DarkLight: Looking for a dark forces boson at the Jefferson Lab Free Electron Laser

Peter Fisher
MIT
10 June 2011

What to keep in mind about dark matter:

All of the concrete information about dark matter comes from measurements of the potential wells of astrophysical objects.

Galaxies and galaxy clusters are the venues where dark matter is important. Dark energy dominates on cosmological scales, baryons on sub galactic scales.

The classical SUSY WIMP < 1 TeV picture is being pushed to higher energies by the (so far) non-observation of new physics at the LHC.

My standard experimental particle physics dark matter talk:

Blah, blah, blah, Zwicky, blah, blah, Coma Cluster, blah, blah, Dark Matter!, blah, blah, rotation curve, blah, blah, blah, 23% of universe, blah, blah, NOT SM! blah, blah, GREAT MYSTERY! blah, blah, blah, two candidates: blah, blah, axions, blah, blah, blah, blah, WIMPs, blah, blah, supersymmetry, blah, blah, WIMP miracle, blah, blah, blah, my experiment, blah, blah, blah....

WIMP "Miracle":

The currently observed dark matter density in the universe is consistent with massive particle production in the Big Bang with WIMPs with 100's of GeV mass and weak interaction cross section (~ 1 pb).

A Theory of Dark Matter

Nima Arkani-Hamed,[1] Douglas P. Finkbeiner,[2] Tracy R. Slatyer,[3] and Neal Weiner[4]

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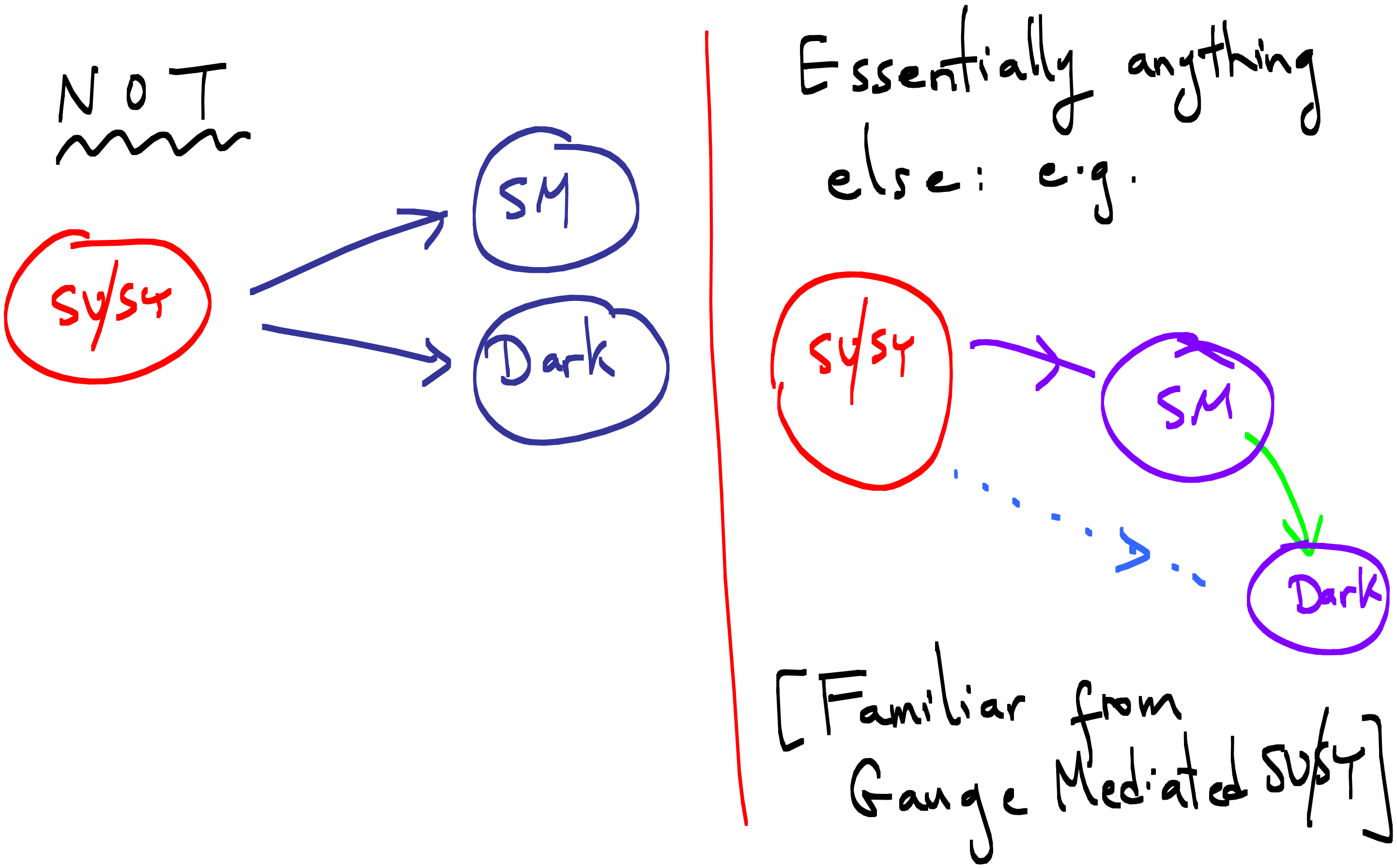
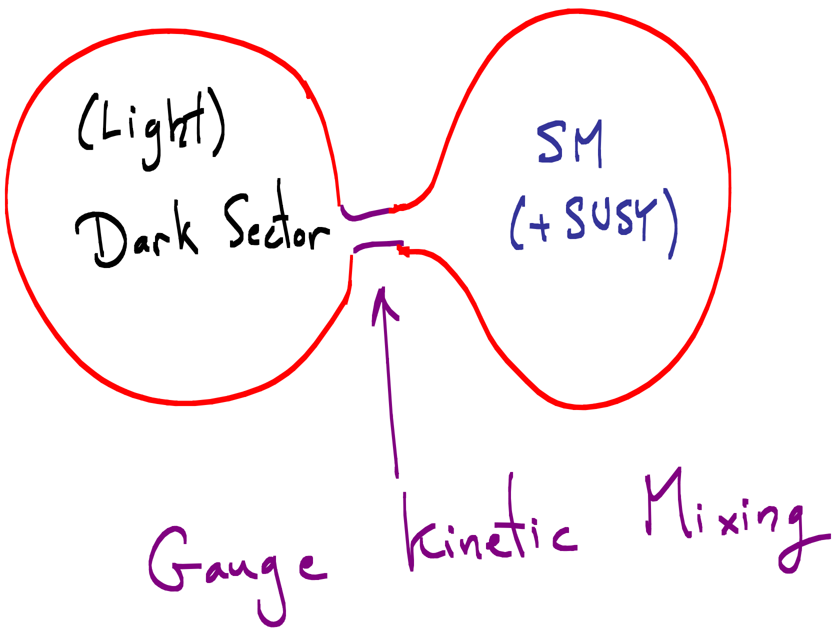
[4]*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*

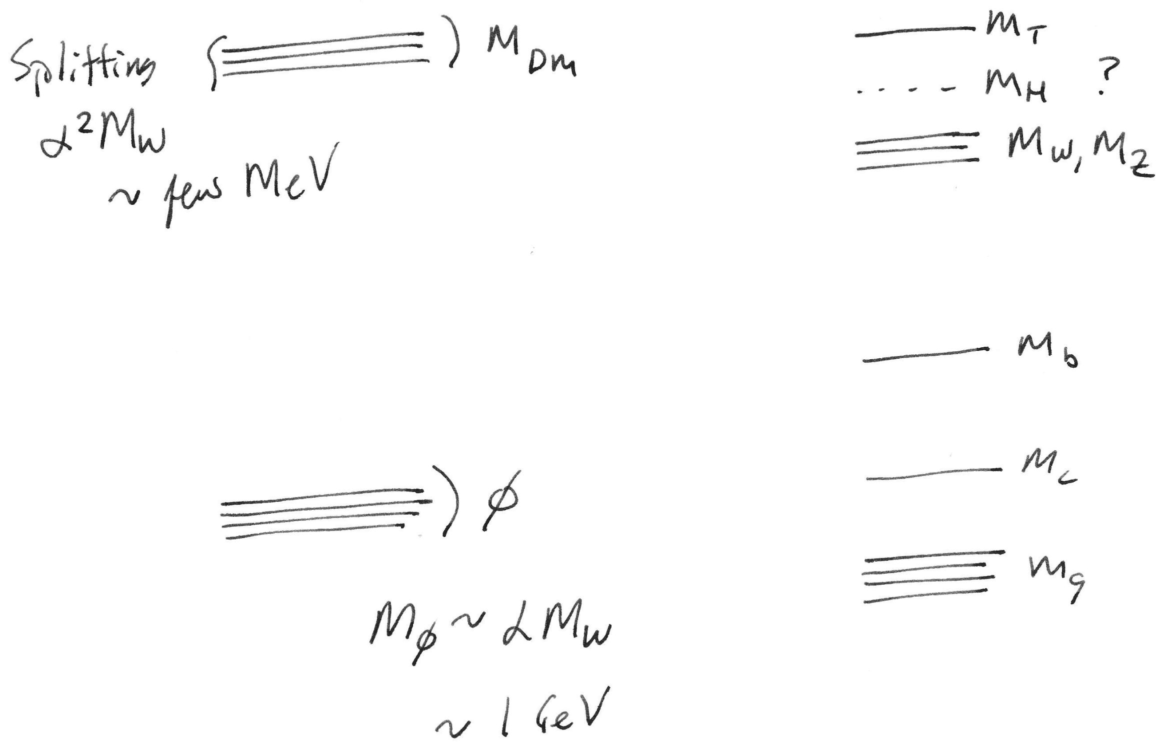
(Dated: January 20, 2009)



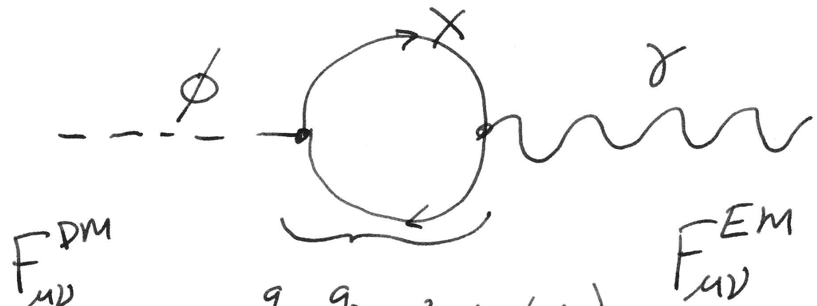
Arkani-Hamed



Arkani-Hamed


Splitting
$\alpha^2 M_W$
~ few MeV
M_{DM}
ϕ
$M_\phi \sim \alpha M_W$
~ 1 GeV
m_T
m_H ?
M_W, M_Z
m_b
m_c
m_q

Kinetic Mixing



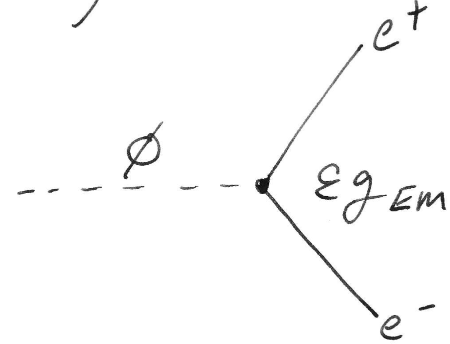
$$\frac{g_{DM}\, g_{\gamma}}{16\pi^2}\,\frac{g^2}{16\pi^2}\,\log\left(\frac{M}{M_X}\right)$$

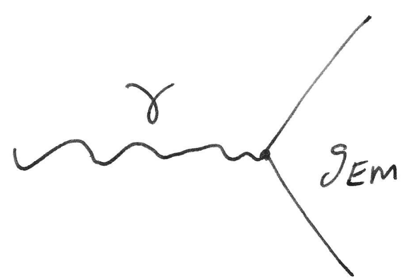
$$\parallel$$

$$\varepsilon = 10^{-5} - 10^{-3}$$

$$\mathcal{L} = \ldots\, \varepsilon F_{\mu\nu}^{DM} F_{EM}^{\mu\nu} \ldots$$

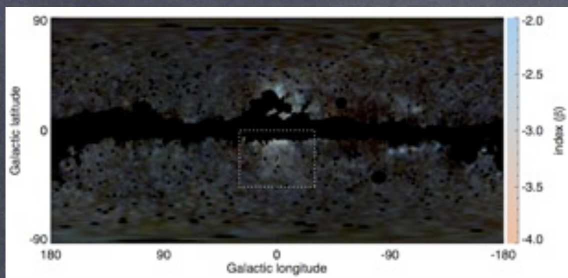
Effectively

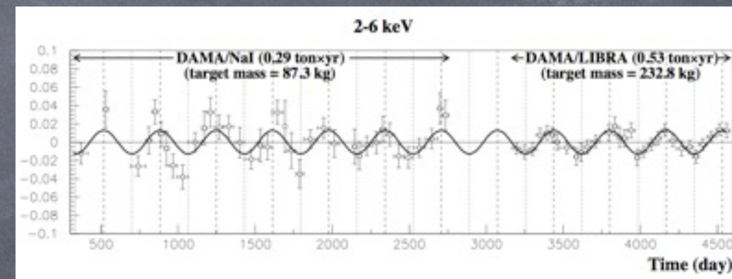


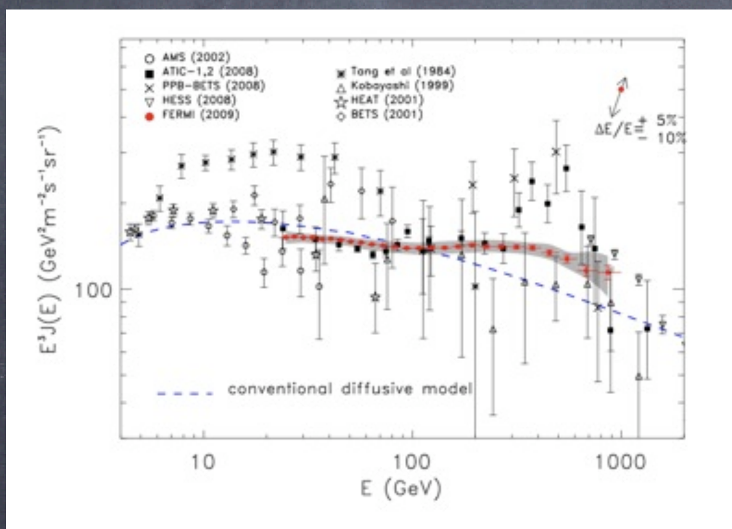


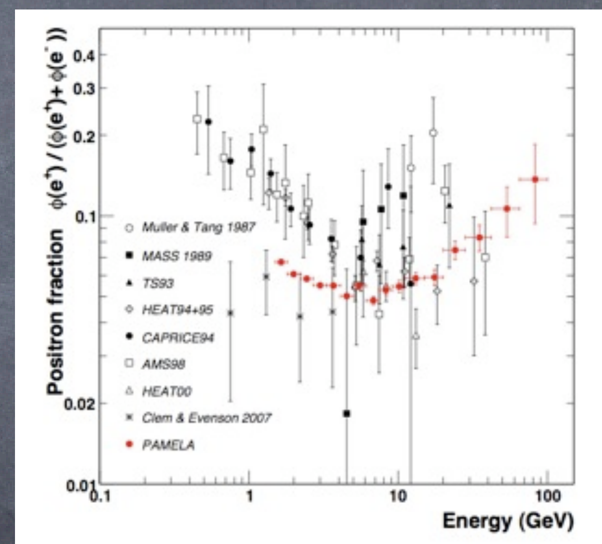
Why?

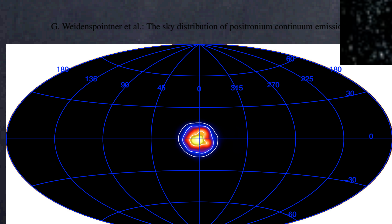
Era of anomalies



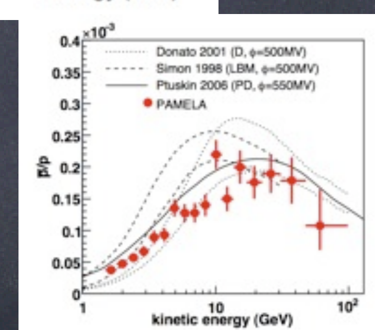








Neil Weiner

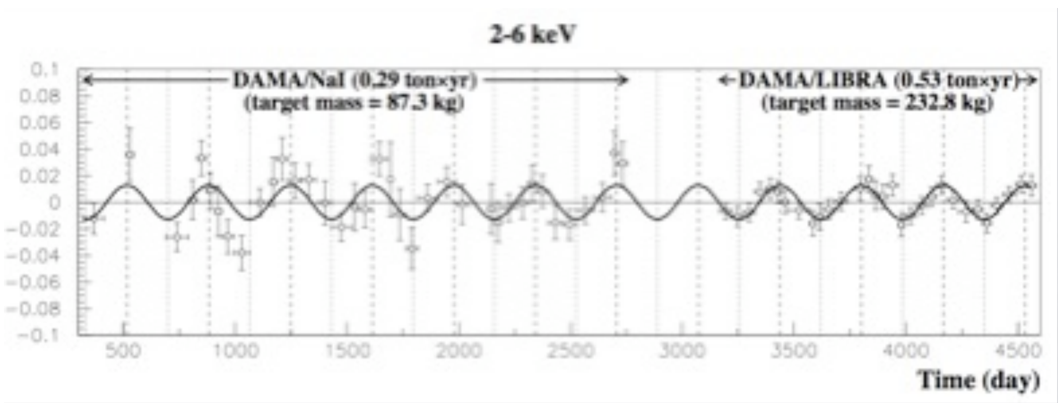


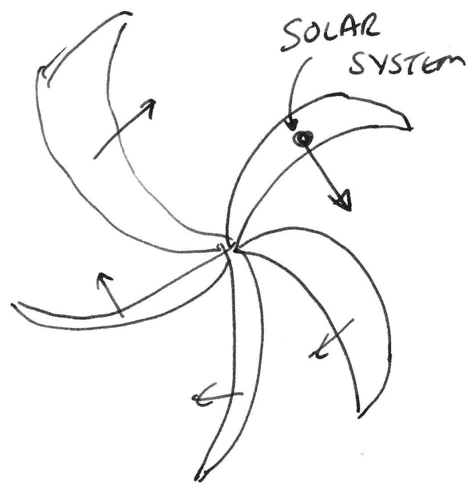
The three ingredients to explain PAMELA/Fermi

- Hard lepton spectrum
- Few/no anti-protons
- Large cross section (much larger than thermal - for annihilation)
- All these can be explained by insisting that the dark matter has a new GeV scale force (Arkani-Hamed, Finkbeiner, Slatyer, NW, '08)
- **Wide** range of models all share similar structure (Pospelov and Ritz, '08; Fox and Poppitz '08; Nomura and Thaler '08; Nelson and Spitzer '08; Katz and Sundrum '08...)

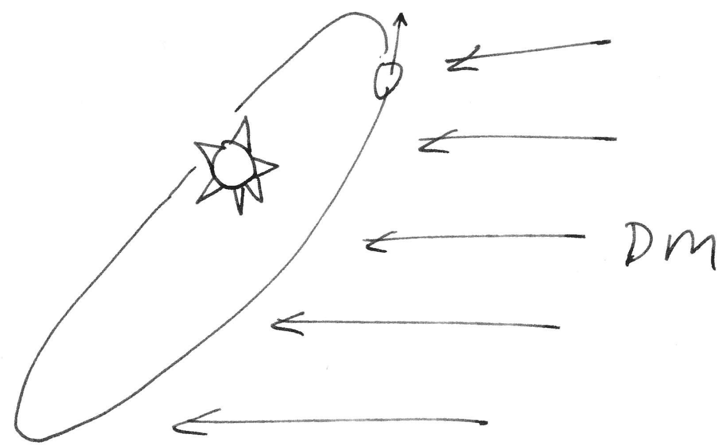
DAMA/Libra

Observes modulation of count rate in the lowest bin over 11 years. Phase and period are within a few days of expected values. Implies a very large elastic scattering cross section, excluded by many experiments.

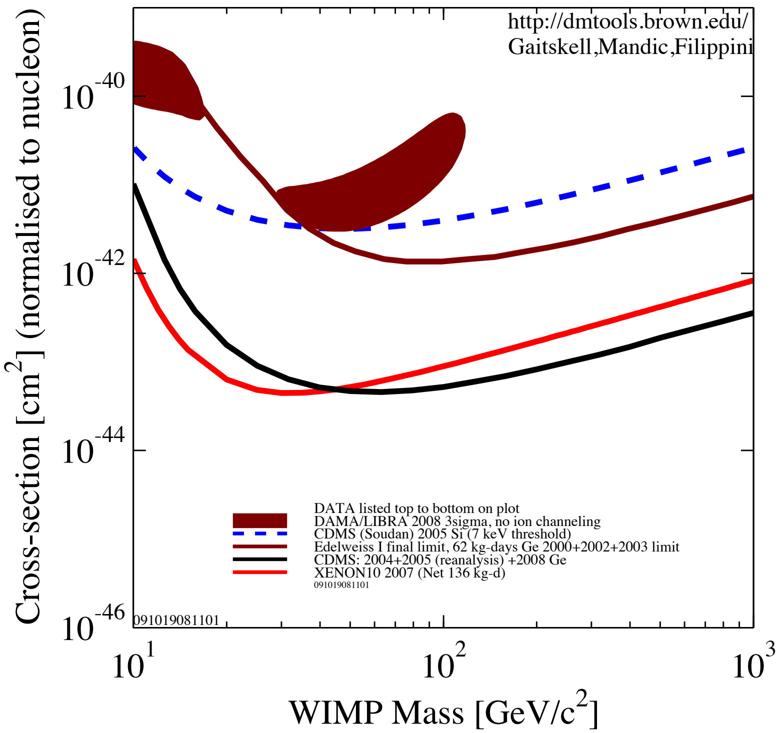




GALAXY



1-2% CHANGE IN EVENT RATE AT few keV THRESHOLD



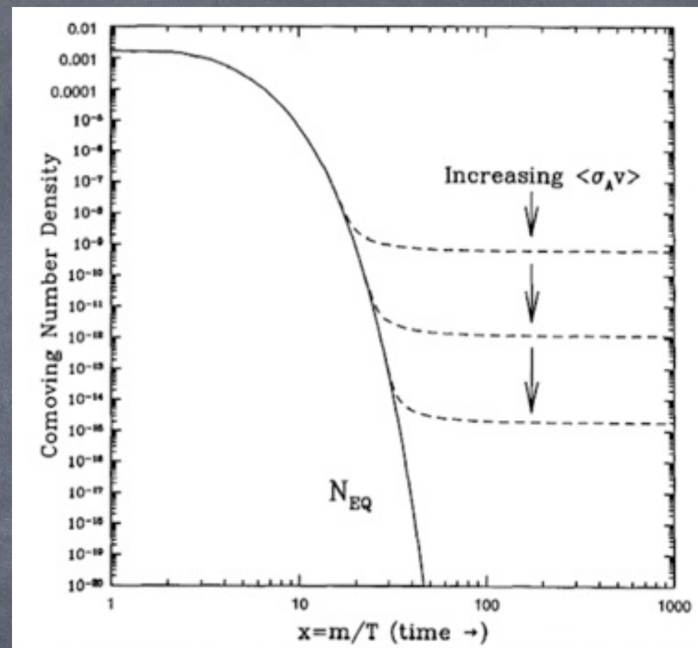
http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
Cross-section [cm^2] (normalised to nucleon)
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^1
10^2
10^3
WIMP Mass [GeV/c^2]
DATA listed top to bottom on plot
DAMA/LIBRA 2008 3sigma, no ion channeling
CDMS (Soudan) 2005 Si (7 keV threshold)
Edelweiss I final limit, 62 kg-days Ge 2000+2002+2003 limit
CDMS: 2004+2005 (reanalysis) +2008 Ge
XENON10 2007 (Net 136 kg-d)
091019081101

assume thermal equilibrium $\chi\chi \leftrightarrow \bar{f}f$

When T<< M_{WIMP}, number density falls as $e^{-M/T}$

$$\Omega h^2 \approx 0.1 \times \left(\frac{3\times 10^{-26} cm^3 s^{-1}}{\langle\sigma v\rangle}\right)$$

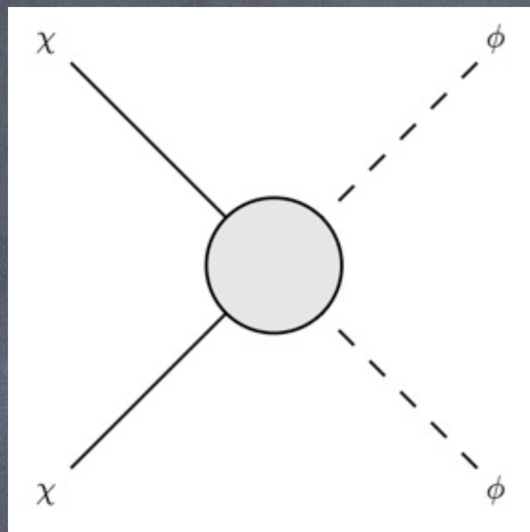
$$\approx 0.1 \times \left(\frac{\alpha^2/(100\mathrm{GeV})^2}{\langle\sigma v\rangle}\right)$$

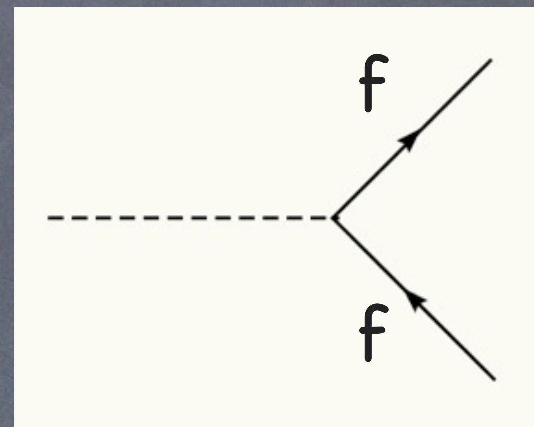


- Any weak- scale particle naturally freezes out within a few orders of magnitude of the correct cross section

New forces = new annihilation modes

Finkbeiner, NW PRD '07; Pospelov, Ritz, Voloshin PLB '08





- "WIMP Miracle" works as before (sigma ~ $1/M^2$)
- No antiprotons comes from kinematics
- Hard positrons come from highly boosted ϕ's

Arkani-Hamed, Finkbeiner, Slatyer, NW, '08

Already “discovered” in astrophysical phenomena
so where else to look?

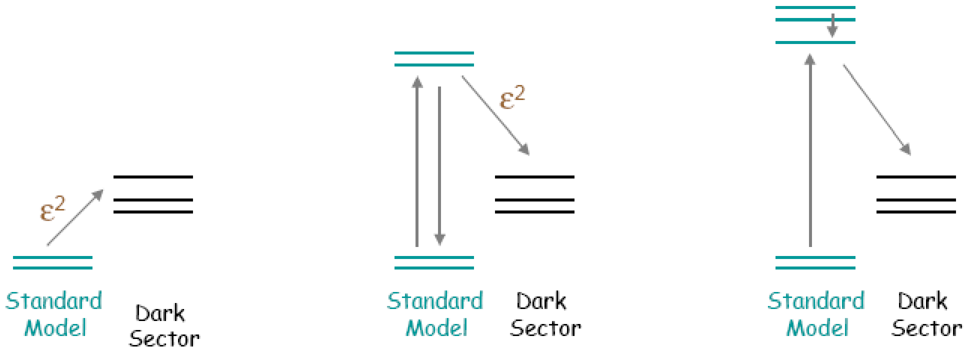
Hadron colliders (LHC, Tevatron)
e+-e- (B, t-charm)
Fixed target

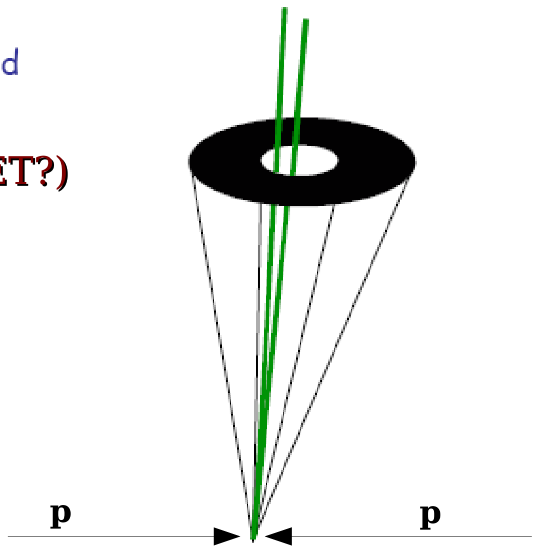
Hadron Colliders

Production Modes

Dark Sector Production at High Energy Colliders

Direct Production	Indirect Production	Indirect Production with Shared Conserved Quantum Number
jet + lj	**Z-> lj lj**	**SUSY-> lj lj (+MET?)**





σ » $O(\varepsilon^2)$ Br » $O(\varepsilon^2)$ σ ¢ Br » $O(\varepsilon^0)$

Which Dark Sector States Populated -
Depends on Production Portals

Portal » ε

Scott Thomas

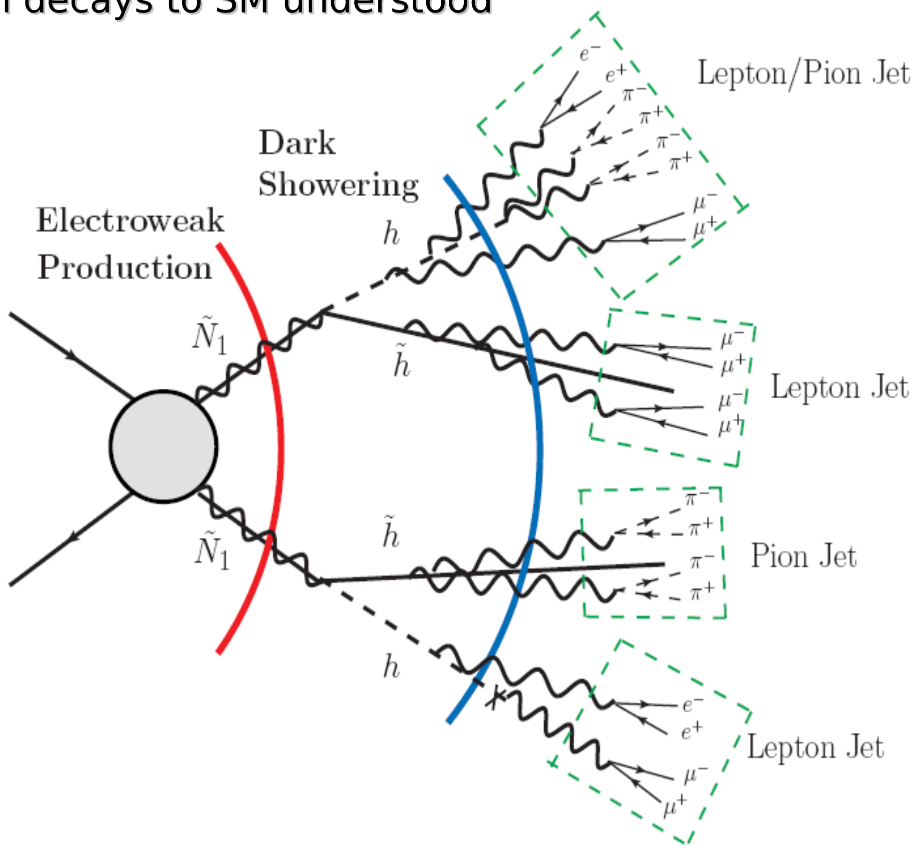
Simulation

For realistic tests of models, we need accurate simulations
- Dark higgs and dark photon decays to SM understood

Dark radiation

$$N_{\gamma_d} \sim \frac{\alpha_d}{2\pi} \log \left(\frac{M^2_{\text{decay}}}{M^2_{\text{dark}}} \right)^2$$

Itay Yavin, Josh Ruderman

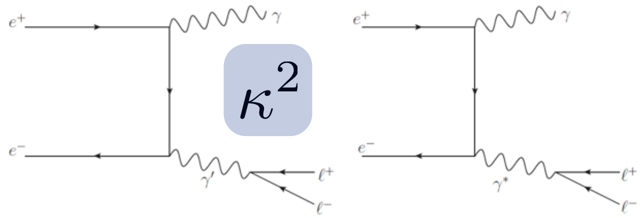


Showering in the dark
- **Abelian**
- Non-abelian

e^+e^- machines

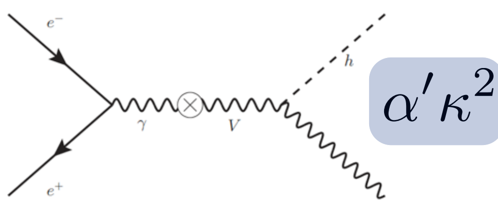
Final States (direct production)

- "Generic": $e^+e^- \to \gamma l^+ l^-$



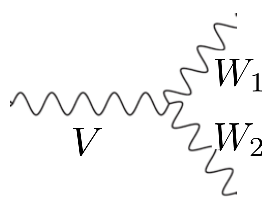
- BaBar [via ϒ-decay search, H. Kim] ✓?
- Belle [Y. Kwon, J. Rorie]
- BES-III [H. Li, Y. Zheng]
- KLOE [F. Bossi]

- "Generic + higgs": $e^+e^- \longrightarrow Vh' \longrightarrow 6l \ \ (or\ 2l + \not{E})$



- not yet!
  [interest from BaBar, Belle, BES-III, KLOE]

- "Nonabelian": $e^+e^- \to V^* \to 4l$



- BaBar [4l, M. Graham] ✓

Also: higher multiplicity (confining), 4l + $\not{E}_T$, ...

Rare meson decays

Various facilities have sensitivity (~$\mathscr{L}$/s) through rare decays

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	BR$(X \to Y + \gamma)$	BR$(X \to Y + \ell^+\ell^-)$	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8a}	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

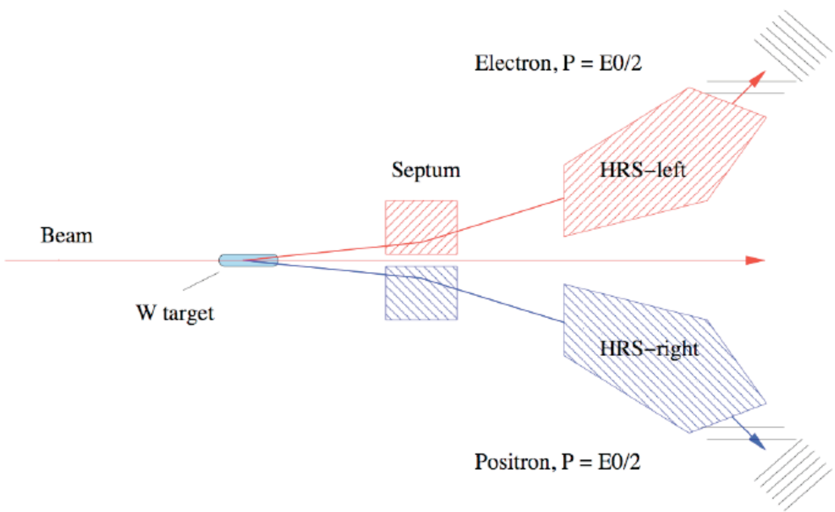
[Reece & Wang '09]

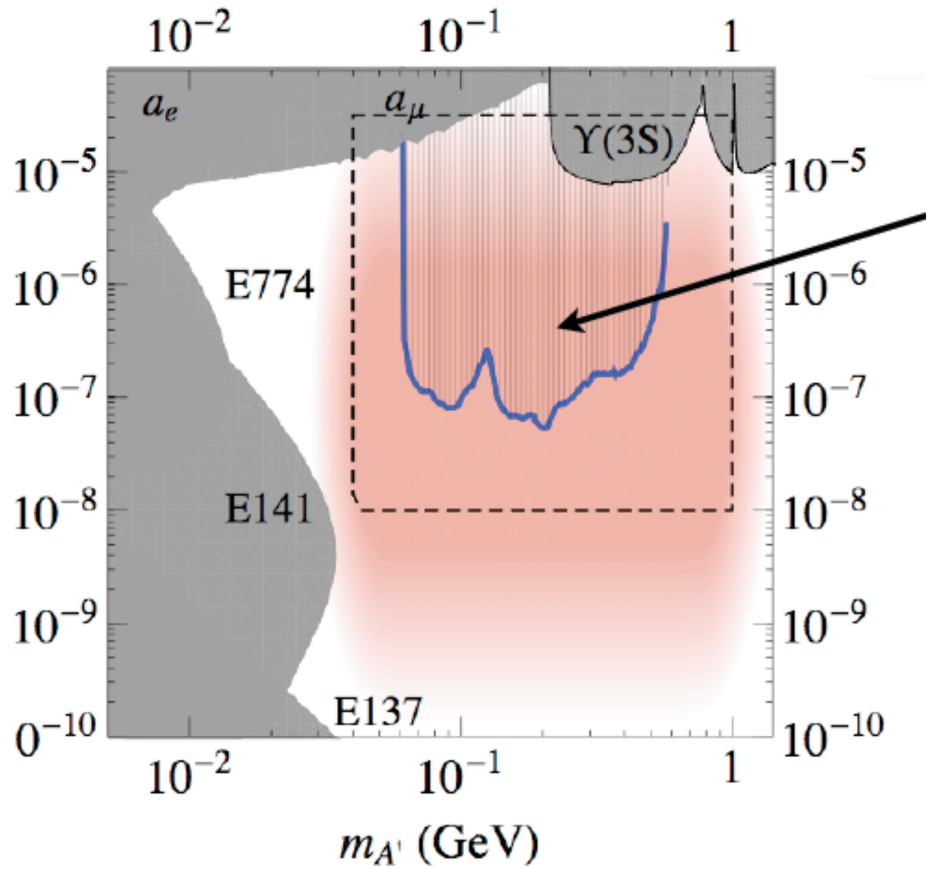
- More existing data - K → eeγ , π → ee, η → ... (kTeV, BaBar/Belle, KLOE?)

- J/ψ→ 6l via higgs'strahlung ⇒ sensitivity to $\kappa \sim 10^{-3}$-10^{-4} given 10^{10} at BES-III in 1yr!
- Rare B-decays....

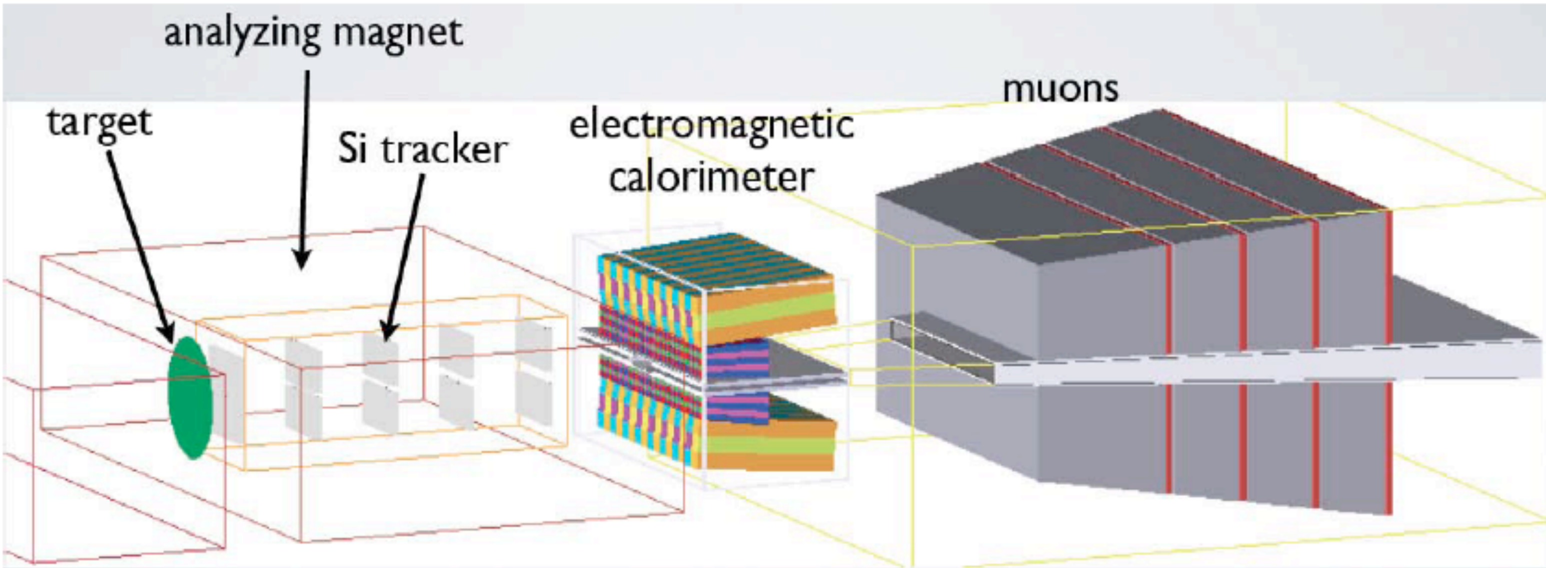
Fixed target accelerators

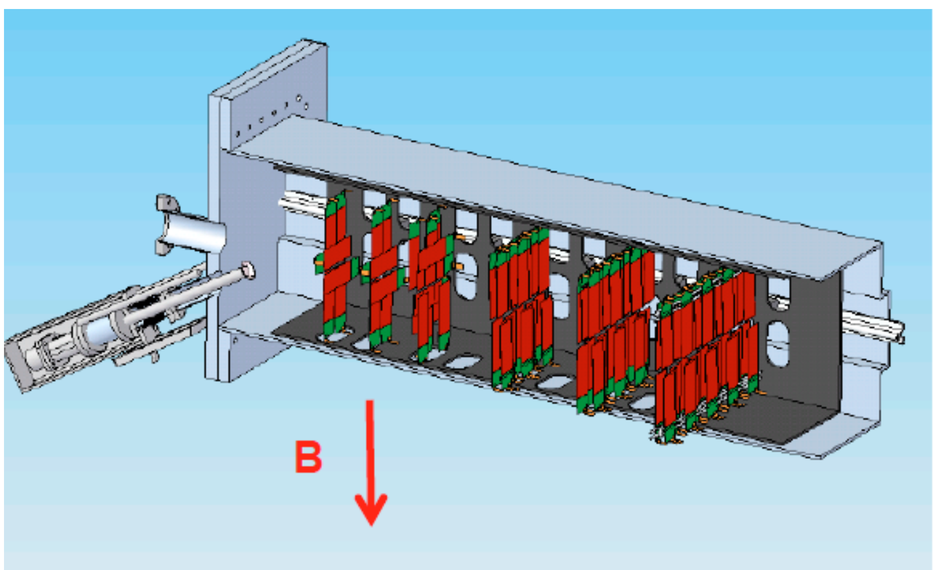
APEX - Hall A
Covers region
90-1,000 MeV

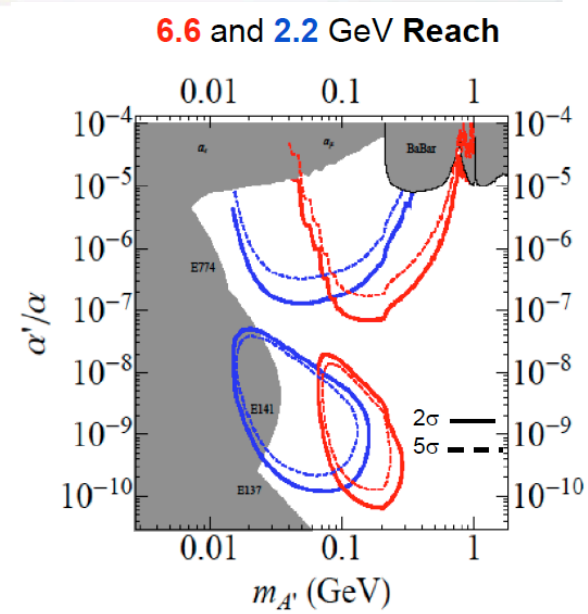




Heavy Photon Search (HPS)

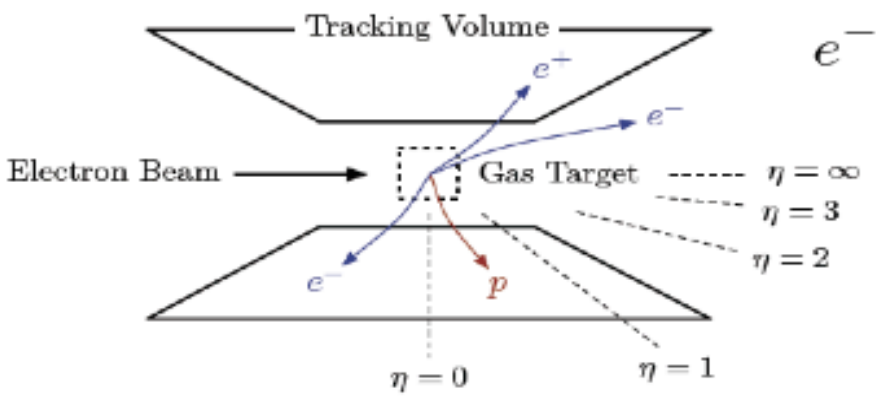






U Boson Search at JLab FEL J. Thaler and P. Fisher

Electron-Proton Collisions

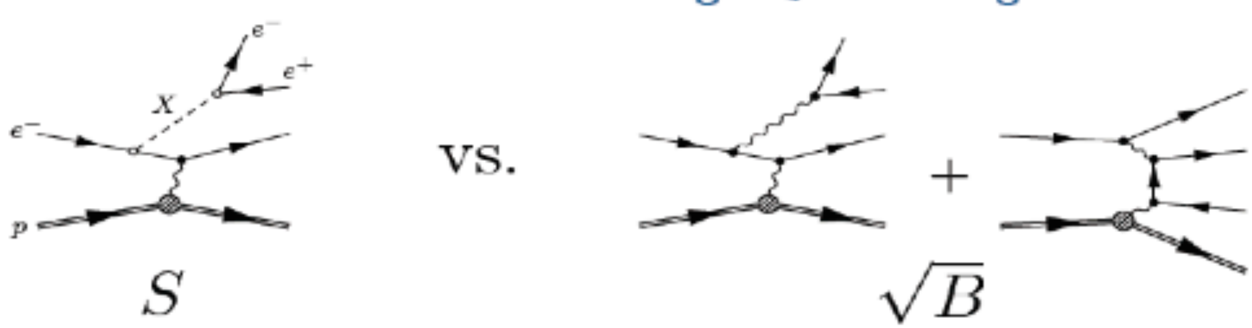


$$e^- p \to e^- p + X$$
$$\hookrightarrow e^+ e^-$$

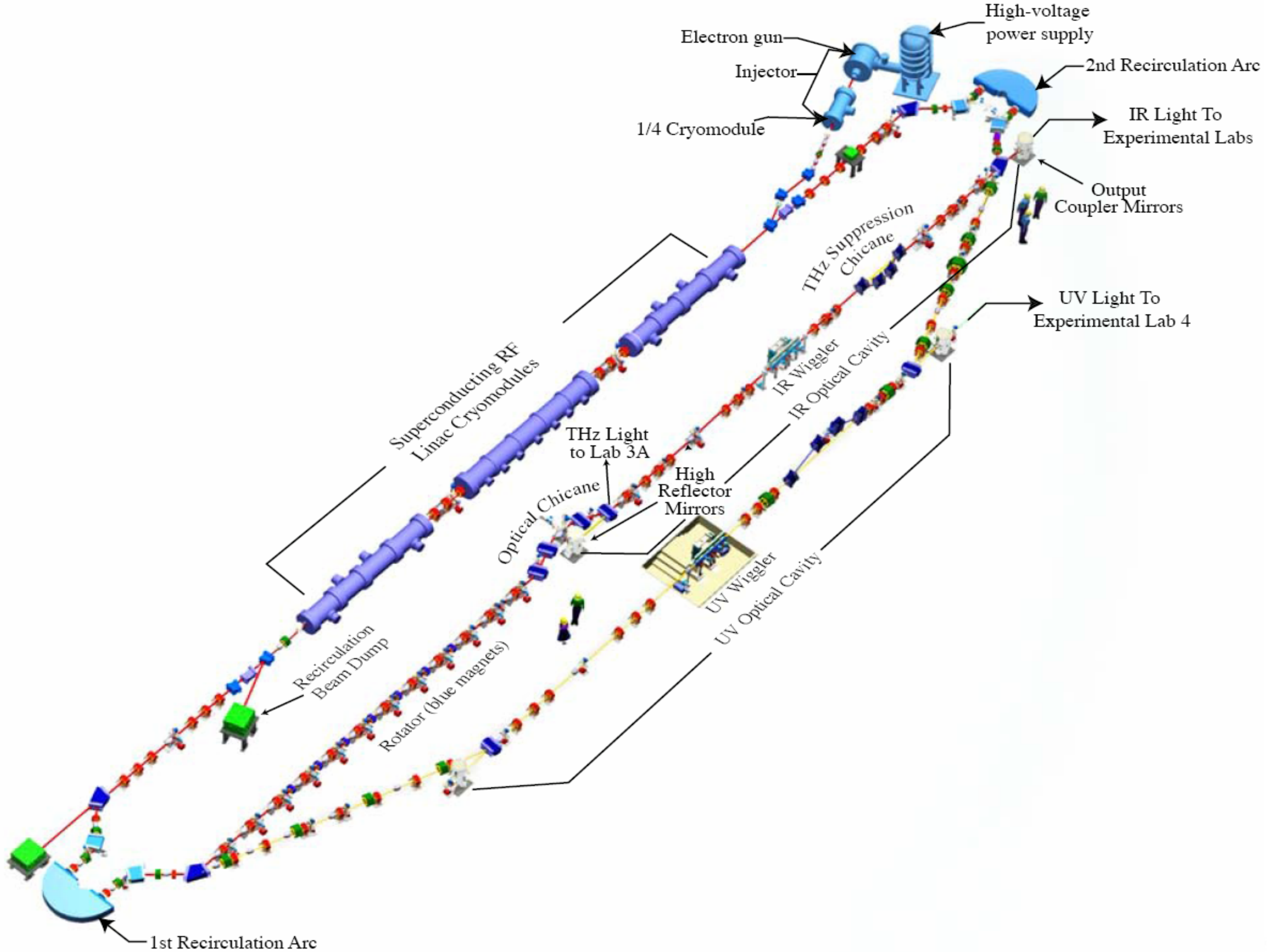
$$E_{\text{beam}} \lesssim 140 \text{ MeV}$$

$$\text{ab}^{-1}/\text{month}$$

Narrow Resonance on Huge QED Background

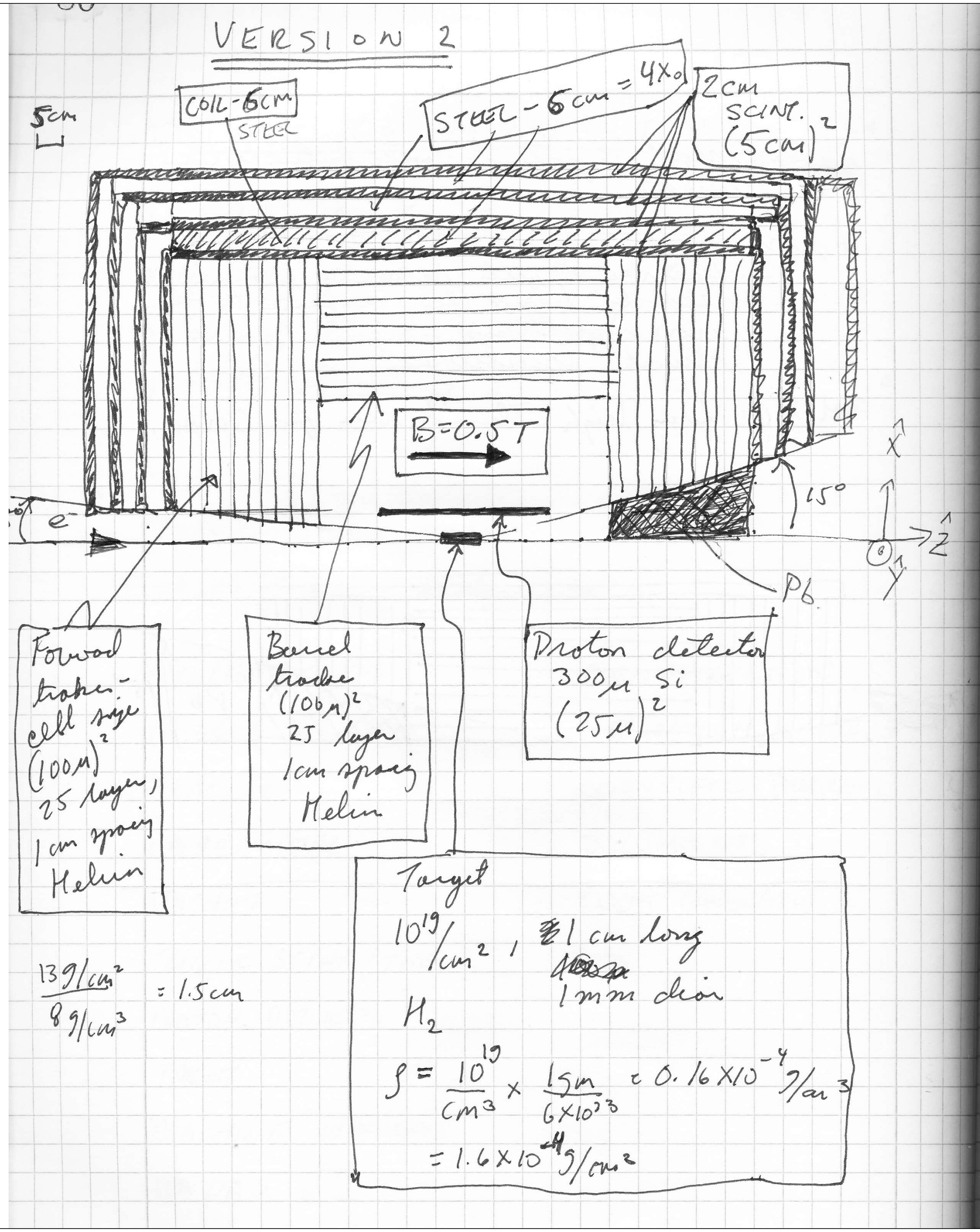


JLab FEL Energy Recovery Linac



Jefferson Lab FEL Specifications

Energy (MeV)	80-200	200	
Charge per bunch (pC)	135	135	**1 MW in beam!**
Average current (mA)	10	5	
Peak Current (A)	270	270	
Beam Power (kW)	2000	1000	
Energy Spread (%)	0.50%	0.13%	
Norm.emittance(mm-mrad)	<30	<11	


VERSION 2
5cm
COIL - 6cm STEEL
STEEL - 6cm = 4X₀
2cm SCINT. (5cm)²
B=0.5T
e⁻
15°
x
z
y
Pb
Forward tracker - cell size (100μ)² 25 layers, 1cm spacing Helium
Barrel tracker (100μ)² 25 layers 1cm spacing Helium
Proton detector 300μ Si (25μ)²
Target
10¹⁹/cm², 1 cm long 1mm dia
H₂
ρ = 10¹⁹/cm³ × 1gm/6×10²³ = 0.16×10⁻⁴ g/cm³
= 1.6×10⁻⁴ g/cm²
13 g/cm² / 8 g/cm³ = 1.5cm

Collaboration

P. Balakrishnan, J. Bernauer, W. Bertozzi, R. Cowan, K. Dow, C. Epstein, P. Fisher, S. Gilad, A. Kelleher, Y. Kahn, R. Milner, R. Russell, J. Thaler, C. Tschalaer, A. Winnebeck
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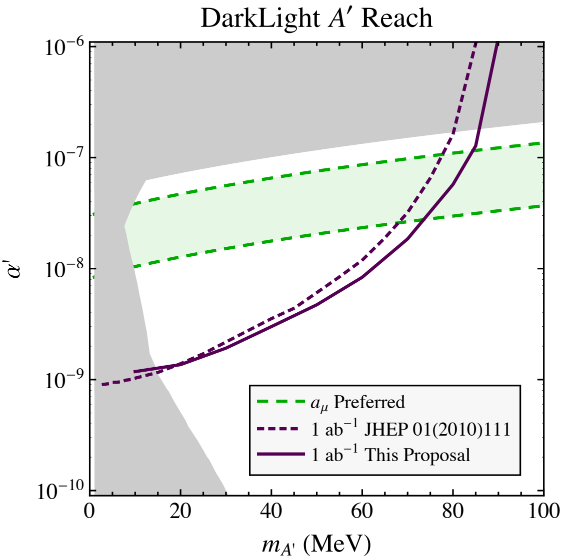
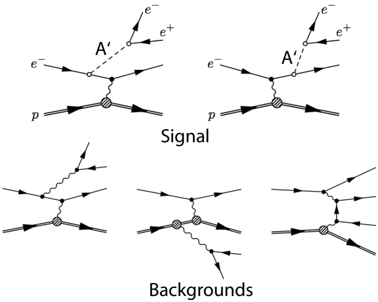
Sensitivity



Signal and backgrounds

For $\alpha' = 10^{-8}$, the signal is 10^{-4} of the QED background processes.



For 5σ sensitivity to a peak with 1 MeV/c^2 width in the continuum e^+e^- spectrum across the 10-90 MeV mass range requires a luminosity of 1/ab.

Experimental Concept

We reduce backgrounds from other sources by requiring full reconstruction of $e^- + p \rightarrow e^- + p + e^+ + e^-$

- 1 MW 100 MeV FEL electron beam gives 10 mA or $1.6 \times 10^{17} e^-/\mathrm{s}$
- Hydrogen gas target with areal density of $10^{19}/\mathrm{cm}^2$
- Lepton spectrometer with momentum resolution to reach $\sigma_{m_{e^+e^-}} < 1 MeV/c^2$
- Proton detector to identify $\sim$2 MeV recoil proton and measure it momentum with 20% precision.

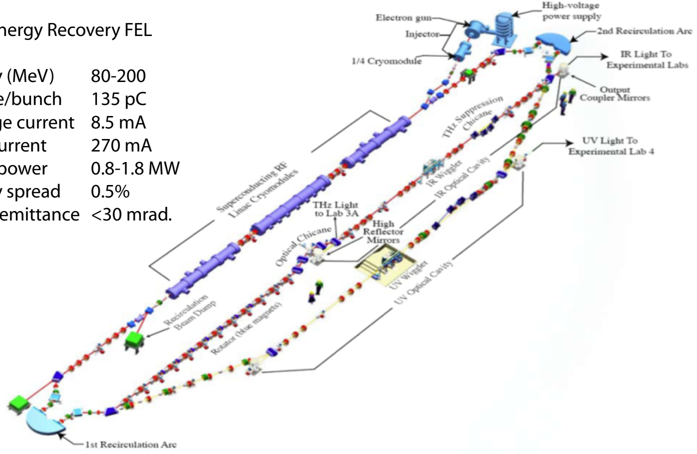
The FEL can deliver 1/ab of beam in one month of continuous running.

FEL

10 kW IR/UV/THz Free-Electron Laser

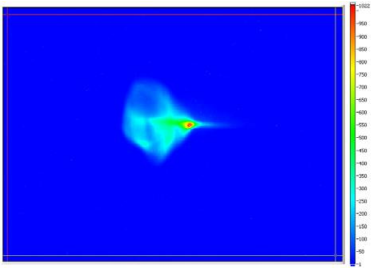
JLab Energy Recovery FEL

Energy (MeV)	80-200
Charge/bunch	135 pC
Average current	8.5 mA
Peak current	270 mA
Beam power	0.8-1.8 MW
Energy spread	0.5%
Norm. emittance	<30 mrad.



Beam halo

The FEL beam profile has a lot of structure: the core is about 50 μ and the emittance is determined by taking the 6σ spread of electrons. To date, understanding the halo has not been important for the FEL's mission. A key part of our program for the next year will be measurement and characterization of the beam halo.



Target

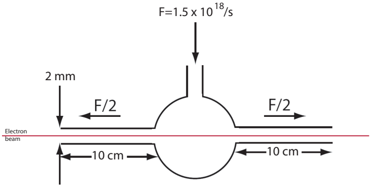
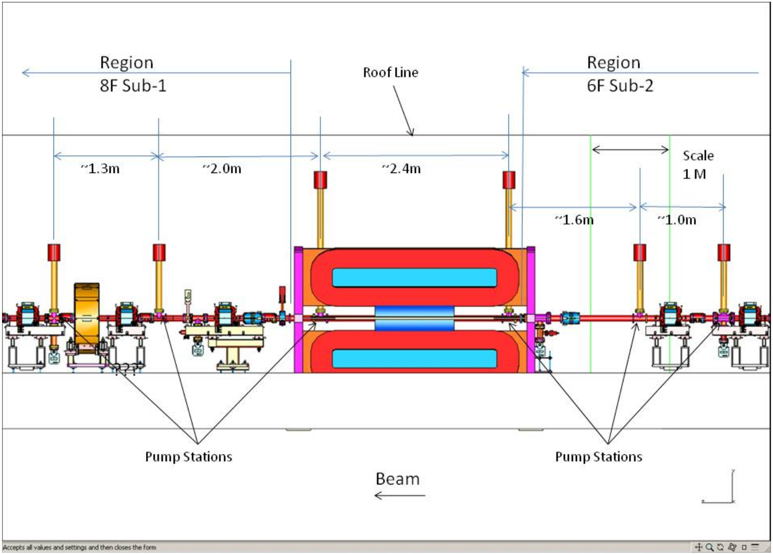


Figure: Target cell

- Areal density of 10^{19} protons/cm^2
- 30 μ kapton evacuated from each end into the machine vacuum.
- Exhaust pumps are located outside of the detector.
- Energy loss and emittance increase small enough to accommodate recirculation of beam

Target



Region
8F Sub-1
Roof Line
Region
6F Sub-2
~1.3m
~2.0m
~2.4m
Scale
1 M
~1.6m
~1.0m
Pump Stations
Pump Stations
Beam
Accepts all values and settings and then closes the form

Toroidal magnet

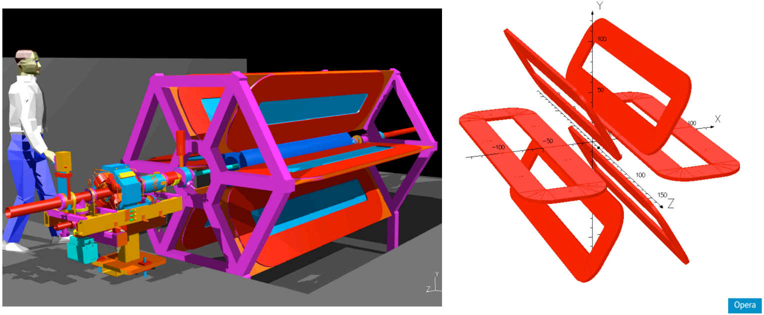


Figure: Toroidal magnet located in the FEL wiggler pit on the UV line. The bending power is 0.05-0.32 T-m. There are several options: water or nitrogen cooled or superconducting. For the configuration shown the acceptance loss is about 13%.

Proton detector

- BONUS design will detect protons and measure their momenta to about 20% precision.
- BONUS type RTPCs have successfully measured recoil proton momenta down to about 1 MeV in high rate environments.

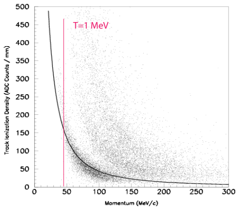
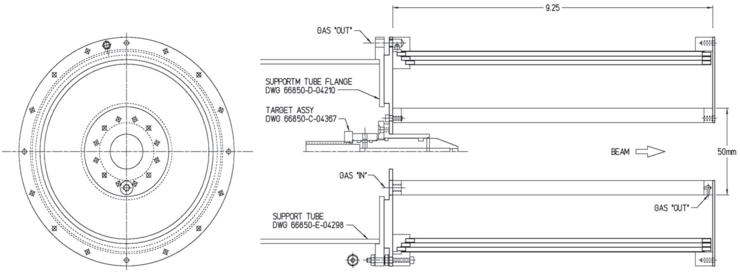


Figure: dE/dx measured by BONUS in the eg6 experiment.

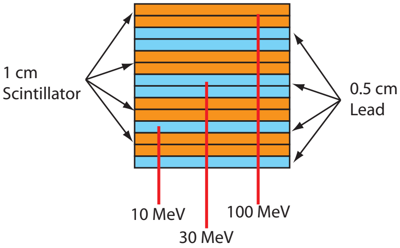


Tracking system

Figure: A drift chamber octant of BLAST.

- 25 layers, 25-50 cm from target, 15^o to 180^o
- Open cell geometry, 1 cm cell size
- Helium based gas, He:C_4H_{10}, 80:20, $X_o = 800$m
- For $\sigma \sim 100\mu$ and $\int \vec{B}_\perp \cdot d\vec{l} = 0.05 - 0.32$ T-m, can tolerate 0.01 X_o before MS dominates position resolution

Trigger scintillator

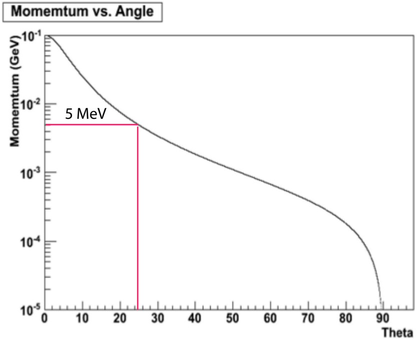


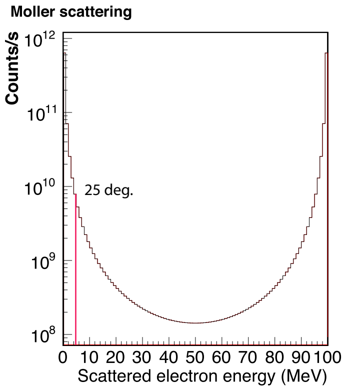
Scintillator covers $25^o < \theta < 165^o$and provides a fast trigger for three final state leptons.

- Requiring one lepton with $\theta > 50^o$ gives a rate of 10 MHz from QED backgrounds
- Requiring two additional leptons in 10 ns window gives 1.2 MHz
- Requiring two negative and one positive lepton gives 0.9 kHz.

Moller scattering

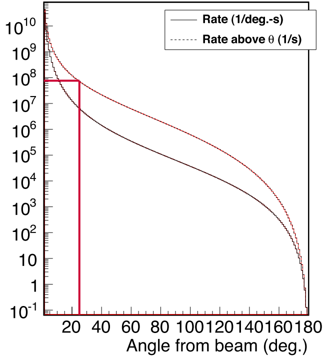
The Moller singles rate with $\theta > 25^o$ is 6×10^{11}/s, all below 5 MeV. Occupancy drive the 25 cm closest tracking element. For 1 cm^2 cells, the rate is 500 MHz/cell, so we will need a 50 G solenoidal sweeper magnet inside the toroid.

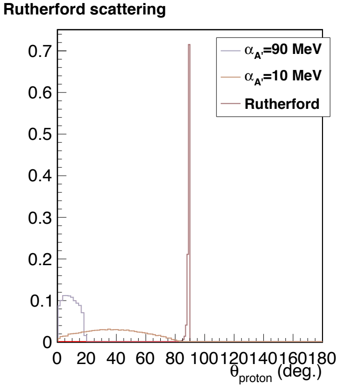




Rutherford scattering

The integral rate above 25^o is 70 MHz, for an occupancy of 500 KHz. The proton detector extends from $5^o < \theta < 85^o$ to miss most of the recoil protons.

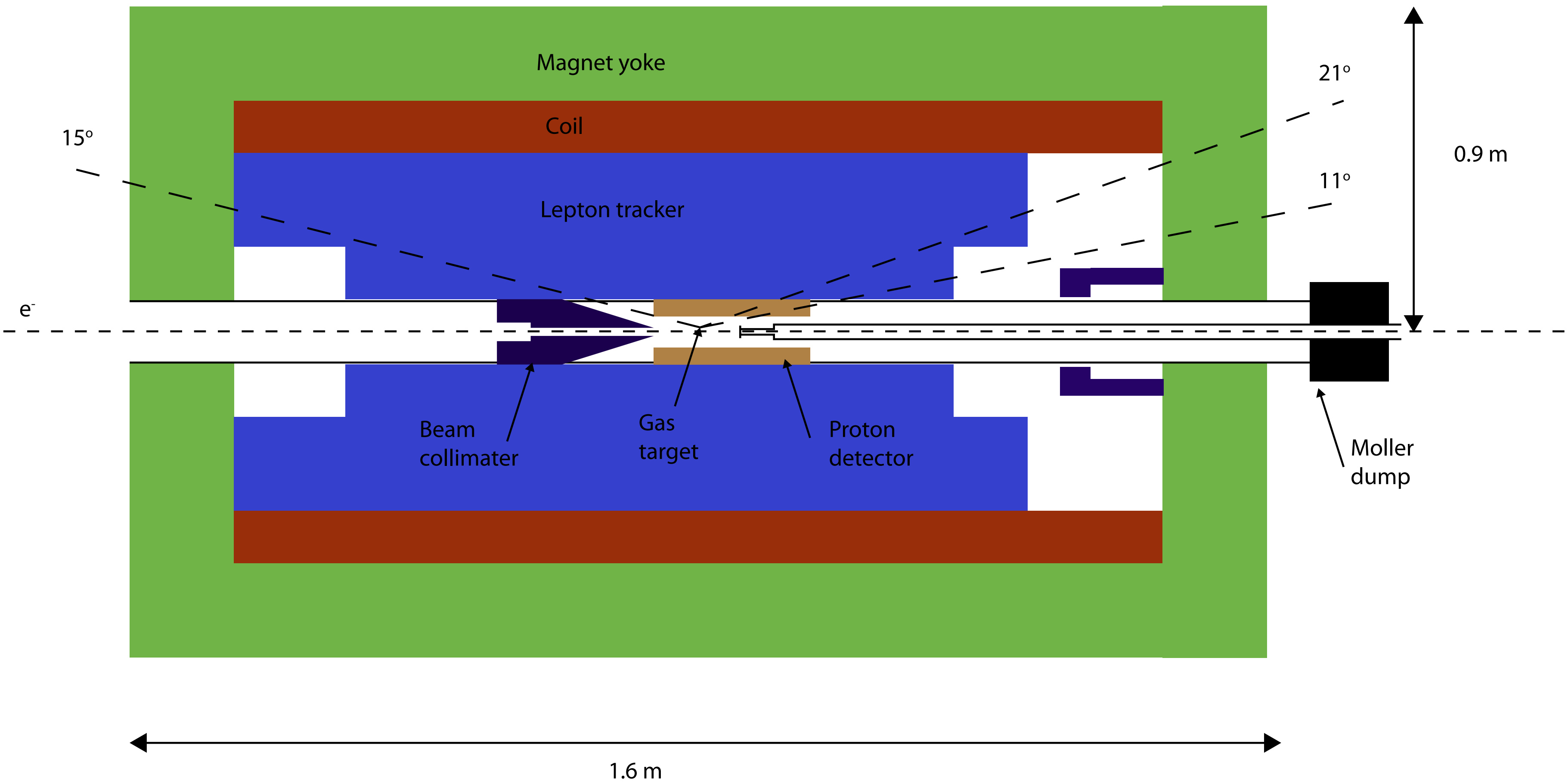




Working design

Integrated target and proton detector

1T solenoidal field



Invariant mass resolution

- Multiple scattering is the dominant contribution to the momentum resolution.
- 1 MeV/c^2 invariant mass resolution requires less than 1% of a radiation length of material along the lepton trajectory.
- With two 1 mm precision points from the RTPC, we can tolerate 5% of a radiation length.

We plan to investigate GEM trackers outside the RTPC to achieve to provide these points.

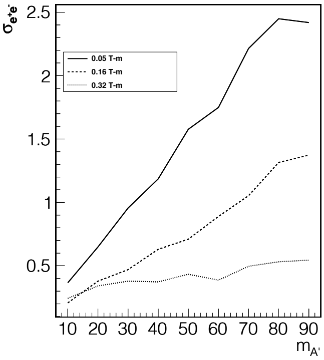


Figure: Pair mass resolution for different field settings. The resolution is calculated using a GEANT4 simulation of the track and a swim fit through the calculated magnetic field.

Timeline

- PAC37 January 2011
- Beam development begins March 2011
- Resources for technical design become available Fall 2011
- Technical review Summer 2012
- DarkLight construction begins Fall 2012
- DarkLight data taking begins 2015

Where? Available Facilities

J Lab CEBAF e- 1-6 GeV 10nA-100μa CW (500 MHz) NOW

FEL e- 100 MeV 5–10 mA CW NOW (internal)

CEBAF upgrade e- 12 GeV 10nA-50μa CW (500 MHz) 2013

FEL upgrade e- 200 MeV 5–10 mA CW 2010 (internal)

SLAC FACET e- 20 GeV 30Hz 10^{11}/pulse 2011

ESTB e- 14 GeV 5Hz few x 10^{9}/pulse 2011??

Damping Ring 1.2 GeV Resonant Extraction? ???

BONN ELSA e- .5-3.5 GeV >=few nA? CW (500 MHz) NOW

MAINZ MAMI e- .18-1.5 GeV fA–100 μA CW (2.5 GHz) NOW

MESA e- 100 MeV 10 mA CW 2014 (internal)

MESA e- 137 MeV 0.15 mA CW 2014 (external)

DESY XFEL e- 17.5 GeV 10Hz 10^{10}/ bunch 3000/pulse 2015

DORIS e+ storage 5 GeV ??? NOW (internal)

CESR e- 5 GeV storage ring resonant extraction?

Other: protons (SNS, LSND... –see M. Pospelov talk), muons (COMPASS, MINOS, ...) , neutrinos (FNAL...) – not discussed.

MESA:

Mainz
Energy recovering
Superconducting
Accelerator

Kurt Aulenbach

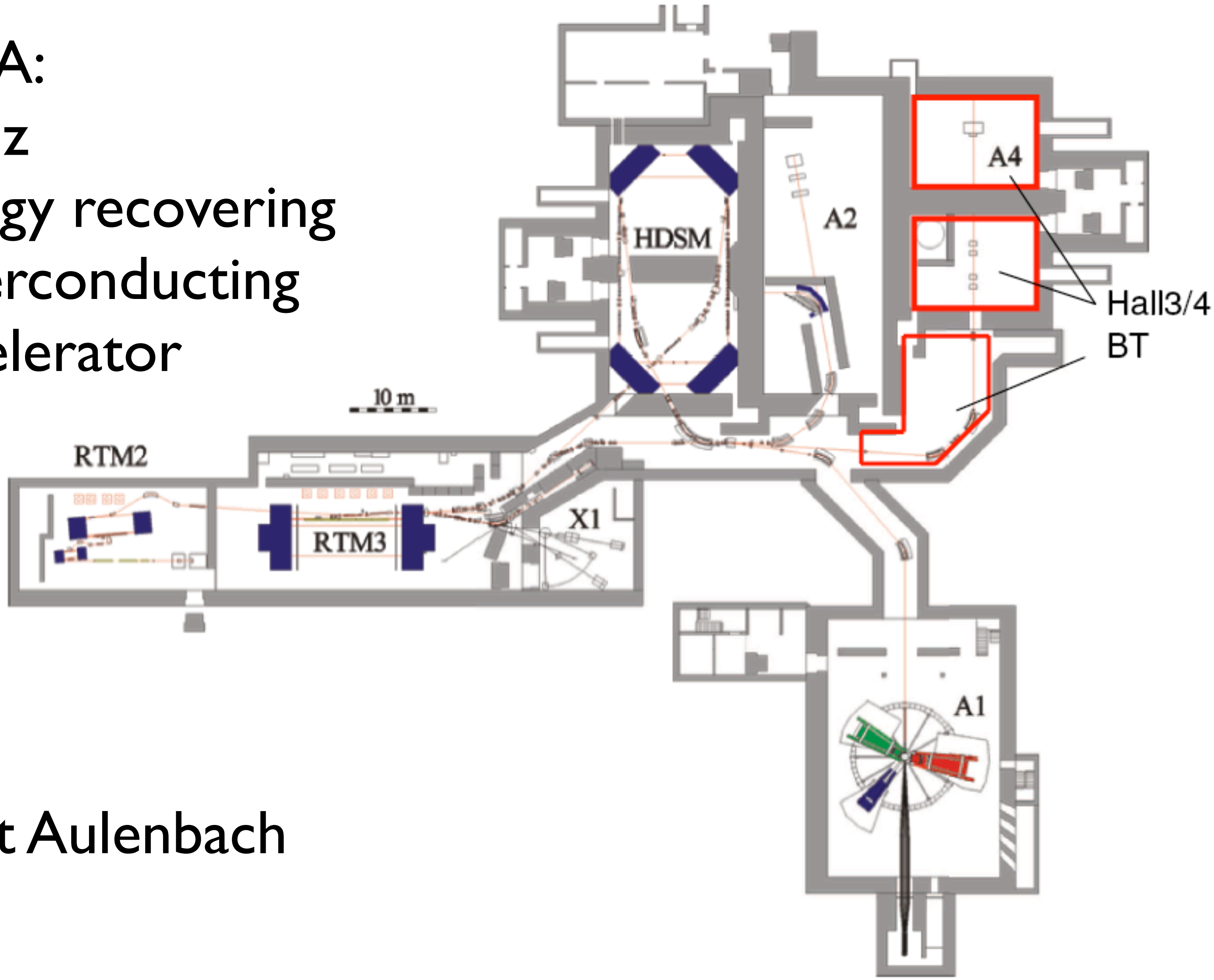


Fig. 1. MAMI-C floor plan with experimental halls. The beamline tunnel ('BT') and Halls 3 and 4 will be available for the installation of MESA and its experiments.

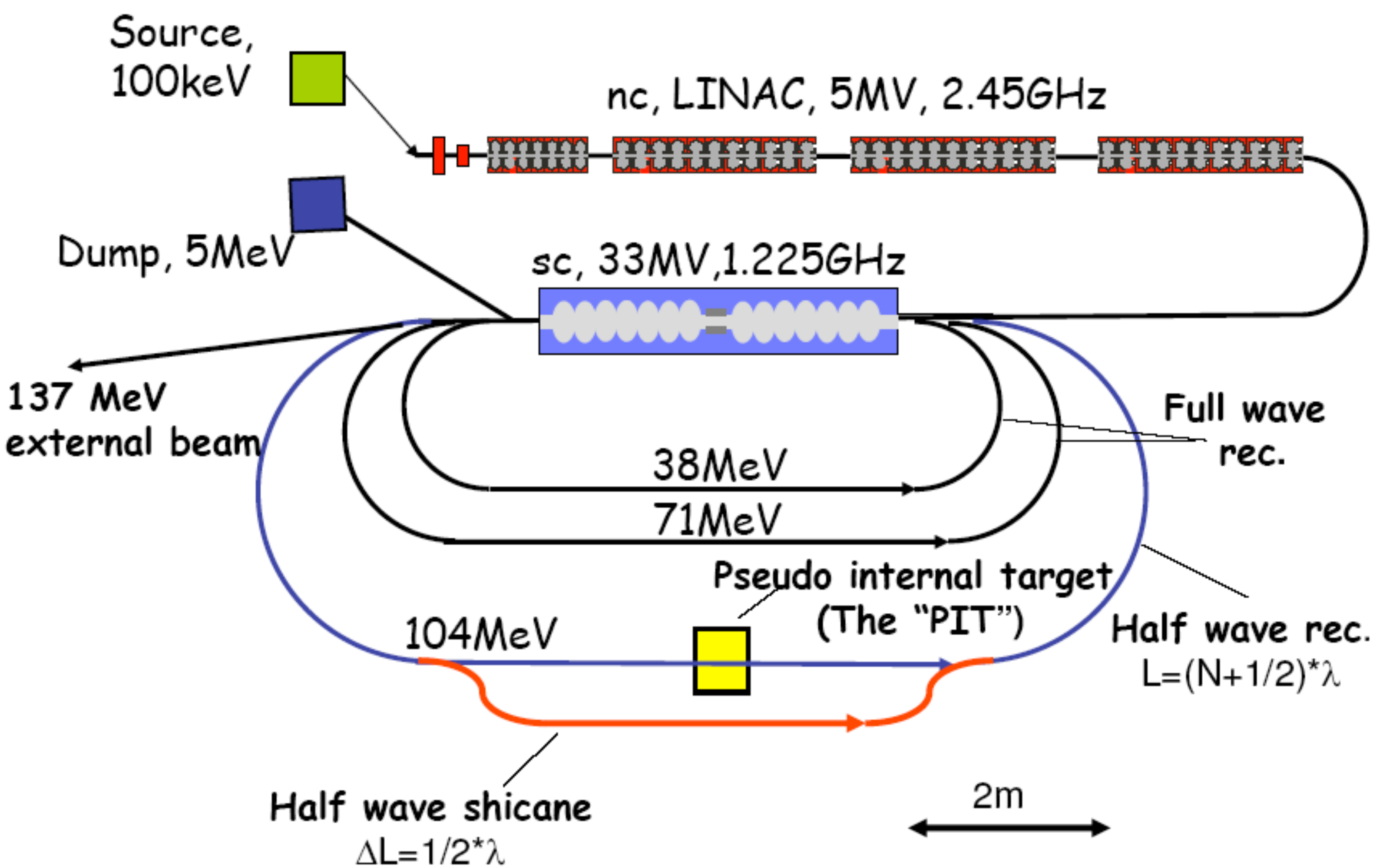


Fig. 2. MESA accelerator layout.

How? Possible Experiments

Data Mining:

- J Lab Existing Data eA->A'->e+e-X (6GeV) .2<m<2 GeV $\varepsilon > 10^{-3}$
- BLAST?
- Proton experiments? Miniboone, Microboone analyzing...
- Muons (COMPASS, MINOS)

J Lab Future Proposals with Existing Apparatus

- 50 MeV up, $\varepsilon > 10^{-4}$? Ticking clock (2 mo. to propose)
- Hall C: muon wall behind Qweak?

New J Lab Experiments

FEL – MIT/Berkeley (LOI this fall, also Mainz) 10<m<80 MeV, $\varepsilon > 10^{-3.5}$

Hall B – JLab/SLAC 100<m<600 MeV, $\varepsilon > 2\ 10^{-5}$ (gap $\sim 10^{-4}$)

New beam dump experiments: m<100 MeV, $\varepsilon \sim 10^{-5}$ ορ 10^{-8}–10^{-7}

Positron Experiments

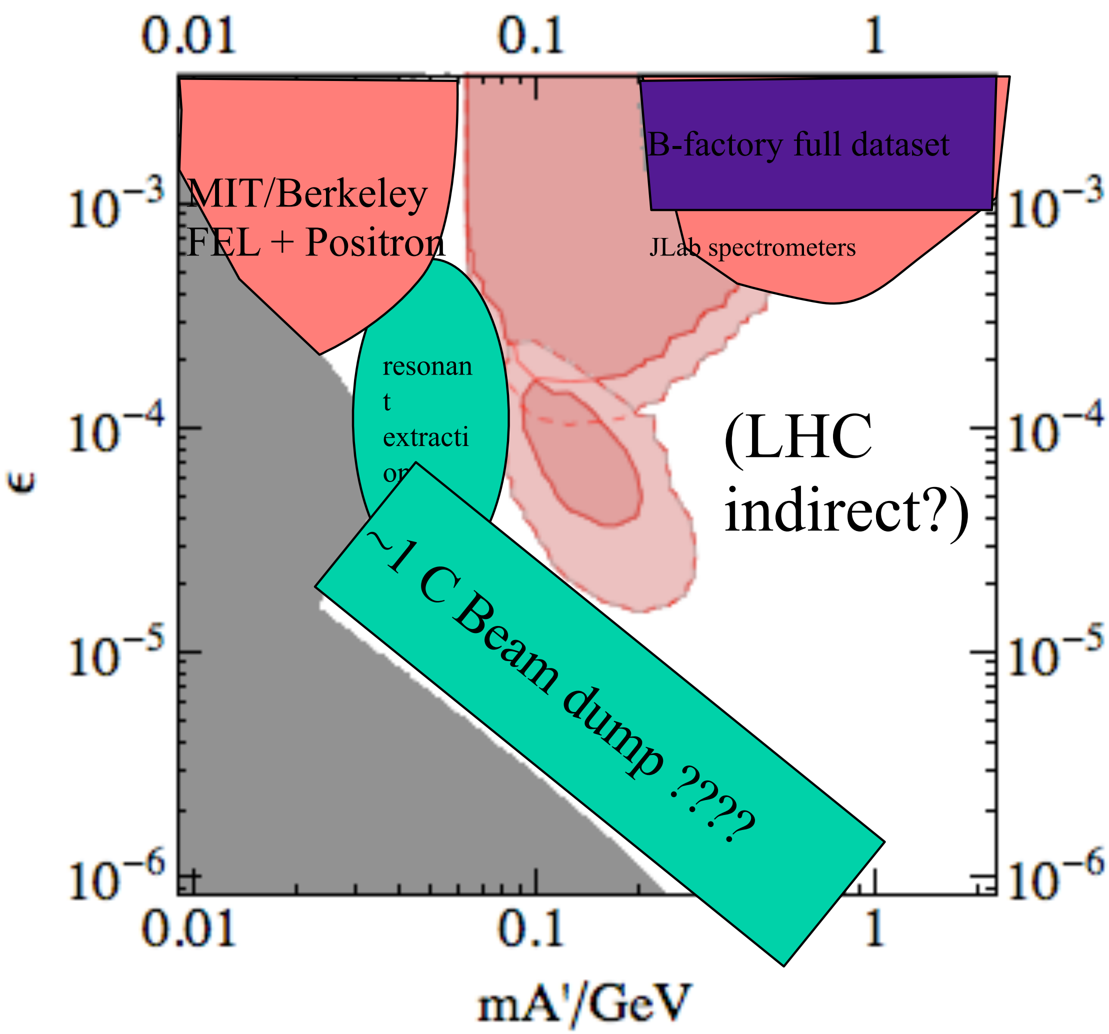
e+ on H: 5<m<30 MeV, $\varepsilon > 10^{-4}$ (indep. of decay mode)

OLYMPUS internal target ep elastic (data taking 2012)

Resonant Extraction from Damping ring experiments:

- Possible opportunities at SLAC, CESR, Bonn, MAMI (cw)

Reach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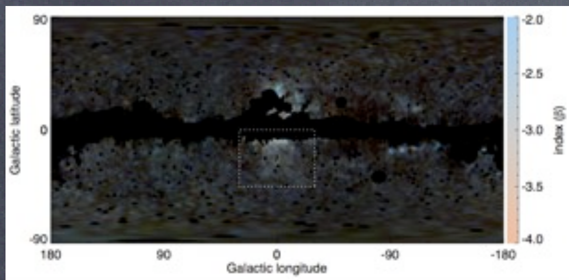
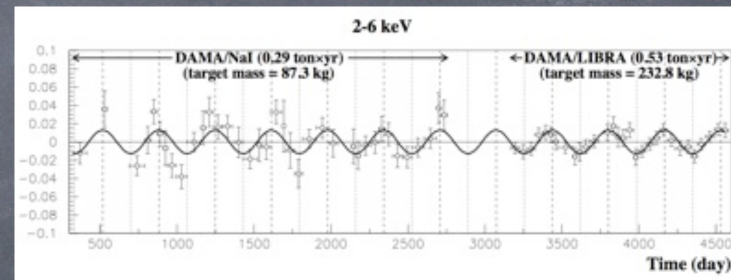
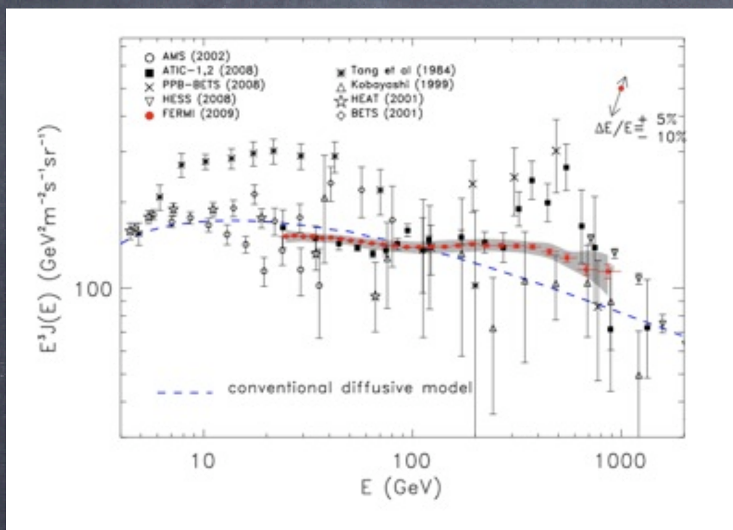
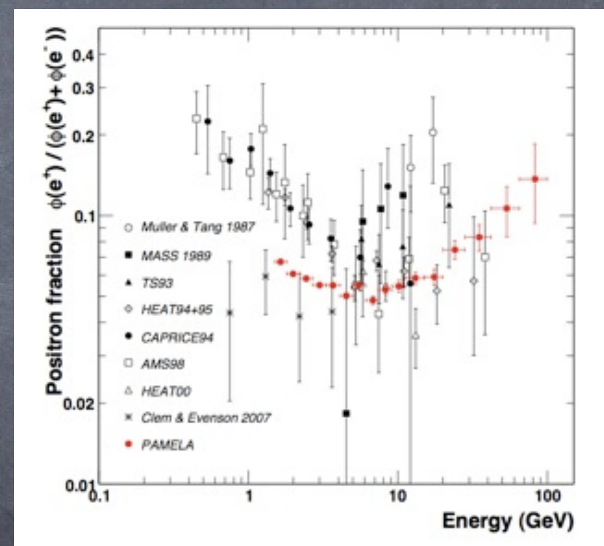
However, if…

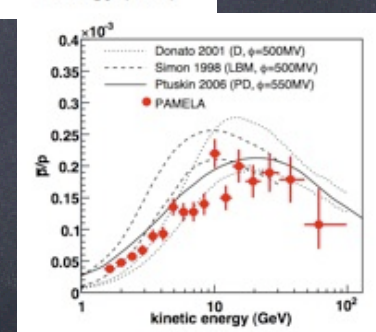
Era of anomalies

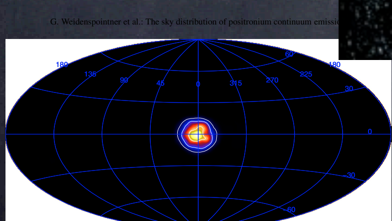












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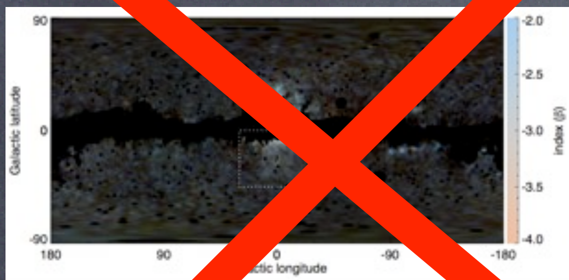

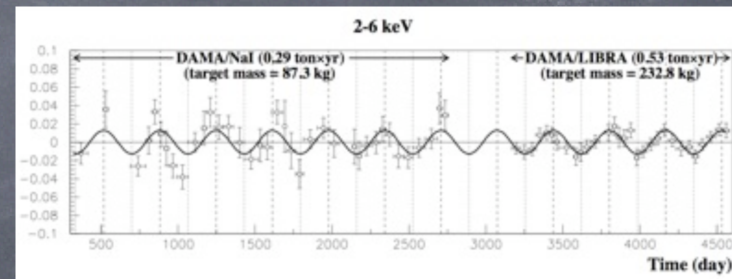

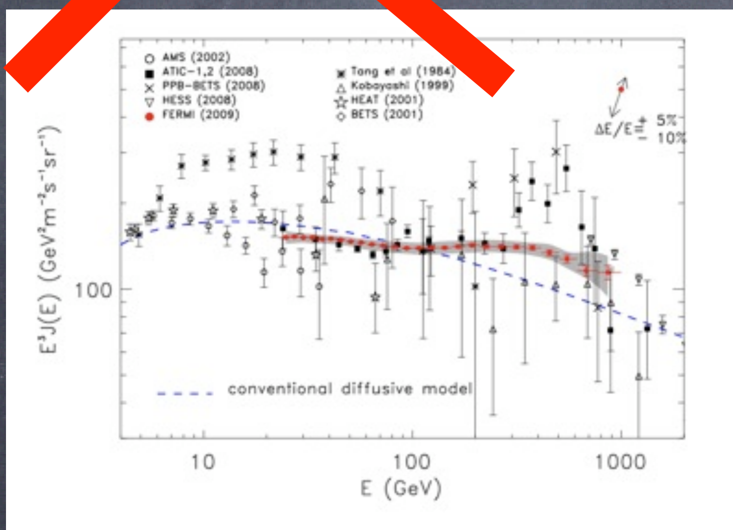

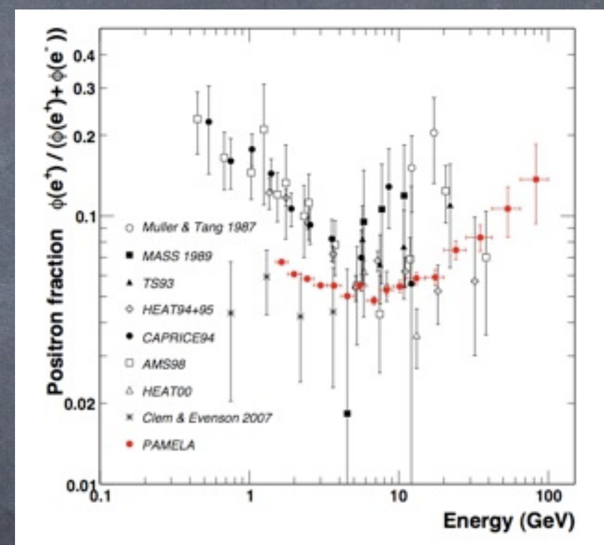

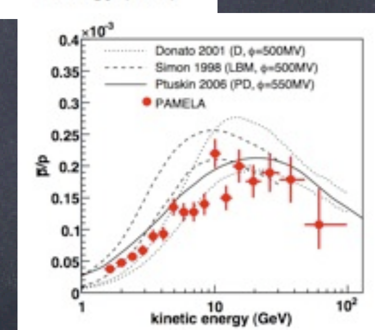

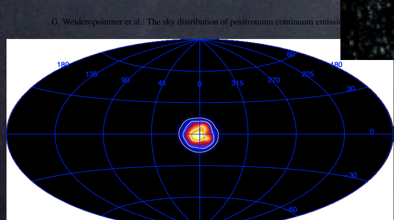

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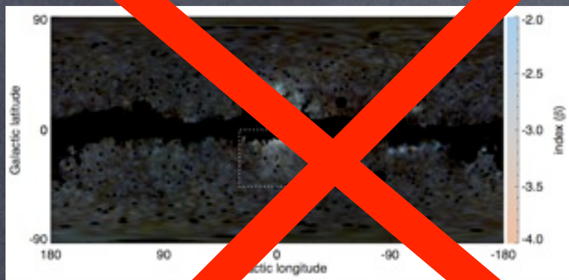

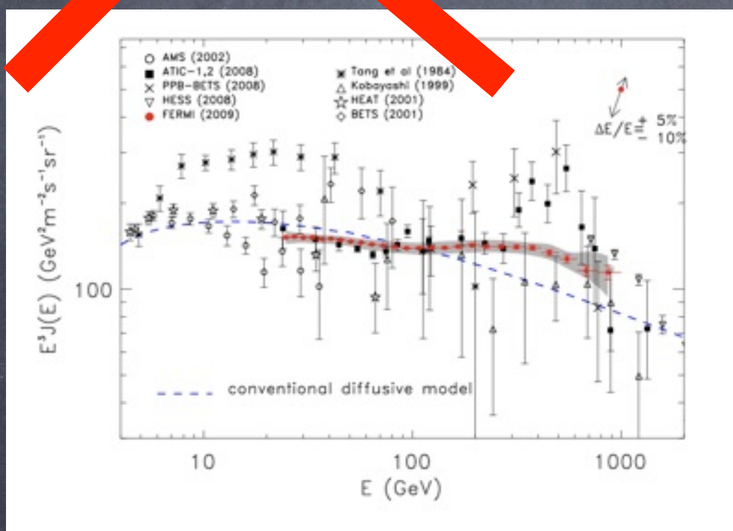

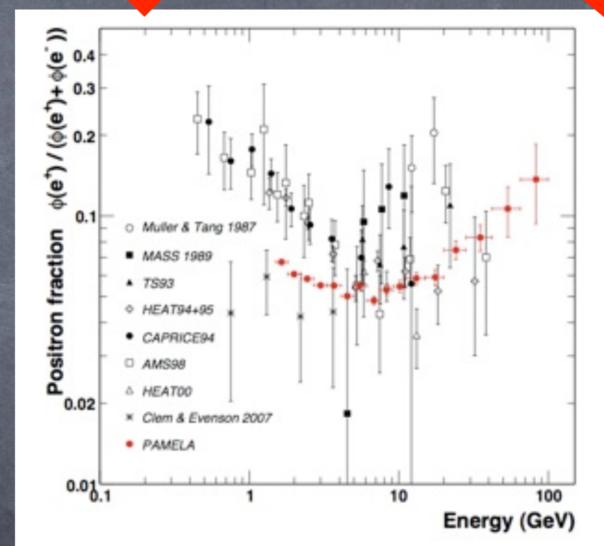

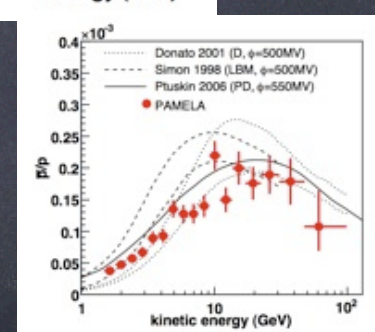

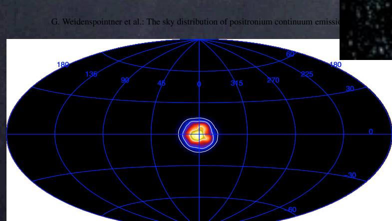

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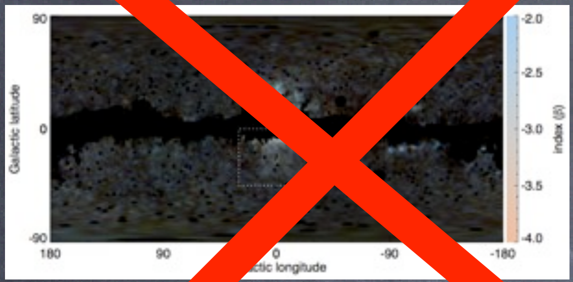

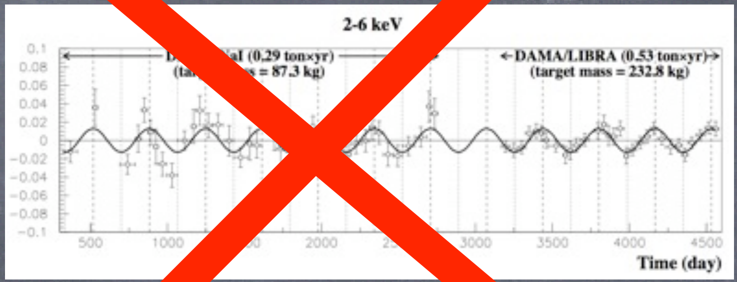

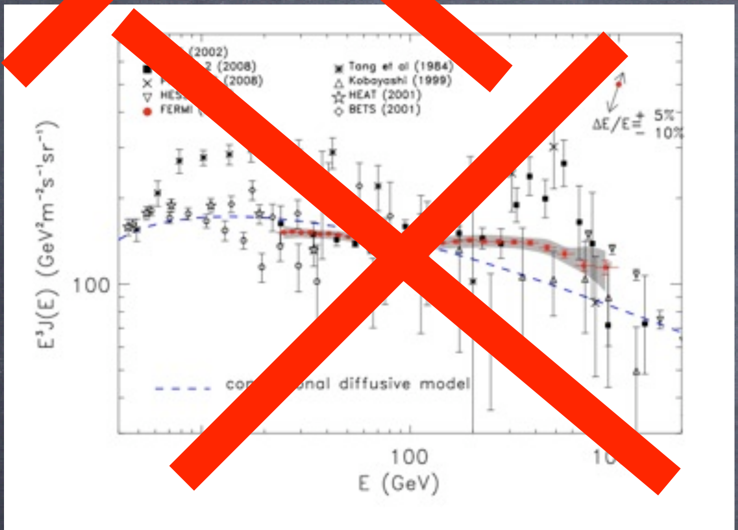

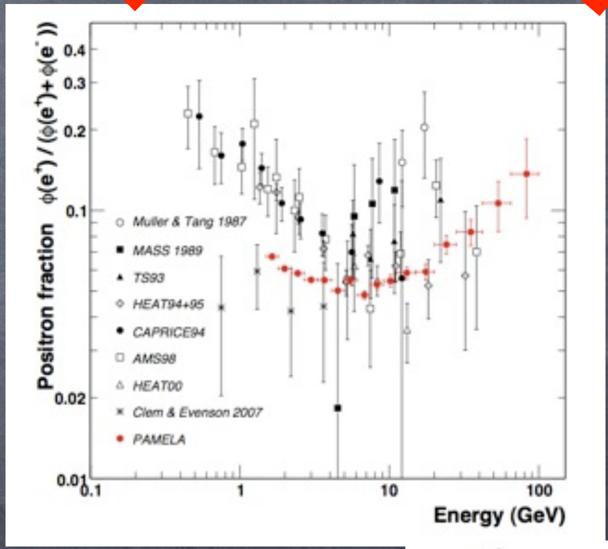

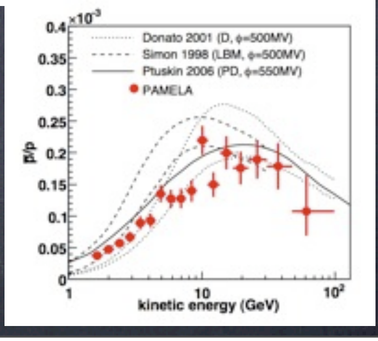

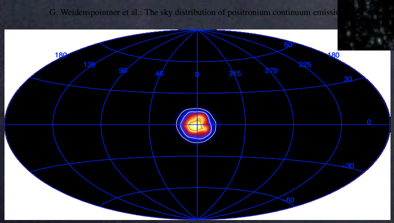

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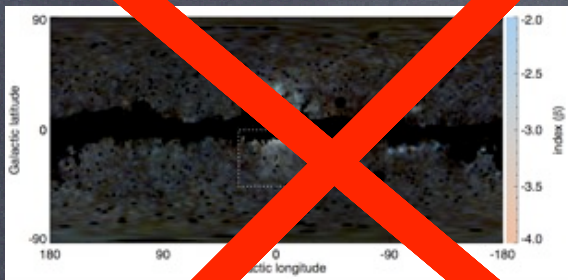

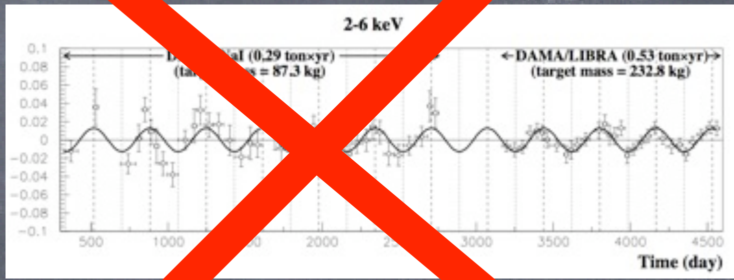

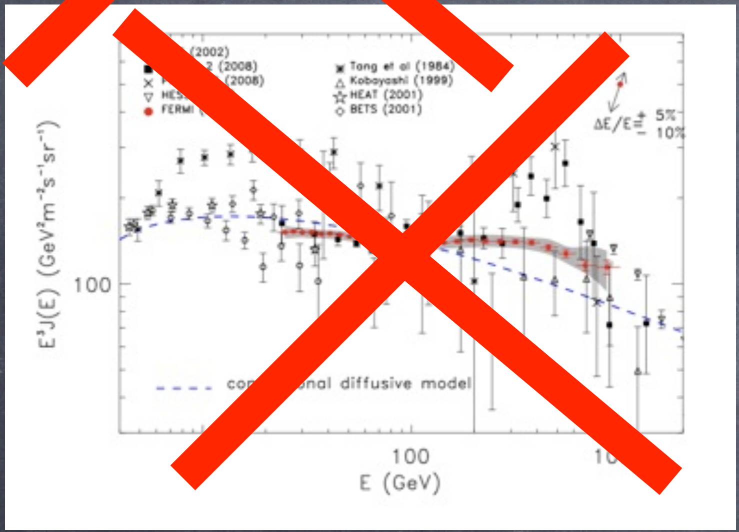

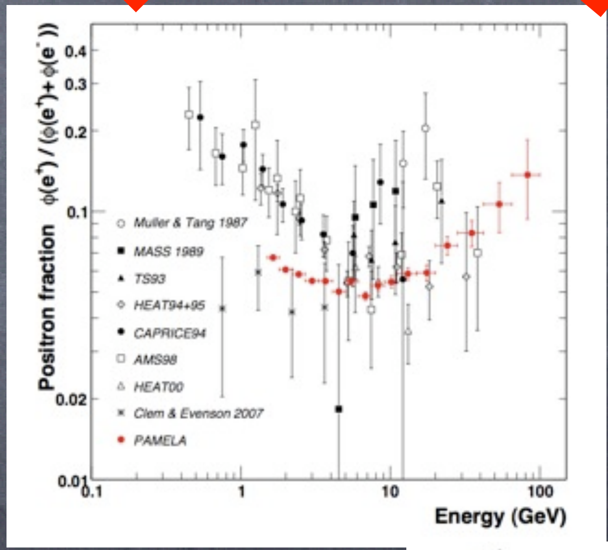

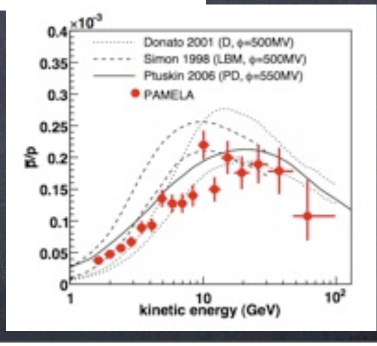

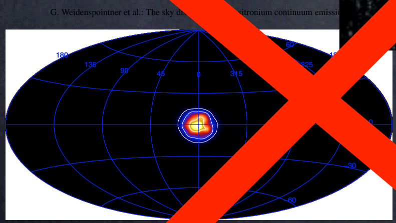

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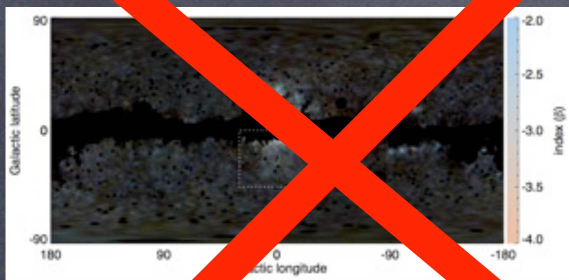

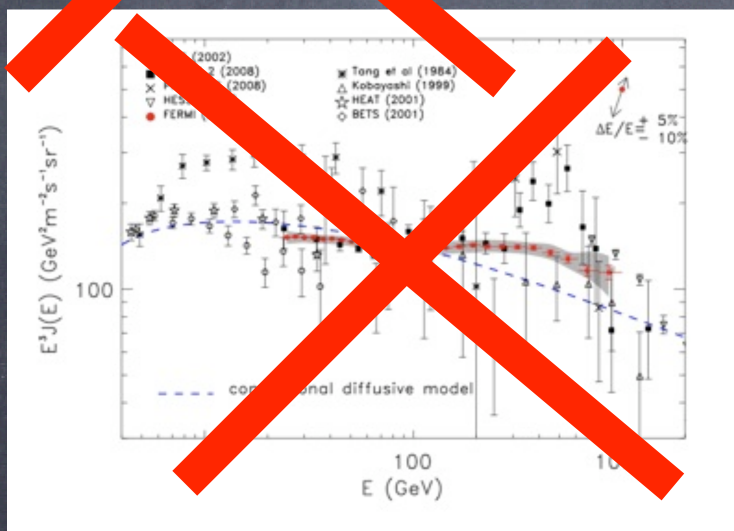

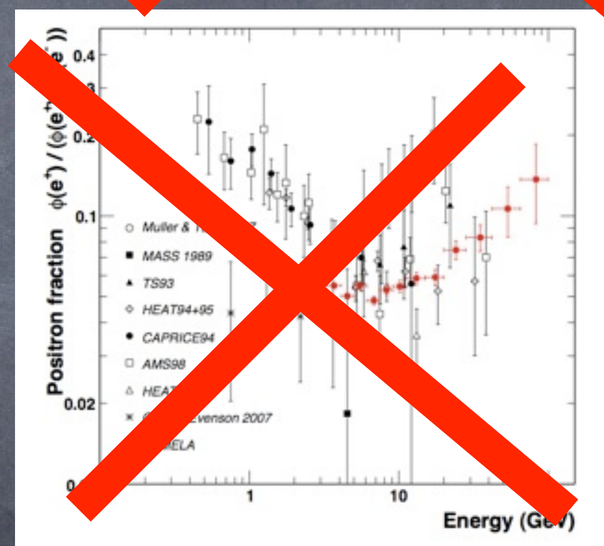

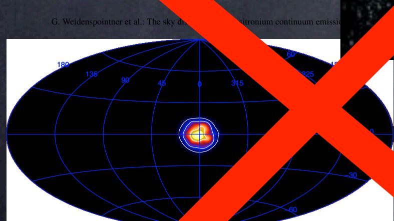

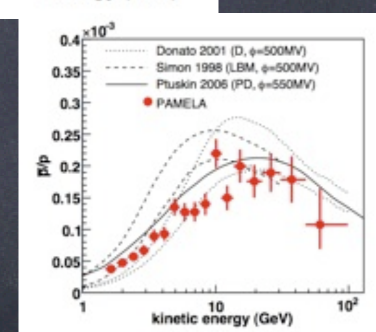

...there is no reason to think this theory is any more or less valid that supersymmetry or axions...

New experimental particle physics dark matter talk:

Blah, blah, blah, Zwicky, blah, blah, Coma Cluster, blah, blah, Dark Matter!, blah, blah, rotation curve, blah, blah, blah, 23% of universe, blah, blah, NOT SM! blah, blah, GREAT MYSTERY! blah, blah, blah, three candidates: blah, blah, axions, blah, blah, blah, blah, WIMPs, blah, blah, Dark Forces, blah, blah, supersymmetry, blah, blah, WIMP miracle, blah, blah, blah, my experiment, blah, blah, blah....