THE HUNT FOR DARK MATTER

Marek Matas

Workshop UPC 13.9.2021

Decin

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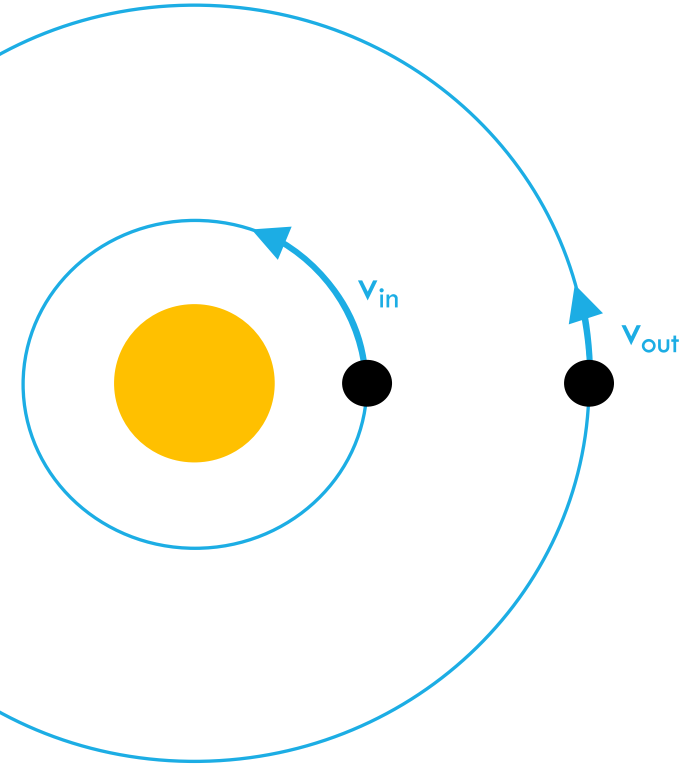
WHAT IS DARK MATTER

GALACTIC ROTATION CURVES



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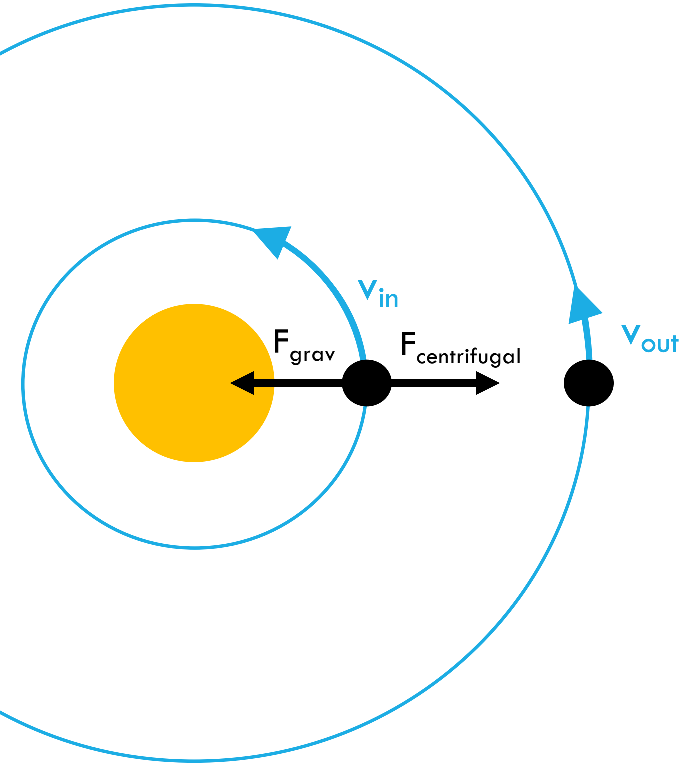

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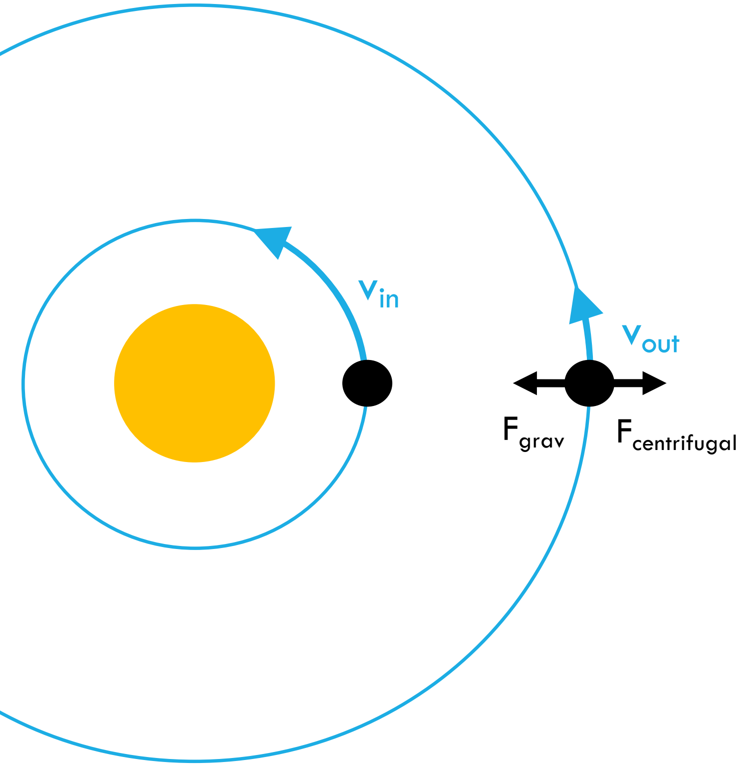

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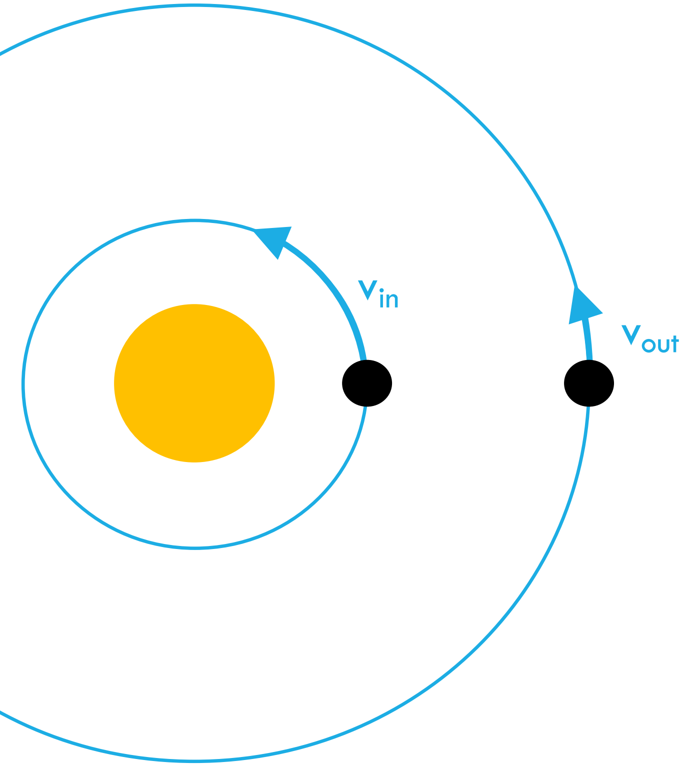

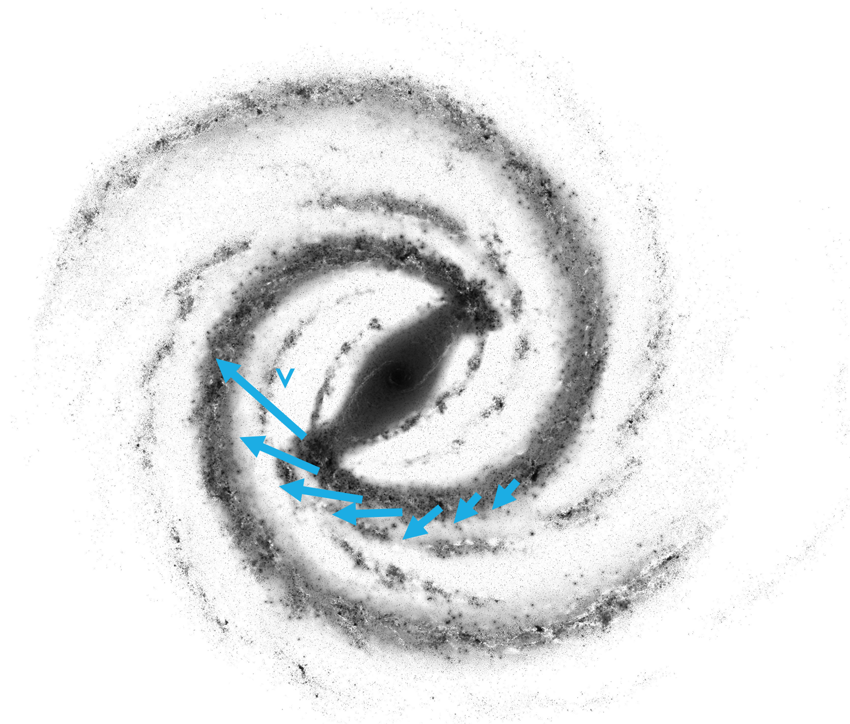

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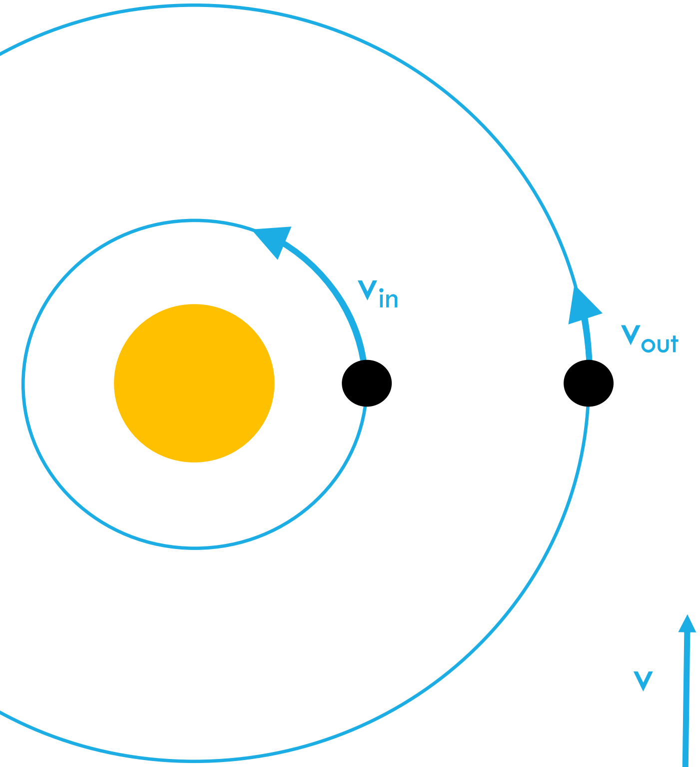

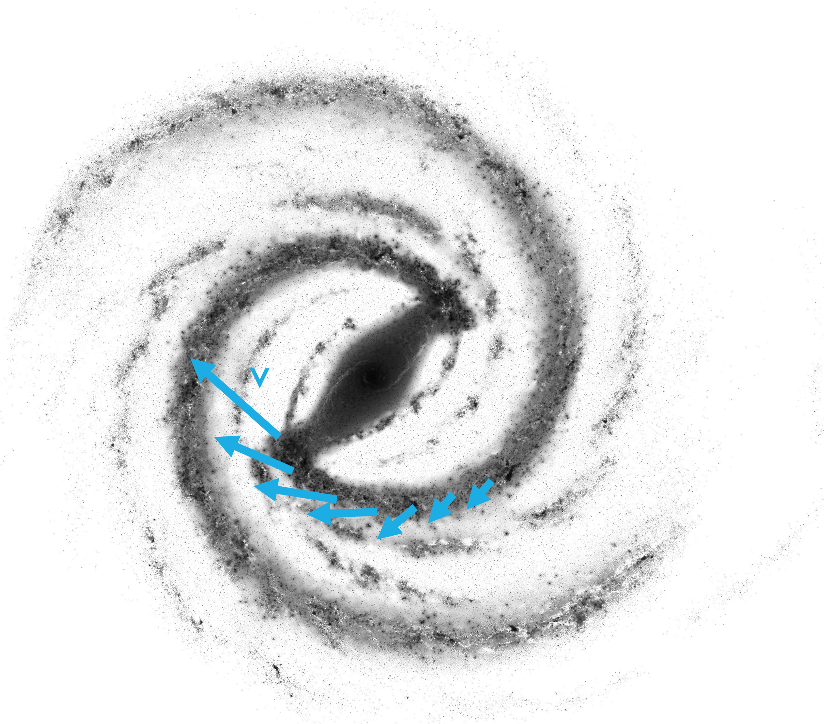

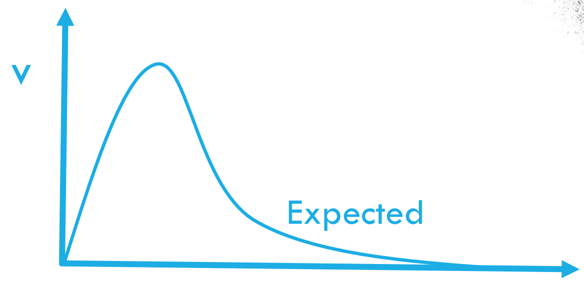

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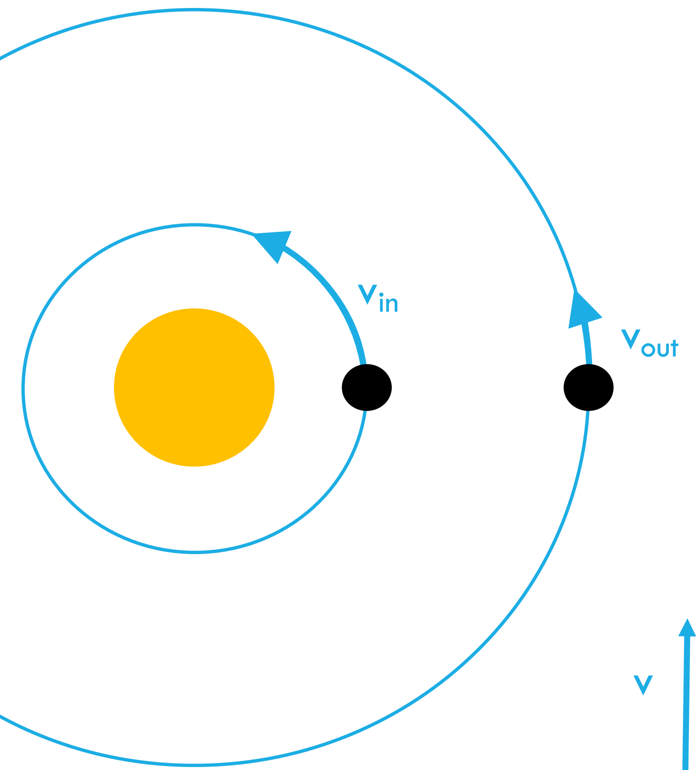

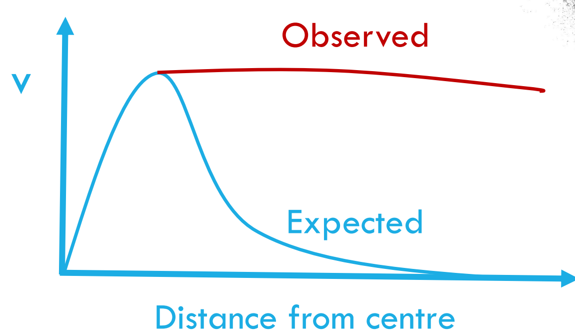

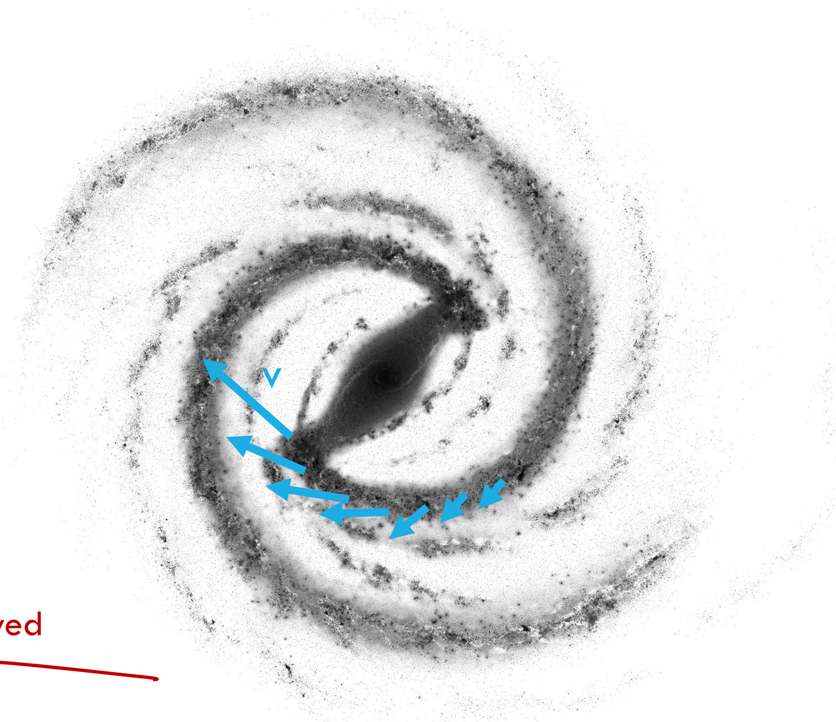

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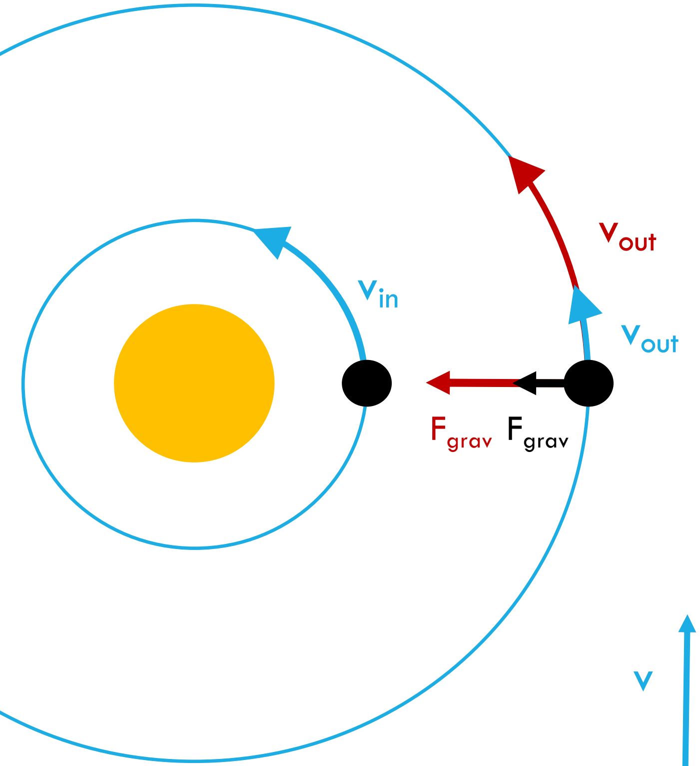

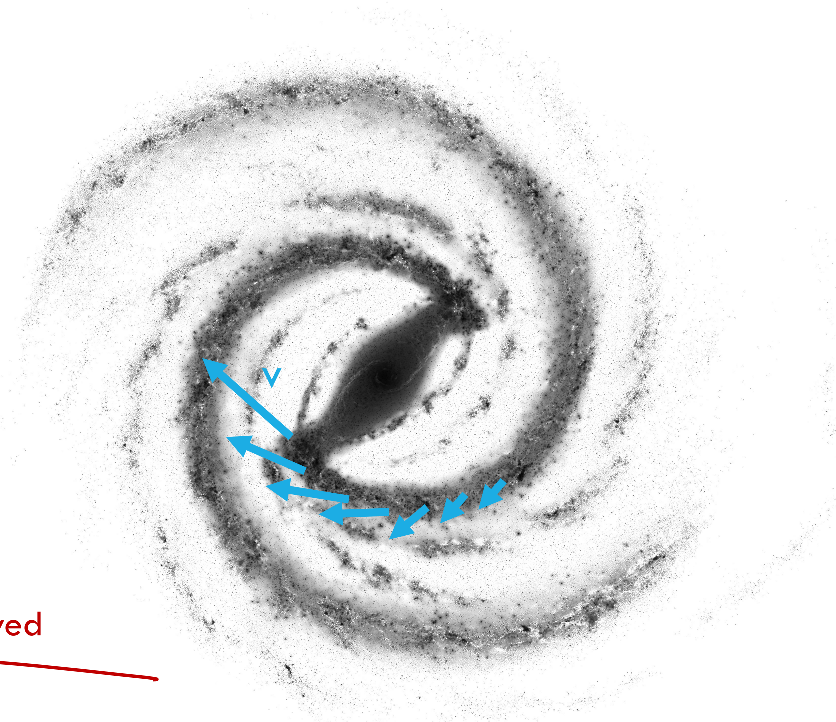

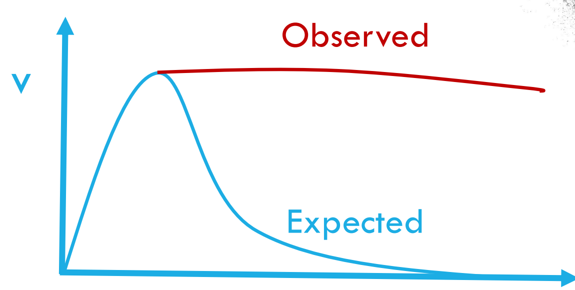

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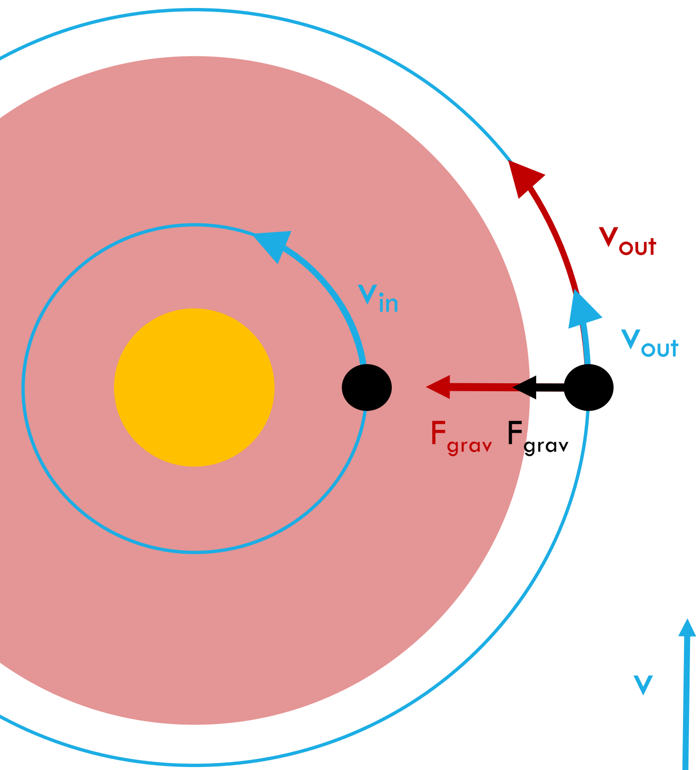

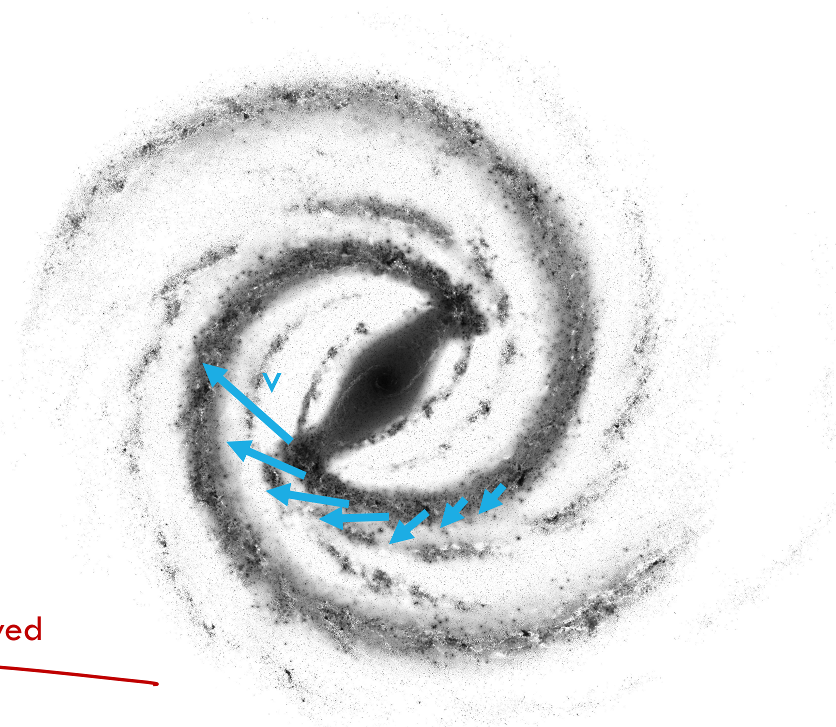

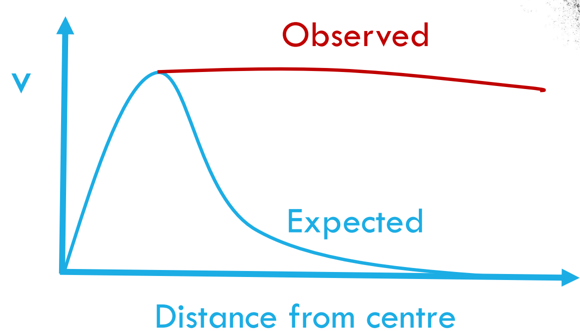

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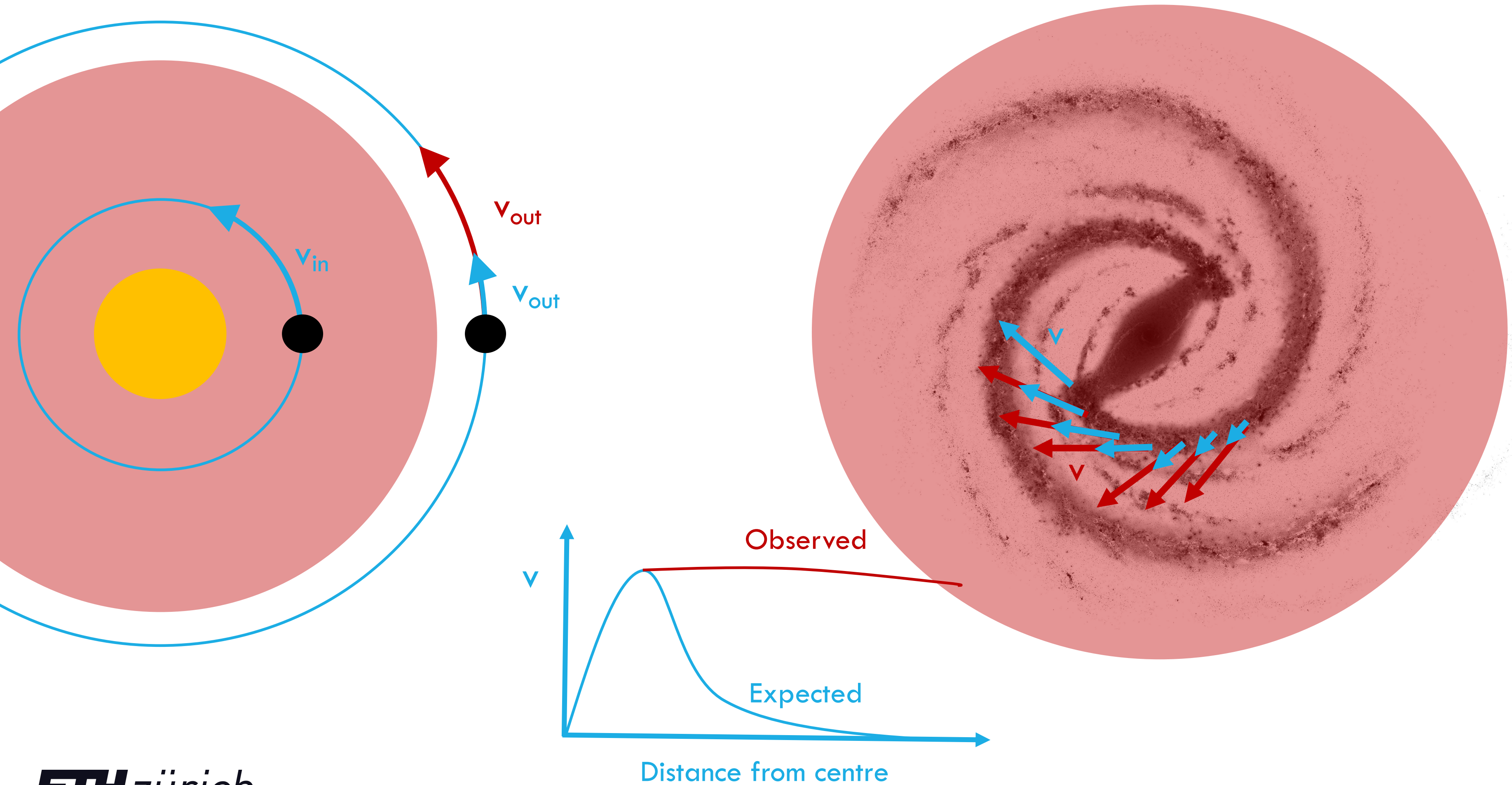
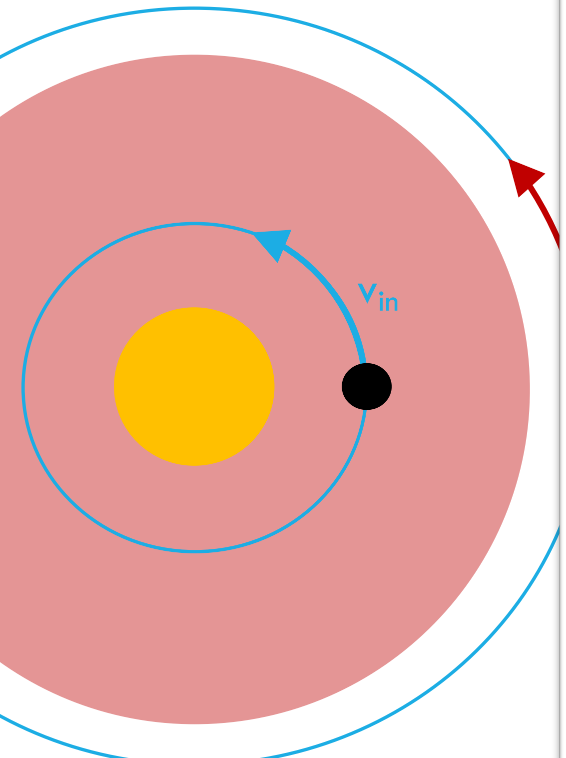
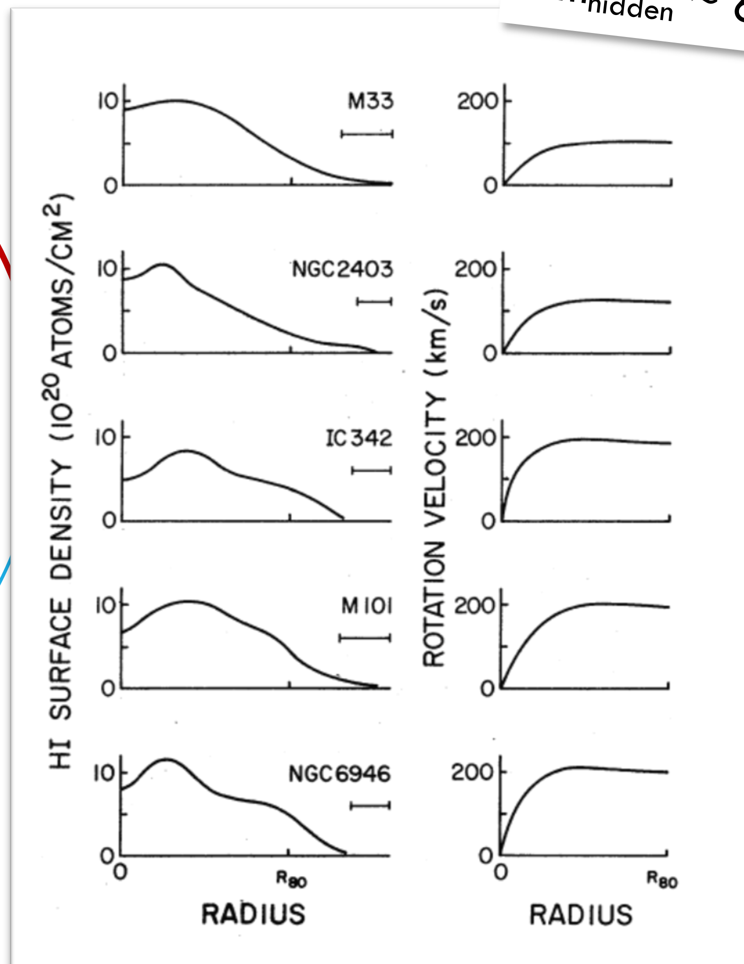
GALACTIC ROTATION CURVES

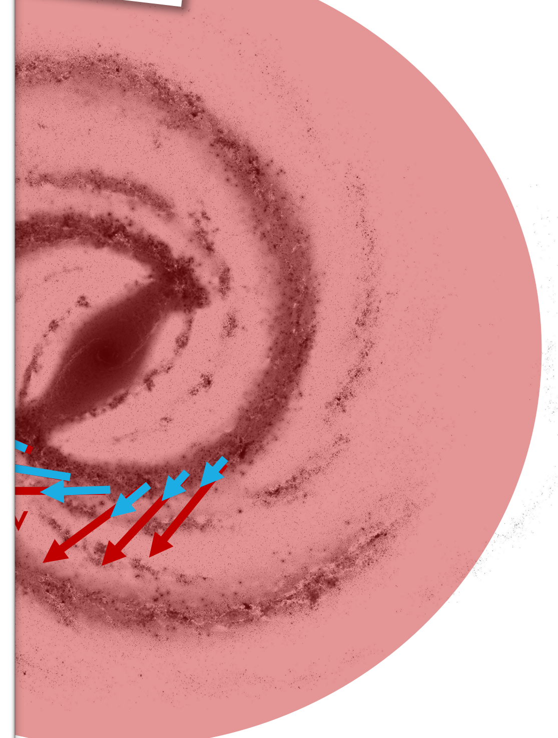


GALACTIC ROTATION CURVES

$m_{hidden} \sim 6 m_{visible}$







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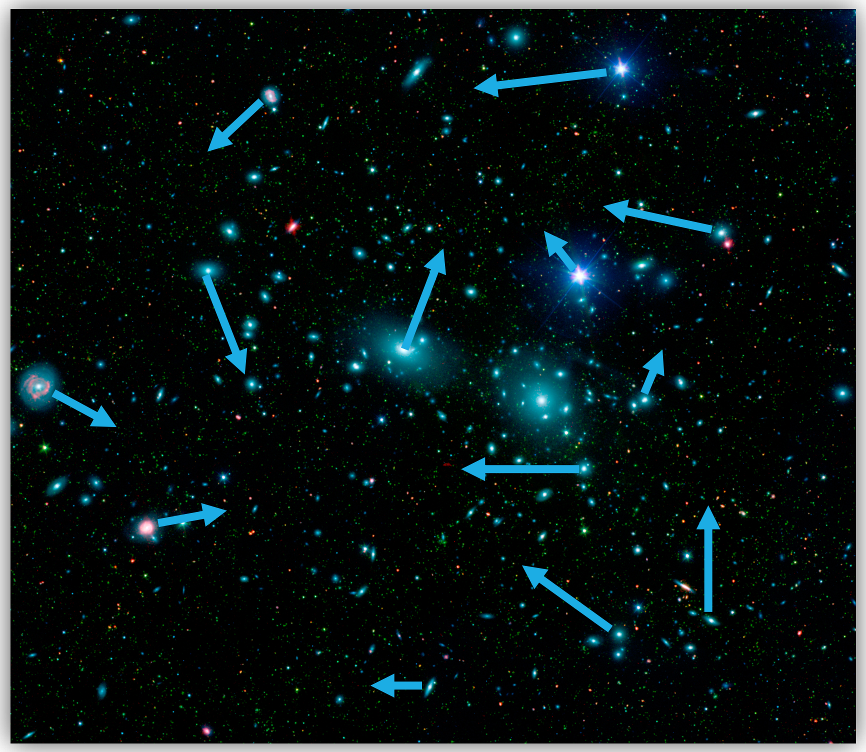
Credit: Rogstad and Shostak 1972

GALAXY CLUSTERS

- Fritz Zwicky – 1933 Coma Cluster
- Velocity dispersion ~ cluster mass



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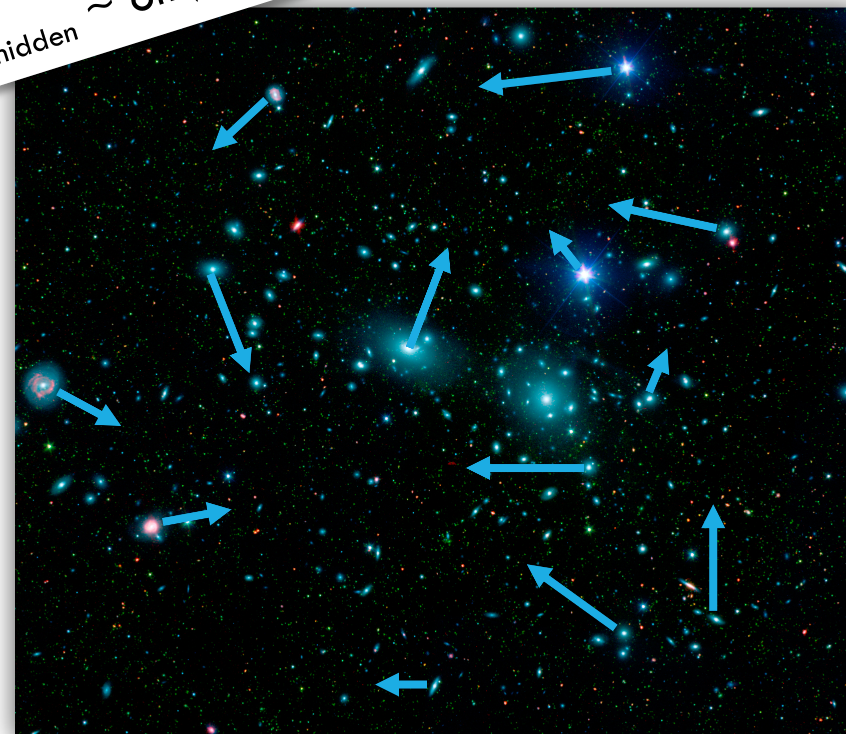
Credit: https://en.wikipedia.org/wiki/Coma_Cluster

GALAXY CLUSTERS

$m_{hidden} \sim 6 m_{visible}$

- Fritz Zwicky – 1933 Coma Cluster
- Velocity dispersion ~ cluster mass
- Expected velocity ~ 80 km/s
- Observed velocity ~ 1000 km/s



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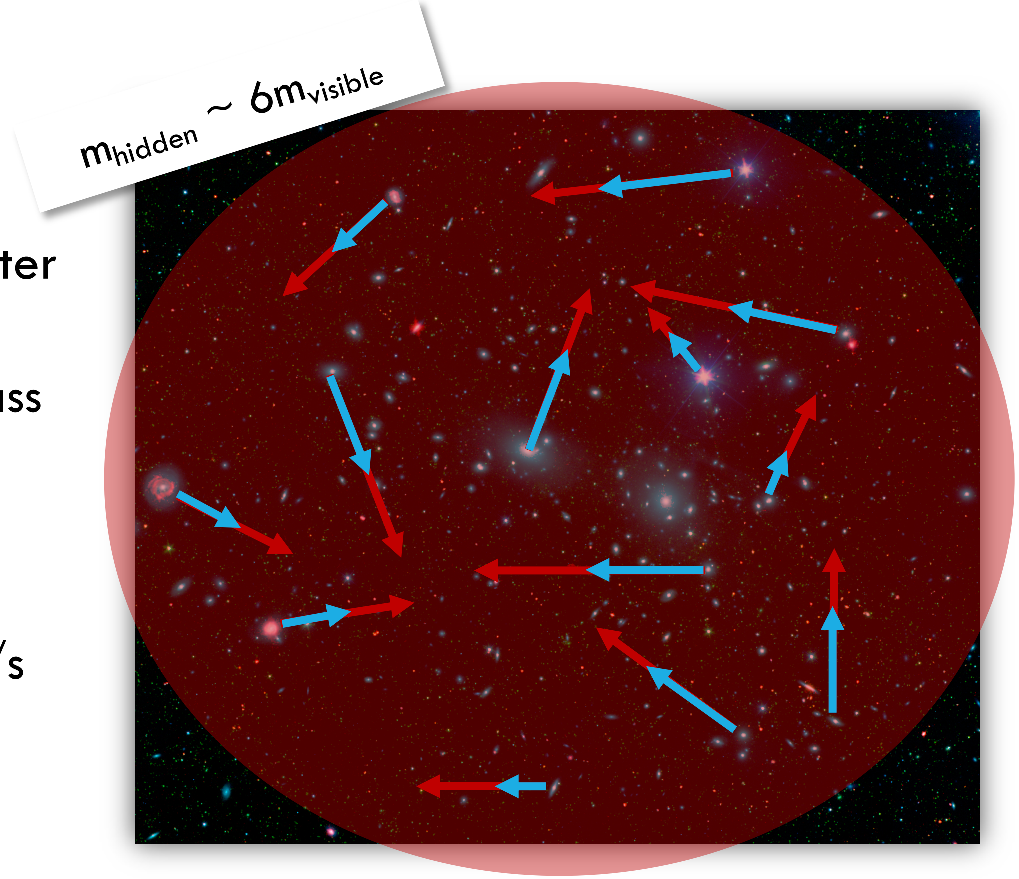
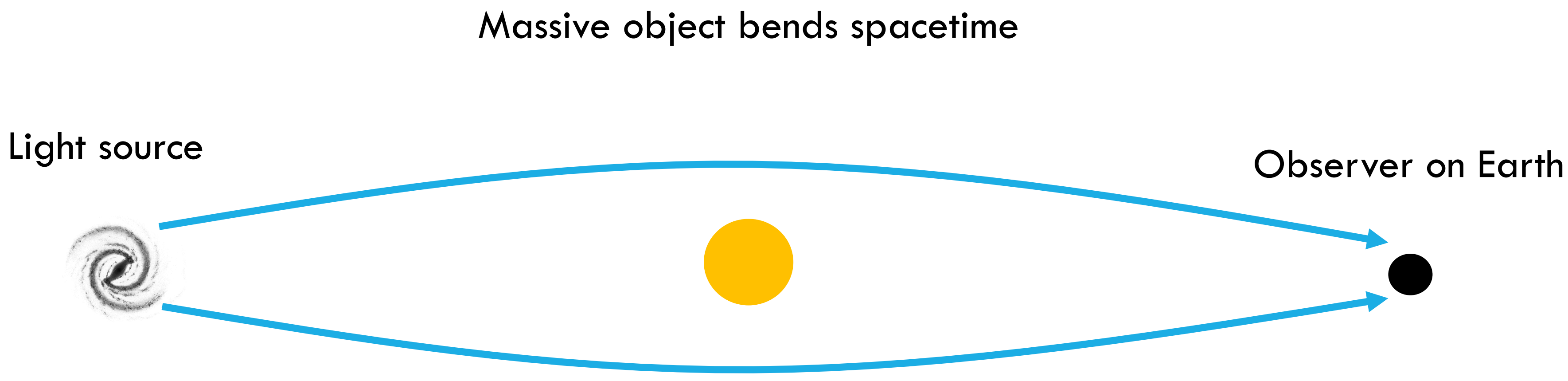


If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter.

Fritz Zwicky 1933

Credit: https://en.wikipedia.org/wiki/Coma_Cluster

GRAVITATIONAL LENSING



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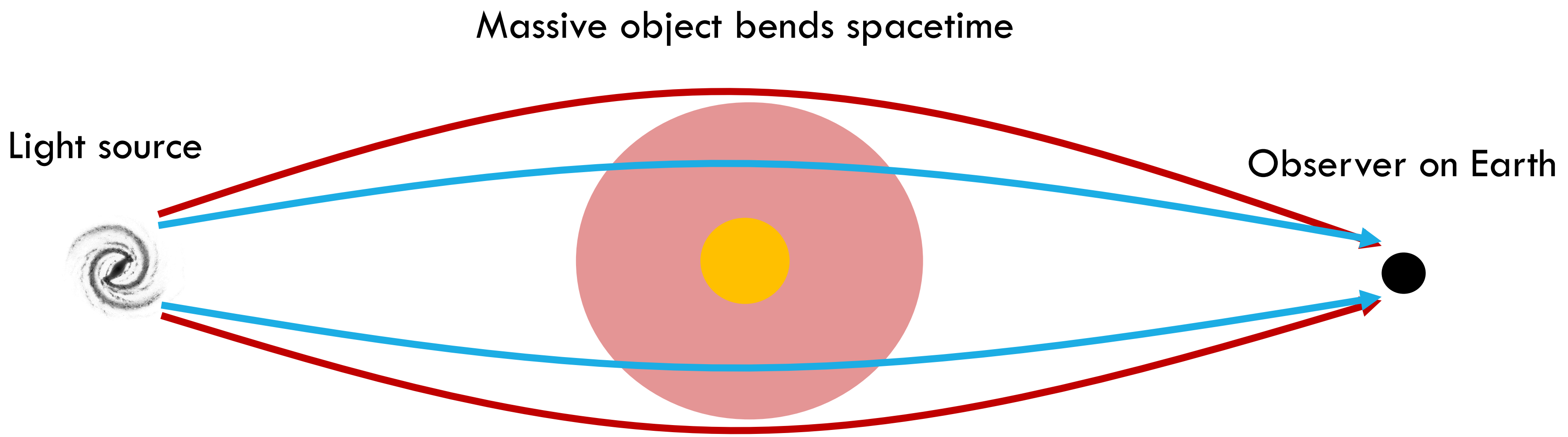
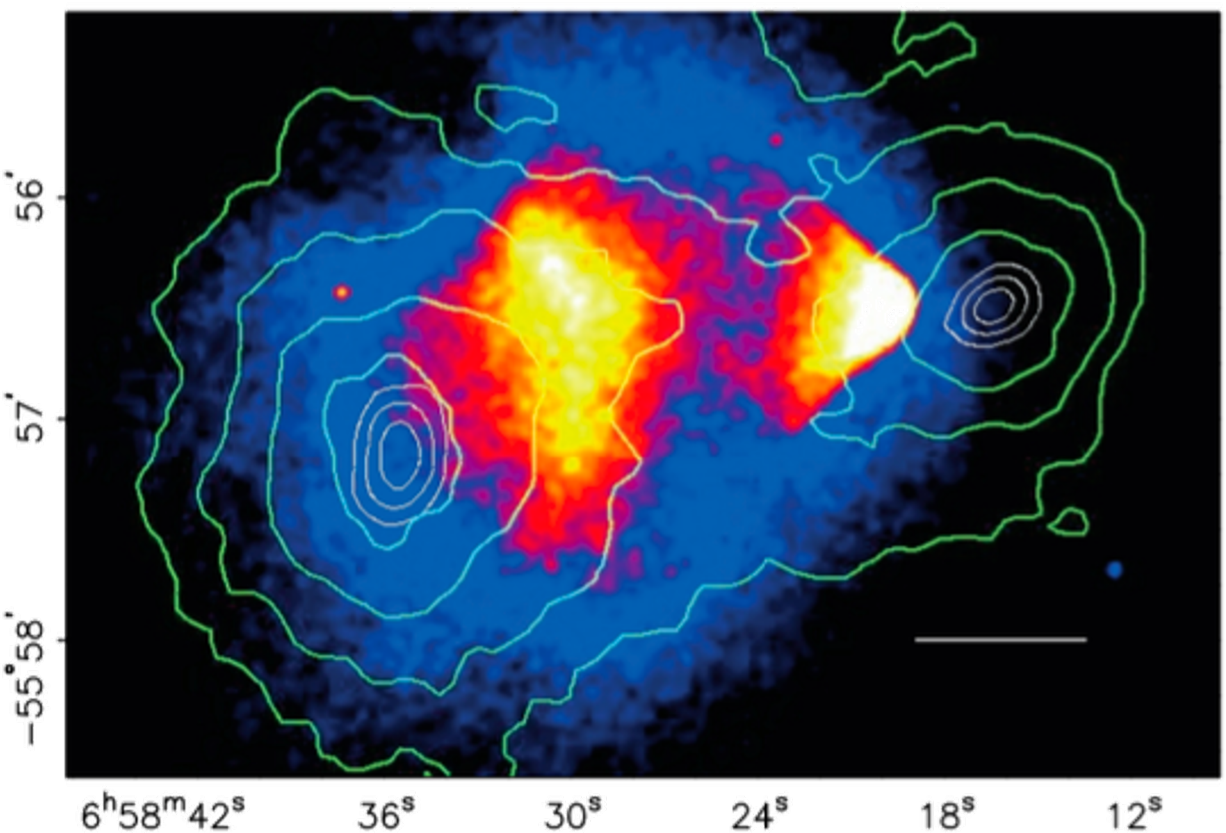


GRAVITATIONAL LENSING

Credit: WIKIPEDIA.ORG

BULLET CLUSTER

"A direct empirical proof of the existence of dark matter"



Credit: Clowe, D. et. al. Astrophys.J.648:L109-L113,2006

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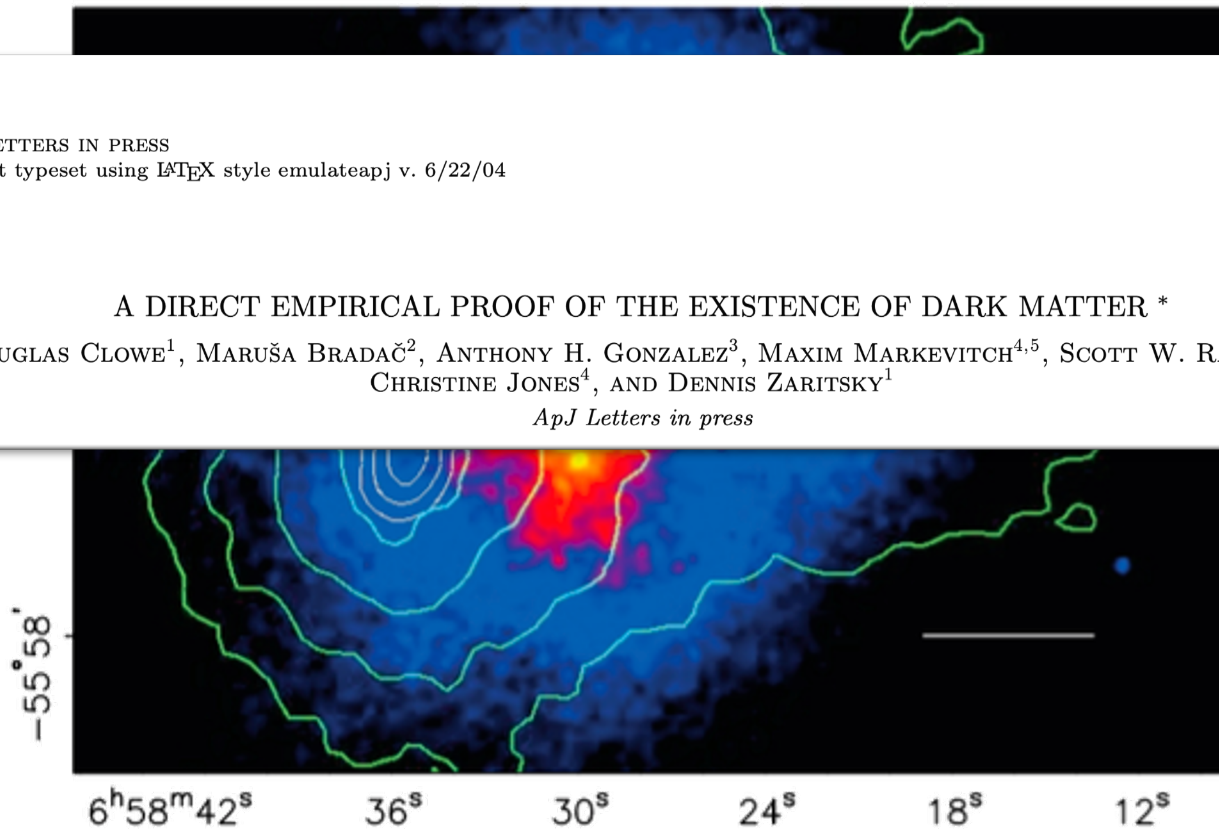


ApJ Letters in press
Preprint typeset using LaTeX style emulateapj v. 6/22/04

A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER *

Douglas Clowe[1], Maruša Bradač[2], Anthony H. Gonzalez[3], Maxim Markevitch[4,5], Scott W. Randall[4], Christine Jones[4], and Dennis Zaritsky[1]

ApJ Letters in press

Credit: Clowe, D. et. al. Astrophys.J.648:L109-L113,2006

WHAT IS DARK MATTER

CLUSTER VELOCITY DISPERSION

+

GRAVITATIONAL LENSING

+

GALACTIC ROTATION CURVES

+

BULLET CLUSTER COLLISION

+

COSMIC MICROWAVE BACKGROUND

+

VERTICAL OSCILLATIONS

+

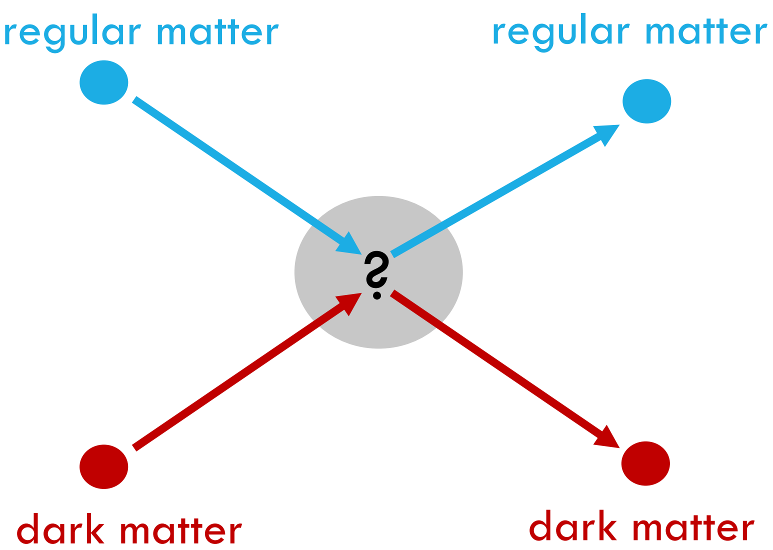
LENSING SEARCH FOR MACHOS

=

UNKNOWN PARTICLES WITH MASS OF 6X THAT OF VISIBLE MATTER

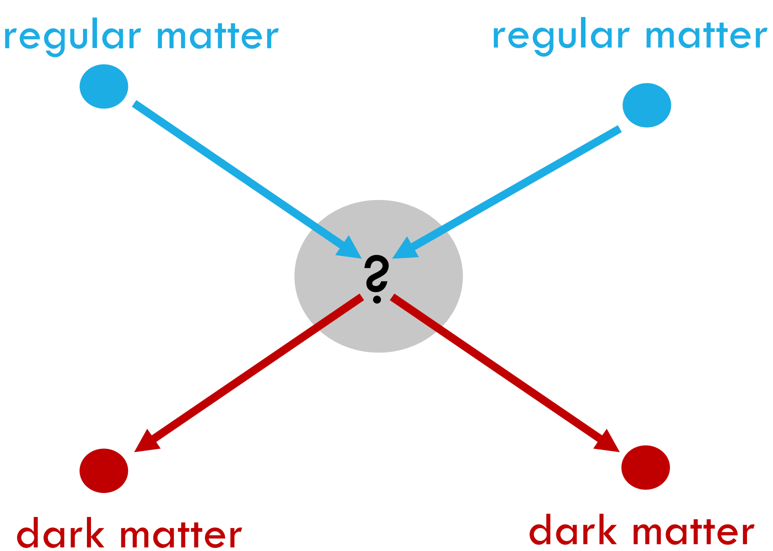
HOW TO DETECT IT

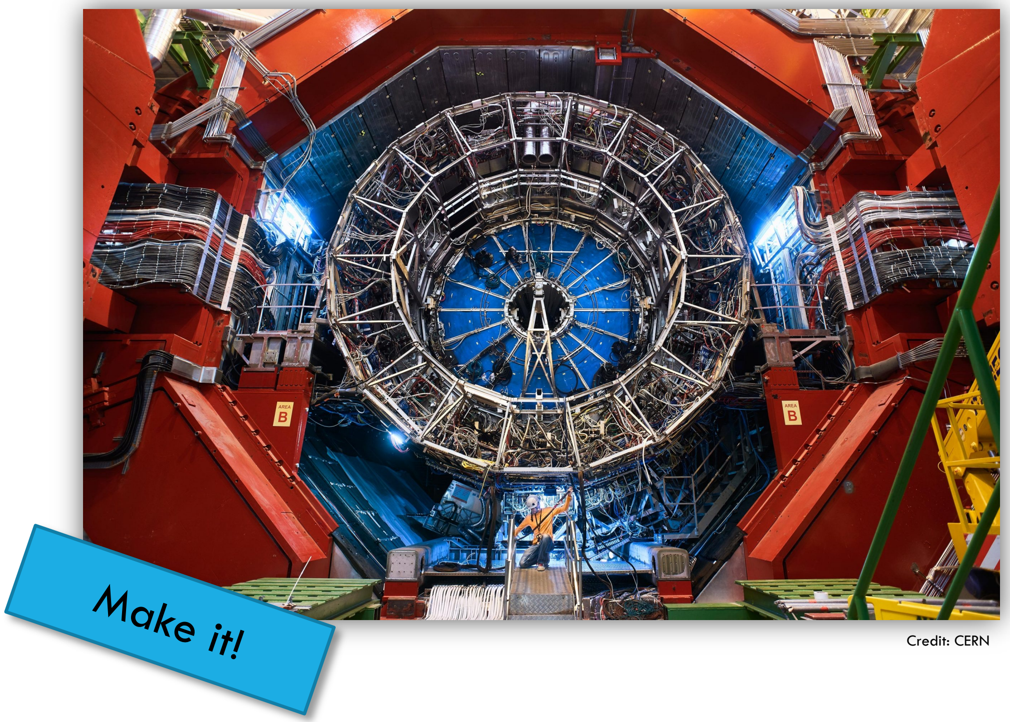
DIRECT DETECTION



Credit: https://news.uchicago.edu/story/worlds-most-sensitive-dark-matter-detector-releases-first-results

COLLIDER EXPERIMENTS





Credit: CERN

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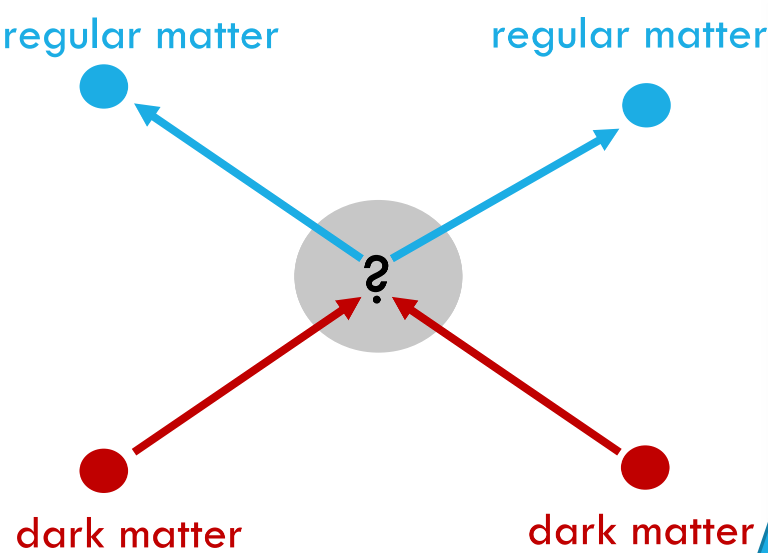
INDIRECT DETECTION



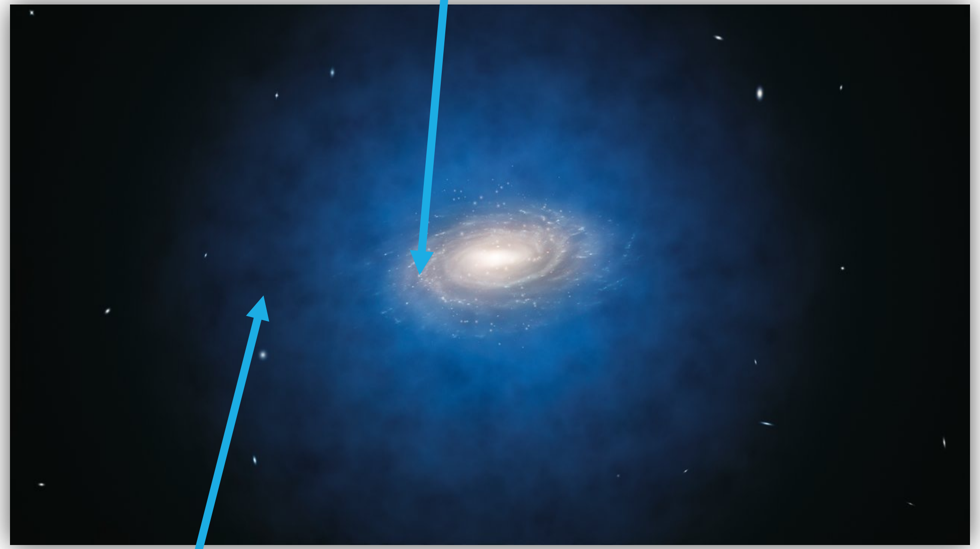
Break it!

Credit: SPANISH NATIONAL RESEARCH COUNCIL (CSIC)

HOW TO DETECT IT

DARK MATTER WIND

You are spinning here

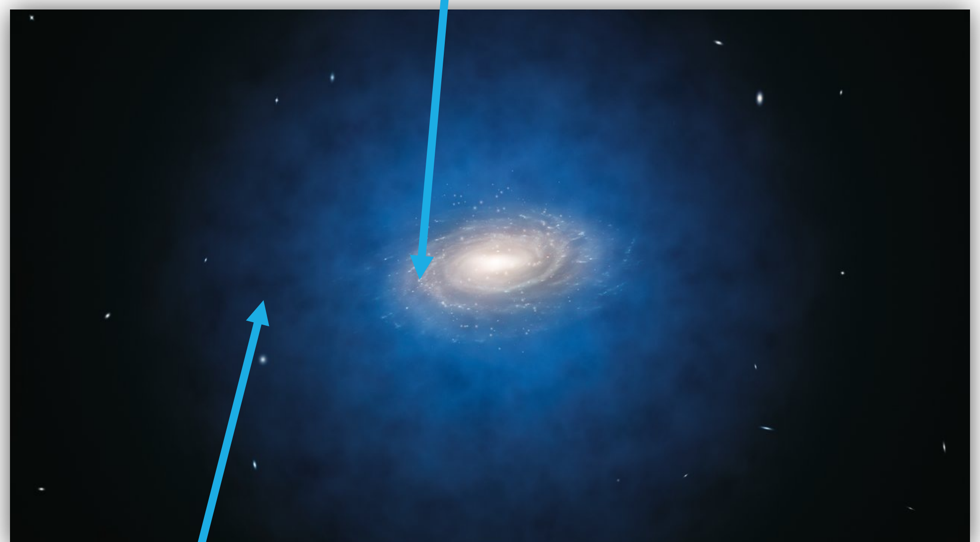


This is the dark matter halo

Credit: ESO, Forbes

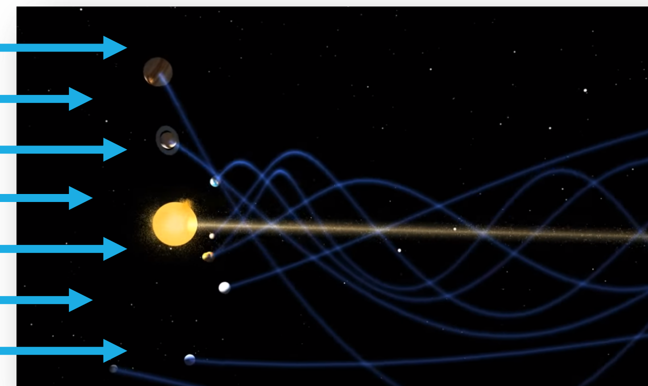
DARK MATTER WIND

You are spinning here



This is the dark matter halo

Dark matter particles are raining down on us each day!



Credit: ESO, Forbes

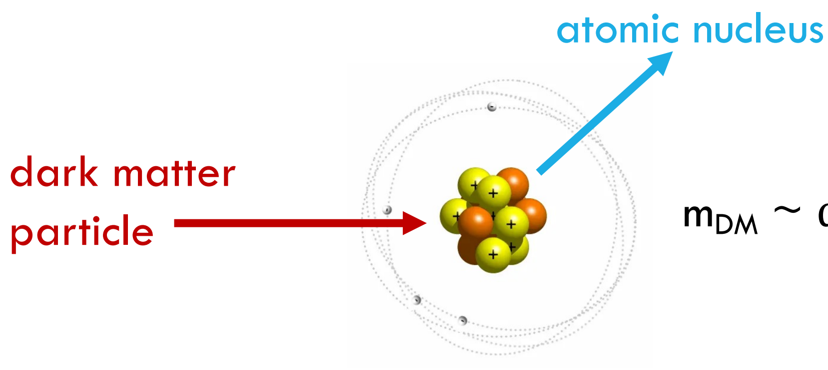
WIMP MIRACLE

Weakly

Interacting

Massive

Particle



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

Focus on DM – nuclear interactions

Credit: https://www.quantamagazine.org/dark-matter-experiment-finds-unexplained-signal-20200617/, https://en.wikipedia.org/wiki/DEAP, Reidar Hahn, Fermilab

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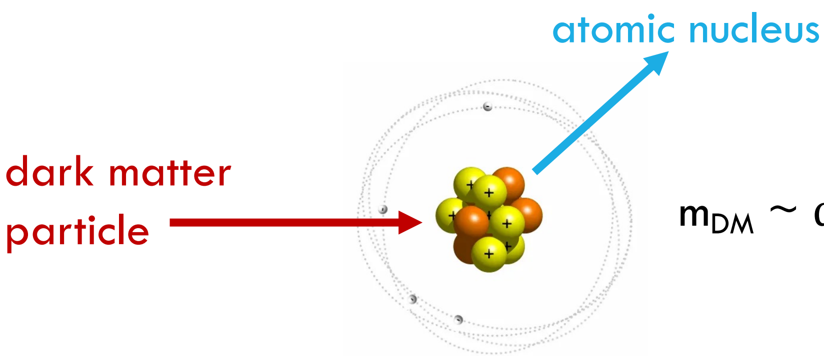

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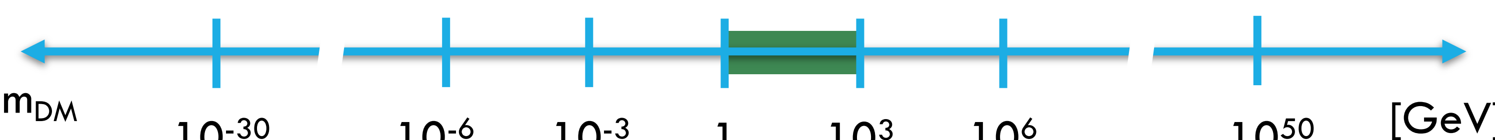

Credit: https://www.quantamagazine.org/dark-matter-experiment-finds-unexplained-signal-20200617/, https://en.wikipedia.org/wiki/DEAP, Reidar Hahn, Fermilab

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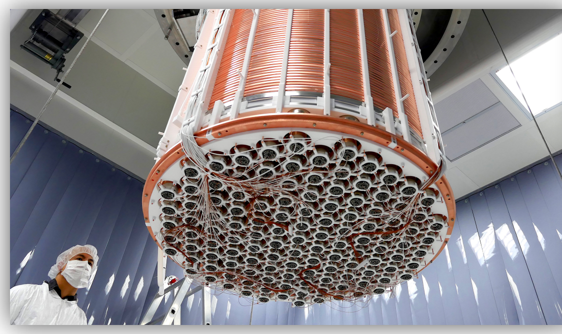
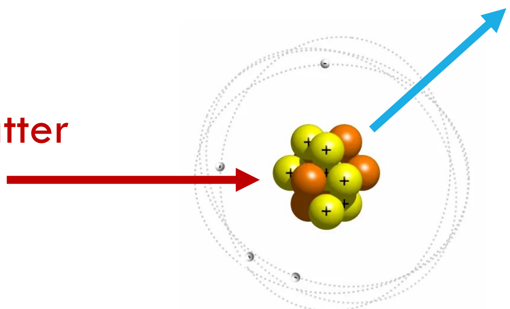


atomic nucleus

dark matter particle



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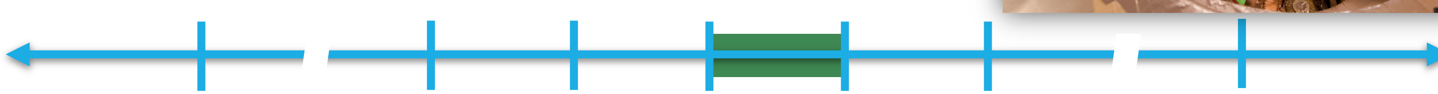
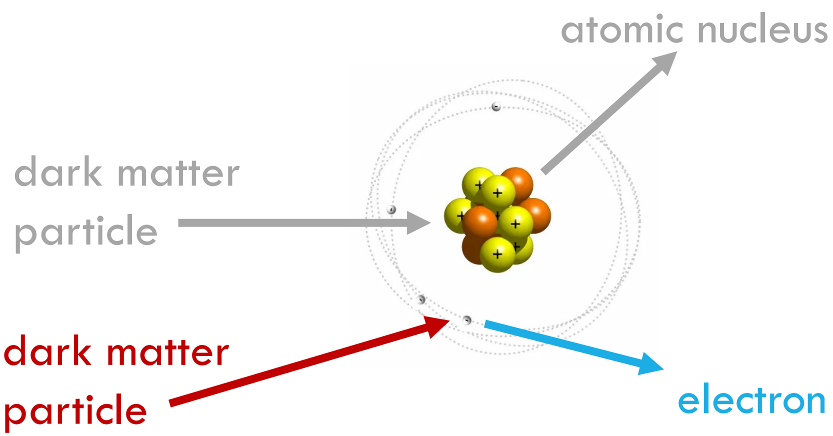
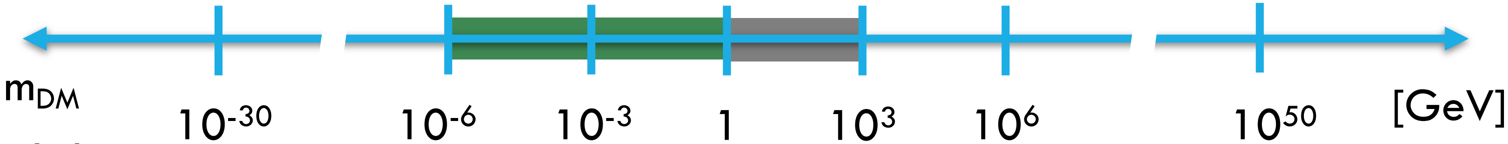


Credit: https://www.quantamagazine.org/dark-matter-experiment-finds-unexplained-signal-20200617/, https://en.wikipedia.org/wiki/DEAP, Reidar Hahn, Fermilab

PAST WIMP – LOWER MASS SCALES

- For lighter DM, nuclei recoils do not transfer enough energy.
- We need to look for interaction with lighter particles – electrons!

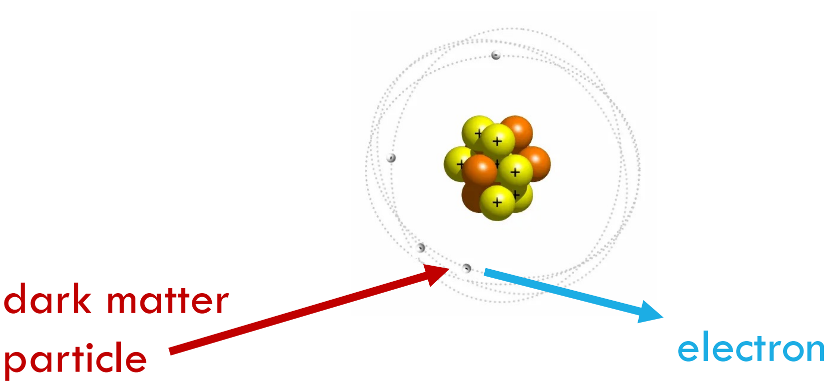




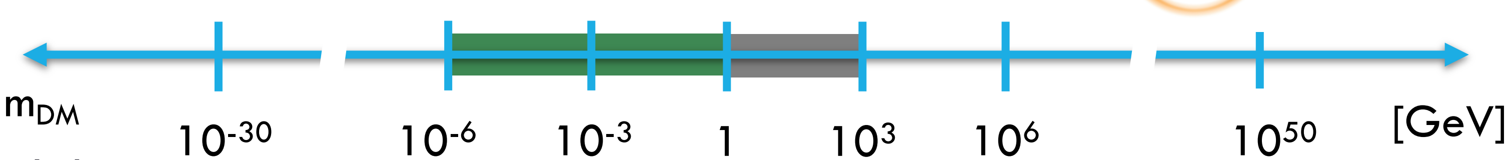
Credit: http://www.zsvltava.cz/fyzika/?p=102, https://pediaa.com/difference-between-elastic-and-inelastic-collision/

CHOOSING A TARGET MATERIAL

- In order to calculate the detection rate, we need to have the electron wavefunction for the initial and final state.



- General QFT can give use some DM-SM interaction estimates.
- You need to know all possible electron and phonon transitions.
- We use density functional theory to calculate them.



Credit: http://www.zsvltava.cz/fyzika/?p=102

OUR WORK

CURRENT RESULTS

- General QFT has been used to determine all general crystal responses.

$\mathcal{O}_1 = \mathbb{1}_\chi \mathbb{1}_e$	$\mathcal{O}_{11} = i\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_e}\mathbb{1}_e$
$\mathcal{O}_3 = i\mathbf{S}_e \cdot (\frac{\mathbf{q}}{m_e} \times \mathbf{v}_{\mathrm{el}}^\perp)\mathbb{1}_\chi$	$\mathcal{O}_{12} = \mathbf{S}_\chi \cdot (\mathbf{S}_e \times \mathbf{v}_{\mathrm{el}}^\perp)$
$\mathcal{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_e$	$\mathcal{O}_{13} = i(\mathbf{S}_\chi \cdot \mathbf{v}_{\mathrm{el}}^\perp)(\mathbf{S}_e \cdot \frac{\mathbf{q}}{m_e})$
$\mathcal{O}_5 = i\mathbf{S}_\chi \cdot (\frac{\mathbf{q}}{m_e} \times \mathbf{v}_{\mathrm{el}}^\perp)\mathbb{1}_e$	$\mathcal{O}_{14} = i(\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_e})(\mathbf{S}_e \cdot \mathbf{v}_{\mathrm{el}}^\perp)$
$\mathcal{O}_6 = (\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_e})(\mathbf{S}_e \cdot \frac{\mathbf{q}}{m_e})$	$\mathcal{O}_{15} = i\mathcal{O}_{11}[(\mathbf{S}_e \times \mathbf{v}_{\mathrm{el}}^\perp) \cdot \frac{\mathbf{q}}{m_e}]$
$\mathcal{O}_7 = \mathbf{S}_e \cdot \mathbf{v}_{\mathrm{el}}^\perp \mathbb{1}_\chi$	$\mathcal{O}_{17} = i\frac{\mathbf{q}}{m_e} \cdot \boldsymbol{\mathcal{S}} \cdot \mathbf{v}_{\mathrm{el}}^\perp \mathbb{1}_e$
$\mathcal{O}_8 = \mathbf{S}_\chi \cdot \mathbf{v}_{\mathrm{el}}^\perp \mathbb{1}_e$	$\mathcal{O}_{18} = i\frac{\mathbf{q}}{m_e} \cdot \boldsymbol{\mathcal{S}} \cdot \mathbf{S}_e$
$\mathcal{O}_9 = i\mathbf{S}_\chi \cdot (\mathbf{S}_e \times \frac{\mathbf{q}}{m_e})$	$\mathcal{O}_{19} = \frac{\mathbf{q}}{m_e} \cdot \boldsymbol{\mathcal{S}} \cdot \frac{\mathbf{q}}{m_e}$
$\mathcal{O}_{10} = i\mathbf{S}_e \cdot \frac{\mathbf{q}}{m_e}\mathbb{1}_\chi$	$\mathcal{O}_{20} = (\mathbf{S}_e \times \frac{\mathbf{q}}{m_e}) \cdot \boldsymbol{\mathcal{S}} \cdot \frac{\mathbf{q}}{m_e}$

PHYSICAL REVIEW RESEARCH **2**, 033195 (2020)

Atomic responses to general dark matter-electron interactions

Riccardo Catena[1,*] Timon Emken[1,†] Nicola A. Spaldin[2,‡] and Walter Tarantino[2,§]
[1]*Chalmers University of Technology, Department of Physics, SE-412 96 Göteborg, Sweden*
[2]*Department of Materials, ETH Zürich, CH-8093 Zürich, Switzerland*

Used for Xe and Ar (atomic wavefuncitons)

Credit: PhysRevResearch 2 033195, https://arxiv.org/pdf/2105.02233.pdf

CURRENT RESULTS

- General QFT has been used to determine all general crystal responses.

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$\mathcal{O}_{10} = i\mathbf{S}_e \cdot \frac{\mathbf{q}}{m_e} \mathbb{1}_\chi$	$\mathcal{O}_{20} = (\mathbf{S}_e \times \frac{\mathbf{q}}{m_e}) \cdot \boldsymbol{\mathcal{S}} \cdot \frac{\mathbf{q}}{m_e}$

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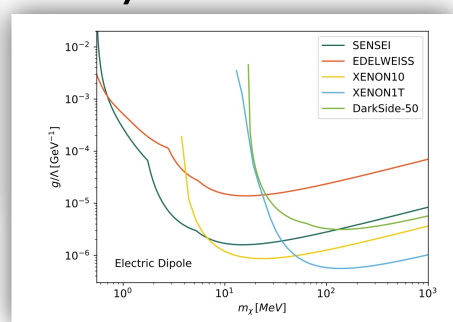
[2]*Department of Materials, ETH Zürich, CH-8093 Zürich, Switzerland*

Used for Xe and Ar (atomic wavefuncitons)

- These general responses have been implemented to Quantum Espresso and we calculated interaction rates for Si and Ge crystals.

Crystal responses to general dark matter-electron interactions

Riccardo Catena,[1,*] Timon Emken,[2,1,†] Marek Matas,[3,‡] Nicola A. Spaldin,[3,§] and Einar Urdshals[1,¶]
[1]*Chalmers University of Technology, Department of Physics, SE-412 96 Göteborg, Sweden*
[2]*The Oskar Klein Centre, Department of Physics, Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden*
[3]*Department of Materials, ETH Zürich, CH-8093 Zürich, Switzerland*

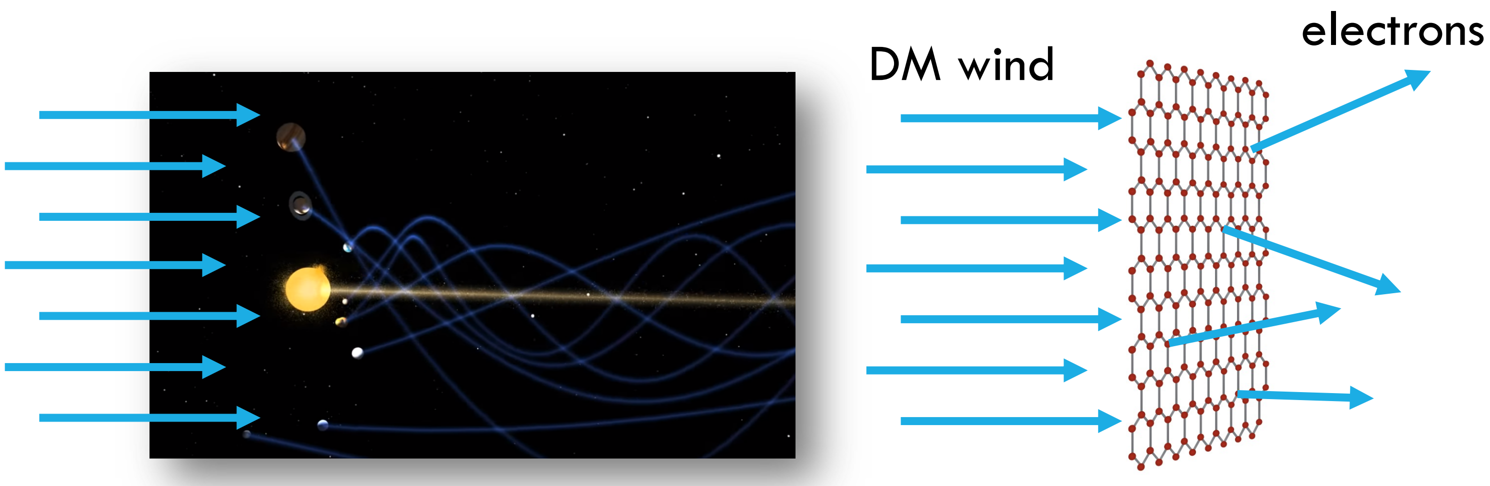


ETH zürich

Credit: PhysRevResearch 2 033195, https://arxiv.org/pdf/2105.02233.pdf

CURRENT GOALS

- Graphene – resolving angular dependence of the interaction with QE and producing predictions for the sensitivity of PTOLEMY.

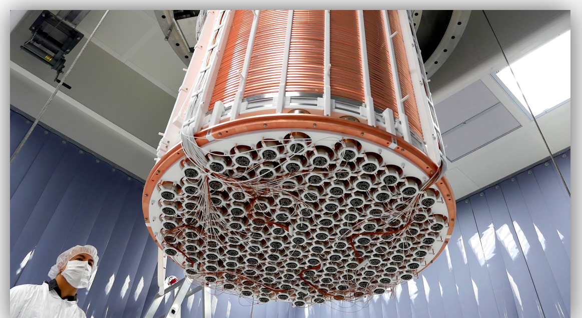
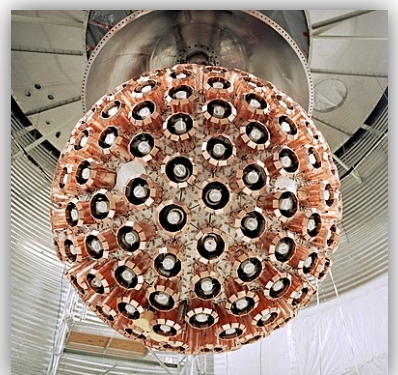
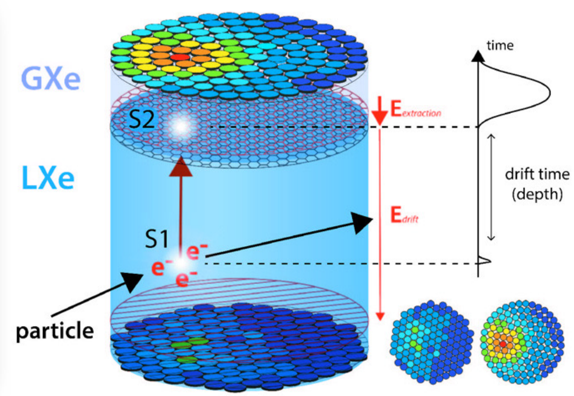


By pointing graphene layer towards and away from the DM wind, we can discriminate background events.

Credit: https://www.hep.shef.ac.uk/research/dm/drift.php, Hochberg et. al.10.1016/j.physletb.2017.06.051 Phys. Lett. B, https://en.wikipedia.org/wiki/Graphene

CURRENT GOALS

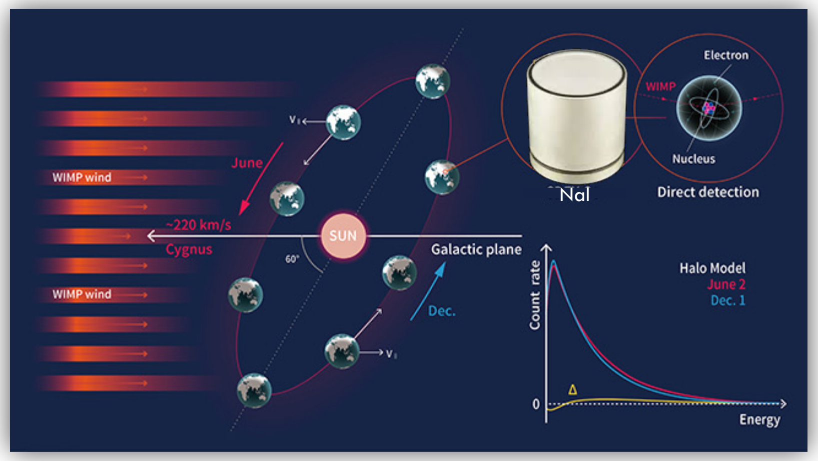
- Graphene – resolving angular dependence of the interaction with QE and producing predictions for the sensitivity of PTOLEMY.
- Noble liquids – modelling liquid Xe and Ar with the use of DFT and general DM responses.

Credit: https://www.quantamagazine.org/dark-matter-experiment-finds-unexplained-signal-20200617/, https://en.wikipedia.org/wiki/DEAP, Reidar Hahn, Fermilab

CURRENT GOALS

- Graphene – resolving angular dependence of the interaction with QE and producing predictions for the sensitivity of PTOLEMY.
- Noble liquids – modelling liquid Xe and Ar with the use of DFT and general DM responses.
- Scintillators – including spin-orbit coupling to correct bandgap and account for spin-dependence in DM interactions.



https://medium.com/starts-with-a-bang/how-the-experiment-that-claimed-to-detect-dark-matter-fooled-itself-6962e7f90e61, https://news.tsinghua.edu.cn/en/info/1002/7885.htm
https://mappingignorance.org/2017/02/13/testing-alternative-dark-matter-hypotesis-clock/

CURRENT GOALS

- Graphene – resolving angular dependence of the interaction with QE and producing predictions for the sensitivity of PTOLEMY.
- Noble liquids – modelling liquid Xe and Ar with the use of DFT and general DM responses.
- Scintillators – including spin-orbit coupling to correct bandgap and account for spin-dependence in DM interactions.
- Determining DM interaction rates from the dielectric function.

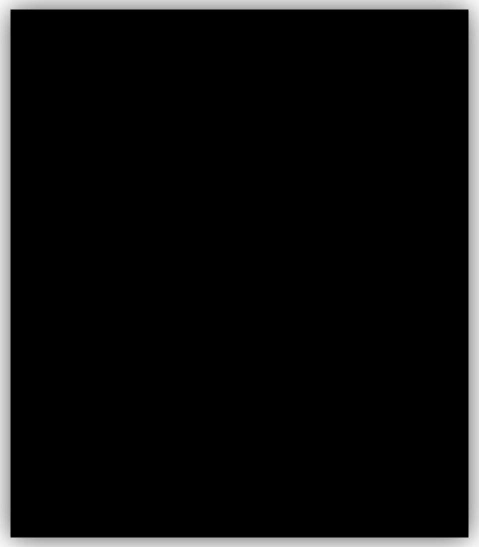
Energy loss function

$$\mathrm{Im}\left[\frac{-1}{\epsilon(\omega, \mathbf{k})}\right]$$

Dielectric function

Credit: arXiv:2101.08275

GOT BETTER IDEAS? JOIN THE HUNT!



THANK YOU FOR YOUR ATTENTION

"Looking for dark matter is like taking a rubber unicorn off a ceiling. Surprisingly hard yet very rewarding."

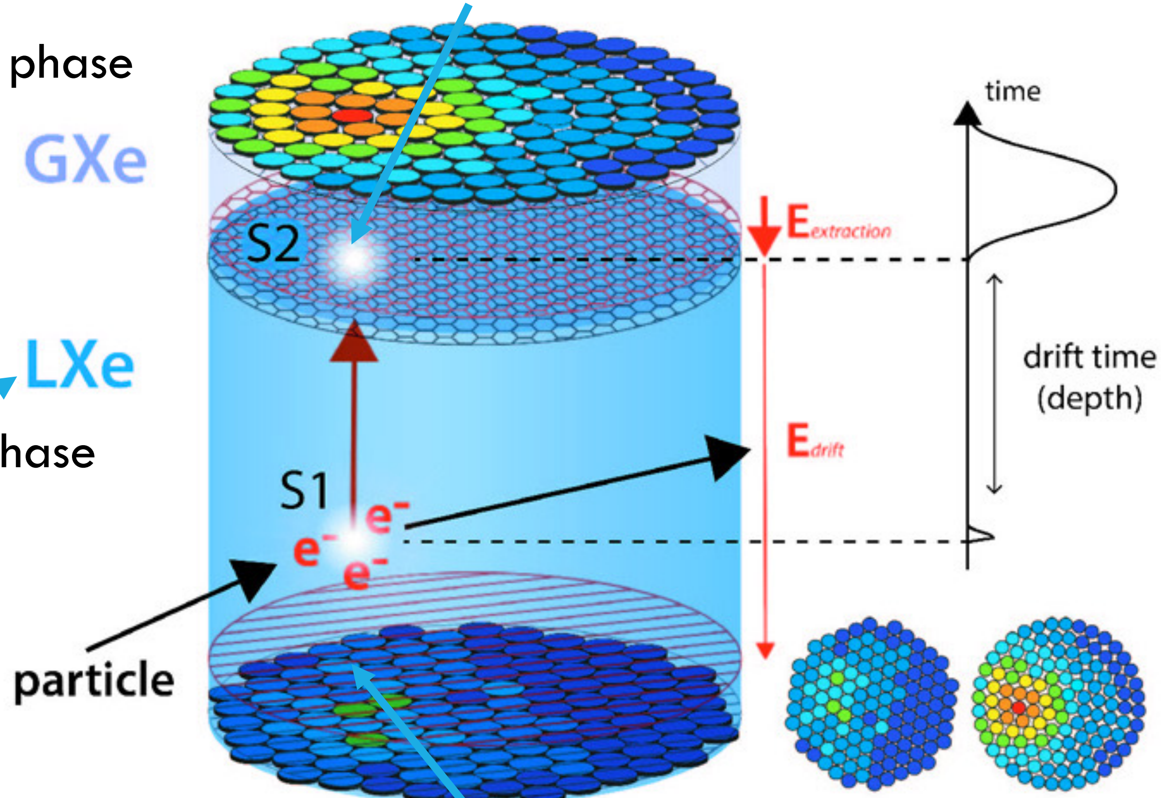
BACKUP SLIDES

MATERIALS OF INTEREST

NOBLE LIQUIDS

Drifting e⁻ produce additional photons in gas

Gasious phase



Liquid phase

~ 7eV excitations produce photons

Credit: https://astronomynow.com/2020/06/21/scientists-ponder-inconclusive-data-from-dark-matter-experiment/,
https://www.gssi.it/communication/news-events/item/67-first-data-from-the-new-dark-matter-hunter-is-ready-darkside-50-a-successful-technology,
https://www.researchgate.net/figure/Timeline-and-evolution-of-the-XENON-Dark-Matter-Project-and-DARWIN-in-its-context_fig5_339240163/actions#reference

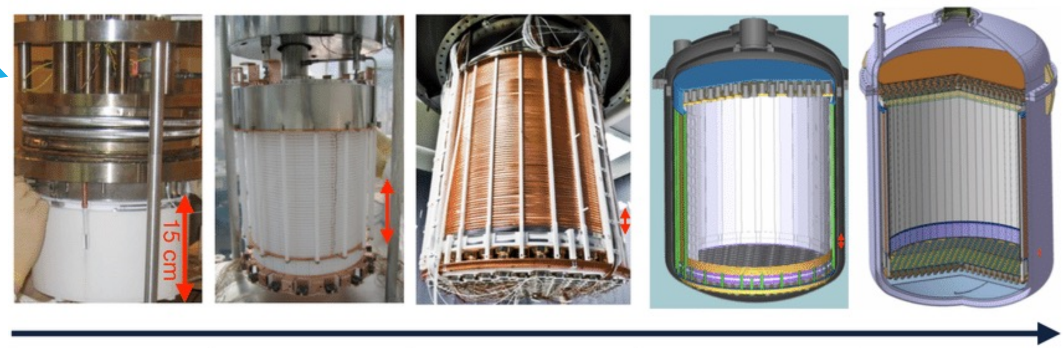
NOBLE LIQUIDS

Xe, Ar detectors primarily for nuclear recoil experiments

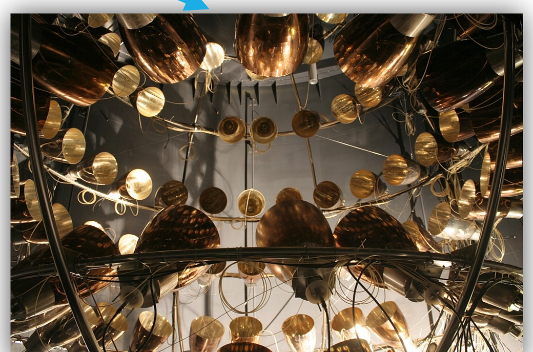
- Similar mass of the nucleus w.r.t. the expected WIMP scale
- Sensitive to single-electron excitations

Xe ~12.4 eV

Ar ~16 eV



XENON10	XENON100	XENON1T	XENONnT	DARWIN
2005 – 2007	2008 – 2016	2012 – 2018	2019 – 2023	2025 –
~15 kg	~62 kg	~2 t	~5.9 t	40 t
15 cm	30 cm	1 m	1.5 m	2.6 m
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2



Darkside experiment

Credit: https://astronomynow.com/2020/06/21/scientists-ponder-inconclusive-data-from-dark-matter-experiment/,
https://www.gssi.it/communication/news-events/item/67-first-data-from-the-new-dark-matter-hunter-is-ready-darkside-50-a-successful-technology,
https://www.researchgate.net/figure/Timeline-and-evolution-of-the-XENON-Dark-Matter-Project-and-DARWIN-in-its-context_fig5_339240163/actions#reference

NOBLE LIQUIDS

Some of the largest constraints on DM!

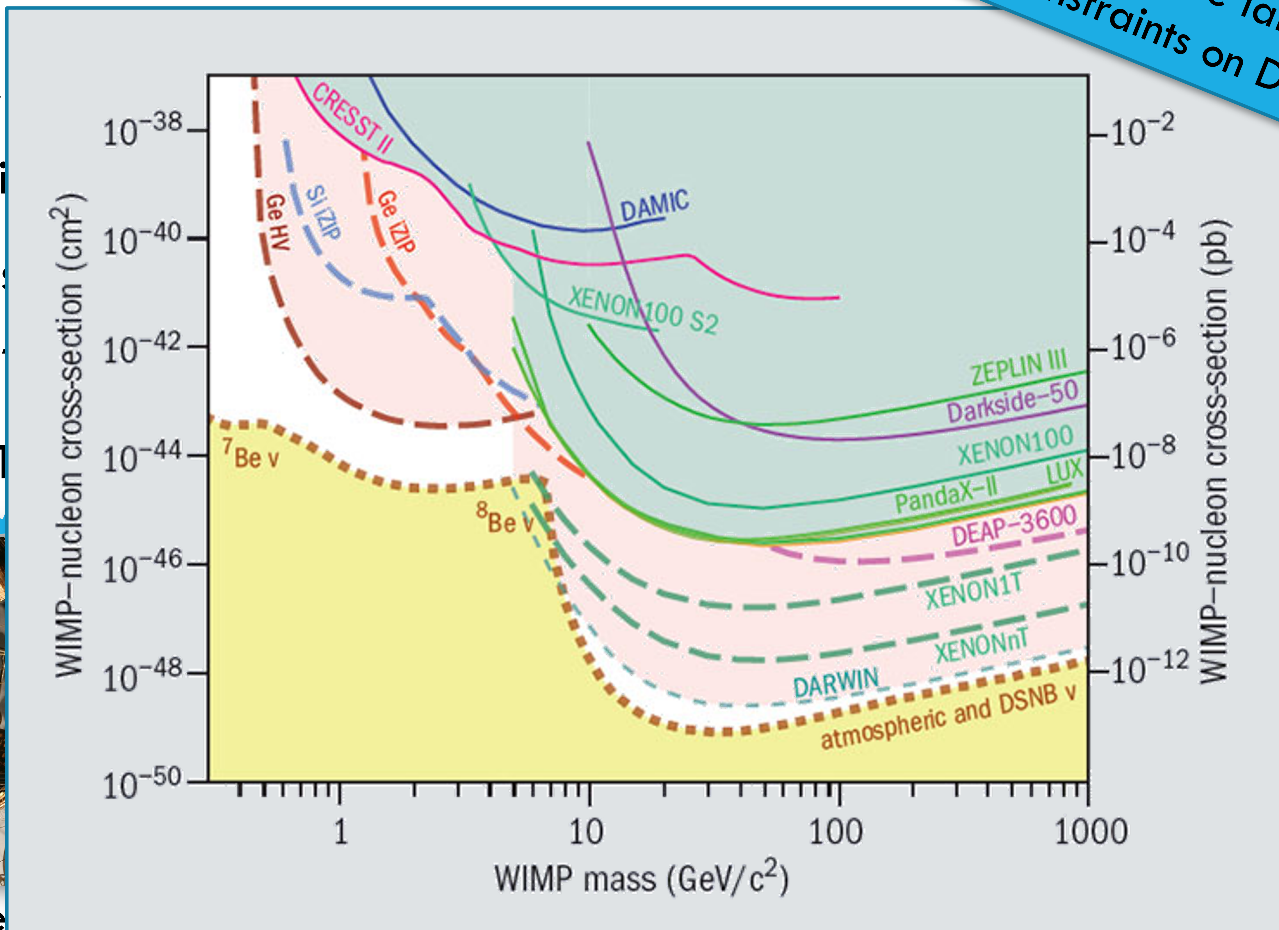
Xe, A

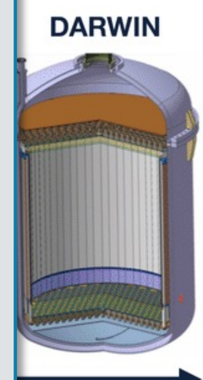
- Simi
- Sens

Xe ~

Ar ~1

Darkside



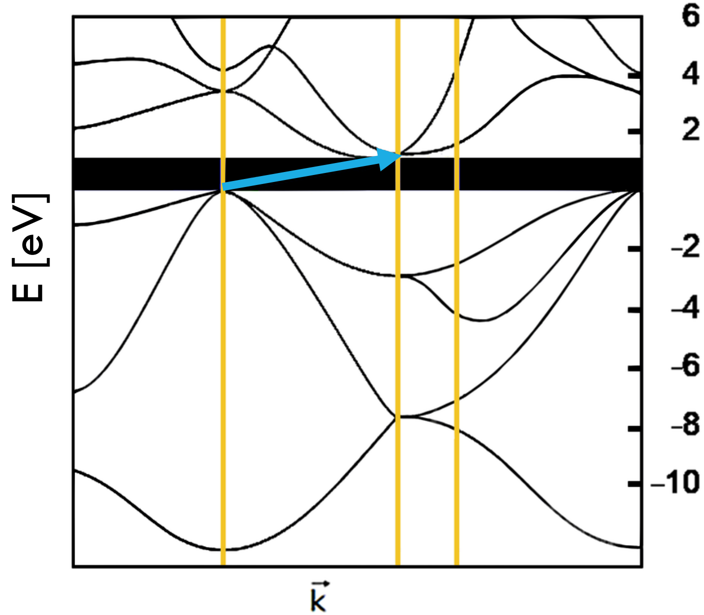


2025 –
40 t
2.6 m
~10^{-49} cm^2

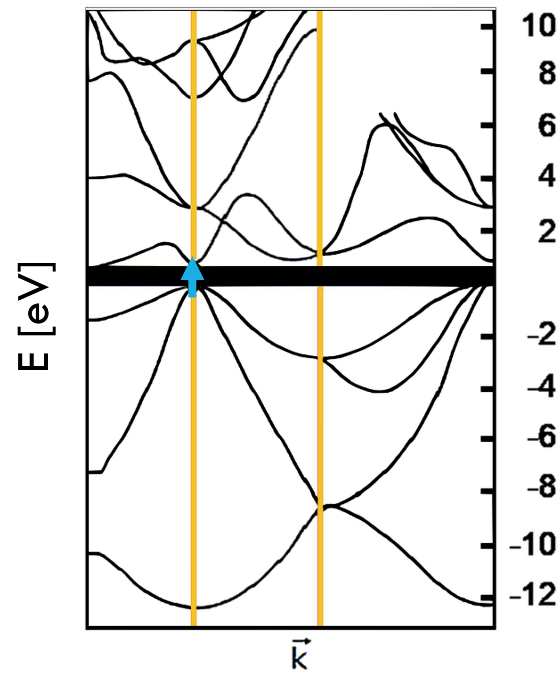
Credit: https://astronomynow.com/2020/06/21/scientists-ponder-inconclusive-data-from-dark-matter-experiment/, https://www.gssi.it/communication/news-events/item/67-first-data-from-the-new-dark-matter-hunter-is-ready-darkside-50-a-successful-technology, https://www.researchgate.net/figure/Timeline-and-evolution-of-the-XENON-Dark-Matter-Project-and-DARWIN-in-its-context_fig5_339240163/actions#reference

SEMICONDUCTORS

Silicon – 1.12 eV



Germanium – 0.67 eV



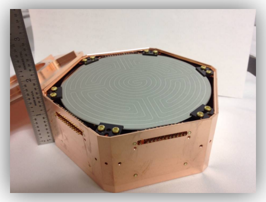
+ indirect bandgap

- larger bandgap

+ smaller bandgap

- direct bandgap

Electron-hole generation and readout similar to CCDs

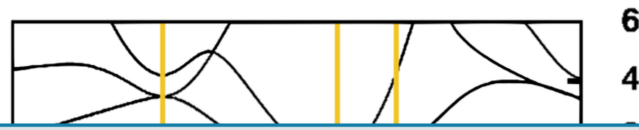


Credit: https://link.springer.com/article/10.1007/s00418-018-1753-y/figures/6, https://astro.fnal.gov/science/dark-matter/supercdms/

SEMICONDUCTORS

Germanium 0.67 eV

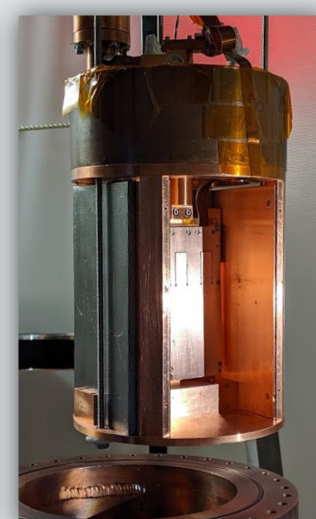
Silicon – 1.12 eV



$E_{gap} \sim eV - m_{DM} \sim MeV$

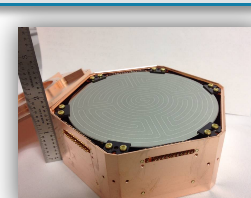
CDMS, SuperCDMS - Ge

SENSEI – Si



Credit: https://www.quantamagazine.org/dark-matter-experiment-finds-unexplained-signal-20200617/, https://news.fnal.gov/2020/06/sensei-gets-quiet/

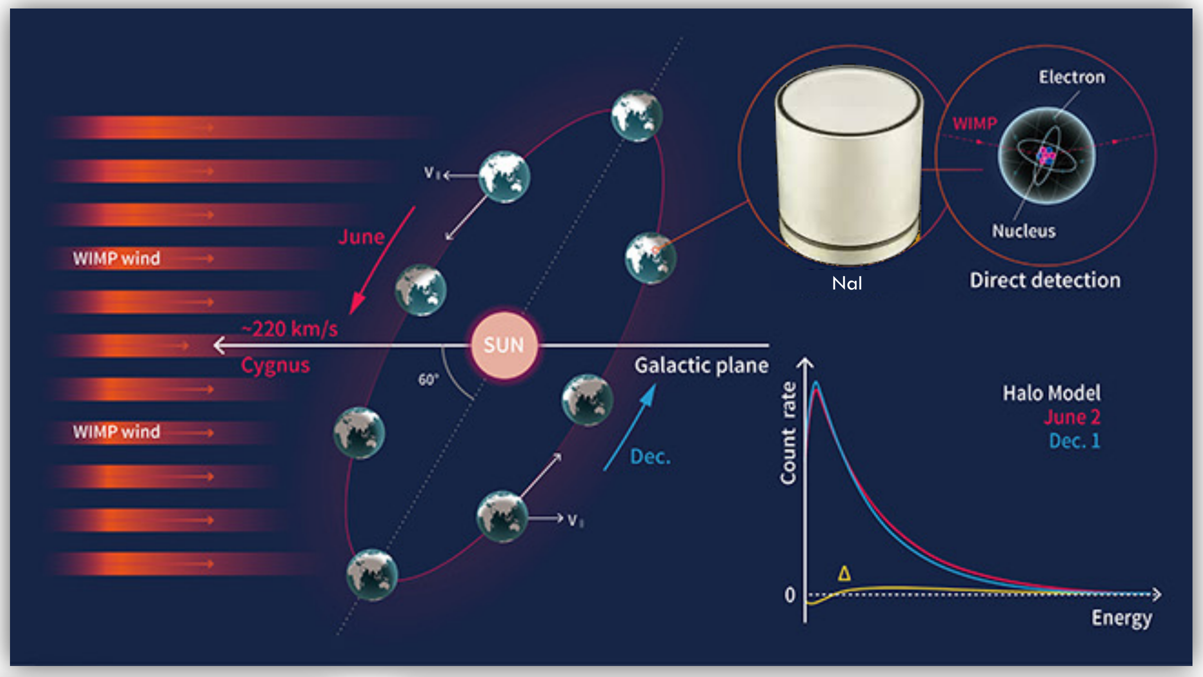
Electron-hole generation and readout similar to CCDs

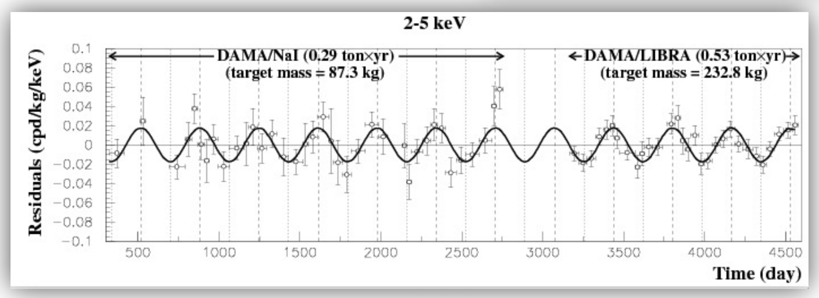


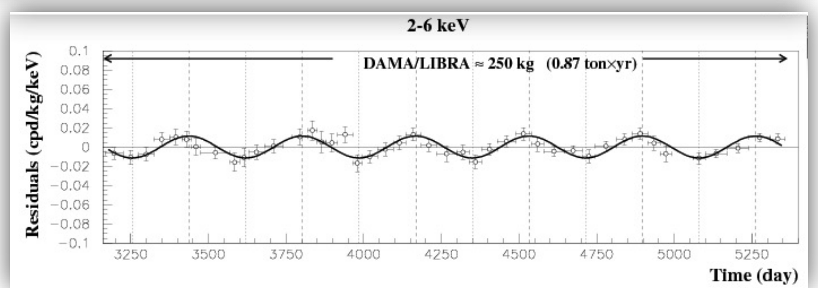
Credit: https://link.springer.com/article/10.1007/s00418-018-1753-y/figures/6, https://astro.fnal.gov/science/dark-matter/supercdms/

SCINTILLATORS

- Annual oscillations
- DAMA/LIBRA
- NaI – 12.9 σ
- E_{gap} ~ 5.8 eV
- E ~ 2-6 keV
- High cross section







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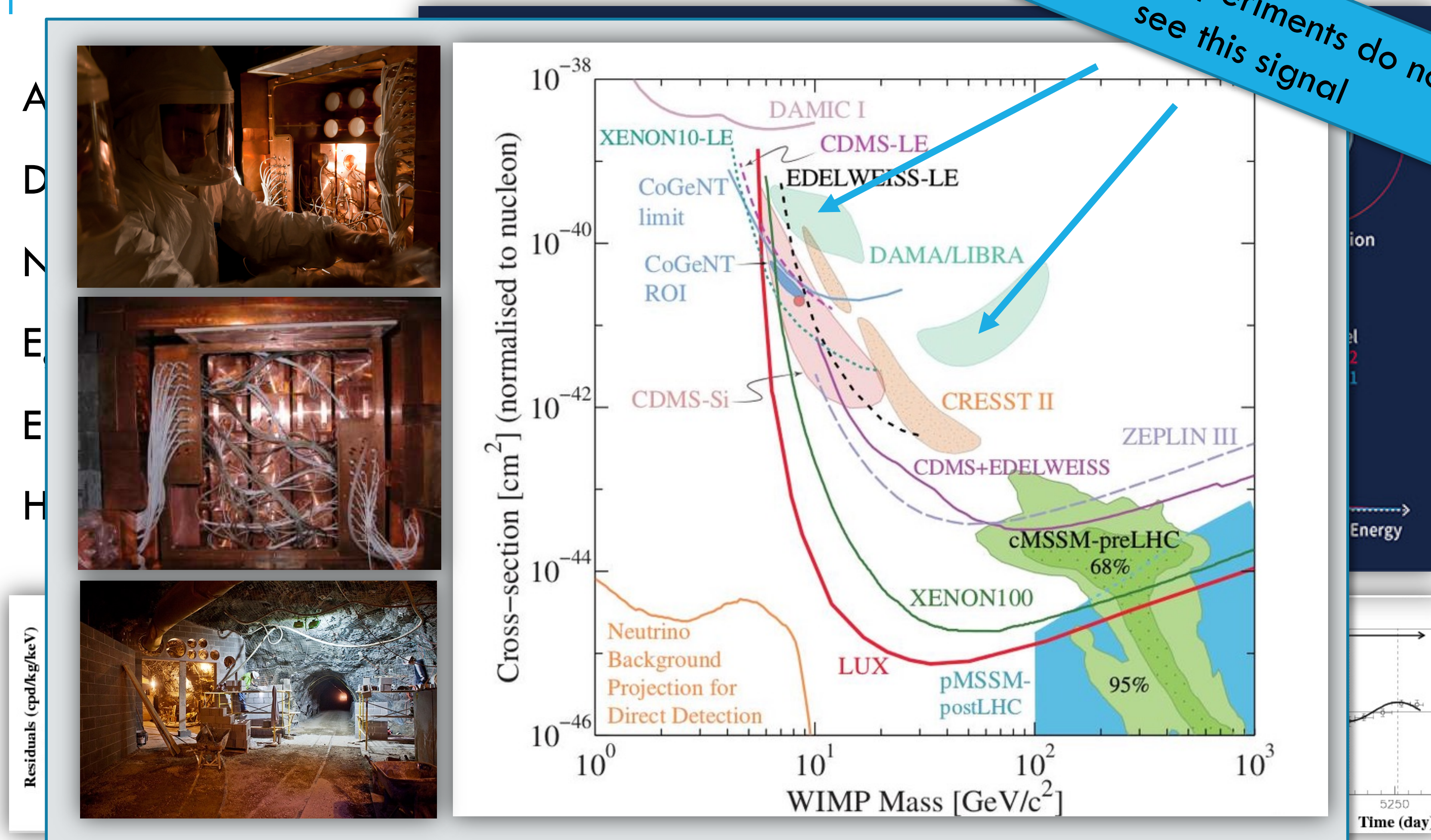
https://medium.com/starts-with-a-bang/how-the-experiment-that-claimed-to-detect-dark-matter-fooled-itself-6962e7f90e61, https://news.tsinghua.edu.cn/en/info/1002/7885.htm
https://mappingignorance.org/2017/02/13/testing-alternative-dark-matter-hypotesis-clock/

SCINTILLATORS

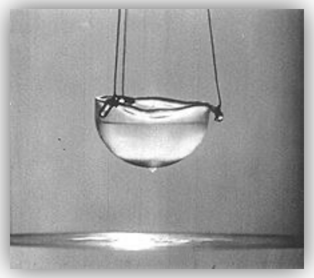
- A
- D
- N
- E
- E
- H

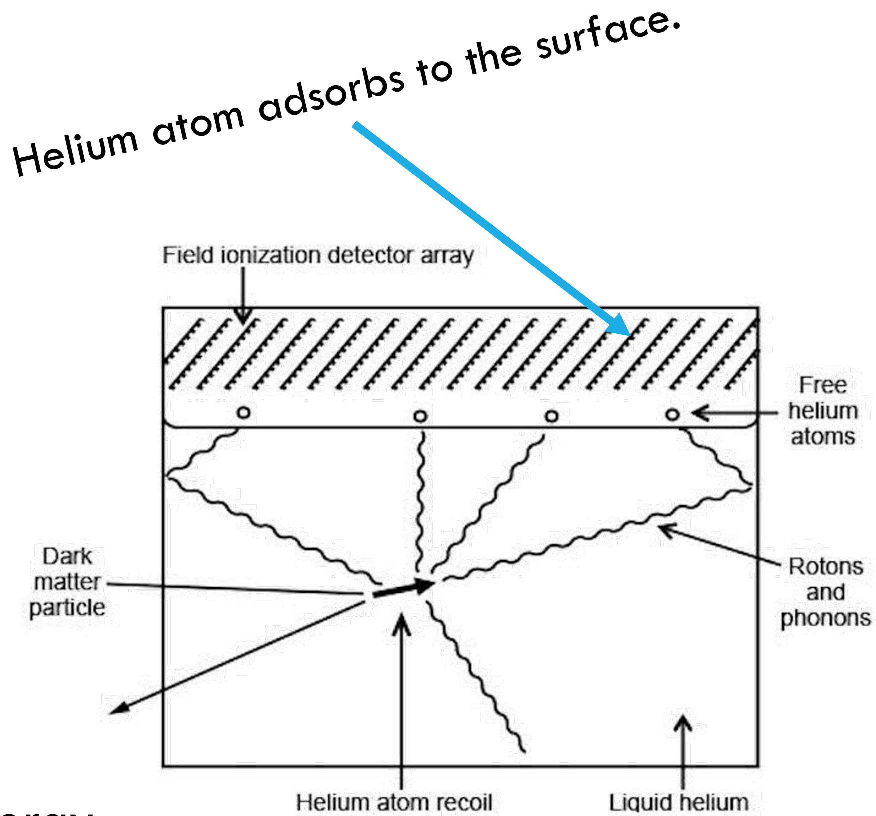


Other experiments do not see this signal

https://medium.com/starts-with-a-bang/how-the-experiment-that-claimed-to-detect-dark-matter-fooled-itself-6962e7f90e61, https://news.tsinghua.edu.cn/en/info/1002/7885.htm
https://mappingignorance.org/2017/02/13/testing-alternative-dark-matter-hypotesis-clock/, https://www.researchgate.net/figure/Particle-dark-matter-searches-current-status-of-constraints-on-WIMP-dark-matter-from_fig2_281896319

LIQUID HELIUM



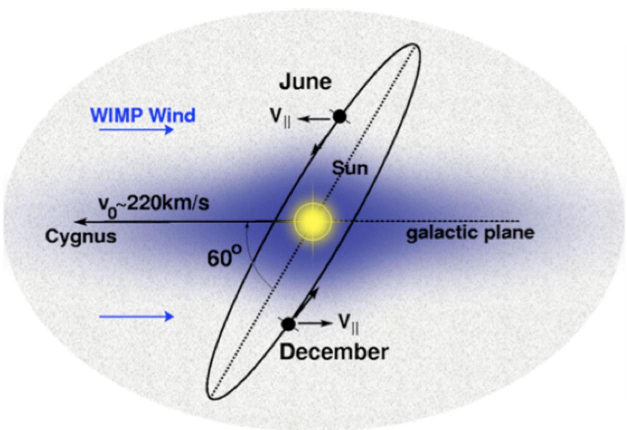


- Low mass for DM-nucleus interactions.
- It can be manufactured very pure.
- meV phonons can eject Helium atoms.
- Adsorption gives ~10x the ejection energy.
- Dark matter of m_{DM} ~ MeV can be probed.
- You can reach keV by using two back-to-back phonons.

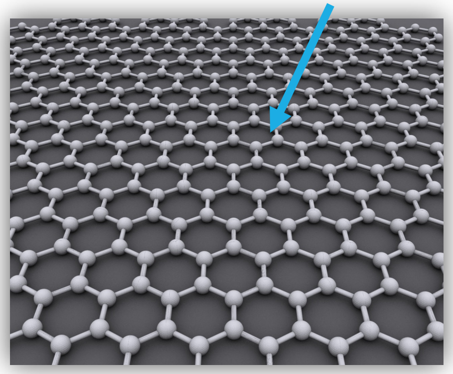
Credit: https://www.brown.edu/news/2017-11-01/darkmatter, https://en.wikipedia.org/wiki/Superfluidity

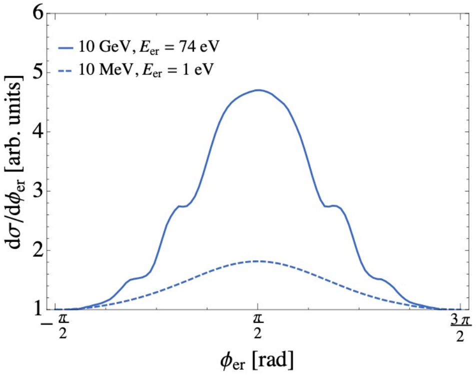
GRAPHENE

Directionality of DM wind is a crucial help to discriminate from background.



2D plane





- Experiment Ptolemy tailored to search for relic neutrinos.
- Stripped of Tritium atoms, can look for DM.
- Is large mass of graphene detector viable?

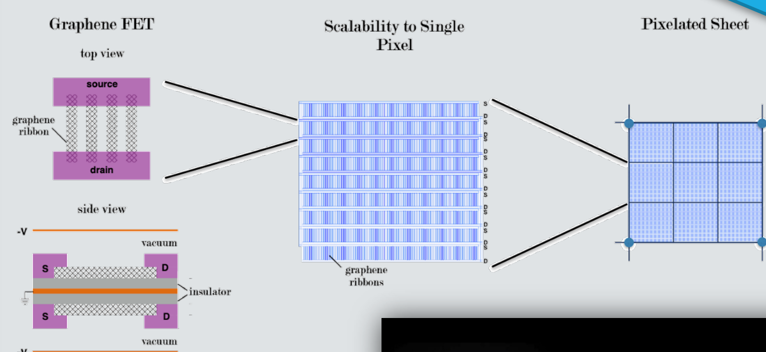
Credit: https://www.hep.shef.ac.uk/research/dm/drift.php, Hochberg et. al.10.1016/j.physletb.2017.06.051 Phys. Lett. B, https://en.wikipedia.org/wiki/Graphene

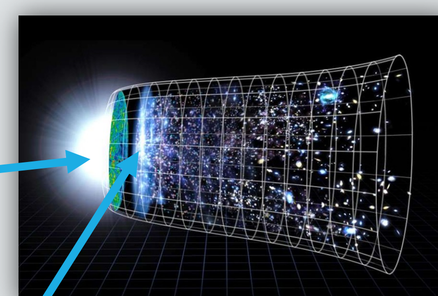
GRAPHENE

Directionality of DM wind is a crucial help to discriminate

~ 5 eV work-function of graphene – $m_{DM} \sim$ few MeV

Ptolemy prototype has been already tested.





The plan:

$\sim$ kg of graphene

$\sim$ cube of the length of 10m

Relic neutrinos – 0.18 s

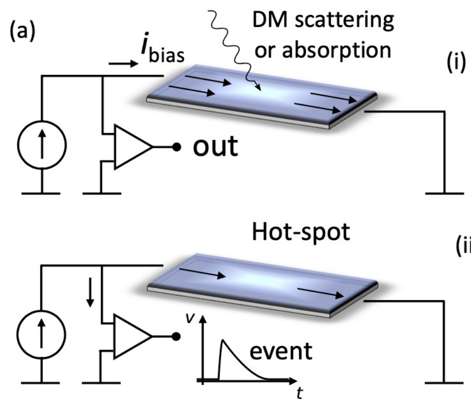
Microwave background – 400 kyr

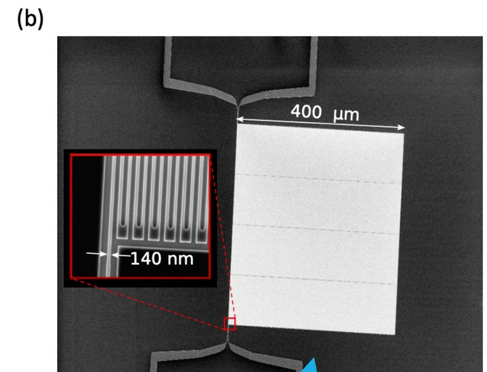
Credit: https://www.quantamagazine.org/dark-matter-experiment-finds-unexplained-signal-20200617/, http://www.palmiaobservatory.com/2019/04/relic-cosmic-neutrino-background.html

Credit: https://www.hep.shef.ac.uk/research/dm/drift.php, Hochberg et. al.10.1016/j.physletb.2017.06.051 Phys. Lett. B, https://en.wikipedia.org/wiki/Graphene

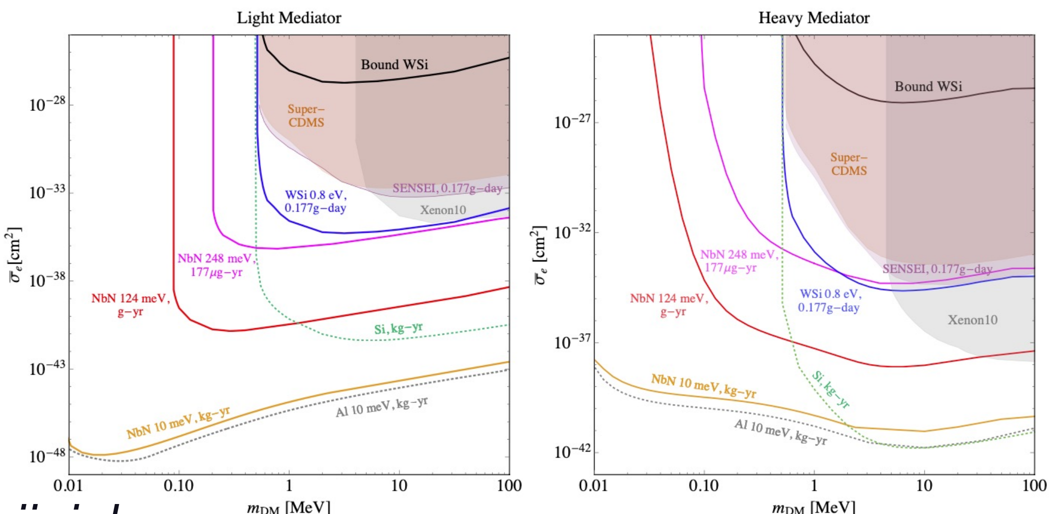
SUPERCONDUCTORS

- Breaking Cooper pairs – meV
- Probed m_{DM} ~ keV
- In bulk with a TES readout.
- As superconducting nanowires.
- Bad for dark photon mediators.





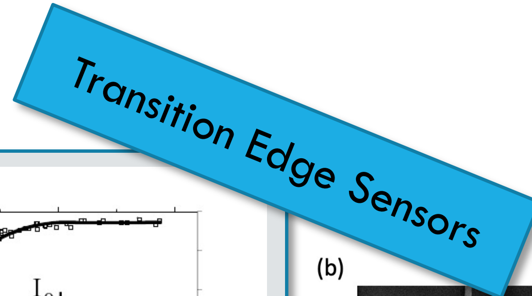
Already probing new parameter space!

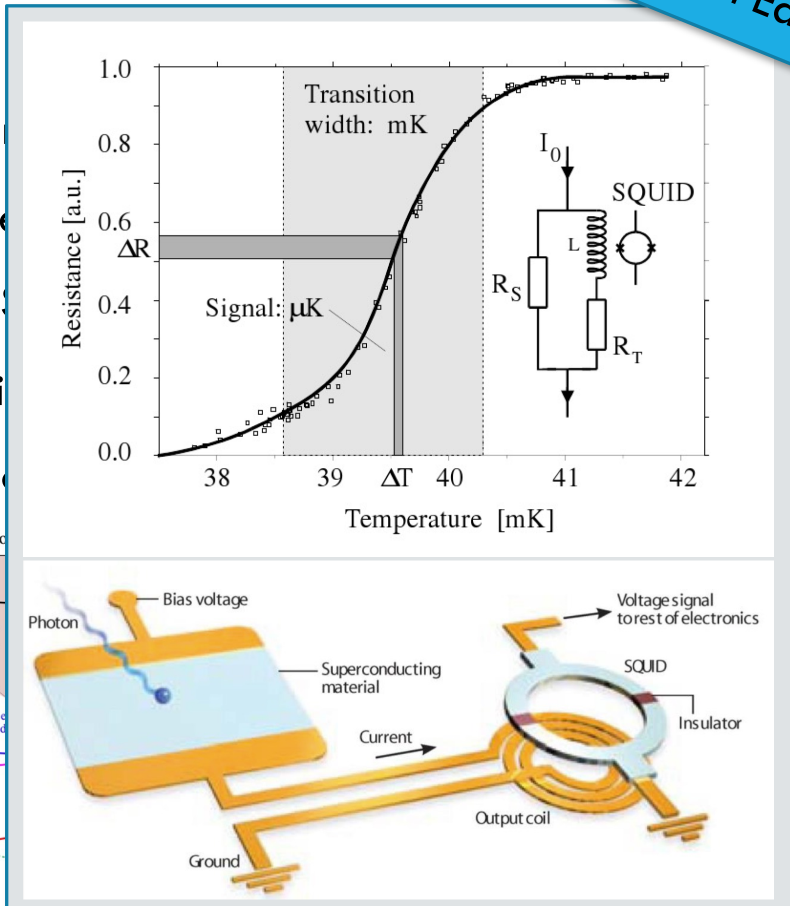


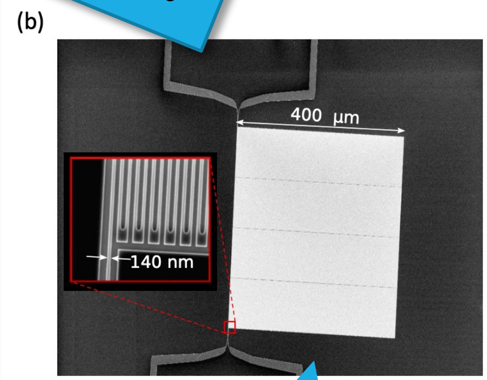
Credit: https://arxiv.org/pdf/1903.05101.pdf

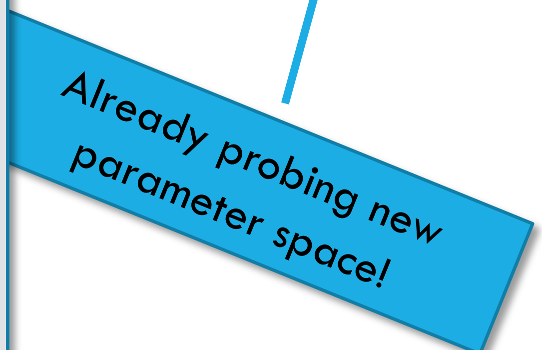
SUPERCONDUCTORS

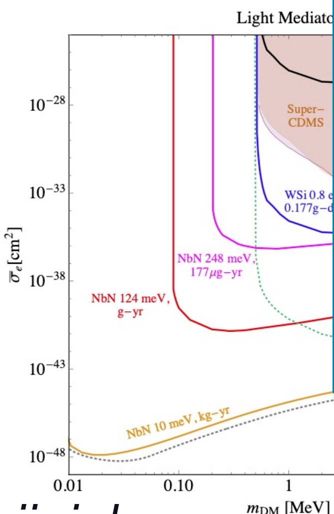
- Breaking Coope
- Probed m_{DM} ~ ke
- In bulk with a TE
- As superconducti
- Bad for dark ph











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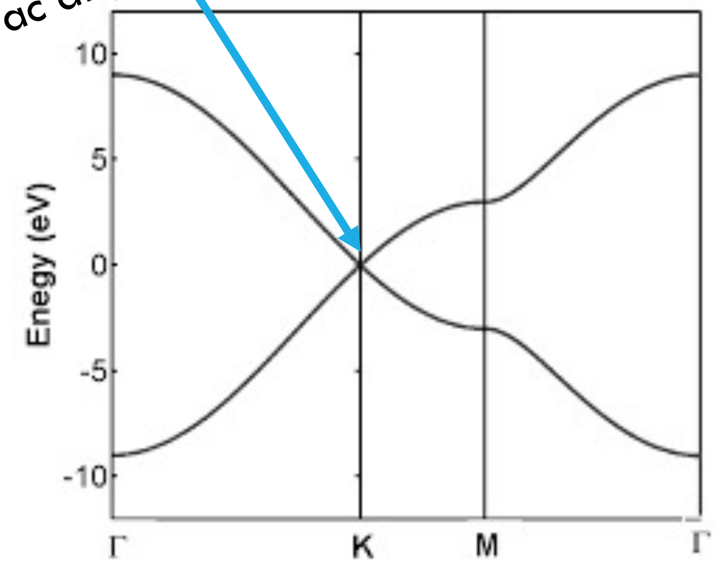
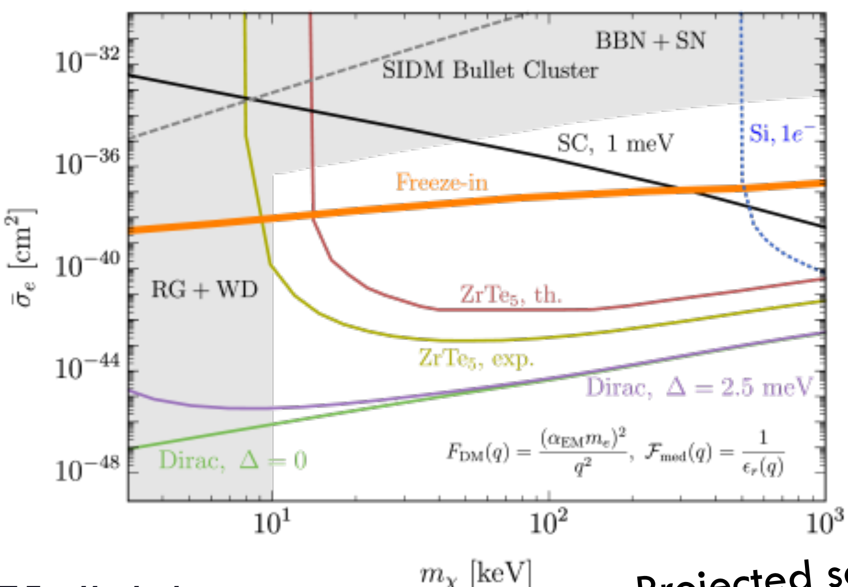
Credit: https://arxiv.org/pdf/1903.05101.pdf, https://www.researchgate.net/figure/Transition-curve-of-a-transition-edge-sensor-TES-between-superconductor-state-and_fig7_30003377
https://www.slac.stanford.edu/econf/C140914/talks/moixb3_talk.pdf

DIRAC MATERIALS

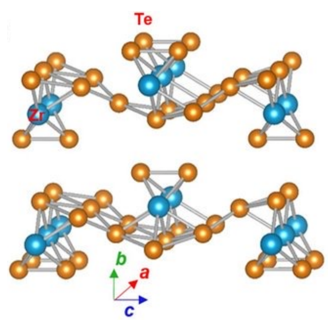
- Similar to a semiconductor (for DM)
- meV bandgap – m_{DM} ~ keV
- Much better for dark photon models
- TES readout

Dirac dispersion – $E \sim v_F k$





$ZrTe_5$ is one of the leading materials



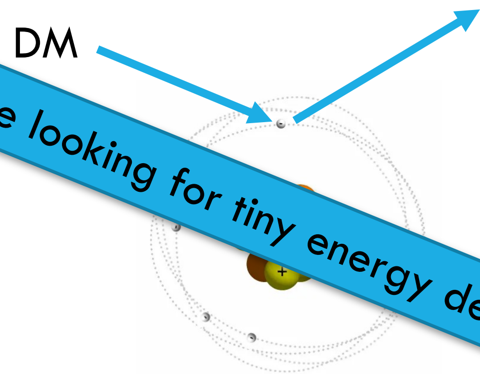
Projected sensitivity is pushing the limits

Credit: https://arxiv.org/abs/1708.08929, https://www.researchgate.net/publication/323998510_Evidence_for_Layered_Quantized_Transport_in_Dirac_Semimetal_ZrTe5

ENERGY TRANSFER

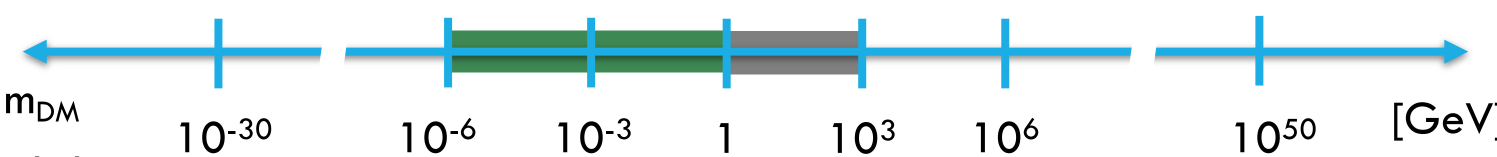
- If all kinetic energy is transferred in the ideal case, we get

$$E_{deposit} \sim m_{DM}v^2 \sim 10^{-6}m_{DM}$$



We are looking for tiny energy depositions!

[keV]	[MeV]	[GeV]	m_{DM}
↓	↓	↓	
[meV]	[eV]	[keV]	$E_{deposit}$



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Credit: http://www.zsvltava.cz/fyzika/?p=102