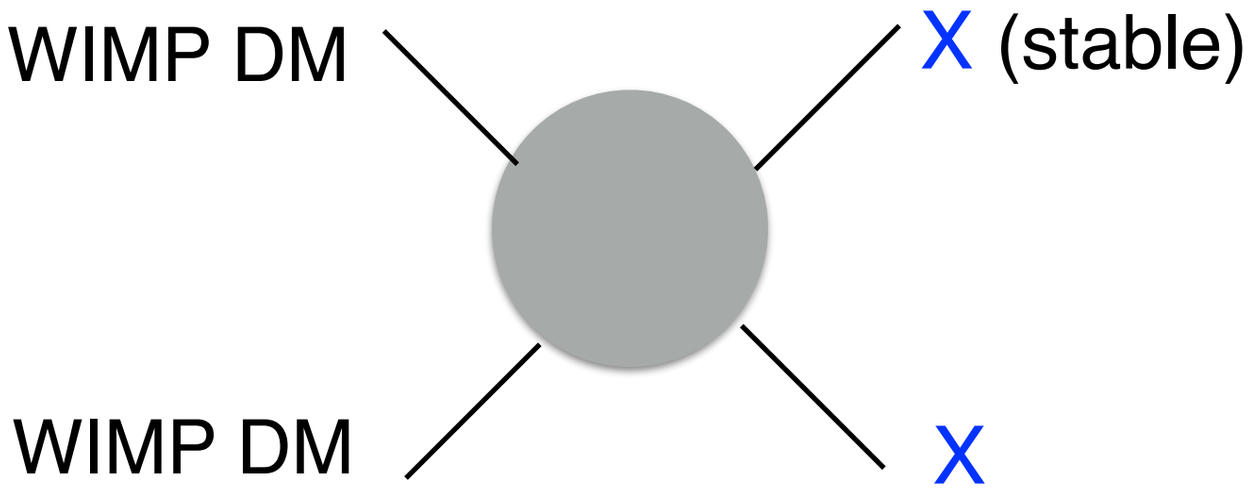

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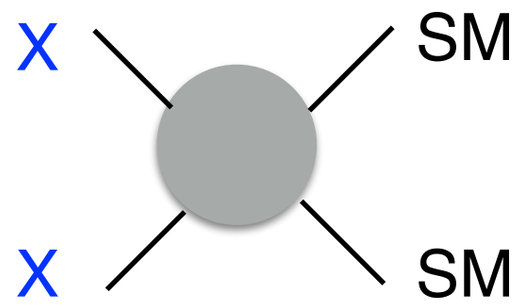
- Massive X ($m_X \gtrsim$ eV): $\Omega_X > 1$

☞ deplete X via annihilation → SM



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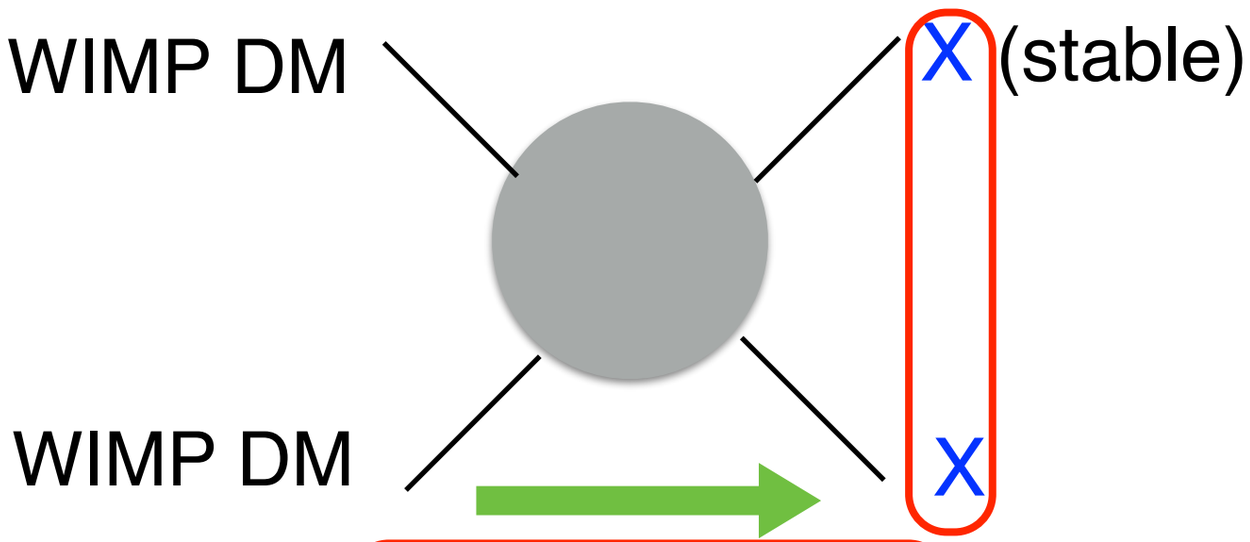

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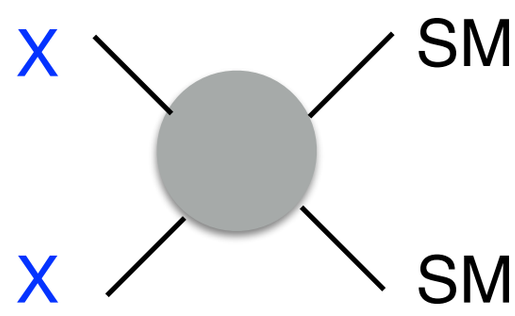

- **Novel signal: Boosted DM** (X) (Vs. "slow" DM) !

YC w/Agashe, Necib, Thaler; **YC** w/Berger, Zhao 2014

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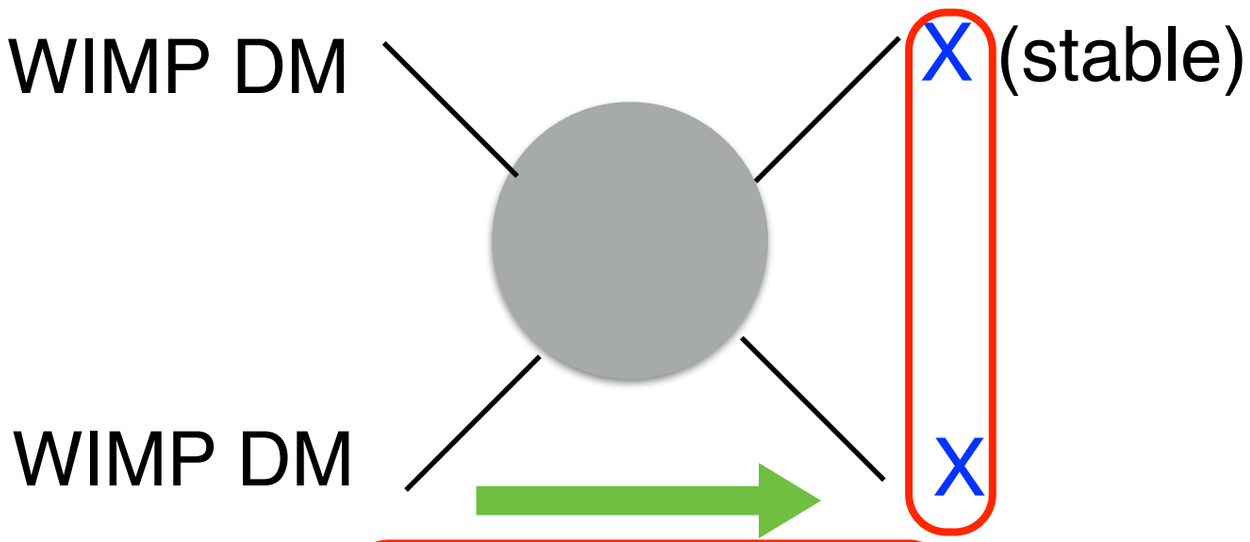

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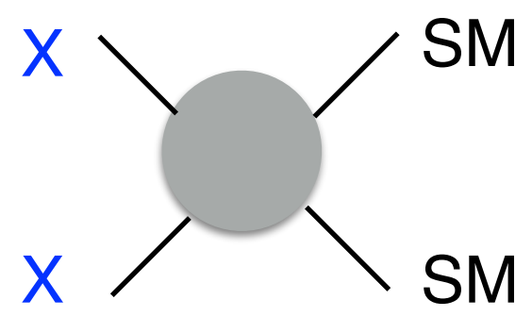

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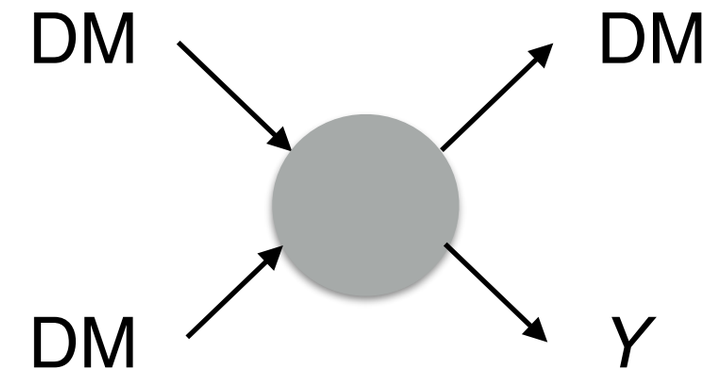
YC w/Agashe, Necib, Thaler; **YC** w/Berger, Zhao 2014

- **Dark matter lives in a hidden sector!** (DM, X, +…)

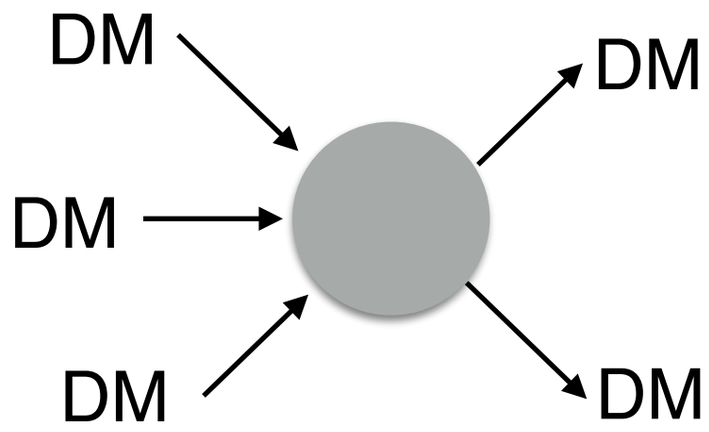
Motivations of Boosted Dark Matter-2

- Z_3 semi-annihilating dark matter:

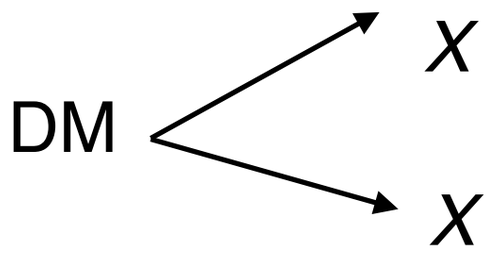


$m_Y < m_{\rm DM}$

- Self-annihilating dark matter:

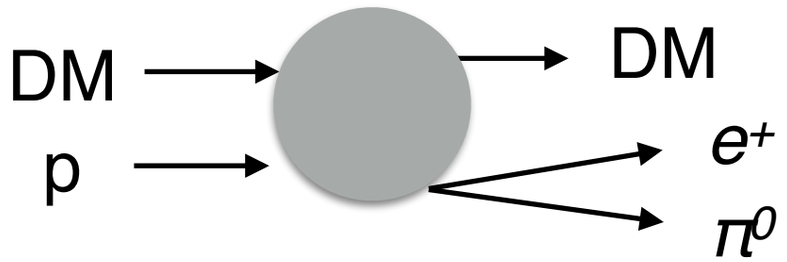


- Decaying dark matter:



$\gamma_X = m_{\rm DM}/2m_X$

- DM-induced nucleon decay:



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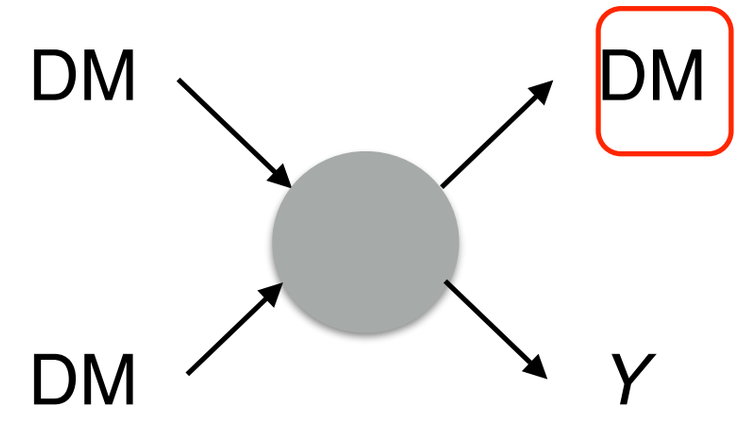

$m_Y < m_{\rm DM}$

$\gamma_{\rm DM} \approx 1.25$

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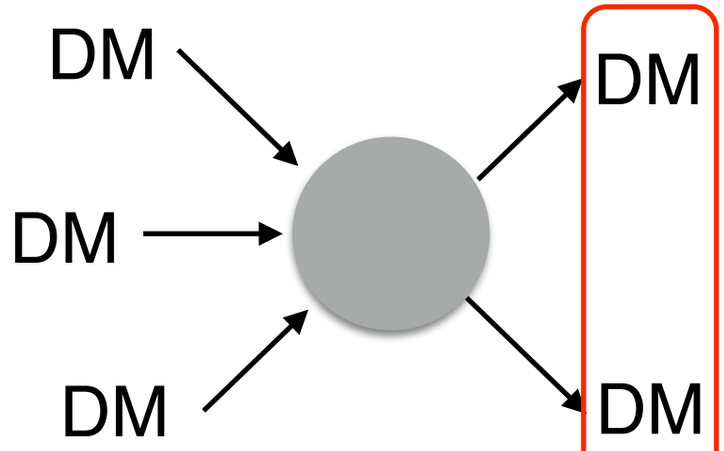

$\gamma_{\rm DM} = 1.5$

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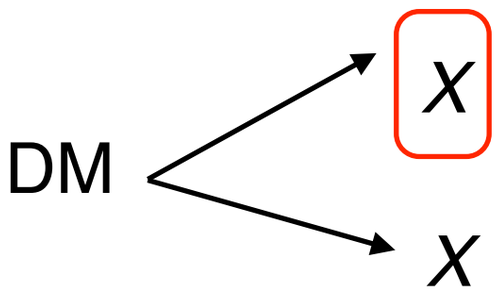

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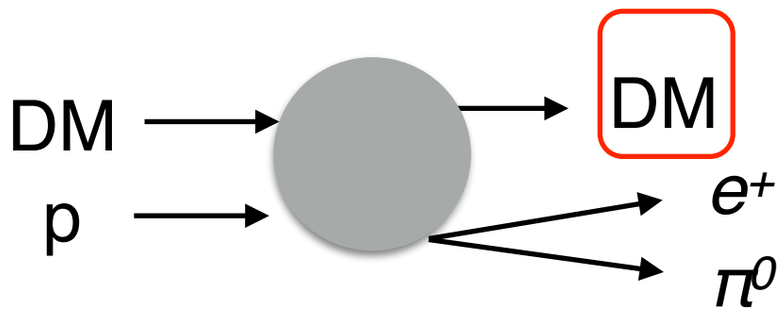
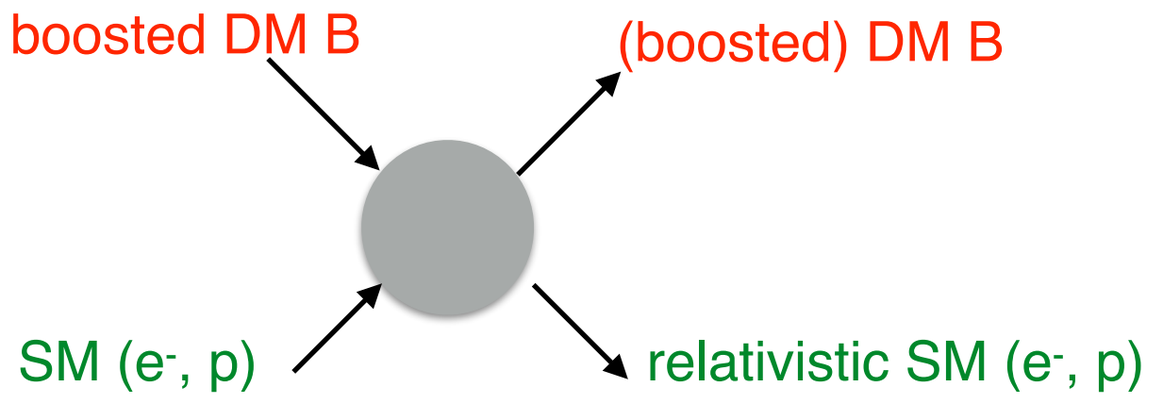


How to Search for Boosted DM?

- Small flux $\propto n^2_{\mathrm{DM-A}}$
- Boosted incoming B

  $\Rightarrow$ Relativistic outgoing e^-, p



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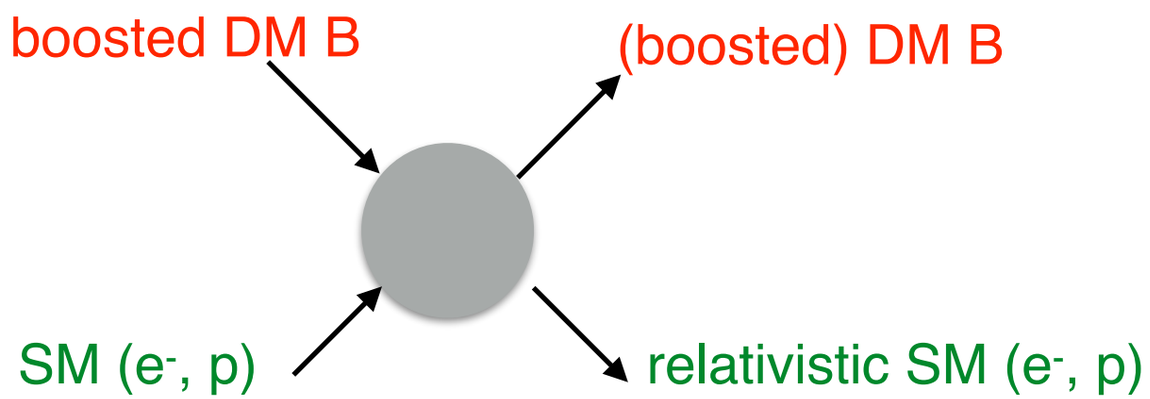

What experiments?

☞ Large volume detector + sensitive to energetic e^-, p

(Conventional DM direct detection ☹ ; opportunity: low energy boosted DM ($E \lesssim O(GeV)$) *Cherry et.al 2015, **YC** w/Pospelov, Pradler 2017*)

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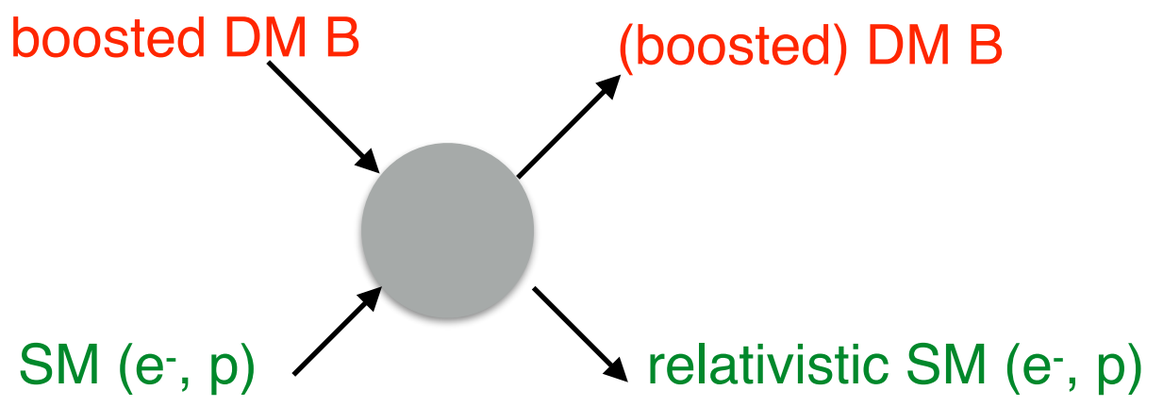

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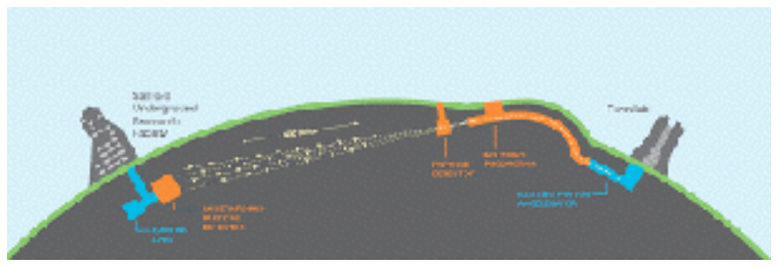
Experiments for neutrinos or proton decay!

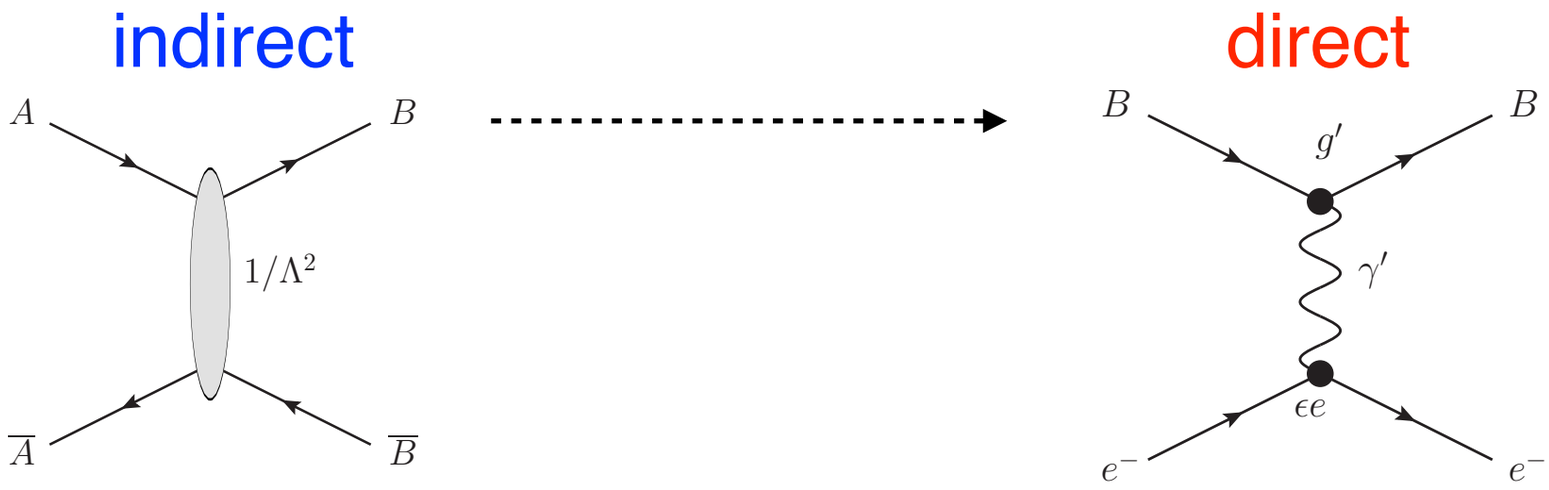
- Cherenkov-radiation: *SuperK/HyperK, IceCube/PINGU…*
- Liquid scintillator: *Borexino, JUNO…*
- Liquid Argon: *DUNE/LBNF!*



Search Strategies for Boosted DM

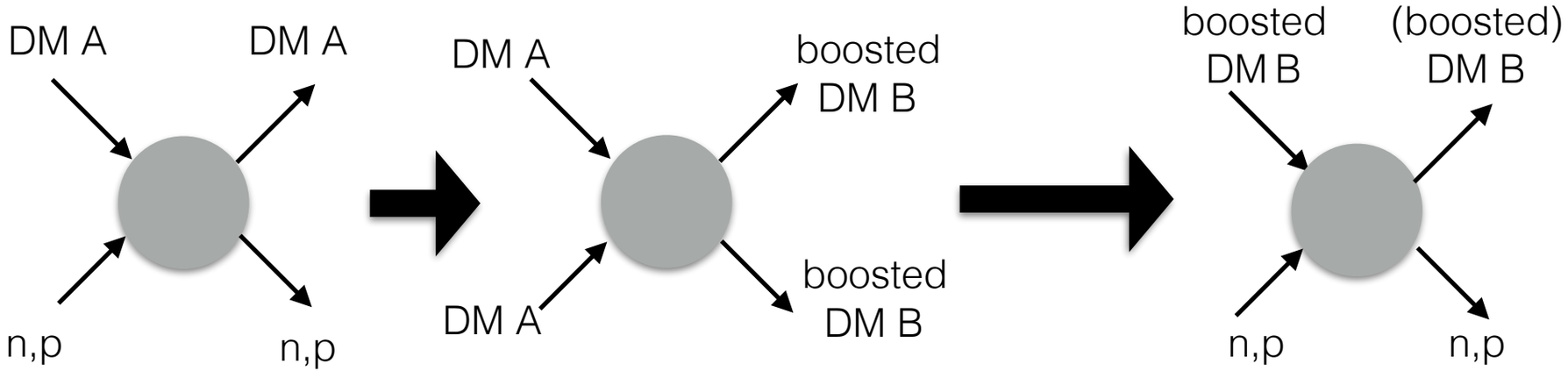
-A <u>combination</u> of conventional DM indirect & direct detections

- **Signals from the galactic center:**



With neutrino detectors!

- **Signals from the Sun:**



Capture in the sun **Annihilation in the sun**

How to Distinguish Boosted DM from Neutrinos?

- **Directionality:**

  Boosted DM: from DM concentrated region,

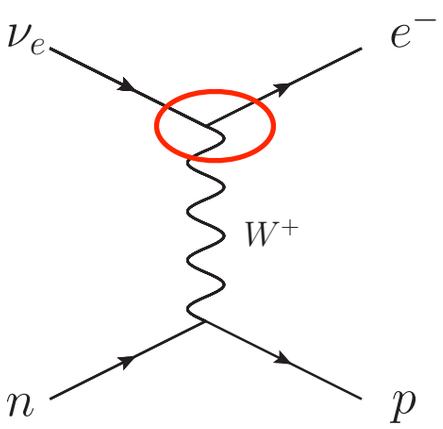
  e.g. GC, Sun…

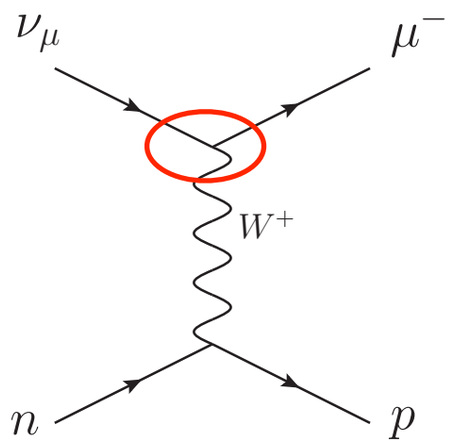
  Vs. (atmospheric) neutrino: isotropic

- **Interaction:**

  Boosted DM interaction: neutral current-like only,

  Vs. Neutrino: neutral current + charged current





No correlated muon, muon veto

BDM Searches at Next Generation ν Experiments (e.g. DUNE)

- **BDM searches at Cherenkov detectors (IceCube/ PINGU, SuperK):** studied in our earlier papers, SuperK official analysis arXiv:1711.05278 PRL 2018

- **BDM searches at DUNE**

  Particular advantages in hadronic channels:

  - Lower E threshold for elastic scattering-*capture more signals!* (Cherenkov cutoff E>1.07 GeV vs. E $\gtrsim$10 MeV @DUNE)
  - Excellent particle track reconstruction for inelastic scattering!-*capture more signals esp. for very boosted DM*

☞ **Confront new challenges, theoretical & experimental**

- Our on-going studies *(w/brand new tools for event generation+detector simulation, see Yun-Tse, Josh's talks)*

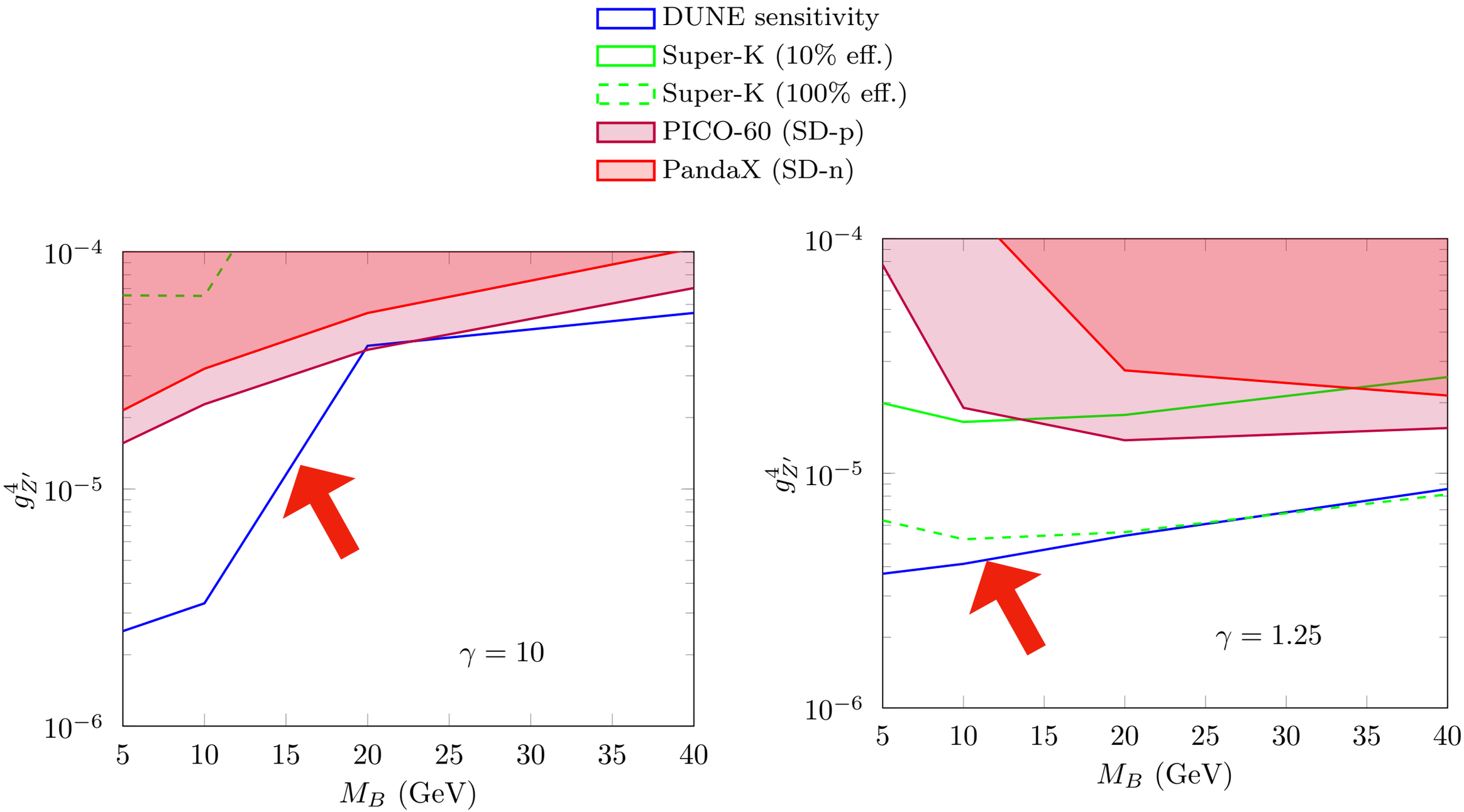
BDM@DUNE through Hadronic Interactions

— *could be the smoking-gun for DM!*

- Benchmark model: BDM from DM annihilation in the Sun

Work in prep with Berger, Tsai, Petrillo, Stocks, Graham, Convery, Necib and Zhao

Preliminary Results

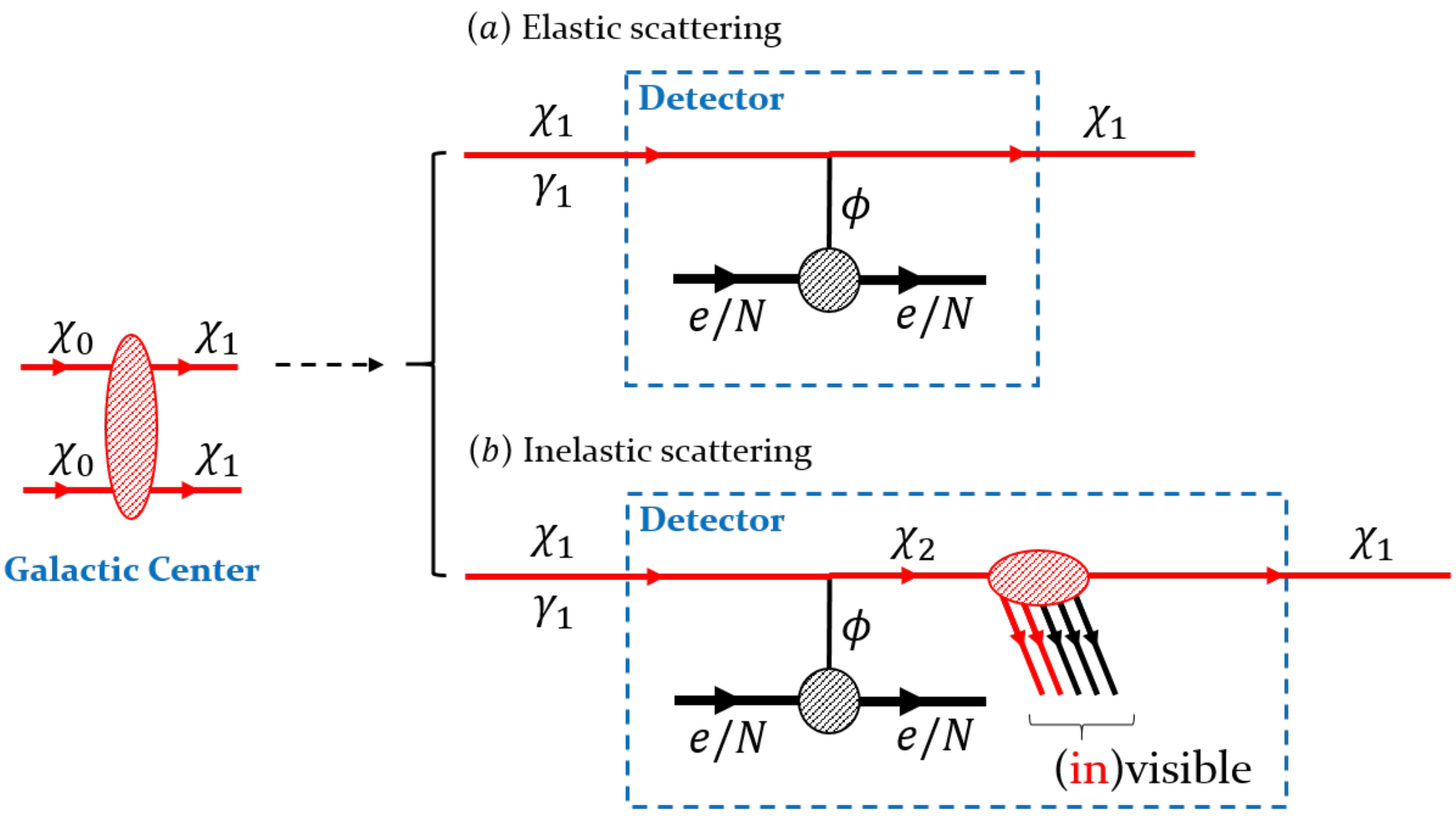


E.g. two-component fermion dark sector, interact via a dark photon (1 GeV)

Example-2: Inelastic BDM

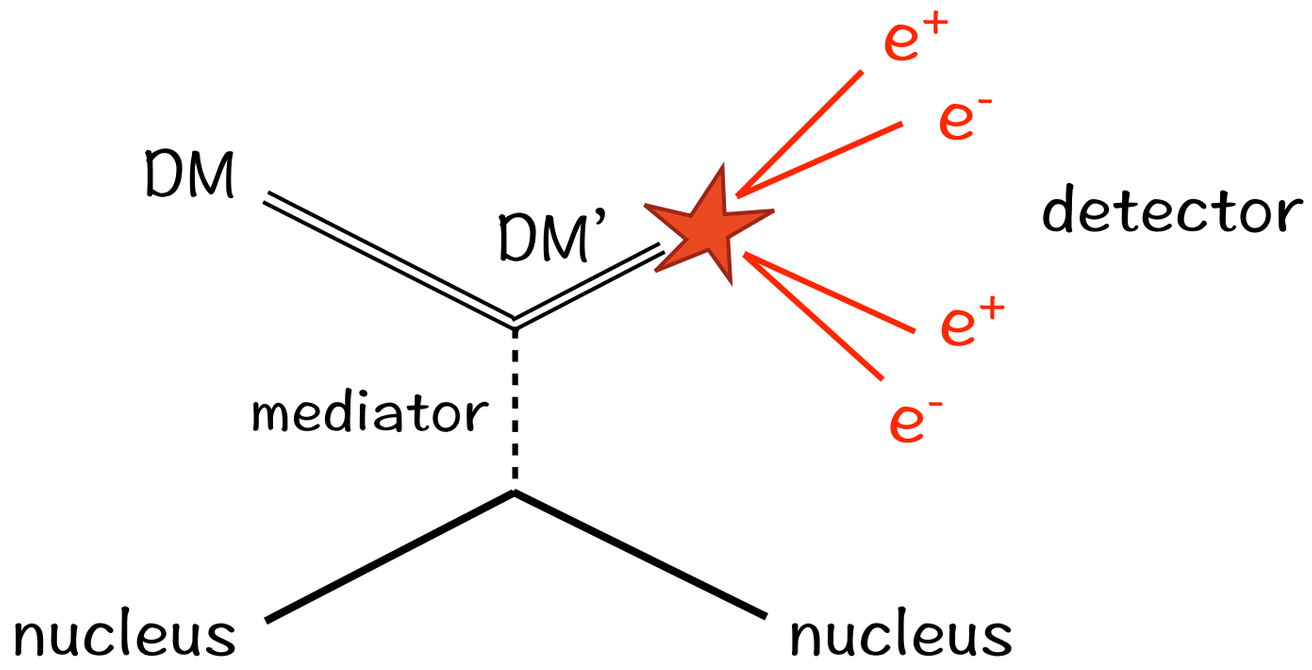
- Work involving Doojin, Seodong, Jae, Animesh, Albert, Jong-Chul (here) + Giudice et al. (2016-)

  More see Doojin's talk



Example-3: Self-destructing DM

- Arxiv:1702.00455 Grossman, Harnik, Telem and Zhang



Produce DM with Accelerator Neutrino Experiments

Low Mass DM @ ν Experiments

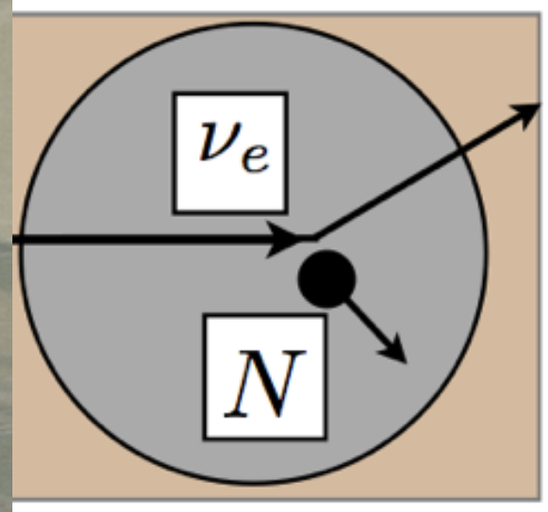
Dark matter discovery

[Batell, Pospelov Ritz, 2009]

Proton Beam

p

Detector



10 m - 100 km

I am dark matter!

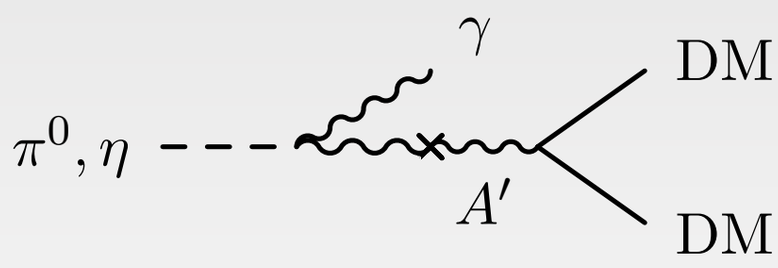
Credit: C. Frugiuele's KITP talk 2018

Production of Low Mass DM Beam

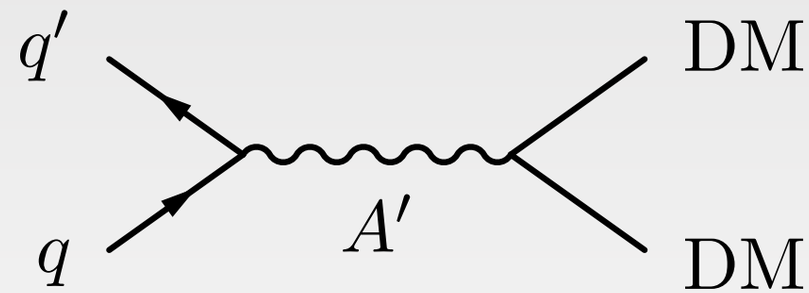
MeV-GeV gauge boson kinetically mixed with the photon $g_{A'}^{\rm SM} = \epsilon e x_{\rm f}$

MeV-GeV scalar DM (no tension with CMB) $g_{A'}^{\phi} \sim \mathcal{O}(1)$

- Production via meson decay



- Direct Production



On shell production of the mediators is essential

High intensity experiments:
order 10^{20} protons on target per year!

Credit: C. Frugiuele's KITP talk 2018

Conclusion/Outlook

- **Exciting opportunities for DM discovery with next gen. neutrino experiments!**
  - Detect cosmic relic background of DM *(the high E_{recoil} regime)*
  - Produce DM beams *(high intensity)*
- **Open questions to brainstorm about:**
  - Other DM candidates to probe
  - Distinguish from neutrinos (model-dependent)
  - Optimize experiments for DM searches at the design stage (esp. for DUNE)
  - Dedicated simulation tools
  - Complementarity among different ν experiments (JUNO, DUNE, HyperK…)

Dark matter discovery at next gen. neutrino experiments?

Thank you!