A Search For Dark Forces At The Jefferson Lab Free Electron Laser

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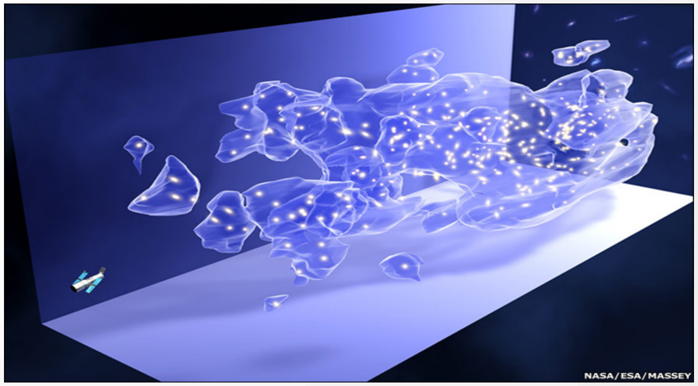
Hampton University

HU Nuclear Physics Seminar

15 October 2013



Outline

- Background/Motivation
- DarkLight Experiment
- JLab PAC Proposals
- Beam Test Run & Background Rad. Measurements
- Timeline
- Summary

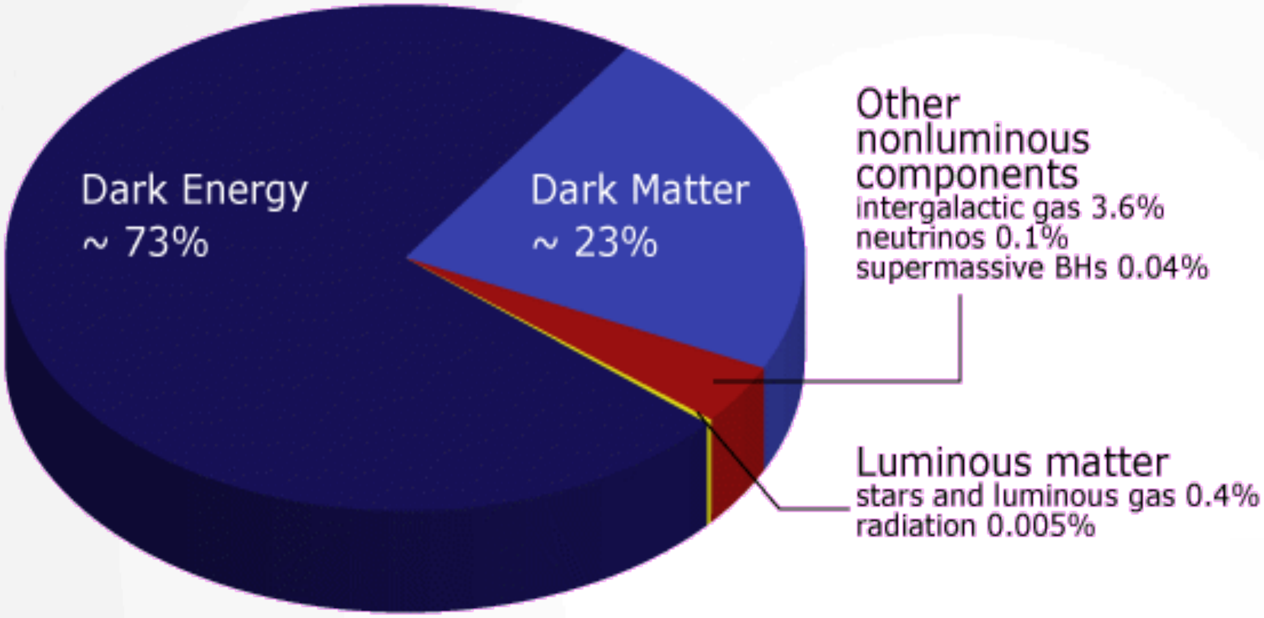
1E 0657-56 “Bullet Cluster”

Mass, accounted for.

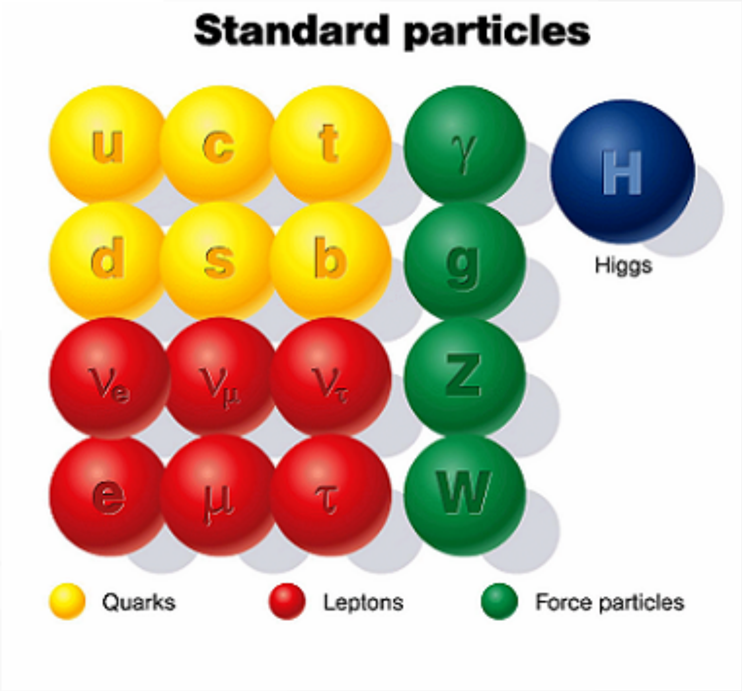
Mass, due to DM.

X-ray: NASA/CXC/CfA/ M. Markevitch et al
Lensing Map: NASA/STScI; ESO WFI; Magellan/U. Arizona/ D. Clowe et al
Optical: NASA/STScI; Magellan/U. Arizona/ D. Clowe et al

Much Ado About (Almost) Nothing



The ordinary matter we observe is actually a trace part of the Universe: ~5%



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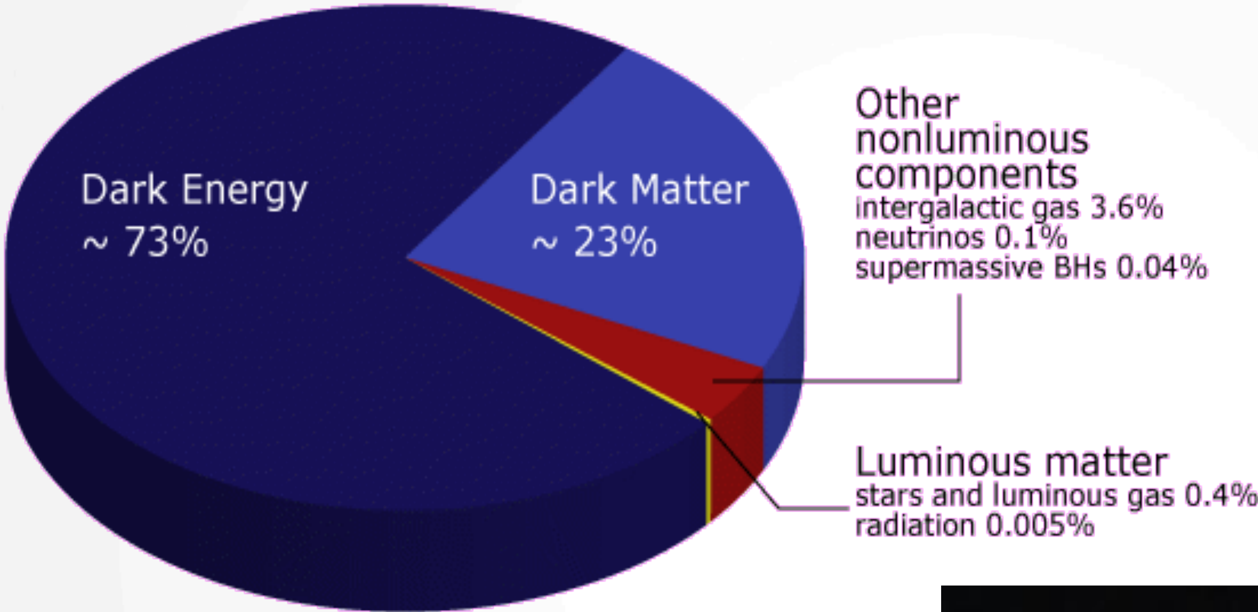
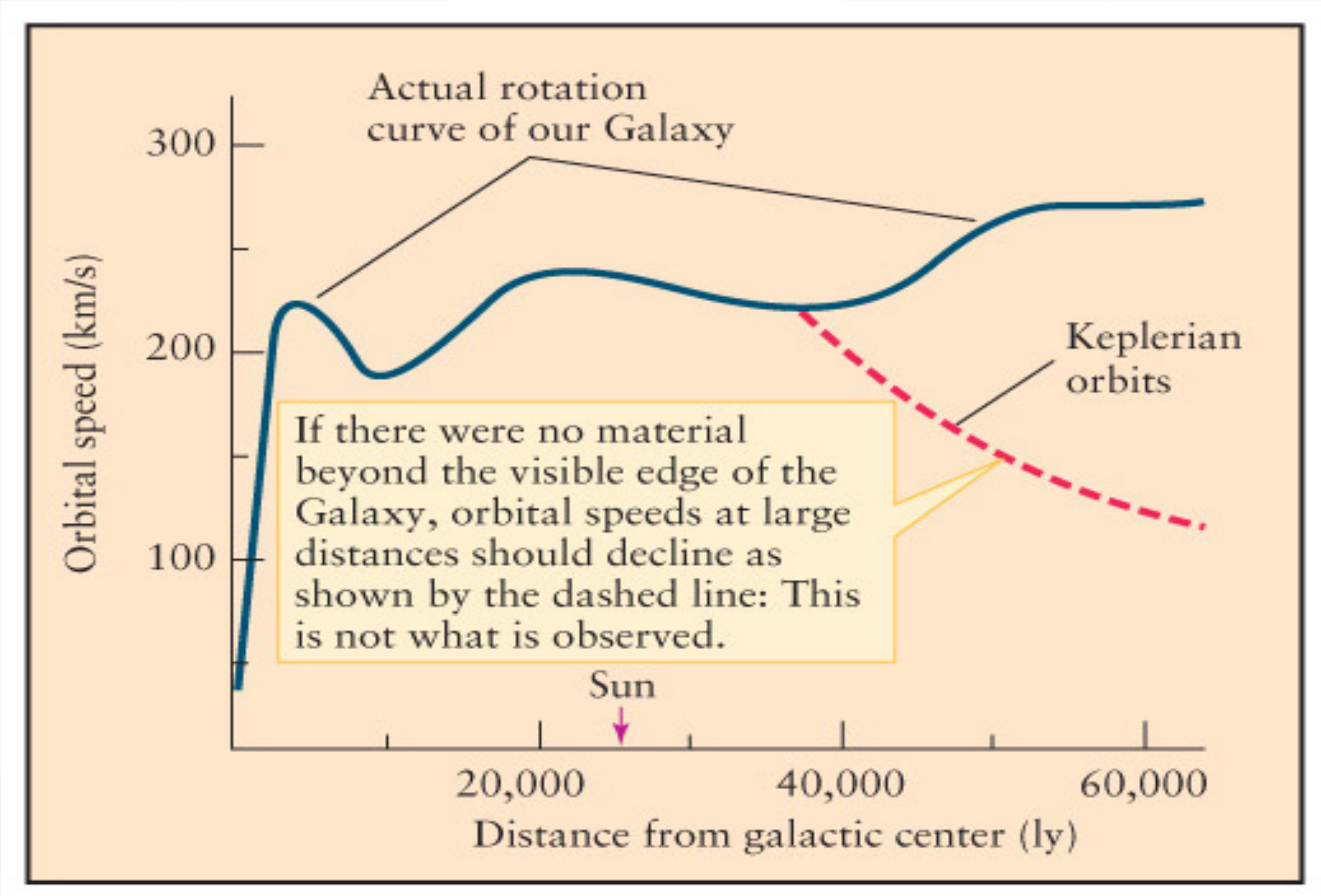


The ordinary matter we observe is actually a trace part of the Universe: ~5%

Indicators for Dark Matter

Astrophysics

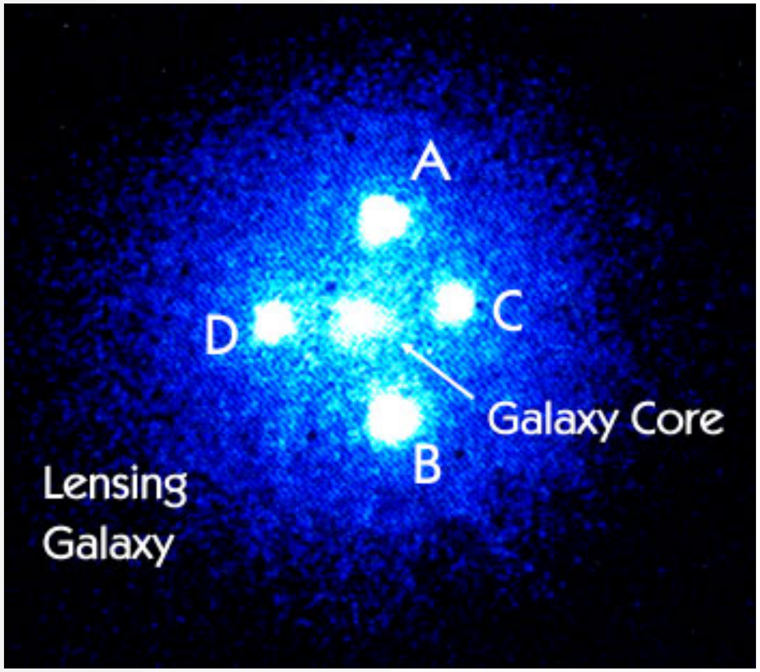


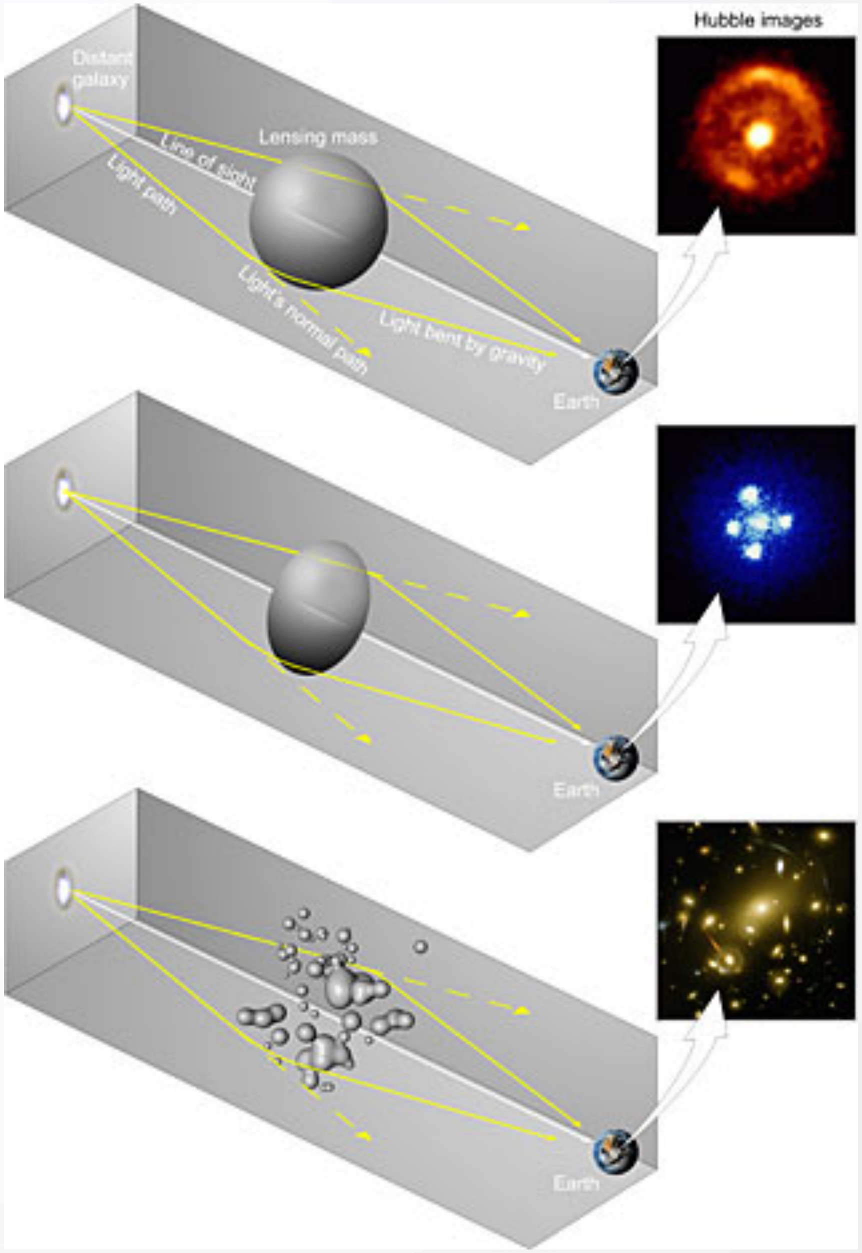
Galaxies: Rotation

Indicators for Dark Matter

Astrophysics

Einstein Cross

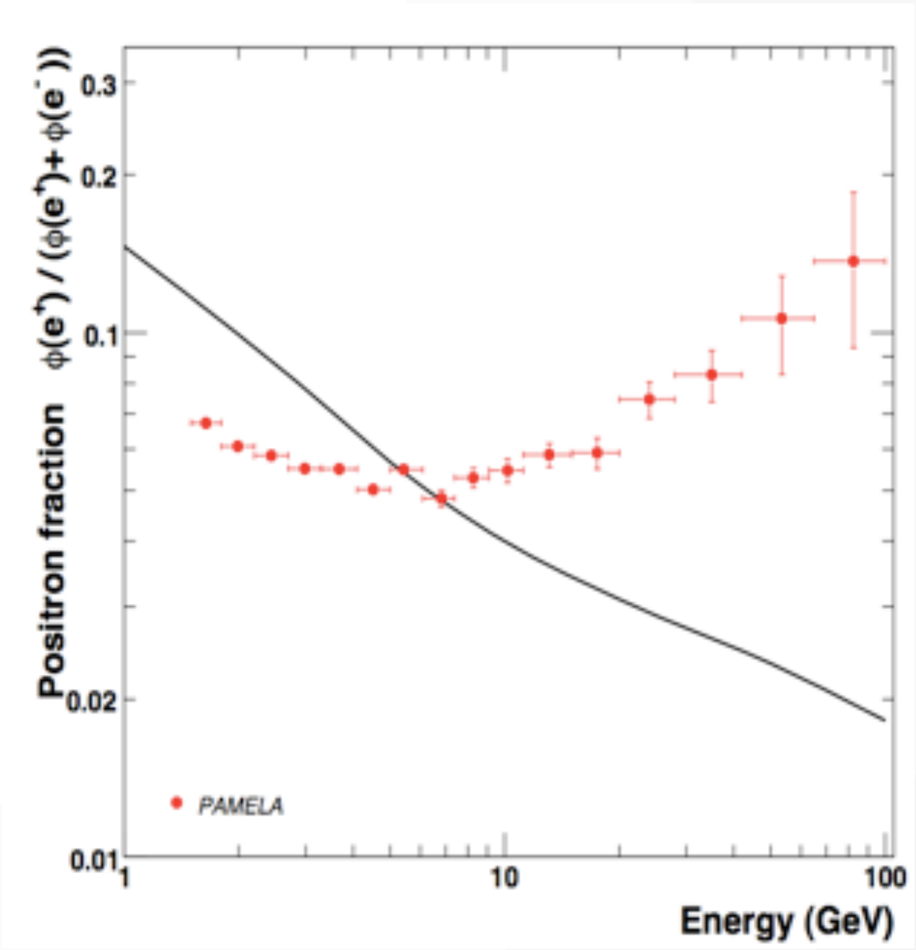




Galaxies: Gravitational Lensing

Indicators for Dark Matter

PAMELA satellite (2008)



Data

Expected curve

<u>Nuclear/Particle Physics</u>

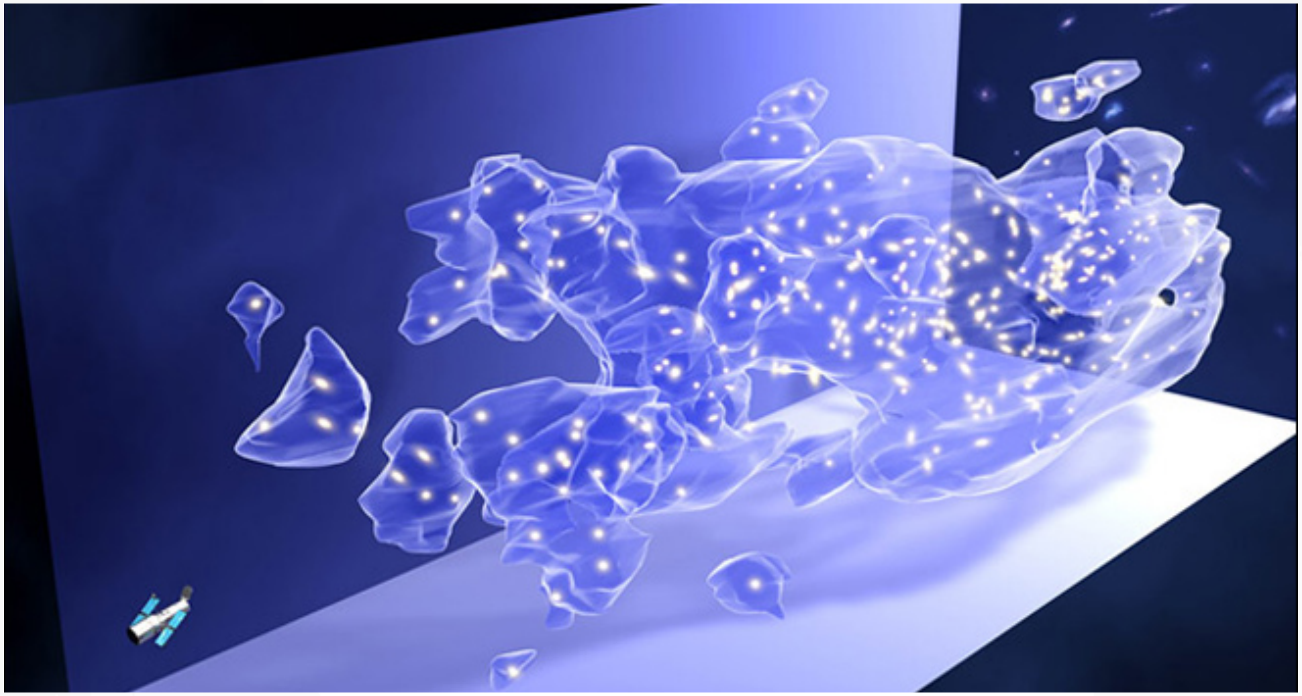
PAMELA Results:
e^+ excess
(not for p^-, though)

Sizable cross-section

Similar result from ATIC

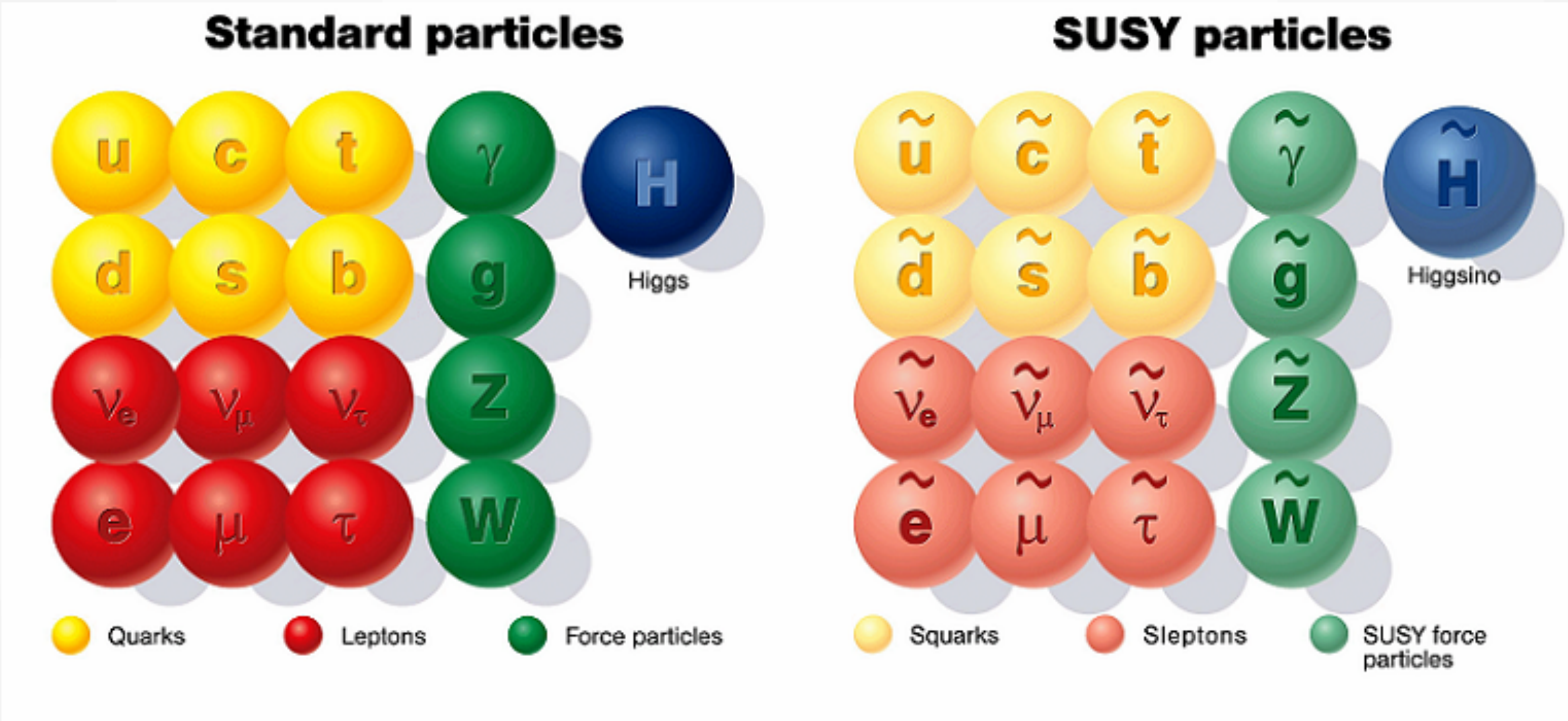
***and now also AMS**
http://www.bbc.co.uk/news/science-environment-22016504

Key Points of Dark Matter (1)



- All of the concrete information about DM comes from measurement/observation of astrophysical objects.
- Galaxies and galaxy clusters are the scales where DM is important. Dark energy is significant on cosmological scales, ordinary quark-matter on sub-galactic scales.

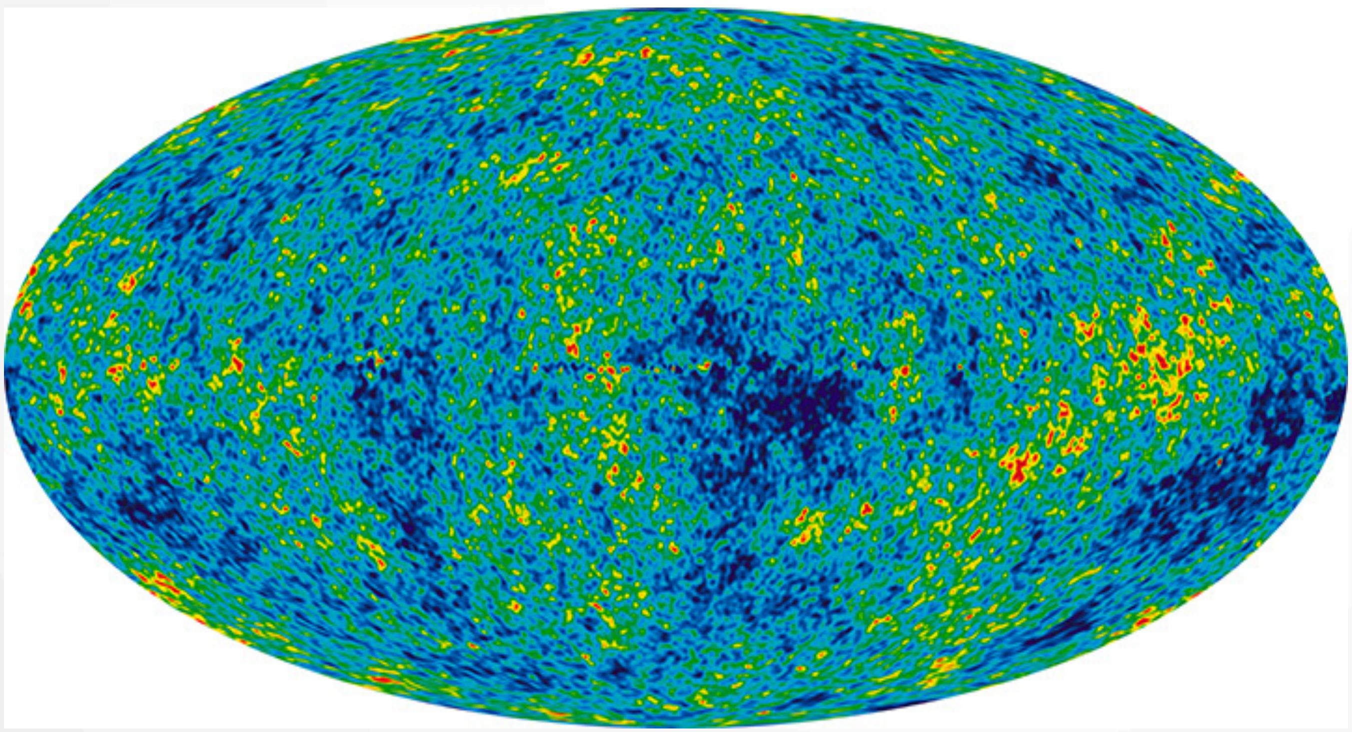
Key Points of Dark Matter (2)



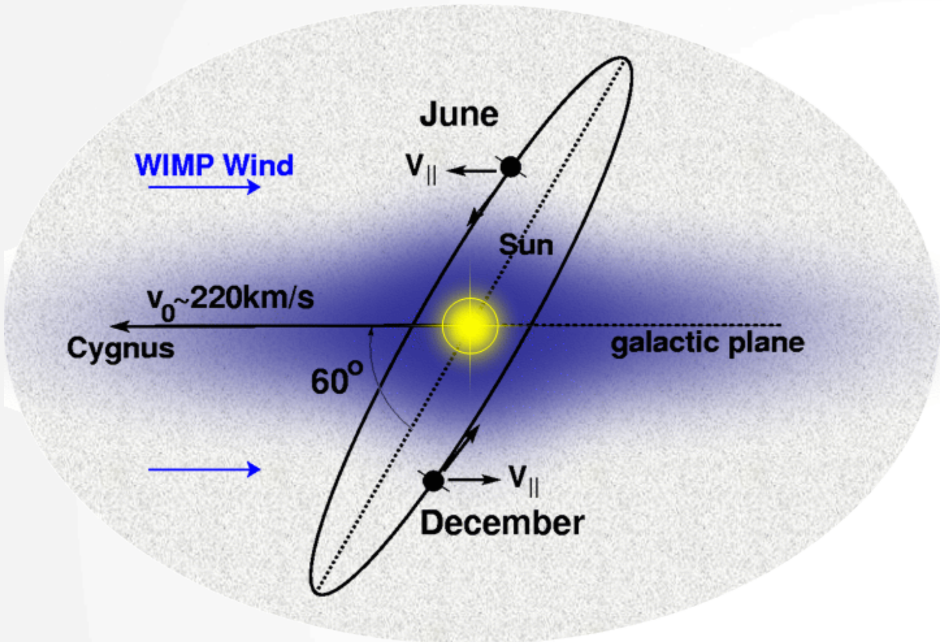
- Primary candidate for DM is the weakly interacting massive particle (WIMP).
- Something beyond SM (+SUSY). Neutrinos are not DM: DM way too massive.
- The original WIMP << 1 TeV picture, which includes SUSY, is being pushed to higher energies by the (so far) non-observation of new physics at LHC.

WIMP "Miracle"

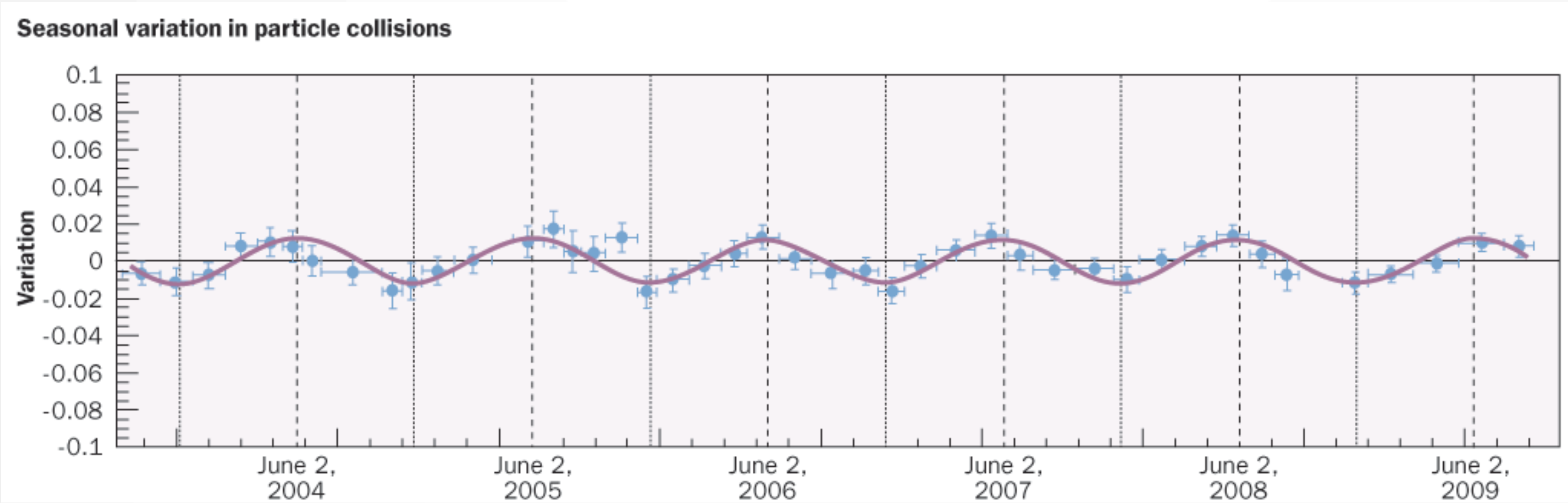
Currently observed dark matter density is consistent with massive particle production in Big Bang theory with WIMPS of 100 GeV+ mass and weak interaction cross-section.



DM Distribution

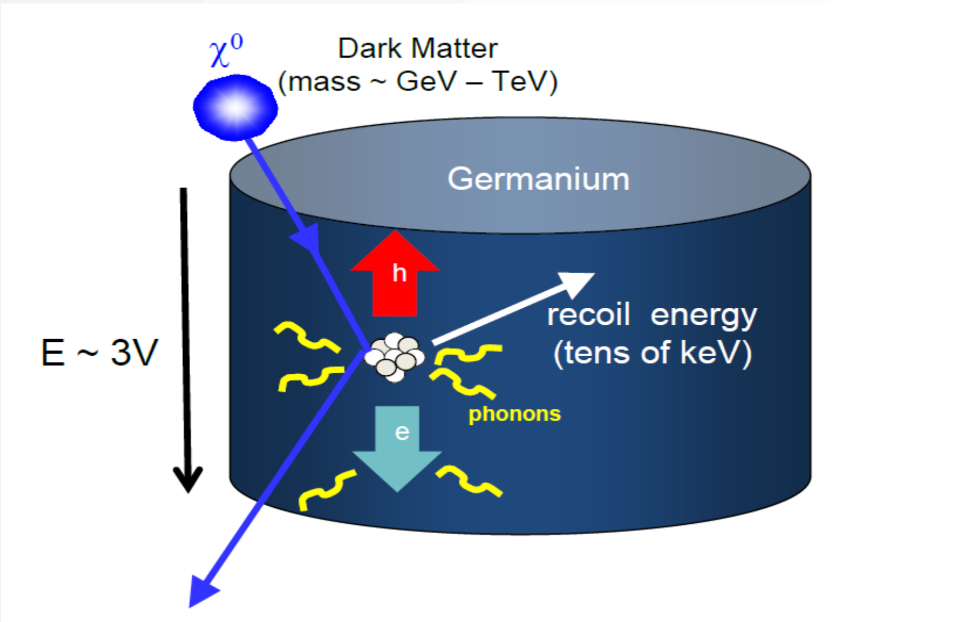


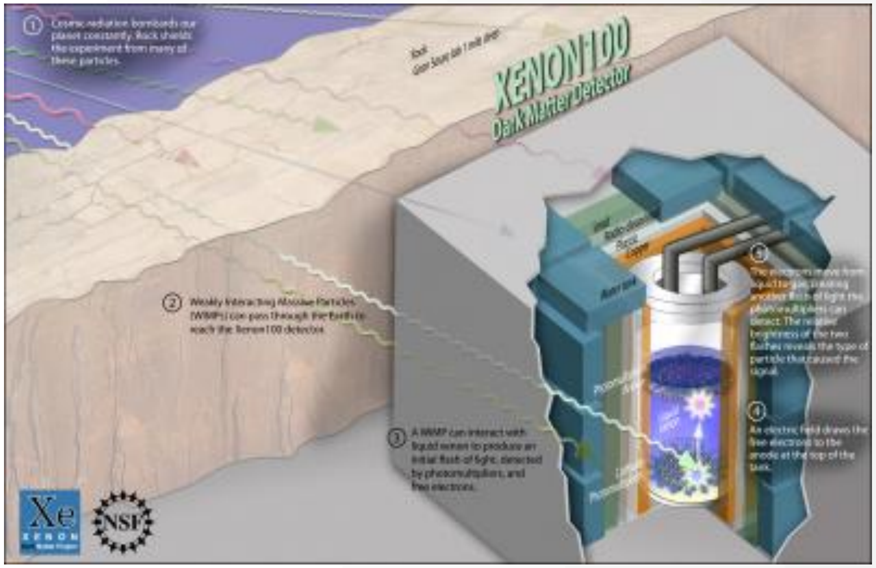
- Originally thought to ~spherical and uniform.
- Data from DAMA and CoGENT suggest somewhat different: cyclical => “wind”.



DAMA/LIBRA (2010)

Searching For Dark Matter Itself





Direct

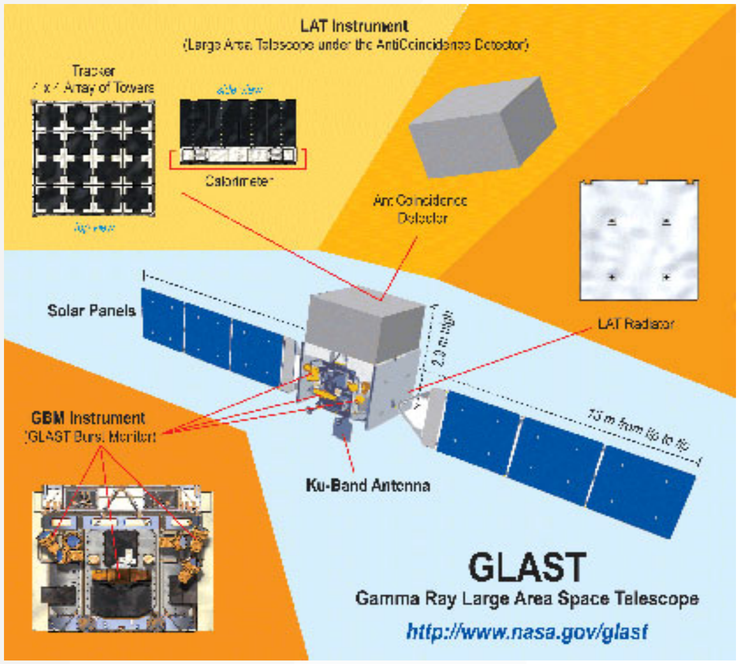
Recoiling Nucleus;

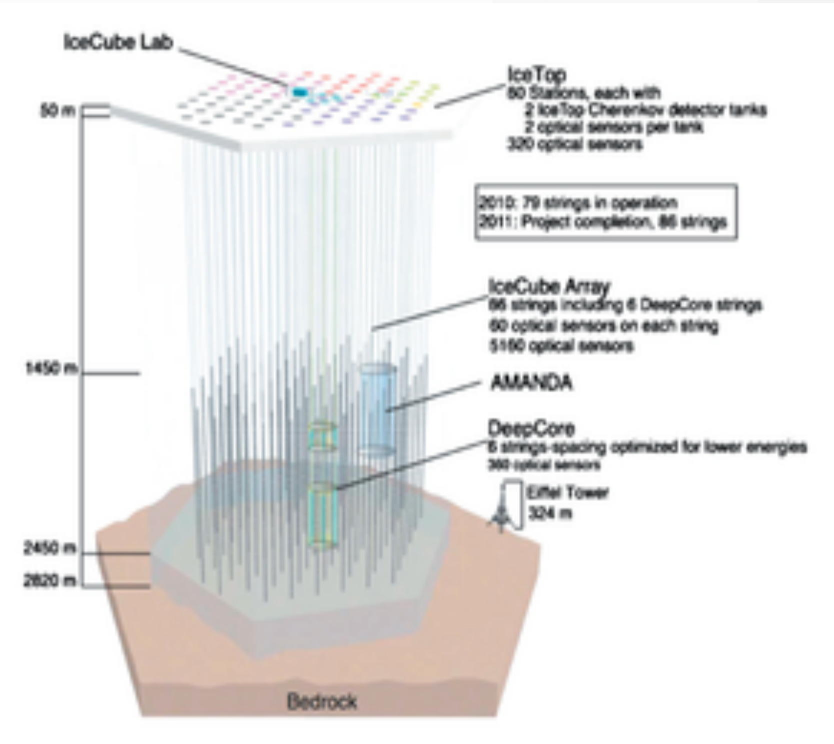
- Deep Underground: Cryogenic (temperature), Noble Gas (scintillation)

-CDMS, XENON, DMTPC, ...

-Nothing conclusive (yet).

Searching For Dark Matter Itself





Indirect

Annihilation signatures;

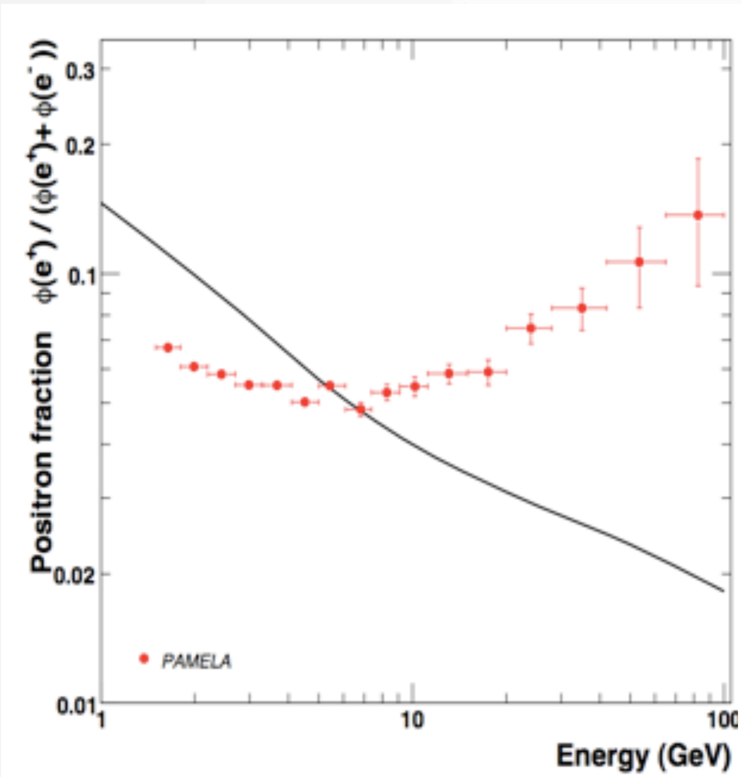
- cosmic rays, particle/anti-particle, ...

-IceCube, FERMI, AMS, ...

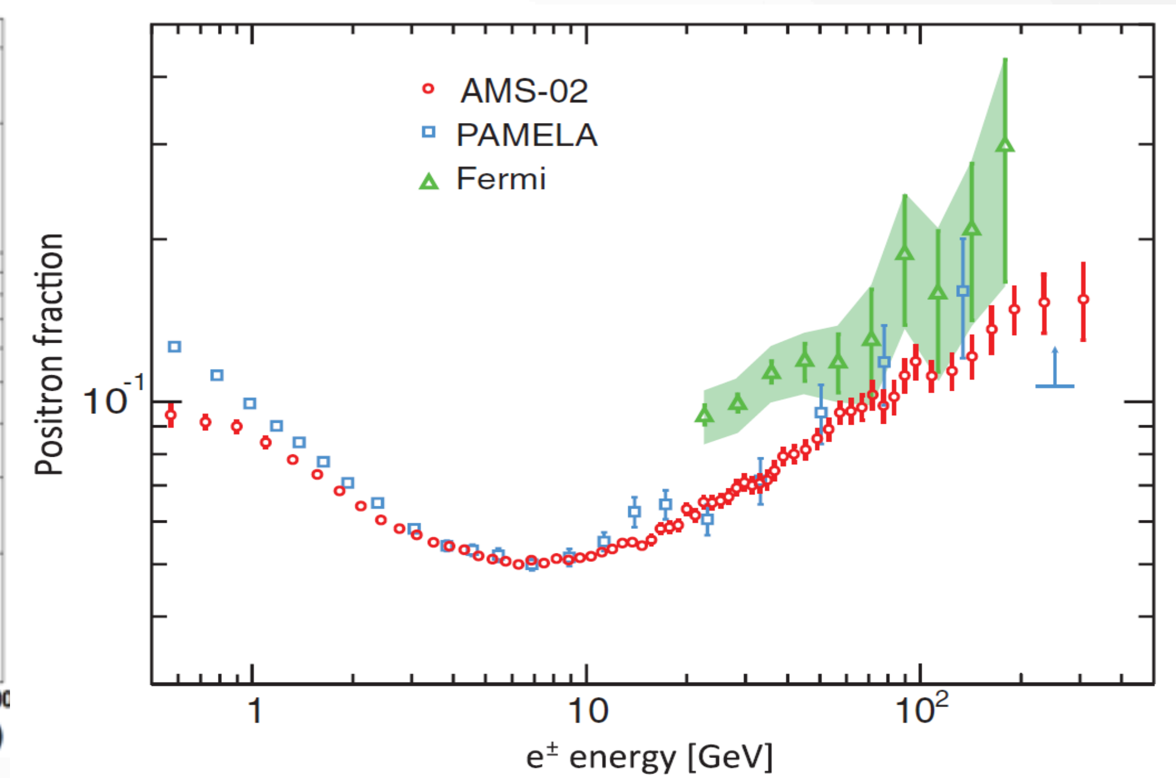
-Suggestive of something, which is yet to be understood.

High Energy e+e- in Cosmic Rays

PAMELA satellite (2008)



Confirmed by FERMI; nailed by AMS (2013)



What's the source of high energy e+e- in the cosmic rays?

Hidden Sectors

- **The universe may include *Hidden Sectors***
  Particles and forces that don't couple directly to the Standard Model

- **Dark matter may be part of a *hidden sector.***
  - Dark Matter, and other particles and forces, may make up this hidden sector.

  - While still massive, and weakly interacting, hidden sector dark matter may be very different from conventional WIMPs. No SM couplings!

- **Hidden sectors would interact with us through gravity or "*portals*"**
  The *photon portal* , through which the SM photon mixes with the hidden sector photon, lets our world interact with the hidden sector

Why Hidden Sector Photons?

Phys.Lett.B **166** (1986) 196

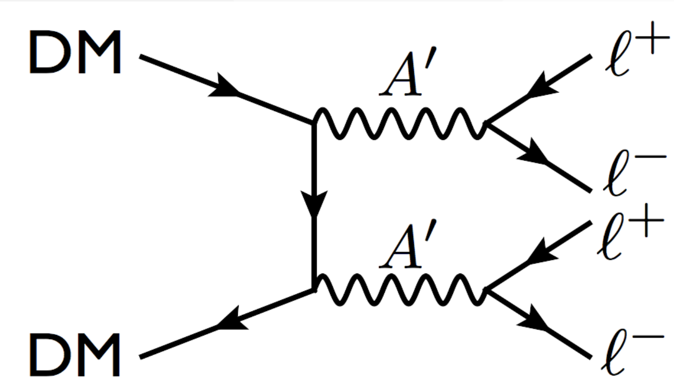
- **Are there more bosons in Nature? More EM-like forces?**
  * Beyond SM theories generate hidden sectors with additional bosons.
  * It's worth looking for them in Nature. Given that only 4% of the universal mass-energy is well-accounted for, there's plenty of room!

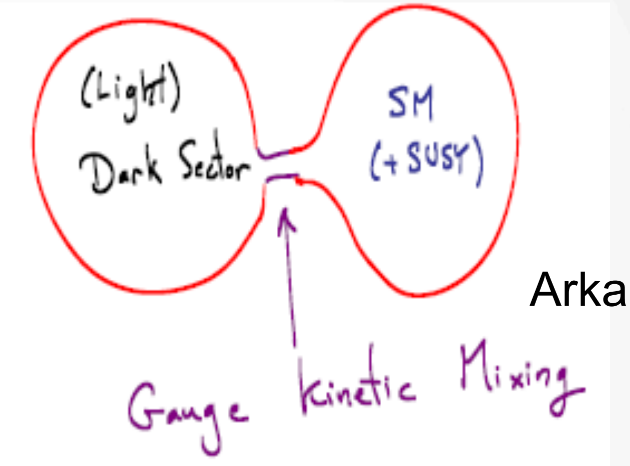
- **A *Hidden Sector Photon* is simply the particle associated with the new force, coupling to dark charge.**

- **Hidden Sector Photons weakly couple to SM Photons through "kinetic mixing"**
  The coupling is ε, where typically $\varepsilon \sim 10^{-3}$, but in fact can range $10^{-2} – 10^{-12}$.

- **So Hidden Sector Photons couple weakly to electric charge and our world.**
  In particular, they couple weakly to electrons, so they can be radiated by electrons, and they can decay into e+e- pairs.

Hidden Sector DM Annihilation





Arkani-Hamed

- **Arkani-Hamed, Finkbeiner, Slatyer, Weiner** and **Pospelov & Ritz** proposed DM annihilation to hidden sector photons (A's) in the mass range 20-1000 MeV/c^2 as the source of HE cosmic e+e-.

- **Accounting for the observed flux is tricky**
  - Relic abundance depends on annihilation rate **ΩDM ~ 1/<σv>**

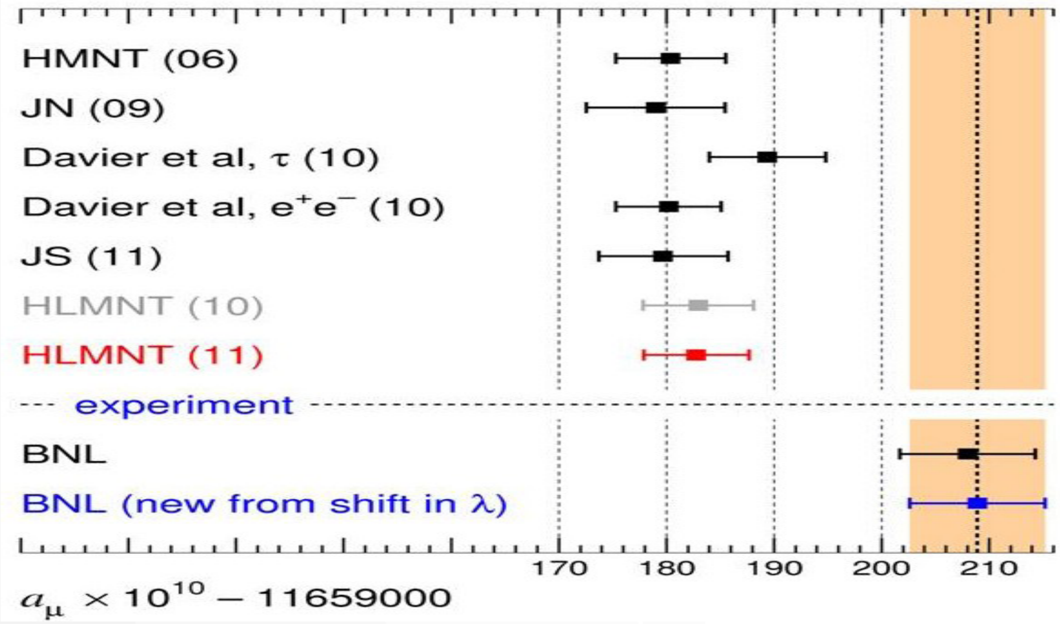
  - Making the annihilation rate **<σv>** large enough to account for the measured flux, makes **ΩDM** too low by a factor 100-1000! Trouble for SUSY models.

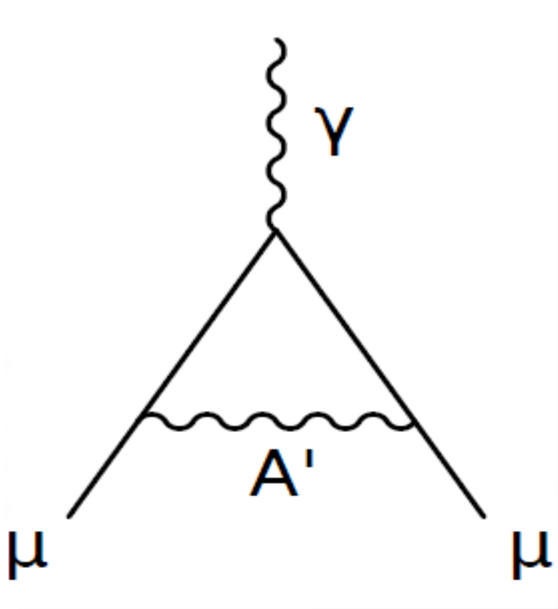
- But, with a low mass A', the cross-section is enhanced when the velocity is very low (Sommerfeld Effect). This boosts the rate now, but lowers it at freeze-out, when v is high.

Why Hidden Sector Photons? (Cont'd)

Muon g-2 experiment disagrees with theory at the 3 sigma level.
A heavy photon with m ~ 10-100 MeV and $\varepsilon \sim 10^{-2} - 10^{-3}$ could solve the problem!

Theory vs Experiment





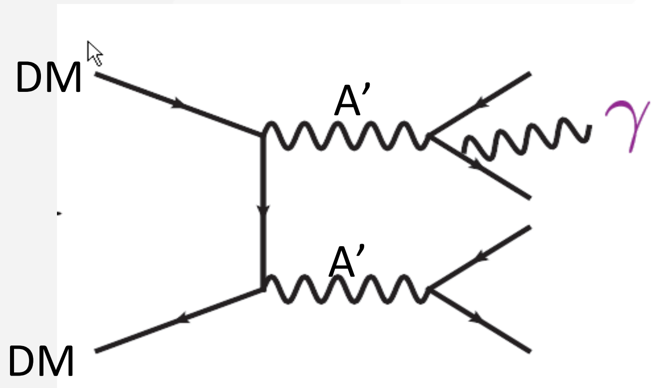
Hidden sector photons may mediate Dark Matter annihilation, giving rise to HE electrons and positrons in the cosmic rays!

Astrophysical Implications

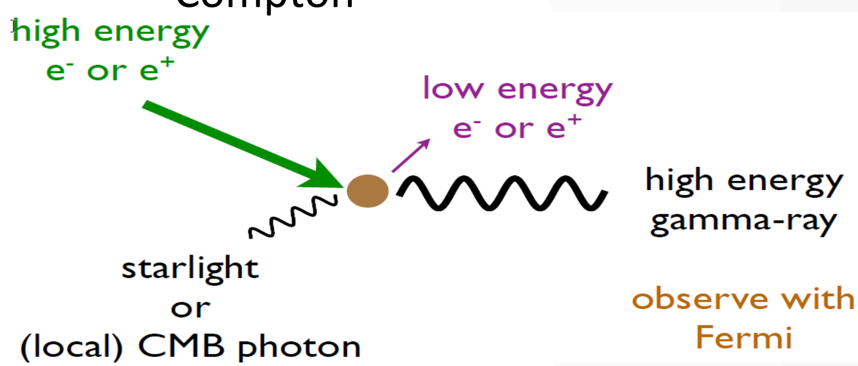
If Hidden Sector DM annihilation is really the cause of the e+e- signal in the cosmic rays, other phenomena must be present too:

Photons must accompany the decay electrons:

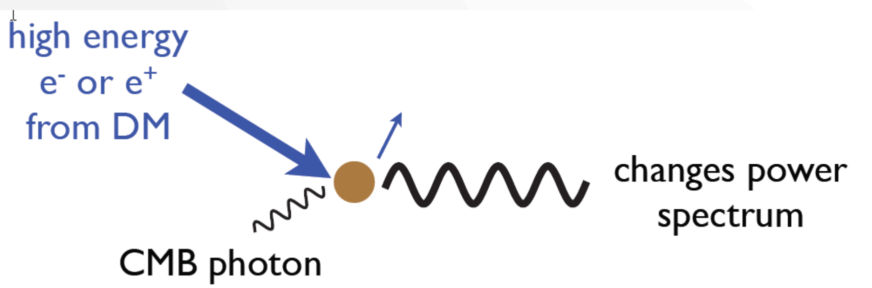
Final State Radiation

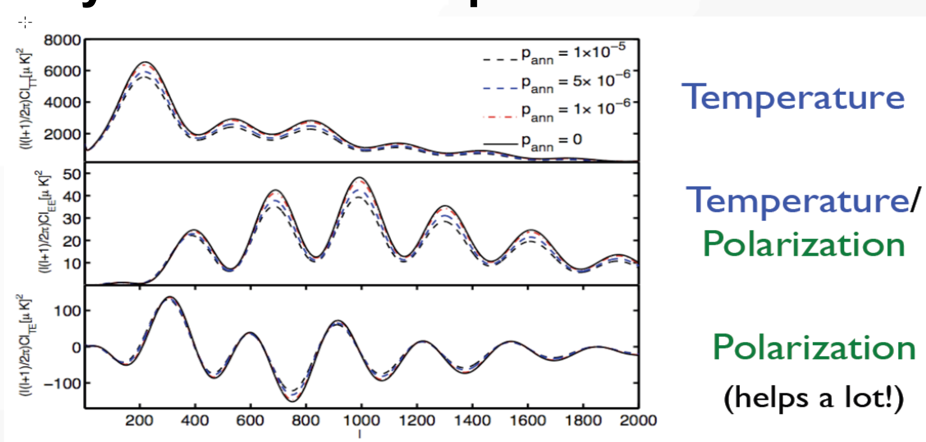


Decay Electrons Inverse Compton



The CMB power spectrum is distorted by electrons from primordial DM annihilations





Particle Physics Implications

- **Particle physics experiments can produce heavy photons.**

- **Searches have to contend with QED Trident backgrounds**

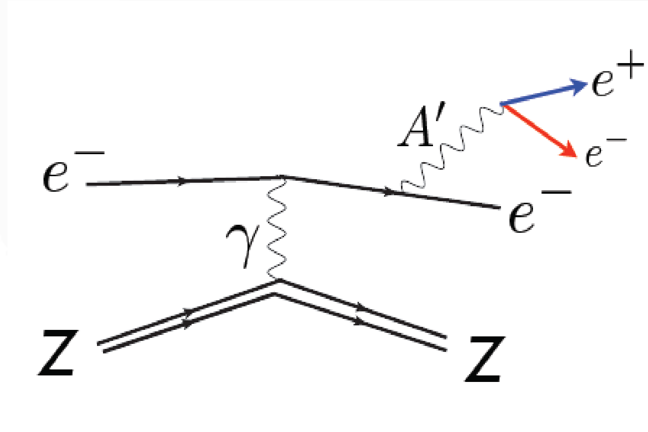
Copious background from virtual photons

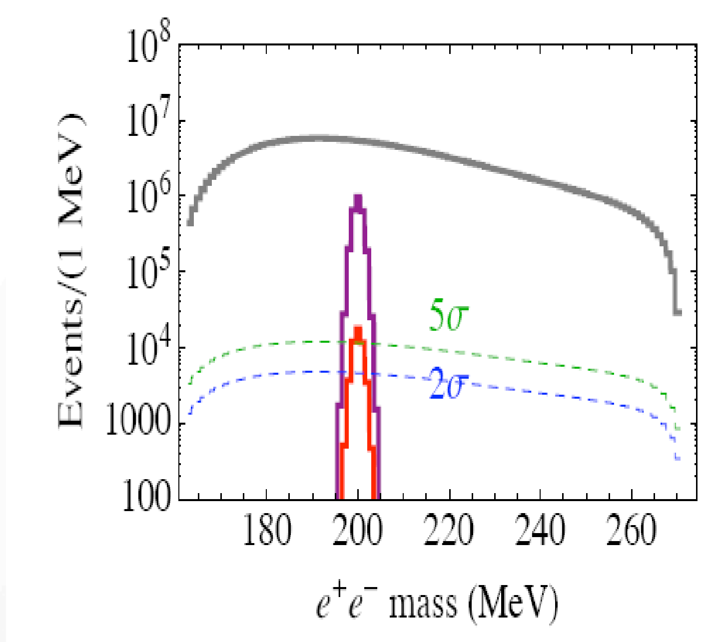
- **A' width small (lifetime is long) since coupling εe is small.**

The small decay width means the A' resonance is very narrow.
The long lifetime can lead to separated decay vertices.

The A' can be identified as a sharp bump in invariant mass.
The A' can have a secondary decay vertex.

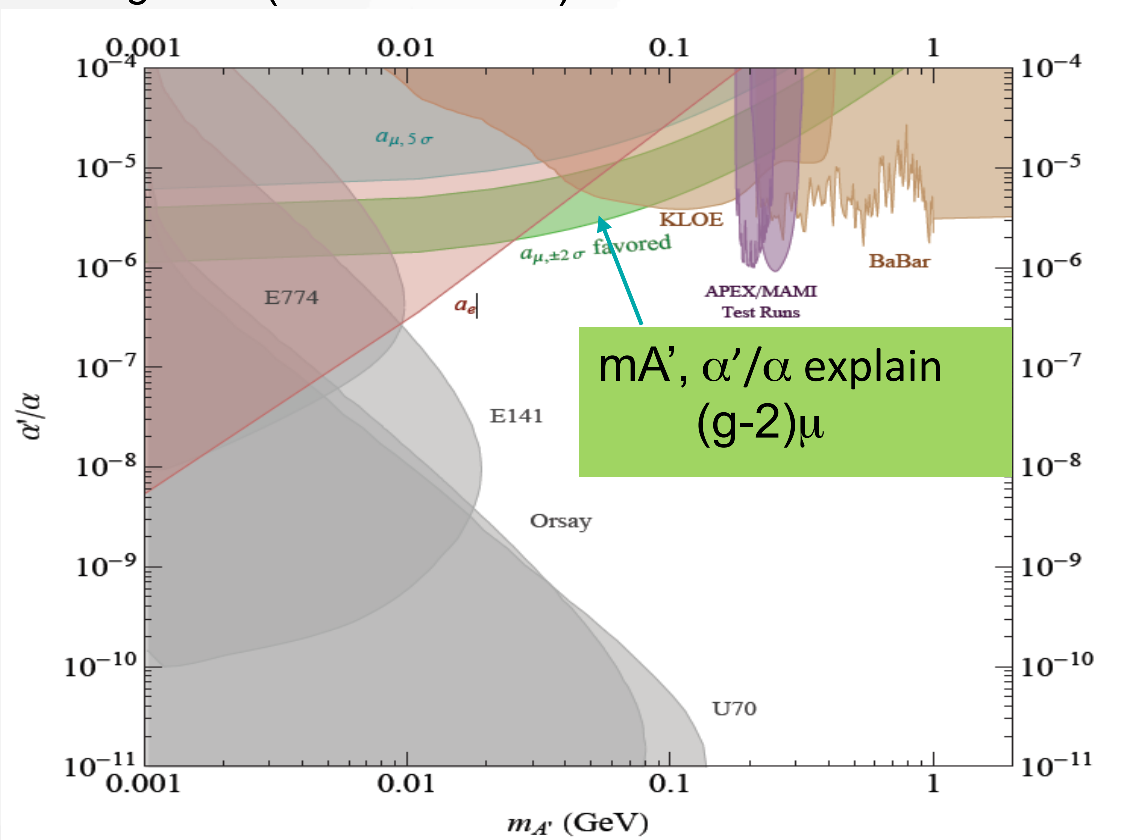
The A' mass can be in the range 10 MeV to 1000 MeV





Present Limits on Mass and Coupling

- **Existing experiments, and existing searches, constrain the A' mass and coupling.**
  Bjorken, Essig, Schuster, Toro (Phys.Rev D **80**, 075018 (2009) and Andreas, Niebuhr, Ringwald (1209.6083v2)



Electron and Muon g-2

Axion Beam Dump Searches
E774, E141, U70

e+e- Colliders
BaBar, KLOE

Dedicated e- Fixed Target
MAMI, APEX

Hidden Sector DM Annihilation valid over much of this plot:

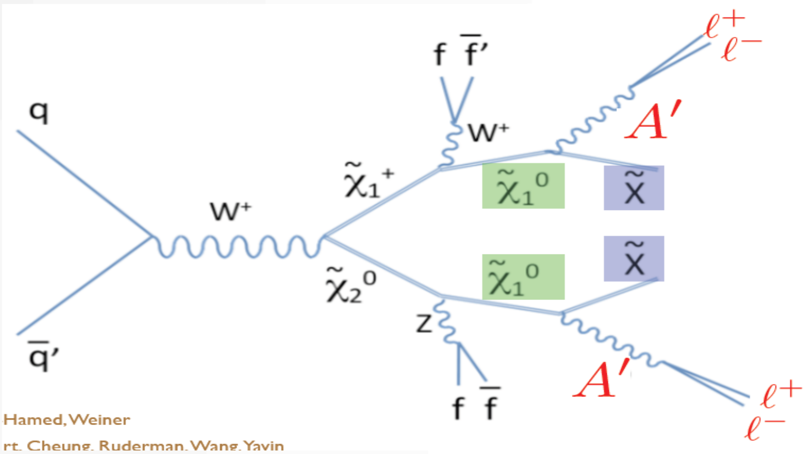
$10 < mA' < 1000$ MeV/c^2 and all $\varepsilon^2 = \alpha'/\alpha$, $\alpha = e^2/4\pi$

Hadron Colliders: LHC

E. Strauss, A. Haas

A' Production gives rise to "Lepton Jets"

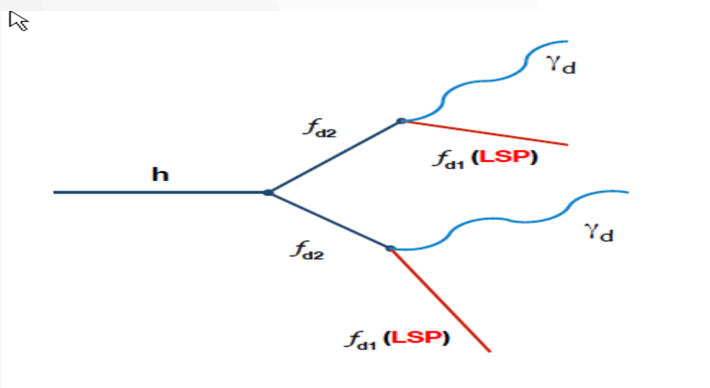
SUSY could produce multiple lepton jets if LSP decays to the dark sector



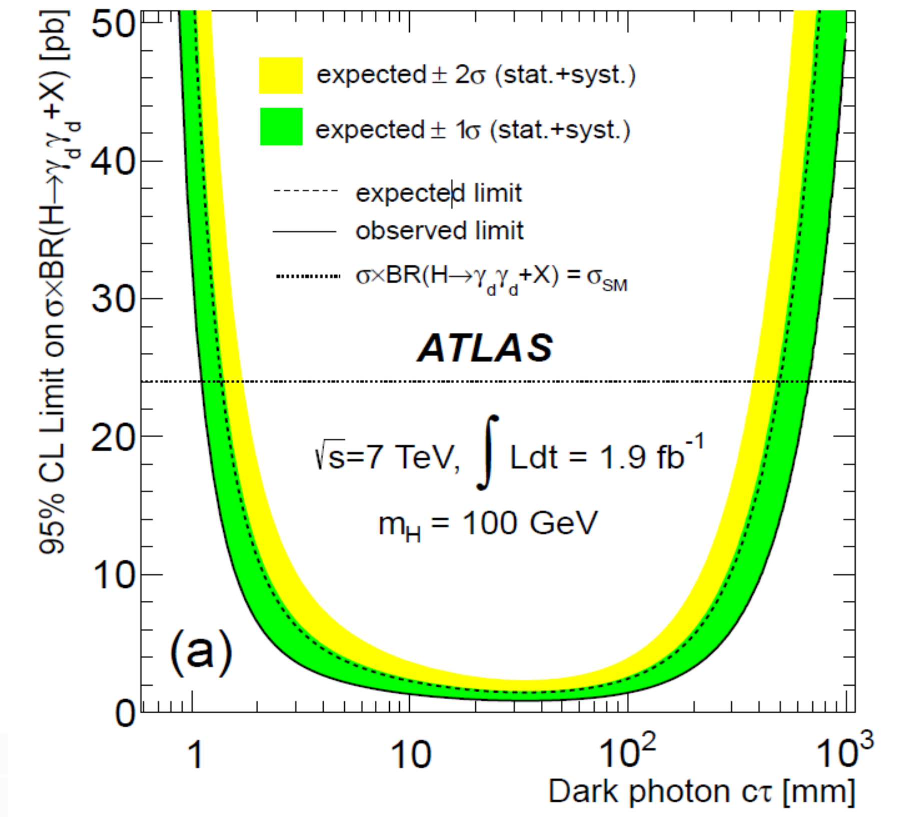
- **But need SUSY particles produced!**

Searched for Higgs → A' + A' + X

http://cdsweb.cern.ch/record/1460408

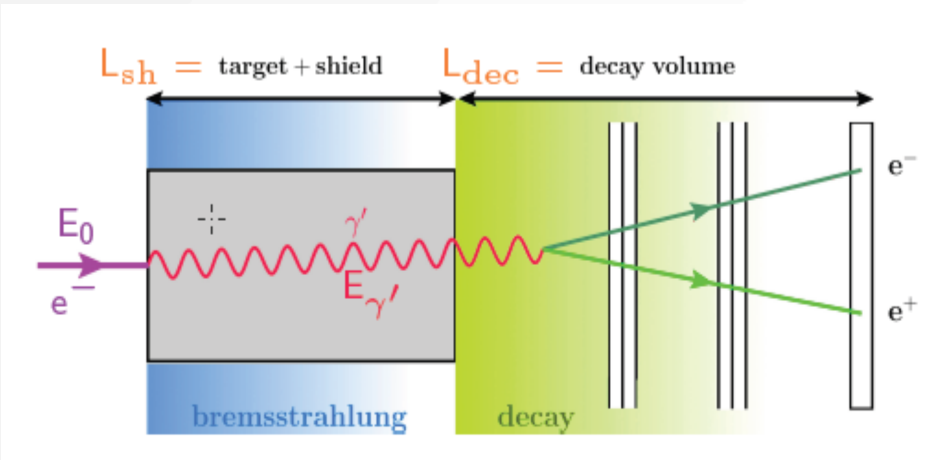


Limits on σ x BR (H → A' A' + X)

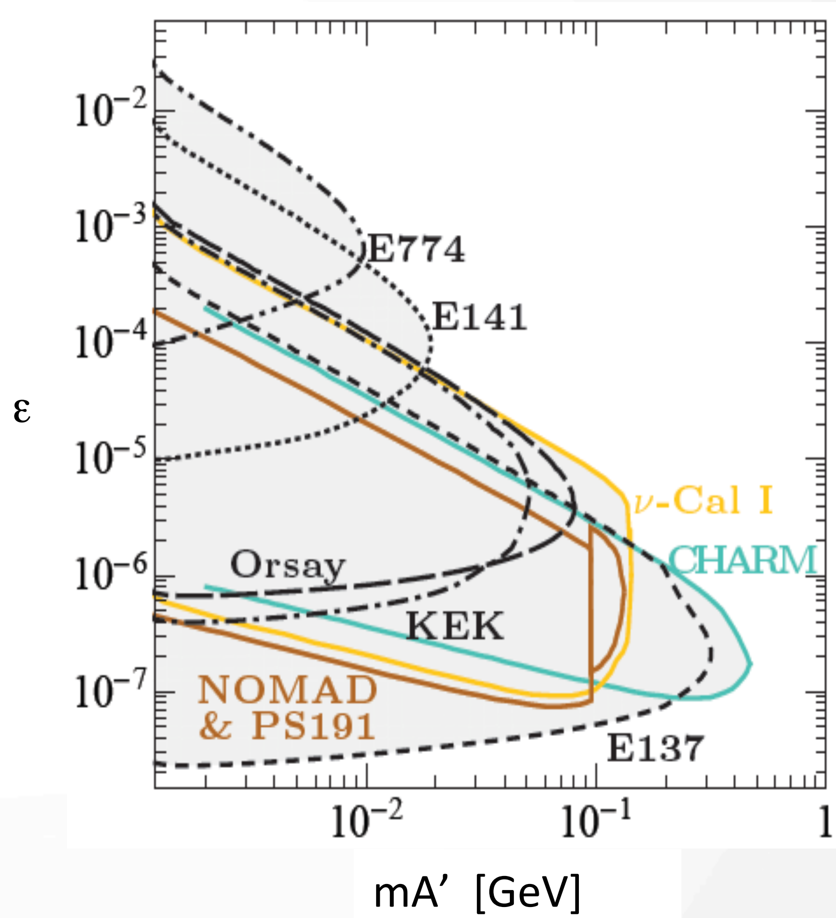


Arkani-Hamed, Weiner
Baumgart, Cheun, Ruderman, Wang, Yavin
Shih, Thomas

Beam-Dump Experiments

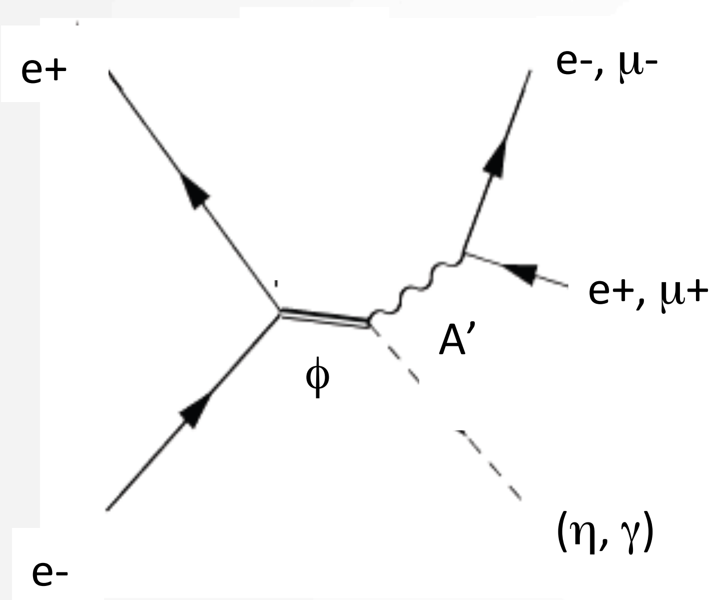


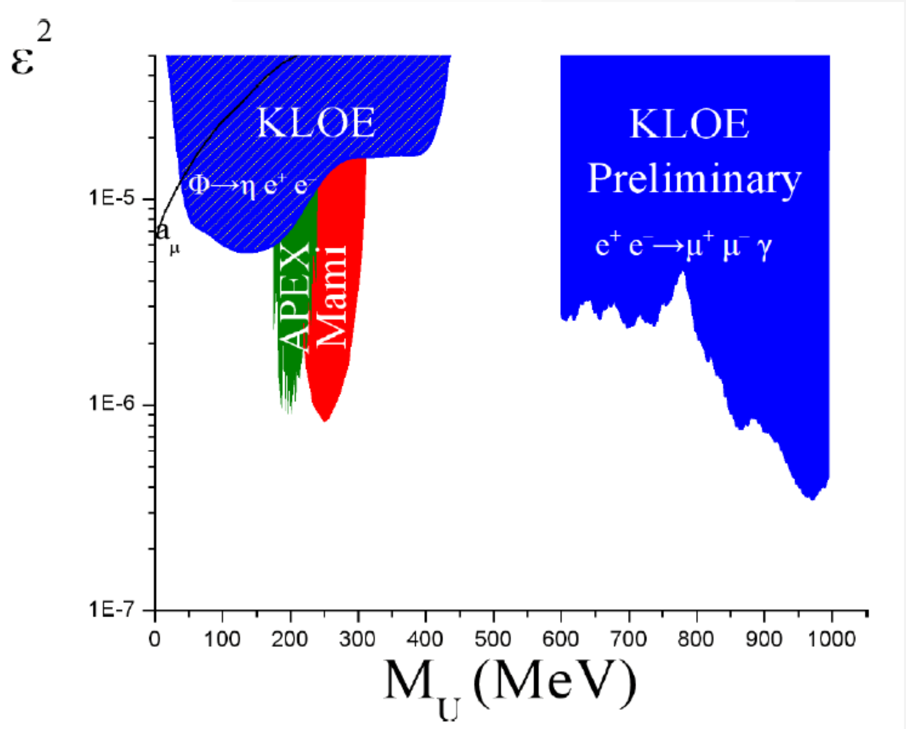
- Beam dump produces EM showers and electrons and positrons.
- Electrons and positrons radiate A's
- A's escape beam dump, can decay near detector.
- Original Beam Dump searches for axions, light higgs bosons, and υ interactions, reinterpreted.



S. Andreas DARK2012

e+e- Colliders: KLOE, BABAR





e+e- → γ A’, A’ → e+e-, μ+μ-, π+π-

F. Curiarella DARK2012

Elisa Guido DARK2012

Fixed Target, Electro-production

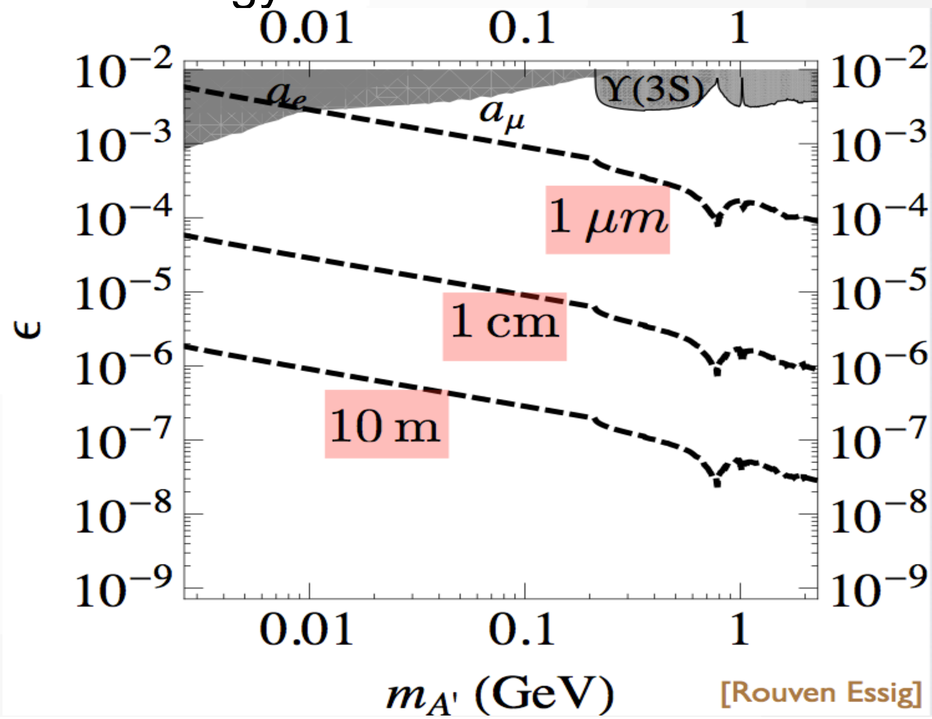
Fixed target experiments enjoy a huge luminosity advantage compared to colliding beam machines for mA’ < 1 GeV

* Much larger cross-sections ($\propto Z^2$)
* Much denser targets!

- **Secondary vertex signature boosts sensitivity significantly**

- **Small signal and large backgrounds**
 demand high currents and high rates and push technology

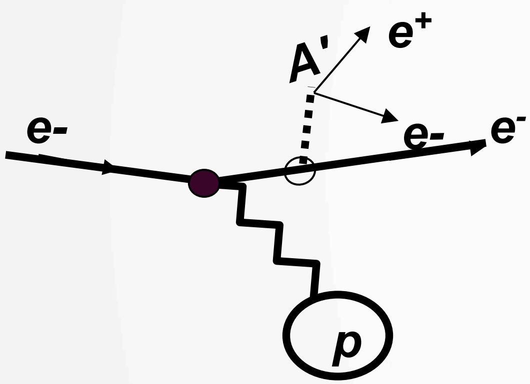
Intensity Frontier Physics!
Intense beams, high rate detectors, and high rate DAQ allow searches for new physics on what was familiar ground

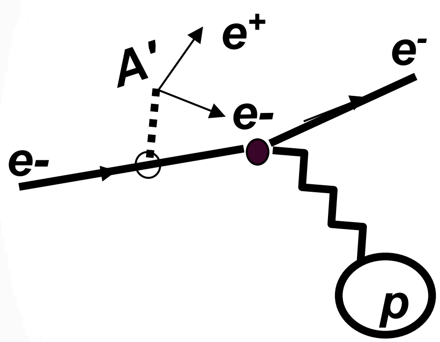


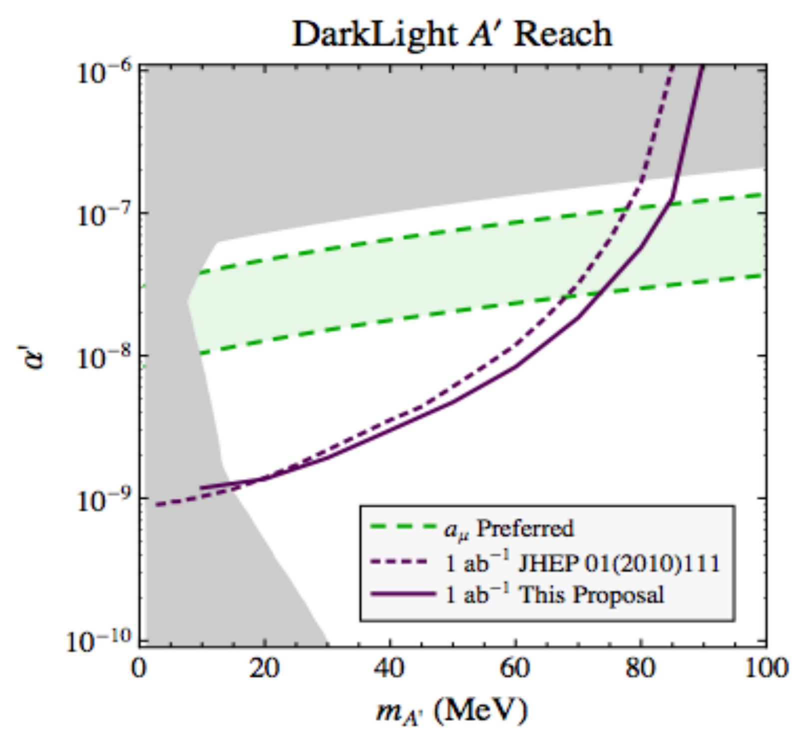
DarkLight

Detecting **A** **R**esonance **K**inematically with e**L**ectrons **I**ncident on a **G**aseous **H**ydrogen **T**arget

A Search for new light bosons using the Jefferson Lab FEL facility.







$$\alpha' \equiv \varepsilon^2\alpha\ ,\ \ (\alpha = e^2/4\pi)$$

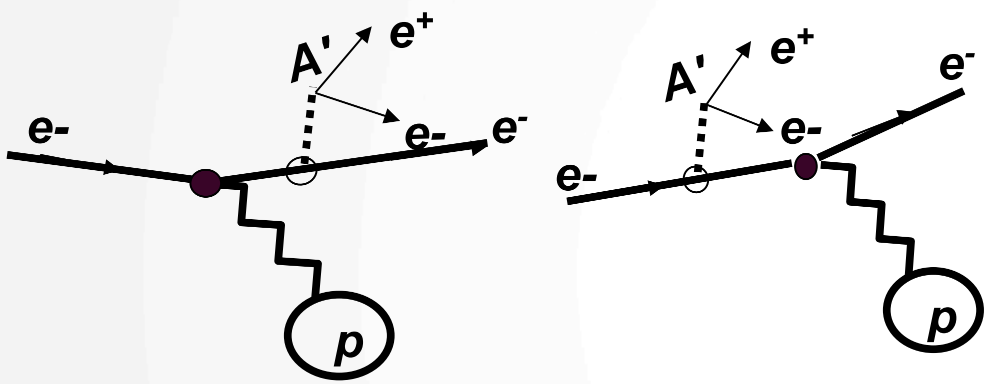
Goal: Explore e^+-e^- invariant mass spectrum using
the process $e^- + p \rightarrow e^- + p + e^- + e^+$
High Intensity, Low Energy Electron Beam
Using JLab's FEL on Thick Hydrogen Gas Target

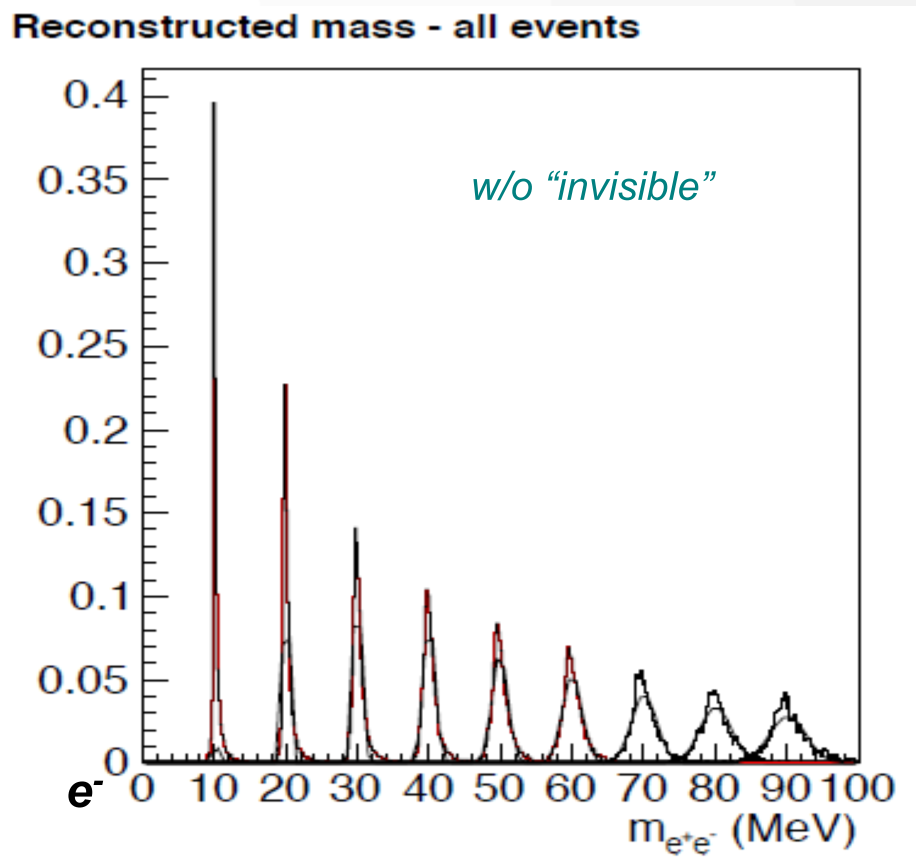
==> Luminosity: 1 ab^{-1}/month

"Dark Force Detection in Low Energy e-p Collisions"
[Freytsis, Ovanesyan, Thalar: arXiv:0909.2862 (JHEP 1001;111)]

DarkLight: Physics Processes

For $\alpha' \sim 10^{-8}$ the expected signal is 10^{-4} of the irreducible QED background:





Signal:
epγ /epA', ep/epA' ("invisible")

Backgrounds:
ep/ep, ep/epγ, ep/epγγ, epγ /epγ

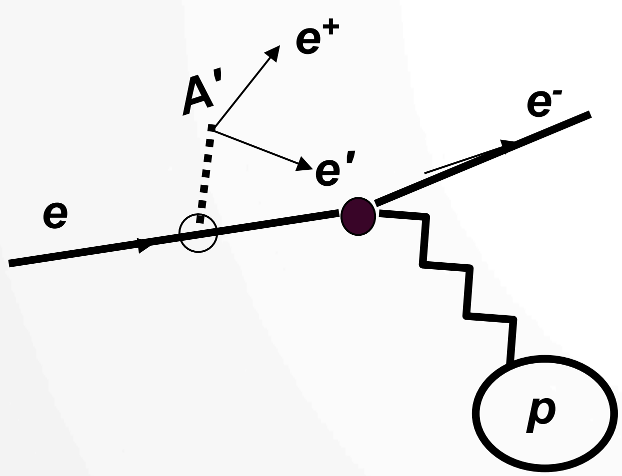
The experiment is basically a measurement of the QED background with 0.1ppm precision. *The detection of all 4 final states is essential.*

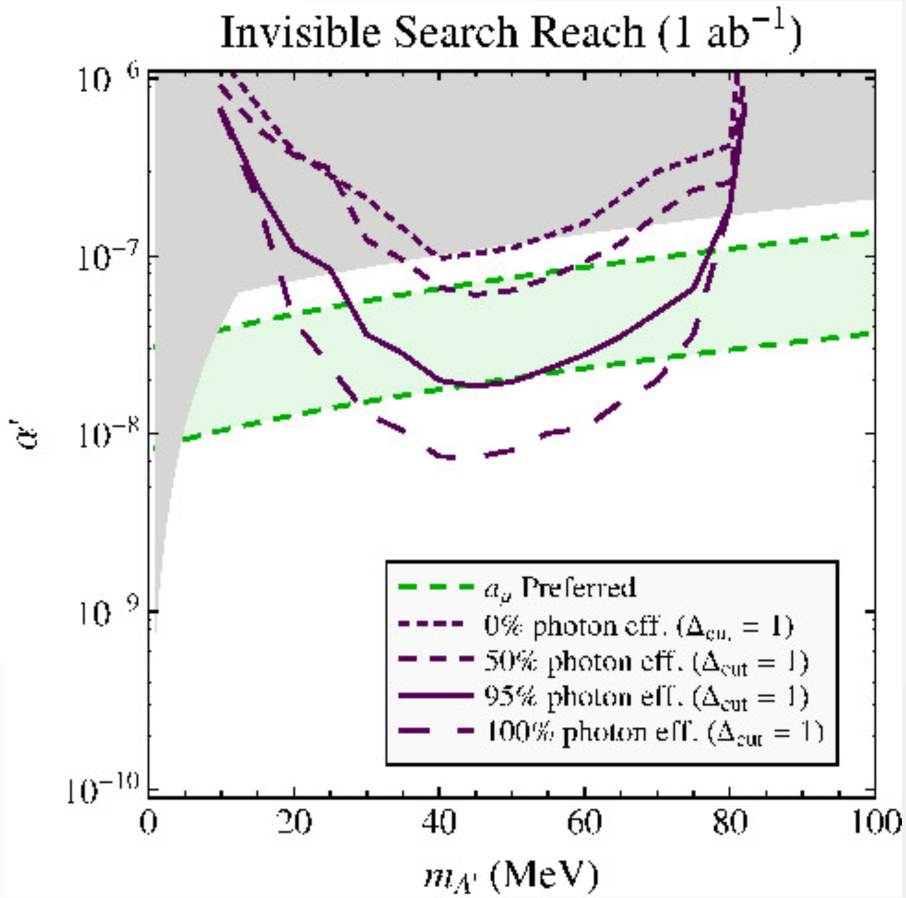
DarkLight: "Invisible"

- *ep → epA' ("invisible")* observe only final state electron and proton

- Backgrounds' kinematics different enough that they can be controlled

- Requires photon tagging; scintillator

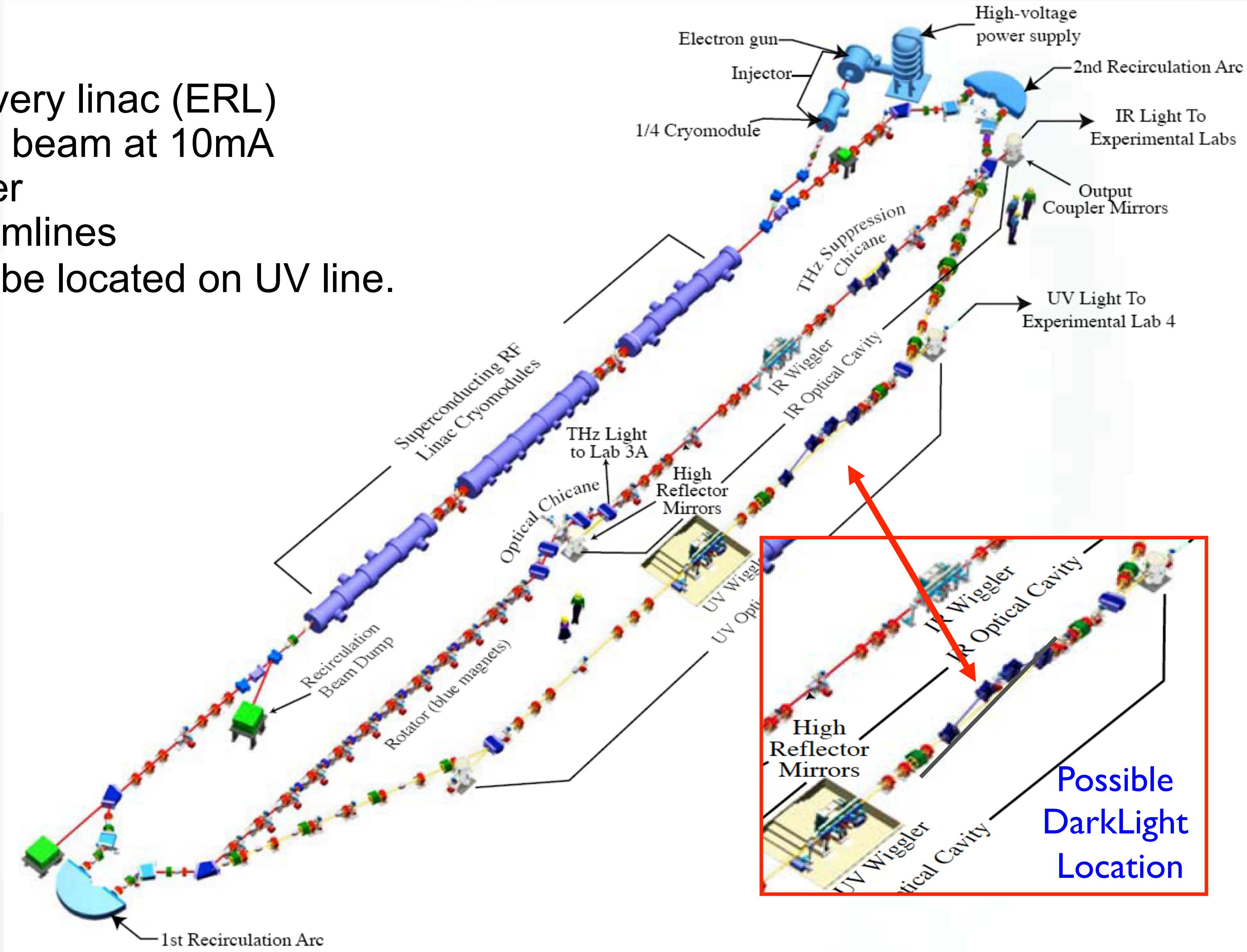




Kahn, Thaler Phys. Rev. D **86** (2012) 115012

DarkLight: At FEL

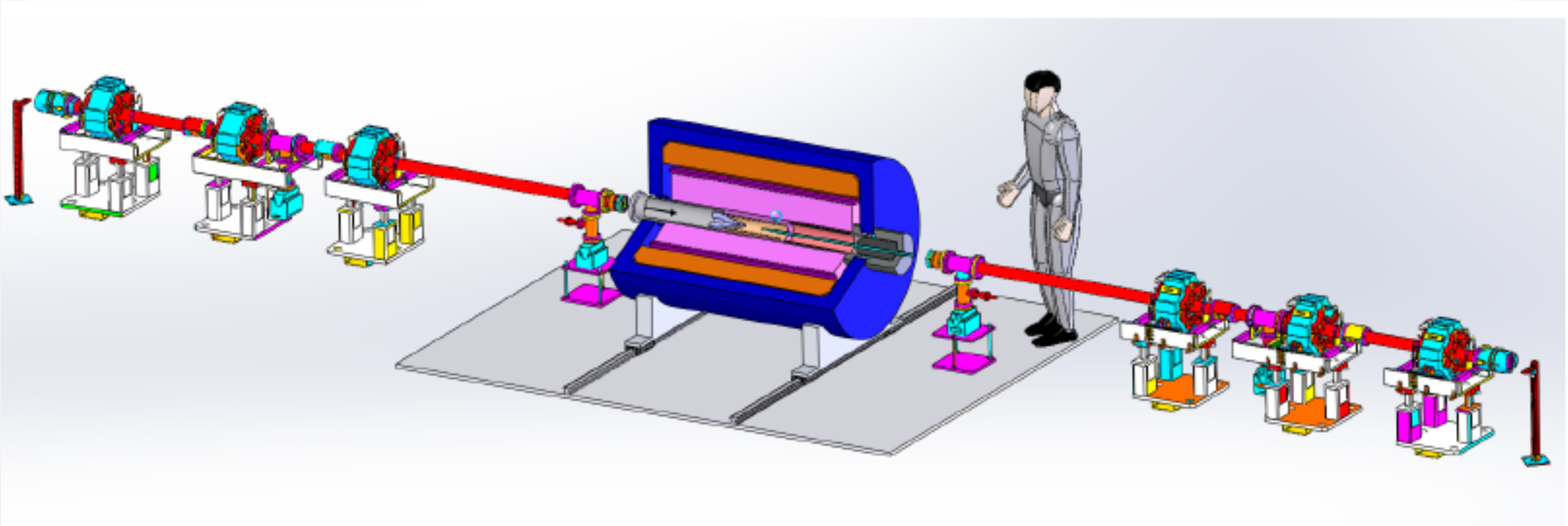
- Energy recovery linac (ERL)
  - 100 MeV e^- beam at 10mA
  - 1 MW power
- IR & UV Beamlines
- DarkLight to be located on UV line.



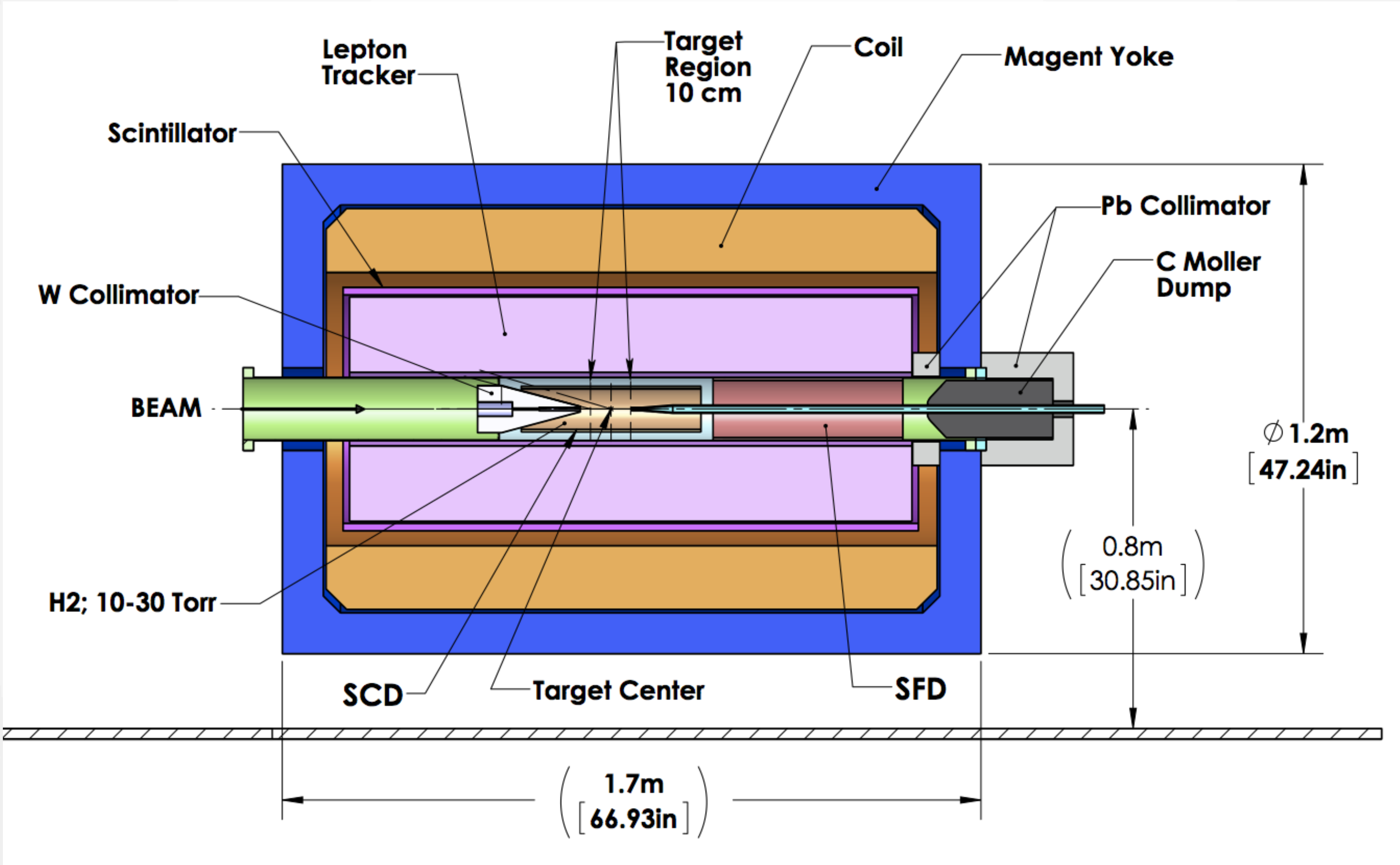
DarkLight: Components

DarkLight has 4 primary components:

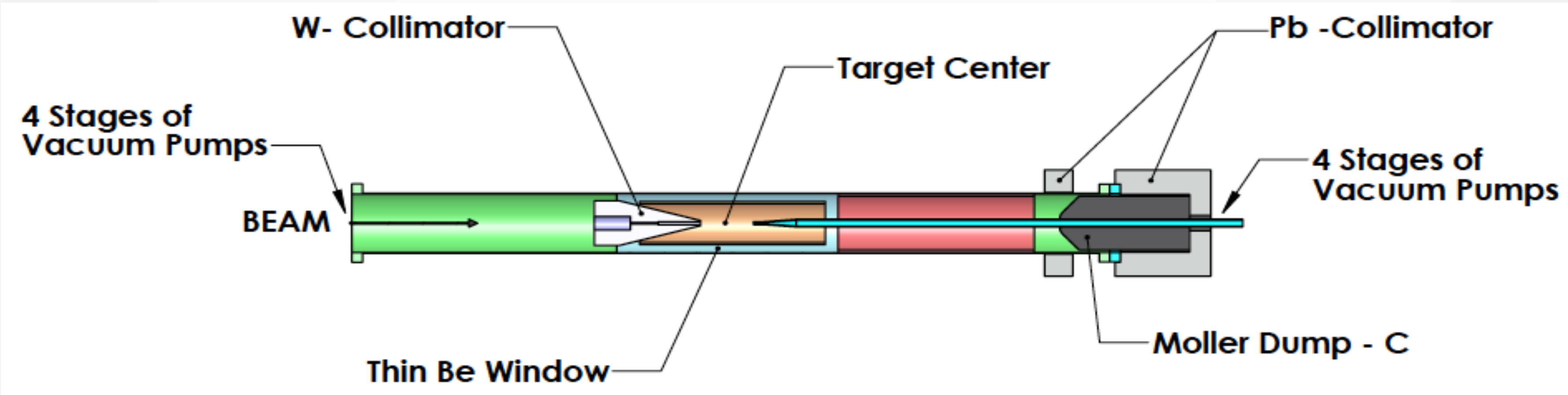
- Target – Differentially pumped hydrogen gas target $10^{19}/cm^2$, 10 cm long.
- Silicon proton detector - ~3.5 cm from beam, single layer of silicon micro-strip detector. Measure energy and angle of recoil proton.
- Lepton tracker – 10-25 cm radius TPC, based on PANDA design.
- Magnet – Solenoid provides 0.5 T B-field to focus Moller e^- and measure lepton momentum and direction.



DarkLight: Schematic



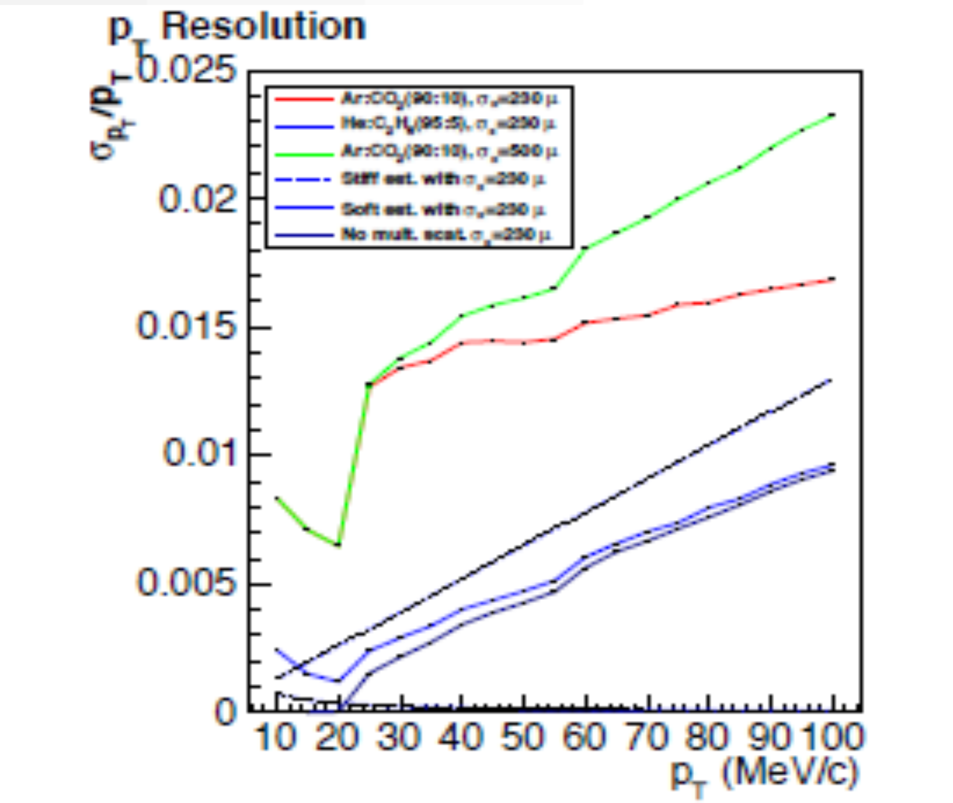
DarkLight: Target

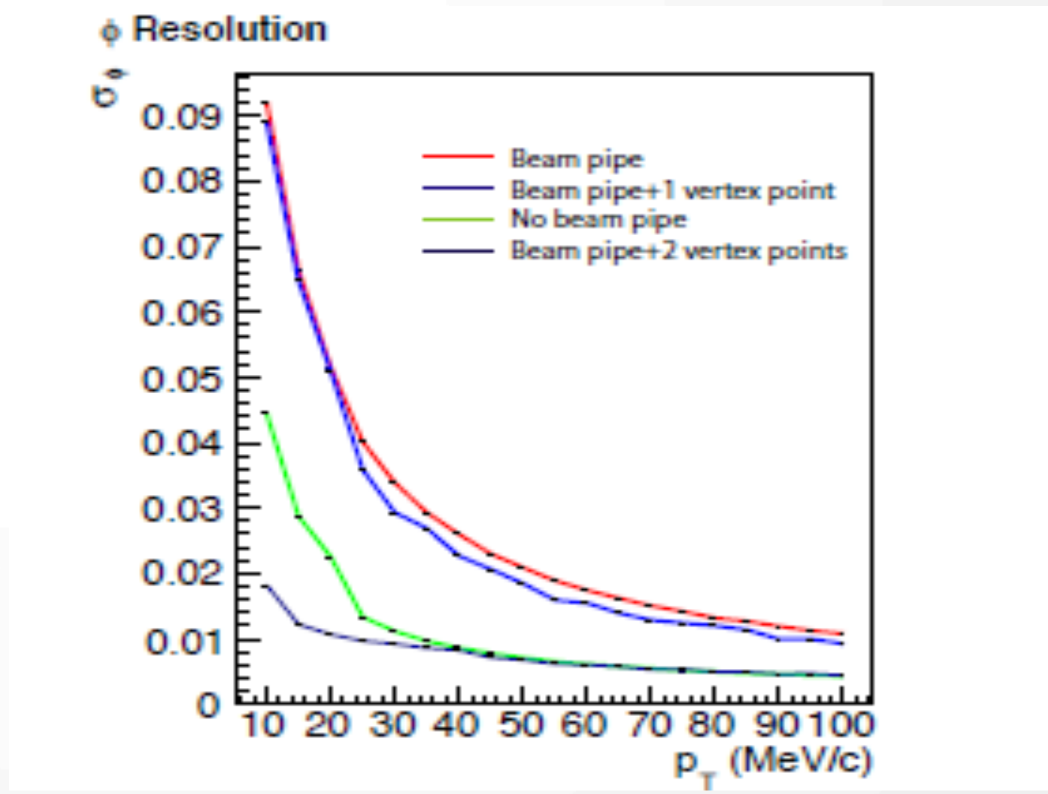


- Hydrogen target realized by flowing gas through narrow apertures
- Aperture diameter: 2 mm
- Aperture length: 50 mm
- Thickness: 10^{19} Hydrogen atoms cm^{-2}
- Flow rate: 24 Torr-liter s^{-1}
- Viscous subsonic flow regime
- Multiple stages of differential pumping required
- Plasma windows under consideration

DarkLight: Lepton Tracker

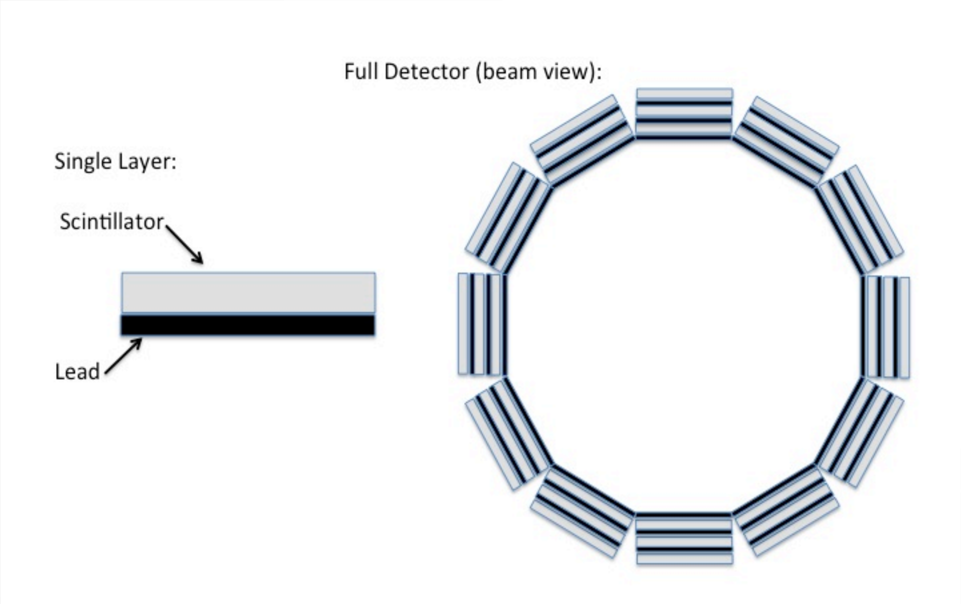
- Similar to PANDA TPC or STAR Forward Tracker.
- Gas Ar(Ne)/CO_2 (90/10)
- $\sim 10^4$ channels
- Triple GEM; gain ~10
- Drift length 725 mm
- Inner/Outer diameter 105/300 mm

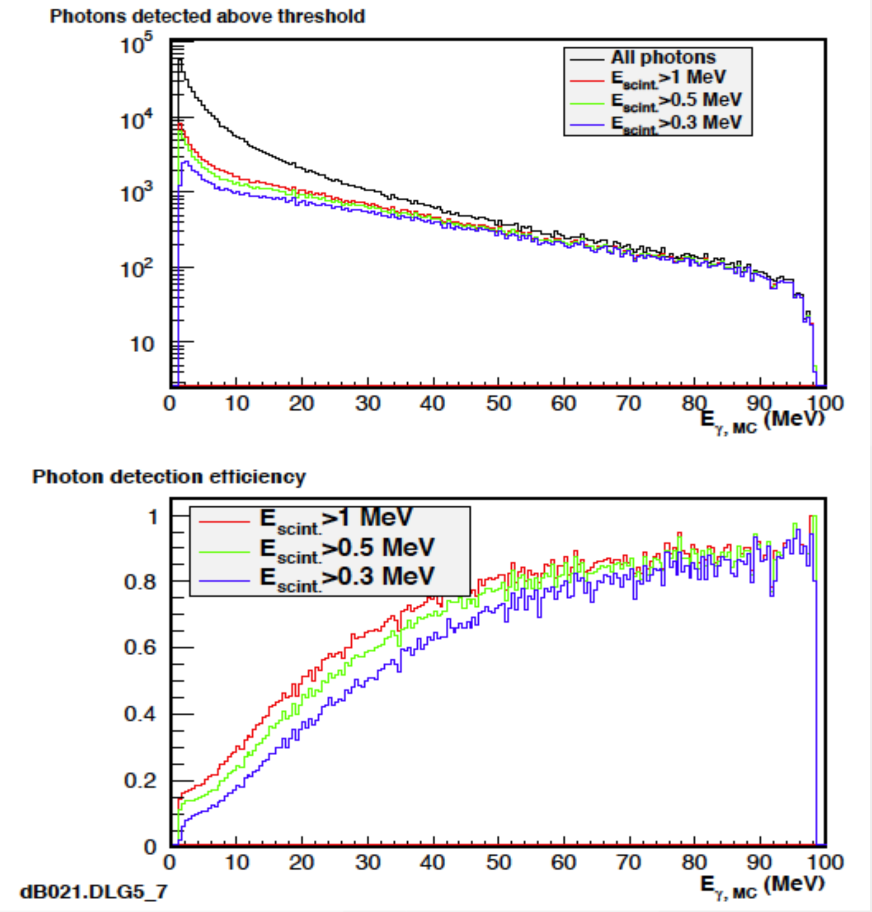




DarkLight: "Invisible"

Detector:
- Cylindrical Array
  60 cm (diam) x 150 cm (length)
- Composed of 10 segments (10 cm wide)
- Segment = Pb (0.5 cm thick) + scintillator (1 cm thick) x 3+
- 3 layers => 90% efficiency.

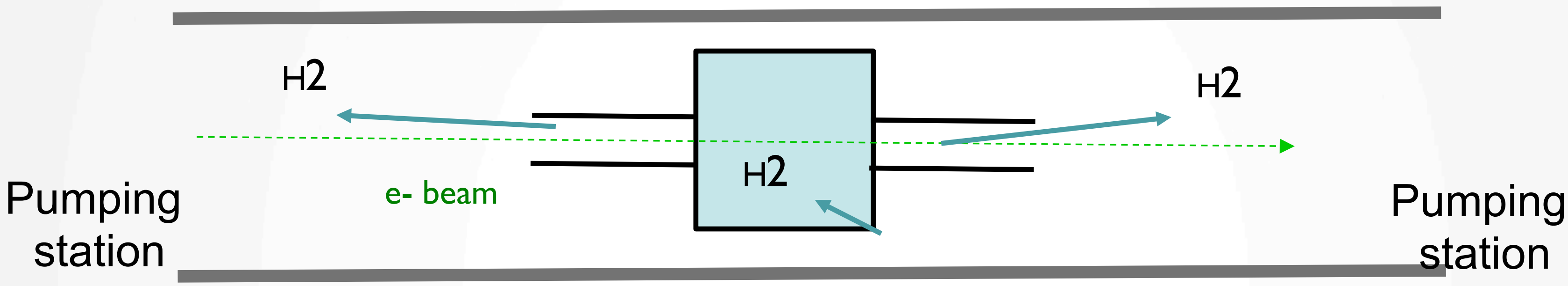


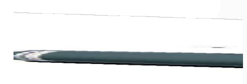


Jlab PAC Proposals

1. PAC 37: DarkLight Collaboration, PAC 37, November 30, 2010.

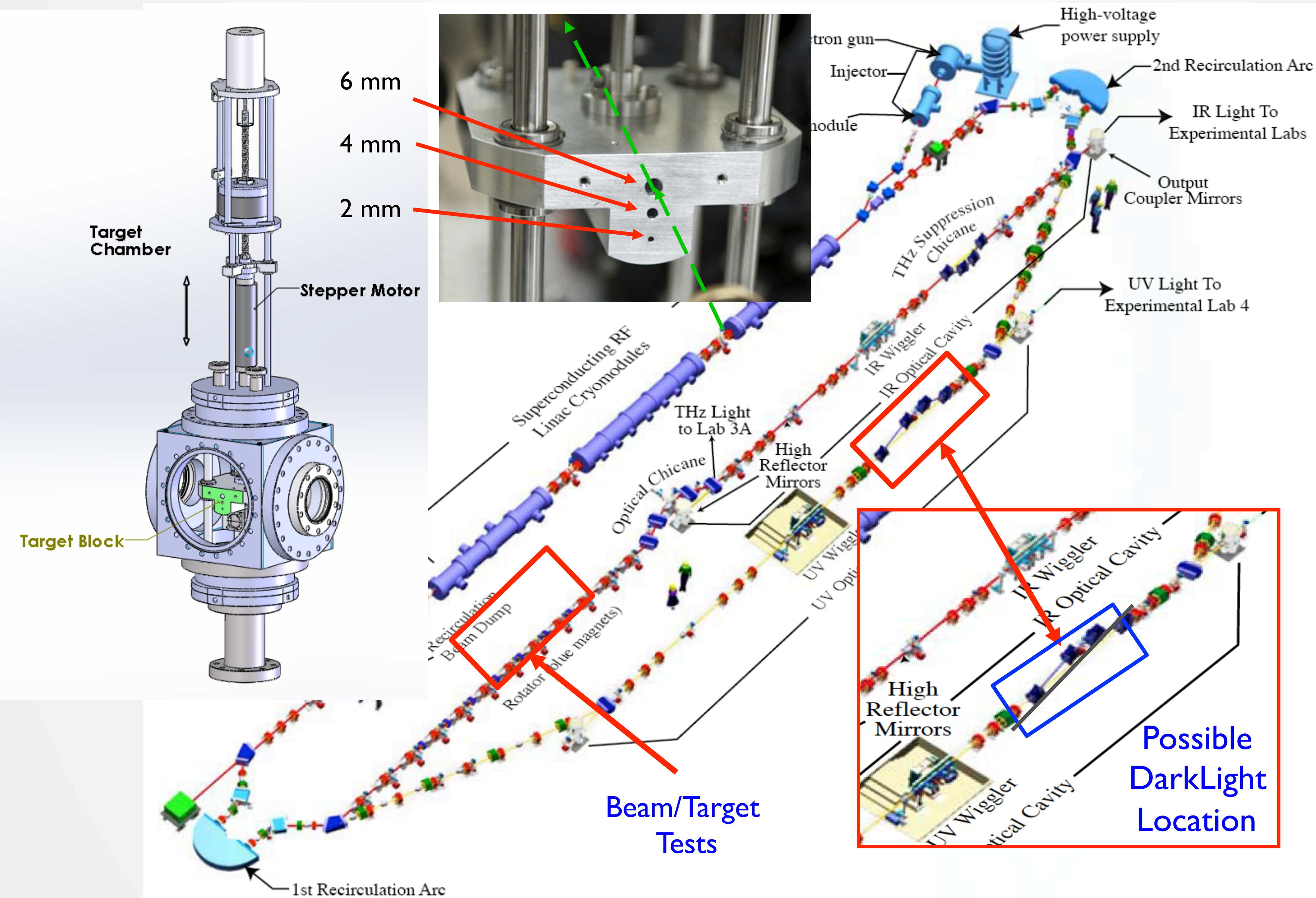
Early concept: electron beam scattering off H2 in a windowless chamber.



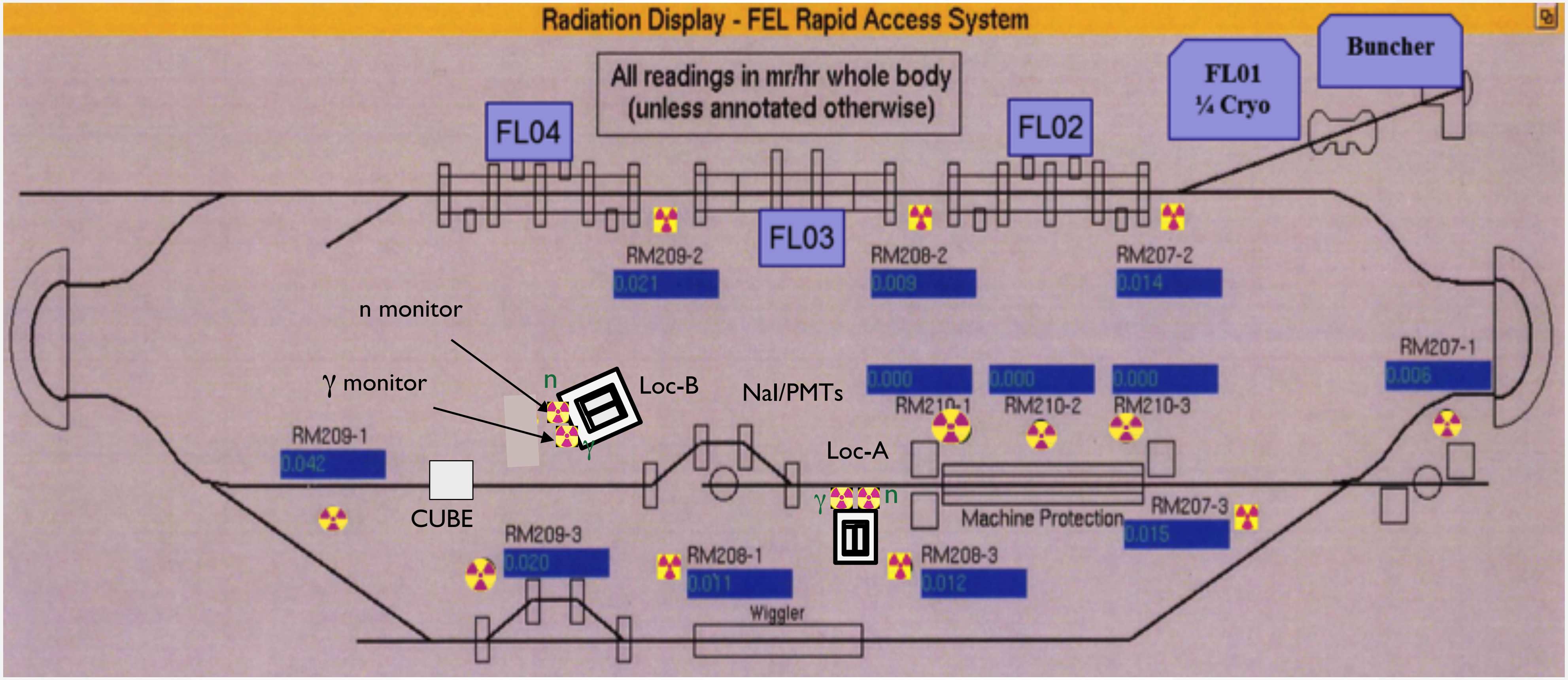


2. PAC 39: DarkLight Collaboration, PAC 39, May 4, 2012.
    - Can DarkLight identify and shield against ambient FEL Vault background radiation.?
    - Can the FEL beam be threaded through the proposed H2 target?
    - Can beam halo be managed?
    - Are there any RF heating/effects on the target entrance/exit?

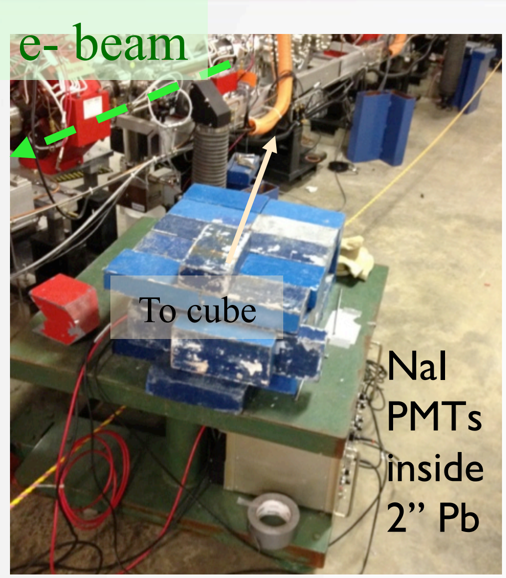
DarkLight: Beam Tests

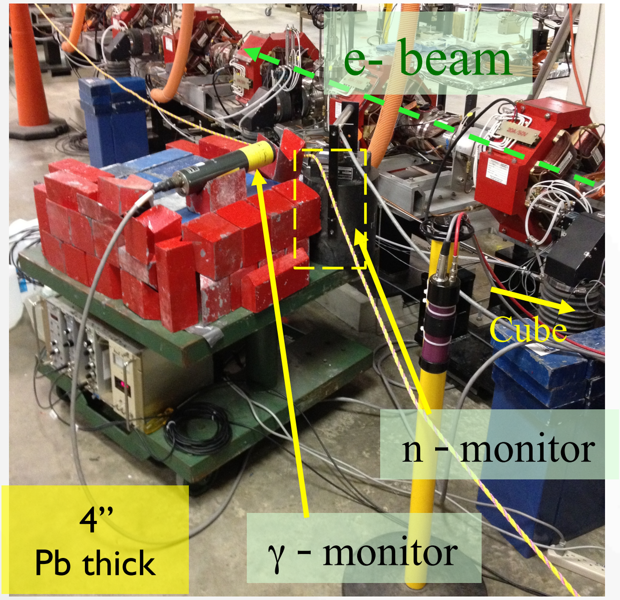


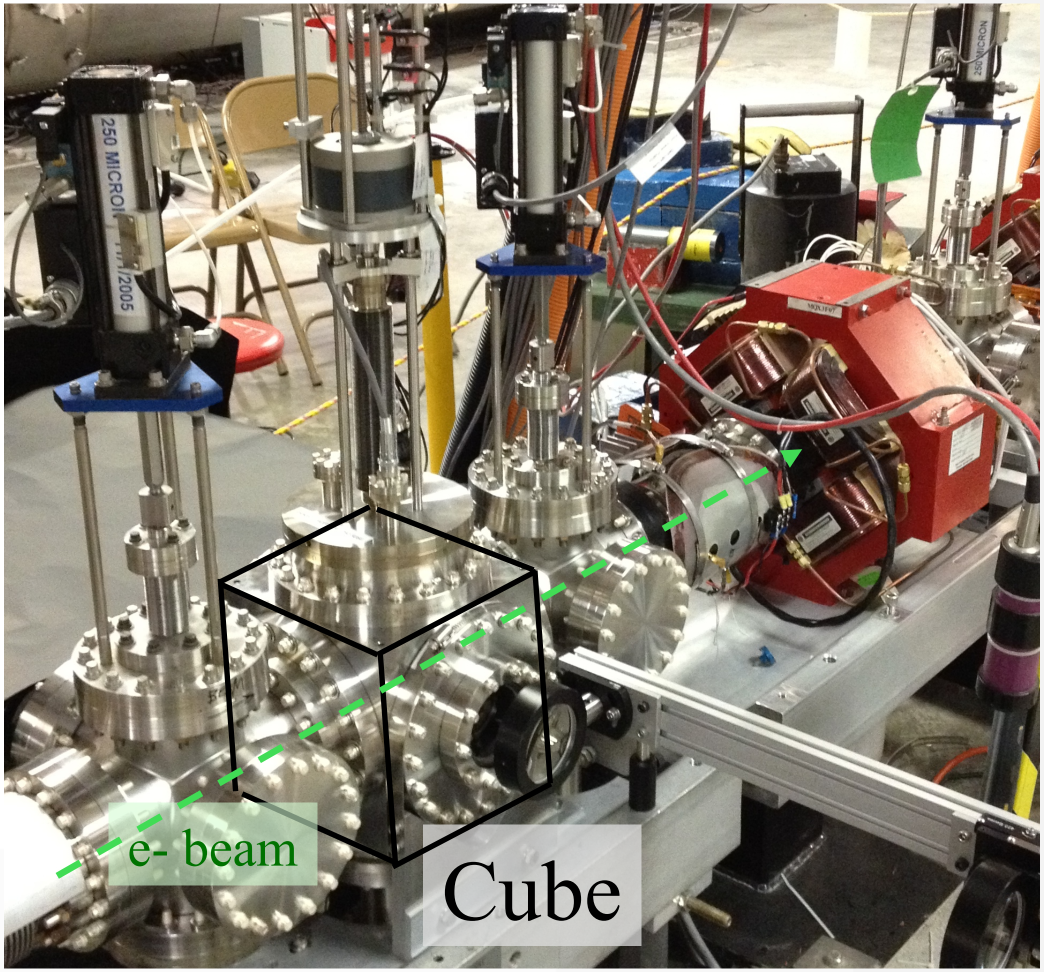
FEL Rapid Access System



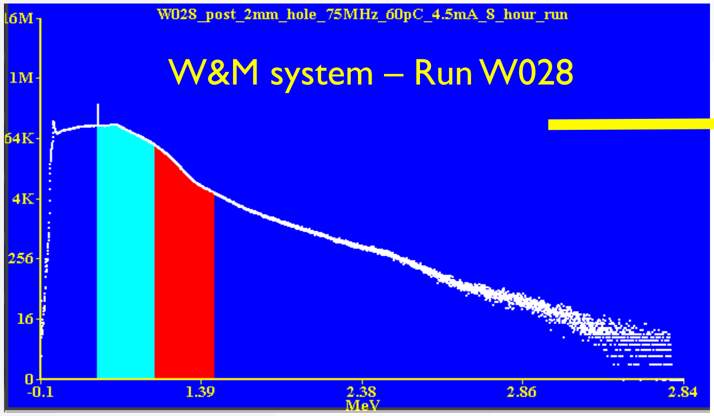
FEL Beam-Target Tests & Radiation Measurements

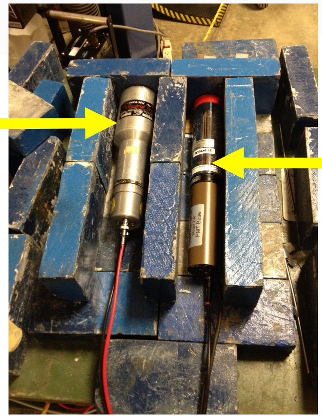


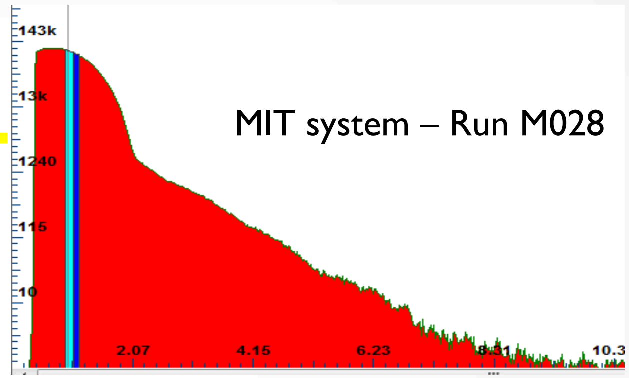


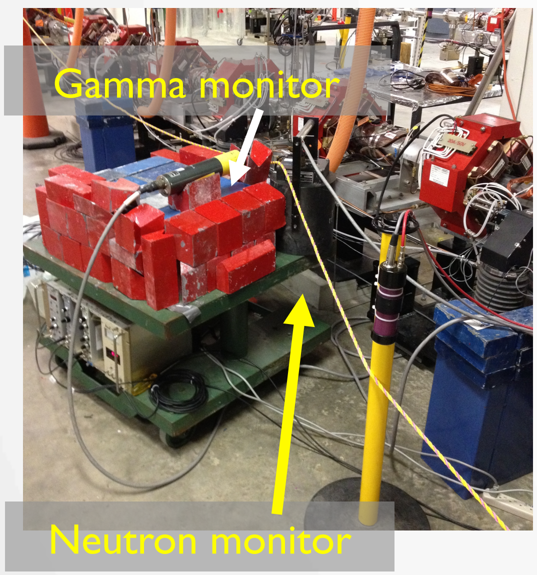


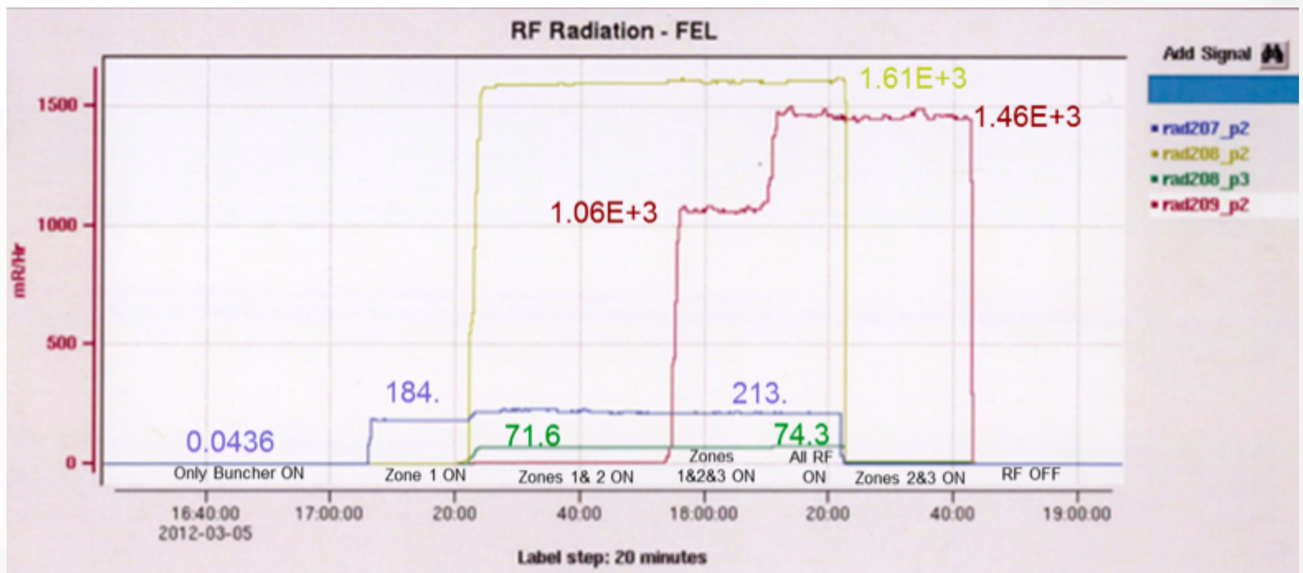
FEL Vault Background Radiation



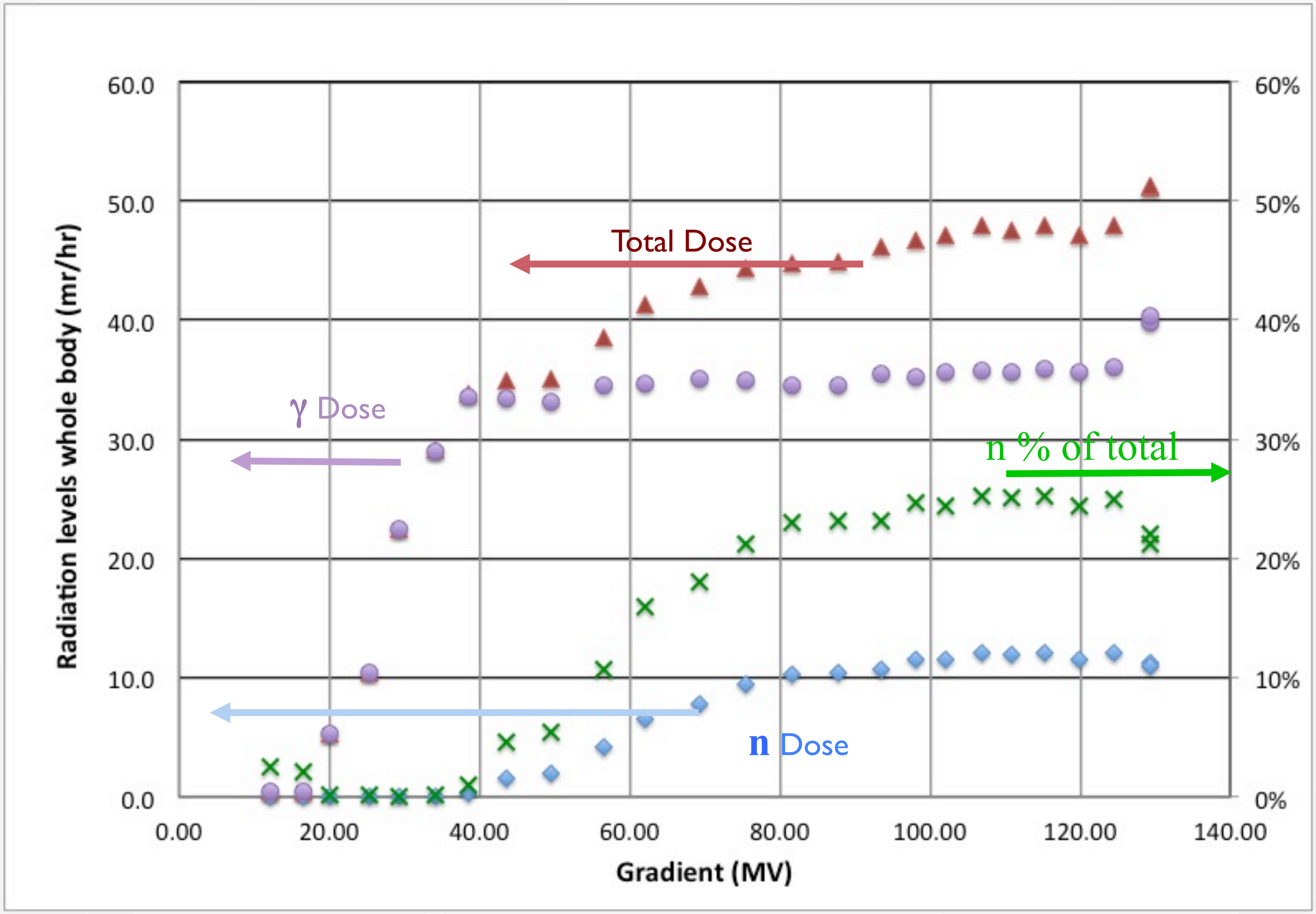




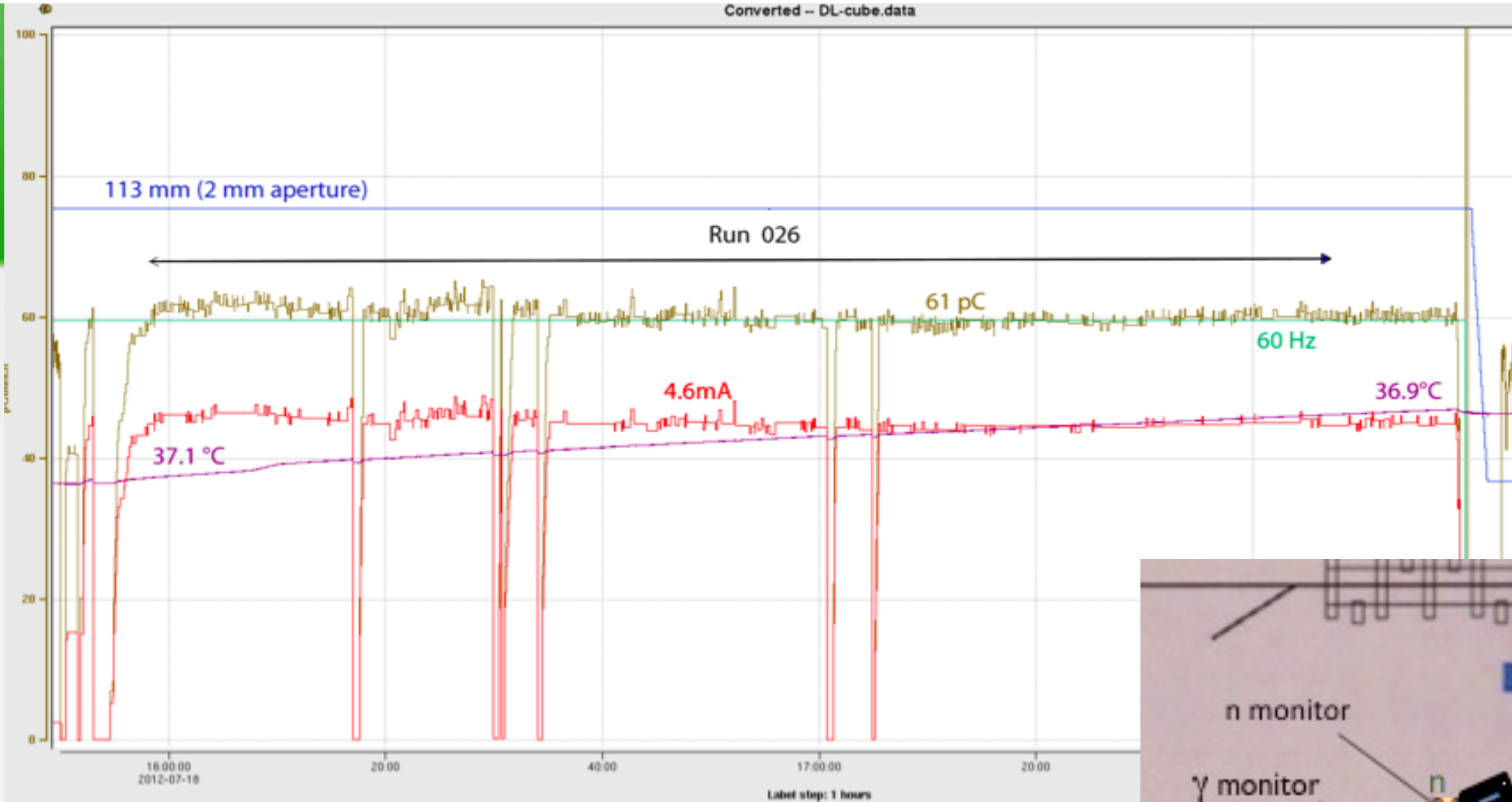


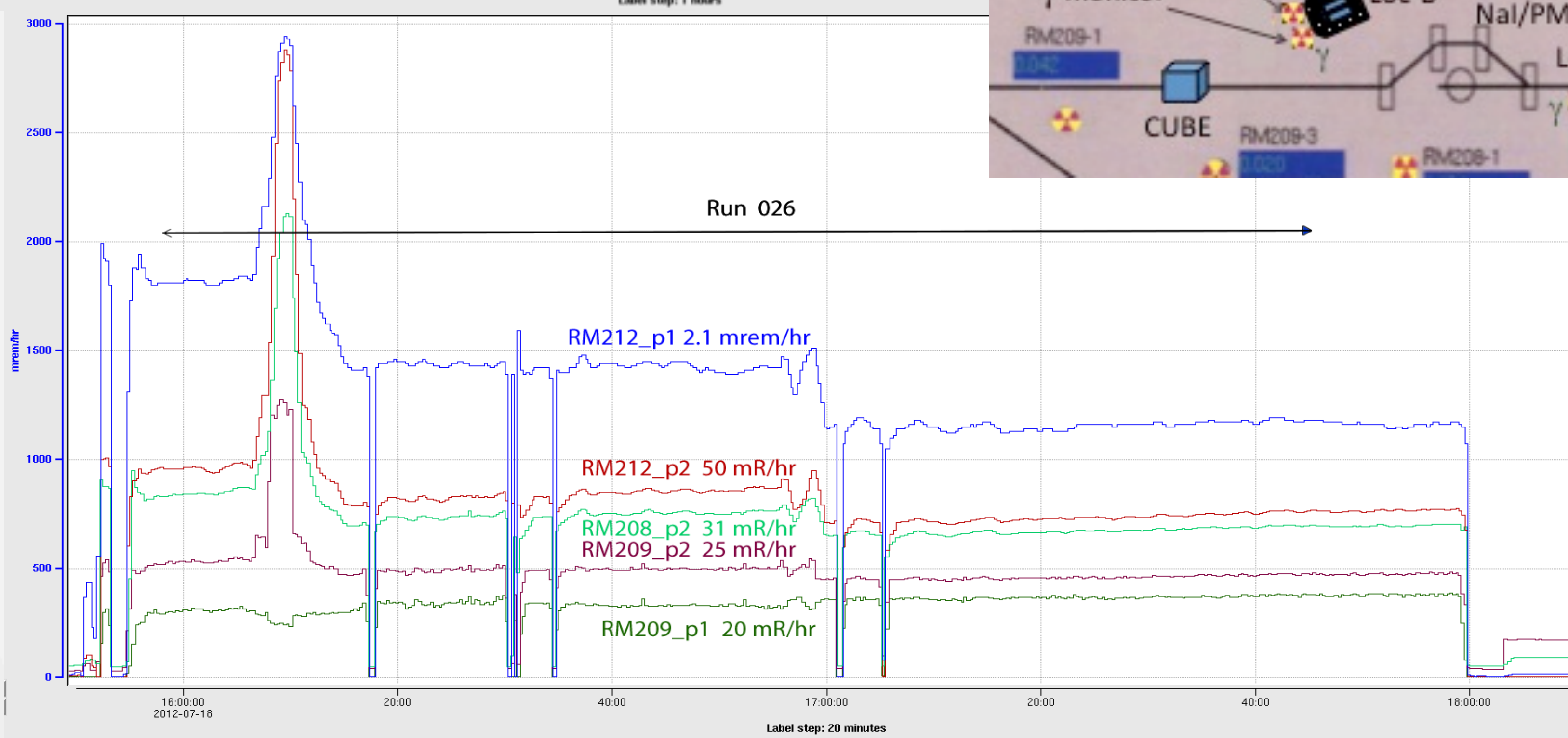


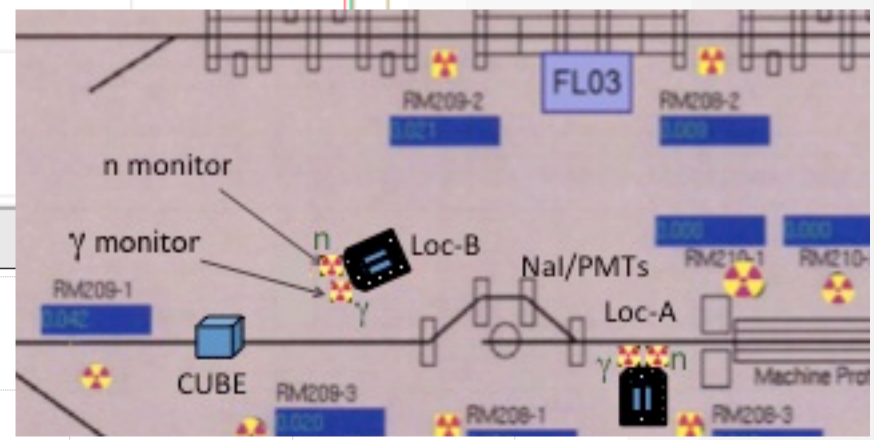
FEL Vault Radiation Levels vs. Total RF Gradient



DL Run 26
Location B







Beam Tests Results

A test e^- beam 100 MeV, 4.5 mA (450 kW power) was successfully transmitted through a 2mm hole, 12.7 cm long, with max loss of 7 ppm for 7 hours. This showed that

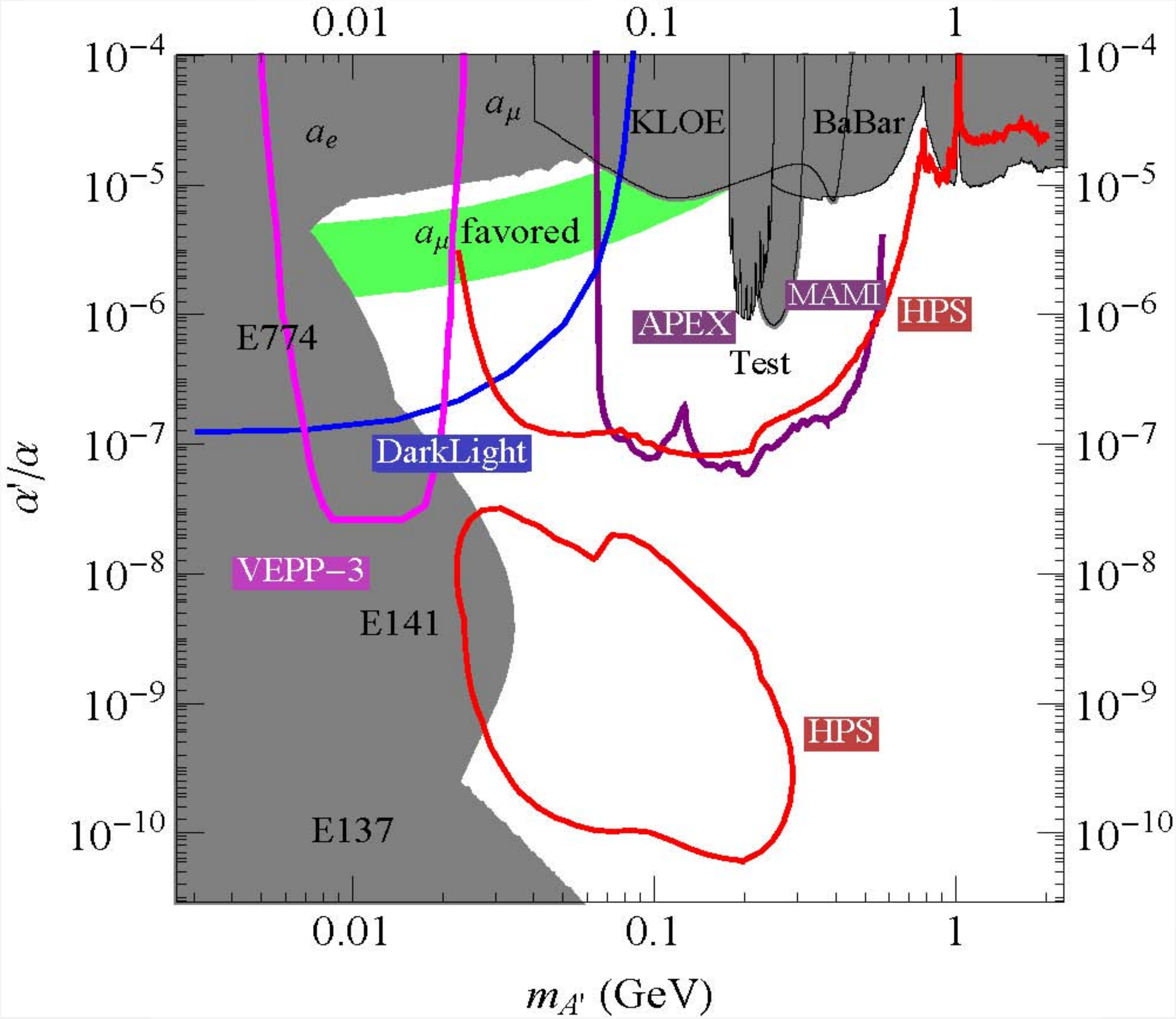
- e^- beam bunch CAN be threaded through a 12.7 cm long, 2 mm hole.
- Halo CAN be minimized.
- The FEL has the stability required for a successful DarkLight experiment.
- Radiation in the vault is manageable.

1 PRL, 2 NIM Articles

Possible Timeline

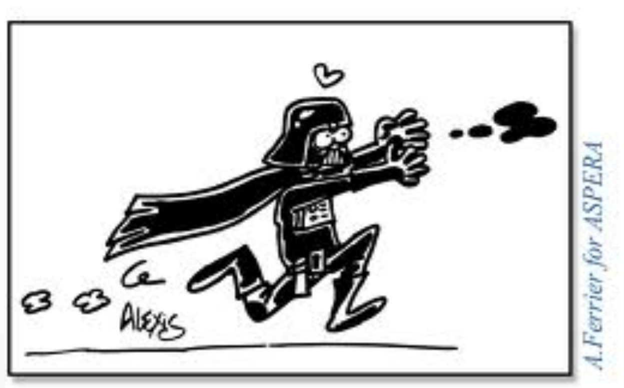
Focus / Year	2012	2013	2014	2015	2016
FEL beam & Radiation limits					
Finalize Design Secure funding					
Technical Review Start Construction					
Detector Commissioning					
DarkLight data taking begins					

Projected Results



Summary and Conlusion

- Fairly recent theoretical developments suggest interaction between dark matter and SM via gauge boson.
- Lepton scattering, fixed-target provides another method for studying dark matter physics.
- DarkLight intends to use the FEL beam (~1 mA, 100 MeV) incident on a H2 gas target. Collect 1/ab in ~ 60 effective days of beam time.
- High acceptance detector inside a 0.5T solenoid: Si-strip recoil detector, TPC for lepton tracking.
- (Jlab) PAC approval and envisioned to run 2016.



Collaboration

Spokespersons: Peter Fisher and Richard Milner

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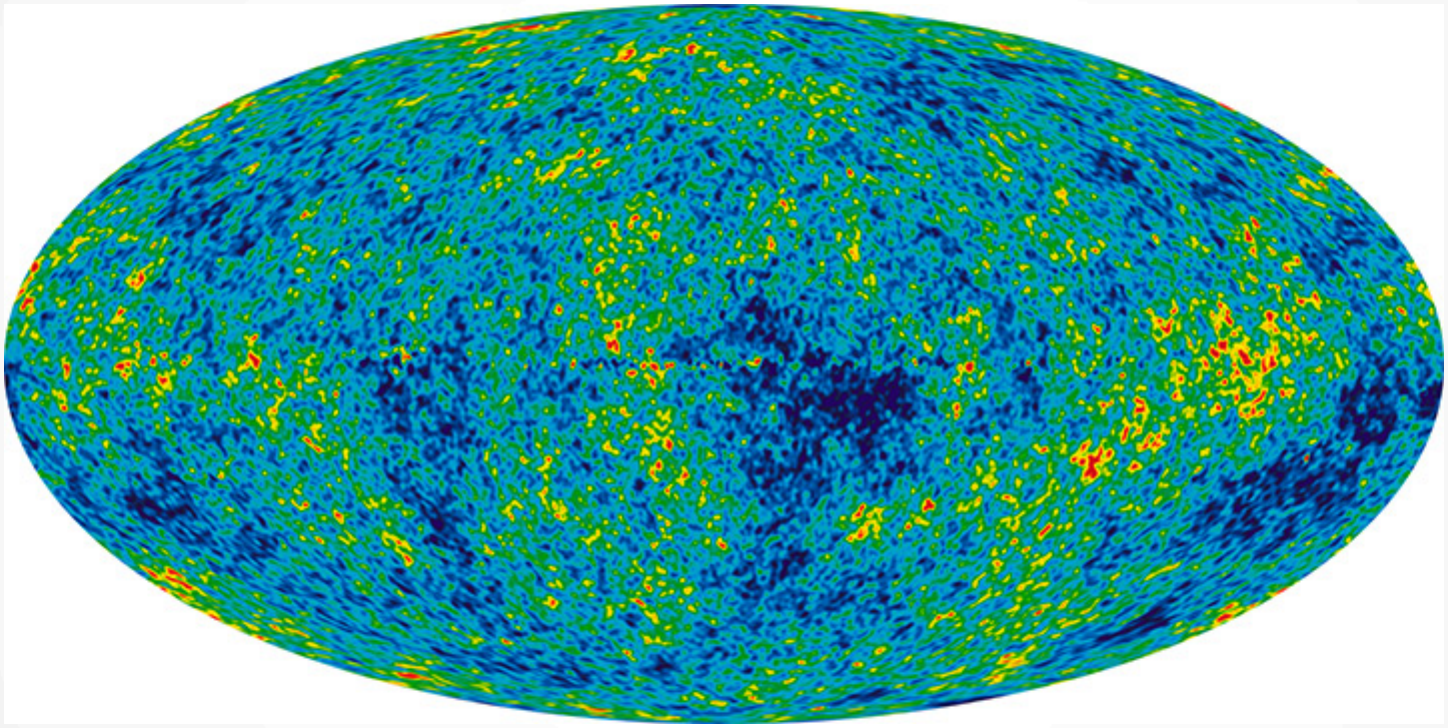
Support Slides

Indicators for Dark Matter

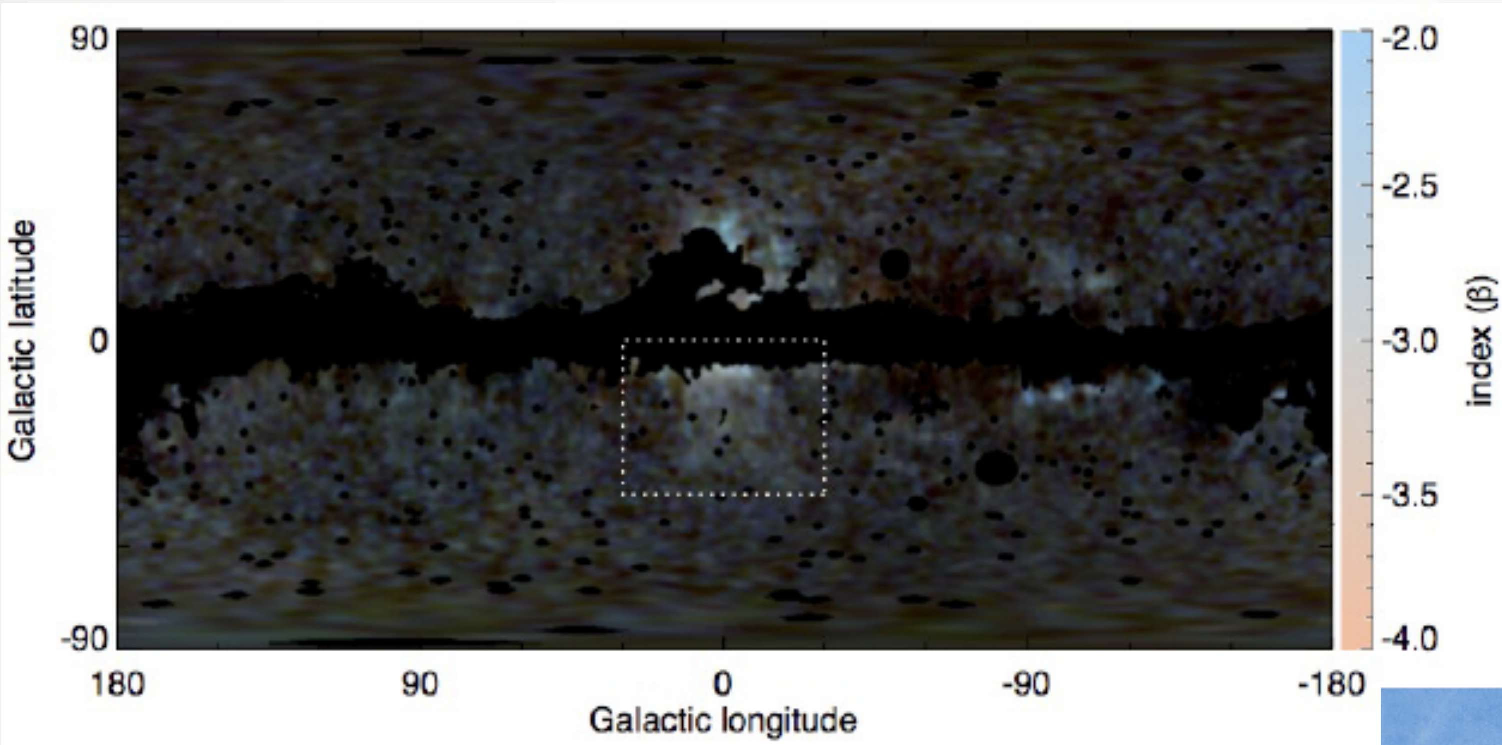
Astrophysics



$$\Omega_C = 0.2402^{+0.0088}_{-0.0087}$$

Large-Scale: Distribution of CMB (COBE, WMAP, PLANCK)

WMAP "Haze"

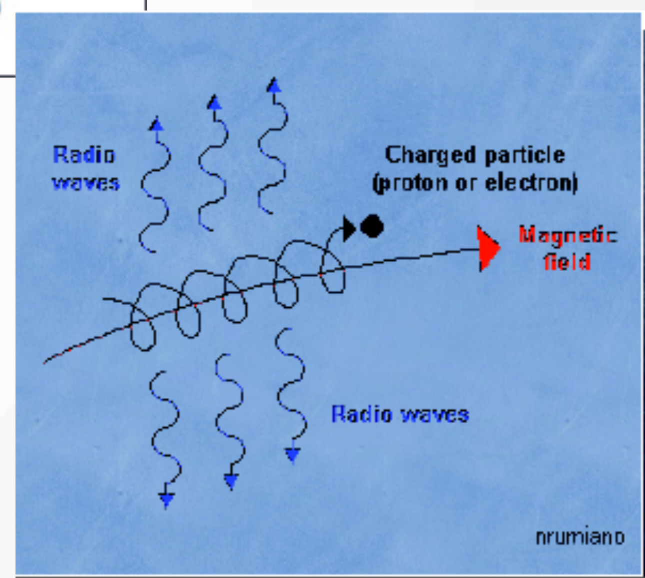


Radiative Flux:

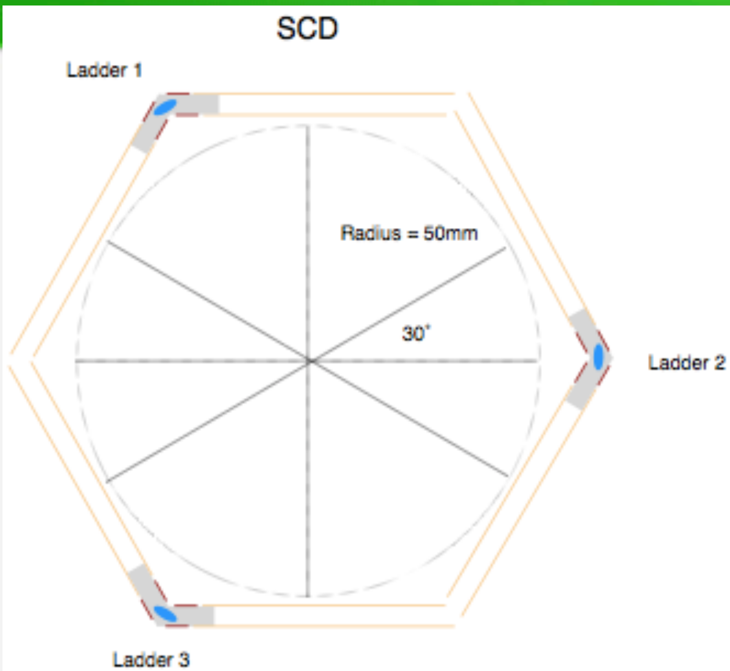
$$S \propto \nu^{-\beta}$$

Dobler & Finkbeiner 2007;
New source of 10+ GeV e^+e^- in galactic center

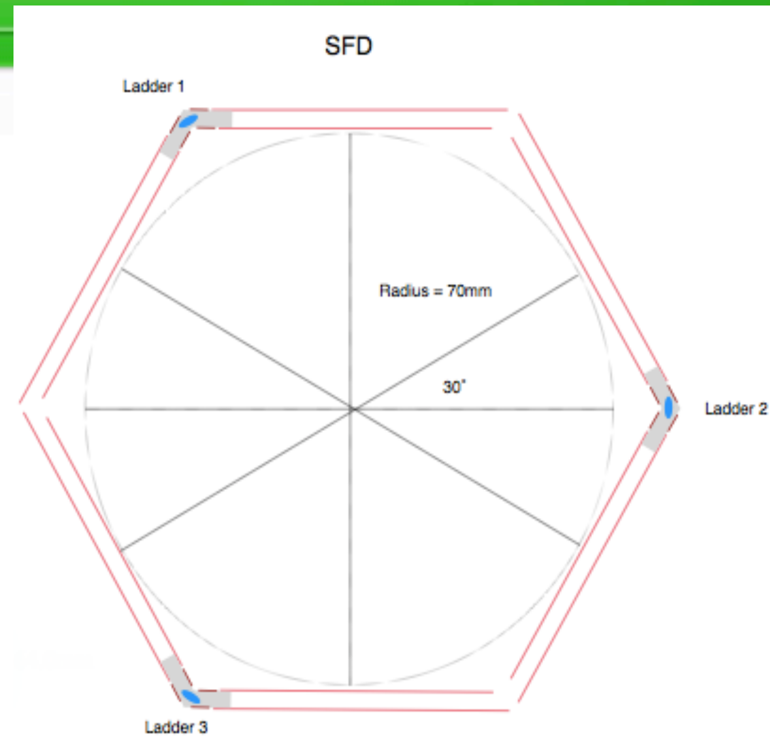
Electrons spiraling in B-fields create microwaves (synchrotron radiation).



DarkLight: Central & Forward Detectors



- Radius: 50mm
- Φ-coverage: 360°
- θ-coverage: 17° - 163°
- Number of ladders: 3
- Ladder length: 430mm
- Sensor dimensions: 56.5mm X 60.0mm / 52.5mm X 60.0mm
- Sensor thickness: 300µm
- Total number of sensors: 84
- Power dissipation: 0.3W per chip / 50W per ladder
- Radiation tolerance of sensors: 1MRad
- Radiation tolerance of readout chip: >>1MRad



- Radius: 70mm
- Φ-coverage: 360°
- θ-coverage: 6.1° - 19°
- Number of ladders: 3
- Ladder length: 458mm
- Sensor dimensions: 78.5mm X 64.0mm / 72.5mm X 64.0mm • Number of sensors: 28 per ladder
- Sensor thickness: 300µm
- Total number of sensors: 84
- Power dissipation: 0.3W per chip / 50W per ladder
- Radiation tolerance of sensors: 1MRad
- Radiation tolerance of readout chip: >>1MRad

DarkLight Specs

$M_{A'}$ 1 MeV (< 1% Rad. Length)

Incident electron energy 100 MeV

Scattered lepton angle 25-165 deg

Scattered lepton energy 10-100 MeV

Recoil proton angle 6-163 deg

Recoil proton energy 1-6 MeV

Position: 250 μm

Elastic rate within acceptance 10 MHz

Trigger Rate ~ kHz

Jlab FEL Capabilities

	Near Term Capability, Dec. 2013	Full Capability	Internal Target (Near Term)
	external target	external target	internal target
E (MeV)	80-320	80-610	80-165
P_{max} (kW)	100	300	1650
I (mA)	0.31-1.25	0.5-3.75	10
f_{bunch} (MHz)	750 / 75	750 / 75	750 / 75
Q_{bunch} (pC)	1.67-0.4 / 16.7-4	5-0.67 / 50-6.7	13.5 / 135
$\varepsilon_{transverse}$ (mm-mrad)	~1 / ~3	~2 / ~5	~3 / ~10
$\varepsilon_{longitudinal}$ (keV-psec)	~5 / ~15	~10 / ~25	~15 / ~50
Polarization	No	Up to 600 μA	No
	750 MHz drive laser; single F100	12 GeV RF drive; three F100s	12 GeV RF drive; three F100s