Age of Endarkenment?

Youngjoon Kwon
Physics, Yonsei Univ.

Nov. 20, 2009 KISTI eScience Workshop

Symphony of Dark Forces

I. Allegro ma non troppo

- What is dark matter? What do we know about it?

II. Scherzo

- WIMP dark matter -- are we sure about it?

III. Andante maestoso

- astrophysical anomalies -- need for new models?
- a new theory and new proposals

IV. Allegro con brio; coda

- searching for the "dark sector" with the most luminous collider

*Age of en**dark**enment?*

> **dark** |därk|
> adjective
> **1** with little or no light *: it's too dark to see much.*
> • hidden from knowledge; mysterious *: a dark secret.*
> • archaic ignorant; unenlightened *: he is dark on certain points of scripture.*
> • (of a theater) closed; not in use *: on Tuesdays he'd wait tables because the theater was dark.*
> **2** (of a color or object) not reflecting much light; approaching black in

- dark matter
- dark energy
- dark force
- dark sector
- dark ... anything else?

MHP

Dark Matter

2.64 Pounds

[view all MHP products]

- Increases Protein Synthesis by 600%
- Absorbs Faster Than Whey

Your Price $37.99

MSRP ~~$ 59.99~~

Select Flavor: Blue Raspberry

Qty: 1 Add to Cart

.:FEATURES

Write a Review

Read Reviews

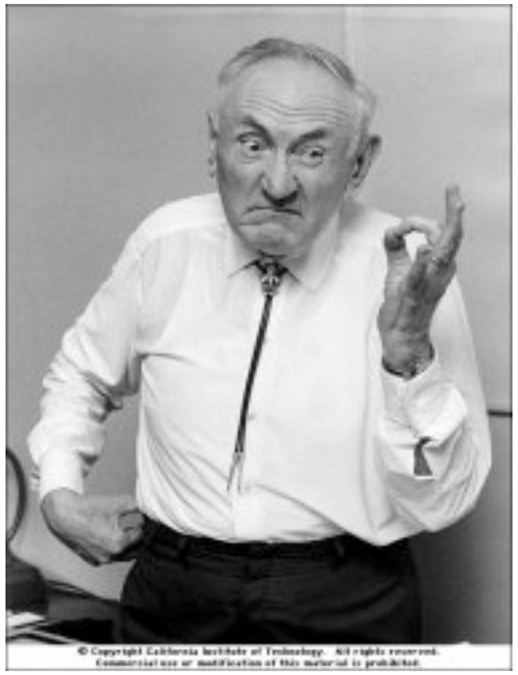
Current Reviews: 0

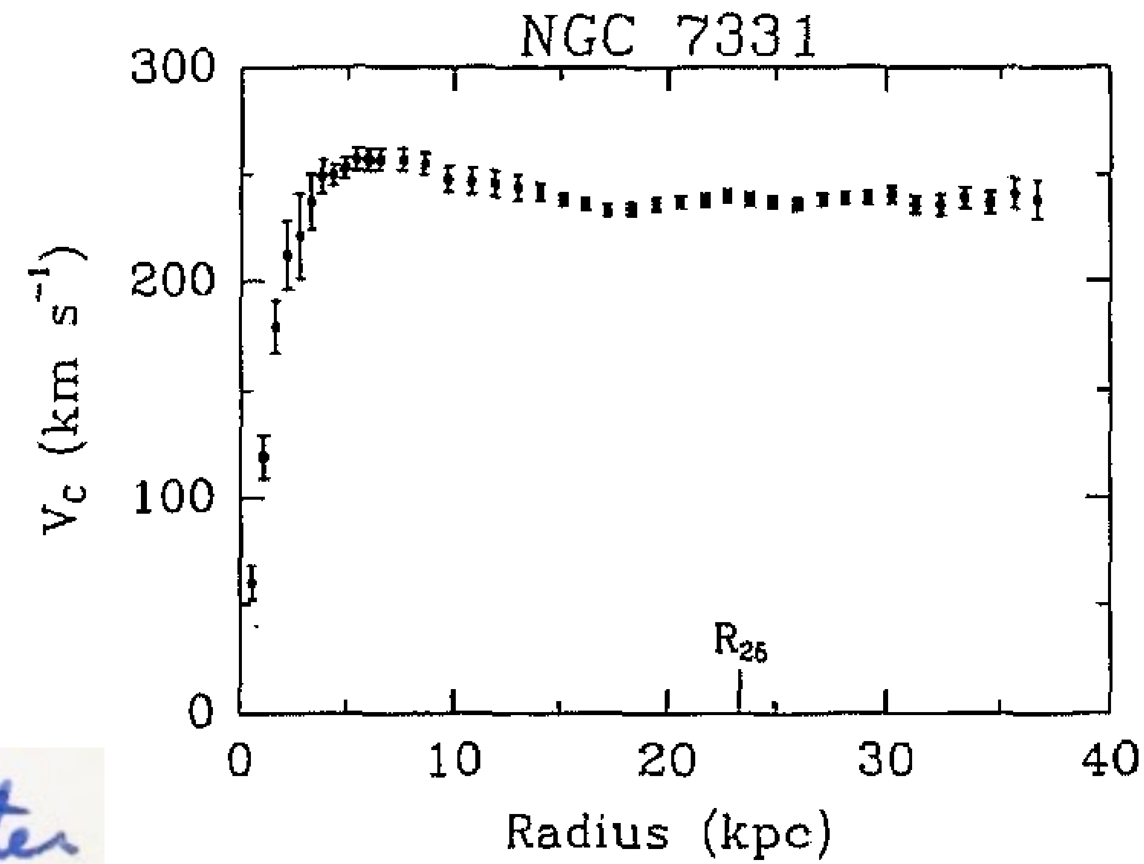
DARK MATTER takes a quantum leap forward into a new dimension of post-workout muscle growth called the ANABOLIC AXIS. The Anabolic Axis is the time and point at which insulin levels simultaneously peak with amino acids, creatine and glycogen transport into muscle tissue during the critical 1 hour period immediately after your workout. Dark Matter is the first and only supplement to employ a new technology called Precision Nutrient Infusion, which allows for this synergistic anabolic reaction to occur at the Anabolic Axis. In order to achieve this major breakthrough, MHP scientists bio-engineered new compounds and a revolutionary High Velocity Nano-Physics Technology. These new developments have rendered all post-workout creatines, whey protein/high carbohydrate combos and all other post-workout formulas inferior and outdated. DARK MATTER blasts open the critical "Anabolic Window" faster, wider and longer allowing you to enter the ANABOLIC AXIS for the most powerful anabolic reaction ever experienced!

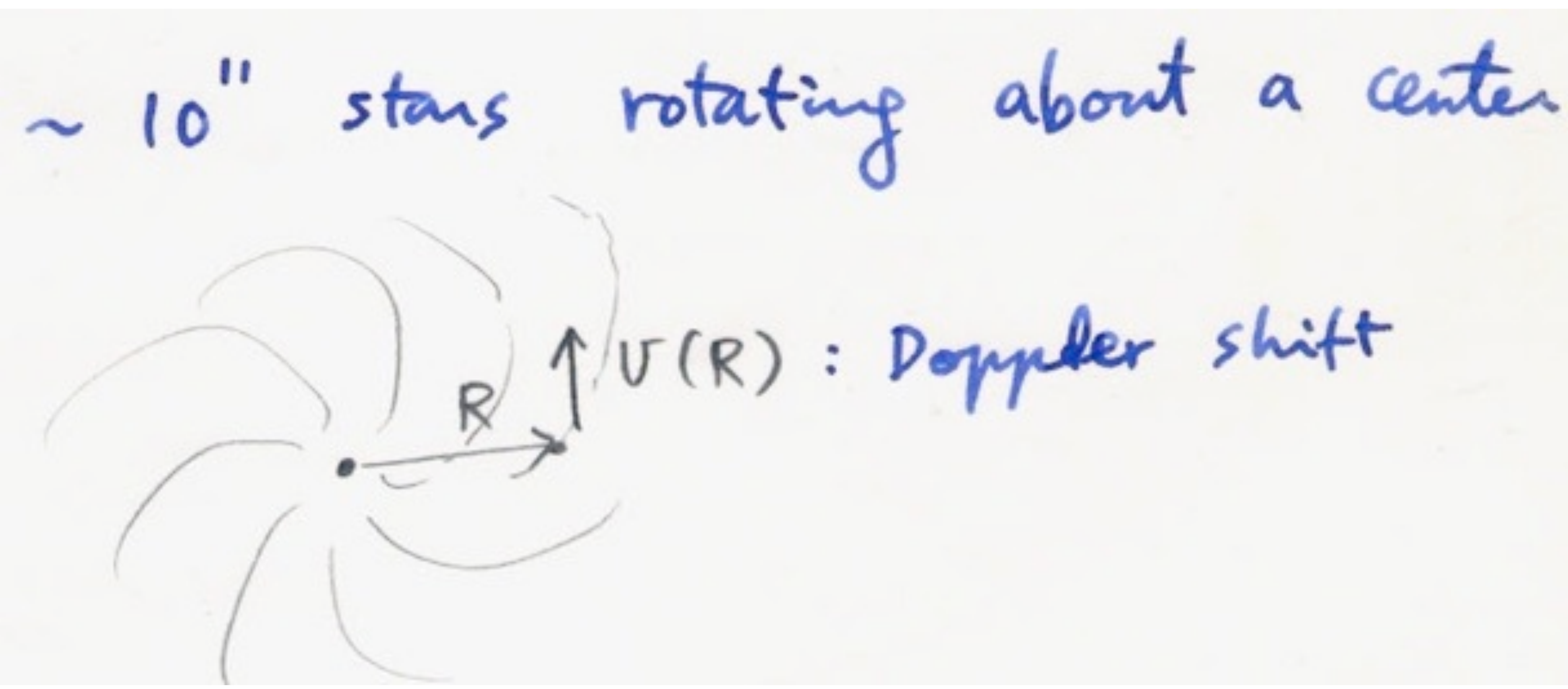
I. Allegro ma non troppo

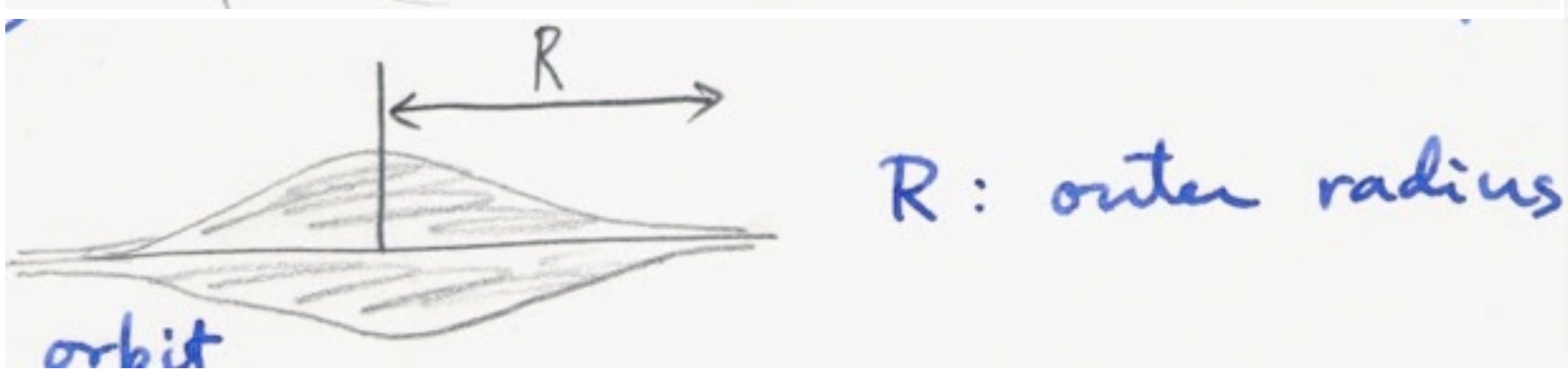
What is dark matter?
What do we know about it?

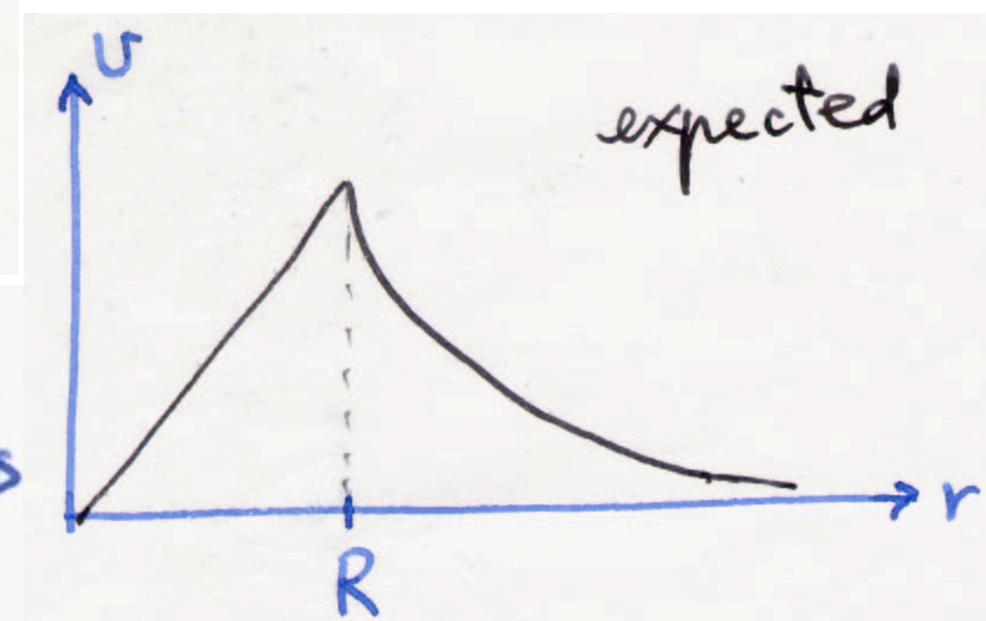
"There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy."
-- W. Shakespeare



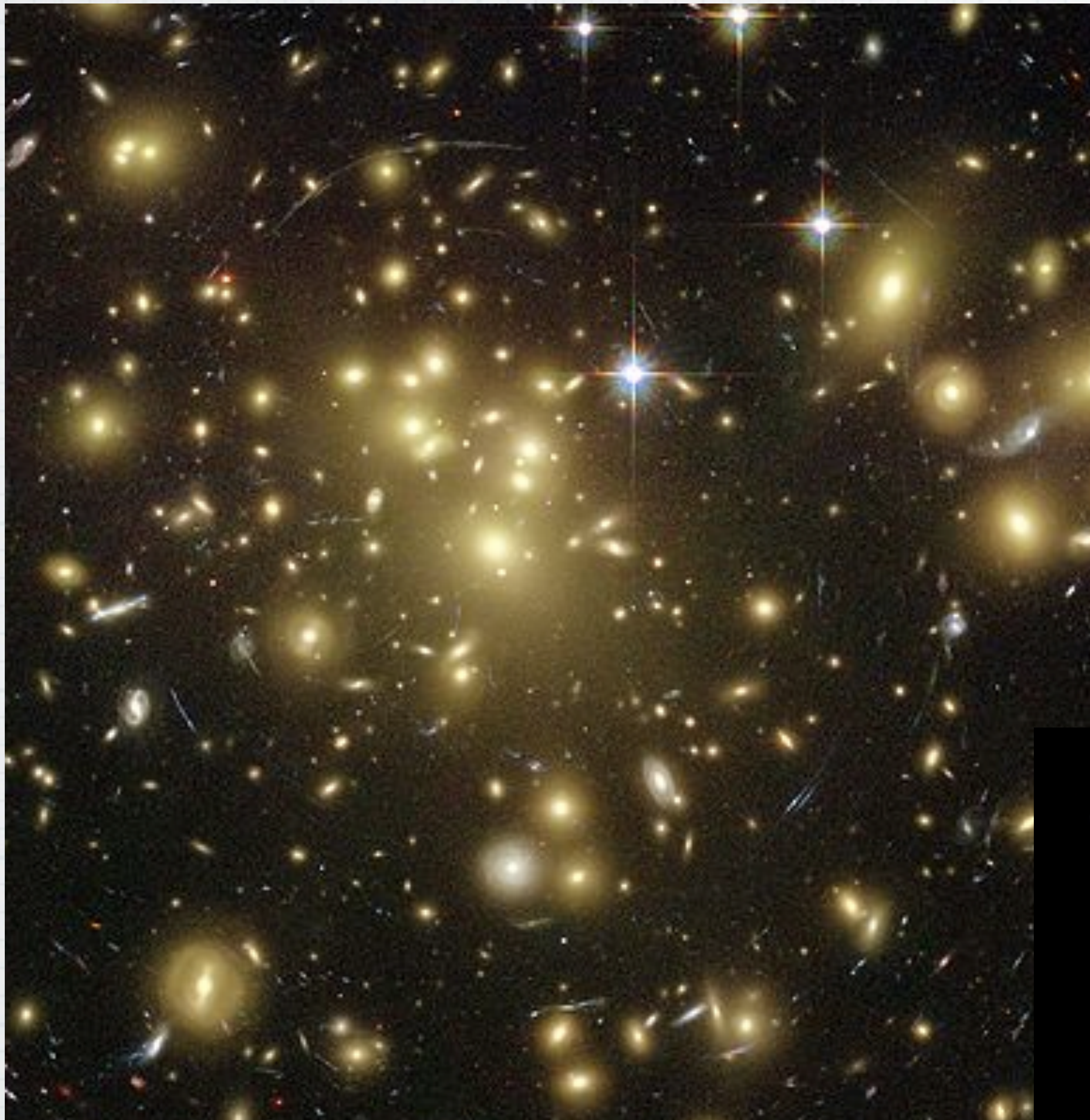

NGC 7331
V_c (km s^{-1})
Radius (kpc)
R_{25}
300
200
100
0
0
10
20
30
40


~ 10'' stars rotating about a center
R
v(R) : Doppler shift

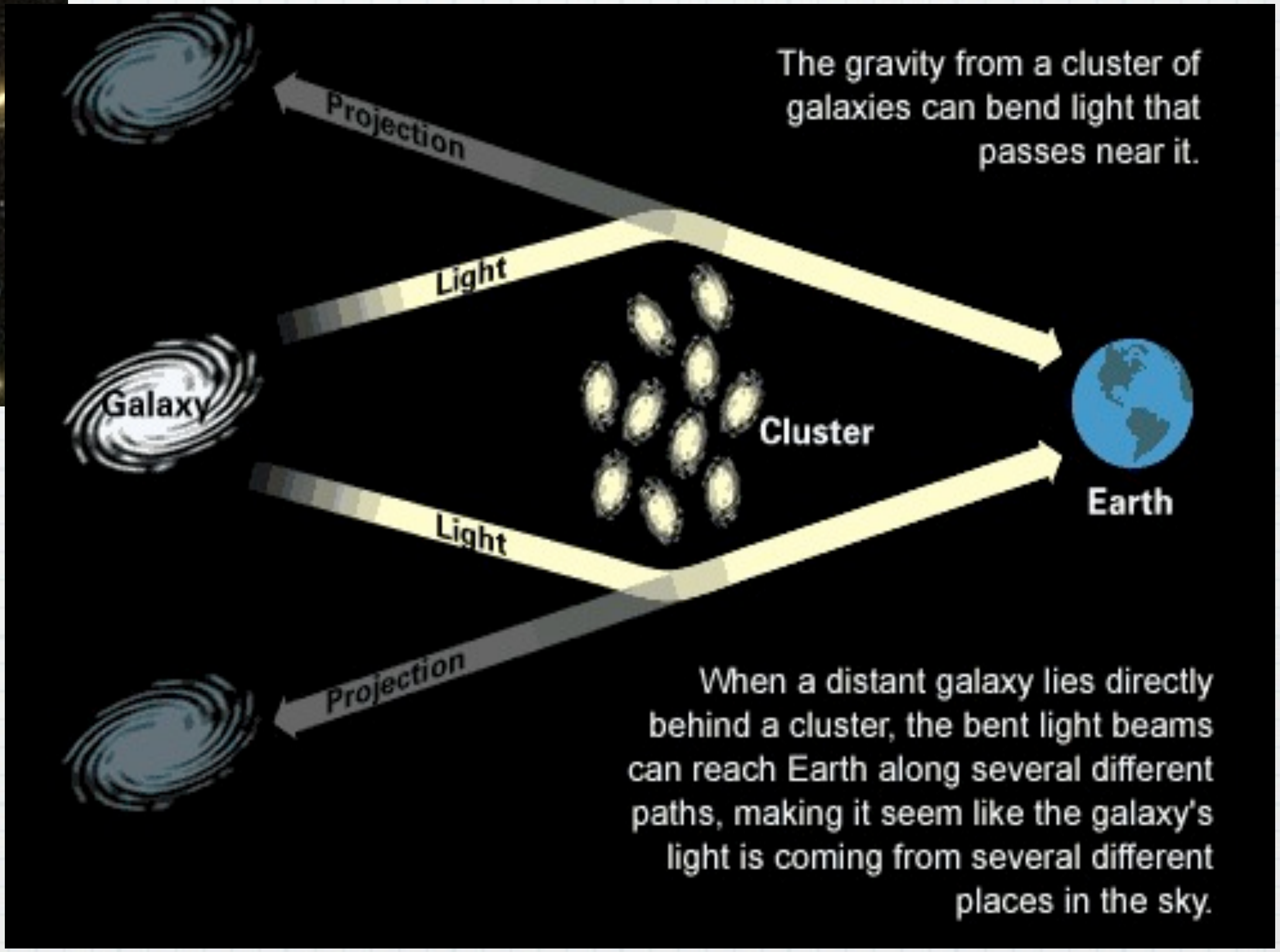

R
R : outer radius
orbit


v
expected
R
r

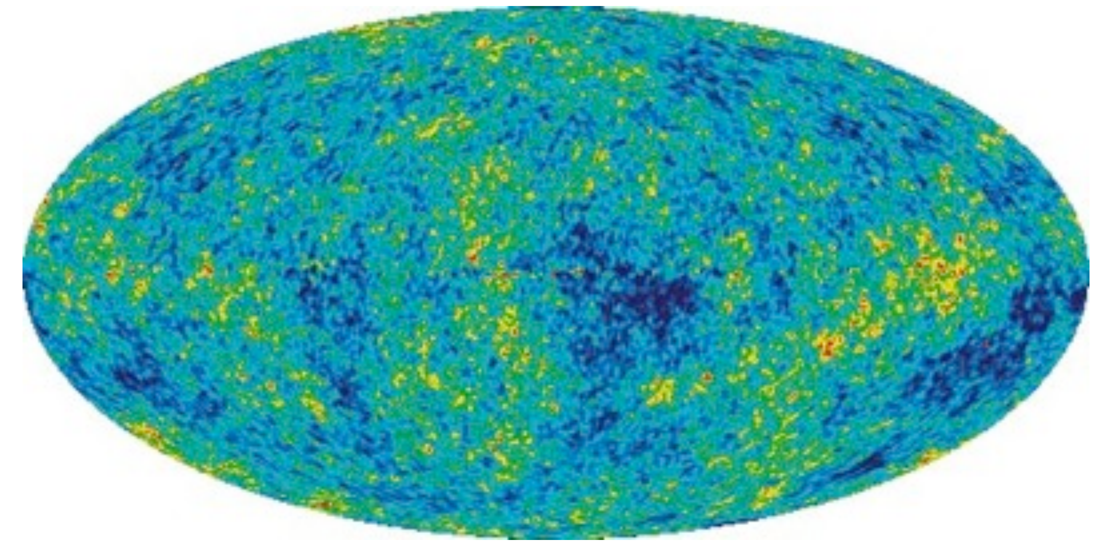
Gravitational Lensing

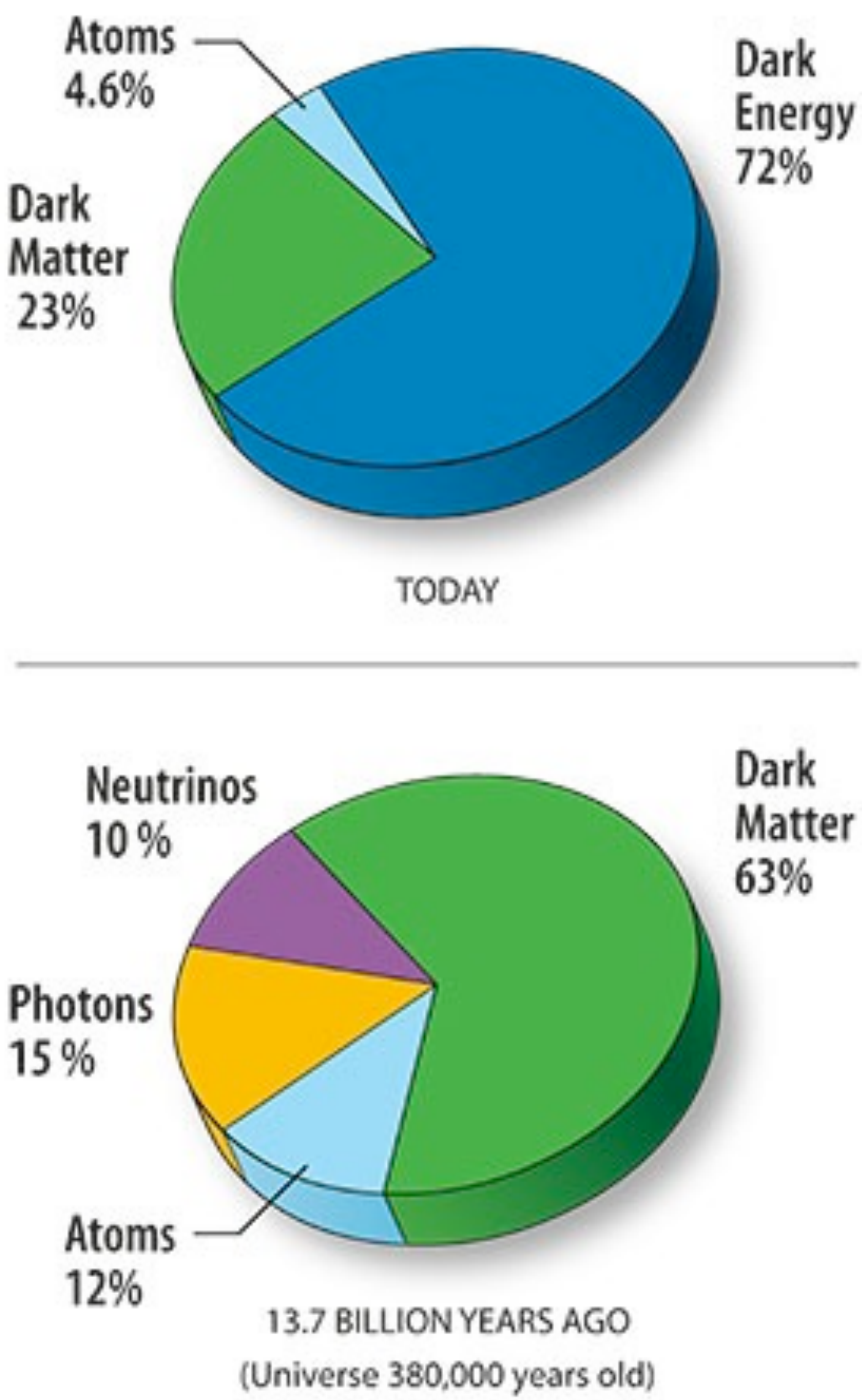


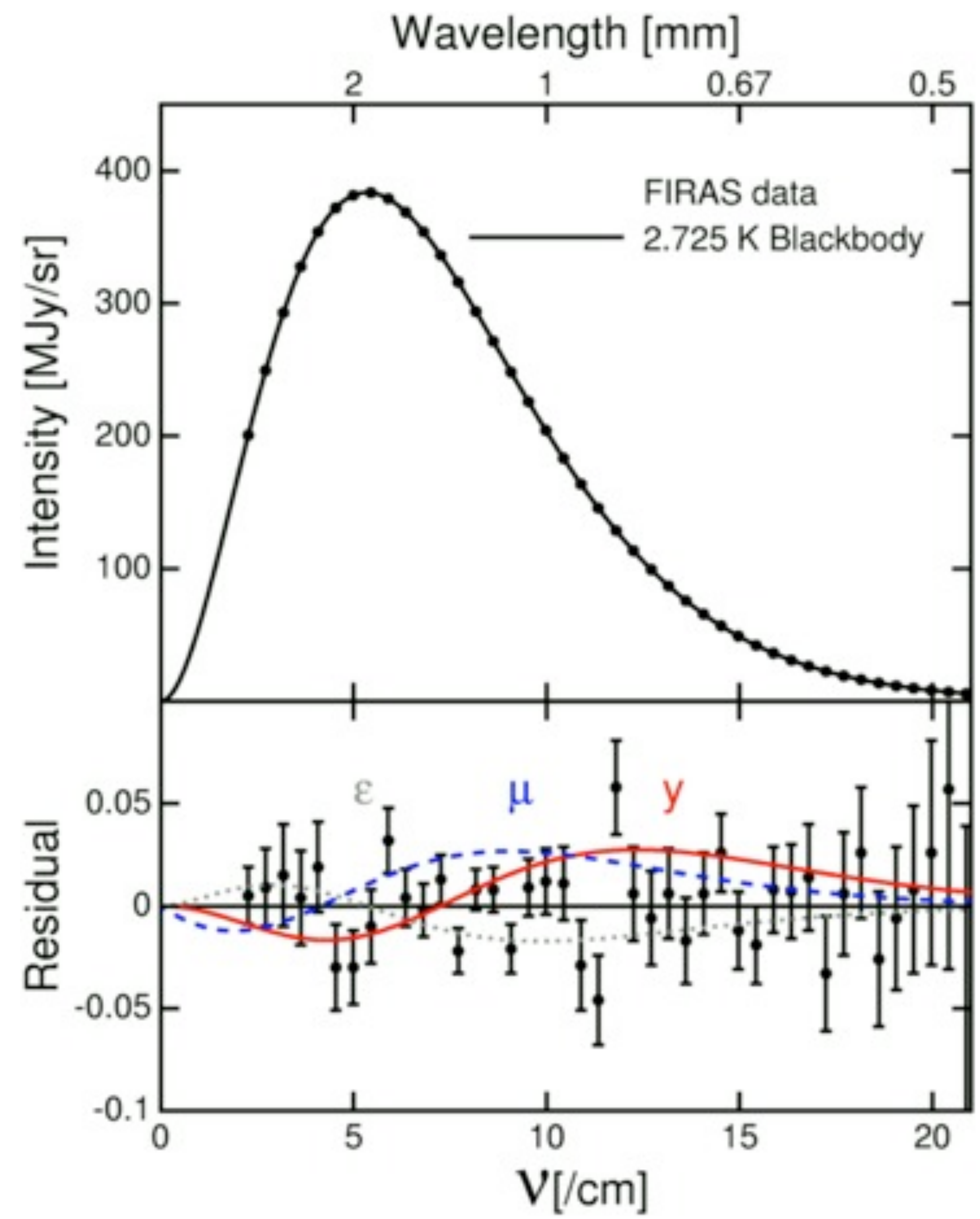
Hubble telescope image of a cluster of galaxies




WMAP
Wilkinson Microwave Anisotropy Probe




Atoms
4.6%
Dark
Energy
72%
Dark
Matter
23%
TODAY
Neutrinos
10 %
Dark
Matter
63%
Photons
15 %
Atoms
12%
13.7 BILLION YEARS AGO
(Universe 380,000 years old)


Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
Intensity [MJy/sr]
FIRAS data
2.725 K Blackbody
Residual
0.05
0
-0.05
-0.1
ε
μ
y
0
5
10
15
20
ν[/cm]

What do we know about DM?

Dark matter must exist!

- but we know not much more ...TT

The questions are:

- What is it (they)?
- How to find it (them)?

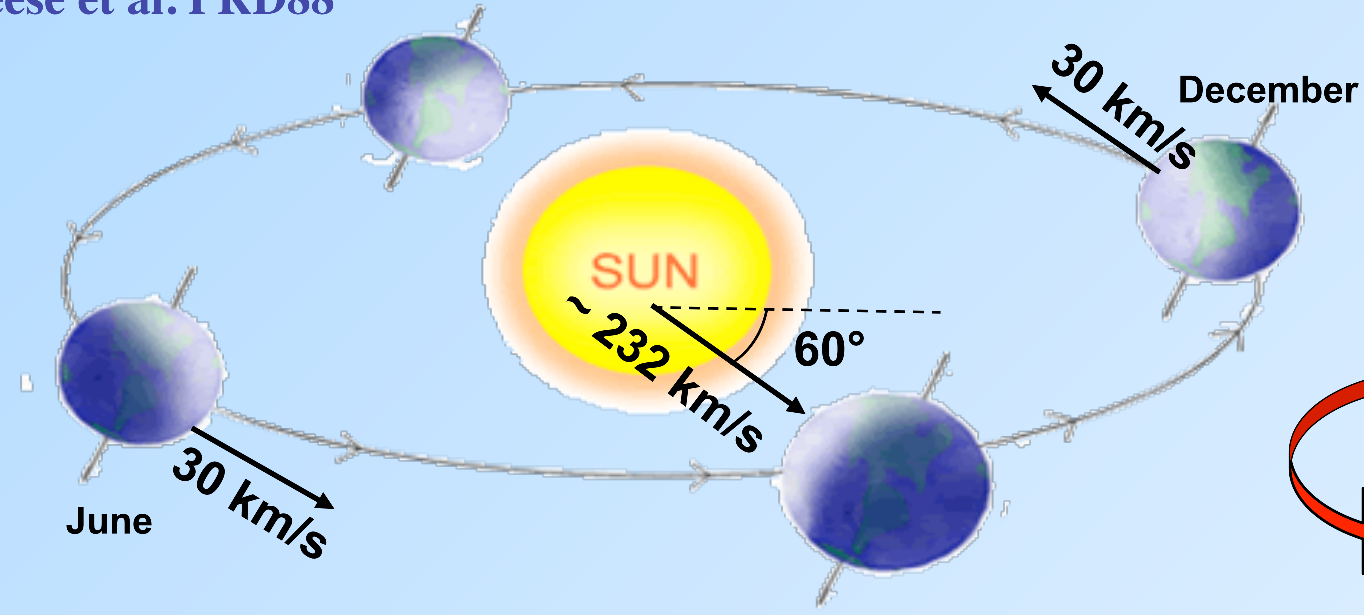
Experiments on dark matter search

- direct search (e.g. KIMS)
- indirect search (astro.)
- collider search

The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small **a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.**

Drukier, Freese, Spergel PRD86
Freese et al. PRD88



- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ T = 1 year
- t_0 = 2nd June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) For single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

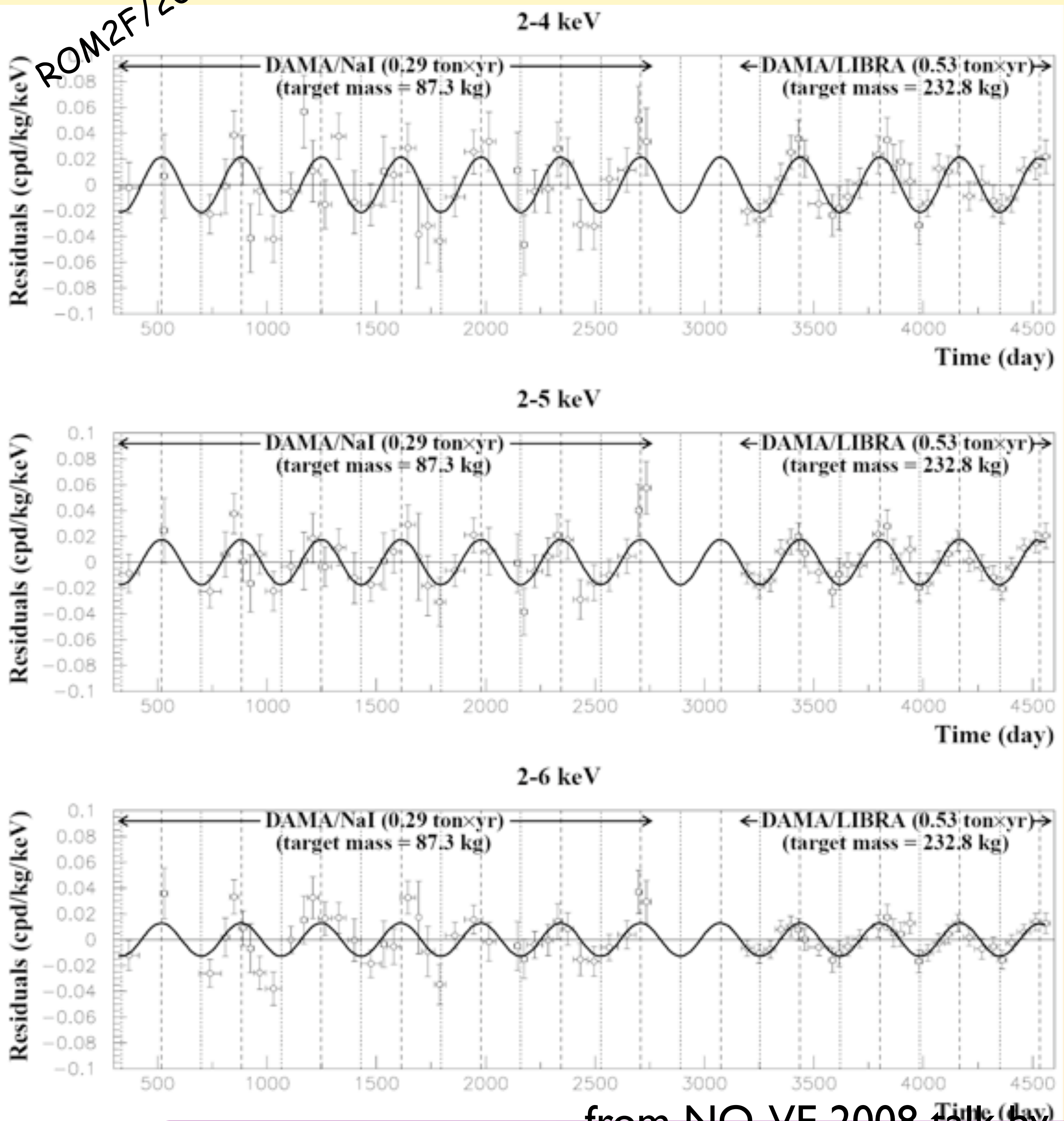
from NO-VE 2008 talk by R. Bernabei (DAMA)

Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (4 years) Total exposure: 300555 kg×day = 0.82 ton×yr

ROM2F/2008/07

experimental single-hit residuals rate vs time and energy



$A\cos[\omega(t-t_0)]$; continuous lines: t_0 = 152.5 d, T = 1.00 y

2-4 keV

A=(0.0215±0.0026) cpd/kg/keV

χ^2/dof = 51.9/66 **8.3 σ C.L.**

Absence of modulation? No

χ^2/dof=117.7/67 ⇒ P(A=0) = 1.3×10^{-4}

2-5 keV

A=(0.0176±0.0020) cpd/kg/keV

χ^2/dof = 39.6/66 **8.8 σ C.L.**

Absence of modulation? No

χ^2/dof=116.1/67 ⇒ P(A=0) = 1.9×10^{-4}

2-6 keV

A=(0.0129±0.0016) cpd/kg/keV

χ^2/dof = 54.3/66 **8.2 σ C.L.**

Absence of modulation? No

χ^2/dof=116.4/67 ⇒ P(A=0) = 1.8×10^{-4}

from NO-VE 2008 talk by R. Bernabei (DAMA)

The data favor the presence of a modulated behavior with proper features at 8.2σ C.L.

Yangyang Underground Laboratory

from SUSY08 talk by S. Myung (KIMS)

Limits on Interactions between Weakly Interacting Massive Particles and Nucleons Obtained with CsI(Tl) Crystal Detectors

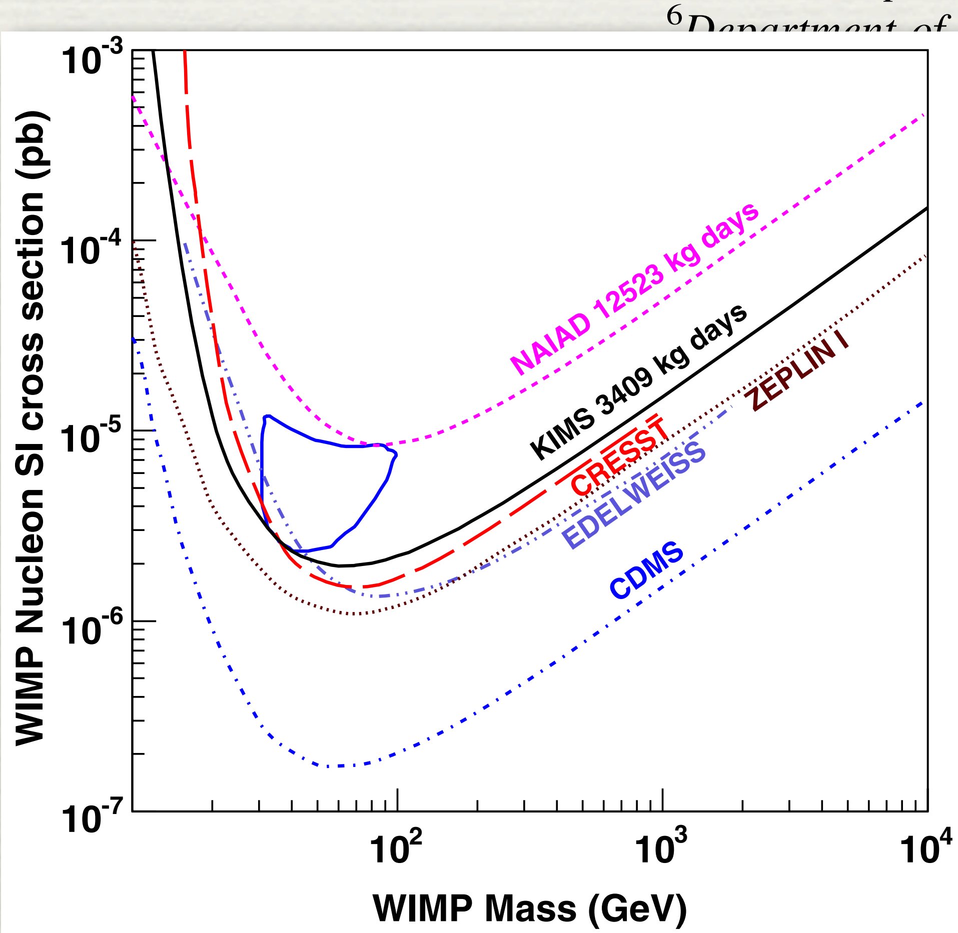
H. S. Lee,[1] H. C. Bhang,[1] J. H. Choi,[1] H. Dao,[6] I. S. Hahn,[4] M. J. Hwang,[5] S. W. Jung,[2] W. G. Kang,[3] D. W. Kim,[1] H. J. Kim,[2] S. C. Kim,[1] S. K. Kim,[1,*] Y. D. Kim,[3] J. W. Kwak,[1,†] Y. J. Kwon,[5] J. Lee,[1,‡] J. H. Lee,[1] J. I. Lee,[3] M. J. Lee,[1] S. J. Lee,[1] J. Li,[6] X. Li,[6] Y. J. Li,[6] S. S. Myung,[1] S. Ryu,[1] J. H. So,[2] Q. Yue,[6] and J. J. Zhu[6]

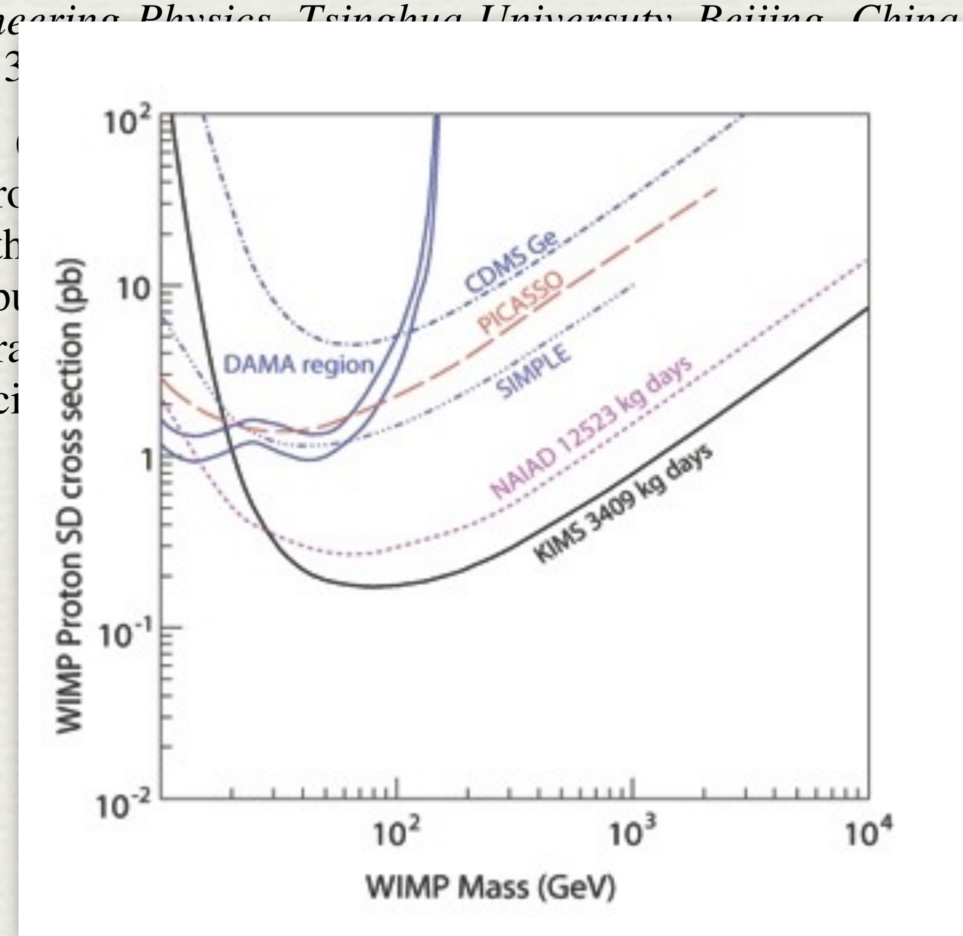
(KIMS Collaboration)

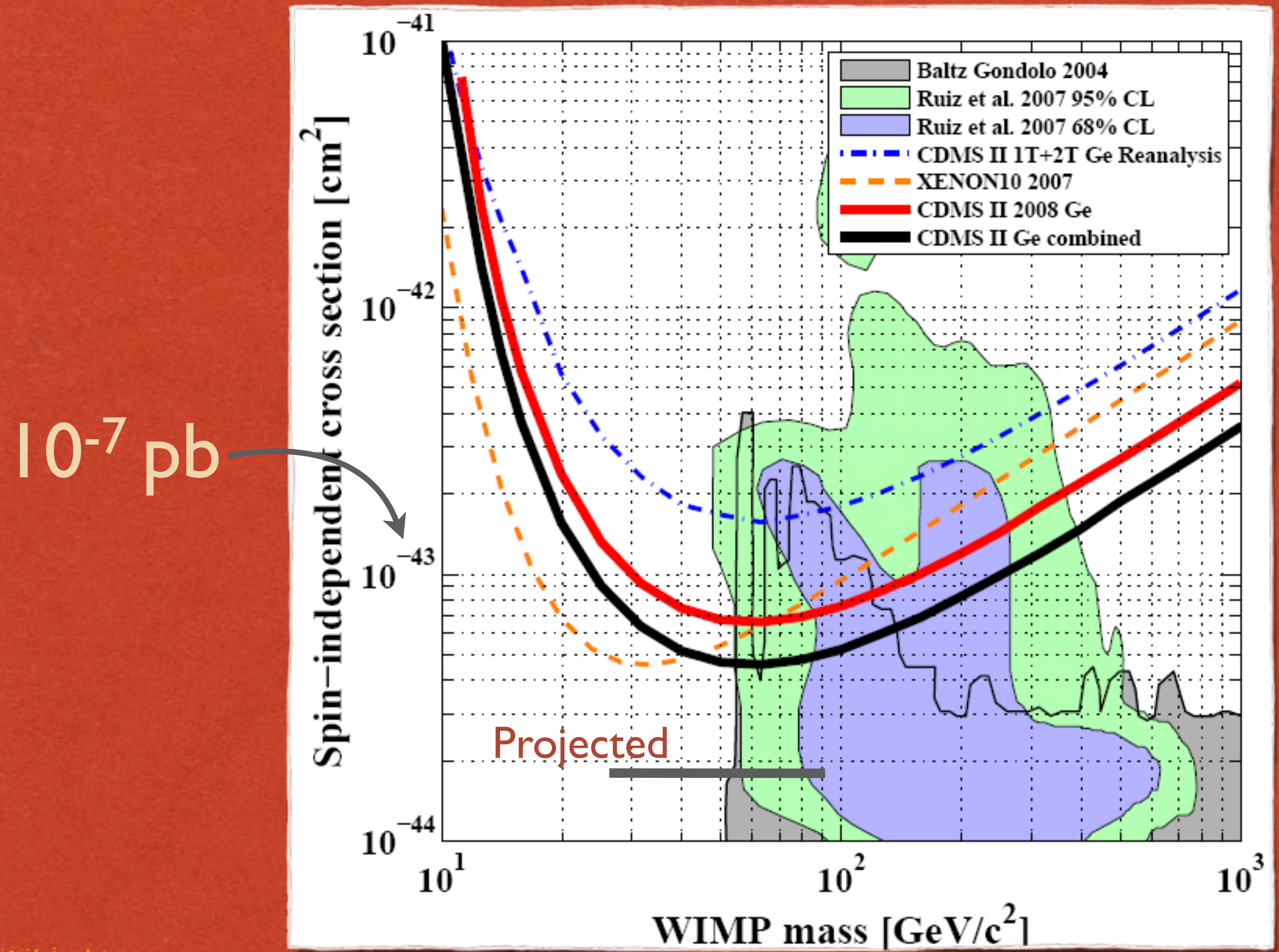
[1]DMRC and Department of Physics and Astronomy, Seoul National University, Seoul, Korea
[2]Department of Physics, Kyungpook National University, Daegu, Korea
[3]Department of Physics, Sejong University, Seoul, Korea
[4]Department of Science Education, Ewha Womans University, Seoul, Korea
[5]Department of Physics, Younsei University, Seoul, Korea
[6]Department of Engineering Physics, Tsinghua University, Beijing, China

eived 3

earch ... kly interacting
eon cro ... d taken with
ls at th ... ngent limit on
for a pu ... for both spin-
t intera ... is excluded by
stal sci







SPIN-INDEPENDENT EXCLUSION LIMIT

from SUSY08 talk by T. Saab (CDMS)

II. Scherzo

Are we sure about WIMP-DM?

The "WIMP miracle"?

wimp

All Dictionary Thesaurus Apple Wikipedia

wimp |wimp| informal

noun

a weak and cowardly or unadventurous person.

verb [intrans.] (**wimp out**)

withdraw from a course of action or a stated position in a way that is seen as feeble or cowardly.

All Dictionary Thesaurus Apple Wikipedia

WIMP 1 |wimp|

noun [often as adj.] Computing

a graphical user interface designed to simplify or demystify computing operations.

ORIGIN 1980s: acronym from *windows, icons, menus, and pointing (device)*.

WIMP 2

noun Physics

a hypothetical subatomic particle of large mass that interacts only weakly with ordinary matter, postulated as a constituent of the dark matter of the universe.

ORIGIN 1980s: acronym from *weakly interacting massive particle*.

The "WIMP miracle"?

(1) Assume a new (heavy) particle χ is initially in thermal equilibrium:

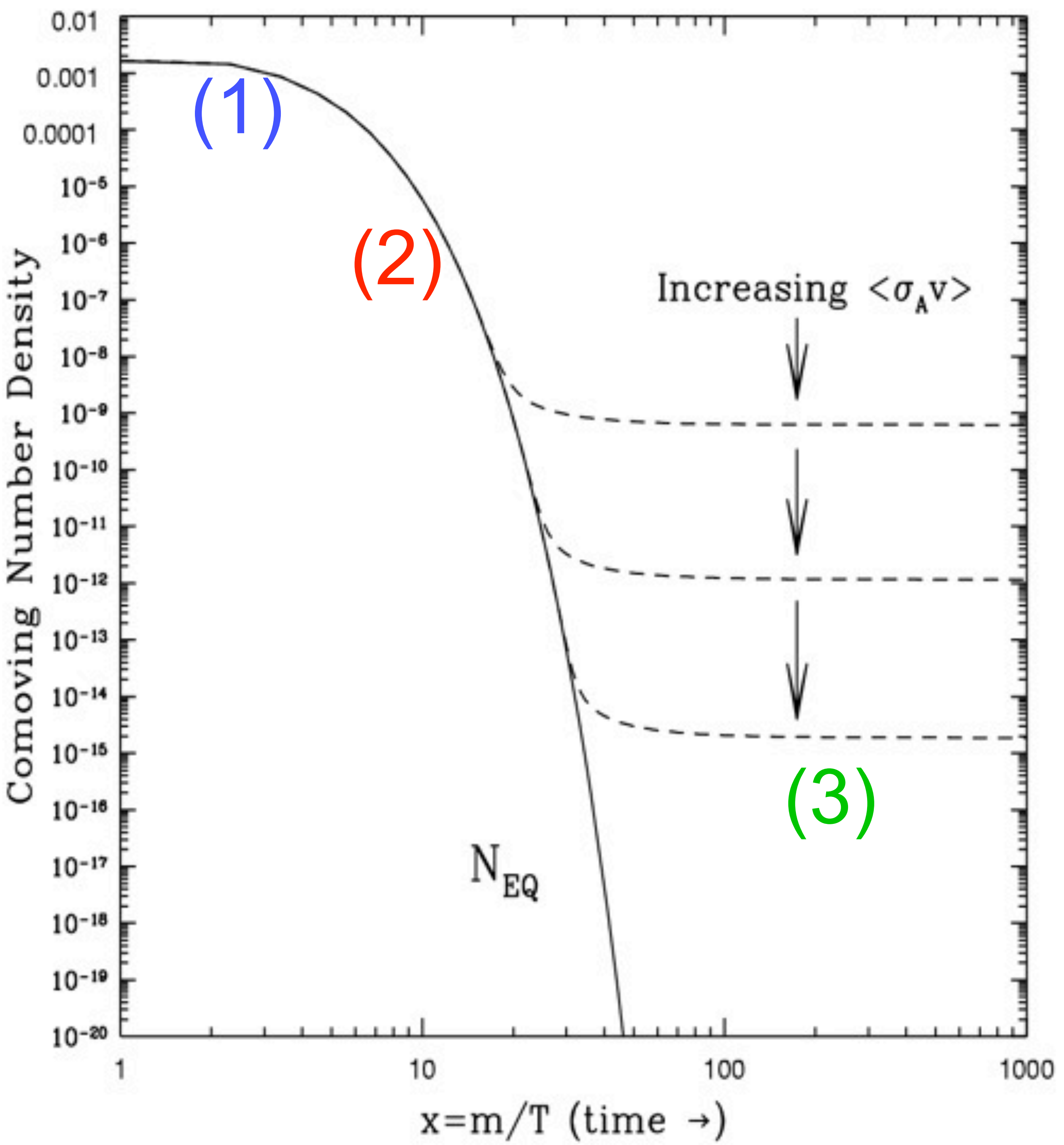
$$\chi\bar{\chi} \leftrightarrow f\bar{f}$$

(2) Universe cools:

$$\chi\bar{\chi} \not\leftarrow\!\!\!\rightarrow f\bar{f}$$

(3) χ's "freeze out":

$$\chi\bar{\chi} \not\leftarrow\!\!\!\not\rightarrow f\bar{f}$$



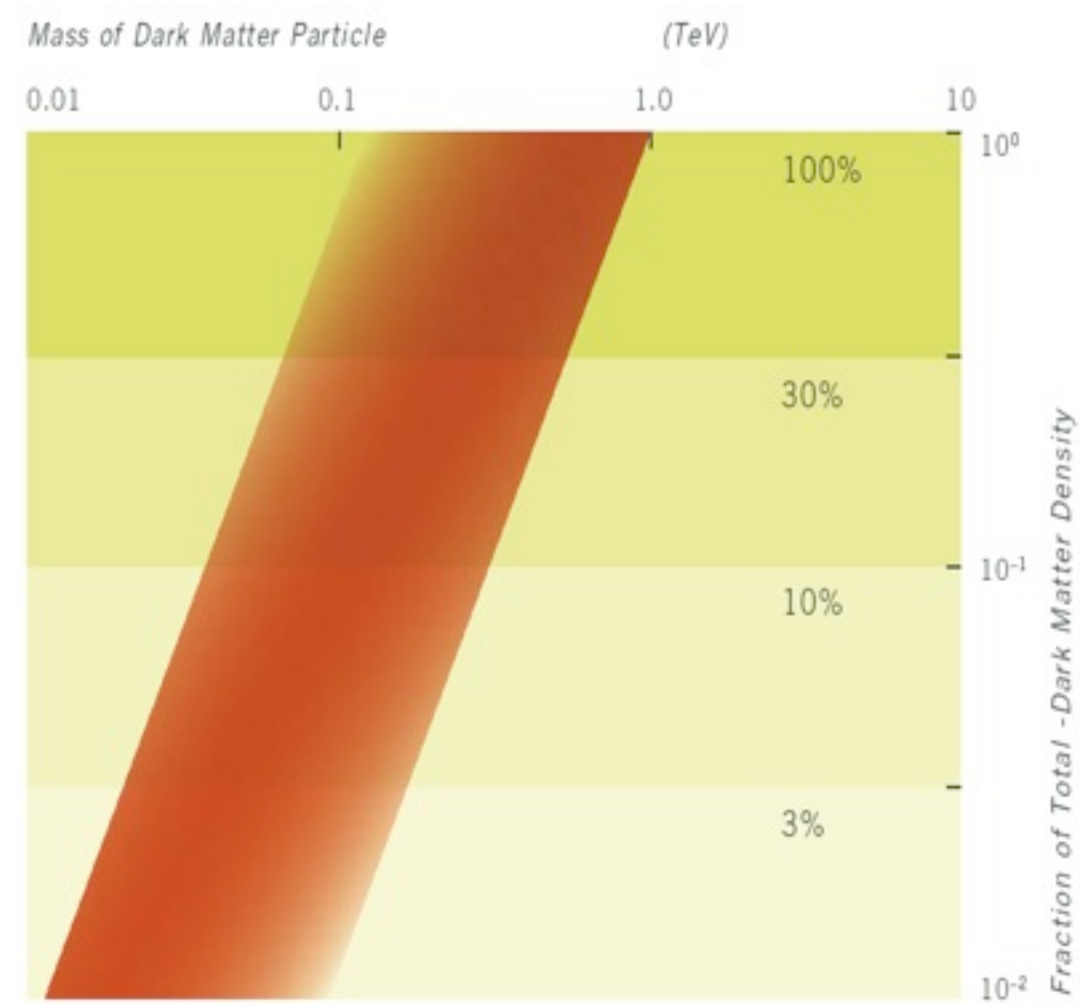
The "WIMP miracle"?

- The amount of dark matter left over is inversely proportional to the annihilation cross section:

$$\Omega_{DM} \sim \langle\sigma_A v\rangle^{-1}$$

- Impose a natural relation:

$$\sigma_A = k\alpha^2/m^2\ ,\ \text{so}\ \Omega_{DM} \sim m^2$$



HEPAP LHC/ILC Subpanel (2006)

[band width from k = 0.5 – 2, S and P wave]

Remarkable "coincidence": $\Omega_{DM} \sim 0.1$ for $m \sim (0.1 - 1)$ TeV

Cosmology alone tells us we should explore the weak scale

The “WIMP miracle”?

- OK, it may be a miracle, but...
- Is WIMP something we really need?
- Perhaps, a lesson from history may be valuable...

Intermezzo

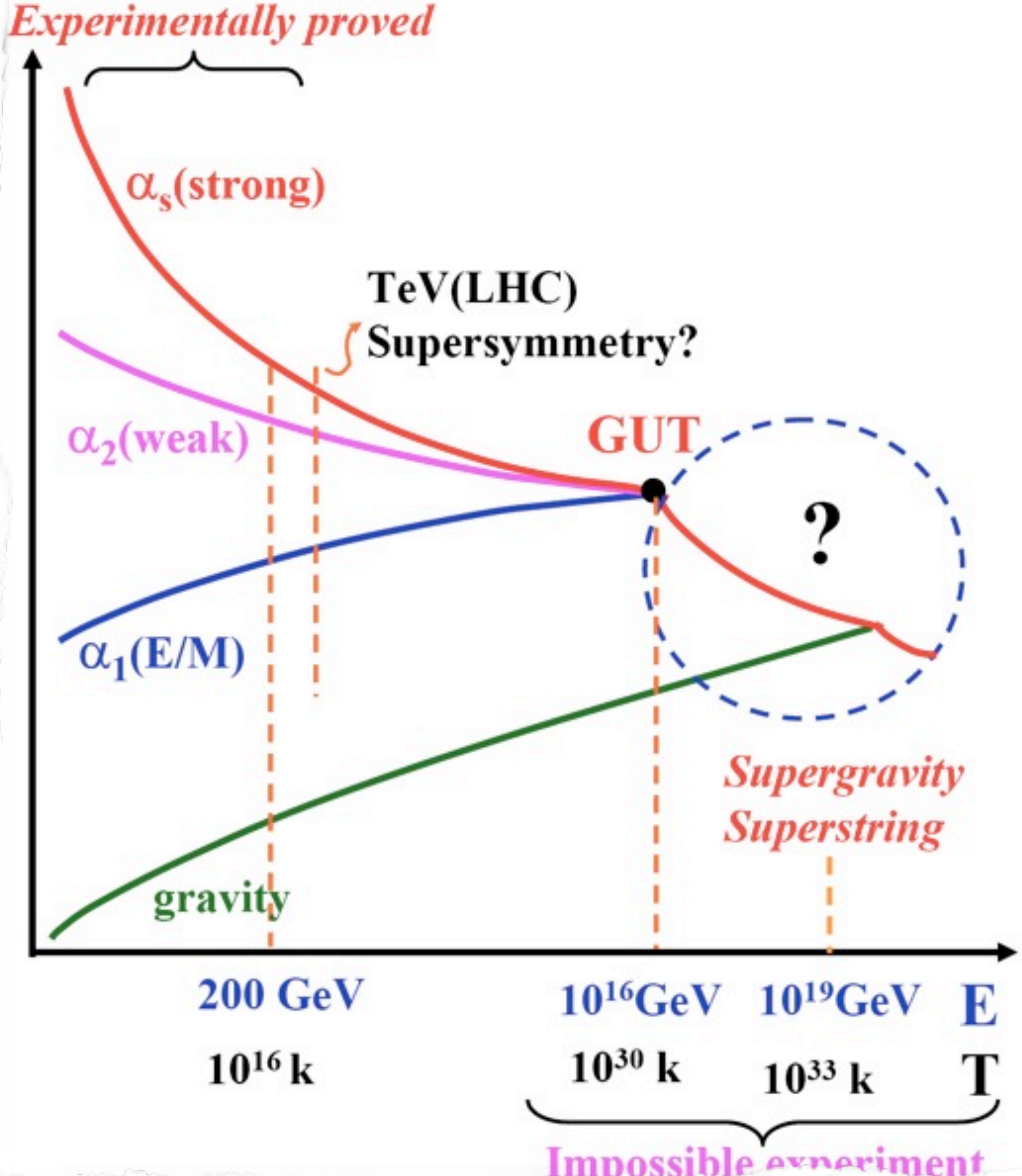
the hierarchy problem in particle physics

Beyond the SM Higgs

- In a few years, hopefully by the end of this decade, we will know whether or not there is a Higgs
- But the discovery will raise even more (new) questions
  - Is this particle fundamental, or composite?
  - Why is its mass ~ 100 GeV, not M(Planck)?
- More importantly, the SM Higgs brings a new problem,

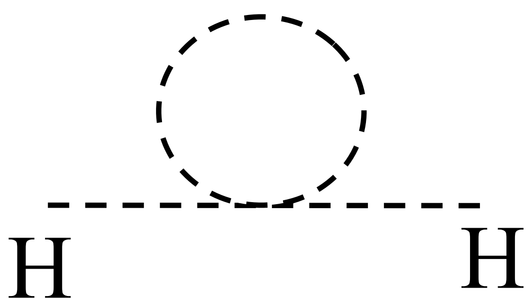
the "Hierarchy Problem"

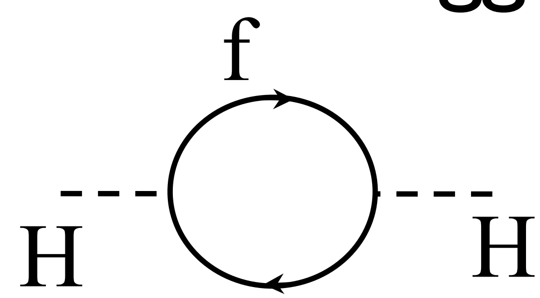
Coupling Constants of Fundamental Forces



Hierarchy problem

(Ex) Radiative corrections to the Higgs mass





RGE ➔ $$M^2(\mu_2) = M^2(\mu_1) + Cg^2(\mu_2^2 - \mu_1^2) + g^2 R + O(g^4)$$

For Higgs at EW-breaking scale (~100 GeV),

$$M_H^2(M_W) \approx M_H^2(M_X) - Cg^2 M_X^2$$

In order to have $M_H \sim O(M_W)$,
need a fine-tuning (to 10^{-26}) in each order of the perturbation

Hierarchy problem in classical EM

- At the end of 19th century,
  a crisis about electron, a point-like particle
  - difficult to keep electron charge in a small pack
  - exp. size(e-) < 10^{-17} cm
  - need a lot of energy to keep it small

$$\Delta m_e c^2 \sim \frac{\alpha}{r_e} \sim \frac{10^{-17}\,\mathrm{cm}}{r_e}(\mathrm{GeV})$$

  - Breakdown of classical EM
    => can't discuss physics below 10^{-13} cm
- Dirac's antiparticle comes to rescue => QED

$$\frac{\Delta m_e}{m_e} \sim \frac{\alpha}{4\pi}\log(m_e r_e)$$

History repeats?

- Just like an electron repelling itself in EM, Higgs boson also repels itself, hence
- need a lot of energy to contain itself in its point-like size

- Breakdown of EW (SM)

$$\Delta m_H c^2 \sim \frac{1}{r_H}$$

- History repeats itself?
  - **doubling the #(particles) with a new kind of symmetry may cure the problem**

SUSY?

$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

Supersymmetry (SUSY)

- A symmetry between boson & fermion
- Supersymmetric particles

$$Q|b\rangle = |f\rangle$$
$$Q^+|f\rangle = |b\rangle$$

particle	SUSY partner	spin of partner	name
γ	$\tilde{\gamma}$	1/2	photino
e_L	$\tilde{e}_L$	0	selectron
u_R	$\tilde{u}_R$	0	u squark
g	$\tilde{g}$	1/2	gluino
ν_μ	$\tilde{\nu}_\mu$	0	μ sneutrino
…	…	…	…

SUSY will do many good things

- mathematically, a beautiful symmetry...
- natural cure for hierarchy problem of SM
    - ➔ stabilize the EW scale
- unify the gauge couplings
- local SUSY includes gravity
- ***SUSY particles can be a non-baryonic dark matter candidate!***

a strong candidate for

the WIMP !

WIMP, THE FAVORITE

- *"There are two types of theorists; those who believe in SUSY and those who do not"* (P. Ko, in private conversation)
- Particle physicists love SUSY and SUSY-motivated WIMPs are many people's favorite candidate for DM
- But.. does it mean we should **not** look for non-WIMP types of DM?

No way!

III. Andante maestoso

A new theory & new proposals

Astrophysical findings

near Earth

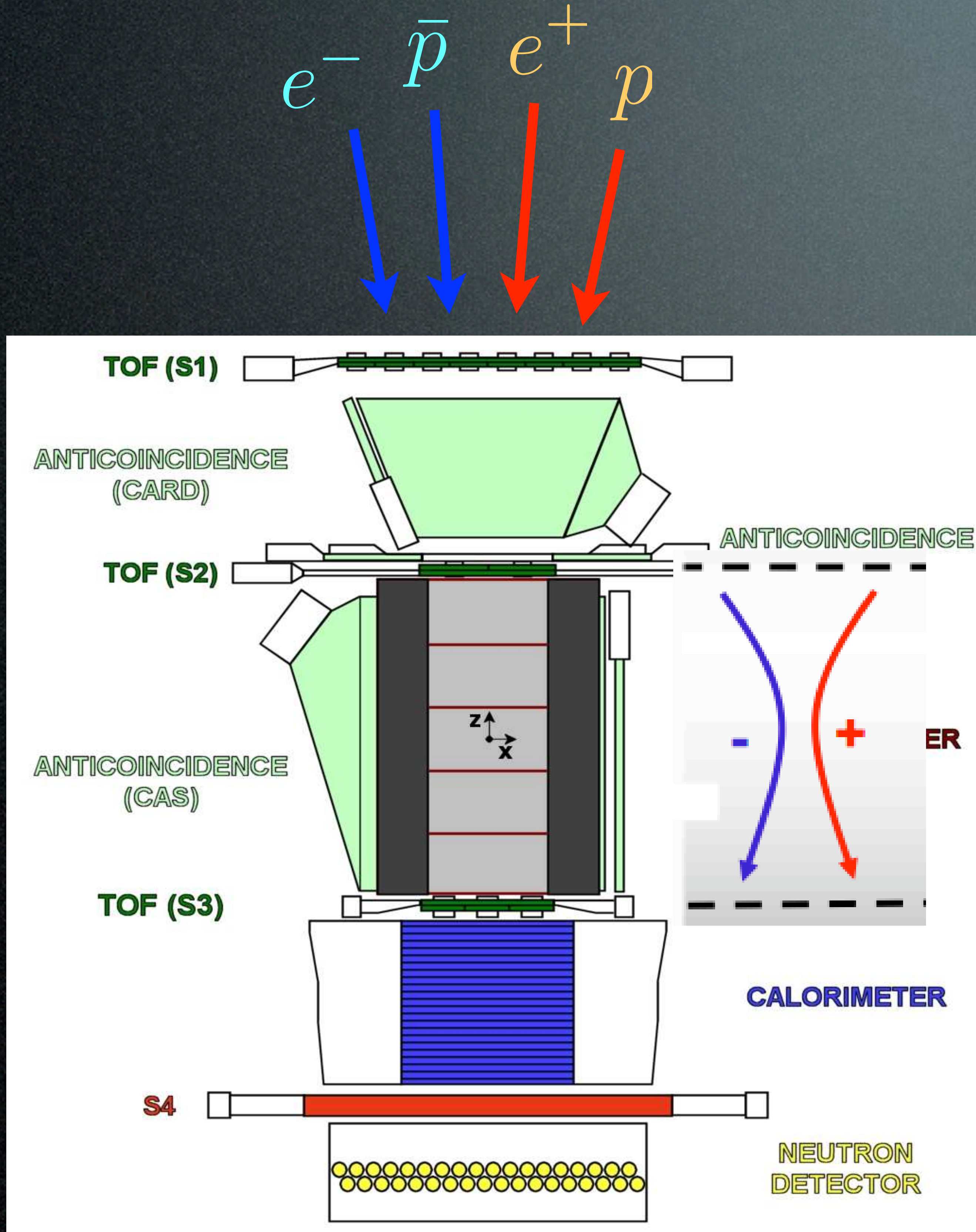
PAMELA
e+/(e- + e+)

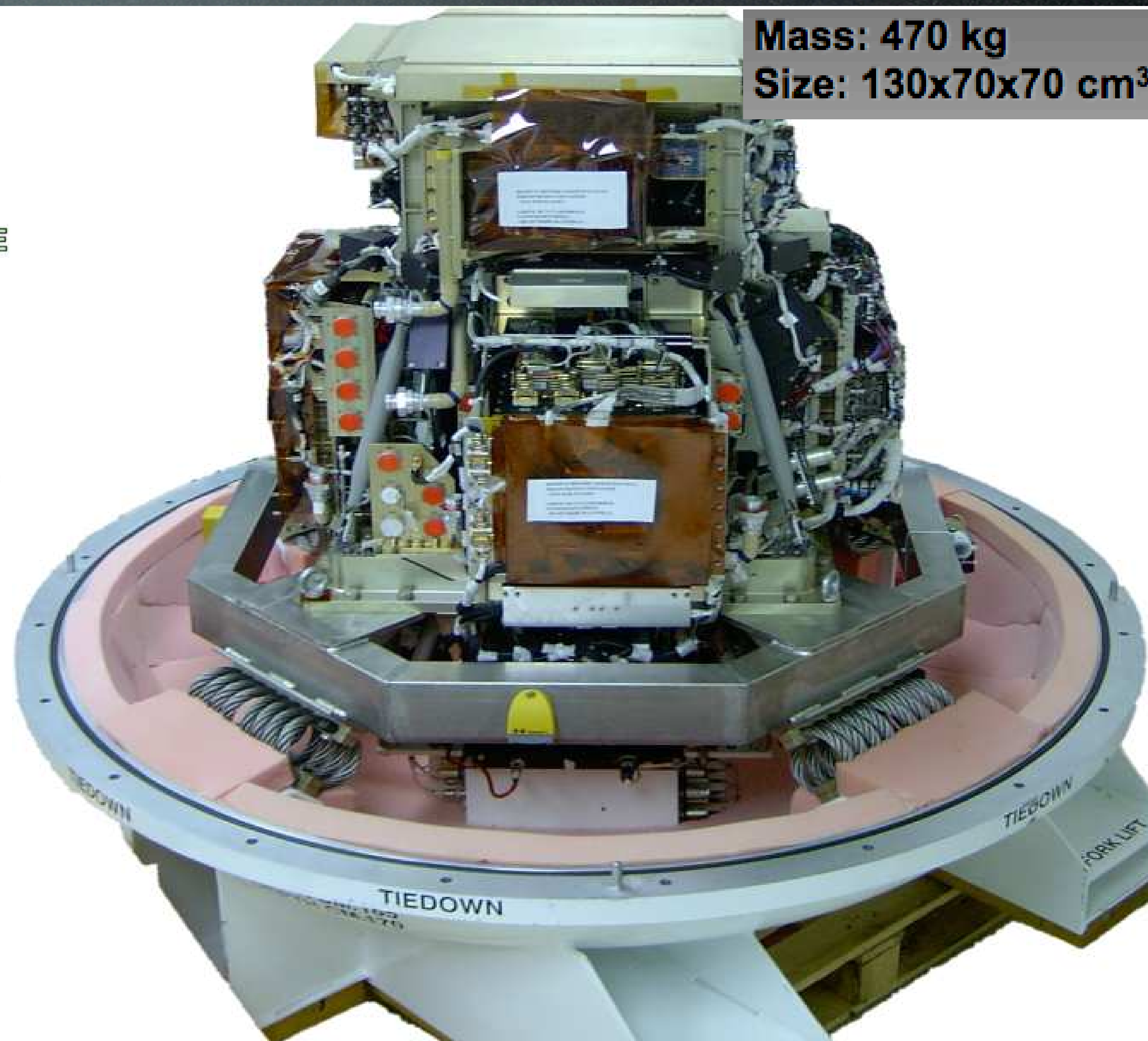
ATIC/Fermi
e- + e+

Dark Matter?

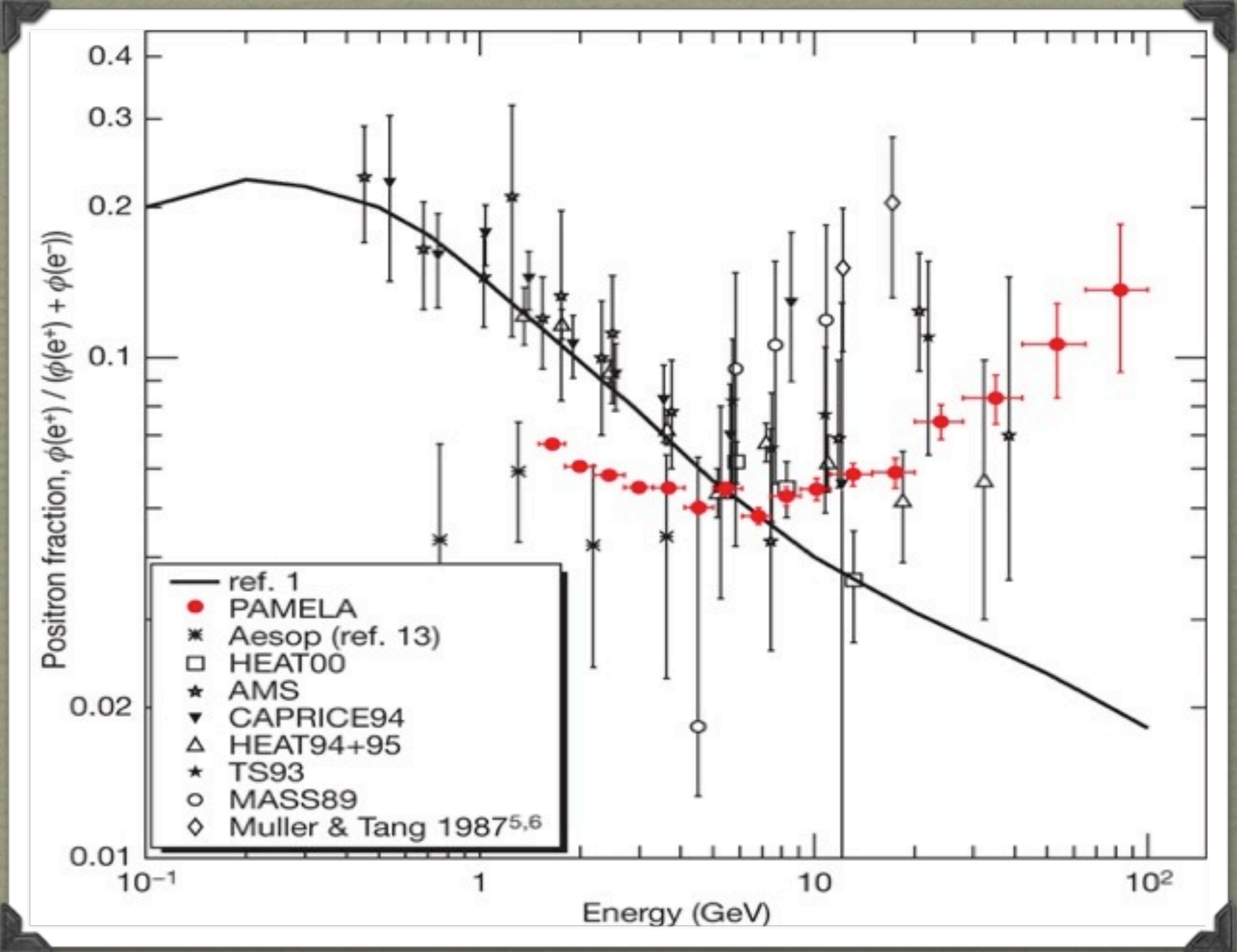
PAMELA

a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics



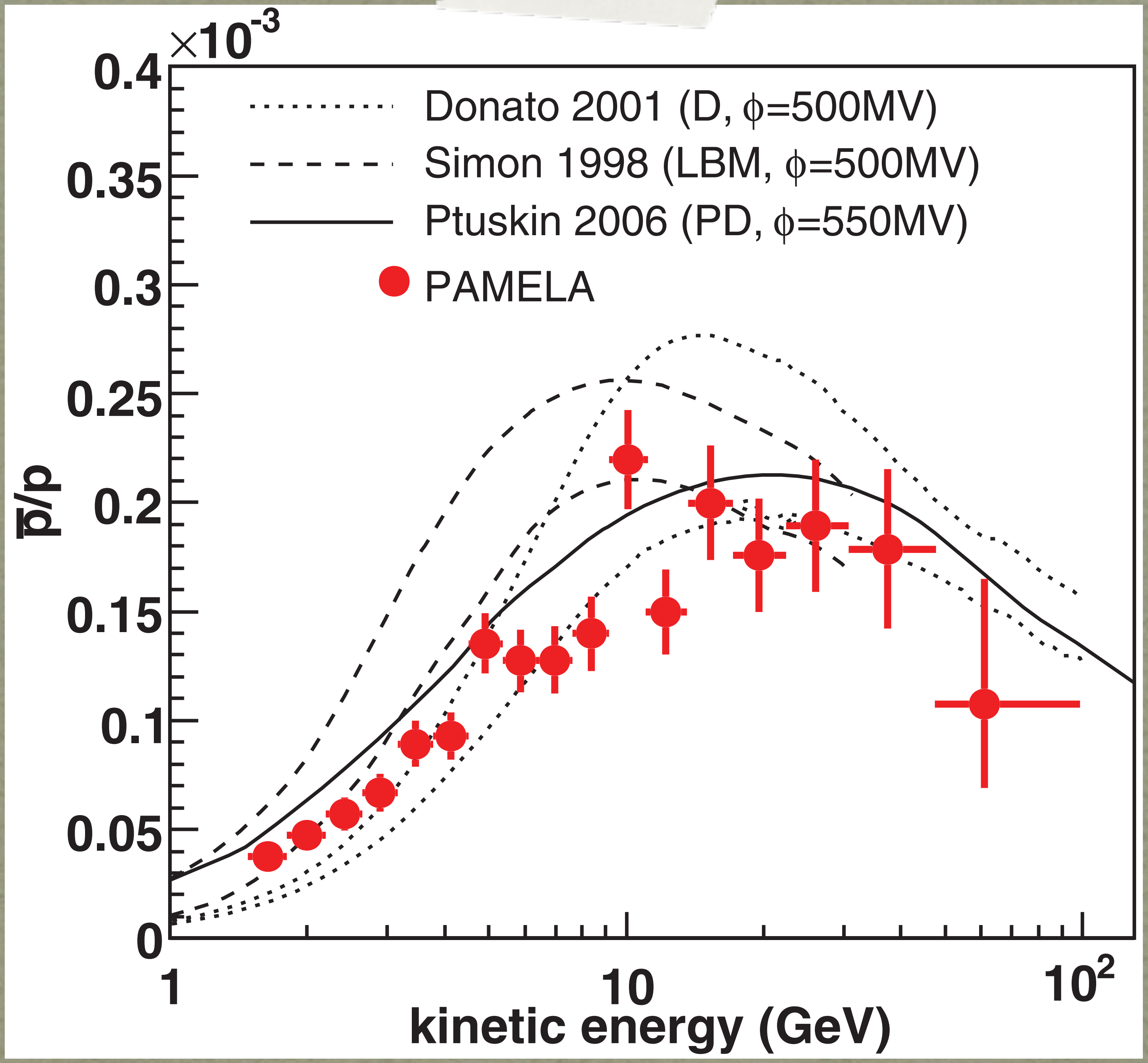


PAMELA e+ fraction



O Adriani *et al. Nature* **458**, 607-609 (2009) doi:10.1038/nature07942 *on the other hand...*

PAMELA antiproton



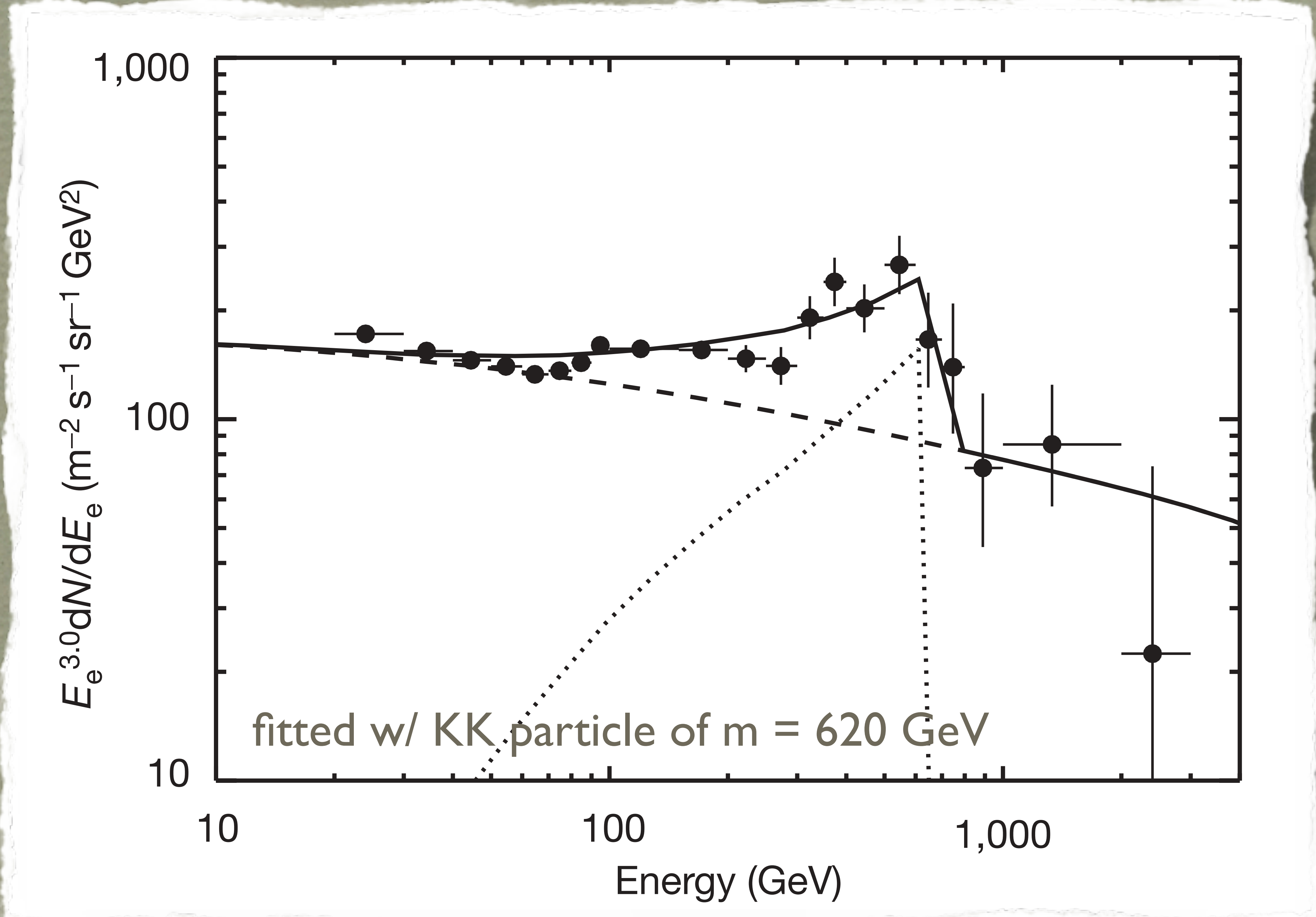
O Adriani *et al.* PRL 102, 051101 (2009)

ATIC & Fermi

- ATIC = Advanced this ionization calorimeter
  - a ballon experiment to observe e+ and e- (cannot tell the diff.) up to ~ 1 TeV
- Fermi = Fermi Gamma-ray Space Telescope
  - pair conversion telescope
  - observes γ up to 300 GeV and particles up to ~ 1 TeV

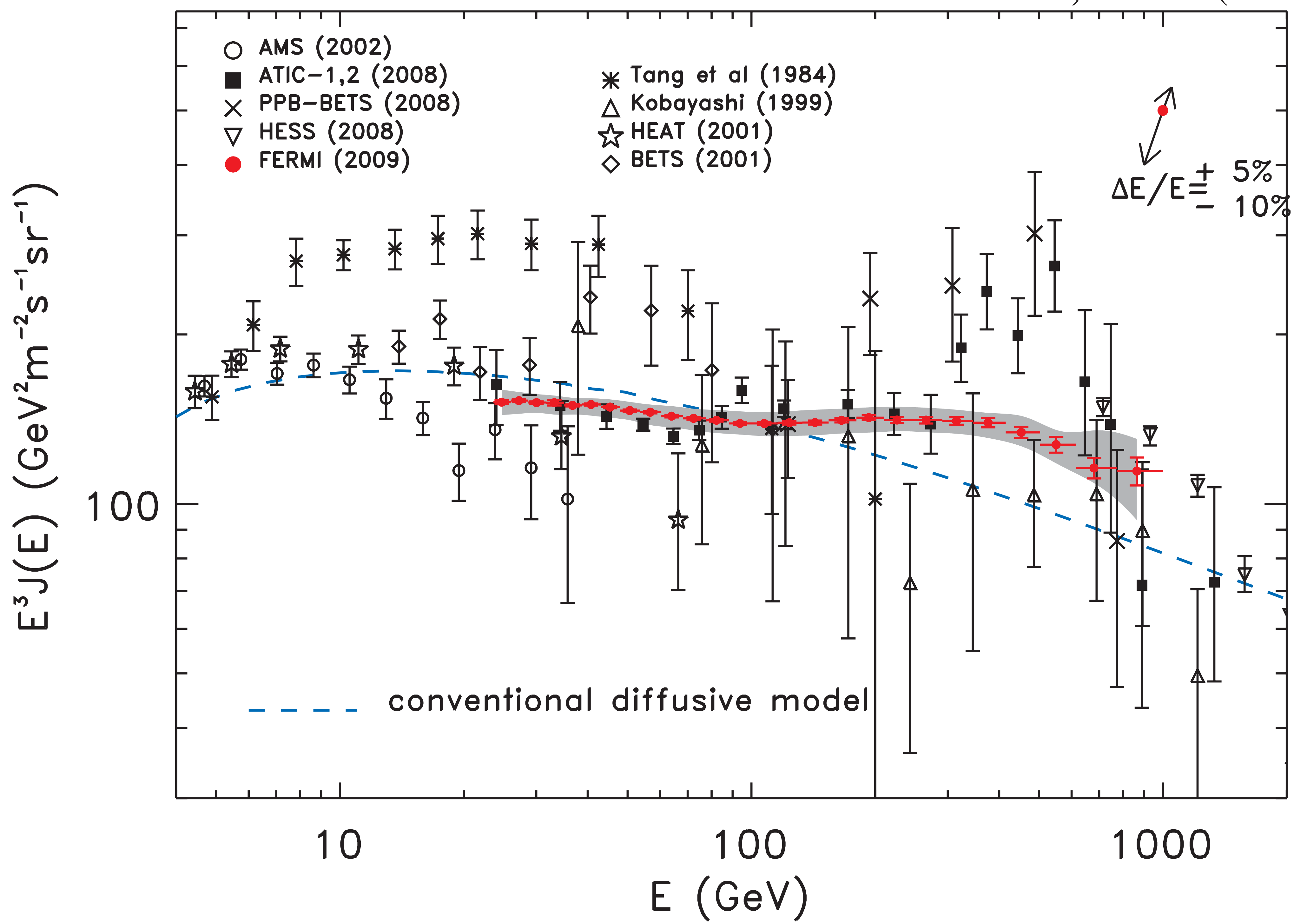
ATIC (2008)

Vol 456|20 November 2008|**doi:10.1038/nature07477**



ATIC & Fermi, etc.

PRL **102,** 181101 (2009)



anomalies?

Astrophysical findings

near Earth

PAMELA
e+/(e- + e+)

ATIC/Fermi
e- + e+

Dark Matter?

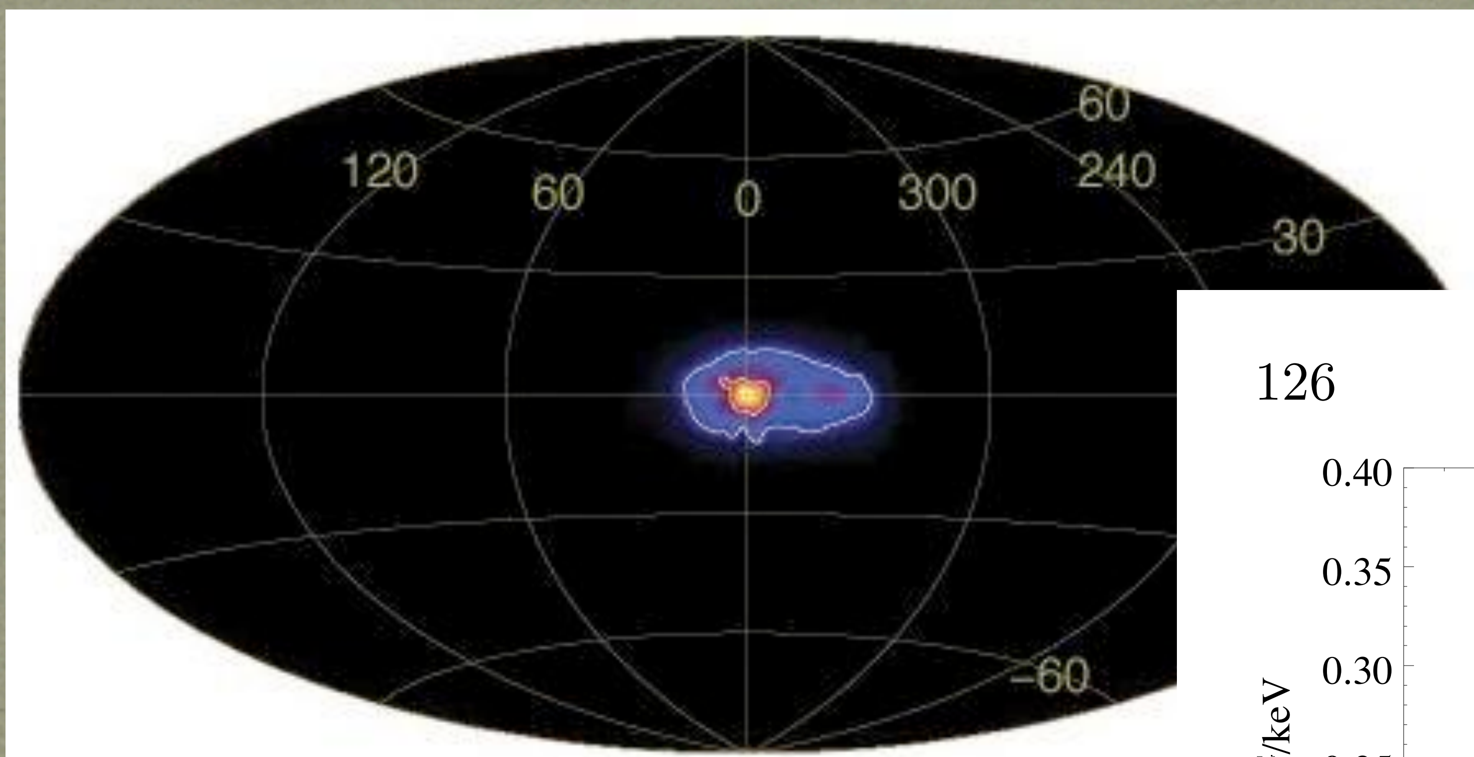
INTEGRAL
511 keV

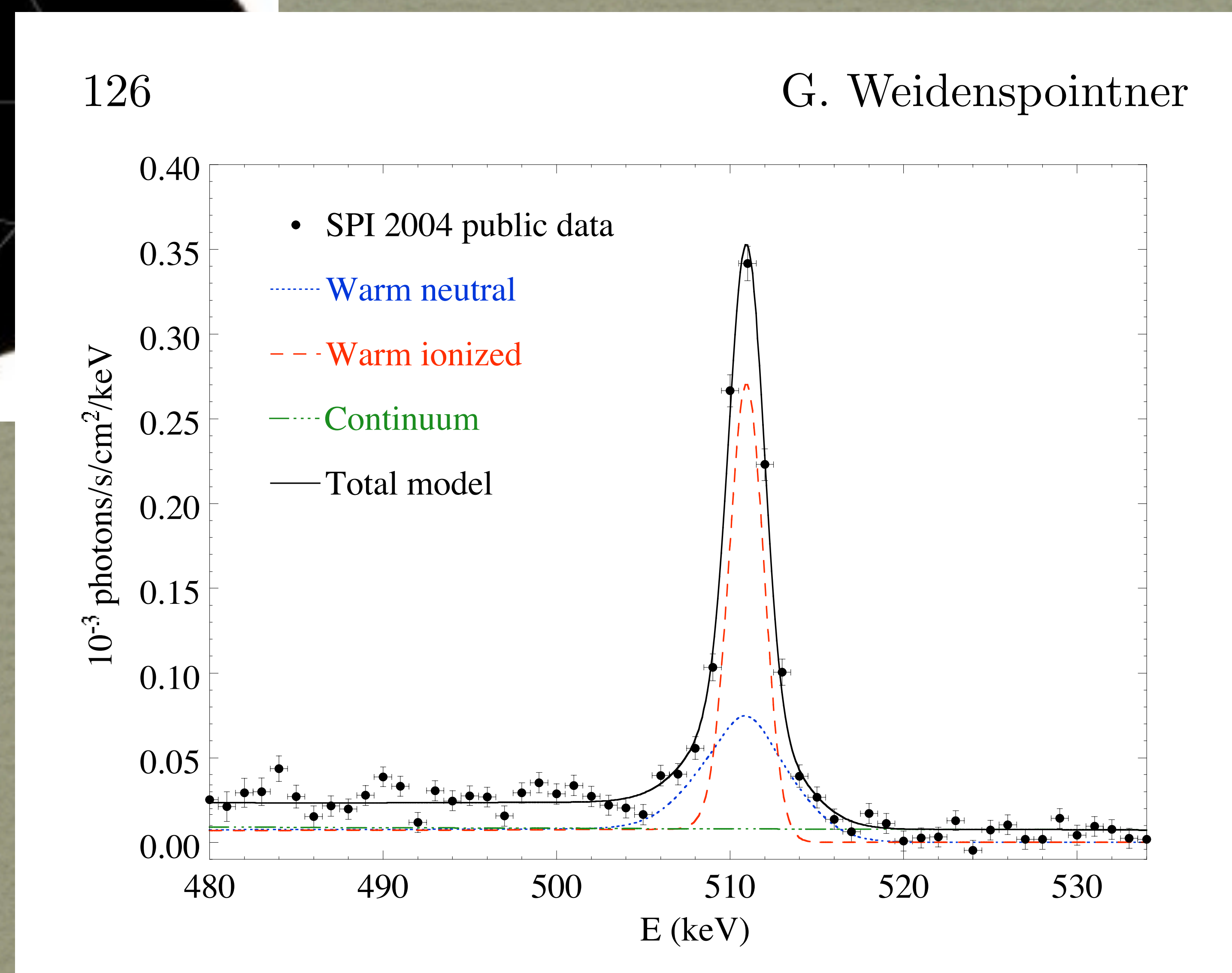
WMAP haze
(CMB)

Galactic Center

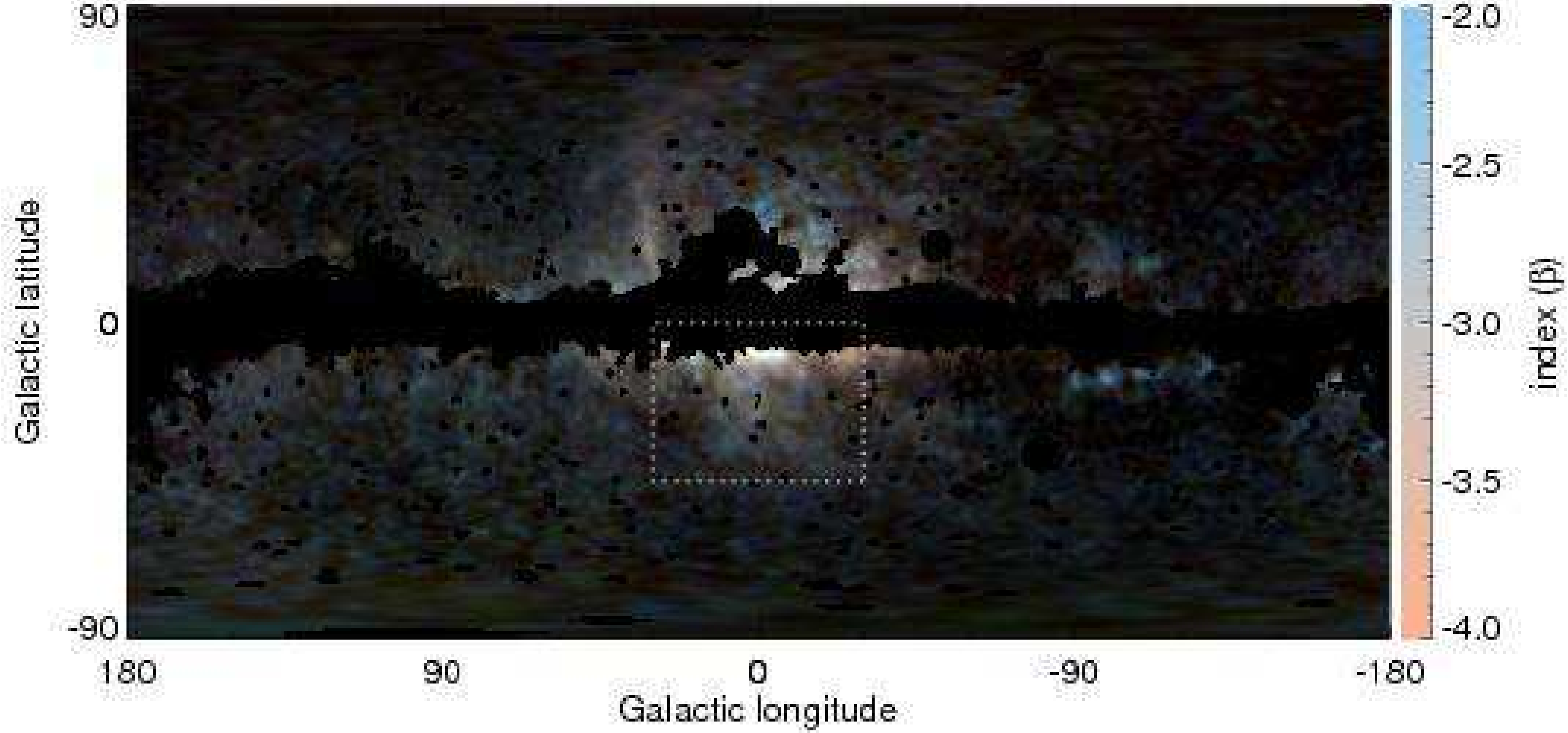
INTEGRAL

- Too many 511 keV photons from center of galaxy
  37 year old result; still not understood





WMAP haze



90
0
-90
Galactic latitude
180
90
0
-90
-180
Galactic longitude
-2.0
-2.5
-3.0
-3.5
-4.0
index (β)

mounting signs of anomalies?

near Earth

PAMELA
e+/(e- + e+)

DAMA
ann. mod.

ATIC/Fermi
e- + e+

Dark
Matter?

Physics

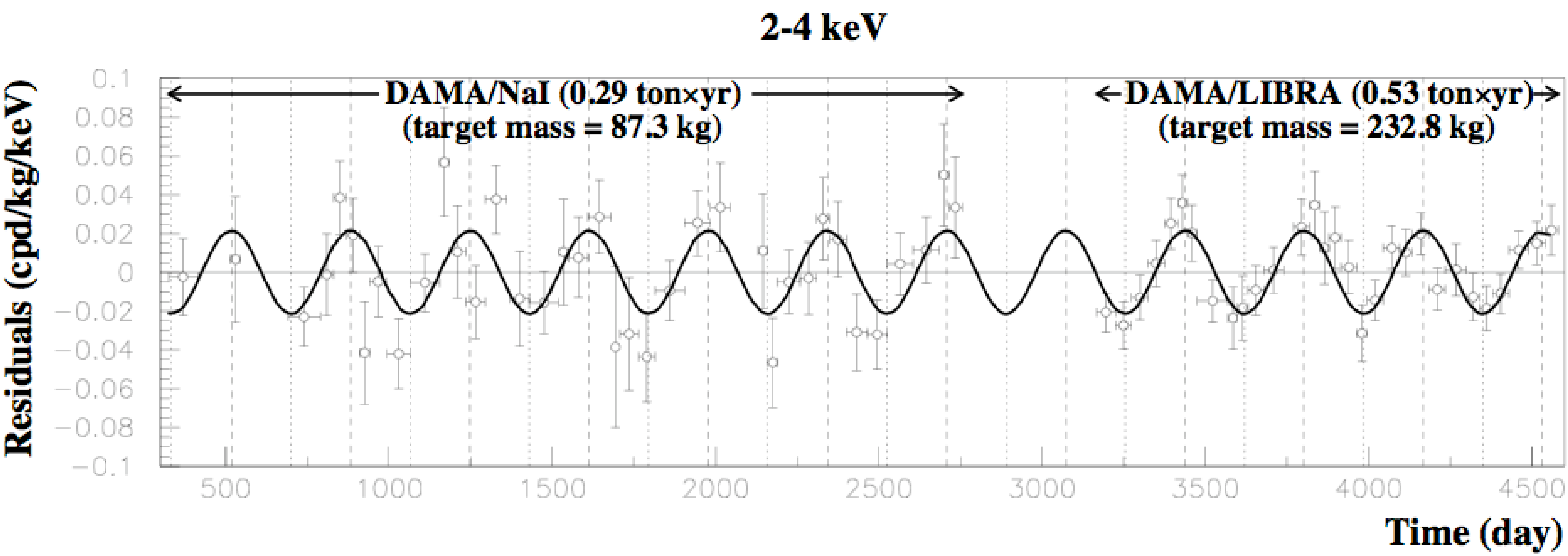
muon
g-2

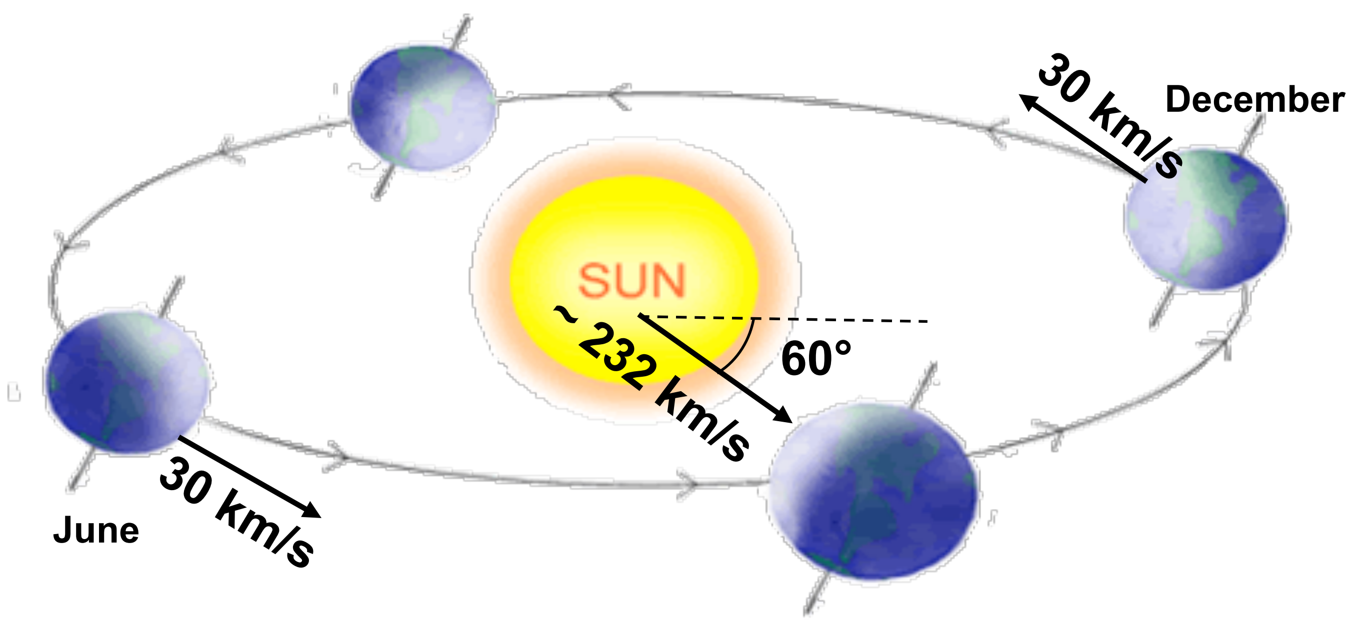
INTEGRAL
511 keV

WMAP haze
(CMB)

Galactic Center

DAMA annual modulation





a new theory...

PHYSICAL REVIEW D **79,** 015014 (2009)

A theory of dark matter

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

[1]*School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA*
[2]*Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA*
[3]*Physics Department, Harvard University, Cambridge, Massachusetts 02138, USA*
[4]*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, New York 10003, USA*

(Received 31 October 2008; published 27 January 2009)

We propose a comprehensive theory of dark matter that explains the recent proliferation of unexpected observations in high-energy astrophysics. Cosmic ray spectra from ATIC and PAMELA require a WIMP (weakly interacting massive particle). with mass $M_\chi \sim 500$–800 GeV that annihilates into leptons at a level well above that expected from a thermal relic. Signals from WMAP and EGRET reinforce this interpretation. Limits on $\bar{p}$ and π^0-γ's constrain the hadronic channels allowed for dark matter. Taken together, we argue these facts imply the presence of a new force in the dark sector, with a Compton wavelength $m_\phi^{-1} \gtrsim 1\ \mathrm{GeV}^{-1}$. The long range allows a Sommerfeld enhancement to boost the annihilation cross section as required, without altering the weak scale annihilation cross section during dark matter

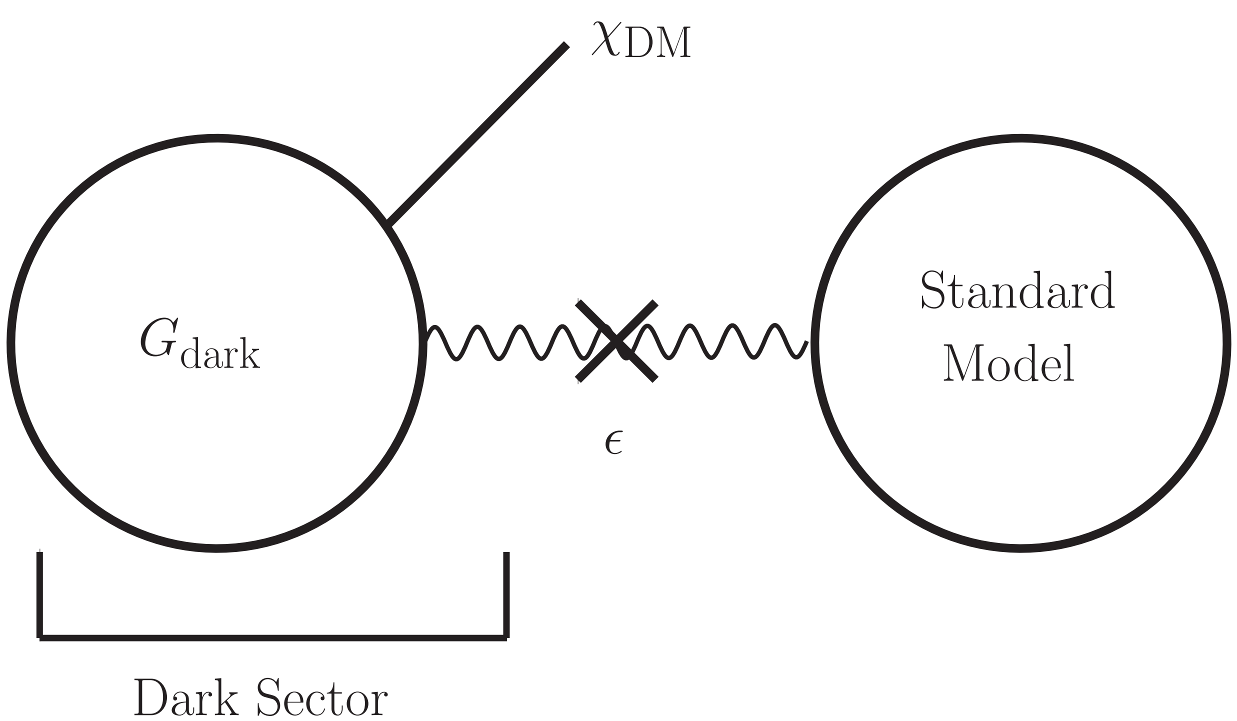
all evidences pointing to hitherto unknown
GeV-scale dark sector

a GeV-scale dark sector?

- Dark matter self-interaction, mediated by

$$b_{\text{dark}} \subset \text{darksector}$$

- Range of dark force $\simeq m_b^{-1} \sim$ GeV
- Dark sector couples to SM with tiny couplings, parametrized by ϵ (typically, $\epsilon \leq 10^{-3}$.



DM interpretation of the excesses:

- Correct thermal relic density fixes DM annihilation rate:

$$\Omega_{\rm DM} h^2 = 0.1 \times \left(\frac{< \sigma v >_{\rm freeze-out}}{3 \times 10^{-26}\ {\rm cm}^3\ {\rm s}^{-1}} \right)^{-1}$$

- Cosmic ray flux:

$$R_{e^+,\gamma,\bar{p}\ldots} \propto (n_{\rm DM}^{\rm halo2}) \times < \sigma v >_{\rm halo}$$

$$\text{Assume } < \sigma v >_{\rm halo} \simeq < \sigma v >_{\rm freeze-out} \to R_{e^+,\gamma,\bar{p}\ldots}$$

- Observed positron and electron excess needs an additional O(10s-100) enhancement.

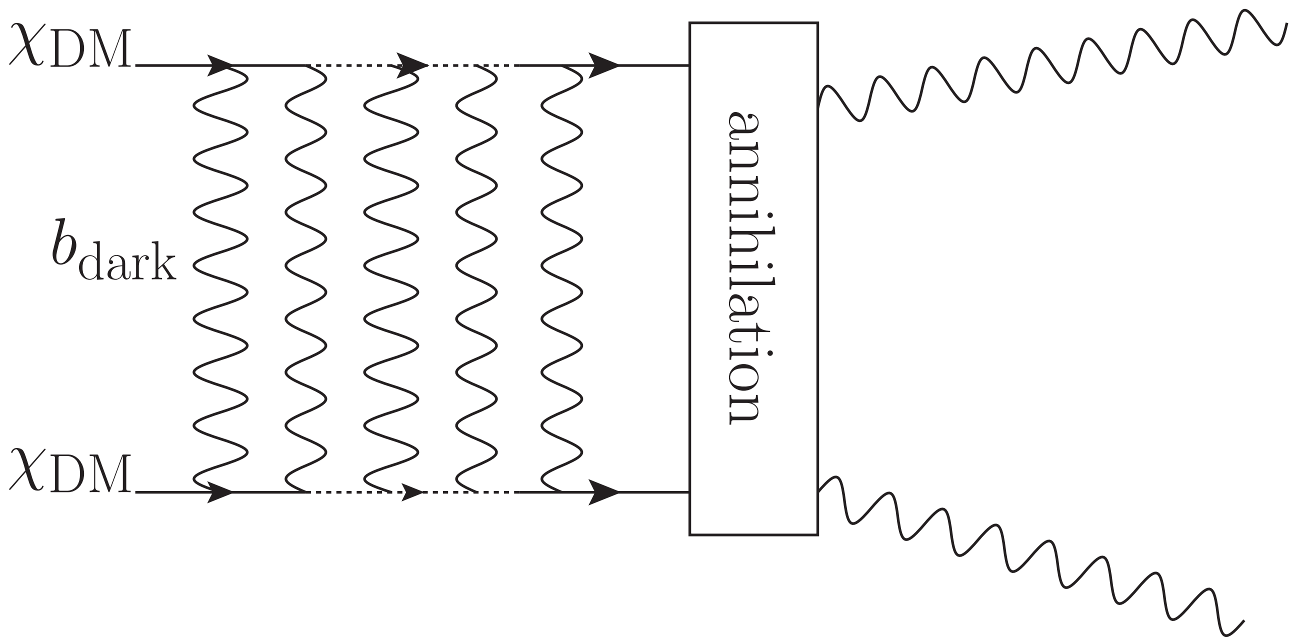
  For example: P. Meade, M. Papucci, A. Strumia, T. Volansky, arXiv:0905.0480

- To preserve the success of relic density prediction, change late time physics.

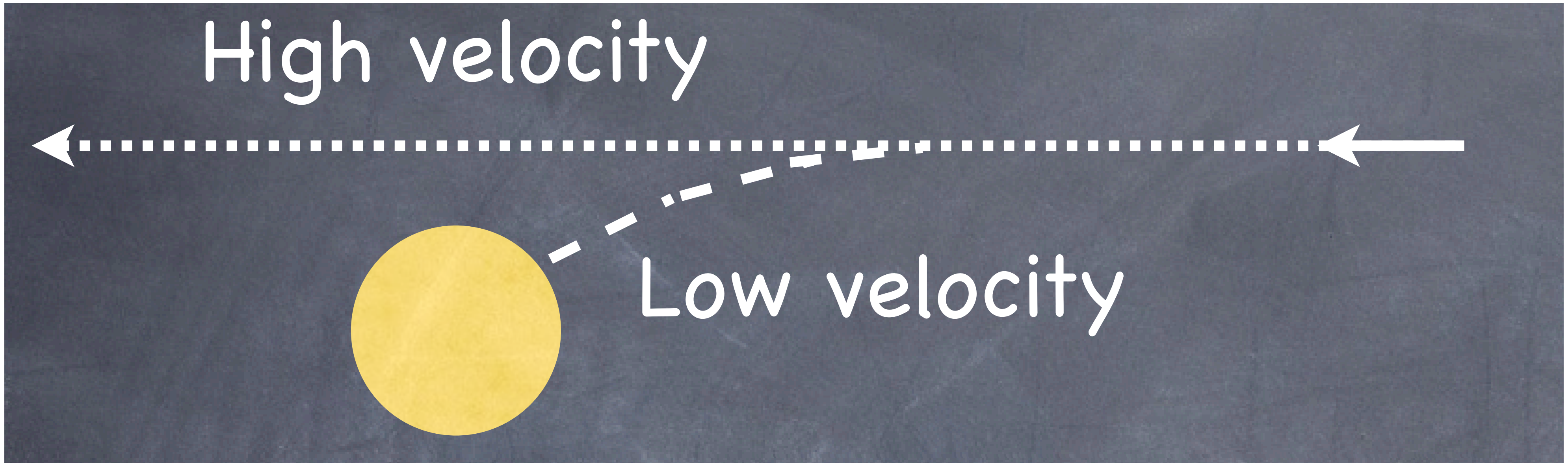
  - Sommerfeld enhancement: $< \sigma v >_{\rm halo} \gg < \sigma v >_{\rm freeze-out}$

taken from the KEK talk by Lian-tao Wang (Princeton)

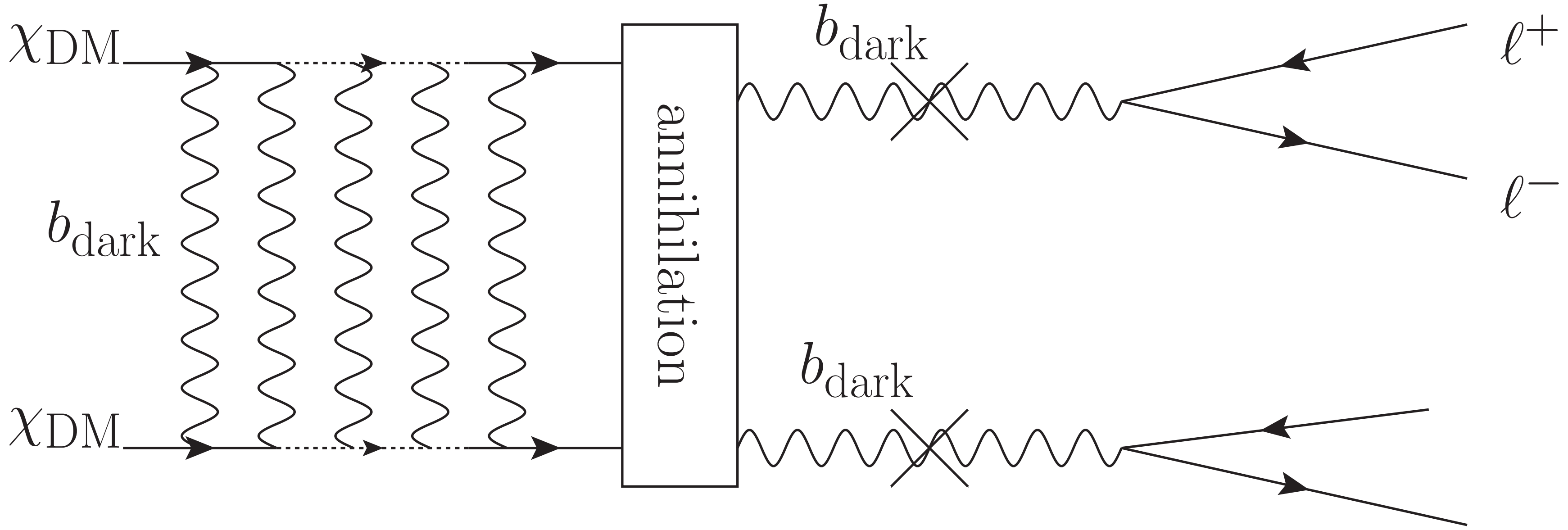
Sommerfeld enhancement



Earlier consideration:
J. Hisano, S. Matsumoto, M. Nojiri, and O. Saito, hep-ph/0412403
J. Hisano, S. Matsumoto, M. Nagai O. Saito, and M. Senami, hep-ph/0610249

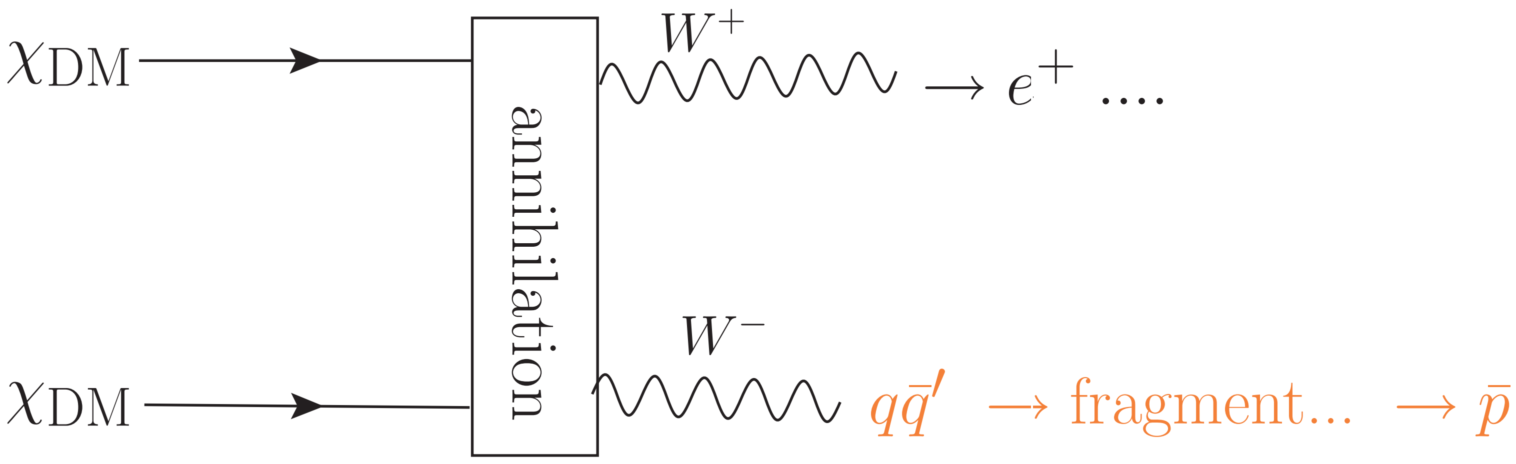


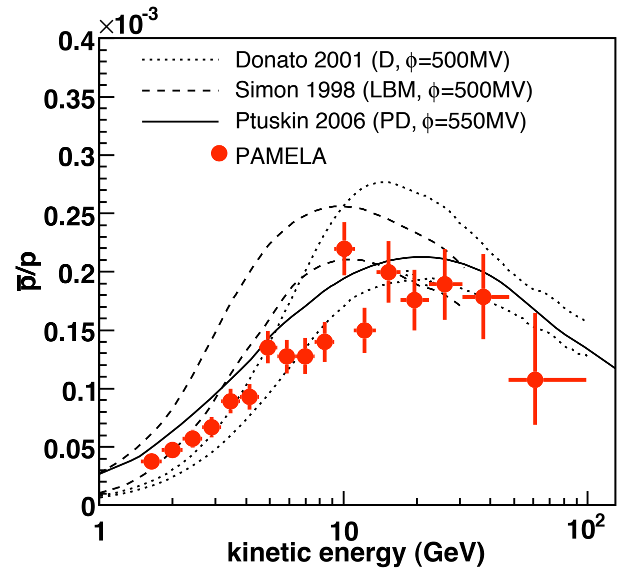
Observed signal from PAMELA / Fermi



- DM particles annihilate to dark force carrier, which then decay to SM states
- As a result, dark sector states must couple to the SM
- But, the coupling has to be small for the existing const'nts

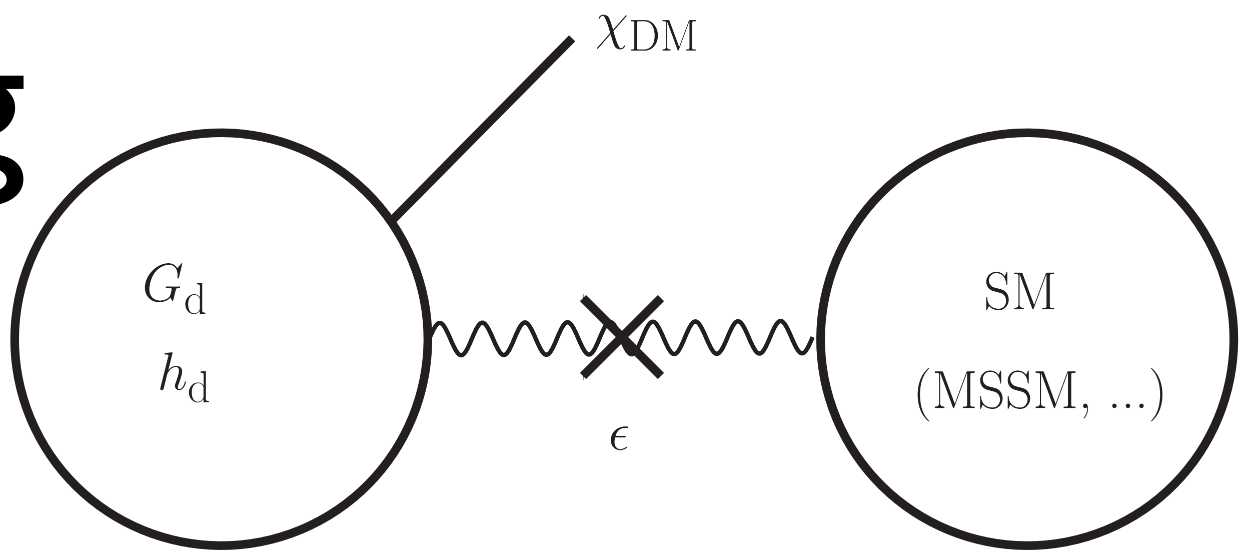
What about anti-p puzzle from PAMELA?





- Conventional WIMP DM annihila'n also involves excess anti-proton flux, which is not observed by PAMELA
- With dark-sector force carrier having a GeV-scale mass, baryon production can be kinematically suppressed

a model-building



- We need
  - DM identity
  - self-interaction, $G_{\rm d}$=U(1)$_{\rm d}$
  - GeV-scale dark higgs, $h_{\rm d}$
  - connection to SM
  - SUSY scenarios
  - etc.

"kinetic mixing"

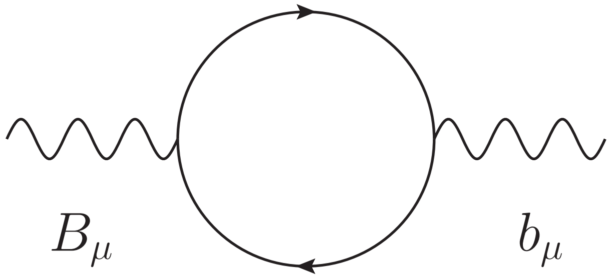
$$\mathcal{L}_{\rm kin.mix} = -\frac{\epsilon}{2} b_{\mu\nu} F_{\gamma}^{\mu\nu}$$

Various constructions:

- Earlier proposals:
  M. Pospelov, A. Ritz and M. Voloshin, arXiv:0711.4866
  N. Arkani-Hamed, D. Finkbeiner, T. Slatyer and N. Weiner, arXiv:0810.0713
- U(1) models:
  E. J. Chun and J. C. Park, arXiv:0812.0308
  C. Cheung, LTW, J. Ruderman, and I. Yavin, arXiv:0902.3246
  A. Katz and R. Sundrum, arXiv:0902.3271
  D. E. Morrissey, D. Poland and K. M. Zurek, arXiv:0904.2567
- Non-abelian model, SUSY:
  M. Baumgart, C. Cheung, LTW, J.~Ruderman, I. Yavin, arXiv:0901.0283
- Scalar Portal:
  Y. Nomura and J. Thaler, arXiv:0810.5397
- More...

Kinetic mixing:

- Expected to be there!
  - Kinetic mixing between dark photon and SM hypercharge gauge boson B_μ is generically present in extensions of the Standard Model.



$$\epsilon = \frac{g_d g_Y}{16\pi^2} \Sigma_i Q_d^i Q_Y^i \log\left(\frac{M_i^2}{\mu^2}\right)$$

- Expected to be small (consistent with constraints).

$$\epsilon \sim \frac{g_d g_Y}{16\pi^2} \log\left(\frac{M}{M'}\right) \sim 10^{-3} - 10^{-4}$$

taken from the KEK talk by Lian-tao Wang (Princeton)

Dark sector coupling to the SM

$$\begin{aligned}\mathcal{L}_{\rm gauge} &\supset -\frac{1}{4}W_{3\mu\nu}W_3^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu} + \frac{\epsilon}{2}B_{\mu\nu}b^{\mu\nu}\\ &= -\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu}\\ &+ \frac{\epsilon}{2}\left(\cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu}\right)b^{\mu\nu}\end{aligned}$$

$$\begin{aligned}A_\mu &\to A_\mu + \epsilon\cos\theta_W b_\mu\\ b_\mu &\to b_\mu - \epsilon\sin\theta_W Z_\mu\end{aligned}$$

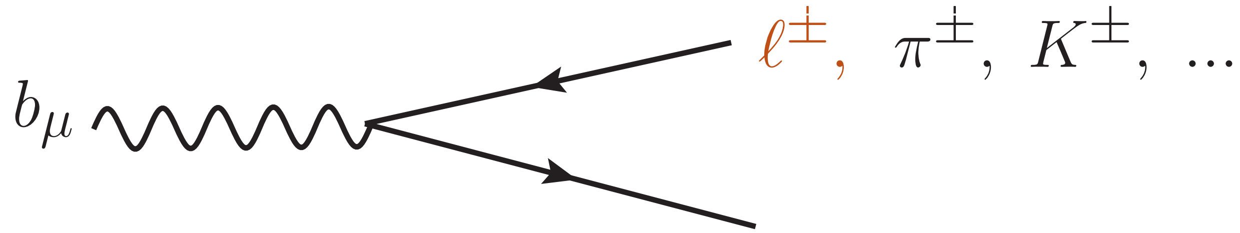
resulting in the interaction,

$$V \supset \boxed{\epsilon\cos\theta_W b_\mu J^\mu_{\rm EM}} - \epsilon\sin\theta_W Z_\mu J^\mu_{\rm dark}$$

The "dark photon" couples just like the SM photon,
but with a much suppressed coupling, ϵ

Decay of dark photon

- Dark photon is the only connection, *i.e.* "portal", to the SM
- Its decay (to SM) is always the last stage of dark sector process, giving rise to observable signals



- $m_b \simeq (0.1 \sim 1)$ GeV; form-factors are important in determining the decay BF's
- For a start, we focus on $b_\mu \to \ell^+\ell^-$.

IV. Allegro con brio

Searching for the dark sector with the most luminous collider

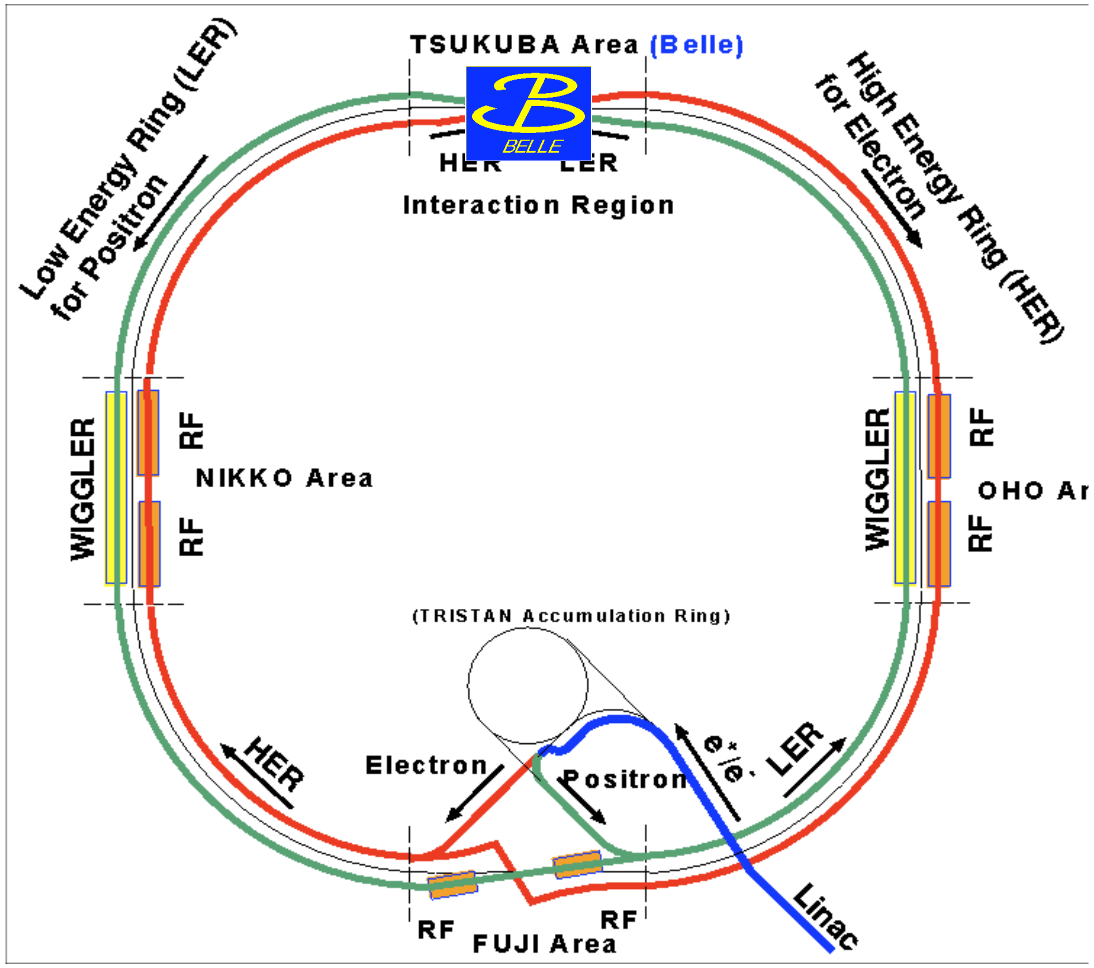
Searches for X(214) in ISR and in B decays at Belle

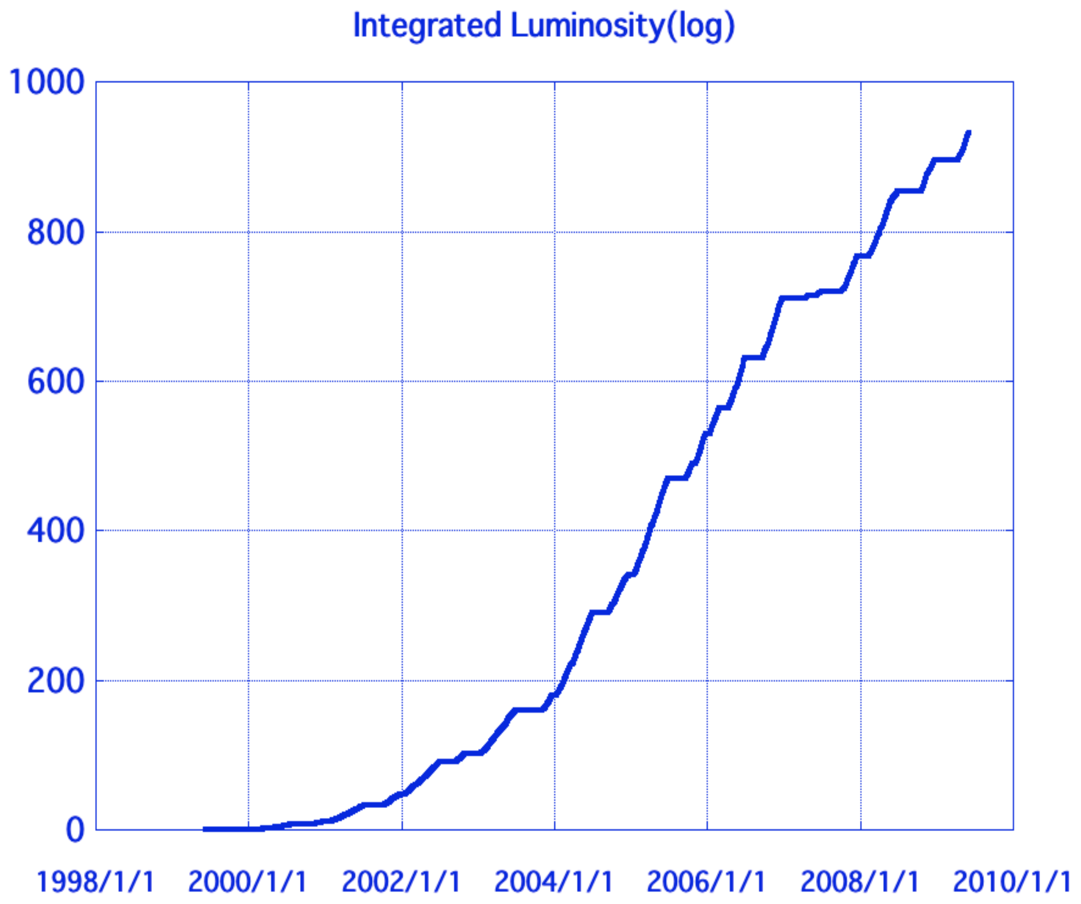
Introduction & Motivation

- Searching for GeV-scale dark sector in e^+e^- collider experiments has been strongly suggested by several theorists
  - ~~*That's what this workshop is for*, 8-)~~
- Why then $X(214)$?
  - Looking for $X(214)$ signal in ISR shares many features with searching for GeV-scale dark sector
  - with a specific goal of confirming or ruling out someone else's results/hypotheses
- What is $X(214)$?
- Belle's search for $X(214)$ in two ways
  - in ISR, of course
  - and in the B decays, too; *why not?*


Mt. Tsukuba
KEKB ring (HER+LER)
Belle detector
Linac
KEK Tsukuba site

KEKB collider

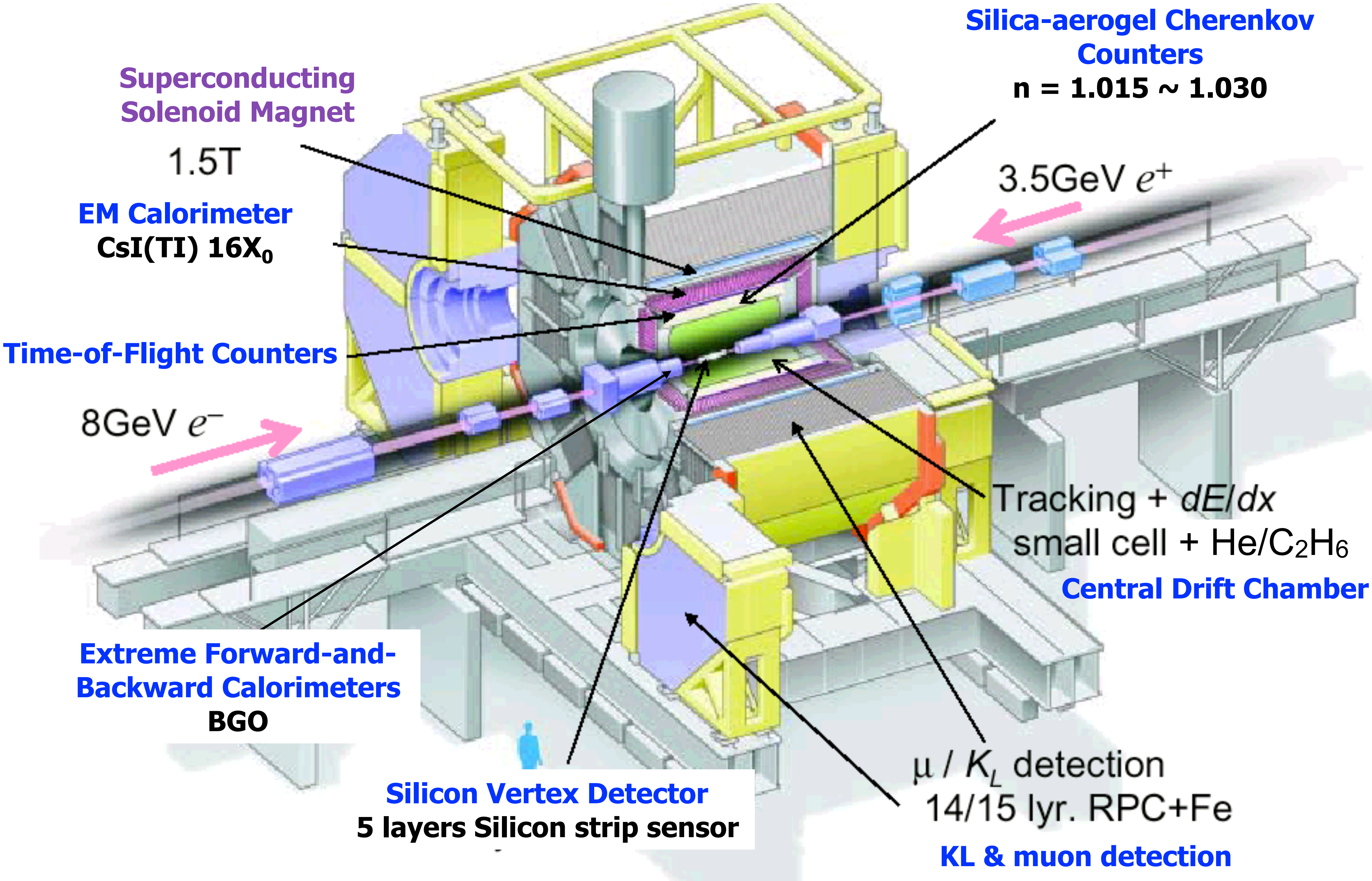




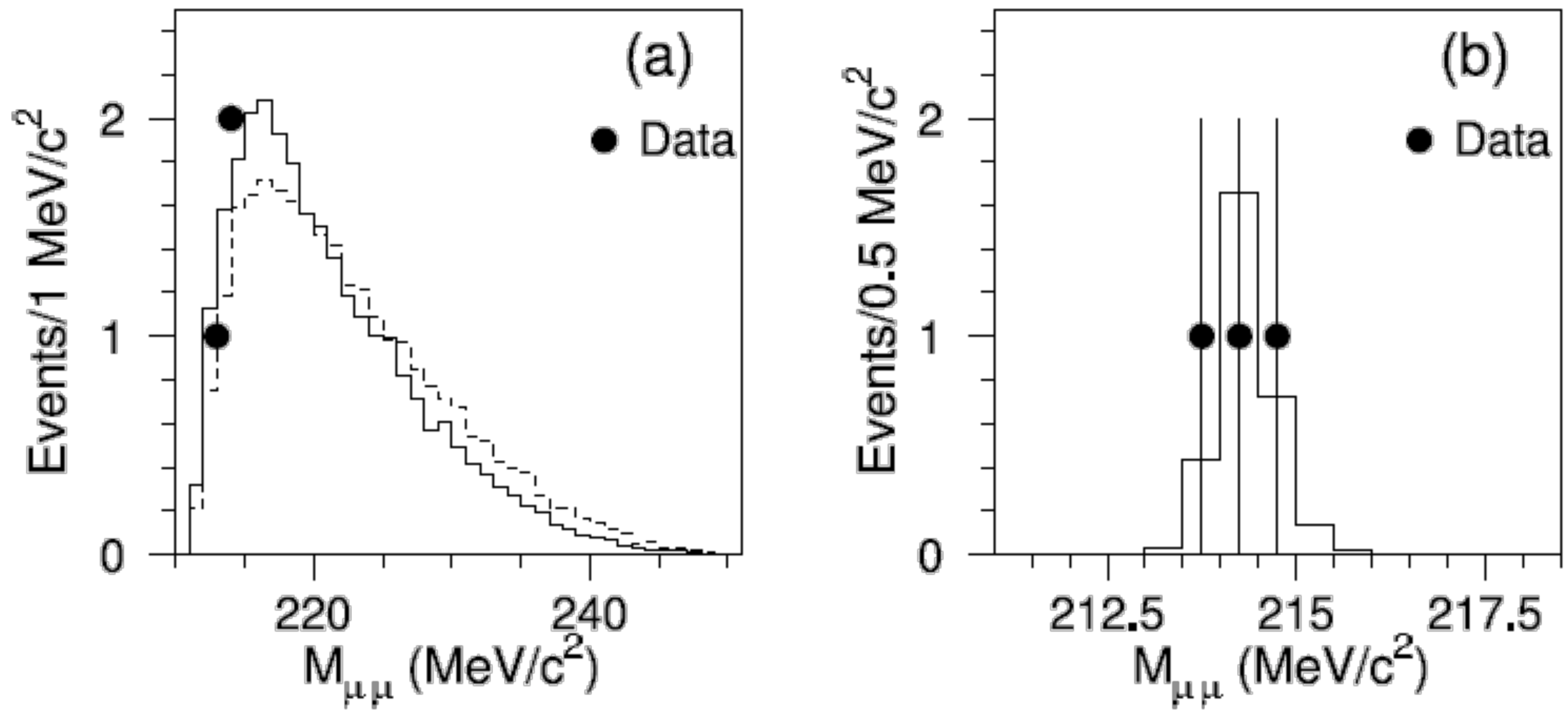
- $\sqrt{s} = 10.58$ GeV on-resonance production of $\Upsilon(4S)$
  - asymmetric energy: e^+ (3.5 GeV) on e^- (8 GeV)
  - ± 11 mrad crossing angle at IP
- Luminosity
  - $\mathcal{L}_{\text{peak}} = 2.11 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
  - $\int \mathcal{L}\, dt \approx 950\ \text{fb}^{-1}$

World record luminosity!

Belle detector

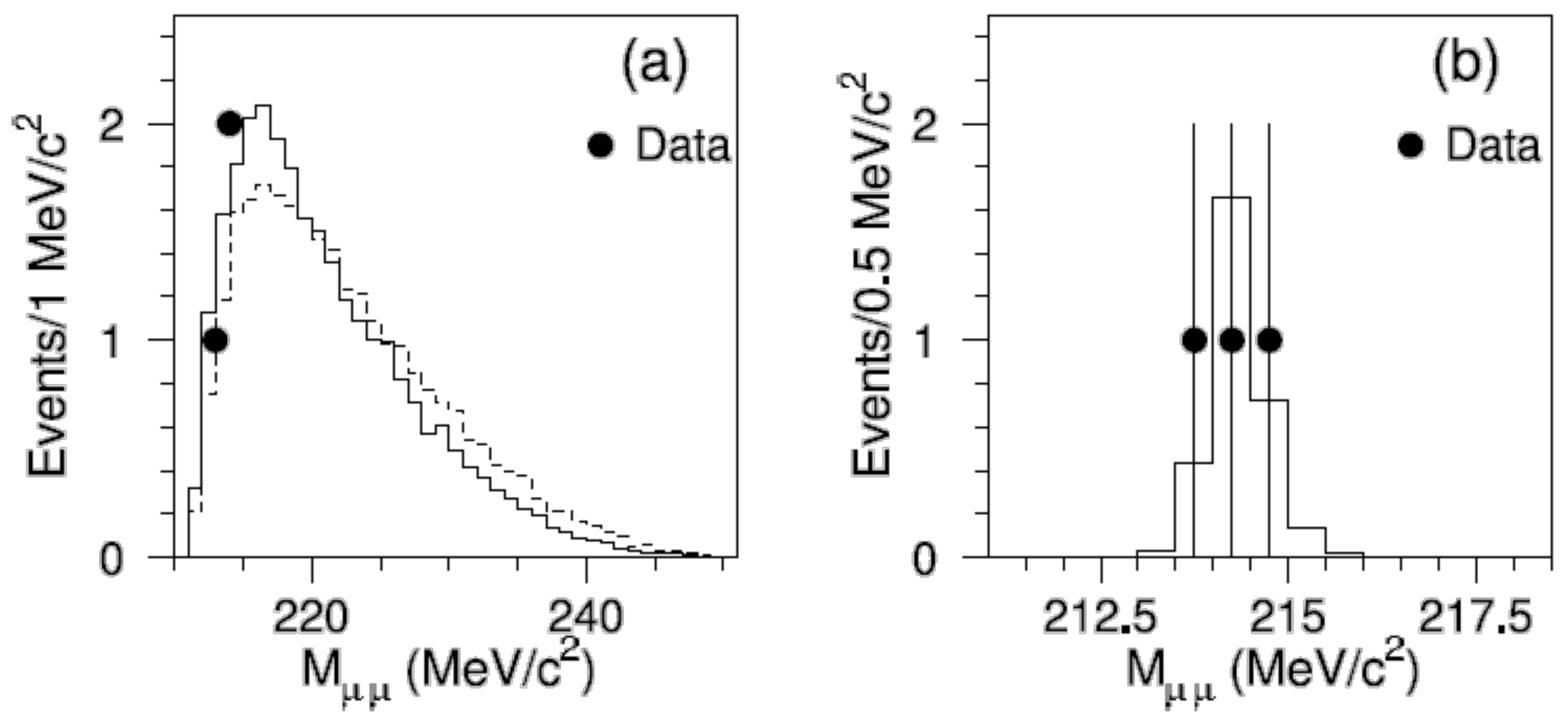


$X(214)$ from HyperCP



- Observed 3 events for $\Sigma^+ \to p\mu^+\mu^-$ — HyperCP Collab., PRL 94, 021801 (2005)
  - All three events near $M_{\mu^+\mu^-} = 214$ MeV/c^2
- Some interpretaions
  - sgoldstino ($10^{-15} \lesssim \tau_X \lesssim 10^{-11}$ s) — Gorbunov & Rubakov, PRD 73, 035002 (2006)
  - low-mass Higgs — He, Tandean & Valencia, PRL 98, 081802 (2007)
  - U-boson — Reece & Wang, JHEP 0907, 51 (2008); Pospelov, 0811.1030; Chen, *et al.* PLB 663, 100 (2008)

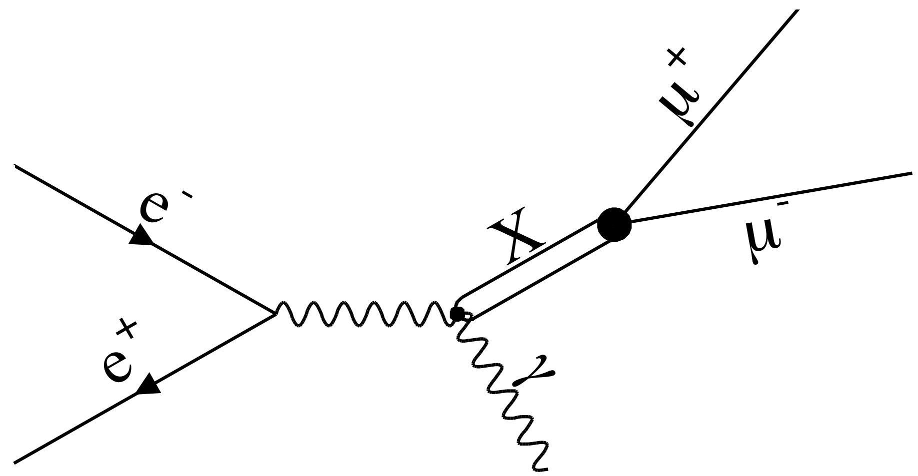
$X(214)$ from HyperCP



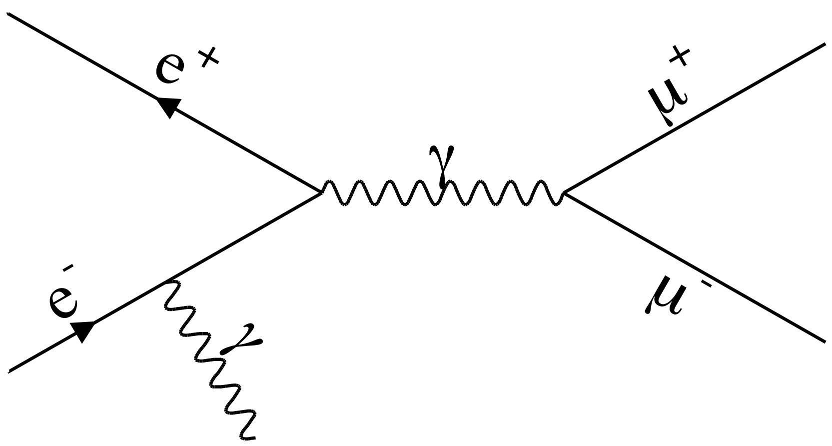
- Observed 3 events for $\Sigma^+ \to p\mu^+\mu^-$ HyperCP Collab., PRL 94, 021801 (2005)
  - All three events near $M_{\mu^+\mu^-} = 214\ \mathrm{MeV}/c^2$
- $\exists$ limits on $X(214)$ from other experiments
  - $\mathcal{B}(K_L^0 \to \pi^0\pi^0 X) \times \mathcal{B}(X \to \mu^+\mu^-) < 9.41 \times 10^{-11}$ (KTeV)
  - also from KEK-E391a (K_L^0 decays) and BaBar ($\Upsilon(3S) \to \gamma X$ decays)

$X(214)$ in ISR

- Search for $e^+e^- \to \gamma\, X(214) \to \gamma\, \mu^+\mu^-$
- Signal and background (ISR) processes

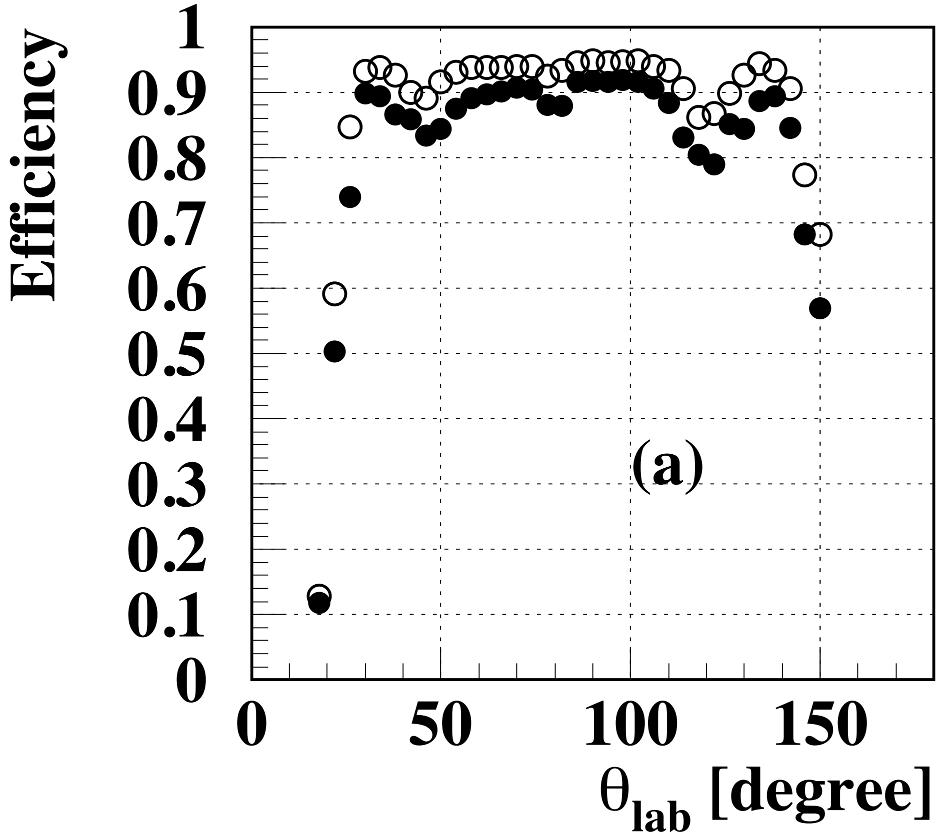


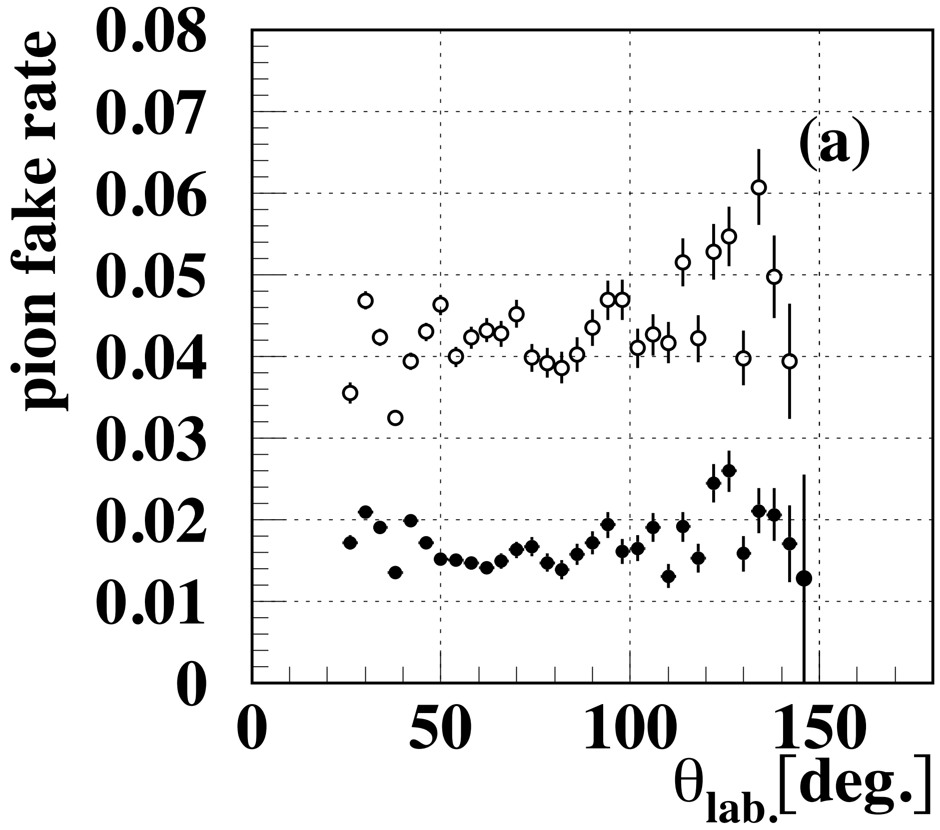
$$e^+e^- \to \gamma X(214) \to \gamma\mu^+\mu^-$$



ISR

Muon identification



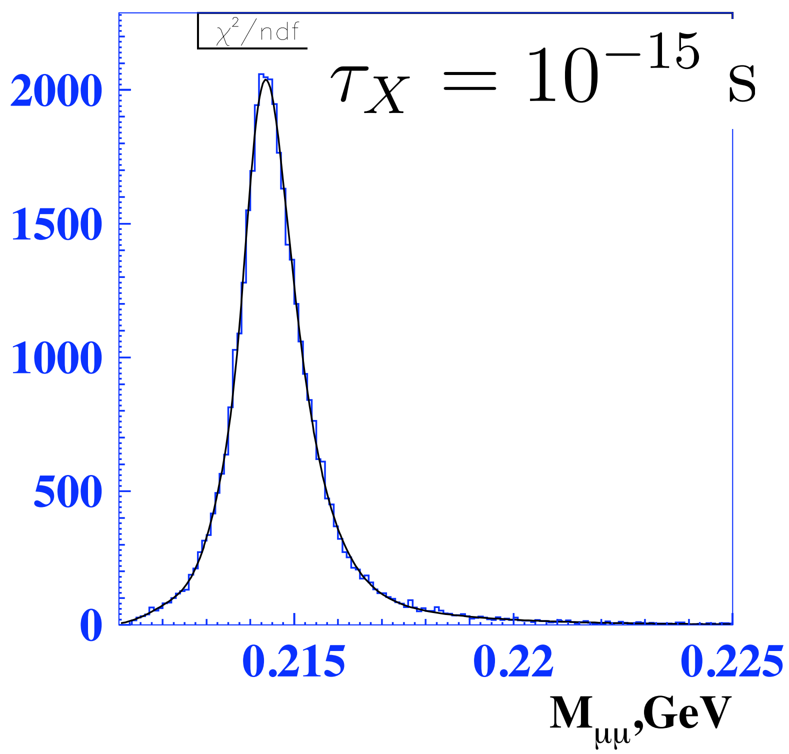


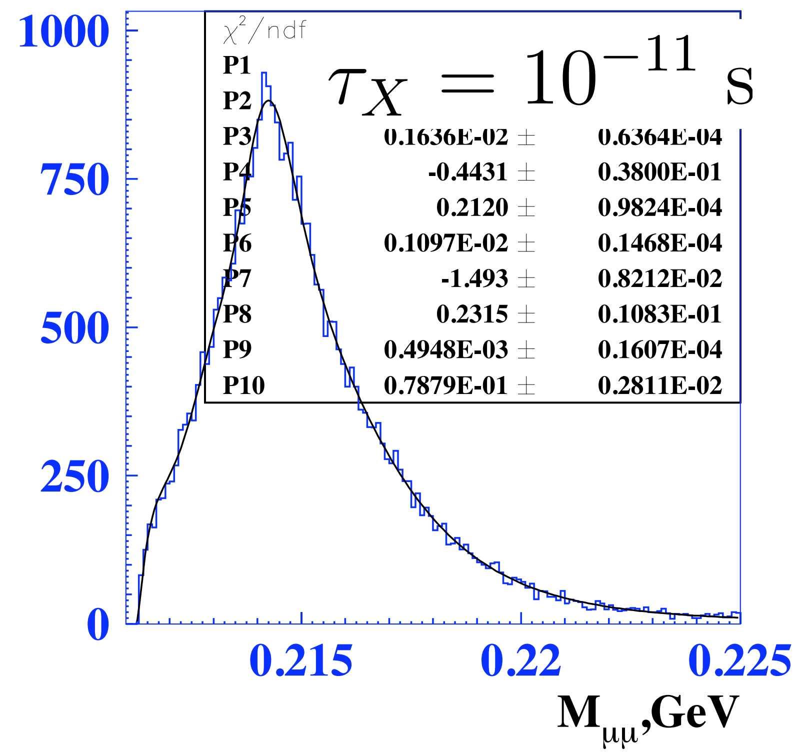
(left) Efficiency measured with $e^+e^- \to e^+e^-\mu^+\mu^-$ events

(right) Fake rate due to pion misidentification (right) measured with $K_S^0 \to \pi^+\pi^-$ events

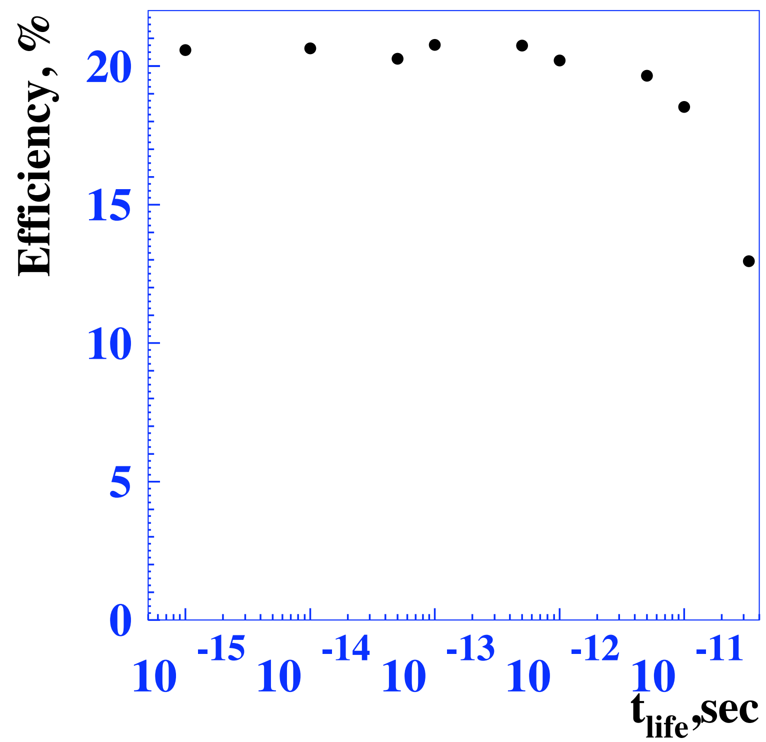
(both) $1.0 < p < 3.0$ GeV/c; $\mathcal{L}_\mu > 0.9$ (•), $\mathcal{L}_\mu > 0.1$ (○)

$X(214)$ in ISR $M_{\mu^+\mu^-}$ signal MC





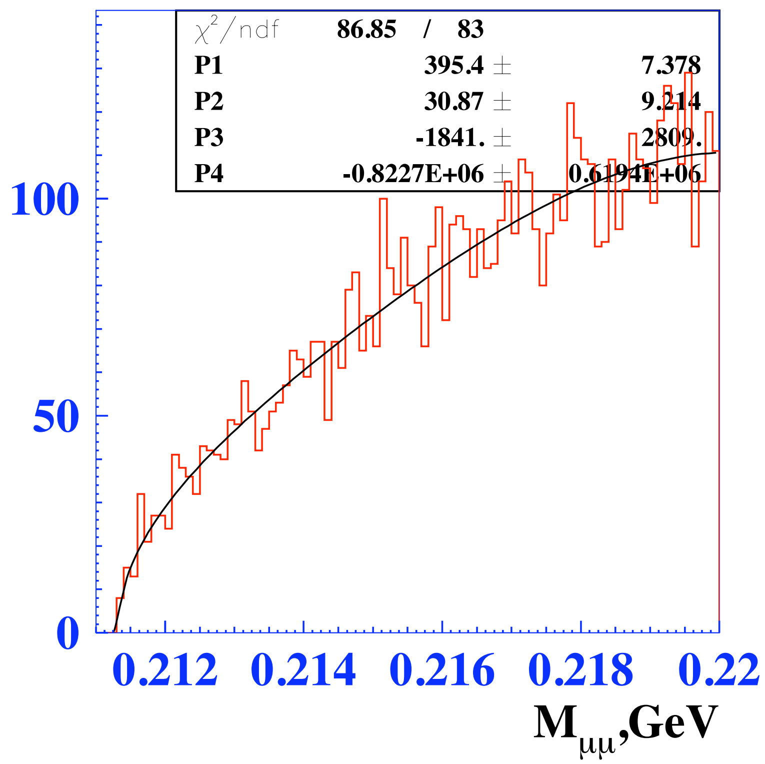
efficiency vs. τ_X



- γ distr. $\propto 1 + \cos^2\theta$
- $M_{\mu^+\mu^-}$ for assumed lifetime τ_X of $X(214)$
  - * $M_{\mu^+\mu^-}$ resolution ~ 0.6 MeV$/c^2$
    shape is well described by 3 log-gaussians
  - * $\epsilon \sim 20\%$ for $10^{-15} \leq \tau_X \leq 10^{-12}$
  - * $\gamma\beta c\tau \approx 7$ cm ($7\ \mu$m) for $\tau_X = 10^{-11}$ s (10^{-15} s)

$X(214)$ in ISR

$M_{\mu^+\mu^-}$ bkgd. shape



$M_{\mu^+\mu^-}$ from KKMC

- Background parametrization for $M_{\mu^+\mu^-}$

$$f(x) = A\beta(x)(1 + a_1 x + a_2 x^2 + a_3 x^3) \qquad (1)$$

where $\beta(x) = \sqrt{1 - (2m_\mu/x)^2}$.

- QED cross-section
$\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-) \propto \beta\,(1 - \beta^2/3)$,
but including experimental smearing effects, it can be parametrized as Eq. 1.

- for a rough estimate of sensitivity, assuming no signal
    - $\sqrt{N_{\rm bkgd}} \sim 50$ within $\sim 1\sigma$ region (see Slide 13) for $\int \mathcal{L}\,dt \approx 0.56\ {\rm ab}^{-1}$
    - Efficiency $\sim \mathcal{O}(20\%)$ (also Slide 13)
    - Estimated sensitivity: $\sigma_X \lesssim \mathcal{O}(1\ {\rm fb})$

$X(214)$ in B decays

- Why in B decays?
  - B decaying almost at rest
    gives very tight kinematic constraints, *i.e.* $M_{\rm bc}, \& \Delta E$
  - Hence B decays have been good place to find new particles, *e.g.* $X(3872)$..
  - Ample experiences of B decays to $\ell^+\ell^-$ states, *e.g.* $B \to J/\psi K^*$, $K^*\ell^+\ell^-$, etc.
  - It's good to confirm or disconfirm with two independent processes
- Some predictions for $B \to \mathcal{V}\, X(214)$ where $\mathcal{V} = K^*, \rho$, etc.

Demidov & Gorbunov, JETP Lett, 84, 479 (2006)

$$\mathcal{B}(B \to K^* X(214)) \times \mathcal{B}(X \to \mu^+\mu^-) = 10^{-9} \sim 10^{-6}$$
$$\mathcal{B}(B \to \rho\, X(214)) \times \mathcal{B}(X \to \mu^+\mu^-) = 10^{-9} \sim 10^{-7}$$

$B \to \mathcal{V}\, X(214)$ Modes of study

- Search for $B \to \mathcal{V}\, X(214)$ with $N(B\bar{B}) = 657\text{M}$

  $B^0 \to K^{*0} X(214)$ with $K^{*0} \to K^+\pi^-$ and $X(214) \to \mu^+\mu^-$
  $B^0 \to \rho^0\, X(214)$ with $\rho \to \pi^+\pi^-$ and $X(214) \to \mu^+\mu^-$

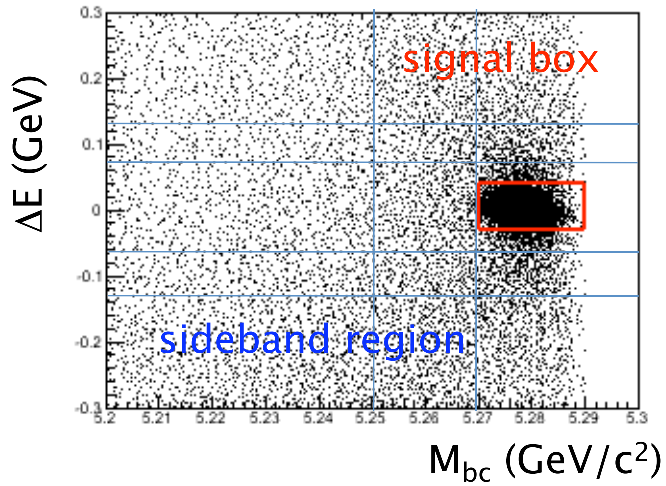
  - both pseudoscalar and axialvector assumptions for $X(214)$ are tried
    - * *only pseudoscalar results today*

- Event selection

  - good charged track: $dr < 1$ cm, $|dz| < 5$ cm
  - μ ID is tightened compared to ISR study: $\mathcal{L}_\mu > 0.95$
  - Belle standard K/π ID
  - mass windows for K^* and ρ are $\pm 1.5\Gamma$ and $\pm 1\Gamma$, respectively

- usual kinematic variables $M_{\rm bc}$ & ΔE to make sure it came from B decays

$$\Delta E = \textstyle\sum_B E^* - E^*_{\rm beam}$$
$$M_{\rm bc} = \sqrt{(E^*_{\rm beam})^2 - |\textstyle\sum_B \vec{p}^*|^2}$$



$B \to \mathcal{V} X(214)$ Signal efficiency

Decay mode	Dimuon mass resolution [keV/c²]	Signal efficiency (ε)
$B \to K^{*0}X^0$	427 ± 14	$(26.3 \pm 0.1)\%$
$B \to \rho^0 X^0$	428 ± 15	$(23.5 \pm 0.1)\%$

- Signal mass window for $X(214)$ is

$$211.5 < M_{\mu^+\mu^-} < 217.1 \text{ MeV}/c^2$$

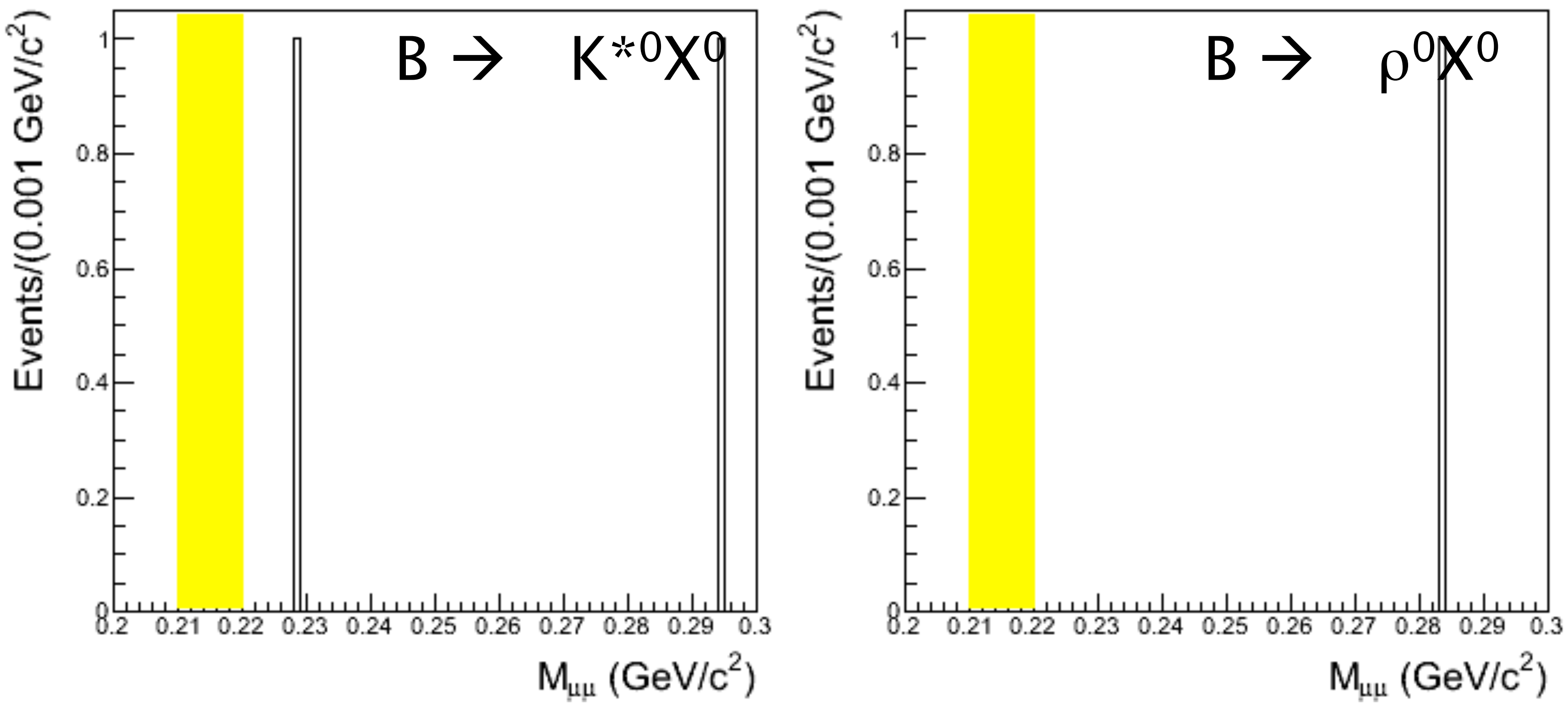
  $\sim 3\sigma$ range considering HyperCP uncertainty plus Belle resolution

- $X(214)$ is assumed to decay promptly, say $\tau_X \sim 10^{-20}$ s, such that lifetime effect can be neglected w/o noticeable effects on the width
- Other (more realistic) choices for τ_X are also tried: 10^{-15} s, 10^{-12} s,

  $\Rightarrow$ *no significant difference!*

$B \to \mathcal{V}\, X(214)$

Results



- No events in the signal region in both modes
- Systematic uncertainty
  - * mostly efficiency error due to particle ID, tracking
  - * 5.2% for $B \to K^* X(214)$, 5.7% for $B \to \rho\, X(214)$
  - * 'prompt' decay w/o noticeable effect in the width is assumed
- Upper limits (@ 90% CL.) *preliminary*

$$\mathcal{B}(B \to K^* X(214)) \times \mathcal{B}(X(214) \to \mu^+\mu^-) < 2.01 \times 10^{-8}$$
$$\mathcal{B}(B \to \rho\, X(214)) \times \mathcal{B}(X(214) \to \mu^+\mu^-) < 1.51 \times 10^{-8}$$

$B \to \mathcal{V}\, X(214)$ Theory B.F. as sgoldstino

Branching ratios of decays $P_{B,D} \longrightarrow VP(P \longrightarrow \mu^+\mu^-)$ in the models I, II, and III. Branching ratios of decays $P_{B,D} \longrightarrow VP(P \longrightarrow \gamma\gamma)$ are given by the same numbers multiplied by $\Gamma(P \longrightarrow \gamma\gamma)/\Gamma(P \longrightarrow \mu^+\mu^-)$

Decay	h_{jl}	$A_0^{(P_{B,D},V)}$	$\mathrm{Br}_{(\text{model I})}$	$\mathrm{Br}_{(\text{model II})}$	$\mathrm{Br}_{(\text{model III})}$
$B_s \longrightarrow \phi P(P \longrightarrow \mu^+\mu^-)$	$h_{23}^{(D)}$	0.42 [18]	6.5×10^{-9}	8.8×10^{-6}	8.7×10^{-6}
$B_s \longrightarrow K^{*0} P(P \longrightarrow \mu^+\mu^-)$	$h_{13}^{(D)}$	0.37 [18]	5.3×10^{-9}	7.2×10^{-6}	2.3×10^{-7}
$B_c^+ \longrightarrow D^{*+} P(P \longrightarrow \mu^+\mu^-)$	$h_{13}^{(D)}$	0.14 [19]	3.2×10^{-10}	4.4×10^{-7}	1.4×10^{-8}
$B_c^+ \longrightarrow D_s^{*+} P(P \longrightarrow \mu^+\mu^-)$	$h_{23}^{(D)}$	0.14[a]	3.0×10^{-10}	4.0×10^{-7}	4.0×10^{-7}
$B_c^+ \longrightarrow B^{*+} P(P \longrightarrow \mu^+\mu^-)$	$h_{12}^{(U)}$	0.23 [20]	4.1×10^{-10}	4.4×10^{-8}	8.2×10^{-7}
$B^+ \longrightarrow K^{*+} P(P \longrightarrow \mu^+\mu^-)$	$h_{23}^{(D)}$	0.31 [17]	3.8×10^{-9}	5.2×10^{-6}	5.1×10^{-6}
$B^0 \longrightarrow K^{*0} P(P \longrightarrow \mu^+\mu^-)$			3.5×10^{-9}	4.8×10^{-6}	4.7×10^{-6}
$B^0 \longrightarrow \rho P(P \longrightarrow \mu^+\mu^-)$	$h_{13}^{(D)}$	0.28 [17]	3.1×10^{-9}	4.2×10^{-6}	1.4×10^{-7}
$B^+ \longrightarrow \rho^+ P(P \longrightarrow \mu^+\mu^-)$			3.3×10^{-9}	4.6×10^{-6}	1.3×10^{-7}
$D^0 \longrightarrow \rho P(P \longrightarrow \mu^+\mu^-)$	$h_{12}^{(U)}$	0.64 [17]	1.4×10^{-9}	1.5×10^{-7}	2.8×10^{-6}
$D^+ \longrightarrow \rho^+ P(P \longrightarrow \mu^+\mu^-)$			3.5×10^{-9}	3.7×10^{-7}	7.0×10^{-6}

[a] We did not find any estimate of this form factor in literature and use this value as an order-of-magnitude estimate, which is sufficient for our study.

Demidov & Gorbunov, JETP Lett, 84, 479 (2006)

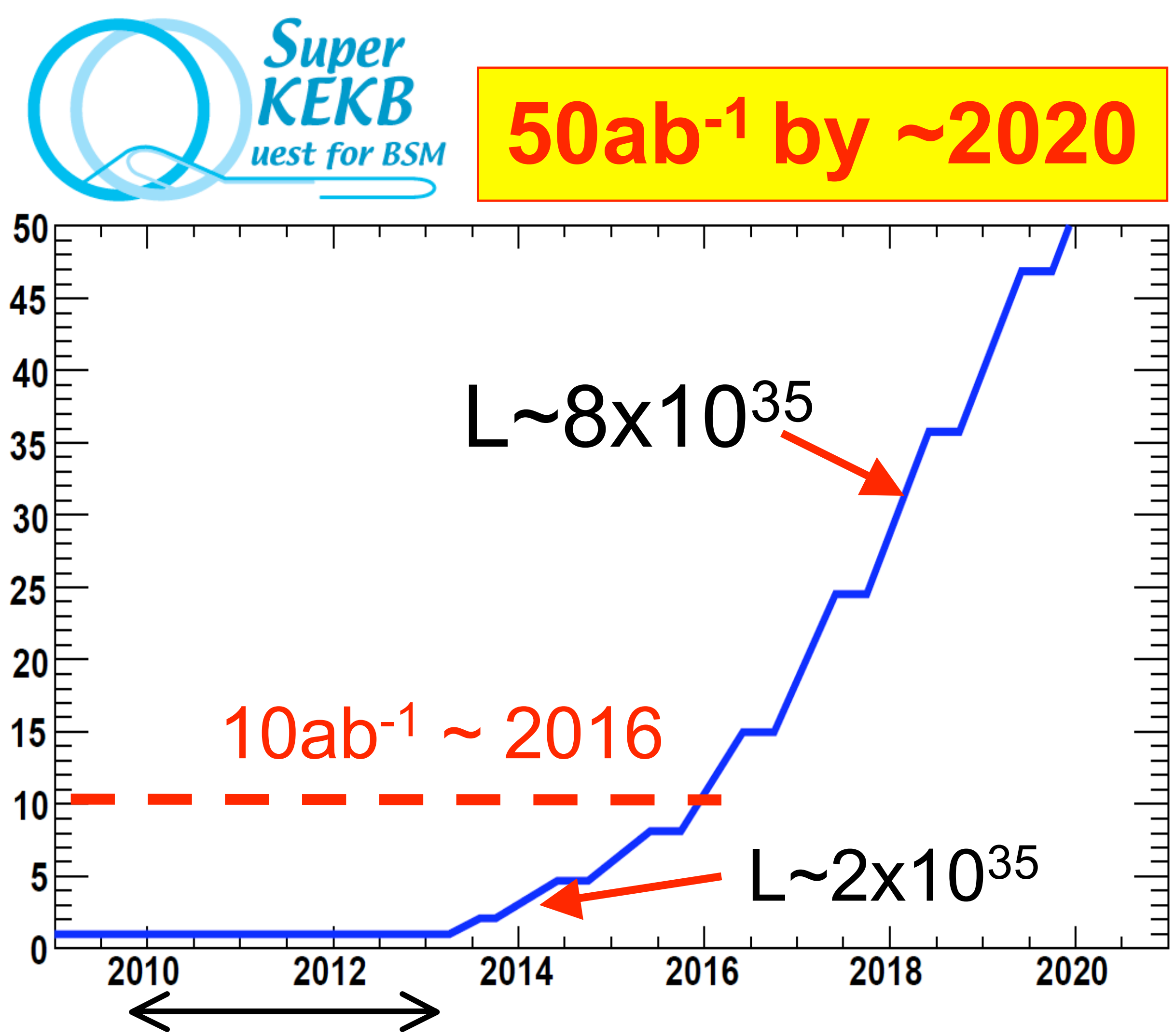
Our upper limits are not consistent with models II and III.

Summary and Prospects

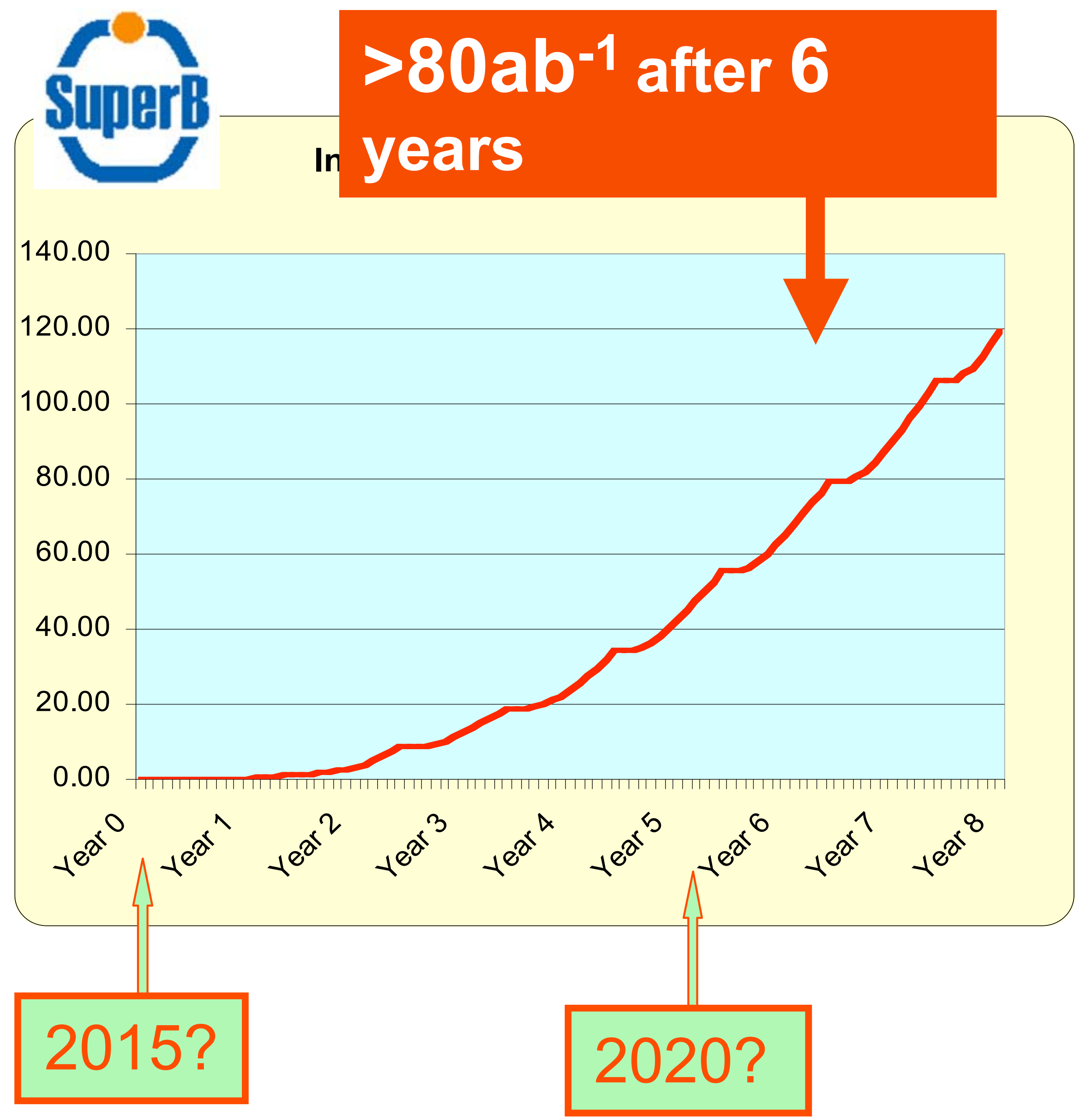
- Belle is searching for $X(214)$ in both ISR and B decays
- ISR
  - basic machineries are ready, including optimized vertexing
  - currently checking systematic issues
- in $B \to K^* X(214)$ and $B \to \rho X(214)$ decays
  - preliminary upper limits for *promptly-decaying* **pseudoscalar** assumption of $X(214)$ is available

    $\mathcal{B}(B \to \mathcal{V}\, X(214)) \times \mathcal{B}(X(214) \to \mu^+\mu^-) \lesssim \mathcal{O}(10^{-8})$
  - extending the search to be model-independent (*wider ranges of* m_X *and* τ_X) as well as trying **axialvector** assumptions
- After completing the $X(214)$ analysis, we will continue the search for general masses and lifetimes, which can be related to the search for GeV-scale Dark Sector

Luminosity prospects for future e+e- collider(s)

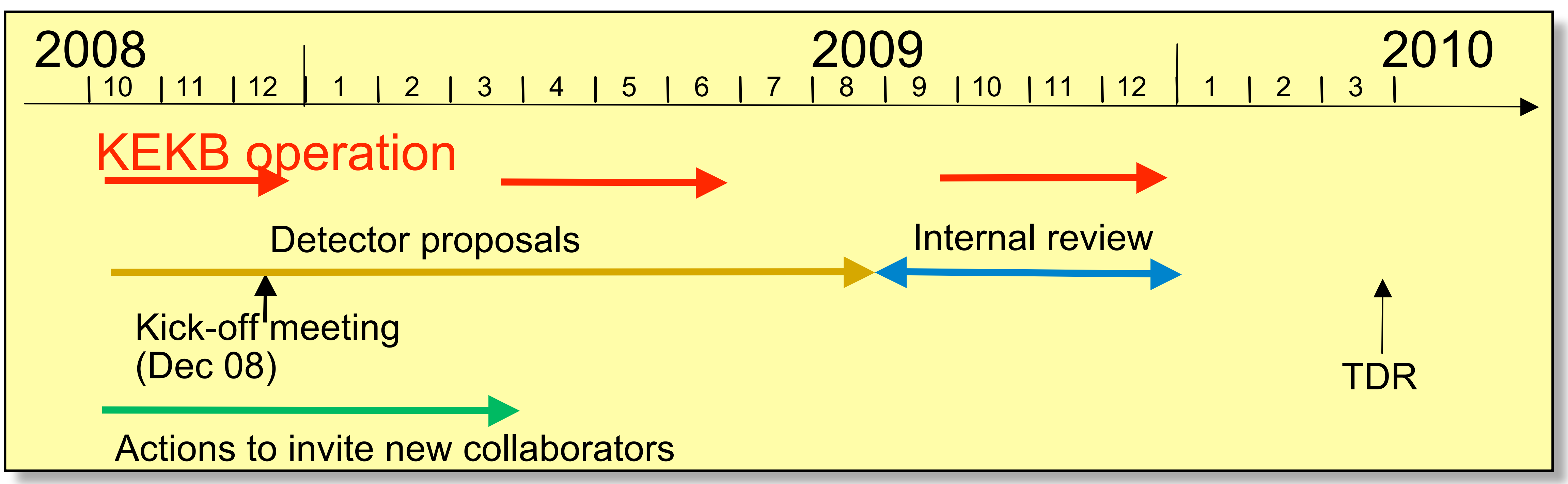


3 year shutdown for upgrade



The Belle II experiment

- Jun 2004: Letter of Intent for SuperKEKB/Belle II
- Jan 2008: KEK roadmap
  - SuperKEKB is identified as KEK lab priority
- Dec 2008: Belle II collaboration officially formed
  - 13 countries, 43 institutes, about 300 collaborators
- May 2009: supplemental budget
  - 5 M$ for Belle II, 27 M$ for KEKB upgrade
- Nov 2009: 4th open collaboration meeting



Summary

- While SUSY-motivated WIMP is still the favorite candidate for DM,
- very recently, new models of DM, based on GeV-scale dark sector have been proposed and very actively discussed along w/ many expt'l plans
- Belle, with the world's most luminous collider KEKB, also has joined this search
- With Super-KEKB/Belle-II, we will have x100 more data
  - massive data-mining shall/will be done
  - stay tuned for exciting news!

Nuclear Physics B347 (1990) 1–11
North-Holland

NEUTRINO MOMENTS, MASSES AND CUSTODIAL SU(2) SYMMETRY *

Howard GEORGI and Michael LUKE

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Received 17 April 1990

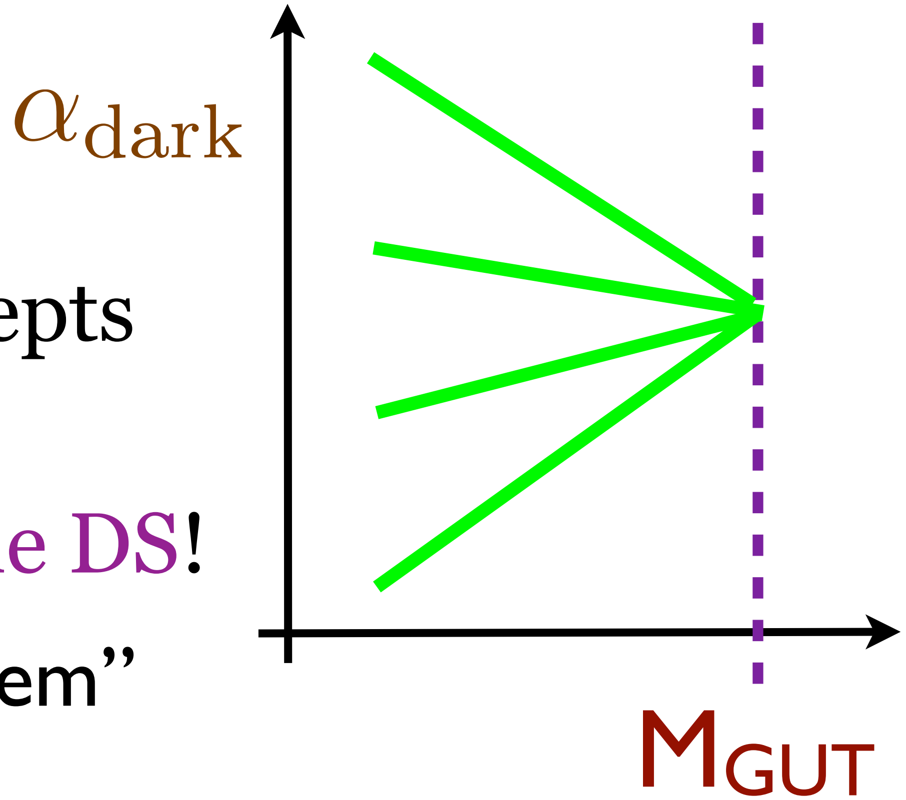
We identify and exemplify a new mechanism which leads to a nonzero magnetic moment for a neutrino, while suppressing the neutrino's mass. The mechanism requires that the contribution to the neutrino mass of the new particles that are responsible for its magnetic moment is approximately canceled by a contribution from neutral particles, related by a custodial SU(2) symmetry.

1. The problem

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent modulation of the flux of solar neutrinos with the sun-spot cycle, is certainly intriguing [3]. It is, of course, possible that this is an astrophysical problem rather than a particle physics problem. But that would require a synchronization of cycles of the interior of the sun with those of the convective layer, both in frequency and in *phase*. Thus it seems particularly interesting that there may be a particle physics explanation of this effect [4], involving a magnetic moment of the electron neutrino of the order of $10^{-11}\mu_B$.

Epilogue

- Two methods of probing the dark sector
  - not paying for ϵ -- direct detection of DM
  - paying for ϵ -- use high-L / low-E collider
- If such a sector is discovered,
  - it could allow us to study the core concepts which we care about, *at low-E* !
  - e.g. probe SUSY & SUSY-breaking in the DS!
    - analogy: Galilei's discovery of "solar system" in Jupiter & its moons



Thank You!