ASPECTS OF INDIRECT DETECTION OF HIDDEN SECTOR DARK MATTER

BIBHUSHAN SHAKYA

NEXT FRONTIERS IN THE SEARCH FOR DARK MATTER
GGI, FLORENCE
SEPTEMBER 24, 2019

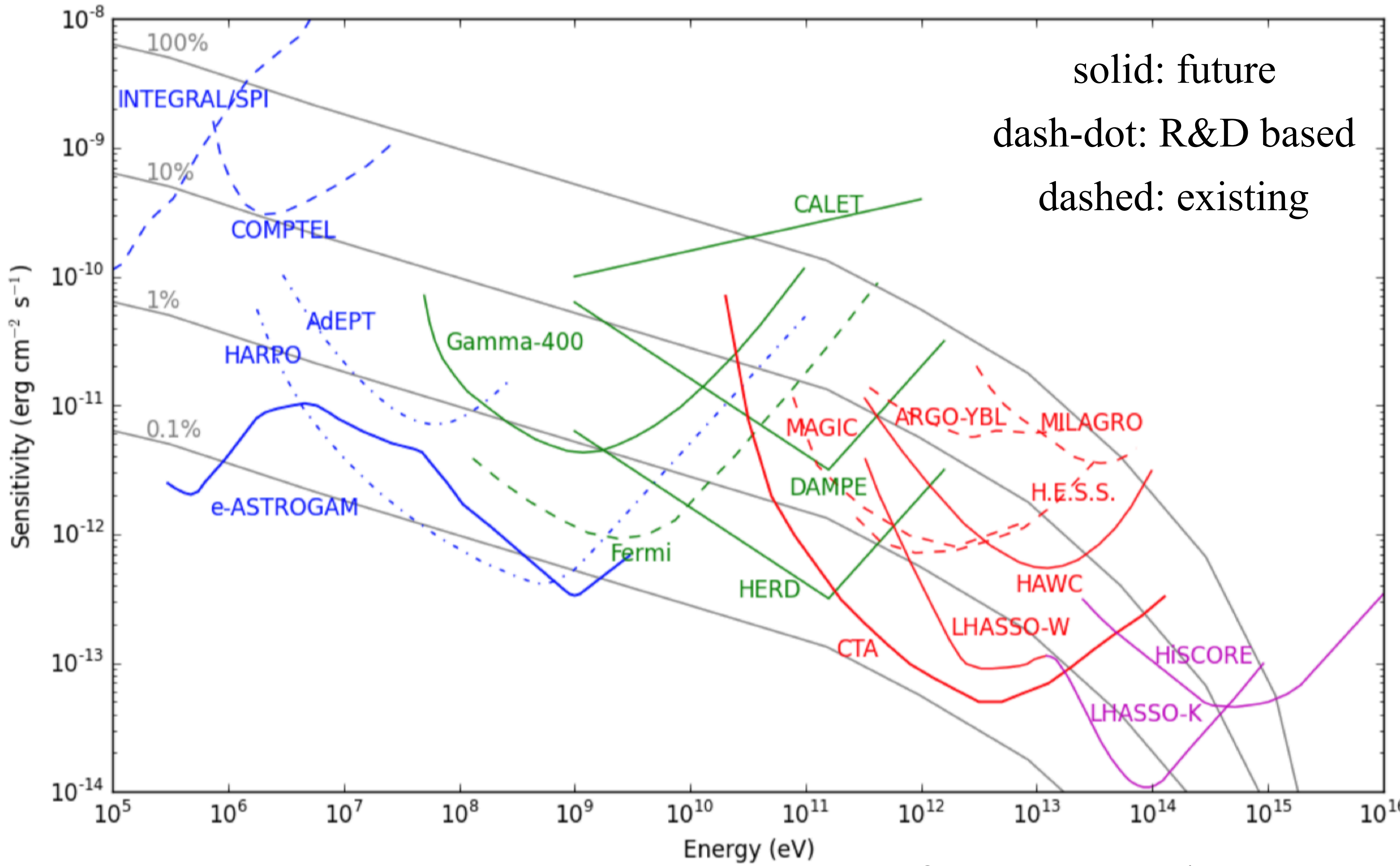
THE WEAK SCALE DARK MATTER INDIRECT DETECTION FRONTIER

- one of our “bread and butter" frontiers in the past decades
- cornerstone: the **WIMP miracle**. many candidates inspired by weak scale solutions to the hierarchy problem (e.g. neutralino LSP)
- the WIMP picture **severely constrained by stringent direct detection limits**, as well as **null results at the LHC**, although some candidates remain untested (eg Higgsino)
- increasingly explored possibility: **dark matter as part of a hidden sector**, coupled to us via some tiny portal. well motivated + **diverse array of possibilities** + straightforward way to avoid direct detection/ collider limits. **indirect detection usually the best bet to probe such models**

REASONS TO CONTINUE PUSHING THE FRONTIER

- **Experiment (I):** continuous emergence of new experiments+improvement in sensitivity on various fronts
- **Experiment (II):** enhanced capabilities of new detectors allow for searches of exotic effects of dark matter
- **Theory:** failure (?) of traditional ideas invite us to revisit our notions of what the underlying nature of dark matter could be: explore connections to other outstanding problems in physics and our evolving understanding of what their solutions might be

INDIRECT DETECTION IN GAMMA RAYS



from astro-ph 1602.02728

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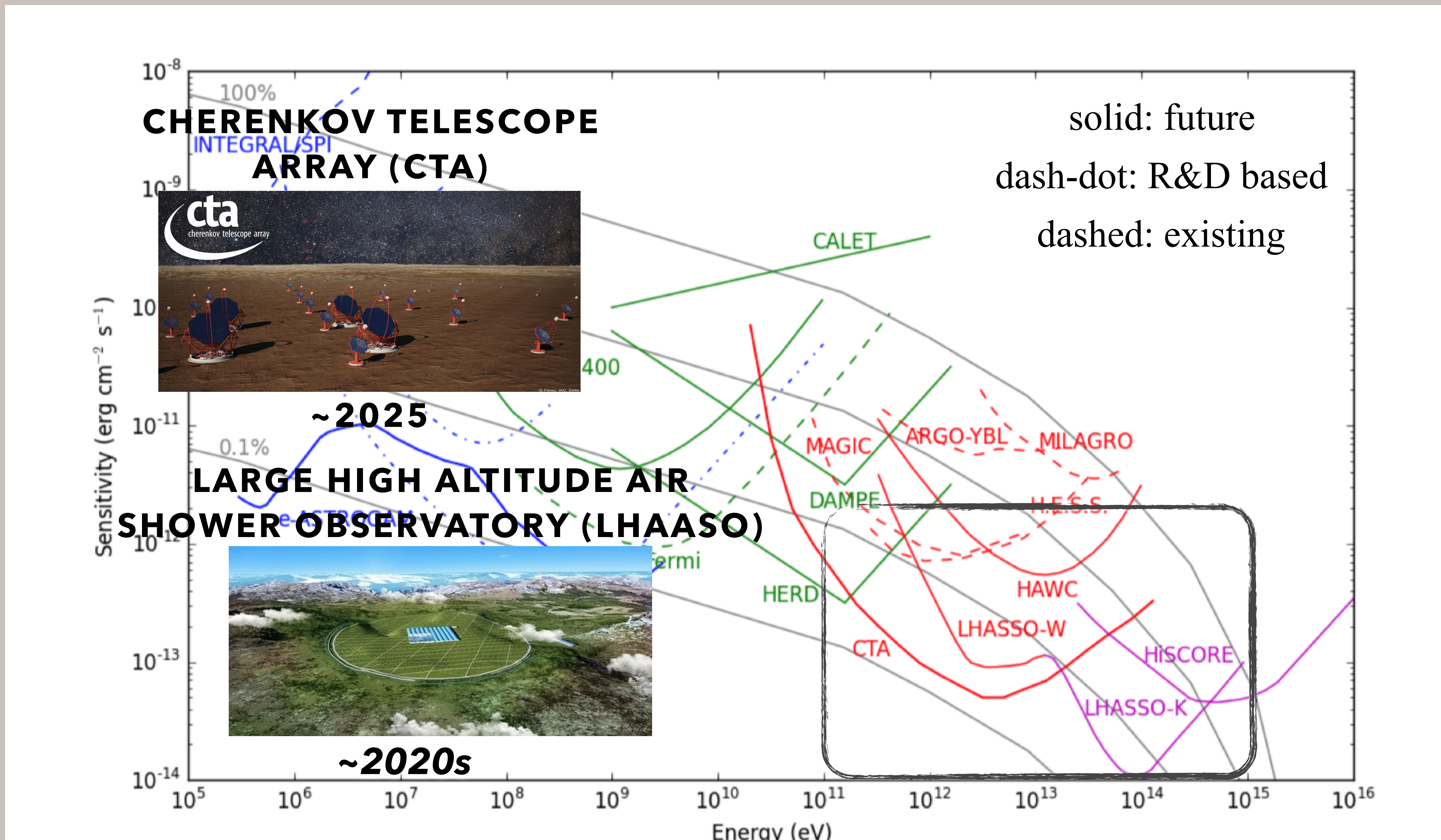

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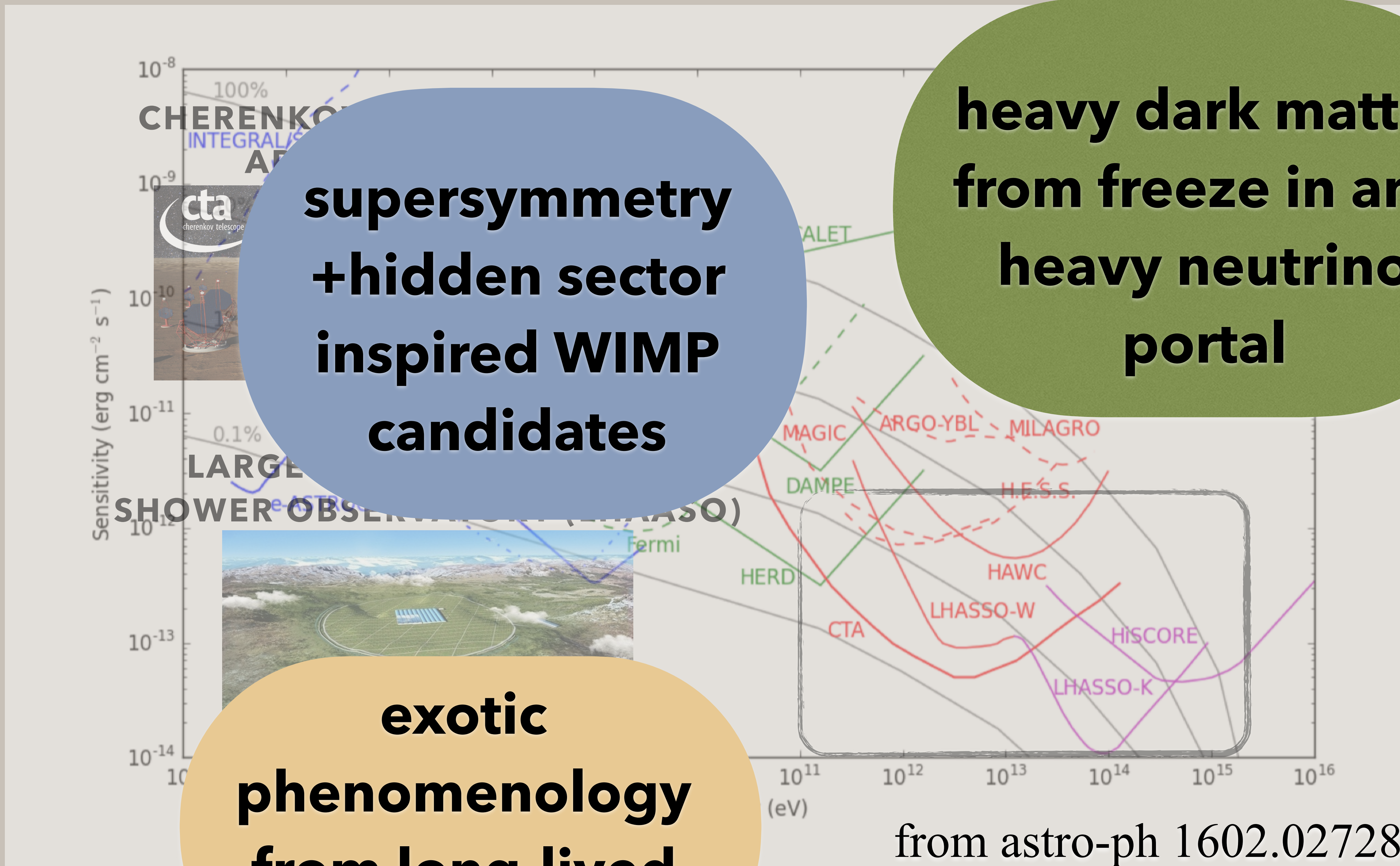
CTA/LHAASO will open up unprecedented windows into VHE/UHE gamma rays, enabling us to probe multi TeV-PeV scale dark matter

THREE STORIES



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supersymmetry +hidden sector inspired WIMP candidates

heavy dark matter from freeze in and heavy neutrino portal

exotic phenomenology from long-lived mediators

CTA/LHA… edented windows into VHE/UHE gamma ray… multi TeV-PeV scale dark matter

DARK MATTER IN RPV SUSY+HIDDEN SECTOR U(1)′ FRAMEWORKS

work in progress (191x.maybe) with

Patrick Barnes, Zachary Johnson, Aaron Pierce

HOW I LEARNED TO STOP WORRYING AND LOVE SUSY (AGAIN)

✓ many of the **primary motivations for supersymmetry are as appealing as ever**: extension of spacetime symmetries, stability of vacua, gauge coupling unification. reasons to believe SUSY is a part of the underlying description of nature

✗ **hierarchy problem:** no evidence of superpartners @LHC suggests SUSY does not solve this, **might not be at the weak scale**. electroweak scale might be **accidentally fine-tuned** (or explained by other ideas)

✗ **neutralino LSP WIMP dark matter**: requires R-parity, but SUSY **might not be R-parity conserving** (might be attractive, for instance, for baryogenesis; e.g. A. Pierce, B. Shakya, JHEP 1906 (2019) 096, hep-ph 1901.05493)

✓ **hidden sectors** plausibly do not suffer from the hierarchy problem, and plausibly contain dark matter candidates

HIDDEN SECTOR U(1)′ + RPV SUSY

THE “SIMPLEST”(?) DARK MATTER SETUP

RPV -> none of the MSSM superpartners stable

hidden sector U(1)’, broken by a hidden sector Higgs vev, kinetic mixing with visible sector: all hidden sector particles (hidden gauge boson, gaugino, Higgsino, Higgs boson) can decay into the visible sector

for dark matter, need additional field content in the hidden sector

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adding fields charged under the U(1)′: need to ensure anomaly cancellation

If U(1)′ broken by a hidden Higgs vev, (at least) need something to cancel the charge of this hidden Higgs

minimal (?) extension:

$$\mathcal{W}_{hid} = \lambda S T H'$$

U(1)' charges: 0 +1 -1

HIDDEN SECTOR U(1)′ + RPV SUSY

THE "SIMPLEST"(?) DARK MATTER SETUP

$$\mathcal{W}_{hid} = \lambda S T H'$$

U(1)' charges: 0 +1 -1

Field content

- S, T sfermions, mass scale v'
- Dirac fermion (S-T), mass $\lambda v'$
- gauge boson Z', mass g'v'
- higgs boson H', mass g'v' (+ loop corrections)
- neutralinos χ'_1, χ'_2 (Higgsino, gaugino mixtures), mass ~ g'v', split by soft gaugino mass

Dark matter candidate: Lightest particle in the S-T system (scalar or fermion) is stabilized by an effective Z_2 symmetry, cannot decay away into visible sector stuff

HIDDEN SECTOR U(1)′ + RPV SUSY

THE "SIMPLEST"(?) DARK MATTER SETUP

Plausible Numbers

absence of stops/gluino at LHC does not mean all superpartners need to be heavy!

assuming gauge coupling (including hidden coupling g′) unification at GUT scale and soft masses within O(1) of each other in the UV gives

$v' \sim$ few hundred GeV - few TeV

$g' \sim 0.5$

for stop masses ~ 5 TeV (compatible with m_h = 125 GeV without significant stop mixing)

Furthermore, RGE has a fixed point at $\lambda = g'$, where the S-T Dirac fermion becomes degenerate with the dark Higgs, Z′, and neutralinos

DARK MATTER HISTORY

- The lighter of the fermion or the scalars in the S-T system is stable
- mass~ few hundred GeV - few TeV
- can undergo WIMP freezeout, get the right relic density
- RG running from UV to IR tends to make hidden sector particles degenerate; all might be relevant for the dark matter story!

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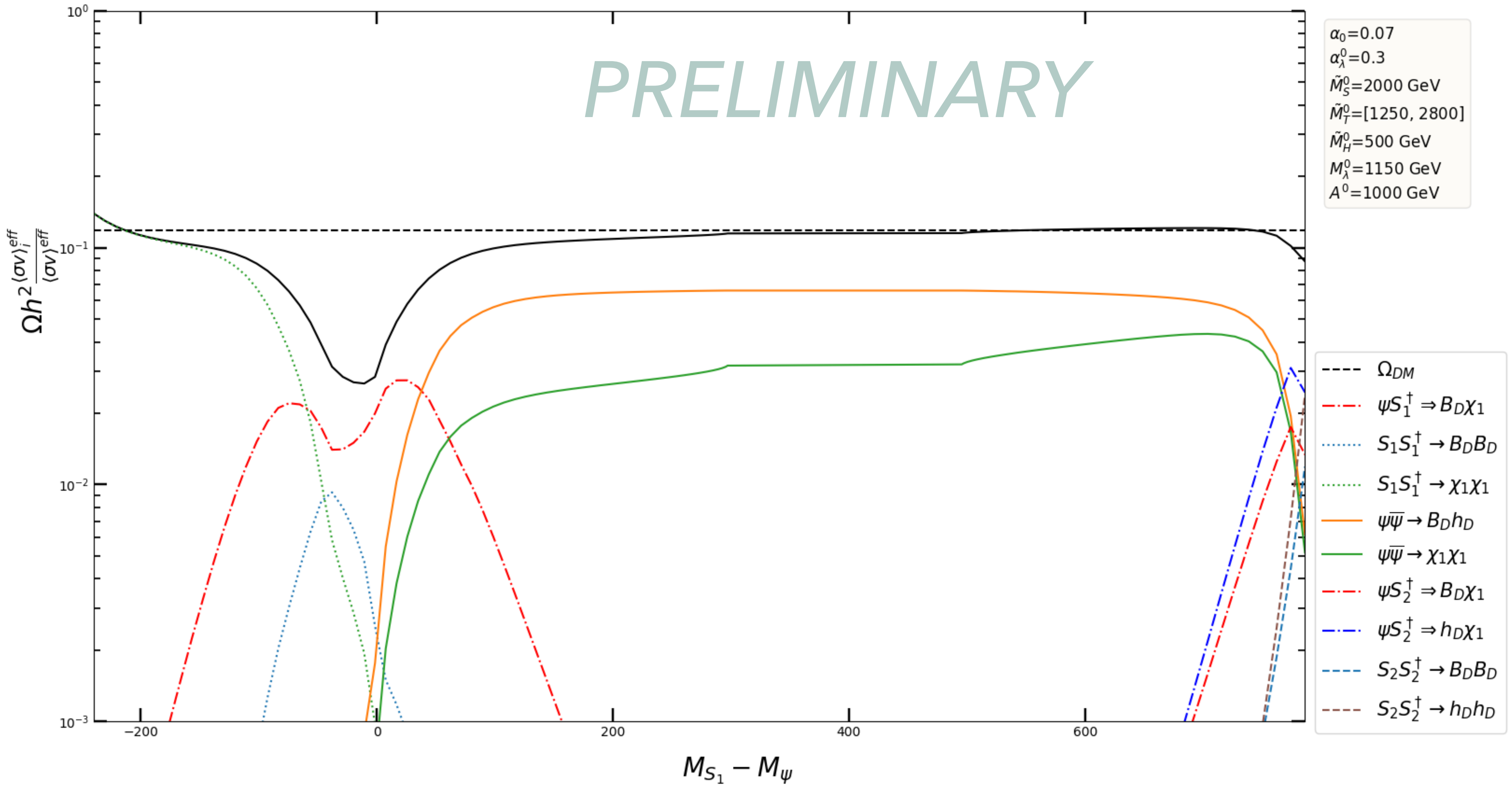
A sample:



DARK MATTER INDIRECT DETECTION

Dark matter undergoes annihilation into hidden sector particles with weak scale cross sections; these hidden sector particles undergo cascade decays into SM final states

A representative annihilation process:

$$\psi\psi \to Z'h'$$

$$Z'/h' \to \chi_1'\chi_1'$$

$$\chi_1' \to \chi_1(Z/h)$$ hidden to visible sector decay via kinetic mixing portal

$$\chi_1 \to fff$$ (RPV decay of would-be LSP)

- Decay products can be detected by experiments such as CTA
- Due to cascade decays, unlikely to have sharp features; perhaps multiple bumps from the multiple cascade steps?

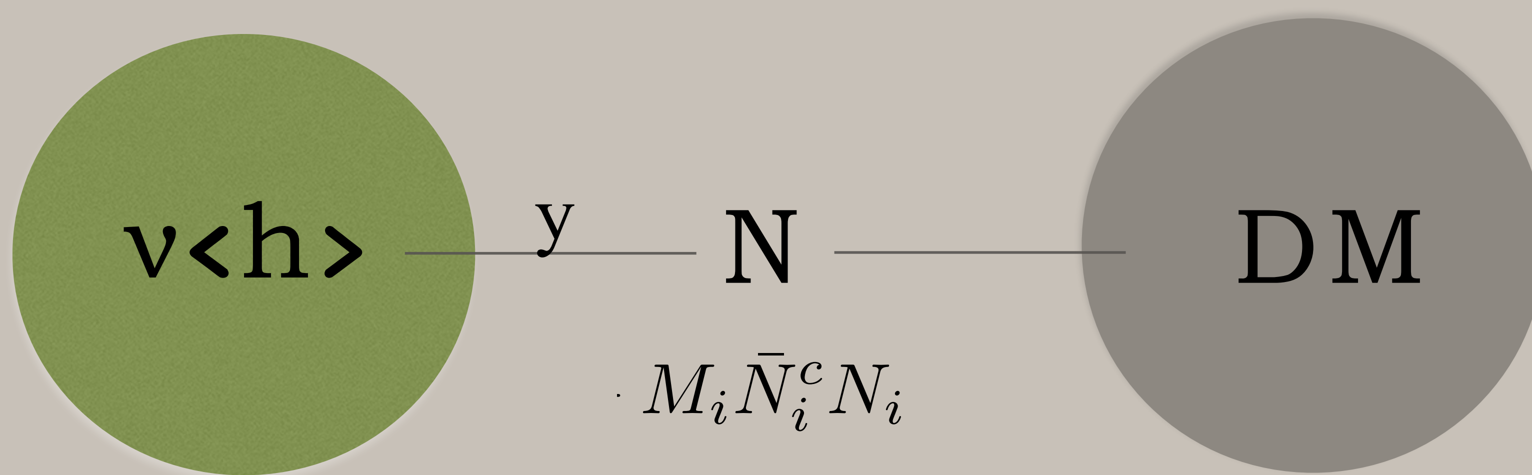
IMPORTANCE OF LOOP CORRECTIONS TO DARK MATTER SIGNALS VIA HEAVY NEUTRINO PORTAL

work in progress (191x.maybe)

with Hiren Patel, Stefano Profumo

A PLAUSIBLE FRAMEWORK

Dark matter resides in a hidden sector, communicates with the Standard Model via a heavy sterile neutrino portal



N’s singlet under all symmetries, likely much heavier than dark matter (GUT scale?)

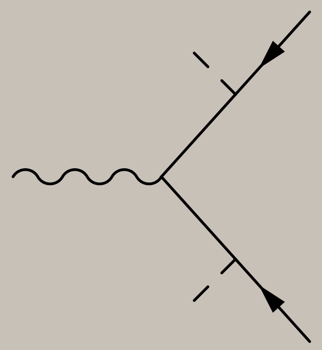
For simplicity, assume decaying DM that couples to NN.

Integrate out N to get effective coupling DM(LH)^2

DARK MATTER DECAY

$$DM \to \nu\nu$$

via active-sterile neutrino mixing

DM  $\sim \frac{v^2}{M_N^2}$

leading tree level decay, mixing angle suppressed

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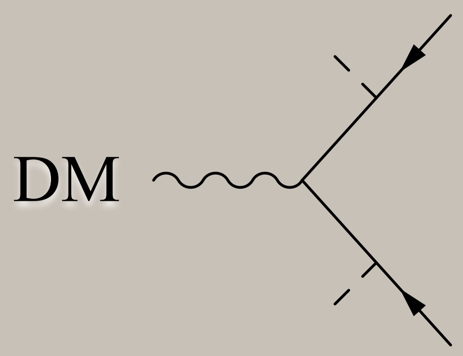
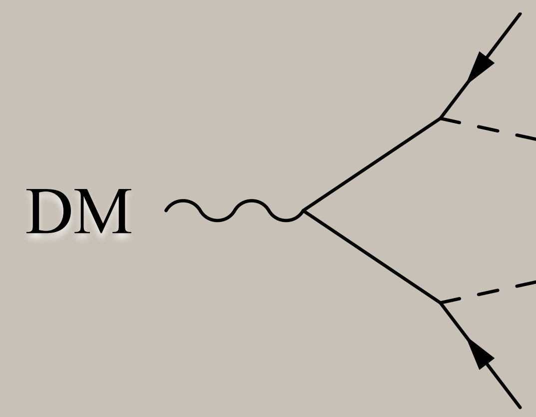


$$\sim \frac{v^2}{M_N^2}$$

leading tree level decay, mixing angle suppressed

If DM heavier than the weak scale, can replace vev insertion with physical Higgs/gauge bosons



$$\sim \frac{m_{DM}^2}{m_N^2}$$

can beat 2-body decay, since v replaced by the higher mass scale mDM

[also involved: SU(2) counterparts, 3-body decays]

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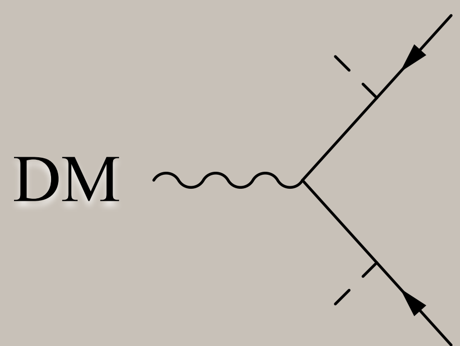

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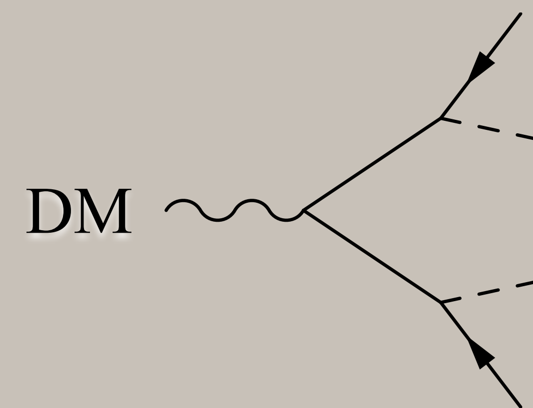

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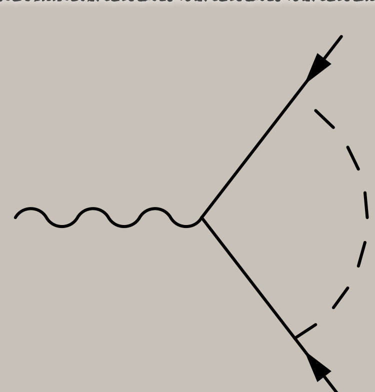


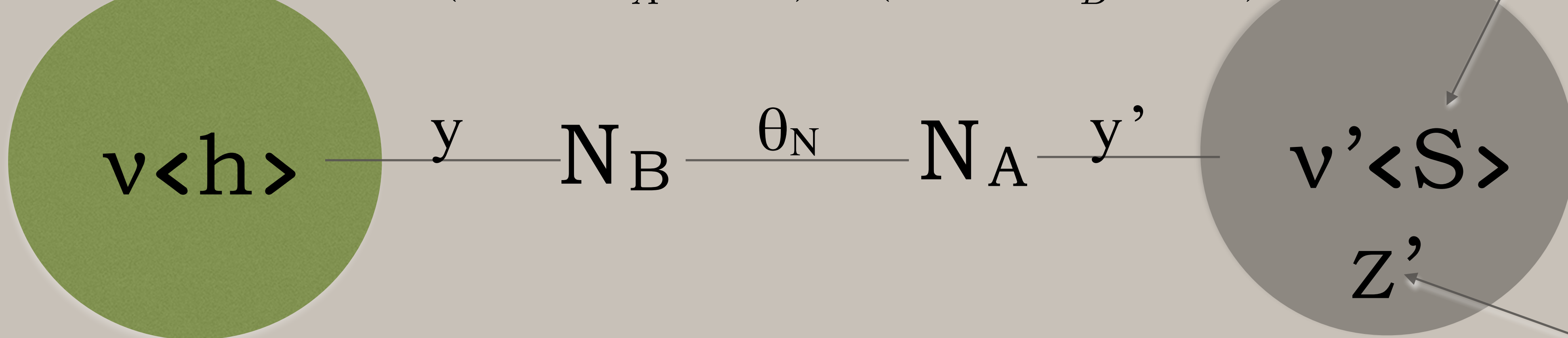
What about closing the higgs loop? Is this…

allowed? calculable (finite)? dominant?

A PATHOLOGY-FREE MODEL

Loop diagram **generally UV-divergent**. But can model build around it.
A simple working example:

$$-\frac{1}{2}(M_A N_A^\dagger N_A^\dagger + \theta_N M_{AB} N_A^\dagger N_B^\dagger + M_B N_B^\dagger N_B^\dagger + \\ -(y' S \nu'^\dagger N_A^\dagger + \text{c.c.}) - (y_\nu \tilde{H} L^\dagger N_B^\dagger + \text{c.c.})$$

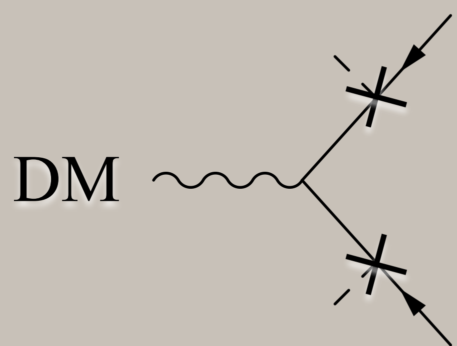


Hidden sector "neutrinos" ν' get mass $M_1 \sim \frac{(y'v')^2}{M_N}$

In this model, the loop diagram is finite and calculable!

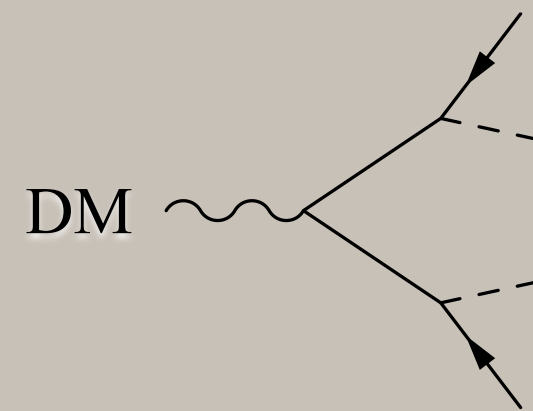
DARK MATTER DECAY CHANNELS

2 body tree



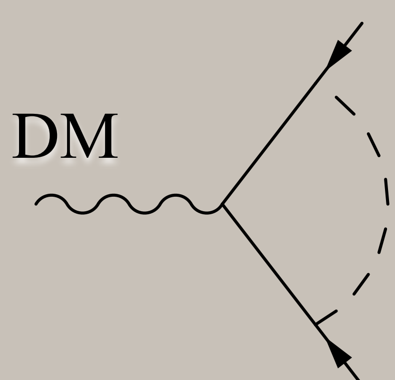
$$\sim \frac{v^2}{M_N^2}$$

4 body tree



$$\sim \frac{m_{DM}^2}{m_N^2}$$

2 body 1-loop



$$\sim \frac{{m_1}^2}{m_N^2}\, ln\left(\frac{m_N}{m_1}\right)$$

DARK MATTER DECAY CHANNELS

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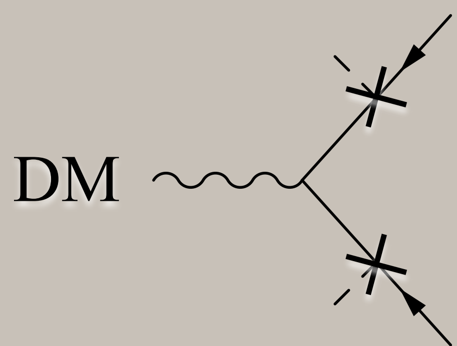

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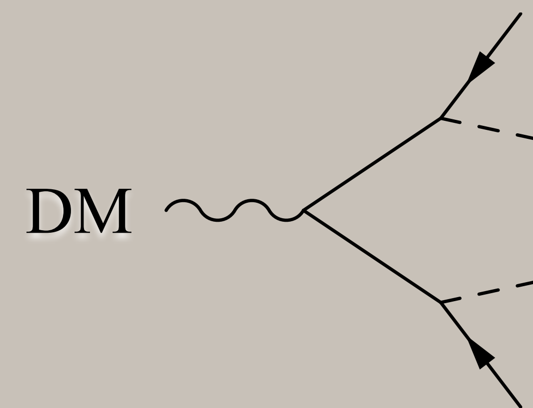

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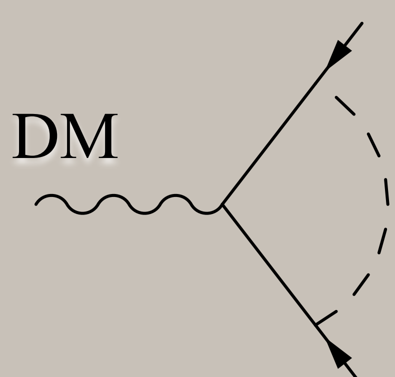
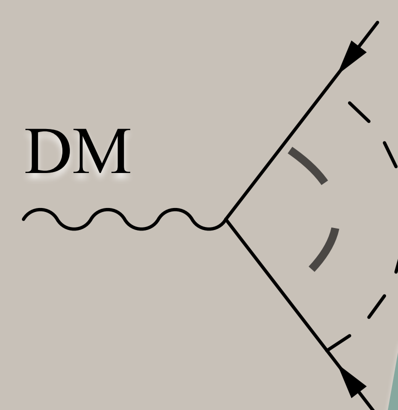


$$\sim \frac{{m_1}^2}{m_N^2}\, ln \left(\frac{m_N}{m_1}\right)$$

2 body 2-loop



$$\sim ln \left(\frac{m_N}{m_1}\right)\, ln \left(\frac{m_N}{m_1}\right)$$

PRELIMINARY

CASE STUDY:
MAJORON DARK MATTER

Majoron: Goldstone boson of a spontaneously broken global symmetry related to lepton number (associated with Majorana mass for sterile neutrinos)

$$\mathcal{L} = -\overline{L} y N_R H - \frac{1}{2}\overline{N}_R^c \lambda N_R \sigma + \text{h.c.},$$

$$\sigma = (f + \sigma^0 + \mathrm{i} J)/\sqrt{2}$$

Goldstone boson
(``Majoron")

Extensively studied as a dark matter candidate.
Primary channel: decay to 2 neutrinos at tree level (via active-sterile mixing)

Aforementioned loop diagram never mentioned. Why??

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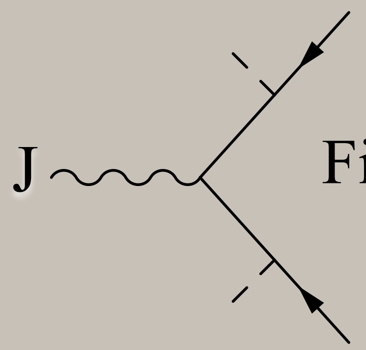
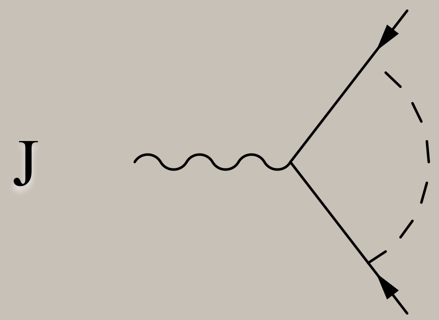
Goldstone boson (``Majoron")



Majoron carries lepton number +2.
Final state is 2 neutrinos (not neutrino+antineutrino); carries 2 units of hypercharge.
Need 2 Higgs vev insertions to compensate!



Aforementioned loop diagram would violate hypercharge conservation!
Need 2 Higgs vev insertions somewhere in the diagram…suppresses loop to be smaller than tree

Takeaway message: Information on tree vs loop can tell us something about lepton number (non)conservation in the dark matter decay process!

DARK MATTER DECAY SIGNALS

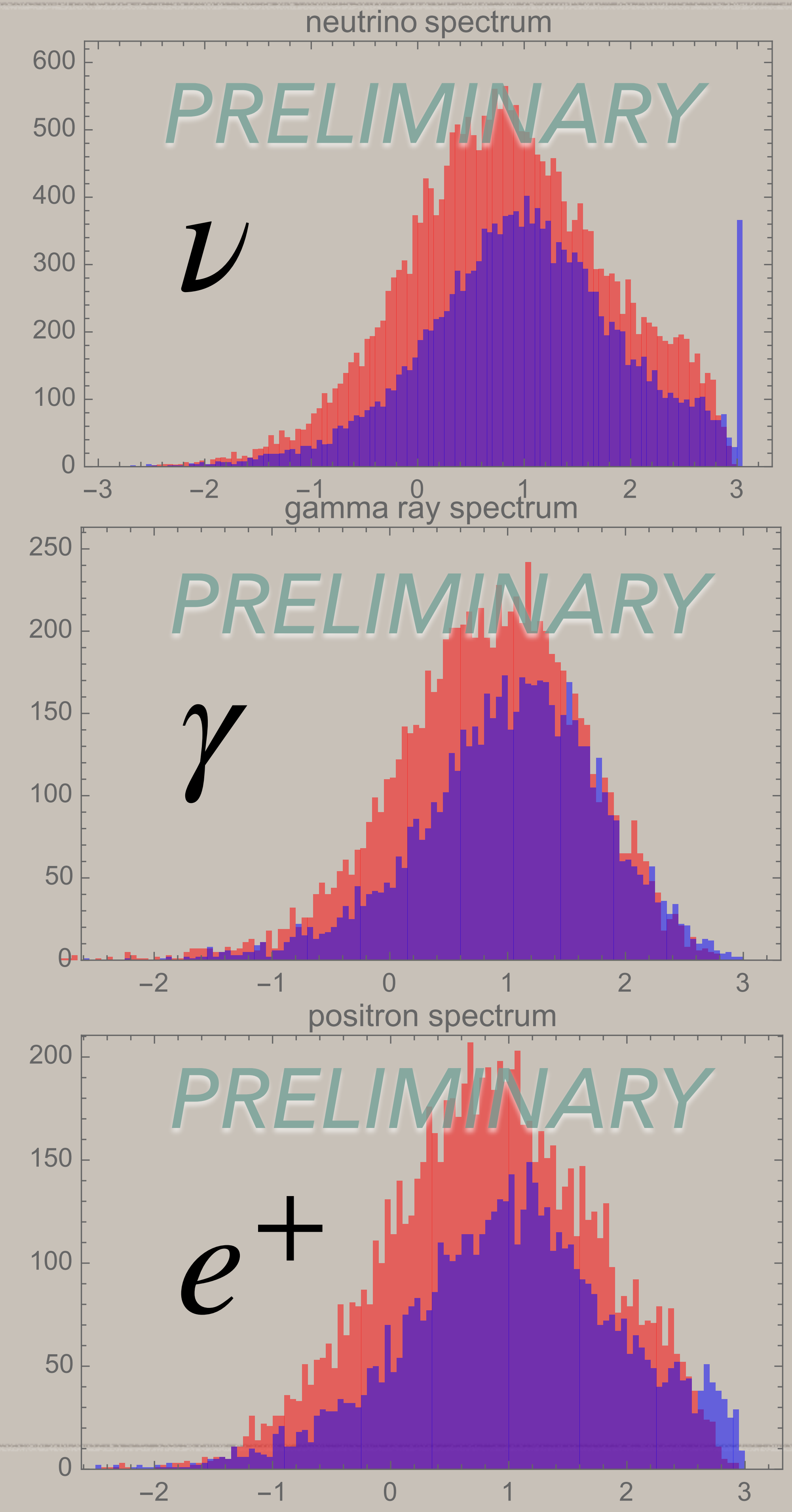
dark matter mass: 2 TeV
coupling dominantly to muon-type lepton doublet

x-axis: $log_{10}(E/GeV)$
y-axis: number count (arbitrary normalization)

RED: 4-body tree
BLUE: 2-body 1-loop

gamma ray and positron spectra from loop decays significantly harder than from 4-body decay

neutrino spectrum features a prominent line at the dark matter mass (so will the positron spectrum, if significant coupling to electron-type doublet)



SIGNALS OF DARK MATTER ANNIHILATION INTO LONG-LIVED MEDIATORS

based on

Stefania Gori, Stefano Profumo, Bibhushan Shakya,

Phys.Rev.Lett. 122 (2019) no.19, 191103

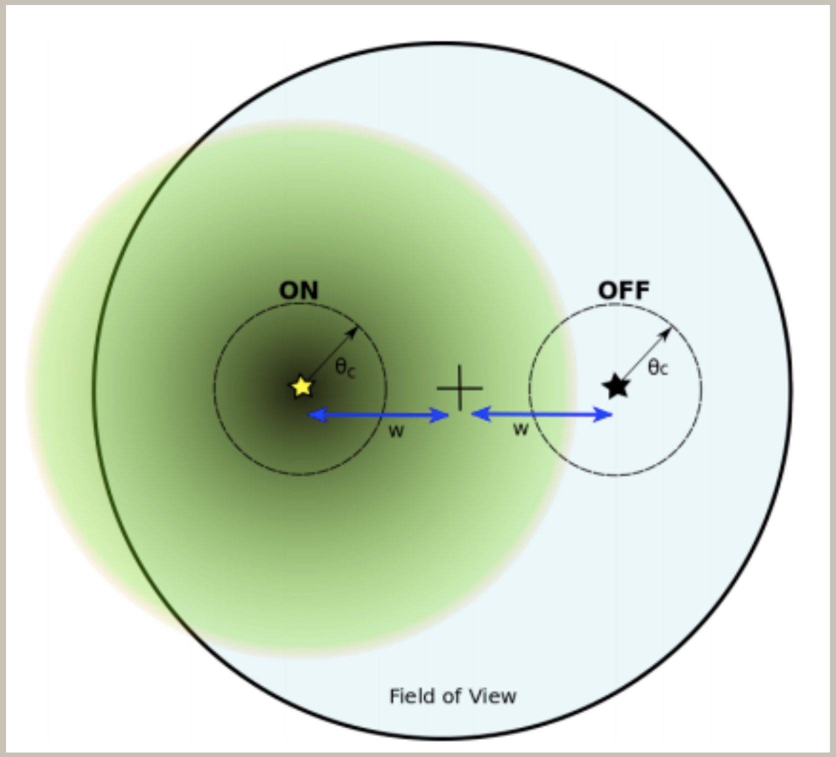
hep-ph 1812.08694

DM ANNIHILATION INTO LONG-LIVED MEDIATORS

DM can annihilate into mediators that are **long lived on astrophysical scales**

- need them to travel ~kpc distances; implies lifetimes ~years
- consistent with early Universe bounds if the abundance of the mediators is sufficiently suppressed
- distribution of DM signal does not follow the distribution of dark matter!

DM ANNIHILATION INTO LONG-LIVED MEDIATORS OBSERVATION OF DWARF GALAXY WITH CTA



from 1808.00559

wobble mode

CTA wobble mode DM signal extraction strategy:

model background from OFF region, correct this in the ON region
(effectively, signal = OFF-ON)

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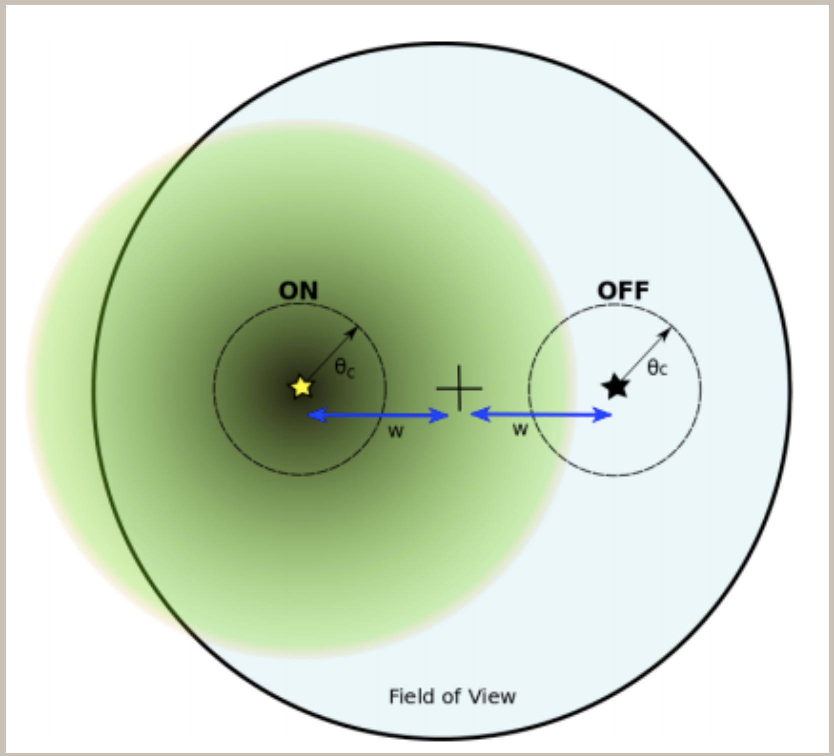
OBSERVATION OF DWARF GALAXY WITH CTA



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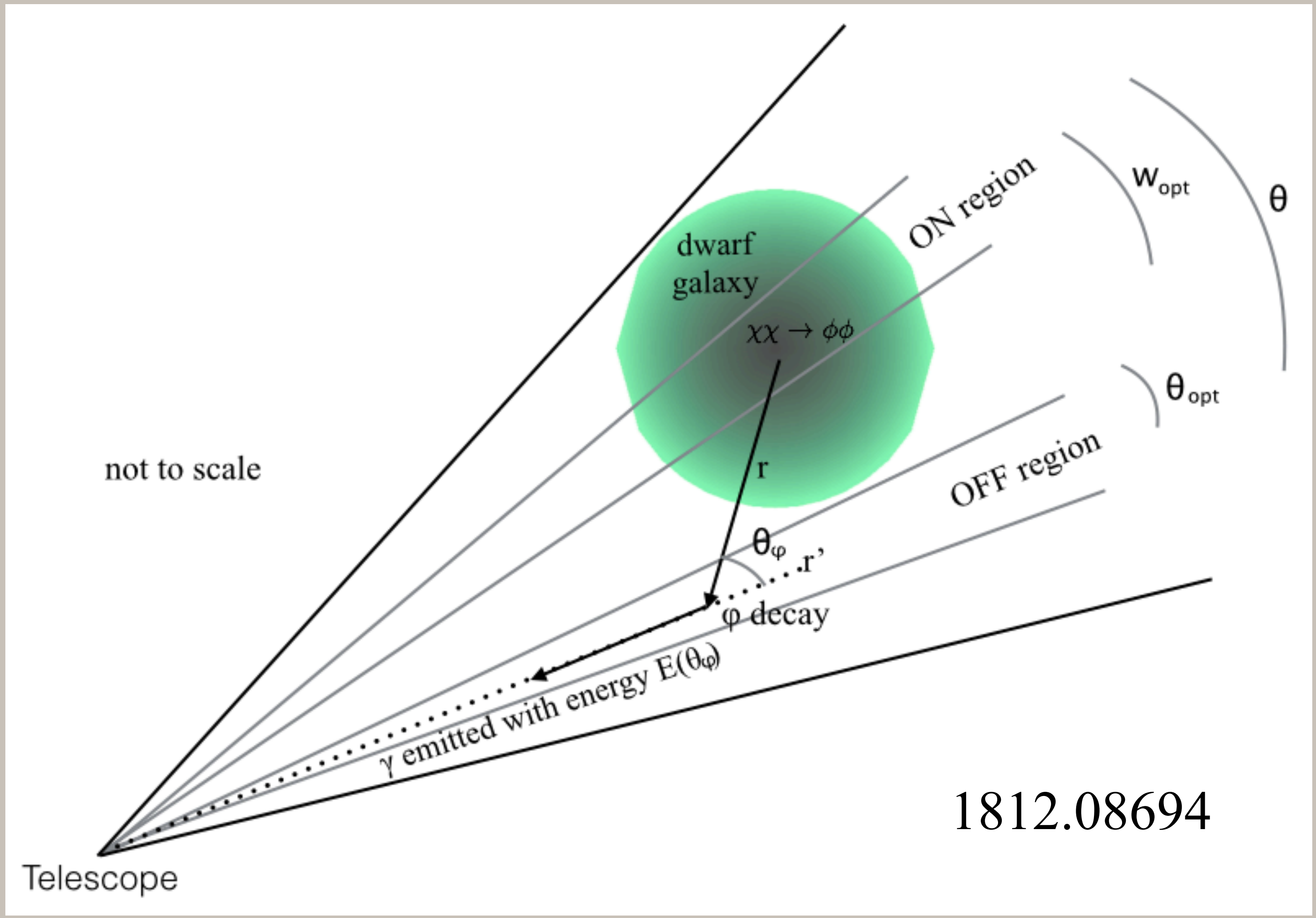


CTA wobble mode DM signal extraction strategy:

model background from OFF region, correct this in the ON region
(effectively, signal = OFF-ON)

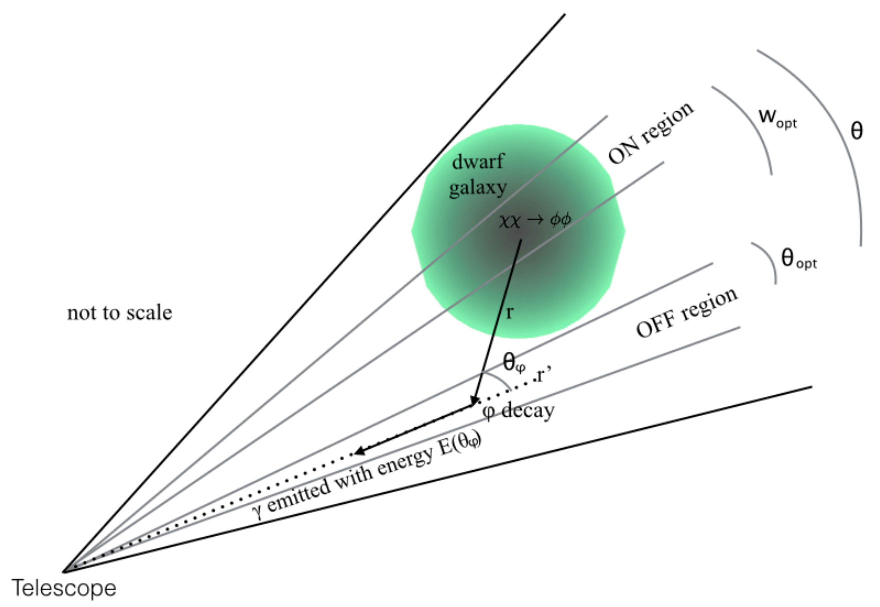
CASE STUDY: OBSERVATION OF DWARF GALAXY DRACO WITH CTA

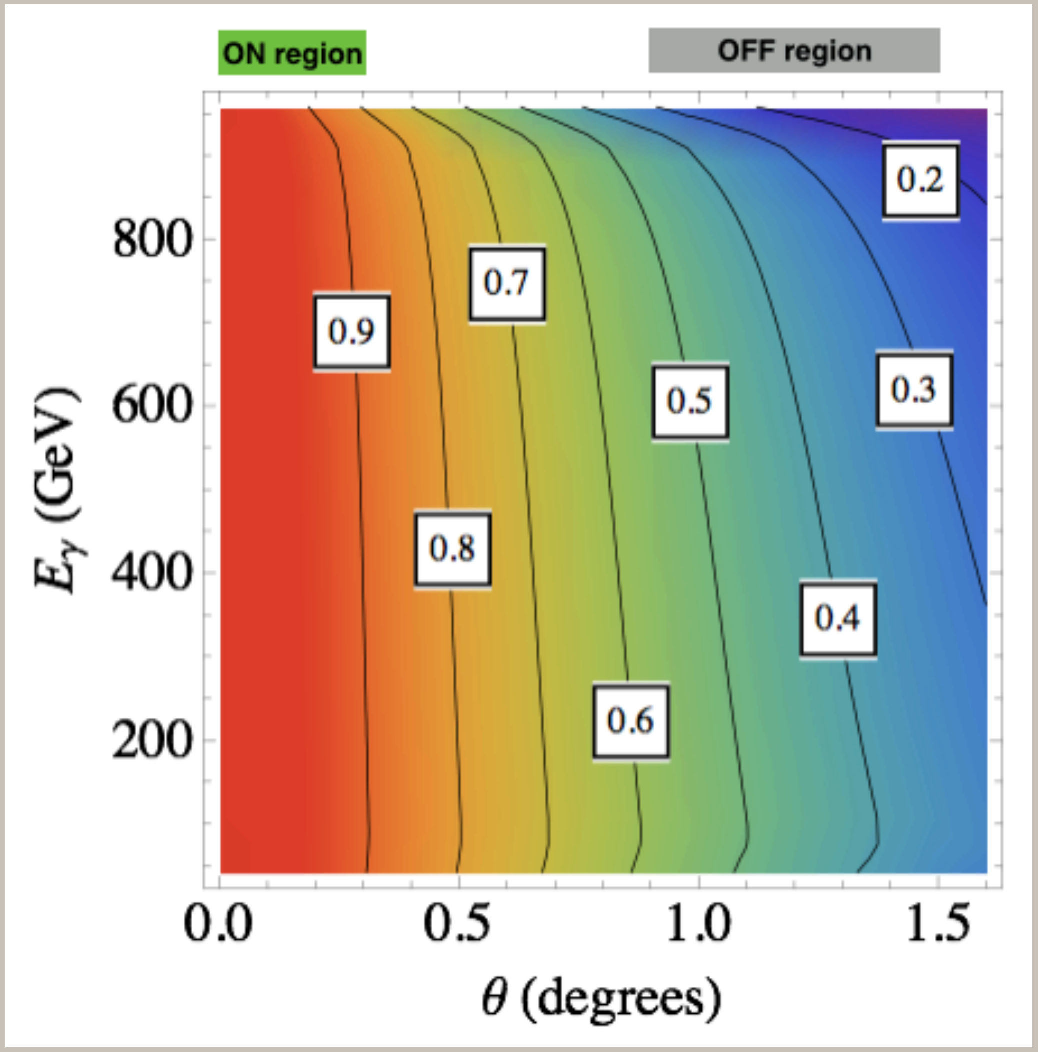
If mediator decays to monochromatic photons, **one-to-one relation between photon energy and emitted direction**

$$E_\gamma = \frac{m_\phi^2/(2m_\chi)}{1-\beta_\phi \cos\theta_\phi}$$

certain energies more "preferred" in certain directions

gamma ray energy spectra from different directions are different!



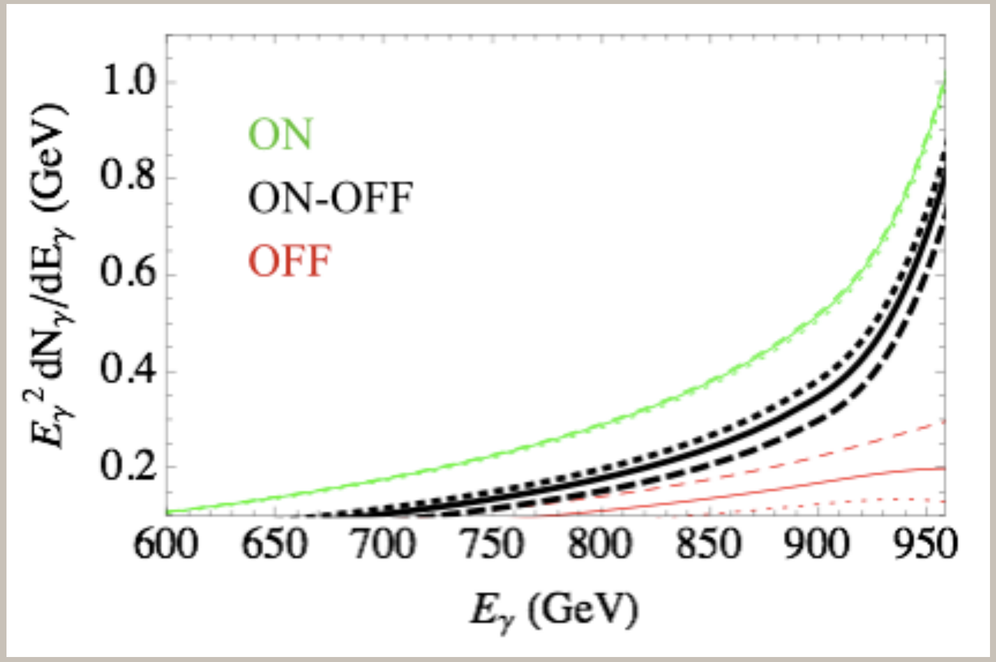


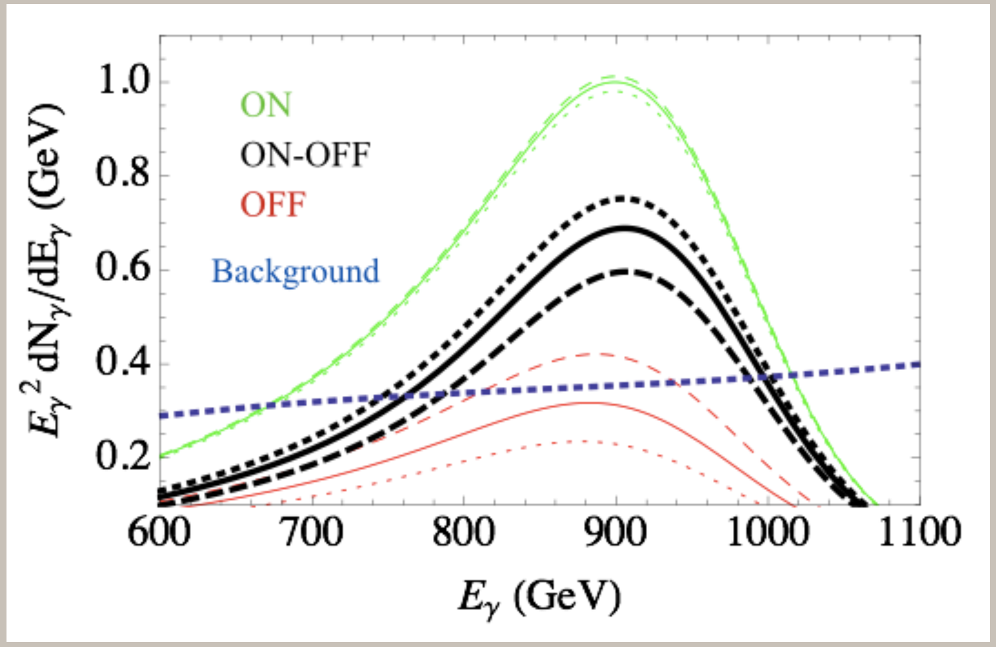
Contours of $\Phi(E\gamma, \theta)/\Phi(E\gamma, \theta = 0)$

$m_\chi = 1\,TeV$, $m_\phi = 400\,GeV$

mediator decay length $l_d = 10\,kpc$

CASE STUDY: OBSERVATION OF DWARF GALAXY DRACO WITH CTA





left, right: signal without, with instrumental effects

dashed->solid->dotted: increasing angle between ON and OFF regions

the extracted **signal is reduced** because of **signal contamination in the background region**; however, **the peak feature** in the extracted spectrum **gets enhanced**!

SUMMARY

Exciting progress in the multi-TeV indirect detection frontier in the coming years. Invites us to think harder about theoretically motivated dark matter ideas and their signatures

supersymmetry + R-parity violation + hidden sector with U(1)'

- "easy" to arrange WIMP-like freezeout of a stable hidden sector DM candidate
- Generically, many superpartners involved, signals involve cascade decays of hidden sector particles

loop corrections for heavy dark matter decay via a heavy neutrino portal:

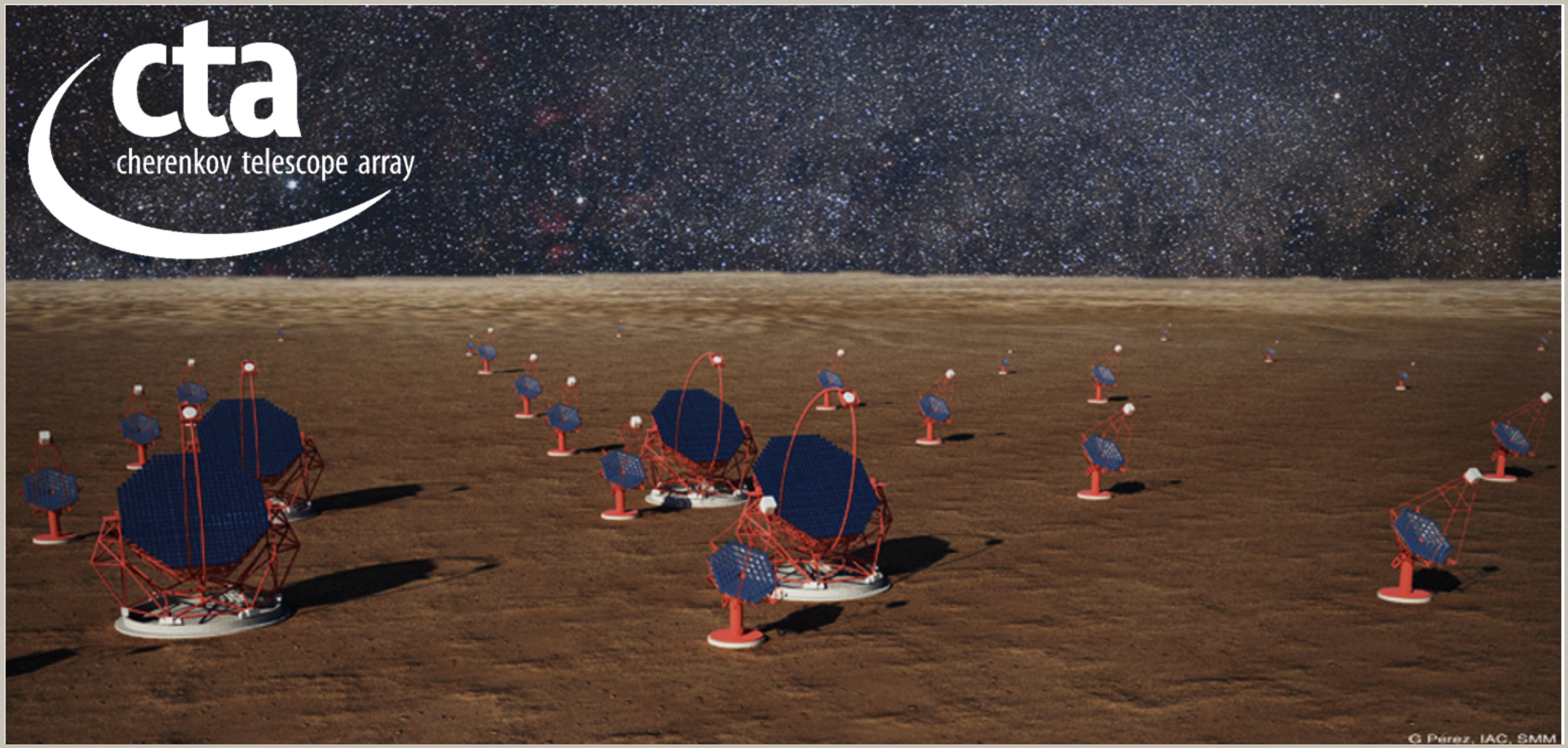
- neutrino loop diagrams can provide the dominant decay channels despite the presence of tree-level channels
- strength of tree vs loop can shed light on lepton number (non)conservation in the decay process

dark matter annihilation into long lived mediators

- affects wobble-mode observations of point-like DM sources
- could lead to exotic signals where signal spectrum varies across the sky

BACKUP SLIDES

CHERENKOV TELESCOPE ARRAY (CTA)



- northern (Las Palmas) and southern (Chile) hemisphere sites
- sensitivity about a factor 10 better than current instruments such as H.E.S.S, MAGIC and VERITAS
- energy coverage from a few tens of GeV to several tens of TeV, and a field of view of up to 10°.
- operational ~2025

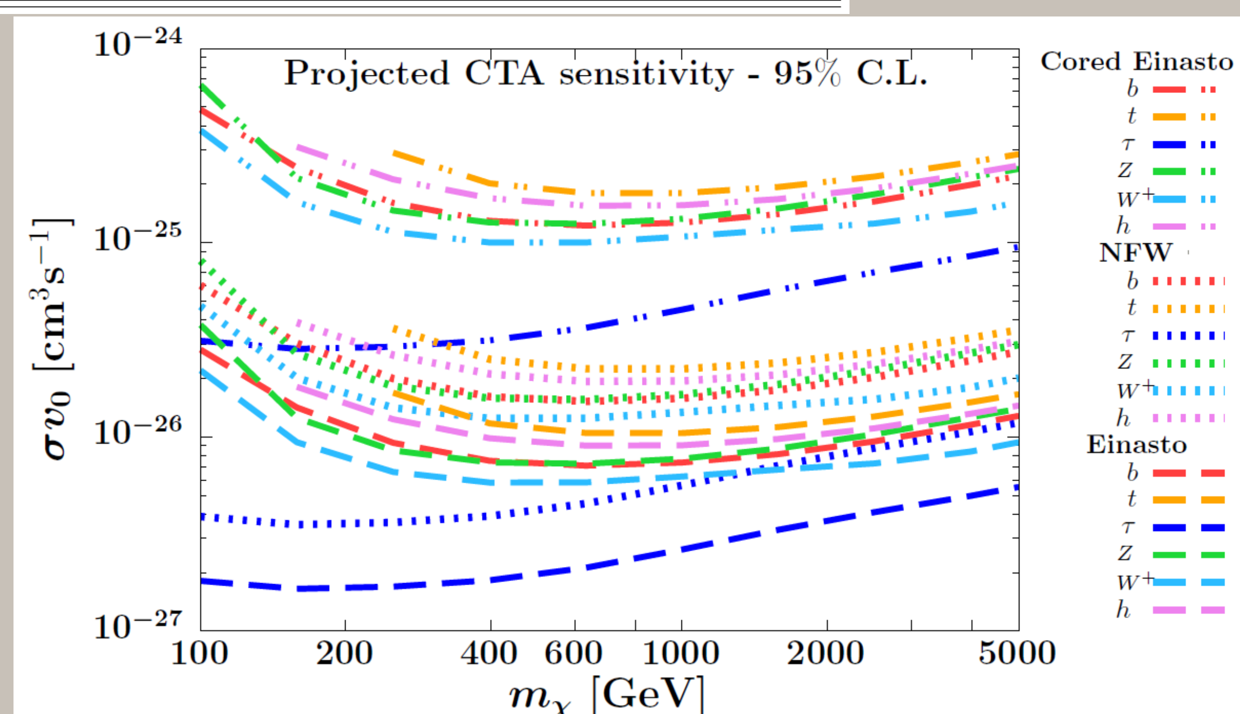
CHERENKOV TELESCOPE ARRAY (CTA)

CTA sensitivity

- 500h,
- 20 bin E > 30 GeV,
- latitude & longitude bins 0.5° (up to ±5°),
- excl. band ±0.3° also 0.4° around HESS J1745-303,
- CTA IRFs based on MC simulations for Southern array

$$\rho_{\rm NFW}(r) = \rho_s \left[\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2\right]^{-1} \qquad \rho_{\rm E}(r) = \rho_s \exp\left\{-\frac{2}{\alpha_s}\left[\left(\frac{r}{r_s}\right)^{\alpha_s} - 1\right]\right\}$$

Profiles	Einasto (E)	NFW	Cored Einasto (CE)
ρ_s (GeVcm^{-3})	0.079	0.307	0.079
r_s (kpc)	20.0	21.0	20.0
α_s	0.17	–	0.17
r_c (kpc)	–	–	3.0



from hep-ph 1905.00315

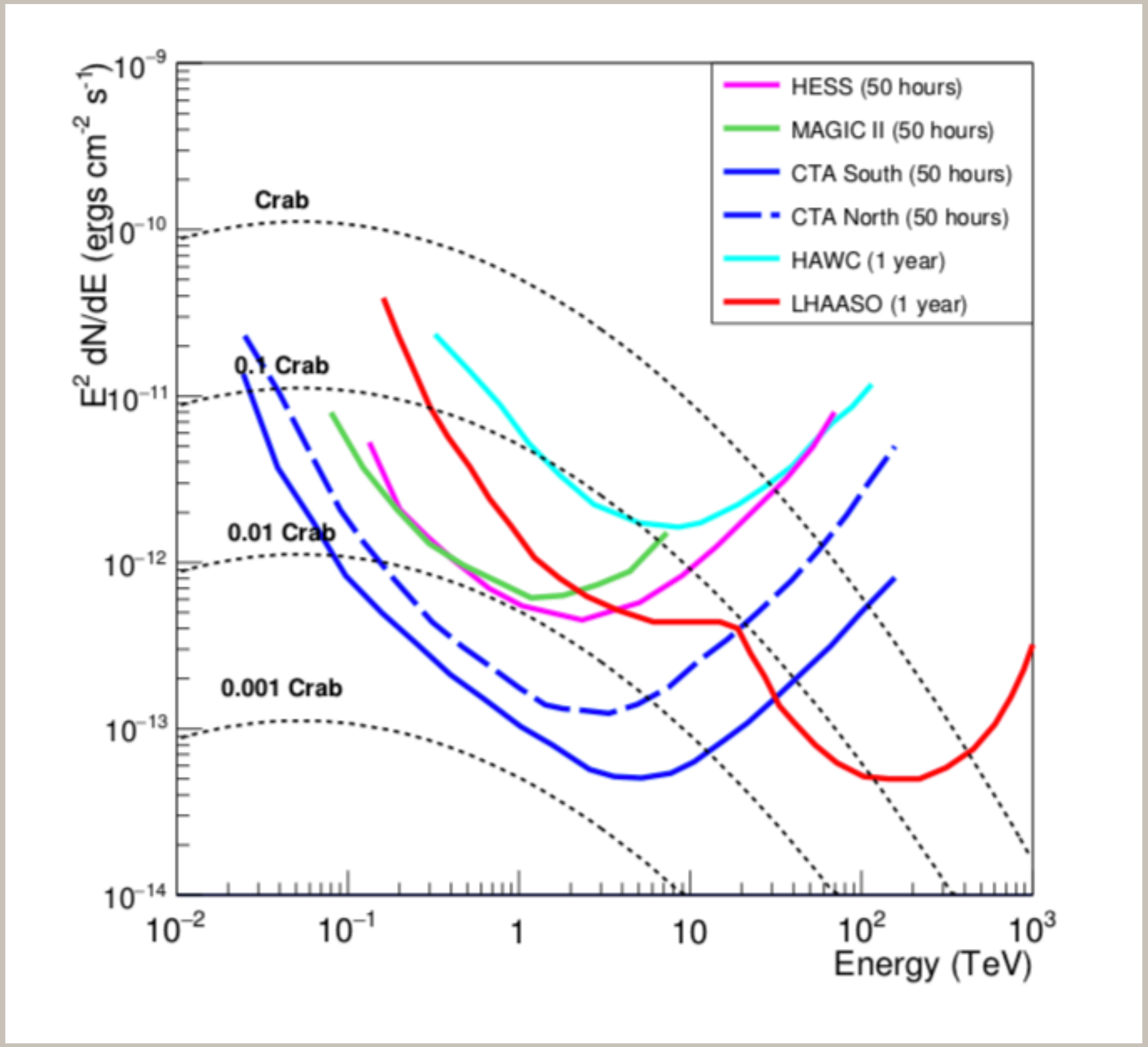
LARGE HIGH ALTITUDE AIR SHOWER OBSERVATORY (LHAASO)

LHAASO will be located at high altitude (4410 m asl, 600 g/cm^2, 29° 21' 31" N, 100° 08'15" E) in the Daochen site, Sichuan province, P.R. China. The commissioning of one fourth of the detector will be implemented in 2018. The completion of the installation is expected by the end of 2021.

The first phase of LHAASO will consist of the following major components:

- 1 km^2 array (LHAASO-KM2A) for electromagnetic particle detectors (ED) divided into two parts: a central part including 4931 scintillator detectors 1 m^2 each in size (15 m spacing) to cover a circular area with a radius of 575 m and an outer guard-ring instrumented with 311 EDs (30 m spacing) up to a radius of 635 m.
- An overlapping 1 km^2 array of 1146 underground water Cherenkov tanks 36 m^2 each in size, with 30 m spacing, for muon detection (MD, total sensitive area ~42,000 m^2).
- A close-packed, surface water Cherenkov detector facility with a total area of about 78,000 m^2 (LHAASO-WCDA).
- 12 wide field-of-view air Cherenkov telescopes (LHAASO-WFCTA).

GAMMA RAYS: THE TEV SCALE FRONTIER



from astro-ph 1602.07600

CTA/LHAASO will open up unprecedented windows into VHE/UHE gamma rays, enabling us to probe multi TeV-PeV scale dark matter!