Phenomenology of Particle Dark Matter

Rebecca K. Leane

PhD Completion Seminar
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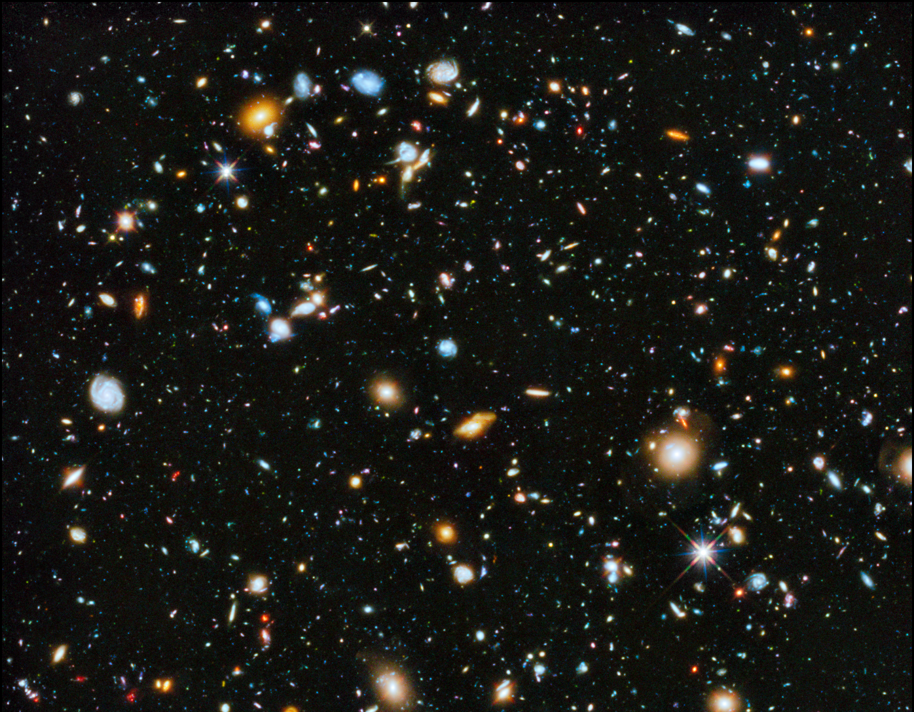
Featuring work with
Nicole Bell, Yi Cai, Tom Weiler,
James Dent, Kenny Ng and John Beacom

THE UNIVERSITY OF MELBOURNE

CoEPP



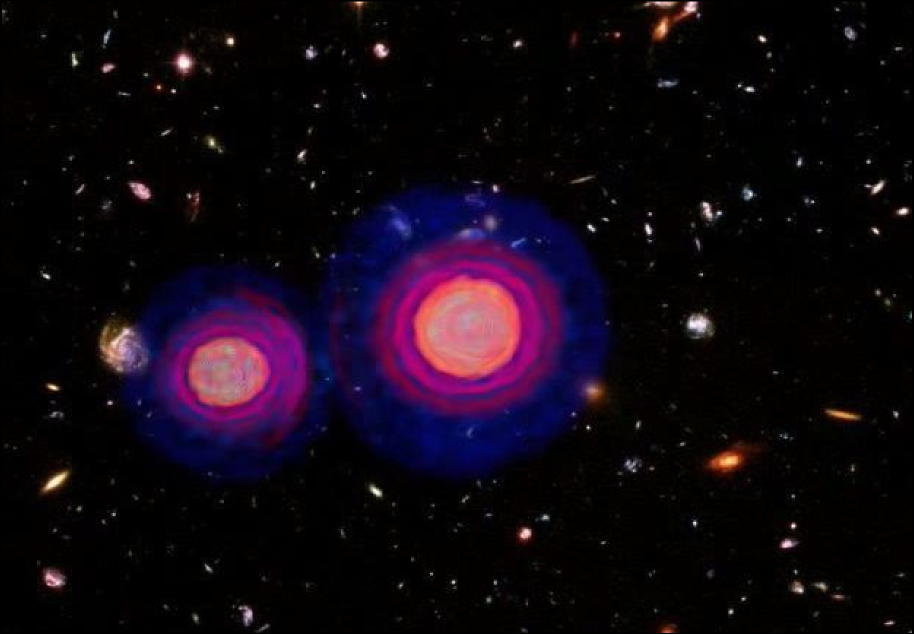
We don't know what

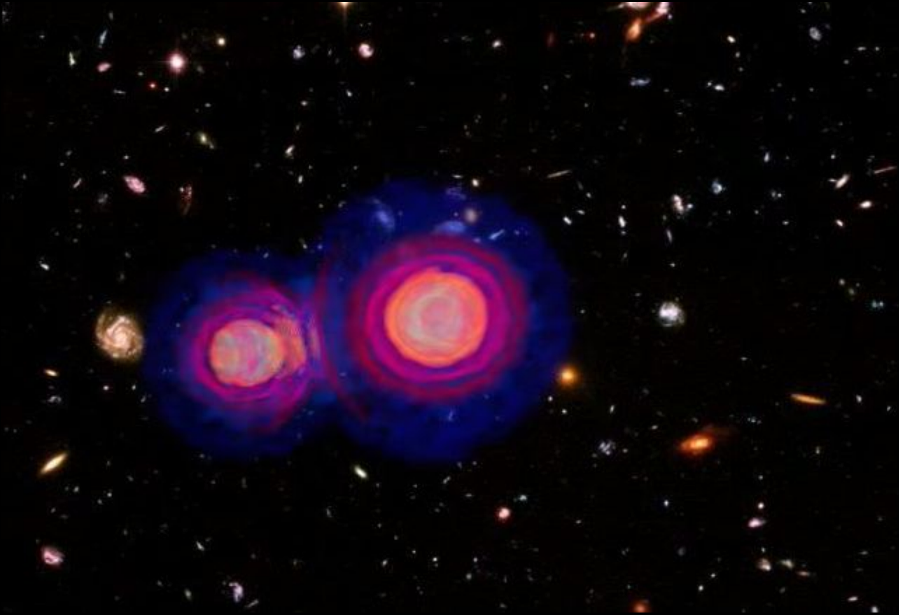
95%

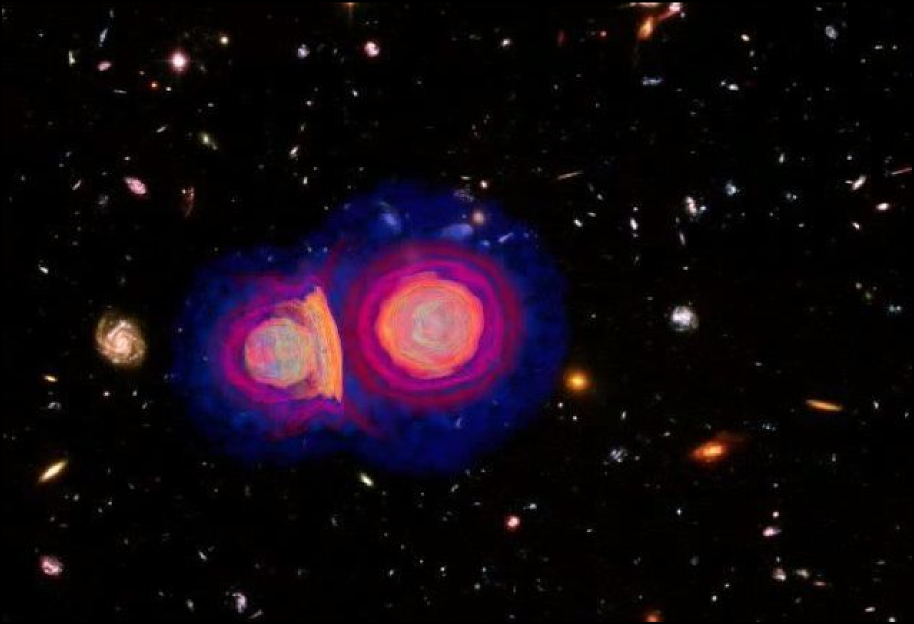
of the universe is!

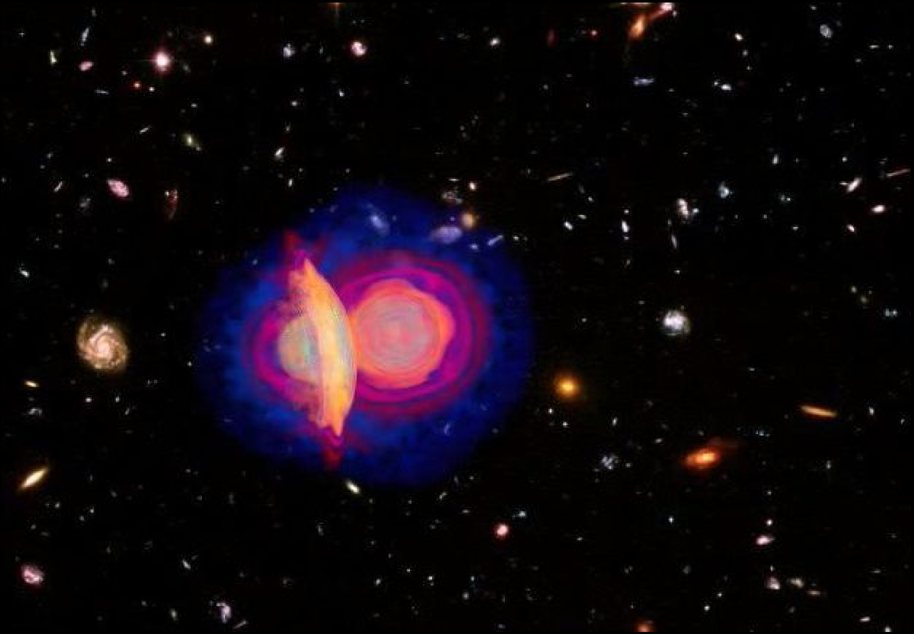
The rest is “dark” stuff.

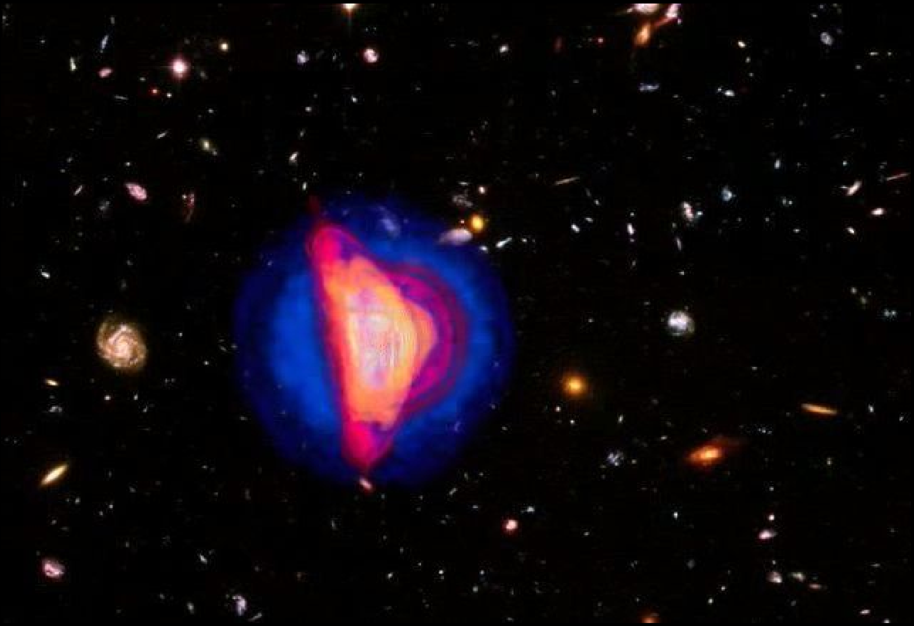
Dark matter, and dark energy.

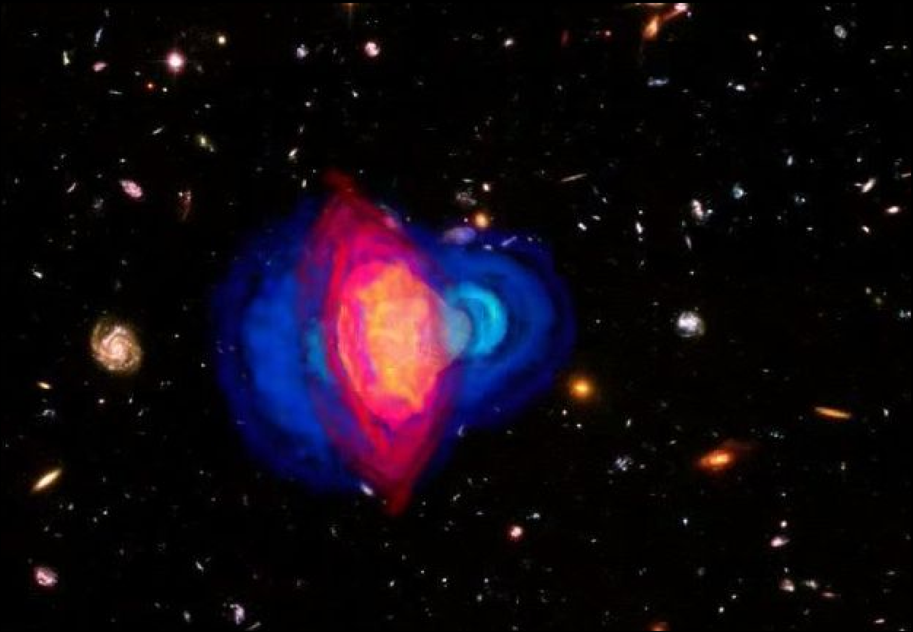


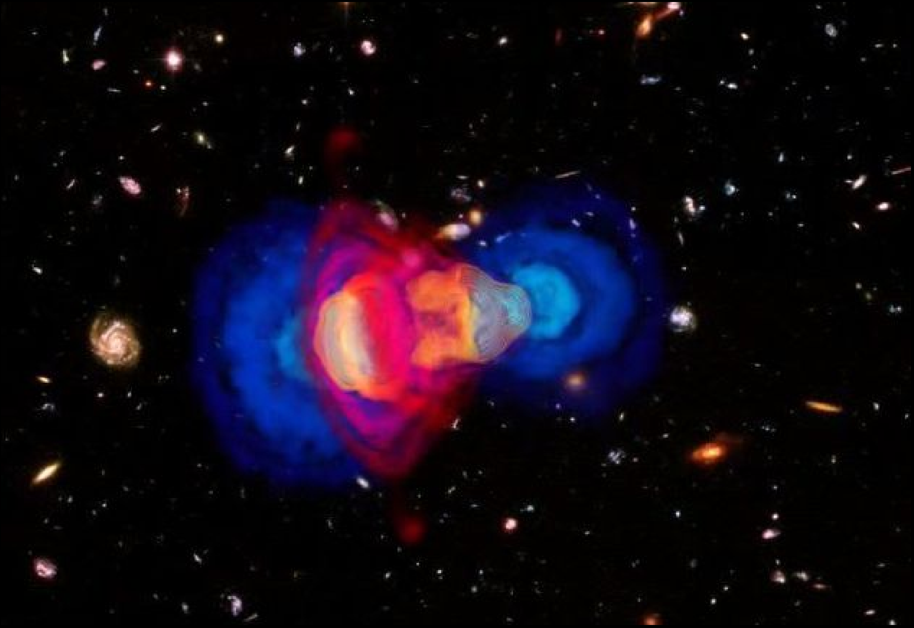


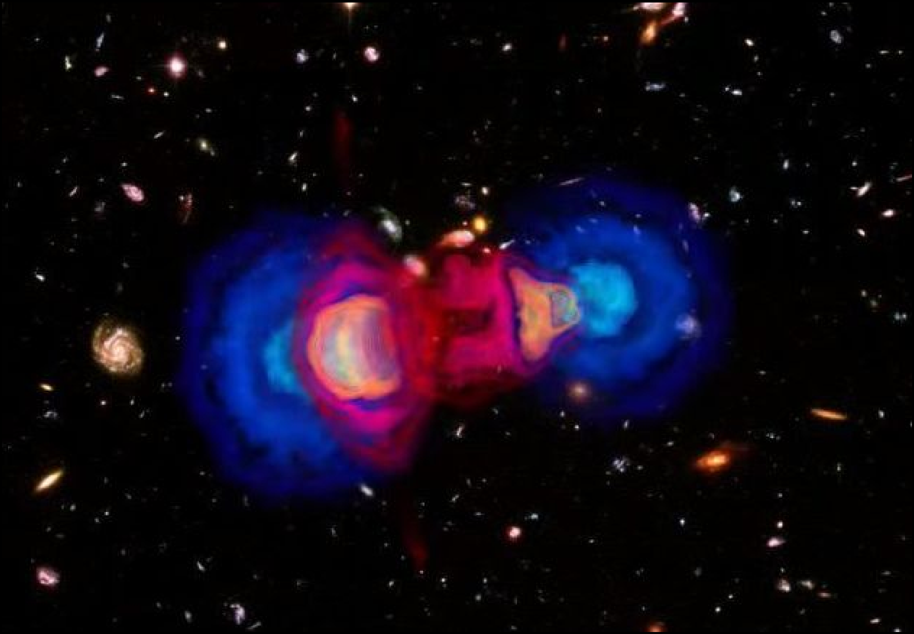


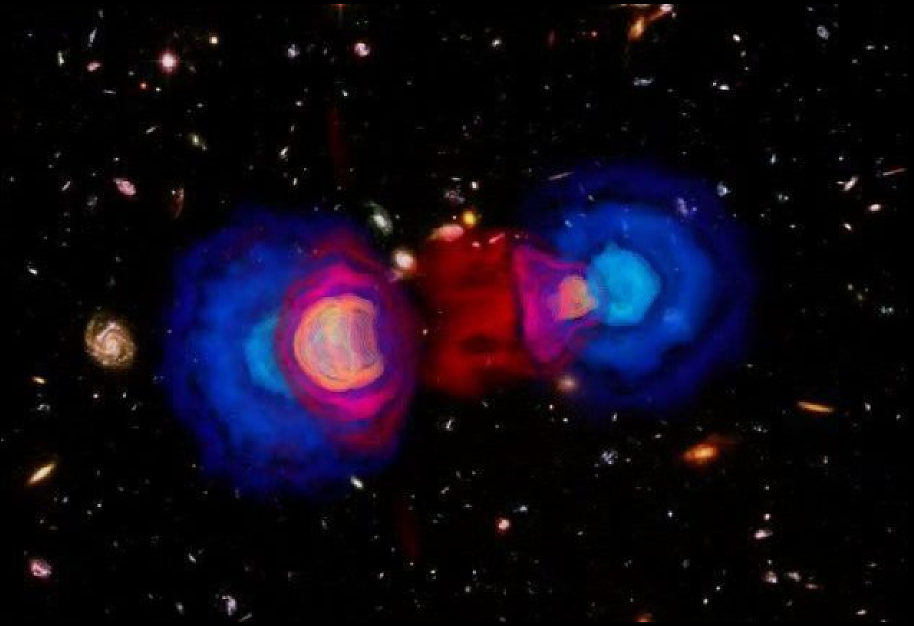






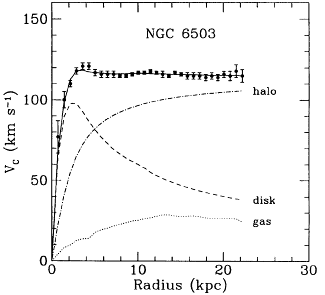


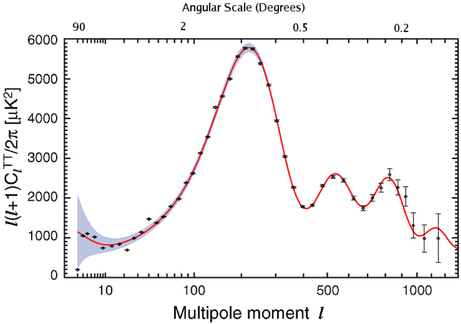


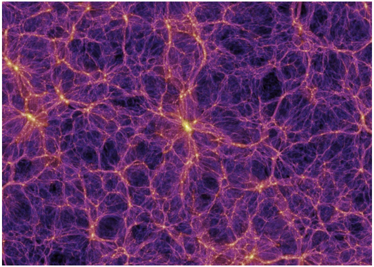



Bullet Cluster
Chandra X-Ray Telescope
Hubble Space Telescope

Abundance of evidence





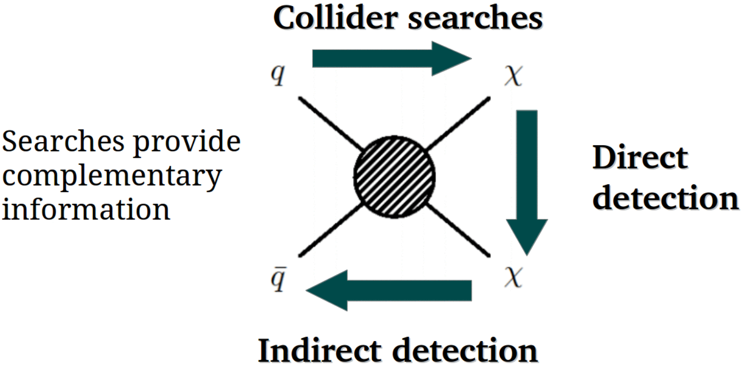


Yet little is known...

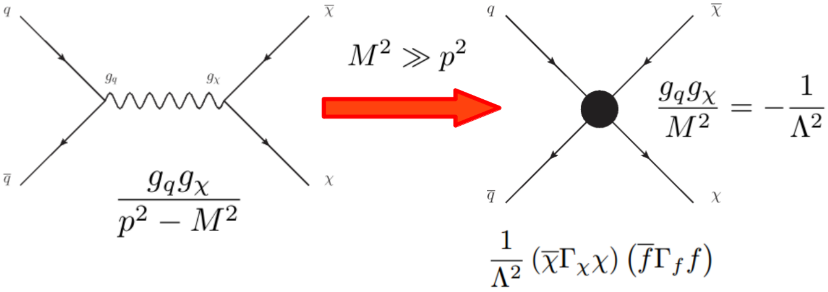
- There is overwhelming evidence that dark matter is the dominant form of matter in the universe, yet little is known about its physical properties.
- To better understand our universe at a fundamental level, it is necessary to develop theories which can be correctly probed at experiments.

Searches for particle dark matter

- WIMP dark matter well motivated: weak scale masses and interaction strengths
- Realistic detection prospects



Effective field theories for dark matter



- Model independent
- Useful at low energies, i.e. direct detection
- Colliders? Need to be careful. Cutoff at new physics scale.

Other times EFTs are invalid?

- In the Standard Model, electroweak symmetry is broken by Higgs mechanism, giving rise to longitudinal modes. Allows masses for W and Z gauge bosons.

$$SU(3) \otimes SU(2)_L \otimes U(1)_Y \to SU(3)_C \otimes U(1)_{QED}$$

- Any breaking of electroweak symmetry is linked to the "scale" of the Higgs field, called the "vev"
- If an EFT does not respect the electroweak gauge symmetries of the SM, it may be invalid around the electroweak scale, rather than the scale of new physics.

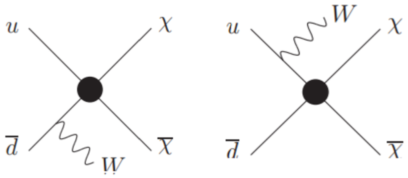
$$\frac{\mathrm{vev}^2}{\Lambda^4}(\overline{\chi}\gamma^\mu\chi)(\overline{u}_L\gamma_\mu u_L)$$

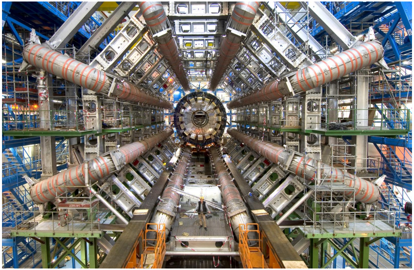
Mono-X signal at colliders

- Dark matter $\rightarrow$ missing energy in the detector
- Visible matter recoils against this missing energy
- Examples include mono-Z, mono-W, mono-photon, mono-jet

$$\text{pp} \rightarrow \overline{\chi}\chi + \text{SM particle}$$

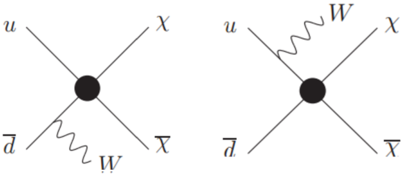
$$\text{pp} \rightarrow \text{MET} + \text{SM particle}$$





ATLAS experiment, CERN

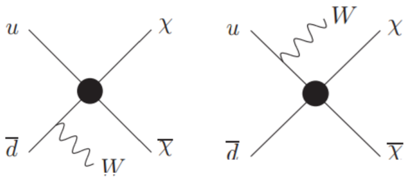
Mono-W EFT



$$\frac{1}{\Lambda^2}(\overline{\chi}\gamma^\mu\chi)(\overline{u}\gamma_\mu u + \xi\overline{d}\gamma_\mu d)$$

- Theorists set $\xi \neq +1$, claimed to find “interference effect”
- Analysis was repeated by ATLAS and CMS

Mono-W EFT



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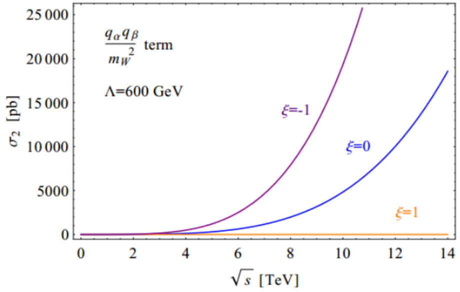
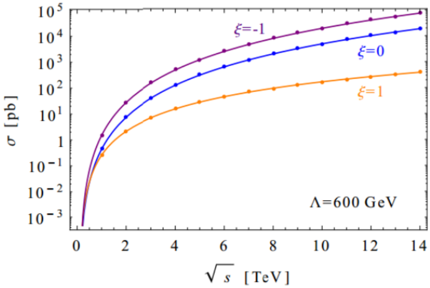
Up and down quarks are related by $SU(2)_L$ symmetry...

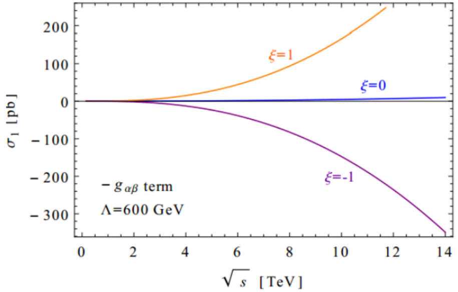
$$\begin{pmatrix} u \\ d \end{pmatrix}_L$$



$\frac{q_\alpha q_\beta}{m_W^2}$ term
Λ=600 GeV
ξ=-1
ξ=0
ξ=1
σ_2 [pb]
25 000
20 000
15 000
10 000
5000
0
0 2 4 6 8 10 12 14
$\sqrt{s}$ [TeV]

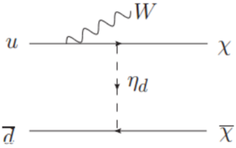


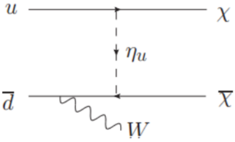
ξ=-1
ξ=0
ξ=1
Λ=600 GeV
σ [pb]
10^5 10^4 10^3 10^2 10^1 1 10^{-1} 10^{-2} 10^{-3}
0 2 4 6 8 10 12 14
$\sqrt{s}$ [TeV]

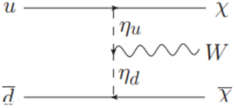


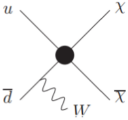
ξ=1
ξ=0
ξ=-1
$-g_{\alpha\beta}$ term
Λ=600 GeV
σ_1 [pb]
200 100 0 −100 −200 −300
0 2 4 6 8 10 12 14
$\sqrt{s}$ [TeV]

PANIC

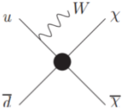








$$\frac{1}{\Lambda_u^2}(\overline{u}\Gamma u)(\overline{\chi}\Gamma\chi)$$

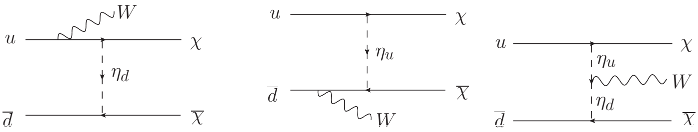


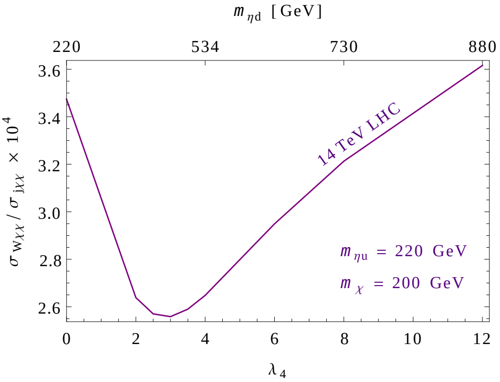
$$\frac{1}{\Lambda_d^2}(\overline{d}\Gamma d)(\overline{\chi}\Gamma\chi)$$

$$\boxed{\delta m_\eta^2 \equiv m_{\eta_d}^2 - m_{\eta_u}^2 = \lambda_4\, v_{\rm EW}^2}$$

$$\xi = 1/(1+\delta m_\eta^2/\Lambda^2)$$
$$= 1/(1+\lambda_4\, v_{EW}^2/\Lambda^2)$$

Longitudinal effects



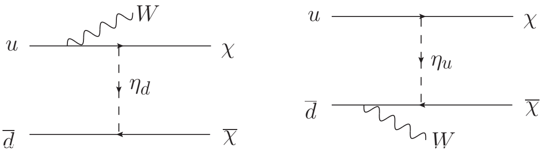


- Cross section first suppressed due to increase in propagator mass, then increases when third diagram begins to dominate
- However, enforcing gauge invariance and perturbativity, this effect can't be large

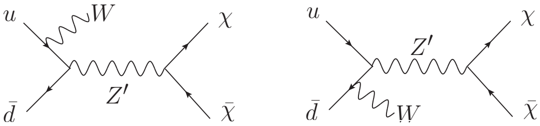
N. Bell, Y. Cai, RKL, 1512.00476

Generic simplified models for mono-W signal

<u>t-channel colored scalar:</u>



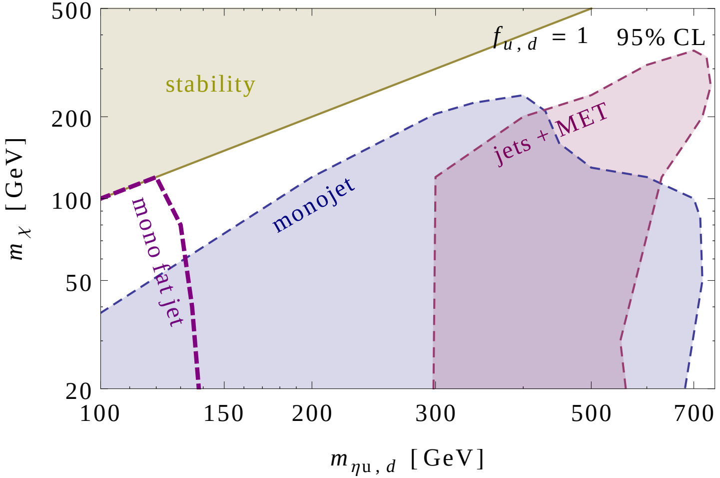
<u>s-channel Z':</u>



Consider both:

- Mono-lepton channel
- Mono-fat jet channel

t-channel LHC limits and reach summary



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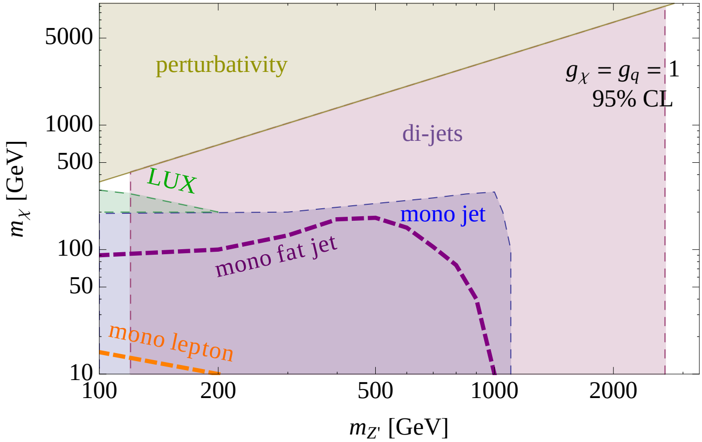
s-channel LHC limits and reach summary



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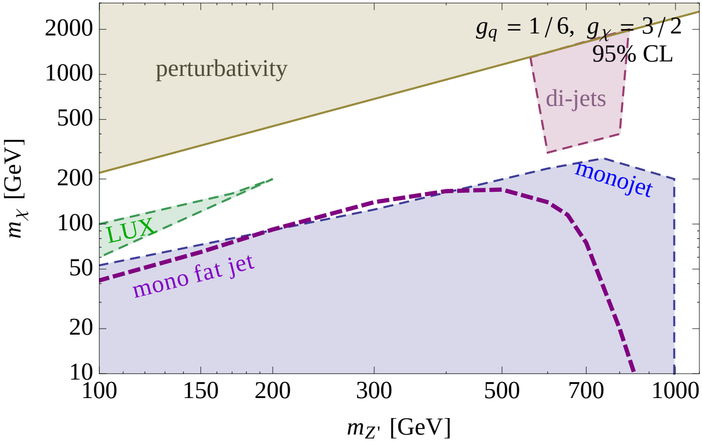


N. Bell, Y. Cai, RKL, 1512.00476

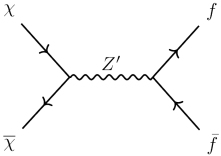
Implications of gauge invariance in other searches?

Simplified models for dark matter

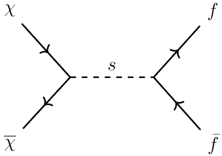
- Still no idea about fundamental nature of DM, model independent framework desirable where possible
- EFTs $\rightarrow$ issues at high momentum transfer, not generically applicable
- Simplified models: only lightest mediator is retained, set limits on couplings and mediators. Allow for richer phenomenology.

Benchmark Simplified Models:

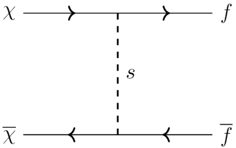
s-channel spin-1



s-channel spin-0



t-channel spin-0



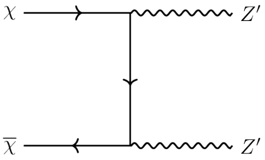
...this can run into problems!

- Not intrinsically capable of capturing full phenomenology of UV complete theories
- Separate consideration of these benchmarks can lead physical problems and inconsistencies
  - Results may not map to any viable model!
- To avoid this, important to consider minimal ingredients of gauge invariant models, ensuring valid interpretation of experimental data

Issues with Spin-1 Simplified Models

Common model is $SM \otimes U(1)_{\mathrm{dark}}$.

Consider the high energy production of longitudinal Z' bosons:



$$\epsilon_L^\mu(k) = k^\mu / m_{Z'}$$

violates unitarity at high energies, for axial-vector Z'-DM couplings.

Kahlhoefer et al, 1510.02110

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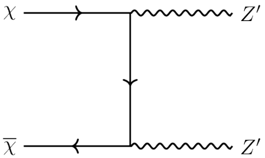

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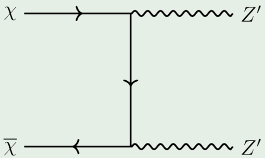
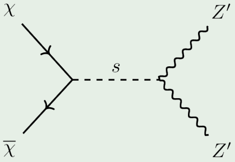
Kahlhoefer et al, 1510.02110





Bad high energy behaviour cancelled by additional scalar!

Issues with Spin-1 Simplified Models

Consequences for both Majorana and Dirac DM.

For Majorana DM, vector current is vanishing, leaving pure axial-vector interactions.

** Inclusion of the dark Higgs is unavoidable! **

Furthermore, can't write down Majorana mass term without breaking the $U(1)_{\mathrm{dark}}$ symmetry.

Minimal Simplified Setup

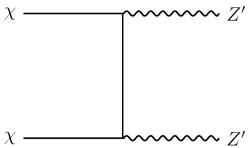
New fields:

- Majorana DM candidate, χ
- Spin-1 dark gauge boson, Z',
- Dark Higgs field, S.

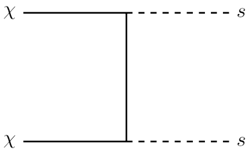
- S obtains a vev to give mass to χ and Z'
- $U(1)$ charges of χ and S related by gauge invariance: $Q_S = 2Q_\chi$
- Parameters tied together: $y_\chi/g_\chi = \sqrt{2}m_\chi/m_{Z'}$

Annihilation Processes: Standard Simplified Models

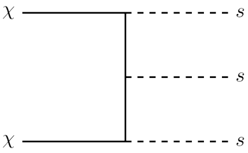
- To investigate phenomenology, focus on hidden sector models, where couplings to SM are small
- In universe today, only s-wave contributions to the annihilation cross section are relevant. P-wave contributions are negligible, suppressed as DM velocity $v_\chi^2 \approx 10^{-6}$



s-wave



p-wave

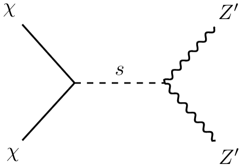


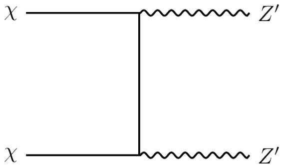
p-wave /
phase space suppressed

What happens when we consider the self-consistent dark sector?

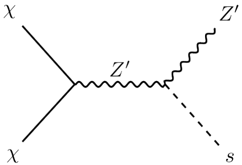
Annihilation Processes: Self-Consistent Scenario

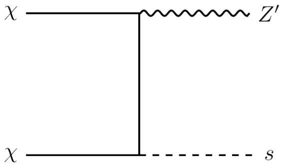
N. Bell, Y. Cai, R. Leane, 1605.09382





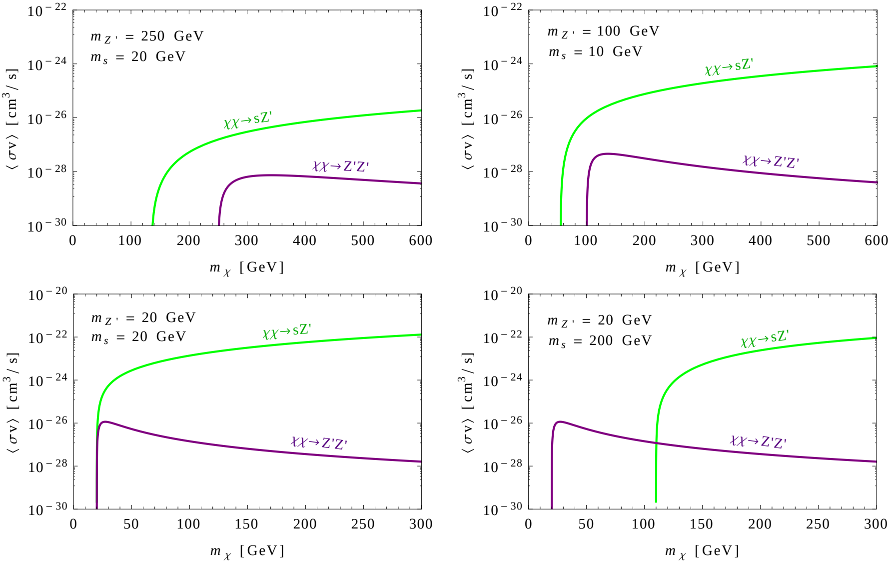
New addition to $\chi\chi \to Z'Z'$ process.





New s-wave annihilation process!
Further, this allows us to probe the nature of the scalar with comparable strength to the Z'.

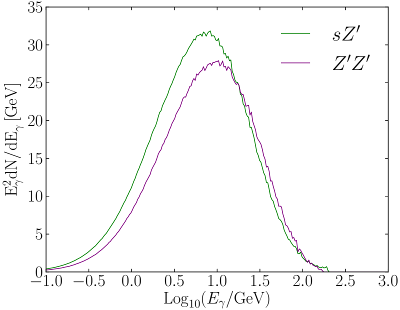
Annihilation Processes: Comparison

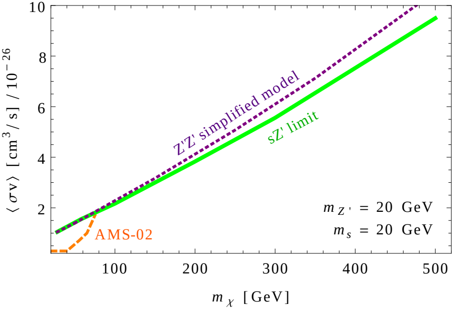


N. Bell, Y. Cai, R. Leane, 1605.09382

Indirect Detection Limits

- Best limits from Dwarf Spheriodal Galaxies, most DM dense objects in our sky
- Use PYTHIA to generate gamma-ray spectra, compare to Fermi Pass 8 data and find limits





N. Bell, Y. Cai, R. Leane, 1605.09382

Linked to Dark Sector Mass Generation

Majorana DM:

- Pure axial-vector couplings to Z'
- Both DM and Z' masses arise from dark Higgs mechanism

Dirac DM:

- Both vector and axial-vector couplings possible
- If Z' has pure vector couplings:
  - Z' mass: either Higgs or Stueckelberg mechanism
  - DM mass: bare mass or Higgs mechanism
  - Mass generation mechanisms not necessarily connected
- If Z' has non-zero axial couplings:
  - Dark Higgs gives mass to both Z' and DM (like Majorana)

N. Bell, Y. Cai, R. Leane, 1610.03063

Other Ingredients for DM Discovery?

- Correctly enforcing gauge invariance is key for DM models, leads to important phenomenology missed in "over-simplified" model approach

- Another important avenue is finding distinctive new signatures, exploiting strengths of different experiments

Complementary probe of the DM scattering cross section

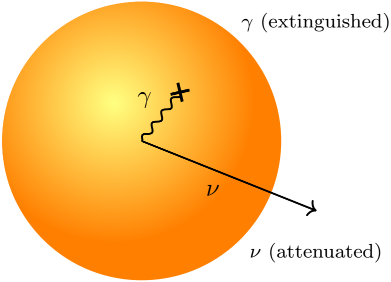
DM can be captured in the Sun by scattering with solar nuclei.

- Of possible DM annihilation modes, only neutrinos weakly interacting enough to escape
- These neutrinos are measured at SuperK and IceCube, provide probe of DM scattering cross section
- What if DM annihilates to long-lived mediators instead?

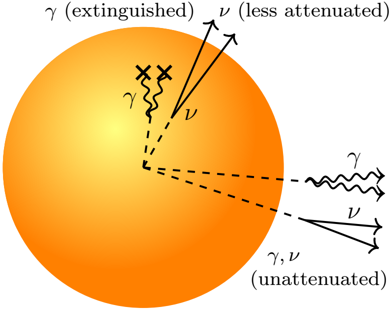
Solar Signatures of Long-lived Dark Mediators

If annihilation proceeds via long-lived dark mediators:

1. Neutrinos will be less attenuated
2. Other particles such as gamma-rays can escape



Short-lived mediators



Long-lived mediators

RKL, K. Ng, J. Beacom (to appear)

Measuring gamma-rays with new Fermi-LAT data

Standard annihilation fluxes of DM to gamma-rays are enormous.
For example, if 100 GeV DM with scattering $\sigma_{\chi P}^{SD} \sim 10^{-40}\,\mathrm{cm}^2$ annihilates directly to gamma-rays, the energy flux is

$$\sim 10^{-4}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}.$$

In this region, the sensitivity of Fermi-LAT is

$$\sim 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}.$$

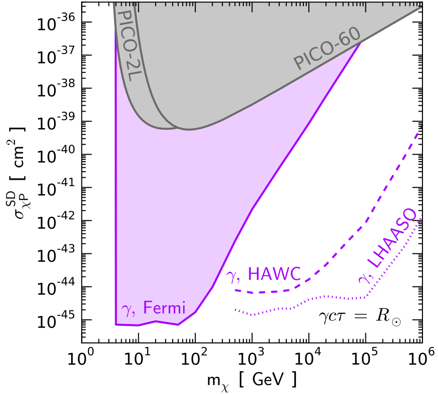
The annihilation flux is in excess of sensitivity by a factor of $\mathbf{10,000}$!

$\rightarrow$ Long-lived mediators open a window to otherwise lost DM signals, potentially large rates!

RKL, K. Ng, J. Beacom (to appear)

DM scattering cross section limits: Gamma-rays

Can outperform direct detection exps by several orders of magnitude!

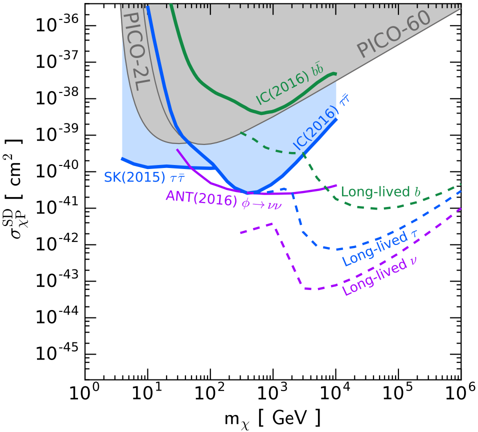


$$\chi\chi \to YY \to 2\,(\,\mathrm{SM} + \mathrm{SM}\,) \to \ldots\gamma\ldots$$

RKL, Ng, Beacom (in preparation)

DM scattering cross section limits: Neutrinos

Outperforms both direct detection exps and neutrino telescopes



$$\chi\chi \to YY \to 2\,(\,\mathrm{SM} + \mathrm{SM}\,) \to \ldots\nu\ldots$$

RKL, Ng, Beacom (in preparation)

Summary

Understanding the nature of DM is one of the foremost goals of the physics community. Important steps forward for discovery include:

Theoretically consistent models:

- EFT consistency, LHC mono-W enhancements not possible
- Single mediator Simplified Models not always self-consistent
- Two mediators can be required by gauge invariance
  - Leads to different phenomenology
  - New s-wave process, which dominates the annihilation rate

New ways of exploiting complementarity of DM searches:

- DM annihilation to long-lived mediators in the Sun provides probe of DM scattering cross section
- Can outperform direct detection exps by several orders of magnitude

Acknowledgements

Special thanks to:

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- Collaborators
  - Nicole Bell, Yi Cai, John Beacom, Kenny Ng, Tom Weiler, James Dent, Anibal Medina
- PhD contemporaries
- Advisory Panel
  - Nicole Bell, Ray Volkas, Andrew Melatos
- Other mentors
  - John Beacom, Tom Weiler, Matt Dolan
- CoEPP and the School of Physics

Backup slides

Searches in gamma-ray and neutrino channels

Gamma-rays:

- Current limits use Fermi data on solar gamma-rays
  - 2011 and 2015 analyses
- Future sensitivity with water cherenkov telescopes HAWC and LHAASO
  - HAWC has data, sensitive to very high ($>$TeV) gamma-rays
  - LHAASO upcoming, also extremely sensitive to very high ($>$TeV) gamma-rays

Neutrinos:

- Best gain for long-lived mediators is at higher ($>$TeV) energies
  - Less neutrino absorption by the solar matter
  - Less cooling of the secondaries (pions, muons etc)
- Use gigaton neutrino telescopes IceCube and KM3Net

Long-lived dark mediator flux

$$E^2 \frac{d\Phi}{dE} = \frac{\Gamma_{\rm ann}}{4\pi D_\oplus^2} \times E^2 \frac{dN}{dE} \times {\rm Br}({\rm Y} \to {\rm SM}) \times P_{\rm surv}, \tag{1}$$

where

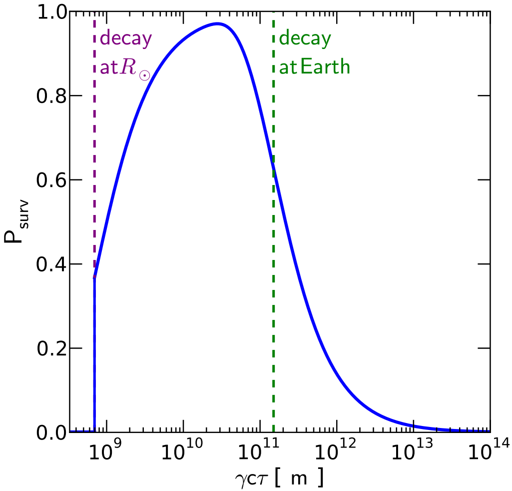
- $D_\oplus = 1$ A.U. is the distance between the Sun and the Earth
- $E^2 dN/dE$ is the particle energy spectrum per DM annihilation
- ${\rm Br}({\rm Y} \to {\rm SM})$ is the branching fraction of the mediator Y to SM particles
- $P_{\rm surv}$ is the probability of the signal surviving to reach the detector, given by

$$P_{\rm surv} = e^{-R_\odot/\gamma c\tau} - e^{-D_\oplus/\gamma c\tau}. \tag{2}$$

Need mediator Y to have sufficiently long lifetime τ or boost factor $\gamma = m_\chi/m_Y$, leading to a decay length L that exceeds the radius of the Sun, $R_\odot$, as

$$L = \gamma c\tau > R_\odot. \tag{3}$$

Signal survival probability



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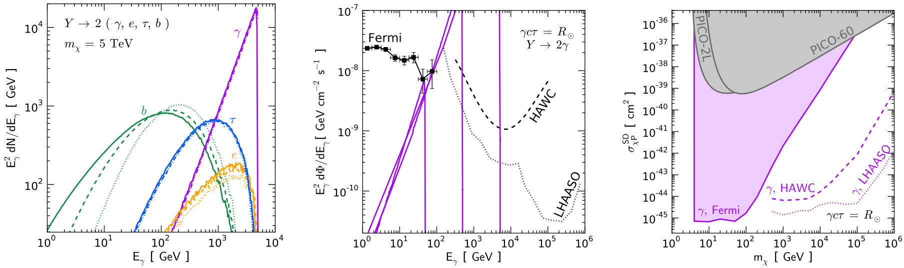
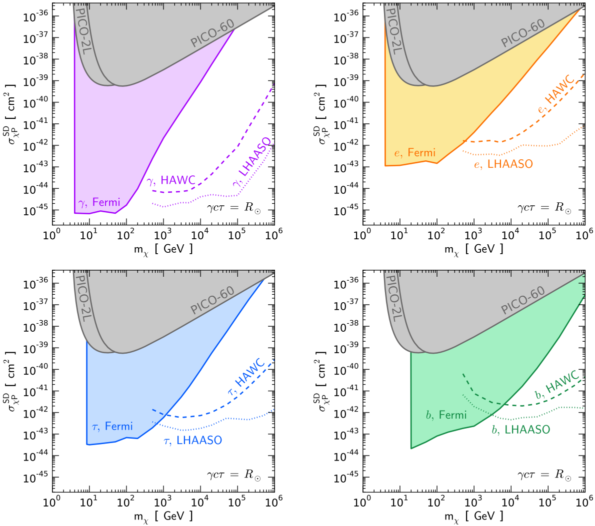
Gamma-ray limit procedure



$$\chi\chi \to YY \to 2\,(\,\mathrm{SM} + \mathrm{SM}\,) \to \ldots\gamma\ldots$$

RKL, Ng, Beacom (in preparation)

Gamma-ray limits



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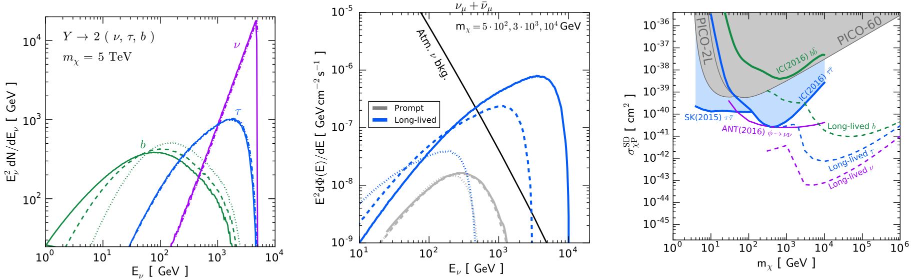


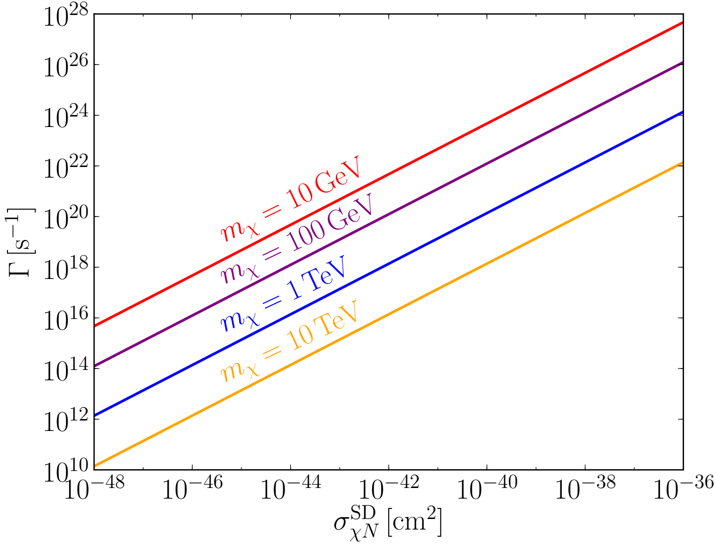
$$\chi\chi \to YY \to 2\,(\,\mathrm{SM} + \mathrm{SM}\,) \to \ldots\nu\ldots$$

RKL, Ng, Beacom (in preparation)

Long-lived dark mediator constraints

- **BBN:** The observed relic abundance of SM particles by BBN implies any new mediator must have lifetime τ which satisfies $\tau < 1$s.
- **CMB:** DM annihilation to SM products in the early universe is constrained by the CMB.
- **Supernovae:** Particularly for low mass mediators ($<$GeV), from mediator decay and supernova cooling.
- **Colliders:** If the dark sector is secluded, may be negligible. Otherwise, Belle, BaBar, ATLAS and CMS
- **Beam Dump/Fixed Target experiments:** Most relevant when the mediator has $\sim$sub-GeV mass. E137, LSND and CHARM
- **Other indirect detection signals:** Fermi-LAT and DES measurements of dSphs at low DM mass, and large positron signals can be constrained by AMS-02
- **Thermalization and Unitarity:** Issues with thermalization for > 10 TeV DM, and unitarity issues over $\mathcal{O}(100)$ TeV DM mass. Furthermore bound state effects at high DM mass.

Capture rate



Minimal Simplified Setup

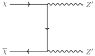
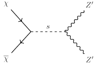
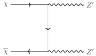
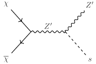
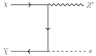
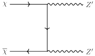
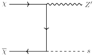
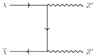
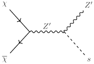
New fields: Majorana DM candidate, χ, Spin-1 dark gauge boson, Z', Dark Higgs field S.

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{dark}} + \mathcal{L}_{\mathrm{mix}}$$

$$\mathcal{L}_{\mathrm{dark}} = \frac{i}{2}\overline{\chi}\partial\!\!\!/\chi - \frac{1}{4}g_\chi Z'^\mu\overline{\chi}\gamma_5\gamma_\mu\chi - \frac{1}{2}y_\chi\left(\overline{\chi}_L^C\chi_L S + h.c.\right) \\ + \left(D^\mu S\right)^\dagger\left(D_\mu S\right) - \mu_s^2 S^\dagger S - \lambda_s(S^\dagger S)^2$$

- S obtains a vev to give mass to χ and Z'
- $U(1)$ charges of χ and S related by gauge invariance: $Q_S = 2Q_\chi$
- Parameters tied together: $y_\chi/g_\chi = \sqrt{2}m_\chi/m_{Z'}$

Impact of Specifying Mass Generation

Scenario	χ mass	Z' mass	Required $\chi - Z'$ coupling type	Annihilation processes	Z' pol
I	Bare mass term	Stueckelberg mechanism	Vector		Z'_T
II	Yukawa coupling to Dark Higgs	Dark Higgs mechanism	Non-zero axial-vector The $U(1)$ charge assignments of χ_L and χ_R determine the relative size of the V and A couplings.	   	Z'_T & Z'_L
III	Yukawa coupling to Dark Higgs	Stueckelberg mechanism	Vector	 	Z'_T
IV	Bare mass term	Dark Higgs mechanism	Vector	 	Z'_T

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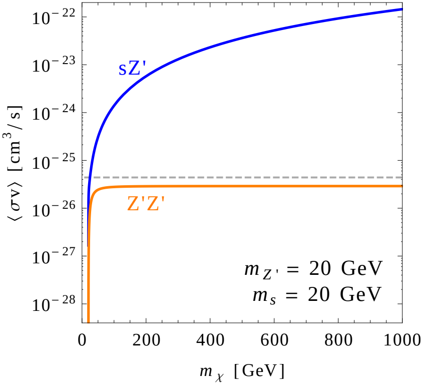
DM and Z' Mass from Dark Higgs



- Couplings related: $y_\chi / g_\chi = \sqrt{2} m_\chi / m_{Z'}$
- sZ' dominates over Z'Z' when kinematically allowed
- Cross sections enhanced by longitudinal Z' (for Z'Z' this only occurs when both vector and axial couplings are non-zero)

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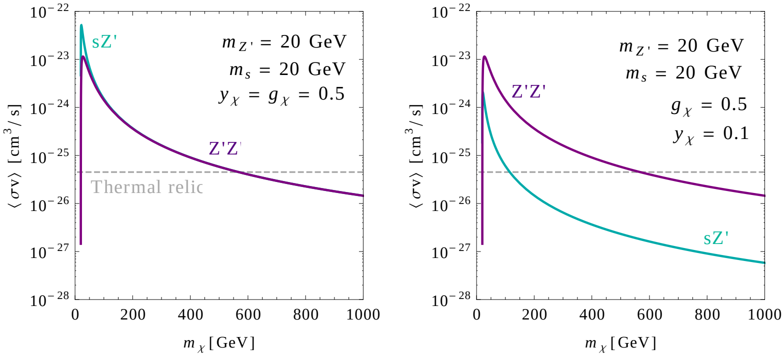
DM mass from Dark Higgs, Z' mass from Stueckelberg

- Gauge and Yukawa couplings no longer related, freedom in processes
- Z' is only transversely polarized



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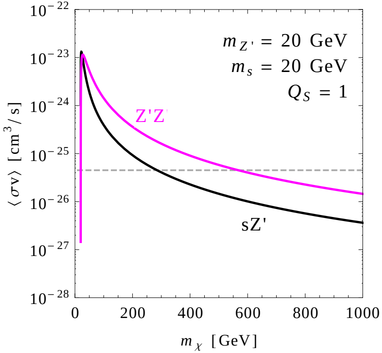
Bare DM Mass, Z' Mass from Stueckelberg

- Gauge and Yukawa couplings no longer related, $U(1)$ charges of Z' and dark Higgs unrelated
- Z' is only transversely polarized



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Two-Mediator Scenario: Charge Assignments

Yukawa term is

$$\mathcal{L}_{\mathrm{Yukawa}} = -\left(y_\chi \overline{\chi}_R \chi_L S + h.c.\right), \tag{4}$$

and so the charges of the dark sector field must be chosen to satisfy

$$Q_{\chi_R} - Q_{\chi_L} = Q_S \ . \tag{5}$$

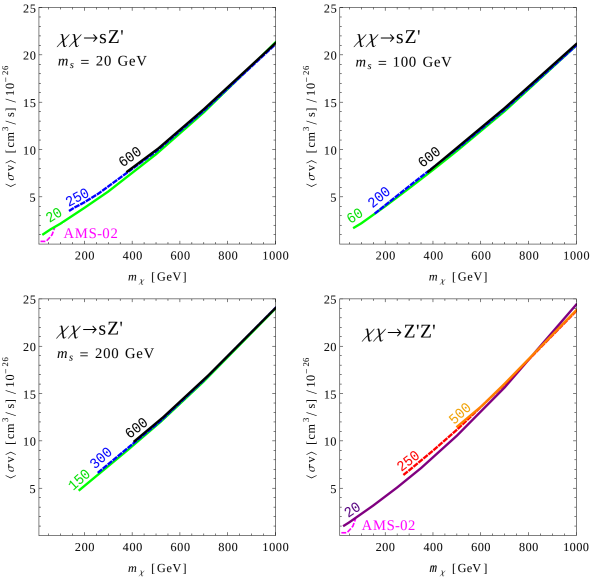
Set the dark Higgs charge to $Q_S = 1$. The χ charges therefore satisfy

$$Q_A \equiv \frac{1}{2}(Q_{\chi_R} - Q_{\chi_L}) = \frac{1}{2}, \tag{6}$$

$$Q_V \equiv \frac{1}{2}(Q_{\chi_R} + Q_{\chi_L}) = \frac{1}{2} + Q_{\chi_L}. \tag{7}$$

These charges determine the vector and axial-vector couplings of the Z' to the χ. Q_A is completely determined, while there is freedom to adjust Q_V by choosing $Q_{\chi_{L,R}}$ appropriately.

Two-Mediator Scenario: Indirect Detection Constraints



Lagrangian: Scenario I

In all scenarios, the gauge group is: $SM \otimes U(1)_\chi$, and so the the covariant derivative is $D_\mu = D_\mu^{SM} + iQg_\chi Z'_\mu$, where Q denotes the $U(1)_\chi$ charge.

Bare DM Mass, Z' Mass from Stueckelberg

This is the most minimal spin-1 setup, and no additional fields are introduced, as Z' obtains mass via Stueckelberg and DM is vectorlike so a bare mass term is allowed. The lagrangian is

$$\mathcal{L} = \mathcal{L}_{SM} + i\,\overline{\chi}(\partial_\mu + ig_\chi Q_V Z'_\mu)\gamma^\mu \chi - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} - m_\chi \overline{\chi}\chi + \frac{1}{2} m_{Z'}^2 Z'^\mu Z'_\mu. \tag{8}$$

Lagrangian: Scenario II

In this scenario, the vev of the dark Higgs field provides a mass generation mechanism for the dark sector fields Z' and χ. Before electroweak and $U(1)_\chi$ symmetry breaking, the most general Lagrangian is

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{\chi}_L \not{D}\chi_L + i\overline{\chi}_R \not{D}\chi_R - (y_\chi \overline{\chi}_R \chi_L S + h.c.) - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} \\ + (D^\mu S)^\dagger (D_\mu S) - \mu_s^2 S^\dagger S - \lambda_s (S^\dagger S)^2 - \lambda_{hs} (S^\dagger S)(H^\dagger H). \quad (9)\end{aligned}$$

After symmetry breaking, this becomes

$$\begin{aligned}\mathcal{L} \supset & -\frac{1}{2} m_s^2 s^2 + \frac{1}{2} m_{Z'}^2 Z'^\mu Z'_\mu - m_\chi \overline{\chi}\chi \\ & + g_\chi^2 w Z'^\mu Z'_\mu s - \lambda_s w s^3 - 2\lambda_{hs} h\, s(v\, s + w\, h) + g_f \sum_f Z'_\mu \overline{f}\Gamma_f^\mu f \quad (10) \\ & - g_\chi Q_V Z'_\mu \overline{\chi}\gamma^\mu \chi - g_\chi Q_A Z'_\mu \overline{\chi}\gamma^\mu\gamma_5 \chi - \frac{y_\chi}{\sqrt{2}} s\overline{\chi}\chi\,.\end{aligned}$$

DM Mass from Dark Higgs, Z' Mass from Stueckelberg

The most minimal Lagrangian for this scenario is

$$\mathcal{L} = \mathcal{L}_{SM} \quad + \quad i\,\overline{\chi}\left(\not{\partial} + ig_{\chi}Q_V \not{Z}'\right)\chi - \frac{y_{\chi}}{\sqrt{2}}\overline{\chi}\chi\phi - \frac{\sin\epsilon}{2}Z'^{\mu\nu}B_{\mu\nu} \quad (11)$$
$$+ \quad \frac{1}{2}\partial_{\mu}\phi\partial^{\mu}\phi - \frac{1}{2}\mu_s^2\phi^2 - \frac{1}{4}\lambda_s\phi^4 - \frac{1}{2}\lambda_{hs}\phi^2(H^{\dagger}H),$$

with the real scalar $\phi = w + s$, where w is the vev of ϕ and s is the dark Higgs. The vectorlike charge Q_V can be chosen freely.

Lagrangian: Scenario IV

Bare DM Mass, Z' Mass from Dark Higgs

The most minimal gauge invariant Lagrangian is

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{SM} + i\,\overline{\chi}\left(\partial\!\!\!/ + ig_\chi Q_V Z\!\!\!/'\right)\chi - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} - m_\chi \overline{\chi}\chi \qquad (12)\\ &+ \left[(\partial^\mu + ig_\chi Q_S Z'^\mu)S\right]^\dagger \left[(\partial_\mu + ig_\chi Q_S Z'_\mu)S\right] - \mu_s^2 S^\dagger S\\ &- \lambda_s (S^\dagger S)^2 - \lambda_{hs}(S^\dagger S)(H^\dagger H).\end{aligned}$$

The vectorlike charge Q_V and dark Higgs charge Q_S under the dark $U(1)_\chi$ can be chosen freely.

Unitarity bounds

$$\sqrt{s} < \frac{\pi m_{Z'}^2}{g_\chi^2 m_\chi}$$

$$m_f < \sqrt{\frac{\pi}{2}} \frac{m_{Z'}}{g_f^A}$$

Parameters related, sensible choices required to avoid unitarity problems:

$$m_{Z'} = g_\chi w$$

$$m_\chi = \frac{1}{\sqrt{2}} y_\chi w$$

$$y_\chi / g_\chi = \sqrt{2} m_\chi / m_{Z'}$$

Examples of SU(2) breaking operators

Scalar operator:

$$\frac{m_q}{\Lambda^3}\left(\overline{\chi}\chi\right)\left(\overline{q}q\right) = \frac{m_q}{\Lambda^3}\left(\overline{\chi}\chi\right)\left(\overline{q}_L q_R + h.c.\right)$$

LH quark SU(2) doublet, DM and RH quark singlets.

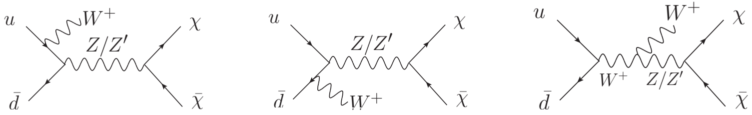
Vector operator:

$$\frac{1}{\Lambda^2}\left(\overline{\chi}\gamma^\mu\chi\right)\left(\overline{q}\gamma_\mu q\right) = \frac{1}{\Lambda^2}\left(\overline{\chi}\gamma^\mu\chi\right)\left(\overline{q}_L\gamma_\mu q_L + \overline{q}_R\gamma_\mu q_R\right)$$

OK provided same coefficients for each LH up and down quark.

N. Bell, Y. Cai, J.Dent, RKL, T, Weiler, 1503.07874

Other UV model



- Quark-Z' couplings like that of the Z, which are of opposite sign for u and d quarks due to their weak isospin assignments of $T_3 = \pm 1/2$. In the EFT limit, where the Z' is integrated out, this would give negative value of ξ.
- However, the strength of the DM-quark interactions would be suppressed by the Z/Z' mixing angle, which is of order $\mathrm{vev}^2/\mathrm{m}_{\mathrm{Z}'}$ and thus the operator arises only at order $1/\Lambda^4$

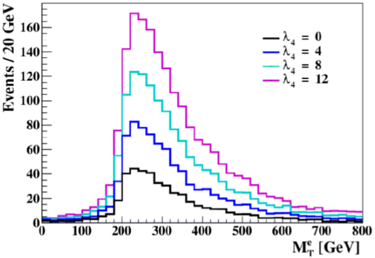
N. Bell, Y. Cai, RKL, 1512.00476

Mono-lepton channel

Follow CMS mono-lepton search (arXiv: 1408.2745).
Main background W > lv. Important kinematic variable:

$$M_T = \sqrt{2 p_T^{\ell} \not{E}_T (1 - \cos \Delta\phi_{\ell,\nu})}$$

MC with MadGraph, Showering with Pythia, Detector effects with Delphes / Fastjet. Run two regions, with low pt and high pt cuts



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Mono-lepton cuts

- E_T of the leading electron > 100 GeV
- E_T of the next-to-leading electron < 35 GeV
- At least one electron
- M_T for the electron, $M_T^e > 220$ GeV
- Pseudorapidity for the electron must be in the range $-2.1 < \eta(\ell_e) < 2.1$
- Jet $P_T < 45$ GeV
- The electron P_T and $\not{E}_T$ ratio must be in the range $0.4 < P_T/\not{E}_T < 1.5$
- $\Delta\phi_{e,\not{E}_T} > 2.5$.

Mono fat jet channel

- Follow ATLAS Hadronic W/Z + MET (arXiv:1309.4017). Main backgrounds are $Z > vv$ and $W > lv$
- Large radius jet, "fat jet" comes from boosted W or Z bosons, Cambridge Aachen jet algorithm
- Mass drop/filter used to examine substructure of fat jet, anti-kt jet algorithm
- Allows to differentiate from large QCD backgrounds
- MadGraph → Pythia → Fastjet /Delphes / Root

Mono fat jet cuts

- $\not{E}_T > 350$ GeV
- At least one large radius jet with $P_T > 250$ GeV
- $\sqrt{y} > 0.4$
- $50 < m_{jet} < 120$ GeV
- $-1.2 < \eta < 1.2$
- No more than one narrow jet with $P_T > 40$ GeV and $-4.5 < \eta < 4.5$ which is separated from the leading large radius jet as $\Delta R > 0.9$
- $\Delta\phi(jet, \not{E}_T) < 0.4$ for narrow jets.