Light
Dark Matter Physics

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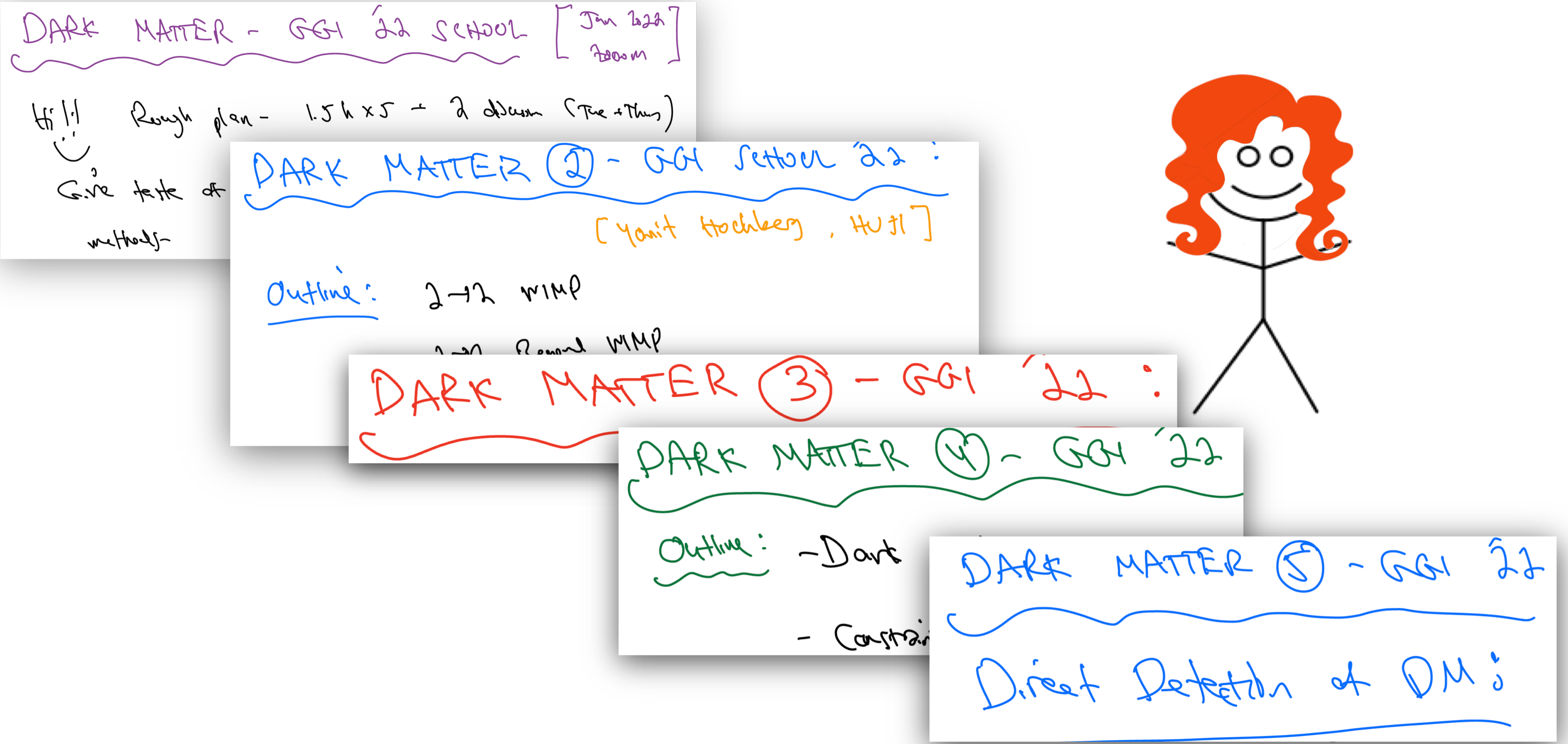
of Physics

Hi!


DARK MATTER - GGI '22 SCHOOL
[Jan 2022 Zoom]
Hi !!
Rough plan - 1.5 h x 5 + 2 discussion (Tue + Thurs)
Give taste of
methods
DARK MATTER (2) - GGI School '22 :
[Yonit Hochberg, HUJI]
Outline: 2→2 WIMP
DARK MATTER (3) - GGI '22 :
DARK MATTER (4) - GGI '22
Outline: - Dark
- Constrai
DARK MATTER (5) - GGI '22
Direct Detection of DM:

Hi!

DARK MATTER - GGI '22 SCHOOL [Jan 2022 Zoom]

Hi !! Rough plan - 1.5 h x 5 + 2 discussion (Tue + Thurs)

Give taste of methods -

DARK MATTER (2) - GGI School '22 :

Crocodile challenge

[Yonit Hochberg, HUJI]

Crocodile challenge

Outline: - Dark

- Constrai

DARK MATTER (5) - GGI '22

Direct Detection of DM :

Outline

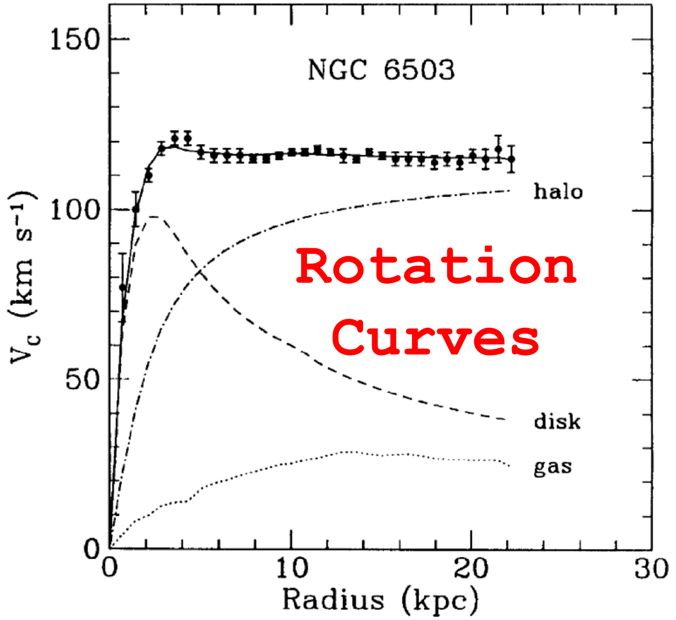
- Why?
- Theory
- Experiment

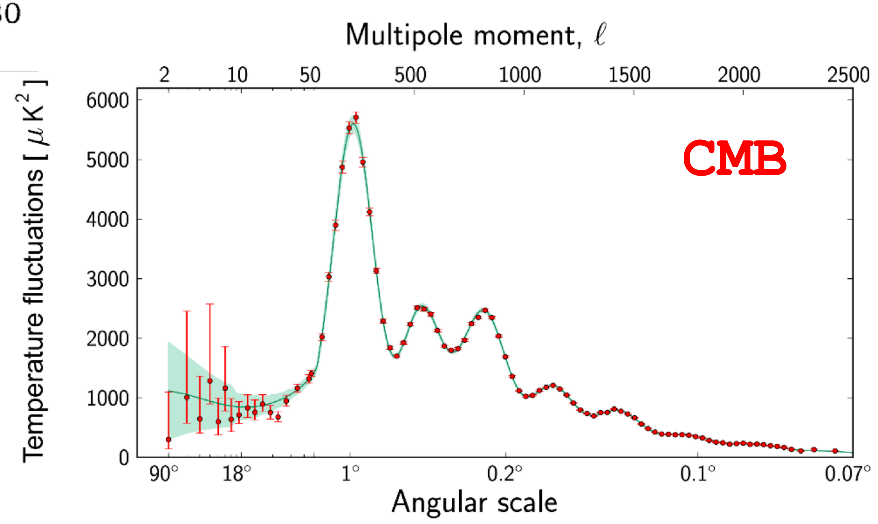
Why?

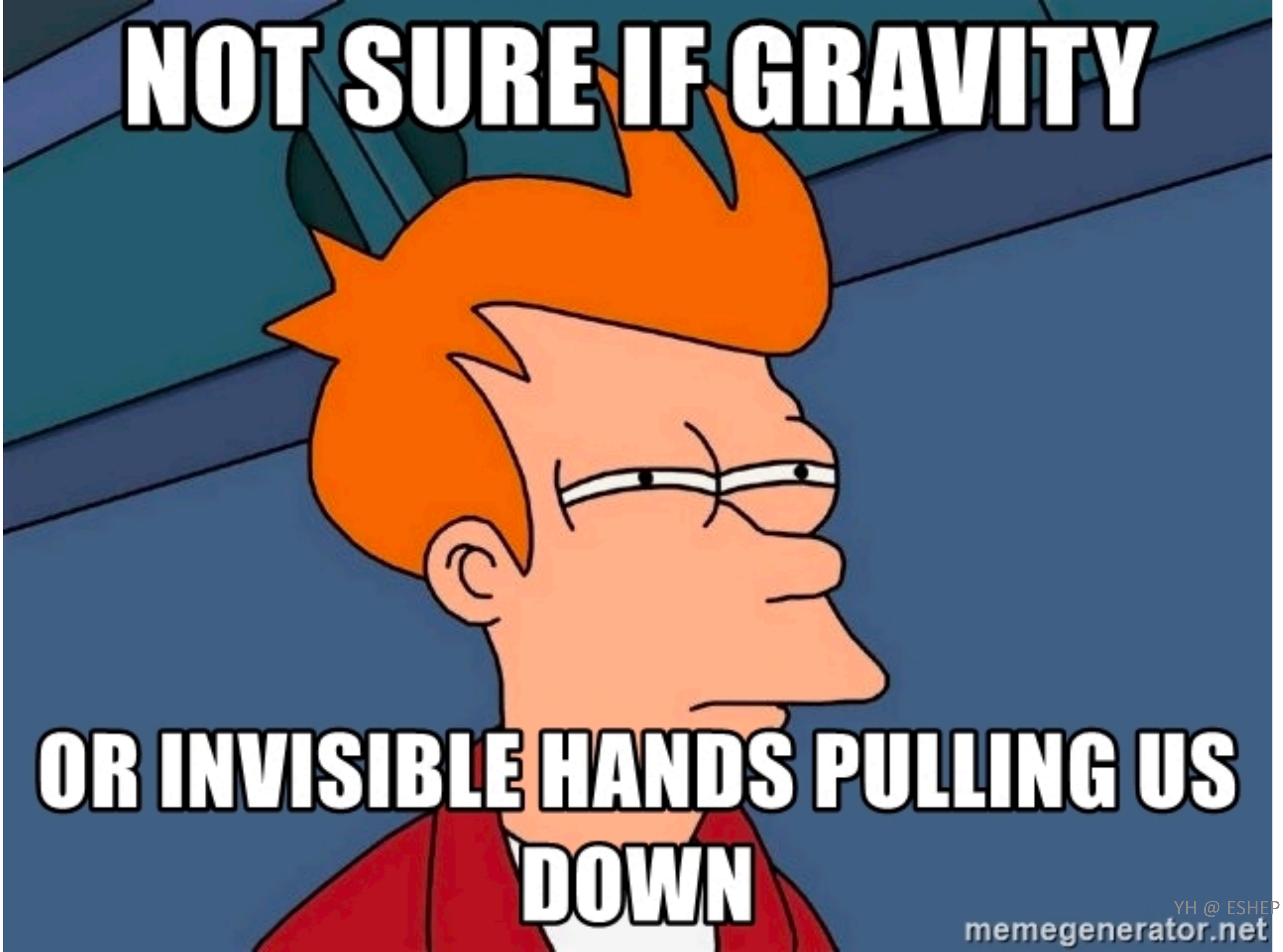
How much matter is out there?

What we see $\neq$ What we feel

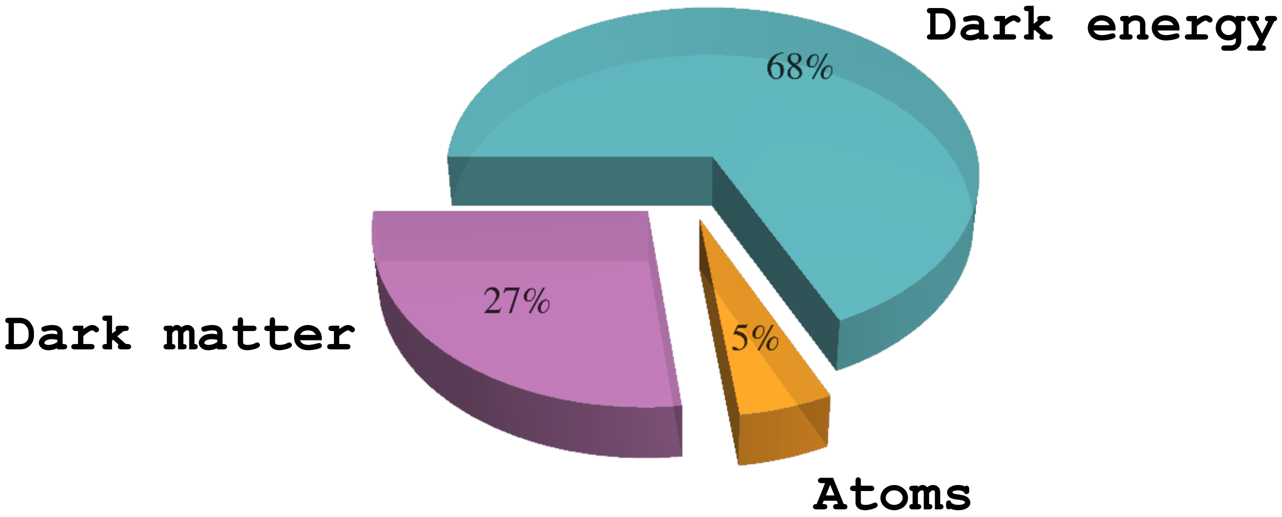
Evidence for Dark Matter

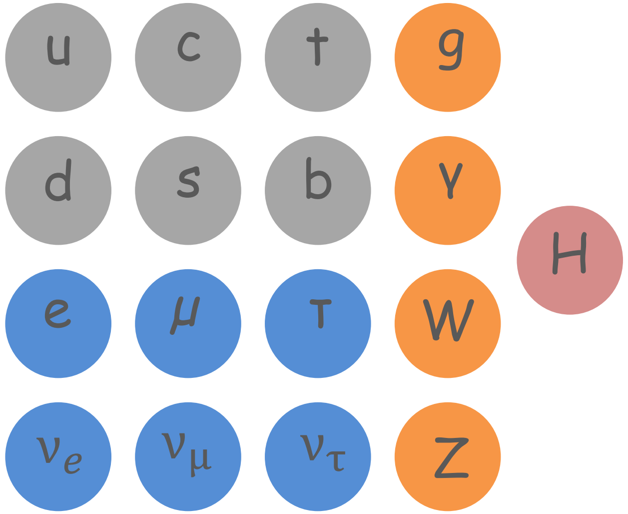





NOT SURE IF GRAVITY
OR INVISIBLE HANDS PULLING US DOWN
memegenerator.net

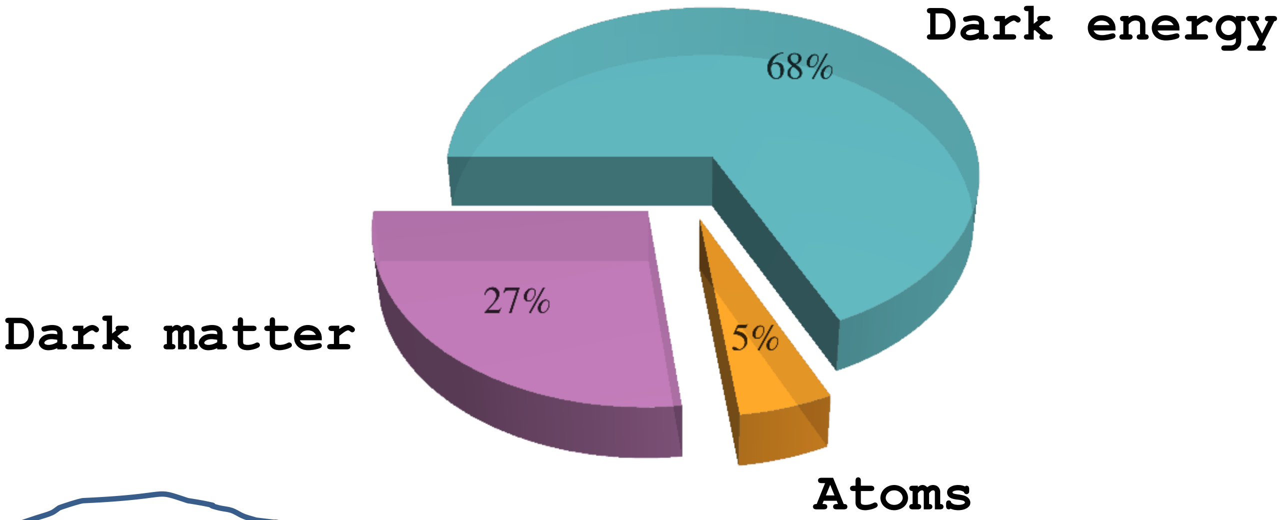
The Universe is Dark

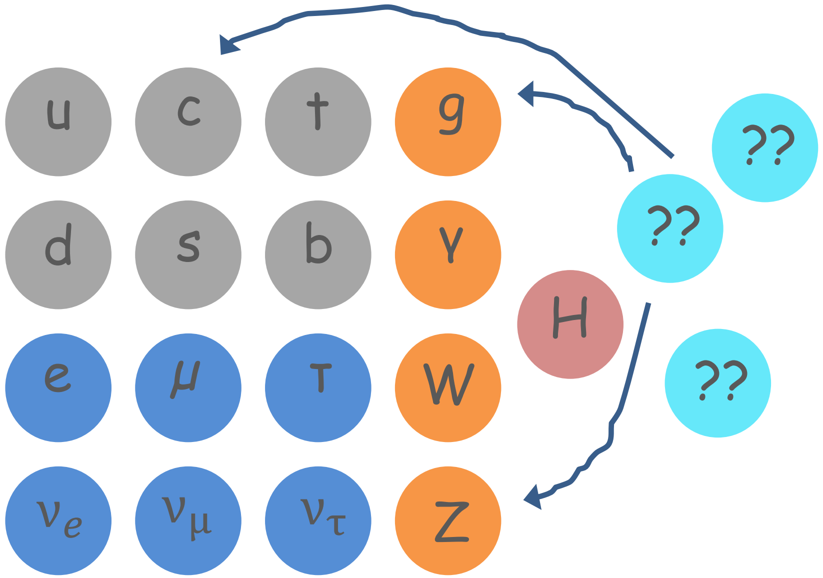




No suitable candidate within the Standard Model of particle physics

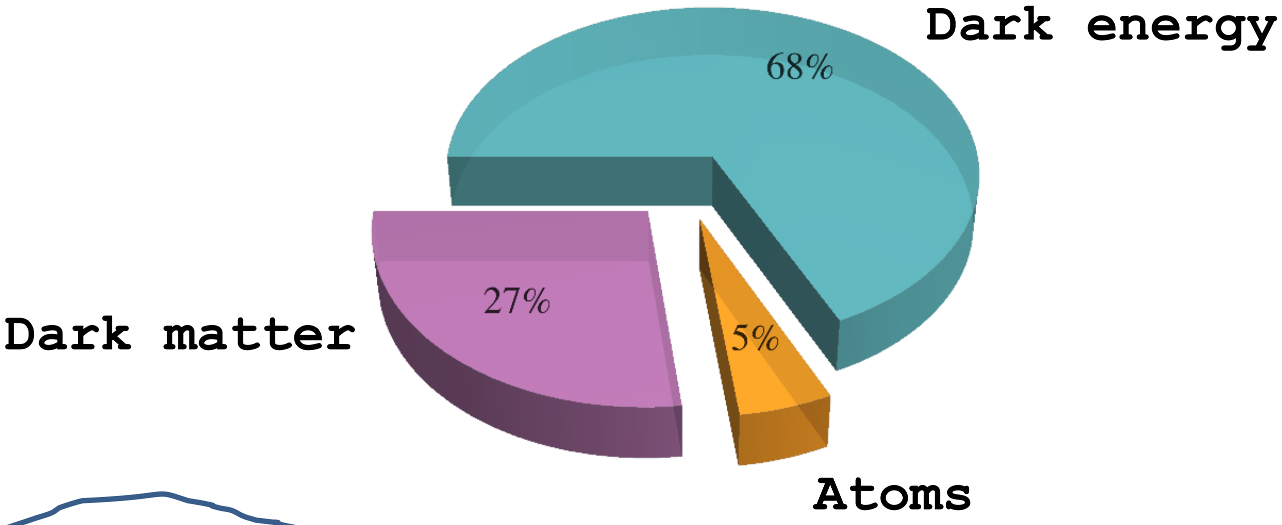
The Universe is Dark

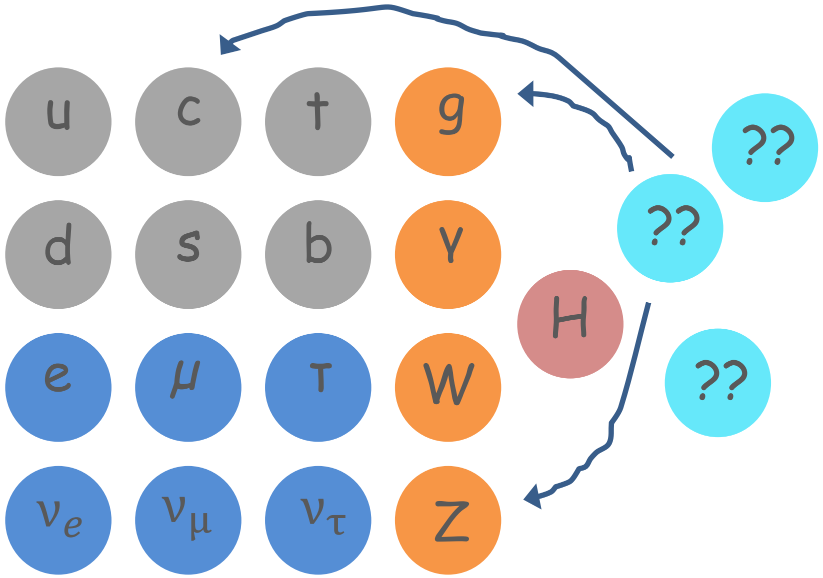




Must be at least one
new particle existing today

The Universe is Dark



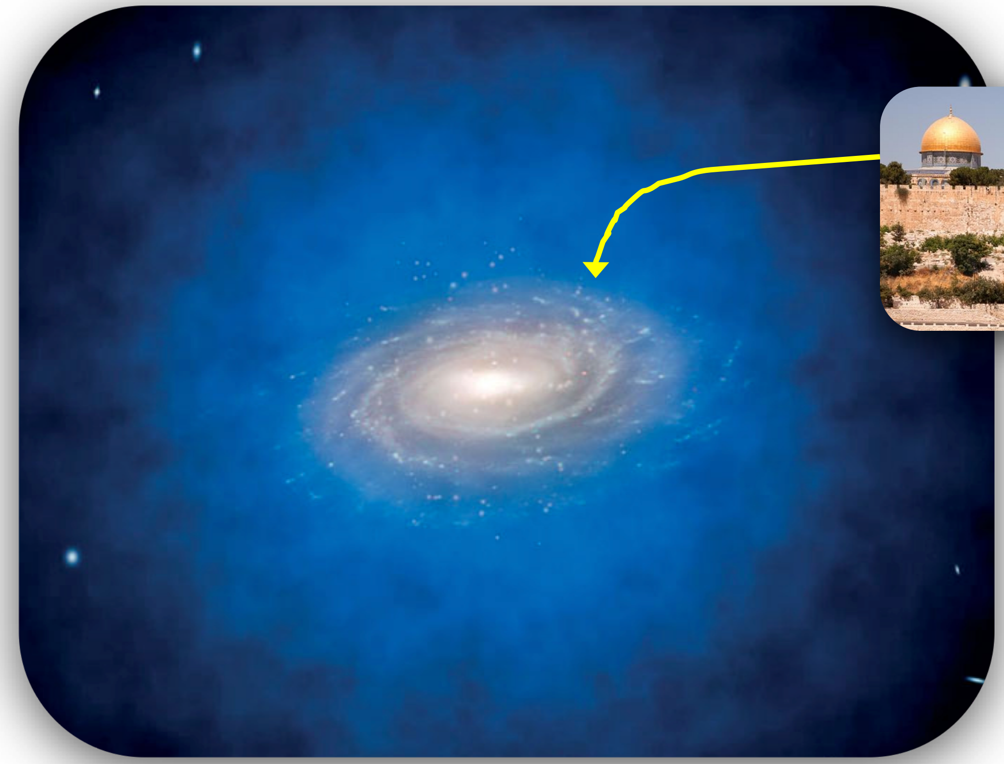


What is it?
How does it interact?

What do we know?

- Dark matter has 5 times the mass density of baryons
- Massive (m=???)
- Can’t interact too strongly with QED and QCD
- Doesn’t interact too strongly with itself

Dark matter in a halo; we're in a disk



Relative velocity of dark matter wind $v \sim 10^{-3}c$

Past 40 years

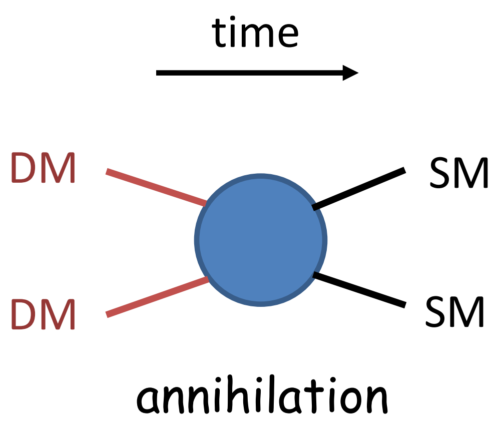
WIMP, glorious WIMP*

{ *Also axions, of course
also axions :-) }

Dark Matter in the Early Universe

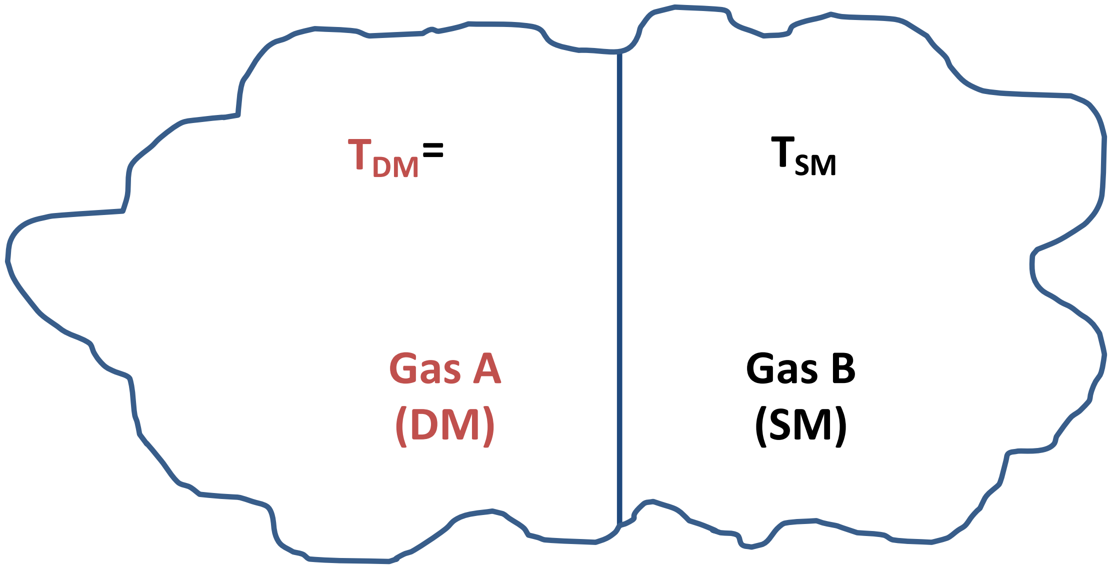
Is possible to link dark matter with early universe cosmology.

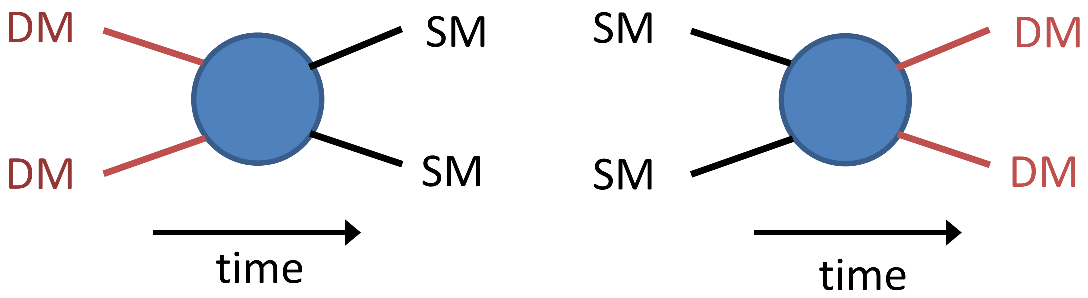
If new particle has 2 → 2 interactions with the Standard Model,
there will be a relic density left over.



Lee and Weinberg, 1977

Dark Matter in the Early Universe



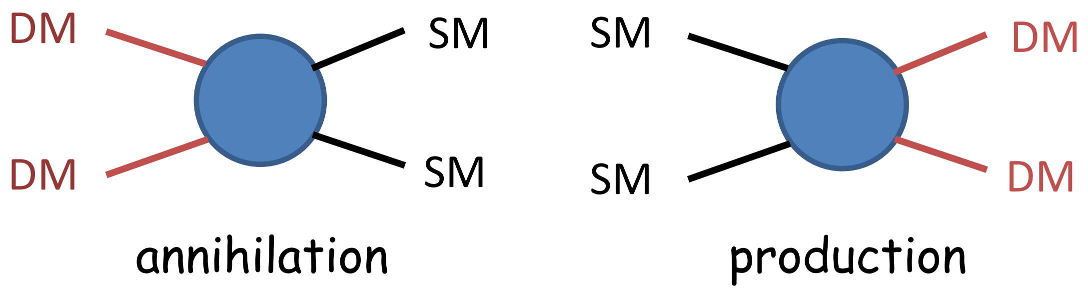


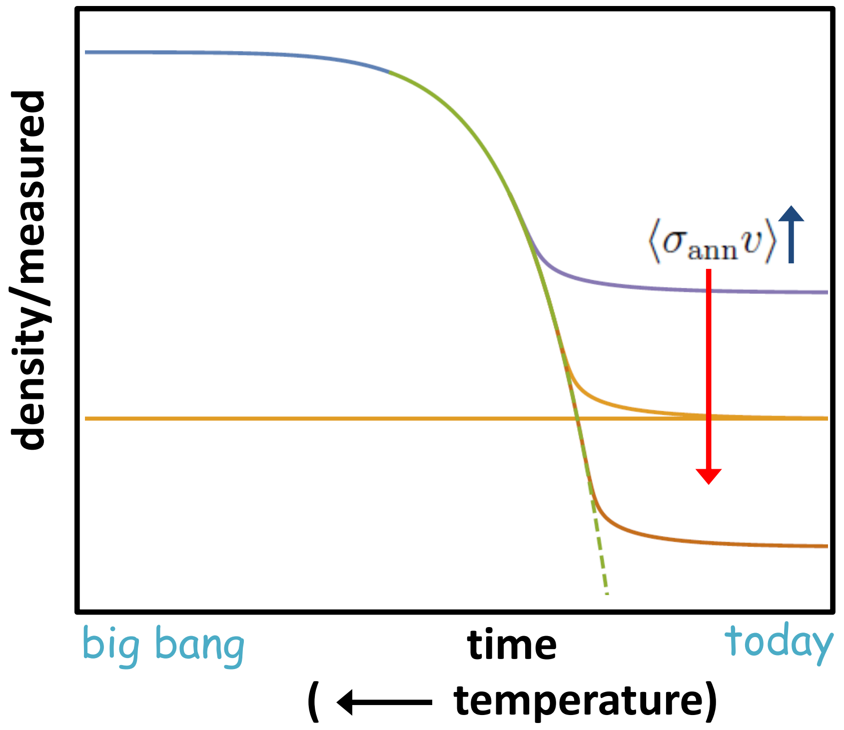
Dark Matter Freeze Out

Boltzmann eq.:

$$\partial_t n + 3Hn = -(n^2 - n_{\rm eq}^2)\langle\sigma_{\rm ann} v\rangle$$

Expanding universe





The WIMP Miracle

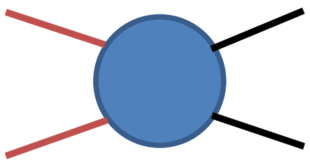
Correct thermal relic abundance:

$$m_{\rm DM} \sim \alpha \times 30\ {\rm TeV}$$

For weak coupling, weak scale emerges.

Weakly Interacting Massive Particle (WIMP)

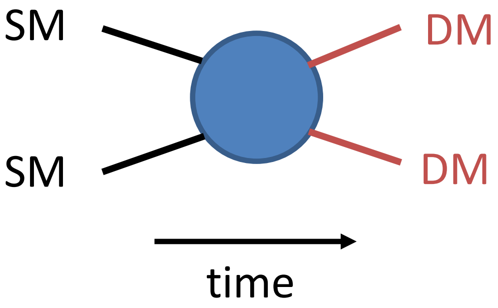
The dominant paradigm for ~40 years.



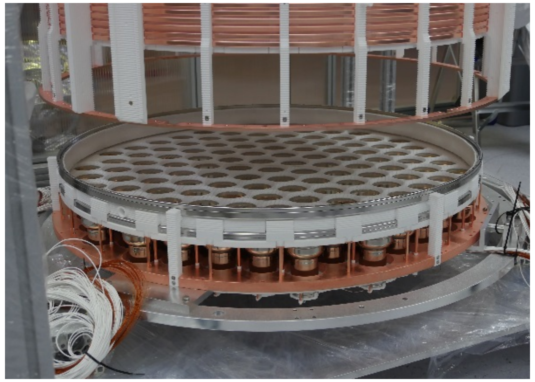
$$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2}$$

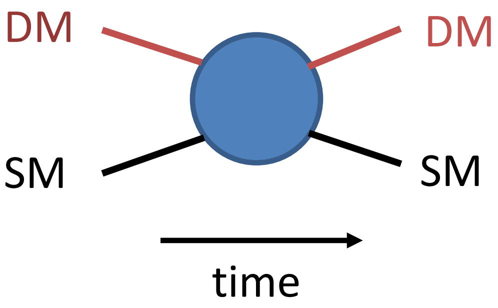
Searching for WIMPs

Colliders

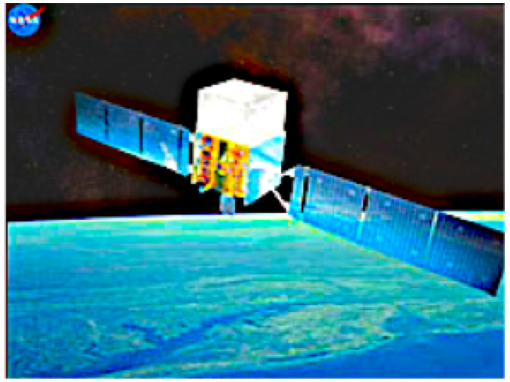


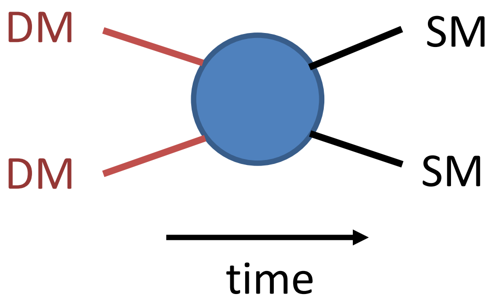
Targets in lab





Telescopes

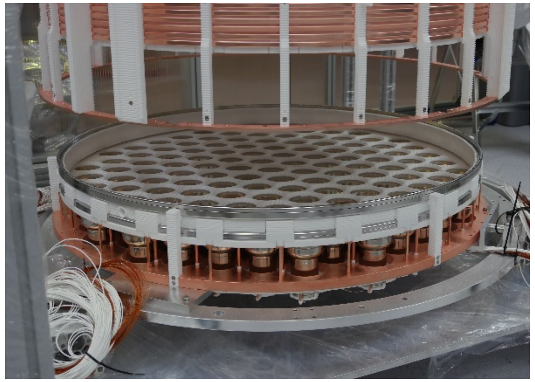




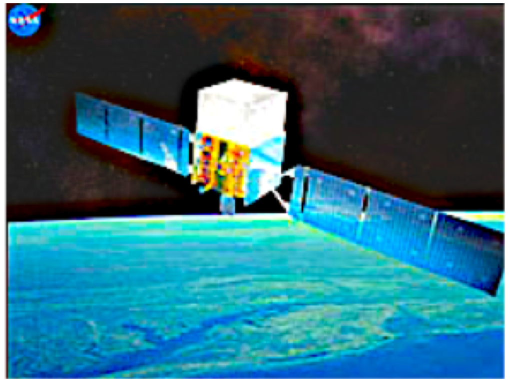
Searching for WIMPs

Colliders

Targets in lab



Telescopes

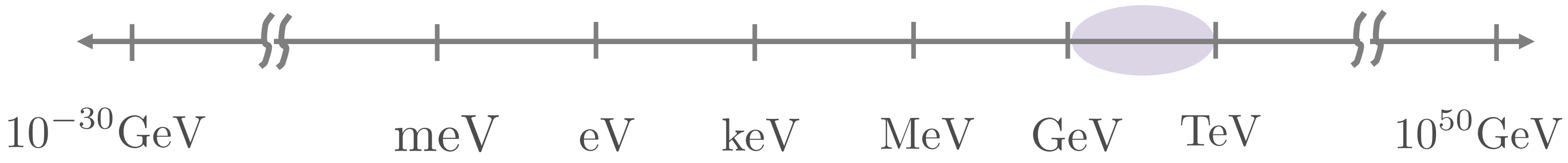


Experiments getting increasingly sensitive

Haven’t yet detected dark matter

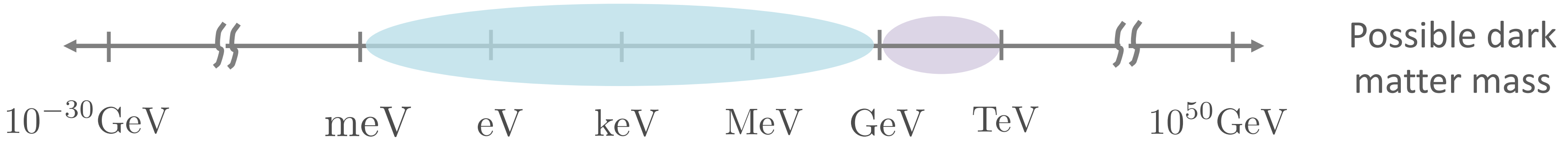
Great opportunity for new ideas.

Beyond the WIMP



Possible dark matter mass

Beyond the WIMP



New Frontier: Light Dark Matter
Theory + Experiment

Theory

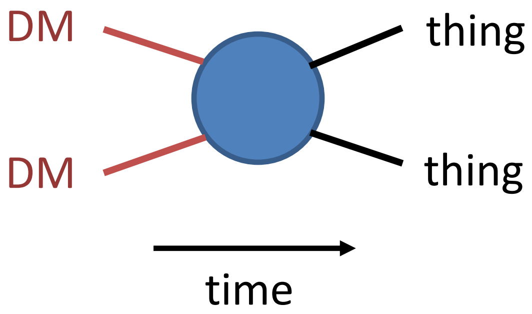
New Theory Ideas

- ……
- Weakly coupled WIMPs — Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008
- Asymmetric dark matter — Kaplan, Luty, Zurek, 2009
- Freeze-in dark matter — Hall, Jedamzik, March-Russell, West, 2009
- SIMPs — **YH**, Kuflik, Volansky, Wacker, 2014 | **YH**, Kuflik, Murayama, Volansky, Wacker, 2015
- ELDERs — Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017
- Forbidden dark matter — Griest, Seckall, 1991 | D'Agnolo, Ruderman, 2015
- Co-decaying dark matter — Dror, Kuflik, Ng, 2016
- Co-scattering dark matter — D'Agnolo, Pappadopulo, Ruderman, 2017
- ……

… Are abundant

By no means a comprehensive list

Ex. #1: Weakly coupled 2 → 2

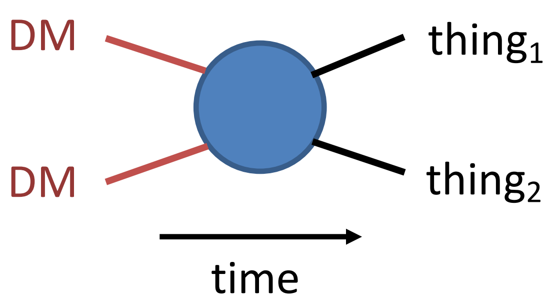


$$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2} \qquad \alpha \ll 1$$

$$m_{\rm DM} \sim \alpha \times 30 \text{ TeV}$$

Pospelov, Ritz, Voloshin 2007 | Feng, Kumar 2008

Ex. #2: Forbidden Channels



$$2m_{\mathrm{DM}} < m_{\mathrm{thing}_1} + m_{\mathrm{thing}_2}$$

$$m_{\mathrm{DM}} \sim \alpha \times (30\ \mathrm{TeV}) \times e^{-x_F \Delta}$$

freezeout temp'

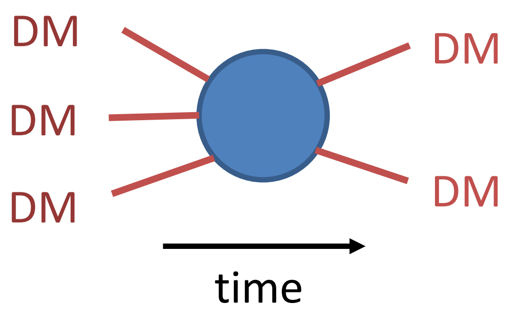
mass difference

Forbidden @ T=0;
Boltzmann suppressed @ finite T

Griest, Seckel, 1991 | D'Agnolo, Ruderman, 2015

Ex. #3: SIMPs

What if dark matter mostly interacted with itself?



$$\langle \sigma v^2 \rangle_{3\to 2} \equiv \frac{\alpha^3}{m_{\rm DM}^5}$$

$$m_{\rm DM} \sim \alpha \times 100 \text{ MeV}$$

3 → 2 self-annihilations

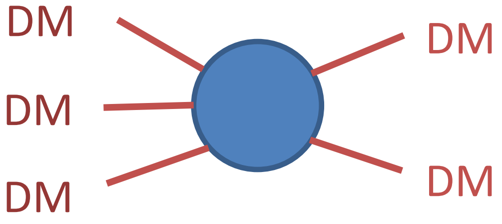
For strong coupling, the strong scale emerges.

SIMP = Strongly (self) Interacting Massive Particle

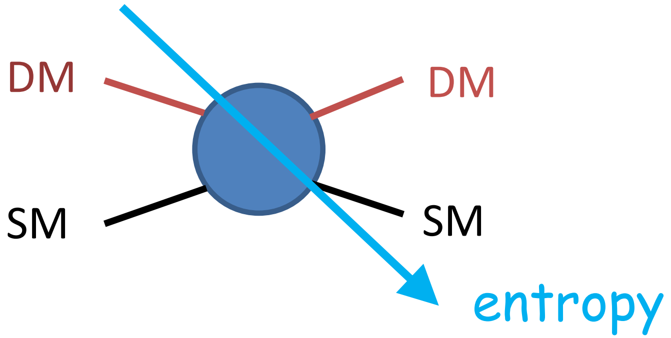
Carlson, Hall, Machacek, 1992 | **YH**, Kuflik, Volansky, Wacker, 2014

Ex. #3: SIMPs

Pumps heat into the system: need to shed the heat



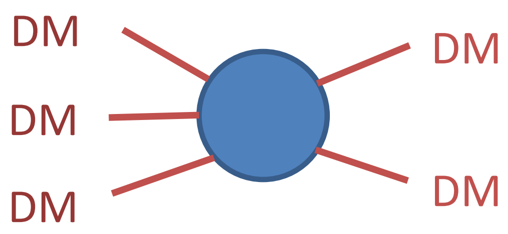
3 → 2 self-annihilations



thermalize with
light SM species
(active during freeze-out)

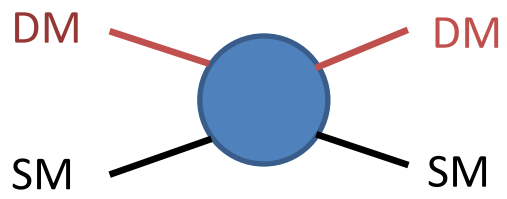
YH, Kuflik, Volansky, Wacker, 2014

Ex. #3: SIMPs



decouples 1^{st}

Determines
DM relic density

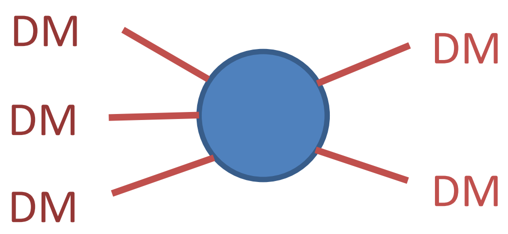


decouples 2^{nd}

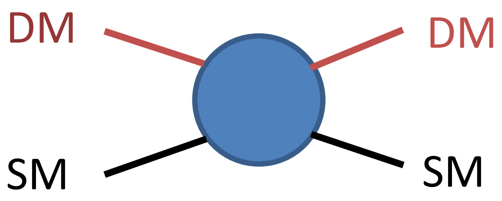
What if the order was reversed?

Ex. #4: ELDERs

ELastically DEcoupling Relic (ELDER)



decouples 2nd



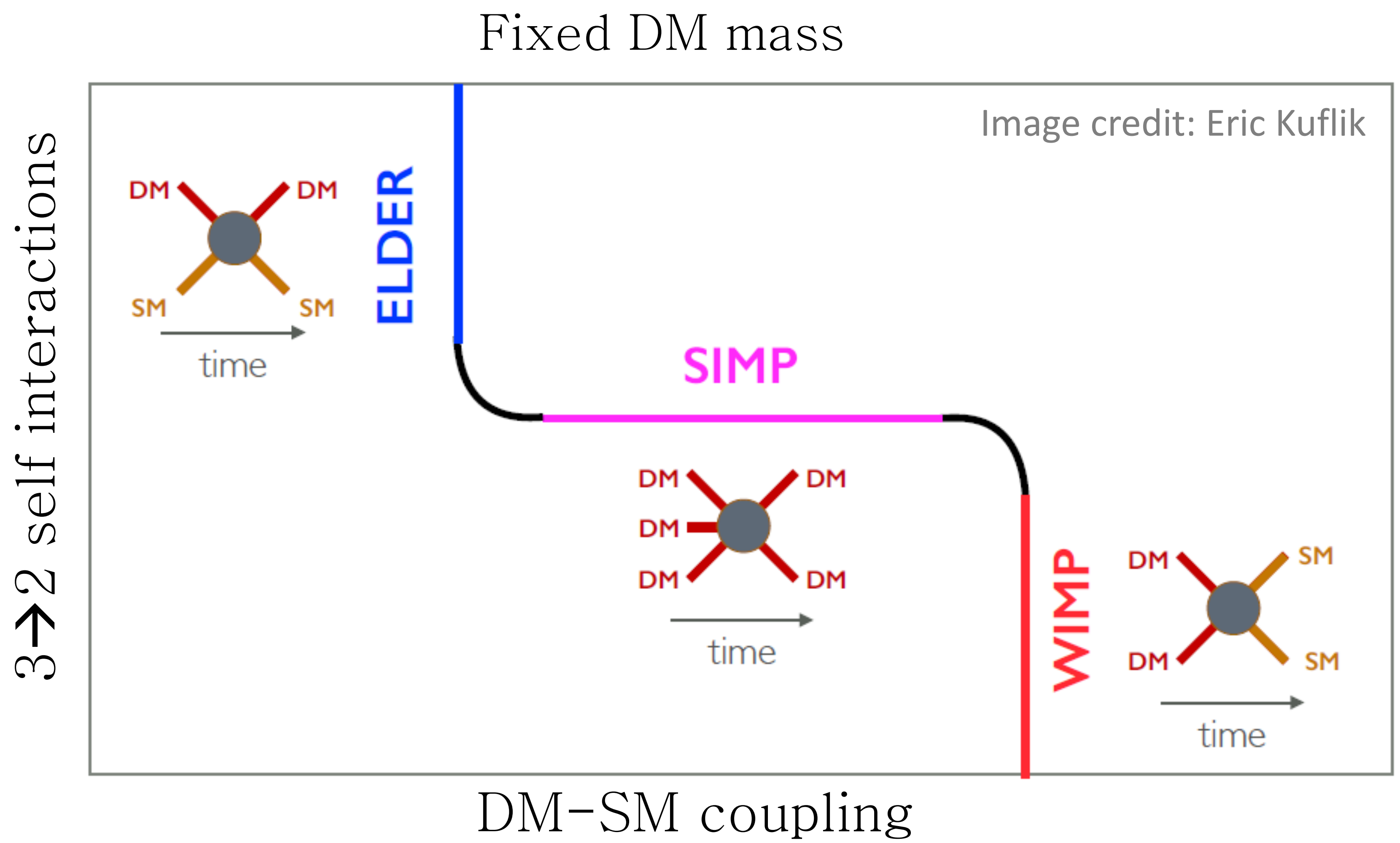
decouples 1st

Determines
DM relic density

$$\Omega_{\rm DM} \propto e^{-\langle \sigma v \rangle_{\rm el} \#}$$

Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017

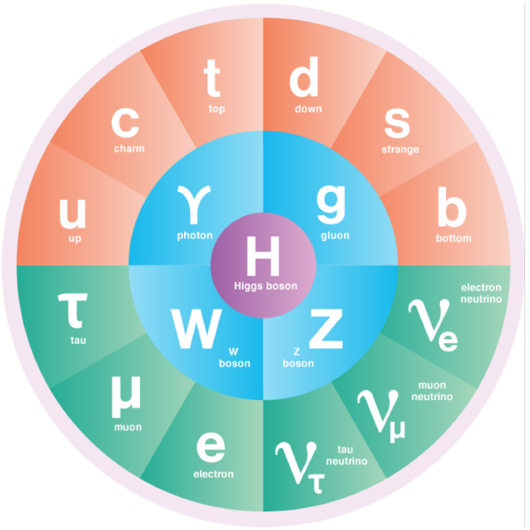
WIMP/SIMP/ELDER



Generic.

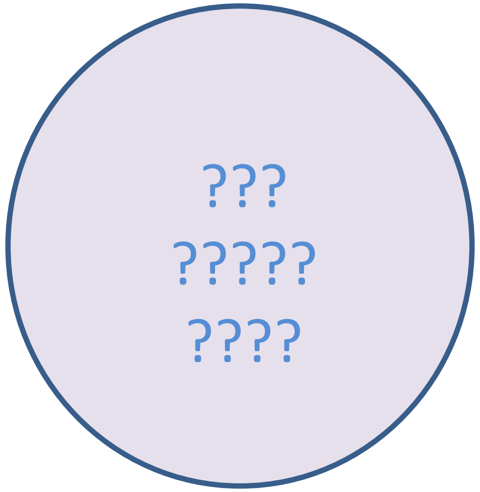
Dark Sectors

Visible sector



Zoo of particles
w/structure
$SU(3)_c x\ SU(2)_L\ x\ U(1)_Y$

Dark sector



Why not in the
dark sector too?
New gauge symmetries?

Dark Sectors

Think Standard Model!

Dark matter from strongly coupled gauge theories

E.g. $SU(3)_{dark} \times U(1)_{dark}$

$Sp(N_c)$, $SU(N_c)$, $SO(N_c)$

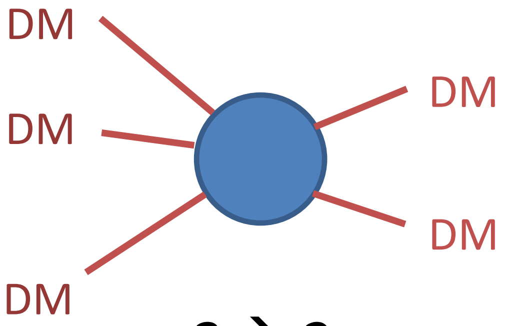
Kinetically mixed dark photon (V)

QCD-like theories, pions = dark matter

Many processes, many dark matter mechanisms.

E.g. SIMPs

Think QCD!



3→ 2

QCD has 5-point interactions! $K^+K^-\rightarrow\pi^+\pi^0\pi^-$

WZW term

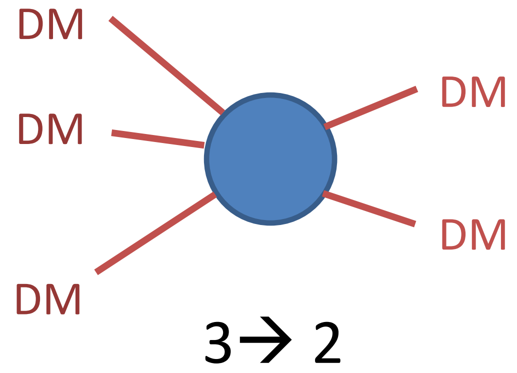
If calculate the rate, find that is just right for SIMPs with mass ~ few hundred MeV

YH, Kuflik, Murayama, Volansky, Wacker, 2015

E.g. SIMPs

Think QCD!

$Sp(N_c)$, $SU(N_c)$, $SO(N_c)$



$$\mathcal{L}_{\rm WZW} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi]$$

WZW term

pion decay constant

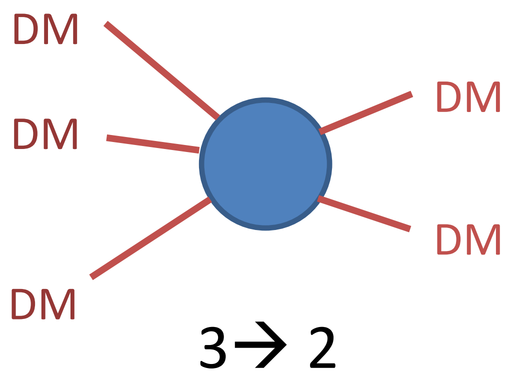
Wess and Zumino, 1971 | Witten x 2, 1983

YH, Kuflik, Murayama, Volansky, Wacker, 2015

E.g. SIMPs

Think QCD!

$Sp(N_c)$, $SU(N_c)$, $SO(N_c)$



Stable dark matter = dark pions

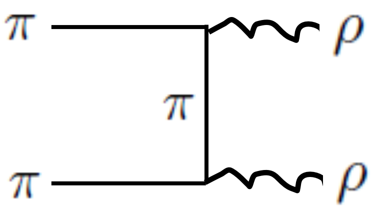
mass ~ few hundred MeV

Non-exotic!

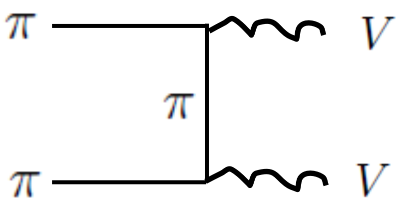
{ **3→ 2 dark glueballs:** Carelson, Hall, Machacek, 1992 | Soni, Zhang, 2016 | Forestell, Morrissey, Sigurdson, 2017 }

YH, Kuflik, Murayama, Volansky, Wacker, 2015

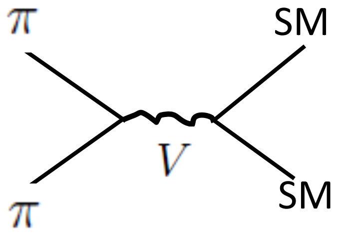
E.g. 2→2



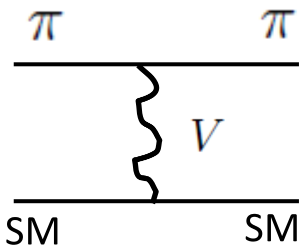
forbidden annihilations



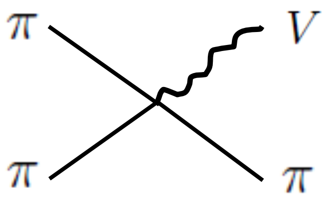
2→2 annihilations



2→ 2 annihilations



elastic scattering

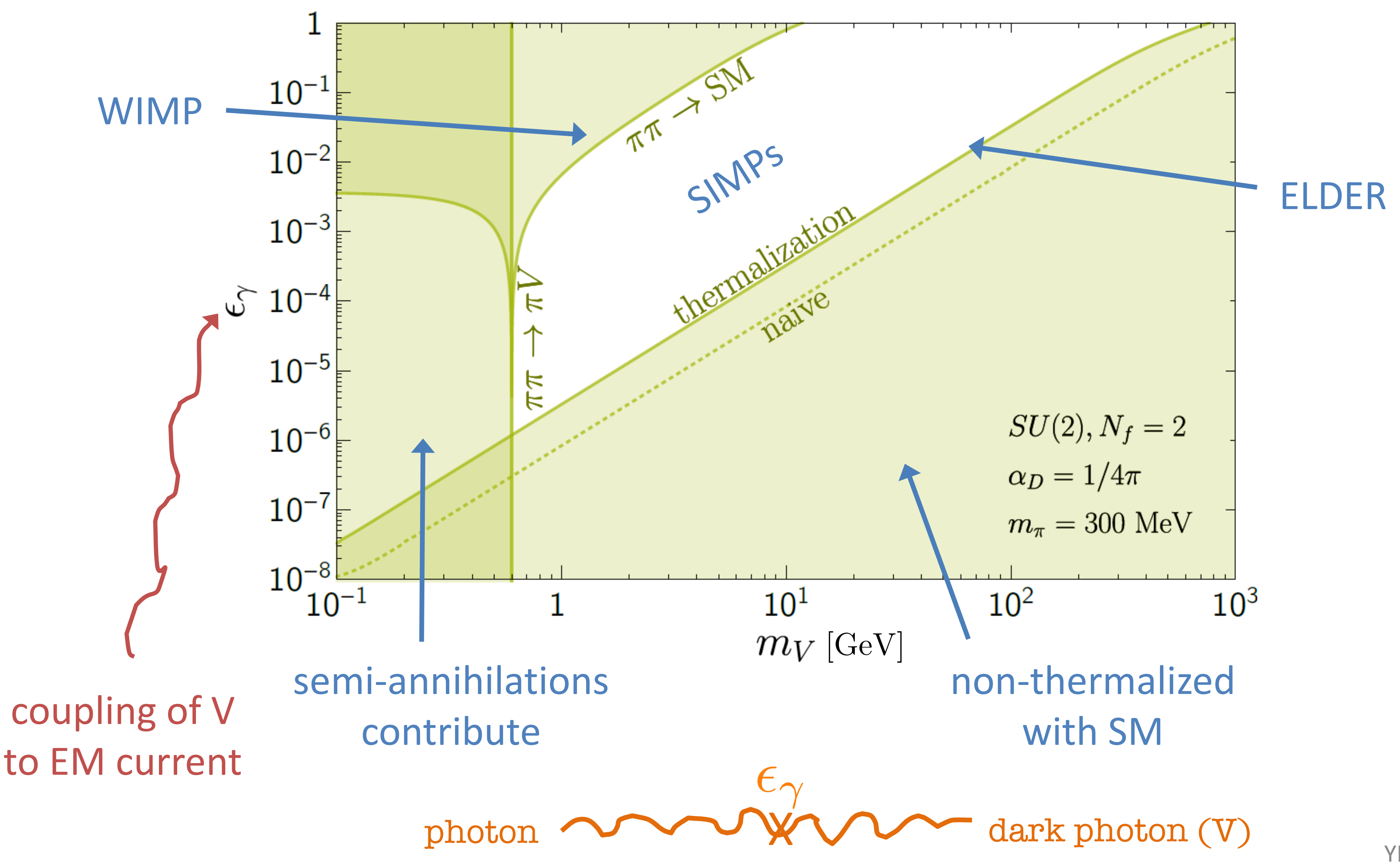


semi-annihilations

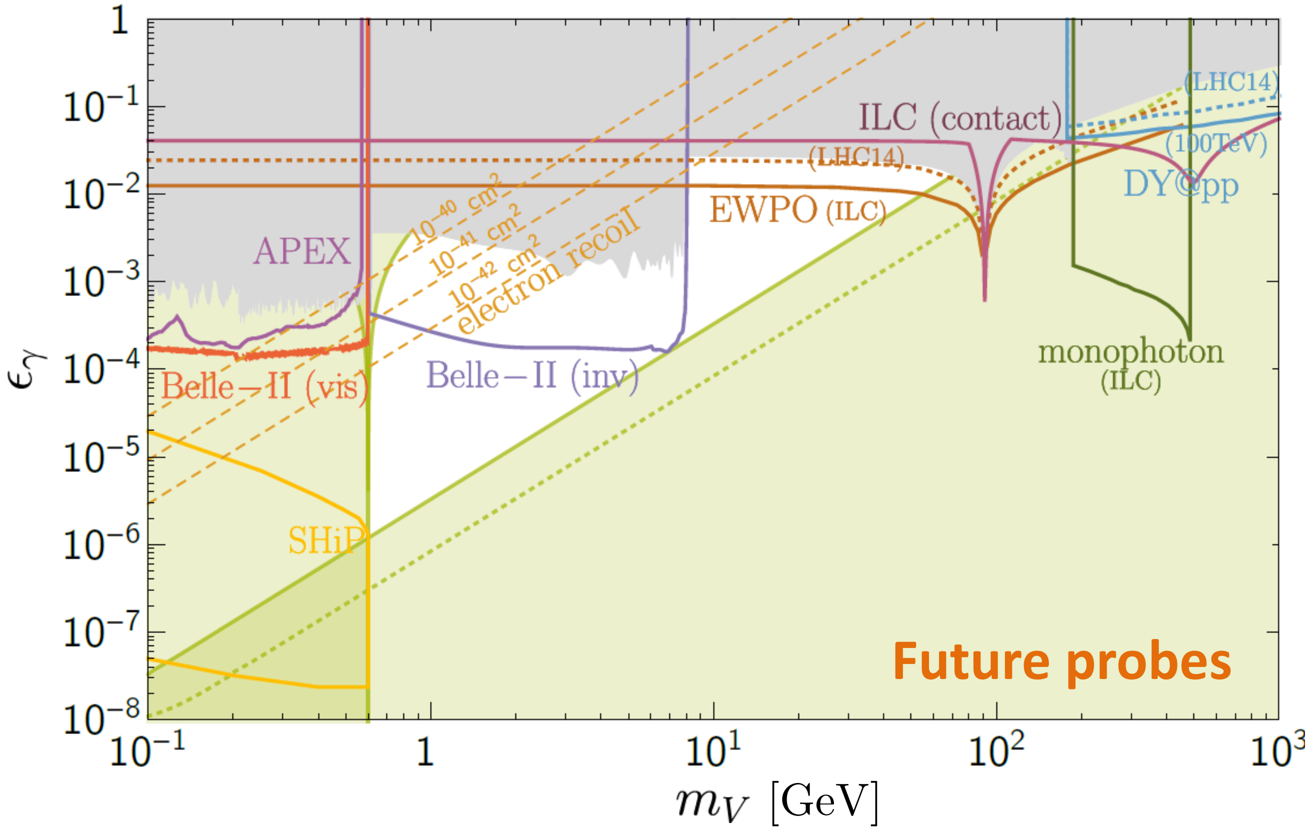
Lee, Seo, 2015 | **YH**, Kuflik, Murayama, 2016 | Harigaya, Nomura, 2016
Berlin, Blinov, Gori, Schuster, Toro, 2018

Predictive.

Dark Electromagnetism



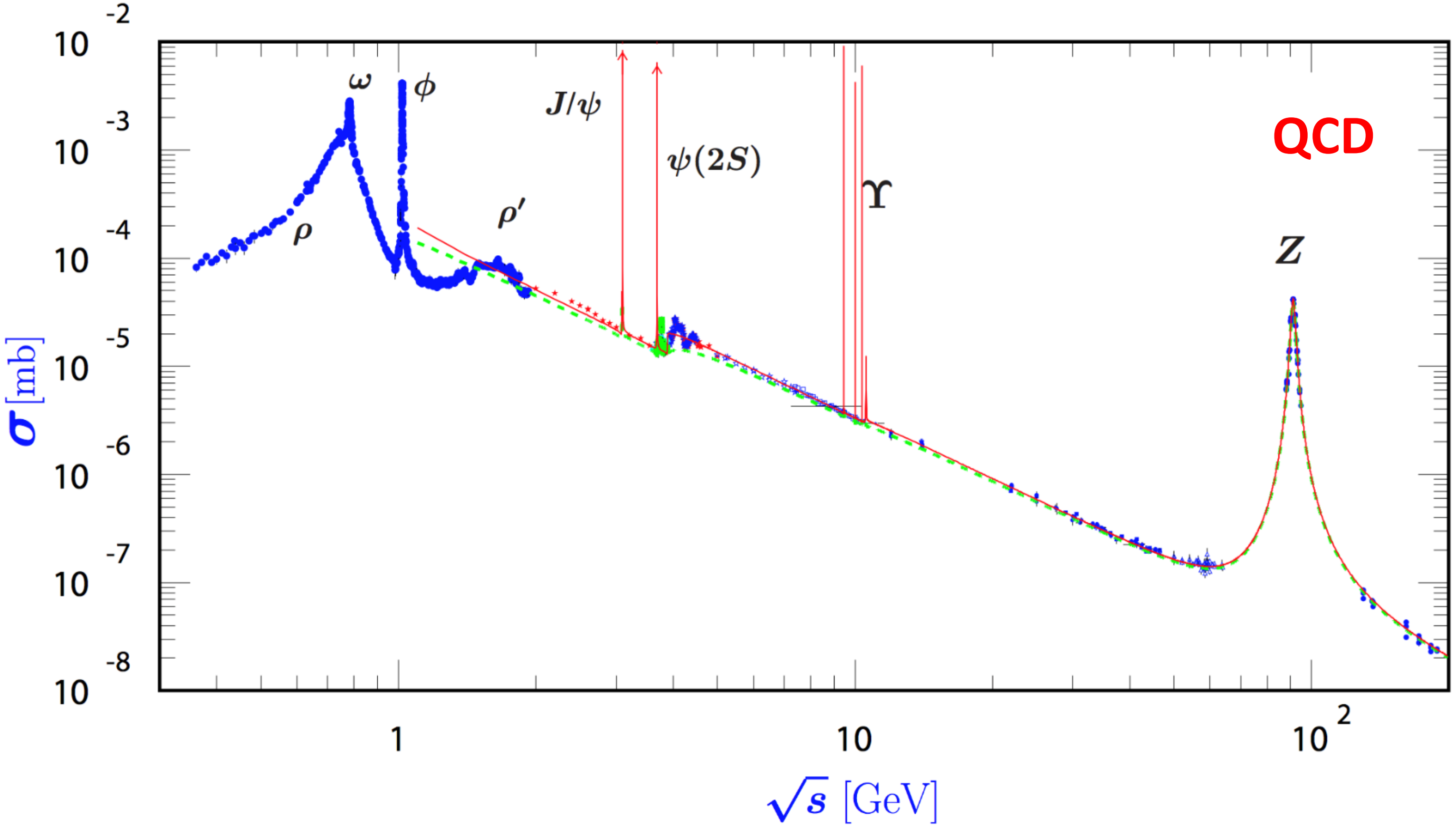
Dark Electromagnetism



Plot: **YH**, Kuflik, Murayama, 2016

Dark Spectroscopy

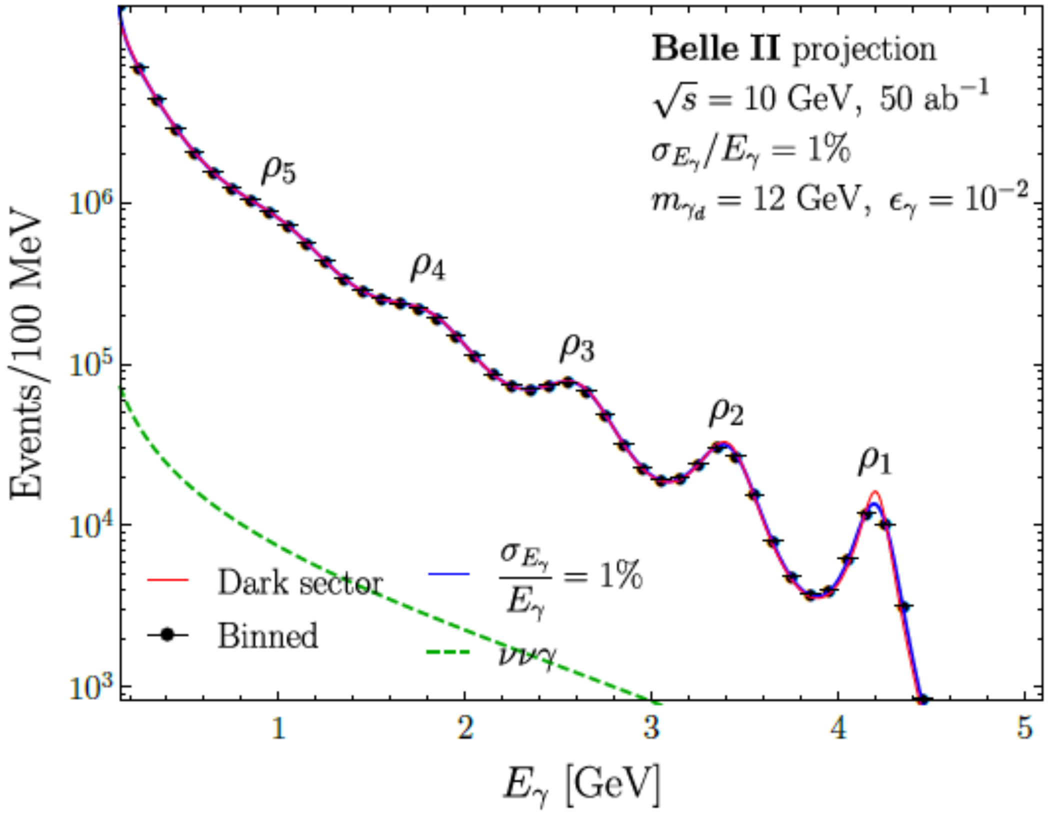
$e^+e^- \to \text{resonances}$: center of mass energy traces the QCD resonance structure

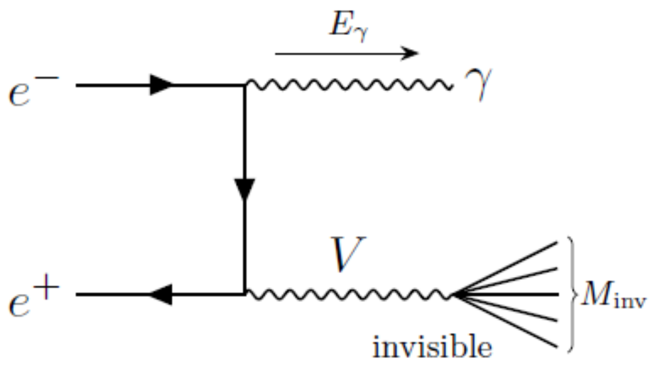


Dark Spectroscopy

$$e^+e^- \to \gamma + \text{inv}:$$

Mono-photon traces the resonance structure of the dark sector





$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\text{inv}}^2}{s}\right)$$

YH, Kuflik and Murayama, 2016 & 2017

Experiment

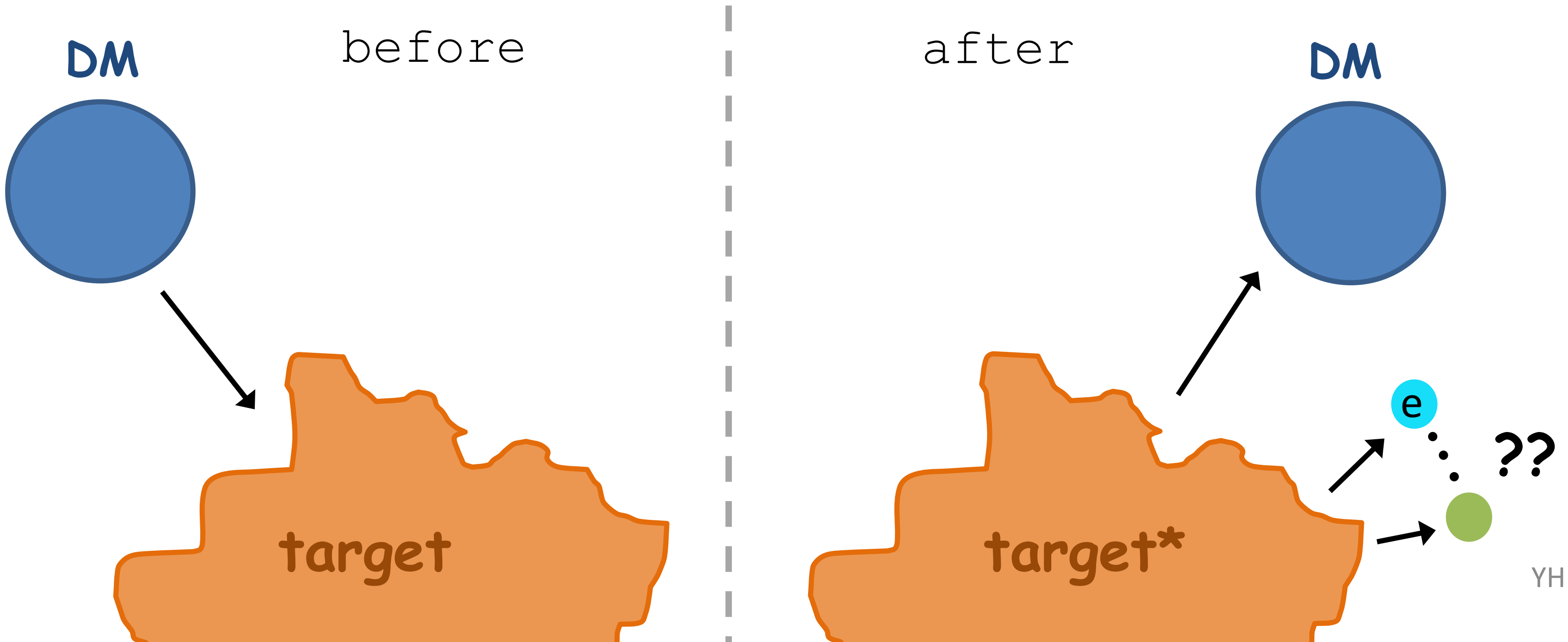
Detection Blueprints

Dark matter particle comes in

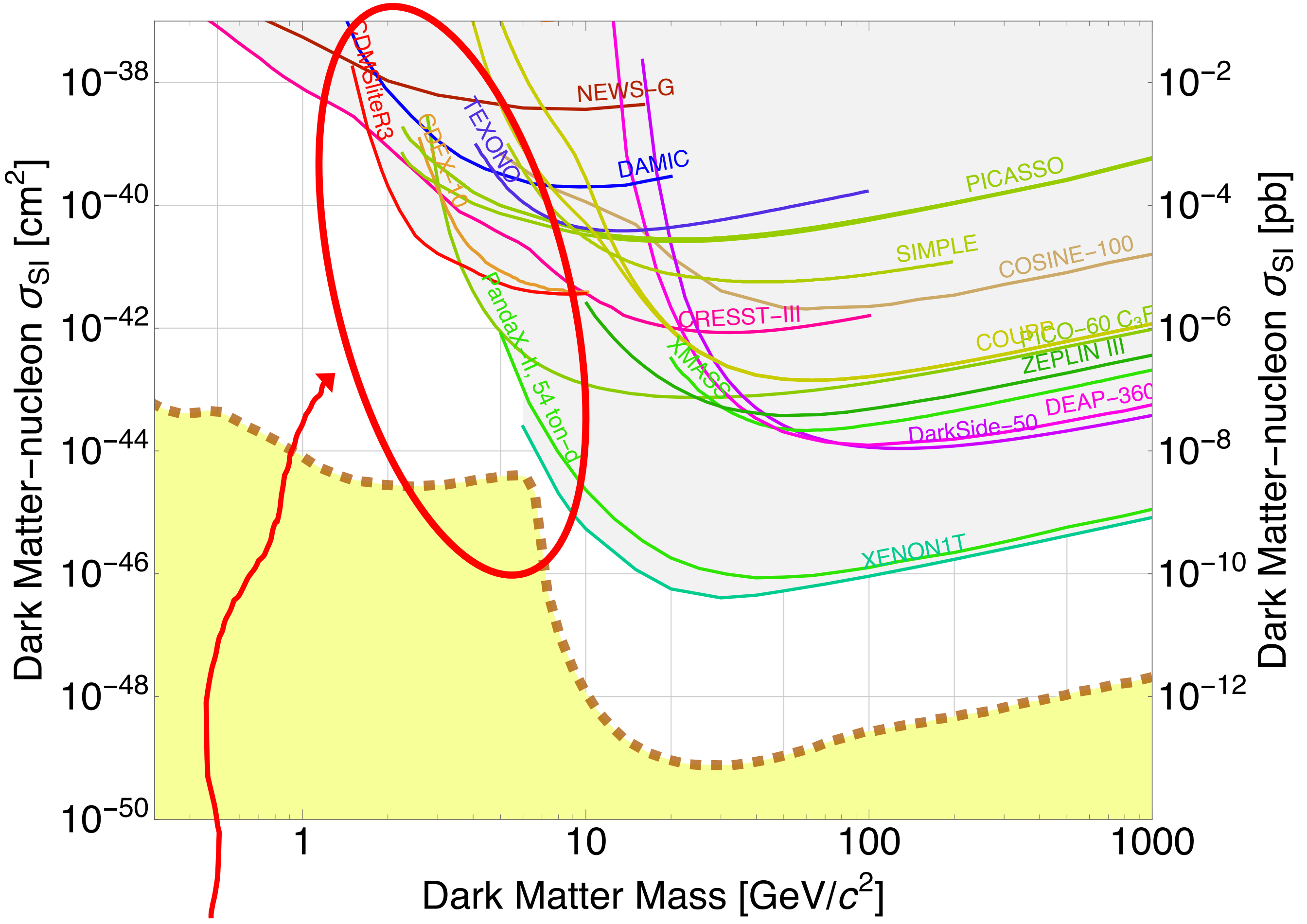
Hits a target in the lab

System reacts

Measure the reaction



Direct Detection



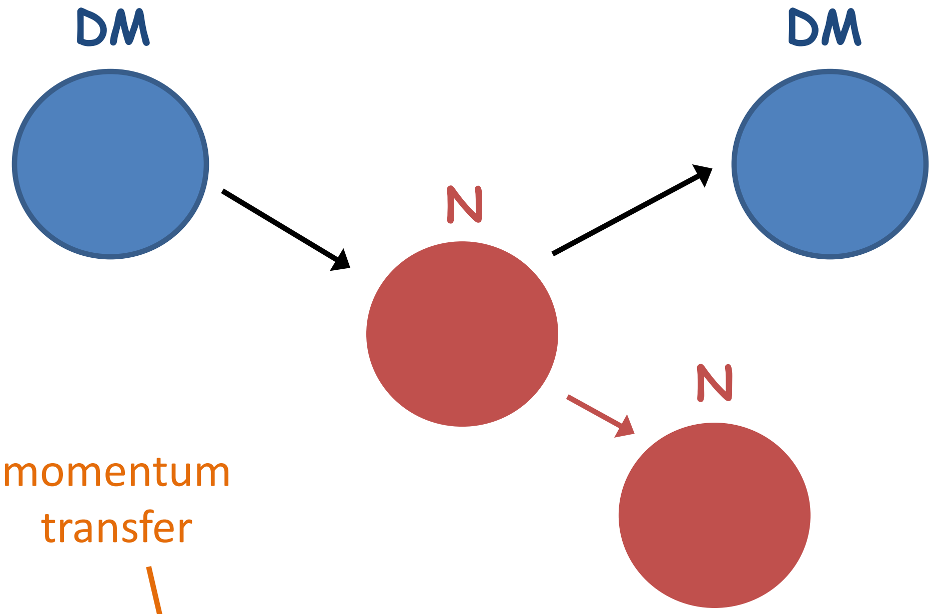
What's going on?

[*website:* supercdms.slac.stanford.edu/dark-matter-limit-plotter]

Current Experiments

Looking for nuclear recoils:

think billiard balls

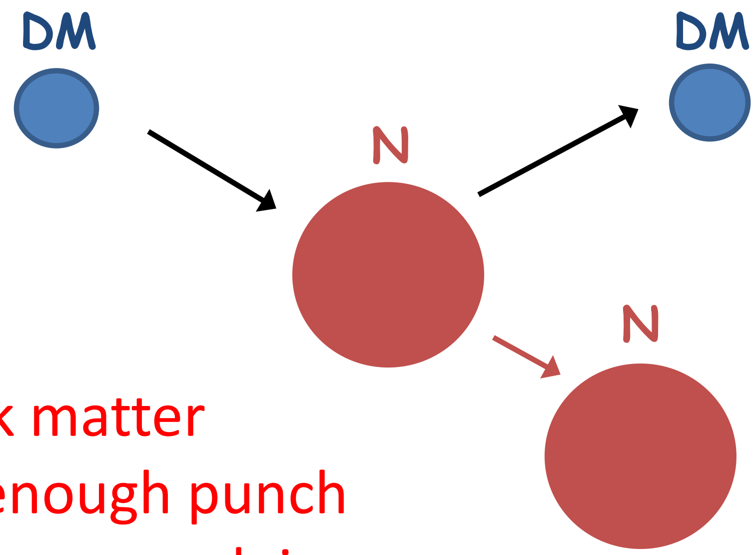


momentum transfer

$$E_{\rm NR} = \frac{q^2}{2m_N} = \frac{(m_{\rm DM}v)^2}{2m_N} \gtrsim E_{\rm threshold} \sim {\rm keV}$$

Current Experiments

Looking for nuclear recoils:
think billiard balls

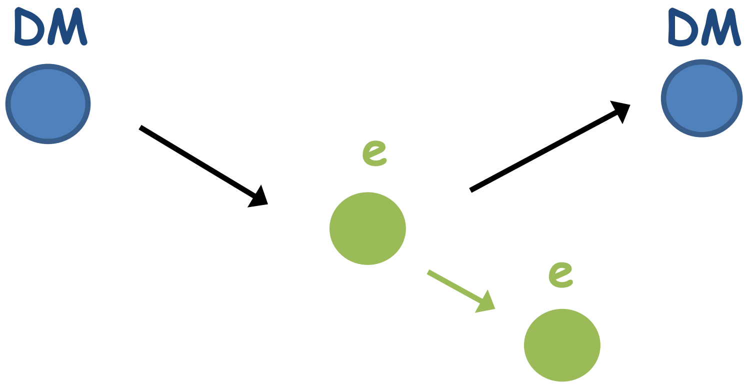


light dark matter
doesn’t have enough punch
to kick the heavy nuclei

Lose sensitivity @ O(GeV) masses

New Avenues

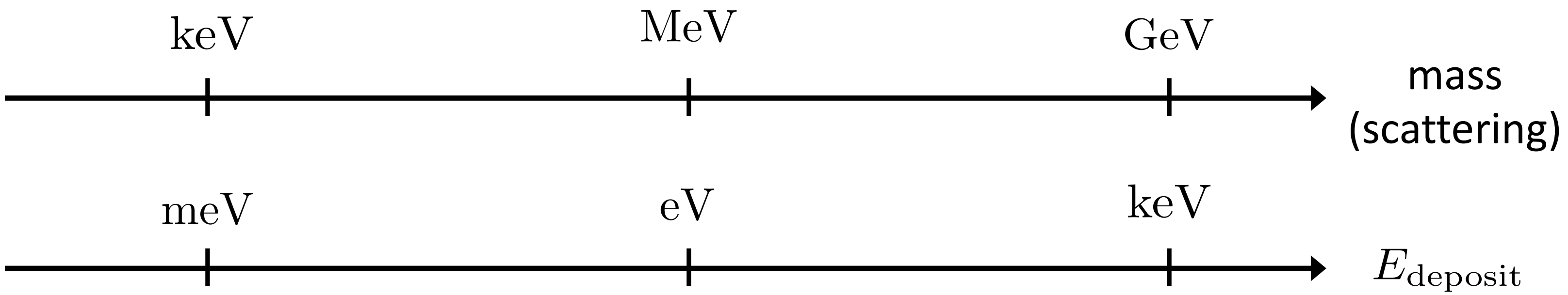
Light dark matter: scatter off electrons!

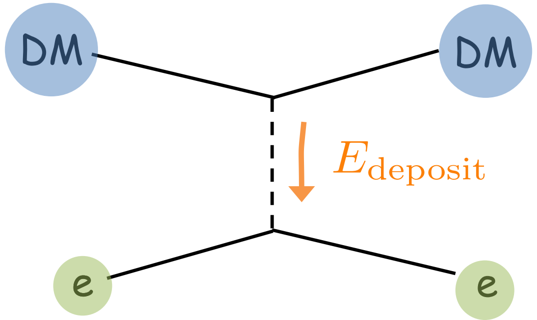


light dark matter
can give enough punch
to kick the light electrons

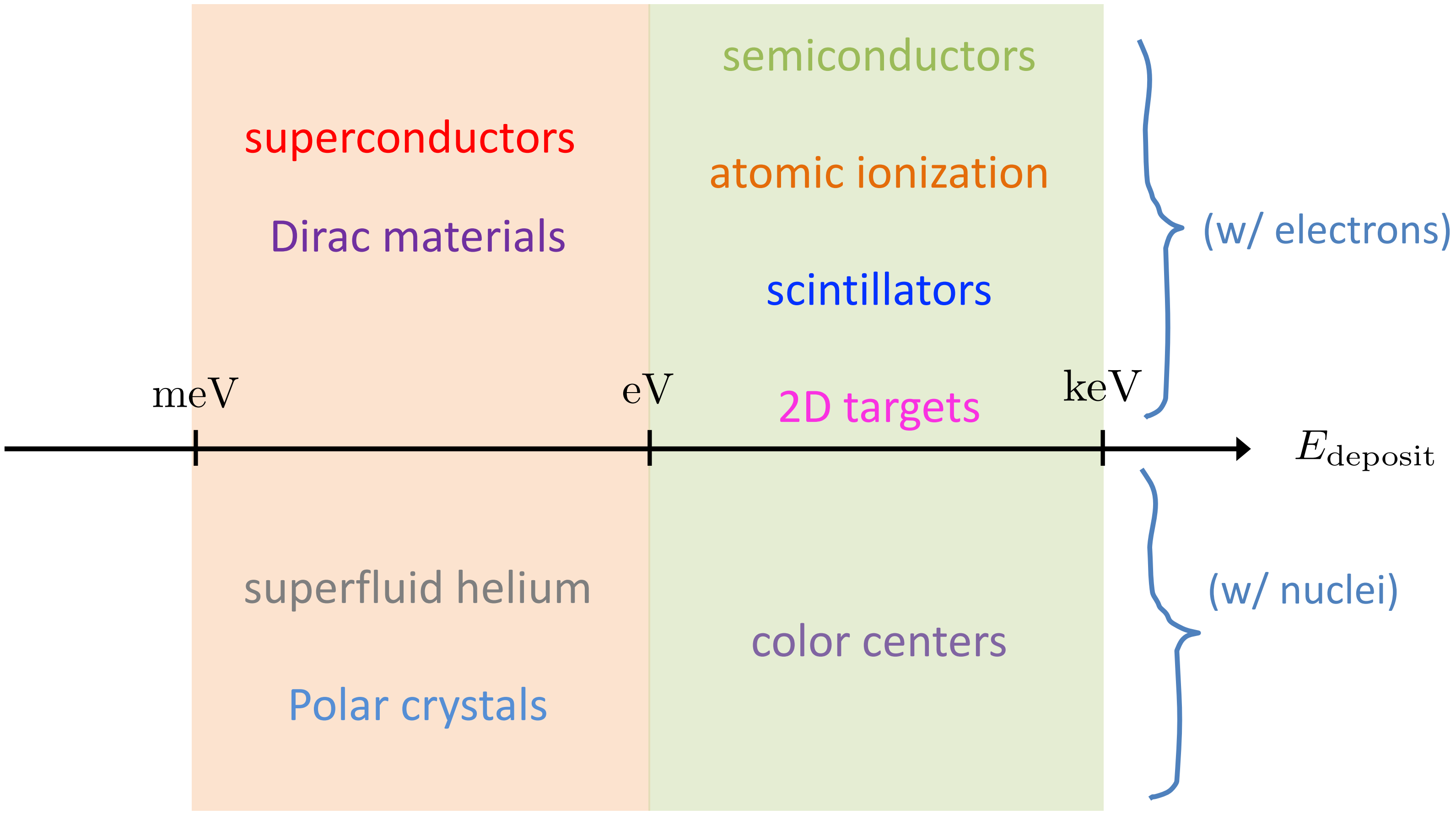
Energy guideline

Dark matter scattering: kinetic energy $m_{\rm DM} v^2 \sim 10^{-6} m_{\rm DM}$





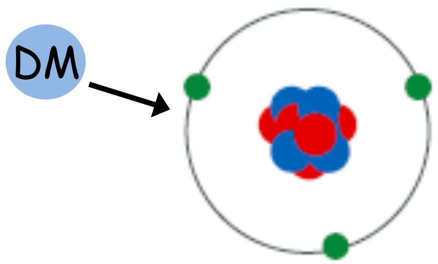
New proposals



Explosion of interest and ideas in recent times

Ex. #1: First ideas

Atomic ionization

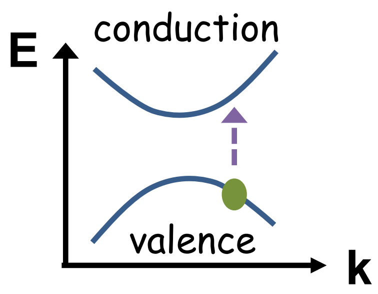


Xenon: ~12 eV

$$m_{\rm DM} \gtrsim 10 \text{ MeV}$$

Essig, Mardon, Volansky, 2012

Semiconductors



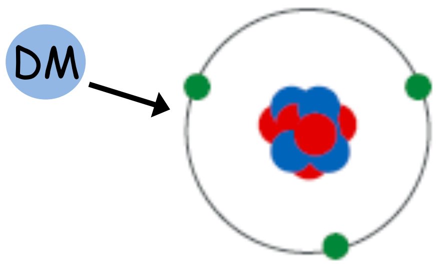
Ge, Si, Diamond, SiC: ~eV

$$m_{\rm DM} \gtrsim \text{MeV}$$

Essig , Mardon, Volansky, 2012
Graham, Kaplan, Rajendran, Walters, 2012
Kurinsky, Yu, **YH**, Blas, 2019
Griffin, **YH,** et al, 2020

Ex. #1: First ideas

Atomic ionization

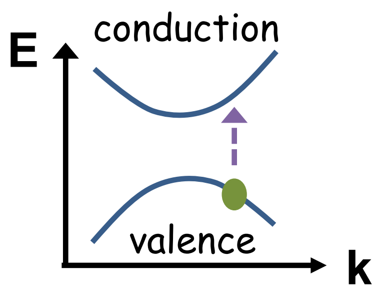


Xenon10/100/1T

$$m_{\rm DM} \gtrsim 10\ {\rm MeV}$$

Essig et al 2012 | Xenon100 2016 | Xenon1T 2020

Semiconductors



SuperCDMS, SENSEI

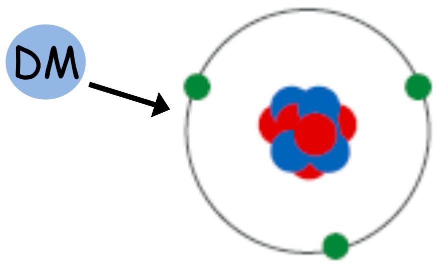
$$m_{\rm DM} \gtrsim {\rm MeV}$$

SuperCDMS 2020 | SENSEI 2020

Are being experimentally realized

Ex. #1: First ideas

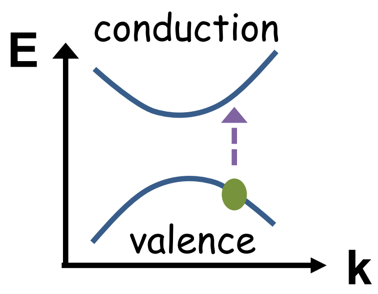
Atomic ionization



Xenon10/100/1T

$m_{\rm DM} \gtrsim 10~{\rm MeV}$

Semiconductors



SuperCDMS, SENSEI

$m_{\rm DM} \gtrsim {\rm MeV}$

Smaller masses?

Ex. #2: Superconductors

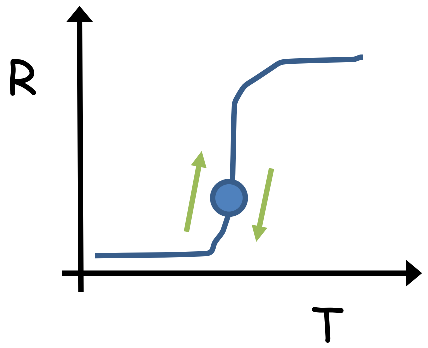
- Ground state = Cooper pairs;
  Binding energy (gap) $\sim \mathrm{meV}$ ⟹ $m_{\mathrm{DM}} \sim \mathrm{keV}$
- <u>The idea:</u>
  DM scatters with Cooper pairs, deposits enough energy, breaks Cooper pairs → detect

Excitations

Excitation concentration philosophy	Sensor + target philosophy
YH, Zhao, Zurek, PRL 2015 **YH**, Pyle, Zhao, Zurek, JHEP 2015	**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019

Ex. #2A: Superconductors

Ram an electron, create excitations which random walk until collected by e.g. a Transition Edge Sensor (TES)



Heat calorimeter

TESs used to
detect microwaves and x-rays
in astro applications
(e.g. ACT, SPT, SuperCDMS)

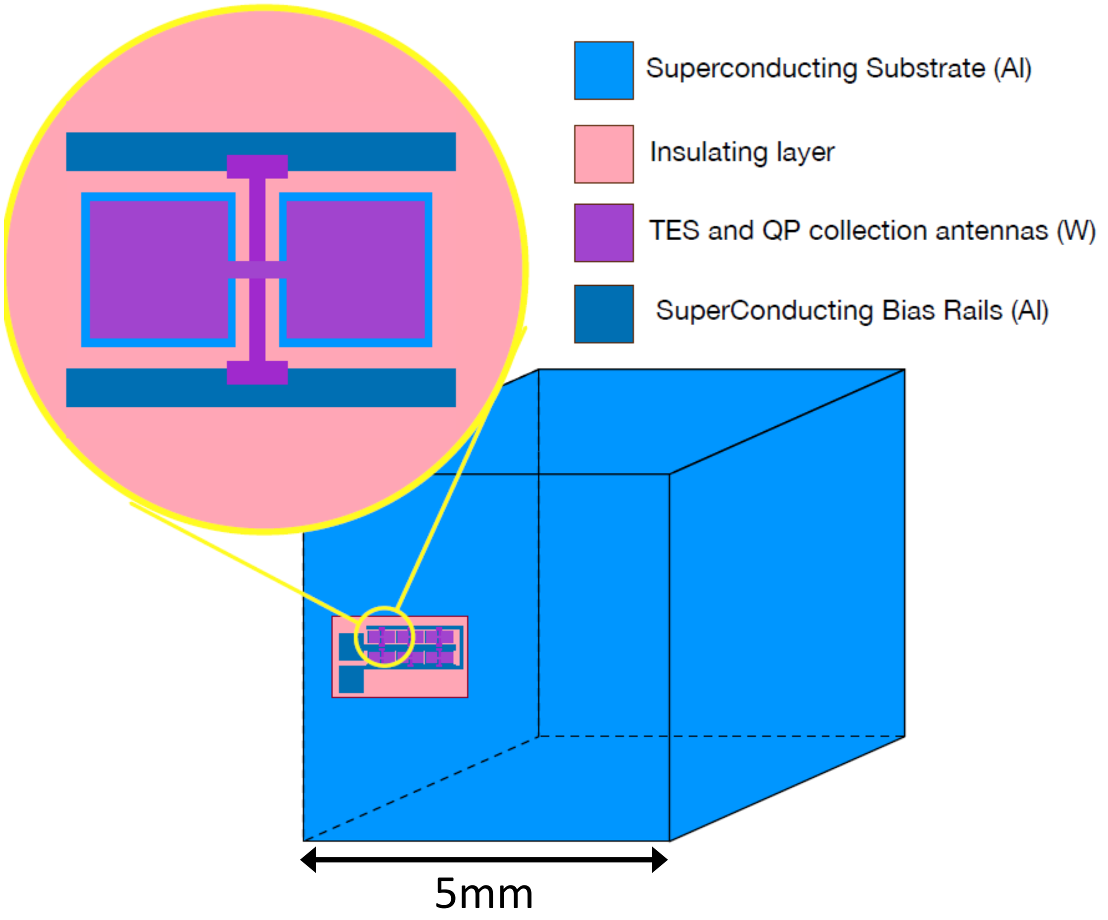
YH, Zhao, Zurek, PRL 2015; **YH**, Pyle, Zhao, Zurek, JHEP 2015

Ex. #2A: Superconductors

Excitation concentration

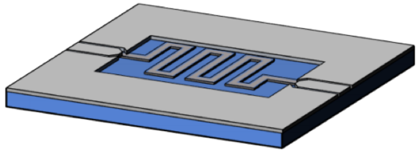
Absorber →
Collection fins→
sensitive bolometer

(& Multiplex)



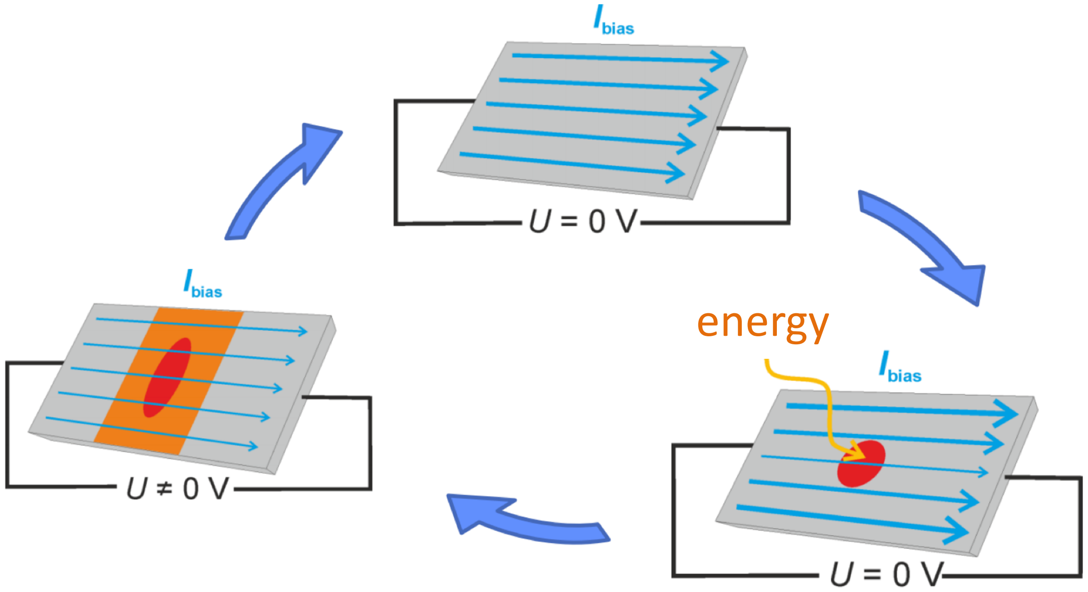
Ex. #2B: Superconductors

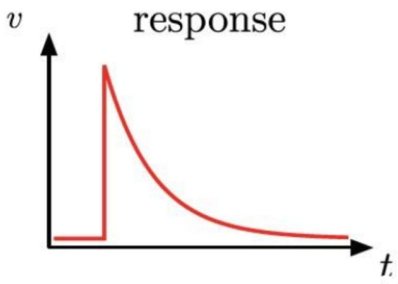
- Superconducting Nanowire Single Photon Detectors (SNSPDs)



Broadly used in quantum information science

- Ram an electron, create a hotspot, electrons diffuse away, resistive region across the nanowire → voltage pulse

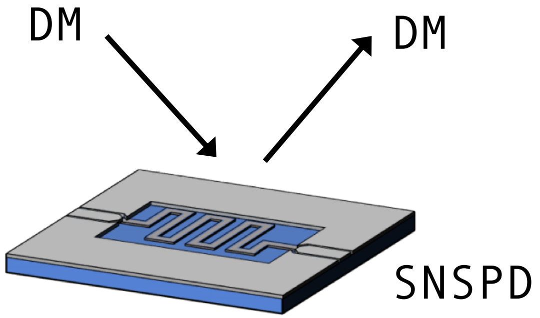




YH, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019

Ex. #2B: Superconductors

Use as simultaneous target + sensor (& multiplex)

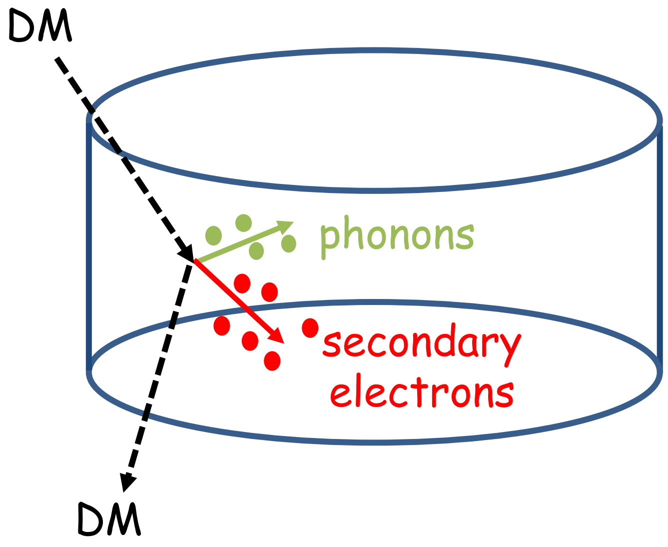


[Existing prototype]

YH, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019

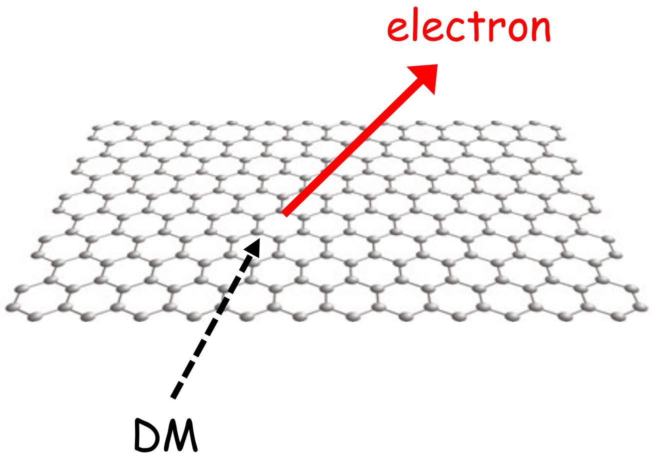
Directional Info?

Lose directional information
if detecting secondaries



**e.g. semiconductors,
bulk superconductors**

Retain directional information
if observe primary!

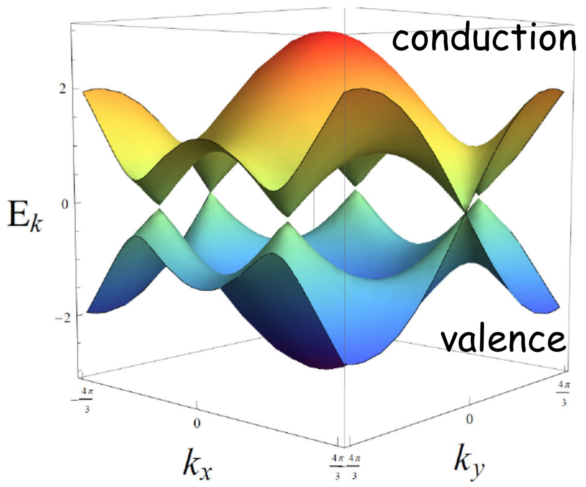


**2D targets;
graphene (& SNSPDs)**

But see **YH**, Kramer, Kurinsky, Lehmann 2109.04473

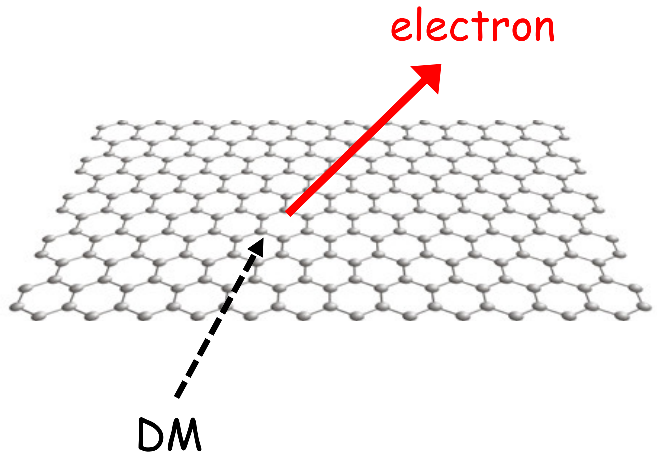
Ex. #3: Graphene

Dark matter scatters with valence electrons, deposits enough energy, ejects electron → detect



$$E_{\rm eject} \sim \mathcal{O}(\text{few eV})$$

$$\Rightarrow \quad m_{\rm DM} \gtrsim \text{MeV}$$



Eject and detect philosophy

YH, Kahn, Lisanti, Tully, Zurek, 2017

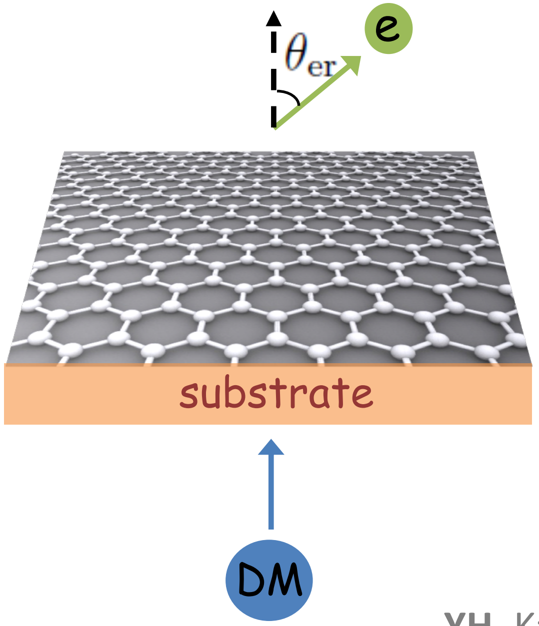
Ex. #3: Graphene

Electron follows incoming dark matter direction.

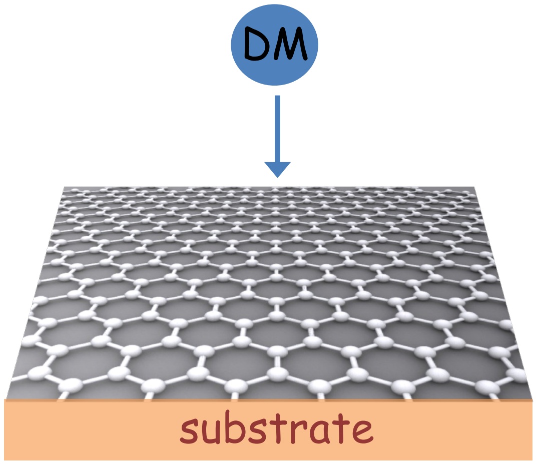
Naturally gives forward/backward discrimination

(separates signal from background)

Electron detected



electron not detected

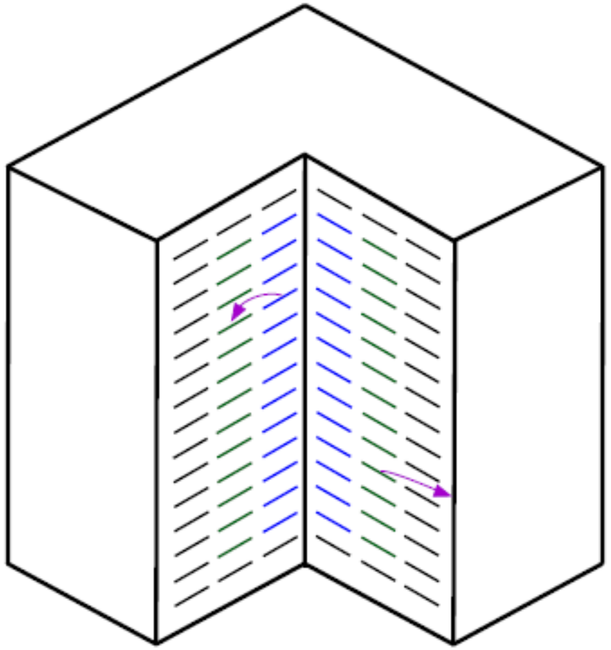


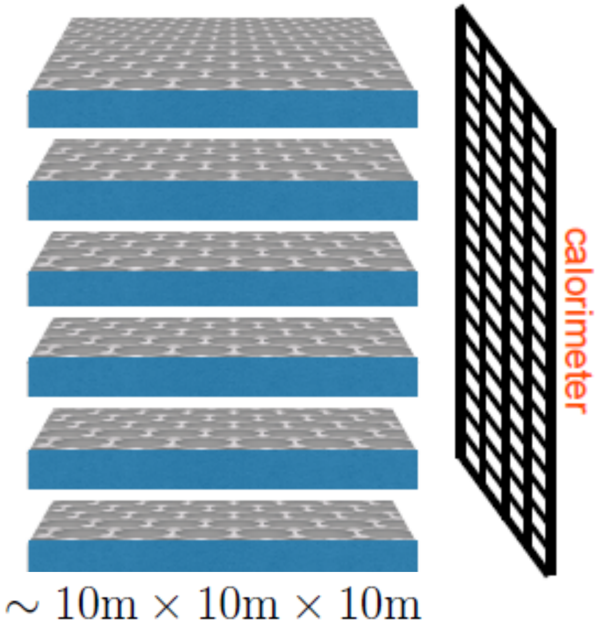
12 hours later

YH, Kahn, Lisanti, Tully, Zurek, 2017

Ex. #3: Design Concept

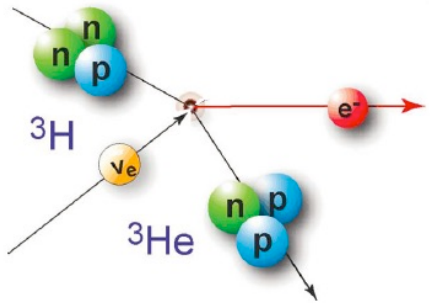
- ~0.5 kg graphene = area of Jerusalem old city = billions of cm^2 crystals
- Compact geometry: large mass via many stacks





Implement in PTOLEMY

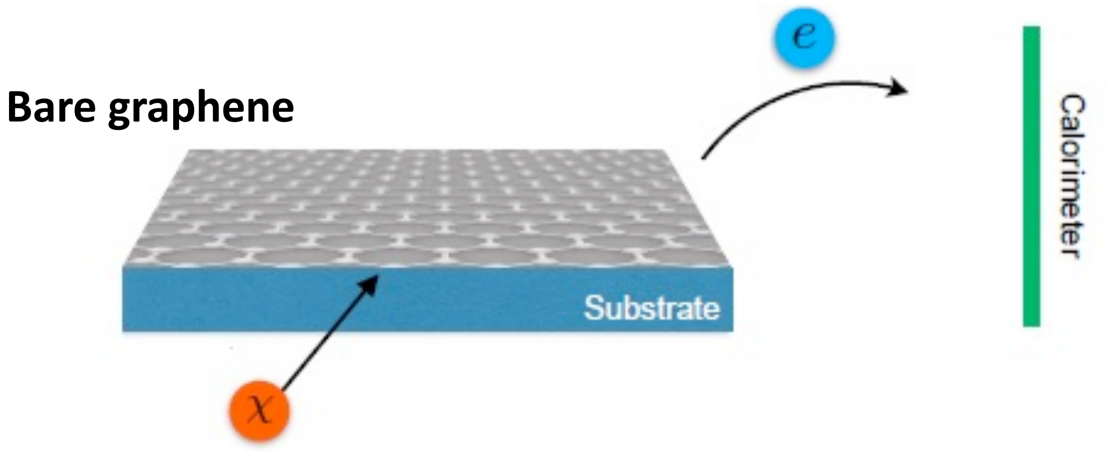
Experiment to detect relic neutrinos via capture on tritium.



Betts et al, 2013

Will use tritiated graphene (~0.5 kg).

Borrow pure (un-tritiated) graphene for dark matter experiment!



PTOLEMY World-Wide Collaboration

PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter

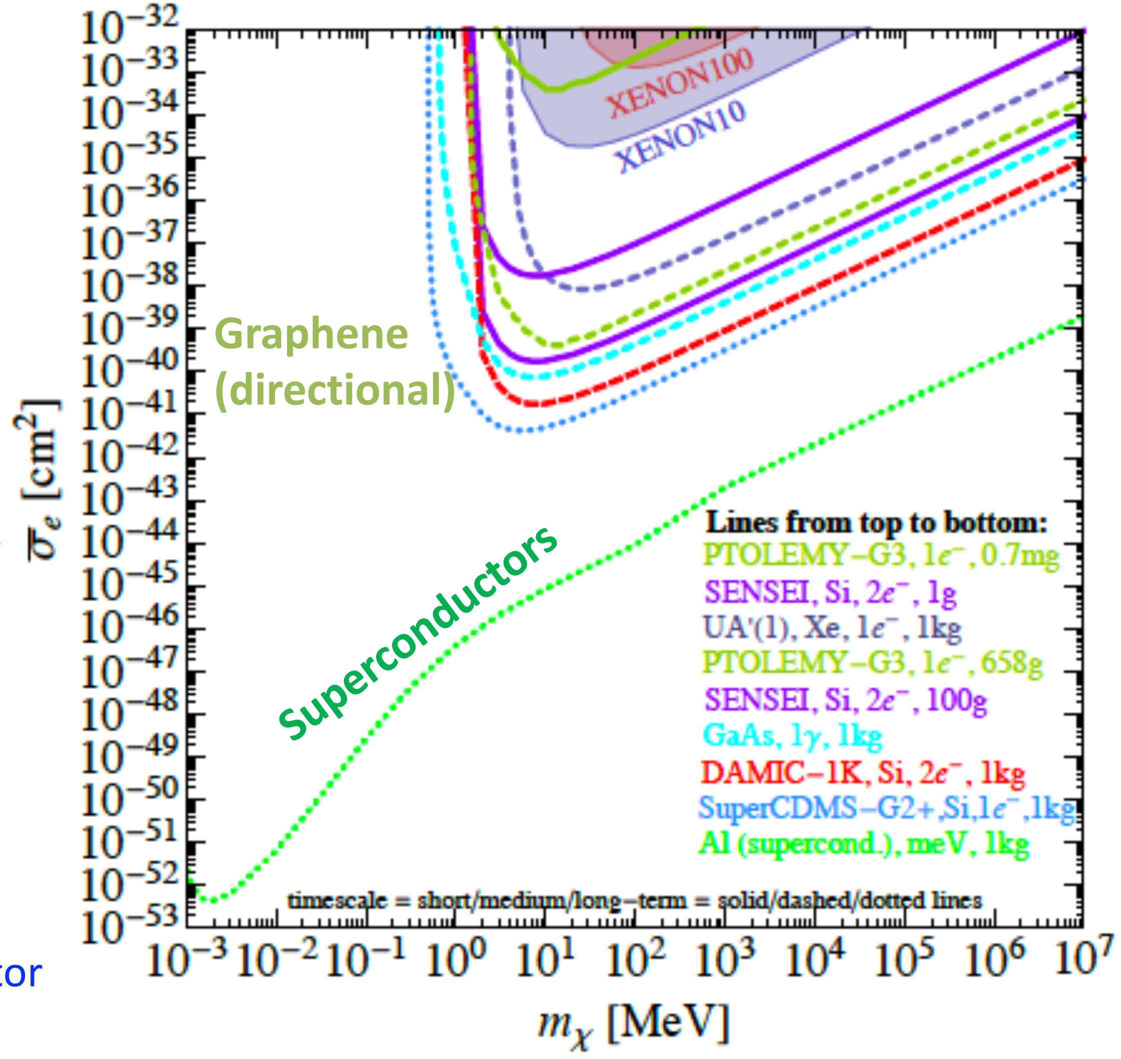
Compute Event Rate

[Events/unit time/unit mass]

$$\text{Rate} \propto \underbrace{\frac{1}{\rho_{\text{target}}}}_{\text{Target density}} \times \underbrace{\frac{\rho_{\text{DM}}}{m_{\text{DM}}} \times v_{\text{DM}}}_{\text{dark matter flux (astrophysics)}} \times \underbrace{\text{target properties}}_{\text{condensed matter physics}} \times \underbrace{\sigma_{\text{int}}}_{\text{particle physics}}$$

Scattering Reach

DM-electron scattering xsec @ $q = \alpha m_e$ w/ light mediator



[a few events in kg-year exposure]

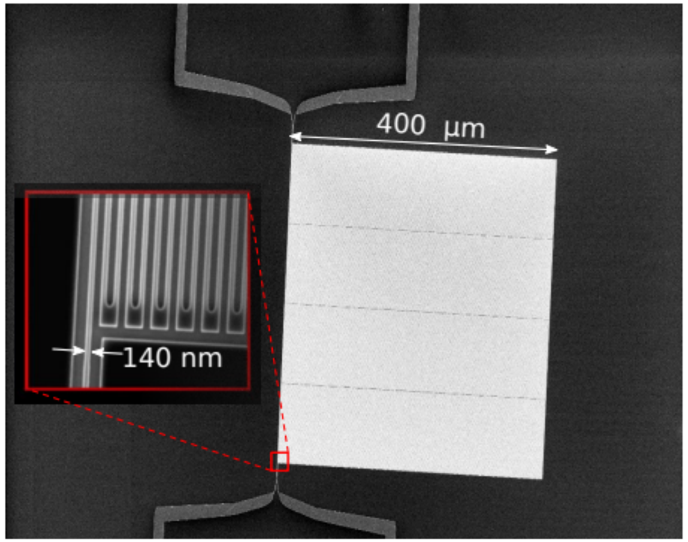
Amazing reach!

Community report, 2017

Existing Prototype Device

WSi SNSPD, 4.3 nanogram, 0.8 eV threshold,

no dark counts in 10000 seconds (~3 hours)

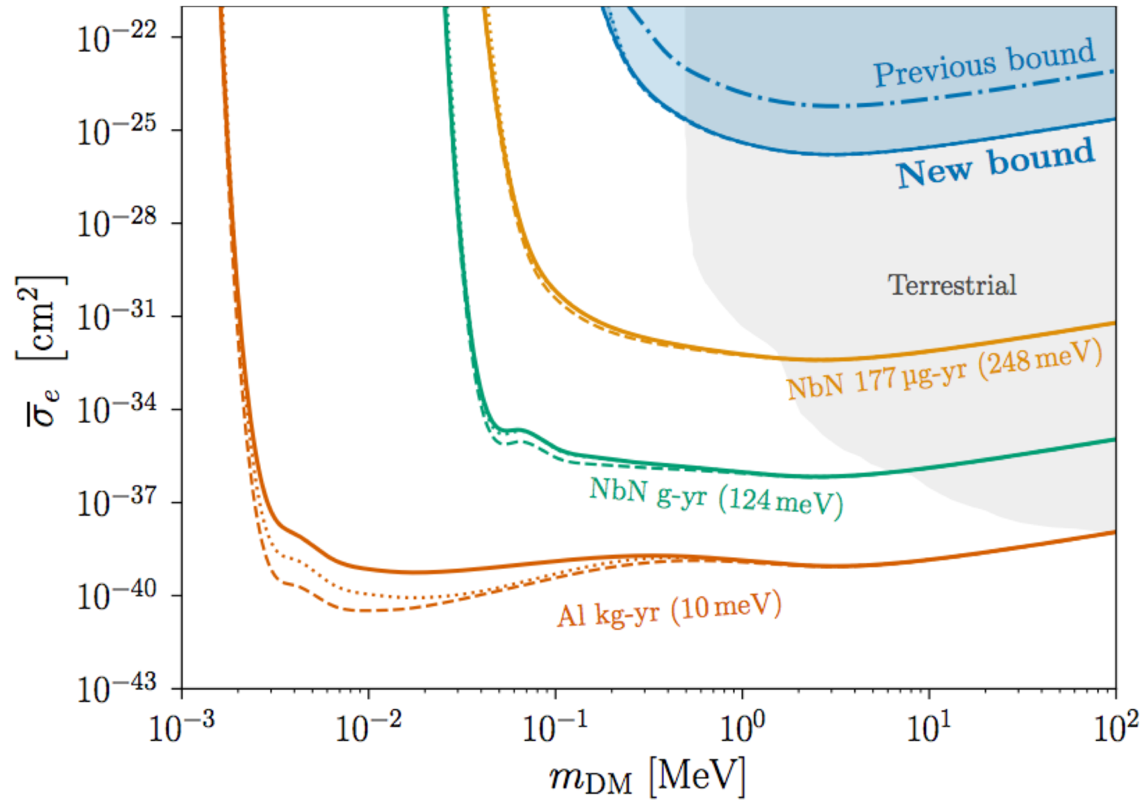


By now have 180 hours of data

YH, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019 + w/ Lehmann, PRD Editor's Choice 2021

Scattering Reach

Colored curves:
Large array, low threshold, low dark count SNSPDs



DM-electron scattering xsec @ $q = \alpha m_e$ w/ light mediator

Non-solid curves: geometry effects

Lasenby, Prabhu 2021

YH, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019 + w/ Lehmann, PRD Editor's Choice 2021

Pushing Thresholds Lower

Single-photon detection in the mid-infrared up to 10 micron wavelength using tungsten silicide superconducting nanowire detectors

V. B. Verma,[1,a)] B. Korzh,[2,b)] A. B. Walter,[2] A. E. Lita,[1] R. M. Briggs,[2] M. Colangelo,[3] Y. Zhai,[1] E. E. Wollman,[2] A. D. Beyer,[2] J. P. Allmaras,[2] B. Bumble,[2] H. Vora,[1] D. Zhu,[3] E. Schmidt,[2] K. K. Berggren,[3] R. P. Mirin,[1] S. W. Nam,[1] and M. D. Shaw[2]
[1)] *National Institute of Standards and Technology, Boulder, CO, USA.*
[2)] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA, USA*
[3)] *Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, USA.*

(Dated: 21 December 2020)

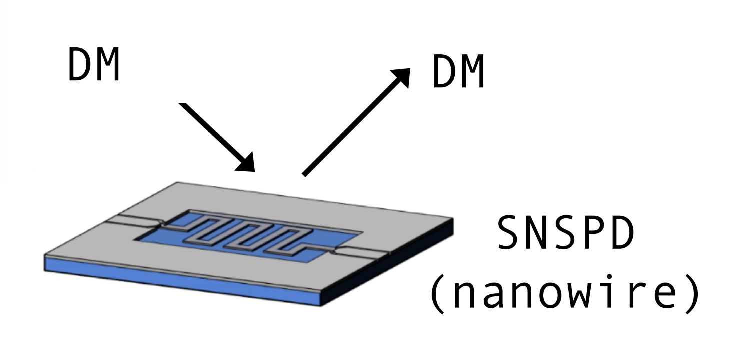
We developed superconducting nanowire single-photon detectors (SNSPDs) based on tungsten silicide (WSi) that show saturated internal detection efficiency up to a wavelength of 10 µm. These detectors are promising for applications in the mid-infrared requiring ultra-high gain stability, low dark counts, and high efficiency such as chemical sensing, LIDAR, dark matter searches and exoplanet spectroscopy.

Demonstrated WSi SNSPDs w/ 125meV energy threshold

arXiv:2012.09979

Quantum sensoR cryOgeniC search fOr Dark matter In Light mass rangE

Crocodile



Newly forming interdisciplinary collaboration
(particle theory | condensed matter | DM experiment | quantum sensing)

Massachusetts Institute of Technology

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

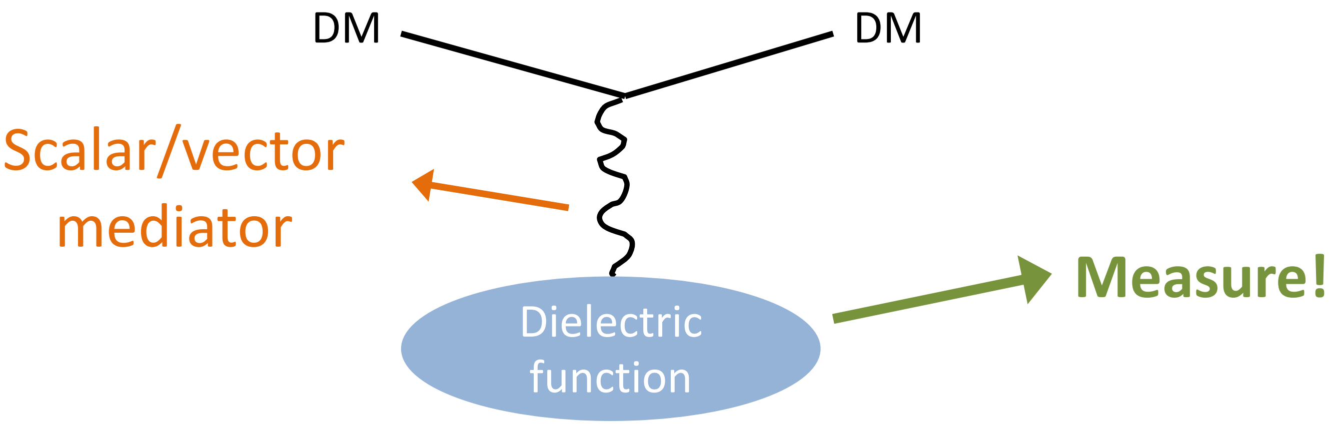
Universität Zürich UZH

New Formalism

DM-electron scattering in any material

is determined by the dielectric function.

For any DM interaction that couples to electron density



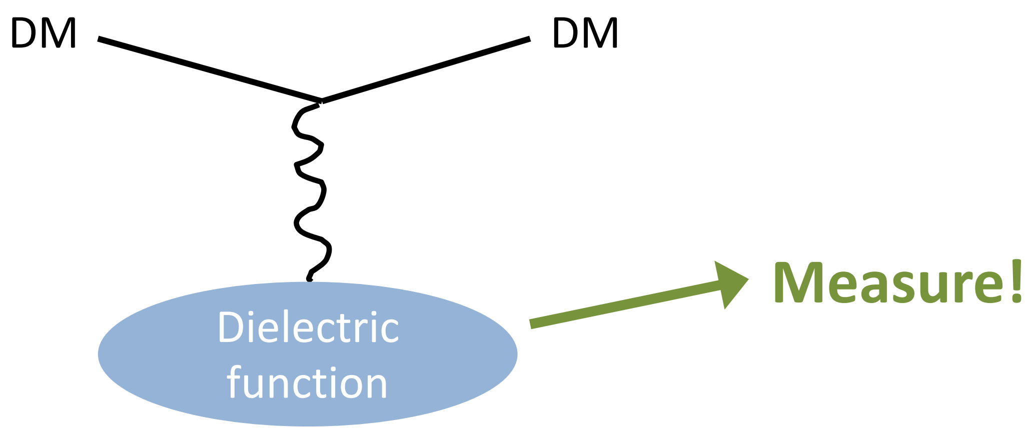
YH, Kahn, Kurinsky, Lehmann, Yu, Berggren, PRL 2021

[See also arXiv: 2101.08275]

New Formalism

Automatically includes many-body effects of the material

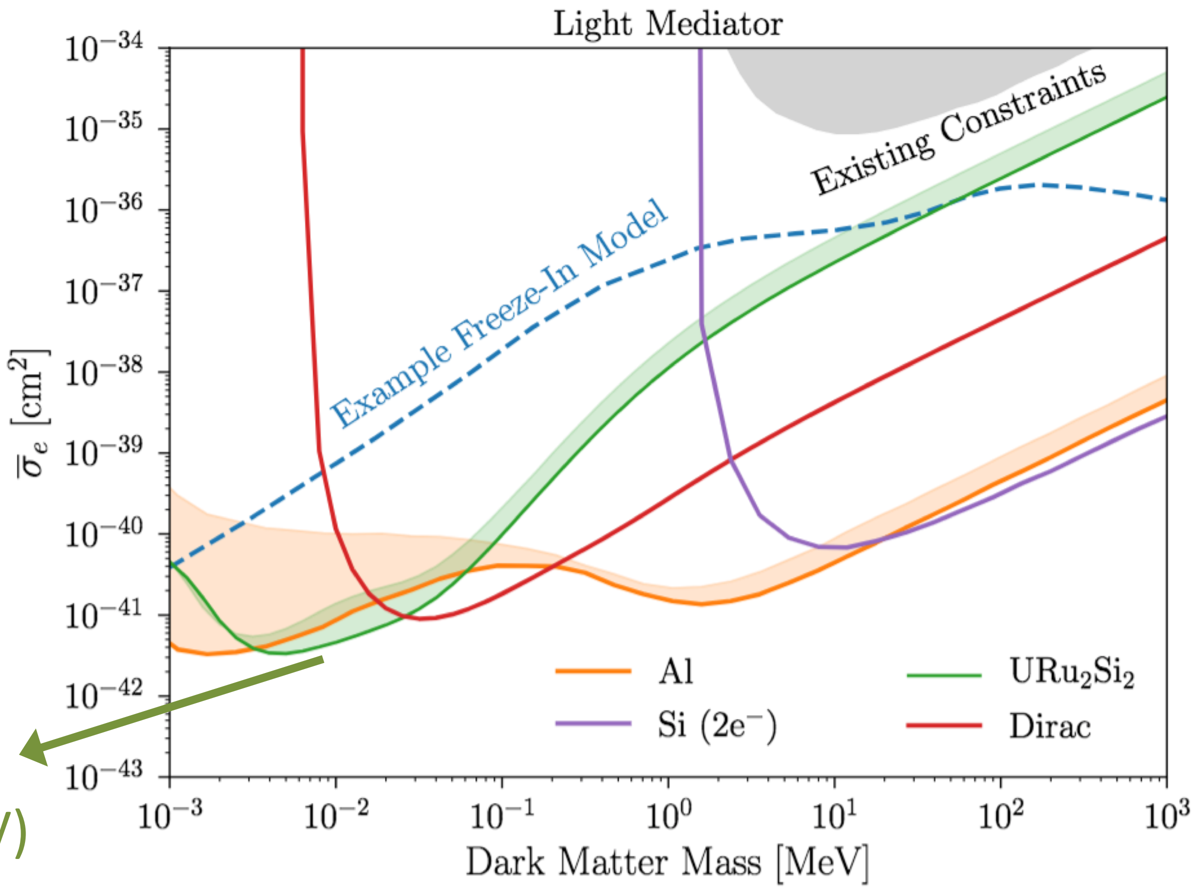
Collective modes (e.g. plasmon),
not just single particle excitations



Identify promising materials for DM detection

YH, Kahn, Kurinsky, Lehmann, Yu, Berggren, PRL 2021

Ex. #4: Heavy Fermions



Plasmon
@ O(10meV)

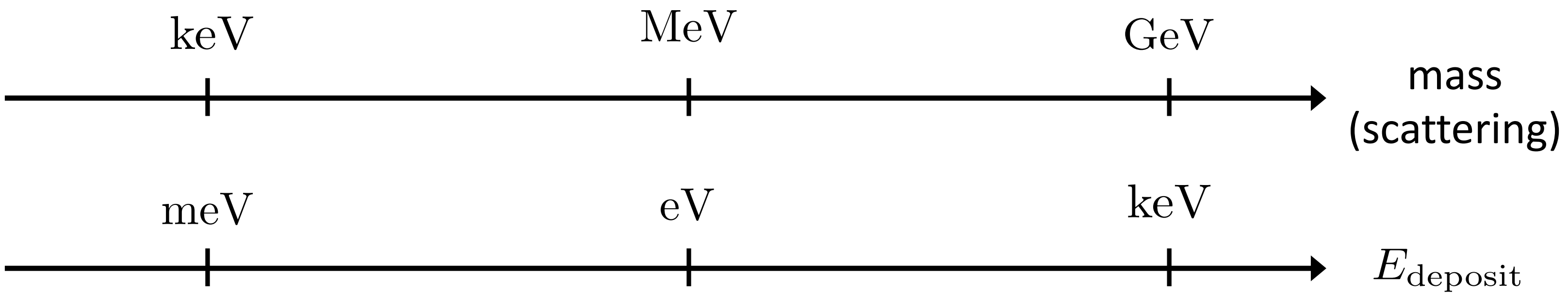
Identify promising materials for DM detection

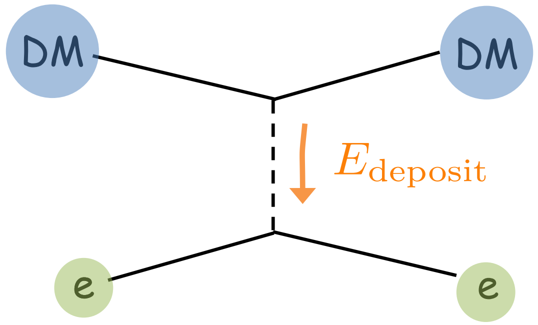
YH, Kahn, Kurinsky, Lehmann, Yu, Berggren, PRL 2021

Any given target material can go even further.

Absorption vs. Scattering

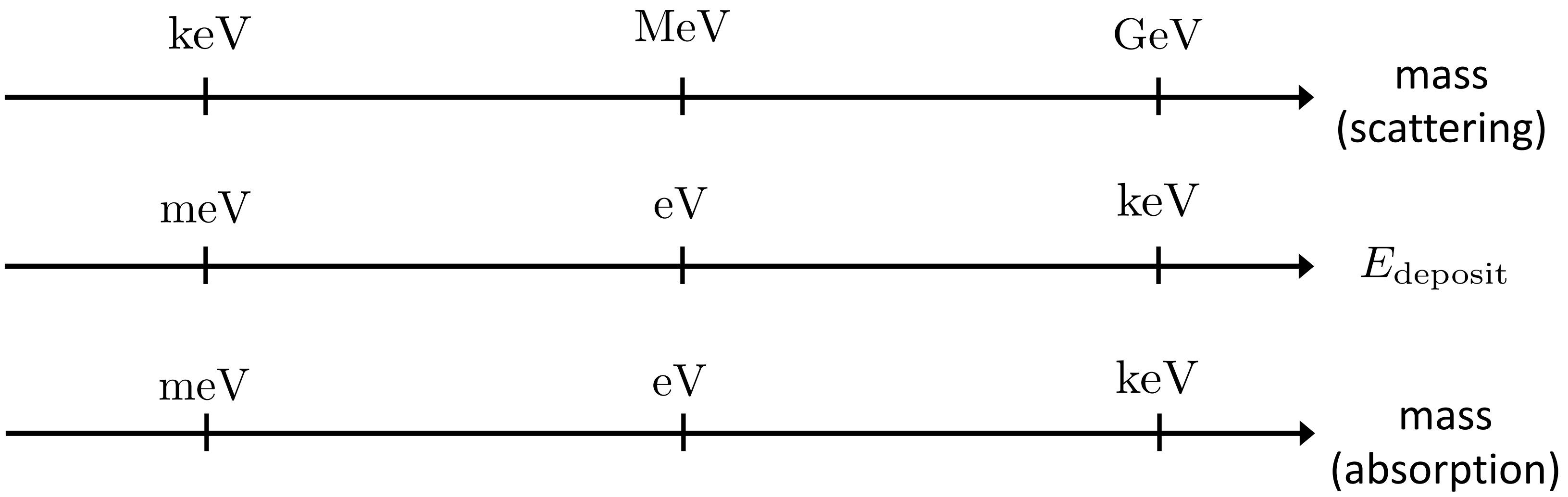
Dark matter scattering: kinetic energy $m_{\rm DM} v^2 \sim 10^{-6} m_{\rm DM}$

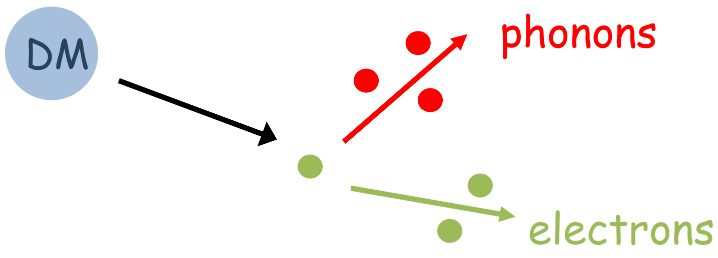




Absorption vs. Scattering

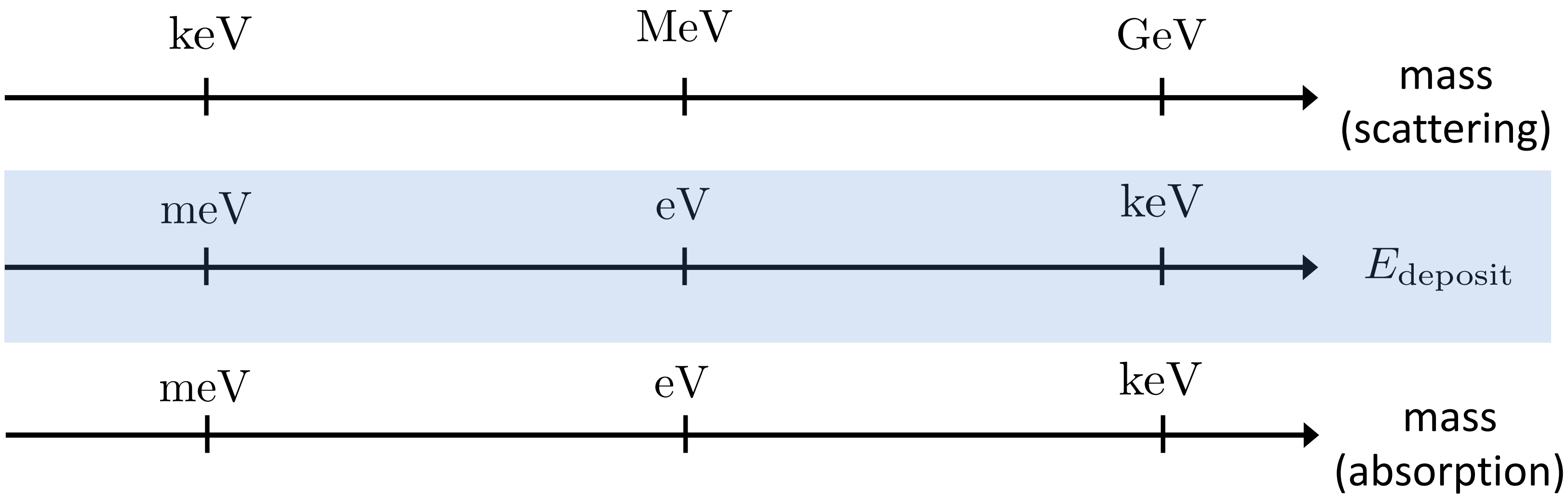
Dark matter absorption: all the mass-energy m_{DM}





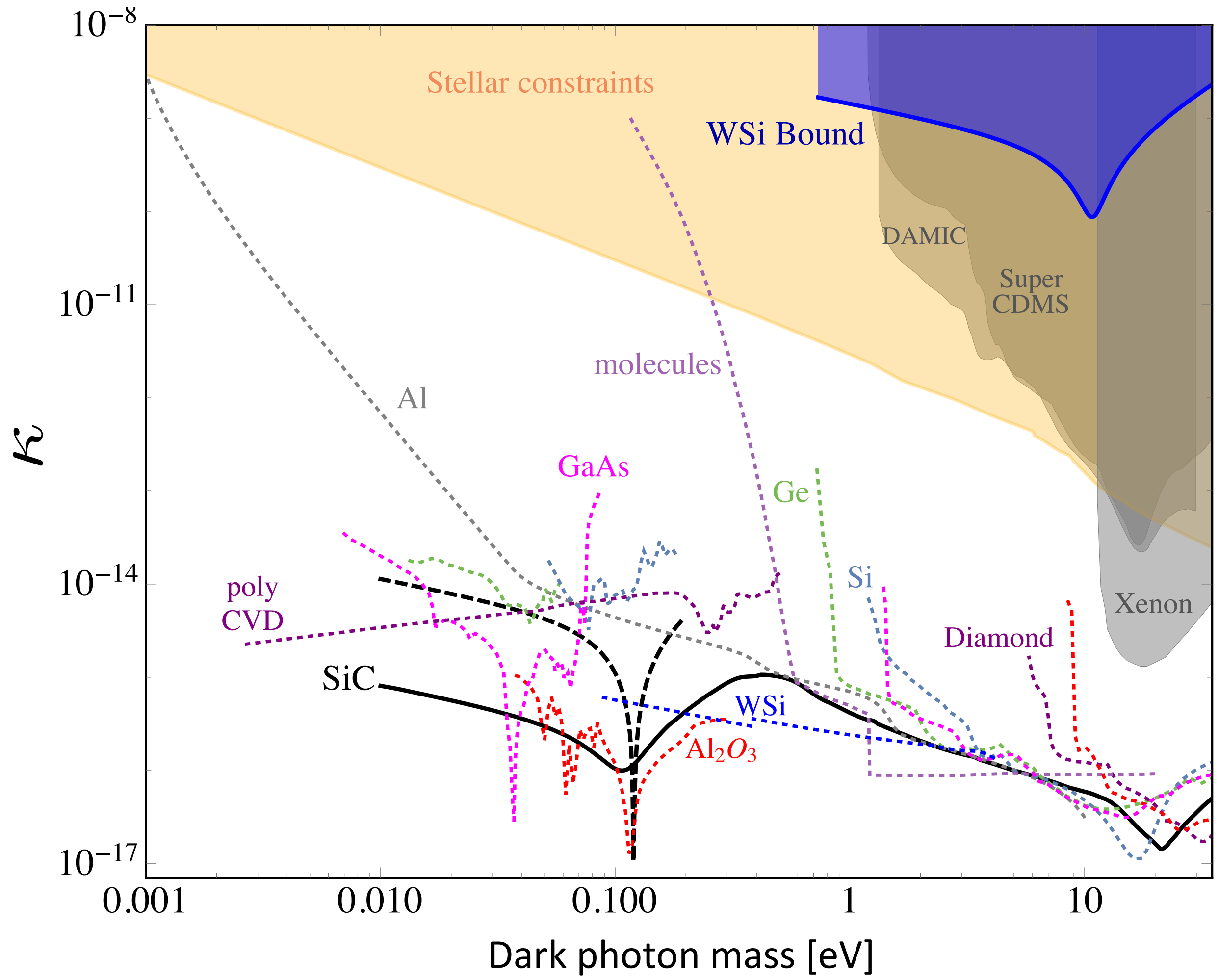
Absorption vs. Scattering

Two (mass ranges) for the price of one :-)



Absorption Reach

[projections for kg-year]



New bound:
WSi SNSPD
prototype
4.3ng in 180
hours

Kurinsky, Yu, **YH,** Cabrera, PRD 2019
Griffin, **YH**, et al, 2020
YH et al, 2021

Wish List

- Single/rare-event sensitivity
- Build up to large target mass: many small units ok & multiplex
- Target can/cannot be the sensitive sensor itself
- Small gap and low thresholds
- Low dark counts ideally
- Directionality a major plus
- Data

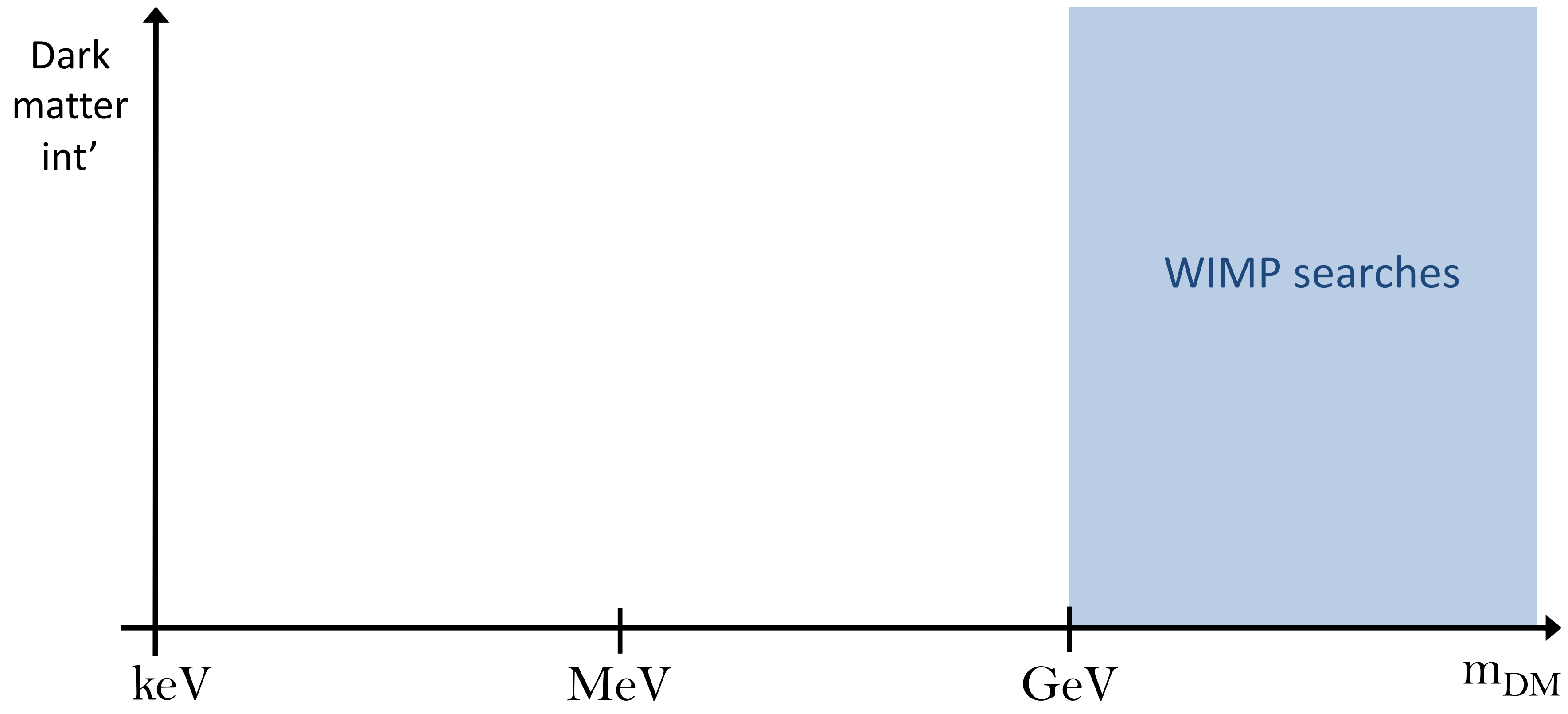
Think detection philosophy & target & sensor

Take aways

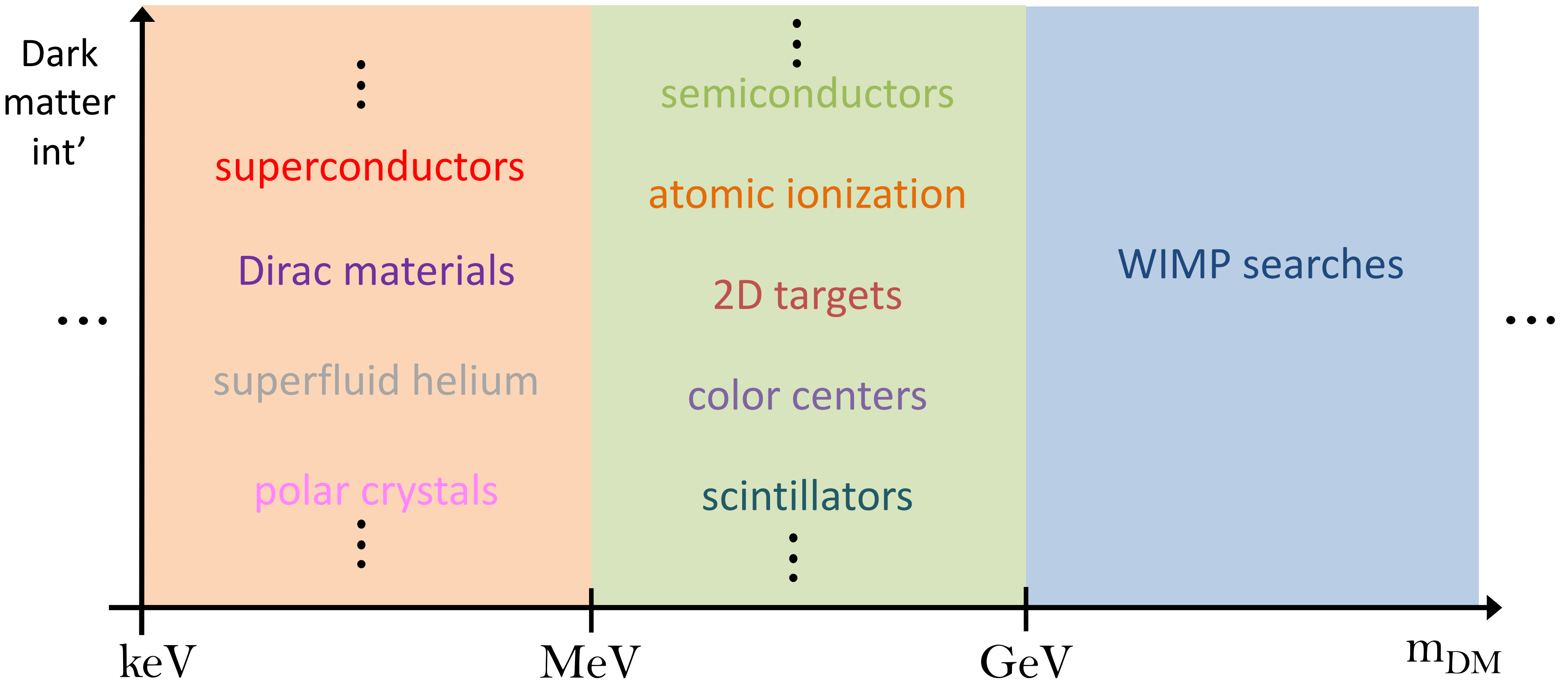
Outlook

- Lots of activity for light dark matter
- Theory ←→ experiment
- By no means exhausted…
- It’s ok for an idea to seem crazy at first
- The best ideas might still be ahead

Prospects

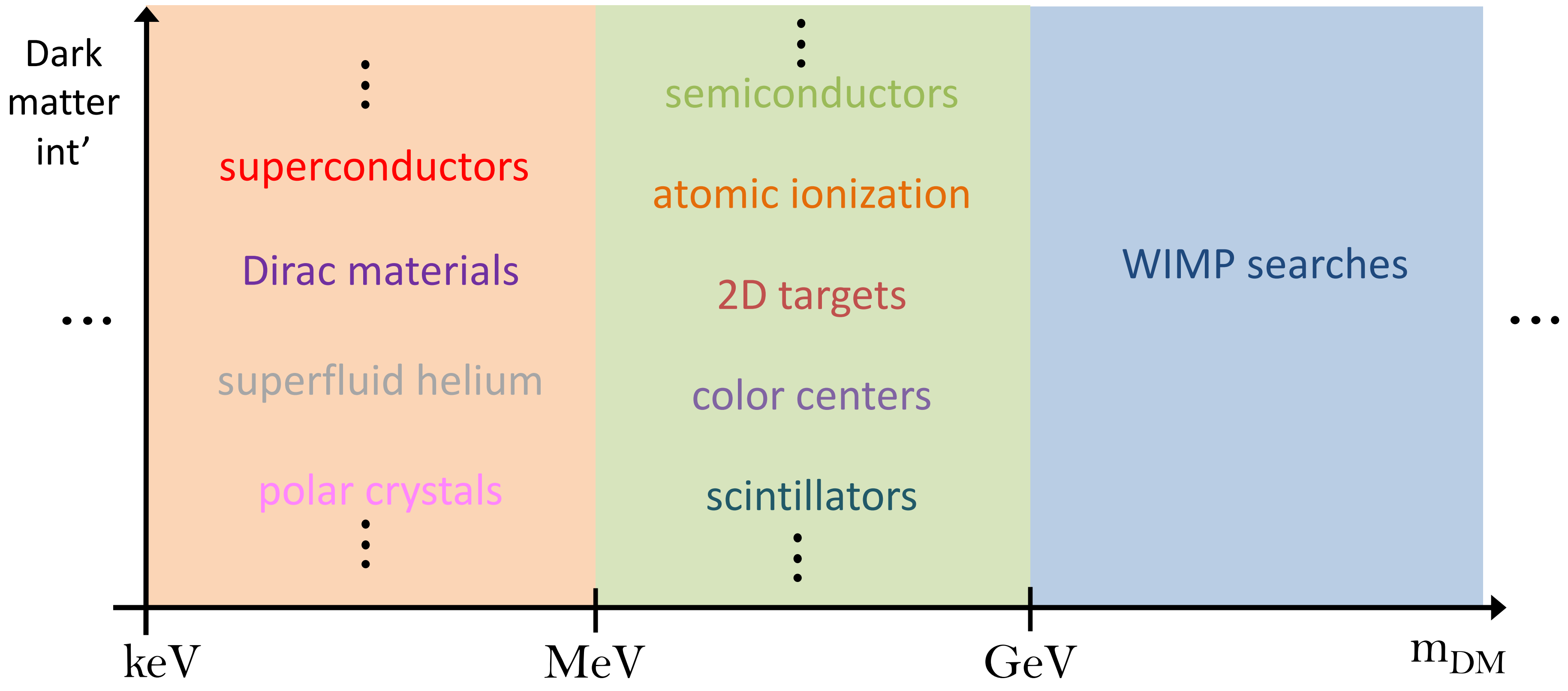


Prospects



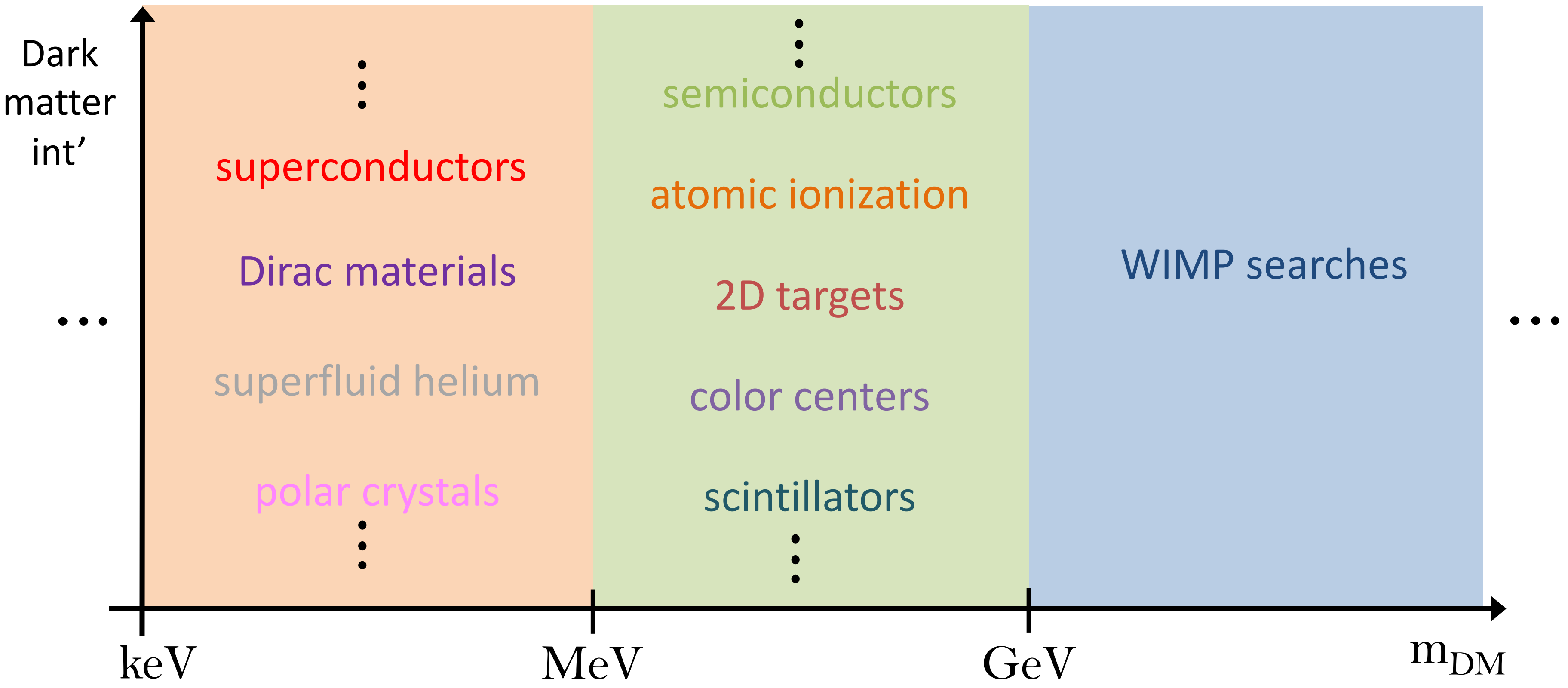
Burgeoning field in recent years

Prospects



Experimentalists are going after these ideas now!

Prospects



Interface particle physics/condensed matter physics/
quantum information science/precision measurements

If you have any (crazy) new ideas,

please be in touch :-)

Thanks!