The PTOLEMY-G^3 experiment for light dark matter direct detection

Identification of Dark Matter 2018
23-27 July 2018

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Brown University, July 23, 2018

Content

Introduction

The need for Dark Matter

- I do not need to convince you about the presence of Dark Matter in the Universe
- The dark matter puzzle remains fundamental: dark matter is matter - it leads to the formation of structure and galaxies in our universe
- We have a standard model of CDM, from "precision cosmology" (CMB, LSS): however...

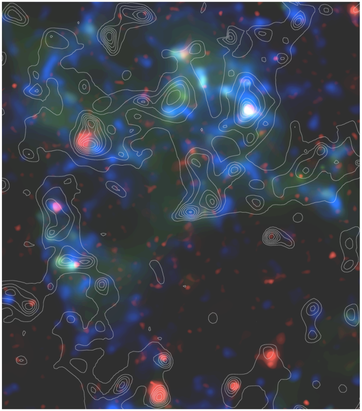

Figure: Large scale distribution of dark matter, probed through gravitational lensing
HST COSMOS survey; Nature 445 (2007), 268

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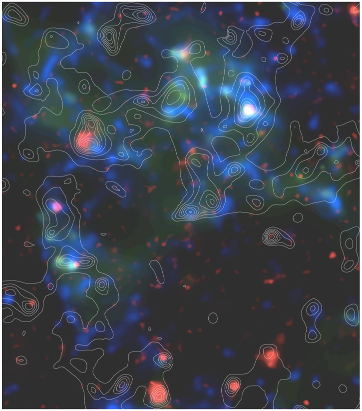

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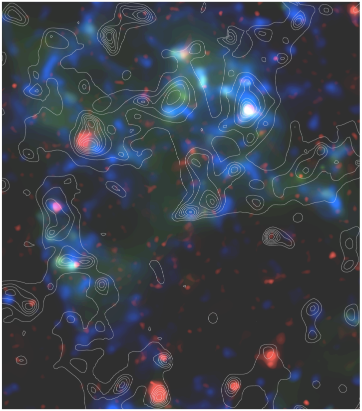
$\sim$ 85% of matter in the universe is of unknown nature



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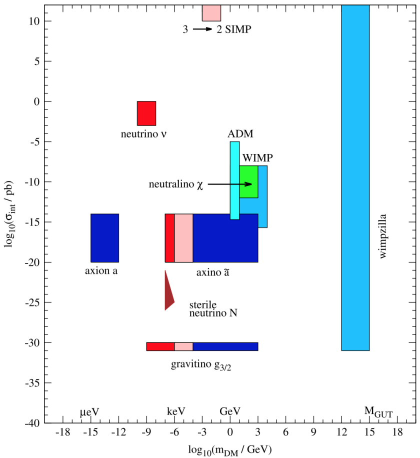
What do we know about Dark Matter?

- Exists today and is there since the early Universe
- Constraints from astrophysics and searches for new particles
- Massive (gravitation)
- Long-lived (Big Bang relic)
- Electrically neutral (No colour charge, no electric charge, no strong self-interaction, i.e. dark)
- Non-baryonic (BBN)
- Collisionless (Bullet cluster)
- Cold, i.e. dissipationless and negligible “free-streaming” effect (Structure formation)
- **Can’t be** made of standard model particles!

Particle Dark Matter

- very many candidates
- masses and interaction strength span over a lot of orders of magnitudes
- but we prefer one specific class: Weakly Interacting Massive Particles (WIMPs)

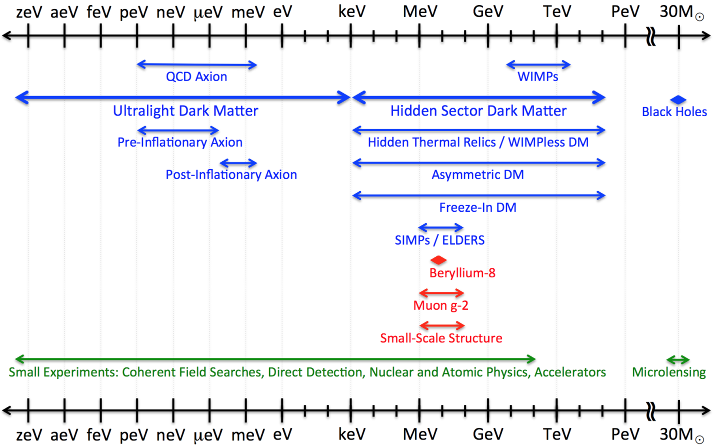
H. Baer et al. / Physics Reports 555 (2015) 1–60



Particle Dark Matter

Another way of looking at it

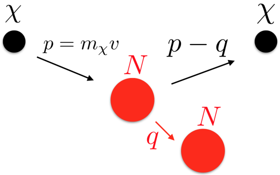
Dark Sector Candidates, Anomalies, and Search Techniques



US Cosmic vision: New Ideas in Dark Matter 2017 – arXiv:1707.04591

Nuclear or electronic recoils?

Latter for light $\lesssim$ GeV DM particles



$$T = \frac{1}{2} m_\chi v^2 \sim 1\text{eV}\left(\frac{m_\chi}{\text{MeV}}\right)$$

Nuclear recoil only visible until $m_\chi \sim m_N$

Below...

$$q \sim 2 m_\chi v, \quad E_{NR} = \frac{q^2}{2 m_N} \sim 10^{-4}\text{eV}\left(\frac{m_\chi}{\text{MeV}}\right)\left(\frac{10\text{GeV}}{m_N}\right)$$

For light ($\lesssim$ GeV) DM particles detection need:

- MeV-scale target particle (electron)
- eV threshold

Moreover

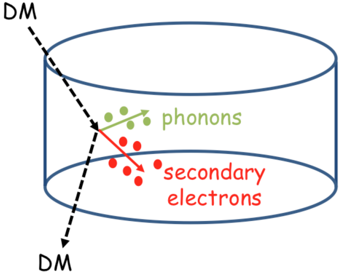
1. The initial state of the electron is not a momentum eigenstate
   $\Longrightarrow k_f$ and q are independent $\longrightarrow \Delta E_e = \epsilon + \frac{k_f^2}{2m_e} = \vec{v} \cdot \vec{q} - \frac{q^2}{2m_\chi}$
2. There is a wavefunction suppression at large q
   $\Longrightarrow$ rate maximised when $\Delta E_e \lesssim 4$ eV

(*Essig, Mardon, Volansky PRD 85(2012)076007*)

2D targets for light DM detection

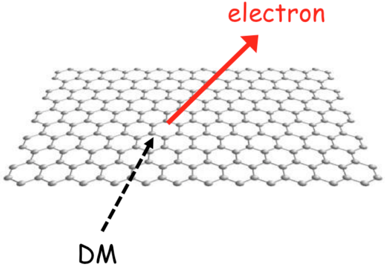
Y. Hochberg et al., Phys. Lett. B 772(2017)239

Detect "secondaries" $\longrightarrow$ loose directional information:



e.g. SuperCDMS or Superconductor

Keep directional information if detect primary



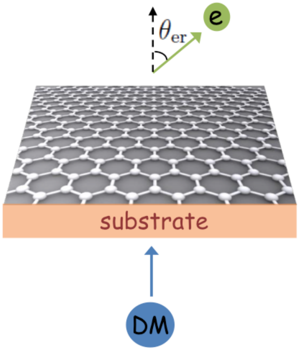
2D Targets: graphene

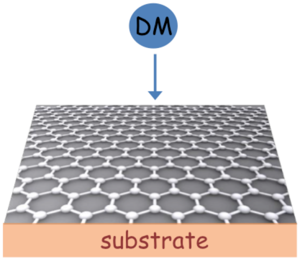
$\epsilon = E_b + \phi$

- E_b: electron binding energy
- ϕ: graphene work function ($\sim$ 4.3 eV)

2D Targets
Modulation signature

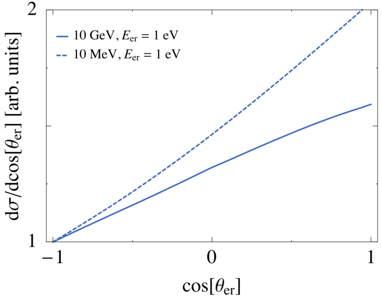
- Dark Matter stream perpendicular to the sheet
- Forward scattering persists
- Naturally gives forward-backward discrimination

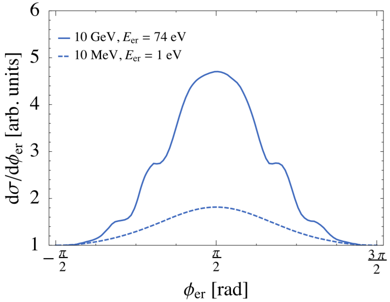




12 hours later

2D Targets
Directional detection





Polar distribution of the final-state electron; assumptions:

- stream oriented perpendicular to the graphene plane
- stream points in the $\hat{z}$ direction of $\cos\theta = 1$
- $E_{er} = 1 eV$

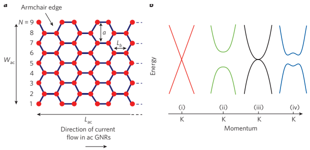
Azimuthal distribution of the final-state electron; assumptions:

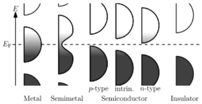
- stream oriented parallel to the graphene plane
- stream points in the $\hat{y}$ direction of $\phi = \pi/2$
- $E_{er} = 1(74)$ eV for the 10 MeV (10 GeV) masses.

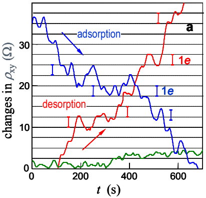
Conceptual experimental design

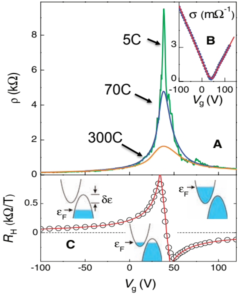
What is special about Graphene?

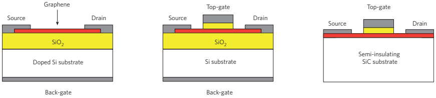
- Geim et al. in 2004 noted gaphene sensitivity to a single electric charge (added or removed) in a Field-Effect Transistor configuration - here at room temperature
- It is a semimetal: Dirac point provides a resistivity spike at a single gate voltage and the height is set by the inverse of the mobility
- Mobility increases by an order of magnitude at cryogenic temperatures
- Small band gap (meV) induced in Graphene could provide clean on/off transitions



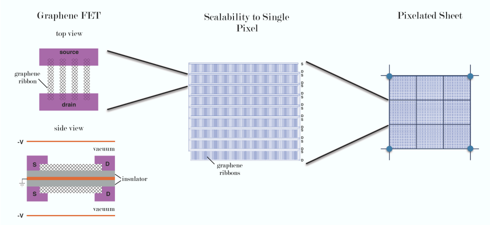


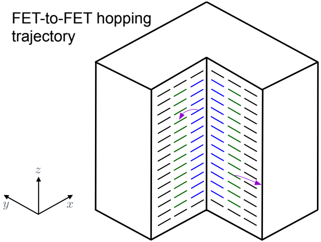


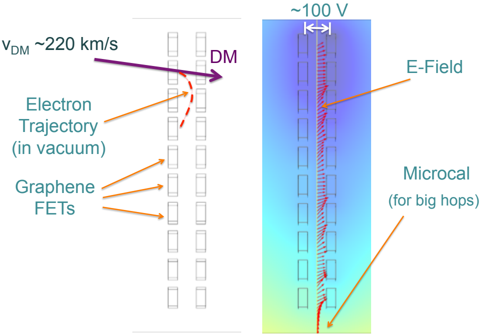




PTOLEMY-G^3
Detector configuration



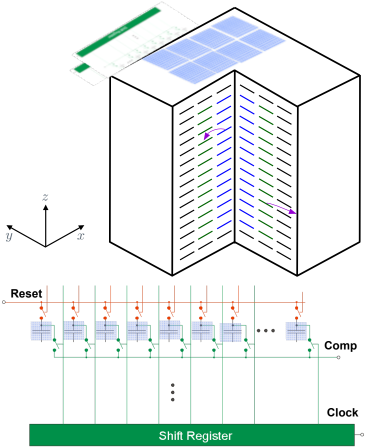




- Scaling up ~mm to ~cm
- Stacked planar arrays of G-FETs
  1kg ~ 10^{10}cm^2 ~ 10^9 cm^3
  Individually vacuum-sealed wafers
  Cryogenically cooled (4.2K)
  Cryopumping of gas contaminants on G3 surface - no line-of-sight trajectories
  Low mass substrates with ALD dielectric

PTOLEMY-G^3
Readout

- Switched Capacitor Array Readout (DRS-style)
  - G-FET “capacitors” compared against threshold, time-multiplexed in a token ring and digital output barrel shifted out
  - Caps are reset following each read
- Number of transistors in PTOLEMY-G^3 comparable to a single Intel G4 processor



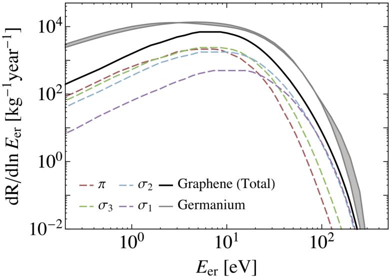
PTOLEMY-G^3

Backgrounds

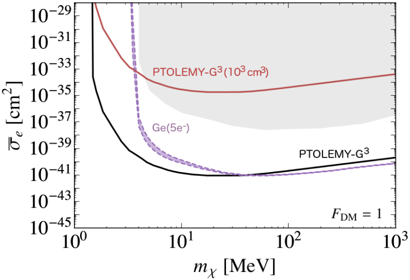
- With an area per plane of 10^6 cm^2, the overburden of cosmic-ray muon flux is an important concern for dead-time associated with a cosmic-ray veto $\longrightarrow$ move to Gran Sasso (LNGS)
- "Any incident particle with sufficient energy to eject a valence electron can in principle pose a background" $\longrightarrow$ high radio-purity wafer-level fabrication
  - Low background contamination lithography has been demonstrated, e.g. Jastram et. al, 2015. NIM A: 772:14-25.
- Main irreducible background: ^{14}C decay in the graphene
  - Ultra-low ratio ^{14}C/C graphene growth $\longrightarrow$ Push forward on the landmark work done for Borexino (source identified)
  - Litherland et. al, 2005. "Low-level ^{14}C measurements and Accelerator Mass Spectrometry" in AIP Conference Proceedings, vol. 785, p. 48. http://dx.doi.org/10.1063/1.2060452

2D Targets
Rates

- Sensitivity exceeds an equivalent mass target of low noise (5 e- threshold) germanium
- With a modest, small-scale deployment of PTOLEMY-G^3, a fiducialized volume of 10^3 cm^3 will search down to $\sigma \sim 10^{-33}$ cm^2 at 4 MeV in one year, uncovering a difficult blind spot inaccessible to current experiments



Differential rate for a 100 MeV DM particle scattering off an electron in graphene with $\overline{\sigma}_e$

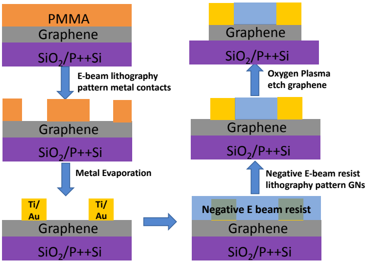


Background-free 95% C.L. sensitivity for graphene 1-kg-year (black) and 10^3 cm^3 (10^4 cm^2) (orange)

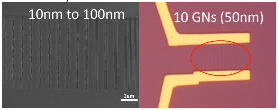
Current status

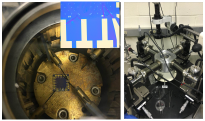
G-FET fabrication

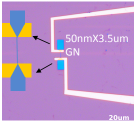
E-beam lithography process:

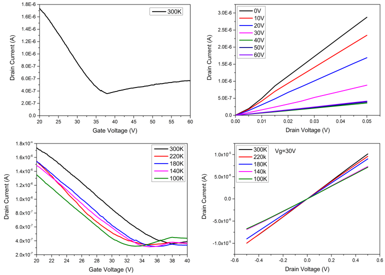


GNs array:



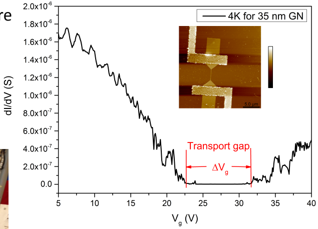


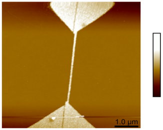


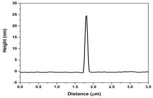


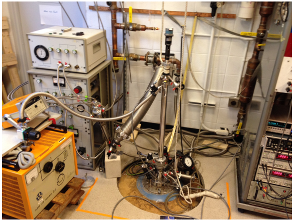
G-FET characterisation

Graphene Nanoribbon bottom gate FETs are fabricated on SiO_2/Si (p++).
GN width: sub 10nm, 20nm, 30nm, 50nm, 80nm.
GN FETs are measured under room temperature, 77K, and 4K.

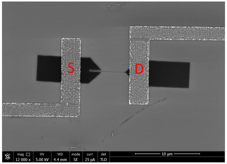


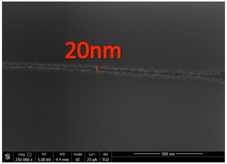






GN properties measurement setup
Electronic Engineering Department, Princeton Uni



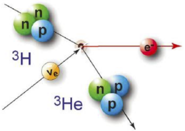


PTOLEMY

The PTOLEMY experiment

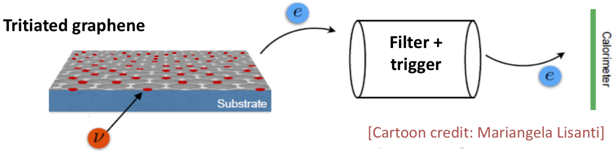
Cosmological Neutrino Background (CNB) direct detection

Experiment to detect relic neutrinos via capture on tritium



[Betts et al, 1307.3748]

100g of atomically bonded $^3\mathrm{H}$; use tritiated graphene (~0.5 kg)



[Cartoon credit: Mariangela Lisanti]

Phase program:

1. Move the "PTOLEMY Prototype" from Princeton to LNGS and run it to test the technology
2. Build and run PTOLEMY in "Dark Matter mode" while preparing the tritium source
3. Run the full PTOLEMY experiment for the CNB program

Conclusions

Conclusions

... and perspectives

- Single-electron sensitivity Graphene FETs has the potential to open new possibilities for light DM scattering experiments
- R&D for PTOLEMY lends itself to develop a “null” low-background high Graphene capacity experiment to explore light DM with a unique sensitivity to directionality and therefore modulation of the DM signal
- The PTOLEMY phase strategy will allow this soon: space already allocated at LNGS (waiting for final approval)
- First G-FET fabrication and characterisation tests successful
- Other R&D on the PTOLEMY technology are ongoing.
- Plan to move the prototype to LNGS after the summer and start commissioning right after its (quick) re-assembly
- 2019 will be THE YEAR!