NEW IDEAS FOR DIRECT DETECTION OF DARK MATTER

Jan Conrad

The puzzle of Dark Matter,
DESY, October 2018

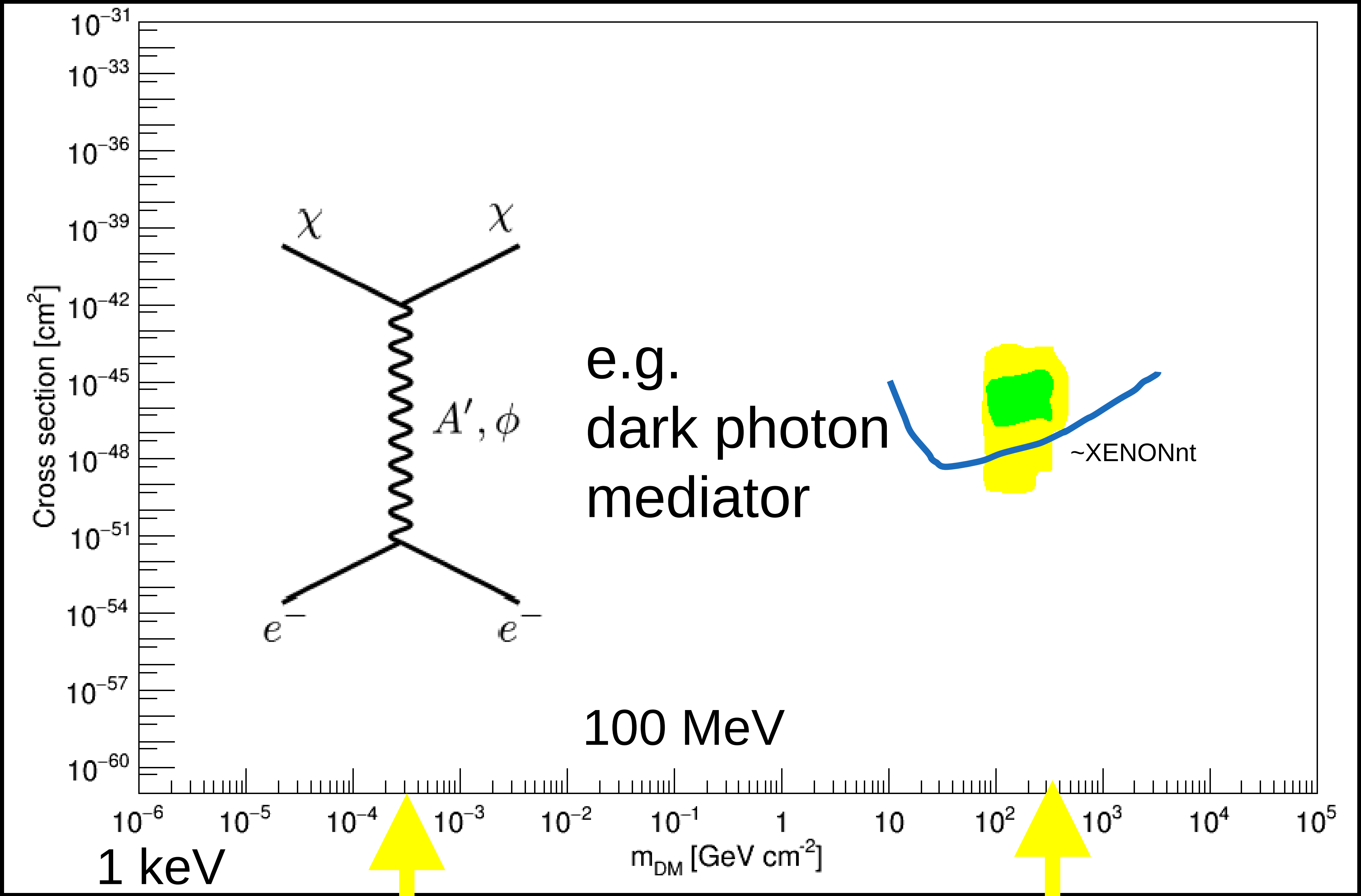
LAST TIME IN HAMBURG 2011

Concluding remarks

- Essentially all bases covered.
- ”Stacking” methodology big step forward
  - We have reached the predicted 5yr sensitivity (optimistic) already now
  - currently constraining thermal WIMP cross-section for masses < 30 GeV (bbar, mumu+) *including J-factor uncertainties*
  - Improvement by around a factor 4-5 until the end of the Fermi-LAT mission (only with dwarfs).
- All-sky diffuse analyses: challenging.
- Line features: robust analysis, clear signature, but detector can fool
- *Close to submission/internal refereeing: Dwarf stacking, DM Satellites, update on line search, further down: clusters, anisotropies, halo.*
- Looking ahead: ”vanilla” CTA will be competitive above ~300 GeV.

Disclaimer: I have an ongoing bet for XENONnT/LZ to discover WIMPs

DARK SECTOR DARK MATTER



Super-light dark matter (absorption)

Light dark matter (scattering) == Dark Sector Dark Matter

WIMPs

KINEMATICS OF DIRECT DETECTION

$$E_D = \frac{q^2}{2m_N} \qquad q_{max} = 2m_{DM}v \qquad \mathrm{v}{\sim}10^{-3}$$

- Nucleon scattering

$$E_D{\sim}1\mathrm{eV} \xrightarrow{\text{yields}} \boldsymbol{m_{DM}{\sim}100\ \mathrm{MeV}}$$

$$E_{kin} = \frac{m_{DM}v^2}{2}{\sim}100\ \mathrm{eV}$$

- Electron scattering

$$E_D{\sim}1\mathrm{eV} \xrightarrow{\text{yields}} \boldsymbol{m_{DM}{\sim}1\ \mathrm{MeV}}$$

$$E_{kin} = \frac{m_{DM}v^2}{2}{\sim}1\ \mathrm{eV}$$

Might want to go to ~keV

COVERED IN THIS TALK

- Future:

$$n_{DM} = \frac{\rho_{DM}}{m_{DM}} \sim \frac{0.4\ GeV}{m_{DM}}$$

Main Science Goal	Experiment	Target	Readout	Estimated Timeline
Sub-GeV Dark Matter (Electron Interactions)	SENSEI	Si	charge	ready to start project (2 yr to deploy 100g)
	DAMIC-1K	Si	charge	ongoing R&D 2018 ready to start project (2 yr to deploy 1 kg)
	UA′(1) liquid Xe TPC	Xe	charge	ready to start project (2 yr to deploy 10kg)
	Scintillator w/ TES readout	GaAs(Si,B)	light	2 yr R&D 2020 in sCDMS cryostat
	NICE; NaI/CsI cooled crystals	NaI CsI	light	3 yr R&D 2020 ready to start project
	Ge Detector w/ Avalanche Ionization Amplification	Ge	charge	3 yr R&D 1 yr 10kg detector 1 yr 100kg detector
	PTOLEMY-G3, 2d graphene	graphene	charge directionality	1 yr fab prototype 1 yr data
	supercond. Al cube	Al	heat	10+ yr program

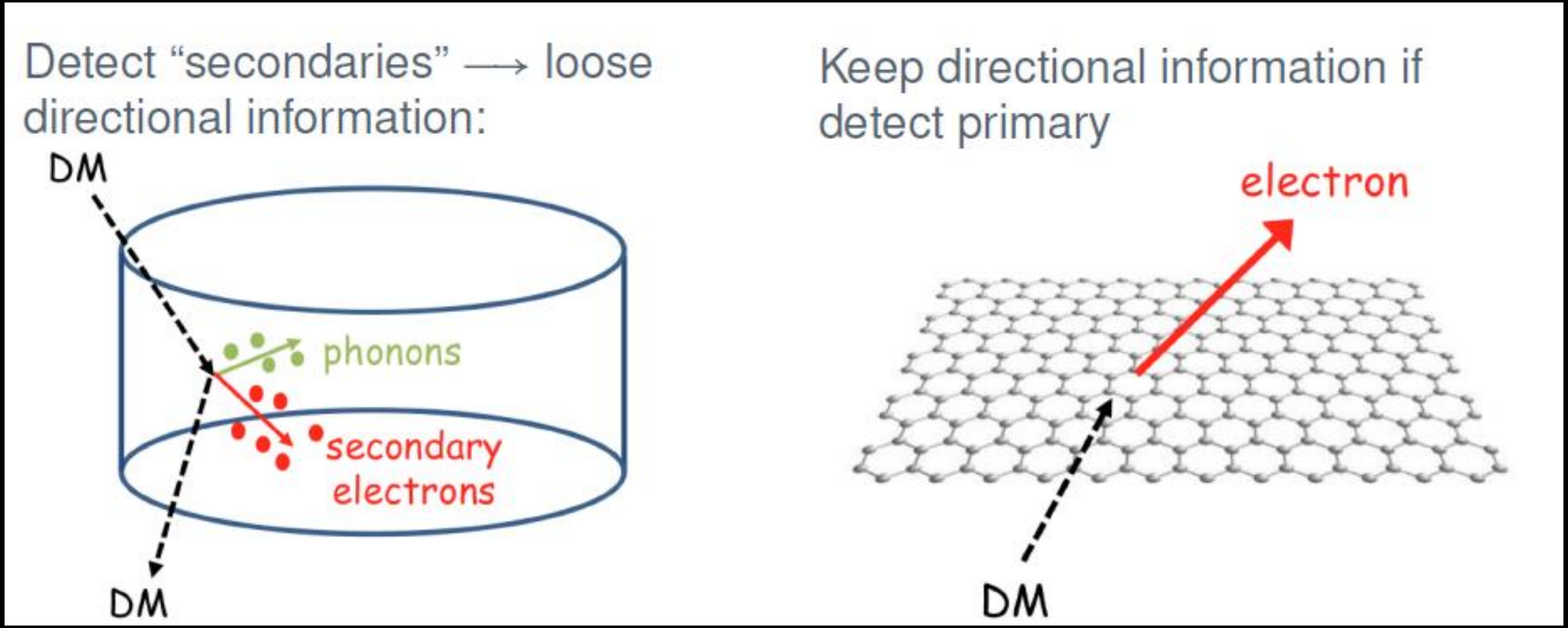
For details and experiments ***targeting nuclear scattering (e.g CRESST etc)***

Battaglieri et al: arxiv:1707.04591

- After the future: Quantum Materials for Dark Matter (QM4DM)

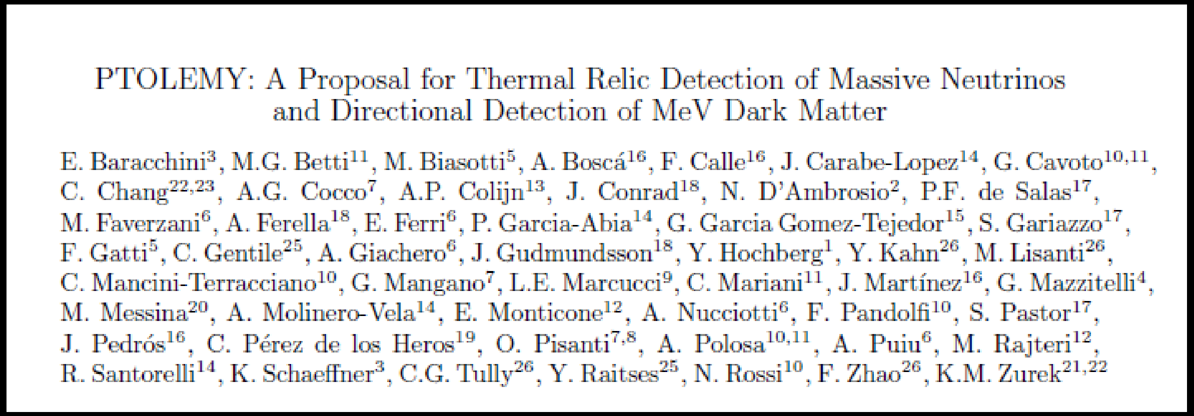
2D TARGETS (E.G. GRAPHENE)

Hochberg et al, Phys. Lett. B 772 (2017) 239



PTOMELY-G3

- Graphene-based
- Main purpose: detection of the cosmic neutrino background
- Phase I: directional dark matter detection
- Phase II: CνB
- Prototype approved for move to LNGS


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

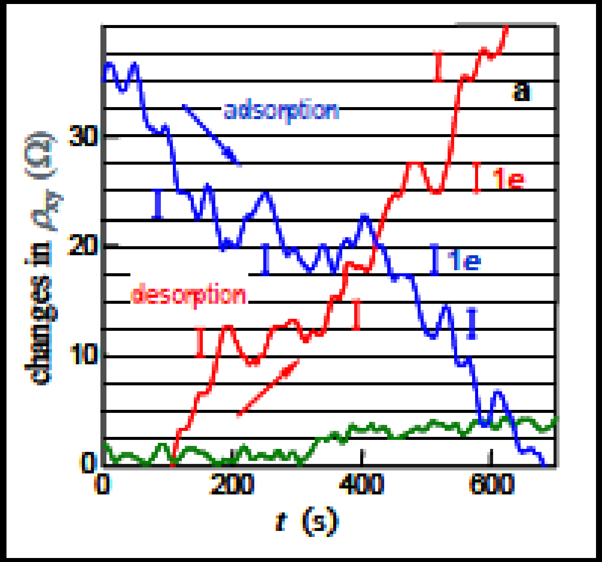
E. Baracchini[3], M.G. Betti[11], M. Biasotti[5], A. Boscá[16], F. Calle[16], J. Carabe-Lopez[14], G. Cavoto[10,11], C. Chang[22,23], A.G. Cocco[7], A.P. Colijn[13], J. Conrad[18], N. D'Ambrosio[2], P.F. de Salas[17], M. Faverzani[6], A. Ferella[18], E. Ferri[6], P. Garcia-Abia[14], G. Garcia Gomez-Tejedor[15], S. Gariazzo[17], F. Gatti[5], C. Gentile[25], A. Giachero[6], J. Gudmundsson[18], Y. Hochberg[1], Y. Kahn[26], M. Lisanti[26], C. Mancini-Terracciano[10], G. Mangano[7], L.E. Marcucci[9], C. Mariani[11], J. Martínez[16], G. Mazzitelli[4], M. Messina[20], A. Molinero-Vela[14], E. Monticone[12], A. Nucciotti[6], F. Pandolfi[10], S. Pastor[17], J. Pedrós[16], C. Pérez de los Heros[19], O. Pisanti[7,8], A. Polosa[10,11], A. Puiu[6], M. Rajteri[12], R. Santorelli[14], K. Schaeffner[3], C.G. Tully[26], Y. Raitses[25], N. Rossi[10], F. Zhao[26], K.M. Zurek[21,22]

Barrachini et al
1808.01892

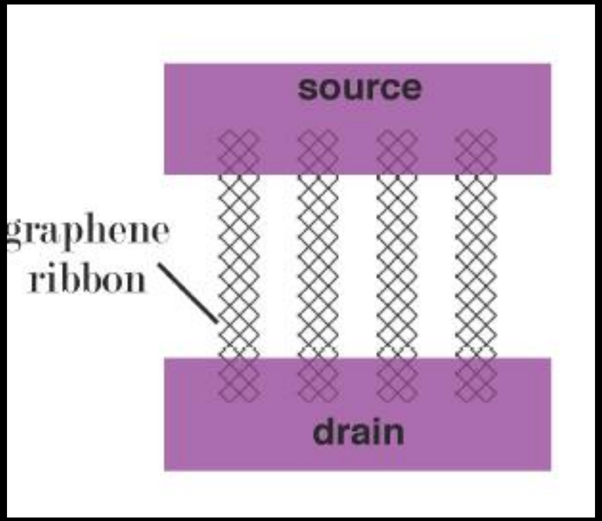
GRAPHENE FIELD EFFECT TRANSISTOR (G-FET)

- The graphene nobel prize was for noting noticable conductivity changes of graphene (in FET configuration) -for added or removed single electrons.

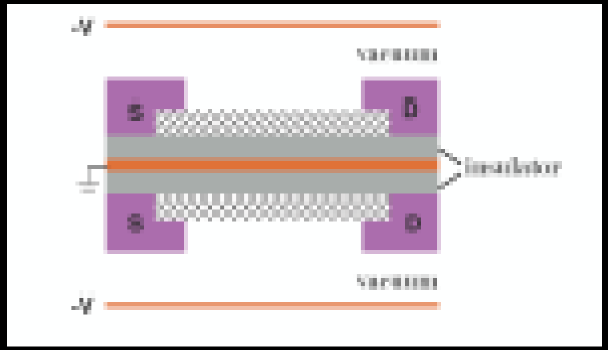
Geim et al, 2004



- Small band gap introduced by cutting into ribbons (~.8eV/width(nm)), i.e. meV gap

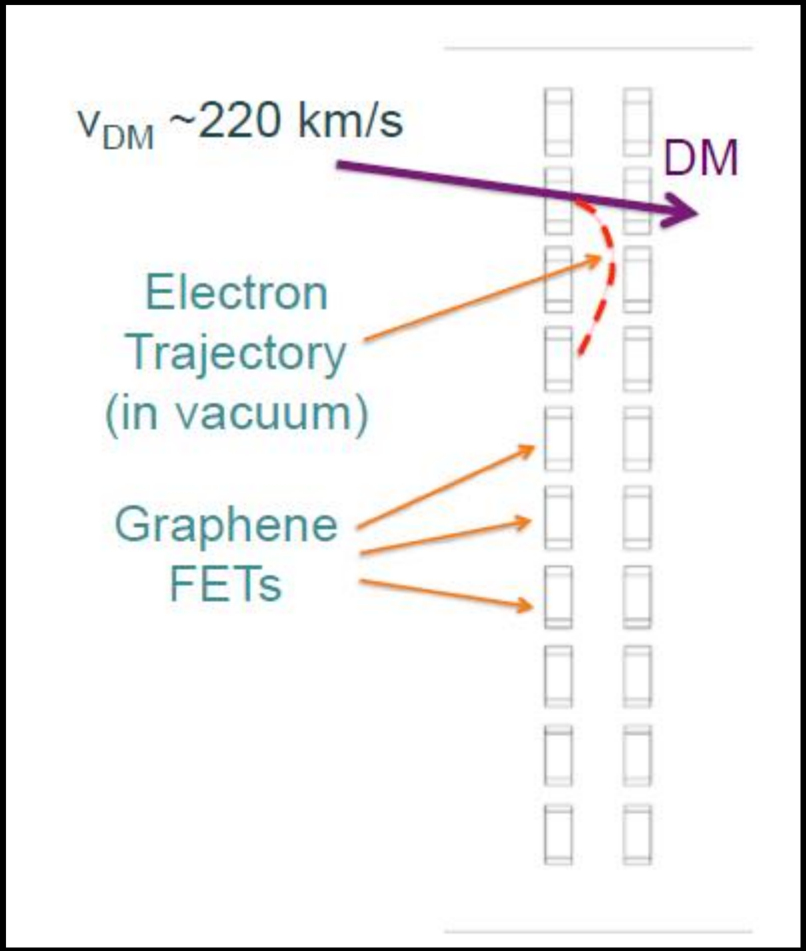


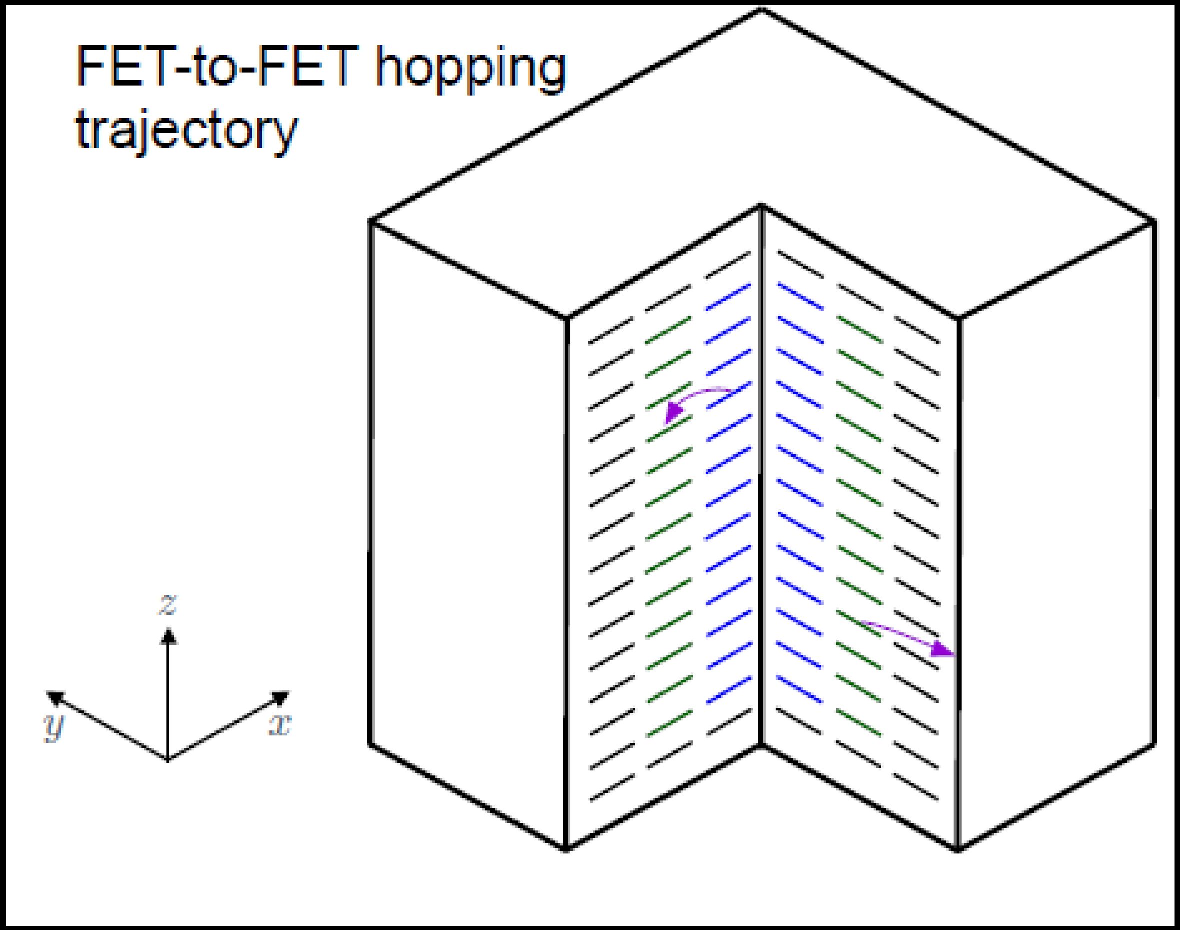
- removing/adding electron makes FET conductive → source/drain current.



DETECTOR CONFIGURATION

Stacked planar arrays of G-FETs
Directionality by FET-to-FET propagation





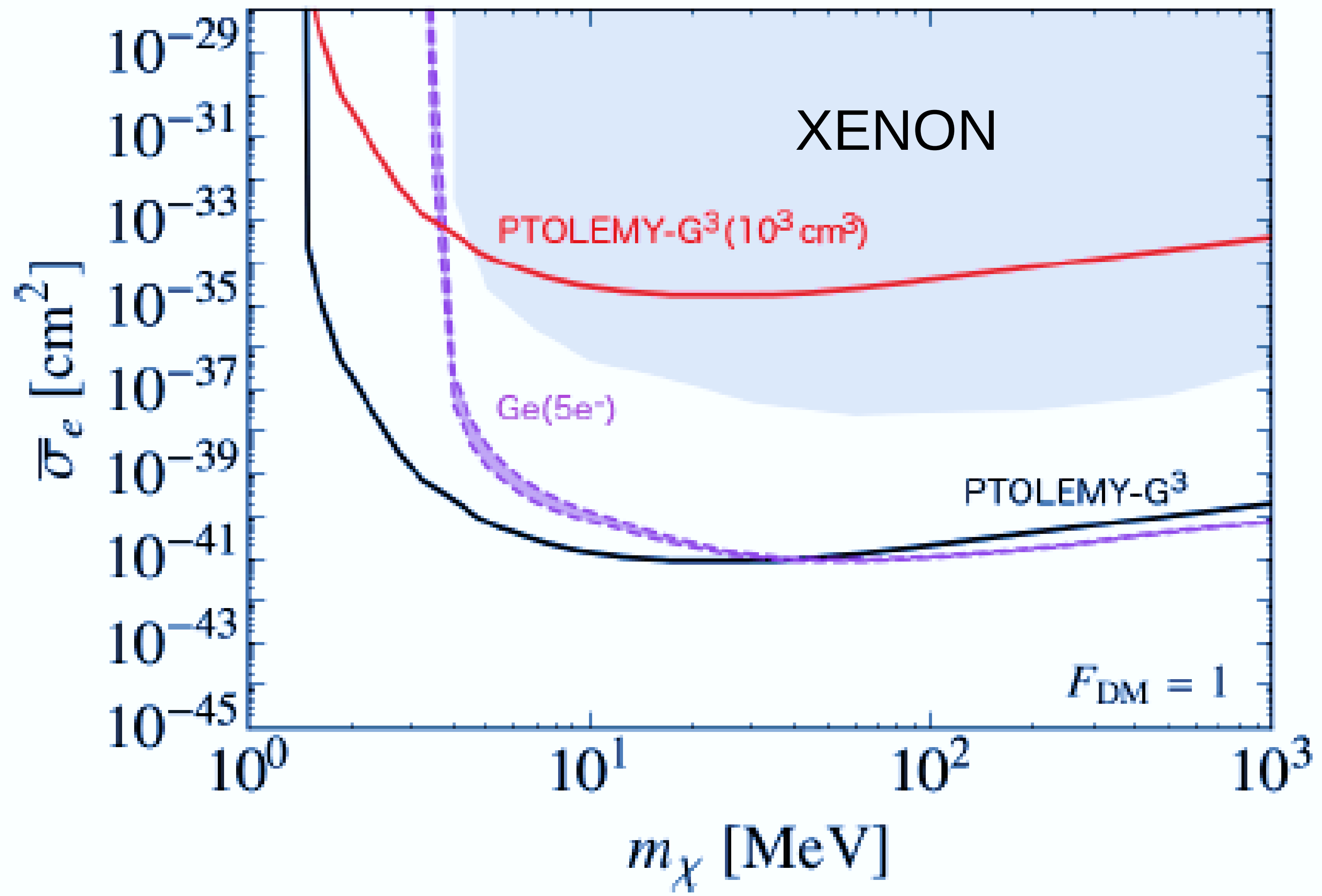
1kg ~ 10^{10}cm^2 ~ 10^9 cm^3

BACKGROUNDS

- Large surface → cosmic rays → underground (LNGS)
- Can you imagine what is the main problem?
  - source identified with low enough contamination (10^{-21})
- High radio-purity wafer-level fabrication proven by e.g. CDMS *Jastram et al. NIM-A 772: 14-25*

Controllable at face value.

REACH



Background-free 95% C.L. sensitivity for graphene 1-kg-year (black) and 10^3 cm^3 (10^4 cm^2) (orange)

Program to launch end of 2019

SUPERCONDUCTING DETECTORS

Hochberg+ JHEP 1608 (2016) 057

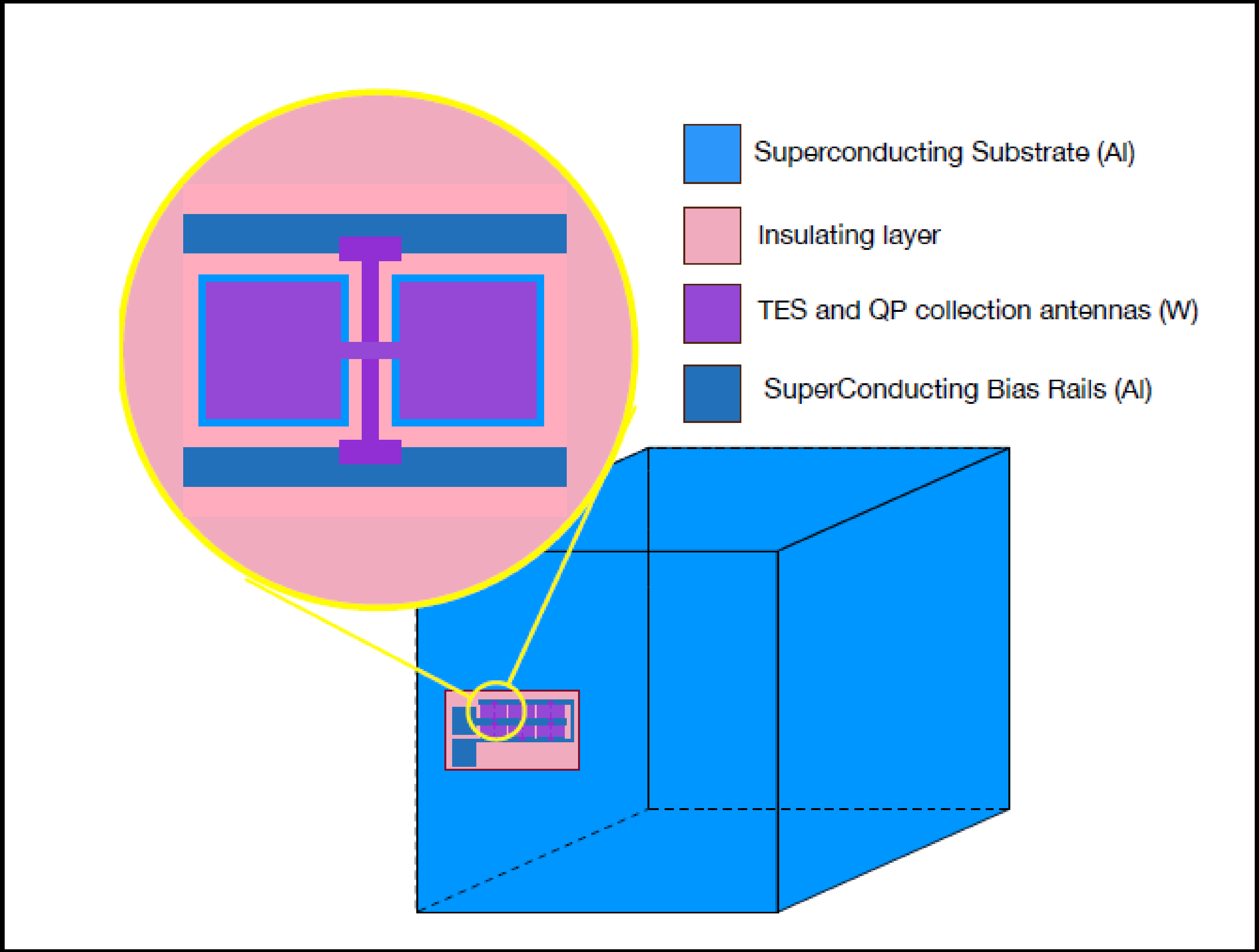
- Simple idea:
  - ”band-gap” becomes binding energy of Cooper pairs

$\Delta \simeq 0.3$ meV

  - interaction produces long-lived (~µs) quasi-particles and phonons

SUPERCONDUCTING DETECTORS

Hochberg+ JHEP 1608 (2016) 057



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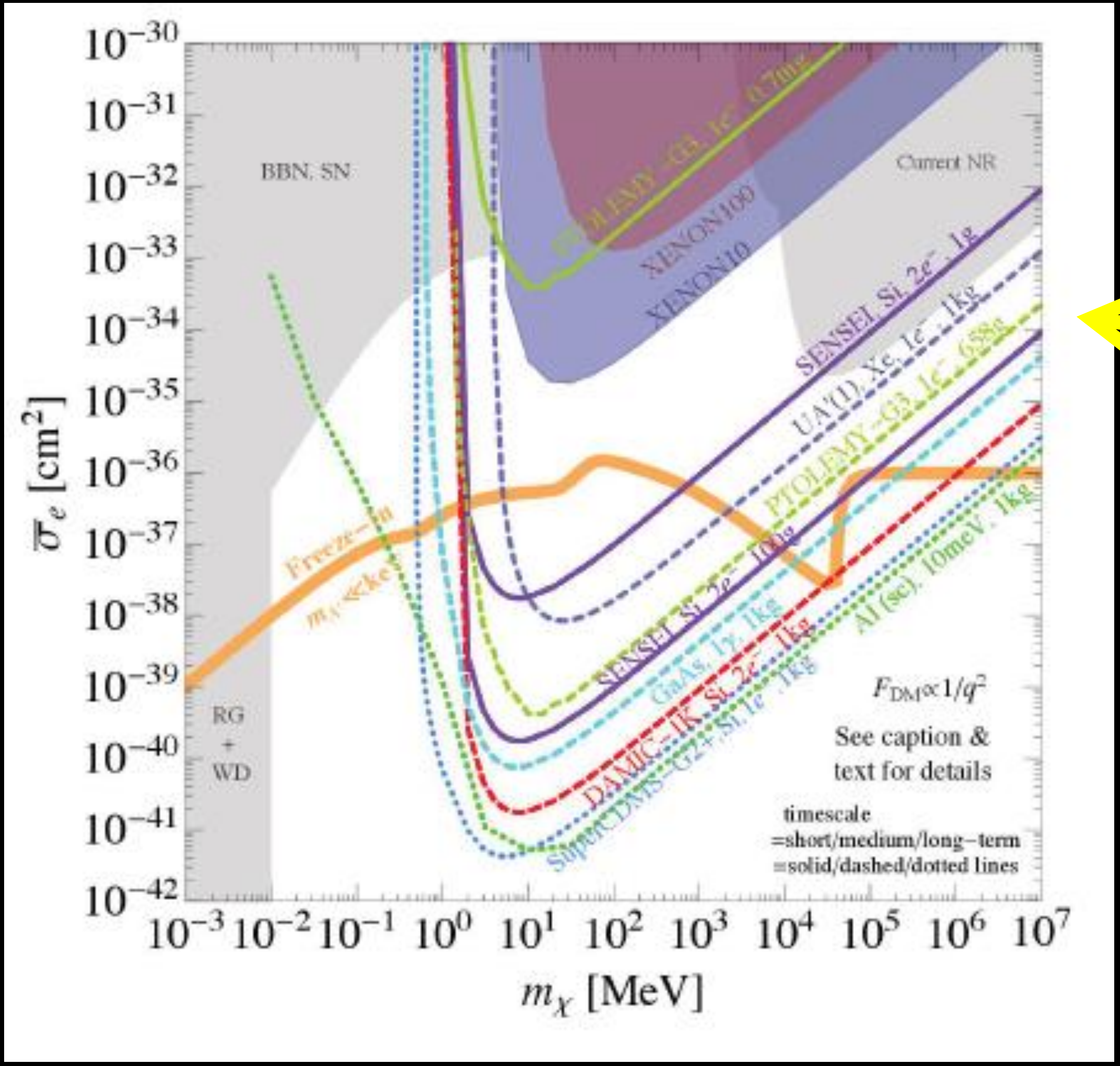


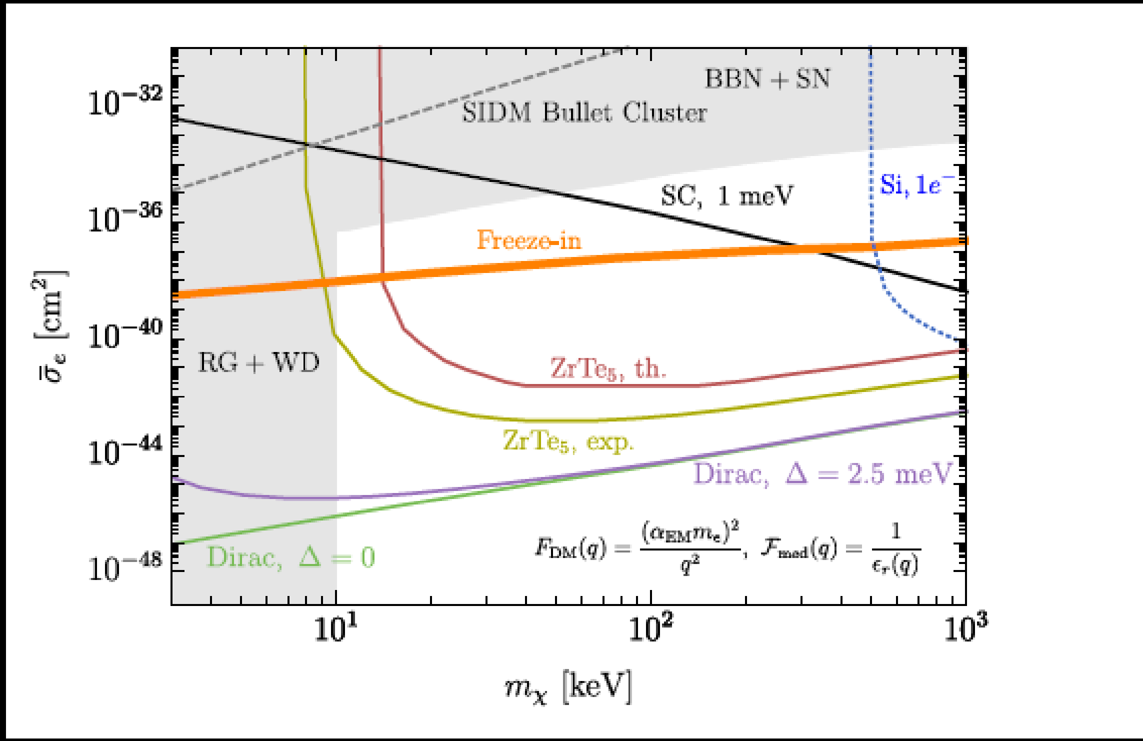
Why is this not better?

Light dark photon mediator, not good for accelerators.

AFTER THE FUTURE:QM4DM

- Advances in solid state physics allow to quantum-engineer materials
  - Detect small energy deposition
  - Directional sensitivity
  - Optical properties
  - Magnetic properties (AXIONS)
  - Boundary conditions:
    - Affordability(graphene is at 1 USD/cm^2)
    - Chemical proerties, safety etc,etc,etc

Hochberg et al



- Example: Dirac material (c.f. graphene) with tunable meV band gap and optical properties

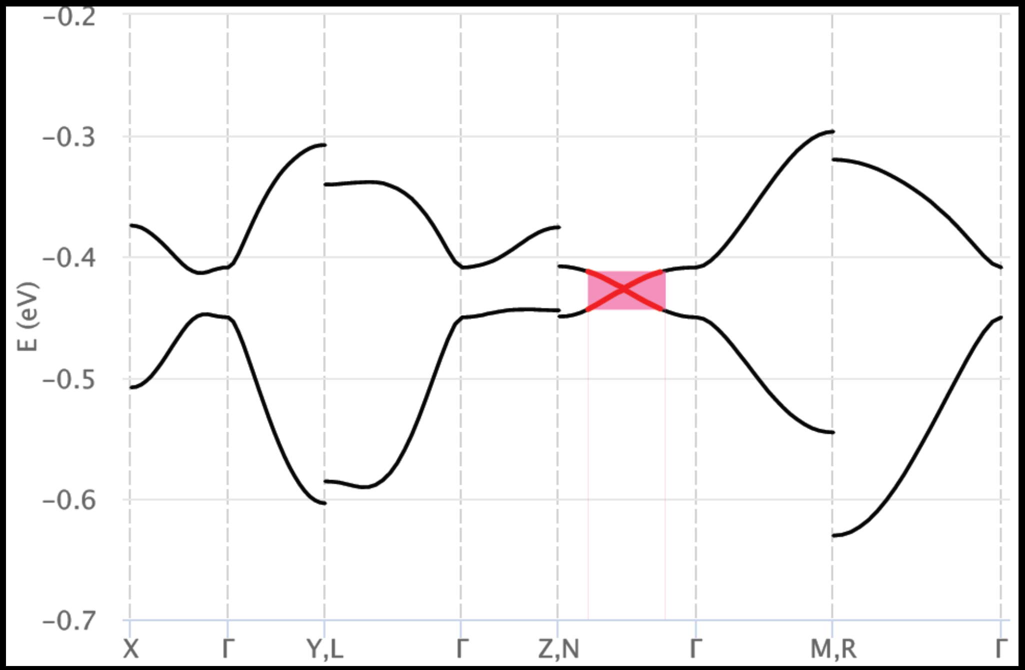
A STRAW MAN EXAMPLE

- Consider target wish: small band gap
- Can we systematically look for a material that has this property?

Geilhufe,Oolsthorn,Kahlhoefer, Ferella,Conrad, Balatsky
Physica Status Solidi RRL 2018, 1800293

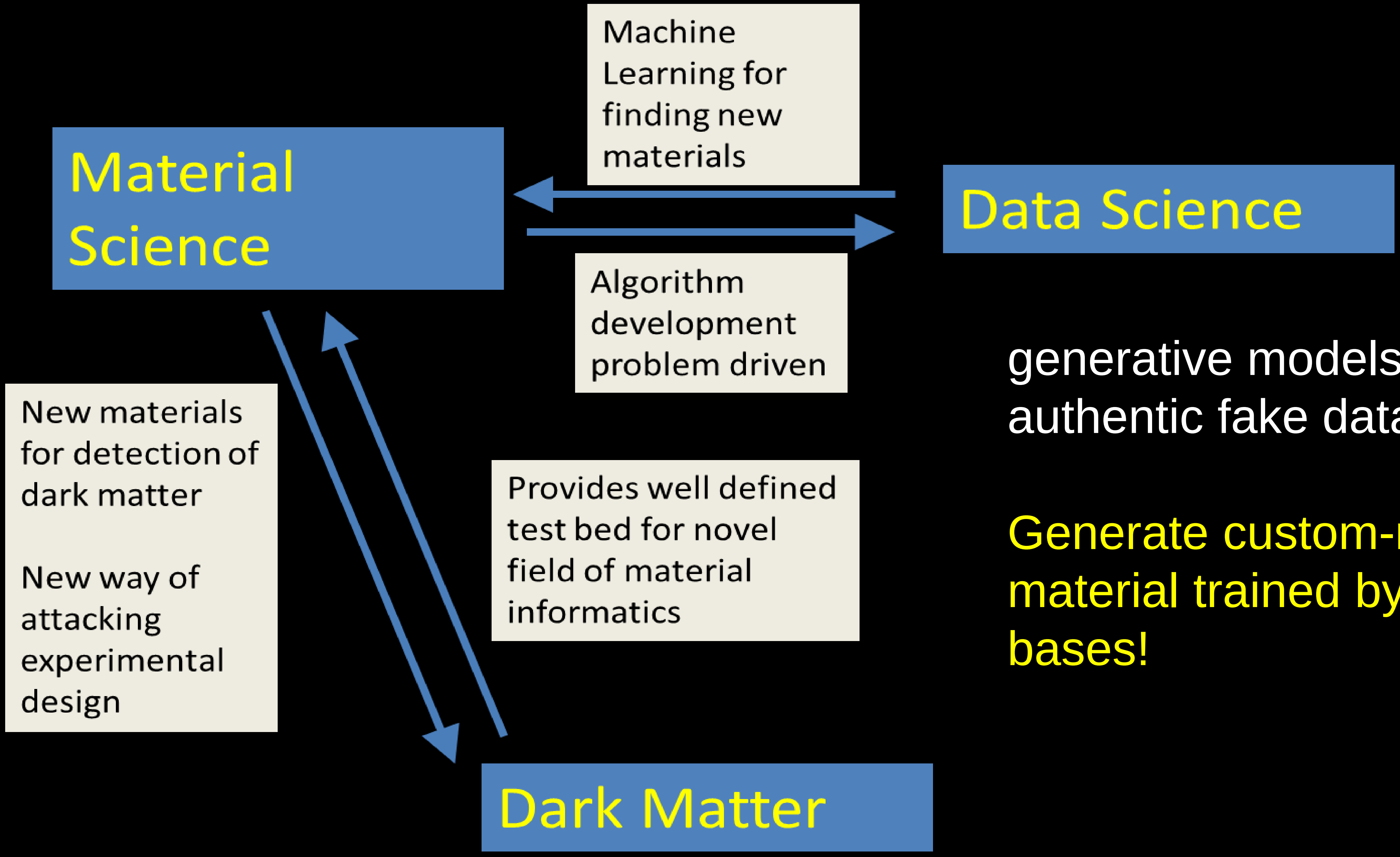
ORGANIC MATERIALS DATA BASE

- Free to use: omdb.diracmaterials.org
- band structures, density of states calculated by density functional theory
- ≈ 27.000 Materials stored
- 3D organic crystals
- Advanced data mining tools: found ~50 meV band gap



QM4DM

Collaboration with
Alexander Balatsky (NORDITA)



generative models produce authentic fake data →

Generate custom-made material trained by data bases!

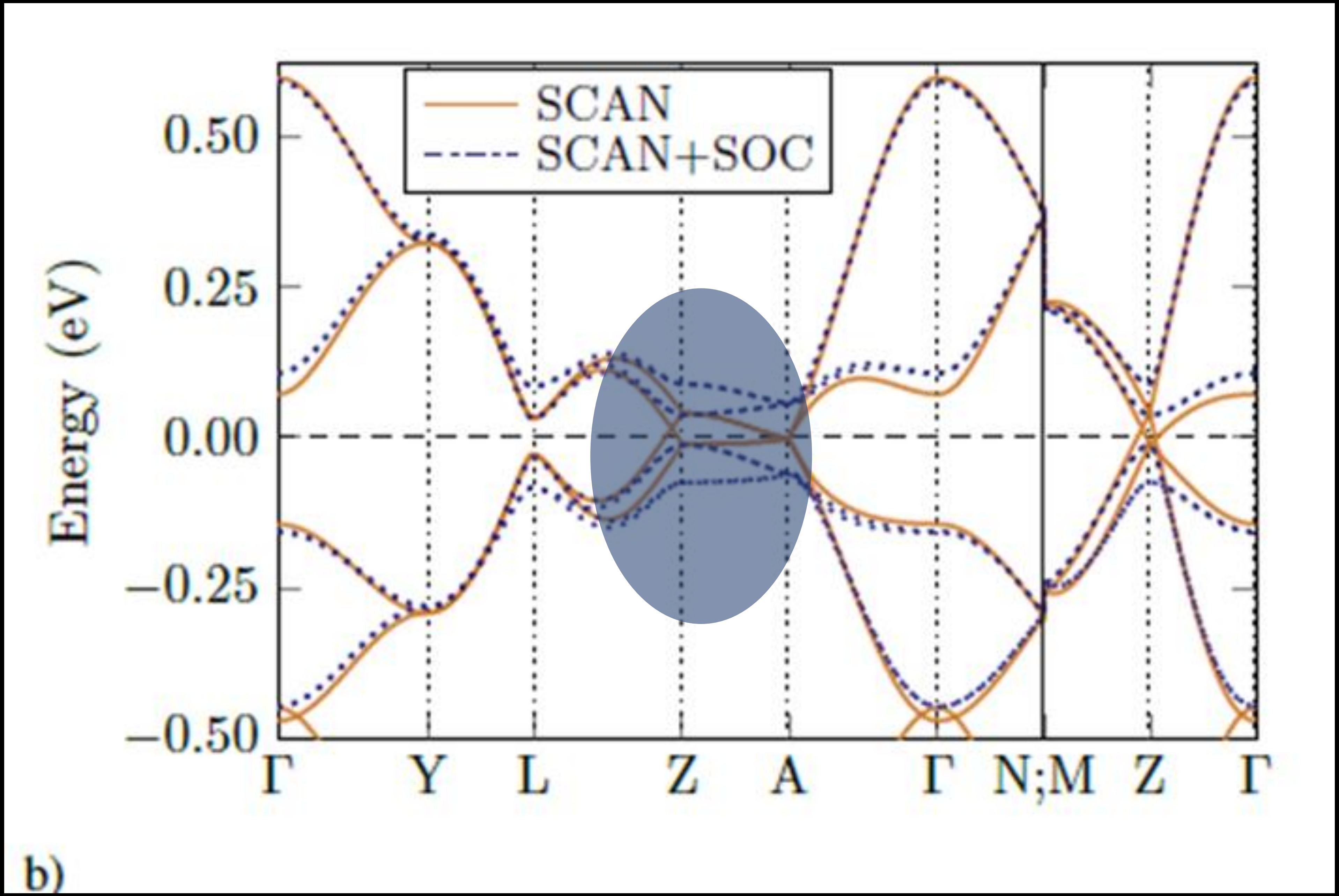
CONCLUSIONS

- New parameter space in direct detection is started to be explored → dark sector dark matter in the sub-GeV range → technology is the drive

- A dozen or so experiments realized within the next five to ten years → we don’t know what is going to work!

- Exciting times leveraging recent advances in solid state physics → taylor-made target materials.

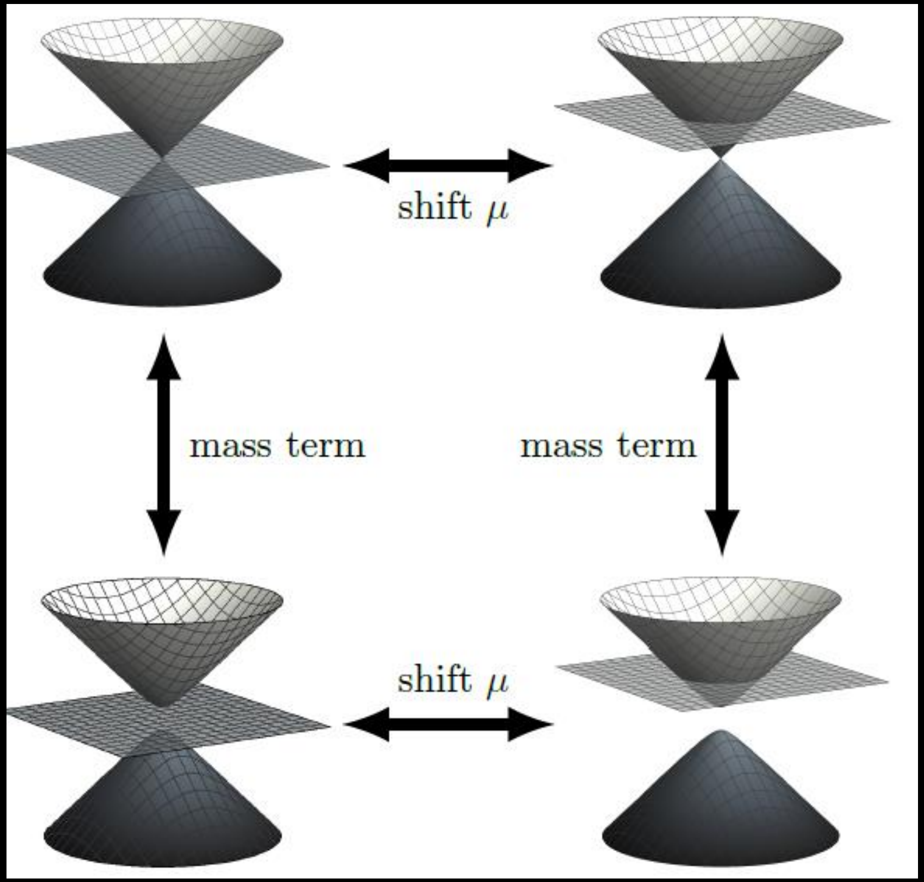
ORGANIC DIRAC MATERIAL

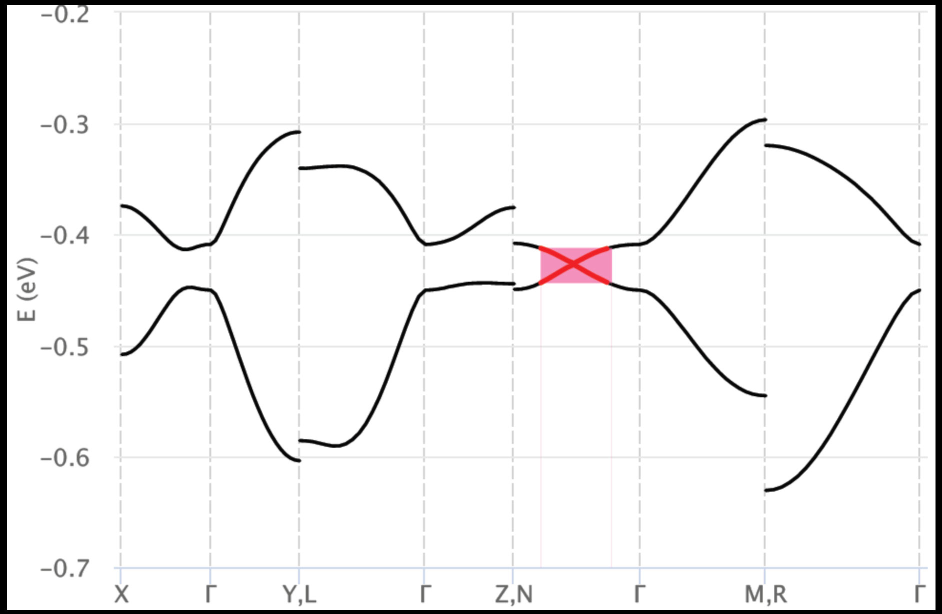


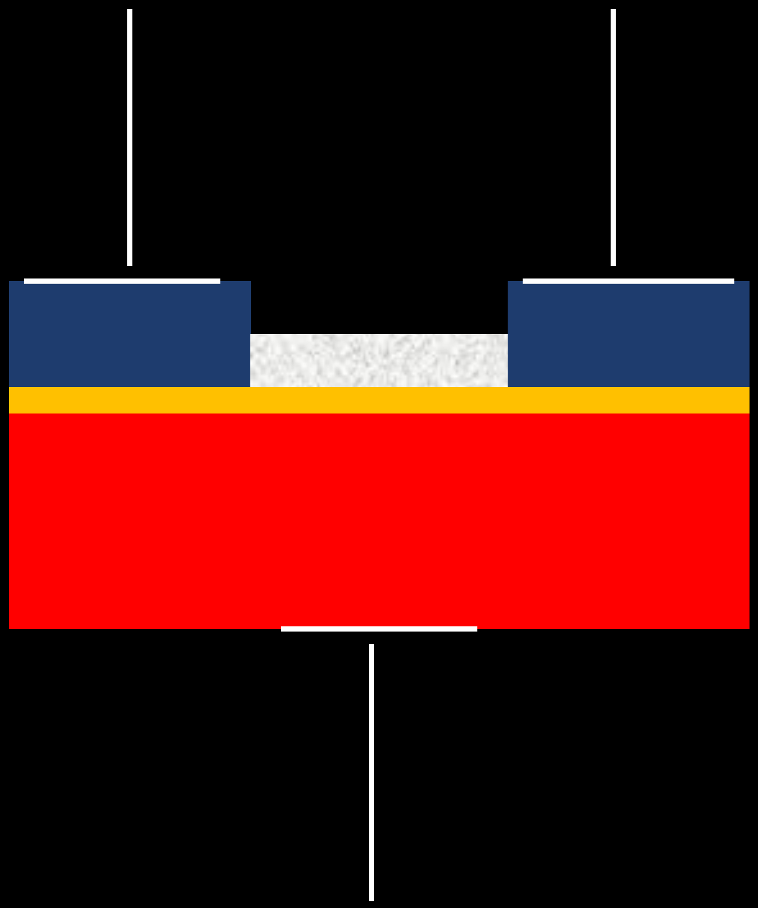
Linear crossing gapped out by spin-orbit coupling
Band gap ~ 50 meV, much smaller gaps should be possible

EXAMPLE 1: DIRAC MATERIALS

- Dirac materials suggested for MeV DM detection (e.g. Hochberg et al Phys.Rev. D97 (2018) no.1, 015004)
- well defined enrgy momentum relation (Dirac Fermions)
- nodes in spectrum protected by symmetry → symmetry breaking induces tiny gaps
- Examples: graphene, topological insulators, Weyl semimetals, . . .
- OMDB: pattern matching for linear crossing or reference density of states







THE THEORETICAL FRAMEWORK

- Scalar DM, dark photon (massive, so better Z’) mediator (production: freeze-out)
- Dirac Fermion, dark photon mediator (production: assymetry)
- ELDER (elastic scattering via dark photon exchange)
- SIMP (Strongly Interacting Massive Particles) 3→2 annihilations
- Majorana Fermion with velocity suppressed intearctions.
- Freeze in, dark photon exchange.
- Dark photon dark matter