New Observational Windows for Probing Hidden Dark Sectors
The Challenges with the WIMP DM Paradigm

The WIMP Miracle!

\[ \Omega_X \propto \langle \sigma_{\text{ann}} v \rangle^{-1} \]

\[ \sim 0.1 \left( \frac{G_{\text{Fermi}}}{G_X} \right)^2 \left( \frac{M_{\text{weak}}}{m_X} \right)^2 \]

WIMP Miracle!
The Challenges with the WIMP DM Paradigm

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

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

WIMP Miracle!
The Challenges with the WIMP DM Paradigm

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

• Expand the theoretical vision: beyond the WIMP paradigm
  light DM, axion, PBH, non-minimal thermal dark sector ★…

• Exciting new pheno: DUNE, CMB-S4, structure formation…
Simple Variations of WIMP Miracle

• Decouple DM thermal relic abundance from DM coupling to the SM
Simple Variations of WIMP Miracle

• Decouple DM thermal relic abundance from DM coupling to the SM

  e.g. *Secluded Dark Matter*
  (Pospelov, Ritz, Voloshin 2007)

Safely evades direct detection, subject to indirect detection
A New Realization of WIMP DM Miracle

- **Determines** $\Omega_{\text{DM}}$!

  WIMP miracle intact!

  $$\Omega_{\chi} \propto \langle \sigma_{\text{ann}} v \rangle^{-1}$$

- All conventional searches absent/suppressed

*Not just “WIMP”, applies to thermal freeze-out of DM with general masses!*
A New Realization of WIMP DM Miracle

- **Determines** $\Omega_{DM}$!
  - WIMP miracle intact!
    - $\Omega_X \propto \langle \sigma_{ann} v \rangle^{-1}$
- *All* conventional searches absent/suppressed

**What is $X$?**

- $m_X \gtrsim \text{eV}: \Omega_X > 1 \implies$ deplete $X$ via annihilation $\rightarrow$ SM
  - Novel signal: **Boosted DM ($X$)!** (Vs. “slow” DM)
    - at **neutrino experiments** (*YC* w/Agashe, Necib, Thaler; *YC* w/Berger, Zhao)
  - $m_X \lesssim \text{eV}: \Omega_X \checkmark$ $X$-SM interaction not necessary
    - $\implies$ relativistic, **dark radiation** in the CMB (*YC* w/Chacko, Hong, Okui)
A New Realization of WIMP DM Miracle

Weak signal ✓

C T

DM scatt

= >

free ➔

N

A, N

1 year

⌫

scatt, A, C, EN e

⌫

:

<

8 (a

Dark matter lives in a

A New Realization

Not just “WIMP”, applies to thermal freeze-out of DM with general masses!

• Determines \( \Omega_{DM} \)!

WIMP miracle intact!

\( \Omega_X \propto \langle \sigma_{\text{ann}} v \rangle^{-1} \)

• All conventional searches absent/suppressed

\[ \begin{align*}
X & \quad \text{(stable)} \\
X & \quad \text{WIMP DM} \\
X & \quad \text{WIMP DM}
\end{align*} \]

\[ \begin{align*}
\text{Not just “WIMP”, applies to thermal freeze-out of DM with general masses!}
\end{align*} \]

• What is \( X \)?

\[ \begin{align*}
\text{m}_X \geq \text{eV}: \Omega_X > 1 \quad & \text{deplete } X \text{ via annihilation} \rightarrow \text{SM} \\
\text{Novel signal: Boosted DM (} X \text{)! (Vs. “slow” DM)} \\
\text{at neutrino experiments} & \quad (YC \text{ w/Agashe, Necib, Thaler; YC w/Berger, Zhao}) \\
\text{m}_X \leq \text{eV}: \Omega_X \checkmark \quad & \text{X-SM interaction not necessary} \\
& \quad \text{relativistic, dark radiation in the CMB} \quad (YC \text{ w/Chacko, Hong, Okui})
\end{align*} \]

Dark matter lives in a non-minimal hidden sector!

(a thermal bath of DM, X, +...) Hidden dark sector freezeout
A Hidden Dark Sector?

Rising interest, covers a great variety of DM models: atomic DM, mirror world DM, SIDM, twin Higgs DM, DDDM...

What can possibly live in the mysterious $\sim 25\%$ of our universe?
A Hidden Dark Sector?

Rising interest, covers a great variety of DM models:

atomic DM, mirror world DM, SIDM, twin Higgs DM, DDDM…

What can possibly live in the mysterious \( \sim 25\% \) of our universe?

- Too “complicated”? Occam’s razor?

Occam’s Razor: No more things should be presumed to exist than are absolutely necessary, i.e., the fewer assumptions an explanation of a phenomenon depends on, the better the explanation.

(William of Occam)
A Hidden Dark Sector?

Rising interest, covers a great variety of DM models:
atomic DM, mirror world DM, SIDM, twin Higgs DM, DDDM…

What can possibly live in the mysterious ~25% of our universe?

‣ Too “complicated”? Occam’s razor?

Occam’s Razor: No more things should be presumed to exist than are absolutely necessary, i.e., the fewer assumptions an explanation of a phenomenon depends on, the better the explanation.

(William of Occam)
A Hidden Dark Sector?

Rising interest, covers a great variety of DM models:
atomic DM, mirror world DM, SIDM, twin Higgs DM, DDDM…

What can possibly live in the mysterious ~25% of our universe?

‣ Too “complicated”? Occam’s razor?

‣ No clue? “Nightmare” for discovery?

Occam’s Razor: No more things should be presumed to exist than are absolutely necessary, i.e., the fewer assumptions an explanation of a phenomenon depends on, the better the explanation.
(William of Occam)
A Hidden Dark Sector?

Rising interest, covers a great variety of DM models:

atomic DM, mirror world DM, SIDM, twin Higgs DM, DDDM…

What can possibly live in the mysterious ~ 25% of our universe?

❖ Too “complicated”? Occam’s razor?

❖ No clue? “Nightmare” for discovery?

✓ Universal guidelines
✓ New observational windows!

(this talk…)

Occam’s Razor: No more things should be presumed to exist than are absolutely necessary, i.e., the fewer assumptions an explanation of a phenomenon depends on, the better the explanation.

(William of Occam)
Episode- #1

Boosted Dark Matter

JCAP 1410 (2014) 062, **YC** w/Agashe, Necib, Thaler;
JCAP 1502 (2015), **YC** w/Berger, Zhao;
**YC et al.** w/Microboone/DUNE collaboration *(in progress)*

• Massive X

\[(DM \rightarrow DM A, X \rightarrow DM B)\]
Boosted Dark Matter

- Determines $\Omega_{\text{DM}}$!
- Conventional signals absent/suppressed

$\nu_{\text{DM}}/c \ll 1$

Boosted $X$: $\gamma_X = m_{\text{DM}}/m_X$

$\nu_X/c \simeq O(0.1)$

$\nu_{\text{DM}}/c < 1$
Boosted Dark Matter

DM

\[ v_{\text{DM}}/c \ll 1 \]

X

(\text{stable})

DM

\[ \gamma_X = m_{\text{DM}}/m_X \]

\[ v_X/c \gtrsim O(0.1) \]

Boosted X:

- Massive X (\( m_{\text{DM}} > m_X \approx \text{eV} \)): \( \Omega_X > 1 \)
- deplete X via annihilation \( \rightarrow \) SM

• Determines \( \Omega_{\text{DM}}! \)
• Conventional signals absent/suppressed

L: loop size
\[ D \ll ML^2 \]: the quadrupole moment
\[ M \ll \mu L \]: the loop's mass

\[ v_{\text{DM}}/c \ll 1 \]

X

SM

SM

+ X-SM scattering!
Boosted Dark Matter

- **Boosted X:**
  - Massive $X$ ($m_{\text{DM}} > m_X \approx \text{eV}$): $\Omega_X > 1$
  - $\gamma_X = m_{\text{DM}}/m_X$
  - $v_X/c \gtrsim O(0.1)$
  - $X$ deplete X via annihilation $\rightarrow \text{SM}$

- **Model Example**
  - Dirac fermion $\psi_A$, $\psi_B$, $m_A > m_B$, stabilized by $\mathbb{Z}_2 \times \mathbb{Z}_2$

\[
\mathcal{L} \supset \frac{1}{\Lambda^2} \bar{\psi}_A \psi_B \bar{\psi}_B \psi_A + \frac{\epsilon}{2} F_{\mu
u}^\prime F^\prime_{\mu\nu}
\]

- Determines $\Omega_{\text{DM}}$!
- Conventional signals absent/suppressed

$\uparrow + \text{X-SM }$ scattering!
Search Strategy for Boosted DM

- A combination of DM indirect and direct detections
Search Strategy for Boosted DM

• A combination of DM indirect and direct detections

![Diagram of DM Indirect and Direct Detections]

**Indirect**

DM \rightarrow X

**Direct**

DM \rightarrow X
Search Strategy for Boosted DM

- A combination of DM indirect and direct detections

![Diagram showing indirect and direct detection processes]
Search Strategy for Boosted DM

- A combination of DM indirect and direct detections

Indirect

\[
\text{DM} \rightarrow X \rightarrow 1/\Lambda^2 \rightarrow X \rightarrow \text{DM}
\]

Direct

\[
\text{DM} \rightarrow X \rightarrow g' \rightarrow \gamma' \rightarrow e^- \rightarrow \text{DM}
\]

★ Small flux \( \propto n_{DM}^2 \)

What experiments?
Large volume detector + sensitive to energetic e\(^-\), p

★ Boosted X \( \rightarrow \) relativistic outgoing e\(^-\), p
Search Strategy for Boosted DM

- A combination of DM indirect and direct detections

★ Small flux $\propto n_{DM}^2$

**What experiments?**
Large volume detector + sensitive to energetic $e^-$, $p$

★ Boosted $X \Rightarrow$ relativistic outgoing $e^-$, $p$

**Use neutrino experiments to directly detect a dark matter sector!**
Search Strategy for Boosted DM

- A combination of DM indirect and direct detections

**Indirect**

DM \xrightarrow{1/\Lambda^2} \ X

**Direct**

\[ g' \]

\[ \gamma' \]

\[ e^+ e^- \]

**Small flux** \( \propto n_{DM}^2 \)

**Boosted X** \( \rightarrow \) relativistic outgoing \( e^-, p \)

**What experiments?**
Large volume detector + sensitive to energetic \( e^-, p \)

**Use neutrino experiments to directly detect a dark matter sector!**

DM direct detection 😞 ; Opportunity:
low energy boosted DM \( (E \approx O(GeV)) \)

(Cherry et.al 2015, **YC** w/Pospelov, Pradler arXiv:1711.04531)
Boosted DM@Neutrino Experiments

- Conventional: Cherenkov detectors; New: LArTpc

IceCube  SuperK

DUNE/LBNF (major future project)
Boosted DM@Neutrino Experiments

- Conventional: Cherenkov detectors; New: LArTpc

IceCube   SuperK

DUNE/LBNF (major future project)

- Boosted DM distinguishable from $\nu$!
  - Directionality
  - No charge current interaction (e.g. muon veto)
Boosted DM@Neutrino Experiments

• Conventional: Cherenkov detectors; New: LArTpc

IceCube  SuperK  DUNE/LBNF (major future project)

• Boosted DM distinguishable from $\nu$!
  ▷ Directionality
  ▷ No charge current interaction (e.g. muon veto)

Boosted DM: New scientific programs for neutrino experiments
Recent Development of Boosted DM

- Substantial recognition + action from major neutrino experimental collaborations
  - **SuperK**: official analysis on boosted DM (arxiv: 1711.05278)
  - **DUNE/Microboone**: a working group (theorists + experimentalists) developed since 2016, recently became a subgroup of DUNE BSM group; will contribute to DUNE TDR
    — We are focusing on high priority benchmarks now, but in the long term open to other related exotic DM signals observable (e.g. self-destructing DM, Grossman et al. arXiv:1712.00455)

- Theoretical development
  - Several groups involved: signals with DM direct detection, IceCube… (e.g. Jia, Seodong, Xiaoping here)
  - Inelastic Boosted DM (e.g. Giudice et al. arXiv:1712.07126)
Episode #2
Dark Radiation in the CMB
(YC w/Chacko, Hong, Okui; w/Adshead, Shelton; w/Brust, Sigurdson)

Case-2: 
(nearly) Massless X

- $m_X \lesssim \text{eV}$: $\Omega_X \surd$, do not need further depletion/interaction w/SM!
Episode #2

Dark Radiation in the CMB

(YC w/Chacko, Hong, Okui; w/Adshead, Shelton; w/Brust, Sigurdson)

WIMP DM \[\xrightarrow{-\text{stable}}\] X

\[m_X \approx \text{eV}: \Omega_X \checkmark,\text{ do not need further depletion/interaction w/SM!}\]

Case-2: (nearly) Massless X

Nightmare for discovery? (gravity…)

\[\text{SM} \xrightarrow{\text{X}} \text{SM}\]
Episode #2

Dark Radiation in the CMB

(YC w/Chacko, Hong, Okui; w/Adshead, Shelton; w/Brust, Sigurdson)

Case-2:
(nearly) Massless X

\[ m_X \approx \text{eV} \quad \Omega_X \checkmark \text{, do not need further depletion/interaction w/SM!} \]

\[ X \text{ is relativistic, dark radiation in the Cosmic Microwave Background (CMB) !} \]
Beyond the SM particle w/m ≲ $T_{\text{CMB}} \sim \text{eV}$ (DR):

- Relativistic at CMB, $\rho_{\text{rad}} \uparrow$, $H_{\text{CMB}} \uparrow$
- Affect CMB spectrum by increasing effective neutrino number, $\Delta N_{\text{eff}}$ ($N_{\text{eff}} = 3.046$ in SM)
e.g. suppress high $\ell$ peak amplitude
Dark Radiation in the CMB

Beyond the SM particle $w/m \lesssim T_{\text{CMB}} \sim \text{eV}$ (DR):
- Relativistic at CMB, $\rho_{\text{rad}} \uparrow$, $H_{\text{CMB}} \uparrow$
- Affect CMB spectrum by increasing effective neutrino number, $\Delta N_{\text{eff}}$ ($N_{\text{eff}} = 3.046$ in SM)
  e.g. suppress high $\ell$ peak amplitude

**Calculation of thermal dark radiation:** (c.f. non-thermal later)

\[
\Delta N_{\text{eff}} = \rho_{\text{DR}} : \rho_{1\nu}, \quad \rho_{\text{DR}} \propto g_{\text{DR}} T_{\text{DR}}^4
\]

- $g_{\text{DR}}$: Number of degrees of freedom in DR
- $T_{\text{DR}}$: determined by when DS and SM kinetically decouple

Initial thermal (kinetic) equilibrium ⇥ effective portal
interaction between DS and SM (e.g. higgs portal)
Dark Radiation in the CMB

Phys.Rev. D92 (2015) 055033, **YC** w/Chacko, Hong, Okui
Dark Radiation in the CMB

A lower limit $\Delta N_{\text{eff}} \geq 0.027$

Phys. Rev. D92 (2015) 055033, YC w/Chacko, Hong, Okui
Dark Radiation in the CMB

A lower limit $\Delta N_{\text{eff}} \geq 0.027$

Forecast for CMB-S4 sensitivity: $\sigma(N_{\text{eff}}) \approx 0.015 - 0.03$

Phys.Rev. D92 (2015) 055033, YC w/Chacko, Hong, Okui

- Likely able to discover or exclude any hidden dark sector once in equilibrium with SM (CMB-S4!)

JHEP 1606 (2016) 016, YC w/Adshead, Shelton
Dark Radiation in the CMB
- Simply extra neutrinos?

• **Does dark radiation interact at the CMB time?**
  
  ‣ **Free-streaming DR:** $L_{\text{mean-free}} > H^{-1}$, e.g. SM neutrinos
    — Implicitly assumed in official expt. analysis (e.g. Planck)
  
  ‣ **Scattering (fluid-like) DR:** $L_{\text{mean-free}} < H^{-1}$, generic in a dark sector
    (e.g. dark gluons, dark photon+dark electrons)
    — Not included in expt. analysis! But…
Observable Difference Between the Two Types of DR

- Free streaming species: \( v_{FS} > v_{sound} \)  \( \rightarrow \)  \( \sigma \): anisotropy in \( T^{\mu \nu} \)
- Observable effects increase with FS energy fraction: \( f_\nu \equiv \frac{\rho_{all\ free\ rad}}{\rho_{all\ rad}} \)

\[
\ddot{d}_\gamma - c_\gamma^2 \nabla^2 d_\gamma = \nabla^2 \Phi_+ 
\]

\( \Delta N_{\text{scatt}}^{\nu,\text{eff}} \)

\( \Delta N_{\text{free}}^{\nu,\text{eff}} \)

\( \Delta \ell \equiv \delta \ell - \delta \ell_{\text{SM}} \)

\[
= -57 (f_\nu - f_\nu|_{\text{SM}}) \frac{\ell_A}{300} \\
\approx -7.8 (0.59 \Delta N_{\text{eff}}^{\text{free}} - 0.41 \Delta N_{\text{scatt}}^{\nu,\text{eff}}) \frac{\ell_A}{300}
\]

(YC, w/Chacko, Hong, Okui 2015)

Add free-streaming DR \( f_\nu \uparrow \)
Add scattering DR \( f_\nu \downarrow \)

Universal phase shift of high \( \ell \) peaks (SM \( \nu \): Bashinsky, Seljak 2003)

Gravitational forcing; w/anisotropy, e.g. \( d_\gamma \) out of phase w.r.t free oscillating
Cosmological Constraints on Interacting Light Particles

(YC with Brust and Sigurdson, JCAP, arXiv: 1703.10732)

- Two param fit: $N_{\text{fld}}, N_{\text{eff}}$
- More robust/physical param: $f_{\text{fs}}, N_{\text{tot}}$

Figure 2. Here we show two different 2d posteriors for three of the five scans (Planck T, Planck P+BAO, and Planck P+BAO+$H_0$+LSS). The solid lines are 1σ contours, and the dot-dashed lines are 2σ contours. The posteriors in the top figure exhibit degeneracy between $N_{\text{eff}}$ and $N_{\text{fld}}$, motivating the parametrization in terms of $N_{\text{tot}}$ and $f_{\text{fs}}$ in the bottom figure, and demonstrating that the strongest constraints arise on the sum $N_{\text{tot}}$.

(also see: Baumann, Green, Meyers, Wallisch v2)

$\Delta N_{\text{tot}} < 0.39$ at 2σ
A Unified Picture of Thermal DM

• A universal guideline:

**Last carrier of the dark sector entropy**, e.g. the \( X \), analogous to SM \( \gamma, \nu \)! (generalized concept of dark radiation)
A Unified Picture of Thermal DM

- A universal guideline:
  Last carrier of the dark sector entropy, e.g. the $X$, analogous to SM $\gamma, \nu$! (generalized concept of dark radiation)

$T$:
- Freezeout (decay)
- Entropy (heat up $X$)
- Relic dark radiation
- CMB $\Delta N_{\text{eff}}$
- DM + $X$...

SM:
- Boosted DM
- Restore WIMP paradigm
A Unified Picture of Thermal DM

• A universal guideline:

Last carrier of the dark sector entropy, e.g. the $X$, analogous to SM $\gamma$, $\nu$! (generalized concept of dark radiation)

$T$  

DM+$X$... entropy (heat up $X$)  

freezeout (decay)  

X  

freezeout (decay)  

relic dark radiation  

CMB $\Delta N_{\text{eff}}$  

SM  

• $X$: subdominant abundance, $\Omega_X < \Omega_{DM}$ yet plays an important cosmological role!
• $X$: may be the smoking-gun for the whole dark sector! New observational directions!
Episode #3

Cosmological Signatures of DM-DR Interactions
(CMB, structure formation)

- YC w/Chacko, Hong, Okui and Tsai JHEP 1612 (2016) 108
- YC and Ran Huo, work in prep
Partially Acoustic DM (PAcDM)
YC with Chacko, Hong, Okui and Tsai, JHEP 1612 (2016)

Puzzles from Large Scale Structure

Comparing to $\Lambda$CDM model, we want to obtain a
- Smaller density perturbation
- Larger Hubble expansion rate at the late time universe

Poulin et. al. JCAP 1608 (2016)
A Dark Sector Offers a Solution?

- **Additional dark radiation** (DR) helps increase Hubble rate at recombination time: $H_0 \propto \sqrt{\rho}$

- **Dark acoustic oscillation**: coupled DM + DR prohibit growth of structure, reduce $\sigma_8$

  - 100% acoustic DM: too much suppression;
  - Other related approach:
Partially Acoustic Dark Matter
- A small fraction ($r$) of DM having acoustic oscillation

\[ \frac{P(r)}{P(0)} \simeq (1 - 2r) \left( \frac{a}{a_{eq}} \right)^{-1.2r} \]

- **analytic solution**

- **Structure grows** slower comparing to CDM
- **Redshift dependent suppression (a modified power law!)**
  Smaller correction to the CMB spectrum vs. 100% AcDM

Recent: may not fully address both $\sigma_8$ and $H_0$, Raveri et al. 2017
Visualizing Invisibly Annihilating DM (IAnDM)

YC with Ran Huo, work in prep

The theoretically minimal, observationally challenging dark sector scenario (IAnDM):

• Thermal relic of DR X ($N_{fld}$, $N_{eff}$ or $f_{fs}$, $N_{tot}$) can be very suppressed for very decoupled, colder dark sector
• Direct smoking-gun signature from the DM invisible annihilation itself? (analogy to DM indirect detection)
  - the non-thermal injection of DR X ($E_X = m_{DM}$)
• Scale-dependent $\Delta N_{\text{eff}}$ : accumulation of DR from DM annihilation over time

- Effects on matter power spectrum (WDM-like but distinguishable)
Conclusion

• Hidden Thermal Dark Sectors:
  ‣ Well motivated: resembles SM, solutions to naturalness problem…
  ‣ A simple variation to WIMP paradigm: DM → stable X annihilation, dramatically different/challenging phenomenology!
  ‣ Systematic studies possible, despite complexity!

• New Observational Windows for Dark Sectors:
  ‣ Secondary stable dark state X as the smoking gun: Boosted DM (neutrino expts., DM direct detection); interacting dark radiation (CMB, DM direct detection)
  ‣ Imprints of DM-X interaction: structure formation, CMB (e.g. PAcDM, IAnDM)
Thank you!