The Theory Landscape of
Dark Matter

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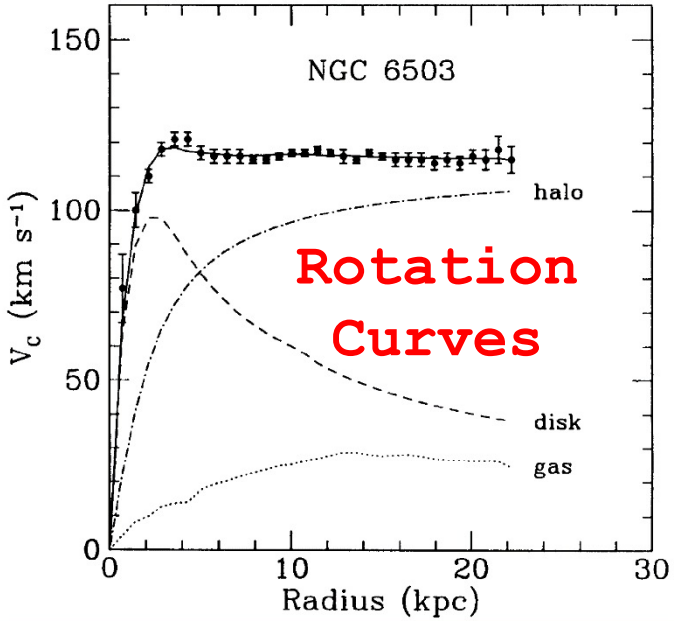
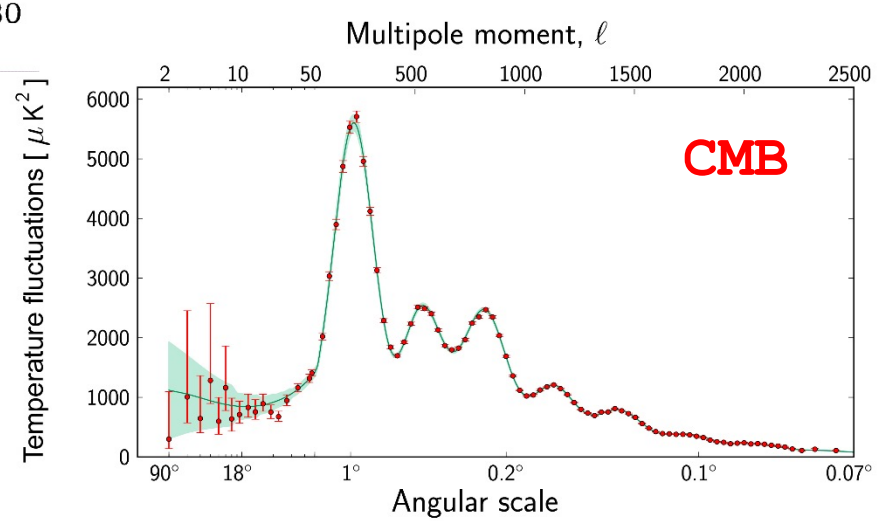
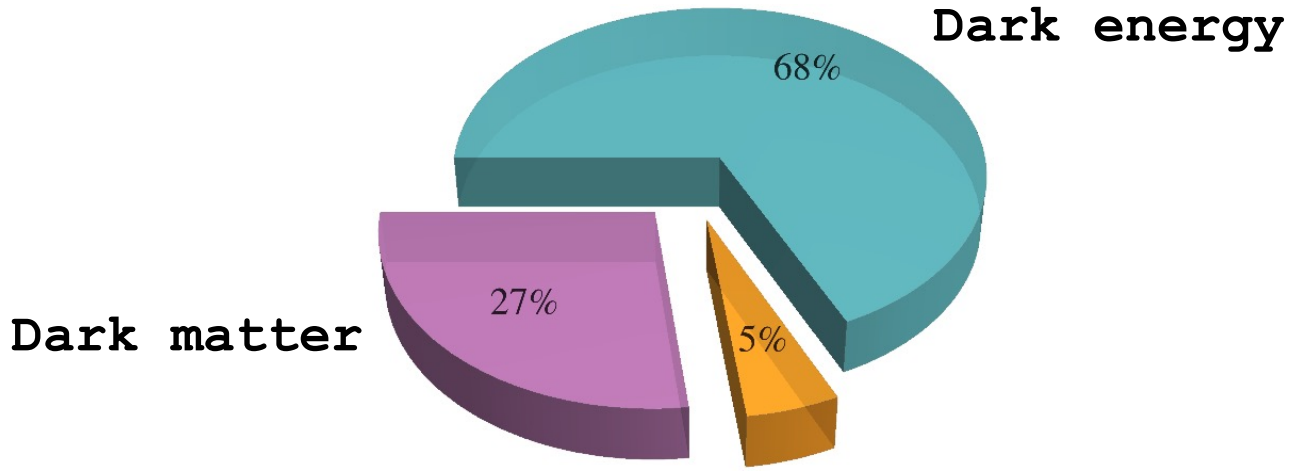
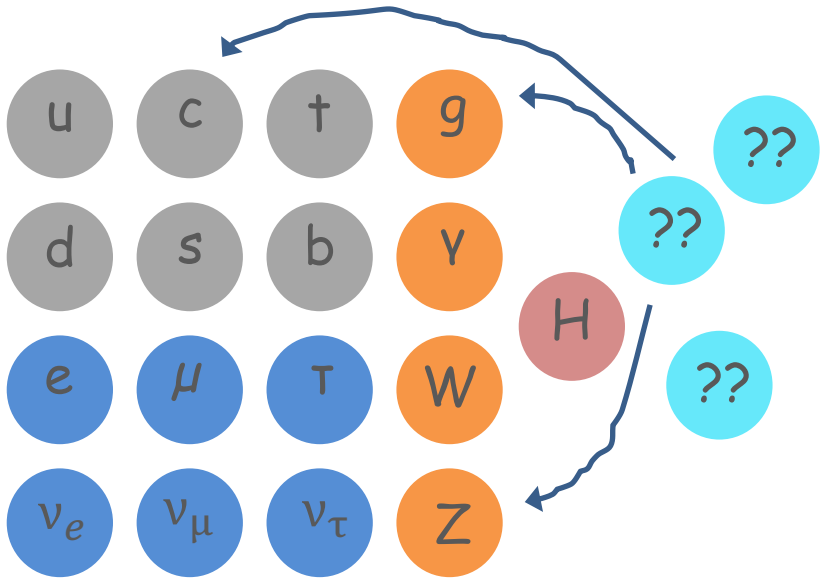
Evidence for Dark Matter





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

Past 40 years

WIMP, glorious WIMP*

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

The WIMP Miracle

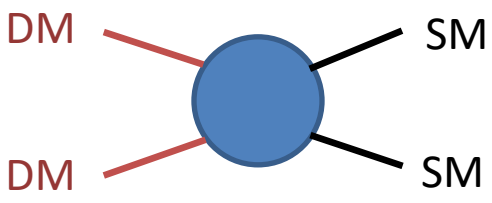
Correct thermal relic abundance:

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

For weak coupling, weak scale emerges.

Weakly Interacting Massive Particle (WIMP)

The dominant paradigm for 40+ years.

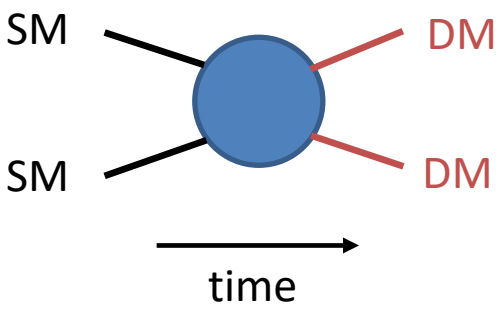


annihilation

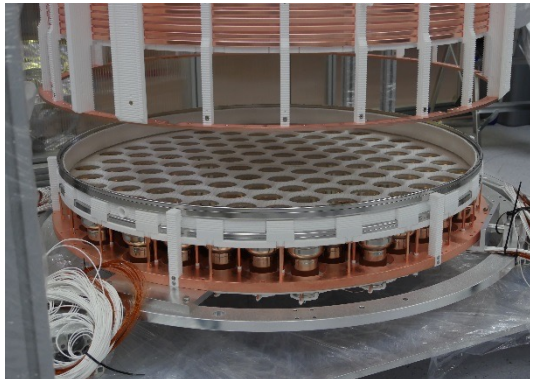
$$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2}$$

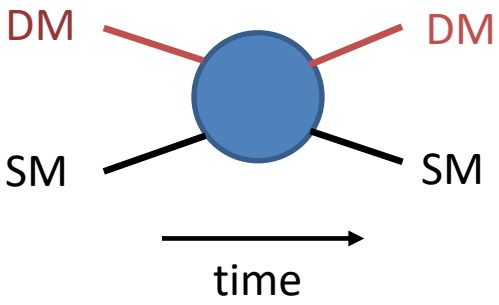
Searching for WIMPs

Direct production

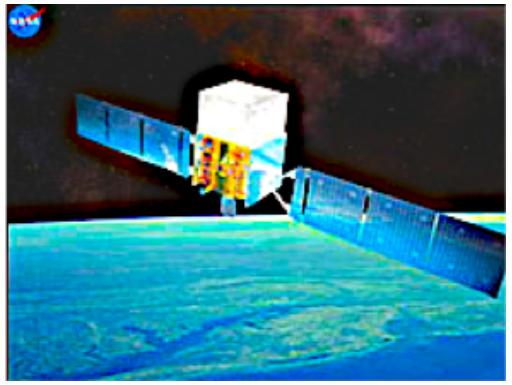


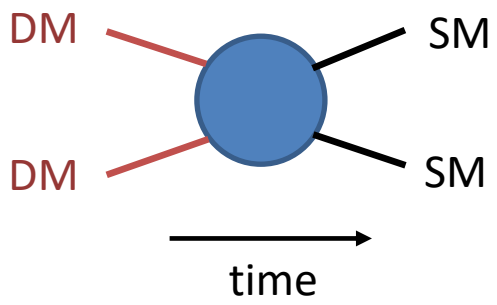
Direct detection





Indirect detection

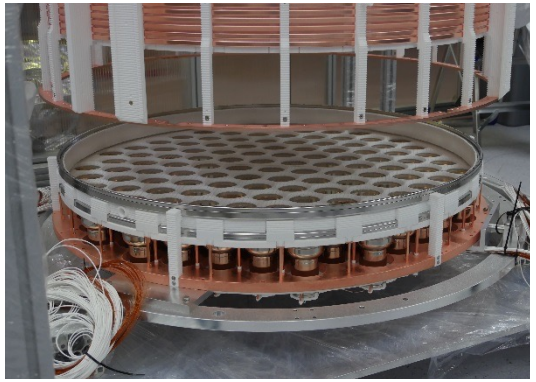




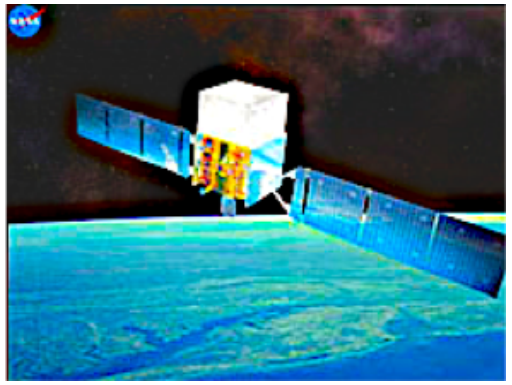
Searching for WIMPs

Direct production

Direct detection



Indirect detection

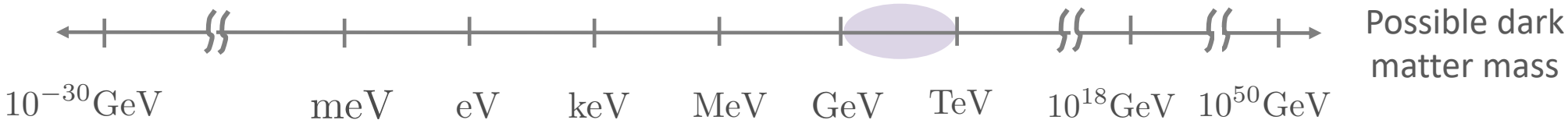


Experiments getting increasingly sensitive

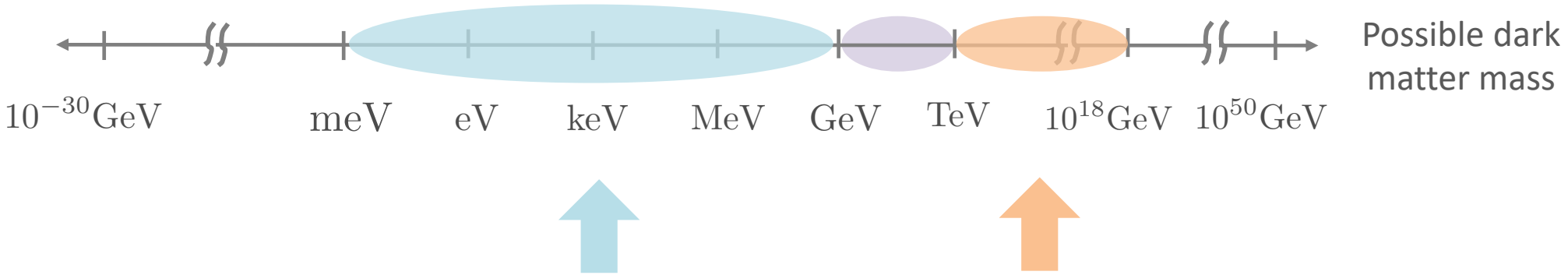
Haven’t yet detected dark matter

Great opportunity for new ideas.

Beyond the WIMP



Beyond the WIMP



New Frontiers: Light Dark Matter (+Heavy)
Theory + Experiment

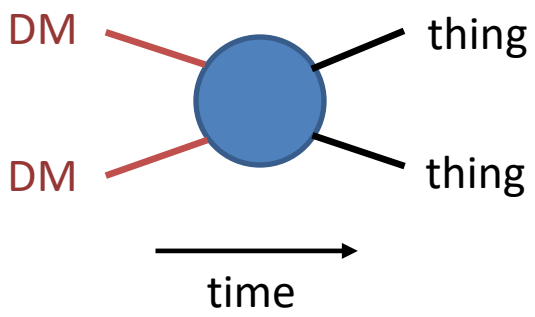
New Theory Ideas

- ……
- 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
- Zombie dark matter — Kramer, Kuflik, Levi, Outmezguine, Ruderman, 2021
- Chain dark matter — Kim, Kuflik, 2019 | Frumkin, Kuflik, Lavie, Silverwater, PRL 2021
- INDY dark matter — Frumkin, **YH**, Kuflik, Murayama, PRL 2022
- ……

… Are abundant

By no means a comprehensive list

Ex. #1: Weakly coupled 2 → 2

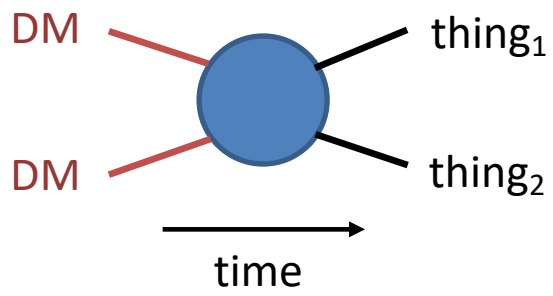


$$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2} \qquad \alpha \ll 1$$

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

Pospelov, Ritz, Voloshin 2007 | Feng, Kumar 2008

Ex. #2: Forbidden Channels



$$2m_{\rm DM} < m_{\rm thing_1} + m_{\rm thing_2}$$

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

freezeout temp'

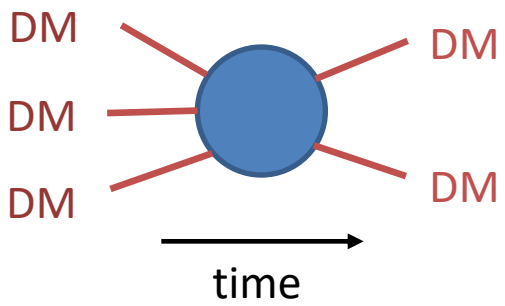
mass difference

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?



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

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

3 → 2 self-annihilations

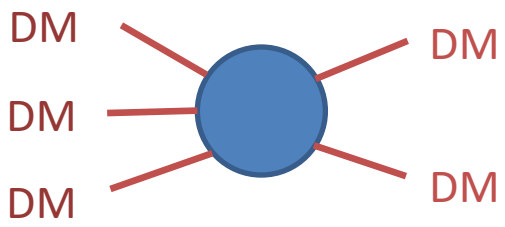
For strong coupling, the strong scale emerges.

SIMP = Strongly (self) Interacting Massive Particle

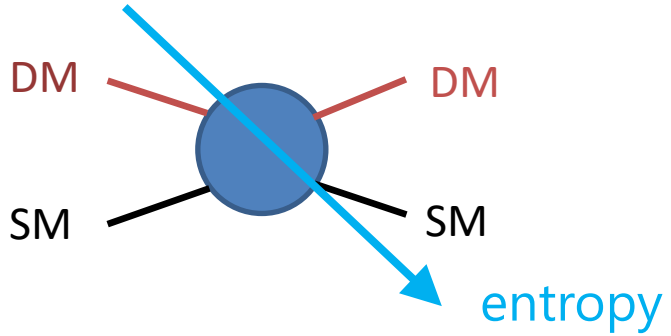
Carlson, Hall, Machacek, 1992 | **YH**, Kuflik, Volansky, Wacker, 2014

Ex. #3: SIMPs

Pumps heat into the system: need to shed the heat



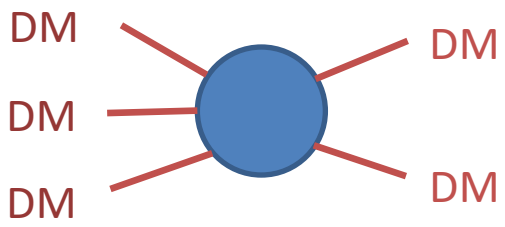
3 → 2 self-annihilations



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

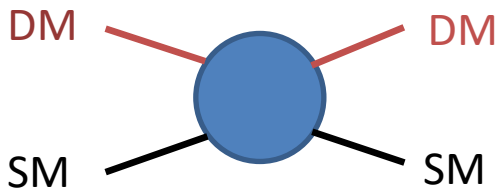
YH, Kuflik, Volansky, Wacker, 2014

Ex. #3: SIMPs



decouples 1st

Determines
DM relic density

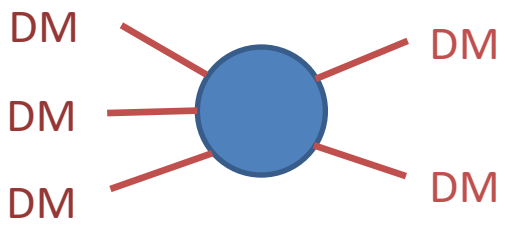


decouples 2nd

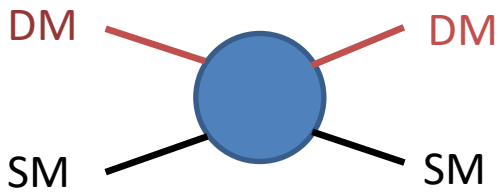
What if the order was reversed?

Ex. #4: ELDERs

ELastically DEcoupling Relic (ELDER)



decouples 2nd



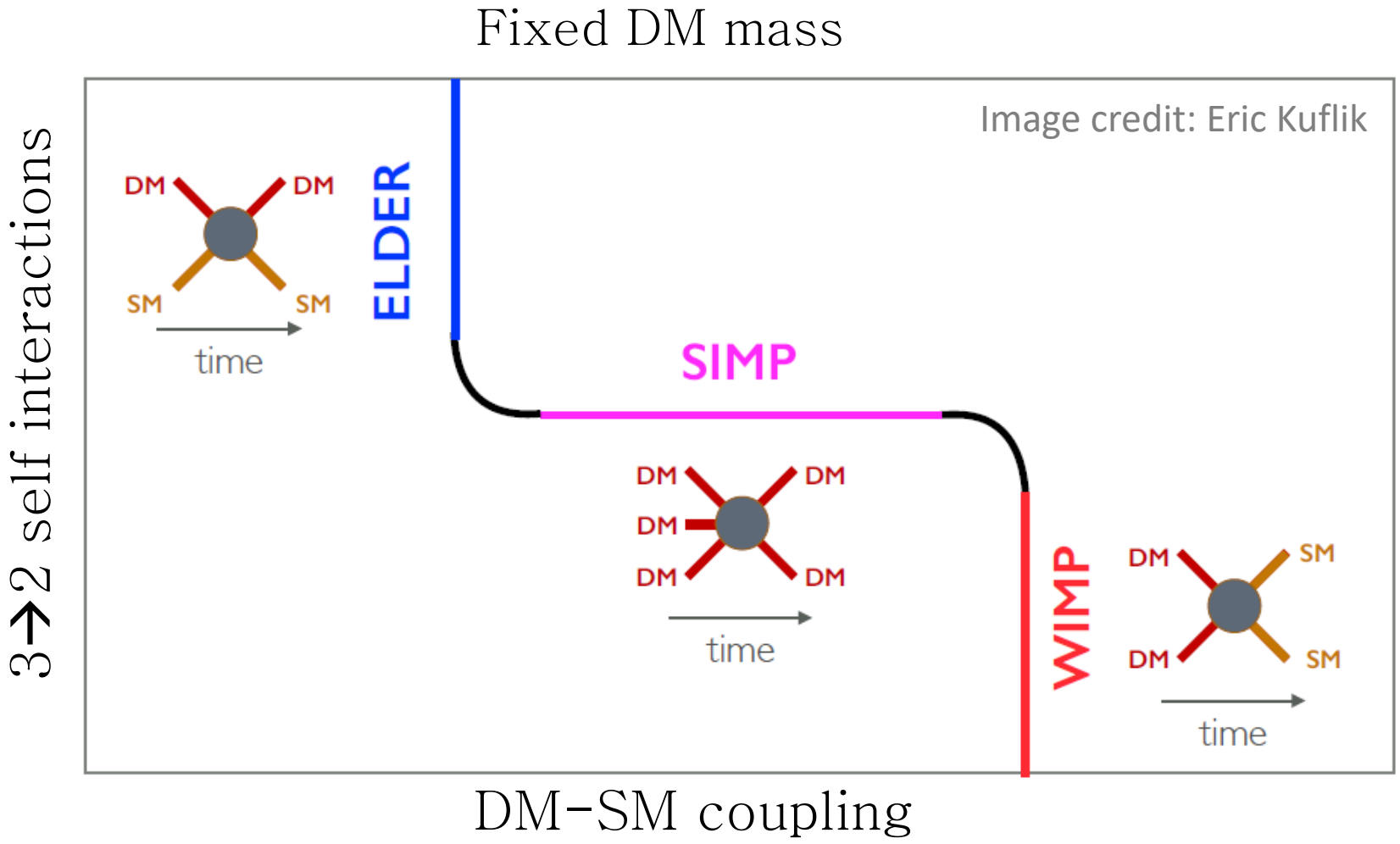
decouples 1st

Determines
DM relic density

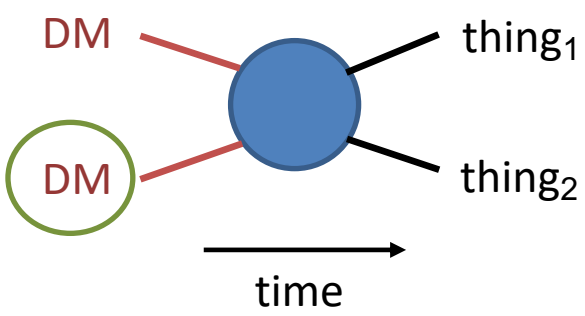
$$\Omega_{\rm DM} \propto e^{-\langle \sigma v \rangle_{\rm el}\#}$$

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

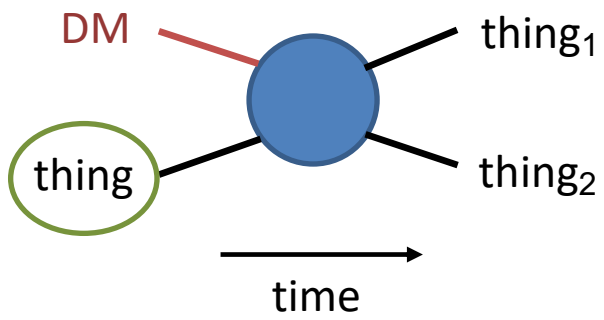
WIMP/SIMP/ELDER



Heavy?



vs.



$$\text{Rate} \propto (n_{\text{DM}} \times \text{cross section})$$

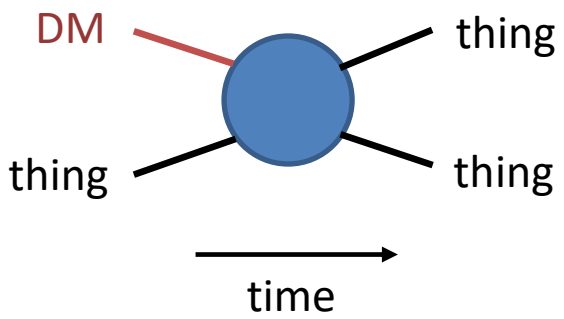
$$\text{Rate} \propto (n_{\text{thing}} \times \text{cross section})$$

If thing = light, less Boltzmann suppressed!

Can reach heavier dark matter masses

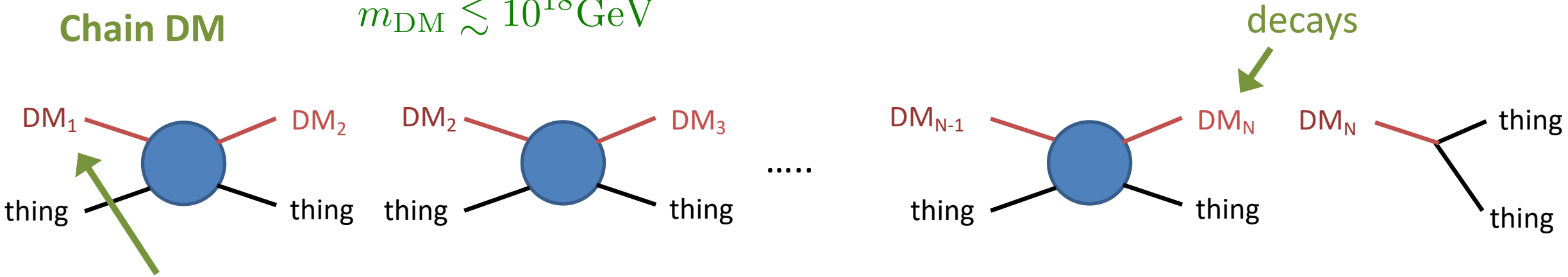
Example #5 + #6: Zombies + Chains

Zombie DM $m_{\rm DM} \lesssim 10^{10}{\rm GeV}$



Kramer, Kuflik, Levi, Outmezguine, Ruderman, PRL 2021

Chain DM $m_{\rm DM} \lesssim 10^{18}{\rm GeV}$

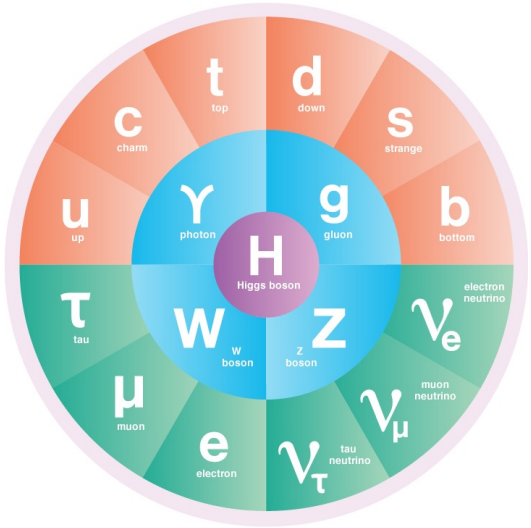


Kim, Kuflik, PRL 2019 | Frumkin, Kuflik, Lavie, Silverwater, PRL 2021

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. $SU(3)_{dark}$ x $U(1)_{dark}$

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

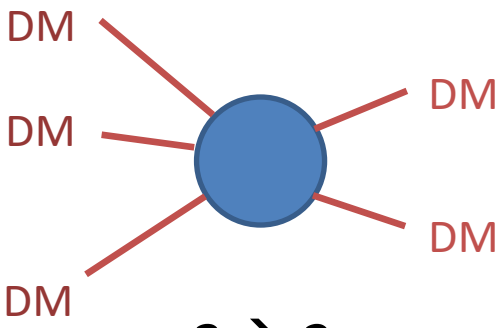
Kinetically mixed dark photon (V)

QCD-like theories, pions = dark matter

Many processes, many dark matter mechanisms.

E.g. SIMPs

Think QCD!



$3 \rightarrow 2$

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

WZW term

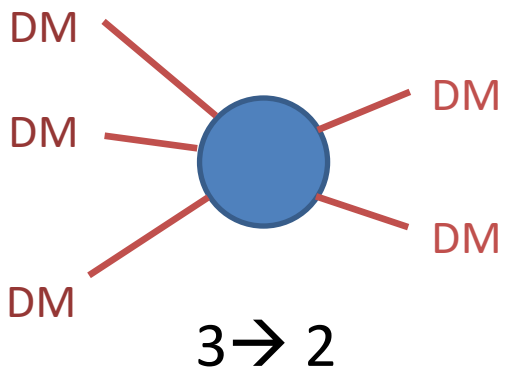
If calculate the rate, find that is just right for SIMPs with mass ~ few hundred MeV

YH, Kuflik, Murayama, Volansky, Wacker, 2015

E.g. SIMPs

Think QCD!

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



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

WZW term

pion decay constant

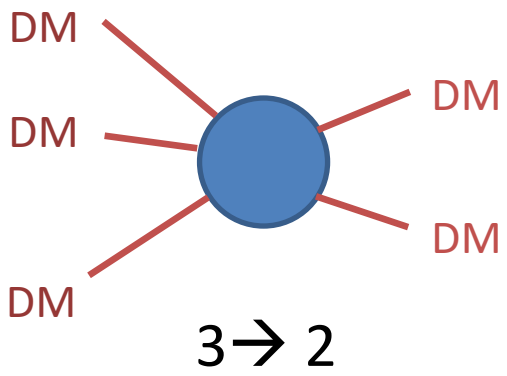
Wess and Zumino, 1971 | Witten x 2, 1983

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

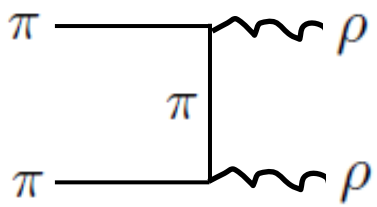
mass ~ few hundred MeV

Non-exotic!

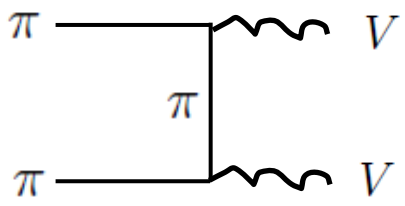
{ **3→ 2 dark glueballs:** Carelson, Hall, Machacek, 1992 | Soni, Zhang, 2016 | Forestell, Morrissey, Sigurdson, 2017 }

YH, Kuflik, Murayama, Volansky, Wacker, 2015

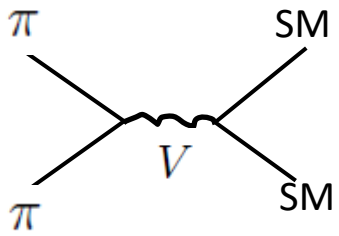
E.g. 2→2



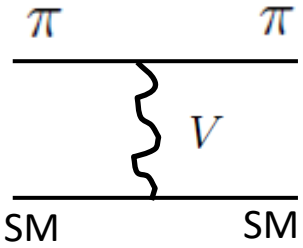
forbidden annihilations



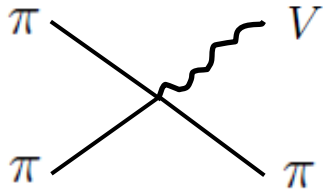
2→2 annihilations



2→ 2 annihilations



elastic scattering

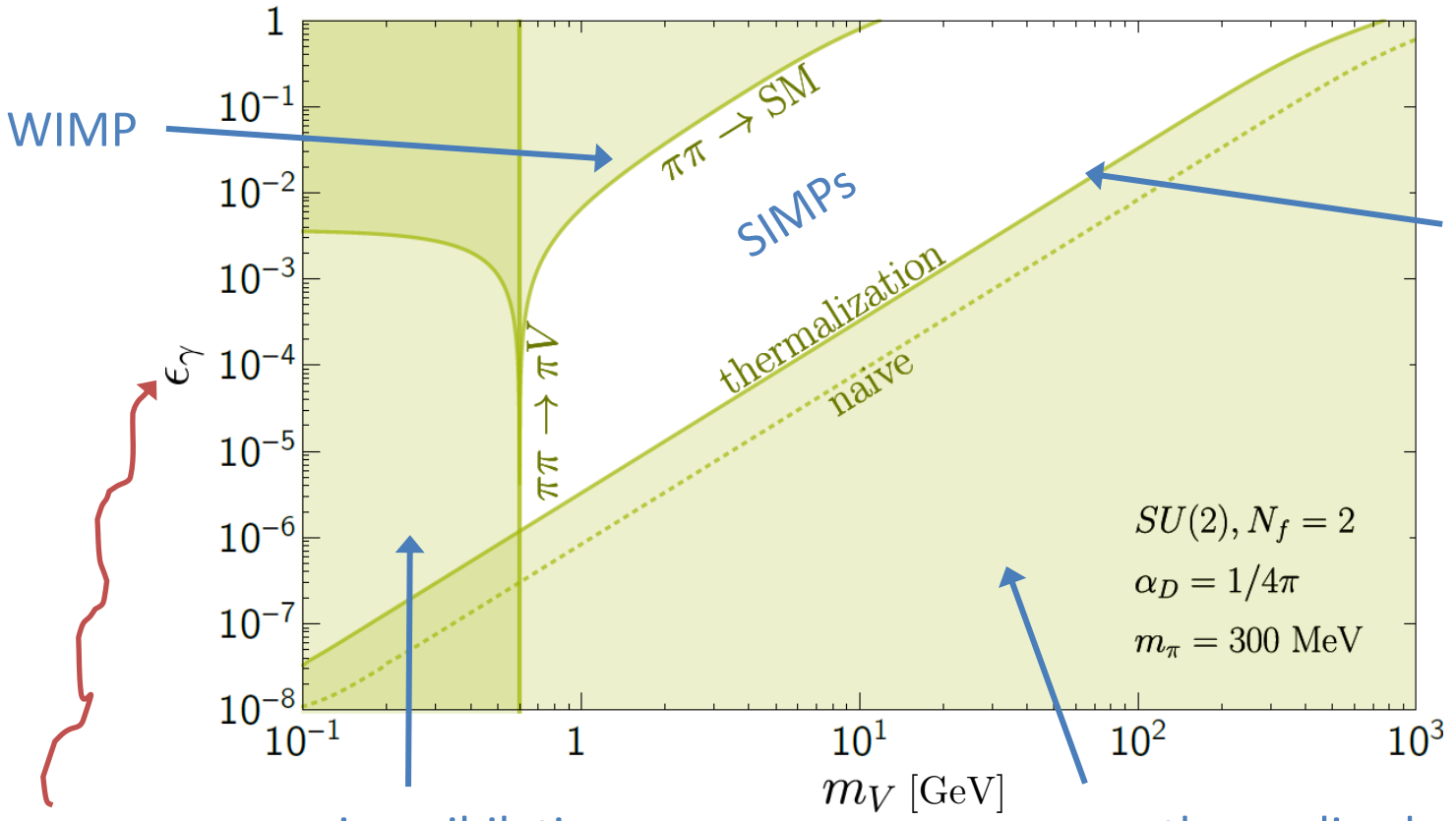


semi-annihilations

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

Predictive.

Dark Electromagnetism

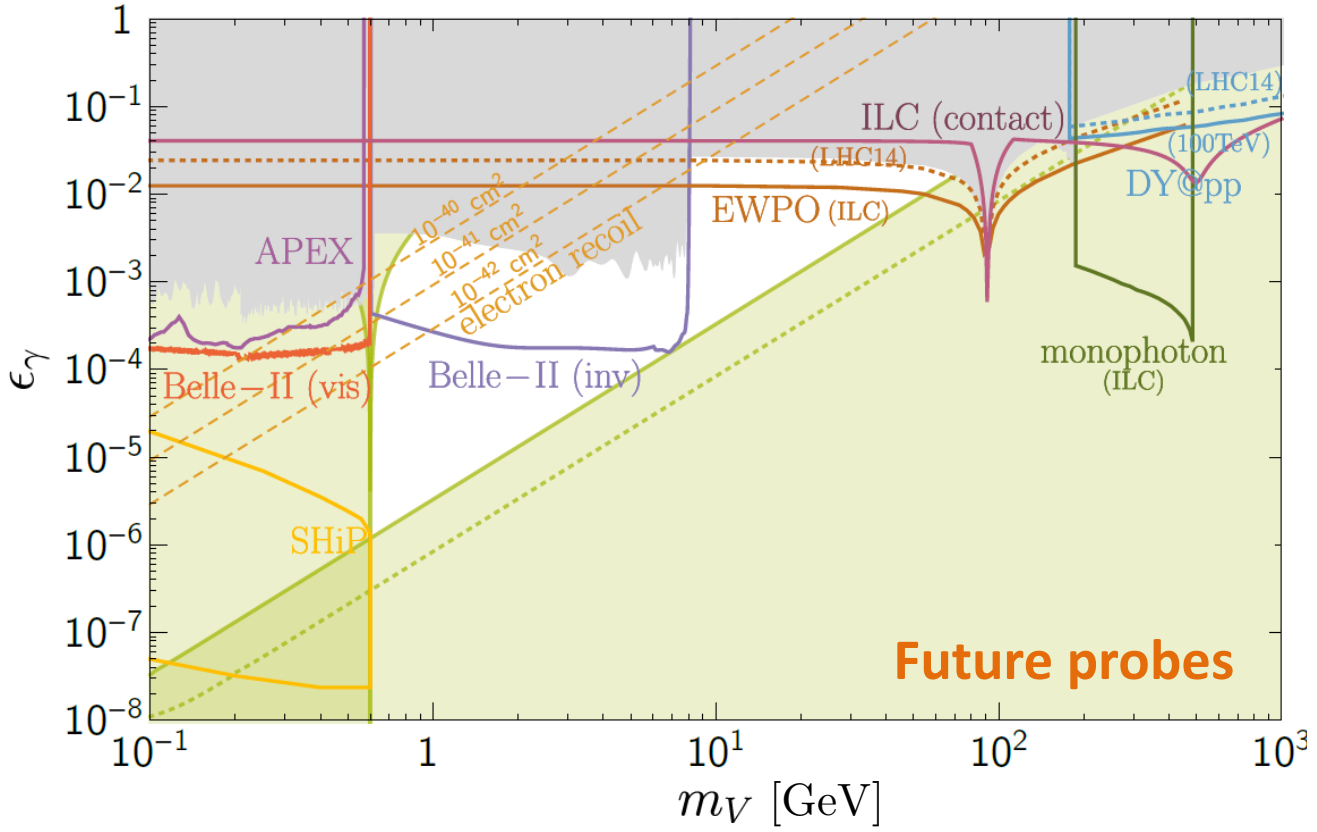


coupling of V to EM current

semi-annihilations contribute

non-thermalized with SM

Dark Electromagnetism

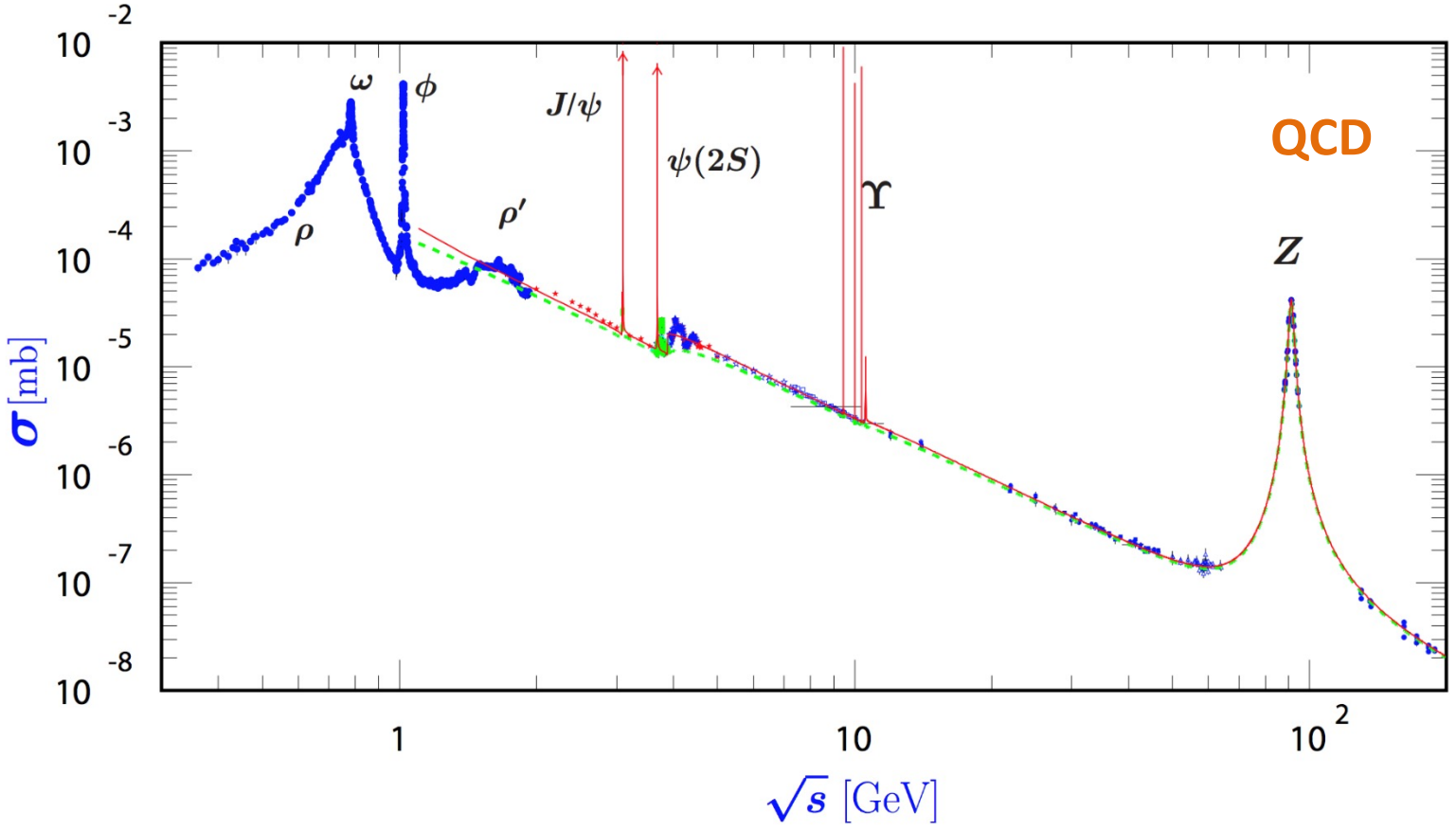


Plot: **YH**, Kuflik, Murayama, 2016

Dark Spectroscopy

$e^+e^- \to$ resonances : center of mass energy

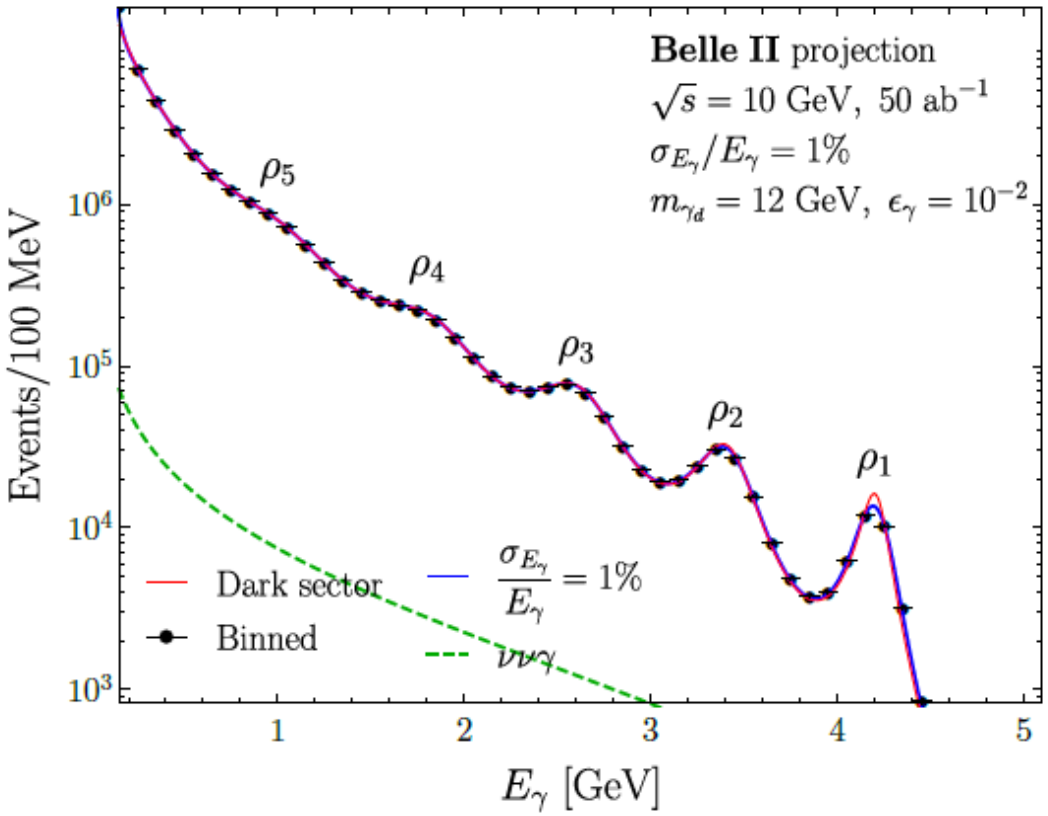
traces the QCD resonance structure

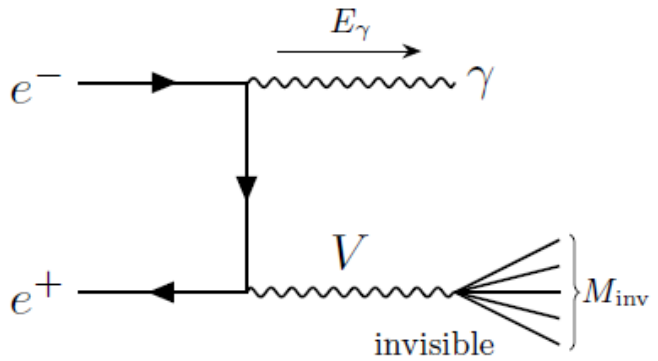


Dark Spectroscopy

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

Mono-photon traces the resonance structure of the dark sector





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

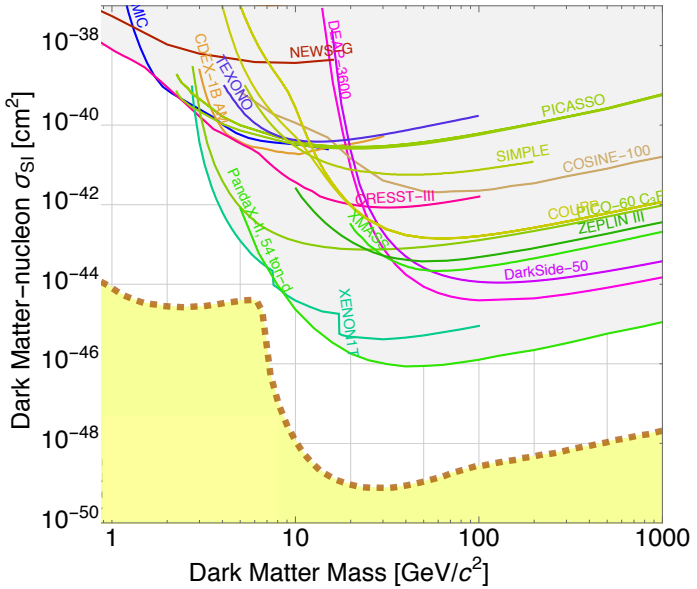
YH, Kuflik and Murayama, 2016 & 2017

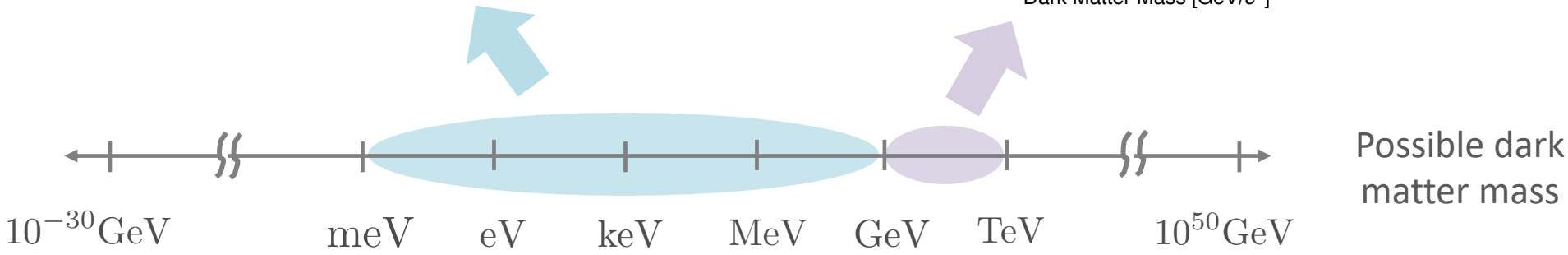
Direct Detection

Explosion of new ideas

Superconductors, semiconductors, 2D targets, scintillators, polar materials, superfluid helium...

Becoming experimental reality



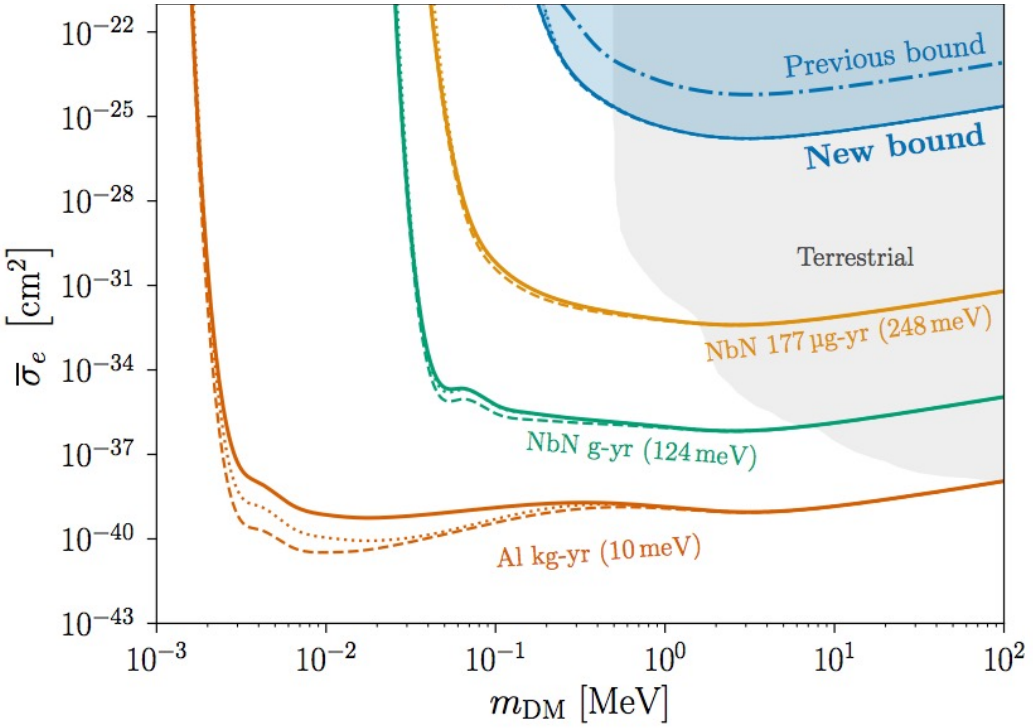


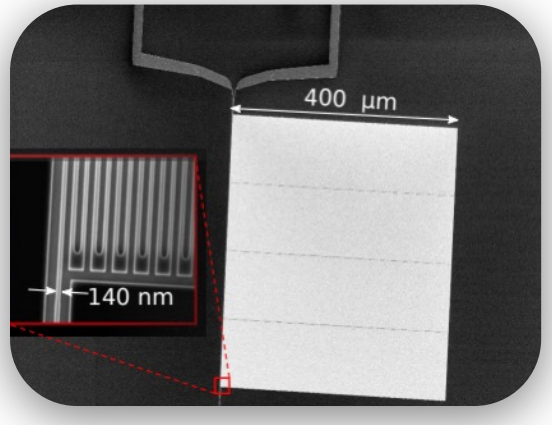
Possible dark matter mass

Essig et al, Snowmass 2021 Whitepapers | **YH** et al, Nature Rev. Phys. 2022

E.g. Superconductors

Superconducting Nanowire Single Photon Detector (SNSPD) (QIS)





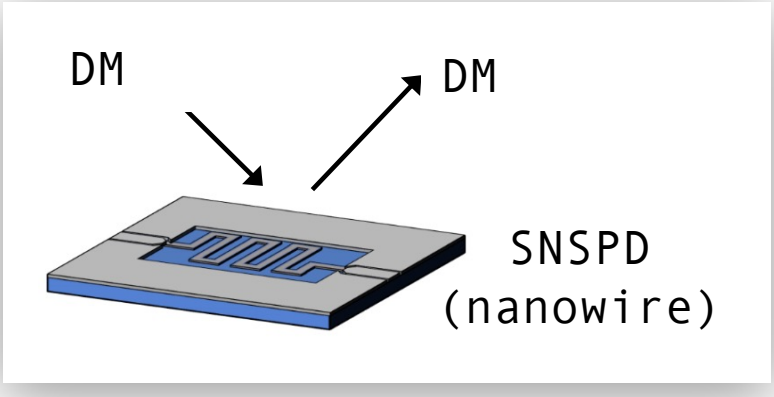
WSi, 4.3ng, 0.73 eV threshold, 180 hours of data

World leading limits on sub-MeV DM

YH, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019 + w/ Lehmann, PRD Editor's Choice 2022

E.g. Superconductors

Superconducting Nanowire Single Photon Detector (SNSPD) (QIS)



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

Quantum sensoR cryOgeniC search fOr Dark matter In Light mass rangE

Massachusetts Institute of Technology

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Universität Zürich[UZH]

E.g. Superconductors

"How can

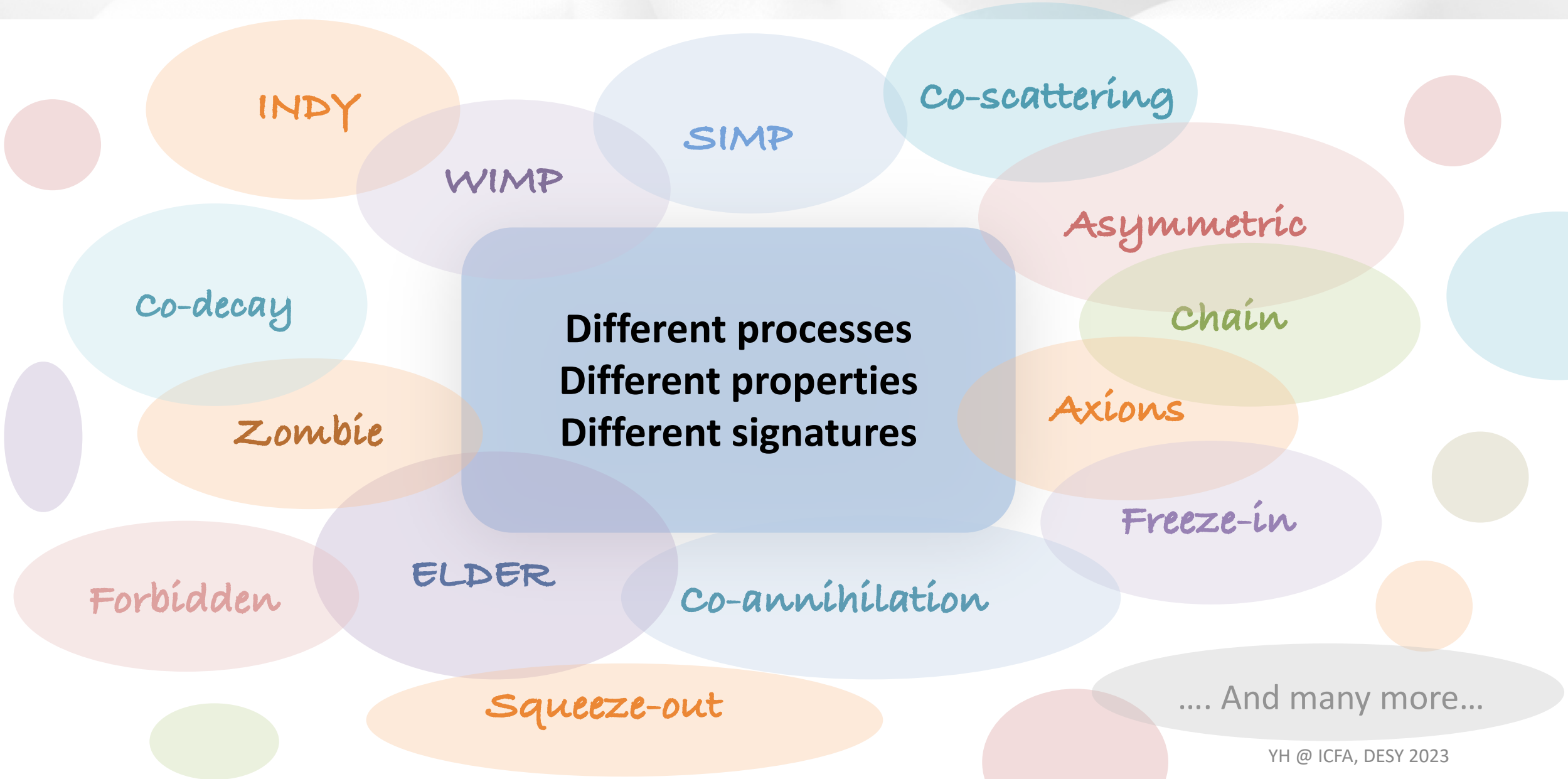
`insert-new-technology-you-hear-of`

be used for the dark matter hunt?"

Outlook

- Lots of activity for 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


INDY
SIMP
Co-scattering
WIMP
Asymmetric
Co-decay
Chain
Different processes
Different properties
Different signatures
Axions
Zombie
Freeze-in
ELDER
Forbidden
Co-annihilation
Squeeze-out
.... And many more...

Prospects

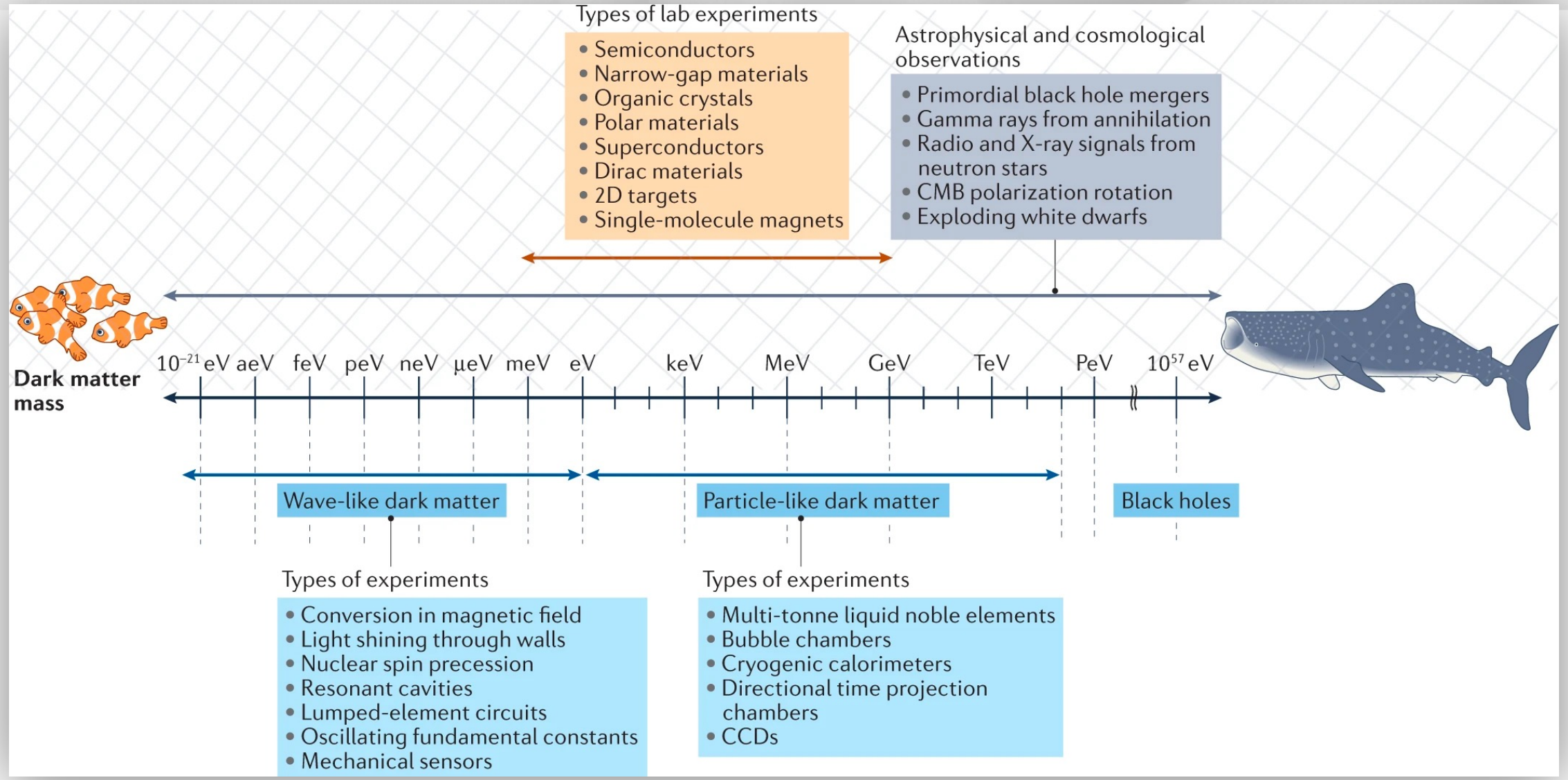


Image: **YH** et al, Nature Rev. Phys. 2022

Prospects

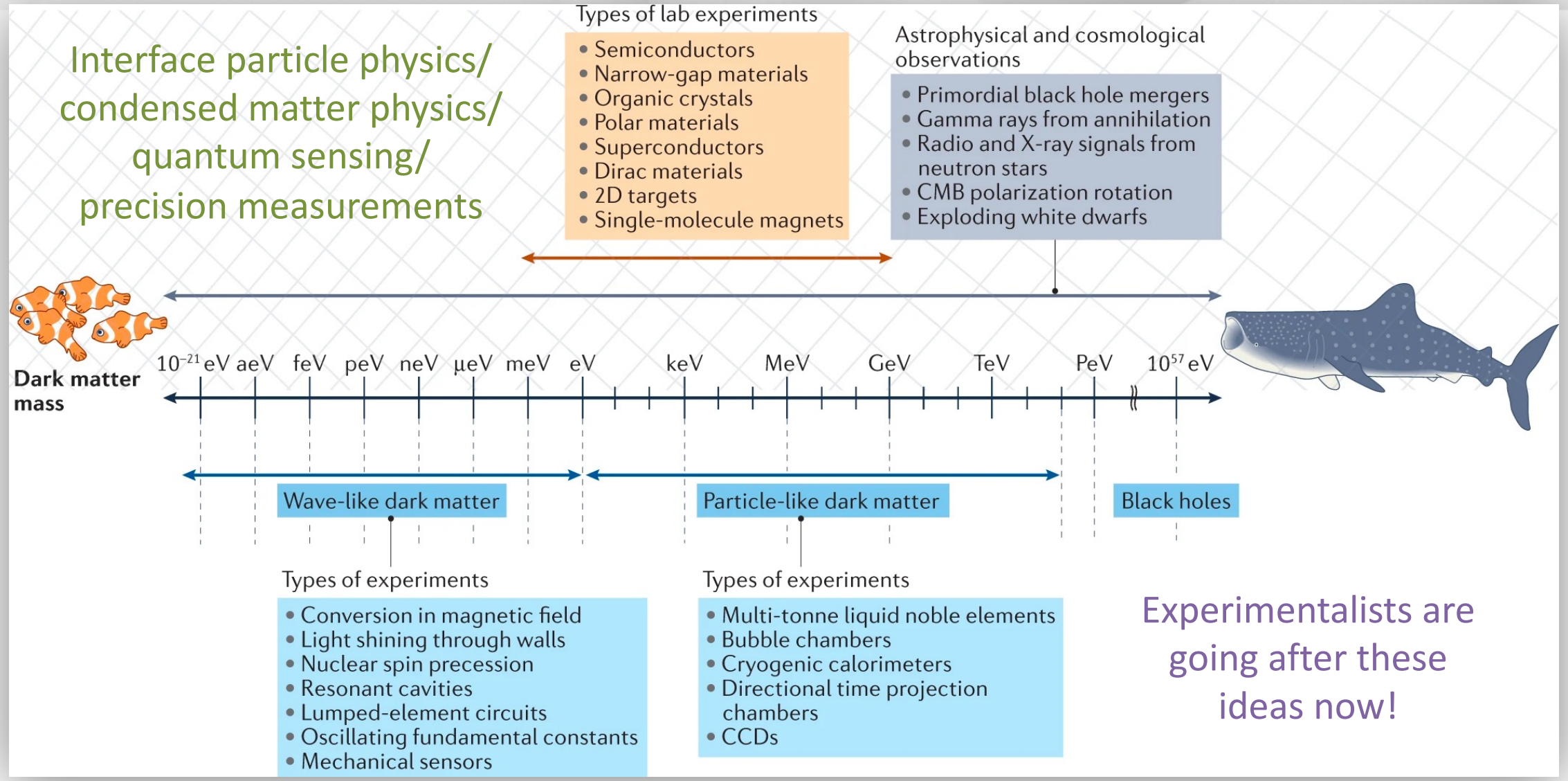


Image: YH et al, Nature Rev. Phys. 2022

Think outside the box.

(Fund outside the box.)

If you have any (crazy) new ideas,

please be in touch :-)

Thanks!