IPP Theory Community Report 2023

Evan McDonough
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IPP Scientific Council

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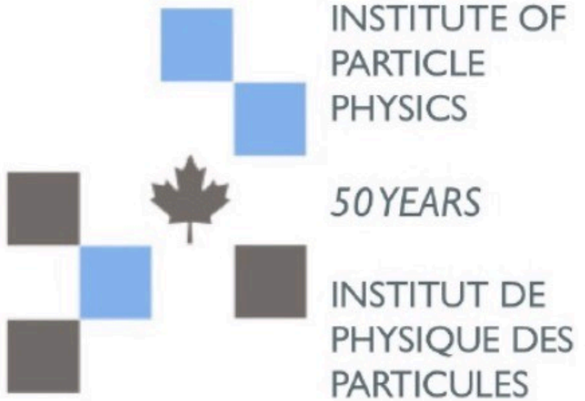
www.evanmcdonoughphysics.com



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June 23, 2023
IPP AGM

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Winnipeg

Outline

1. IPP Theory Community

2. Dawn of the Dark Sectors

3. The Mass Frontiers of DM

4. Synergy Across IPP Experiments

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IPP Theorists

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WEST-COAST

British Columbia:
UBC:
Joanna Karczmarek, Moshe Rozali, G. Semenoff, Kris Sigurdson, Mark Van Raamsdonk, A. Zhitnitsky

U Fraser Valley:
Derek Harnett

U Victoria:
Kristan Jensen, Pavel Kovtun, Adam Ritz

Simon Fraser U:
Levon Pogosian

TRIUMF:
David McKeen, David Morrissey

PRAIRIES

Alberta:
U Alberta:
Alberta Center for Particle Physics
Nassim Bozorgnia, A. Czarnecki, Saeed Rastgoo; Augustana Campus: Blokland, Bouchard, de Montigny

U Calgary:
Rachid Ouyed

Saskatchewan:
U Sask:
Rainer Dick, Tom Steele

Regina:
Nikolay Kolev, Nader Mobed

Manitoba:
Winnipeg Inst. Theoretical Physics

U Winnipeg:
Andrew Frey, G. Kunstatter, Evan McDonough

Brandon:
Margaret Carrington

SOUTH-EAST MEGATROPOLIS

Ontario:
Carleton: Bruce Campbell, Steve Godfrey, Thomas Gregoire, Seyda Ipek, Heather Logan, Daniel Stolarski, Yue Zhang
McMaster: Cliff Burgess
Perimeter: Jaume Gomis, Rob Myers
Queen's: Aaron Vincent, Joe Bramante
U of T: David Curtin, Bob Holdom, Michael Luke, John Moffat, AW Peet, Erich Poppitz
York: Randy Lewis, Kim Maltman, Sean Tulin
Waterloo: Achim Kempf, R. Mann
Western: Alex Buchel, V. Miransky

Quebec:
Laval: Helmut Kroeger, Luc Marleau, Pierre Mathieu
McGill: Robert Brandenberger, Simon Caron-Huot, James Cline, Keshav Dasgupta, Alex Maloney, Katelin Schutz
U de Montreal: David London, Richard MacKenzie, Manu B. Paranjape
UQAM: Gilles Couture

ATLANTIC

New Brunswick:
Mohammad Ahmady

Nova Scotia:
Ruben Sandapen

Newfoundland:
Aleksander Aleksejevs, Svetlana Barkanova

Research Themes

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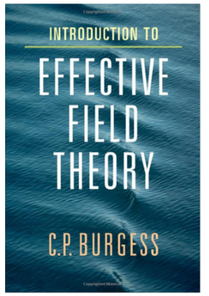
- Precision SM predictions for experiment
- Quantum Gravity & String Theory
- Dark Sectors
  - dark photon; dark QCD;
  - Multicomponent DM
    - complementarity of light and heavy DM components of dark sector
- Tests of the wide possible range of DM mass
  - Synergy of indirect (astro) signals + direct detection
  - Connecting DM origin (production mechanism) with observables

***Note all of this done in the framework of effective field theory**



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Atlantic Particle Theory Group

Evan McDonough
Winnipeg

- Ruben Sandapen (Acadia)
- Mohammad Ahmady (Mount Allison)
- Svetlana Barkanova, Aleks Aleksejevs (MUN-Grenfell)

ACADIA UNIVERSITY

Mount Allison UNIVERSITY

GRENFELL CAMPUS | MEMORIAL UNIVERSITY

Particle Theory From Pheno to Formal

One-Loop Electroweak Radiative Corrections to Bhabha Scattering in the Belle II Experiment

A.G. Aleksejevs (Grenfell Mem. U., Corner Brook), S.G. Barkanova (Grenfell Mem. U., Corner Brook), Yu. M. Bystritskiy (Dubna, JINR), V.A. Zykunov (Dubna, JINR and Gomel State U.) (Sep 17, 2020)

NLO radiative corrections for Forward-Backward and Left-Right Asymmetries at a B-Factory

Aleksandrs Aleksejevs (Grenfell Mem. U., Corner Brook), Svetlana Barkanova (Grenfell Mem. U., Corner Brook), C. Miller, J.Michael Roney (Victoria U.), V. Zykunov (Dubna, JINR)

Pion spectroscopy and dynamics using the holographic light-front Schrödinger equation and the 't Hooft equation

Mohammad Ahmady (Mt. Allison U.), Satvir Kaur (Lanzhou, Inst. Modern Phys. and Beijing, GUCAS), Chandan Mondal (Lanzhou, Inst. Modern Phys. and Beijing, GUCAS), Ruben Sandapen (Acadia U.) Aug 17, 2022

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The Prairie Powerhouse*:

Winnipeg Institute for Theoretical Physics

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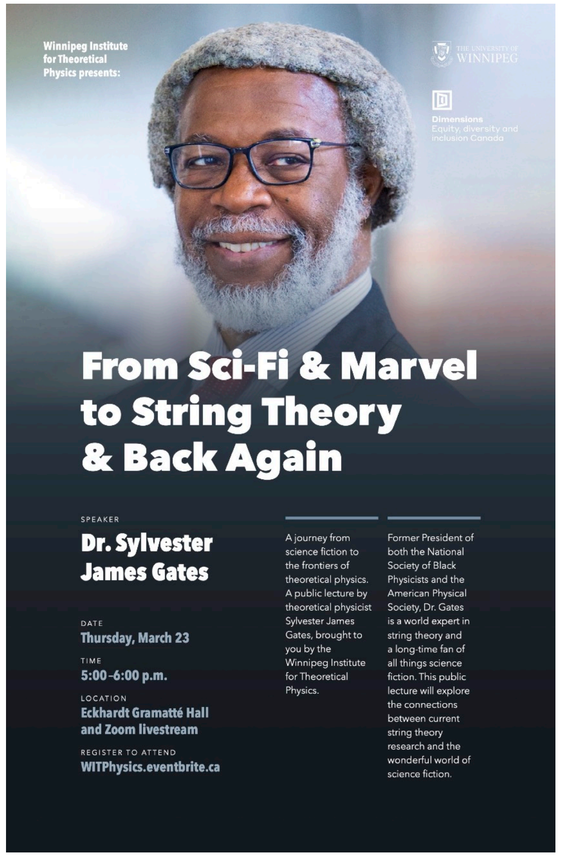
- Executive: Evan McDonough (Director), Andrew Frey (Past-Director), Kyle Shiells (Director-Elect)
- Membership: 27 faculty across Manitoba, across theory subfields
- Scholarly output 2018-2022: 294 published papers
- Big events in 2023: summer school, public lecture

***See also:**
Alberta Center for Particle Physics



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Dawn of the Dark Sectors

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Dark Sectors From Coast-to-Coast: From Pheno to Formal

[Just a few examples— more to come!]

WEST-COAST

Dark sector production via proton bremsstrahlung

Saeid Foroughi-Abari (Victoria U.), Adam Ritz (Victoria U.)

(see last 20 years of Ritz papers)

Relic challenges for vector-like fermions as connectors to a dark sector

Alexandre Carvunis (Ecole Normale Supérieure, Paris and Annecy, LAPTH and TRIUMF), Navin McGinnis (TRIUMF), David E. Morrissey (TRIUMF)

PRAIRIES

The π-axion and π-axiverse of dark QCD

Stephon Alexander (Brown U. (main)), Humberto Gilmer (Brown U. (main)), Tucker Manton (Brown U. (main)), Evan McDonough (Winnipeg U.)

Dark radiation and the Hagedorn phase

Andrew R. Frey (Winnipeg U.), Ratul Mahanta (Harish-Chandra Res. Ins

SOUTH-EAST MEGATROPOLIS

Perspectives on the Dark Sector

Robert Brandenberger (McGill U.)

Dark matter freeze-out during SU(2)$_L$ confinement

Jessica N. Howard (UC, Irvine), Seyda Ipek (Carleton U.), Tim M.P. Tait (UC, Irvine), Jessica Turner (Durham U., IPPP)

+ many others

ATLANTIC

SEARCH FOR DARK MATTER: DARK PHOTON AND Z' BOSON

Thesis by Shihau Wu,
Supervisors: Svetlana Barkanova, Aleksander Aleksejevs

Dark Photons

[See talk by A Ritz]

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Idea: Dark U(1) gauge boson kinetically coupled to SM photon: $\epsilon \left(F_{\rm SM}\right)^{\mu\nu} \left(F_{\rm DM}\right)_{\mu\nu}$

Motivations:

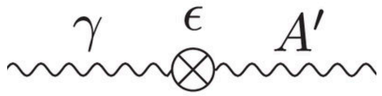
0. Calculable, predictive

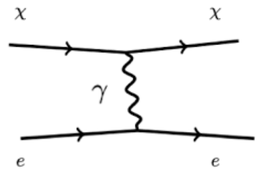
1. No global symmetries in quantum gravity; all U(1)'s local (dark photon) and/or broken (massive);

2. Unavoidable in string theory model building [always get U(N), not SU(N)]

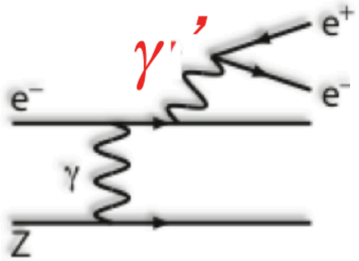
Phenomenology:

1. Rotate fields ⇒ **mixing** of DM & SM photons, SM **millicharges** for DM (and vice versa)
2. May explain anomalies at ATOMKI, others
3. Constrained by Belle-II, will be probed by DarkLight





- Displaced vertex:



DarkLight!
see: Kate Pachal

Distortion of neutrino oscillations by dark photon dark matter

Gonzalo Alonso-Álvarez (McGill U.), Katarina Bleau (McGill U.), James M. Cline (McGill U.)

Note also:

A Standard Model Explanation for the "ATOMKI Anomaly"

A. Aleksejevs (Memorial U., Newfoundland), S. Barkanova (Memorial U., Newfoundland), Yu G. Kolomensky (UC, Berkeley), B. Sheff (Michigan U.)

Dark Photons from Charged Pion Bremsstrahlung at Proton Beam Experiments

David Curtin, Yonatan Kahn, Rachel Nguyen

Inelastic Freeze-in

Saniya Heeba (McGill U.), Tongyan Lin (UC, San Diego), Katelin Schutz (McGill U.)

Dark QCD

[Review: Cline 2021 "Dark atoms and composite dark matter"]

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Dark Sector with N_c colours and N_f flavors,

quark mass m_q , QCD scale Λ_{dQCD}

Ultralight pion and superheavy baryon dark matter

Azadeh Maleknejad (CERN), Evan McDonough (Winnipeg U.)

Mirror Neutron Stars: How QCD Can Be Used to Study Dark Matter Through Gravitational Waves

Maurício Hippert (Illinois U., Urbana), Hung Tan (Illinois U., Urbana), Jacquelyn Noronha-Hostler (Illinois U., Urbana), Nicolás Yunes (Illinois U., Urbana), Jack Setford (Toronto U.), David Curtin (Illinois U., Urbana)

Self-interacting dark baryons

James M. Cline (McGill U.), Cédrick Perron

Dark Matter from Strong Dynamics: The Minimal Theory of Dark Baryons

Anthony Francis (CERN), Renwick J. Hudspith (York U., Canada), Randy Lewis (York U., Canada), Sean Tulin (York U., Canada)

Potential synergy with lattice QCD, holography:

Shapes and sizes of diquarks in lattice QCD

Anthony Francis (NYCU, Hsinchu), Philippe de Forcrand (CERN), Randy Lewis (York U., Toronto (main)), Kim Maltman (York U., Toronto (main) and Adelaide U., Sch. Chem. Phys.)

Pion spectroscopy and dynamics using the holographic light-front Schrödinger equation and the 't Hooft equation

Mohammad Ahmady (Mt. Allison U.), Satvir Kaur (Lanzhou, Inst. Modern Phys. and Beijing, GUCAS), Chandan Mondal (Lanzhou, Inst. Modern Phys. and Beijing, GUCAS), Ruben Sandapen (Acadia U.) (Aug 17, 2022)

Lots of cool phenomena! e.g. Neutron Oscillations:

Dark sectors in neutron-shining-through-a-wall and nuclear-absorption signals

Matheus Hostert (Minnesota U. and Perimeter Inst. Theor. Phys.), David McKeen (TRIUMF), Maxim Pospelov (Minnesota U.), Nirmal Raj (TRIUMF)

neutrino detector deep underground, can look for $n \to n' \to n$ transitions

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Multicomponent Dark Matter

Light and Heavy DM from Dark QCD

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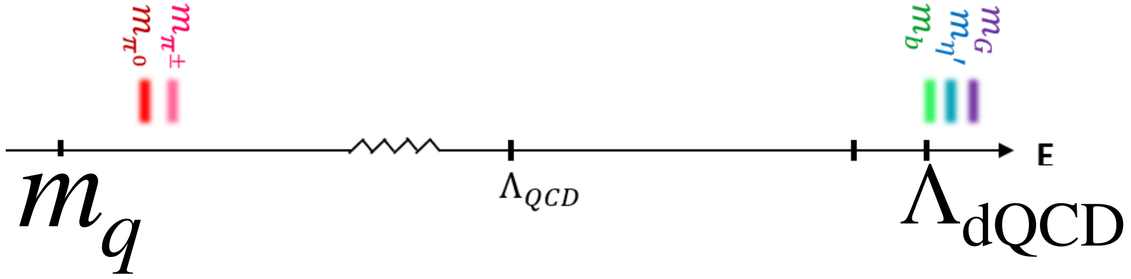
Idea: If $m_q \ll \Lambda_{\rm QCD}$, can have a hierarchy between pions and baryons

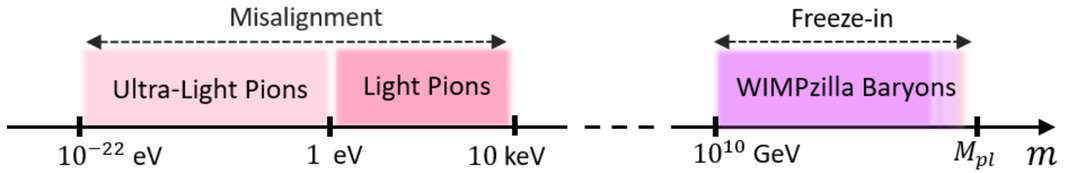
Spectrum:

Dark Pions [stable]: neutral and charged

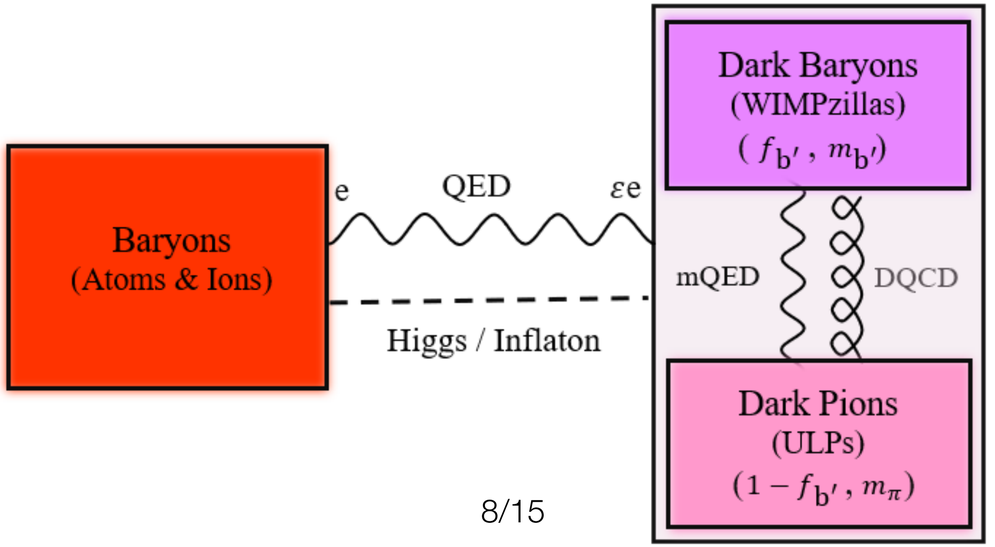
Dark Baryons [stable], eta', glueballs, ….



Production:



Portals to the Standard Model



DM is an admixture of superheavy and ultralight

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The Mass Frontier(s)

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The Superheavy Frontier

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Theory Motivation: new heavy particles abundant in any BSM model!

Historically neglected because both production and detection were challenges

WIMPZILLAS!

Edward W. Kolb, Daniel J. H. Chung, Antonio Riotto

1998 → 2023

Overproduction:

Catastrophic production of slow gravitinos

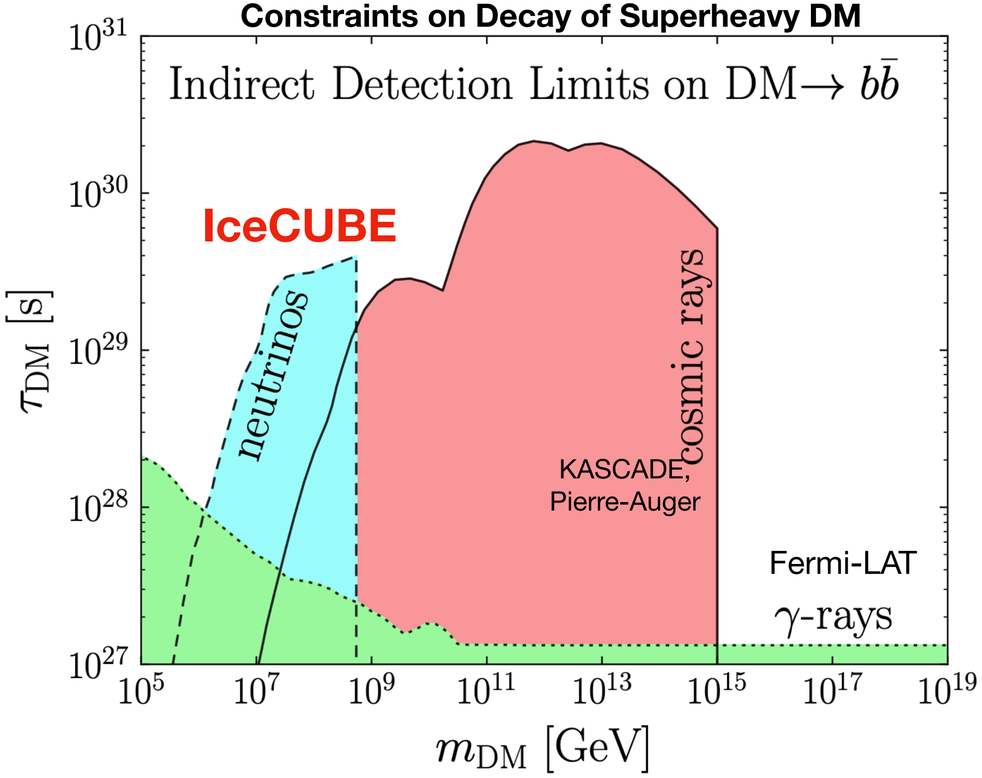
Edward W. Kolb, Andrew J. Long, and Evan McDonough
Phys. Rev. D **104**, 075015 – Published 11 October 2021

Just right:

Ultralight pion and superheavy baryon dark matter

Azadeh Maleknejad and Evan McDonough
Phys. Rev. D **106**, 095011 – Published 9 November 2022

Constraints on Decay of Superheavy DM



Direct Detection!

First direct detection constraints on Planck-scale mass dark matter with multiple-scatter signatures using the DEAP-3600 detector

limits constrain dark matter masses between 8.3×10^6 and 1.2×10^{19} GeV/c^2.

[2108.09405]

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The Ultralight Frontier

$$m_{\rm DM} \ll {\rm eV}$$

Theory Motivation: accidental symmetries (Burgess & Quevedo); string theory axions; dark QCD

Continued relevance to Strong CP:

Long-range axion forces and hadronic CP violation

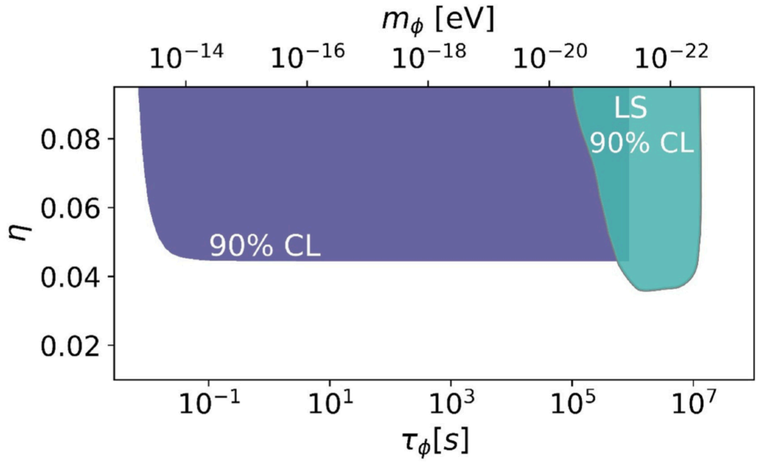
Shohei Okawa (Victoria U. and ICC, Barcelona U.), Maxim Pospelov (Minnesota U. and Minnesota U., Theor. Phys. Inst.), Adam Ritz (Victoria U.)

Neutrino Portal:

Signatures of ultralight dark matter in neutrino oscillation experiments

Abhish Dev ✉, Pedro A. N. Machado & Pablo Martínez-Miravé

DUNE: Modulation of mass splitting



Viable secret neutrino interactions with ultralight dark matter

James M. Cline

+ wealth of cosmological and astrophysical signals

The In-Between

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sub-MeV: **Cosmology of Sub-MeV Dark Matter Freeze-In**

Cora Dvorkin (Harvard U.), Tongyan Lin (San Diego State U.), Katelin Schutz (MIT, Cambridge, Dept. Phys.)

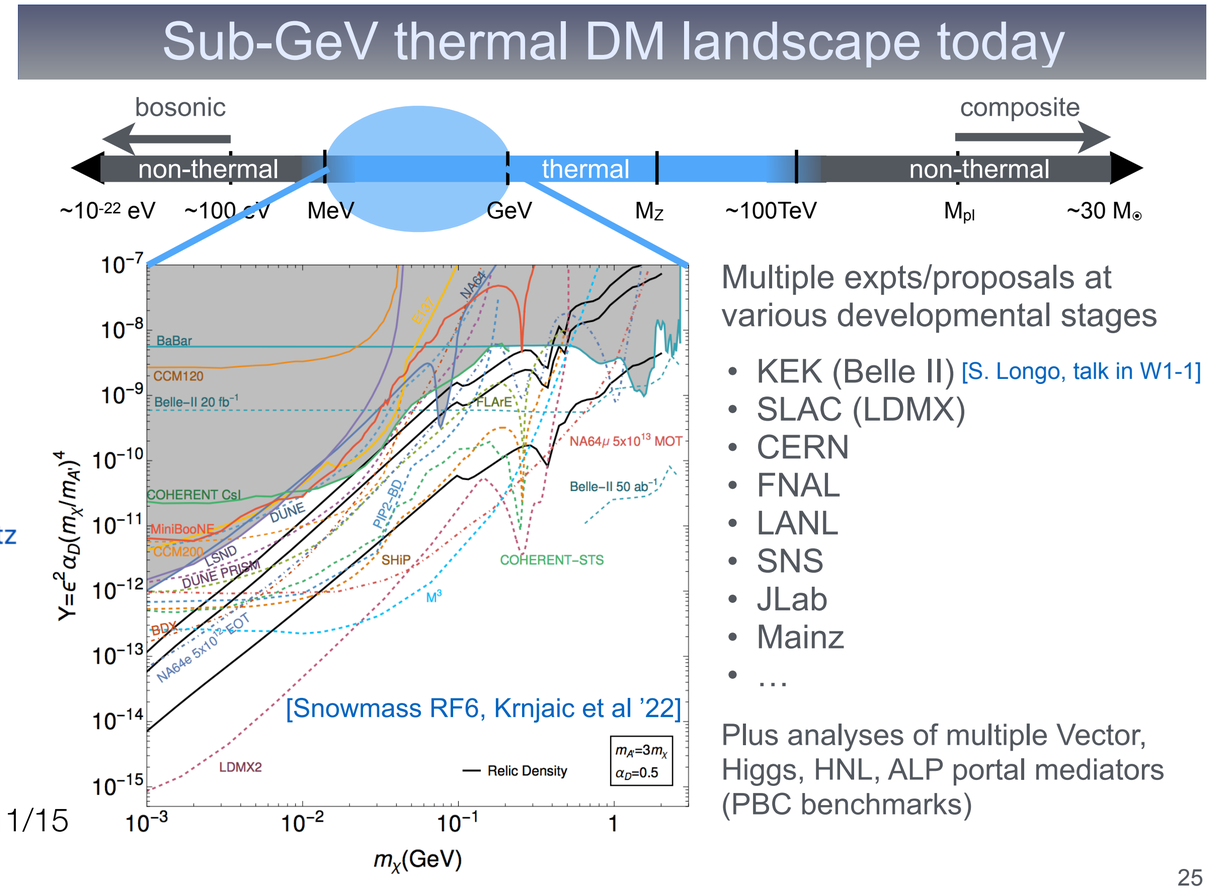
[credit: A Ritz]

sub-GeV: **Sub-GeV dark matter at accelerators**

Adam Ritz (Victoria U.) (2022)

Inelastic Freeze-in

Saniya Heeba (McGill U.), Tongyan Lin (UC, San Diego), Katelin Schutz



Multiple expts/proposals at various developmental stages

- KEK (Belle II) [S. Longo, talk in W1-1]
- SLAC (LDMX)
- CERN
- FNAL
- LANL
- SNS
- JLab
- Mainz
- …

Plus analyses of multiple Vector, Higgs, HNL, ALP portal mediators (PBC benchmarks)

11/15

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Synergy Across IPP Experiments

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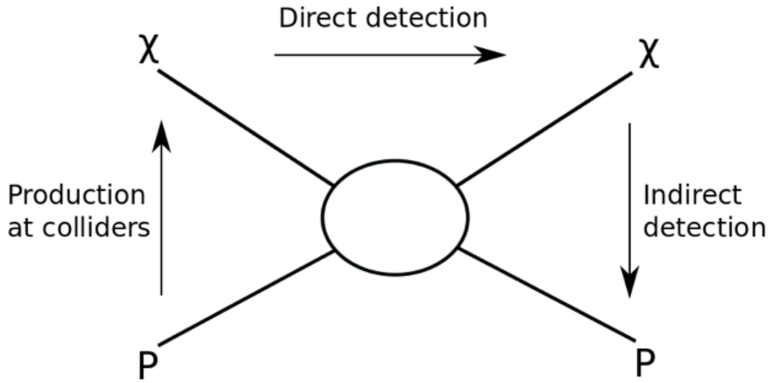
Evolution of the Discovery Strategy

- 1980's vision: triple-detection of DM particle



- 2020's vision: N-detection of dark sector, from detection(s) of each component

Case Study: A Dark Standard Model

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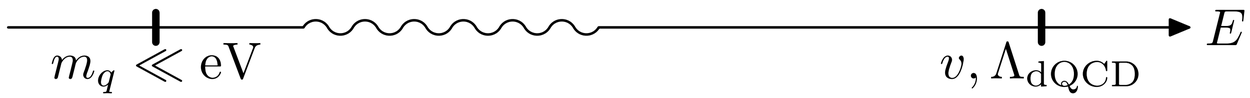
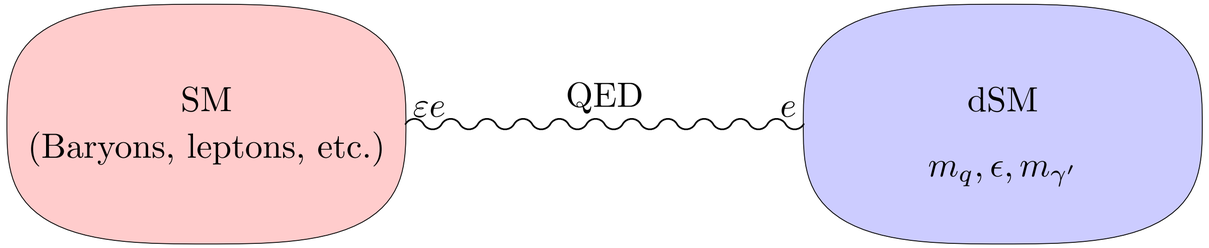
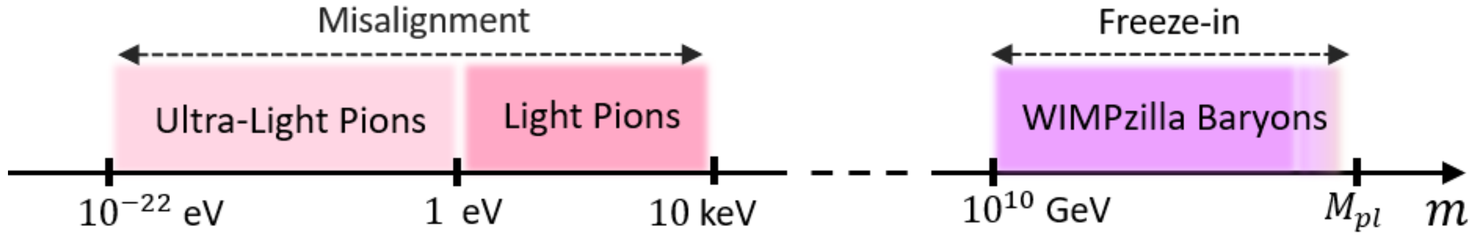
1. Two energy scales



2. SM portal: photon kinetic mixing (millicharges)



3. DM Production



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Synergy of IPP Experiments

Searching for 3 parameters: two mass scales, one coupling

Component:	Experimental Arena(s)	IPP Experiment
sub-eV dark pions	Neutrino oscillations & CP violating phases, oscillating SM parameters, neutron EDM, …..	T2K, HyperK, DUNE,….
Massive Dark Photon	Accelerator	NA62, DarkLIGHT, Belle-II, …
Dark Leptons, Higgs	Accelerator	ATLAS
Superheavy Dark baryons	Direct detection, indirect (cosmic rays)	DEAP-3600 , VERITAS, ICECUBE

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Summary

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Take-Home Messages

- IPP theory effort spans the country, covers SM pheno to quantum gravity
- Significant dark matter effort, moving towards “Dark Sector” paradigm
- IPP experiments provide complementary windows into dark sectors across the DM mass range

Thanks!

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