Search for a "Dark Photon" with the Mainz Microtron

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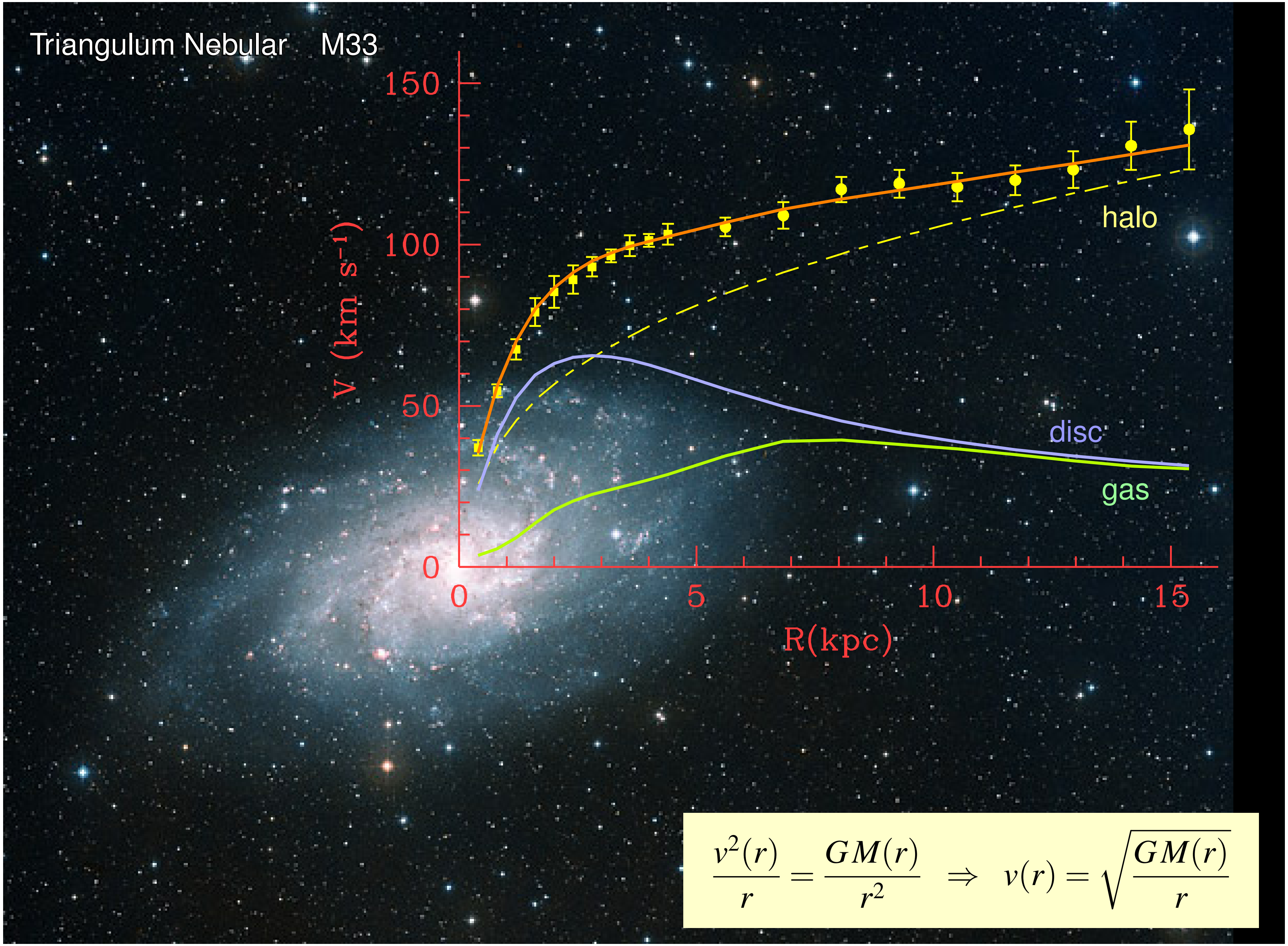
DESY Zeuthen, June 1, 2011

- Motivation
  - Evidence for Physics beyond the Standard Model
  - Candidates from Particle Physics
  - The γ' Boson
- How can we detect a "Dark Photon"?
  - Di-Lepton-Production
  - Cross sections
- Experiment at the Mainz Microtron (MAMI)
  - Experiment
  - Results
- Outline of an experimental program at MAMI
- Summary

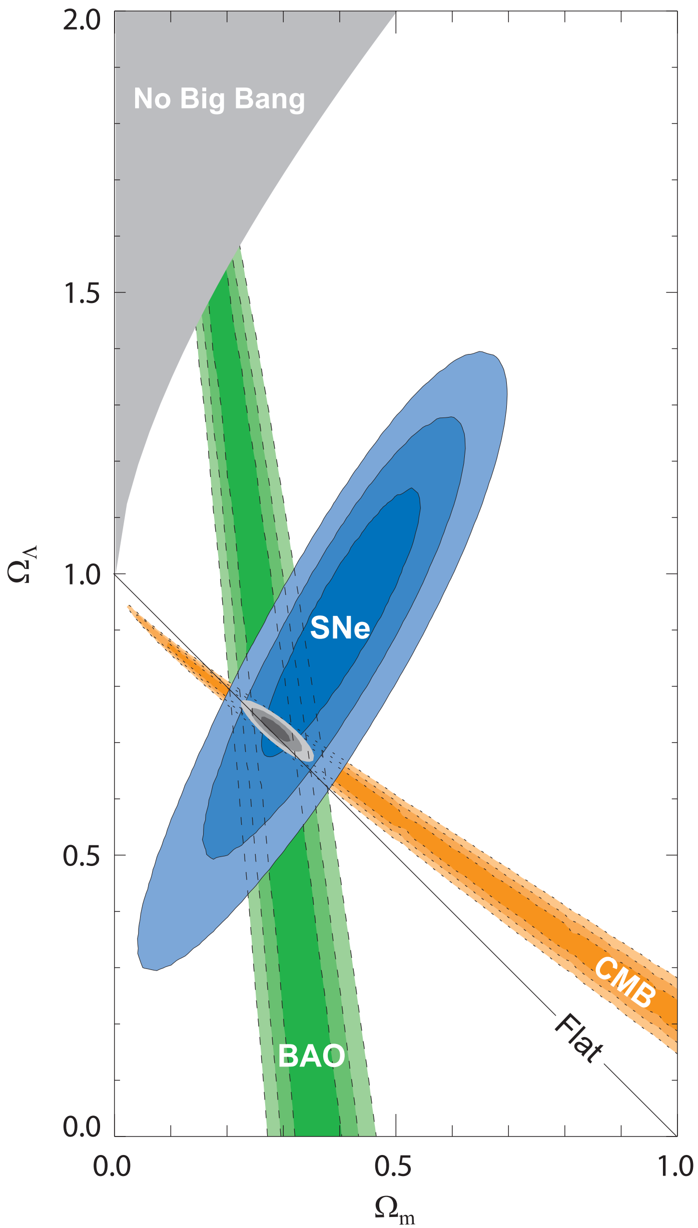
Rotation Curves of Galaxies



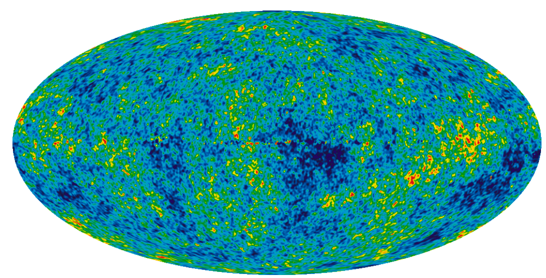
$$\frac{v^2(r)}{r} = \frac{GM(r)}{r^2} \quad \Rightarrow \quad v(r) = \sqrt{\frac{GM(r)}{r}}$$

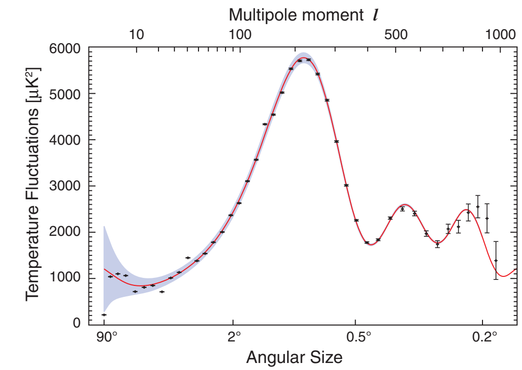
F. Zwicky, ApJ, 86 (1937) 217,   E. Corbelli, P. Salucci, MNRAS 311 (2002), 441 – 447

Dark Matter in Cosmology

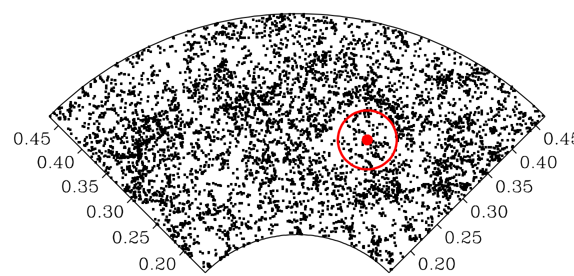


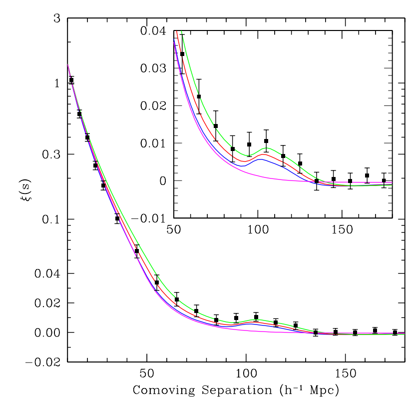
- Supernova Type Ia (SNe)
- Cosmic Microwave Background





- Baryon Acoustic Oscillations





$$\Rightarrow \quad \begin{aligned} \Omega_\Lambda &= 74\% \quad \text{Dark Energy} \\ \Omega_{CDM} &= 21\% \quad \text{Cold Dark Matter} \\ \Omega_b &= 4\% \quad \text{Baryonic Matter} \end{aligned}$$

M. Kowalski *et al.* Ap.J. 686 (2008) 749

Dark matter candidates in particle physics

Properties:

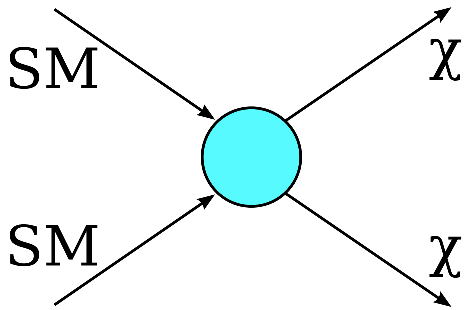
- Massive
- Almost no interaction with standard model matter

Candidates:

- Baryonic dark matter, gas clouds, MACHOs
  ϟ Contradicts primordial nucleosynthesis
- Hot dark matter, e.g. neutrinos
  ϟ Phase space contradicts structure formation
- Cold dark matter
  - WIMPs: Weakly Interacting Massive Particles
  - Axion
  - Lightest Supersymmetric Particle (LSP)
  - Neutralino, Sneutralino, Gravitiono, Axino,...

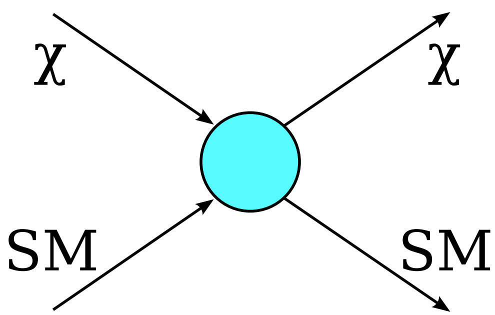
$\Rightarrow$ Cold dark matter

Conventional strategies for dark matter search



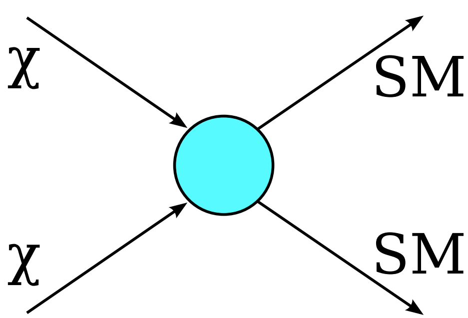
Direct Production:

Tevatron, LHC



Direct Search:

CDMS, DAMA/LIBRA,
XENON, CRESST, LUX,
COUPP, KIMS, ...



Indirect Search:

PAMELA, Fermi, HESS,
ATIC, WMAP, ...

A bottom up approach: Looking for the Interaction

Assumptions:

- There is dark matter (SUSY or something else)
- Dark matter interacts with Standard Model matter (besides gravity)
- Dark matter interacts via a “dark force”

Question:

- What is the character of this “dark force”?
- Scalar, pseudo-scalar, vector bosons?
- Massive or mass-less? Mass range?
- Size of the coupling constant?

?

Or top down Motivation...

- Extra $U(1)$ gauge bosons ubiquitous in well motivated extensions of the SM with large rank local gauge group:
  - large gauge symmetries must be broken
  - $U(1)$s are the lowest-rank local symmetries
- $U(1)$ gauge bosons may be hidden (no interaction with SM)
- $U(1)$ gauge factors in string compactifications:

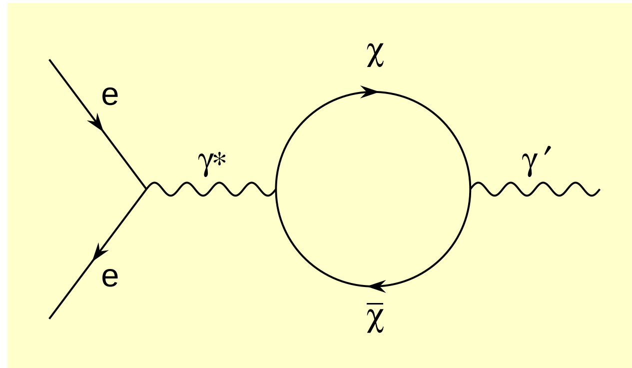
$$E_8 \times E_8 \to E_6 \times E_8 \to \underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y}_{\text{standard model}} \times U(1)_{\text{hidden}}$$

from breaking of second E_8

- No reason for $U(1)$ boson to be heavy!

Kinetic mixing

Dark matter couples to $U(1)$ bosons γ and γ':



$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}^{\rm SM}F^{\mu\nu}_{\rm SM} - \frac{1}{4}F_{\mu\nu}^{\rm hidden}F^{\mu\nu}_{\rm hidden} + \frac{\varepsilon}{2}F_{\mu\nu}^{\rm SM}F^{\mu\nu}_{\rm hidden} + m_{\gamma'}^2 A_\mu^{\rm hidden}A^\mu_{\rm hidden}$$

- Renormalization of charge:

  $\Rightarrow$ Mixing standard-model charge — “dark” charge

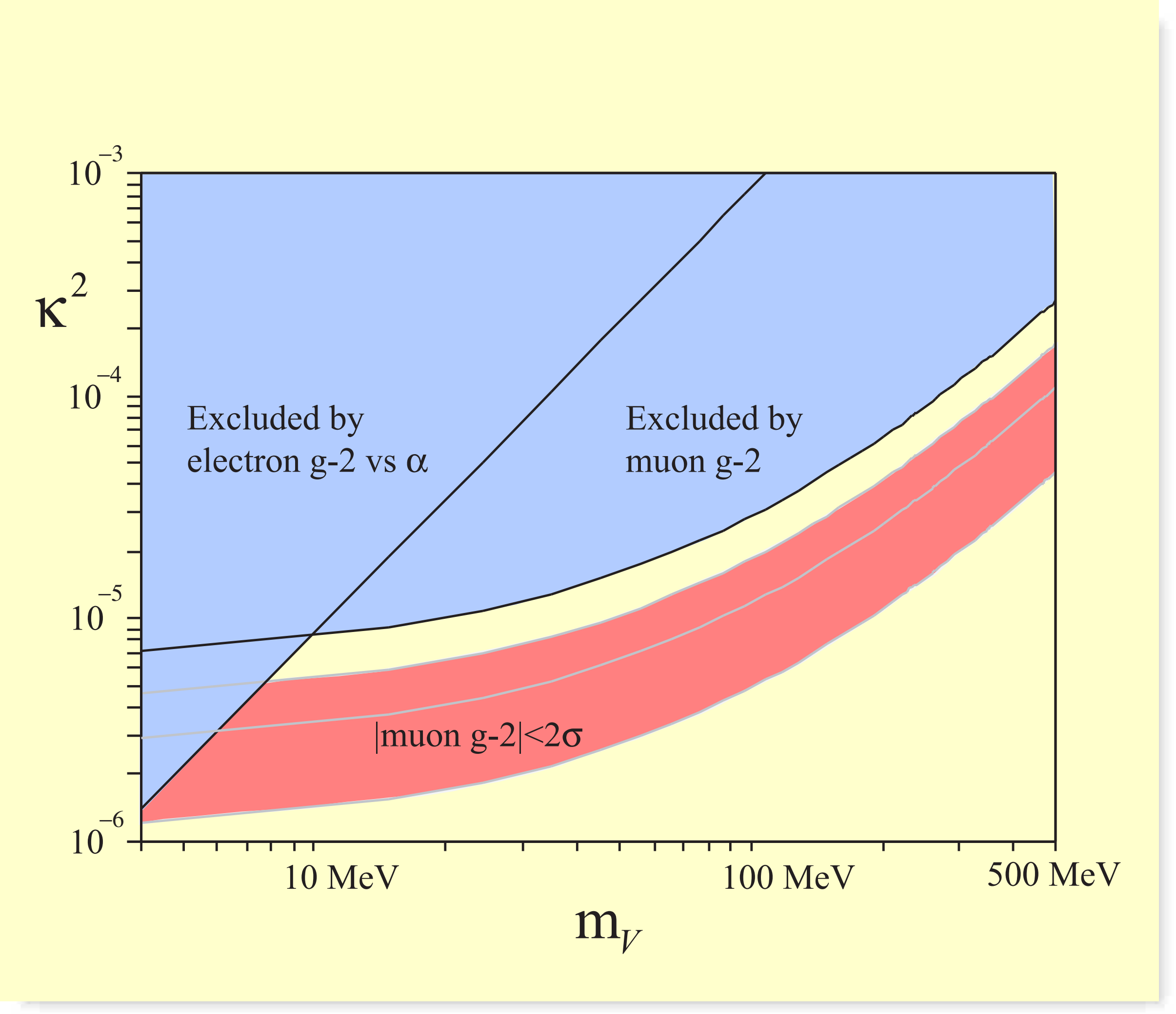
- Coupling constant ε of electric charge to γ'
- Boson mass $m_{\gamma'} > 0$ $\Rightarrow$ decay suppressed, macroscopic lifetime

$\Rightarrow$ Look for χ at high energies OR for γ' at low energies!

B. Holdom, Phys. Lett. B 166 (1986) 196

Is there experimental evidence?

Anomalous magnetic moment of the Muon



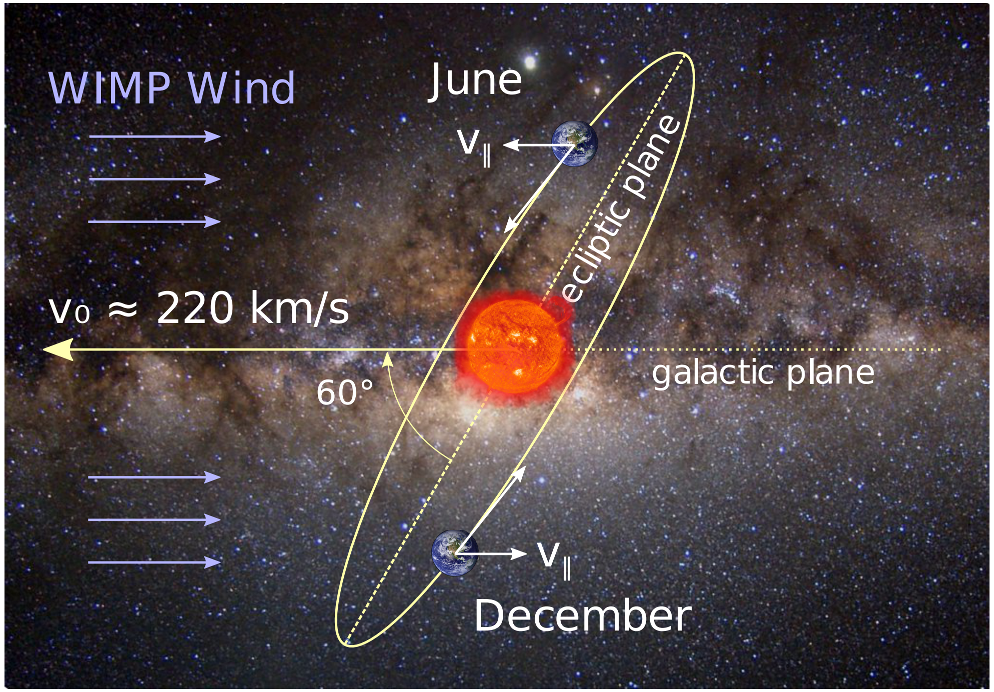
G. W. Bennet *et al.*, Phys. Rev. D 73, 072003 (2006)
M. Pospelov, Phys. Rev. D 80, 095002 (2009)

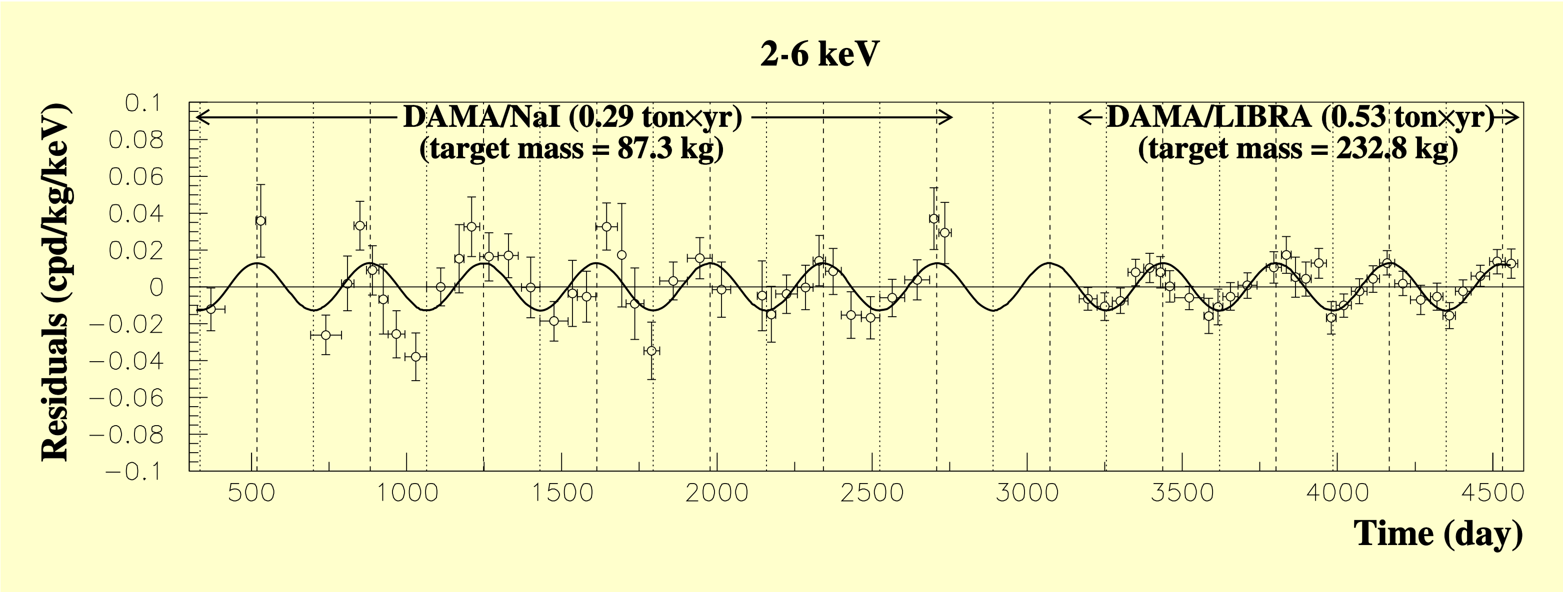
DAMA/NaI and DAMA/LIBRA

- NaI detectors in Gran Sasso
- Elastic scattering $\chi + N \rightarrow \chi + N$
- Seasonal modulation:

$$S_0 + A\cos\omega(t - t_0)$$

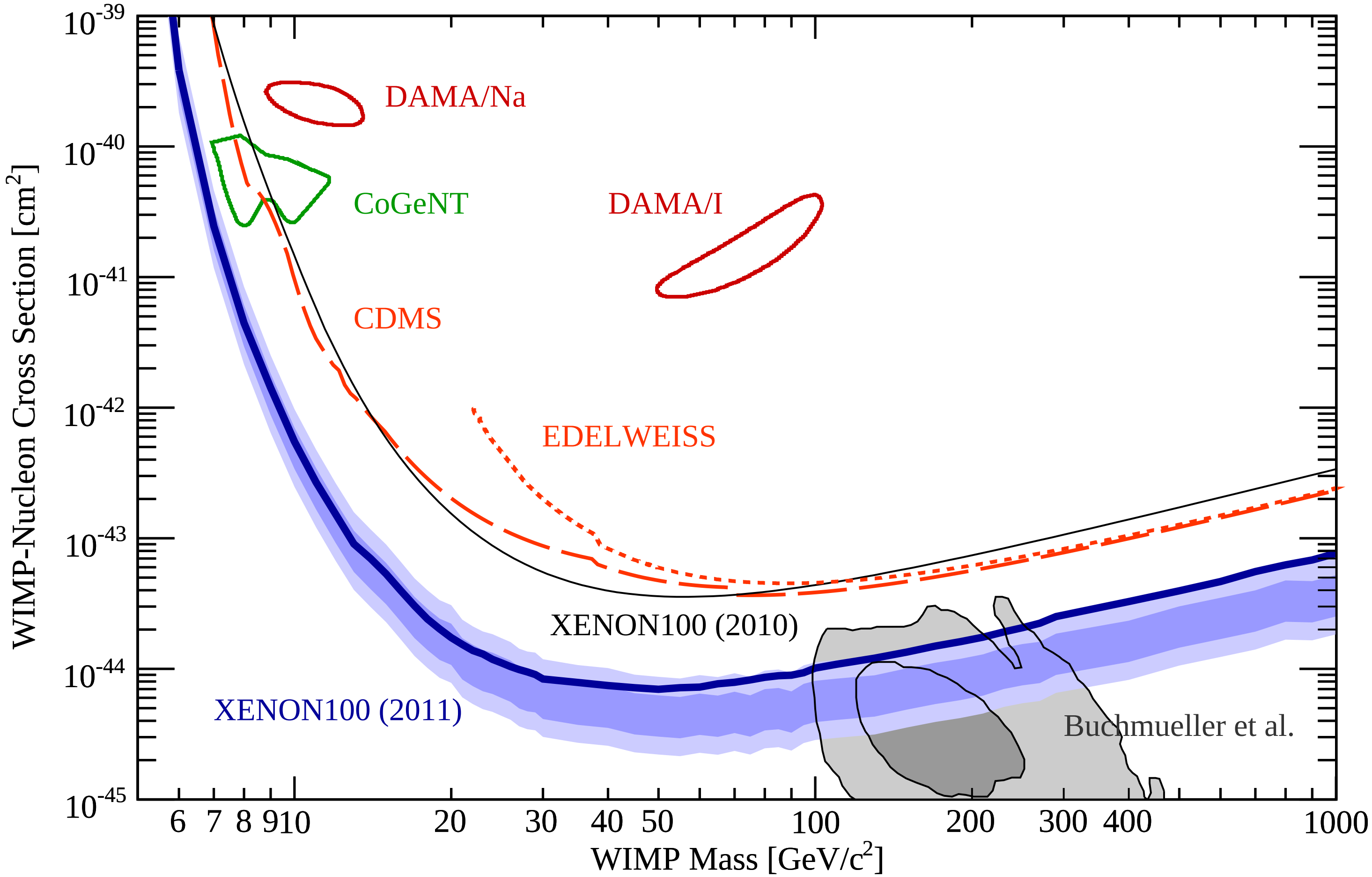
- Expected Phase: June 2nd ($t_0 = 152$)
- 8.2σ signal with $t_0 = 144 \pm 8$





R. Bernabei *et al.*, Eur. Phys. J. C (2008) 56: 333-355

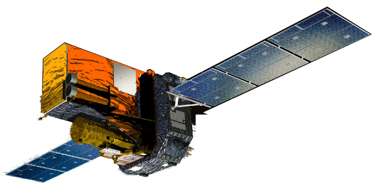
Problem: DAMA/LIBRA and the other experiments...

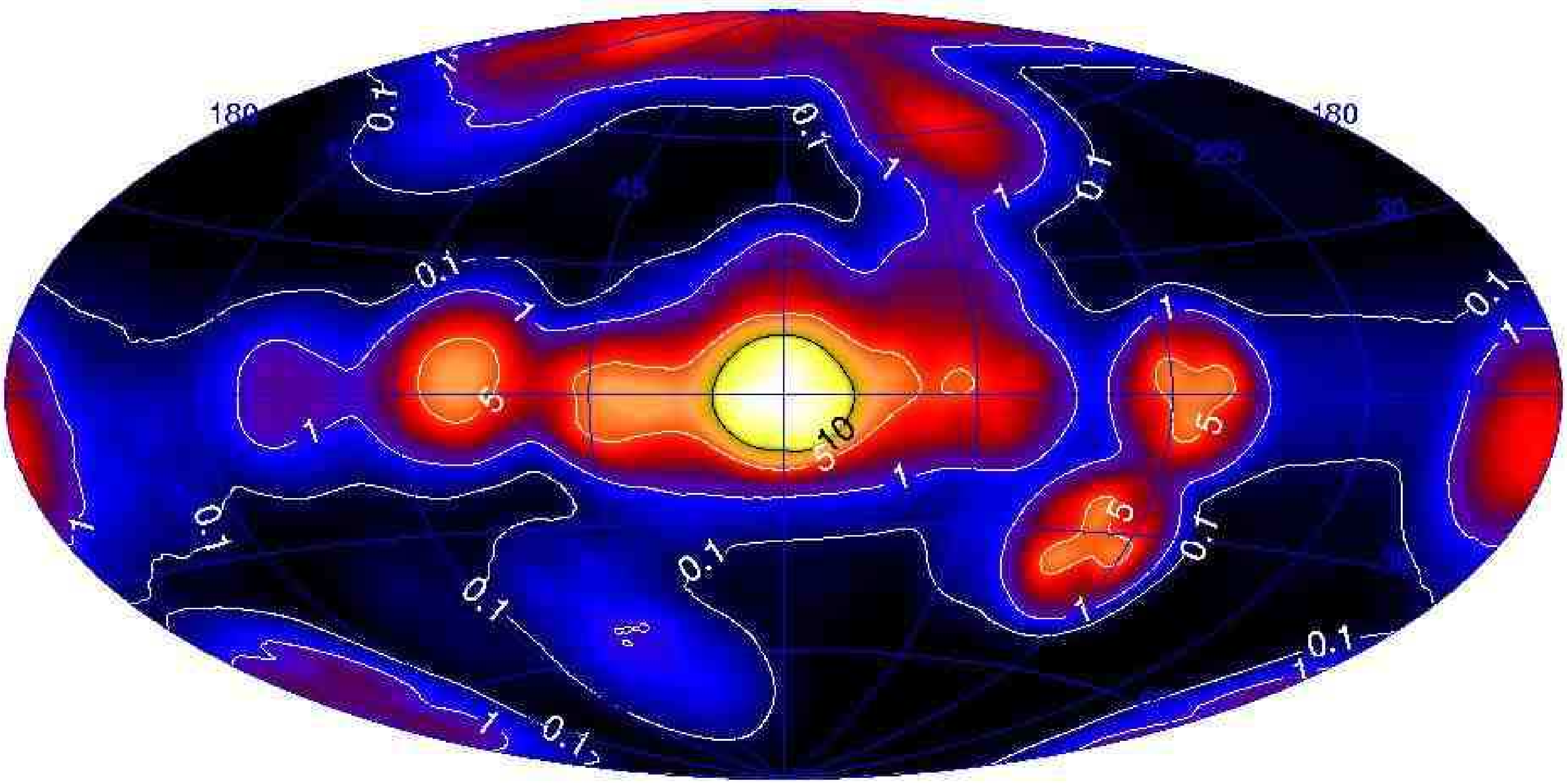


- Signals with annual modulation by DAMA and CoGeNT?
- XENON100, CDMS: coincidence experiments
- $\Rightarrow$ Possible solution: reaction mechanism (electrons, excited DM)

E. Aprile *et al.*, arXiv:1104.2549v2

SPI Spectrometer/INTEGRAL: 511 keV Gamma radiation

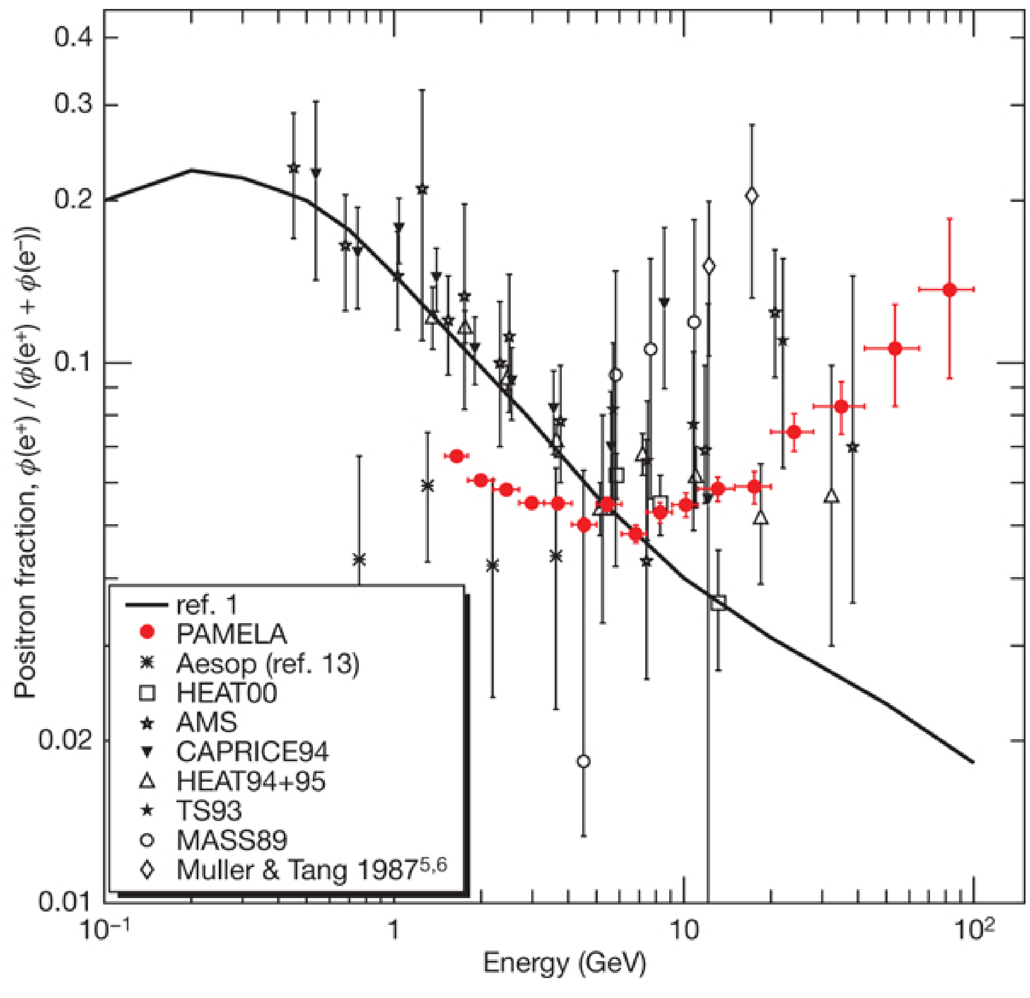




$\Rightarrow$ Positrons from annihilation $e^+ + e^-$

J. Knödlseder *et al.*, Astron. Astrophys. 441 (2005) 513

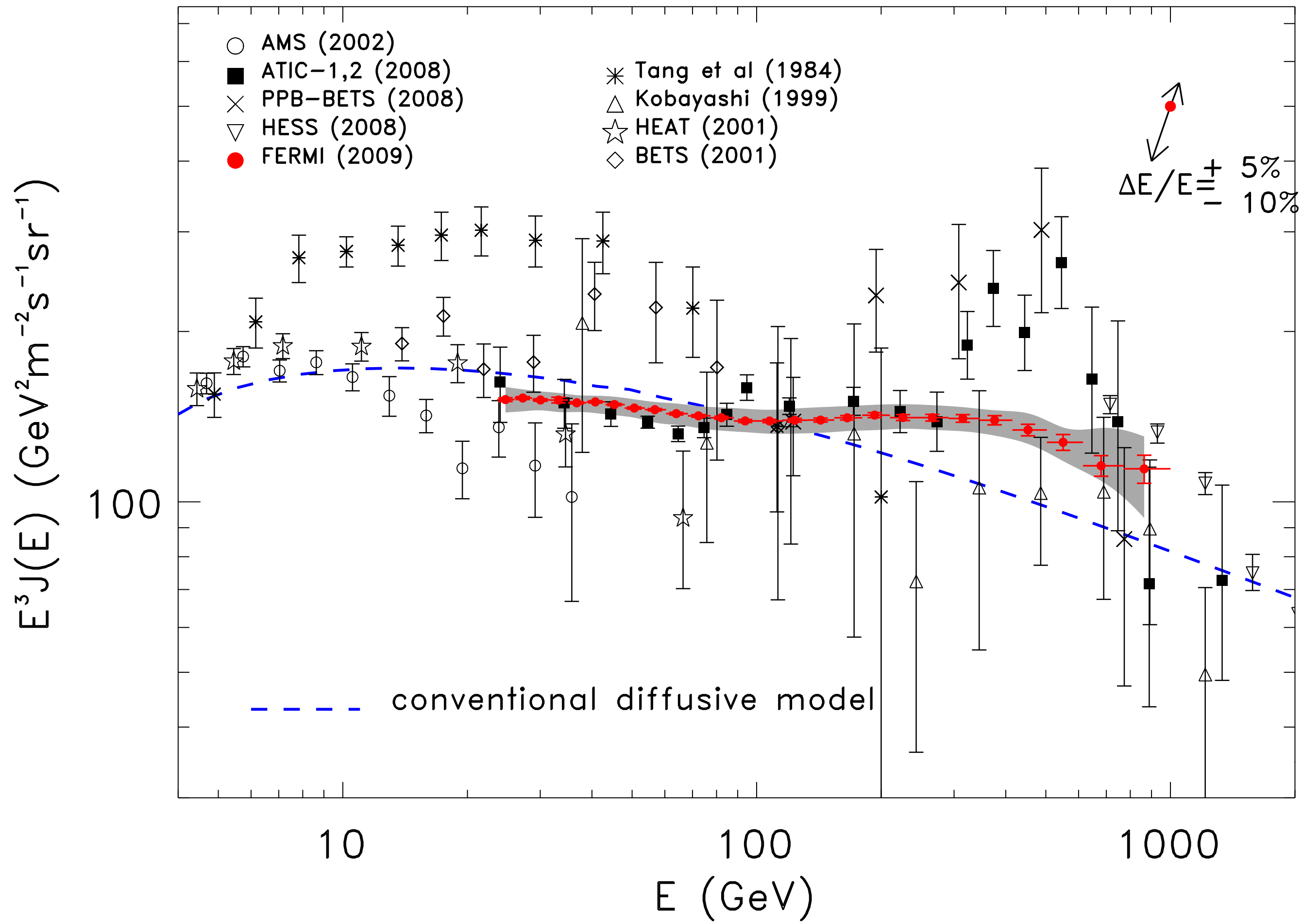
PAMELA: positron excess



⇒ Excess of positrons for $E > 10\,GeV$

O. Adriani *et al.*, Nature 458, 607-609 (2009)

Positron excess



⇒ Candidat for dark matter $E \approx 600\,\text{GeV}$?

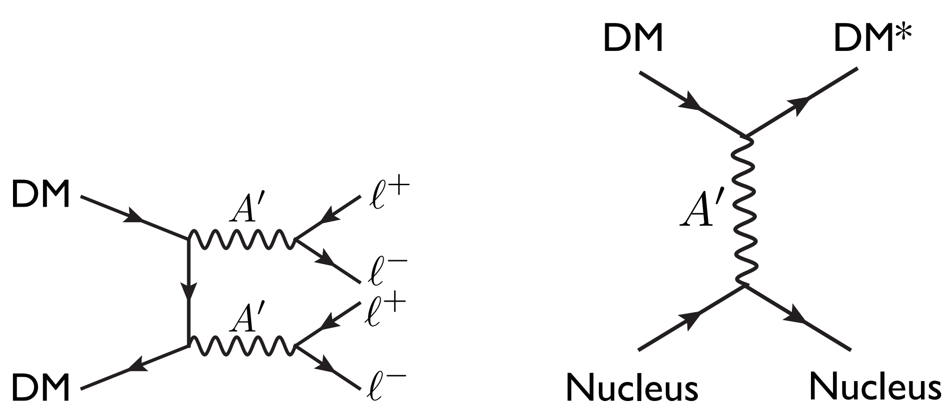
A.A. Abdo *et al.*, Phys. Rev. Lett. 102:181101 (2009)

The γ' Boson (or A', ϕ, ...)

- $g-2$ anomaly of the myon
- Positron excess, but no antiproton excess (PAMELA, INTEGRAL 511 keV line, etc.)
- Large annihilation cross section
- Relic Abundance of DM in cosmology requires low cross section
- Direct Scattering $\Rightarrow$ DAMA/LIBRA modulation

$\Rightarrow$
- Sommerfeld enhancement of cross section for low velocities
- Large cross section in leptons
- Small cross section in hadrons

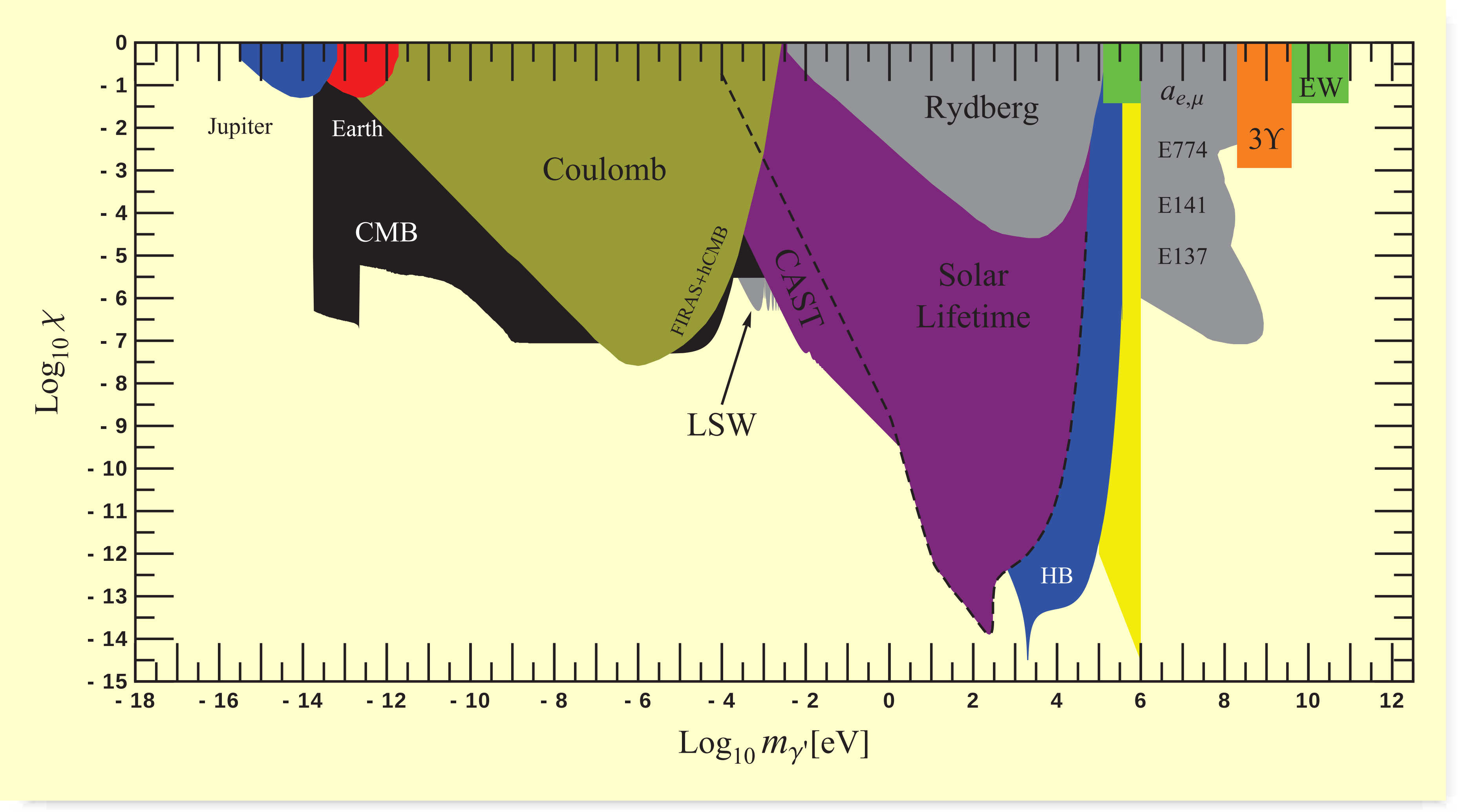
$\Rightarrow U(1)$ Vector Boson γ' with Mass in GeV range



N. Arkani-Hamed, *et al.*, Phys. Rev. D 79 (2009) 015014

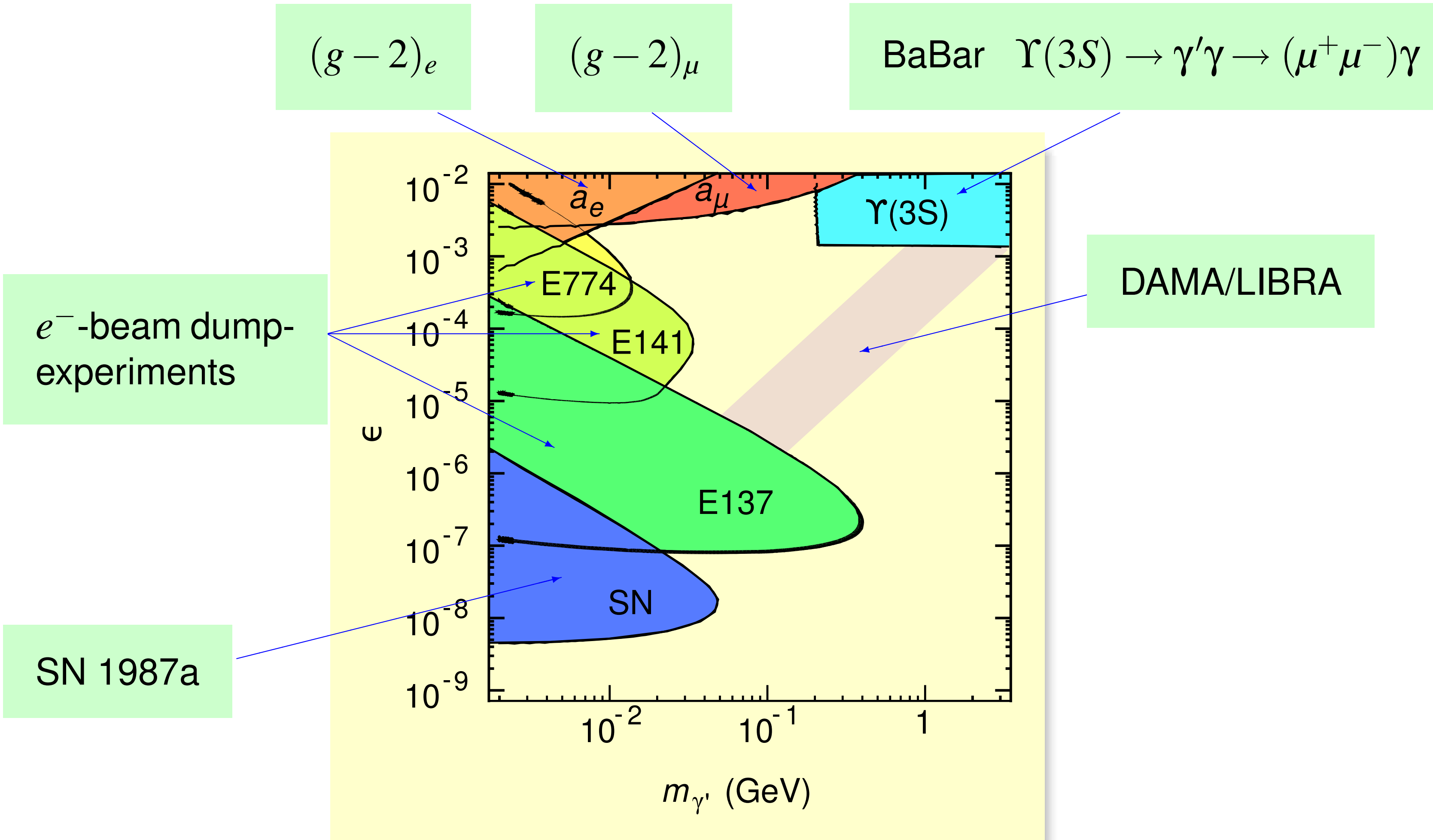
Exclusion limits for the “dark photon”

Existing bounds for dark photons



J. Jaeckel and A. Ringwald, Annu. Rev. Nucl. Part. Sci. (2010) 60:405-437

Parameter range for mass and coupling of γ' boson

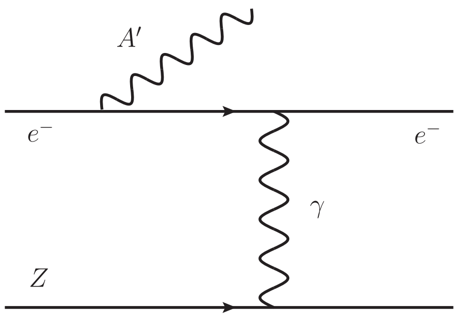


- Interesting range: $10^{-8} < \varepsilon < 10^{-2}$ $\quad 10\,\text{MeV} < m_{\gamma'} < 1000\,\text{MeV}$
- Energy range of MAMI!

J. D. Bjorken *et al.*, Phys. Rev. D 80, 075018 (2009)

Principle of Measurement

Quasi-photoproduction off heavy target



Weizsäcker-Williams approximation:

$$\frac{d\sigma}{dx\,d\cos\theta_{\gamma'}} \approx \frac{8Z^2\alpha^3\varepsilon^2E_0^2x}{U^2}\tilde{\chi}\left[(1-x+\frac{x^2}{2}) - \frac{x(1-x)m_{\gamma'}^2\left(E_0^2x\theta_{\gamma'}^2\right)}{U^2}\right]$$

with $\quad x = \frac{E_{\gamma'}}{E_0}$

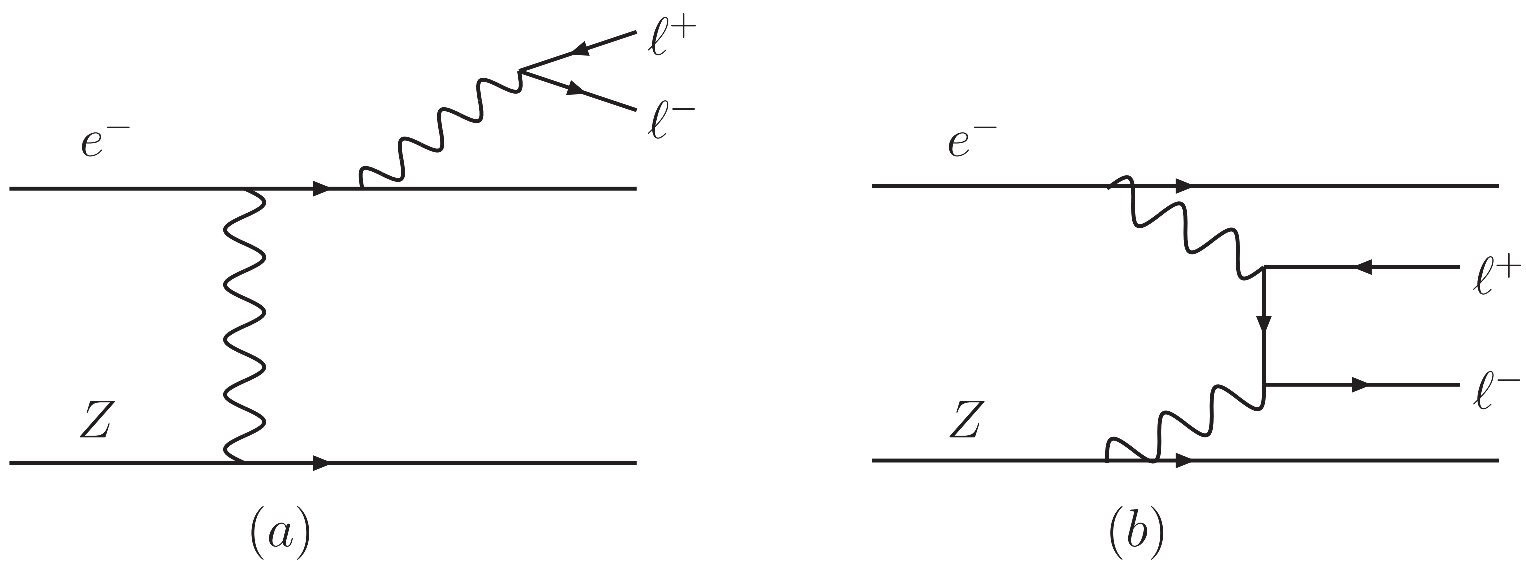
$$U(x,\theta_{\gamma'}) = E_0^2x\theta_{\gamma'}^2 + m_{\gamma'}^2\frac{1-x}{x} + m_e^2x$$

Lifetime:

$$\gamma c\tau \sim 1\text{ mm}\left(\frac{\gamma}{10}\right)\left(\frac{10^{-4}}{\varepsilon}\right)^2\left(\frac{100\,\text{MeV}}{m_{\gamma'}}\right)$$

J. D. Bjorken *et al.*, Phys. Rev. D 80, 075018 (2009)

Backgrounds

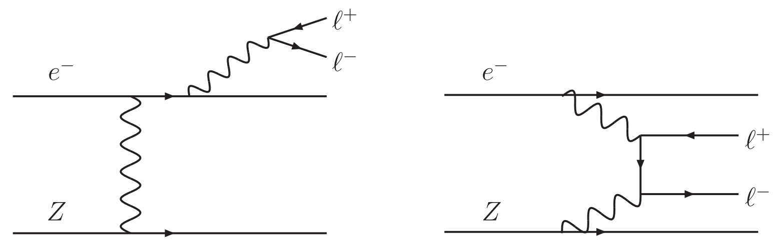


- Virtual photon instead of γ'
- Computable in QED
- Same shape of cross section
- $\Rightarrow$ Not separable

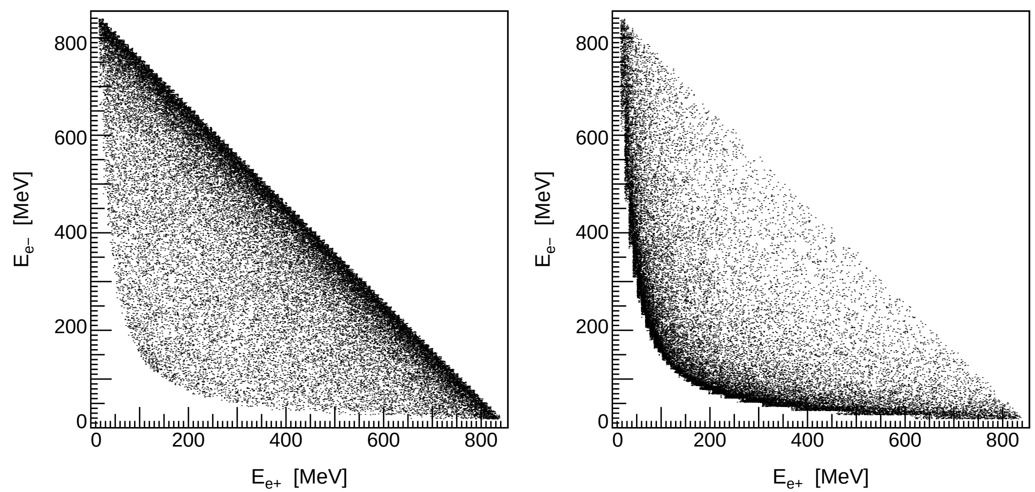
- Computable in QED
- Peak for l^* on mass shell
- Energy transfer to l^- or l^+
- $\Rightarrow$ Kinematically separable

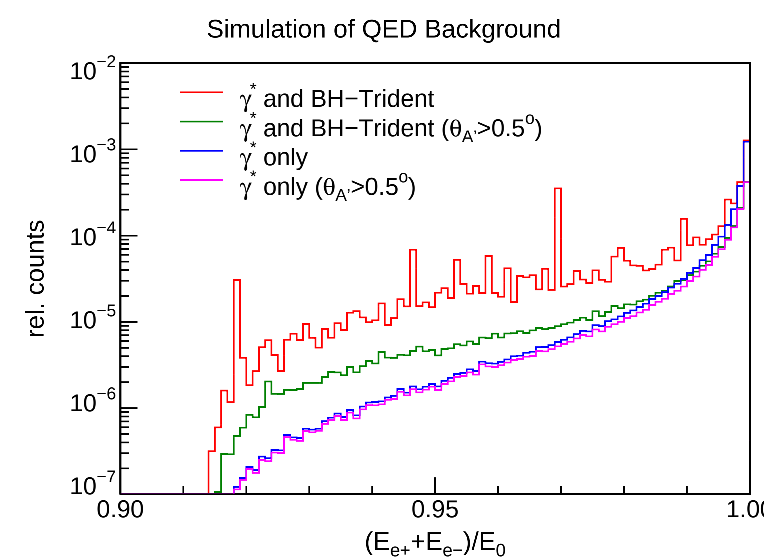
Other backgrounds: measurement!

Bethe-Heitler background



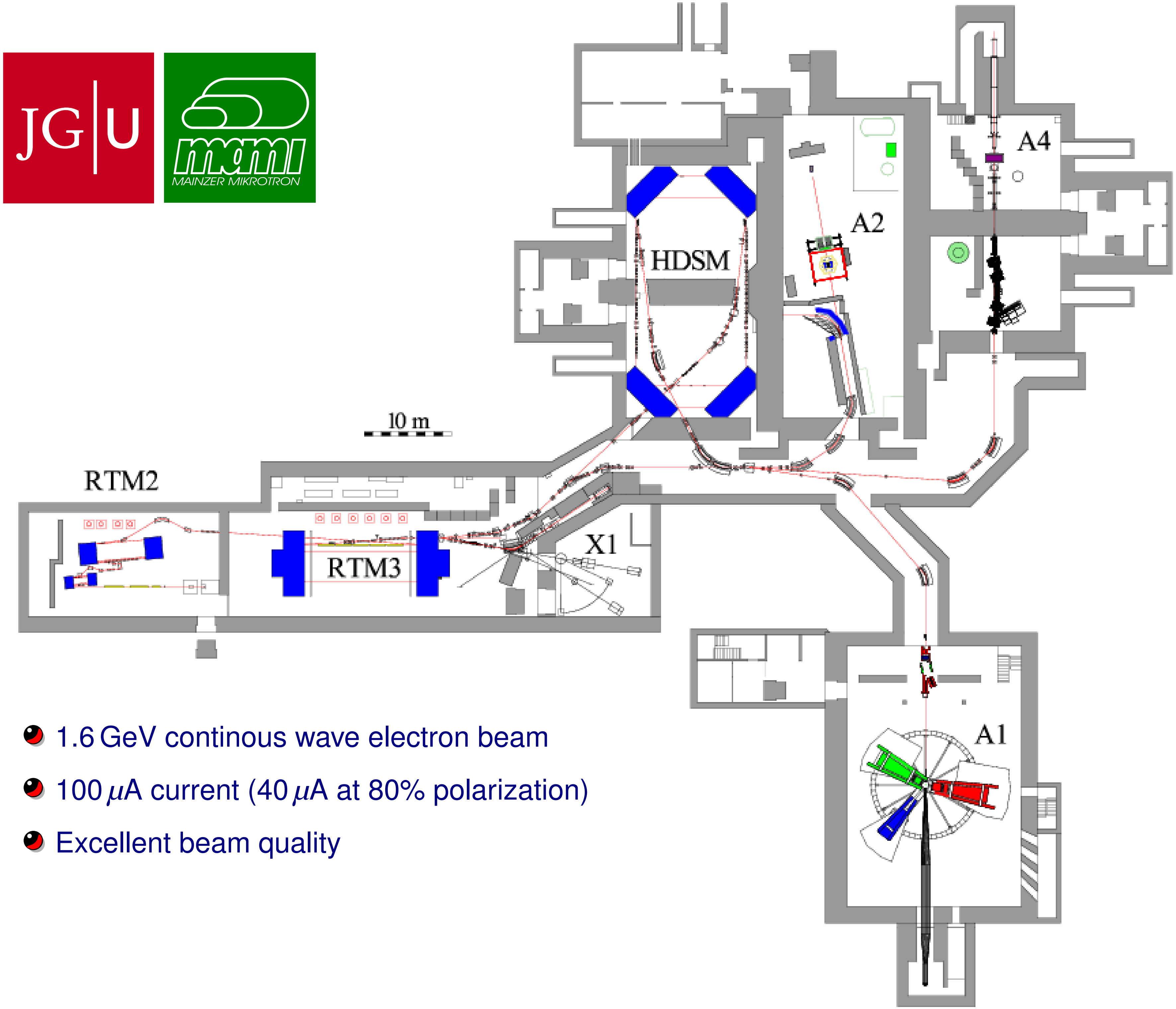
(a) (b)





- Peak at $m_{e^+e^-} = 0$
- Peak for asymmetric production
- Minimum for symmetric production at $x = 1$

The Experiment



- 1.6 GeV continous wave electron beam
- 100 μA current (40 μA at 80% polarization)
- Excellent beam quality

A1: Spectrometer setup at MAMI

Spectrometer A:

$$\alpha > 20^\circ$$
$$p < 735\,\frac{\text{MeV}}{c}$$
$$\Delta\Omega = 28\,\text{msr}$$
$$\Delta p/p = 20\%$$

Spectrometer B:

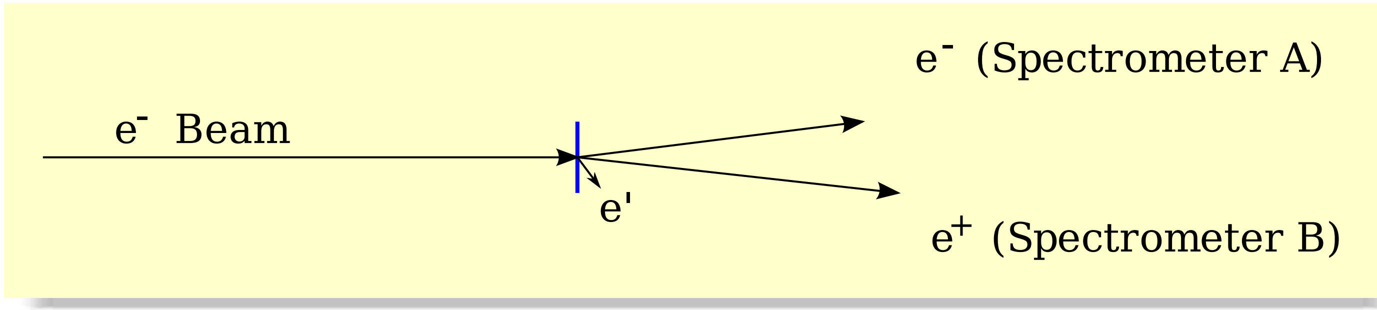
$$\alpha > 8^\circ$$
$$p < 870\,\frac{\text{MeV}}{c}$$
$$\Delta\Omega = 5.6\,\text{msr}$$
$$\Delta p/p = 15\%$$

Spectrometer C:

$$\alpha > 55^\circ$$
$$p < 655\,\frac{\text{MeV}}{c}$$
$$\Delta\Omega = 28\,\text{msr}$$
$$\Delta p/p = 25\%$$

$$\delta p/p < 10^{-4}$$

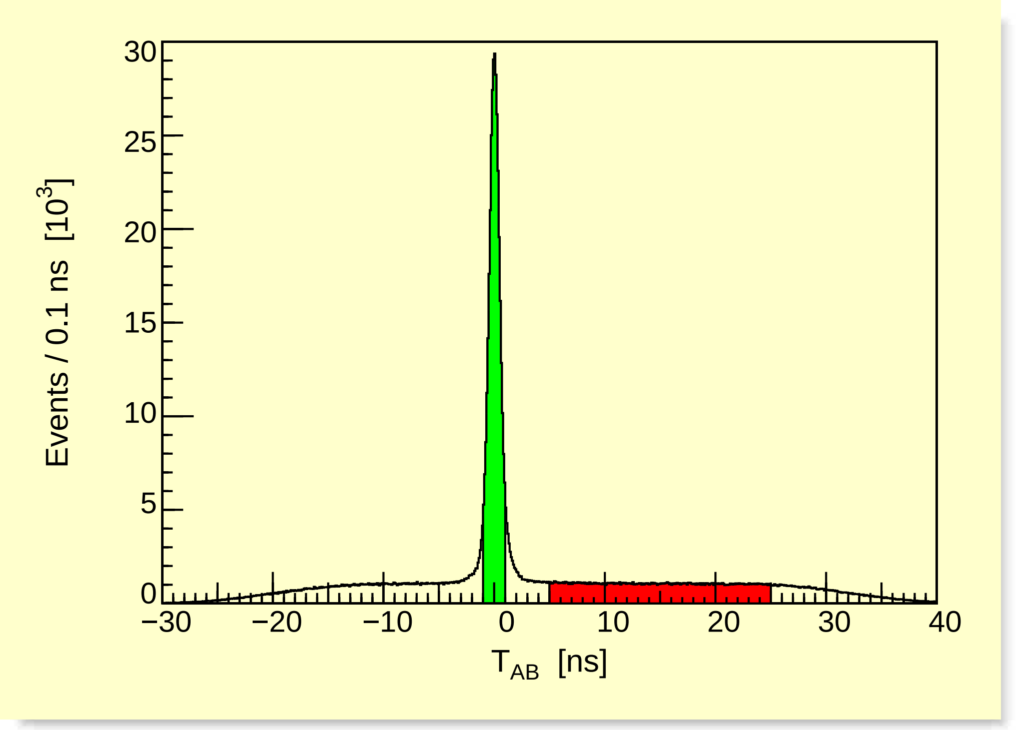
Pilot experiment



- Target: 0.05 mm Tantalum (mono-isotopic ^{181}Ta)
- Beam current: $100\mu\text{A}$
- Luminosity: $L = 1.7 \cdot 10^{35} \frac{1}{\text{s}\,\text{cm}^2}$ $\quad (L \cdot Z^2 \approx 10^{39} \frac{1}{\text{s}\,\text{cm}^2})$
- Complete energy transfer to γ' boson ($x = 1$)
- Minimal angles for spectrometers
- Spectrometer setup as symmetric as possible (background reduction)

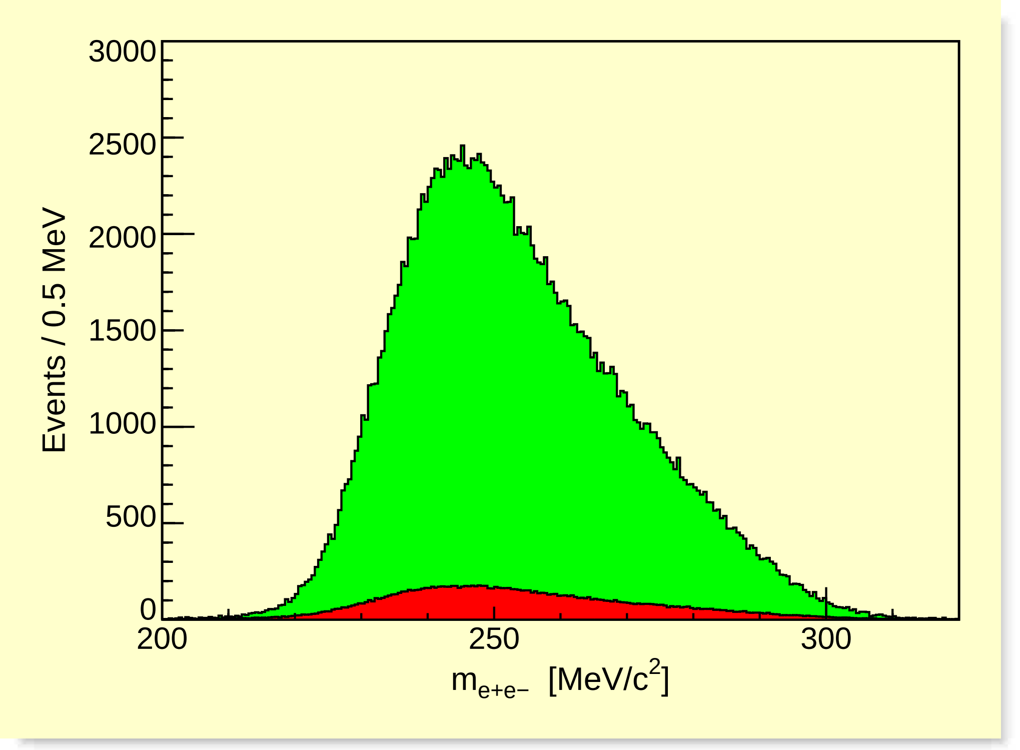
Beam energy	$E_0 =$	855.0 MeV
Spectrometer A	$p_{e^-} =$	338.0 MeV/c
	$\theta_{e^-} =$	22.8 $^\circ$
Spectrometer B	$p_{e^+} =$	470.0 MeV/c
	$\theta_{e^+} =$	15.2 $^\circ$

Reaction identification: coincidence time



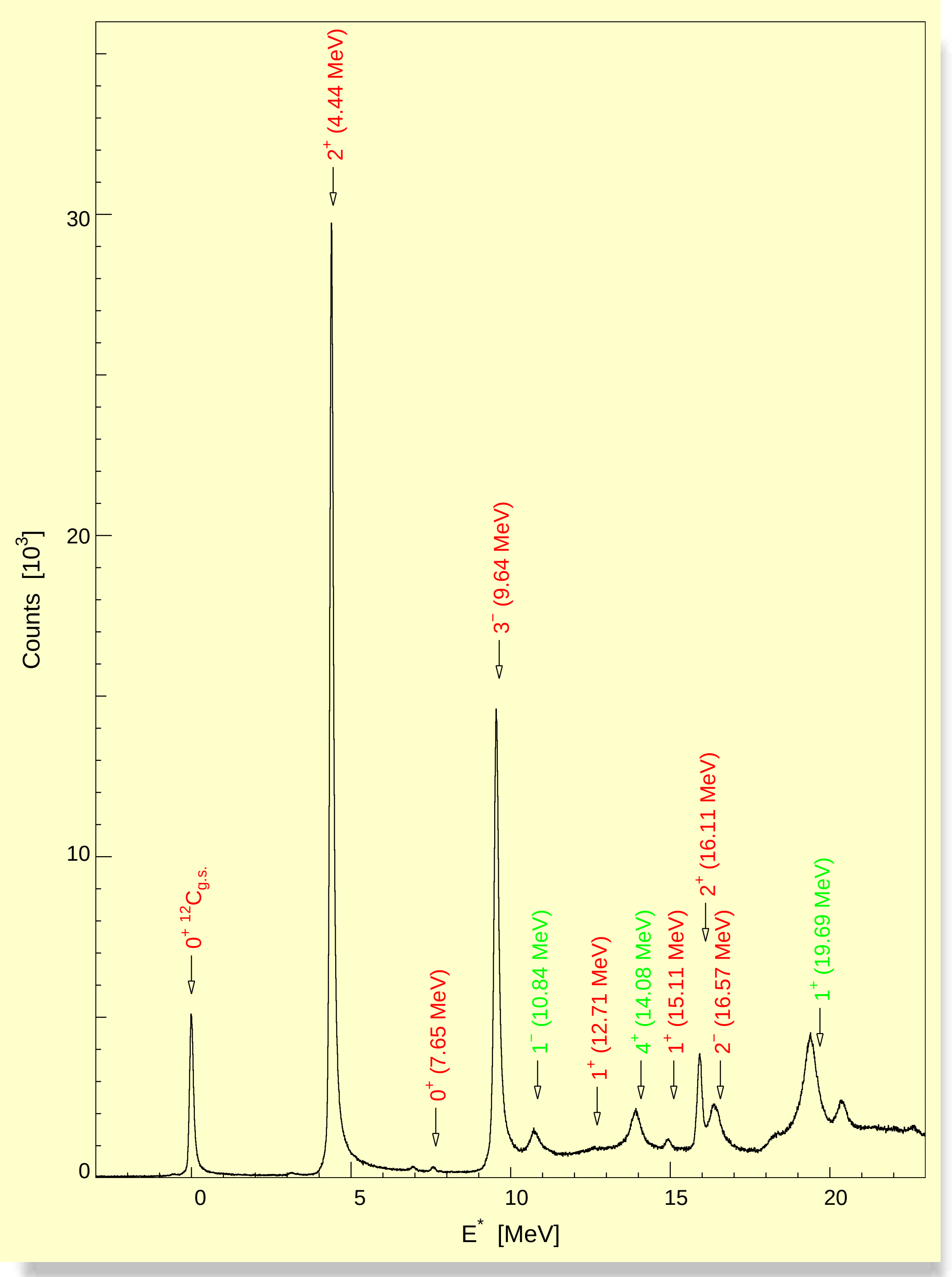
- Particle identification e^+, e^- by Cerenkov detectors
- Correction of path length in spectrometers $\approx 12\,\mathrm{m}$
  $\Rightarrow$ Time-of-Flight reaction identification
- Coincidence time resolution $\approx 1\,\mathrm{ns}$ FWHM
- Estimate of background: side band $5\,\mathrm{ns} < T_{A\wedge B} < 25\,\mathrm{ns}$
- Almost no accidental background $\approx 5\%$
- Above background: only coincident e^+e^- pairs!

Invariant mass of e^+e^- pair



- Mass of e^-e^+ pair $\quad m_{\gamma'}^2 = (e^- + e^+)^2$
- What is the expected peak width?

Determination of the Mass Resolution

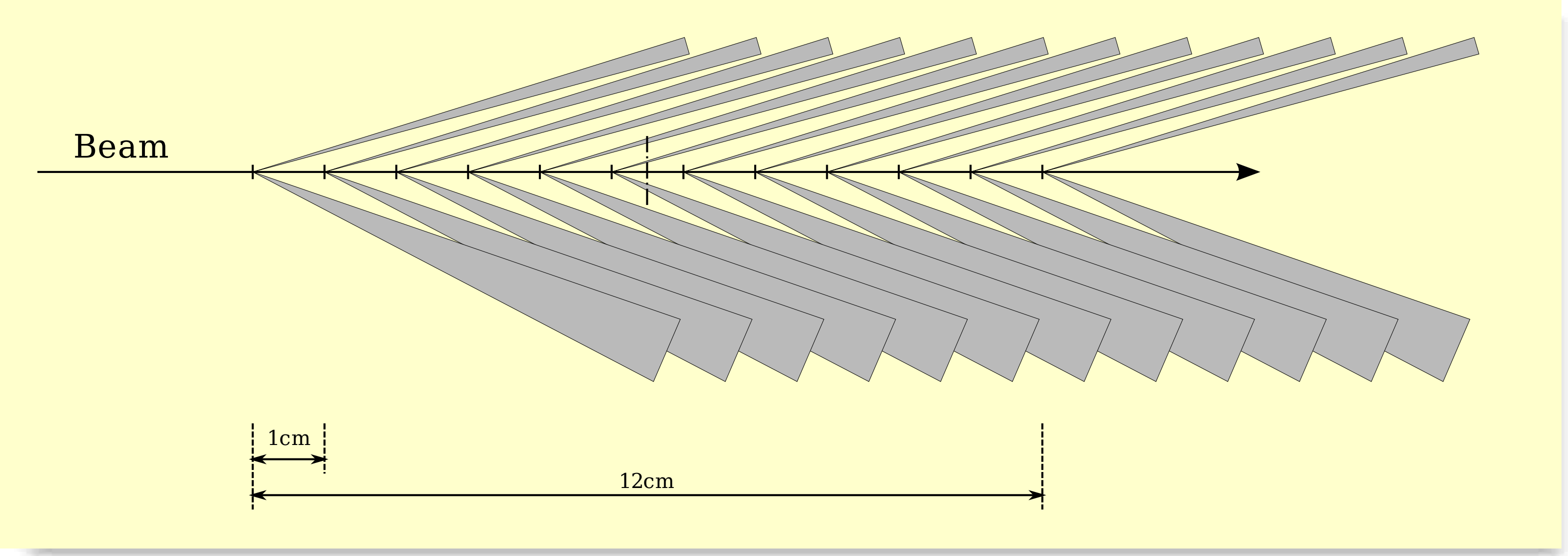


- Elastic Scattering
  - Natural width $\ll$ Resolution
  - Line width gives upper bound
  - $\delta p/p < 10^{-4}$ for Spectrometer
- Input to Full Simulation
  - Multiple Scattering $(-)$
  - Radiation correction $(-)$
  - Decay length $(+)$
  - Missing mass resolution $(+)$

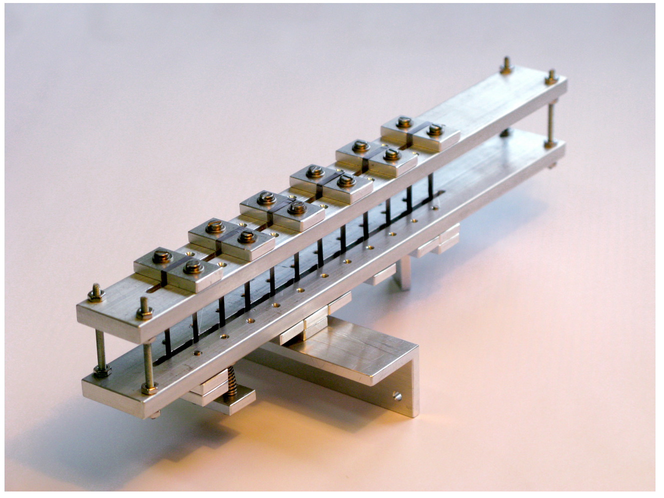
$$\Rightarrow \quad \delta m_{e^+e^-} < 0.5\,\mathrm{MeV}/c^2$$

N.B.: Systematic error of $\delta m_{e^+e^-} < 10^{-3}$!

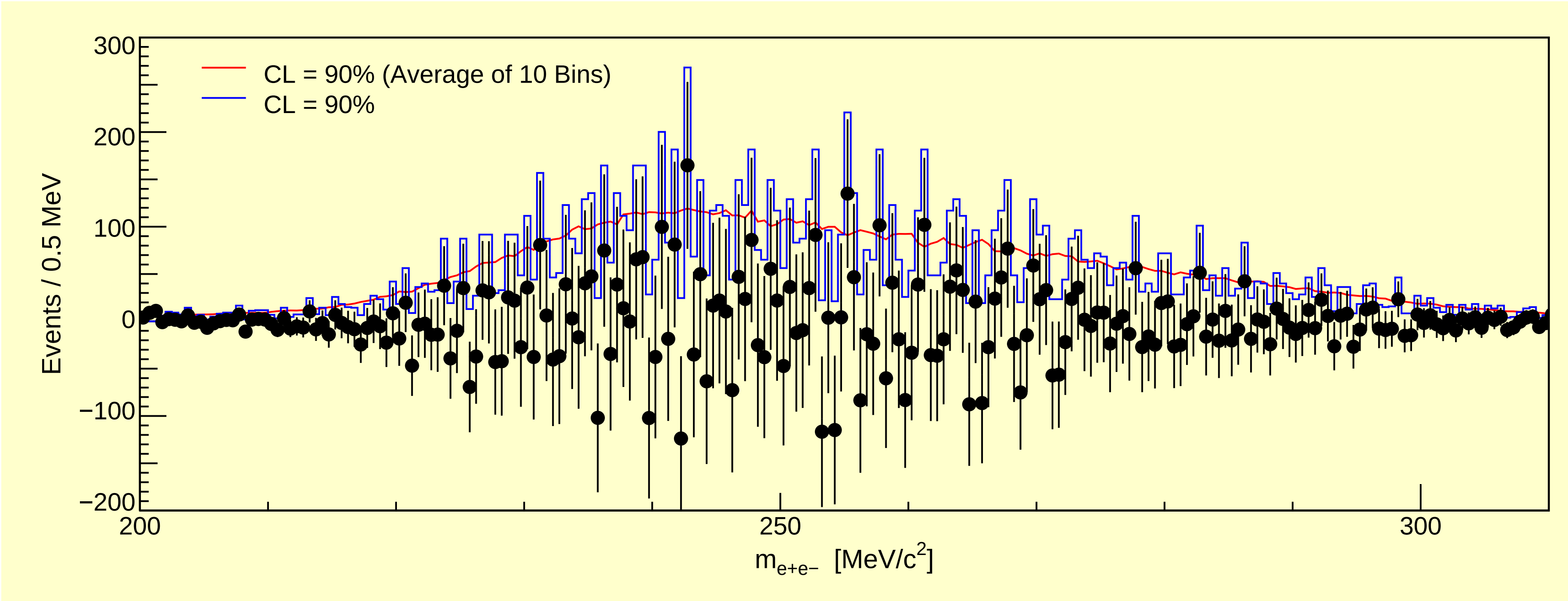
Target Design



- Mass distributed over 12 strips
- Single strip for multiple scattering
- Beam has to hit narrow target (2mm)



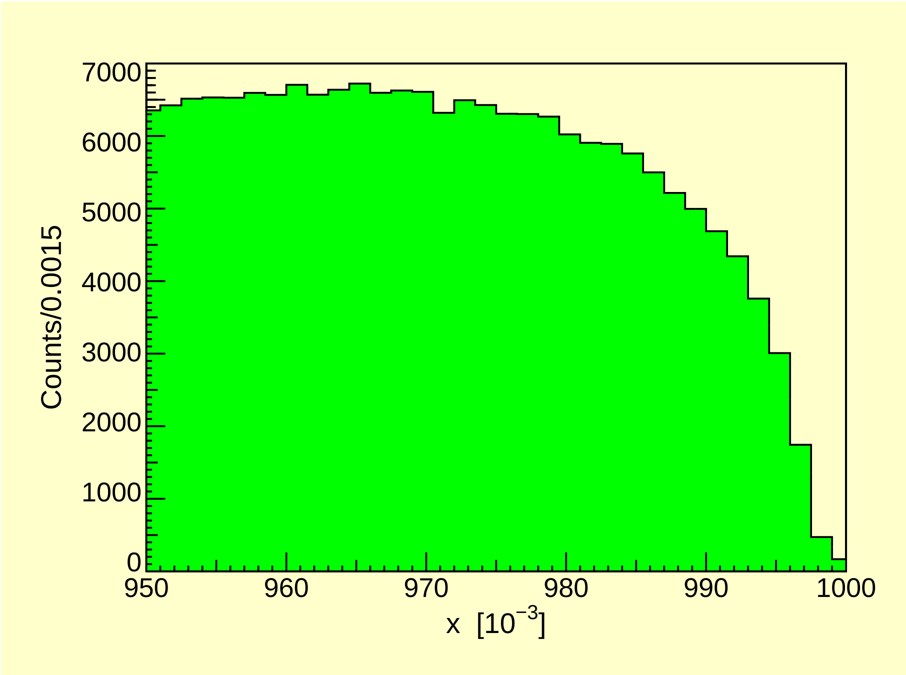
Exclusion limits



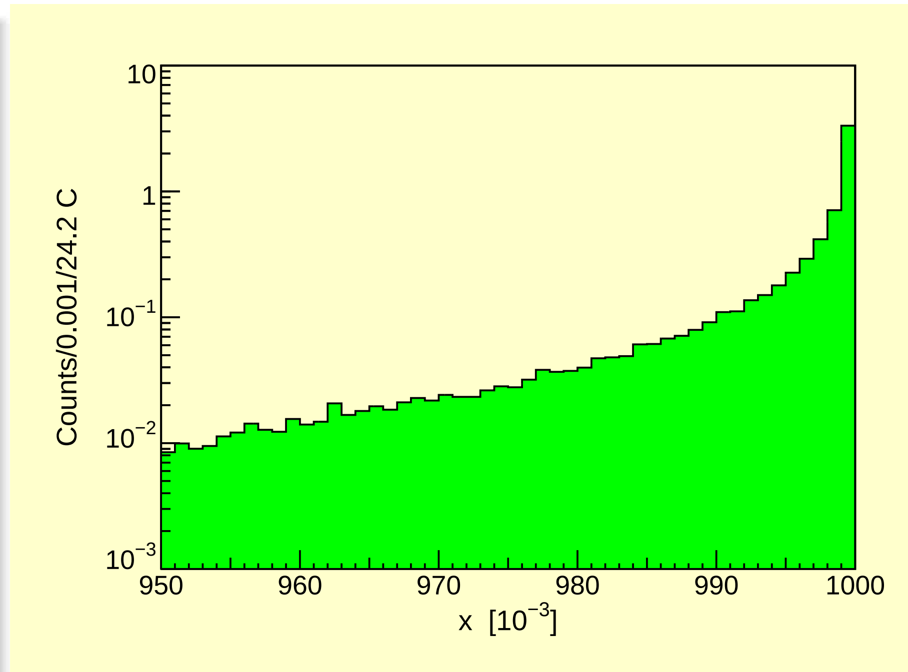
- Confidence interval by Feldman-Cousins algorithm
- "Model" for Background-subtraction:
  average of 3 Bins left and right of central bin
- Resolution $\delta m < 500\,\mathrm{keV} =$ bin width
- Averaging (mean of 10 bins) only for "subjective judgment"

Problem: model for cross section

Experiment:

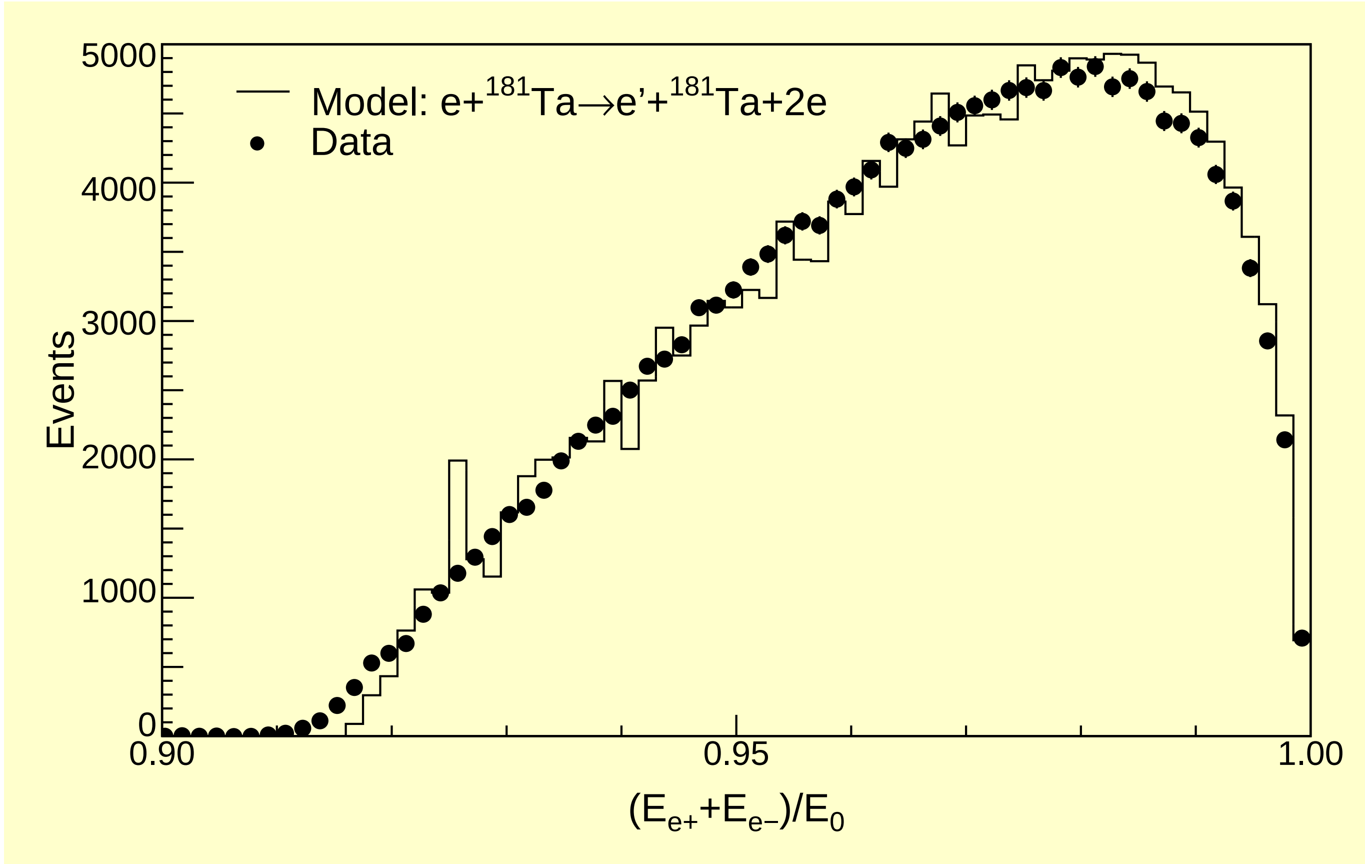


Simulation:



- Fraction of transferred energy $x = E_{\gamma'}/E_0$
- Weizsäcker-Williams approximation does *not* correspond to experiment
- Reason: neglected phase space of recoiling nucleus at $x = 1$
- $\Rightarrow$ Reaction identification!
- $\Rightarrow$ Kinematics of experiment was not (yet) optimal!

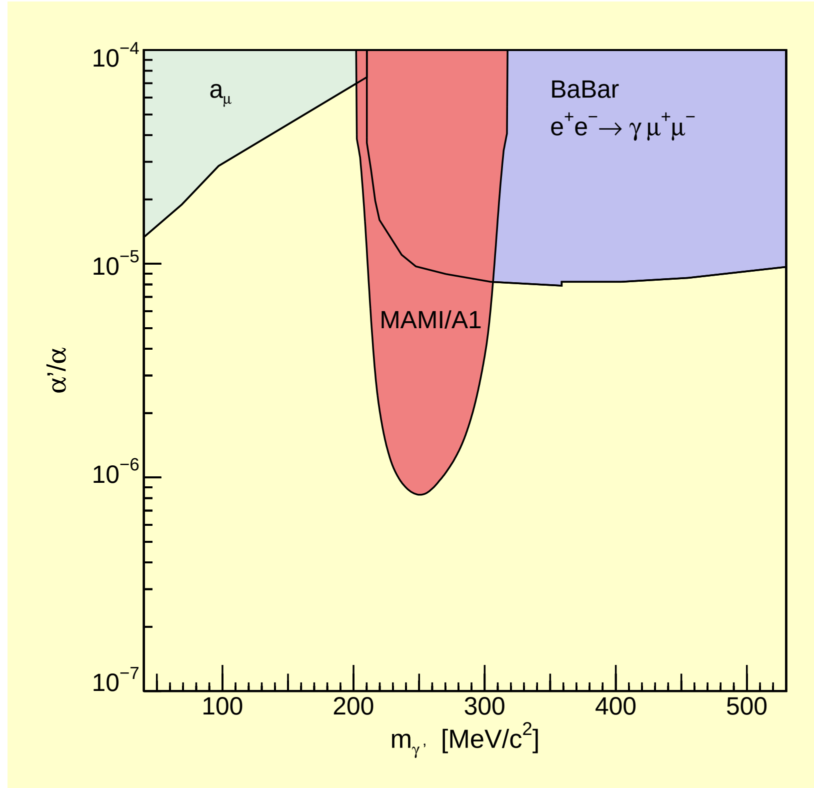
Improved Model



- Electroproduction instead of Photoproduction
- Coherent production off heavy nucleus
- Q.E.D., nuclear form factor, coherent sum of all contributions, radiation corrections, . . .

⇒ Describes data within a few percent

Exclusion limit for coupling ε



- Accidental background + Q.E.D. background
- Model deviates only on nuclear vertex, both for γ' and γ^*
- Conversion from ratio of cross sections:

$$\frac{d\sigma(X \to \gamma' Y \to l^+ l^- Y)}{d\sigma(X \to \gamma^* Y \to l^+ l^- Y)} = \left(\frac{3\pi\varepsilon^2}{2N_f \alpha}\right)\left(\frac{m_{\gamma'}}{\delta_m}\right)$$

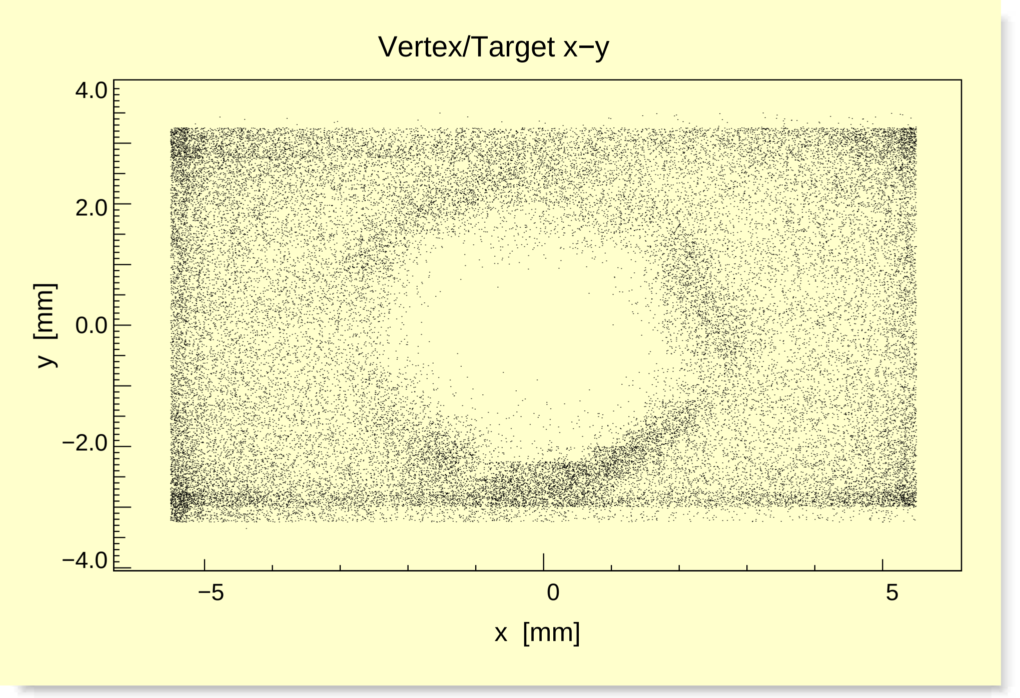
$\Rightarrow$ Exclusion limit from 4 days of beam time $\varepsilon < 10^{-3}$

H.M. *et al.*, arXiv:1101.4091, Phys. Rev. Lett. 106 (accepted)

Future Plans

Limitations of the experiment

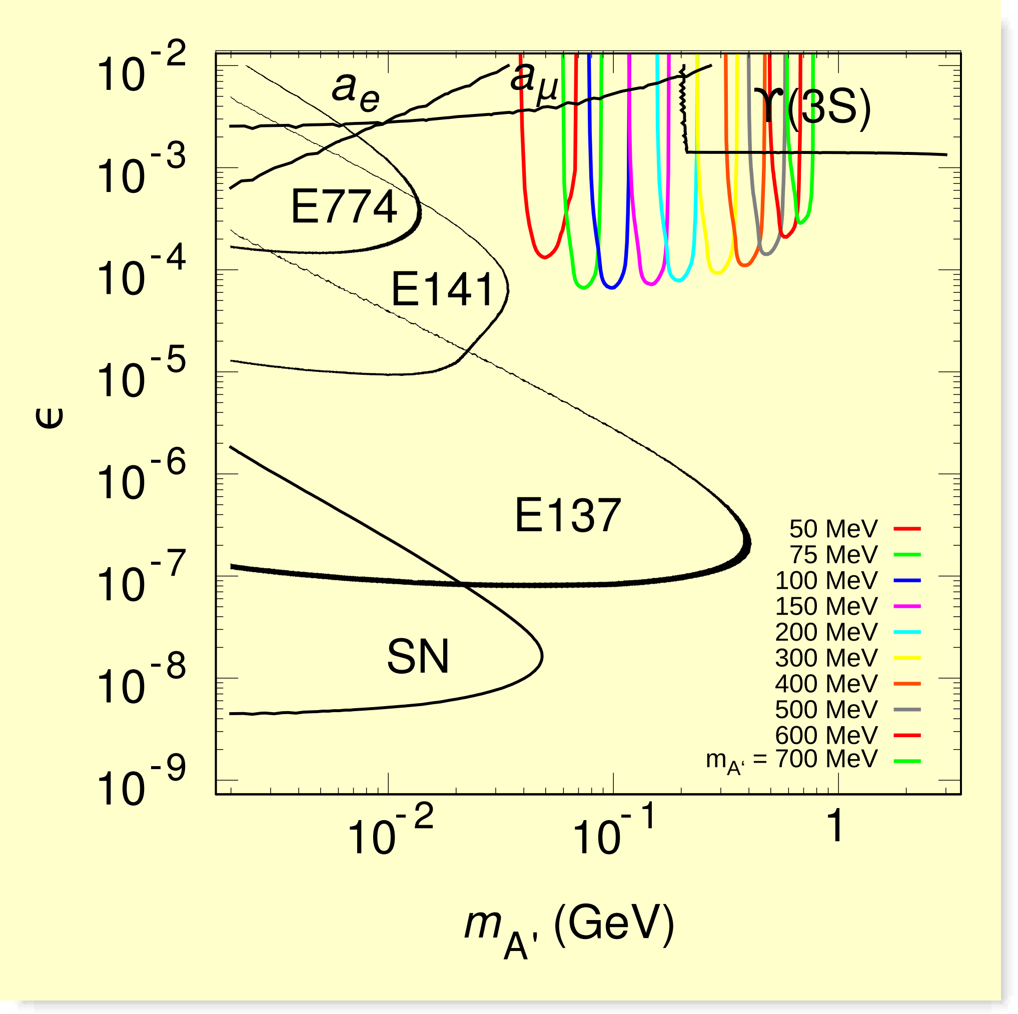
$100\,\mu A$ beam current for 20 min on 0.05 mm ^{181}Ta target (melting point: 3017 °C):



- Air activation
- Optimization of kinematics
- Target cooling
- Shielding

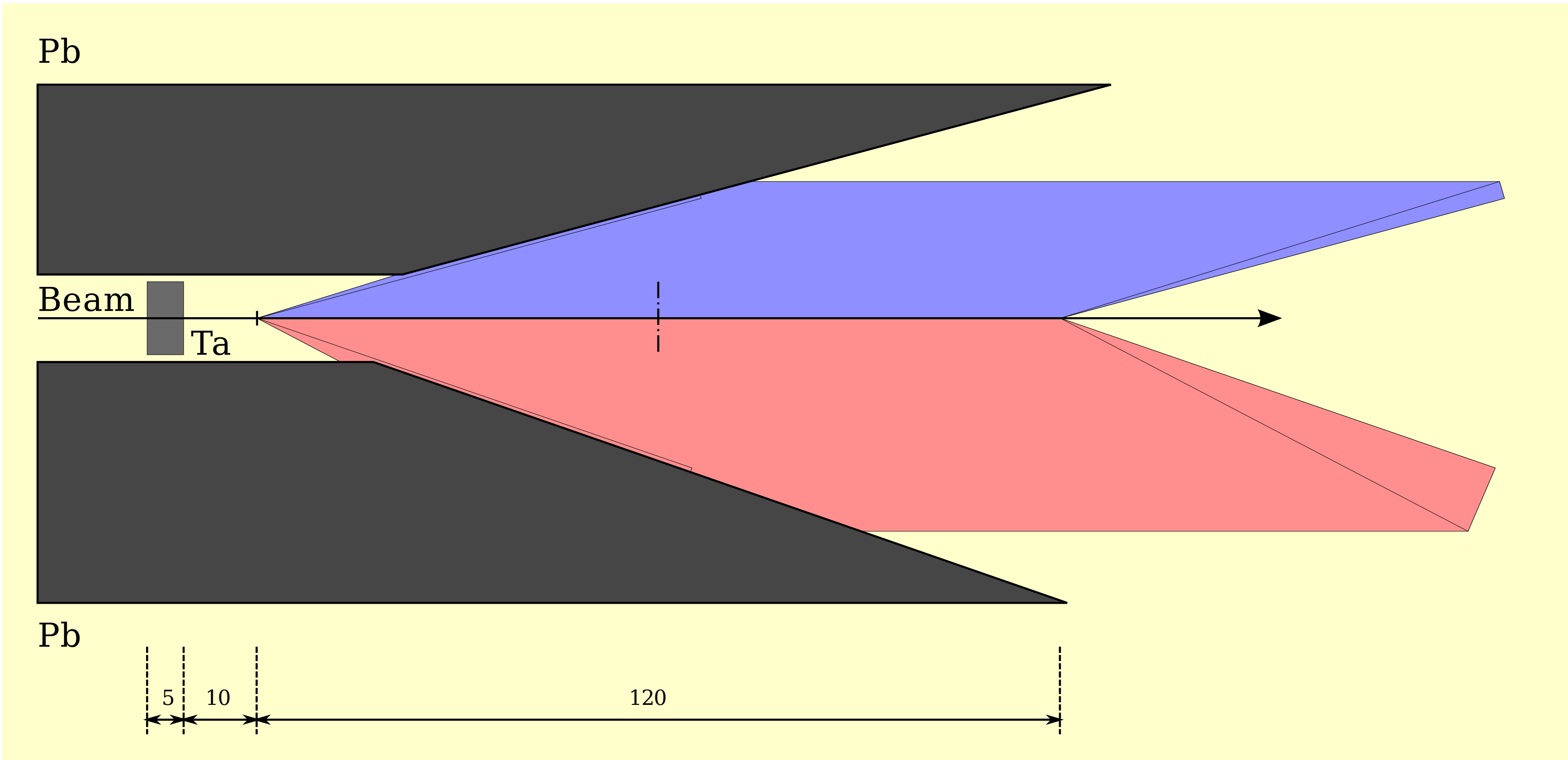
$\Rightarrow$ 1 order of magnitude higher count rates possible

Simulation: exclusion limits



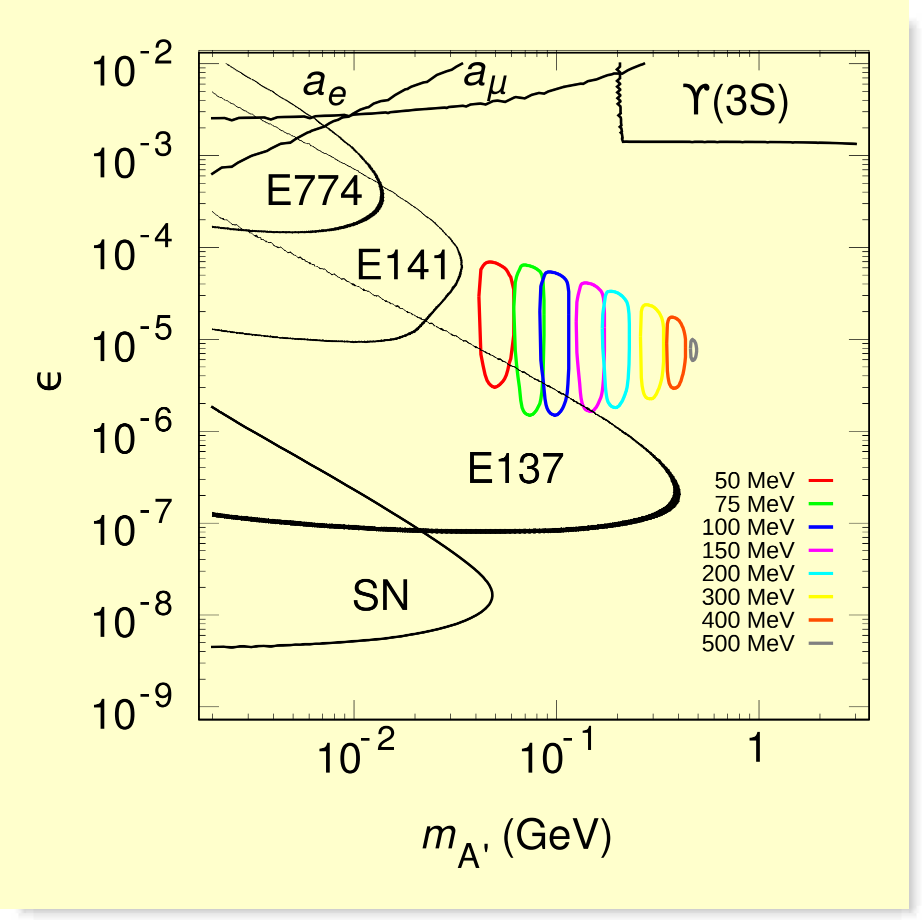
- Background now well understood
- Several settings, change of incident beam energy
- Marked regions: 2σ exclusion

Step 2: Secondary vertex → small coupling



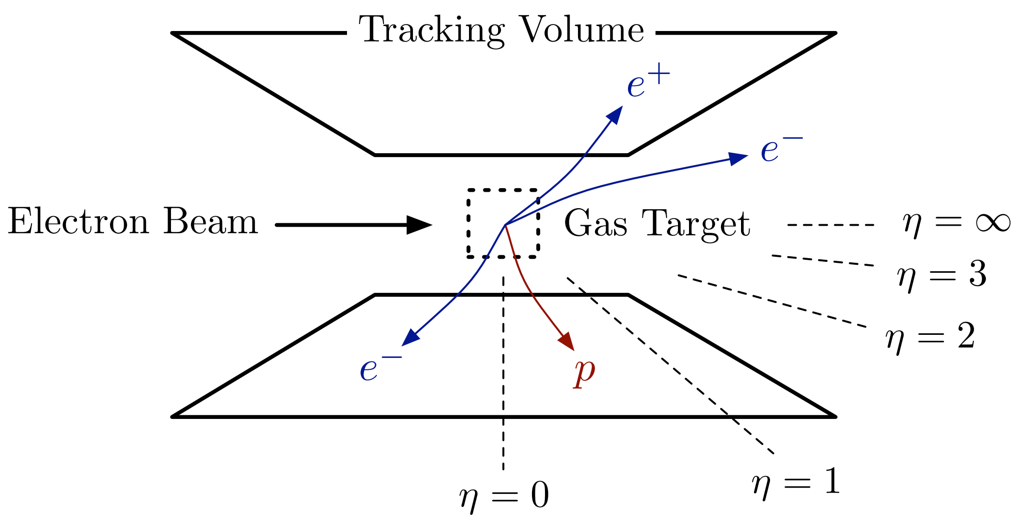
- Sensitive to decay length 10 mm – 130 mm
- $\Rightarrow \gamma c\tau =$4.35 mm – 1120 mm (10%-limit)
- $\Rightarrow \varepsilon = 10^{-6} - 10^{-5}$
- Target: 5 mm Ta $\Rightarrow L = 1.72 \cdot 10^{37} \frac{1}{\mathrm{s\,cm^2}}$ at 100 μA beam current
- Beam stabilization, shielding, target cooling

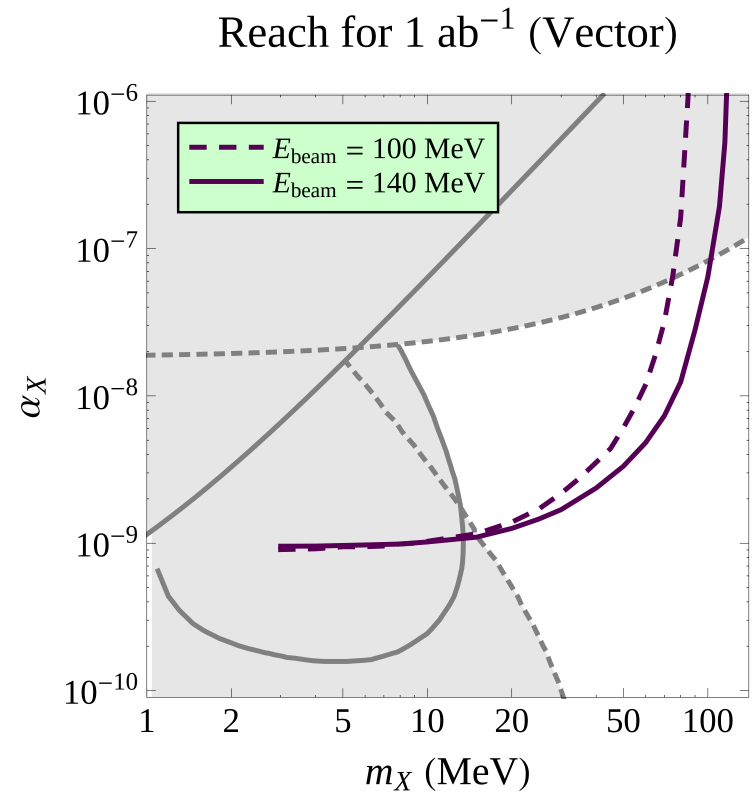
Step 2: Exclusion limits with shielded production vertex



- Macroscopic decay vertex distance $\varepsilon < 10^{-4}$
- Luminosity $\varepsilon > 10^{-6}$
- Coupling vs lifetime $m_{\gamma'} < 500\,\mathrm{MeV}/c^2$
- Angular range $m_{\gamma'} > 30\,\mathrm{MeV}/c^2$

Step 3: Access to low mass region

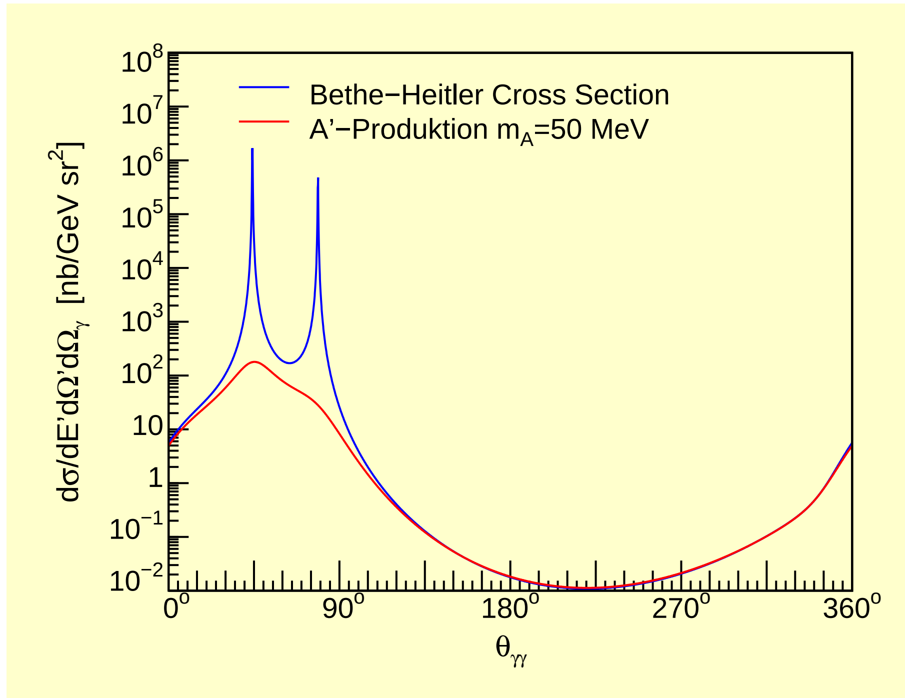




- Minimize multiple scattering by gas target
- Low energy – high current accelerator
- Needs 4π detector at 200 MHz count rate with high resolution
- DarkLight (JLab FEL), MESA at Mainz

M. Freytsis, G. Ovanesyan, J. Thaler, JHEP 01 (2010) 111

Alternative: Production off the proton $\rightarrow$ Missing mass



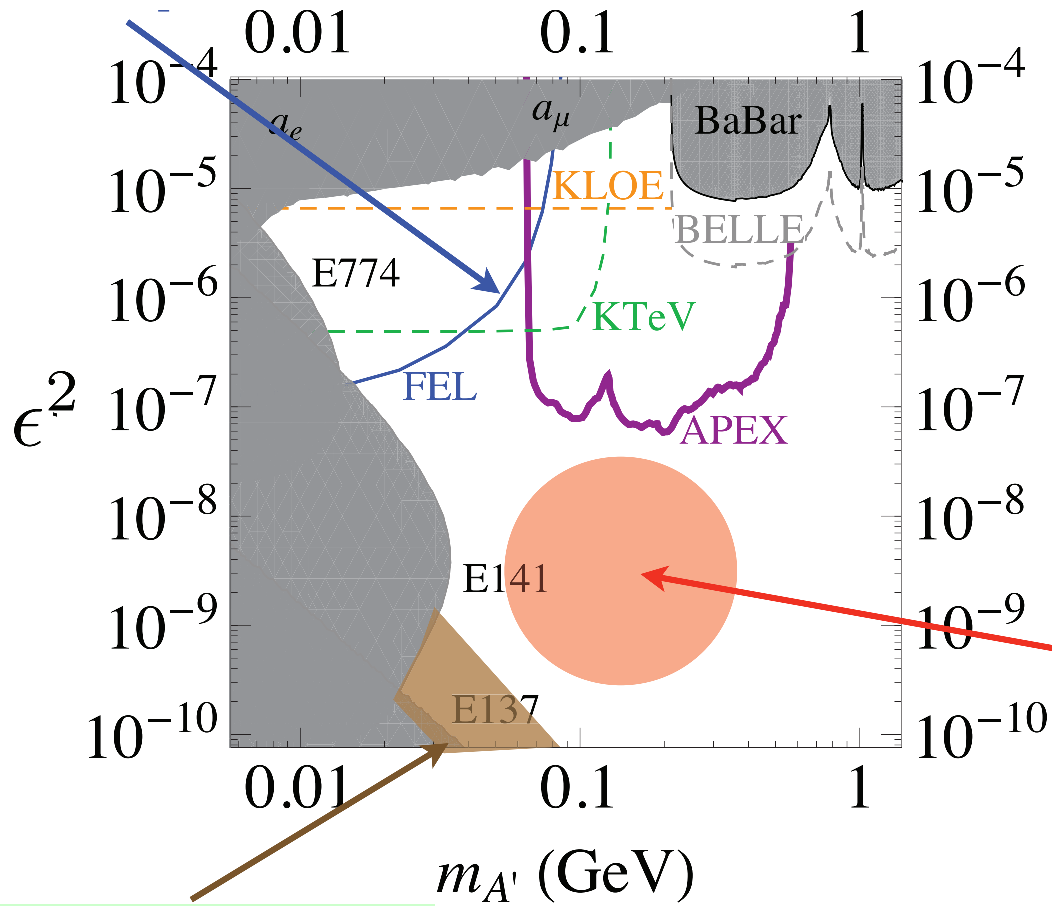
$$e + p \rightarrow e' + p + \gamma'$$
$$\hookrightarrow e^+ + e^-$$

- γ' detection via missing mass $\quad m^2_{\gamma'} = (e + p - e' - p')^2$
- No restriction by decay
- Background: virtual Compton scattering: $e + p \rightarrow e' + p + \gamma$ + radiative tail
- Vertex identification with high suppression factor $(10^8 \ldots 10^{10})$ necessary
- Detector development

Other projects

JLab Free Electron Laser
Freytsis et al. arXiv:0909.2862

KLOE, BELLE: Rare Meson Decays



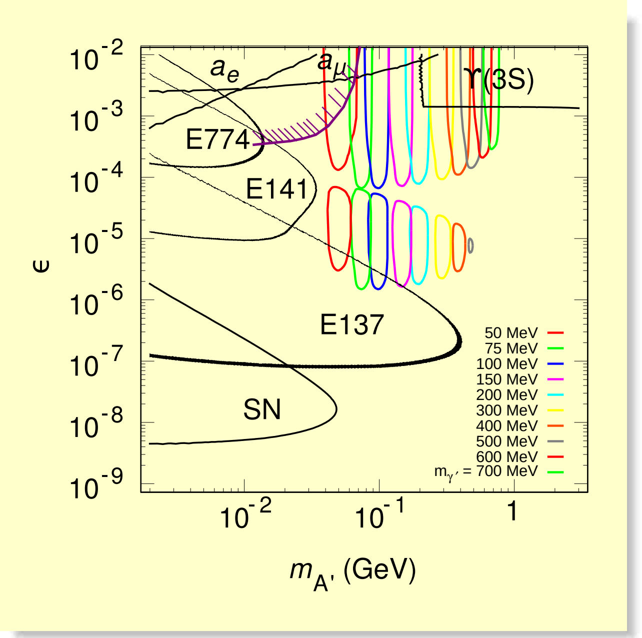
JLab Hall B

HIPS Proposal (Desy)
Beamdump

APEX: JLab Hall A

R. Essig *et al.* JHEP 02 (2011) 9

Summary



- Experimental Program:
  - Step 1: Pair production on heavy target $\varepsilon > 10^{-4}$
  - Step 2: Shielded production vertex $10^{-6} < \varepsilon < 10^{-4}$
  - Step 3: Production on LH_2, Micro-vertex detector $m_{\gamma'} < 40\,\mathrm{MeV}/c^2$
- Pilot experiment
  - Experiment is feasible, background is under control
  - Q.E.D. process well understood
  - First exclusion limit $10^{-3} \to 10^{-4}$ reachable

$\Rightarrow$ Determination of significant exclusion limits for the γ' boson is possible at MAMI/A1

Backup Slides . . .

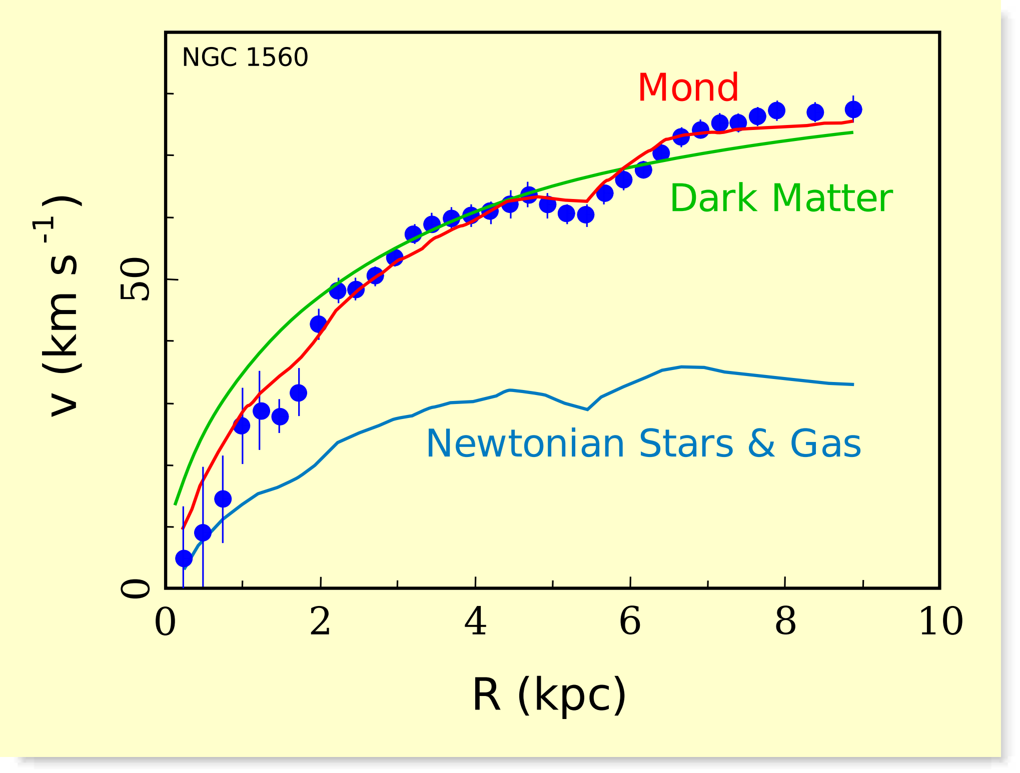
MOND-Hypothesis

MOND modification of Newtonian acceleration g_n (M. Milgrom, 1983):

$$g\,\mu\left(\frac{|g|}{a_0}\right) = g_n$$

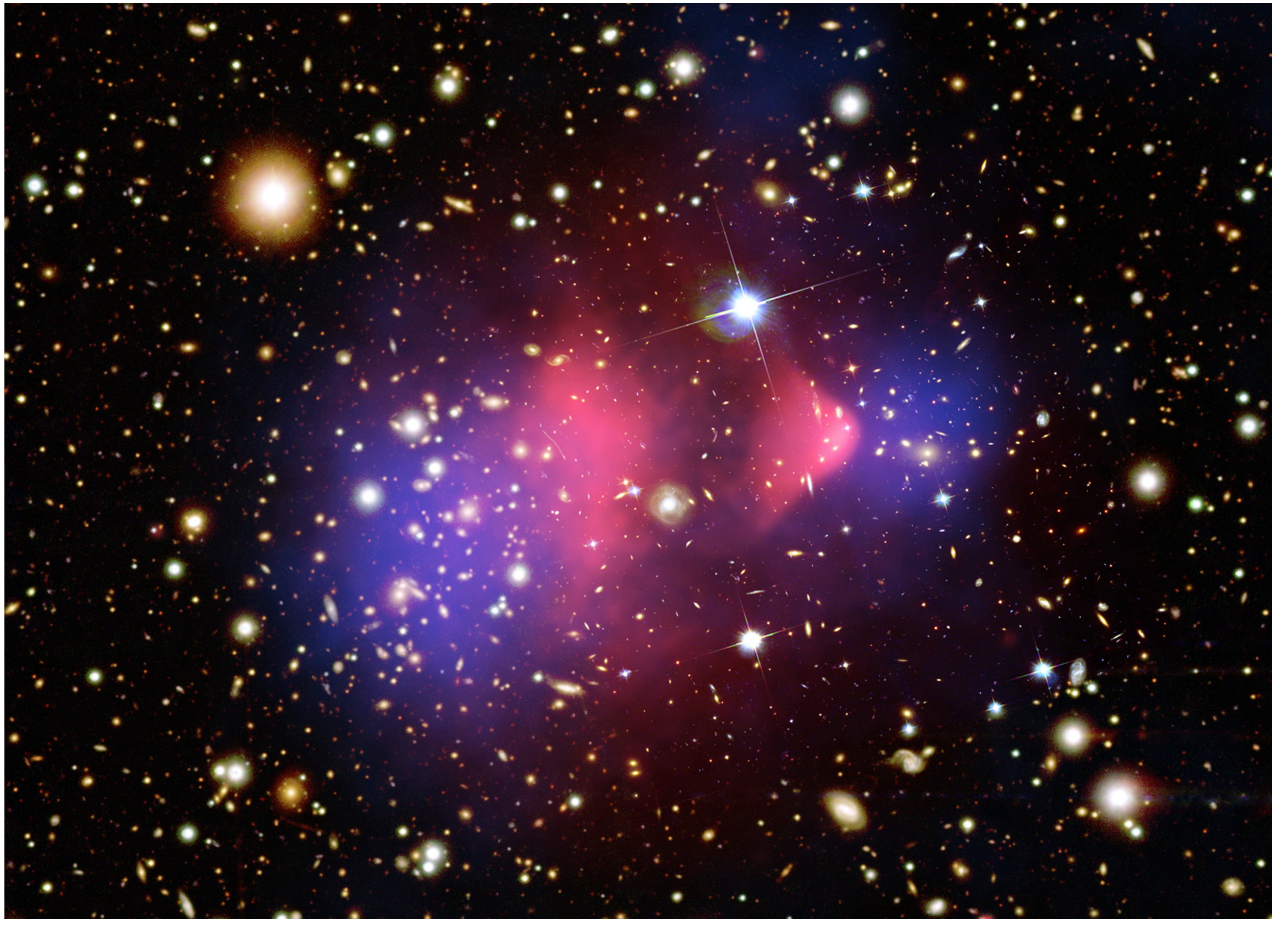
Function $\mu(x)$ with limits

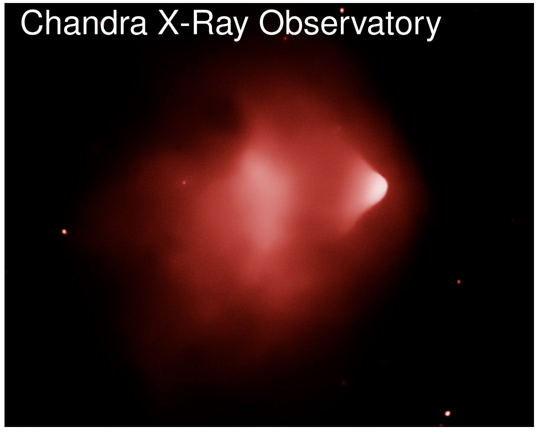
$$\begin{aligned} \mu(x) &= x \quad \text{for} \quad x \ll 1 \\ \mu(x) &= 1 \quad \text{for} \quad x \gg 1 \end{aligned}$$

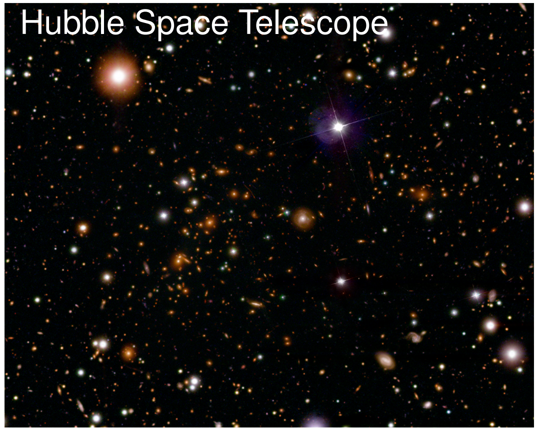


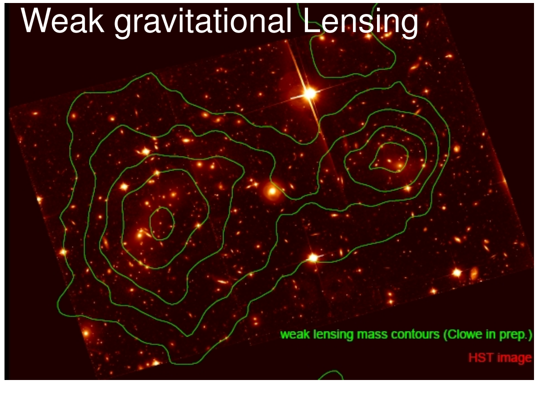
K. G. Begeman, A. H. Broeils, R. H. Sanders, MNRAS 249 (1991) 523

Galaxy Cluster 1E 0657-56 “Bullet-Cluster”







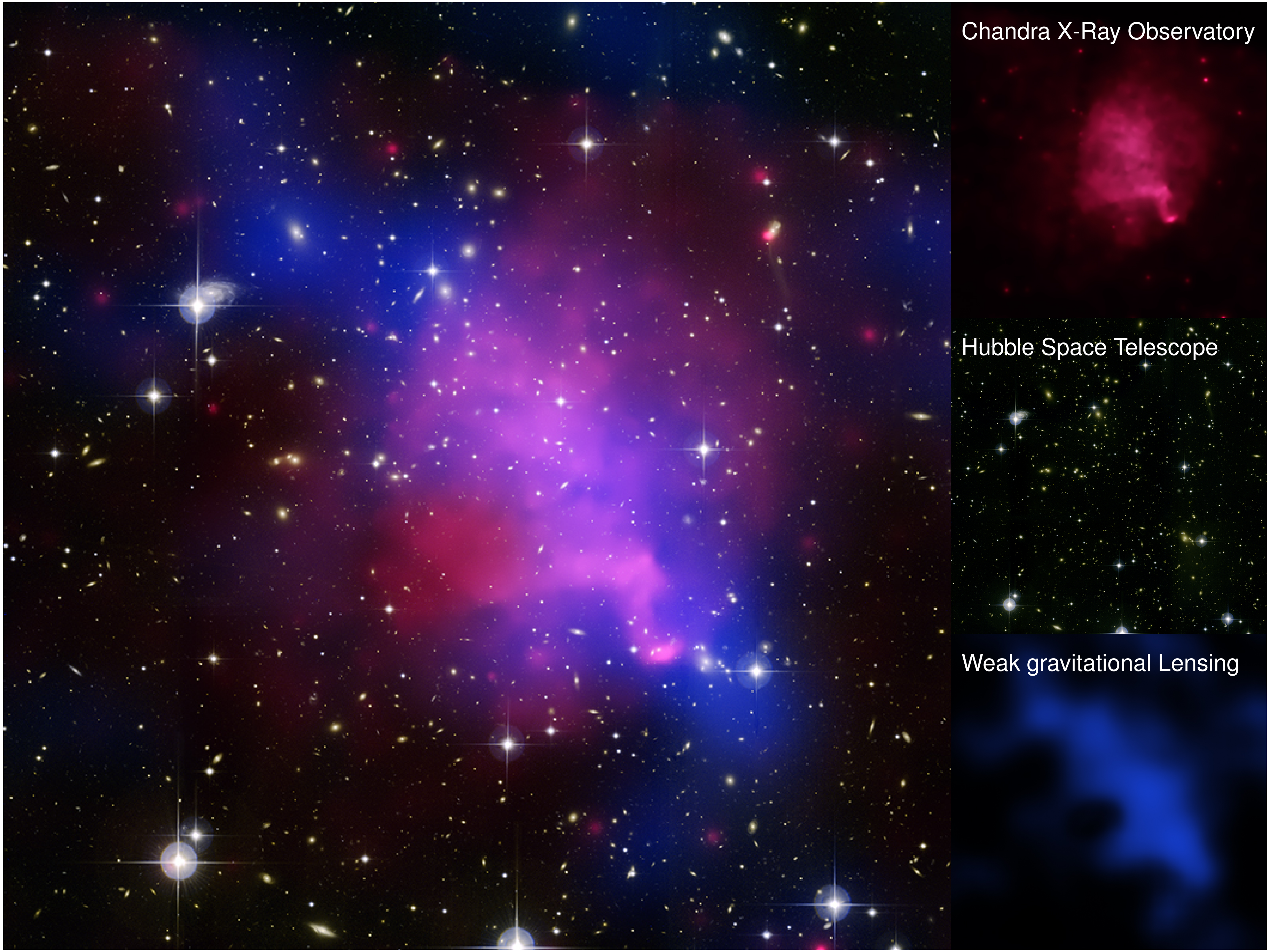


- Visible Light: Stars (no collision)
- X-Rays: Intergalactic gas (Collision, e.m. shock waves)
- Gravitational Lens: Mass distribution (no collision)

$\Rightarrow$ Baryonic mass lags behind total mass

D. Clowe *et al.*, Ap. J. 648 (2006) L109

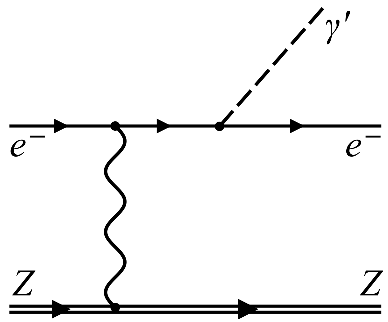
Abell 520 – Counter example to bullet cluster (?)

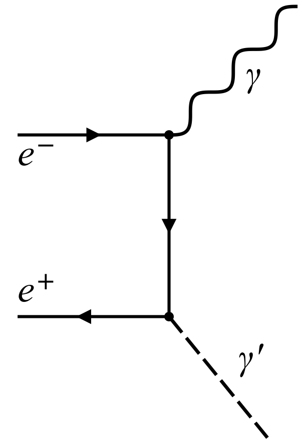


A. Mahdavi et al., Astrophys. J. 668, 806Y814 (2007)

Fixed target or collider?

Cross Section

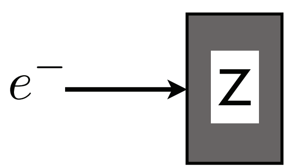


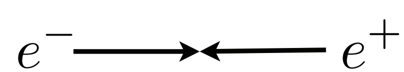


$$\sigma \propto \frac{\alpha^3 \varepsilon^2 Z^2}{m_{\gamma'}^2} \sim 1\,\mathrm{pb}$$

$$\sigma \propto \frac{\alpha^2 \varepsilon^2}{E_{cm}^2} \sim 1\,\mathrm{fb}$$

Luminosity



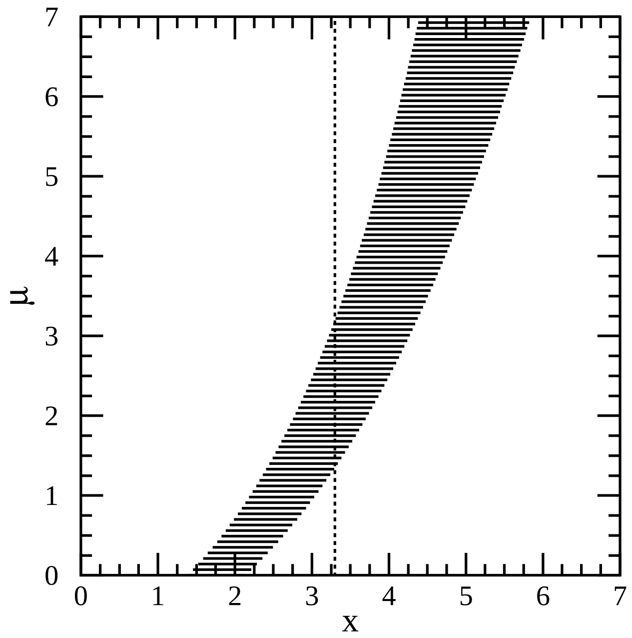


$\sim$ few $ab^{-1}/10\,\mathrm{days}$

$\sim$ few $ab^{-1}/100\,\mathrm{years}$

Feldman-Cousins-Algorithm

Example: $\mu = 0.5$, $b = 3$



n	$P(n\|\mu)$	μ_{best}	$P(n\|\mu_{\text{best}})$	R	rank	U.L.	central
0	0.030	0.	0.050	0.607	6		
1	0.106	0.	0.149	0.708	5	√	√
2	0.185	0.	0.224	0.826	3	√	√
3	0.216	0.	0.224	0.963	2	√	√
4	0.189	1.	0.195	0.966	1	√	√
5	0.132	2.	0.175	0.753	4	√	√
6	0.077	3.	0.161	0.480	7	√	√
7	0.039	4.	0.149	0.259		√	√
8	0.017	5.	0.140	0.121		√	
9	0.007	6.	0.132	0.050		√	
10	0.002	7.	0.125	0.018		√	
11	0.001	8.	0.119	0.006		√	

- n-Values sorted by $R = P(n|\mu)/P(n|\mu_{\text{best}})$ with $\mu_{\text{best}} = \max(0, n-b)$.
- Add to interval by order until confidence limit (e.g. $\alpha = 95\%$) is reached.
- Determine vertical interval for measured $x = n$.