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Updates on particle physics and cosmology

Hitoshi Murayama (IPMU Tokyo, Berkeley)

YITP workshop on quantum field and string theories

Aug 1, 2008

INSTITUTE FO
MATHEMATIC

New intl research institute in Japan

- astrophysics
- particle theory
- particle expt
- mathematics

official language: English

>30% non-Japanese

$14M/yr for 10 years

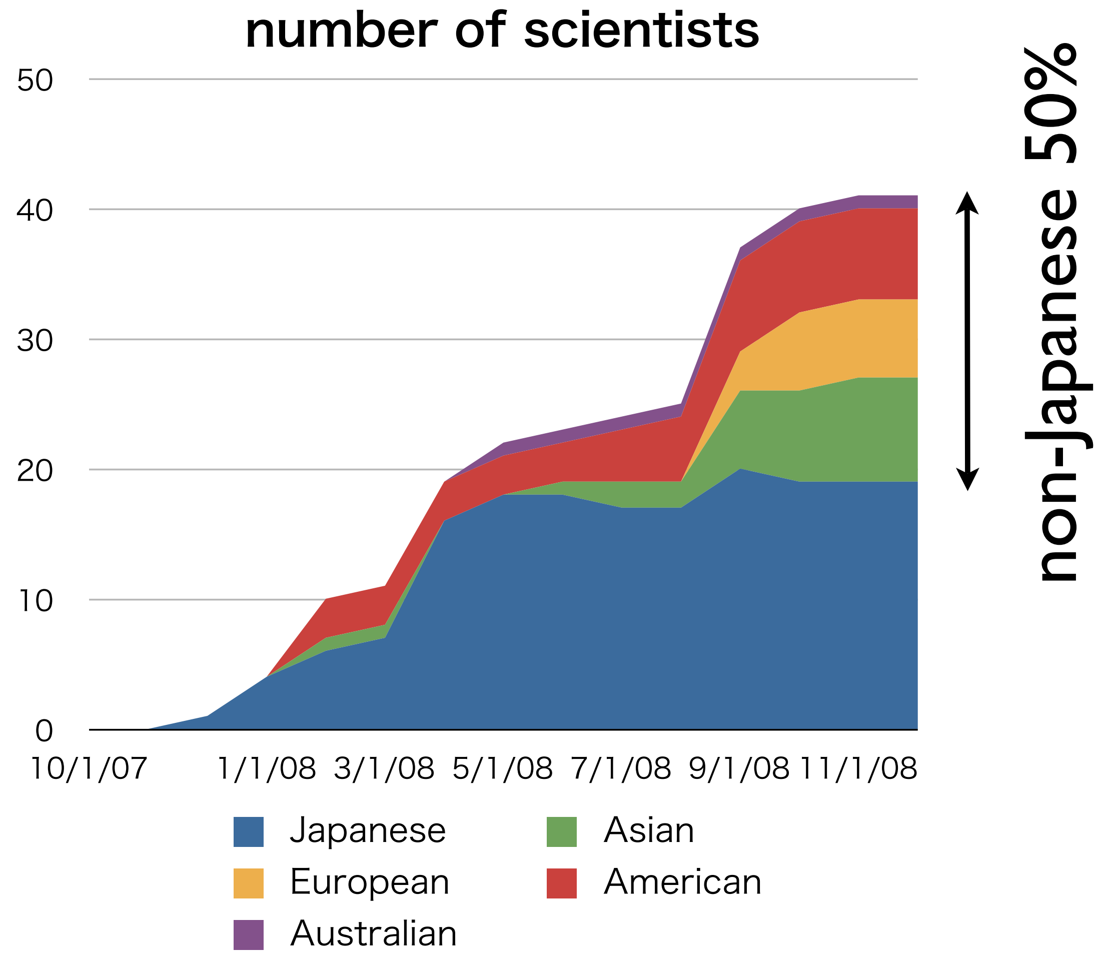
launched Oct 1, 2007

≈20 now, ≈40 in fall

- excellent facul young and dyn
- will hire about 30 mo scientists
- support visitors!
- new building in 2009
- intl guest house in 20
- wkshp about a mont
- quantum black hole (Sep 12-16)
- sympletic manifoleds (Sep 16-1


Winter 2009 occupancy
~5900m^2

On Site Scientists



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Updates on particle physics and cosmology

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What next?

Hitoshi Murayama (IPMU Tokyo, Berkeley)
YITP workshop on quantum field and string theories
Aug 1, 2008

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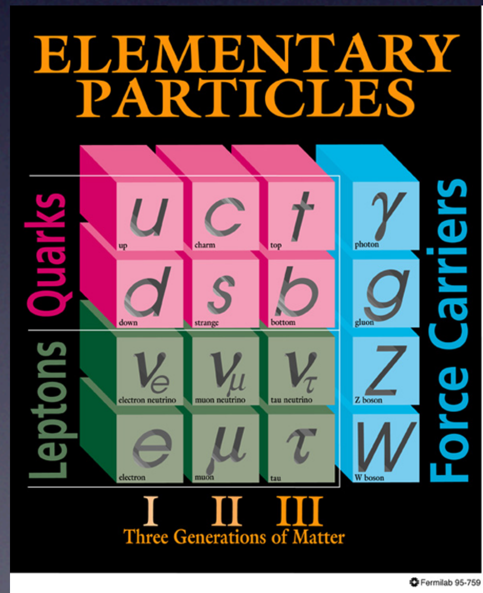
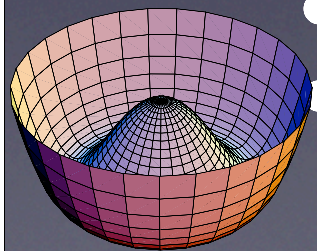
major shift

- particle physics has been trying to understand matter and forces since 1897
- since 60's, standard model has been verified experimentally. Great achievement of the 20th century physics. (*Higgs needed!*)
- At the same time, we did not see the steps beyond, sense of suffocation
- Now totally changed: data require new physics beyond the standard model!

what we used to do

- Given lack of experimental evidence, we’ve focused on *aesthetic* reasons why we need physics beyond the standard model
  - hierarchy problem
  - why three generations?
  - masses and mixings?
  - why only one scalar multiplet?
  - why does it condense?
  - anomaly cancellations
  - why SU(3)>SU(2)>U(1)?





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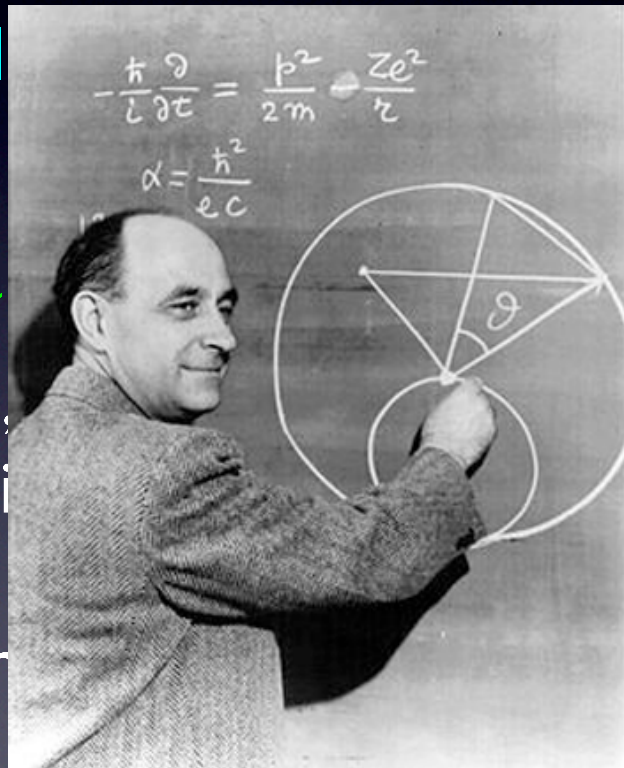
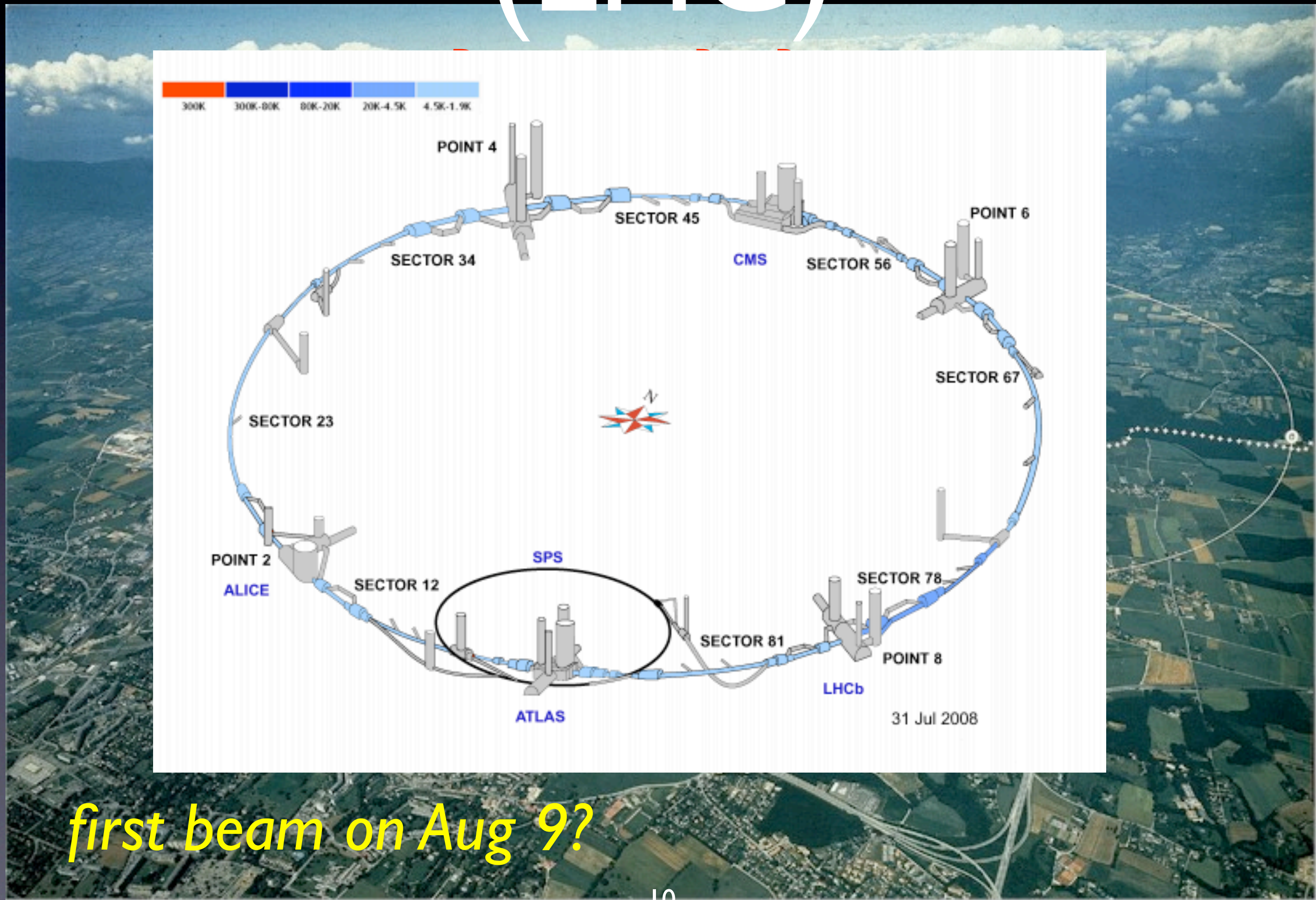
New Era

- ~1900 reached atomic scale 10^{-8}cm≈α/m_e
- ~1970 reached strong scal

  10^{-13}cm≈$Me^{-2\pi/\alpha_s b0}$
- ~2010 will reach weak sca
- known since Fermi (1933),
- presumably it is also a deri fundamental theory
- supersymmetry? extra dim theory?
- If so, we expect rich spectrum of new



Large Hadron Collider (LHC)



first beam on Aug 9?

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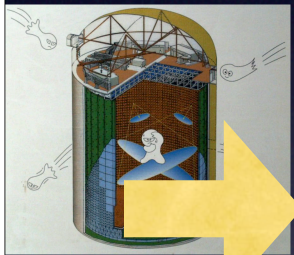
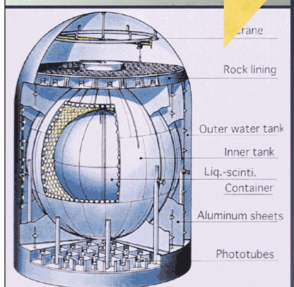
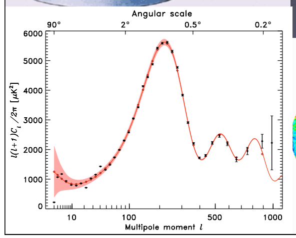
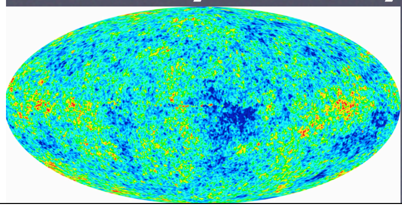
Experimental Facts

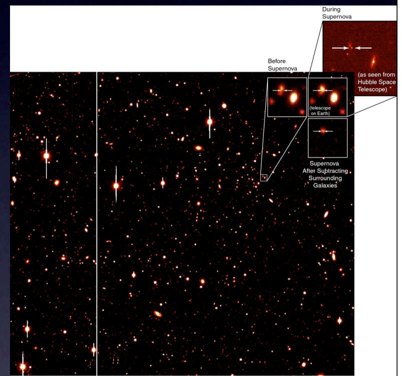
- Five facts standard model cannot explain
  - finite neutrino mass (1998, 2002)
  - accelerating universe (1998)
  - non-baryonic dark matter (2003)
  - acausal nearly Gaussian scale-invariant density fluctuation (2003)
  - baryon asymmetry (reconfirmed 2003)

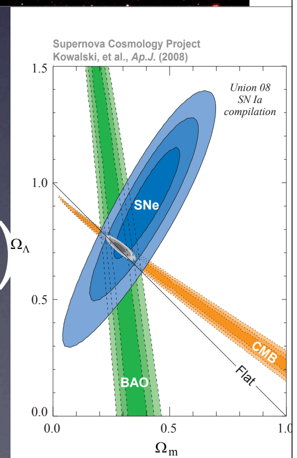












Evidence for non-baryonic dark matter

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Energy Budget of the Universe

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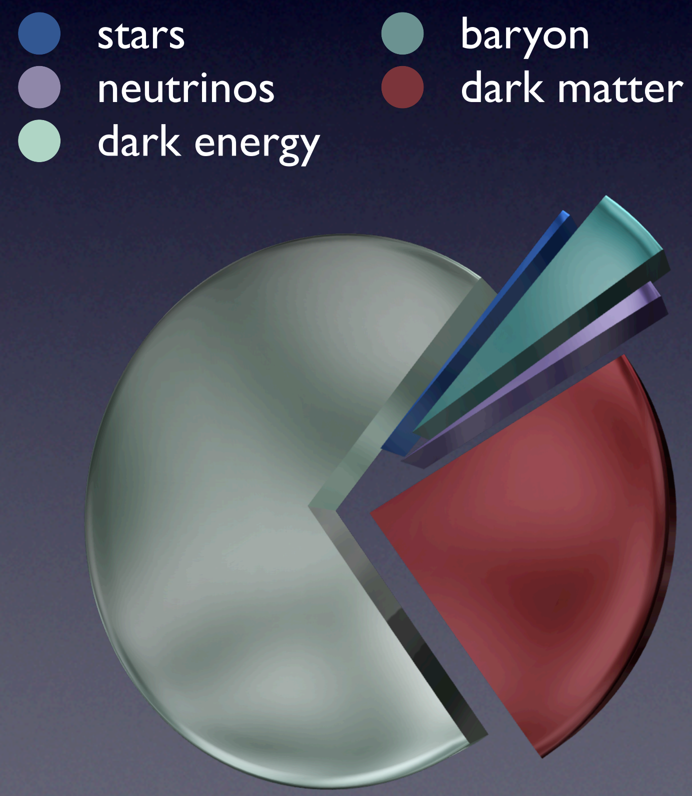
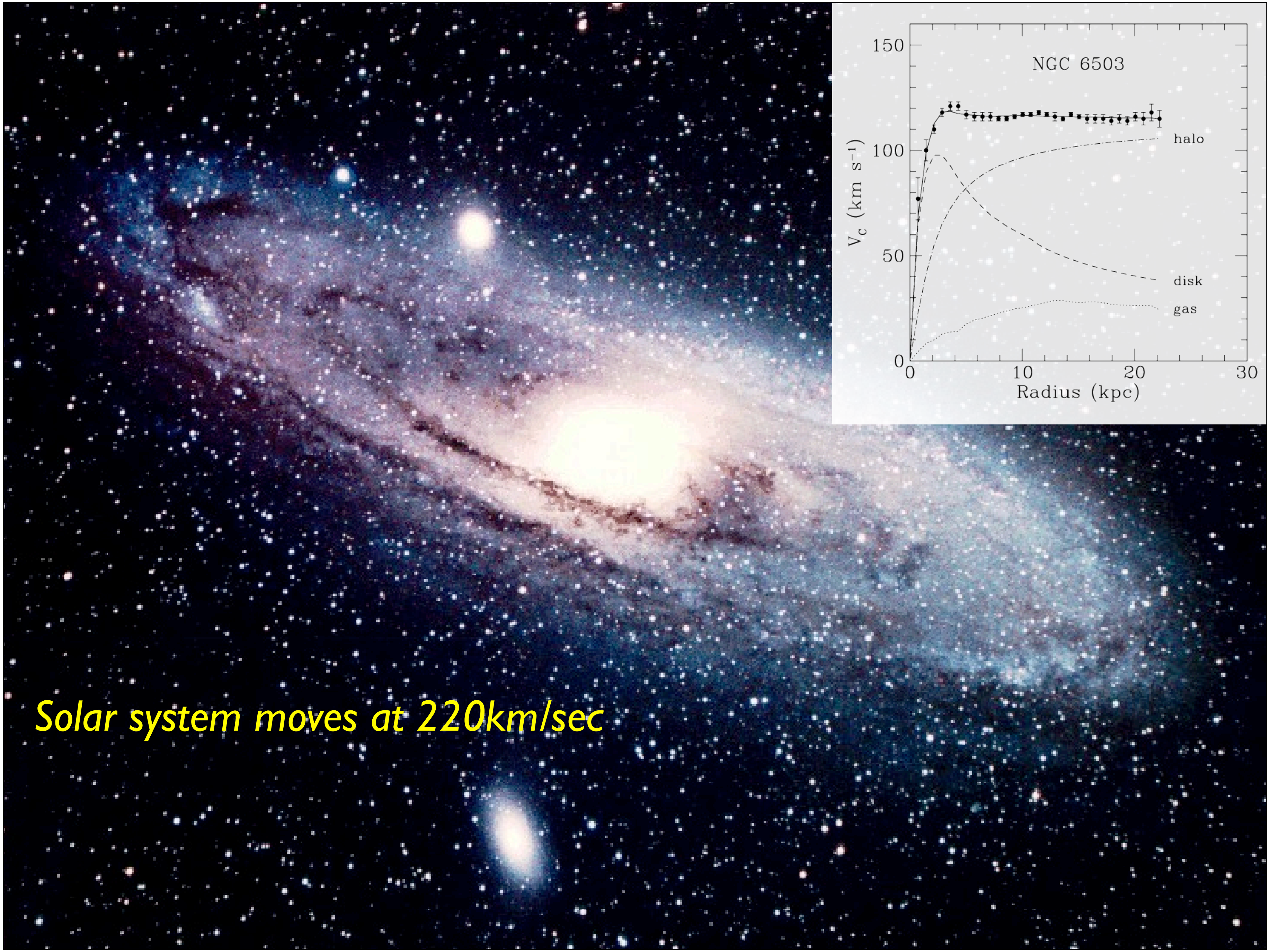
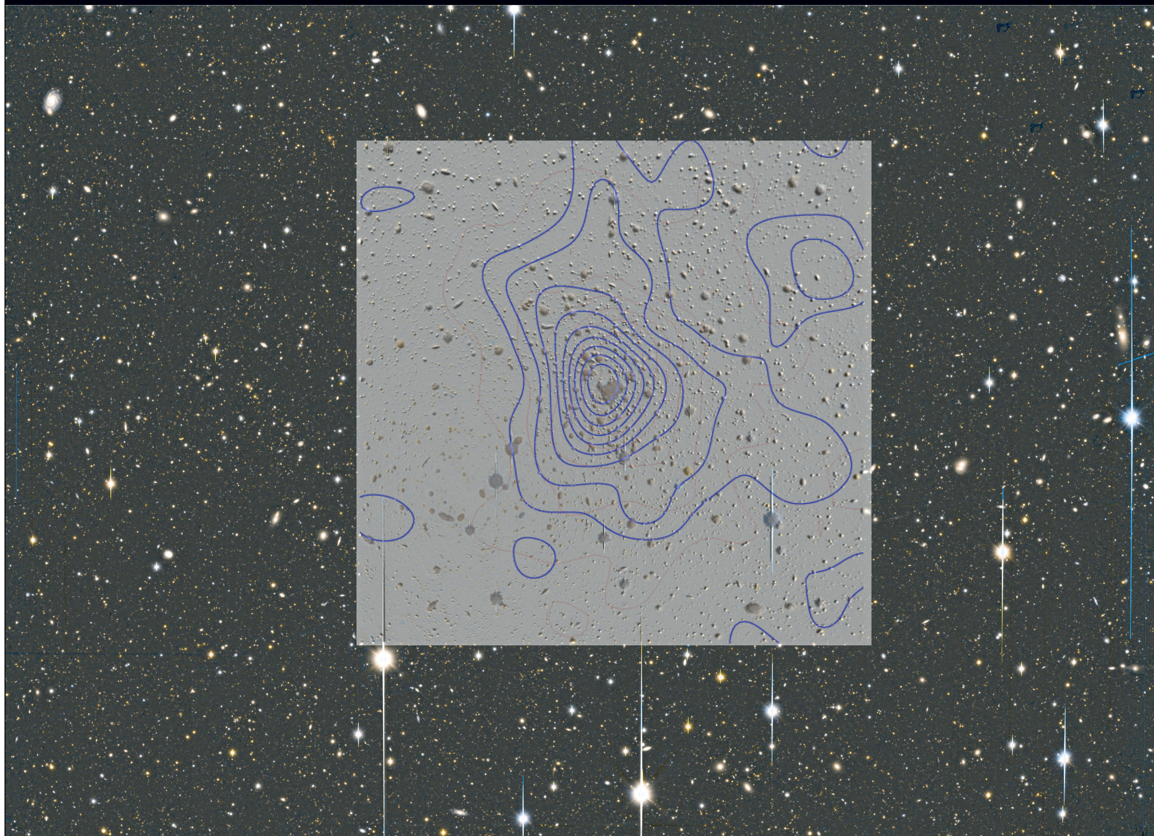
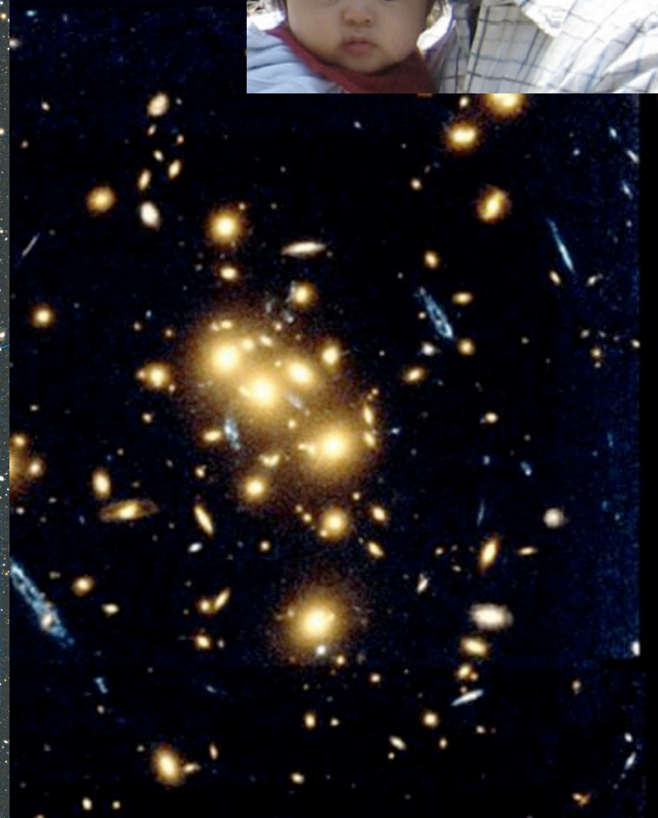
- Stars and galaxies are only ~0.5%
- ν ~0.1–1.5%
- Rest of ordinary matter (e, p & n) 4.4%
- Dark Matter 23%
- Dark Energy 73%
- Anti-Matter 0%
- Higgs ~10^{62}%??



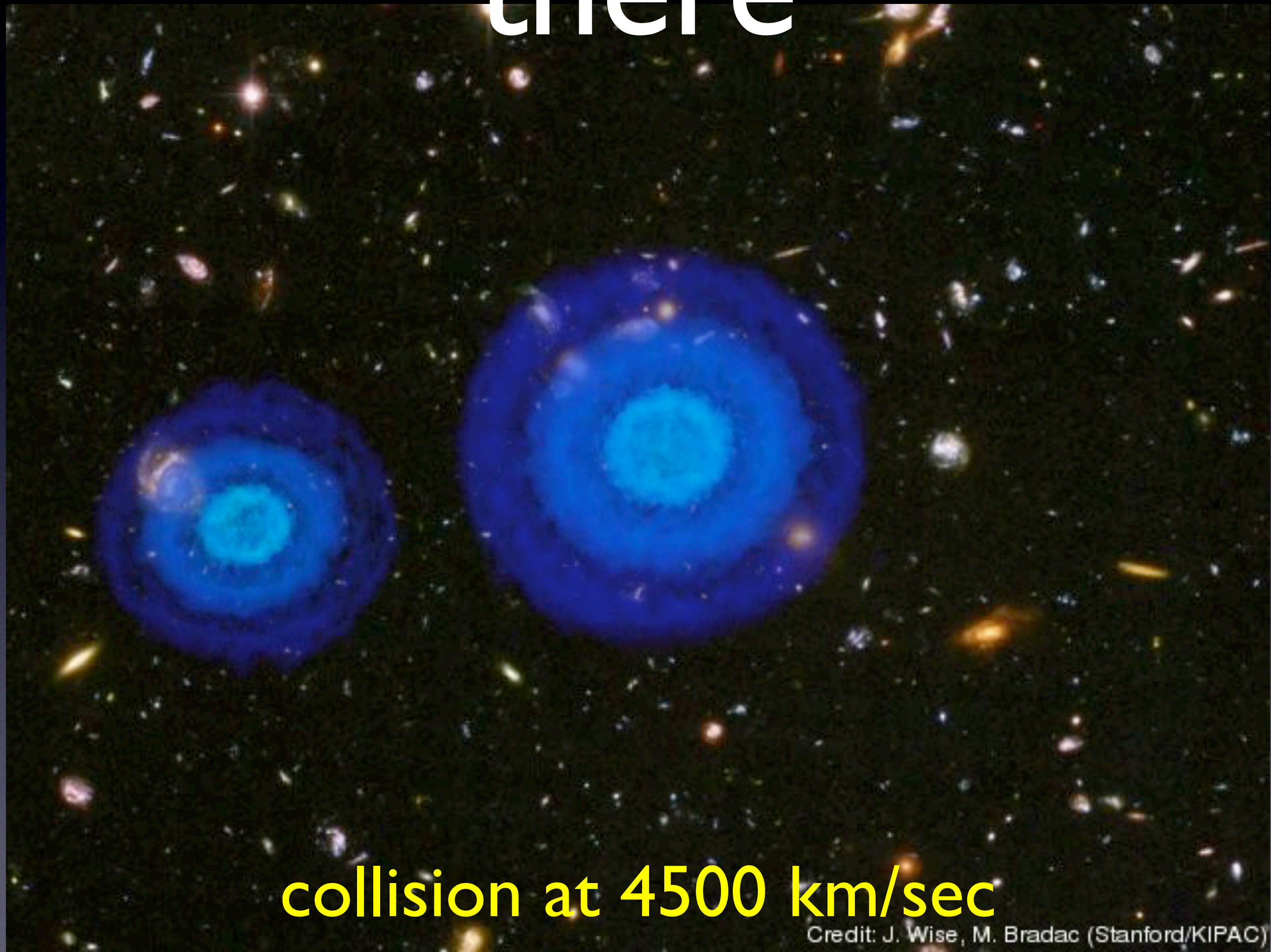

NGC 6503
150
100
50
0
V_c (km s^{-1})
halo
disk
gas
0
10
20
30
Radius (kpc)
Solar system moves at 220km/sec

See the invisible DM through weak lensing

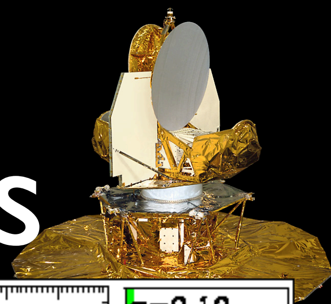


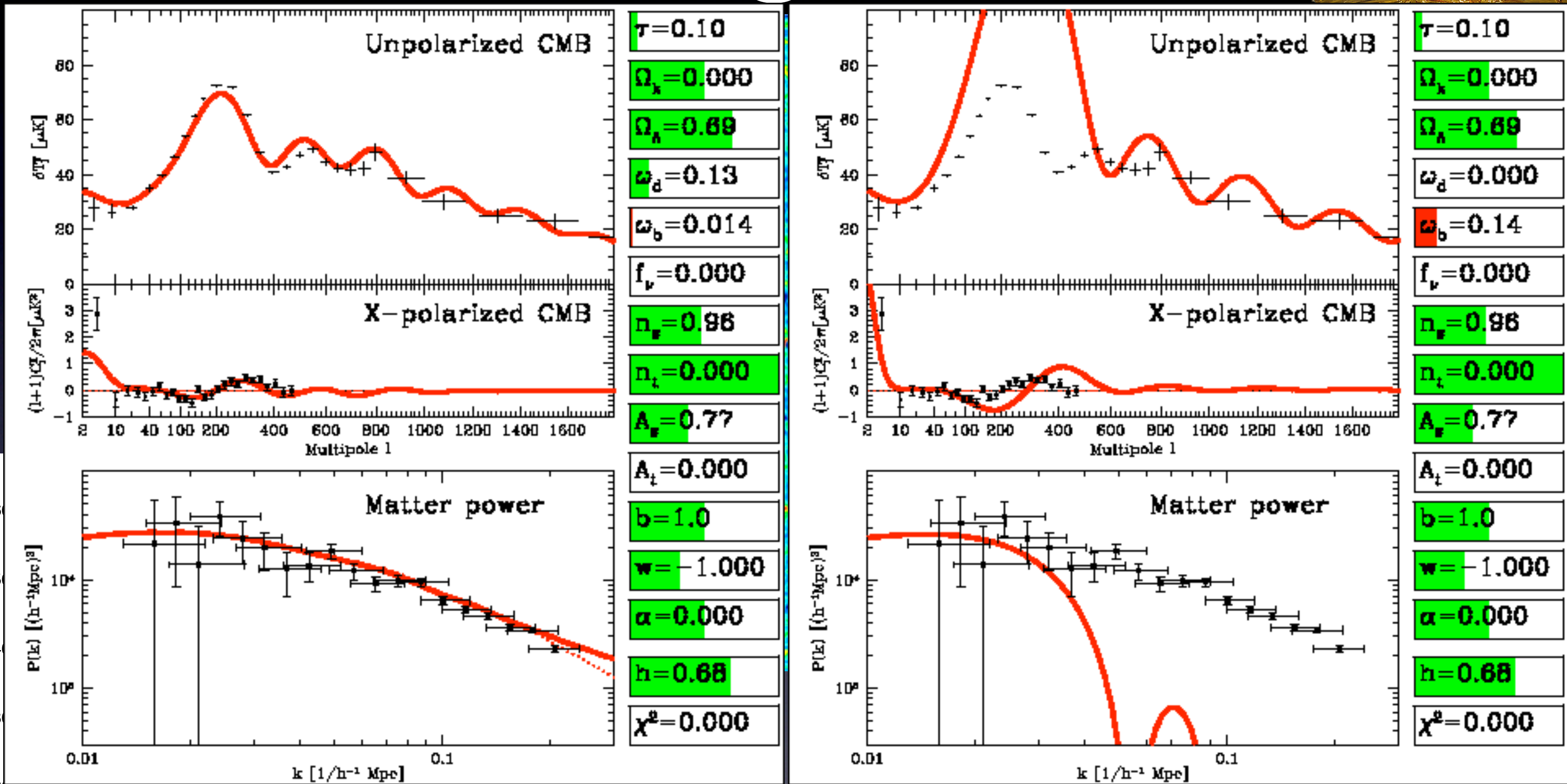


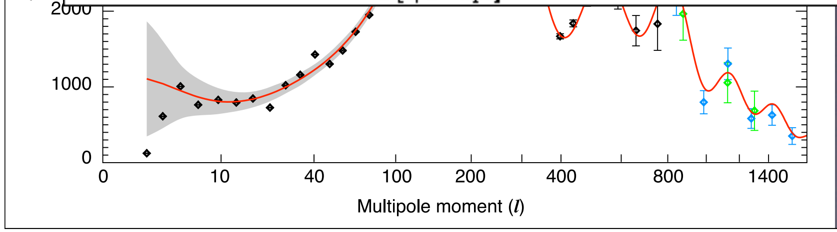
You don't want to be there



Cosmological scales







matter/all atoms=6.03±0.03

See Tegmark movie

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Known Facts about Dark Matter

Cold and Neutral

- By the time of matter-radiation equality and until now, dark matter must be non-relativistic and clump together by gravitational attraction
- must be electrically neutral

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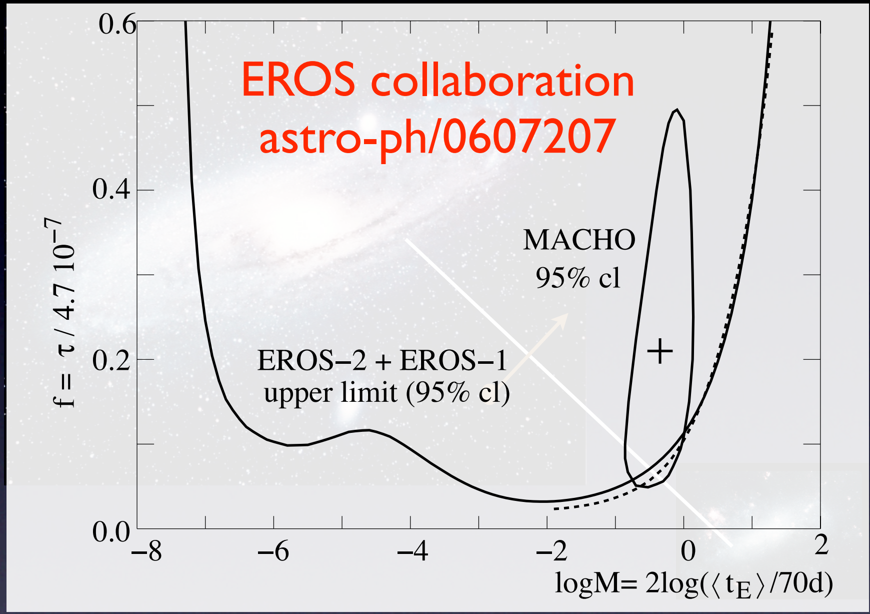
Mass Limits

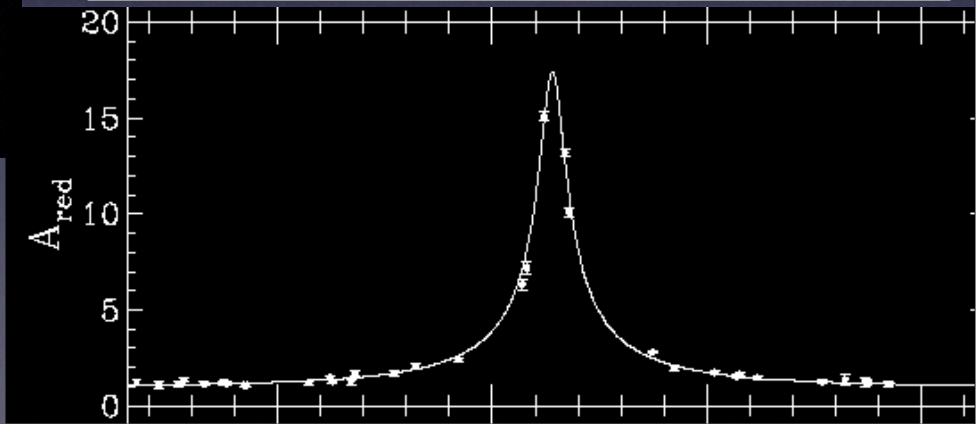
"Uncertainty Principle"

- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- "Bohr radius": $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won't "fit" in a galaxy!
- m >10^{-22} eV "uncertainty principle" bound
  (modified from Hu, Barkana, Gruzinov, astro-ph/0003365)

Dim Stars?

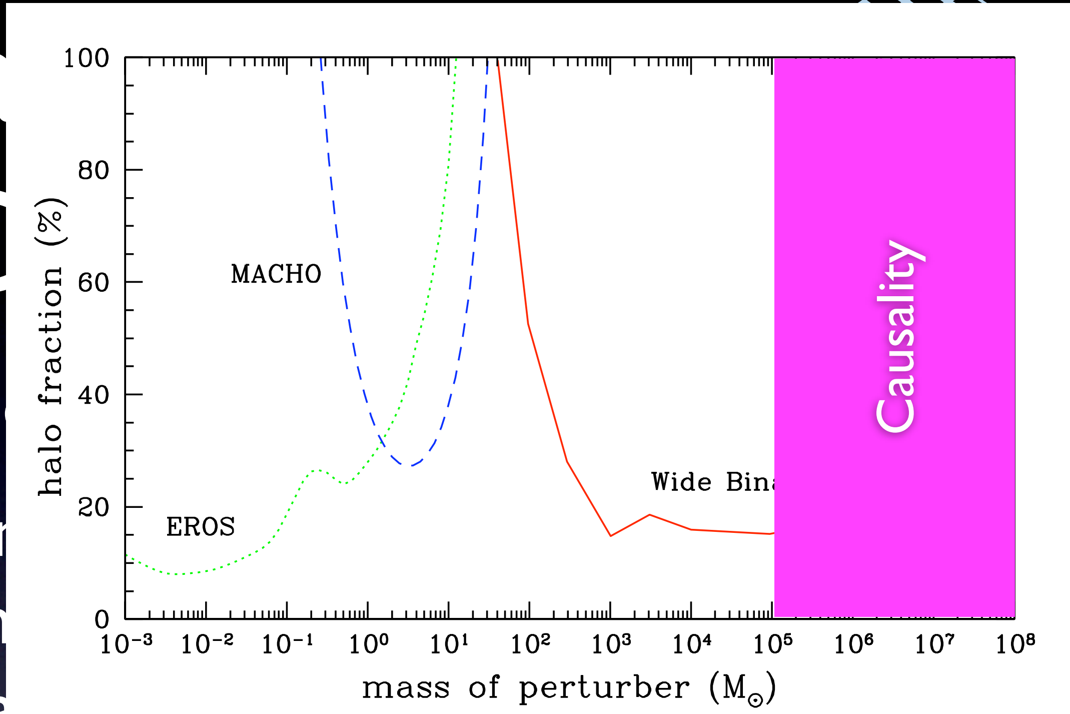
Search for MACHOs
(Massive Compact Halo Objects)





Not enough of them!

Ma
C



- MACHO exclu
- Can’t make pri
  normal smooth
- there can’t be anything violent since BBN
- maximum mass of PBH is horizon mass@BBN

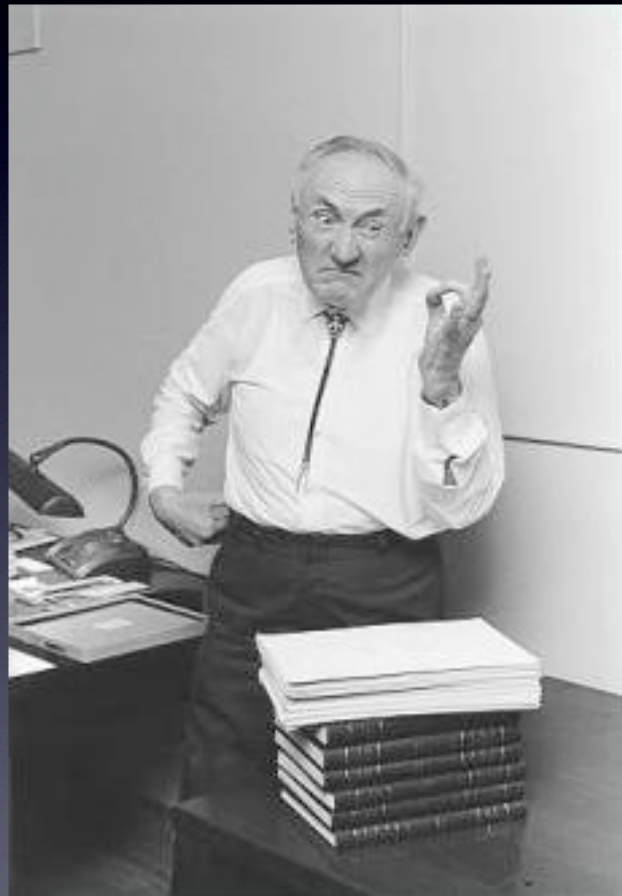
$$M_{\rm horizon} \approx g_* T^4 \left(\frac{M_{Pl}}{g_*^{1/2} T^2} \right)^3 \approx 10^5 M_\odot \left(\frac{\rm MeV}{T} \right)^2$$

- And m < 40M$_\odot$ from wide binaries

(Yoo, Chaname, Gould, astro-h/0307437)

Summary
Mass Limits

- 10^{-31} GeV to 10^{50} GeV
- narrowed it down to within 81 orders of magnitude
- a big progress in 70 years since Zwicky



Self-Couplin

- if self-coupling too big, will "smooth out" cuspy profile at the galactic center
- some people wanted it

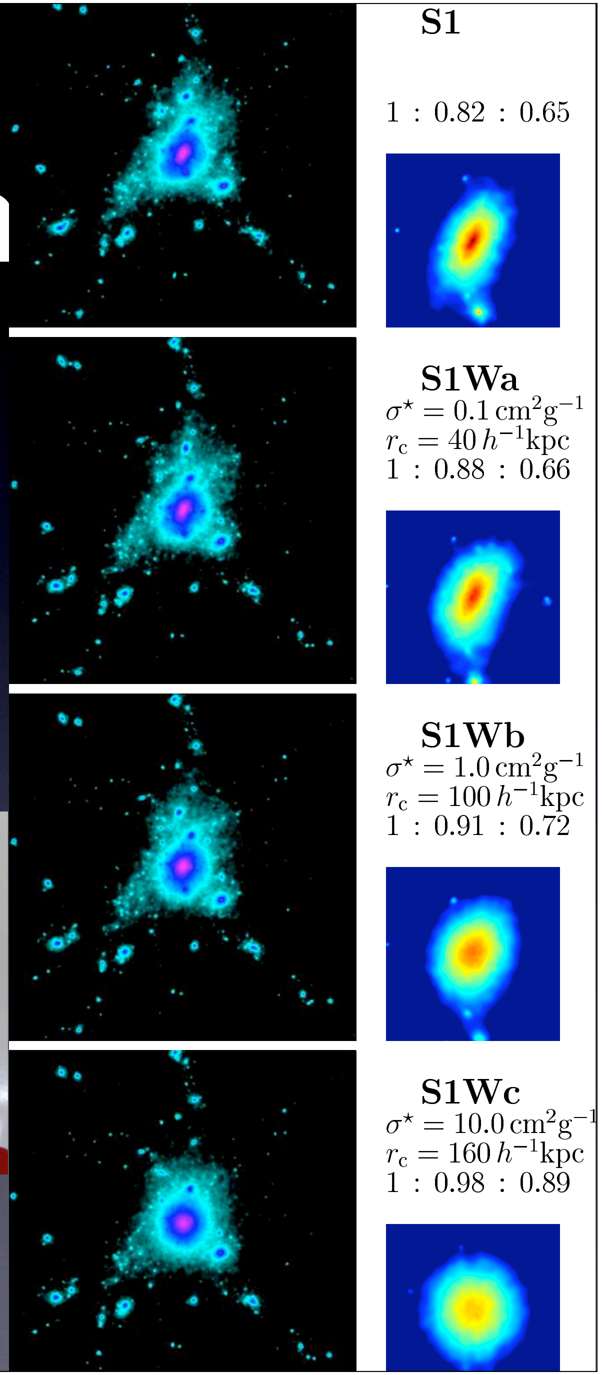
  (Spergel and Steinhardt, astro-ph/9909386)
- need core < 35 kpc/h from data

  $\sigma < 1.7 \times 10^{-25}$ cm^2 (m/GeV)

  (Yoshida, Springel, White, astro-ph/0006134)
- bullet cluster:

  $\sigma < 1.7\text{x}10^{-24}$ cm^2 (m/GeV)

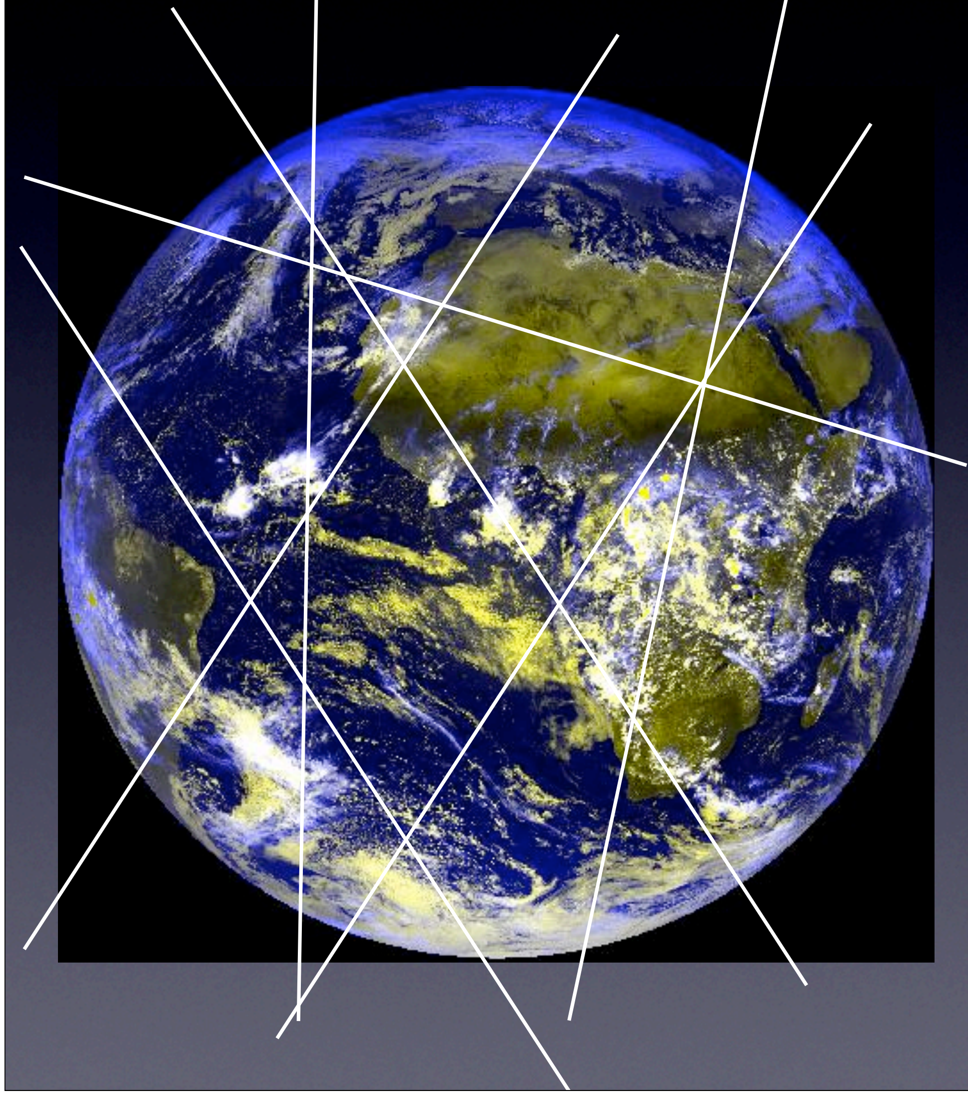
  (Markevitch et al, astro-ph/0309303)



Lifetime

- At least of the order of age of the universe 14Gyr
- Beyond that, it depends on decay modes, branching fractions, all model-dependent

MACHO $\Rightarrow$ WIMP



- It is probably WIMP (Weakly Interacting Massive Particle)
- Stable heavy particle produced in early Universe, left-over from near-complete annihilation
- Will focus on WIMPs for the rest or the talk

WIMP paradigm

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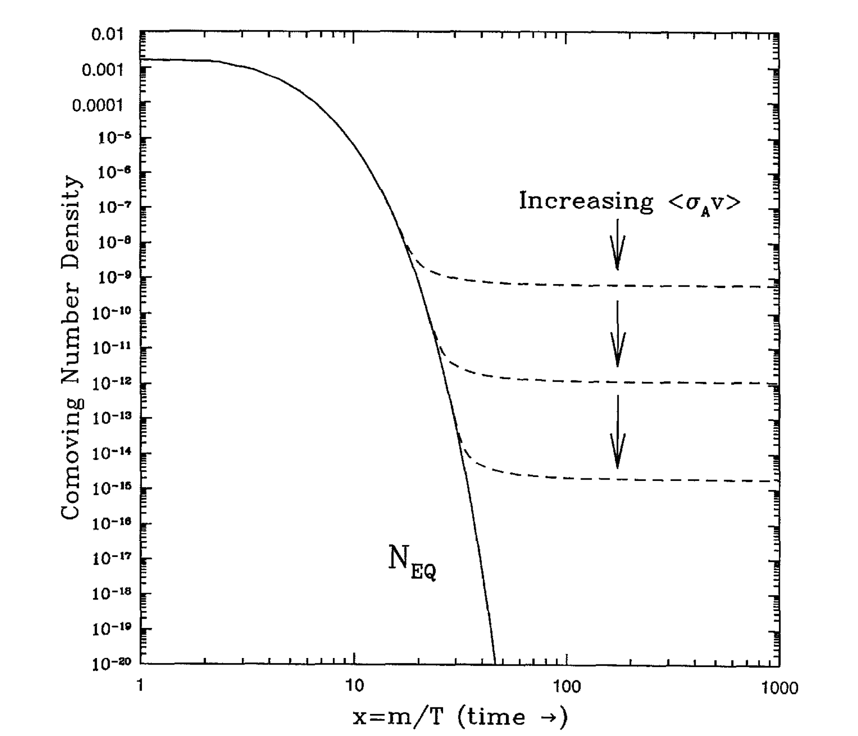
thermal relic

- thermal equilibrium when $T > m_\chi$
- Once $T < m_\chi$, no more χ created
- if stable, only way to lose them is annihilation
- but universe expands and χ get dilute
- at some point they can't find each other
- their number in comoving volume "frozen"



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Freeze-out

- WIMP freezes out when the annihilation rate drops below the expansion rate

- Yield Y=n/s constant under expansion

- stronger annihilation ⇒

  less abundance

$$H \approx g_*^{1/2} \frac{T^2}{M_{Pl}}$$

$$\Gamma_{\rm ann} \approx \langle \sigma_{\rm ann} v \rangle n$$

$$H(T_f) = \Gamma_{\rm ann}$$

$$n \approx g_*^{1/2} \frac{T_f^2}{M_{Pl} \langle \sigma_{\rm ann} v \rangle}$$

$$s \approx g_* T^3$$

$$Y = \frac{n}{s} \approx g_*^{-1/2} \frac{1}{M_{Pl} T_f \langle \sigma_{\rm ann} v \rangle}$$

$$\Omega_\chi = \frac{m_\chi Y s_0}{\rho_c}$$

$$\approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

Order of magnitude

- "Known" Ω_χ=0.23 determines the WIMP annihilation cross section
- simple estimate of the annihilation cross section
- weak-scale mass!!!

$$\Omega_\chi \approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{1.12 \times 10^{-10} {\rm GeV}^{-2} x_f}{g_*^{1/2} \Omega_\chi h^2}$$

$$\sim 10^{-9} {\rm GeV}^{-2}$$

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\pi \alpha^2}{m_\chi^2}$$

$$m_\chi \approx 300 \ {\rm GeV}$$

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WIMP

- A stable particle at the weak scale with "EM-strength" coupling naturally gives the correct abundance
- This is where we expect new particles because of the hierarchy problem!
- Many candidates of this type: SUSY, little Higgs with T-parity, Universal Extra Dimensinos, etc
- If so, we may even create dark matter at accelerators

Minimal Model

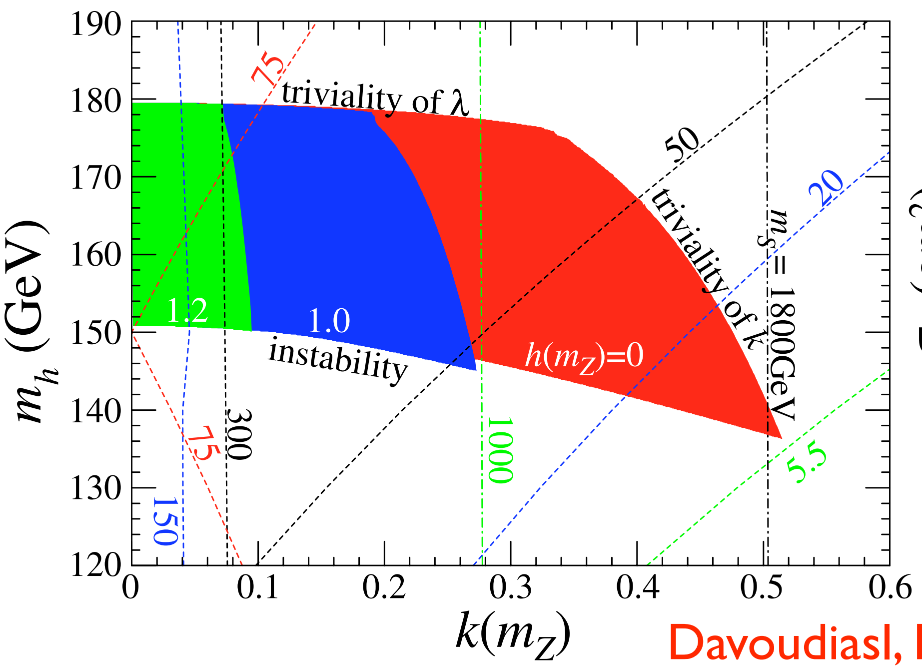
- Dark Matter clearly a new degree of freedom
- The smallest degree of freedom you can add to the QFT is a real Klein-Gordon field S: dof=1
- assign odd Z_2 parity to S, everything else even
- Most general renormalizable coupling

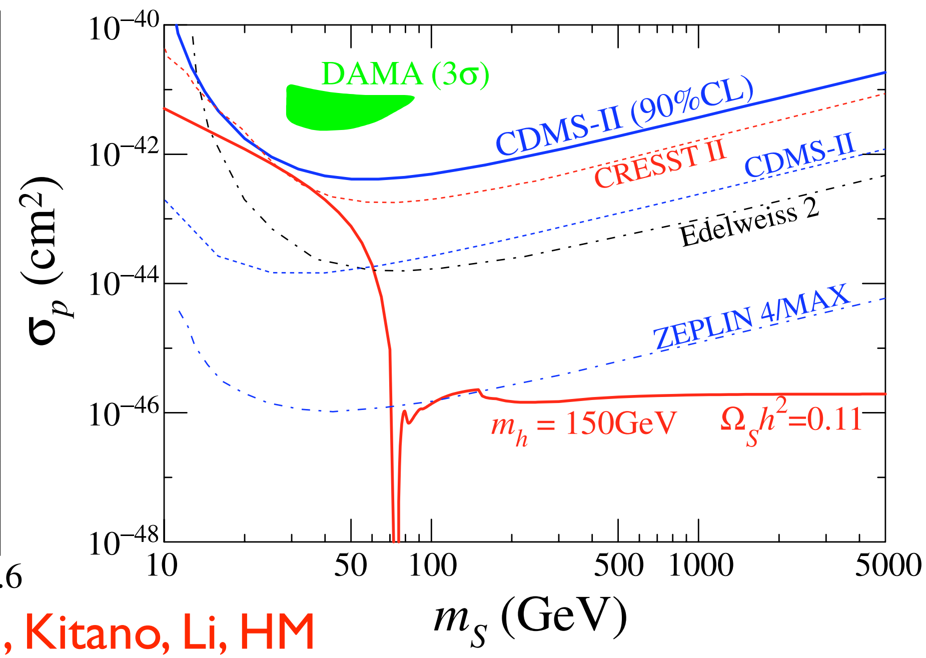
$$L_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!} S^4.$$

Davoudiasl, Kitano, Li, HM

Consistency check

- correct Dark Matter abundance
- evades direct detection limits
- satisfies triviality/instability limits from RGE
- consistent with precision electroweak data





Davoudiasl, Kitano, Li, HM

LSP

- The lightest Supersymmetric Particle is one of the best candidates for dark matter (assuming R-parity conservation)
- In the "Minimal Supergravity" or CMSSM, the LSP is bino-like
- Its annihilation cross section tends to be too small, abundance too large because it is P-wave suppressed $\tilde{B}\tilde{B} \to e^+e^-$
- Coannihilation region $\tilde{B}\tilde{\tau} \to \gamma\tau$
- Funnel region where annihilation goes through a Higgs resonance.

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Example

- exchange of Majorana fermions with a relative minus sign

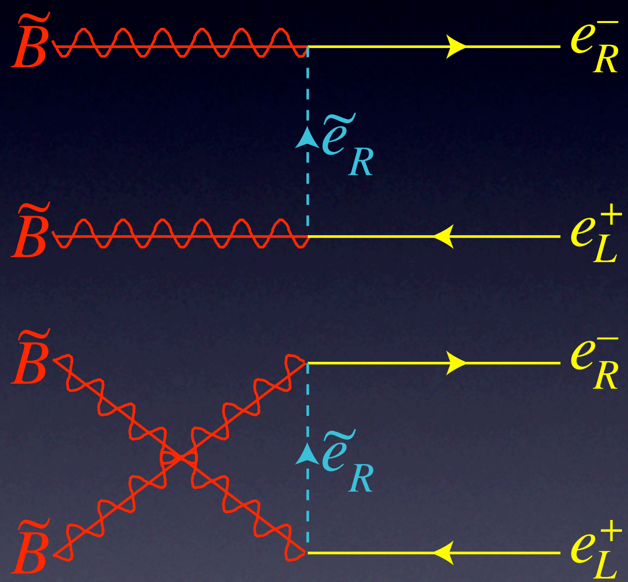
$$\mathcal{M}_{+-} = 8g'^2 \frac{M_{\tilde{B}} p_{\tilde{B}}}{M_{\tilde{B}}^2 + m_{\tilde{e}_R}^2} \cos^2 \frac{\theta}{2}$$

$$\mathcal{M}_{-+} = 8g'^2 \frac{M_{\tilde{B}} p_{\tilde{B}}}{M_{\tilde{B}}^2 + m_{\tilde{e}_R}^2} \sin^2 \frac{\theta}{2}$$

$$\mathcal{M}_{++} = 0$$

$$\mathcal{M}_{--} = 0$$

- P-wave annihilation
- Final state J=1
- L=0, S=1 not possible
- L=1, S=1 allowed



$$\sigma = \frac{4\pi\alpha^2 M_{\tilde{B}}^2 v_{\rm rel}}{3c_W^4 (M_{\tilde{B}}^2 + m_{\tilde{e}_R}^2)^2}$$

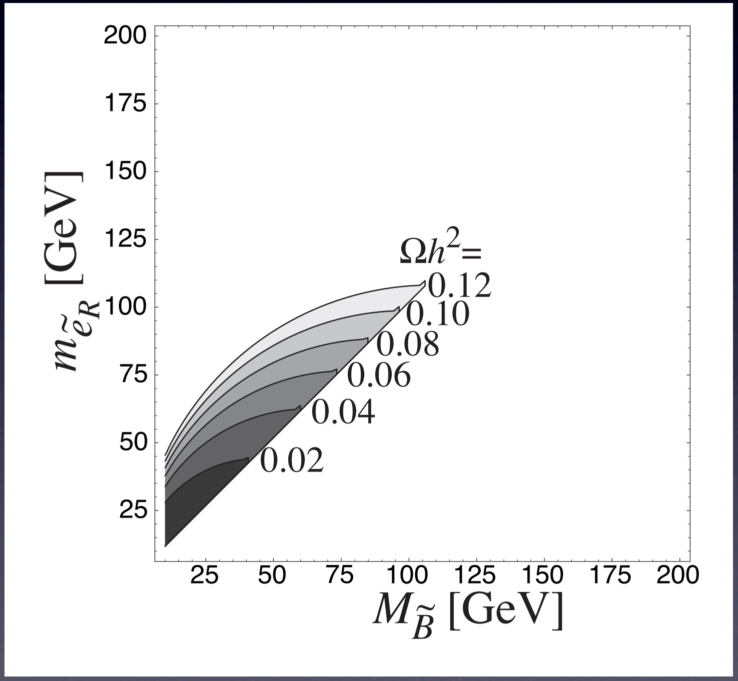
A little too much

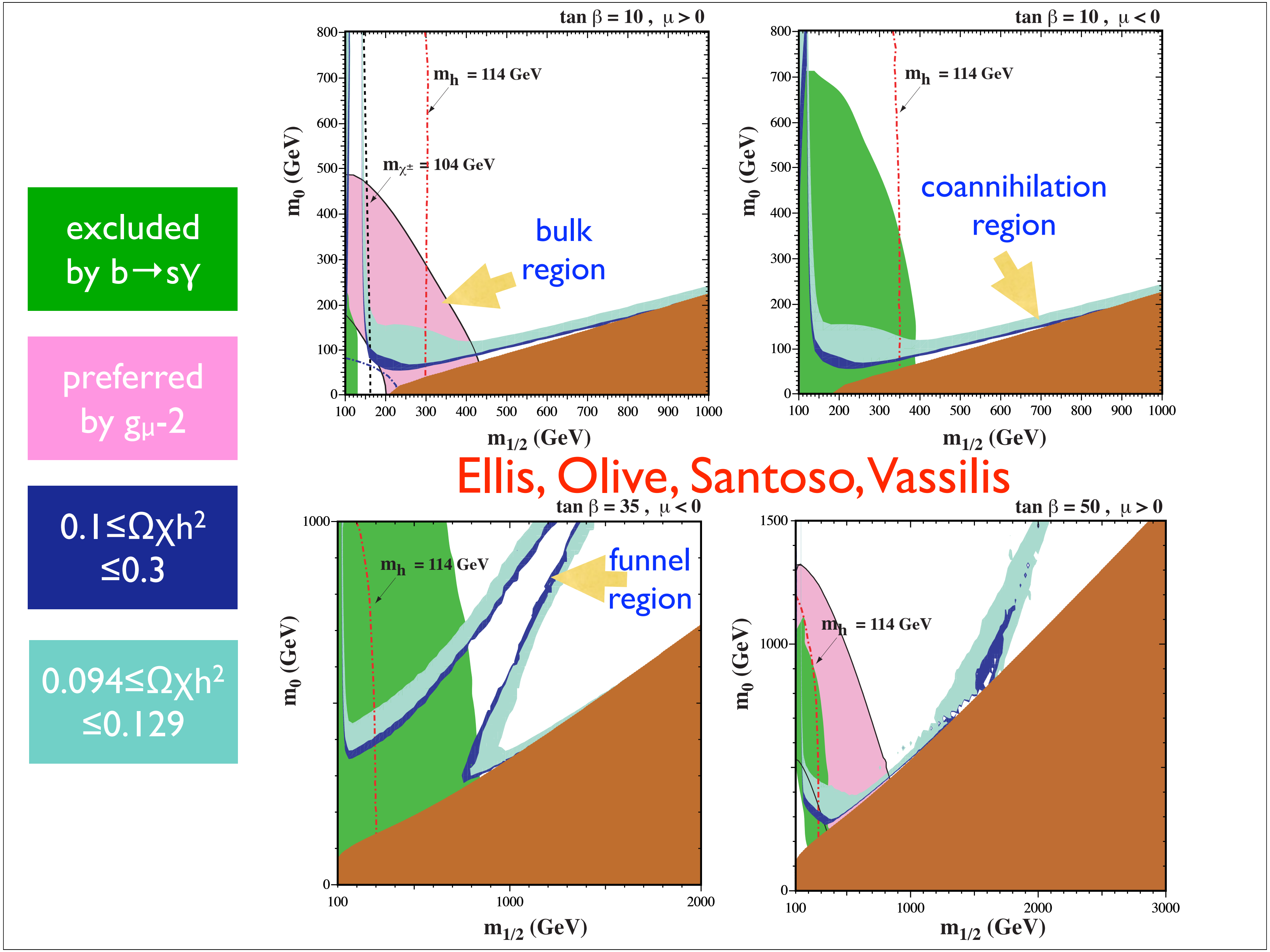
- You get the right order of magnitude!
- But in detail, a little too much beyond the collider limits
- Coannihilation region

$$\tilde{B}\tilde{\tau} \to \gamma\tau$$

- Funnel region where annihilation goes through a Higgs resonance

$$\tilde{B}\tilde{B} \to A^0, H^0$$

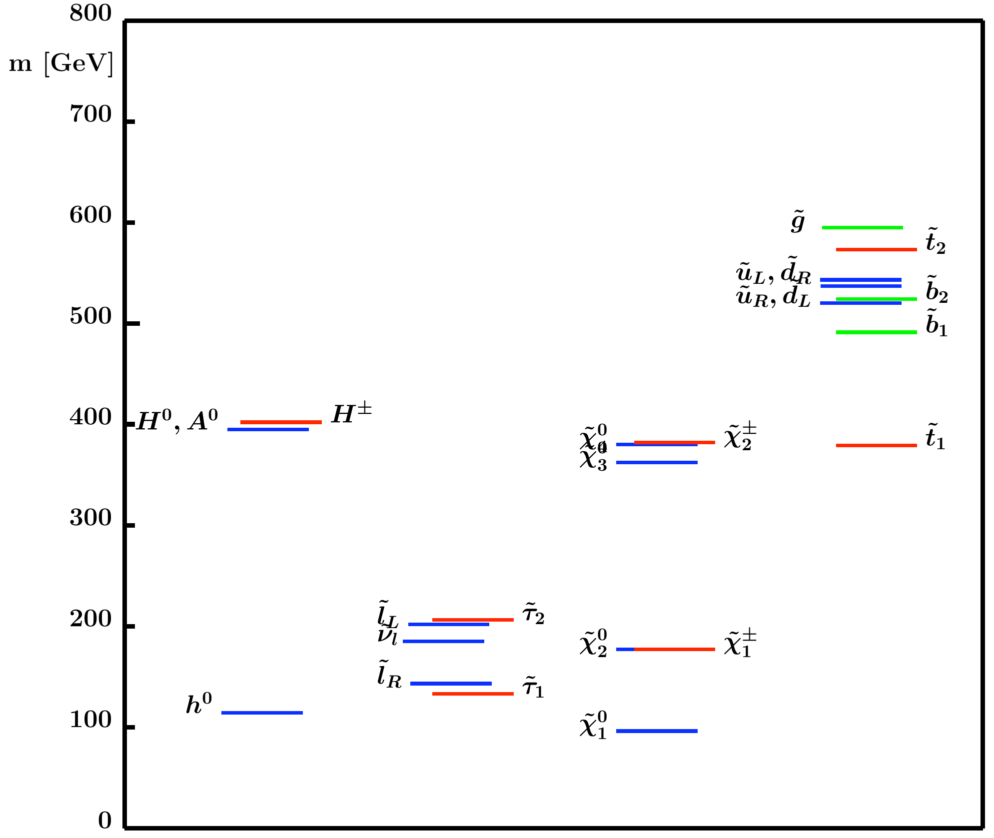




excluded by b→sγ
preferred by gμ-2
0.1≤Ωχh² ≤0.3
0.094≤Ωχh² ≤0.129
tan β = 10 , μ > 0
m_h = 114 GeV
m_χ± = 104 GeV
bulk region
m_0 (GeV)
m_1/2 (GeV)
tan β = 10 , μ < 0
m_h = 114 GeV
coannihilation region
Ellis, Olive, Santoso, Vassilis
tan β = 35 , μ < 0
m_h = 114 GeV
funnel region
tan β = 50 , μ > 0
m_h = 114 GeV

sample spectrum

$m_0 = 100,\ m_{1/2} = 250,\ A_0 = -100,\ \tan\beta = 10,\ \mu > 0$



bulk region

SPS1a

sample spectrum

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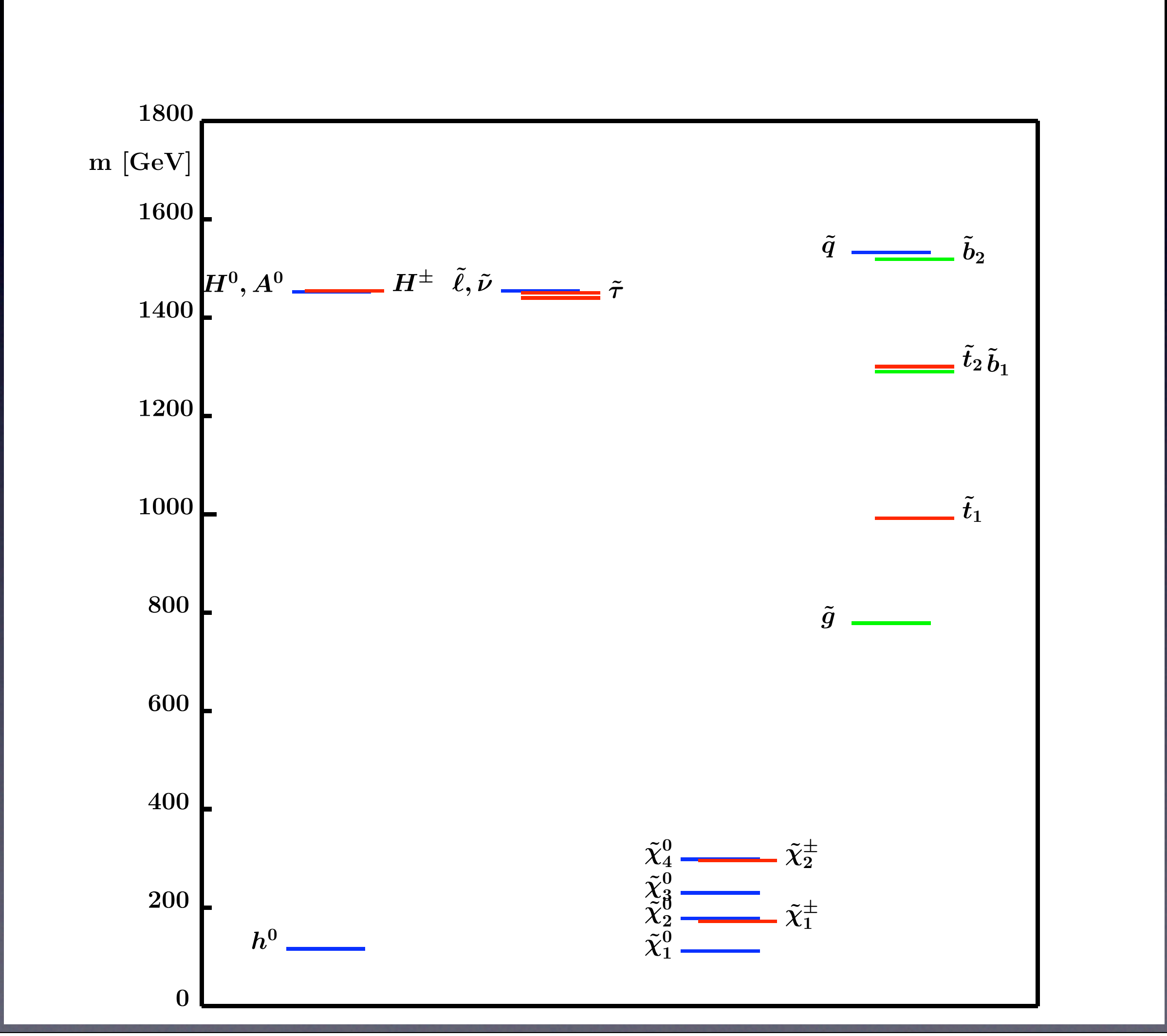
$m_0 = 1450,\ m_{1/2} = 300,\ A_0 = 0,\ \tan\beta = 10,\ \mu > 0$

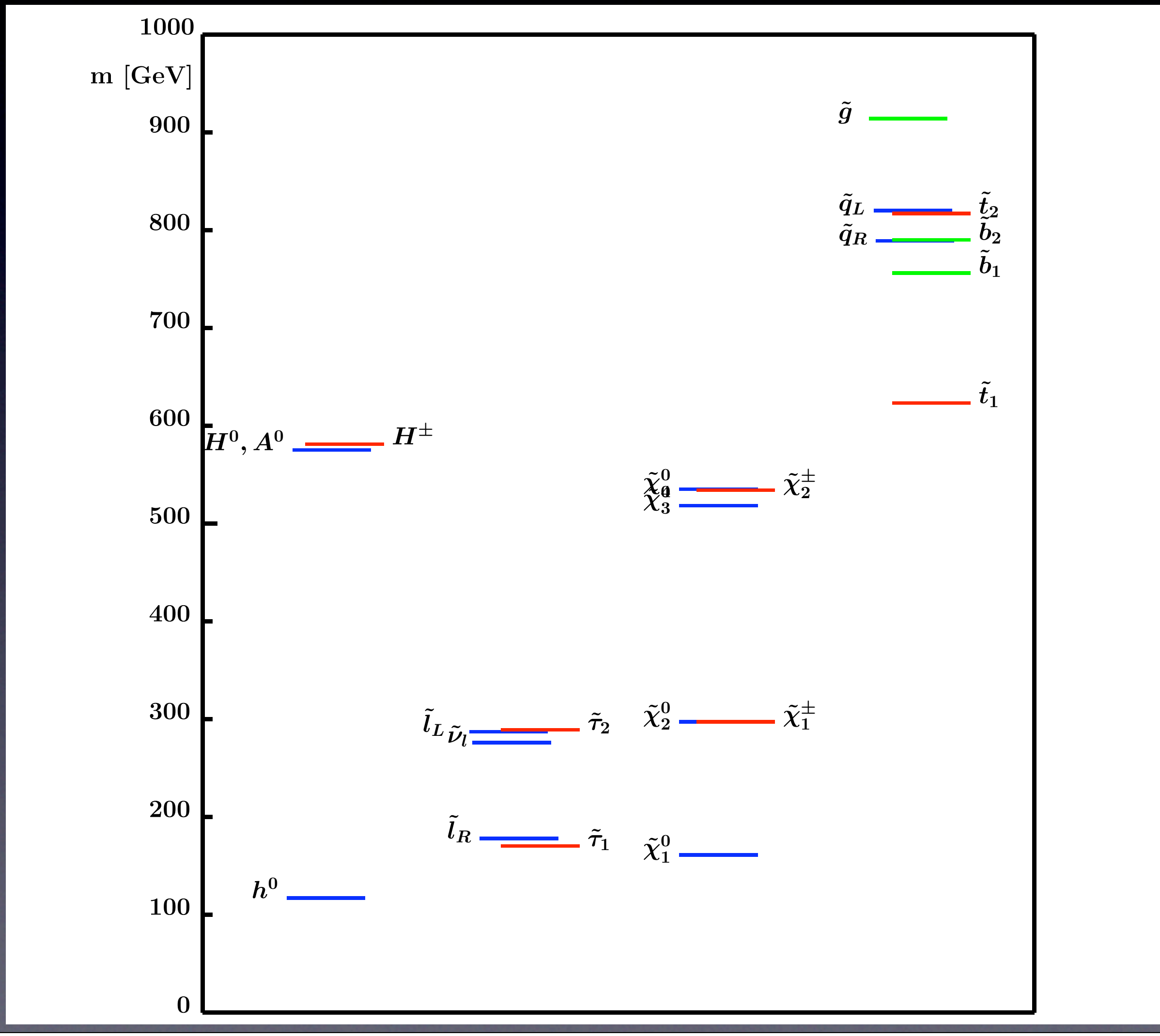


focus point region

SPS2

sample spectrum

$m_0 = 90,\ m_{1/2} = 400,\ A_0 = 0,\ \tan\beta = 10,\ \mu > 0$



coanni-
hilation
region

SPS3

Universal Extra Dimensions

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- 5D Dirac equation
  → vector-like spectrum

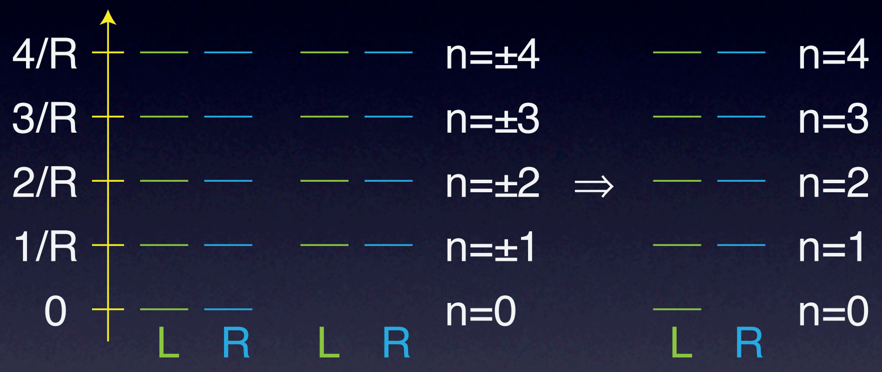
$$(i\gamma^\mu\partial_\mu + \gamma_5\partial_y)\psi(x,y) = 0$$

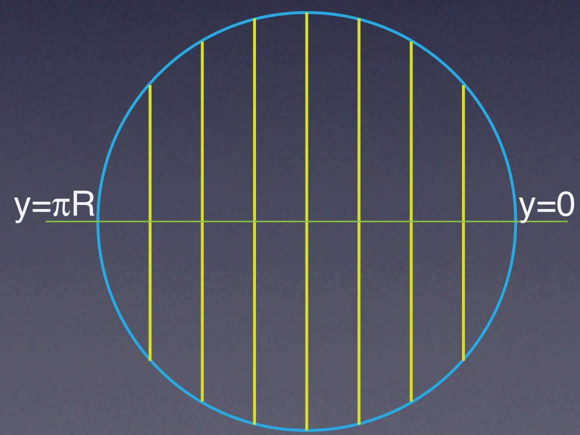
- Use orbifold to get a chiral spectrum in 4D
- $R^4 \times S^1/Z_2$

  $S^1: y \in [0, 2\pi R]$

  $Z_2: y \to -y$
- BC: $\psi(-y) = -\gamma_5\psi(y)$
- cuts the spectrum in a half
- as a result, there is a remaining Z_2 symmetry $y \to \pi - y$

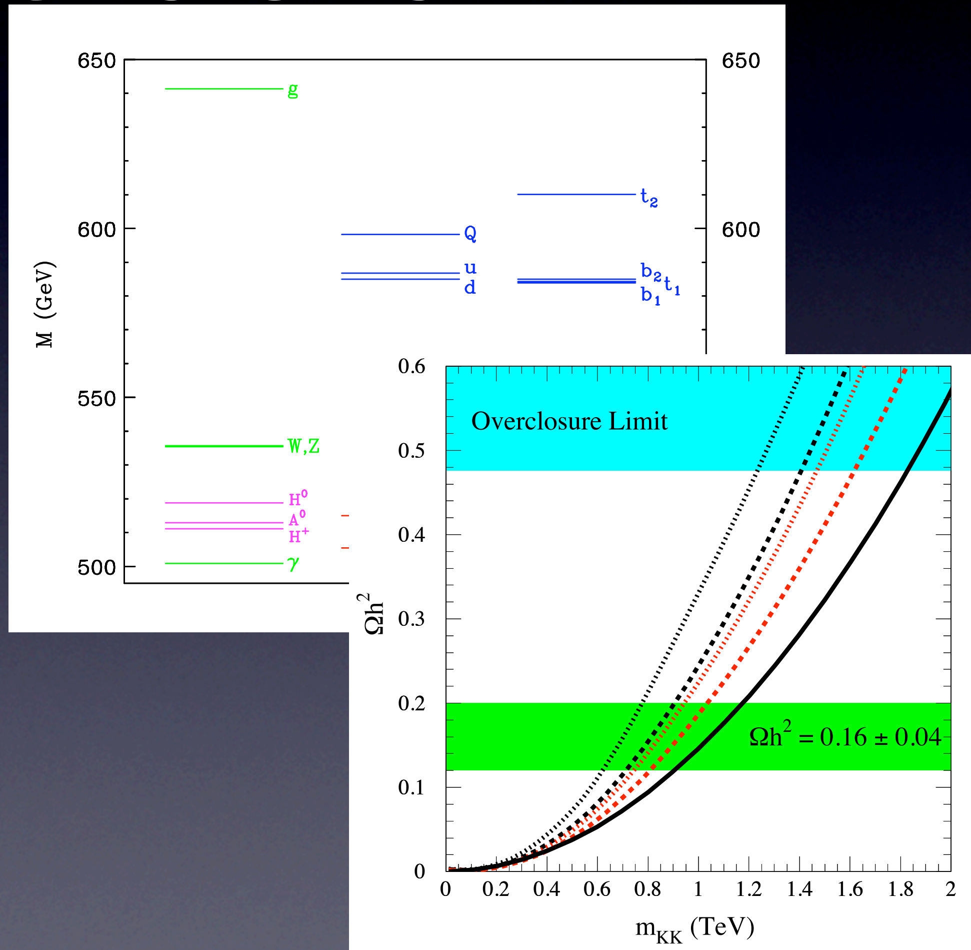
  KK parity: $(-1)^n$





Universal Extra Dimensions

- Put all SM particles in the bulk
- 1st KK states m=1/R
- However, radiative corrections split their masses (Cheng, Matchev, Schmaltz, hep-ph/0205314)
- $B^{(1)}$ can be good DM (Servant, Tait, hep-ph/0206071)



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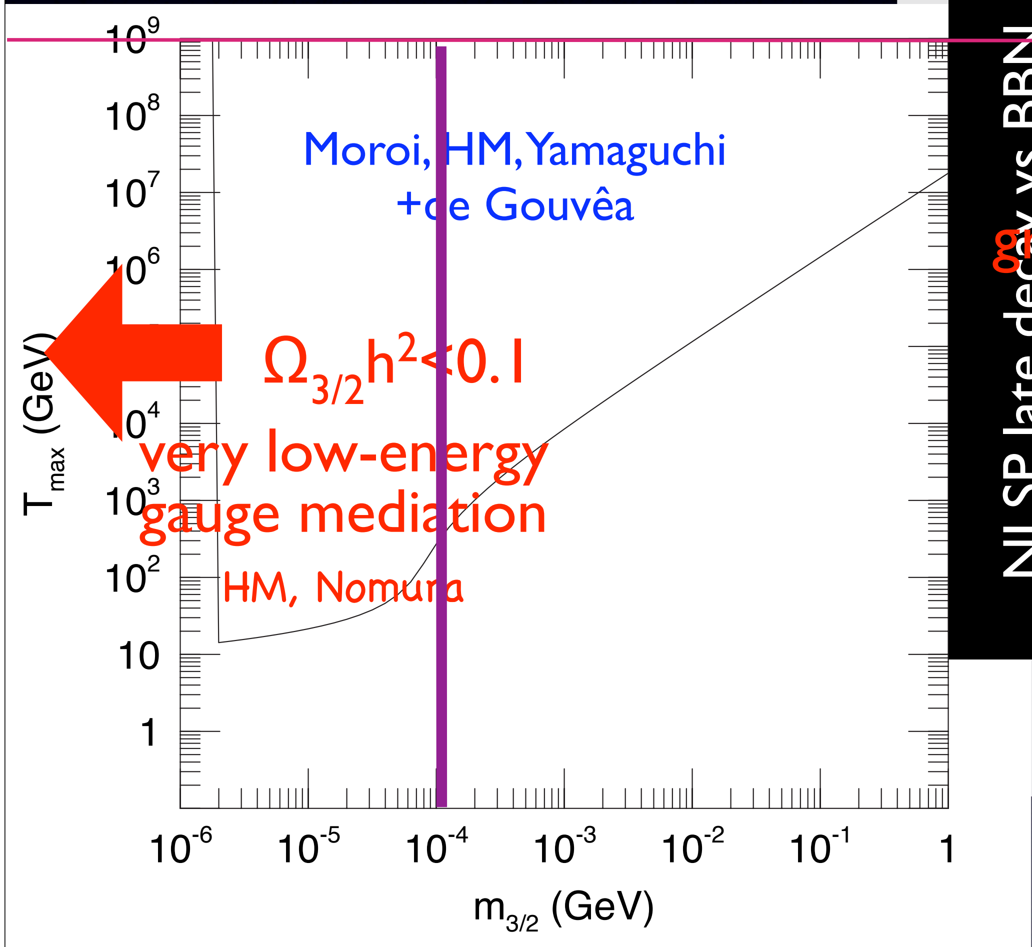
Many WIMP candidates

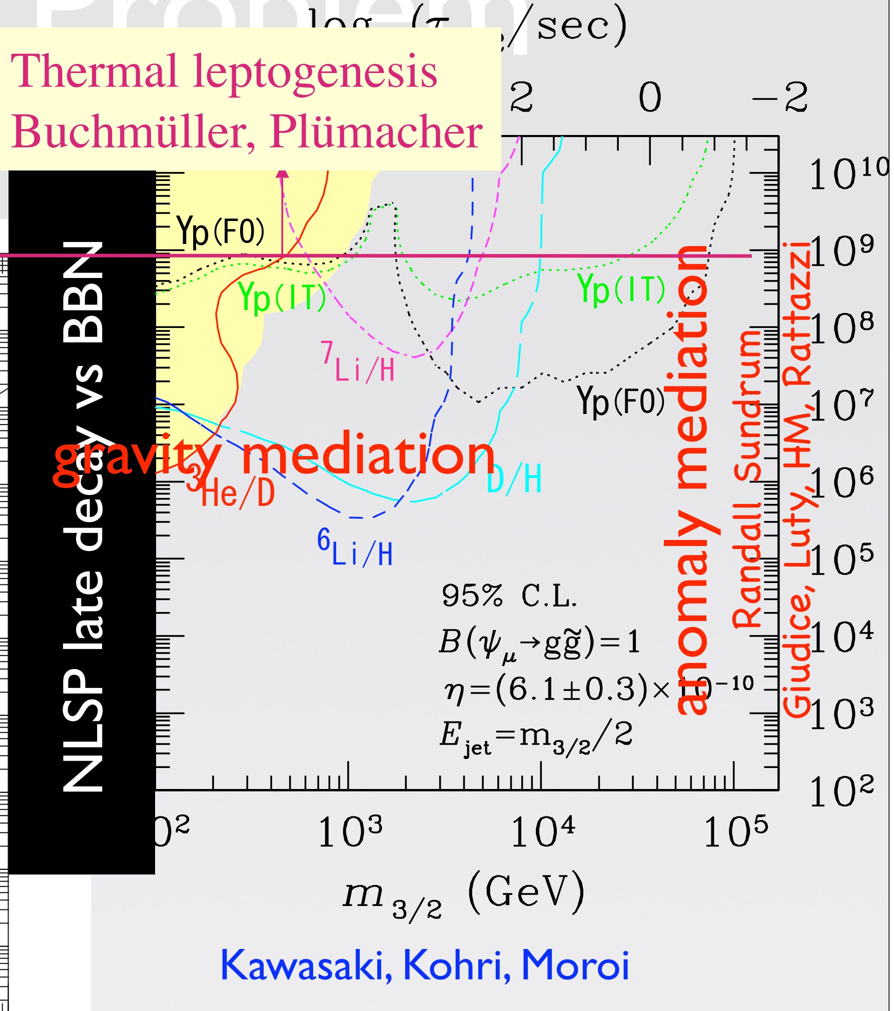
- Warped unification + proton stability (Agashe, Servant, he-ph/0403143)
- Little Higgs and suppressed precision EW corrections ➡ “T-parity”

  (Cheng, Low, Wang, hep-ph/0510225)
- Many, many, more....

Gravitino Problem

$$\frac{n_{3/2}}{s} \approx 1.5 \times 10^{-12} \frac{T_{RH}}{10^{10}\mathrm{GeV}}$$



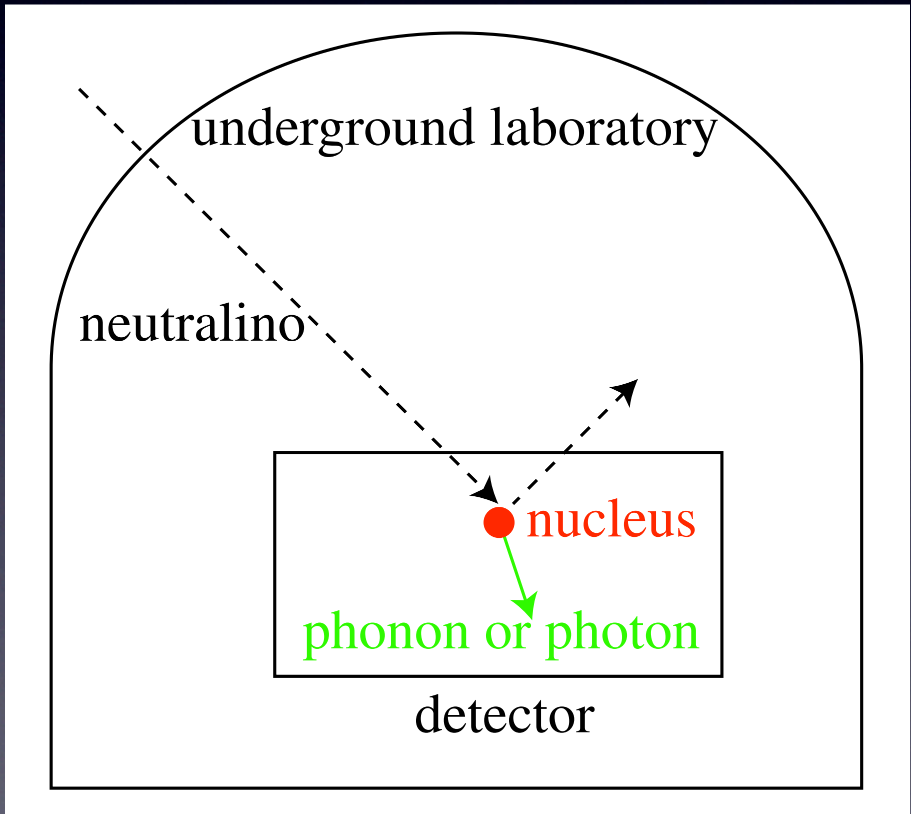


$$m_{3/2} = \frac{\Lambda^2_{SUSY}}{M_{Pl}}$$

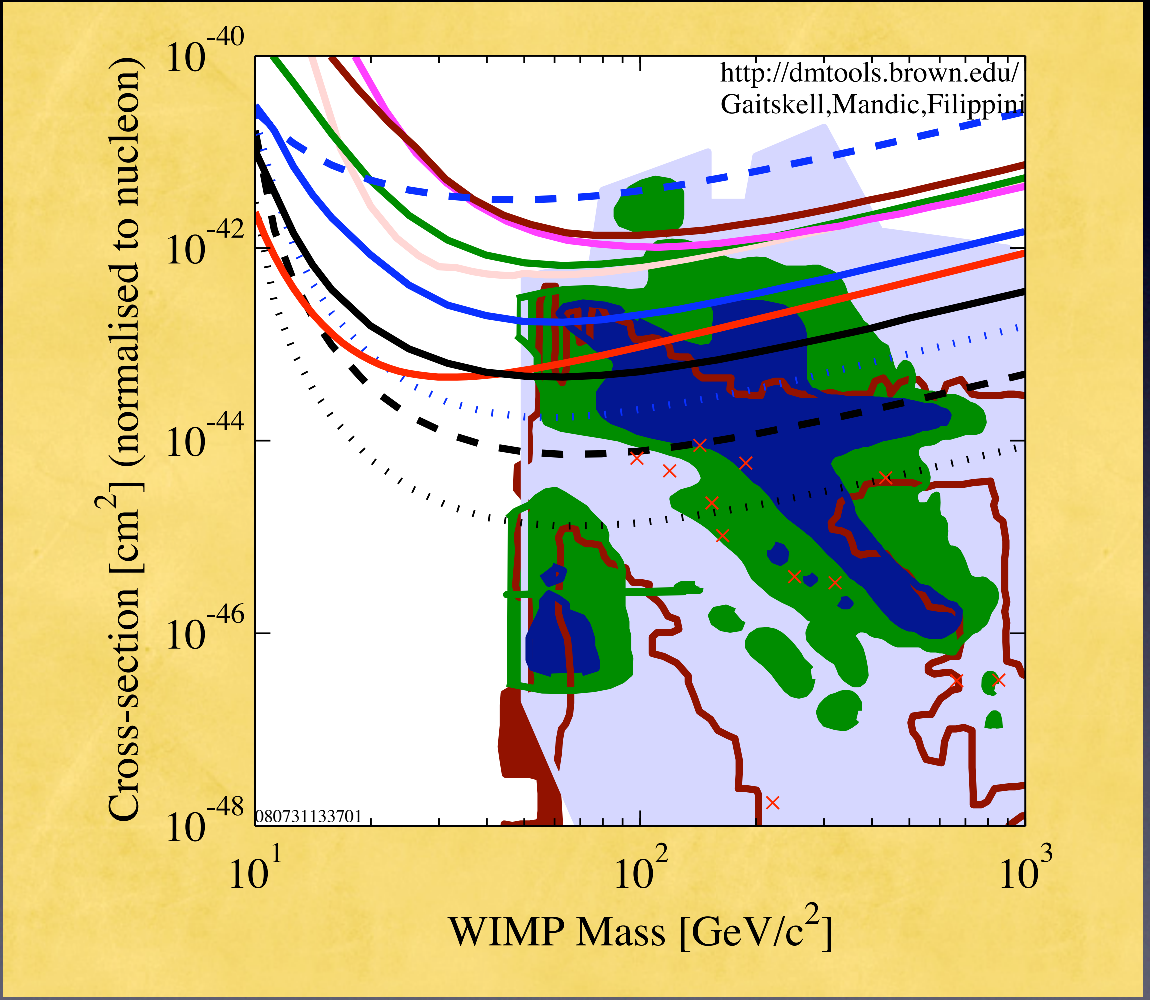
WIMP Searches

Finding Dark Matter

Direct method



Limit

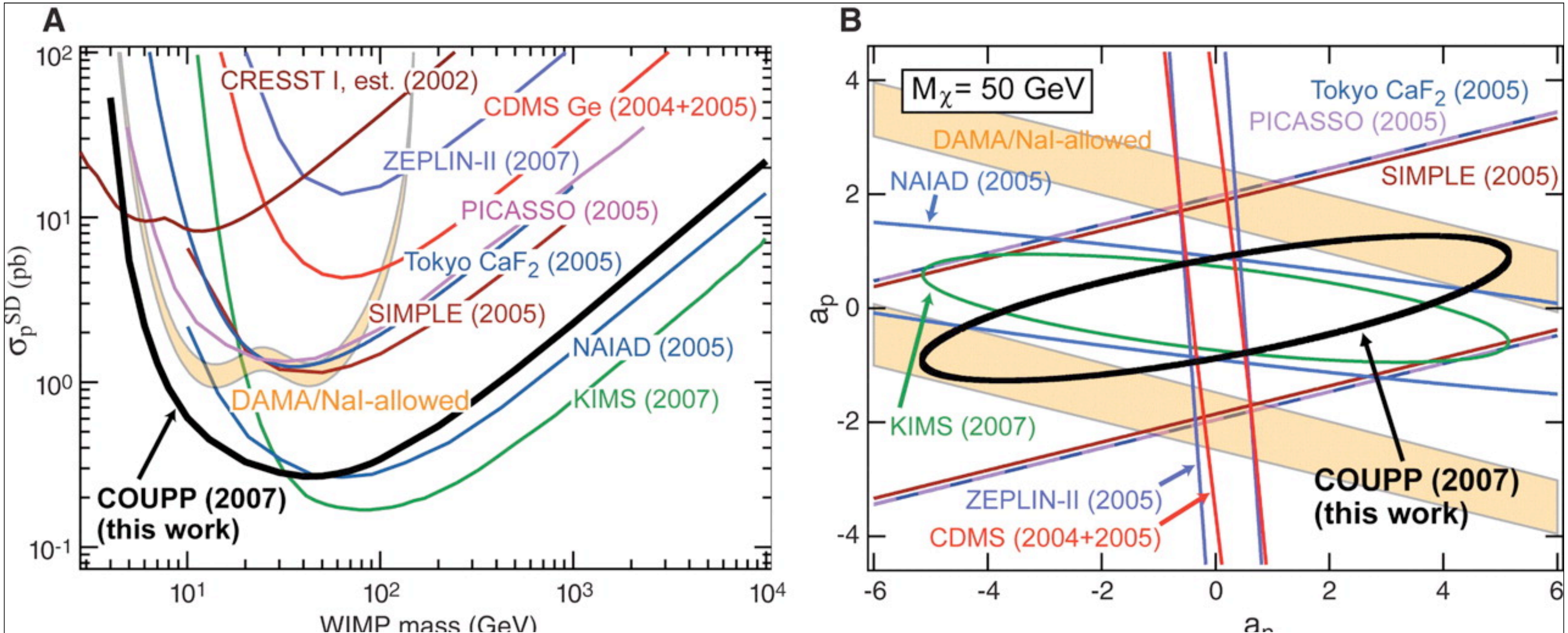


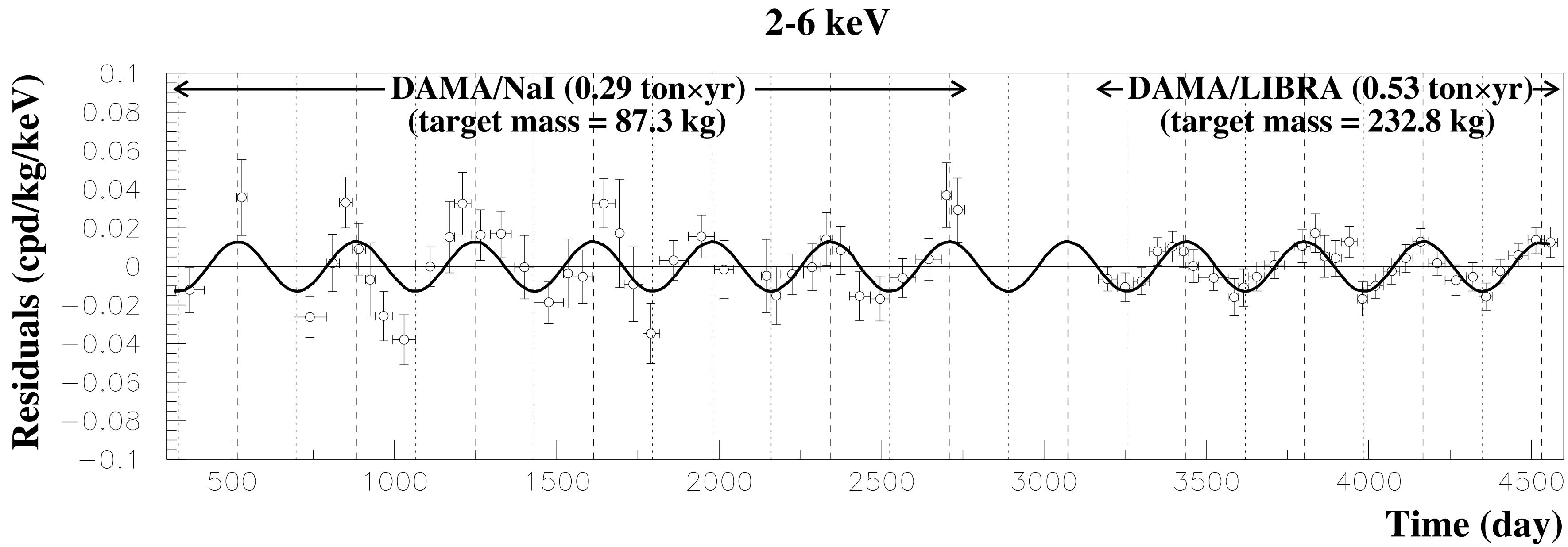
ZEPLIN-II, 2007

CDMS-II, 2005

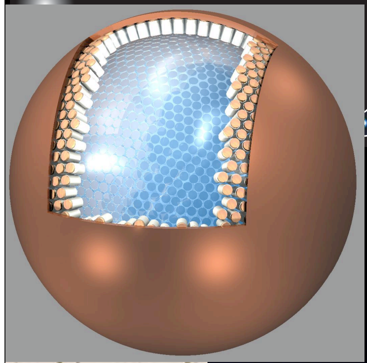
XENON10, 2007

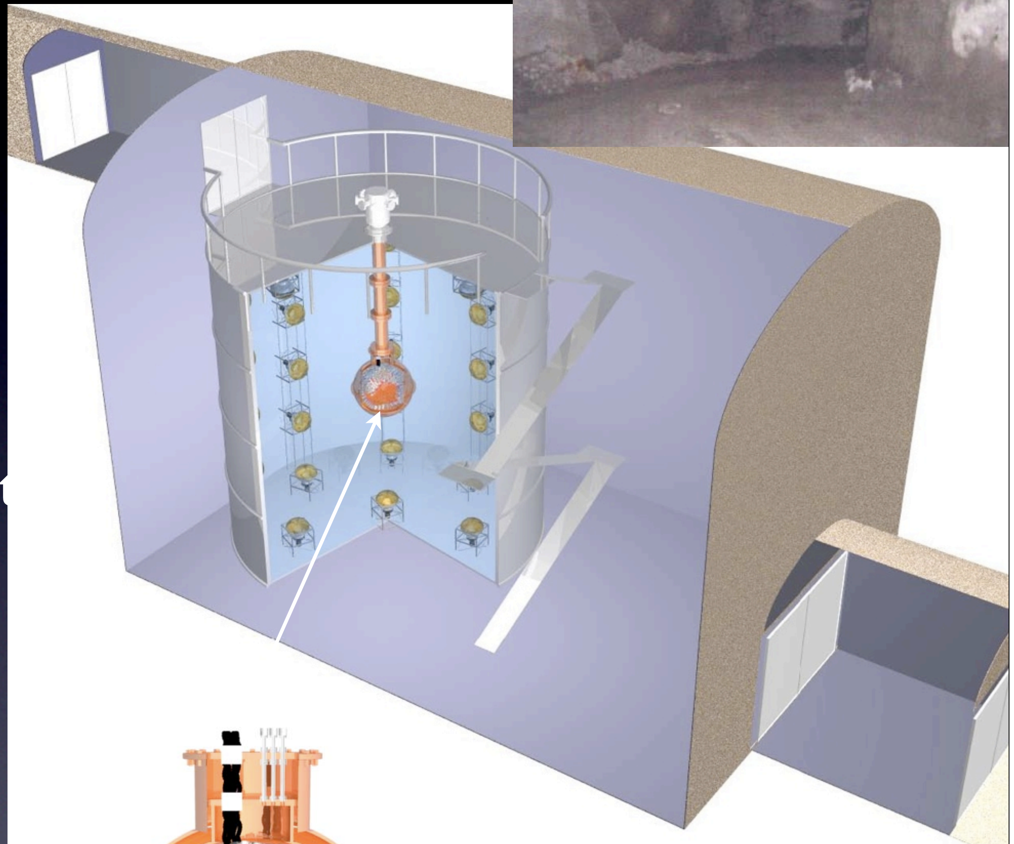
CDMS-II, 2008


A
CRESST I, est. (2002)
CDMS Ge (2004+2005)
ZEPLIN-II (2007)
PICASSO (2005)
Tokyo CaF$_2$ (2005)
SIMPLE (2005)
NAIAD (2005)
DAMA/NaI-allowed
KIMS (2007)
COUPP (2007)
(this work)
σ_p^{SD} (pb)
WIMP mass (GeV)
B
M_χ= 50 GeV
Tokyo CaF$_2$ (2005)
PICASSO (2005)
DAMA/NaI-allowed
SIMPLE (2005)
NAIAD (2005)
KIMS (2007)
COUPP (2007)
(this work)
ZEPLIN-II (2005)
CDMS (2004+2005)
a_p
a_n

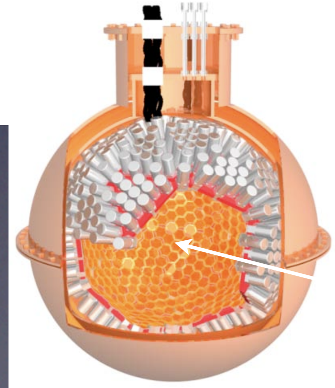

2-6 keV
DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr)
(target mass = 232.8 kg)
Residuals (cpd/kg/keV)
Time (day)

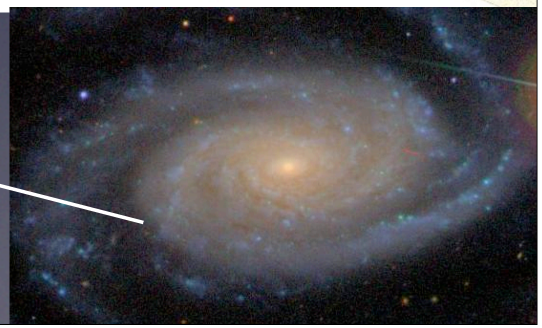
XMASS





- Trying to detect dark matter directly
- PIs Suzuki and Nakahat lead the project
- adding Kai Martens to the project
- start data taking ~2009





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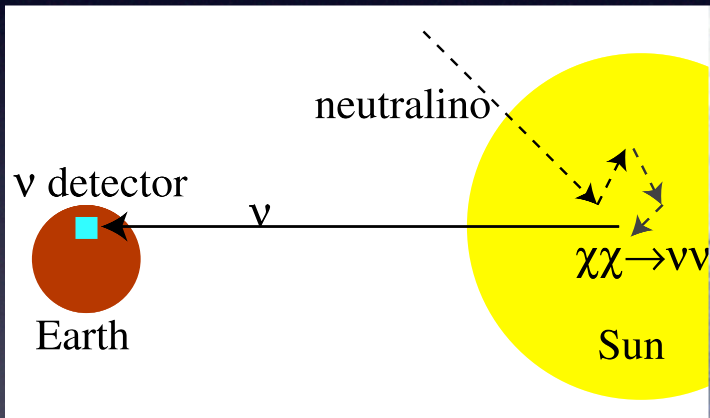
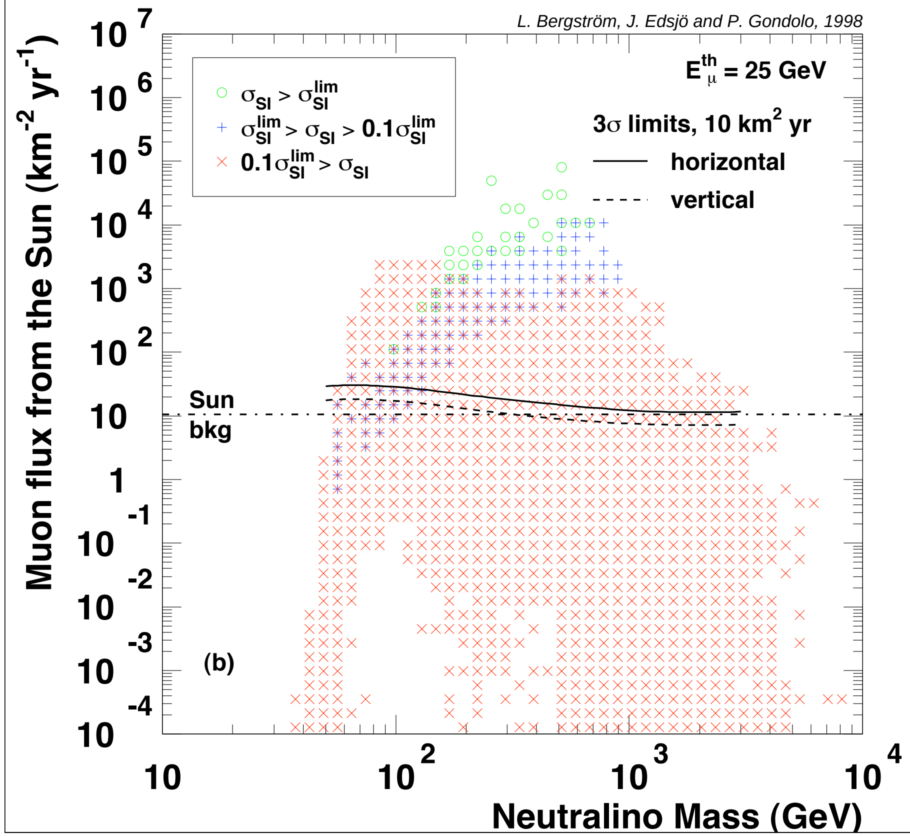
Finding Dark Matter

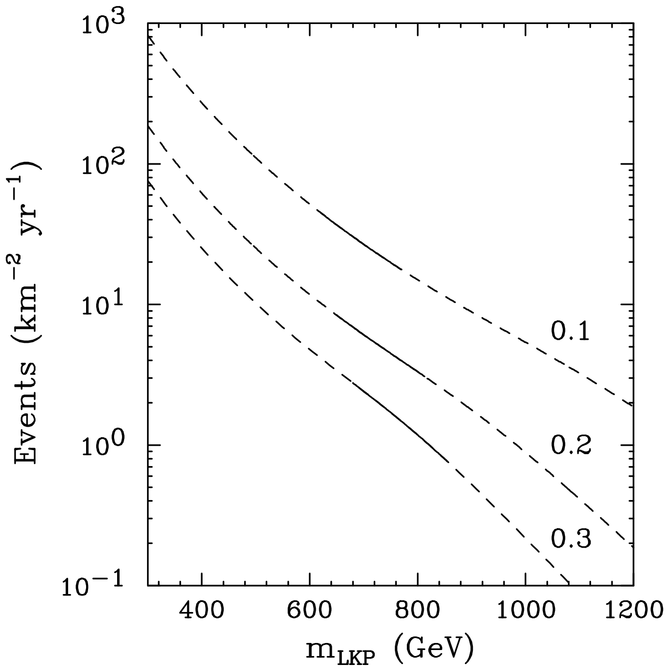
Indirect method
Icecube, Antares, Nestor, Nemo, Baikal



Future Limits

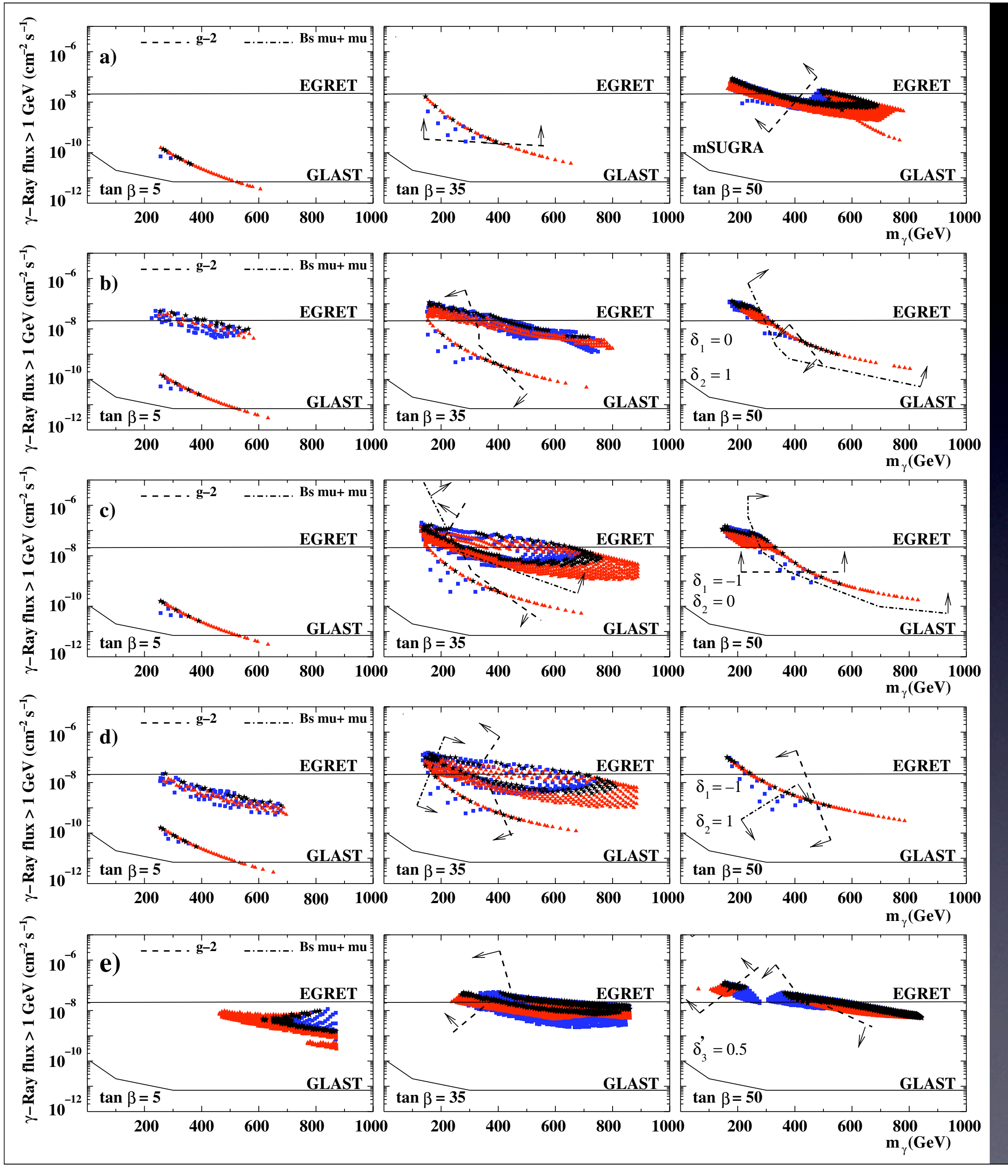
- SUSY (Bergström, Edsjö, Gondolo, hep-ph/98060293)
- UED (Hooper and Kribs, hep-ph/0208261)





Other possibilities

- Given that dark matter is supposed to be in the halo of the galaxy, WIMPs annihilation may lead to signals in gammas, positrons, anti-protons, neutrinos
- look for them from the galactic center, the entire halo, substructures in the halo



GLAST
June 11, 2008
launched

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Colliders

Producing Dark Matter in the laboratory

- Collision of high-energy particles mimic Big Bang
- We hope to create Dark Matter particles in the laboratory
- Look for events where energy and momenta are unbalanced

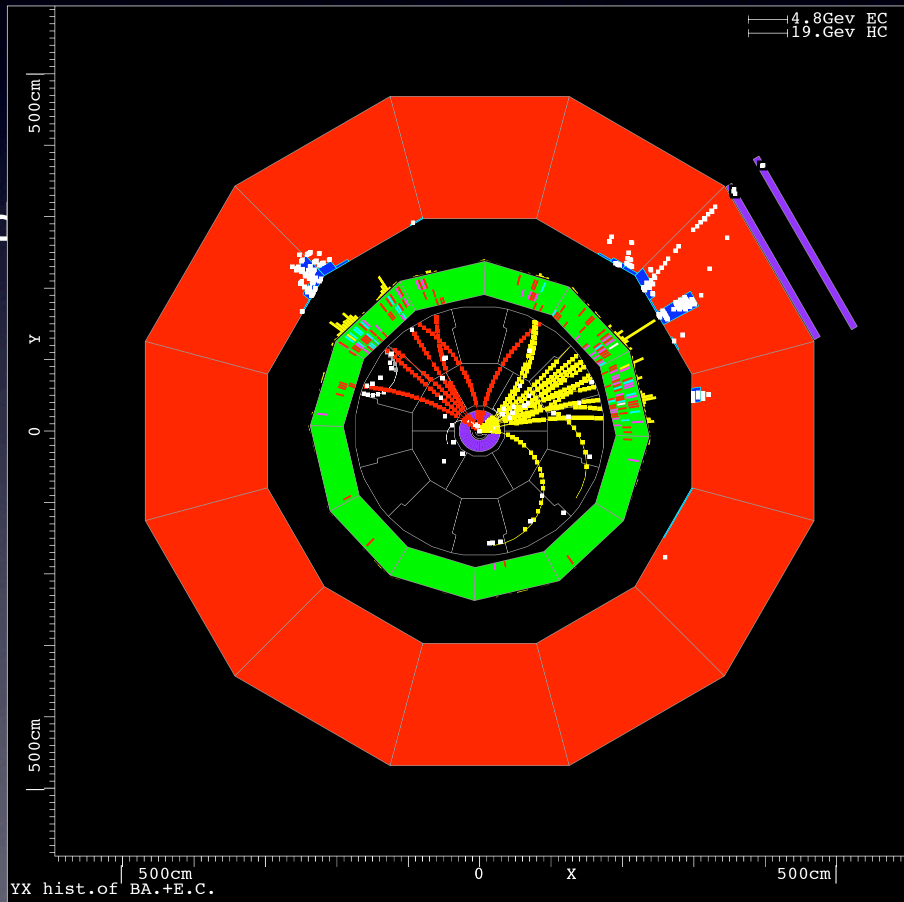
"missing energy" E_{miss}

- Something is escaping the detector
- electrically neutral, weakly interacting

⇒Dark Matter!?

- need to know the model!

⇒spin & mass meaurements



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Helicity and phase

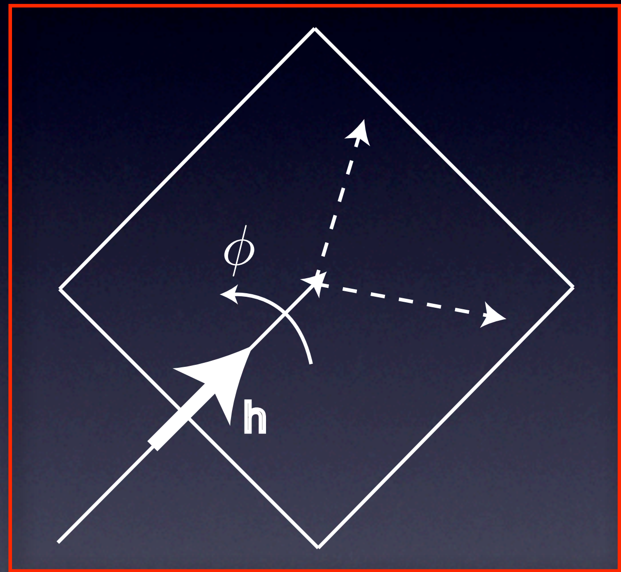
- Decay of particle with spin h along the momentum axis
- Rotations about z-axis of decay plane given by

$$\mathcal{M} \propto e^{iJ_z\phi}$$

$$J_z = \frac{(\vec{s} + \vec{x} \times \vec{p}) \cdot \vec{p}}{|\vec{p}|} = \frac{\vec{s} \cdot \vec{p}}{|\vec{p}|} = h$$

- rotational invariance: a single helicity state has flat distribution in ϕ:

$$\left|e^{ih\phi}\right|^2 = 1$$



Quantum Interference among helicities

(with M. Buckley, W. Klemm, and V. Rentala)

- If particles produced in multiple helicities:

$$\sigma \propto \left| \sum \mathcal{M}_{prod.} \mathcal{M}_{decay} \right|^2$$

$$\mathcal{M}_{decay} = e^{ih\phi} \mathcal{M}_{decay}(h, \phi = 0)$$

- Different helicities interfere once they decay!
- ϕ dependence of cross section tells us what helicities contributed to the interference $\sigma \propto \cos(\Delta h\ \phi)$
- Can measure only helicity differences (akin to neutrino oscillation)

Z+j @ Tevatron

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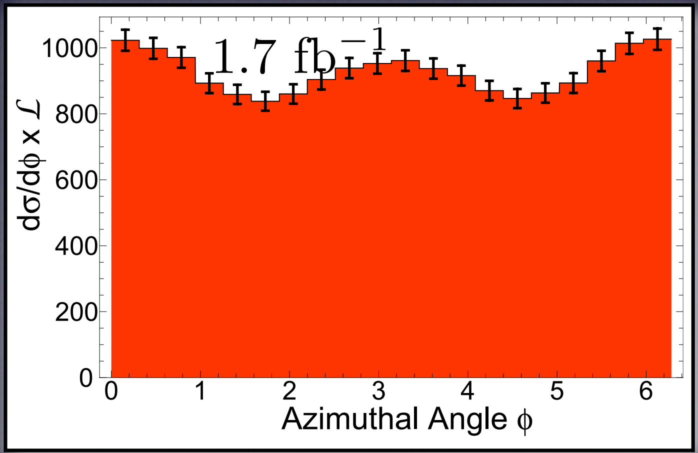
- Applying these rotationally invariant cuts (with looser acceptances at Tevatron: E_T>20GeV, E_T>10GeV, |η|<2.6; BG<5%)

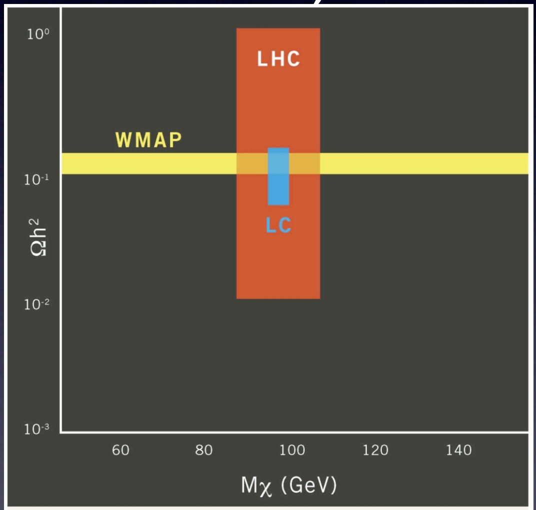


ΔR=0.75

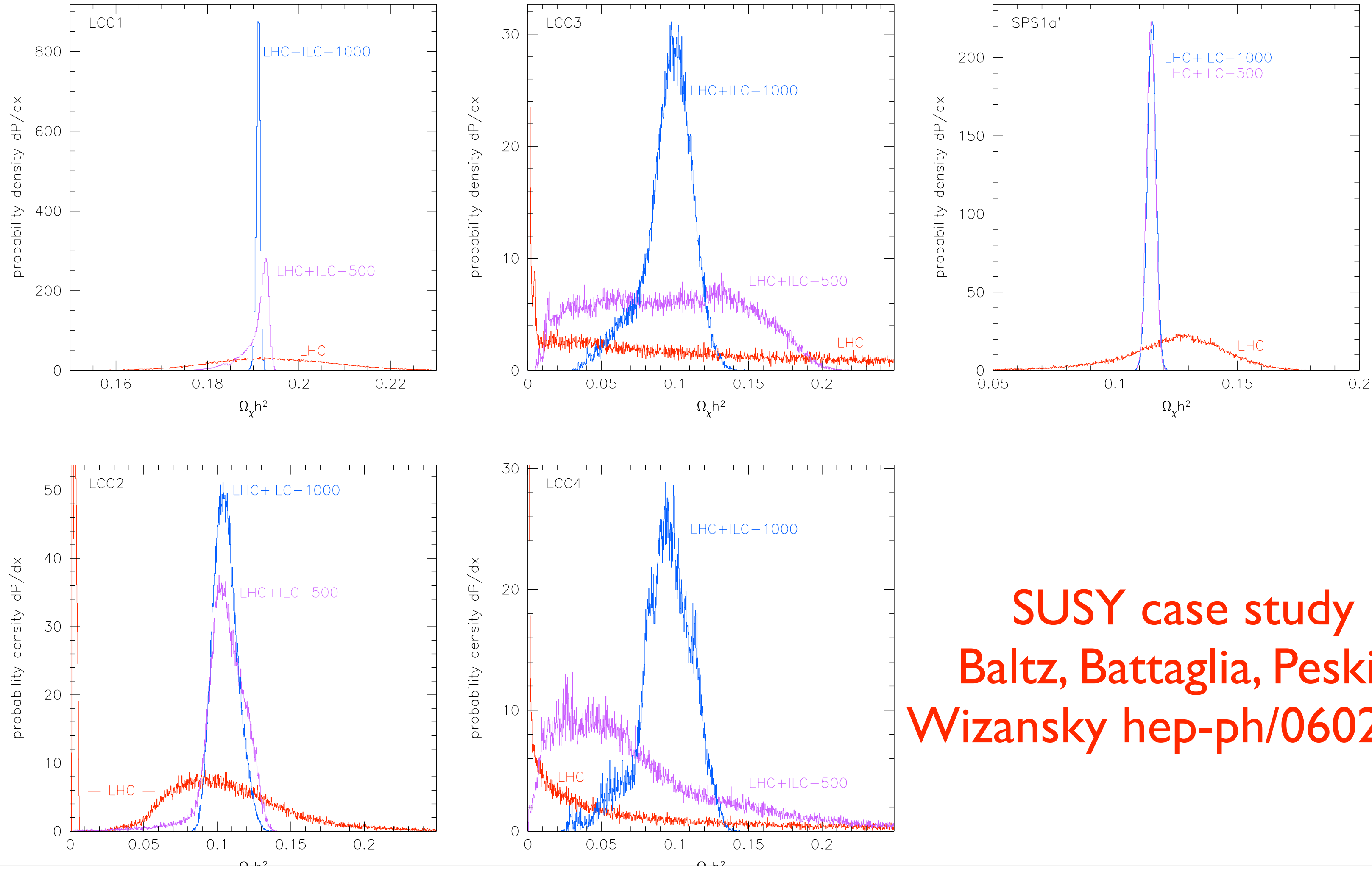
A_1/A_0	0.040 ± 0.023
A_2/A_0	0.082 ± 0.023
A_3/A_0	0.000 ± 0.023
A_4/A_0	0.000 ± 0.024

Concordance model of Dark Matter?

- cosmological measurement of dark matter
  - ⇒ abundance ∝ (annihilation cross section)$^{-1}$
- detection experiments
  - ⇒ scattering cross section
- production at colliders
  - ⇒ mass, couplings
  - ⇒ can calculate cross sections
- Will know what Dark Matter is
- Will understand universe back to t~10^{-10}sec



Omega from colliders



SUSY case study
Baltz, Battaglia, Peskin, Wizansky hep-ph/0602187

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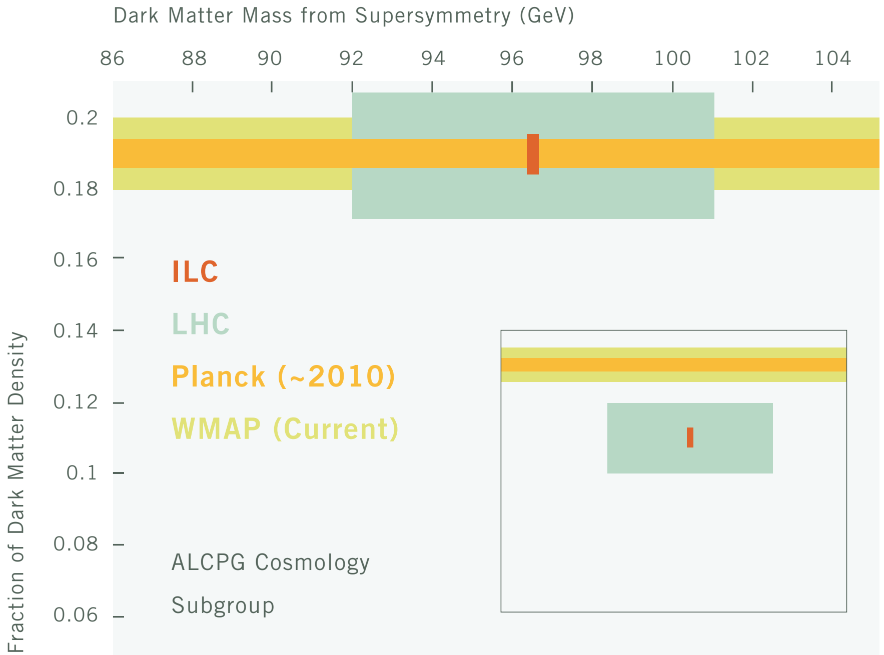
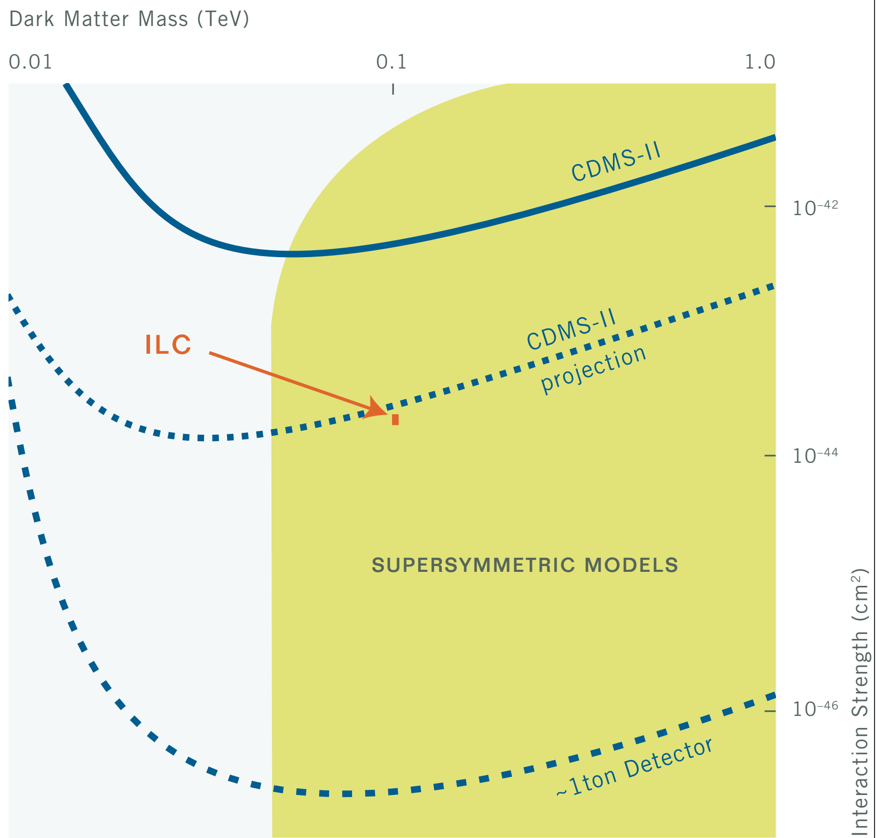
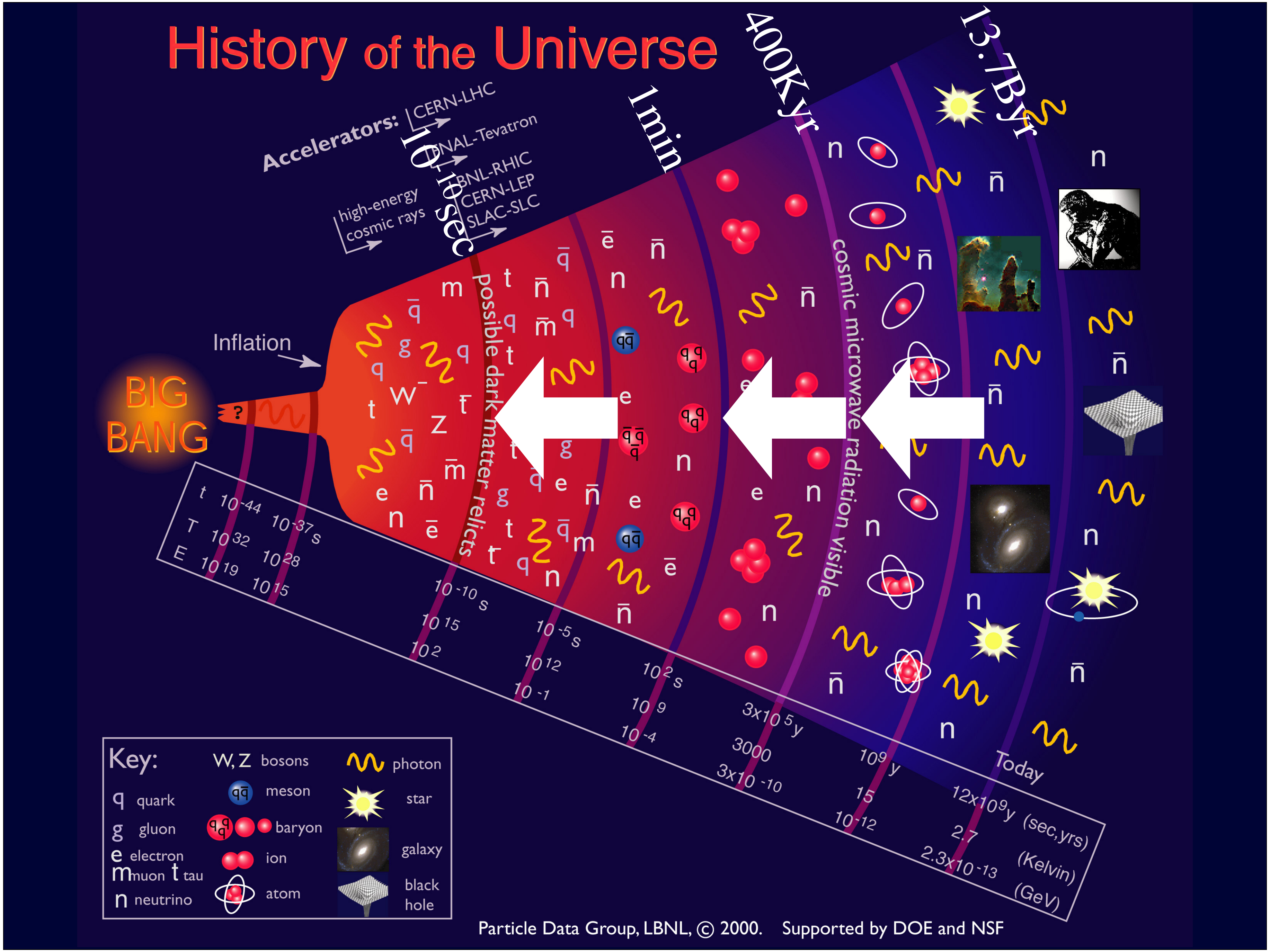
Cross check

abundance



direct cross section

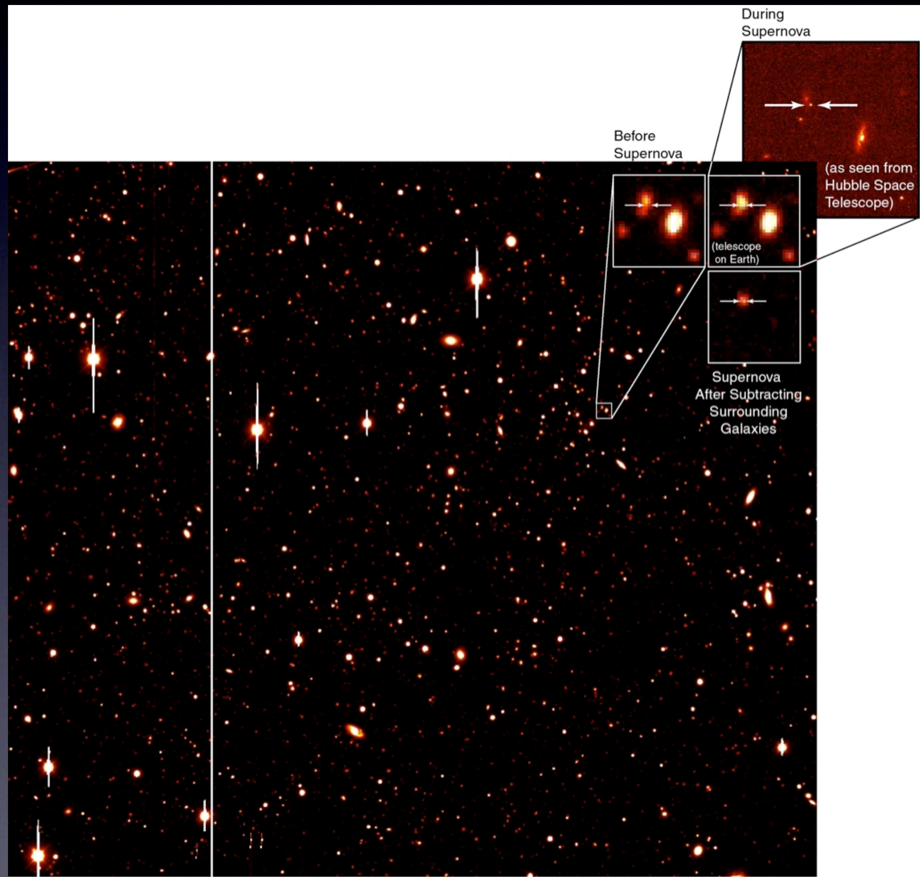



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
10⁻¹⁰sec
1min
400Kyr
13.7Byr
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t 10⁻⁴⁴ 10⁻³⁷ s
T 10³² 10²⁸
E 10¹⁹ 10¹⁵
10⁻¹⁰ s
10¹⁵
10²
10⁻⁵ s
10¹²
10⁻¹
10² s
10⁹
10⁻⁴
3x10⁵ y
3000
3x10⁻¹⁰
10⁹ y
15
10⁻¹²
Today
12x10⁹y (sec,yrs)
2.7 (Kelvin)
2.3x10⁻¹³ (GeV)
Key:
W,Z bosons
photon
q quark
meson
star
g gluon
baryon
e electron
ion
galaxy
m muon t tau
n neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

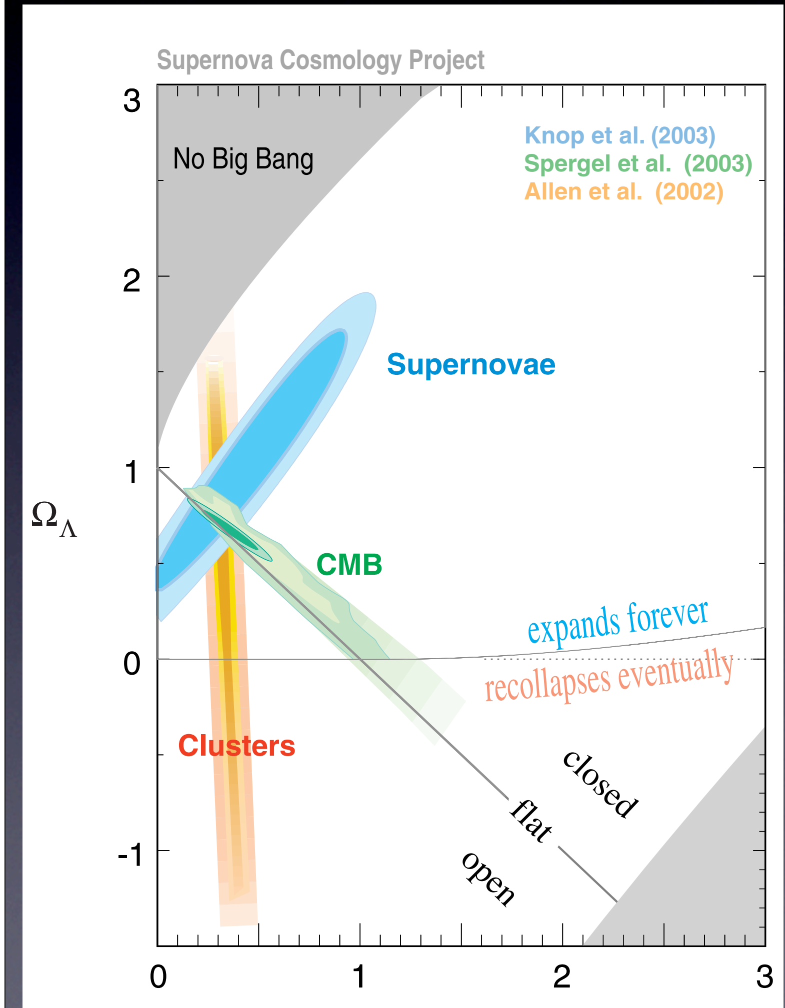
Dark Energy

Type-IA Supernovae

- Type-IA Supernovae "standard candles"
- *Apparent brightness* *$\Rightarrow$ how far (time)*
- *Know redshift* *$\Rightarrow$ expansion since then*
- Expansion of Universe is accelerating



Accelerating Universe



- Einstein's equation

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \rho$$

- If the energy dilutes as Universe expands, it must slow down
- Need something that gains in energy as Universe stretches

  i.e, negative pressure
- *The cosmological constant Λ has the equation of state* $w=p/\rho=-1$
- Generically called "Dark Energy"

Embarrassment

- A naïve estimate of the cosmological constant in Quantum Field Theory:

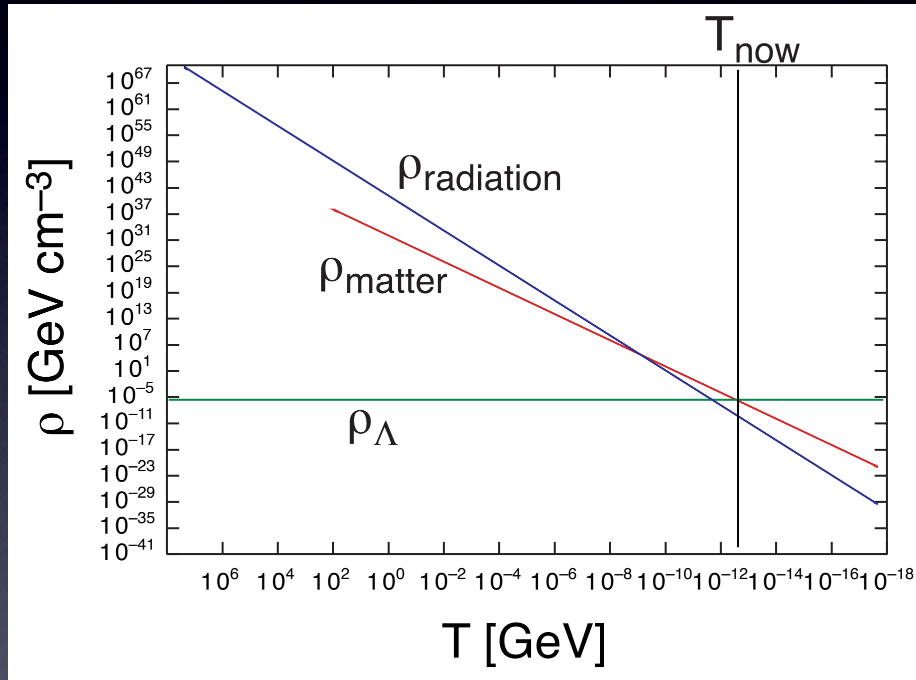
$$\rho_\Lambda \sim M_{Pl}^4 = G_N^{-2} \sim 10^{120} \textit{ times observation}$$

The worst prediction in theoretical physics!

- People had argued that there must be some mechanism to set it zero
- But now it seems finite???

Cosmic Coincidence Problem

- Why do we see matter and cosmological constant almost equal in amount?
- "Why Now" problem
- *Actually a triple coincidence problem including the radiation*
- If there is a deep reason for $\rho_\Lambda \sim ((\text{TeV})^2/M_{Pl})^4$, coincidence natural



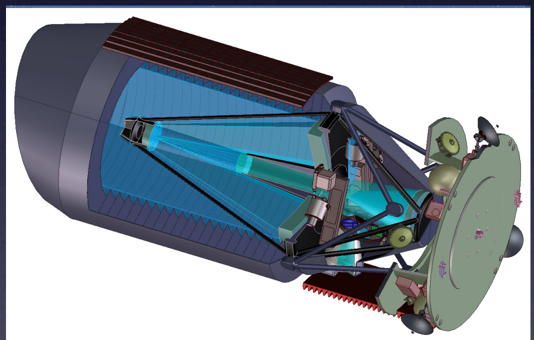
Arkani-Hamed, Hall, Kolda, HM

Does the Universe end?

- If $w<-1$, the Universe ends in a Big Rip
- Expansion becomes so fast that galaxies, stars, eventually atoms and even nuclei get ripped apart
- Universe ends with an infinite speed and empty!
- We need to know the equation of state

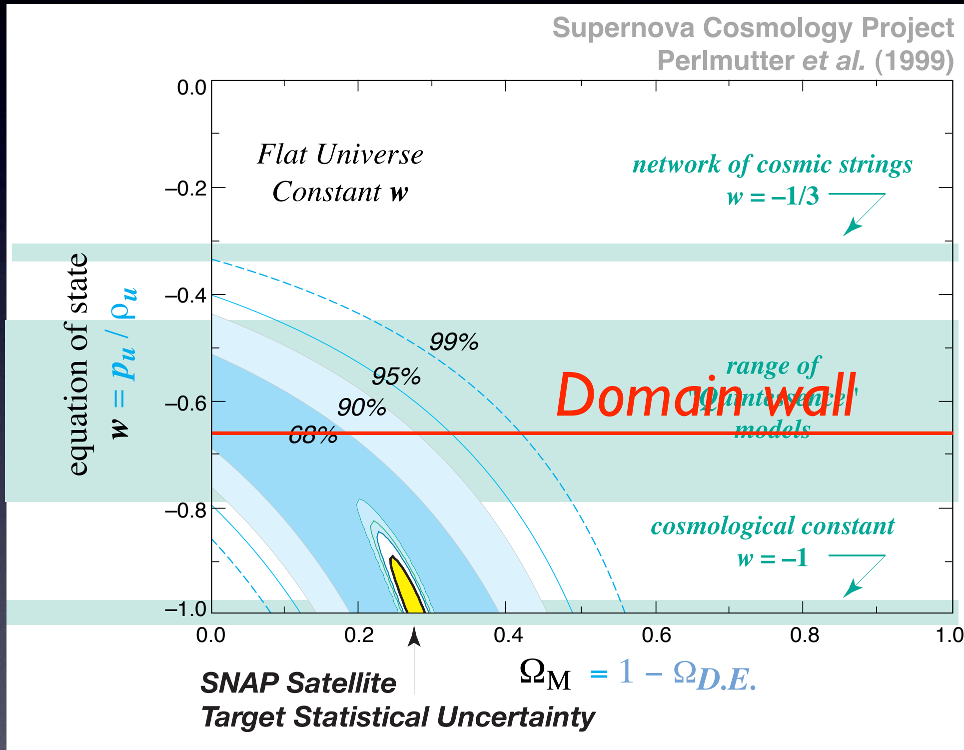
What is Dark Energy?

- We have to measure w
- For example with a dedicated satellite experiment



SNAP

- or on the ground: DES, BOSS, LSST, etc



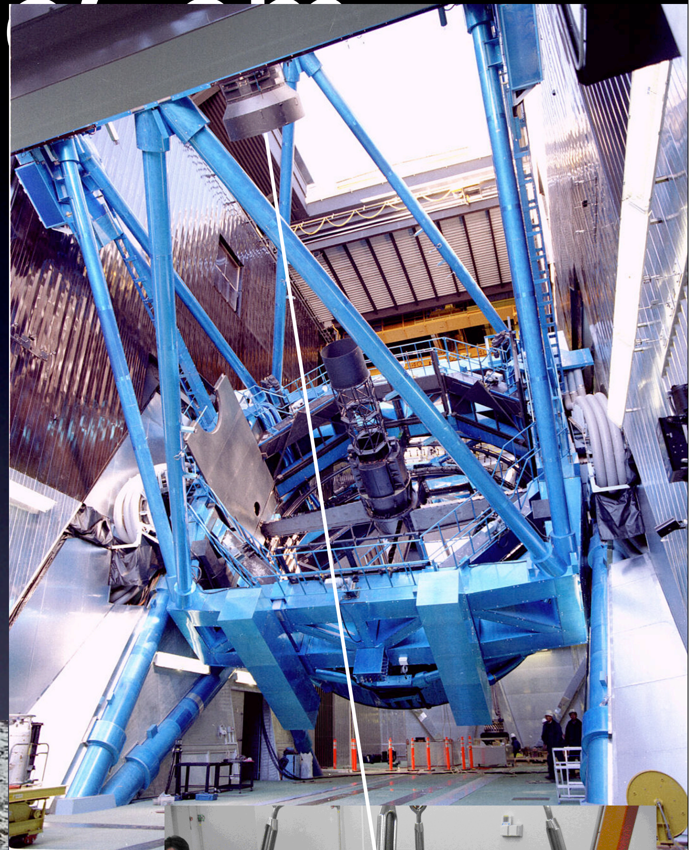
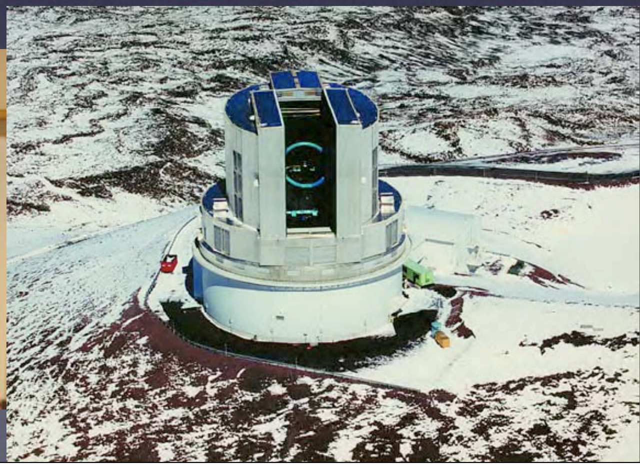
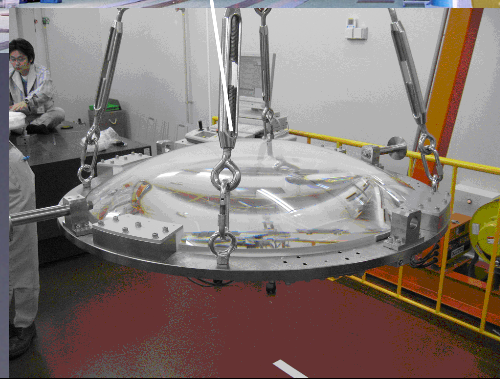
Friedland, HM, Perelstein





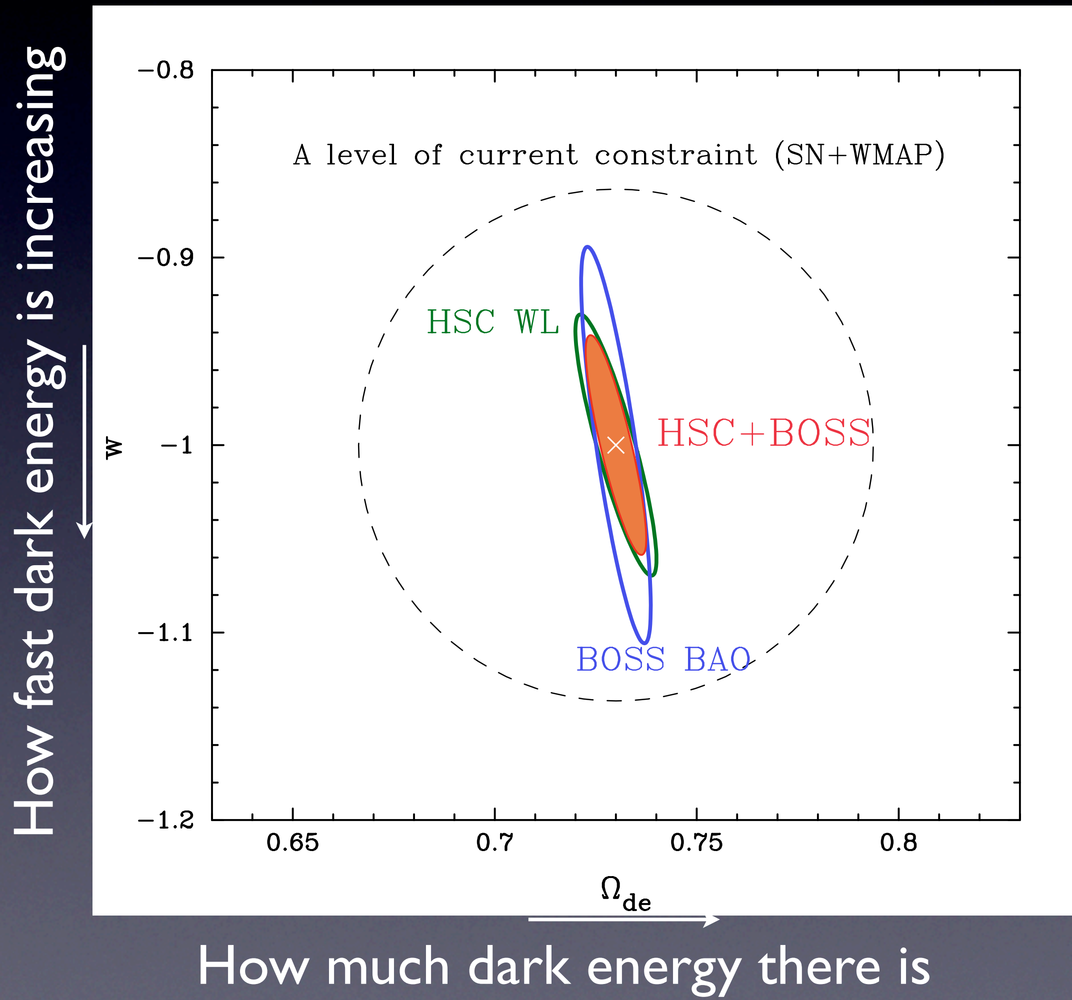
HyperSuprimeCam

- New camera at Subaru
- IPMU, NAOJ, KEK, Princeton
- IPMU leads the design (Aihara)
- IPMU leads the analysis team (Takada, Yoshida)
- map out distribution of dark matter
- constrain dark energy properties

Power of Combination

- SDSS and HSC with very different systematics
- give confidence to the result
- *How fast is dark energy creating energy?*
- *Is dark energy "alive"?*



string theory prediction?

- Bousso's covariant entropy bound says de Sitter universe has only finite entropy
- how can it be consistent with infinite number of dof in string theory?
- de Sitter must tunnel to Minkowski
- create bubbles
- no dark energy in bubble
- "eternal inflation"?
- need criteria!

Conclusions

- New era
  - reaching the Fermi energy scale (1933)
  - five experimental evidence beyond SM
- Among them, dark matter puzzle may well be within reach in the next 10? years
- many theoretical puzzles with dark energy
- experiments addressing other mysteries
- theorist:
  - find ways to extract as much information as possible from precious data
  - data ⇒ models ⇒ predictions ⇒ data