IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Quantum Universe

Hitoshi Murayama (IPMU Tokyo & Berkeley)

三者若手夏の学校 Aug 19, 2008

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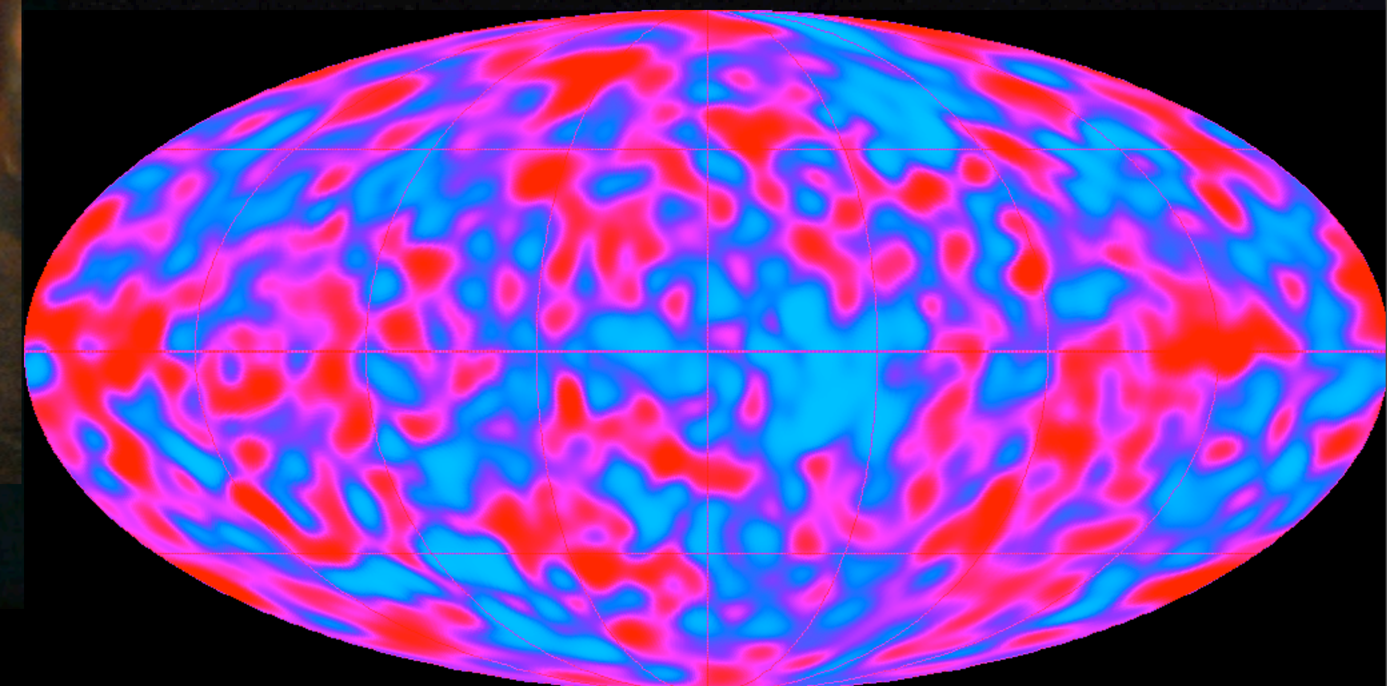
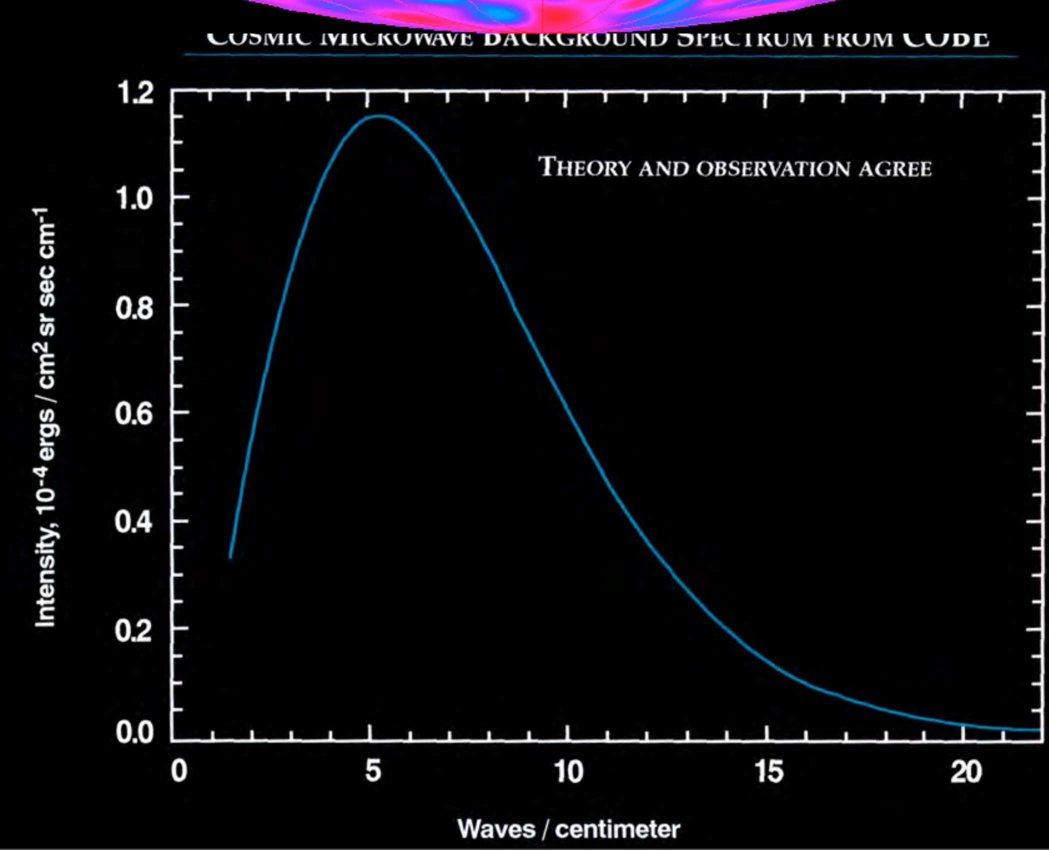
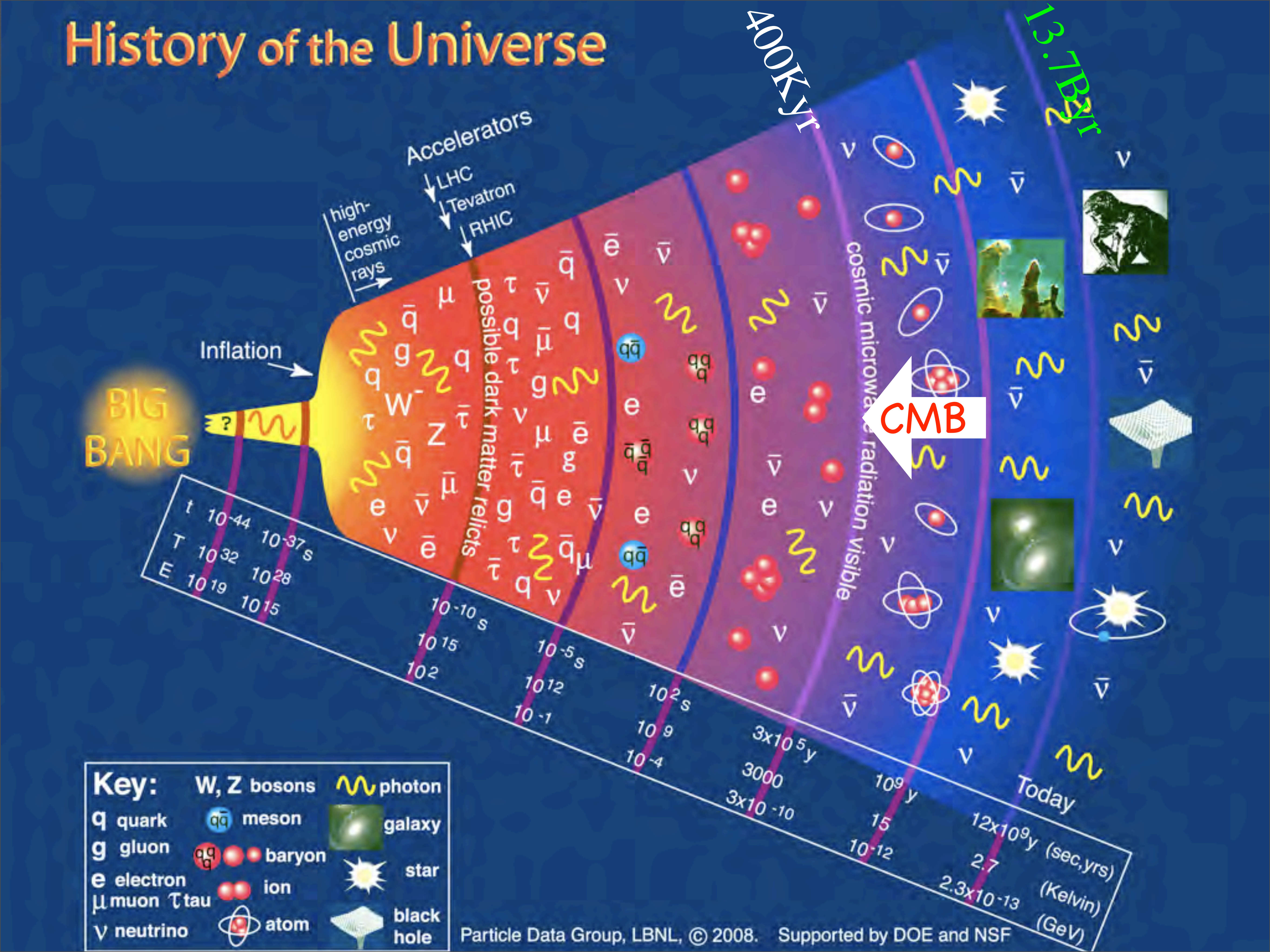
BERKELEY LAB

COBE showed quantum origin of the universe






History of the Universe
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possible dark matter relicts
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t 10-44 10-37s
T 10 32 10 28
E 10 19 10 15
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10 2
10-5 s
10 12
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10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10-12
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12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Quantum Universe

To understand physics at the largest scale:
Universe
we need to understand the smallest scale:
elementary particles

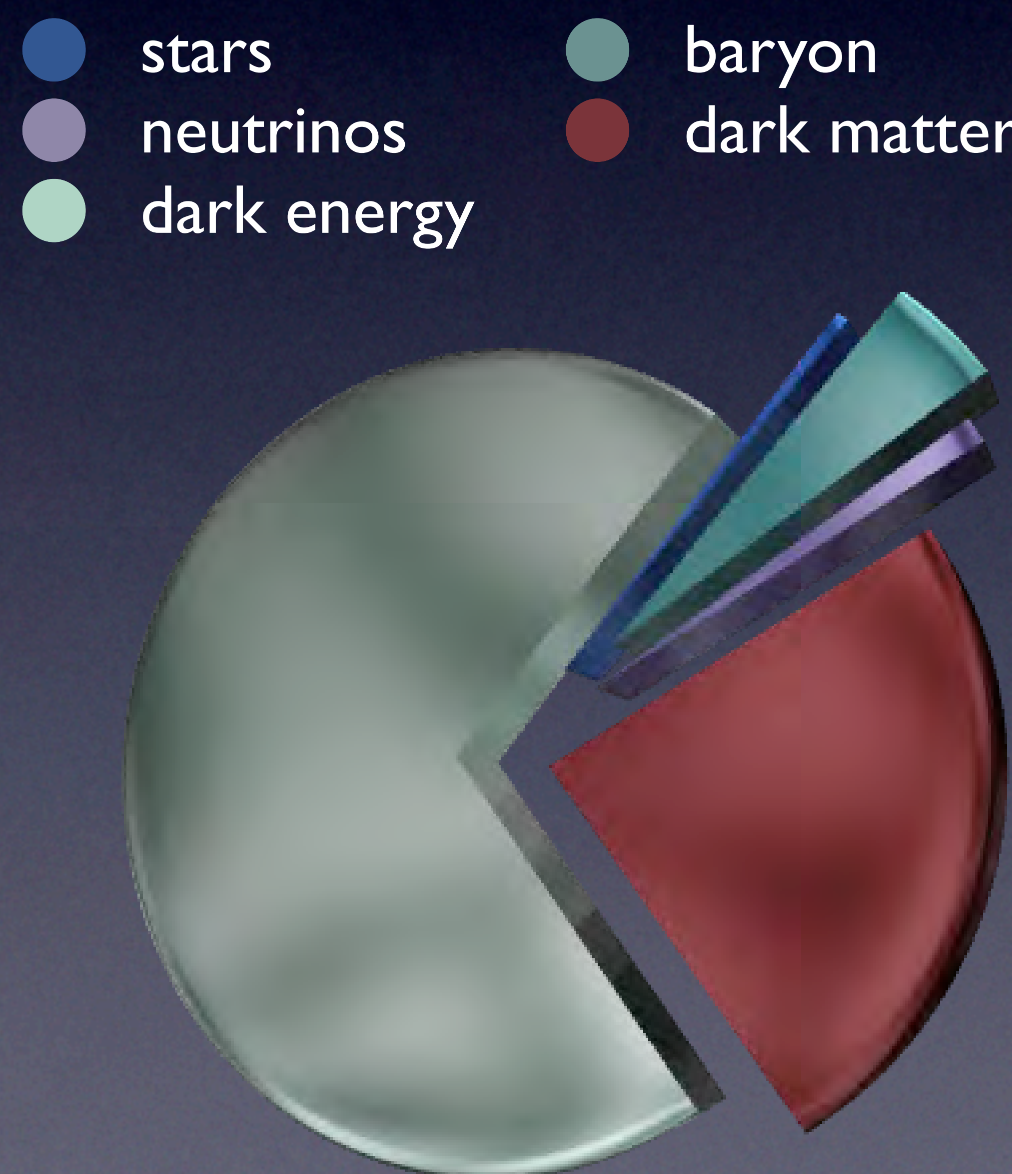
- What is the Universe made of?
- How did it come to be?
- Why do we exist?

Moving from philosophy to physics


There are many
things we don't see

Energy Budget of the Universe

- 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%
- Dark Field ~10^{62}%??

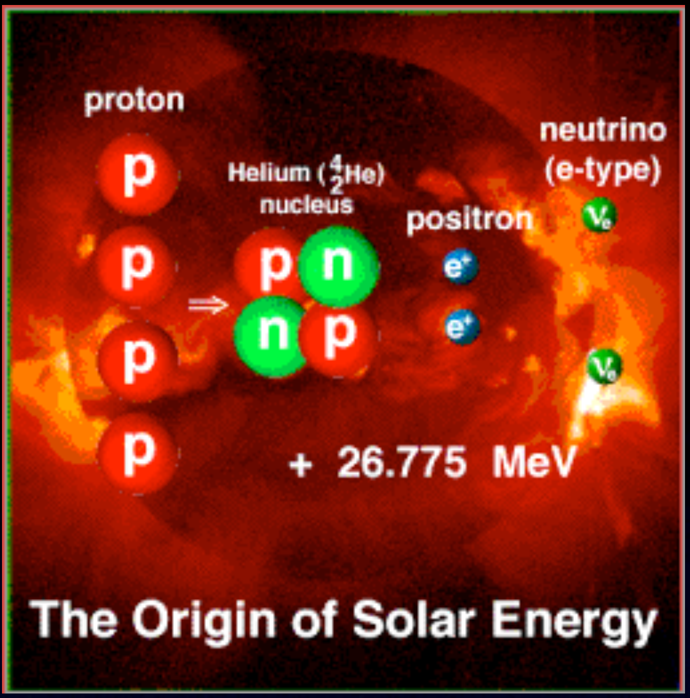


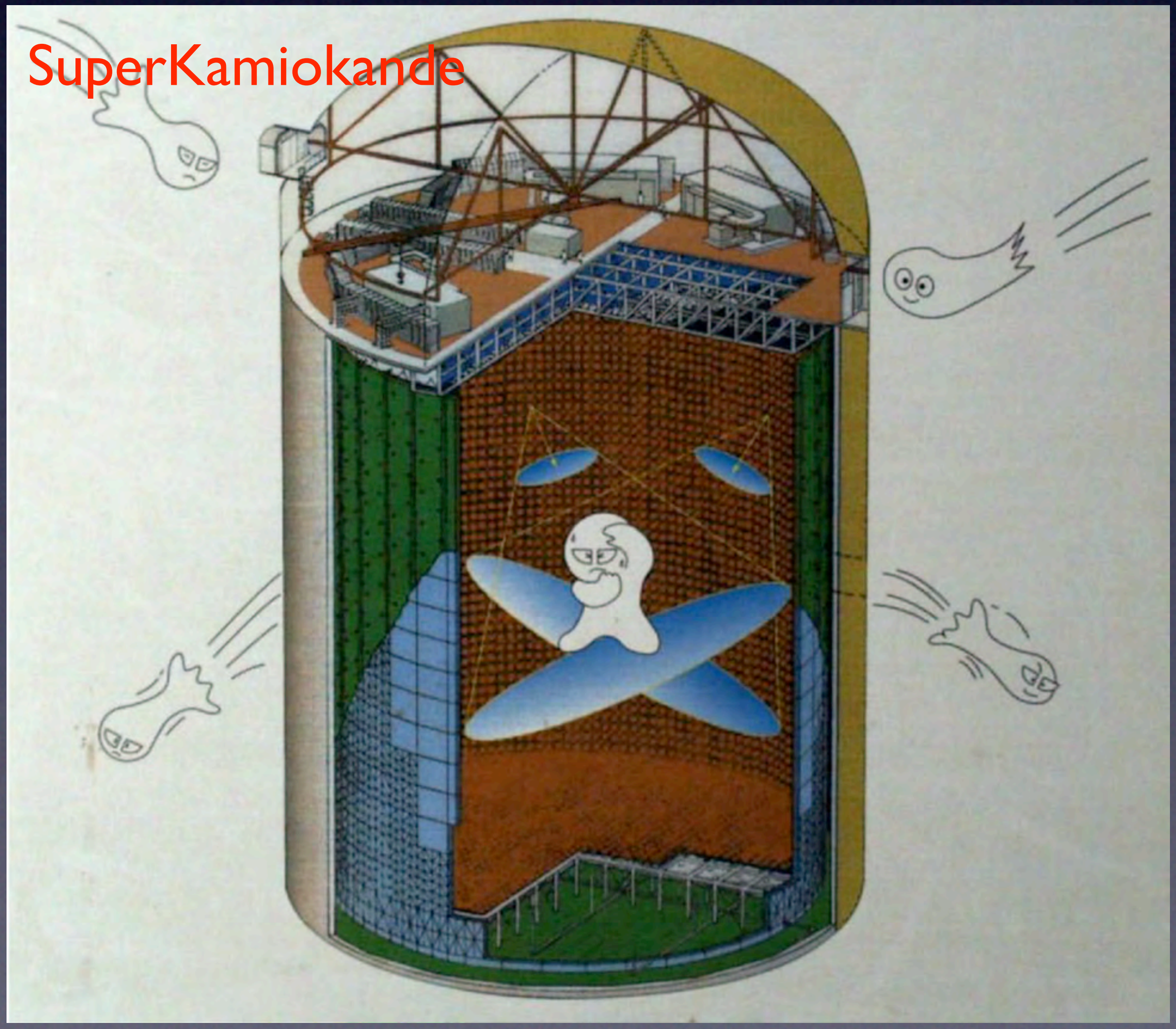

What is Dark Matter?
What is Dark Energy?
Kibo
ELM-PS

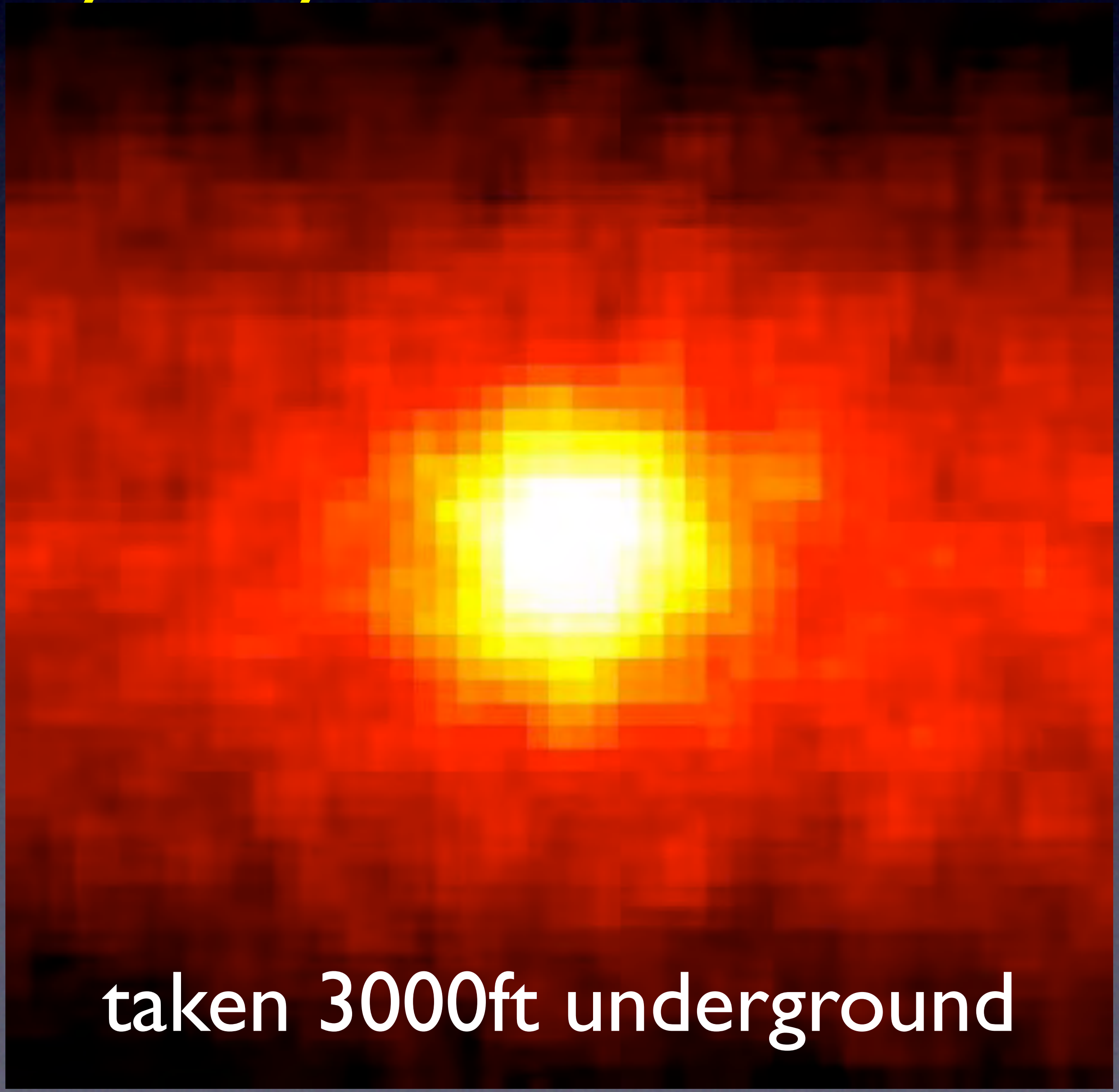
Don't be afraid of invisibles

Pauli regretted to have predicted neutrinos nobody can detect

Trillions of them go through our body every second





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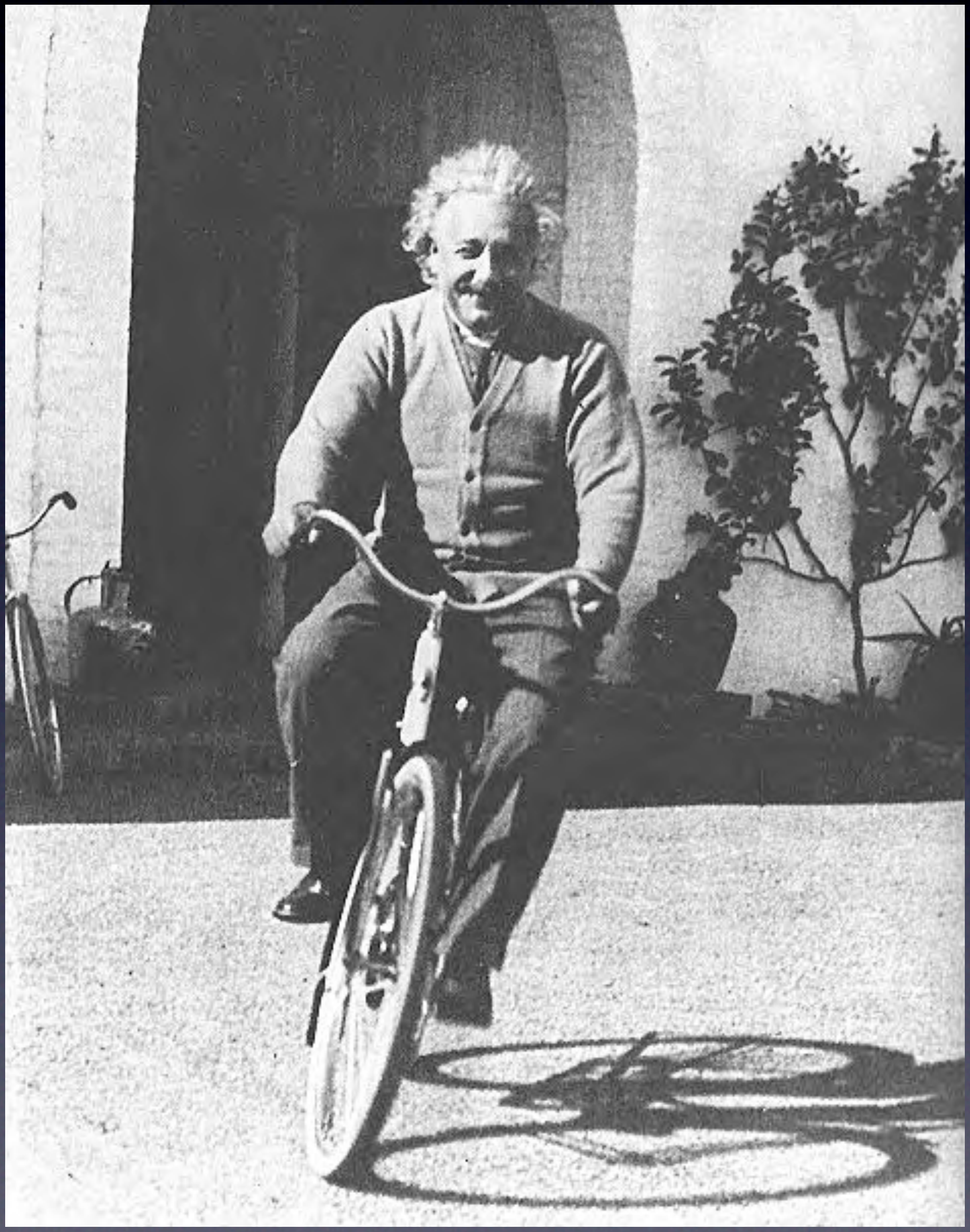
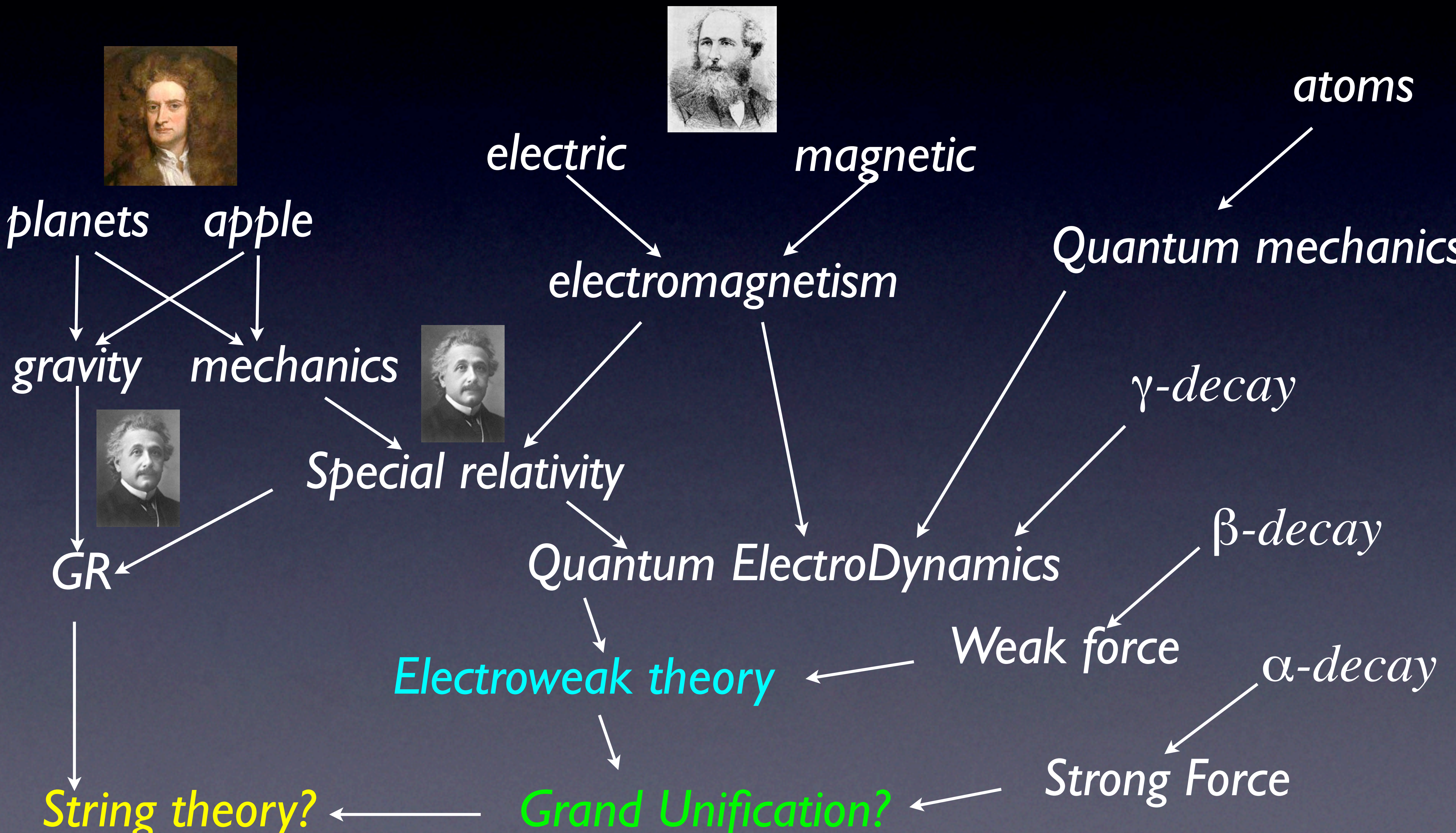
Einstein's Dream

- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a unified description
- But he failed to unify electromagnetism and gravity (GR)



History of Unification



We are just about to achieve another layer of unification

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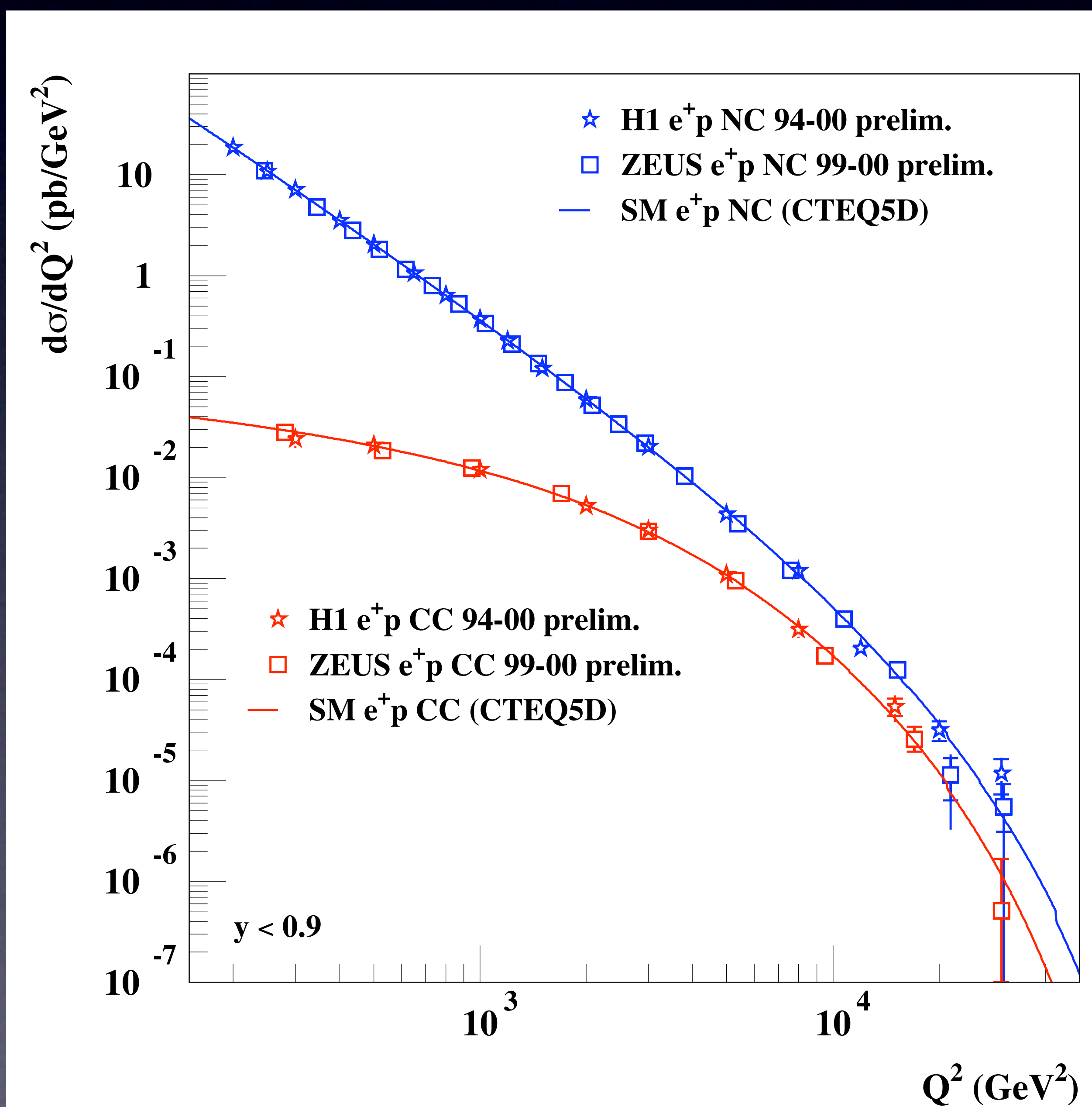
HERA ep collider



- Unification of electromagnetic and weak forces

$\Rightarrow$ electroweak theory

- Long-term goal since ‘60s
- We are getting there!
- The main missing link: Dark Field

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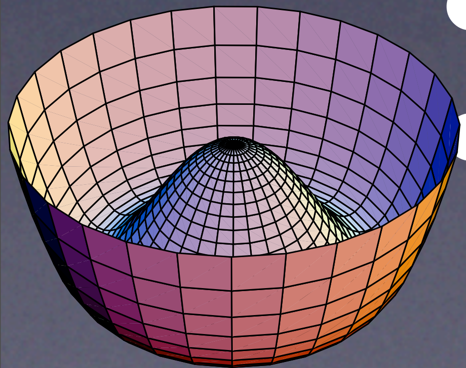
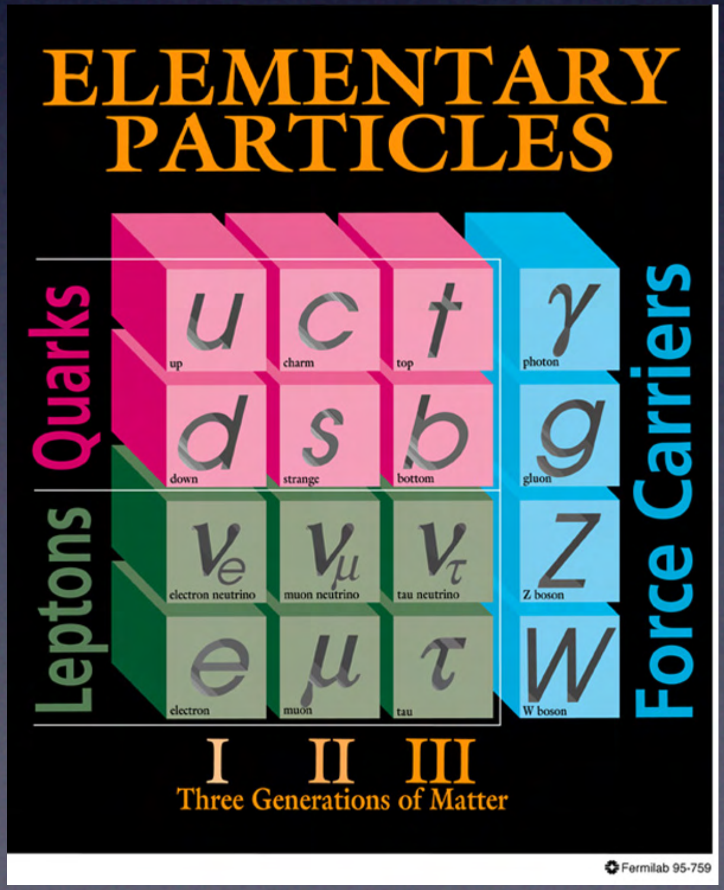
major shift

- 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 still 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

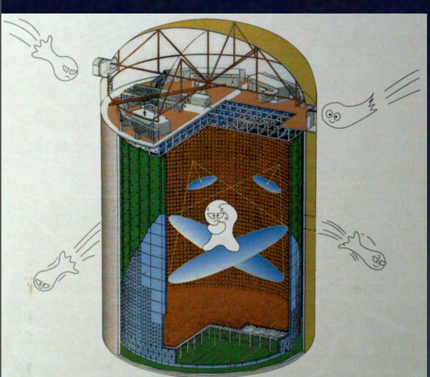
- Given lack of experimental evidence, we've focused on *aesthetic* reasons why we need physics beyond the standard model
  - hierarchy problem
  - why three generations?
  - masses and mixings?
  - why only one scalar multiplet?
  - why does it condense?
  - anomaly cancellations
  - why SU(3)>SU(2)>U(1)?

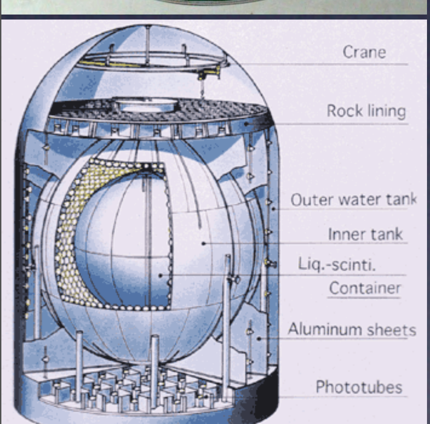


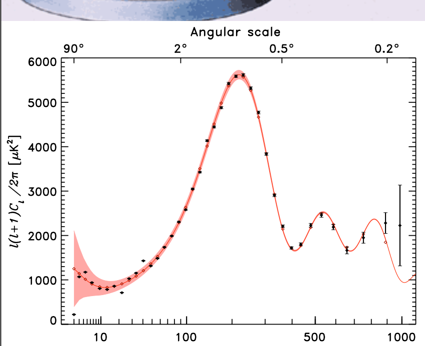


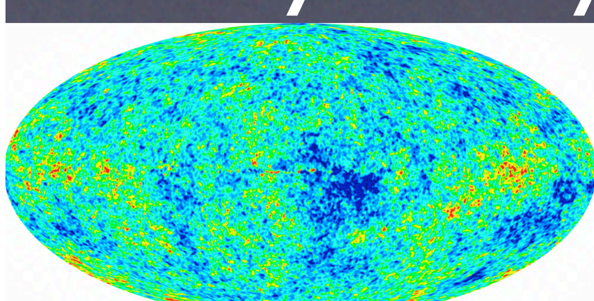
Experimental Facts

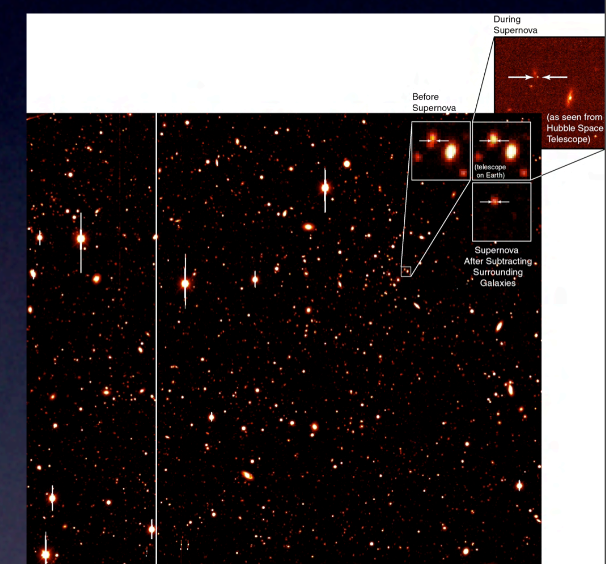
- Five facts standard model cannot explain
  - finite neutrino mass (1998, 2002)
  - accelerating universe (1998)
  - non-baryonic dark matter (2003)
  - acausal nearly Gaussian scale-invariant density fluctuation (2003)
  - baryon asymmetry (reconfirmed 2003)

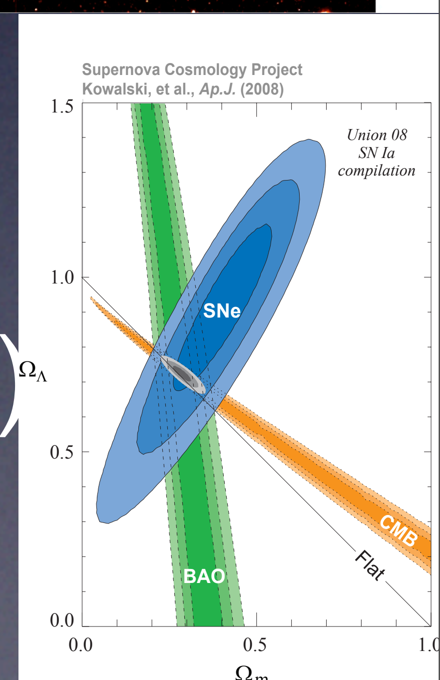












Large Hadron Collider (LHC)

Recreating Big Bang

first beam on Sep 10

New Era

- ~1900 reached atomic scale 10^{-8}cm$\approx\alpha/m_e$
- ~1970 reached strong scale 10^{-13}cm$\approx Me^{-2\pi/\alpha_s b_0}$
- ~2010 will reach weak scale 10^{-17}cm
- known since Fermi (1933), finally there!
- presumably it is also a derived scale more fundamental theory
- supersymmetry? extra dimensions? string theory?
- If so, we expect rich spectrum of new particles!

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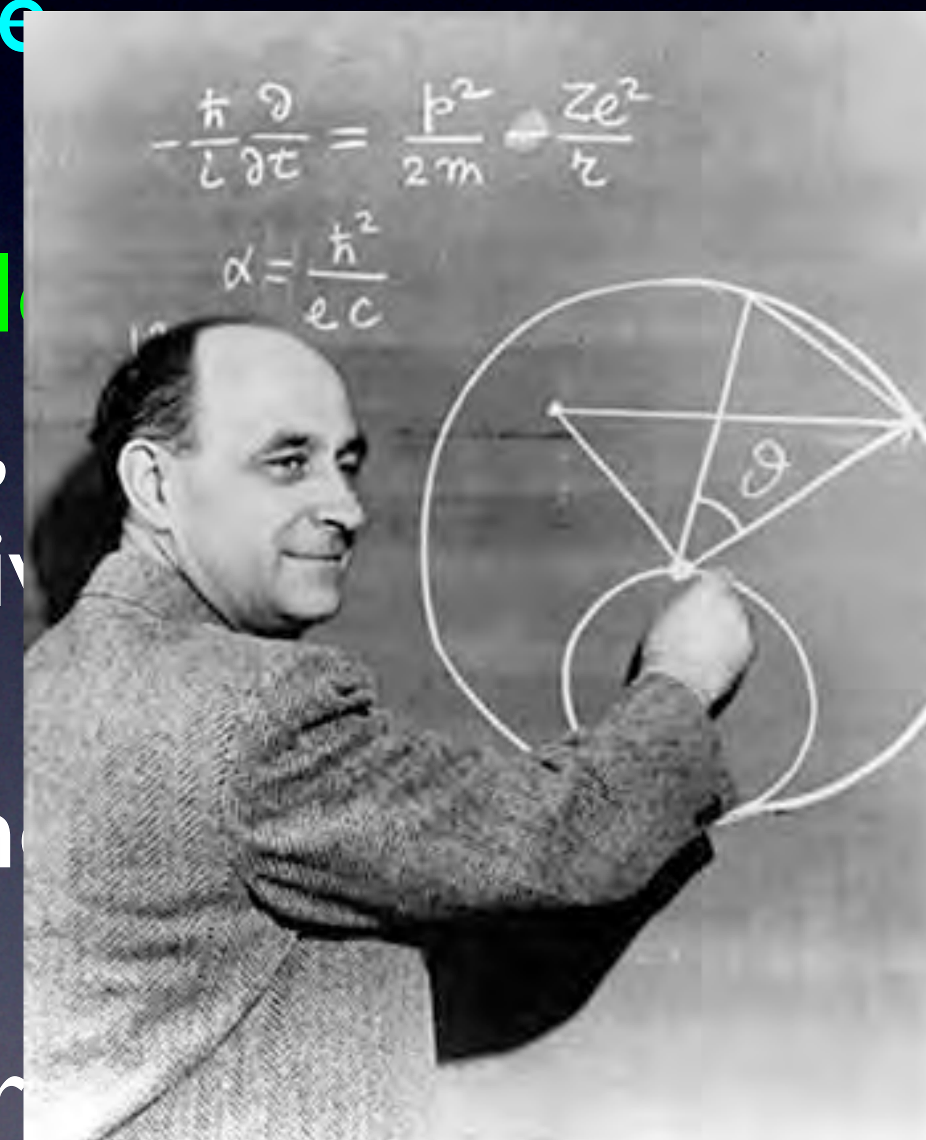
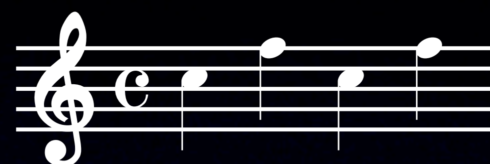


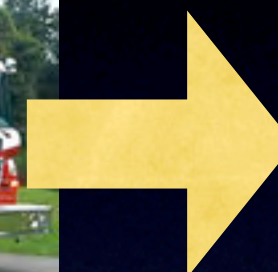
Outline

- Introduction
- Big Bang
- Dark Matter
- Dark Energy
- Dark Field
- Anti-Matter
- Inflation
- Conclusion

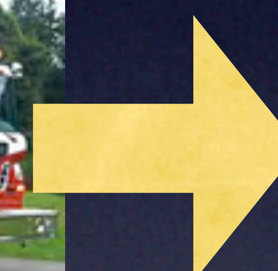
Big-Bang

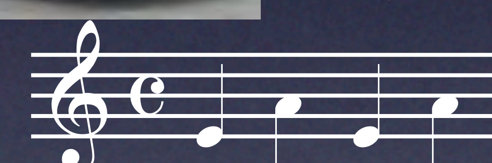
Universe is expanding

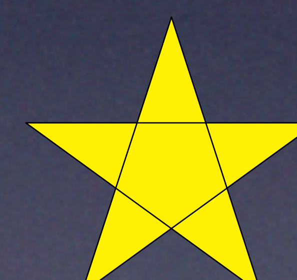


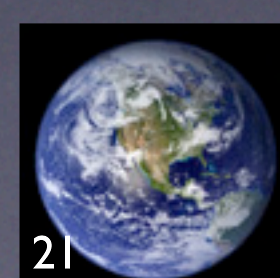


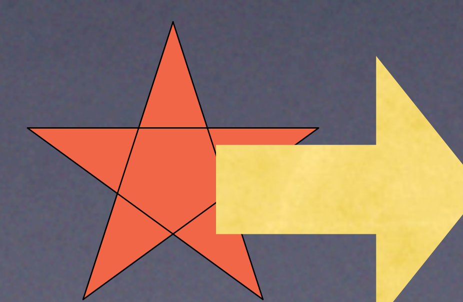
- Approaching ambulance: higher key
- Moving-away ambulance: lower key
- Much the same way, moving-away stars: lower key (redder) in spectrum of light
- We see distant stars/ galaxies are redder





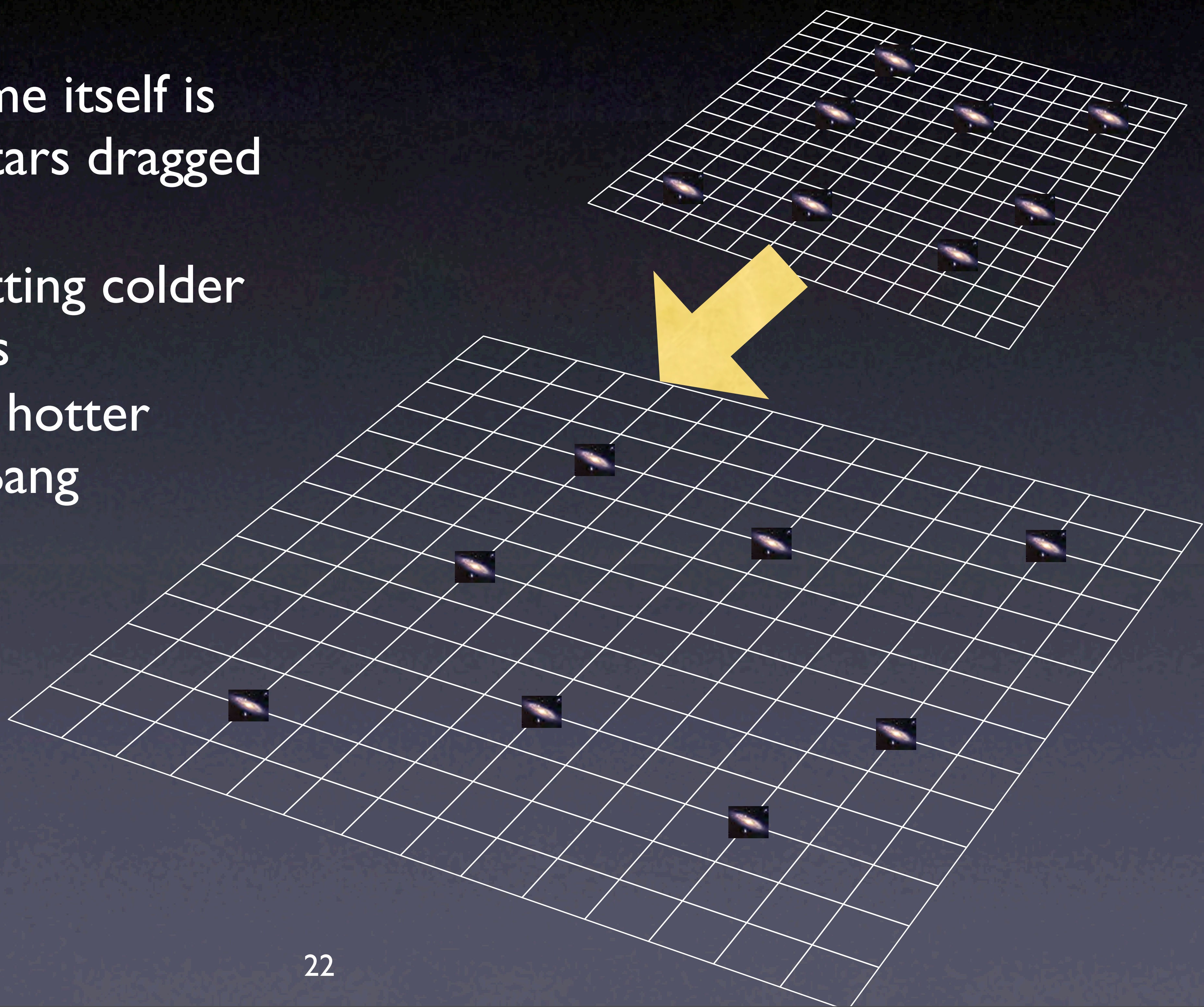


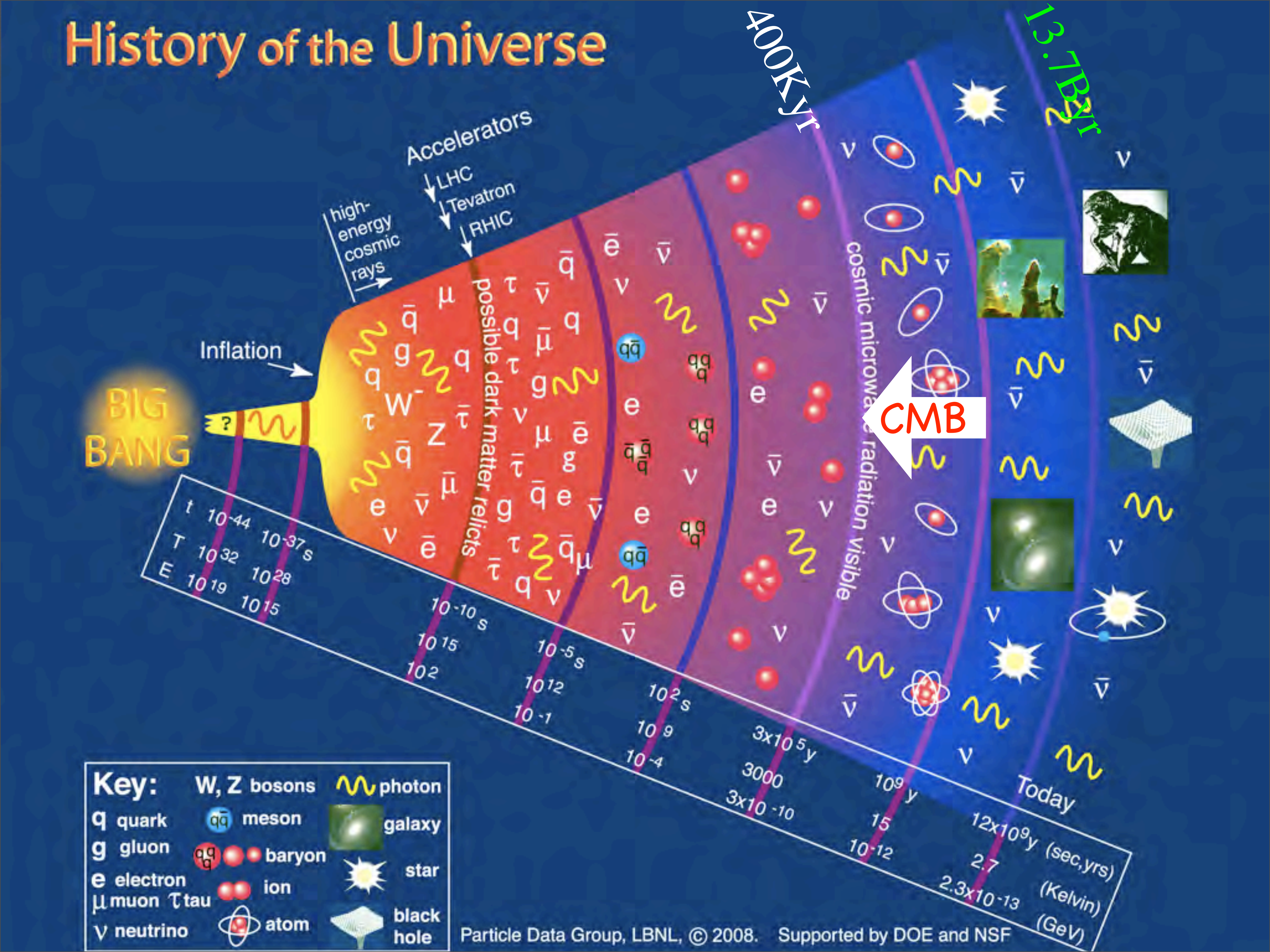




Expansion of Space

- The spacetime itself is stretching, stars dragged away
- Universe getting colder as it expands
- It was much hotter earlier: Big Bang

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10 2
10-5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
ion
star
μ muon τ tau
ν neutrino
atom
black hole
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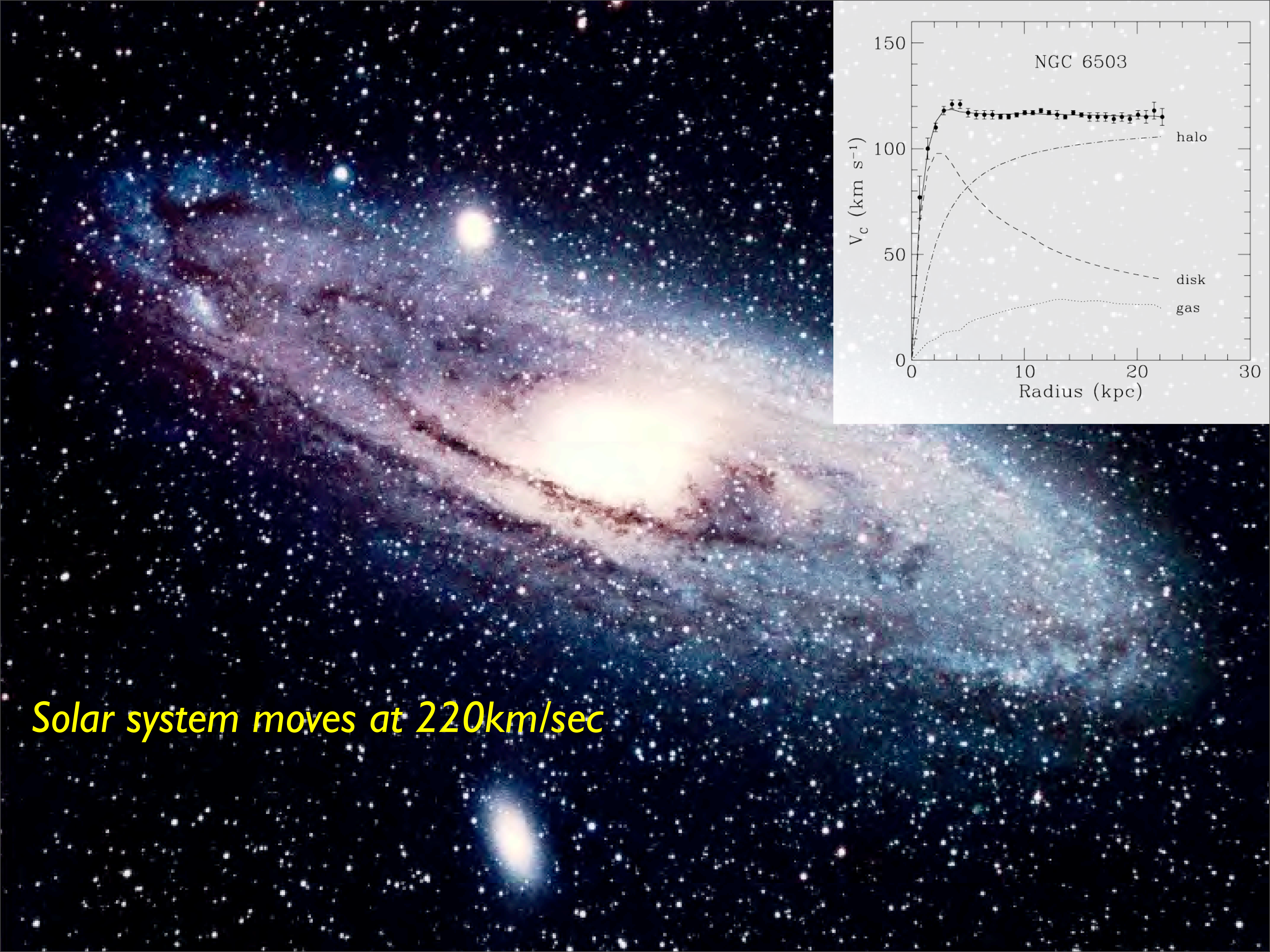
elementary particles and early universe

- early universe: high temperature T
- high energy $E=kT$
- high momentum $p=E/c=kT/c$
- small distance $x=\hbar/p=\hbar c/kT$
- early universe: elementary particles play main roles!

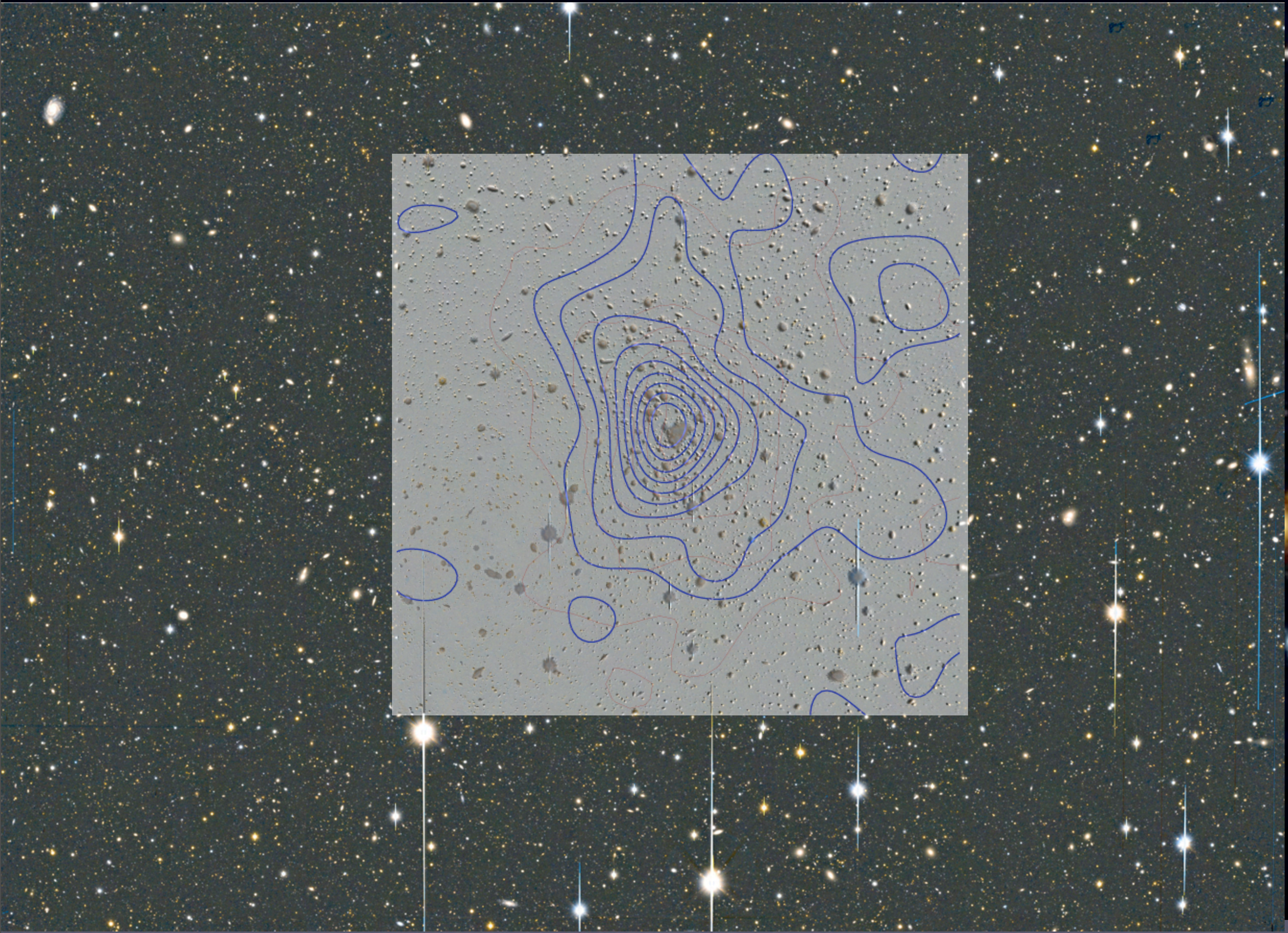
Dark Matter

Evidence for non-baryonic dark matter



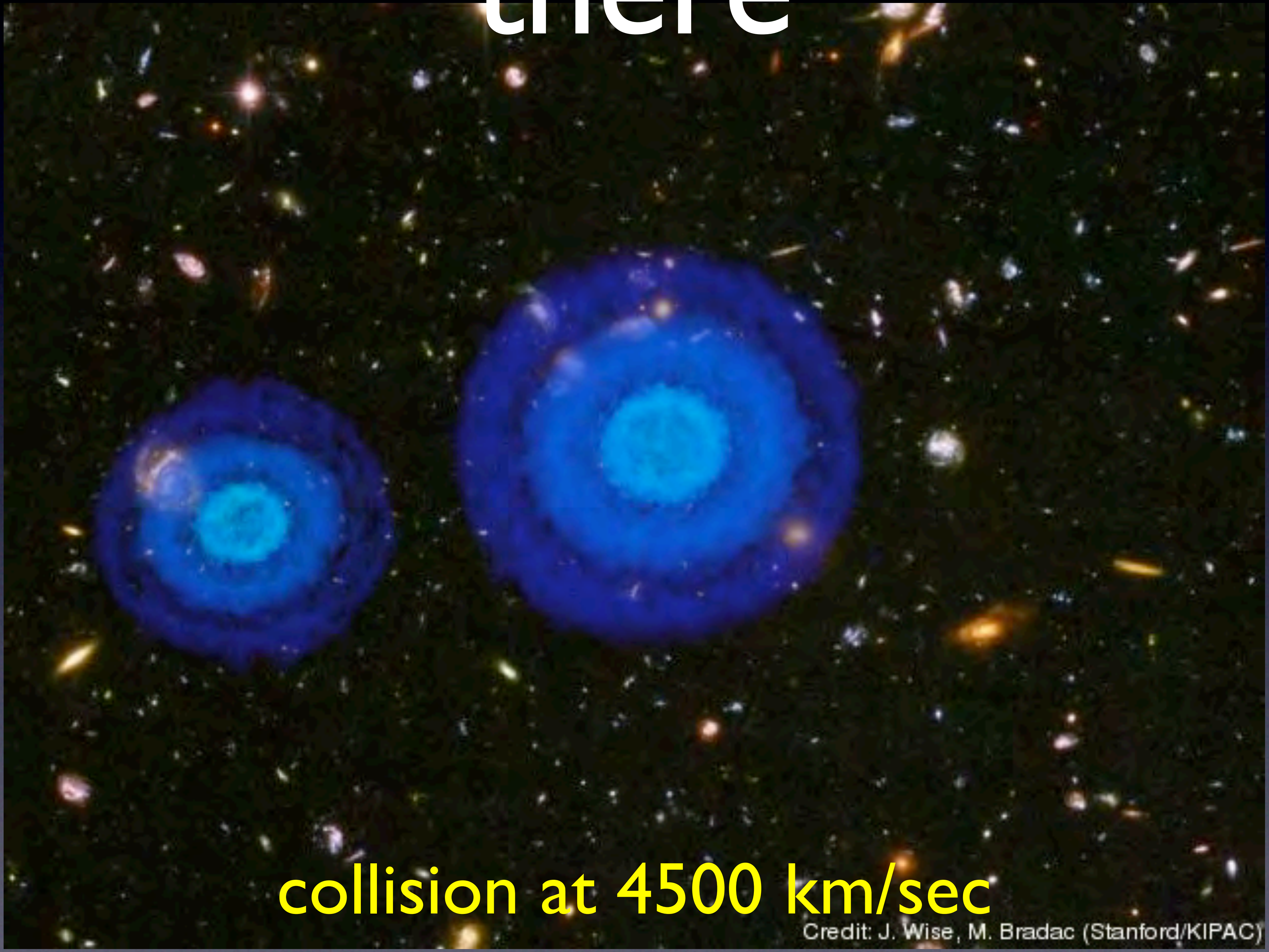
Solar system moves at 220km/sec

See the invisible DM through weak lensing

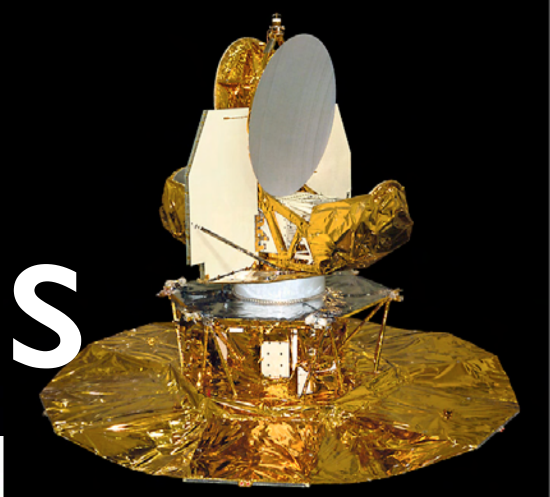


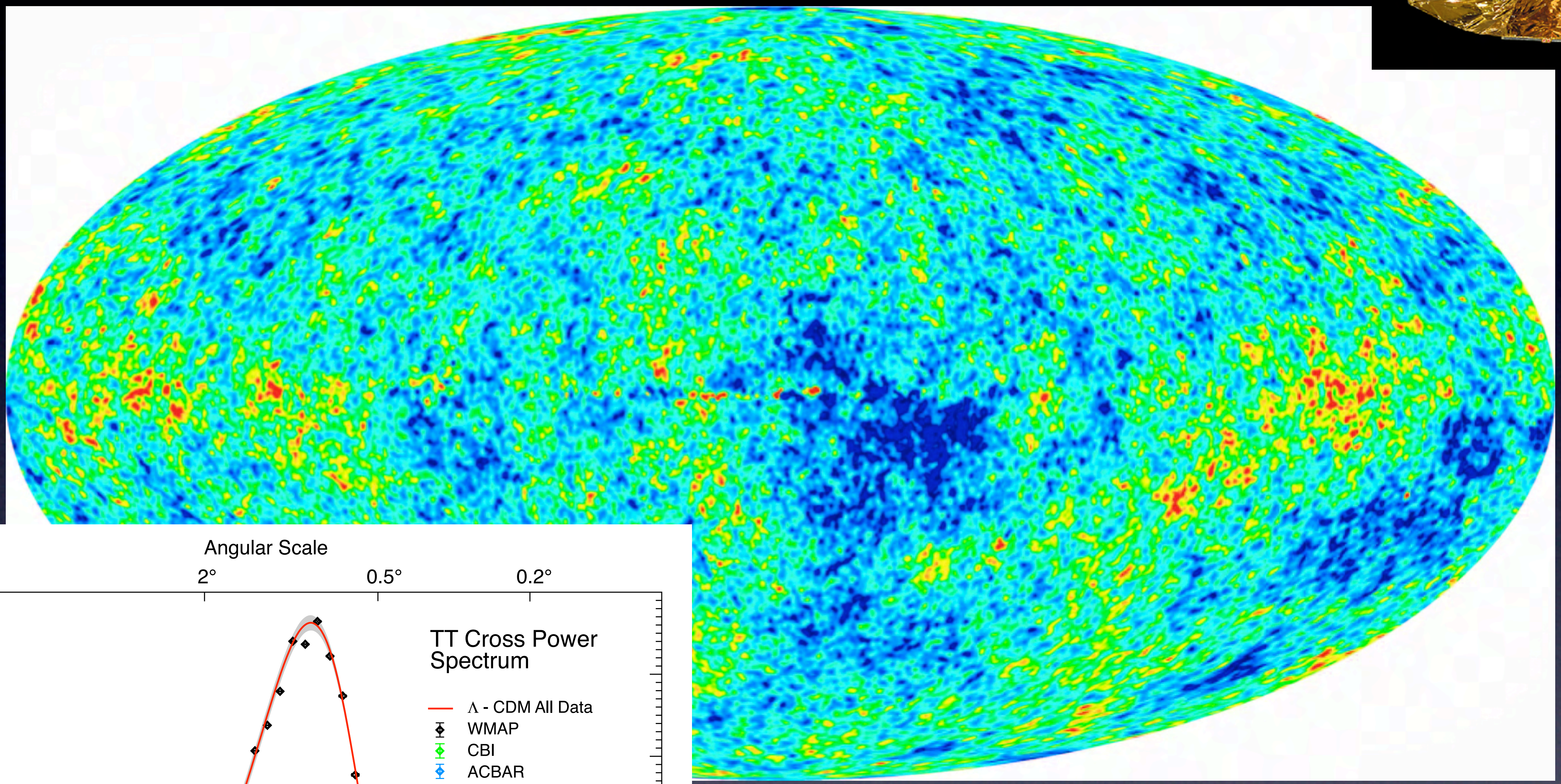
You don't want to be there

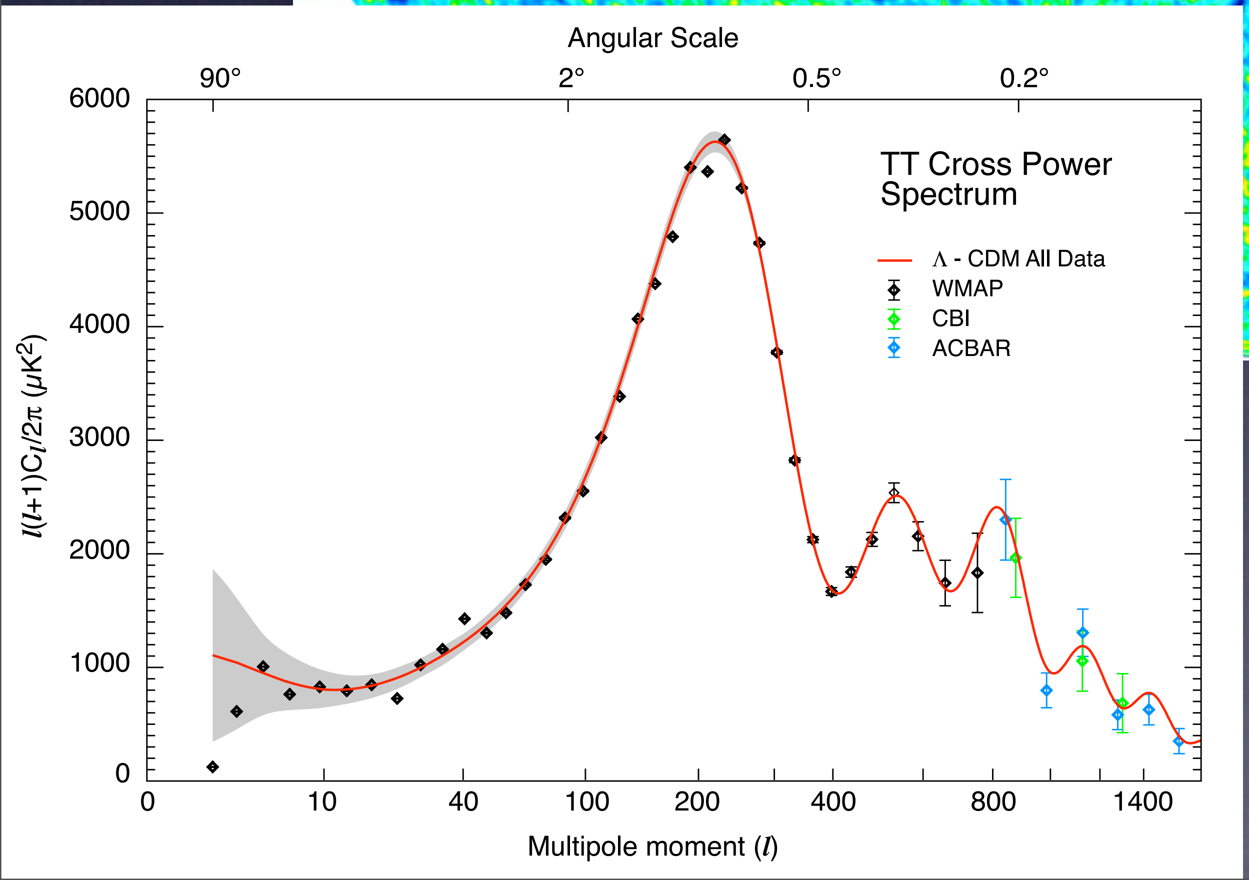
You don't want to be there



Cosmological scales



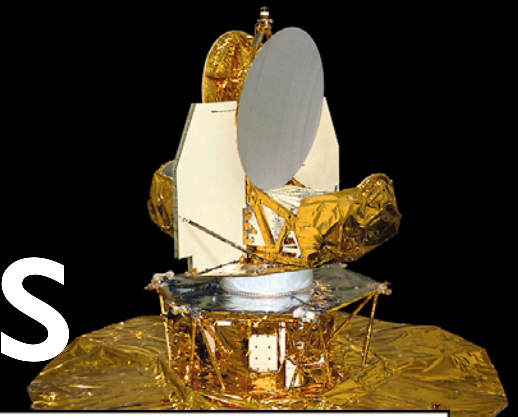


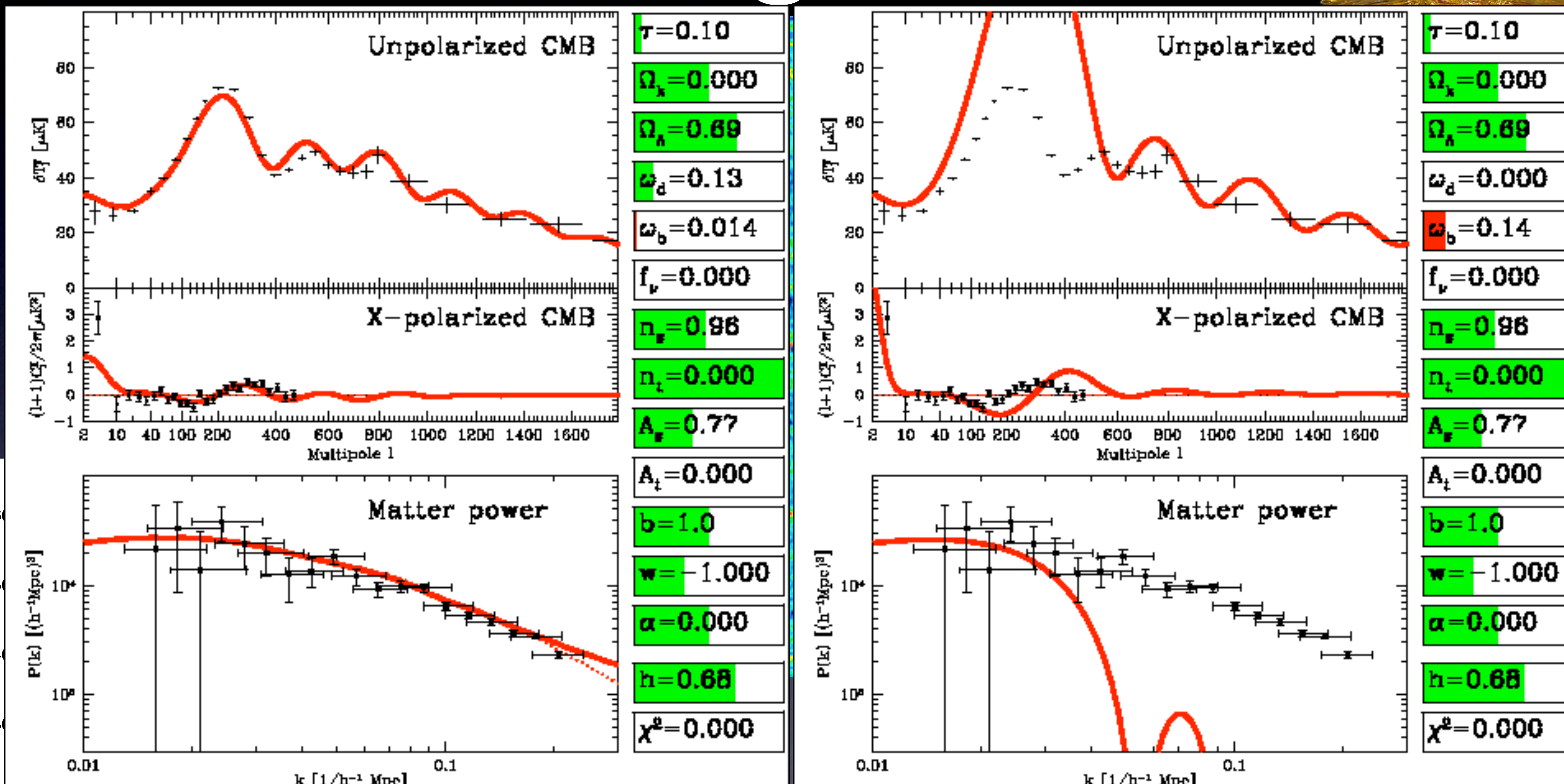


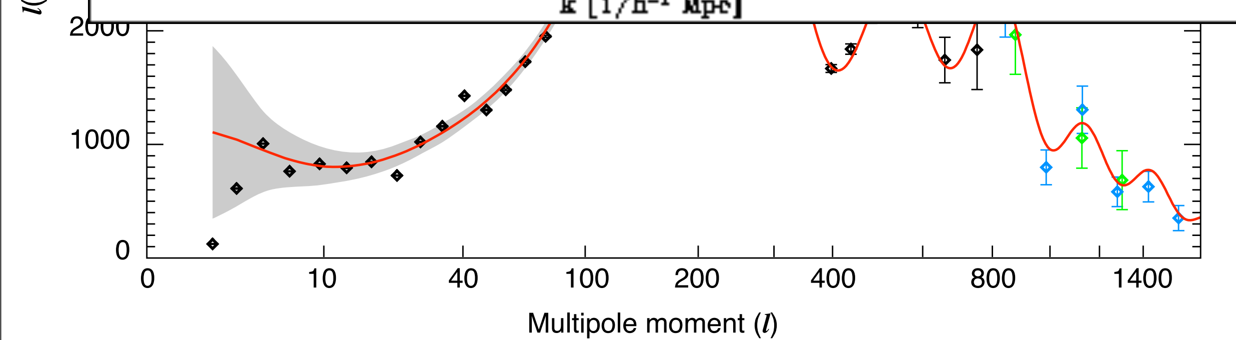
matter/all atoms=6.03±0.03

See Tegmark movie

Cosmological scales







matter/all atoms=6.03±0.03

See Tegmark movie

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

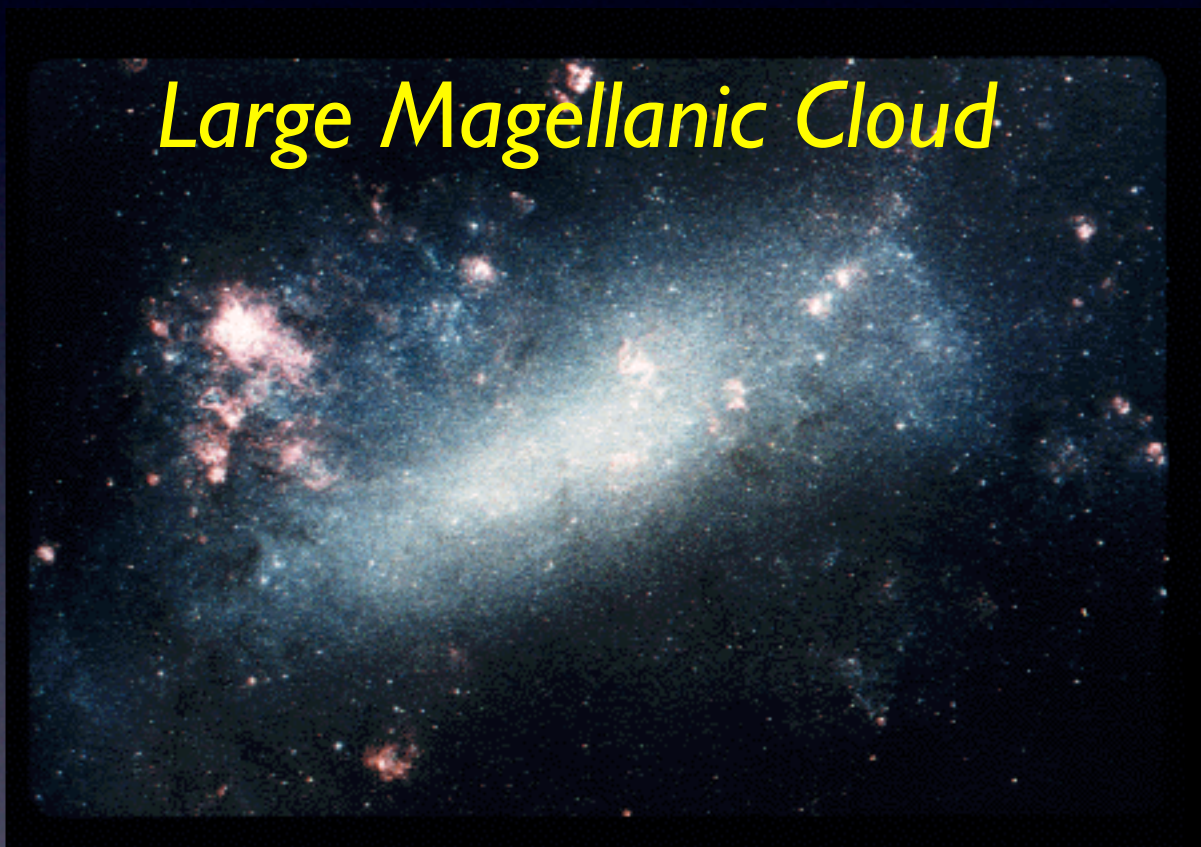
Mass Limits

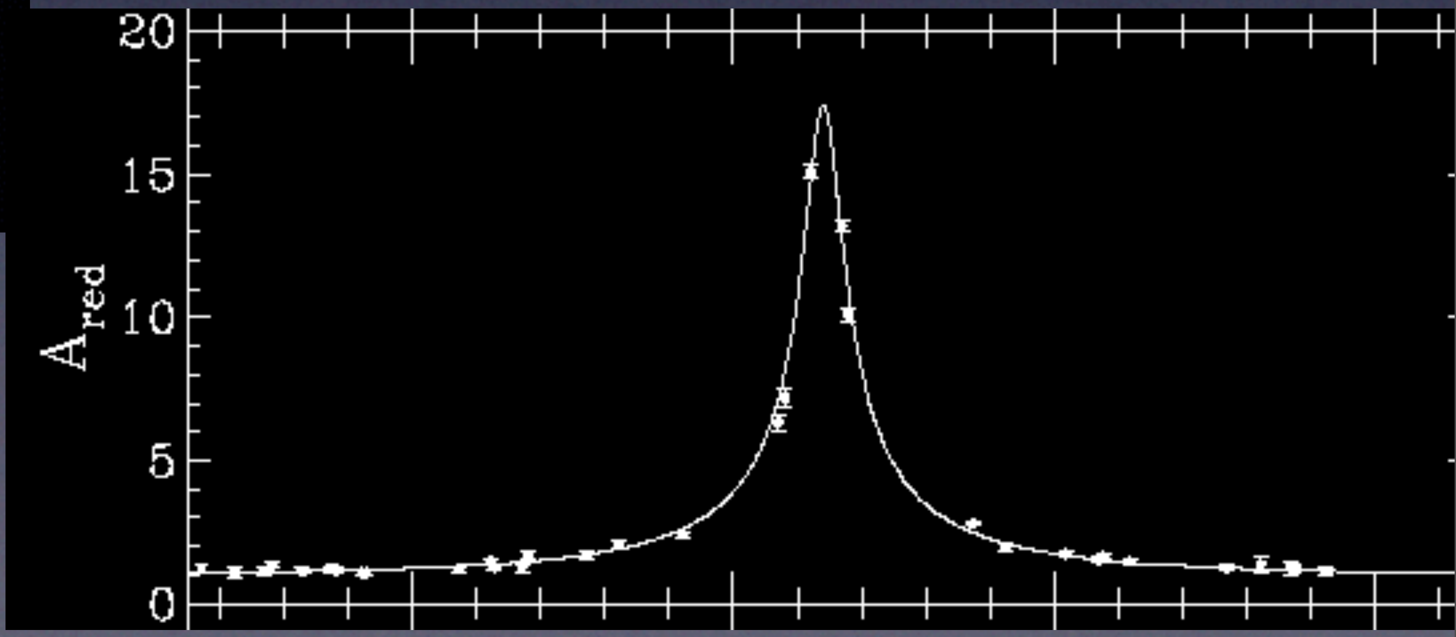
“Uncertainty Principle”

- 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!

Dim Stars?

Search for *MACHO*s
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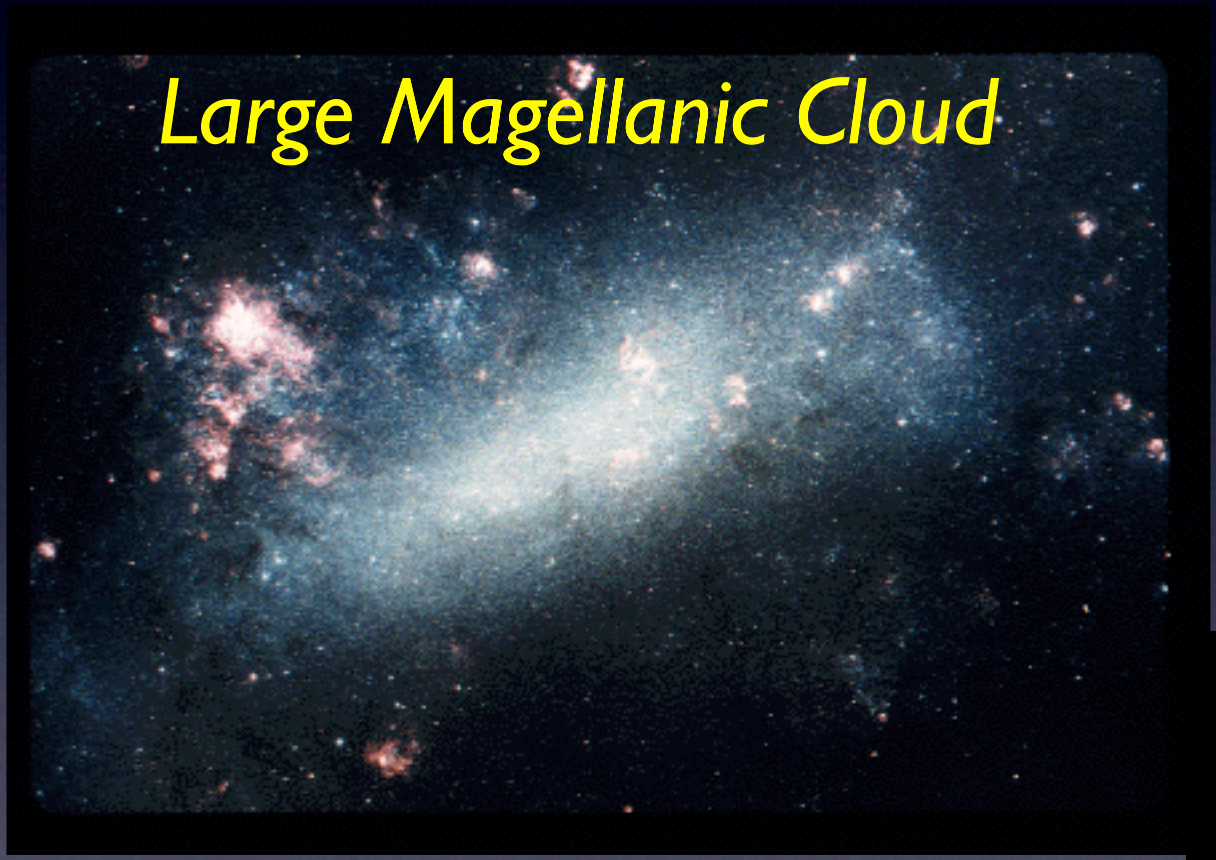
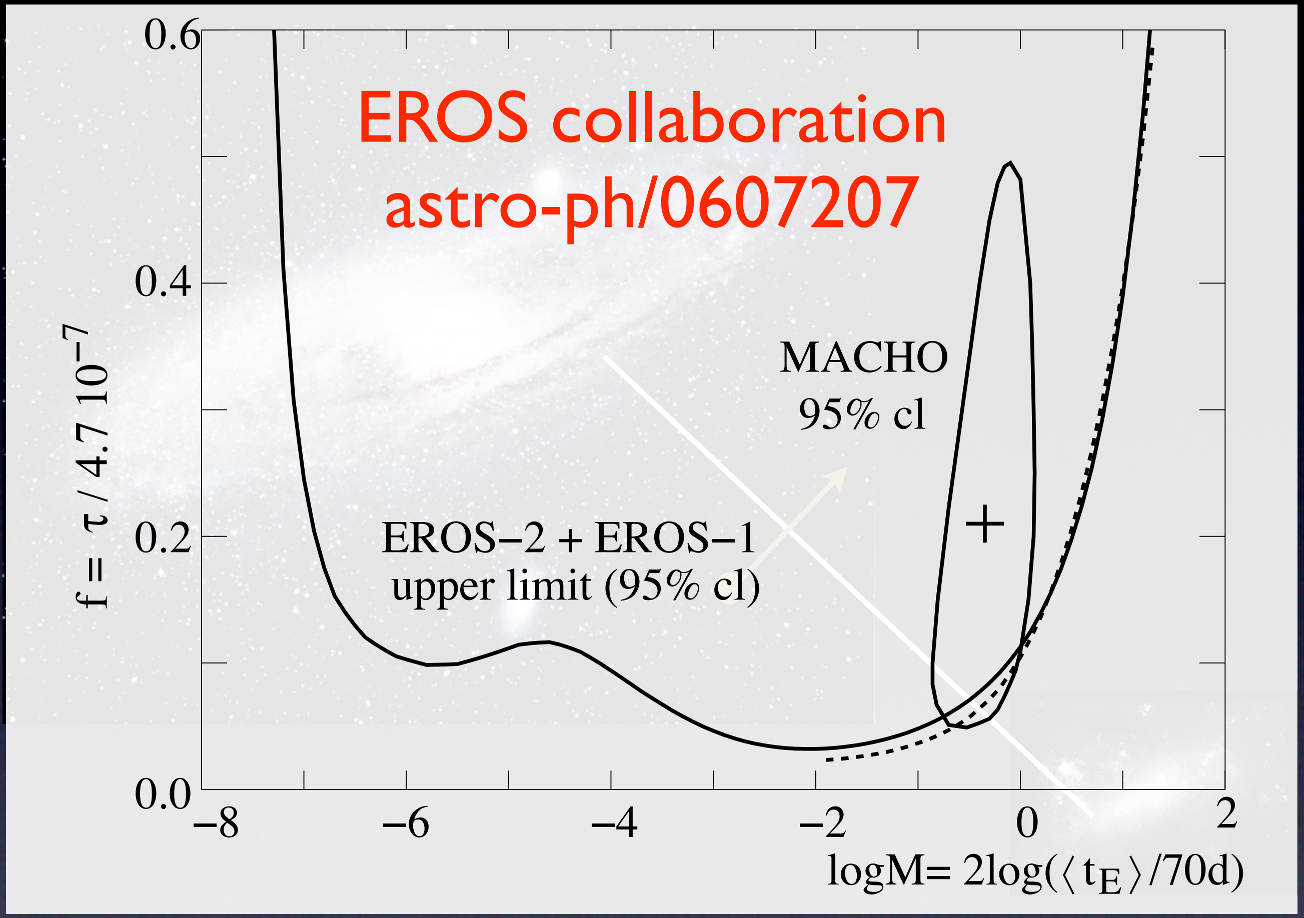
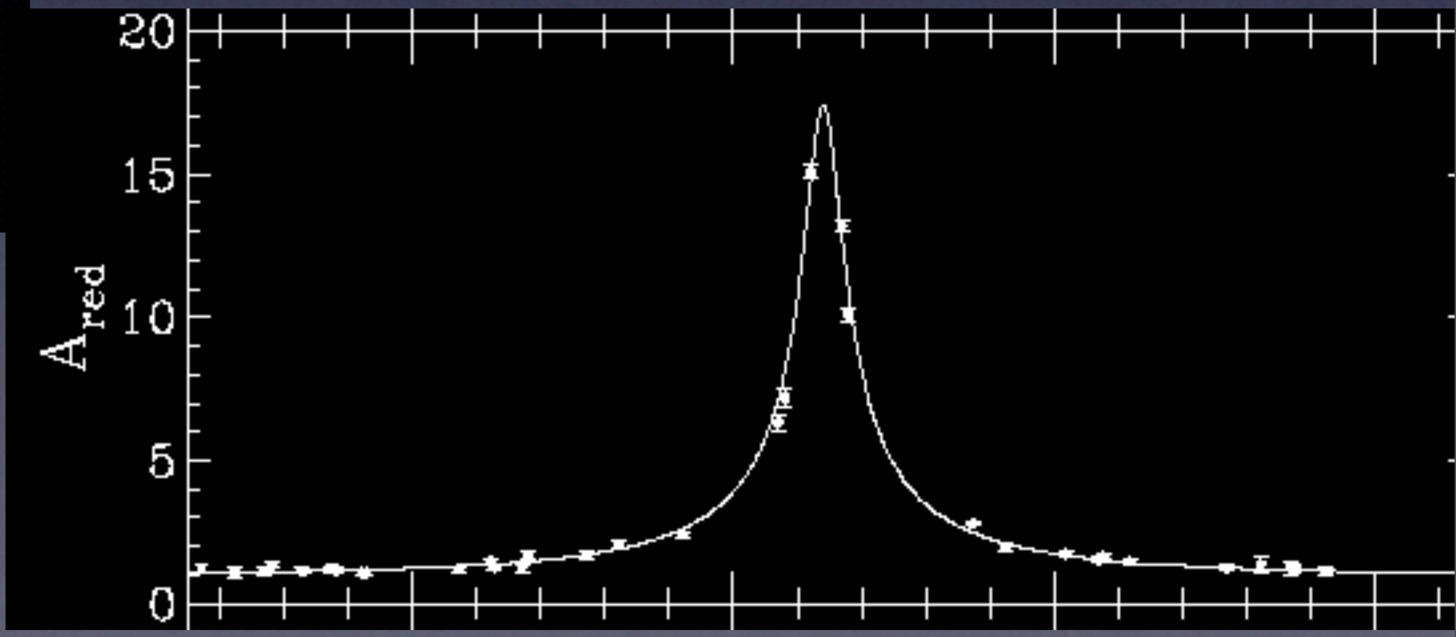






Not enough of them!

Mass Limits Causality

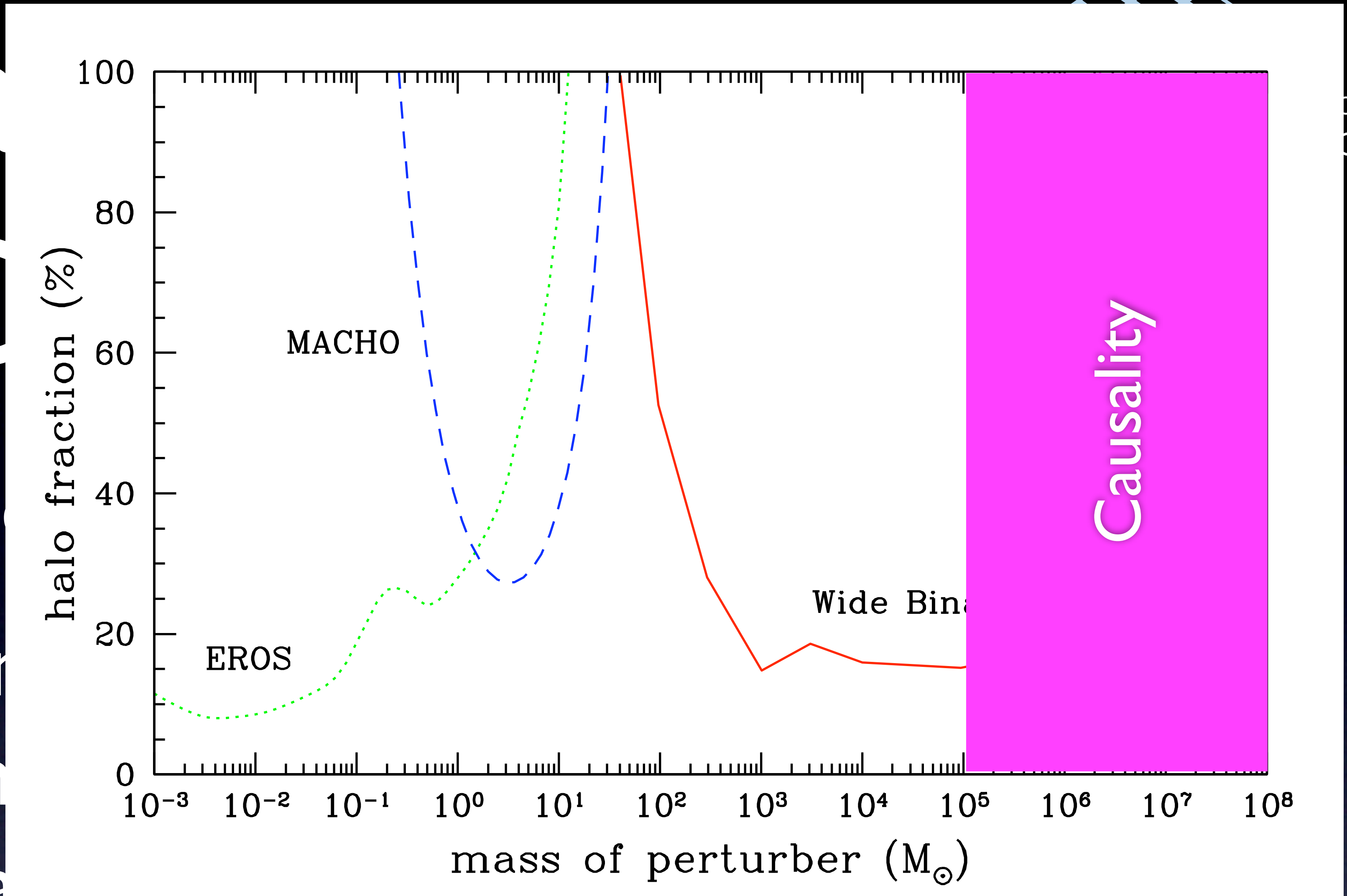
- MACHO excluded $10^{-7}M_\odot < m < 20M_\odot$
- Can't make primordial blackholes (PBH) in a normal smooth Friedmann universe
- there can't be anything violent since BBN
- maximum mass of PBH is horizon mass@BBN

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

- And $m < 40M_\odot$ from wide binaries

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

Ma... O...



- MACHO exclu...
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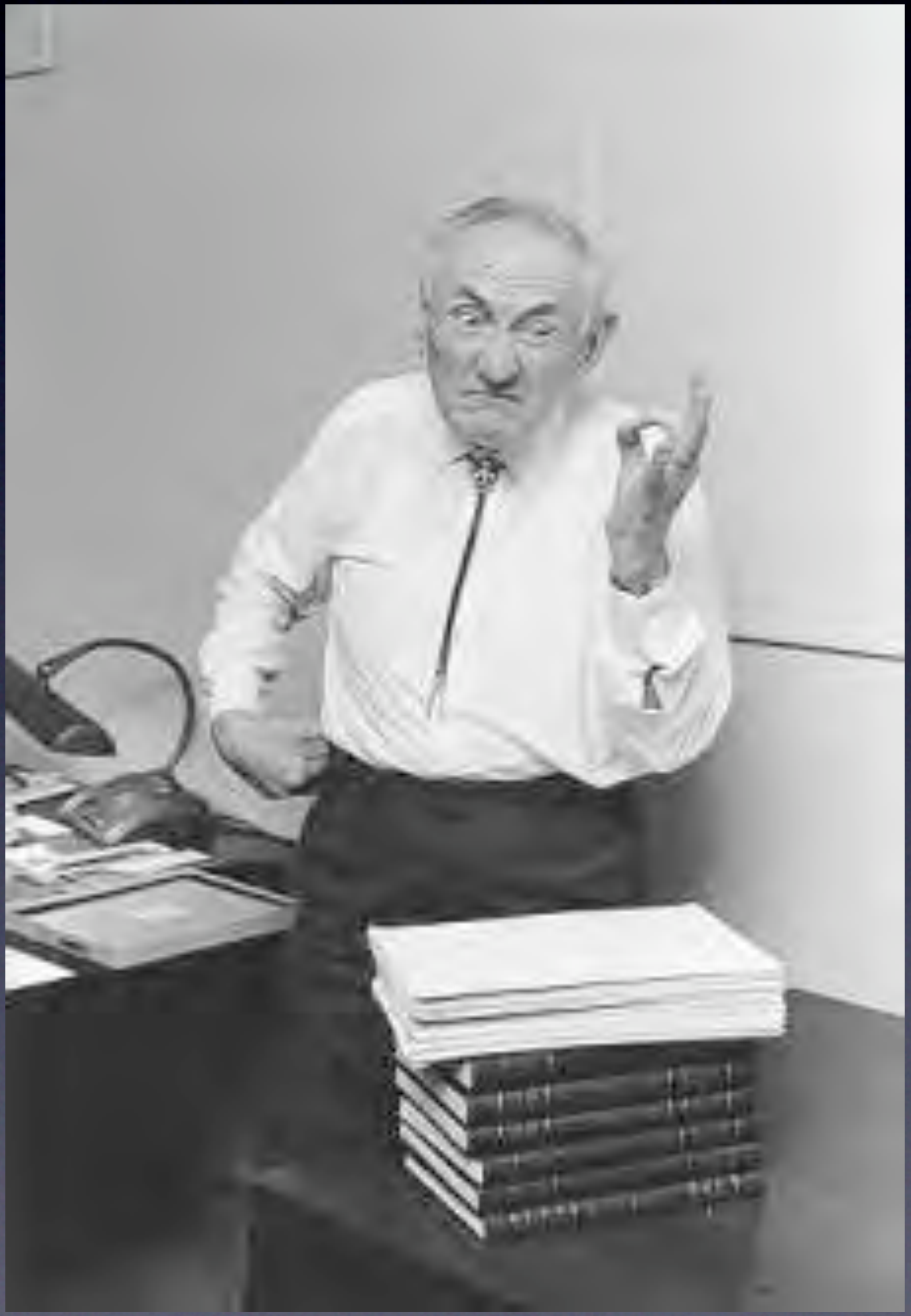
Summary
Mass Limits

- 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

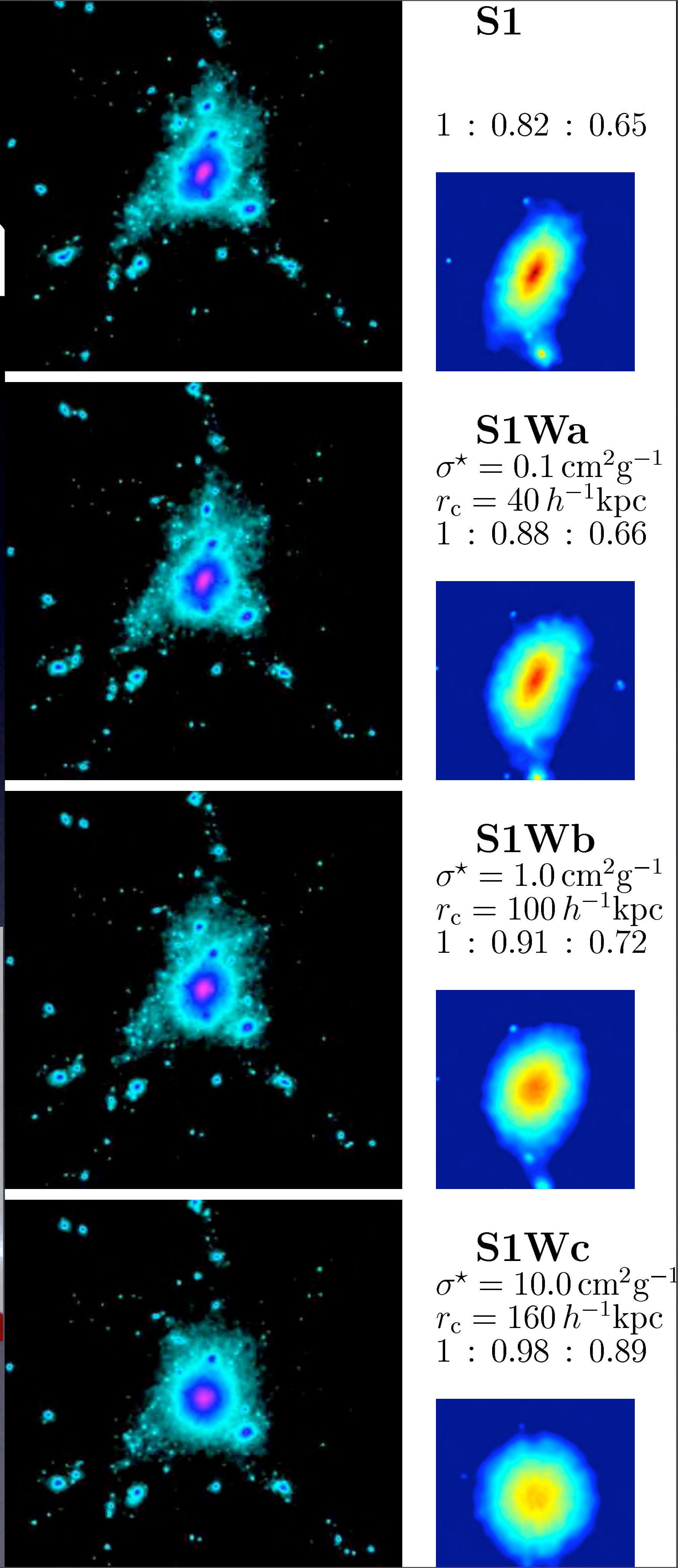
  (Spergel and Steinhardt, astro-ph/9909386)
- need core < 35 kpc/h from data

  $\sigma < 1.7 \times 10^{-25}$ 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

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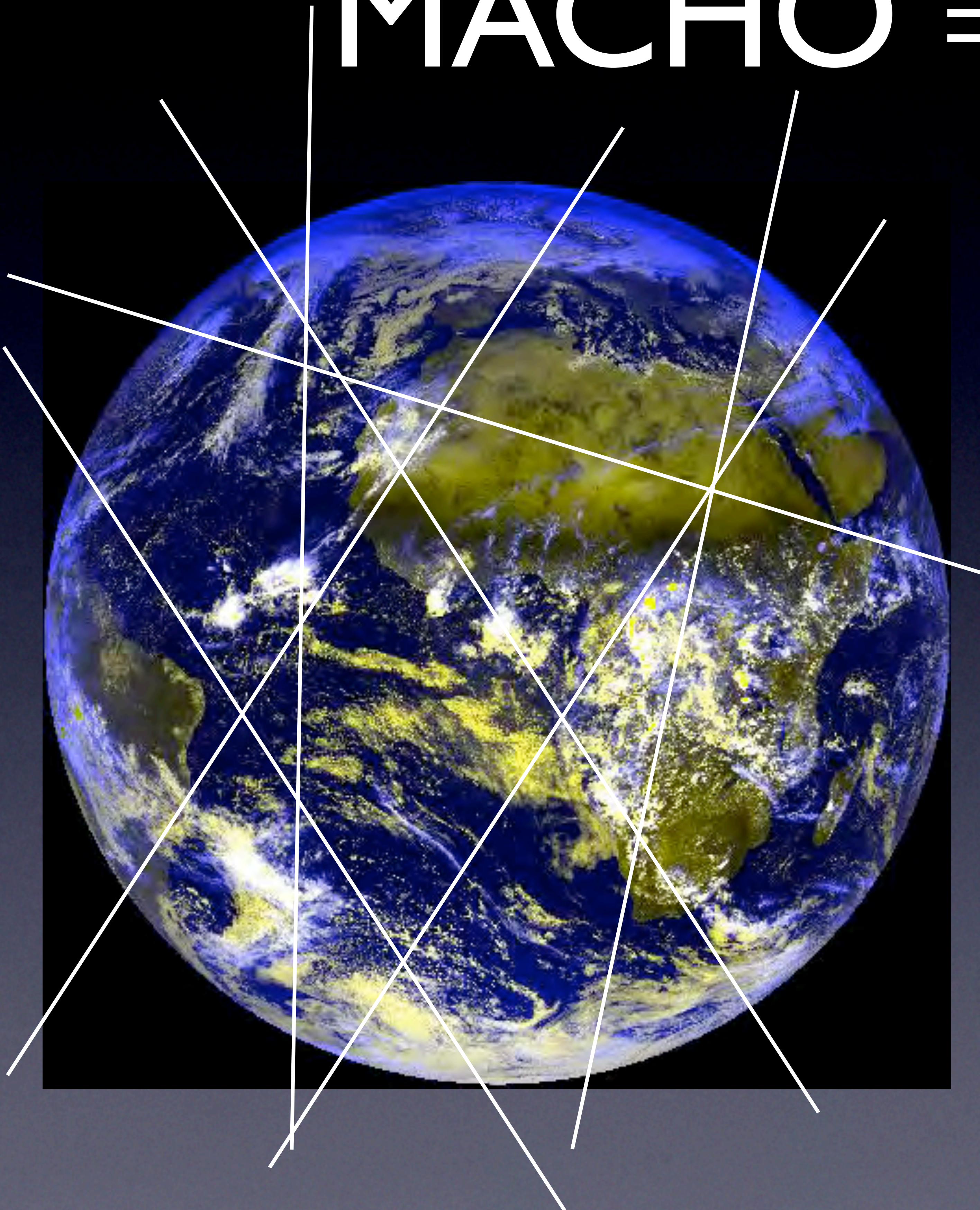
MACHO ⇒ WIMP

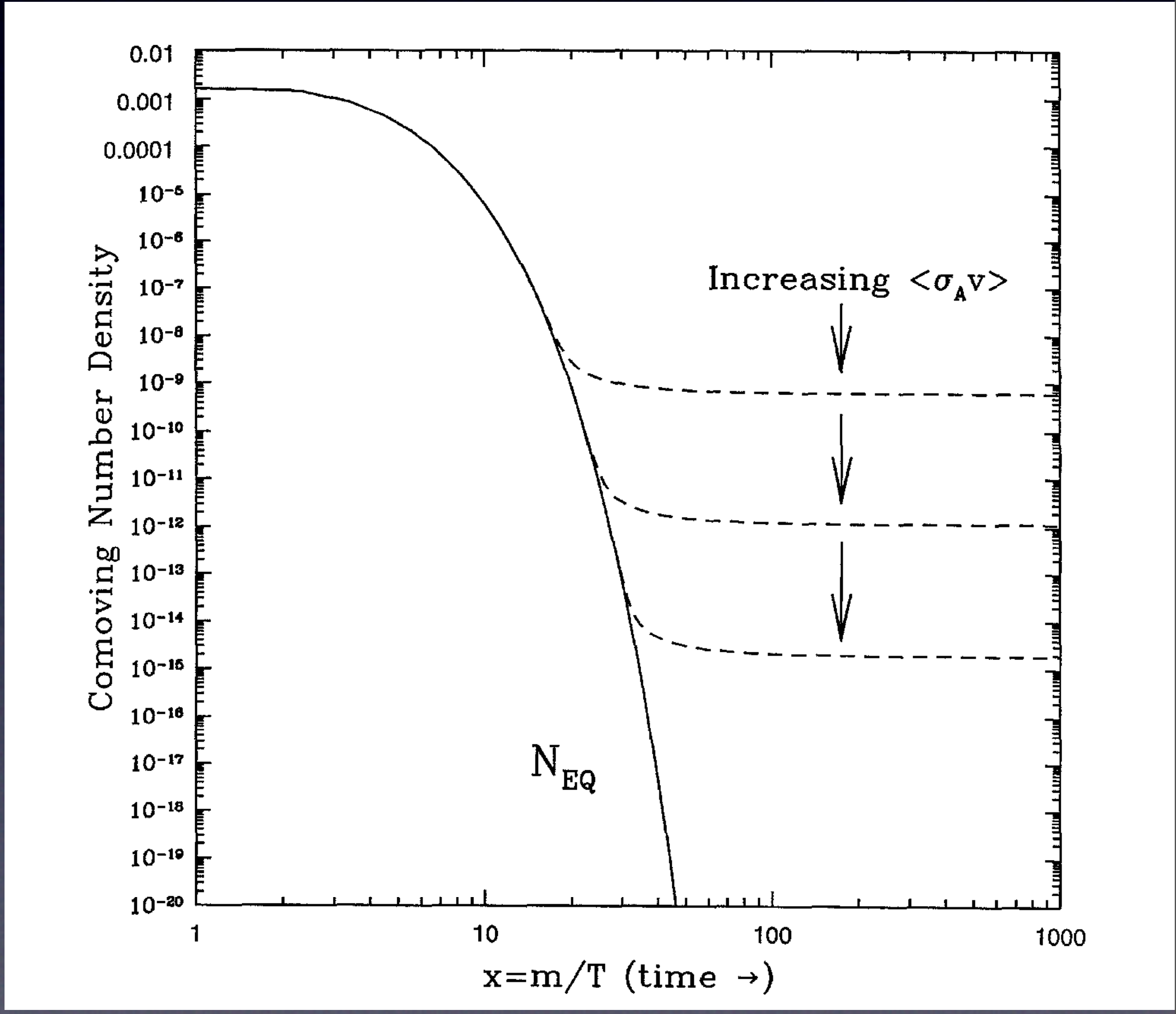


- It is probably WIMP (Weakly Interacting Massive Particle)
- Stable heavy particle produced in early Universe, left-over from near-complete annihilation
- Will focus on WIMPs for the rest or the talk

WIMP paradigm

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"



Freeze-out

- WIMP freezes out when the annihilation rate drops below the expansion rate
- Yield Y=n/s constant under expansion
- stronger annihilation $\Rightarrow$ less abundance

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

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

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

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

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

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

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

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

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Order of magnitude

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

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

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

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

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

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

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

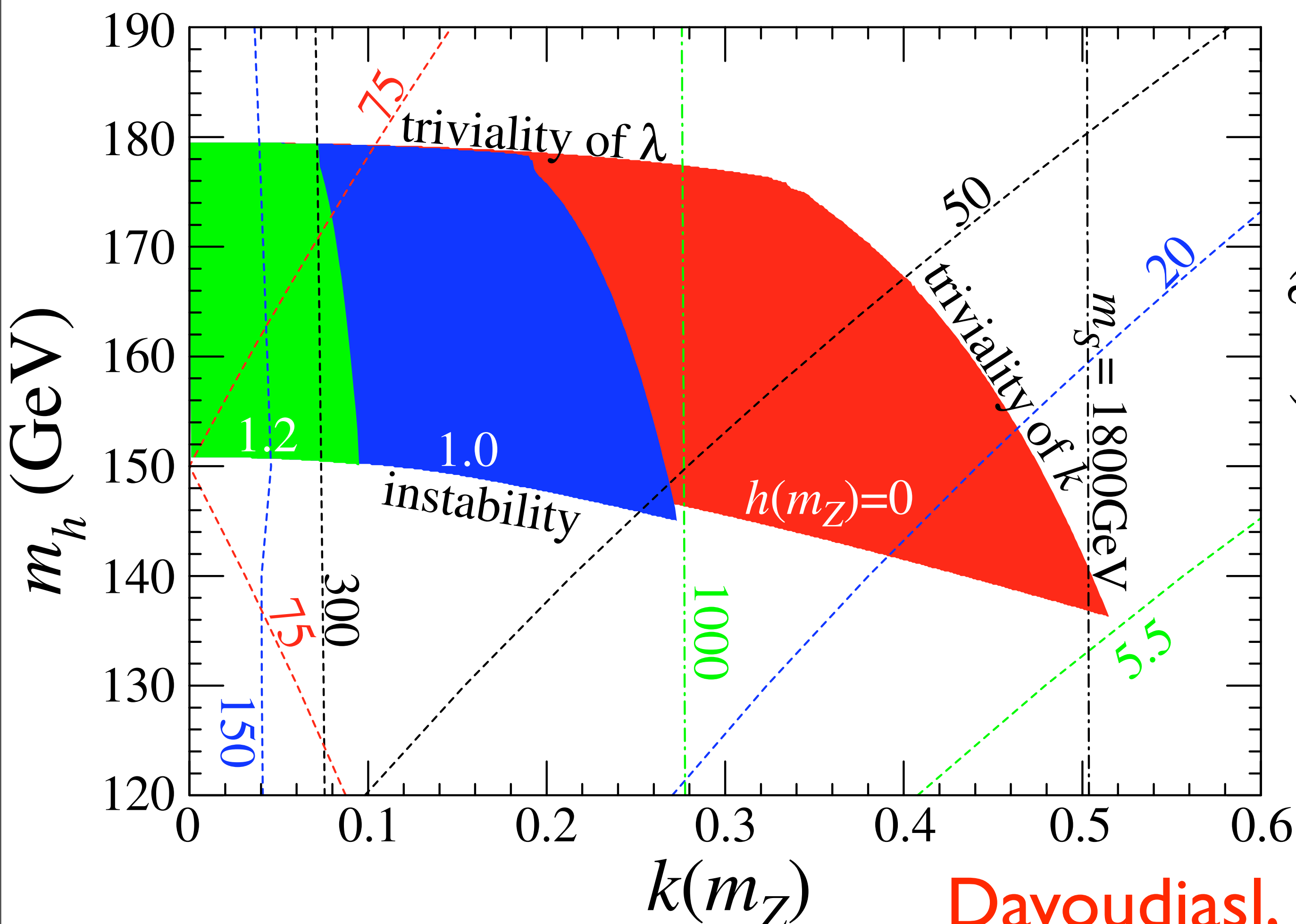
- Dark Matter clearly a new degree of freedom
- The smallest degree of freedom you can add to the QFT is a real Klein-Gordon field S: dof=1
- assign odd Z_2 parity to S, everything else even
- Most general renormalizable coupling

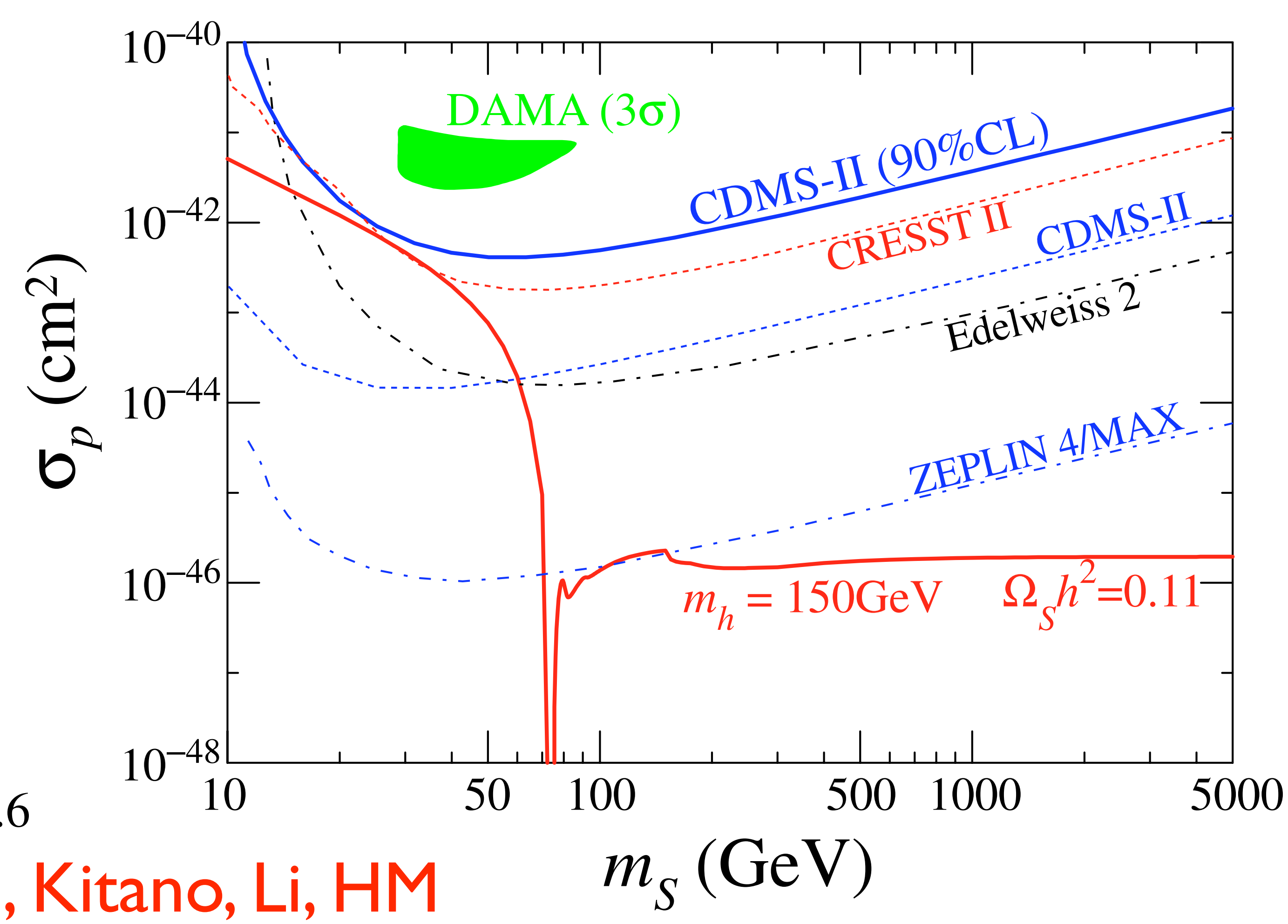
$$L_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!} S^4.$$

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

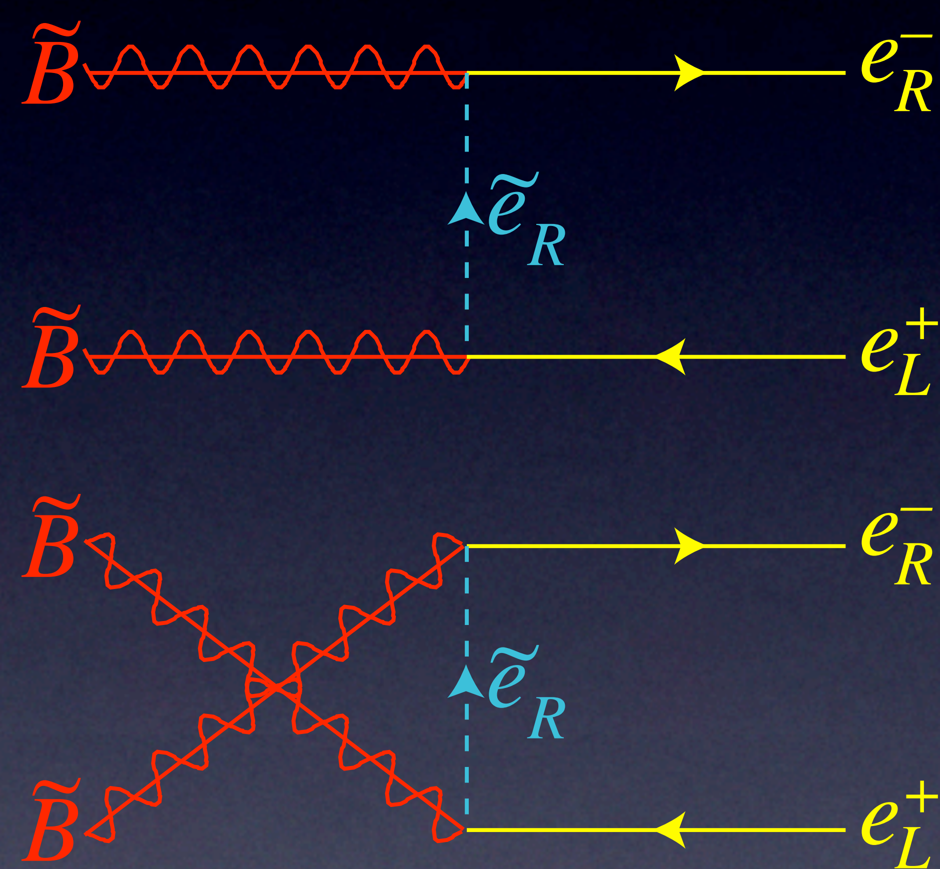
LSP

- 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.

Example

- exchange of Majorana fermions with a relative minus sign

$$
\begin{aligned}
\mathcal{M}_{+-} &= 8g'^2 \frac{M_{\tilde{B}} p_{\tilde{B}}}{M_{\tilde{B}}^2 + m_{\tilde{e}_R}^2} \cos^2\frac{\theta}{2} \\
\mathcal{M}_{-+} &= 8g'^2 \frac{M_{\tilde{B}} p_{\tilde{B}}}{M_{\tilde{B}}^2 + m_{\tilde{e}_R}^2} \sin^2\frac{\theta}{2} \\
\mathcal{M}_{++} &= 0 \\
\mathcal{M}_{--} &= 0
\end{aligned}
$$



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

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

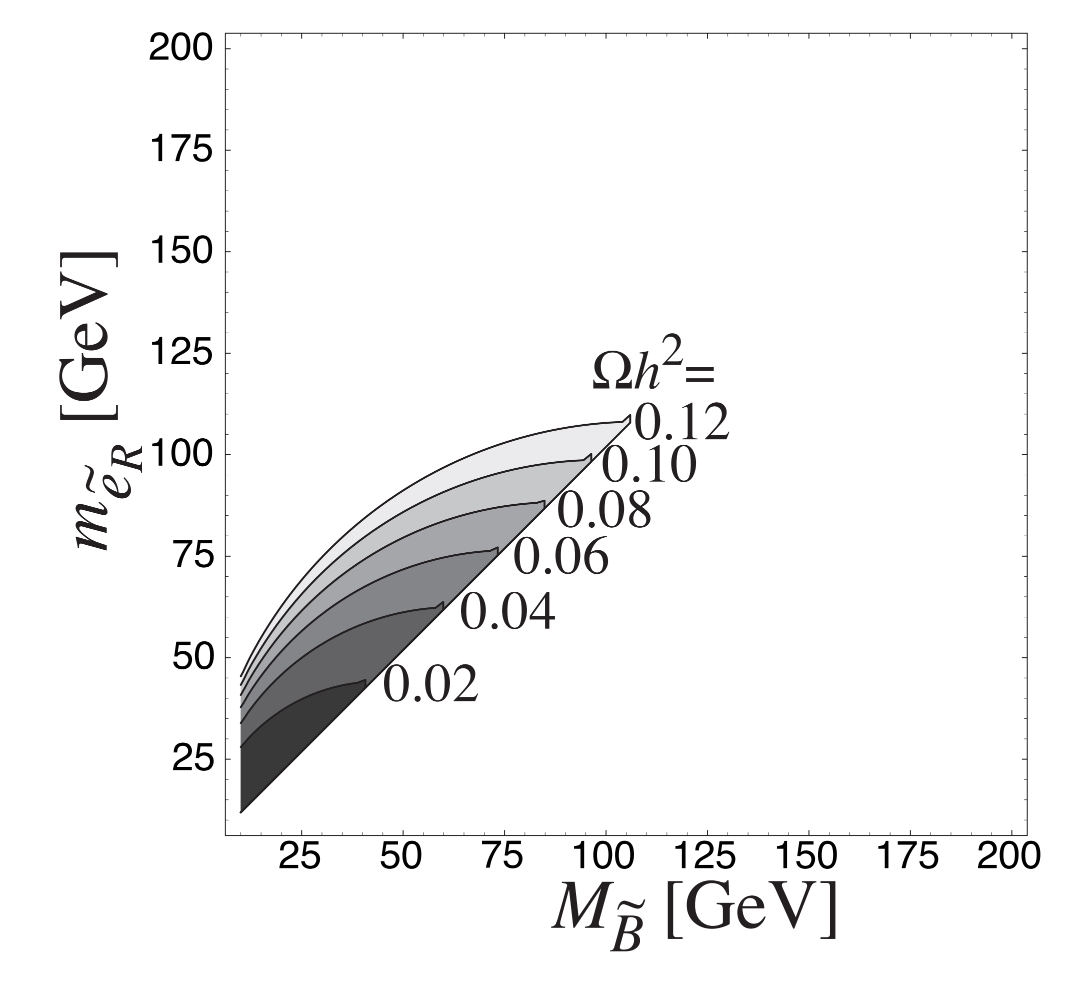
A little too much

- 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

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

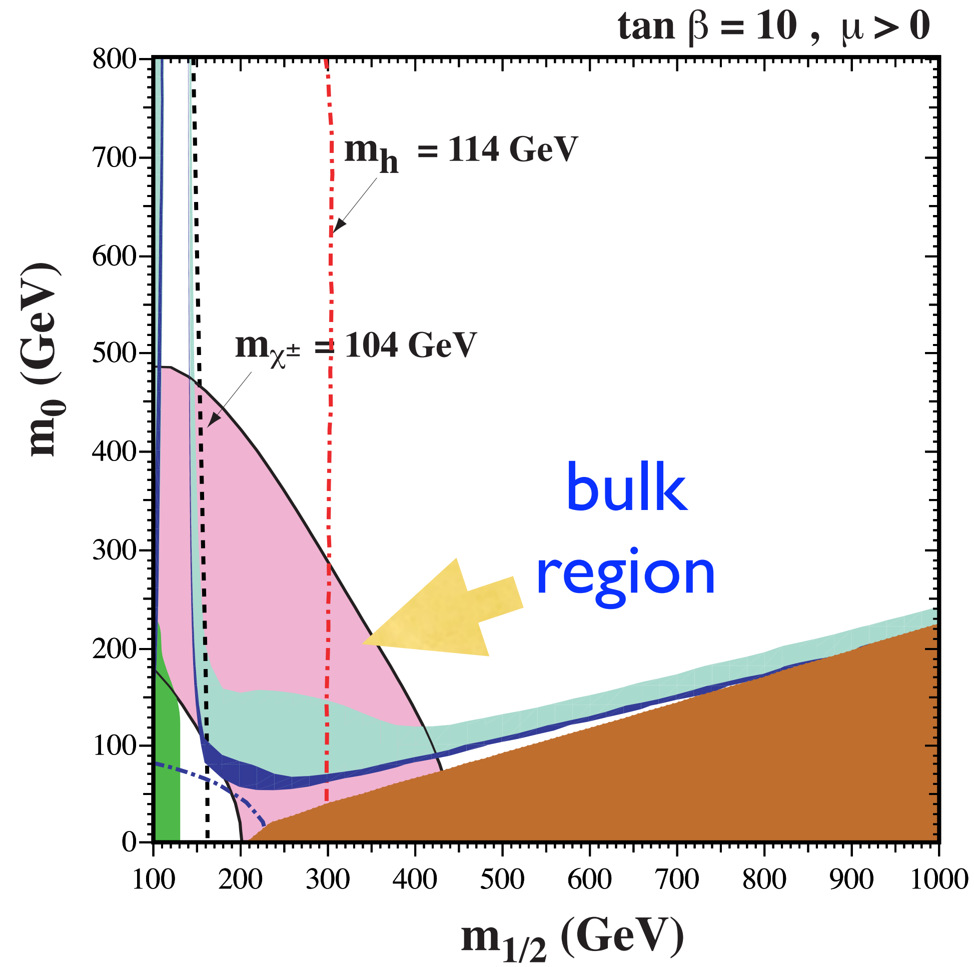


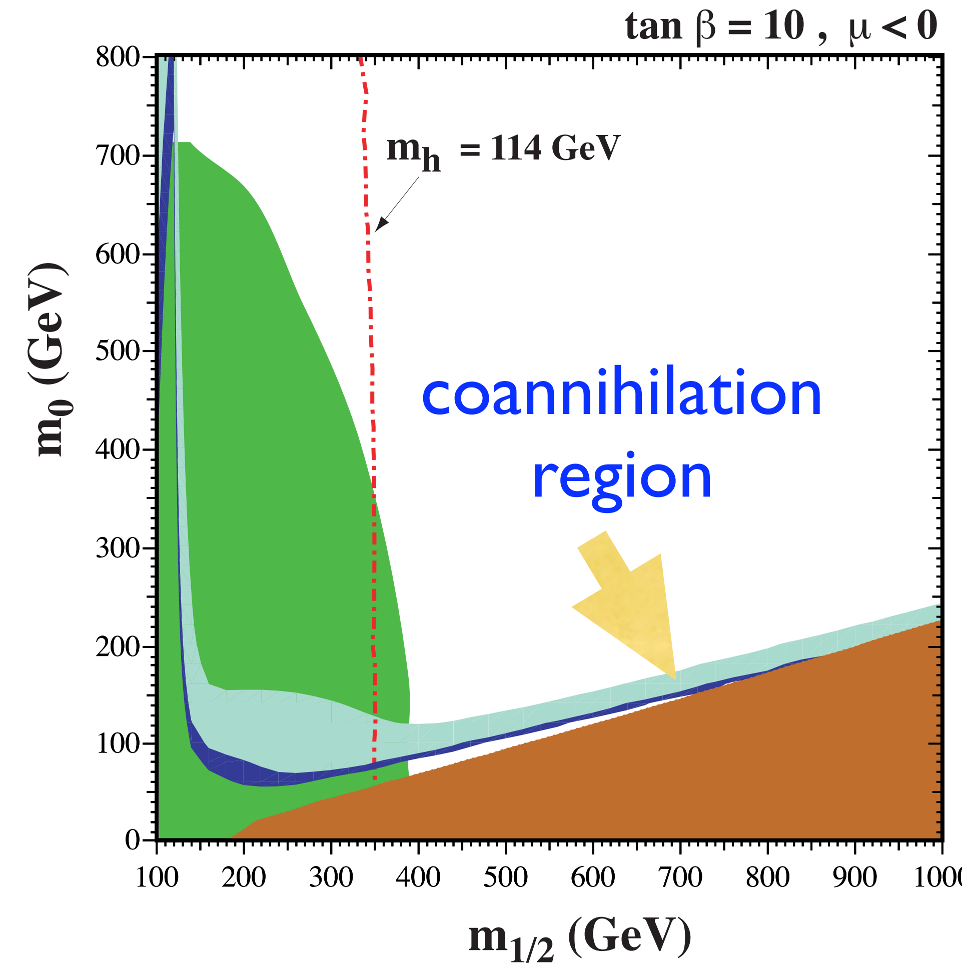
excluded by b→sγ

preferred by g_μ-2

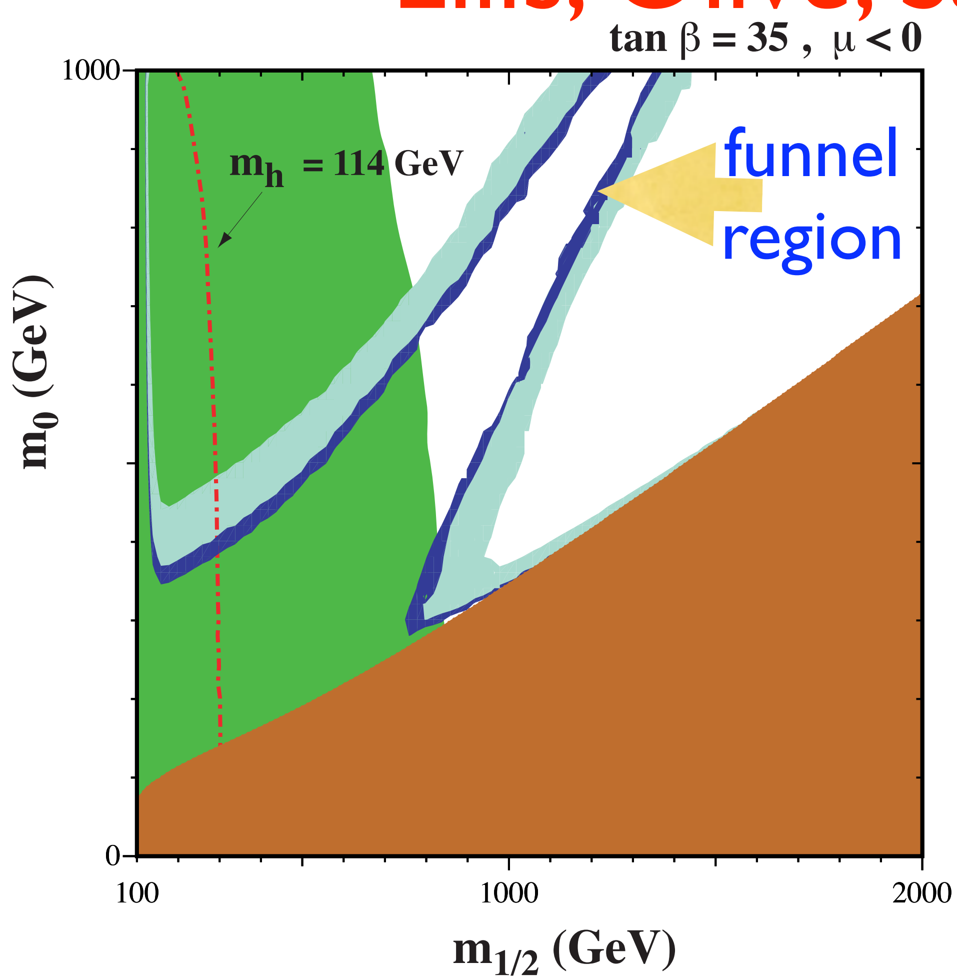
$0.1 \leq \Omega_\chi h^2 \leq 0.3$

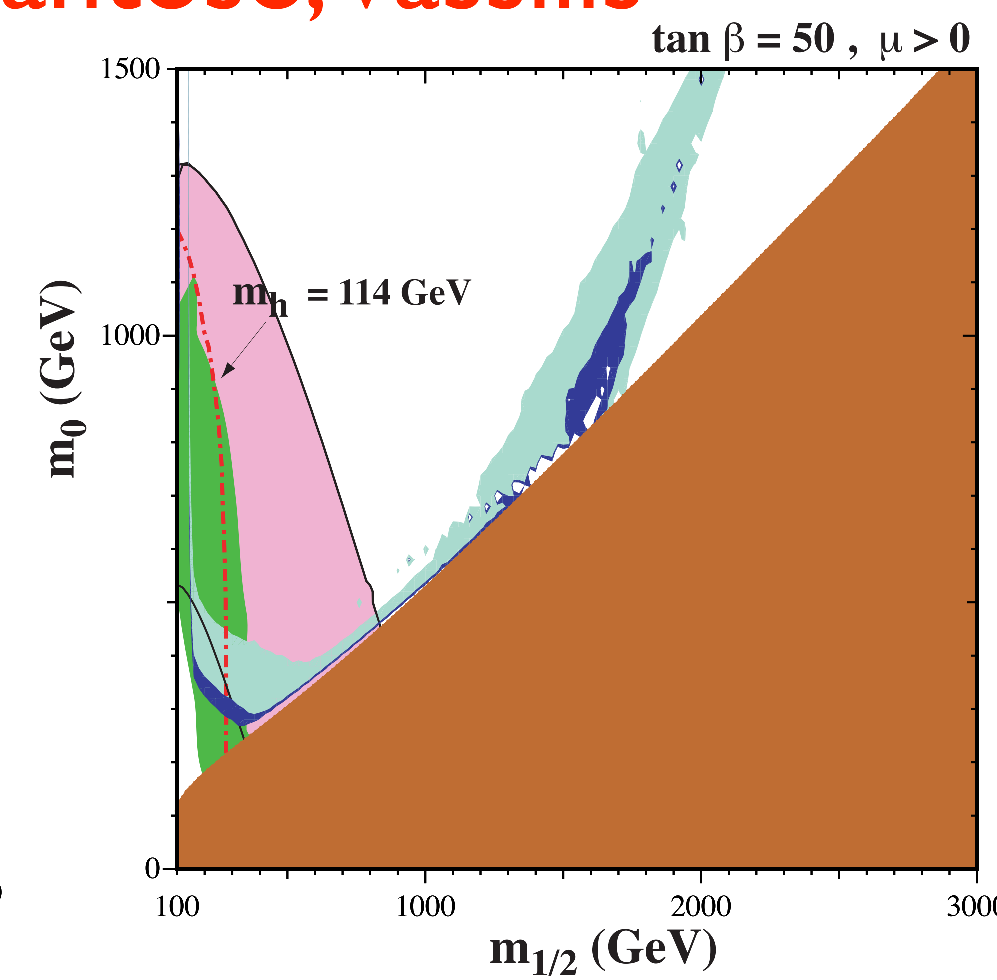
$0.094 \leq \Omega_\chi h^2 \leq 0.129$





Ellis, Olive, Santoso, Vassilis





sample spectrum

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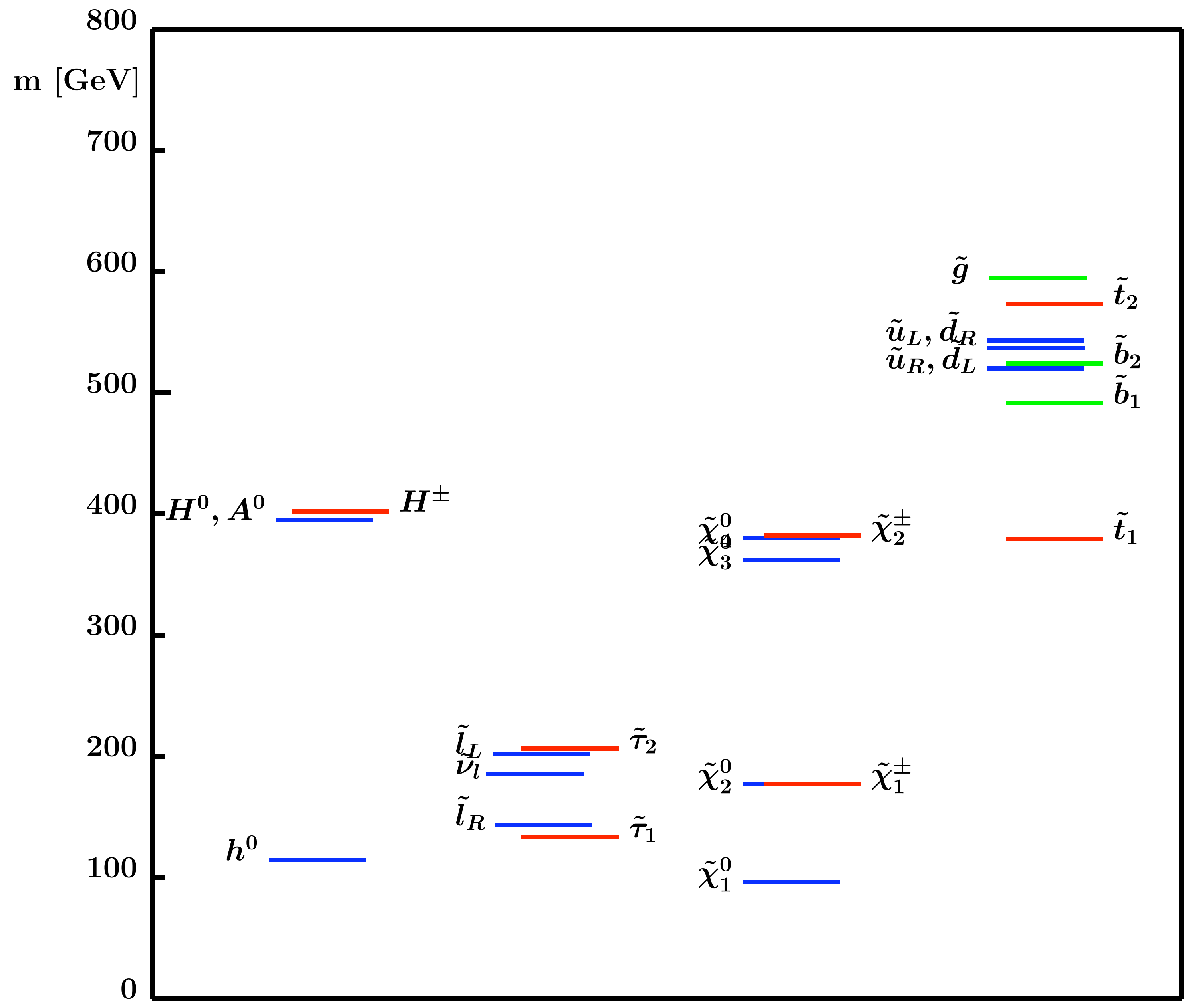
$m_0 = 100,\ m_{1/2} = 250,\ A_0 = -100,\ \tan\beta = 10,\ \mu > 0$

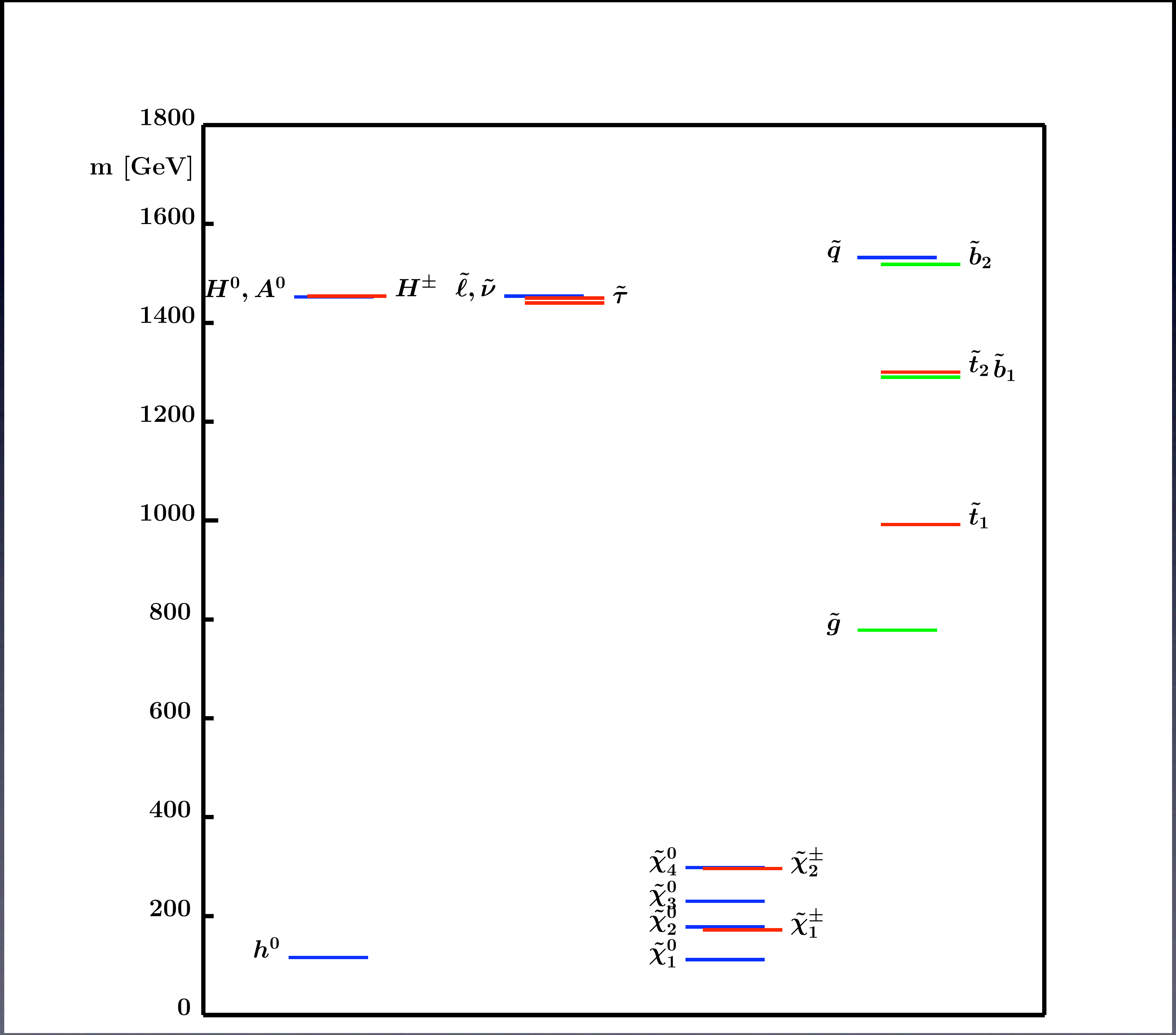


bulk region

SPS1a

sample spectrum

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



focus point region

SPS2

sample spectrum

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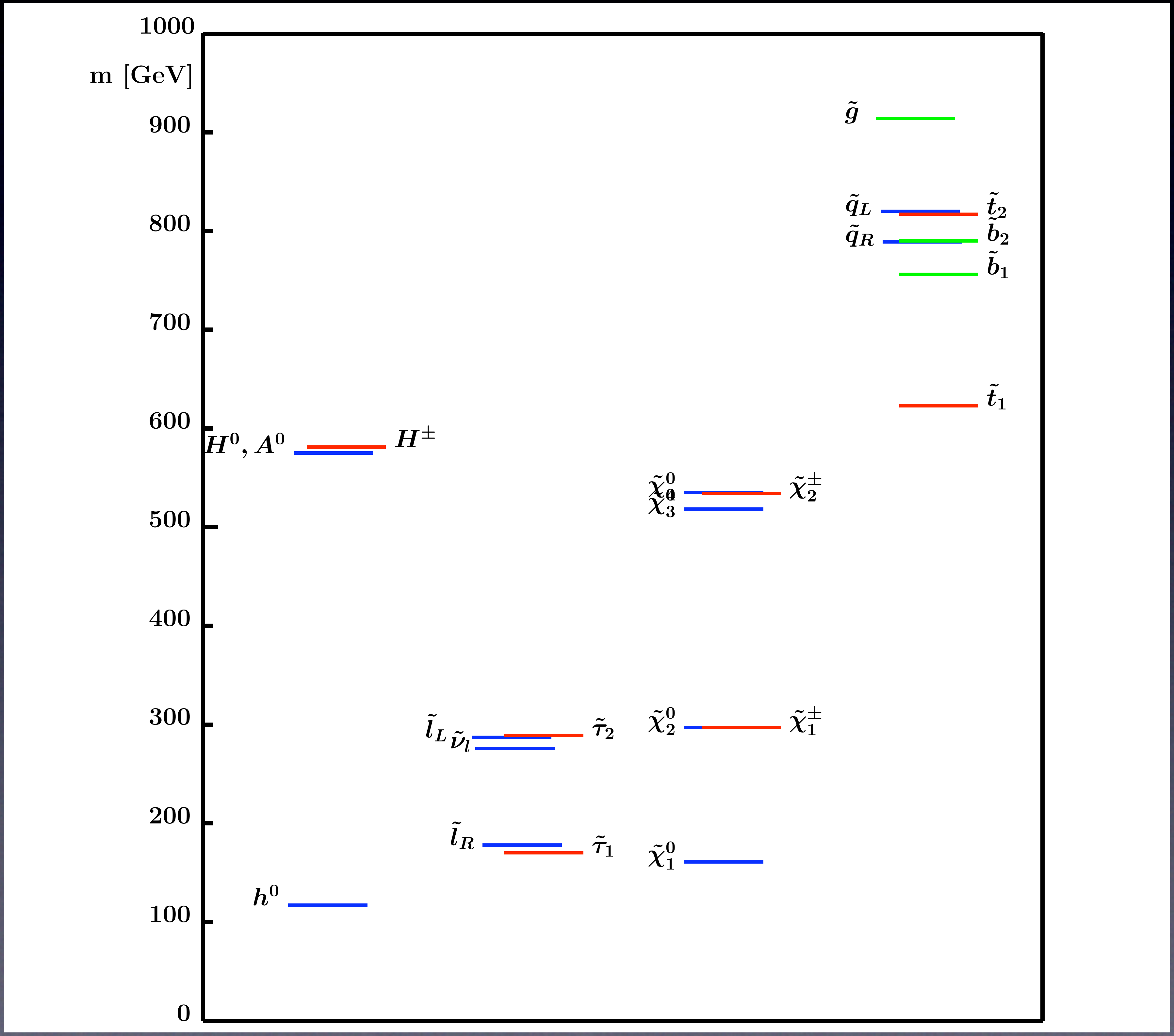
$m_0 = 90,\ m_{1/2} = 400,\ A_0 = 0,\ \tan\beta = 10,\ \mu > 0$



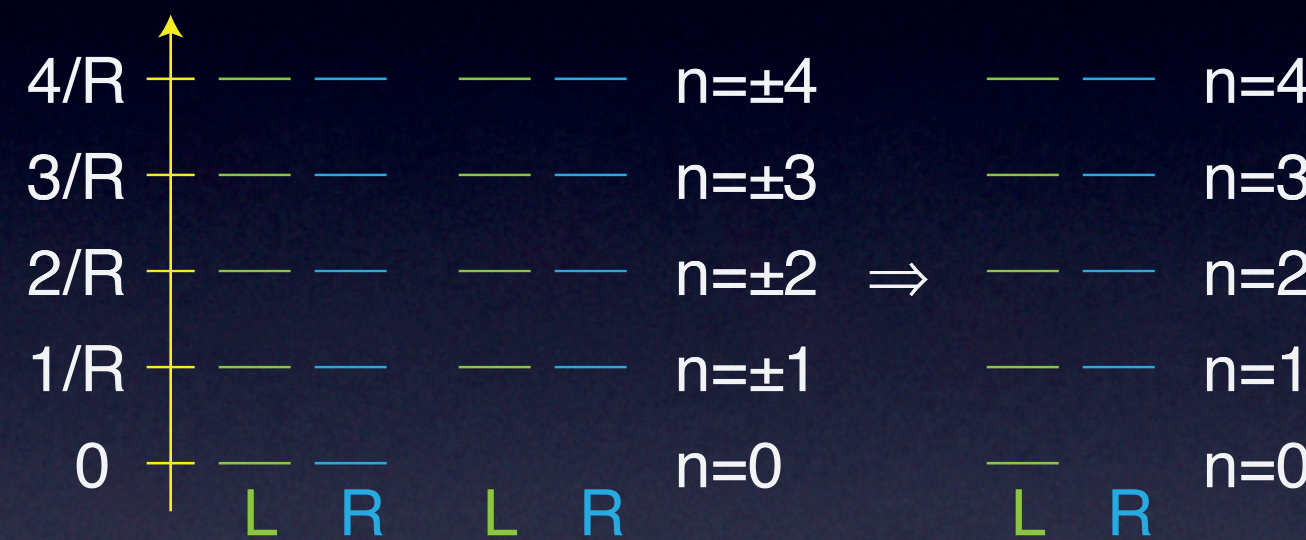
coanni-hilation region

SPS3

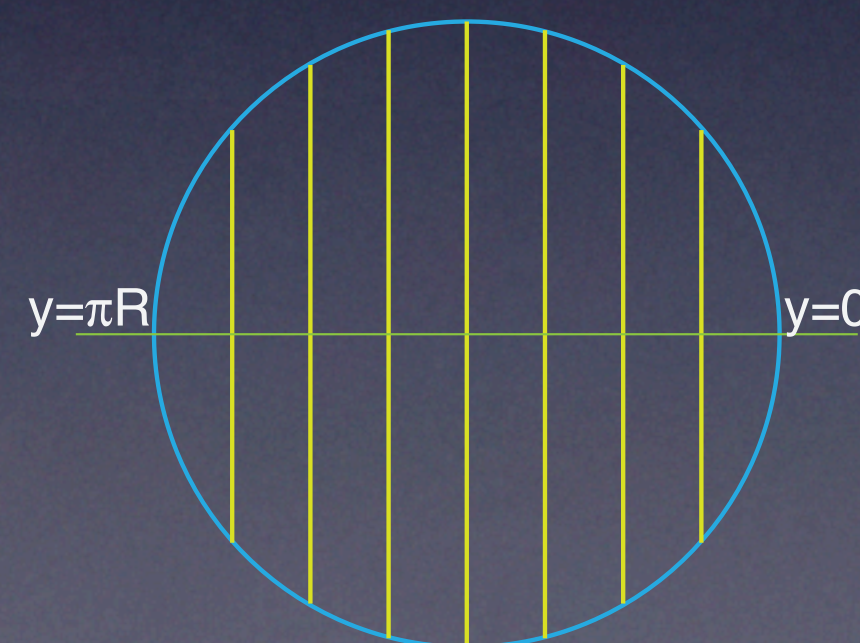
Universal Extra Dimensions

- 5D Dirac equation
  $\rightarrow$ vector-like spectrum

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

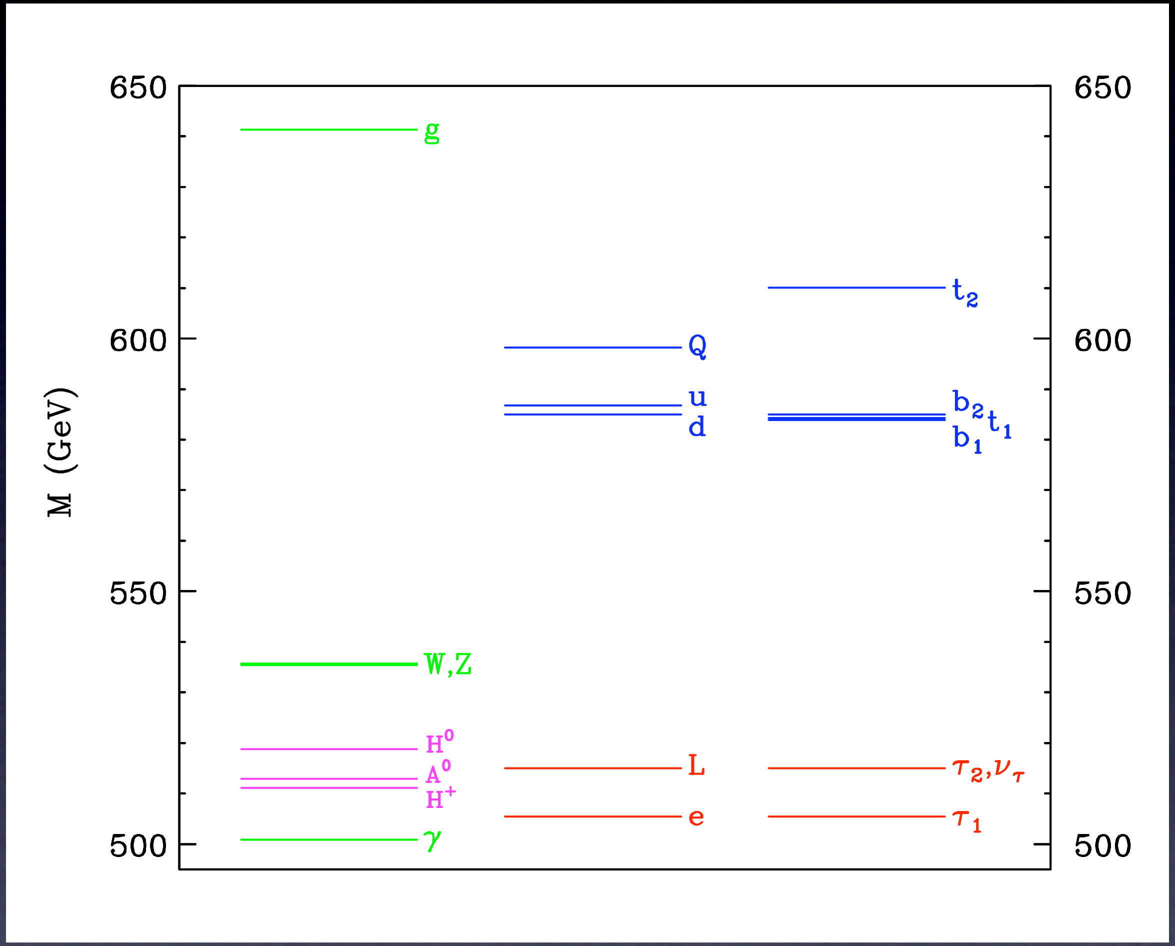


- Use orbifold to get a chiral spectrum in 4D
- R^4 x S^1/Z_2
  S^1: $y \in [0,2\pi R]$
  Z_2: $y \rightarrow -y$
- BC: $\psi(-y) = -\gamma_5 \psi(y)$
- cuts the spectrum in a half
- as a result, there is a remaining Z_2 symmetry $y \rightarrow \pi - y$
  KK parity: $(-1)^n$



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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Universal Extra Dimensions

- Put all SM particles in the bulk
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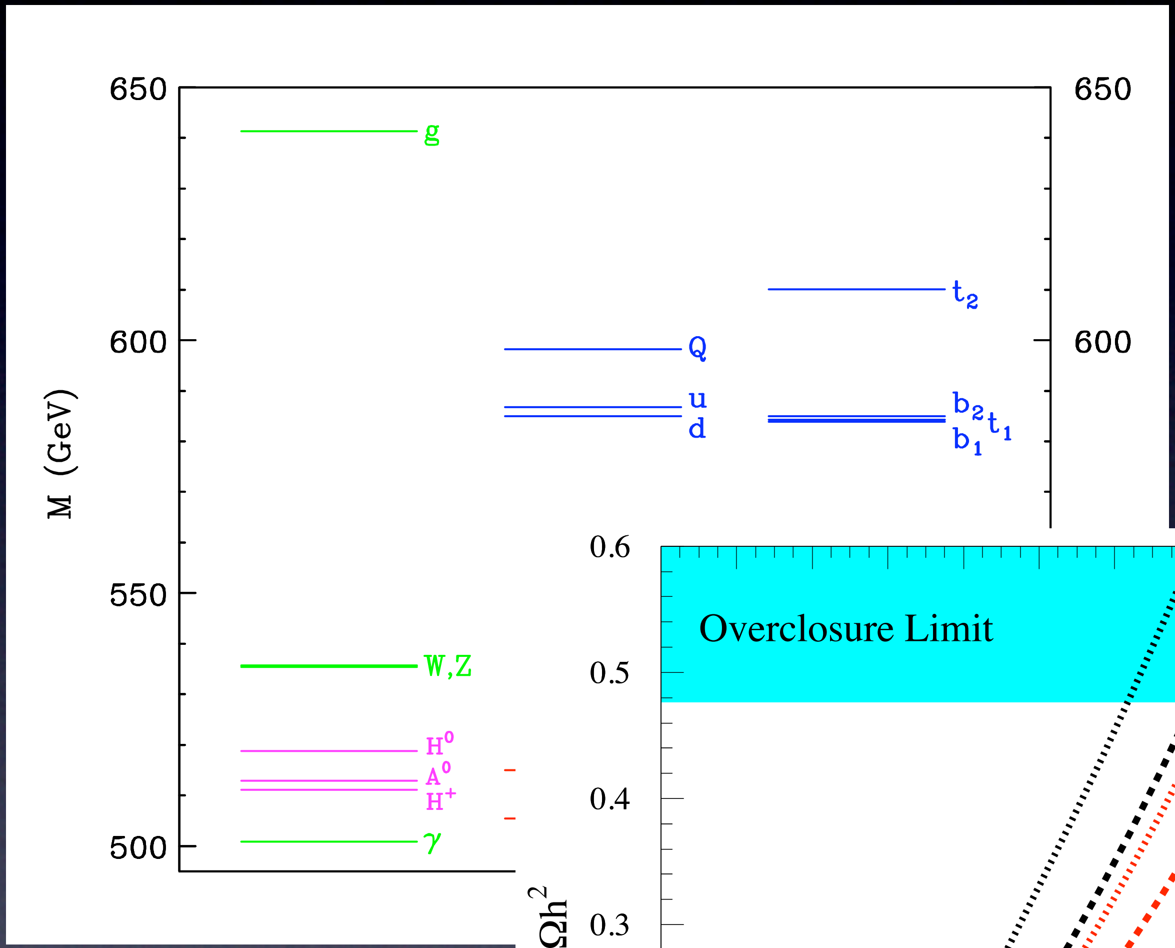
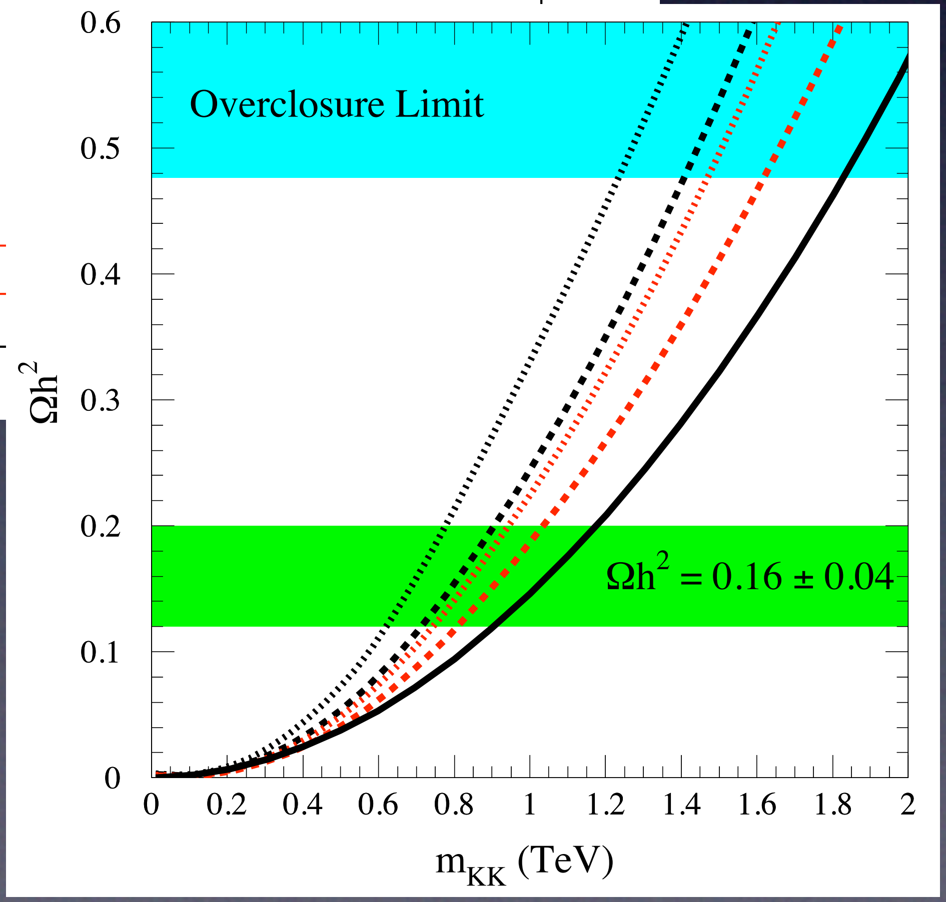




Many WIMP candidates

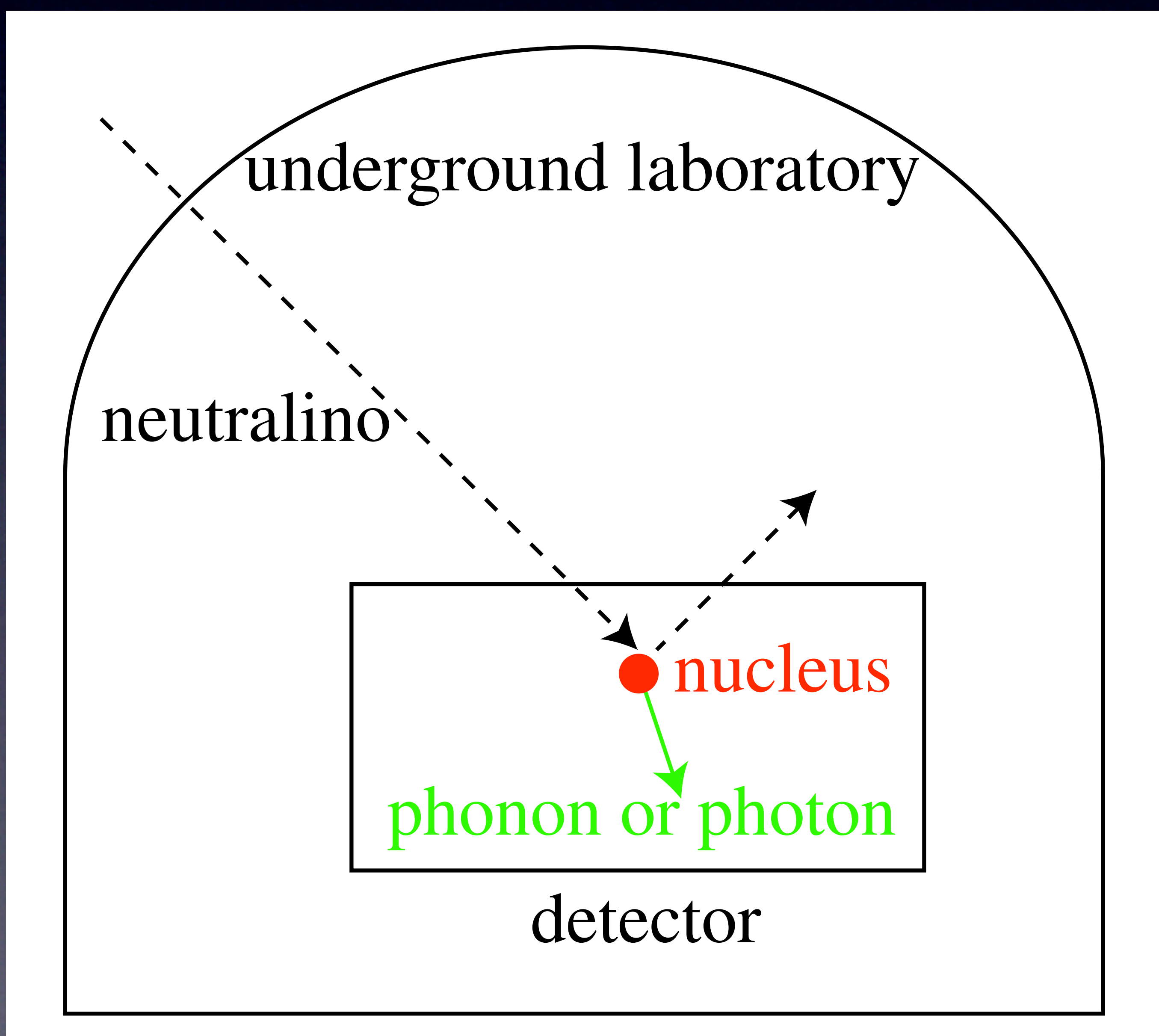
- Warped unification + proton stability (Agashe, Servant, he-ph/0403143)
- Little Higgs and suppressed precision EW corrections ➡ "T-parity"

  (Cheng, Low, Wang, hep-ph/0510225)
- Many, many, more....
- conserved number + sub-TeV ➡ good DM

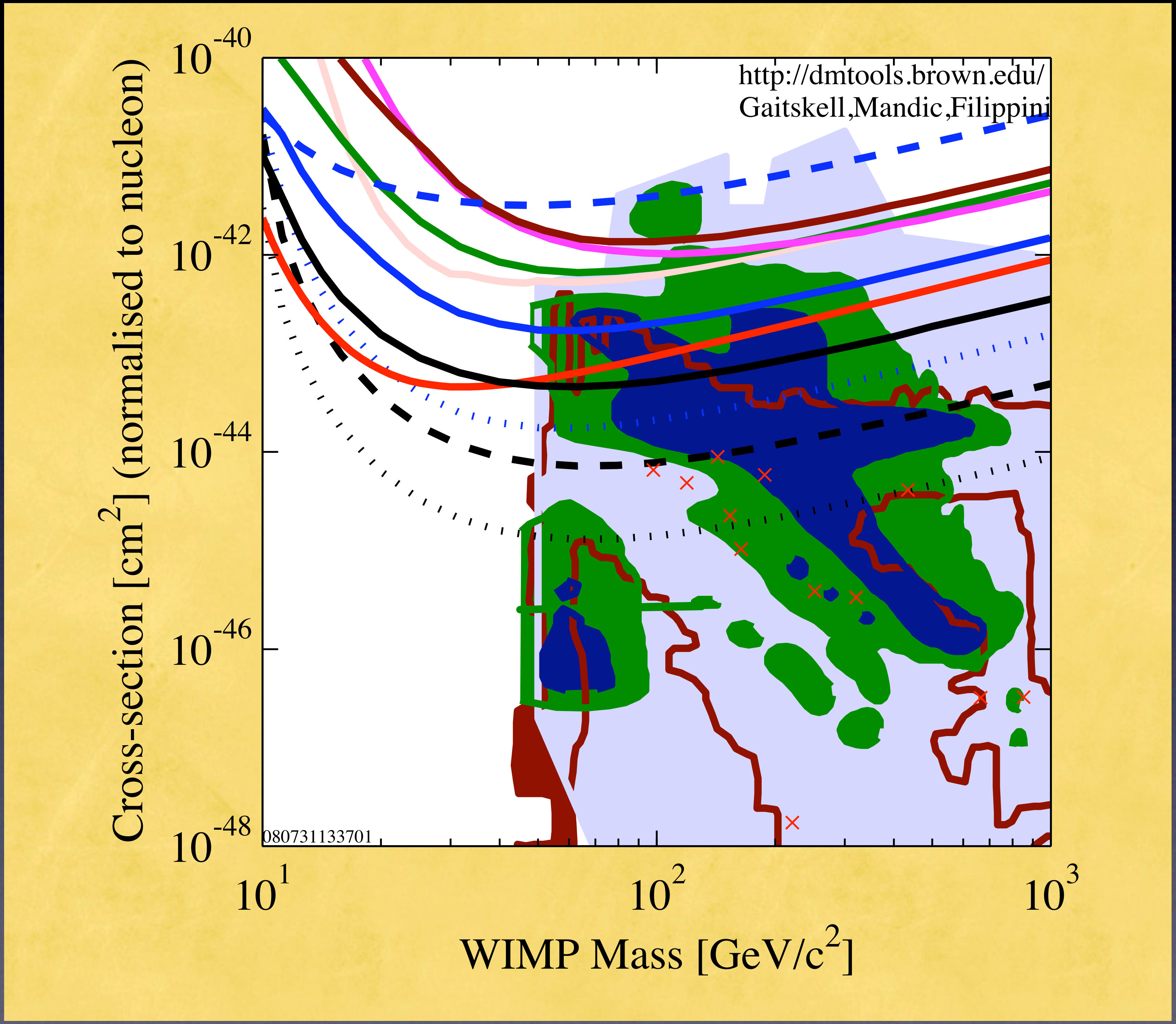
WIMP Searches

Finding Dark Matter

Direct method



Limit



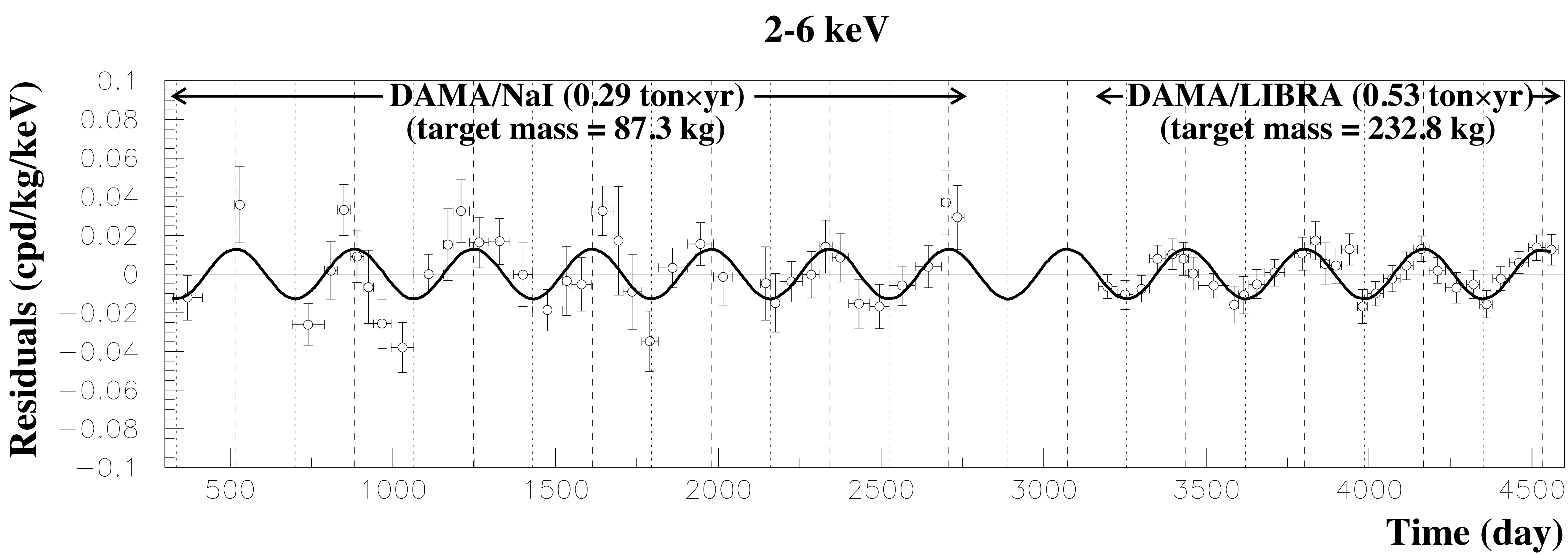
ZEPLIN-II, 2007

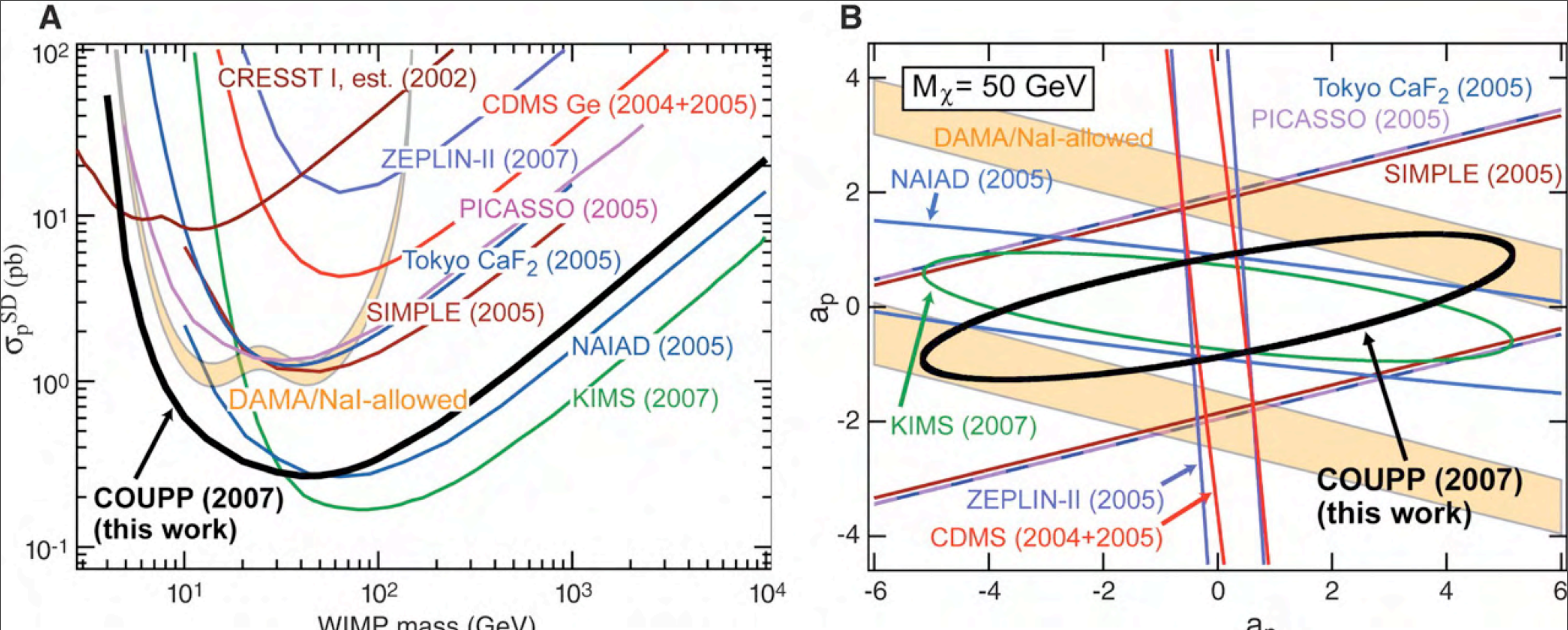
CDMS-II, 2005

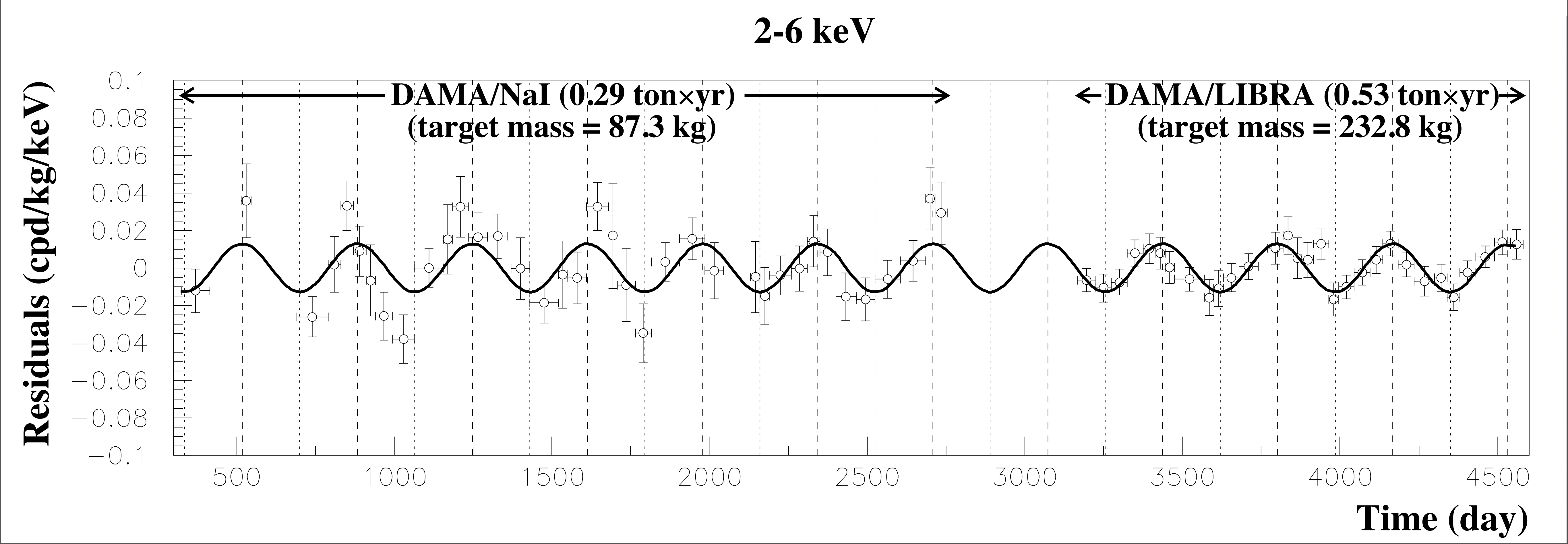
XENON10, 2007

CDMS-II, 2008

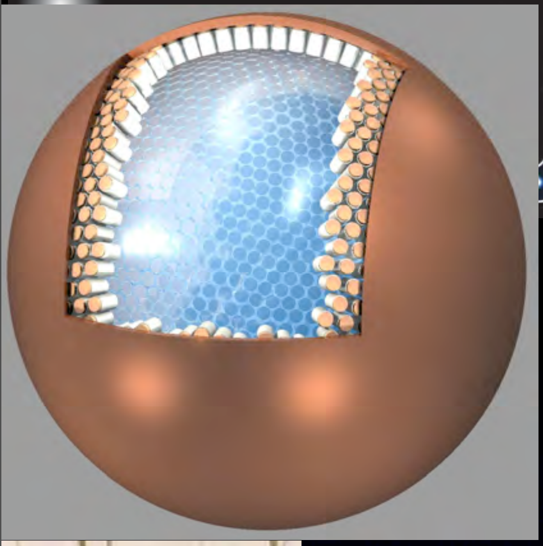
DAMA/LIBRA > 8 sigma!



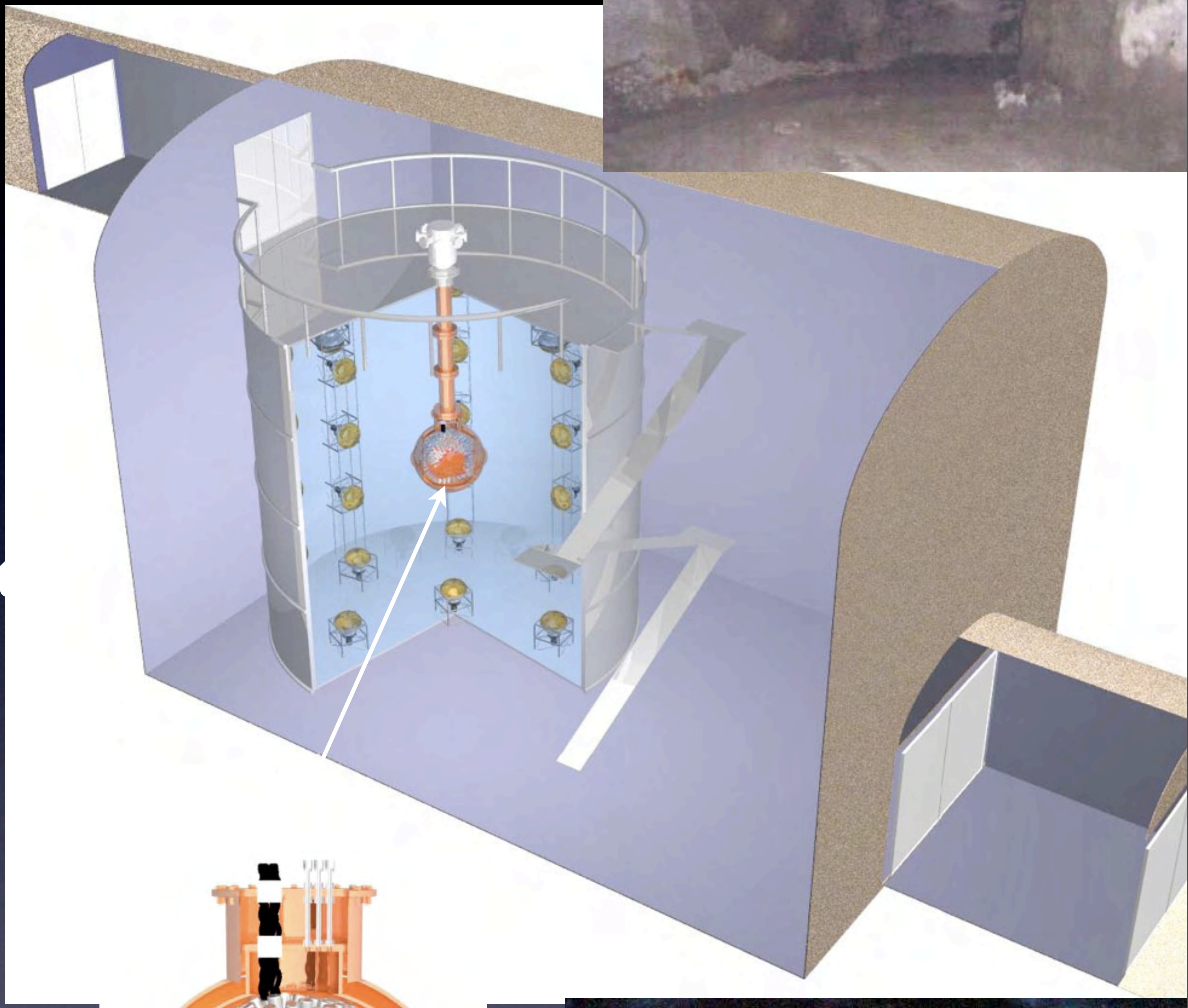

A
B
CRESST I, est. (2002)
CDMS Ge (2004+2005)
ZEPLIN-II (2007)
PICASSO (2005)
Tokyo CaF2 (2005)
SIMPLE (2005)
NAIAD (2005)
DAMA/NaI-allowed
KIMS (2007)
COUPP (2007)
(this work)
σpSD (pb)
WIMP mass (GeV)
Mχ= 50 GeV
ZEPLIN-II (2005)
CDMS (2004+2005)
ap
an

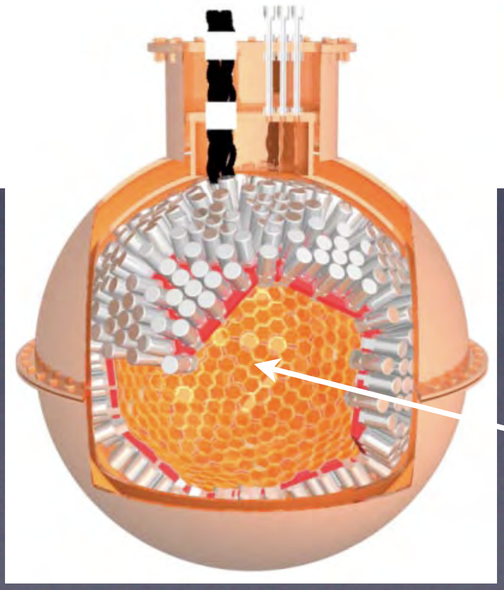

2-6 keV
DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr)
(target mass = 232.8 kg)
Residuals (cpd/kg/keV)
Time (day)

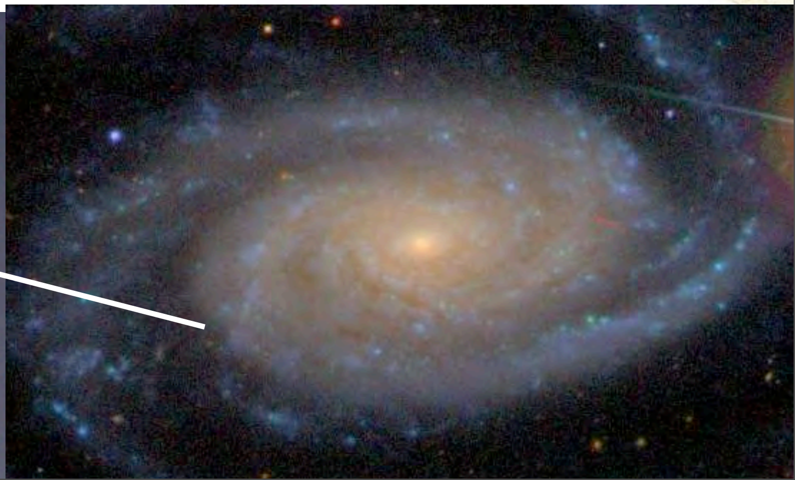
XMASS



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

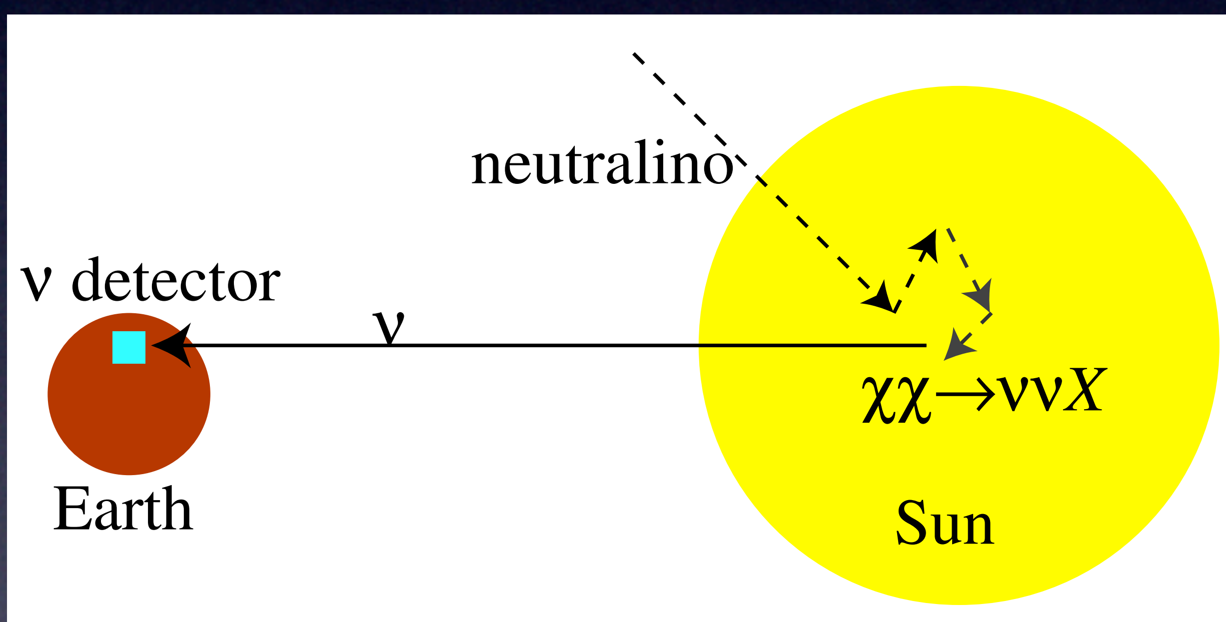


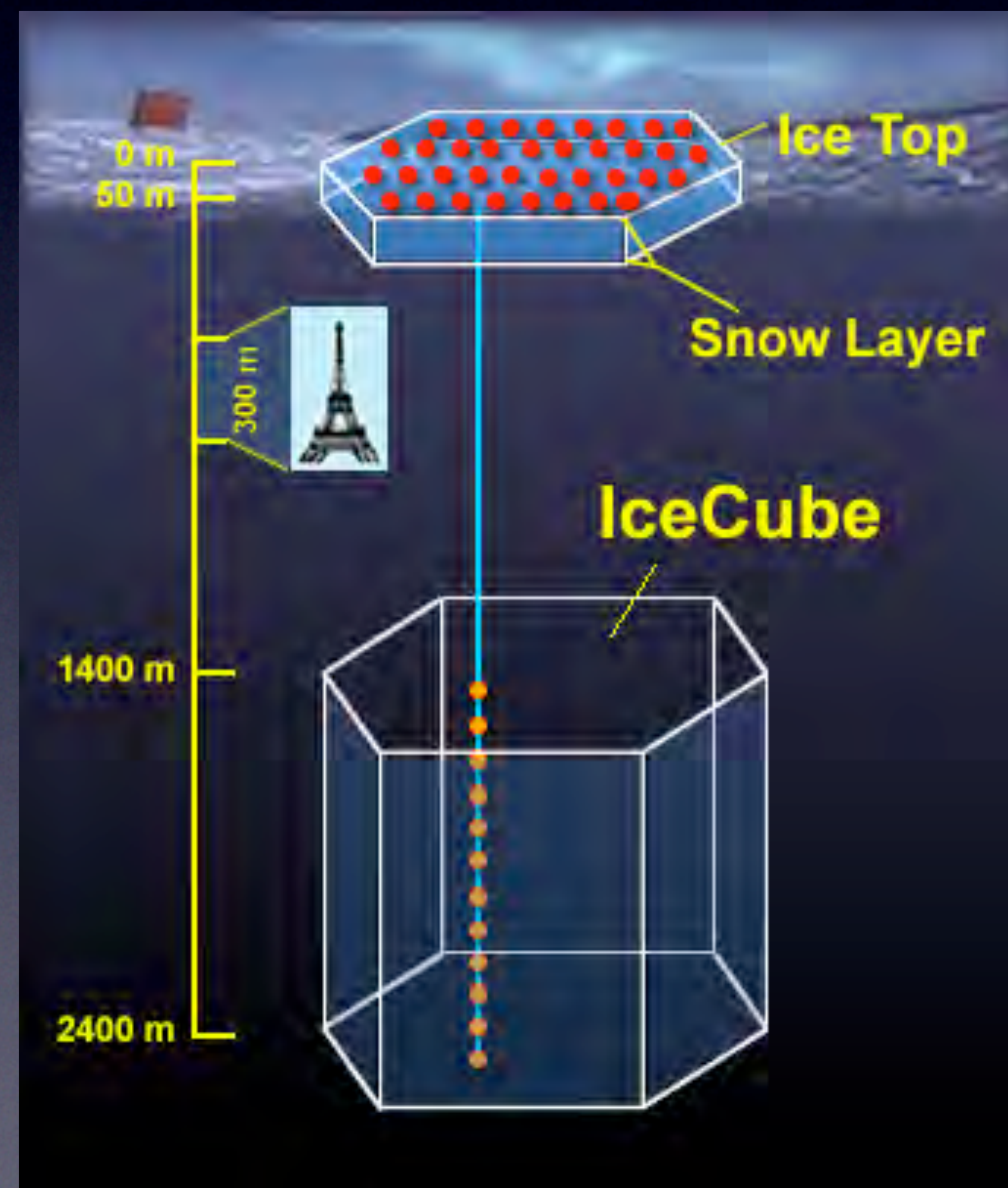




Finding Dark Matter

Indirect method
Icecube, Antares, Nestor, Nemo, Baikal





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Finding Dark Matter

Indirect method
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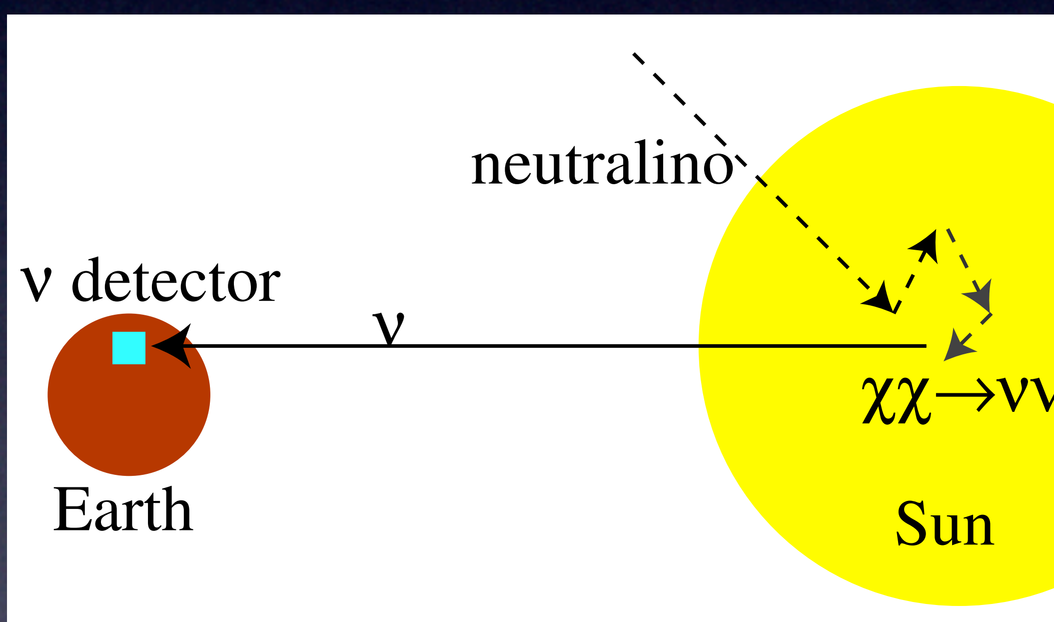
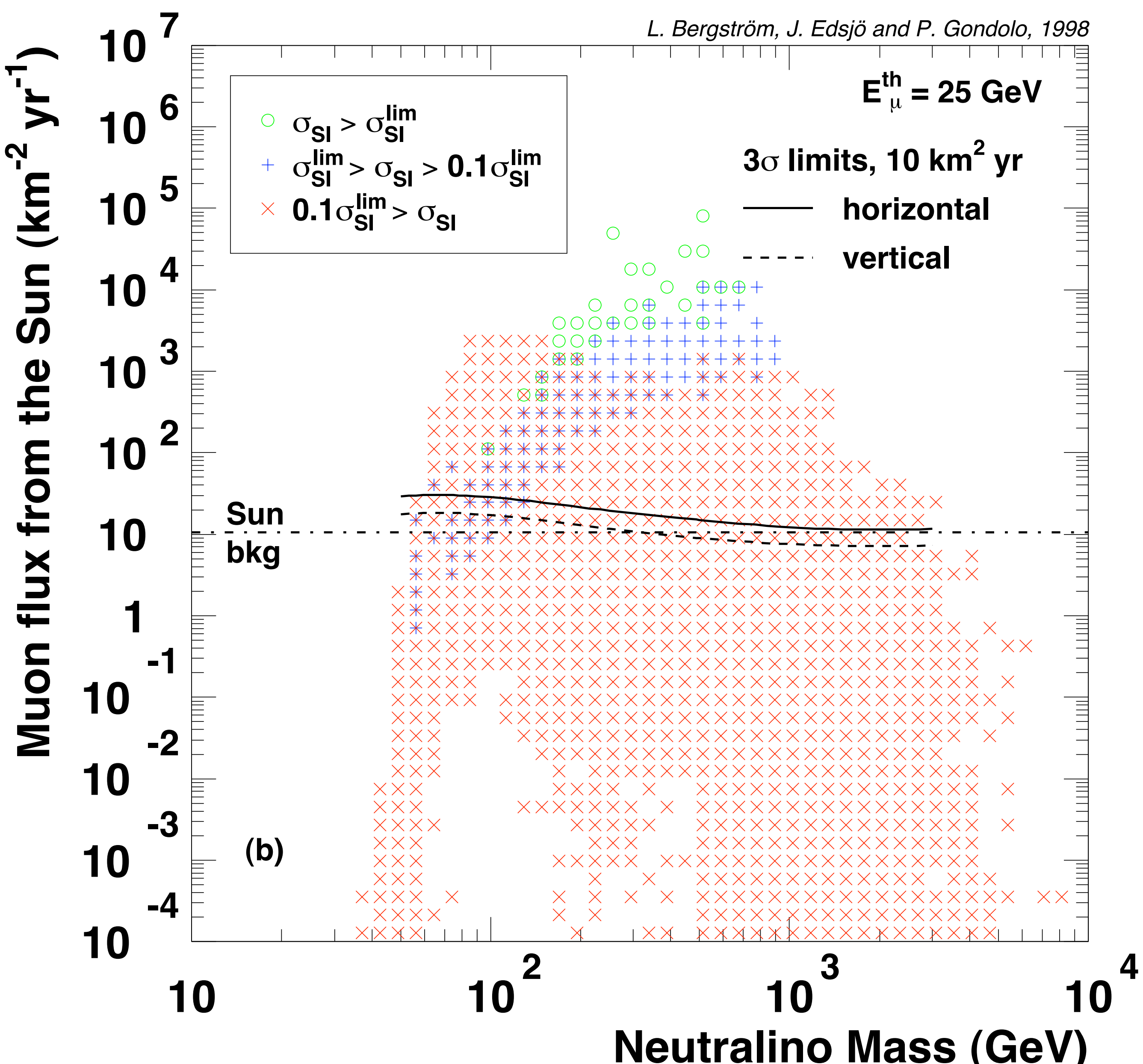
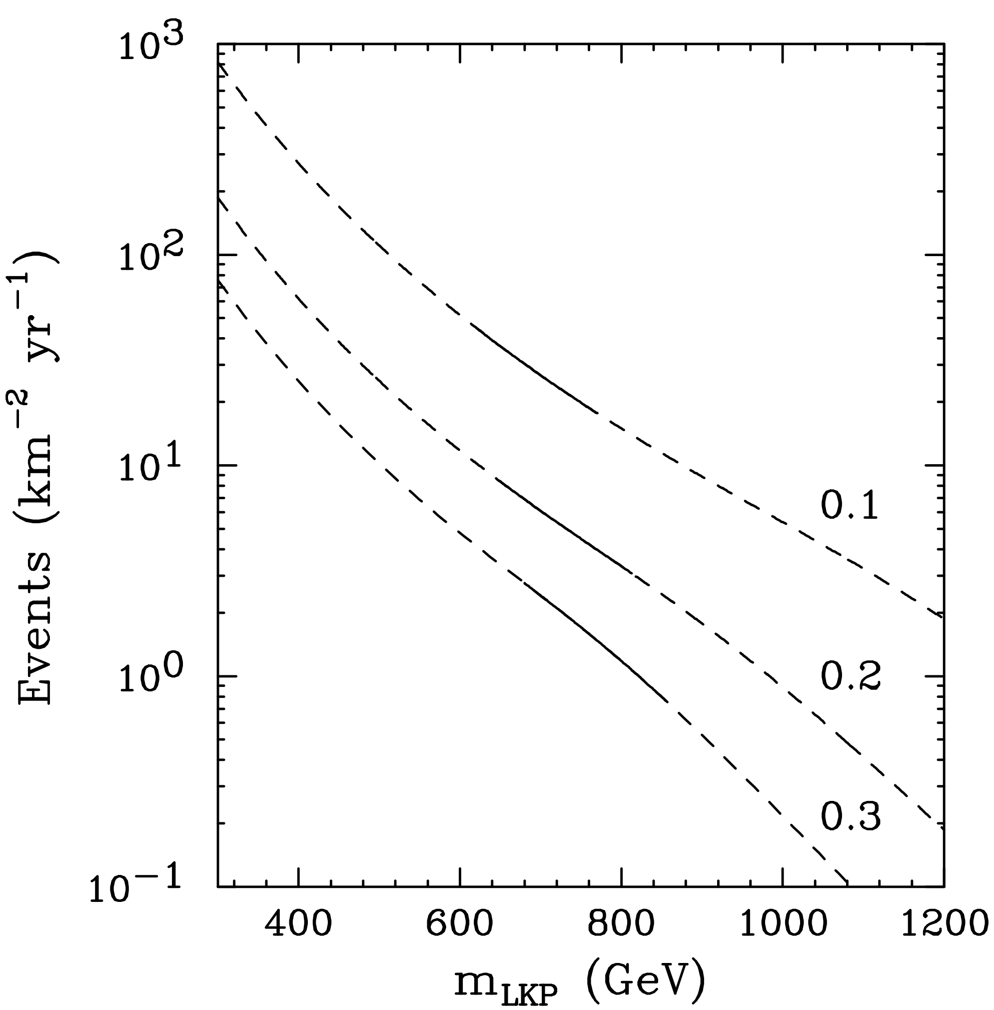


Future Limits

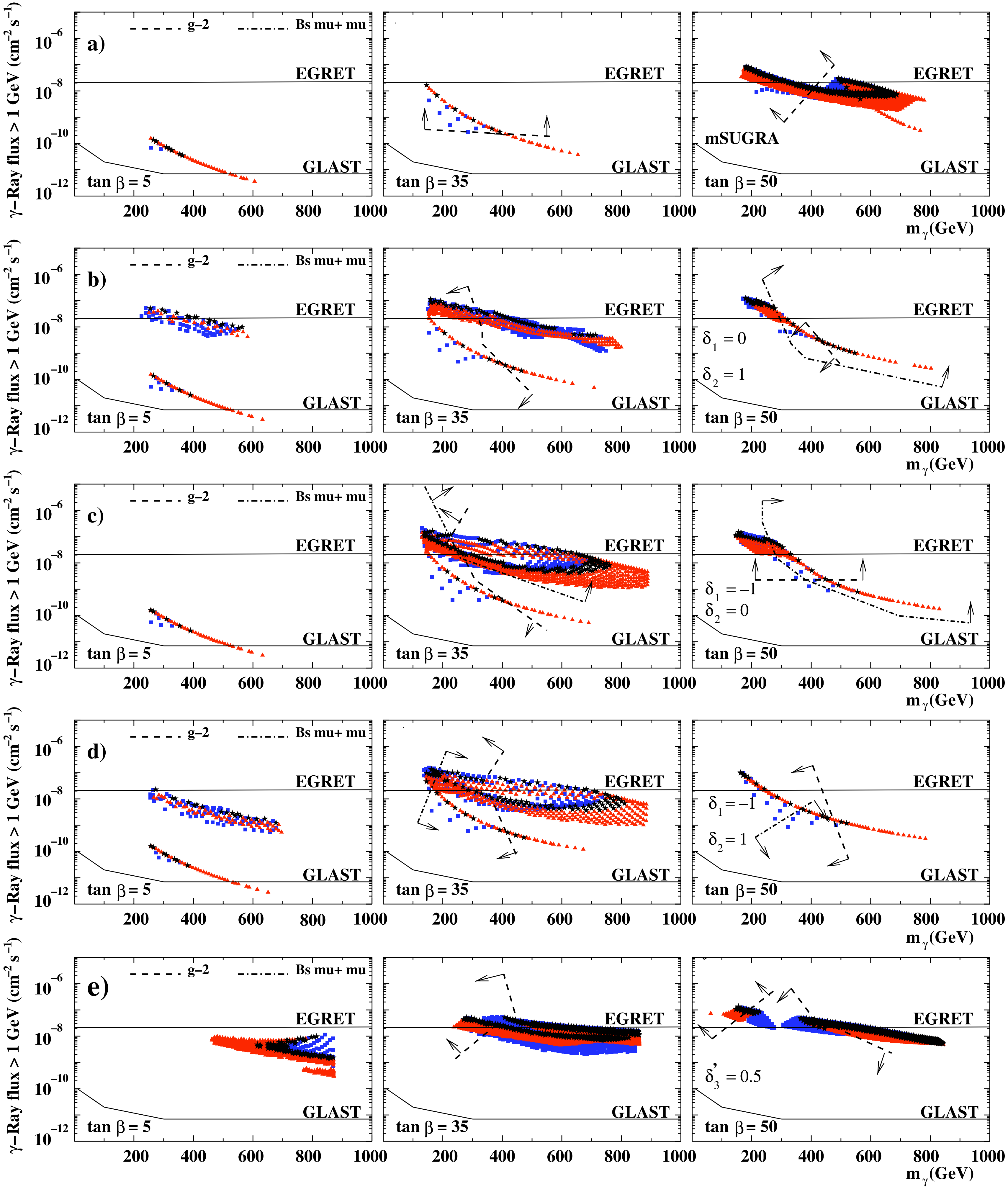
- SUSY (Bergström, Edsjö, Gondolo, hep-ph/98060293)
- UED (Hooper and Kribs, hep-ph/0208261)





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

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

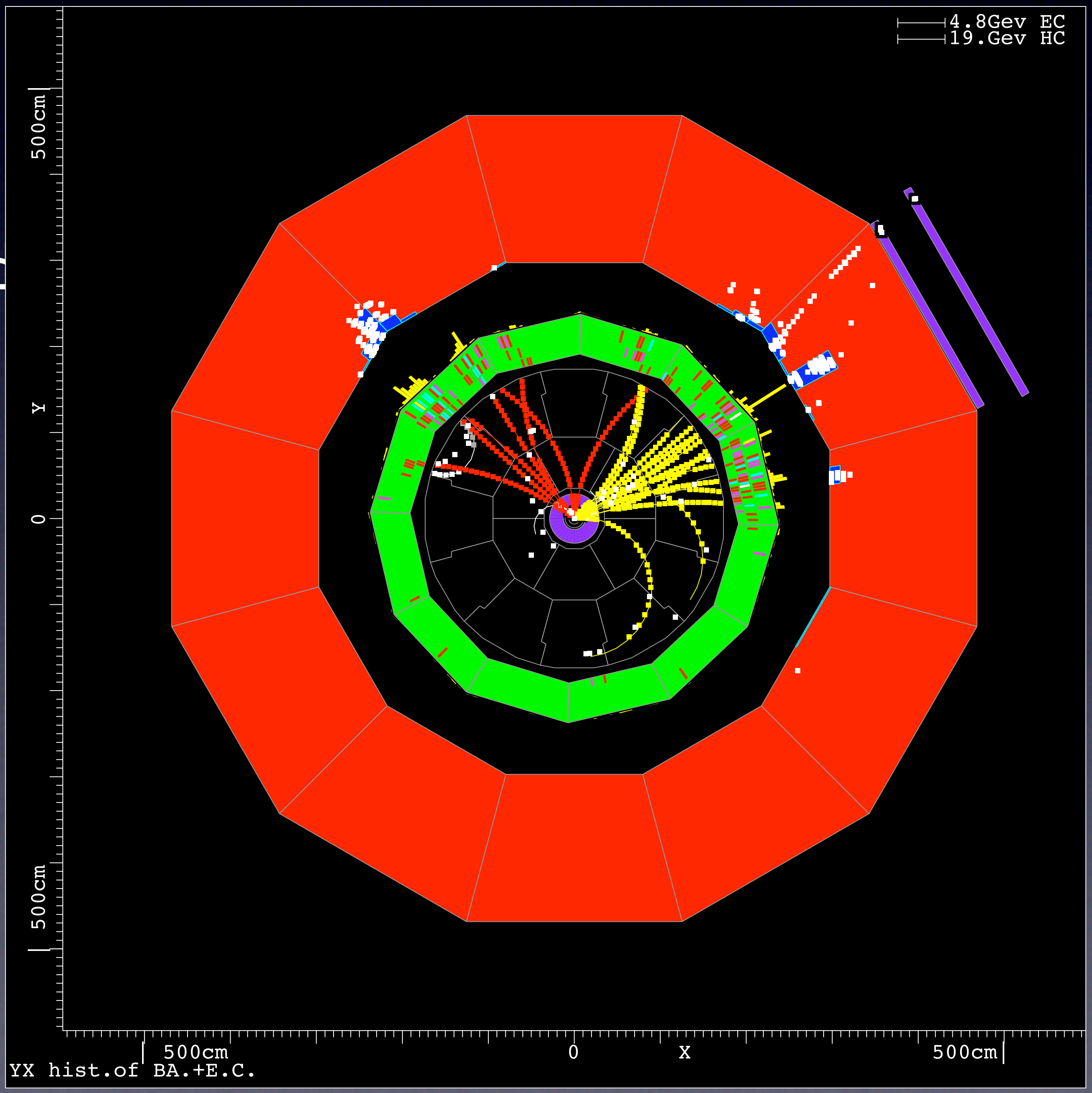
"missing energy" E_{miss}

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

⇒Dark Matter!?

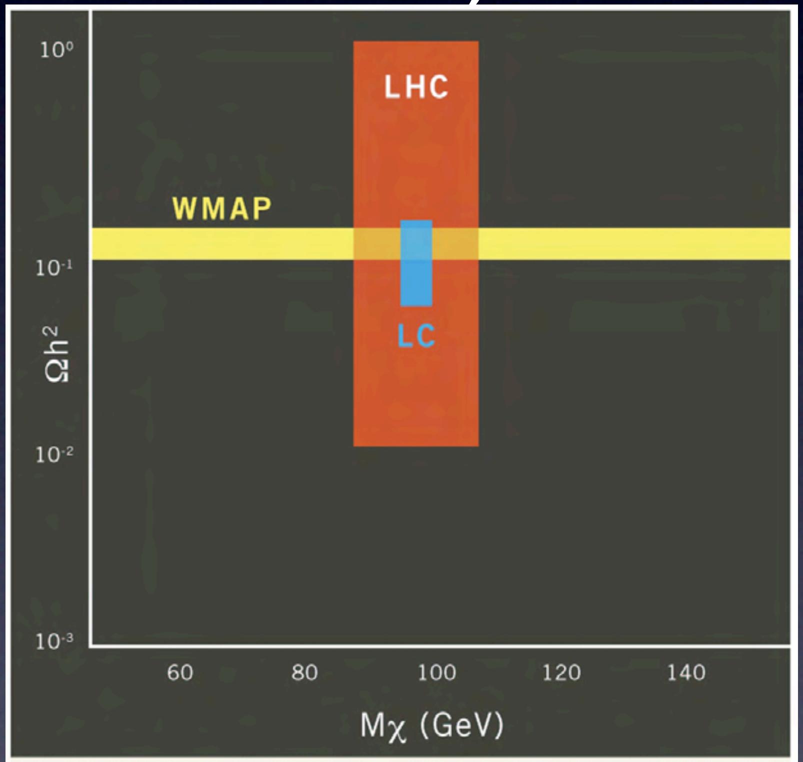
- need to know the model!

⇒spin & mass meaurements



Concordance model of Dark Matter?

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



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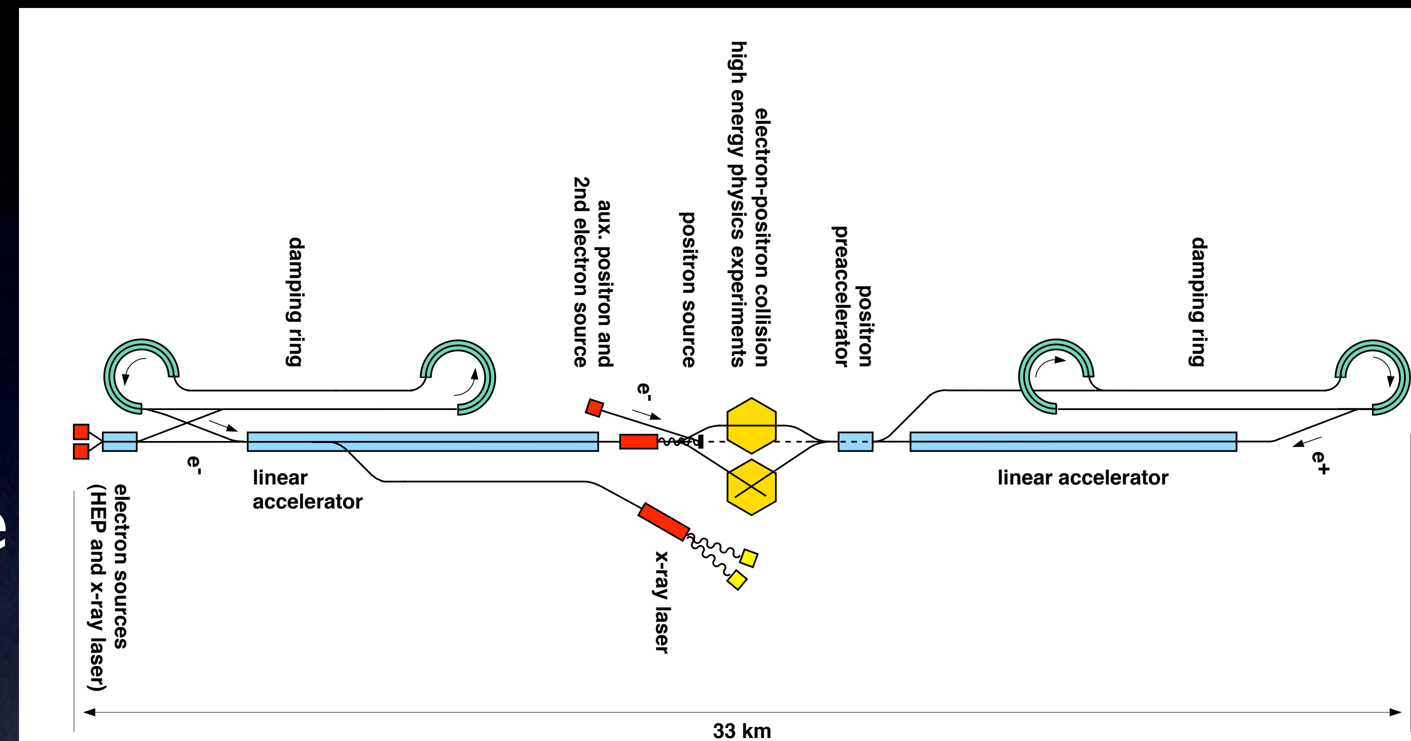
Linear Collider

- Electron-positron collider
- Super-high-tech machine
- Accelerate the beam over ten miles
- Focus beam down to a few nanometers and make them collide
- Precisely measure the dark matter properties



International Linear Collider (ILC)

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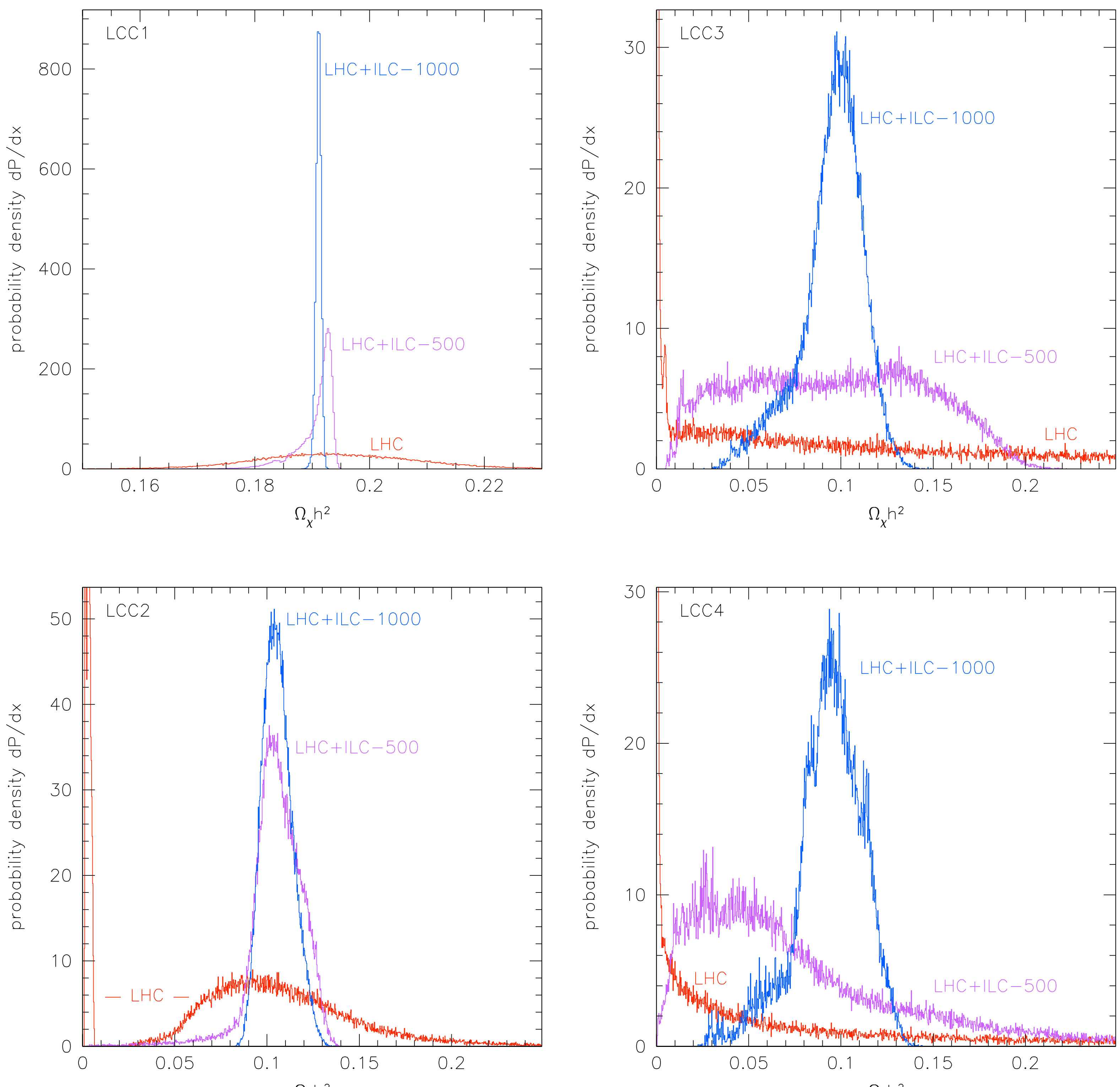
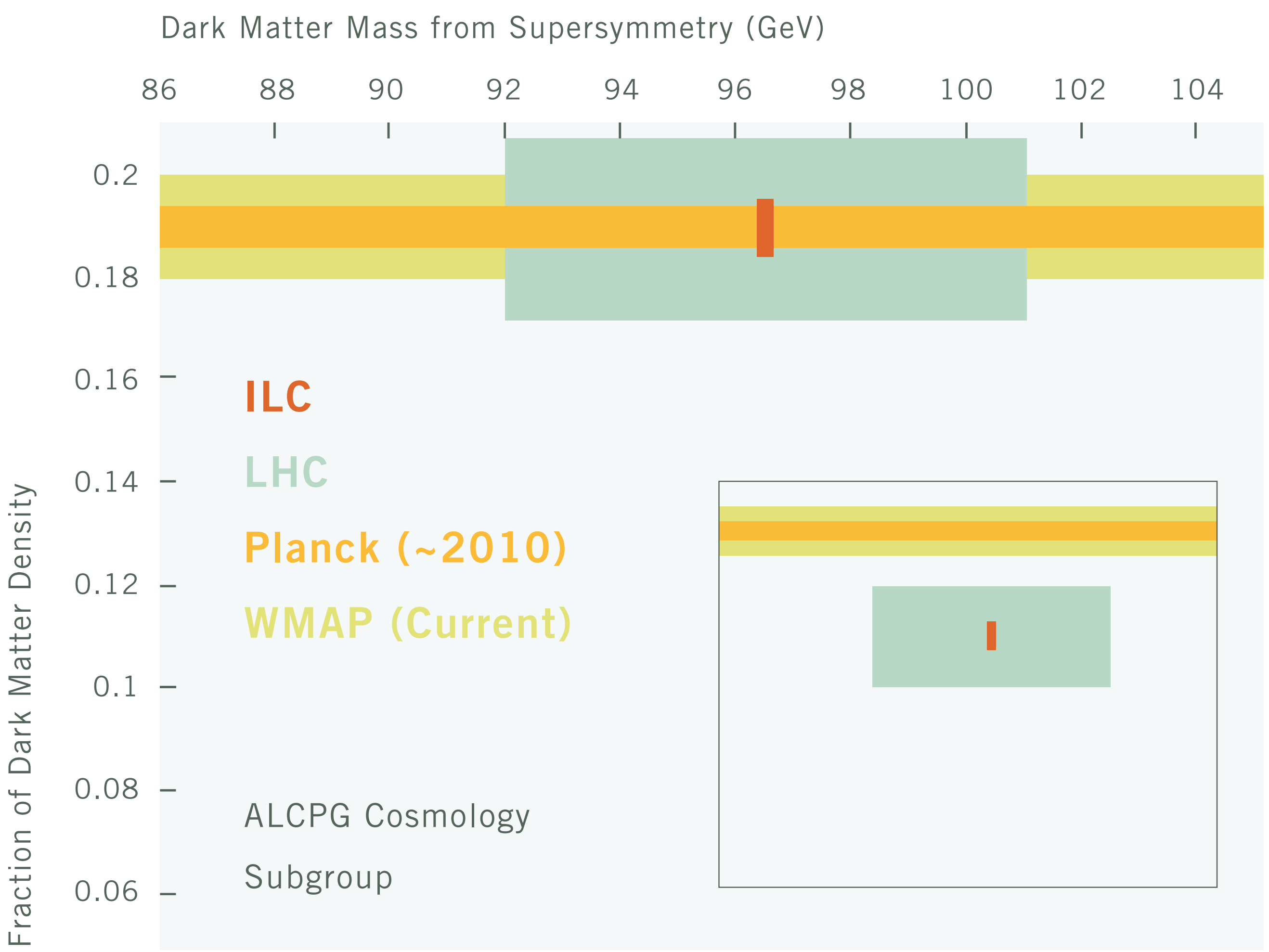
Omega from colliders



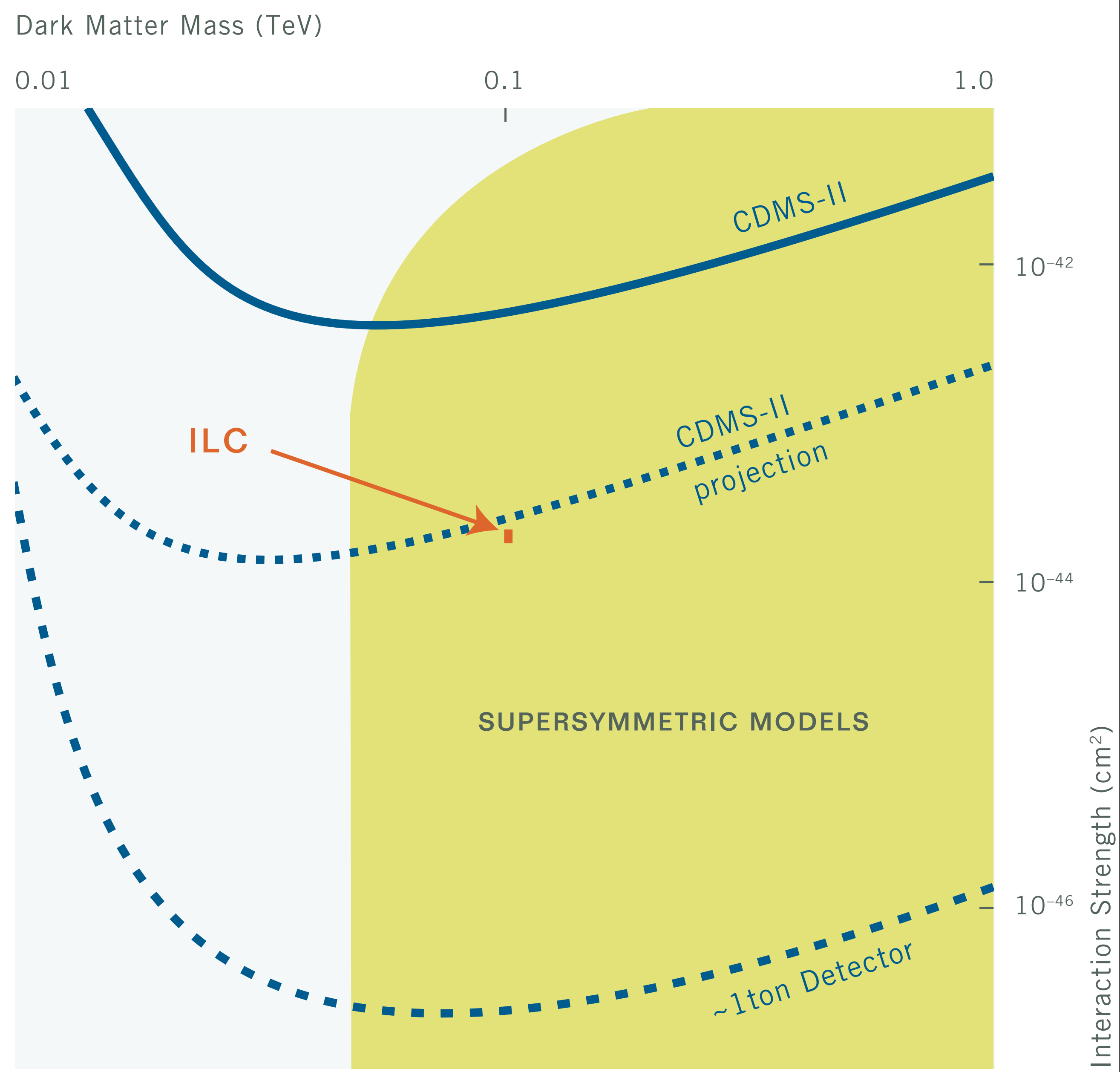
SUSY case study
Baltz, Battaglia, Peskin,
Wizansky hep-ph/0602187

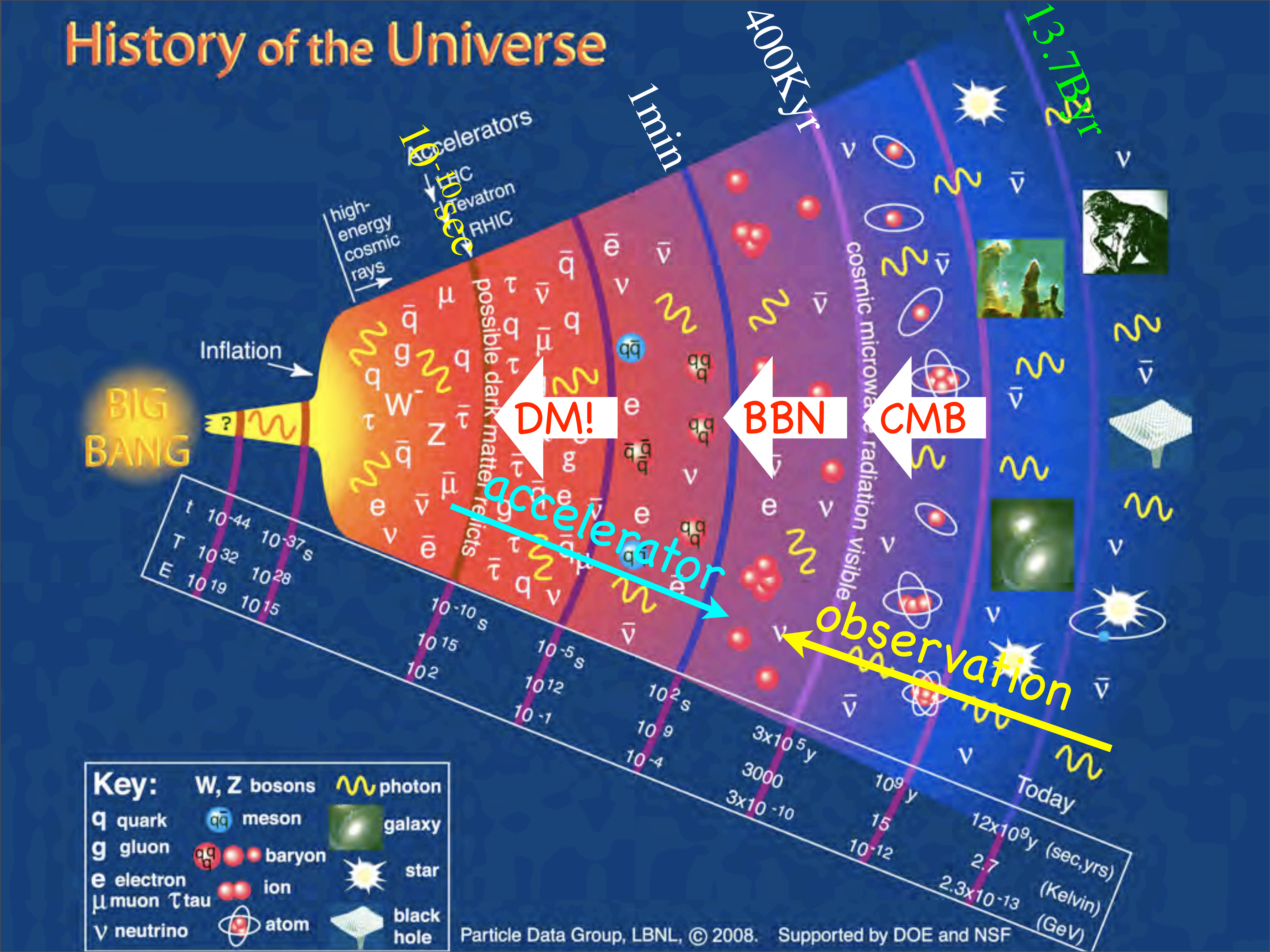
Cross check

abundance



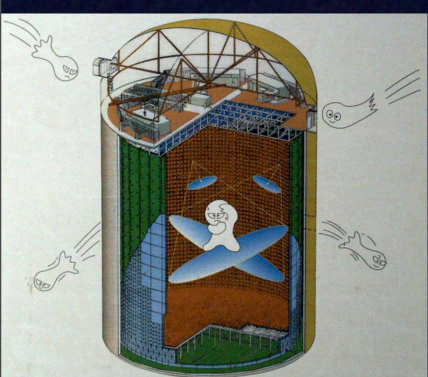
direct cross section

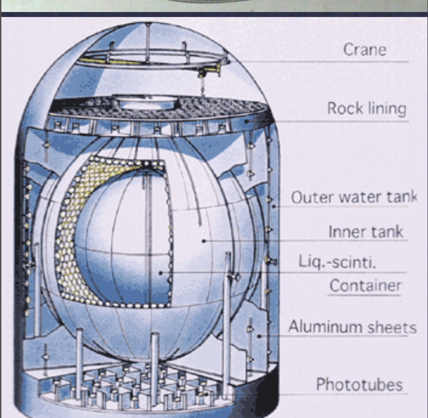


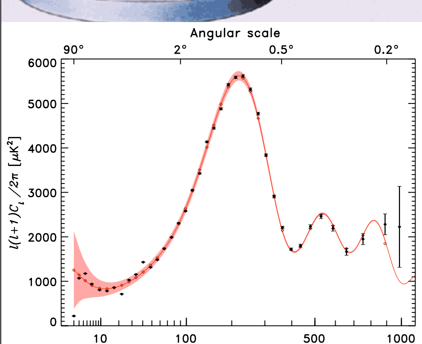

History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
10^{-10}sec
1min
400Kyr
13.7Byr
possible dark matter relicts
cosmic microwave radiation visible
DM!
BBN
CMB
accelerator
observation
t 10^{-44} 10^{-37}s 10^{-10}s 10^{-5}s 10^{2}s 3×10^{5}y 10^{9}y 12×10^{9}y (sec,yrs)
T 10^{32} 10^{28} 10^{15} 10^{12} 10^{9} 3000 15 2.7 (Kelvin)
E 10^{19} 10^{15} 10^{2} 10^{-1} 10^{-4} 3×10^{-10} 10^{-12} 2.3×10^{-13} (GeV)
Today
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
ion
star
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

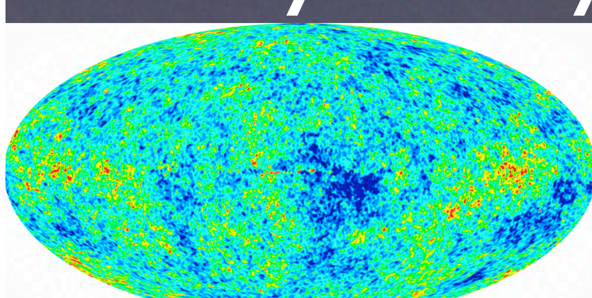
Experimental Facts

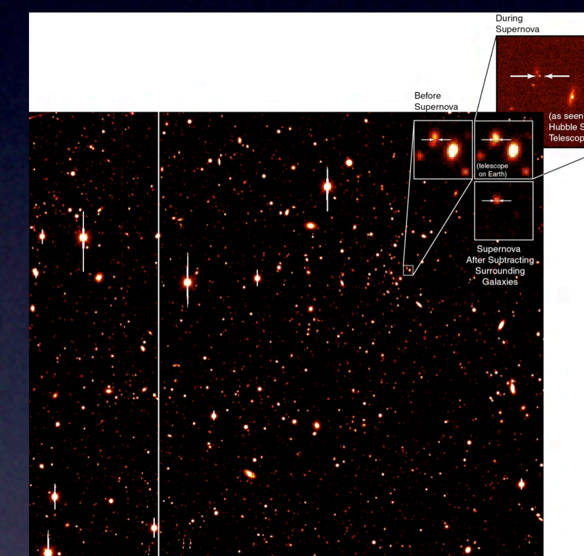
- Five facts standard model cannot explain
  - finite neutrino mass (1998, 2002)
  - accelerating universe (1998)
  - non-baryonic dark matter (2003)
  - acausal nearly Gaussian scale-invariant density fluctuation (2003)
  - baryon asymmetry (reconfirmed 2003)

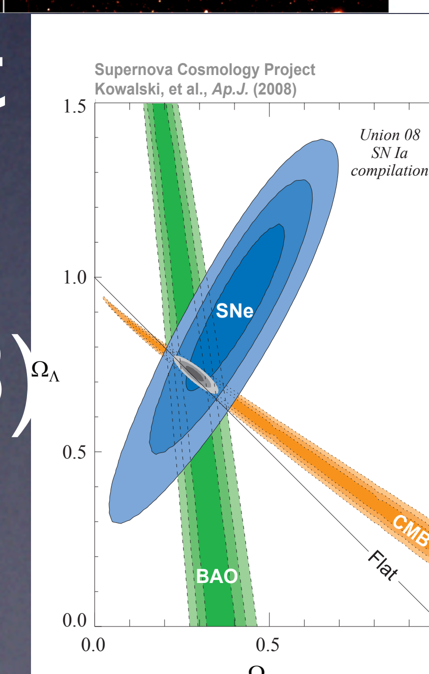








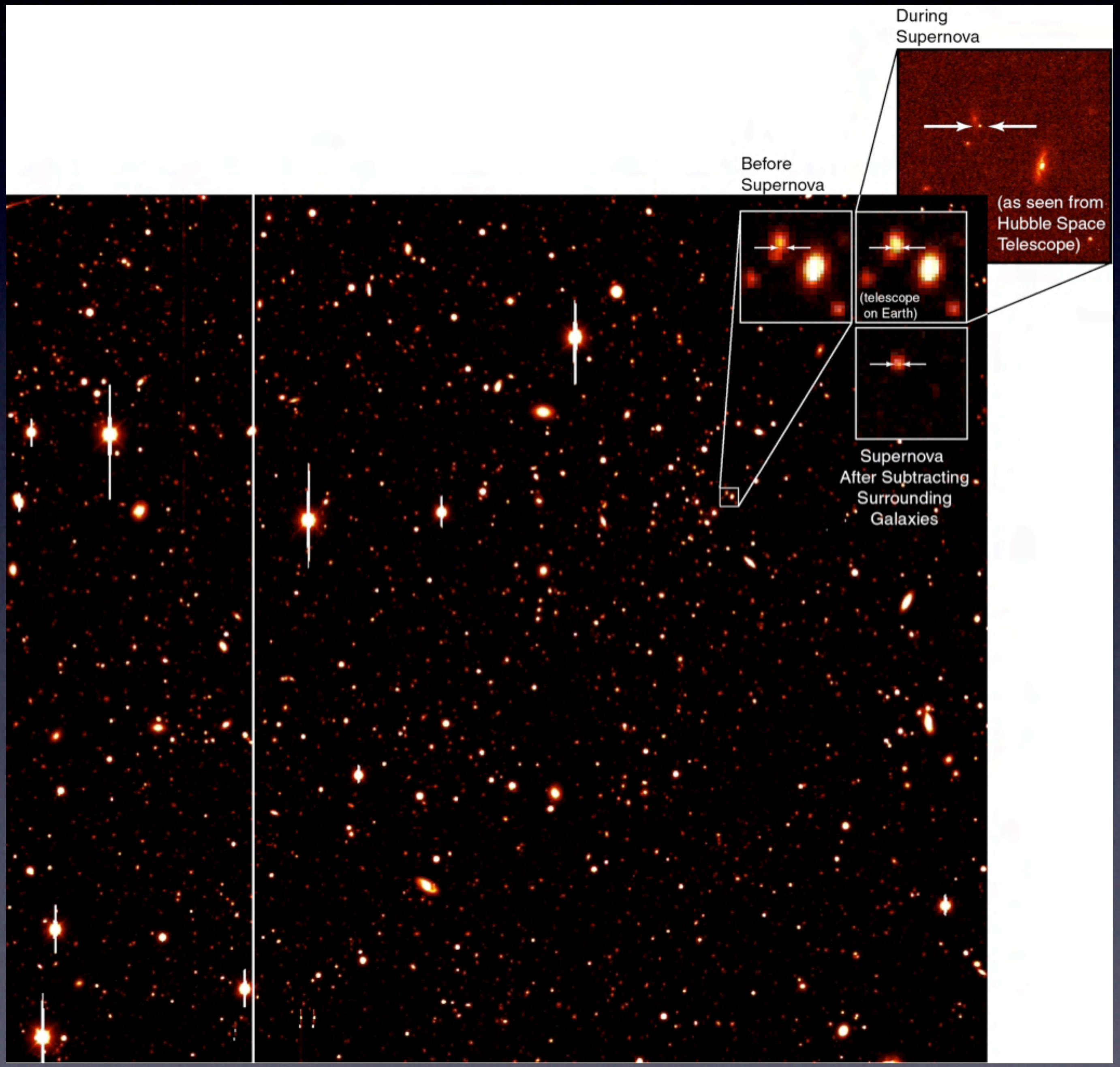




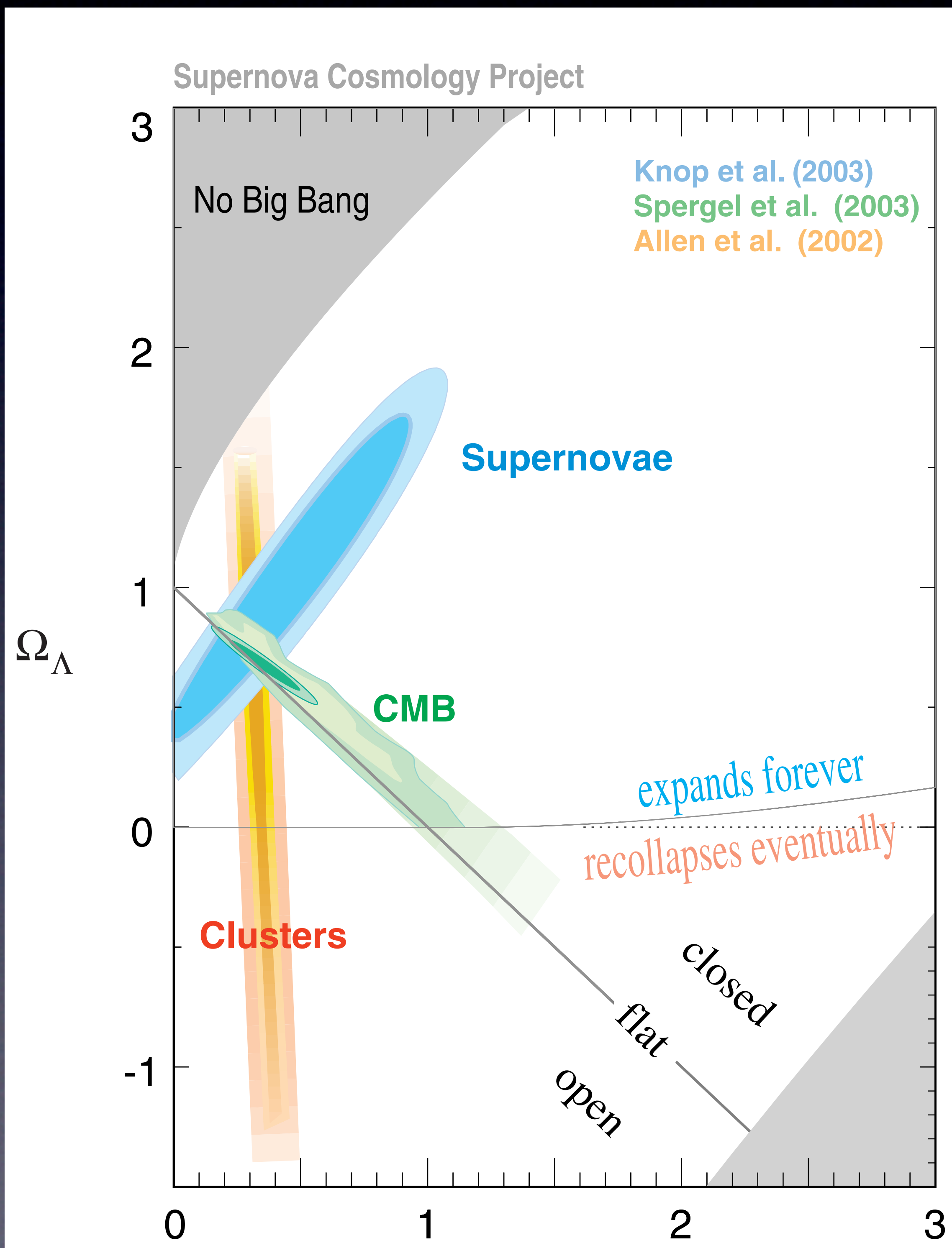
Dark Energy

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:

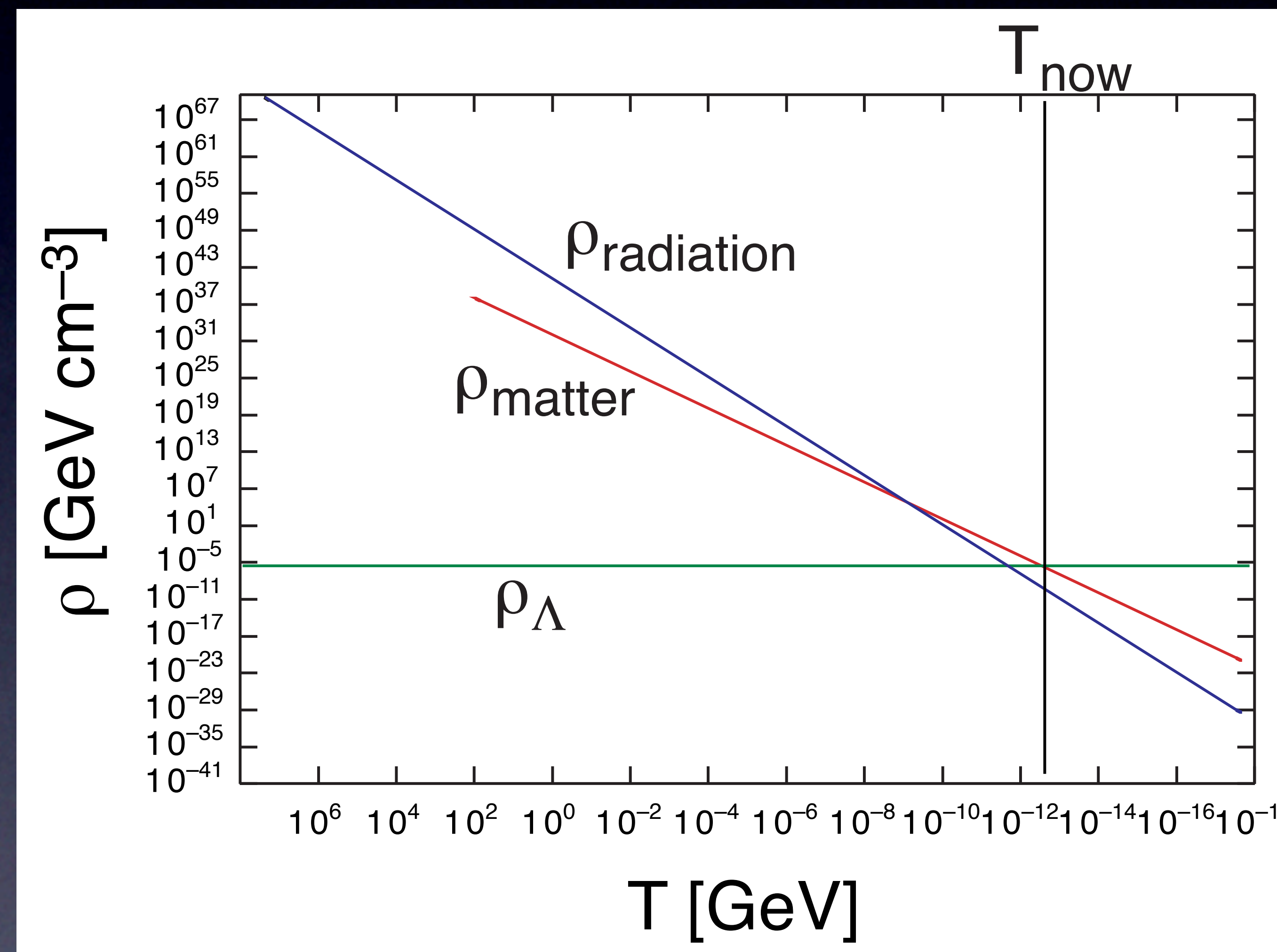
$$\rho_\Lambda \sim M_{Pl}{}^4 = G_N{}^{-2} \sim 10^{120} \textit{ times observation}$$

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 $\rho_\Lambda \sim ((\mathrm{TeV})^2/M_{Pl})^4$, coincidence natural



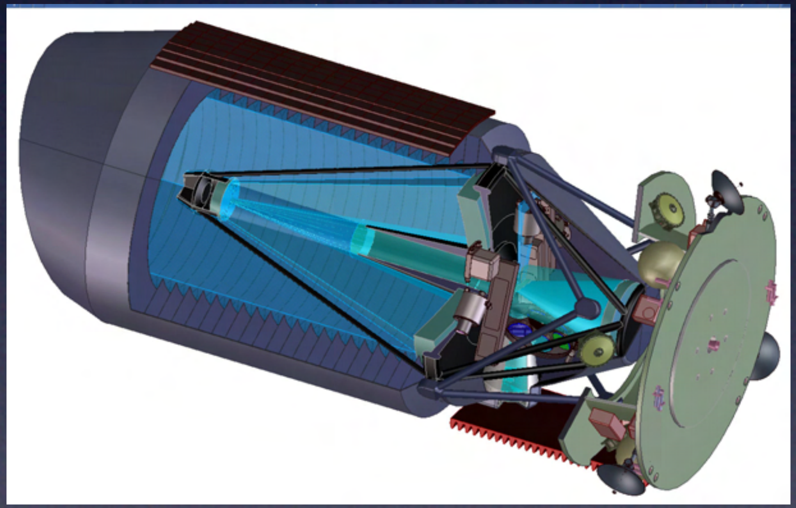
Arkani-Hamed, Hall, Kolda, HM

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

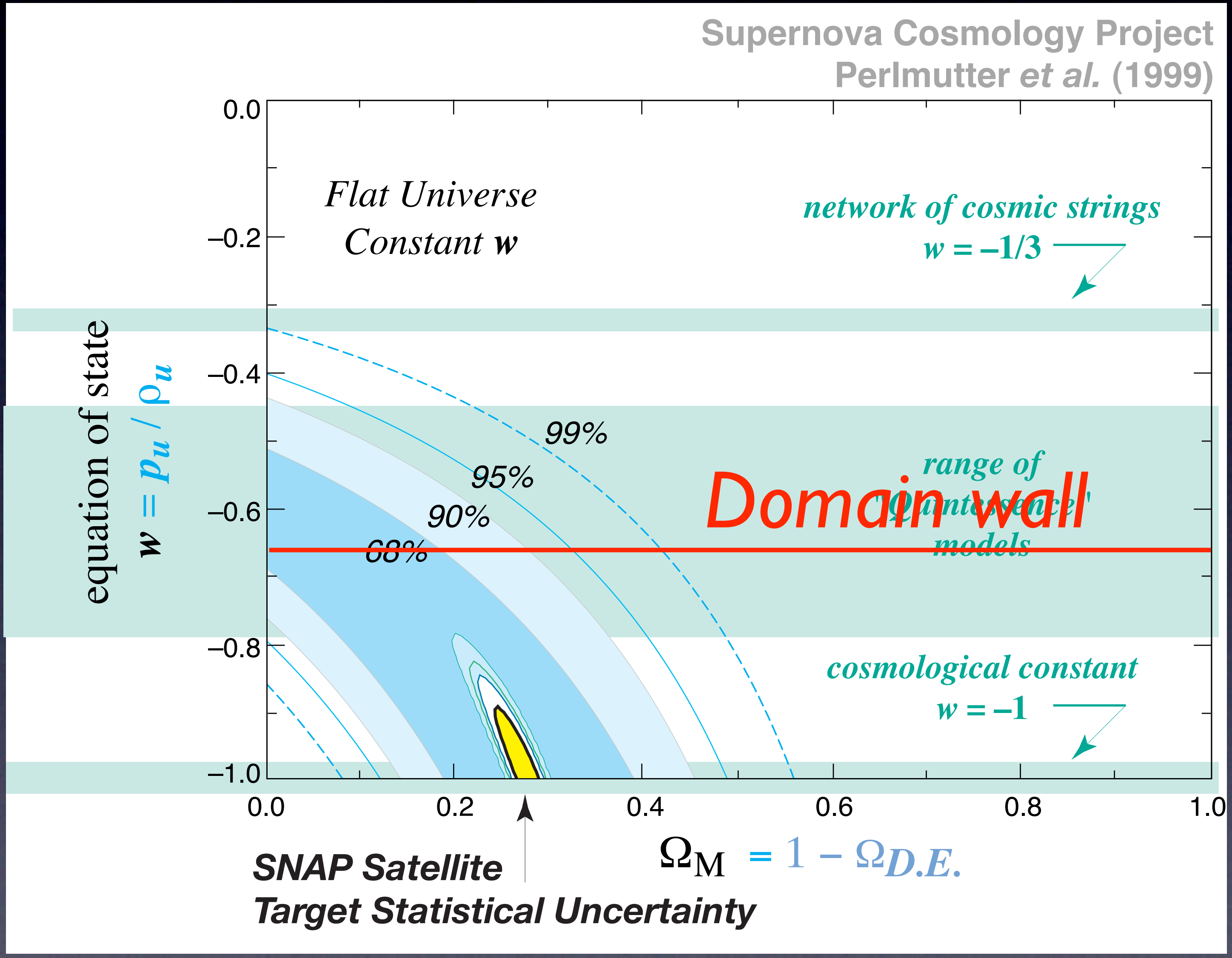
What is Dark Energy?

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



SNAP

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

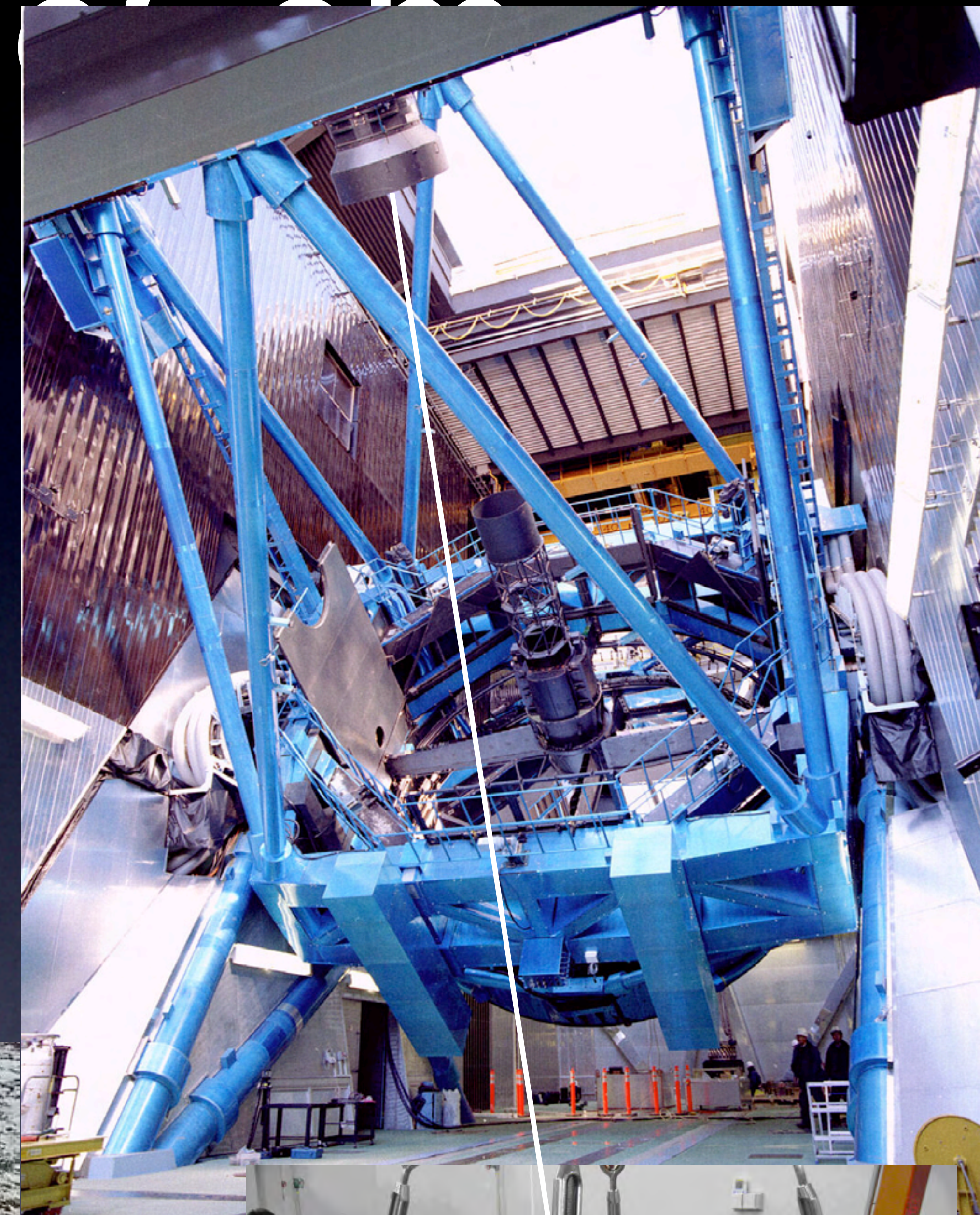


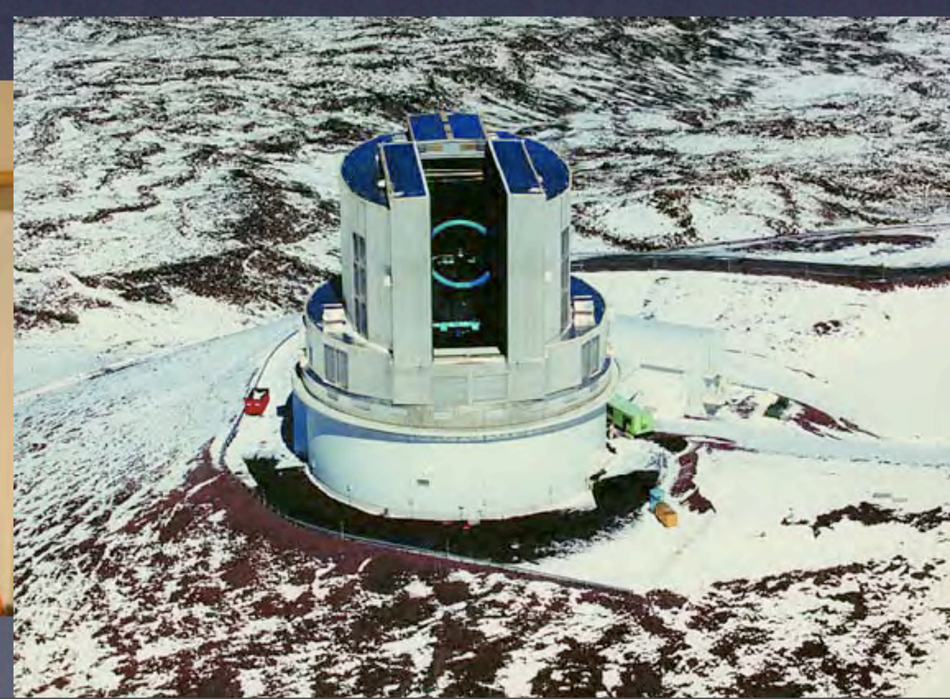
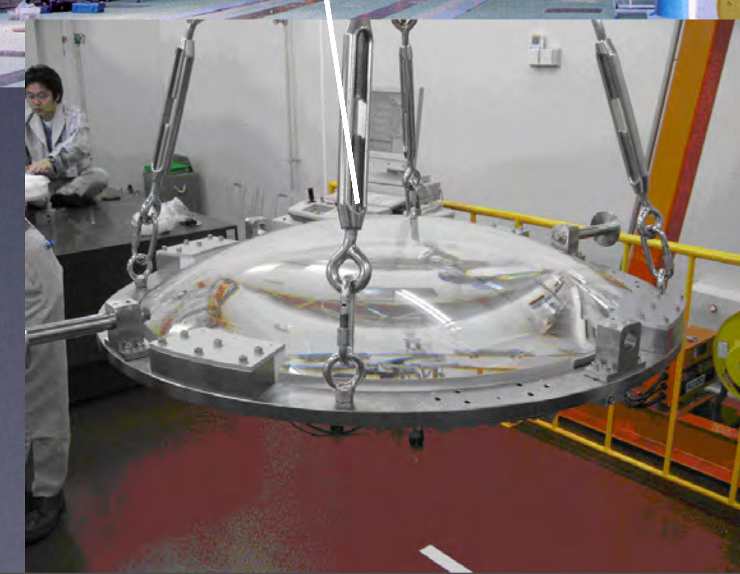
Friedland, HM, Perelstein



HyperSuprim

- 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

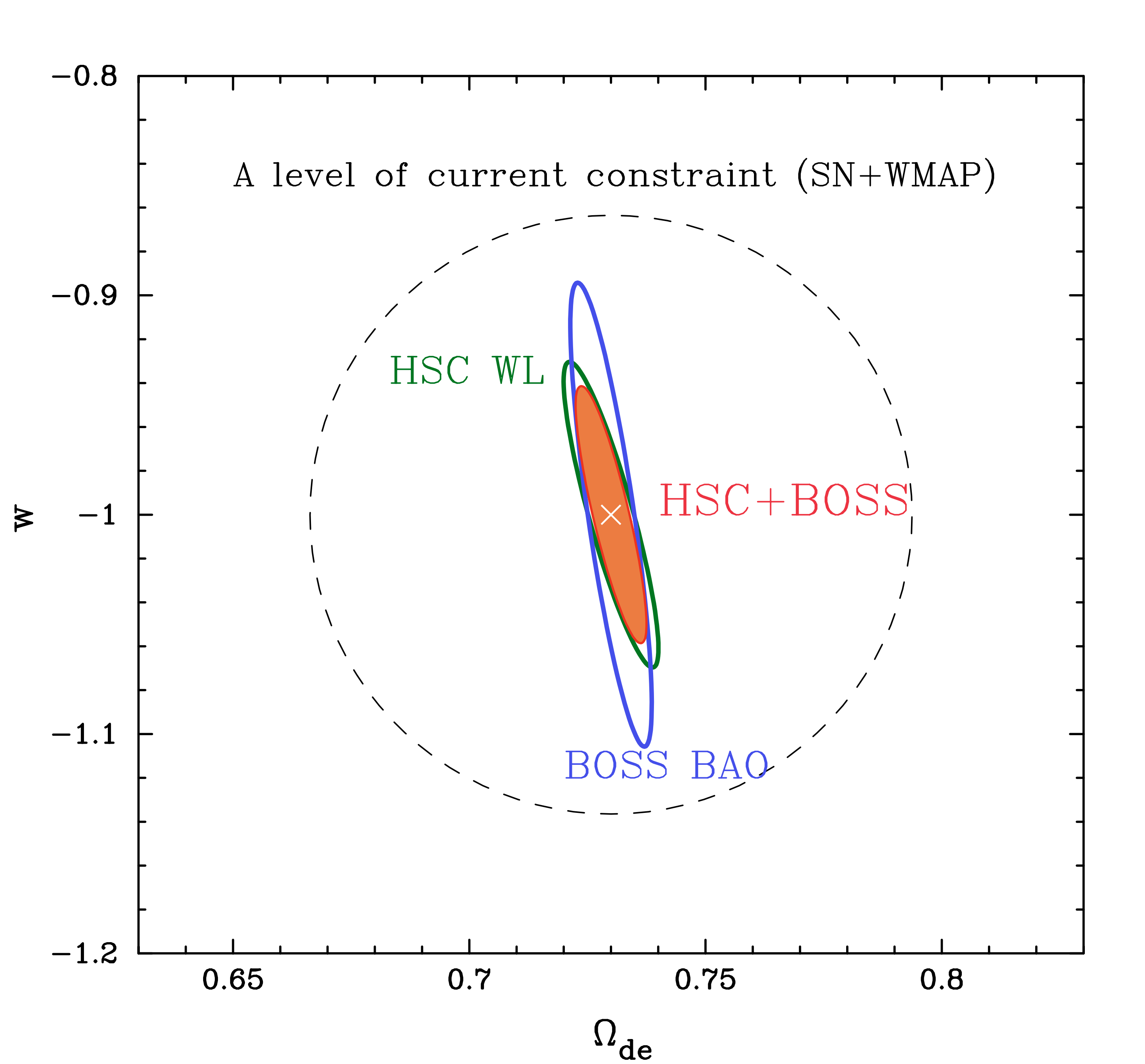


Power of Combination

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

How fast dark energy is increasing



How much dark energy there is

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!

string theory prediction?

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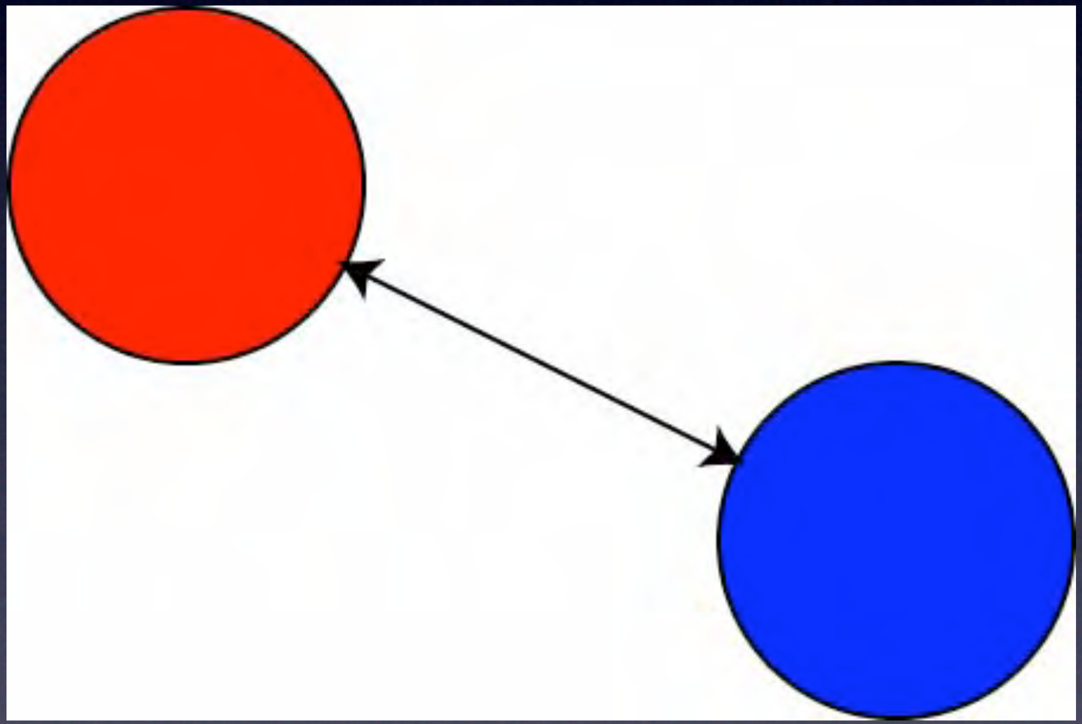
- "eternal inflation"?
- need criteria!

Dark Field
=Cosmic Superconductor

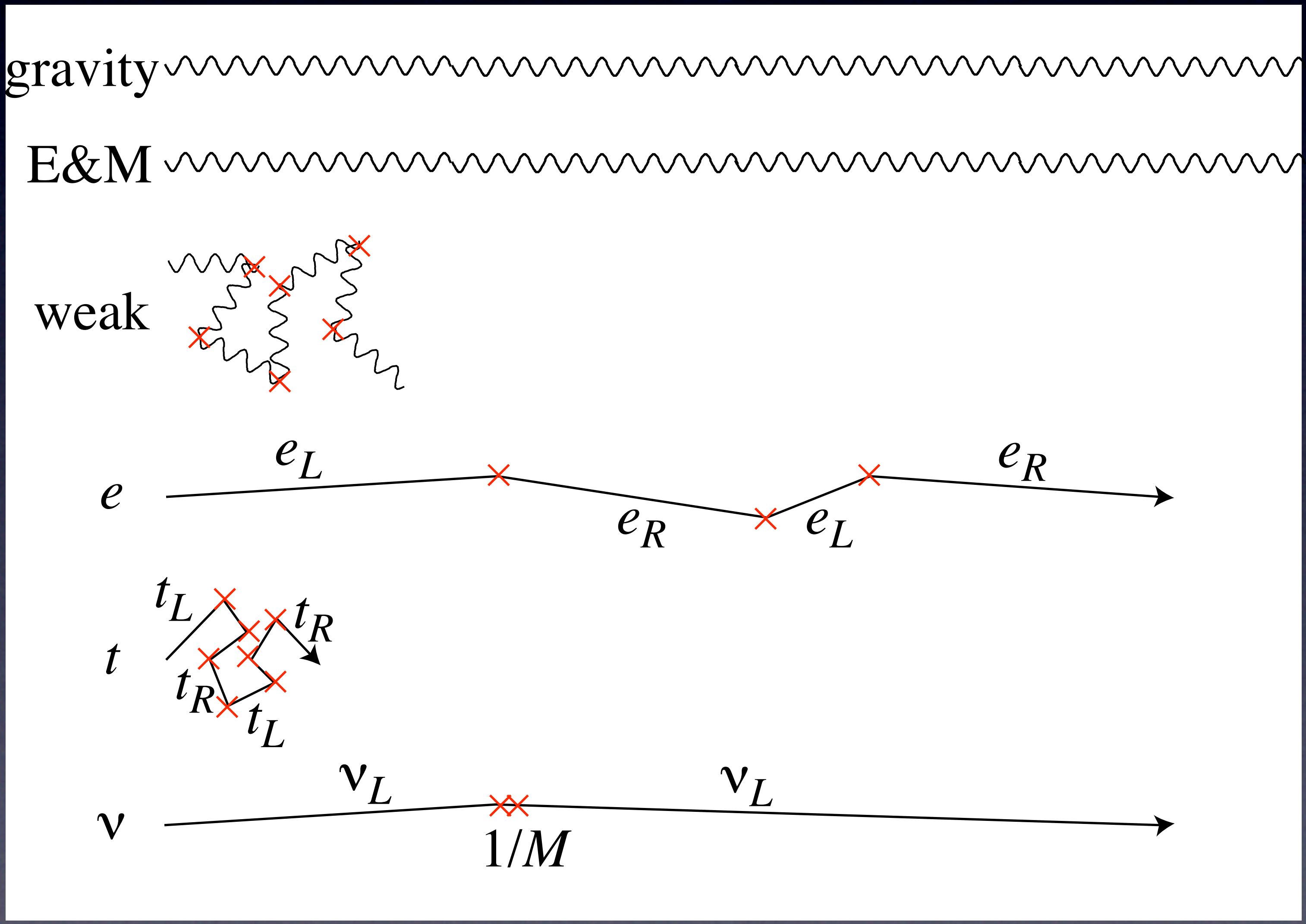
Mystery of the weak force

- Gravity pulls two massive bodies (long-ranged)
- Electric force repels two like charges (long-ranged)
- Weak force pulls protons and electrons (short-ranged) acts only over 0.000000001 nanometer
- We know the energy scale: ~0.3 TeV



We are swimming in Dark Field

- There is quantum liquid filling our Universe
- It doesn't disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- It slows down all elementary particles from speed of light
- otherwise no atoms!
- What is it??



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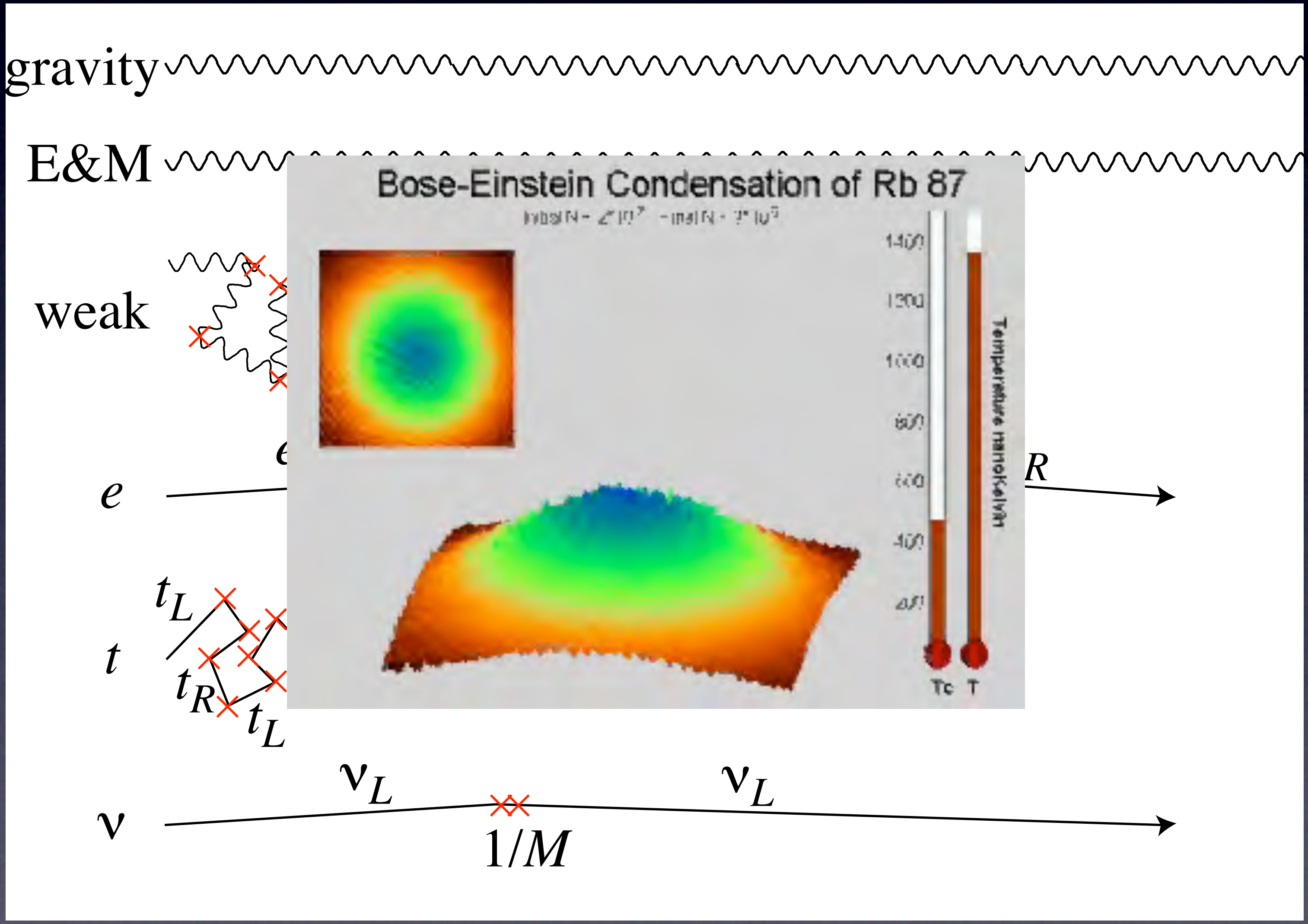


Cosmic Superconductor

- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the "penetration length"

  $\Rightarrow$ Magnetic field is short-ranged!

- Imagine a physicist living in a superconductor
- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two condensate in her "Universe"
  - But doesn't know what the condensate is, nor why it condenses
  - Doesn't have enough energy (gap) to break up Cooper pairs

That's the stage where we are!

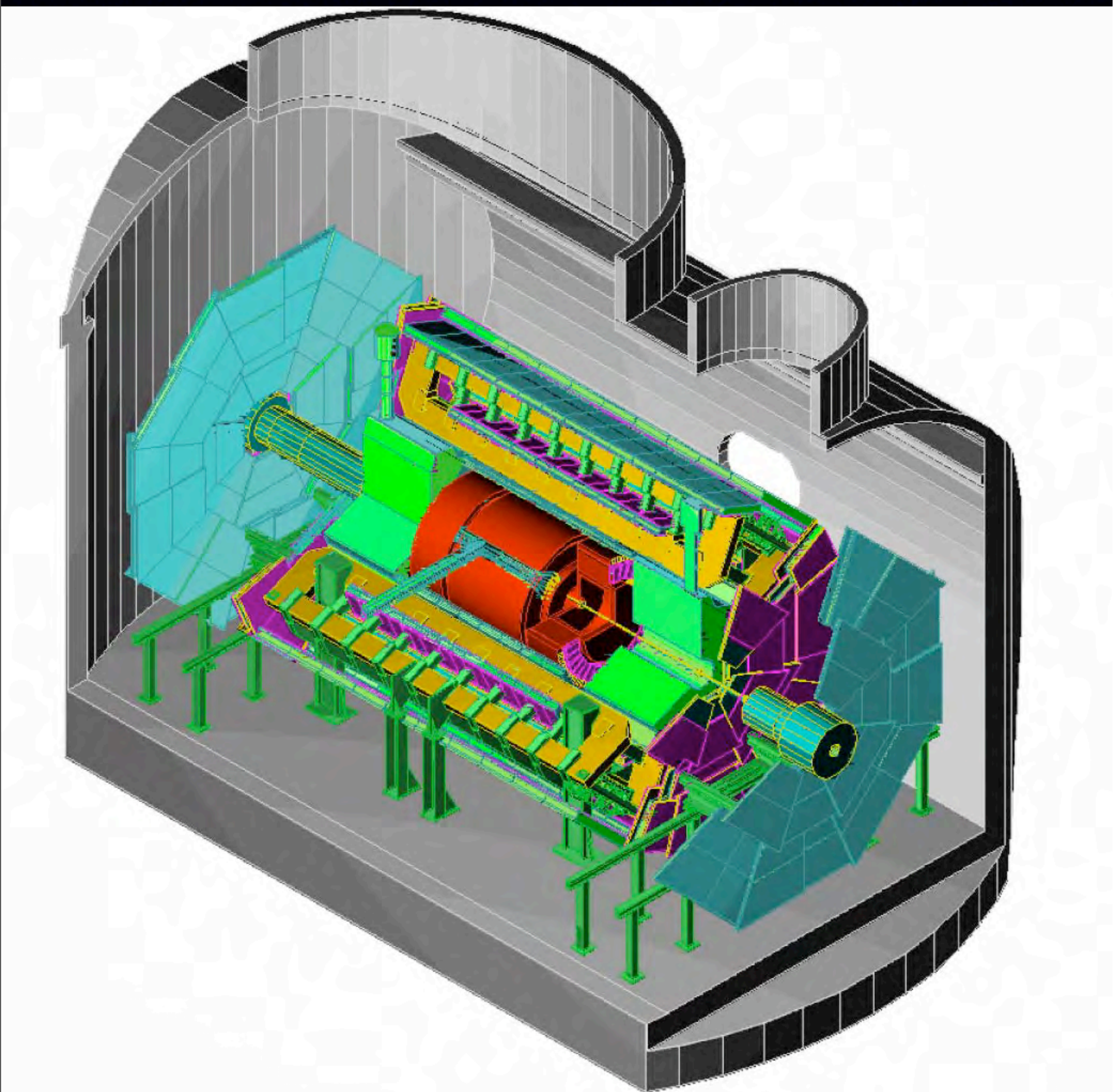
Solving the Dark Field Problem

Tevatron

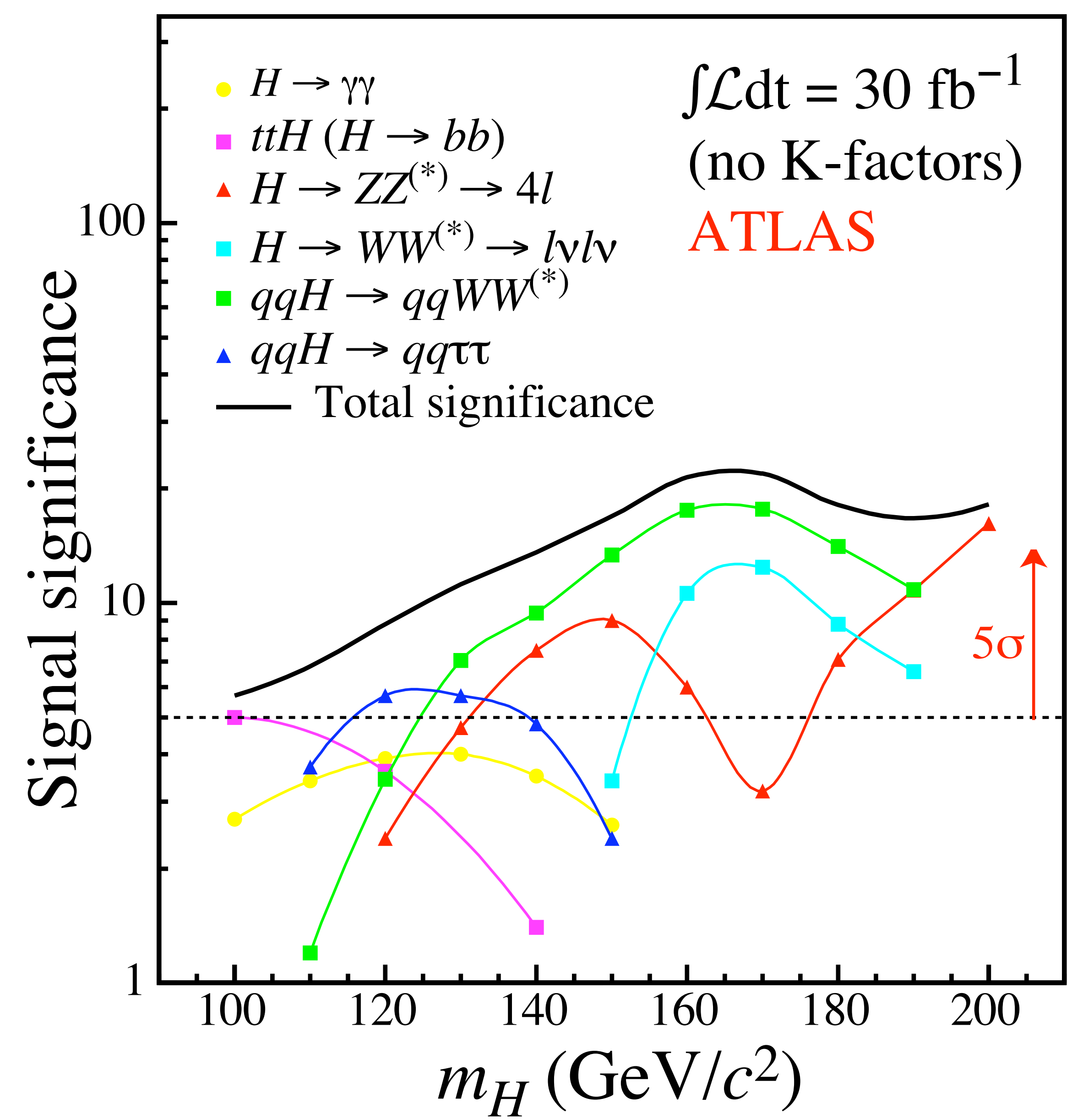
Large Hadron Collider (LHC)

International Linear Collider (ILC)

Higgs at ATLAS



Robust discovery



Post-Higgs Problem

- We see "what" is condensed
- But we still don't know "why"
- Two problems:
  - Why anything is condensed at all
  - Why is the scale of condensation $\sim$TeV$<<M_{Pl}=10^{15}$TeV
- Explanation most likely to be at ~TeV scale because this is the relevant energy scale

Three Directions

History repeats itself

- Crisis with electron solved by anti-matter
- Double #particles again ⇒ supersymmetry

Learn from Cooper pairs

- Cooper pairs composite made of two electrons
- Higgs boson may be fermion-pair composite
  ⇒ technicolor

Physics as we know it ends at TeV

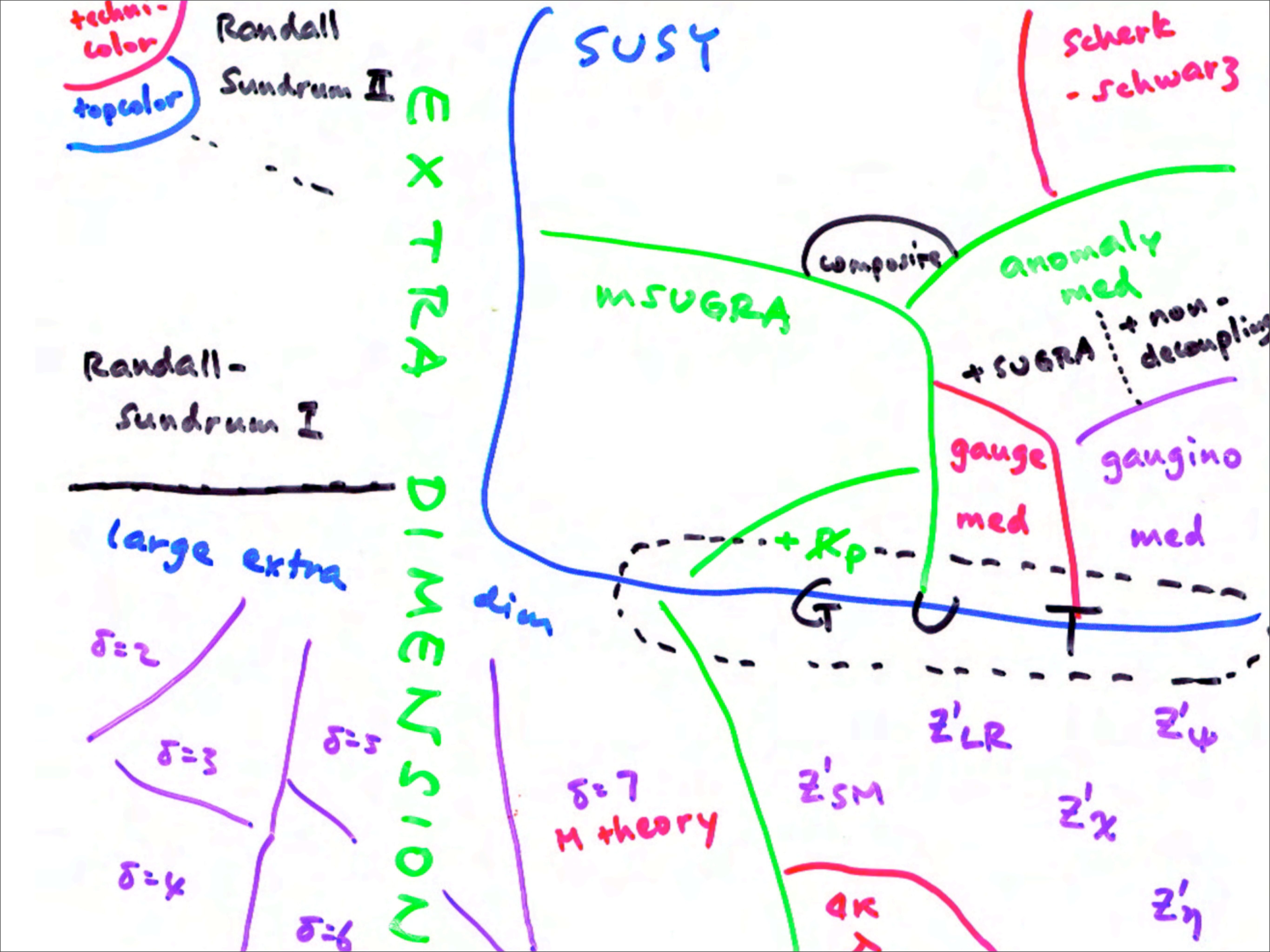
- Ultimate scale of physics: quantum gravity
- May have quantum gravity at TeV
  ⇒ hidden dimensions (0.1 mm to 10^{-17} cm)

IPMU

BERKELEY CENTER FOR THEORETICAL PHYSICS

More Directions

- Higgs boson as a Pseudo-Nambu-Goldstone boson (Little Higgs)
- Higgs boson as an extra-dimensional gauge boson (Gauge-Higgs Unification)
- Fat Higgs (Composite)
- Higgsless and $W^{\pm}$ as Kaluza-Klein boson
- technicolorful supersymmetry

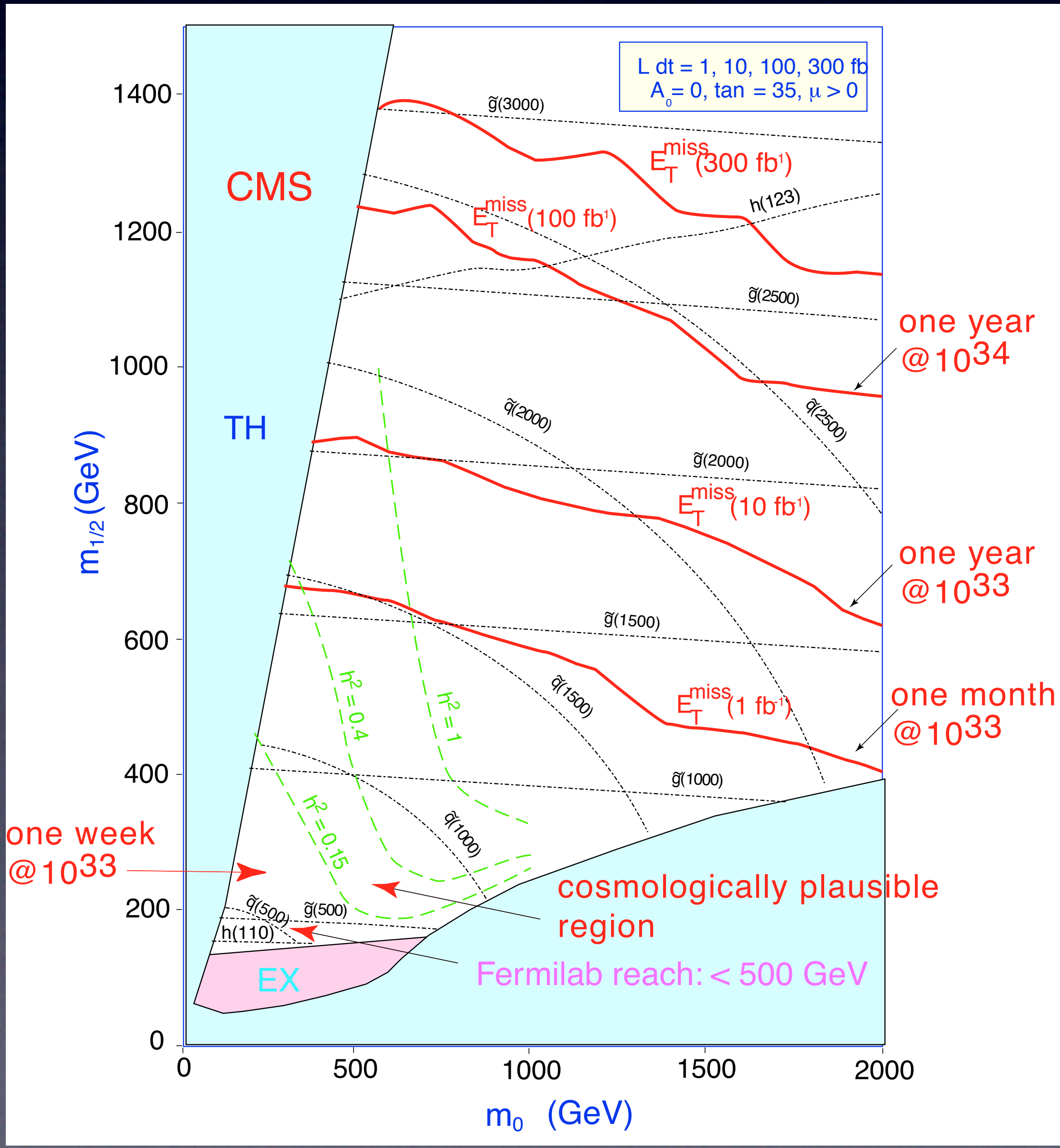


techni-color
topcolor
Randall Sundrum II
EXTRA DIMENSION
SUSY
Scherk-Schwarz
composite
mSUGRA
anomaly med
+SUGRA
+non-decoupling
Randall-Sundrum I
gauge med
gaugino med
large extra dim
+R_p
G U T
δ=2
δ=3
δ=5
δ=4
δ=6
δ=7
M theory
Z'$_{LR}$
Z'$_{\psi}$
Z'$_{SM}$
Z'$_{\chi}$
Z'$_{\eta}$
4K

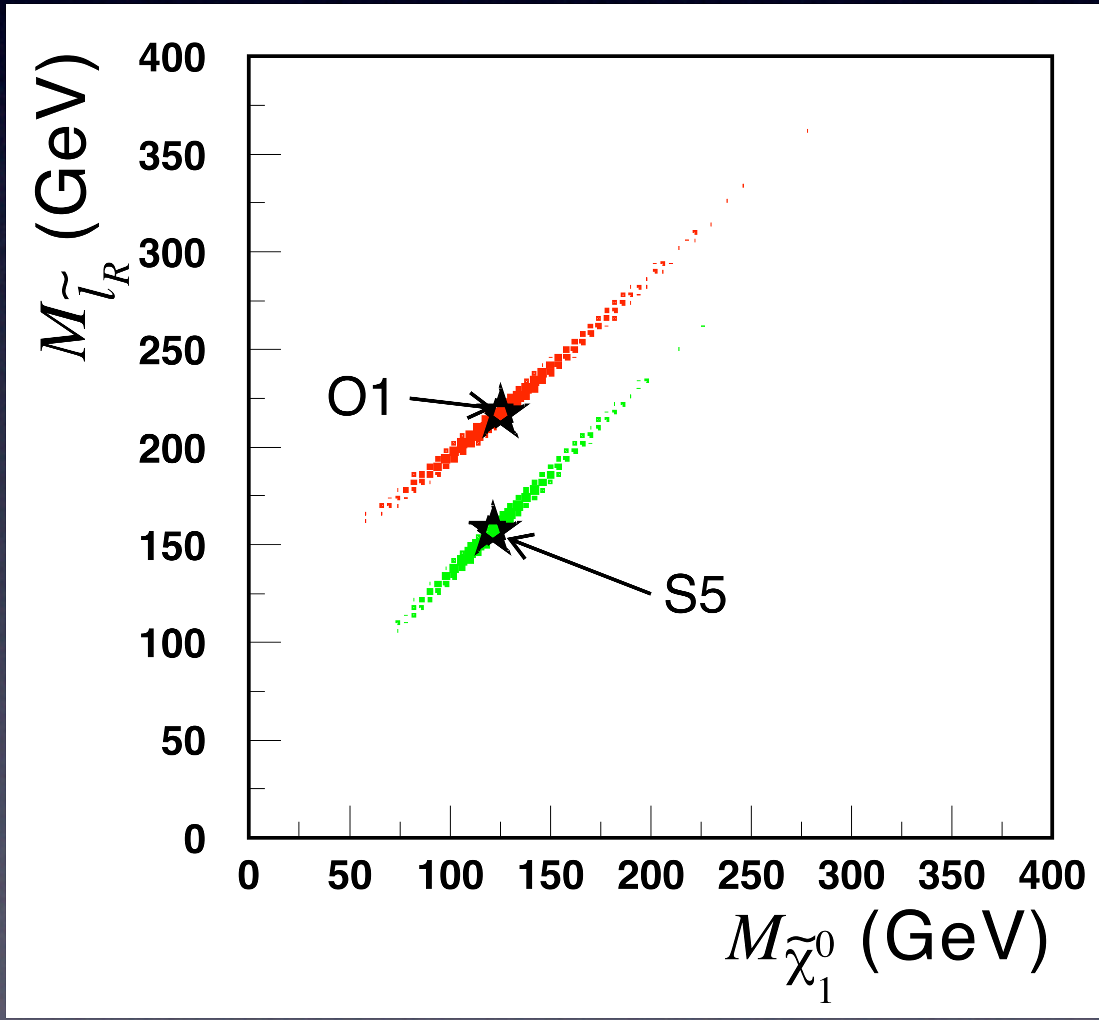
TC
bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
effective SUSY
SUSY
NNMSSM
NMSSM
MSSM +νR
ununified SM
axigluon
sterile ν
heavy Majorana ν
WR
X Y
6th gen
5th gen
4th gen
lepto quark
vector-like family
fractionally charged
milli-charged
mono-pole
S,T,U
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
Weinberg's 3HD
milli-weak
N=2
N=4
N=8
Majoron
axion
saxion
axino
familon
NGB
worm-hole
quintessence
k-ssence
composite W,Z
ℓ,q
contact int.
string
heterotic
matrix M
IIB
IIA
F
I
Extra dim

Supersymmetry

Tevatron/LHC will discover supersymmetry

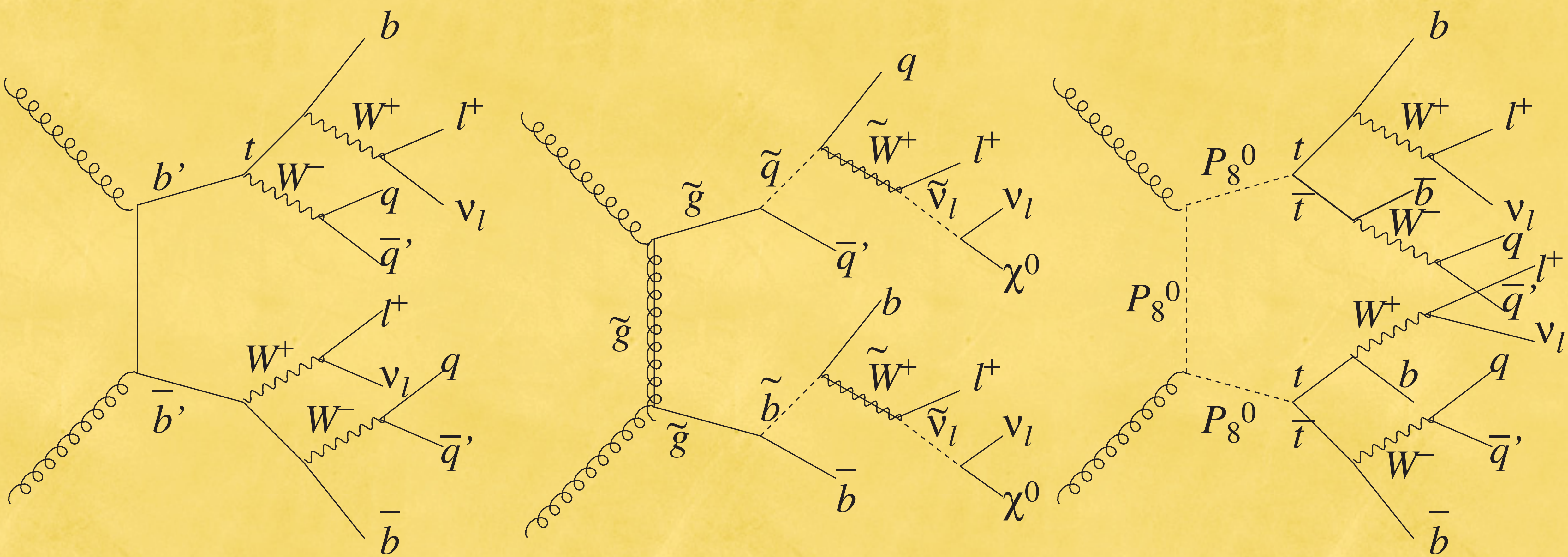


Can do many measurements at LHC



New physics looks alike

missing E_T, multiple jets, b-jets, (like-sign) di-leptons



4th generation　　　SUSY　　　technicolor

+Universal extra dimension, little Higgs with T-parity

Need absolute confidence for a major discovery

As an example, supersymmetry

"New-York Times level" confidence

The New York Times

July 23, 2009

The Other Half of the World Discovered

Geneva, Switzerland

As an example, supersymmetry

"New-York Times level" confidence

still a long way to

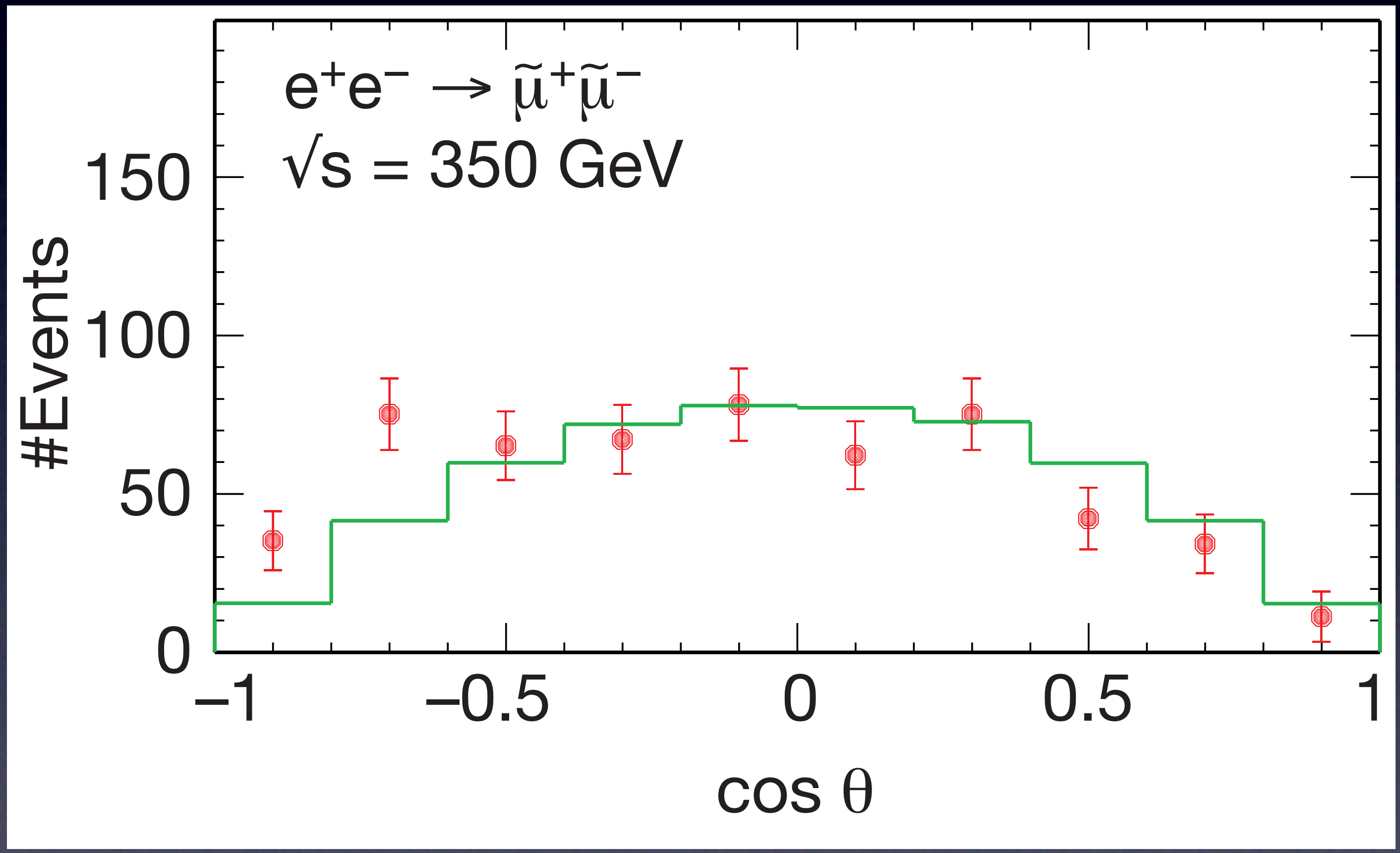
"Halliday-Resnick" level confidence

"We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances."

Prove Superpartners have different spin

Spin 0?

- *Discovery at Tevatron Run II and/or LHC*
- *Test they are really superpartners*
  - *Spins differ by 1/2*
  - *Same SU(3)×SU(2)×U(1) quantum numbers*
  - *Supersymmetric couplings*

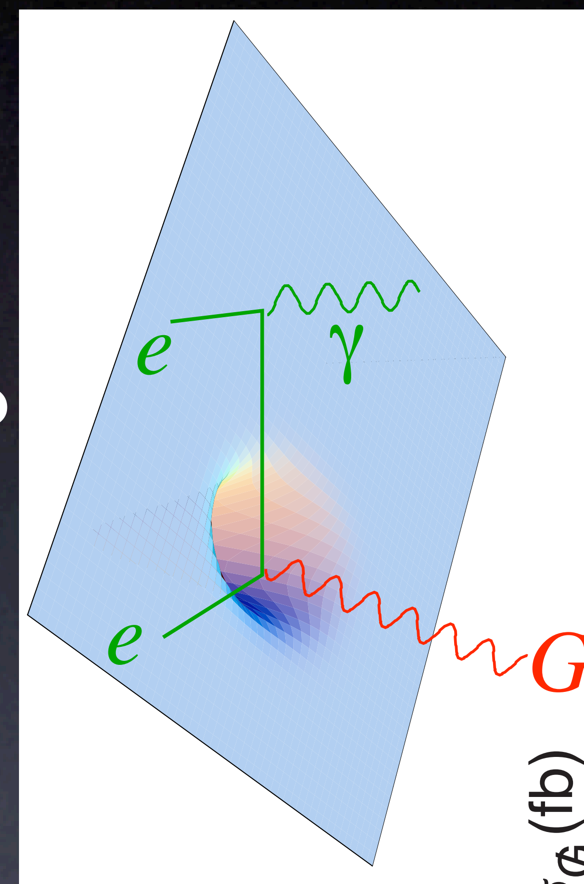


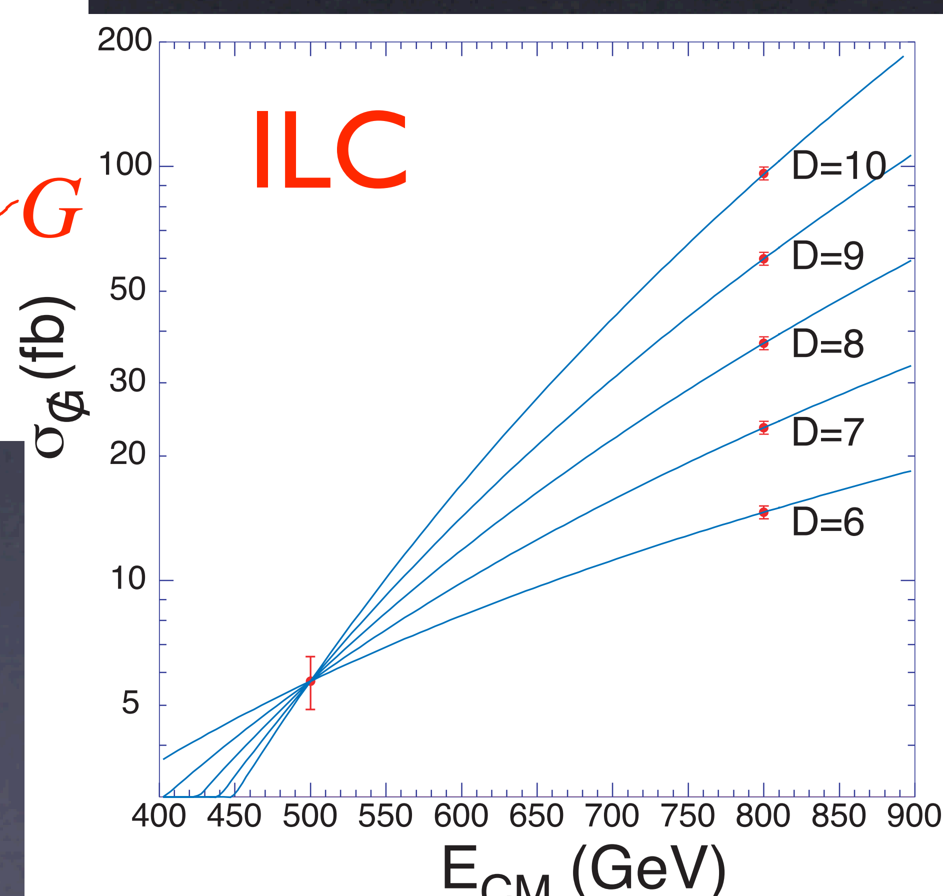
Tsukamoto, Fujii, HM, Yamaguchi, Okada

Hidden Dimensions

- Hidden dimensions
- Can emit graviton into the bulk
- Events with apparent energy imbalance

⇒ How many extra dimensions are there?



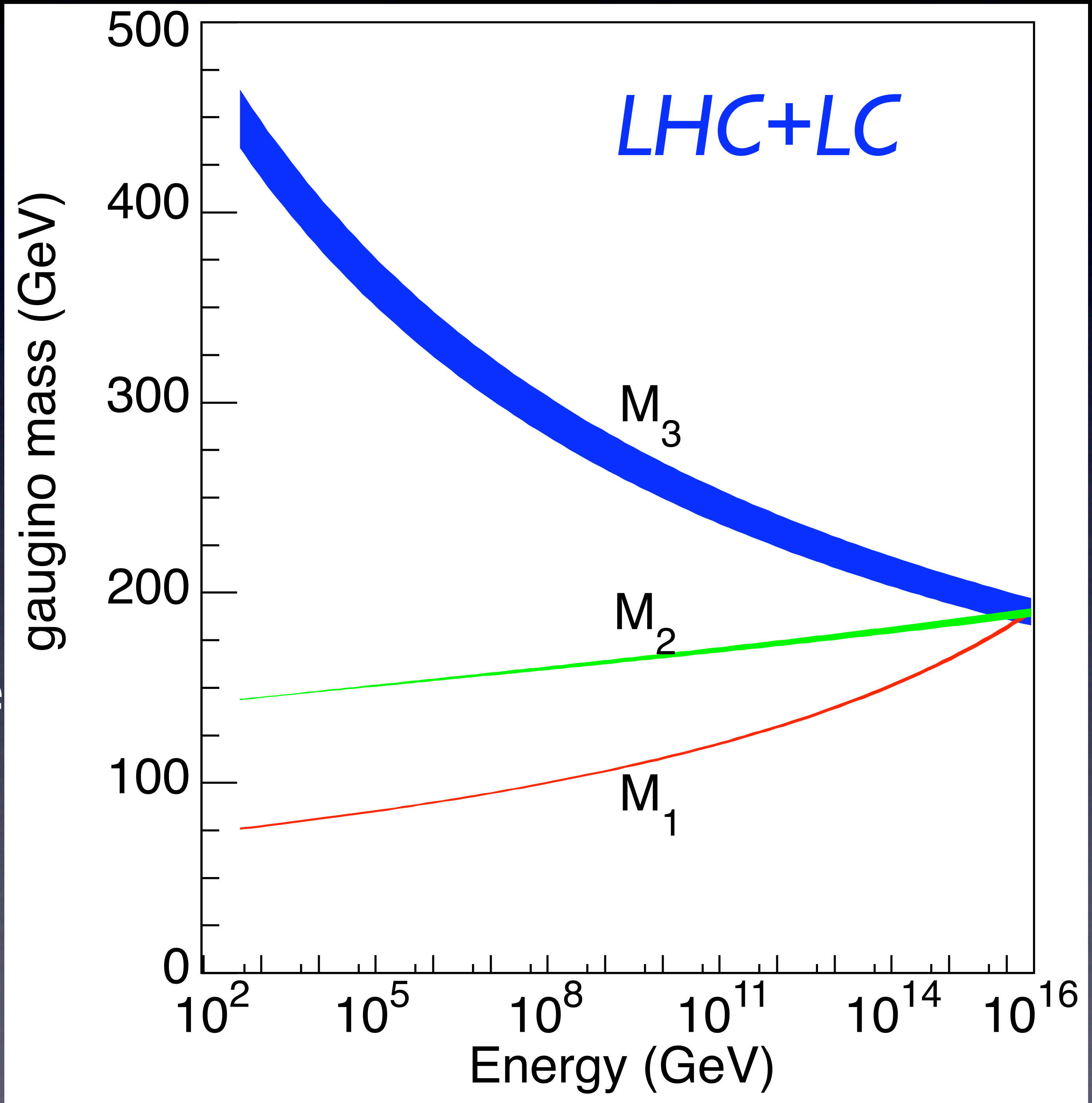


Superpartners as probe

- Most exciting thing about superpartners beyond existence:

They carry information of small-distance physics to something we can measure

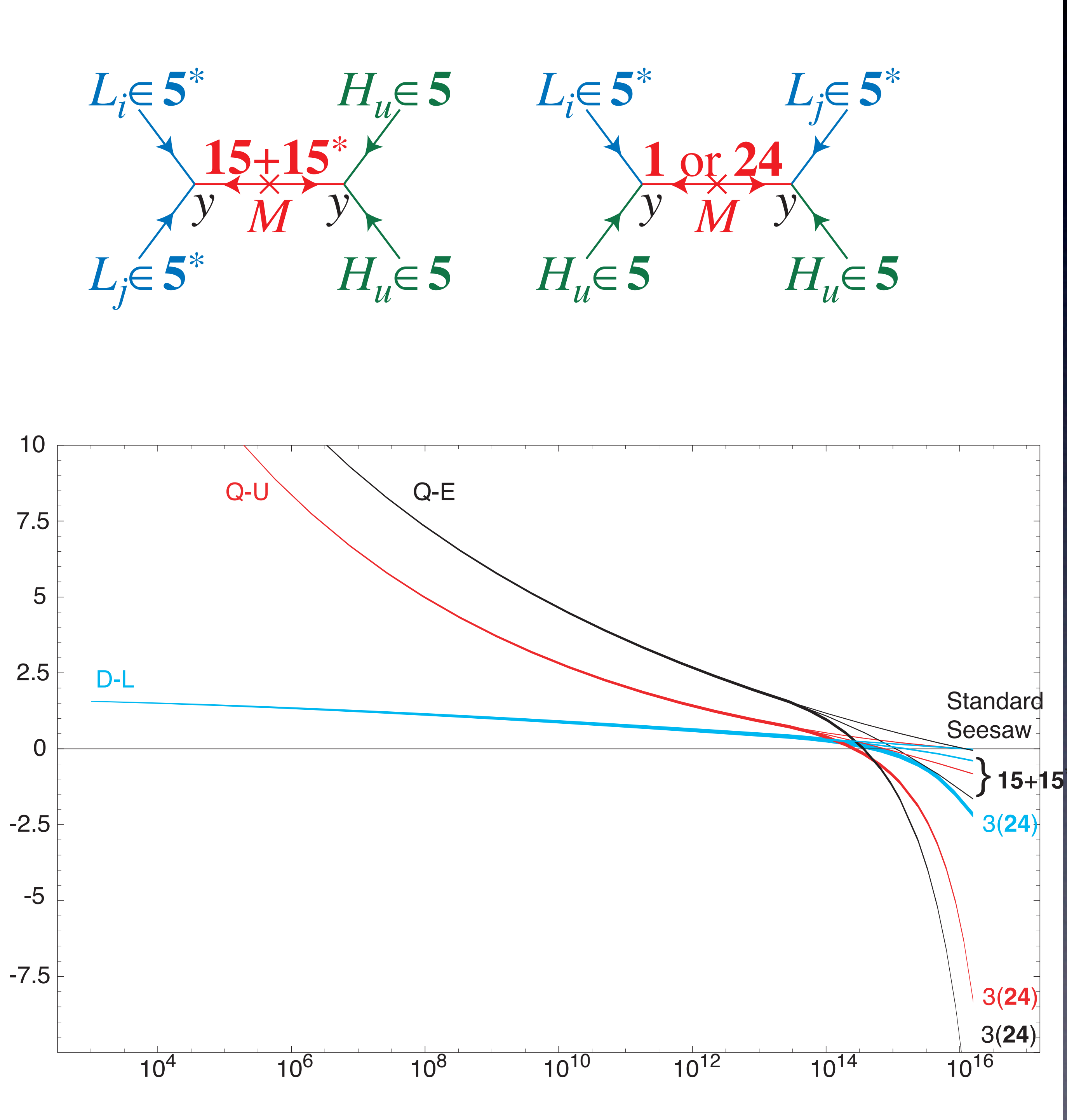
"Are forces unified?"



Why neutrino mass?

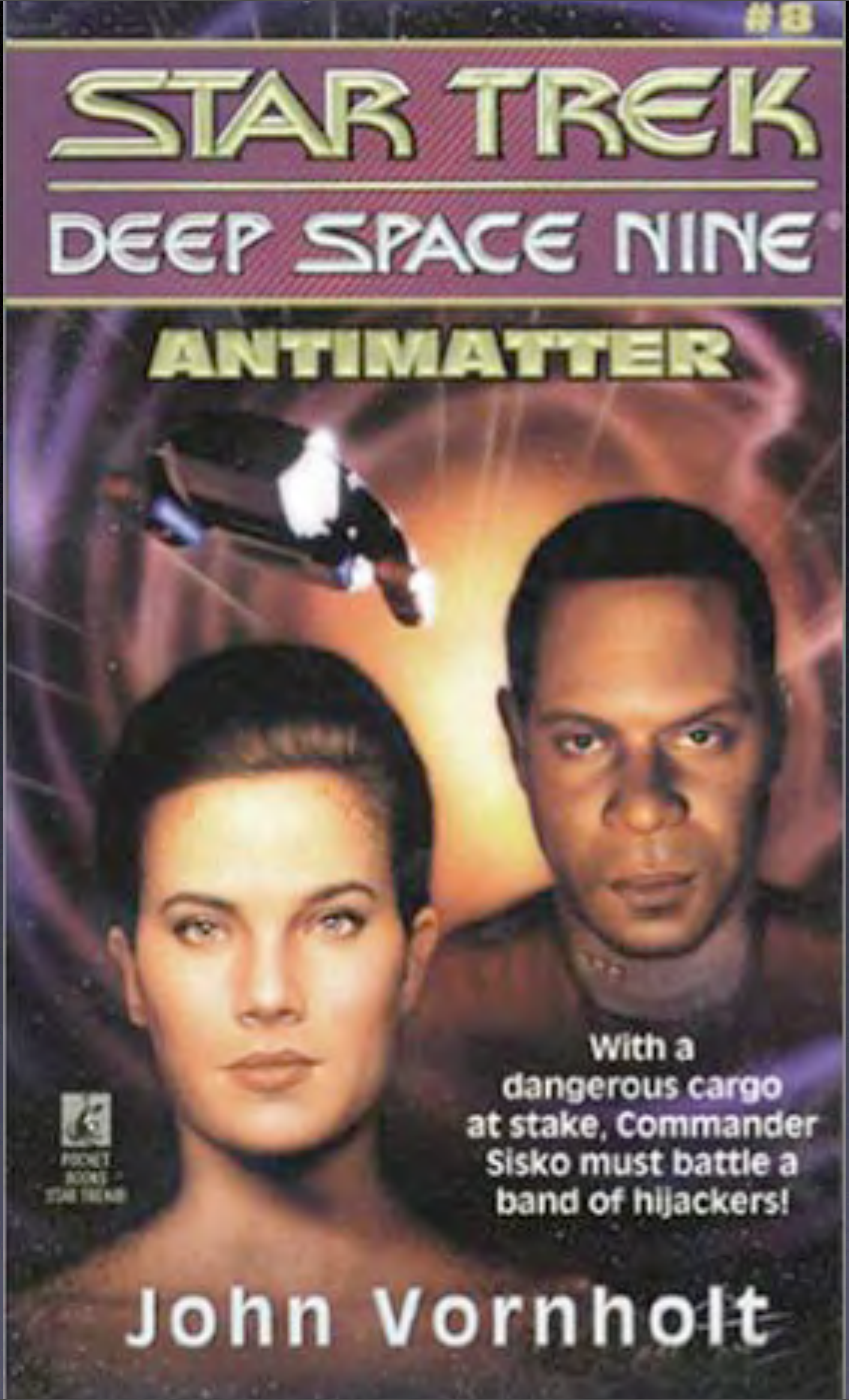
- Neutrino mass likely comes from physics at $>10^{10}$ GeV
- How will we ever know?
- Precision measurements at LHC/ILC determine boundary conditions at 10^{16} GeV
- With both ends fixed, we can constrain physics in between

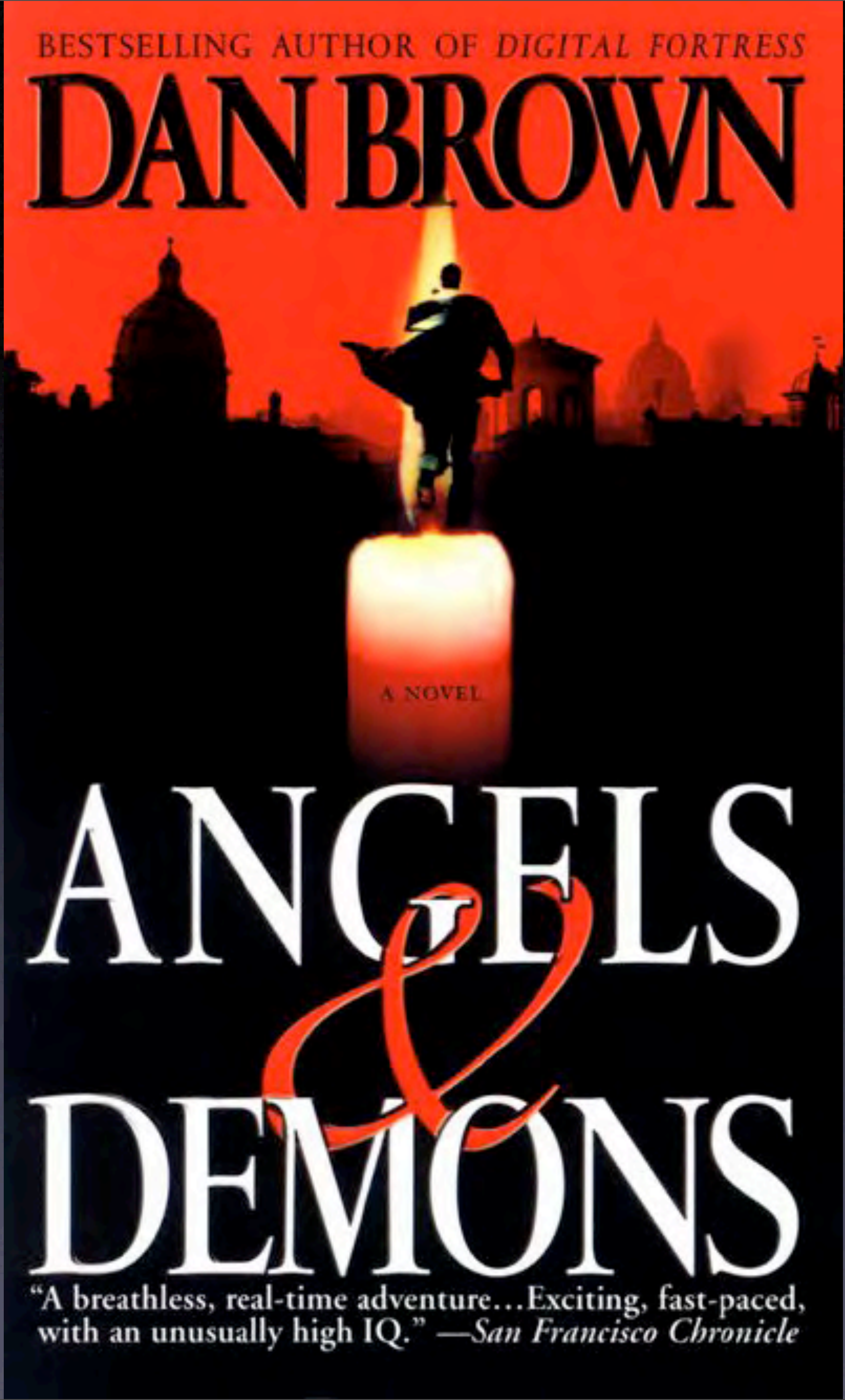
Buckley, HM



Anti-Matter

1955
anti-proton
in Berkeley


#8
STAR TREK
DEEP SPACE NINE
ANTIMATTER
With a dangerous cargo at stake, Commander Sisko must battle a band of hijackers!
John Vornholt


BESTSELLING AUTHOR OF DIGITAL FORTRESS
DAN BROWN
A NOVEL
ANGELS & DEMONS
"A breathless, real-time adventure…Exciting, fast-paced, with an unusually high IQ." —San Francisco Chronicle

Matter and Anti-Matter Early Universe

matter	anti-matter
1,000,000,001	1,000,000,000

Matter and Anti-Matter Current Universe

1

us

matter *anti-matter*

The Great Annihilation

Baryogenesis

- What created this tiny excess matter?
- *Necessary* conditions for baryogenesis (Sakharov):
  - Baryon number non-conservation
  - CP violation

    (subtle difference between matter and anti-matter)
  - Non-equilibrium

  $\Rightarrow \Gamma(\Delta B>0) > \Gamma(\Delta B<0)$
- It looks like it is the matter of quarks...

CP Violation

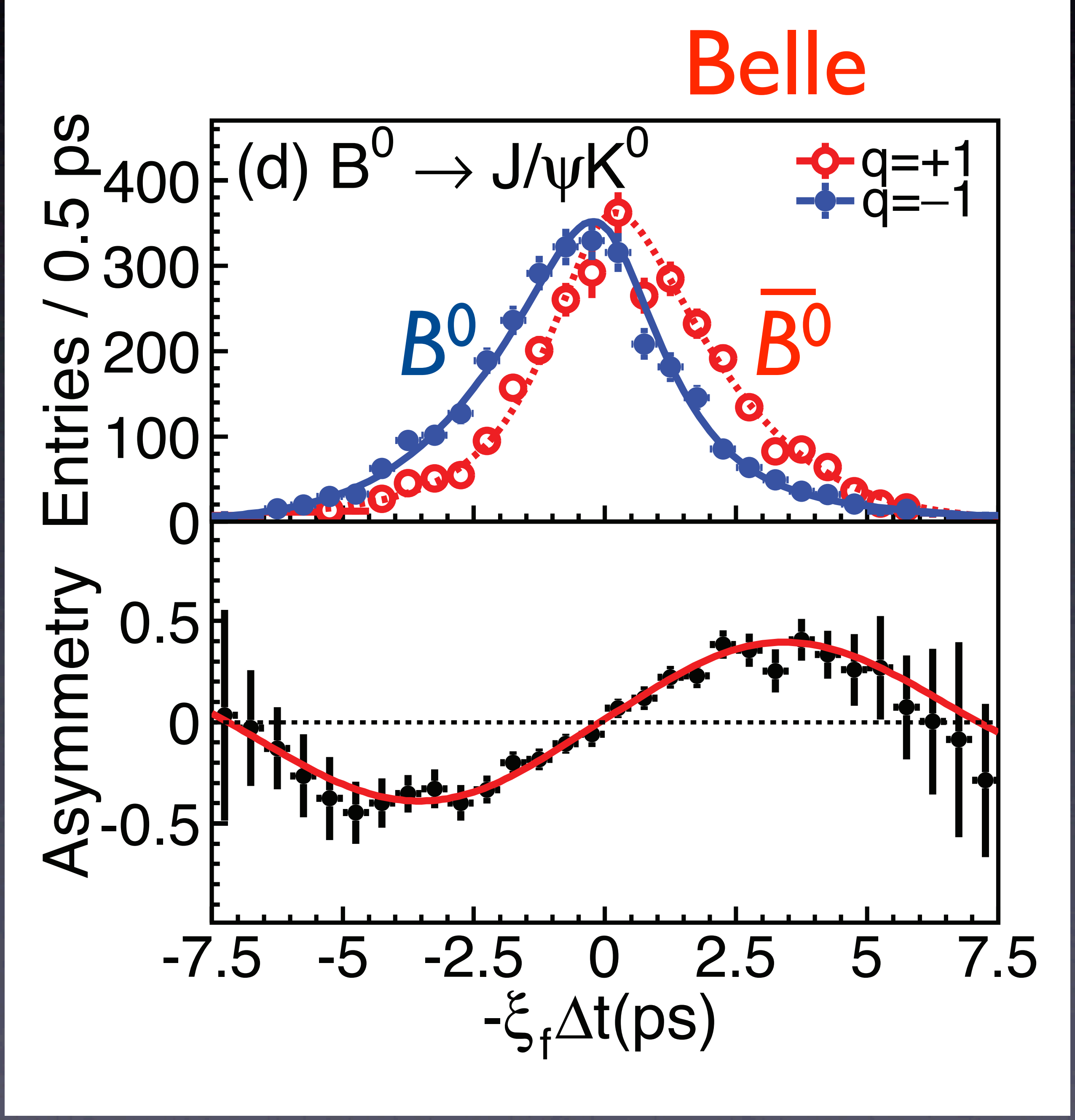
- Is anti-matter the exact mirror of matter?

1964 discovery of CP violation

- But only one system, hard to tell what is going on.

2001, 2002 Two new CP-violating phenomena

- But no CP violation observed so far is not large enough to explain the absence of anti-matter



Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass

$$\begin{pmatrix}\nu_L & \nu_R\end{pmatrix}\begin{pmatrix} & m_D \\ m_D & \end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R\end{pmatrix}$$

Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, but ν_R SM neutral

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

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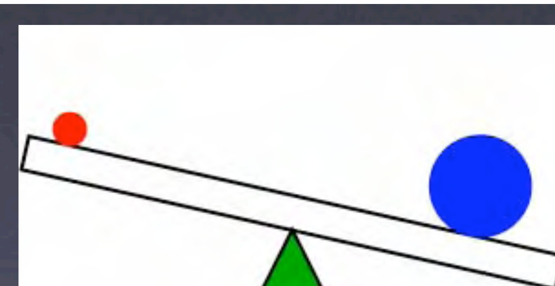

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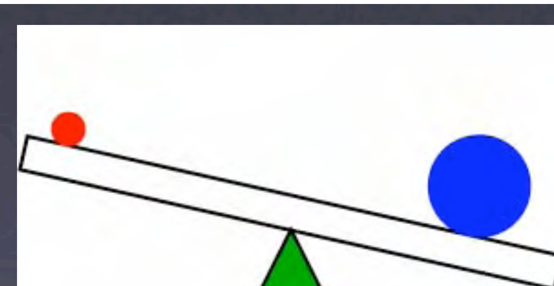
$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad m_\nu = \frac{m_D^2}{M} << m_D$$



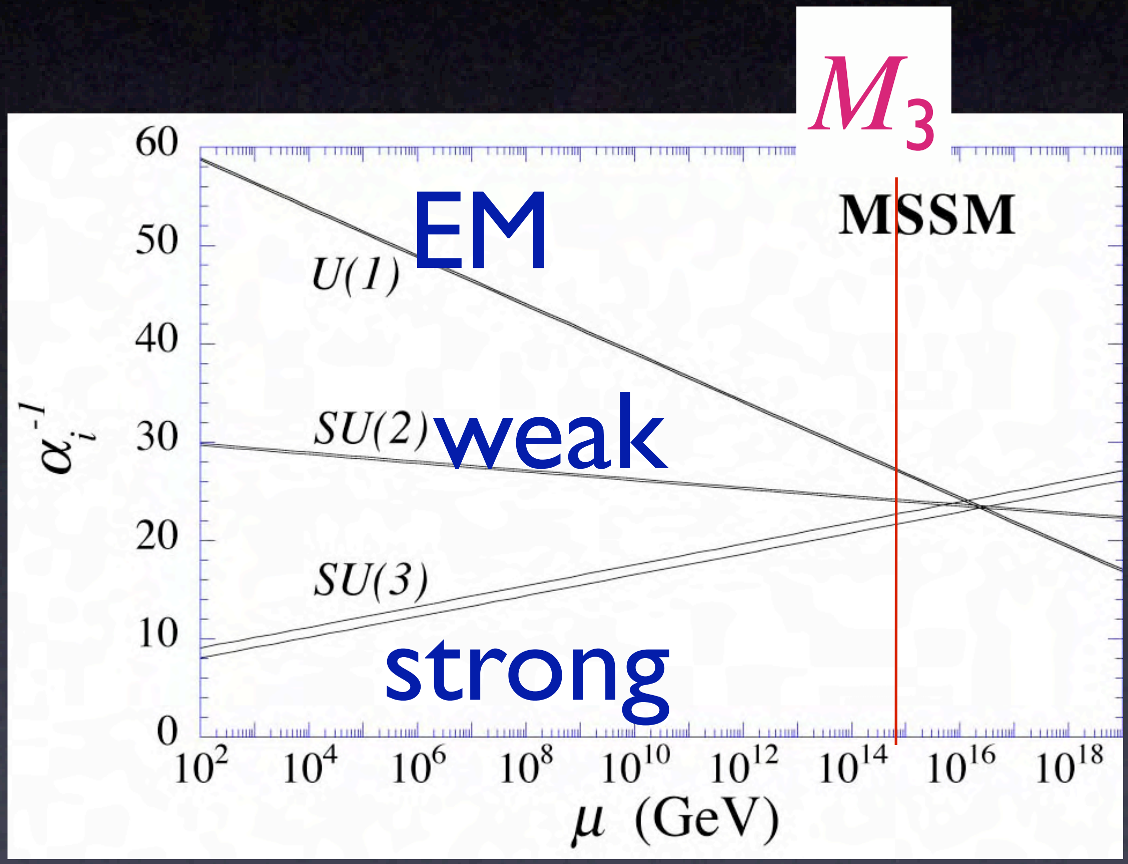
To obtain $m_3 \sim (\Delta m^2{}_{\mathrm{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)

Grand Unification

- electromagnetic, weak, and strong forces have very different strengths
- But their strengths become *the same* at 10^{16} GeV if supersymmetry
- To obtain

$m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}$, $m_D \sim m_t$

$\Rightarrow M_3 \sim 10^{15}$GeV!

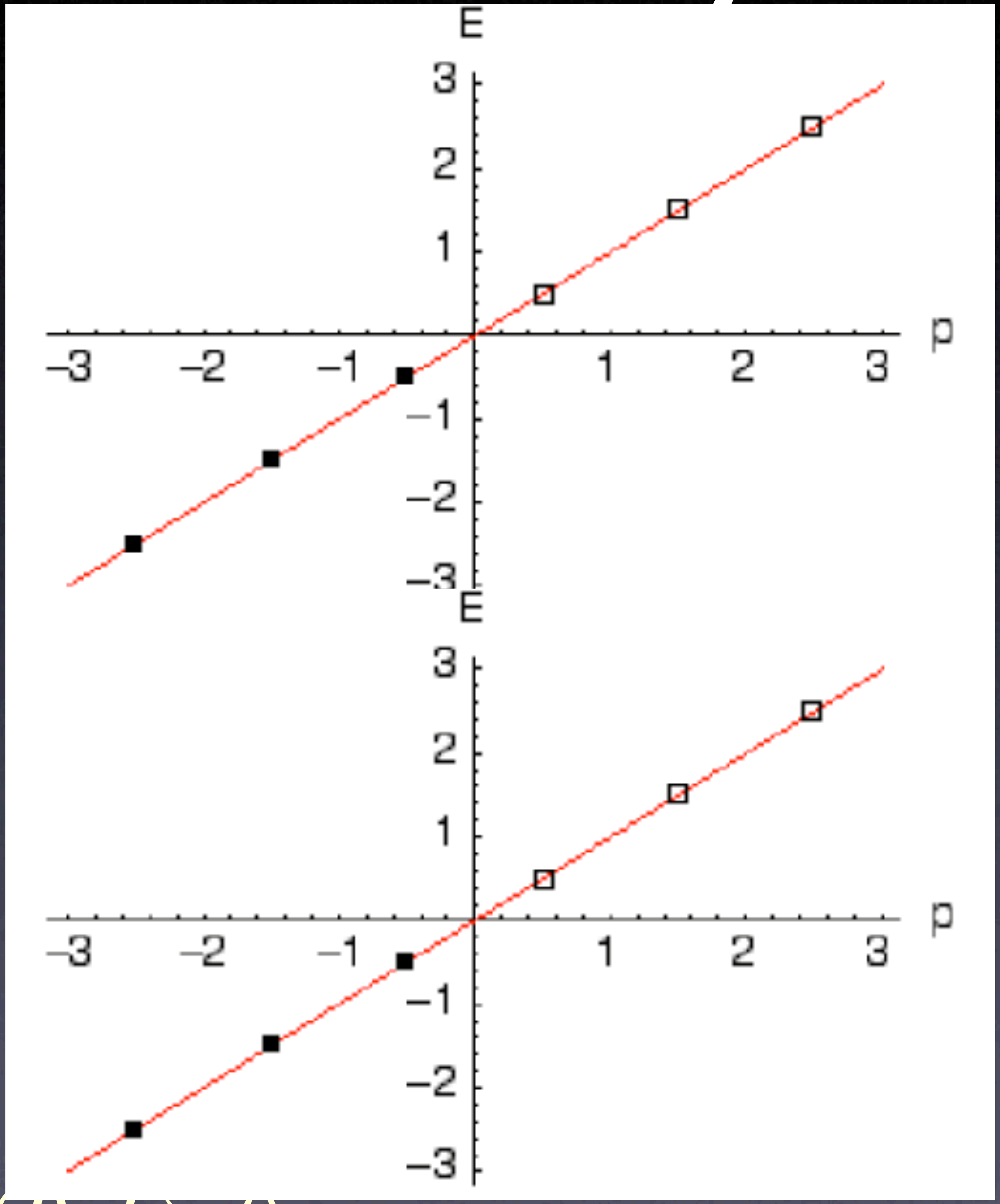


Neutrino mass may be probing unification:

Einstein's dream

Electroweak Anomaly

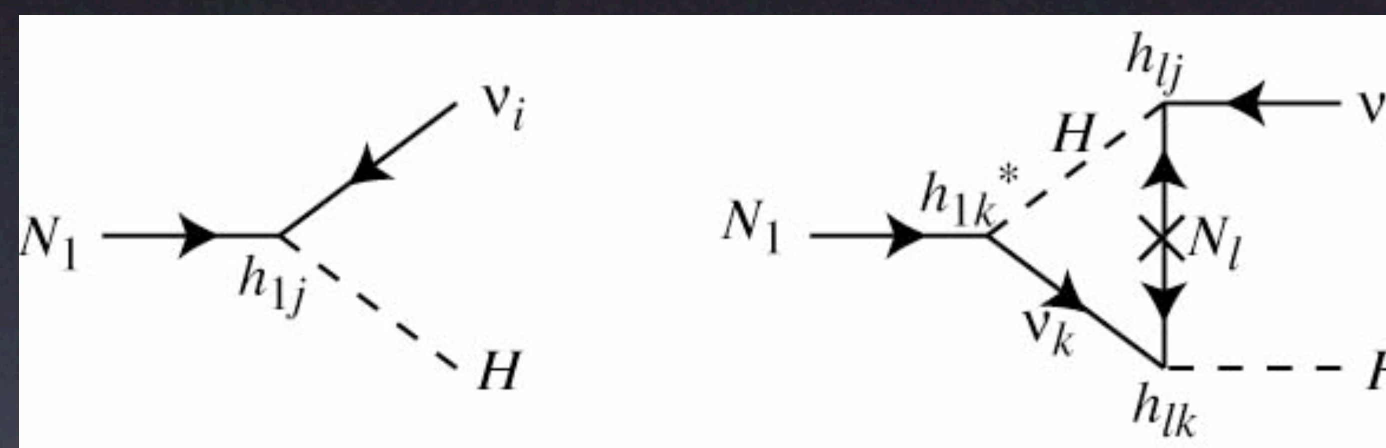
- Actually, SM converts L (ν) to B (quarks).
  - In Early Universe (T > 200GeV), W is massless and fluctuate in W *plasma*
  - Energy levels for left-handed quarks/leptons fluctuate correspon-dingly



$$\Delta L = \Delta Q = \Delta Q = \Delta Q = \Delta B = 1 \Rightarrow \Delta(B-L) = 0$$

Leptogenesis

- You generate *Lepton Asymmetry* first.
- Generate L from the direct CP violation in right-handed neutrino decay



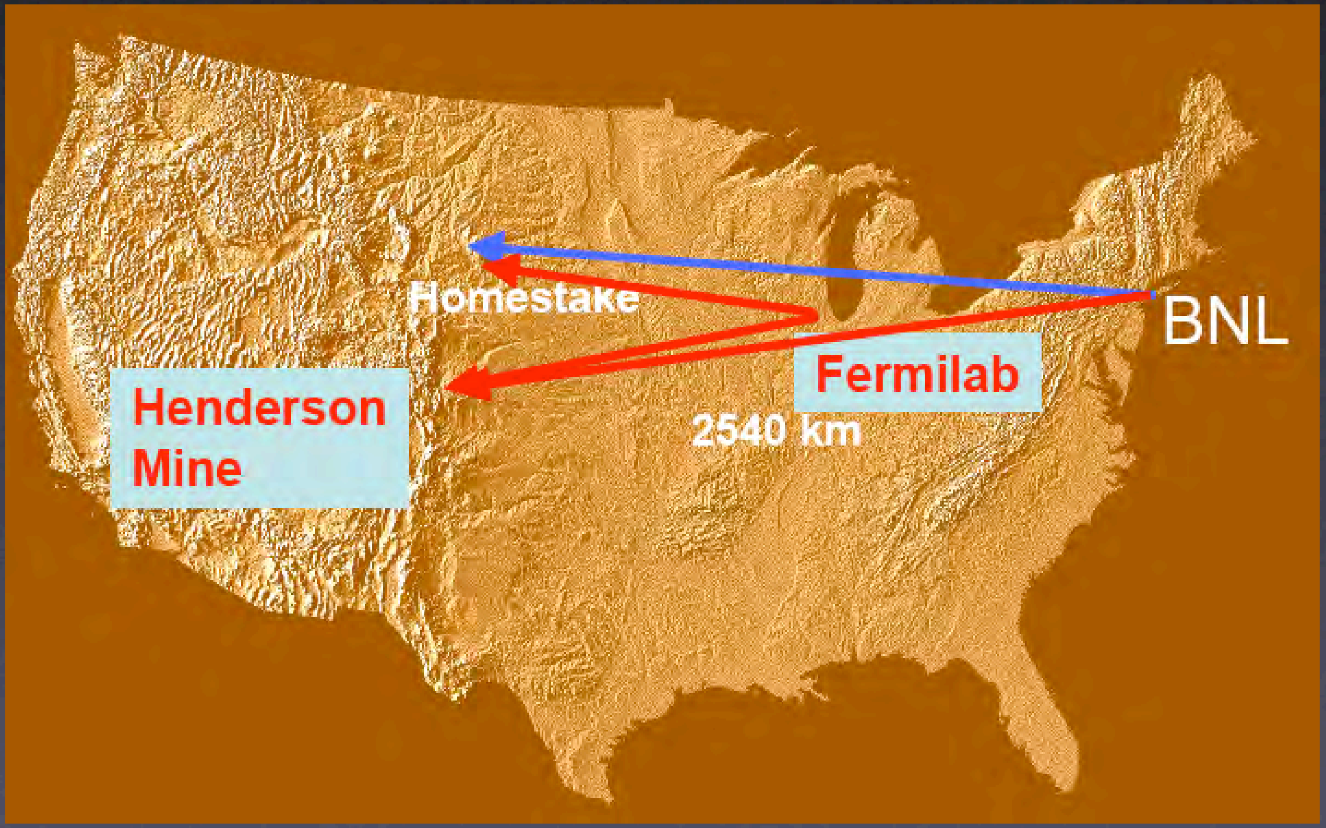
$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H) \propto \mathrm{Im}(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$

- L gets converted to B via EW anomaly
  $\Rightarrow$ More matter than anti-matter
  $\Rightarrow$ *We have survived "The Great Annihilation"*

Leptogenesis

- Neutrinos have mass (1998-2002)
- Neutrinos may be their own anti-particles
- They can transform matter to anti-matter and vice versa
- Maybe they are responsible for our existence!

Shoot the beams over thousands of kilometers to see CP violation in neutrinos



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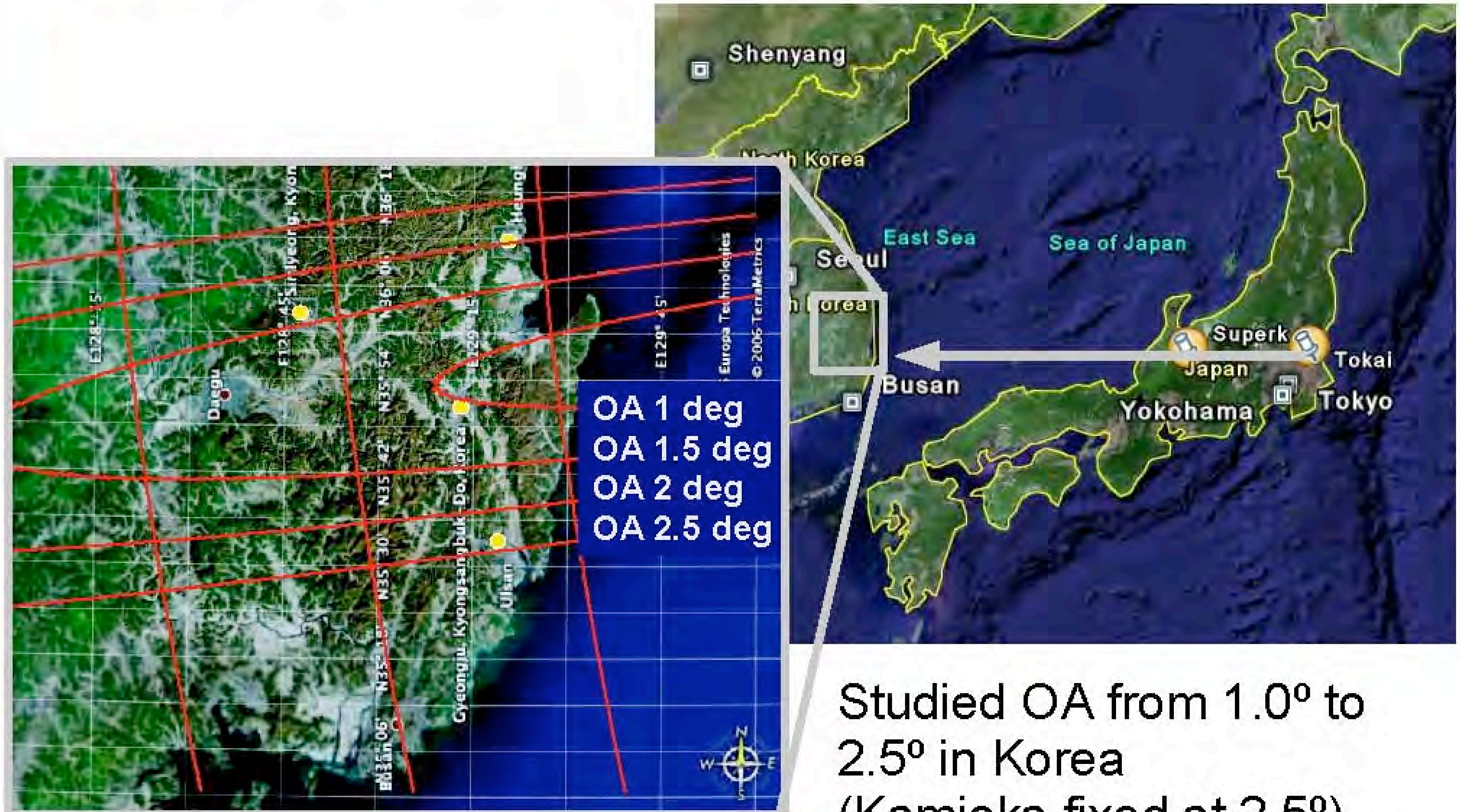
CAL PHYSICS

T2KK (T2K to Korea)

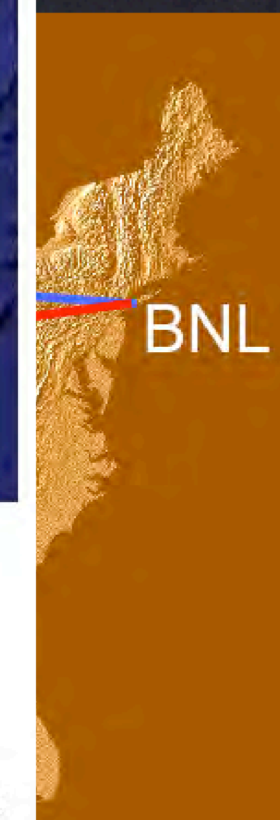
Detecting neutrinos from T2K in Korea → T2KK



Studied OA from 1.0º to 2.5º in Korea (Kamioka fixed at 2.5º)

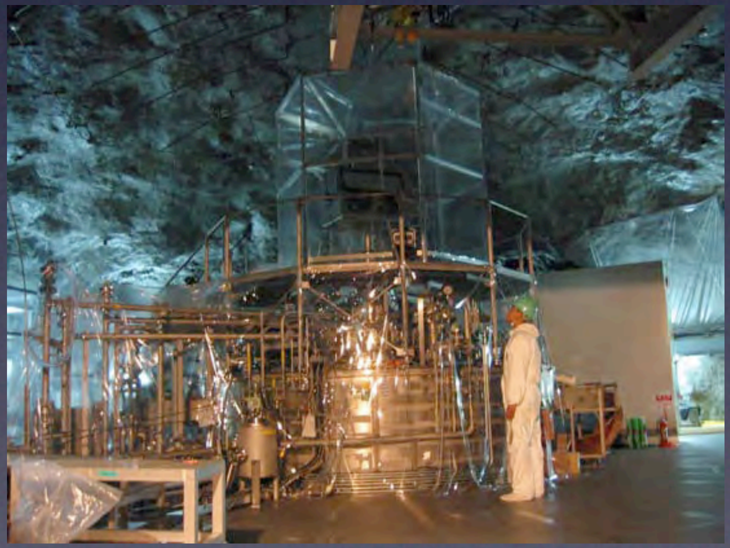
09/16/06 Fanny Dufour, Boston University 6/32

r
o see
os

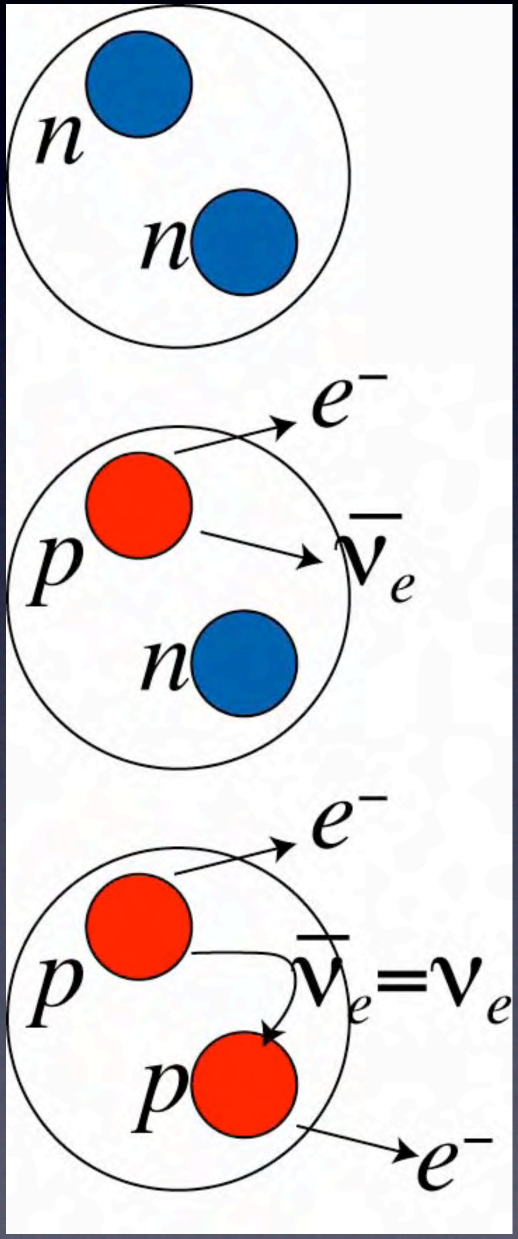


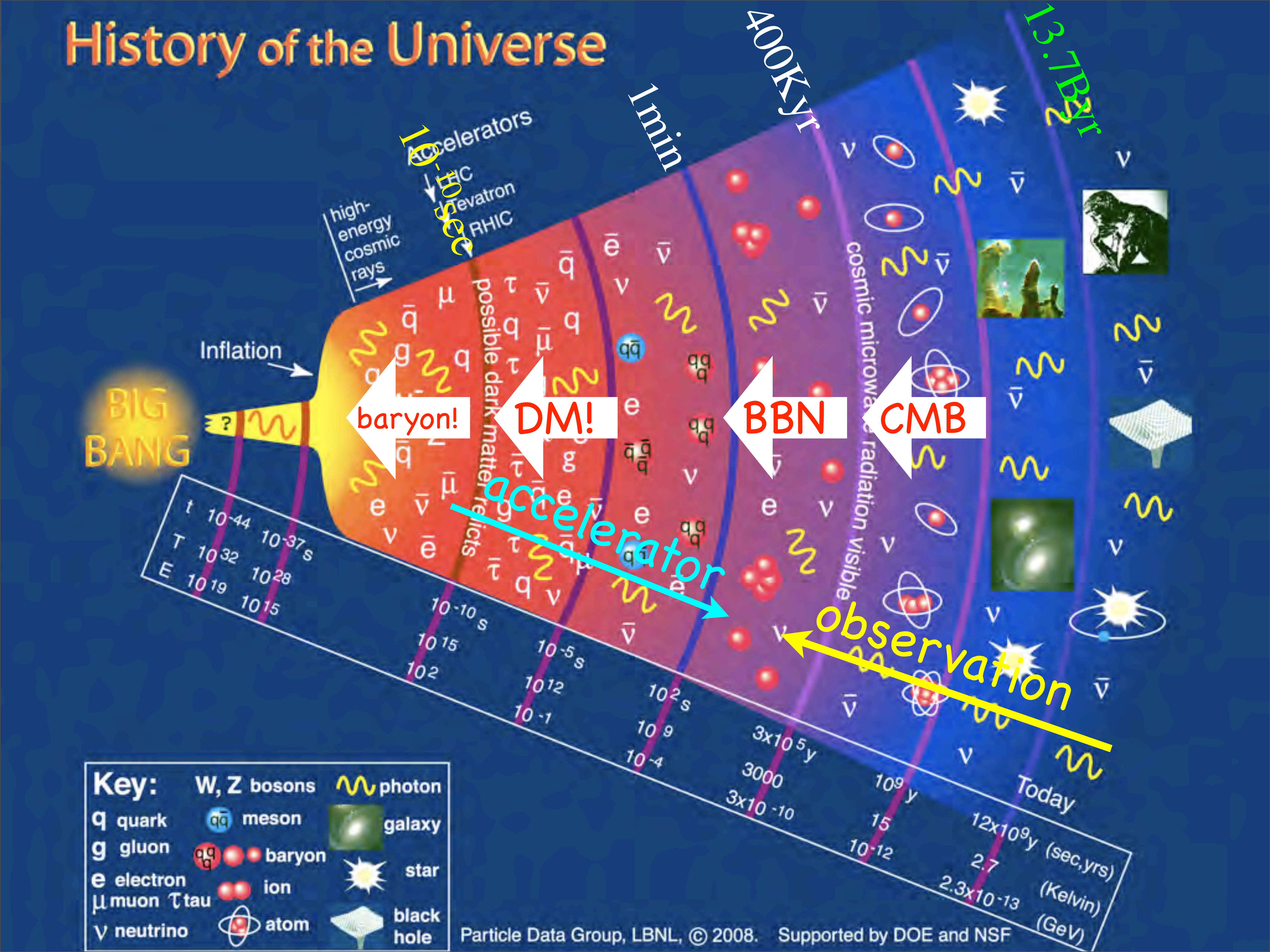
neutrinoless double beta decay

- seesaw mechanism implies Majorana neutrinos
- lepton number is violated
- look for neutrinoless double beta decay
- e.g. dissolve Xe into KamLAND



Sasha Kozlov

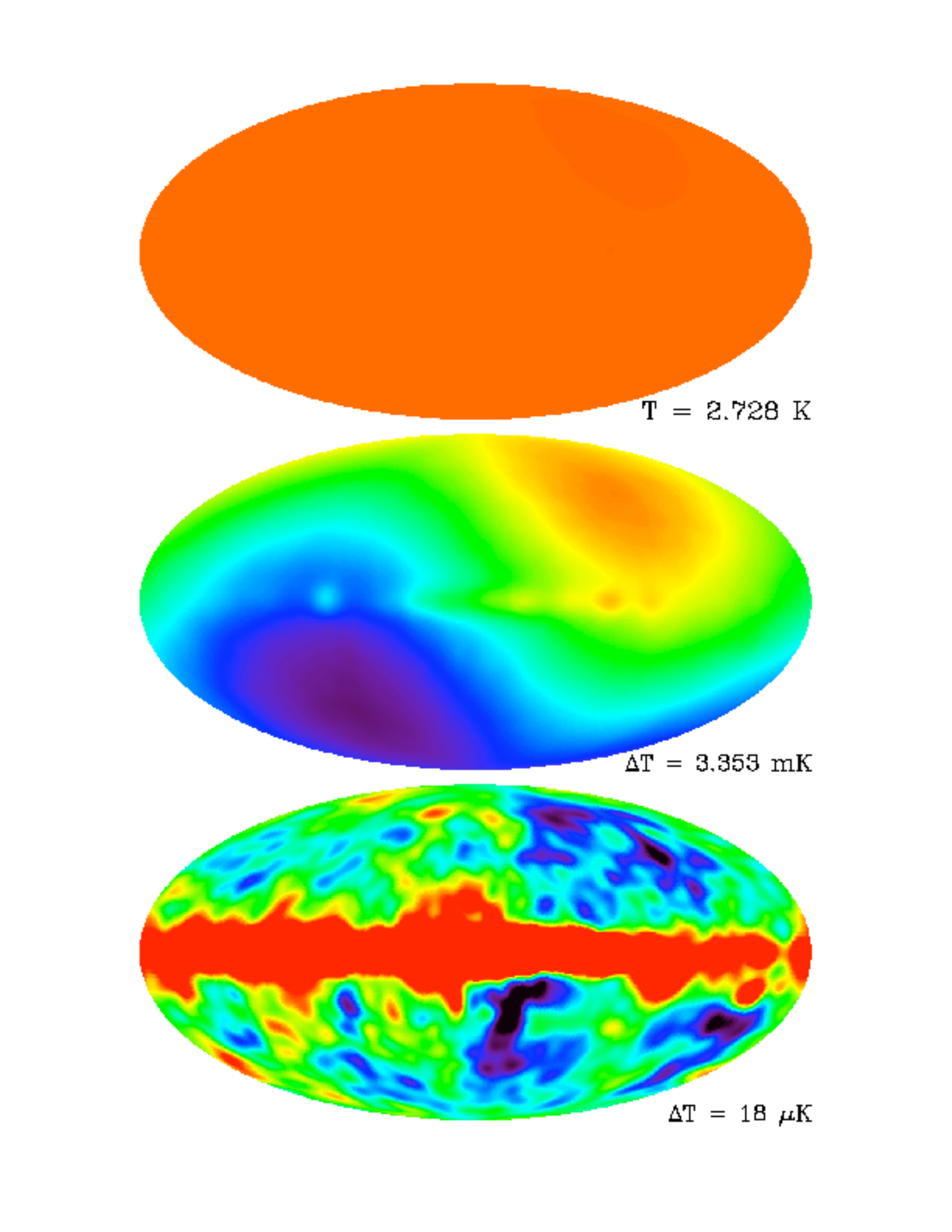




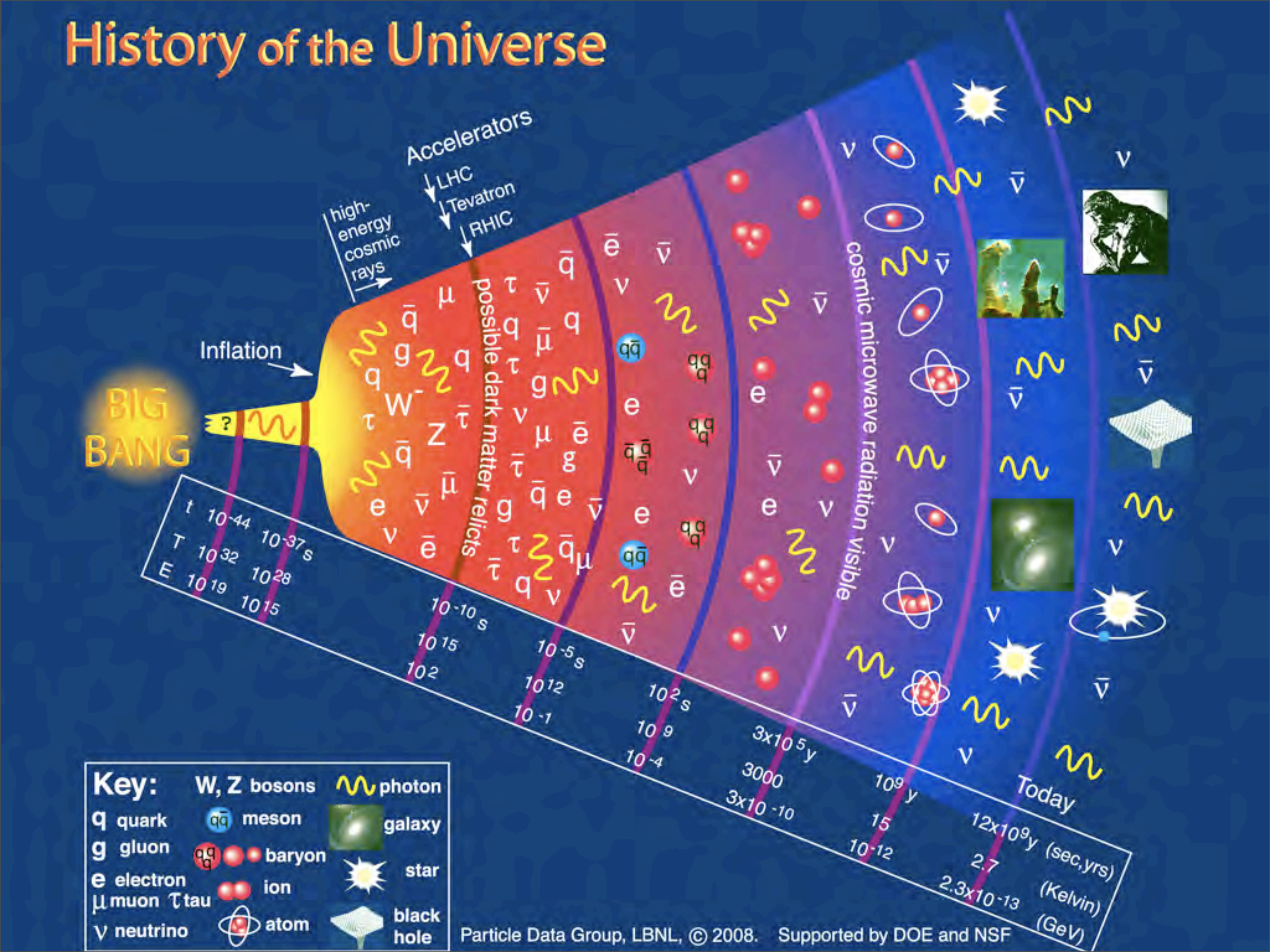
History of the Universe
13.7Byr
400Kyr
1min
10-10sec
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
baryon!
DM!
BBN
CMB
accelerator
observation
t 10-44 10-37 s 10-10 s 10-5 s 102 s 3x105 y 109 y 12x109 y (sec,yrs)
T 1032 1028 1015 1012 109 3000 15 2.7 (Kelvin)
E 1019 1015 102 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Today
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Inflation

Why do they all look the same?

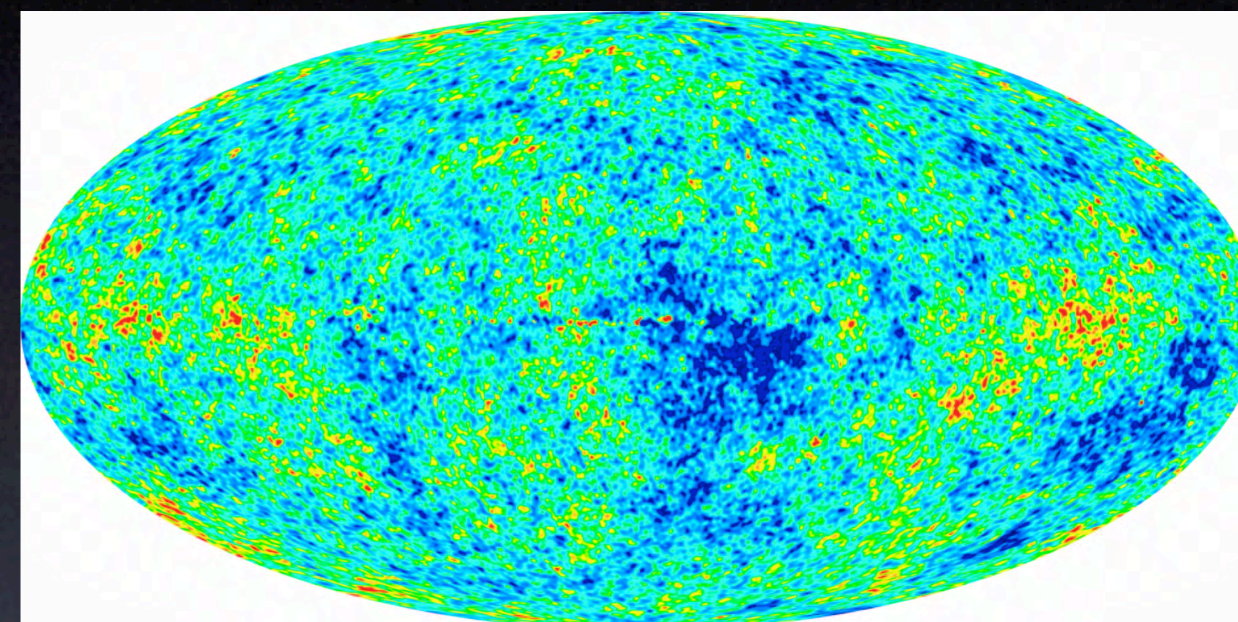


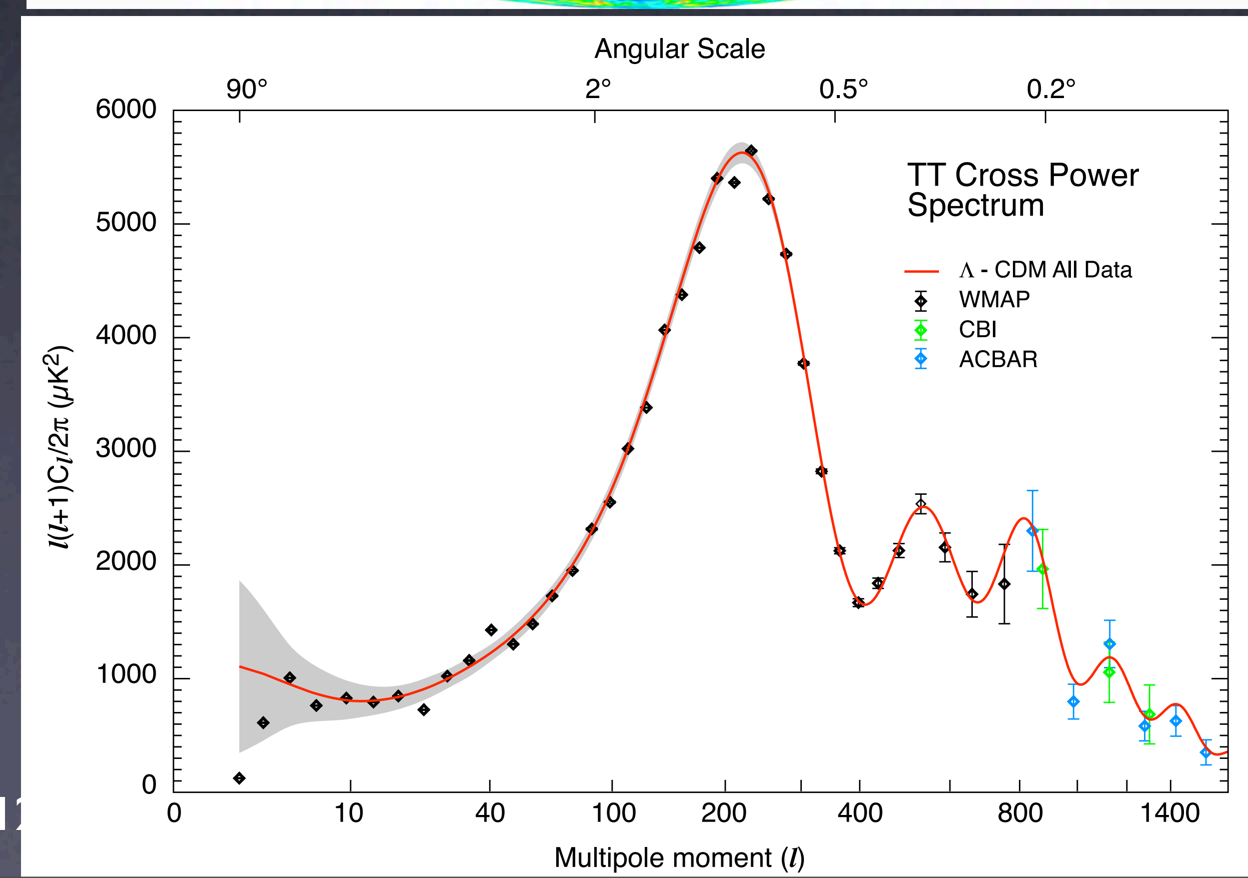
- Like having discovered two remote islands in very different parts of the world, speaking the same language
- even the accents are nearly the same: one part in 100,000
- we suspect they had communication


History of the Universe
BIG BANG
?
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10-10 s
10 15
10 2
10-5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
star
μ muon τ tau
ion
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Seeds for structure

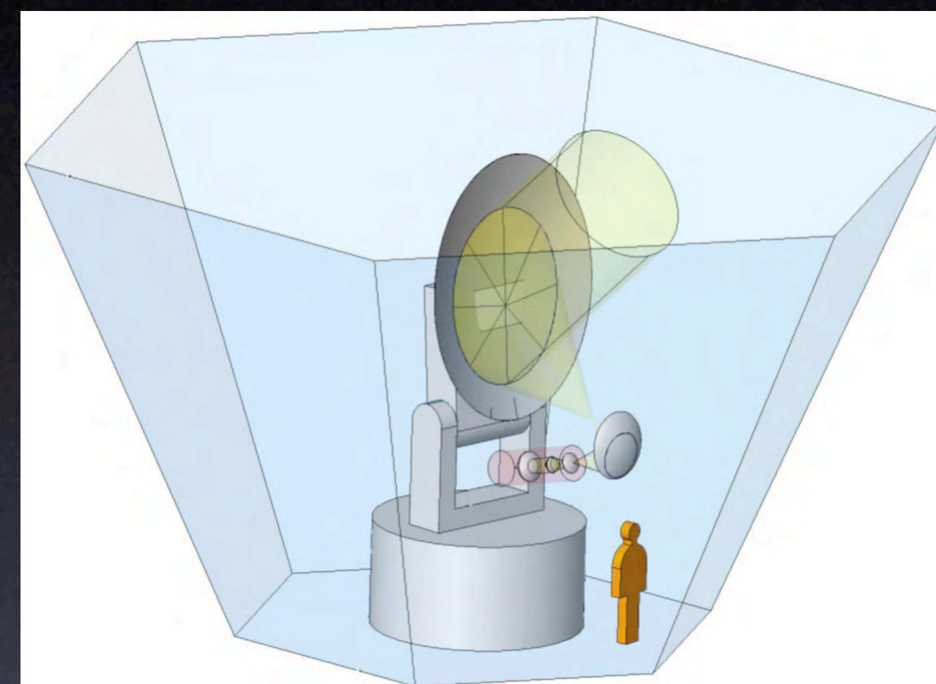
- Cosmic Inflation stretched the new-born microscopic space to our entire visible universe
- Observed density fluctuation is due to quantum fluctuation of inflaton
- E-mode polarization consistent with this picture

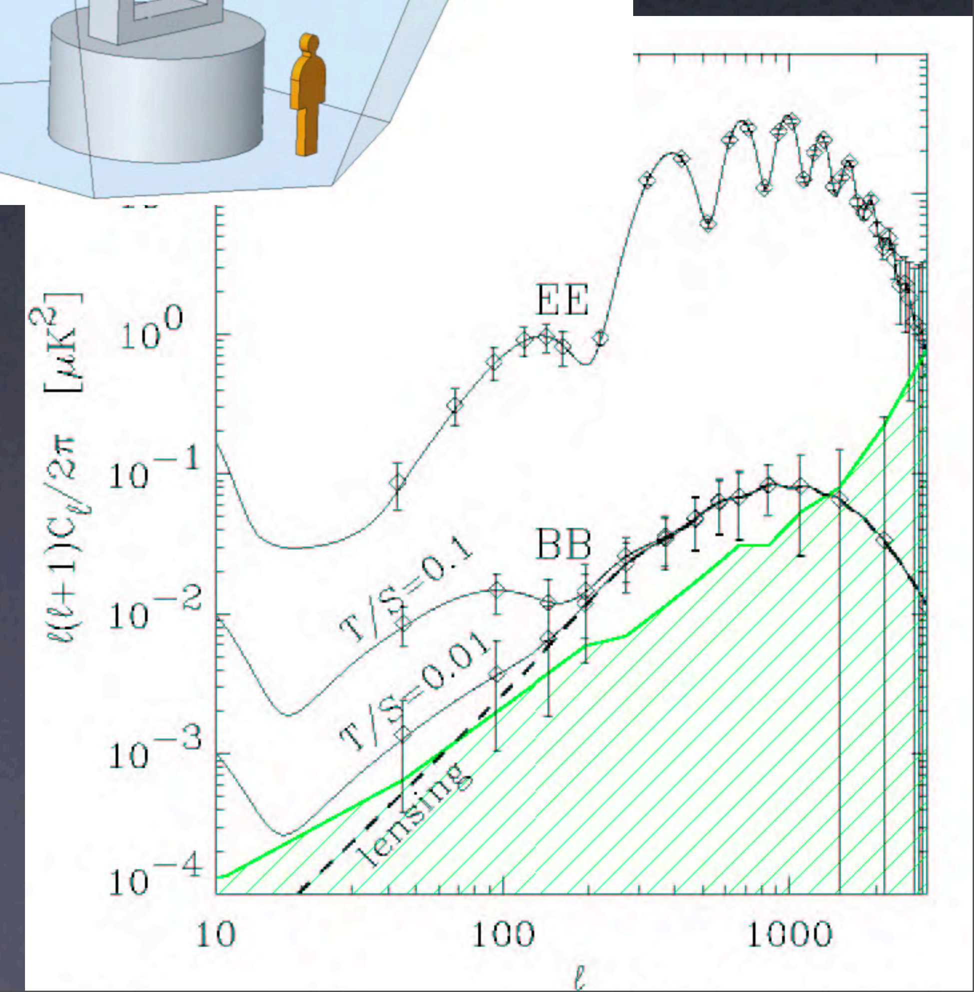




How do we know it really happened?

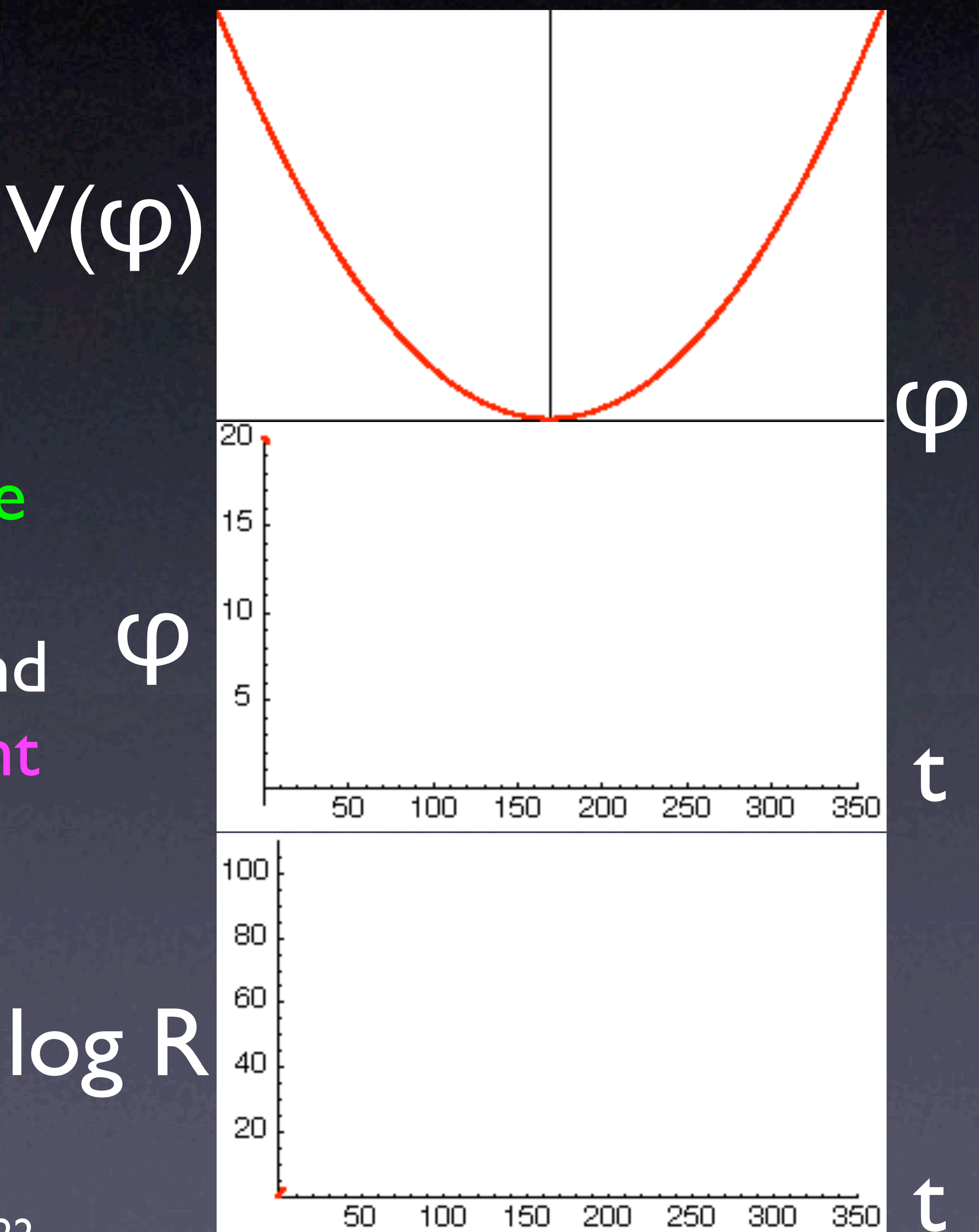
- everything gets quantum fluctuation, including gravitons
- Gravitons from quantum fluctuation gives B-mode polarization in CMB
- The size is directly proportional to the inflationary energy scale
  ⇒e.g., POLARBEAR





Putting them together

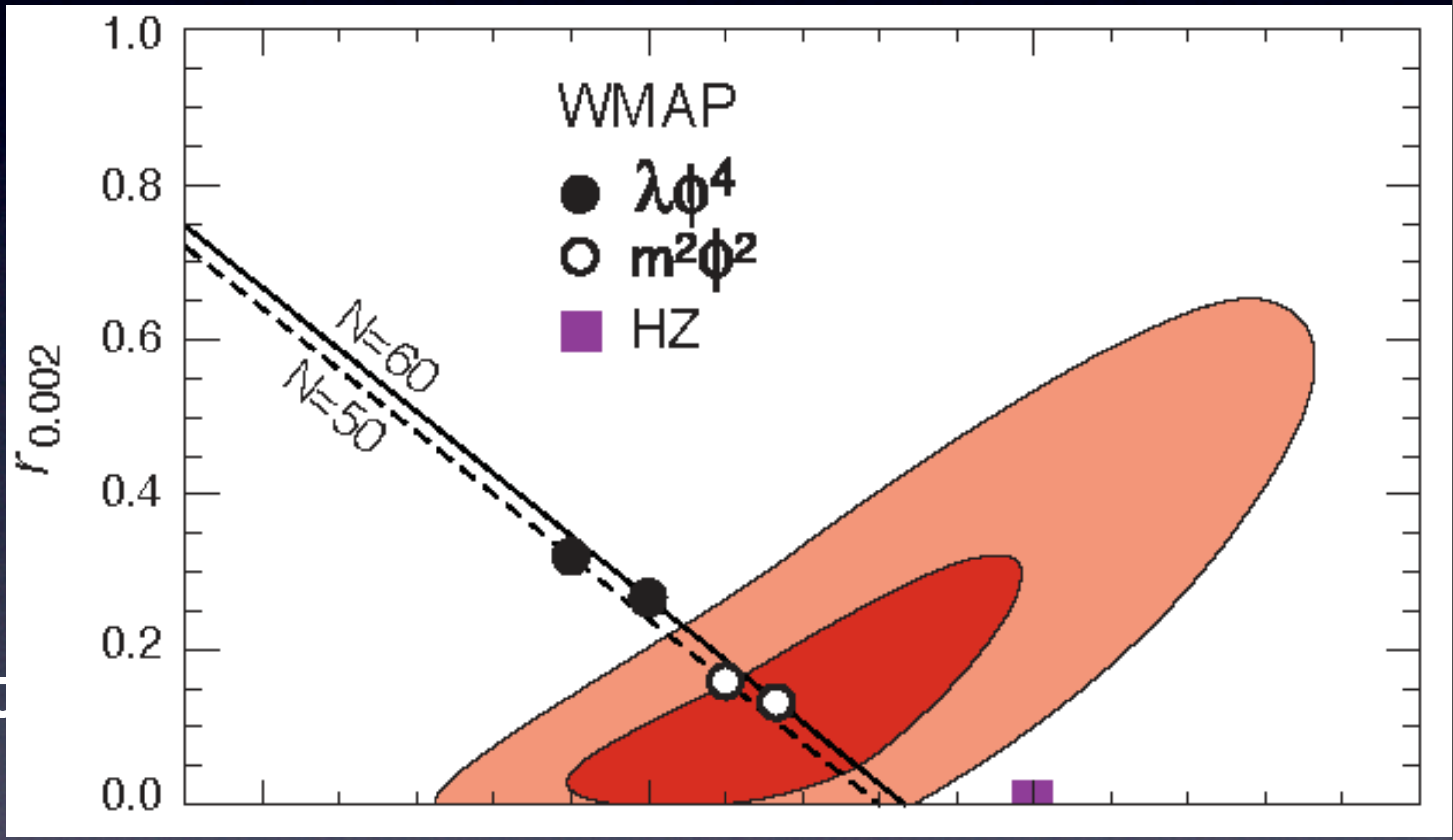
- Superpartner of a heavy neutrino
- displaced from the minimum at the beginning
- rolls down slowly: inflation
- quantum fluctuation source of later structure
- decays into both matter and anti-matter, but with a slight preference to matter
- decay products contain supersymmetry and hence Dark Matter



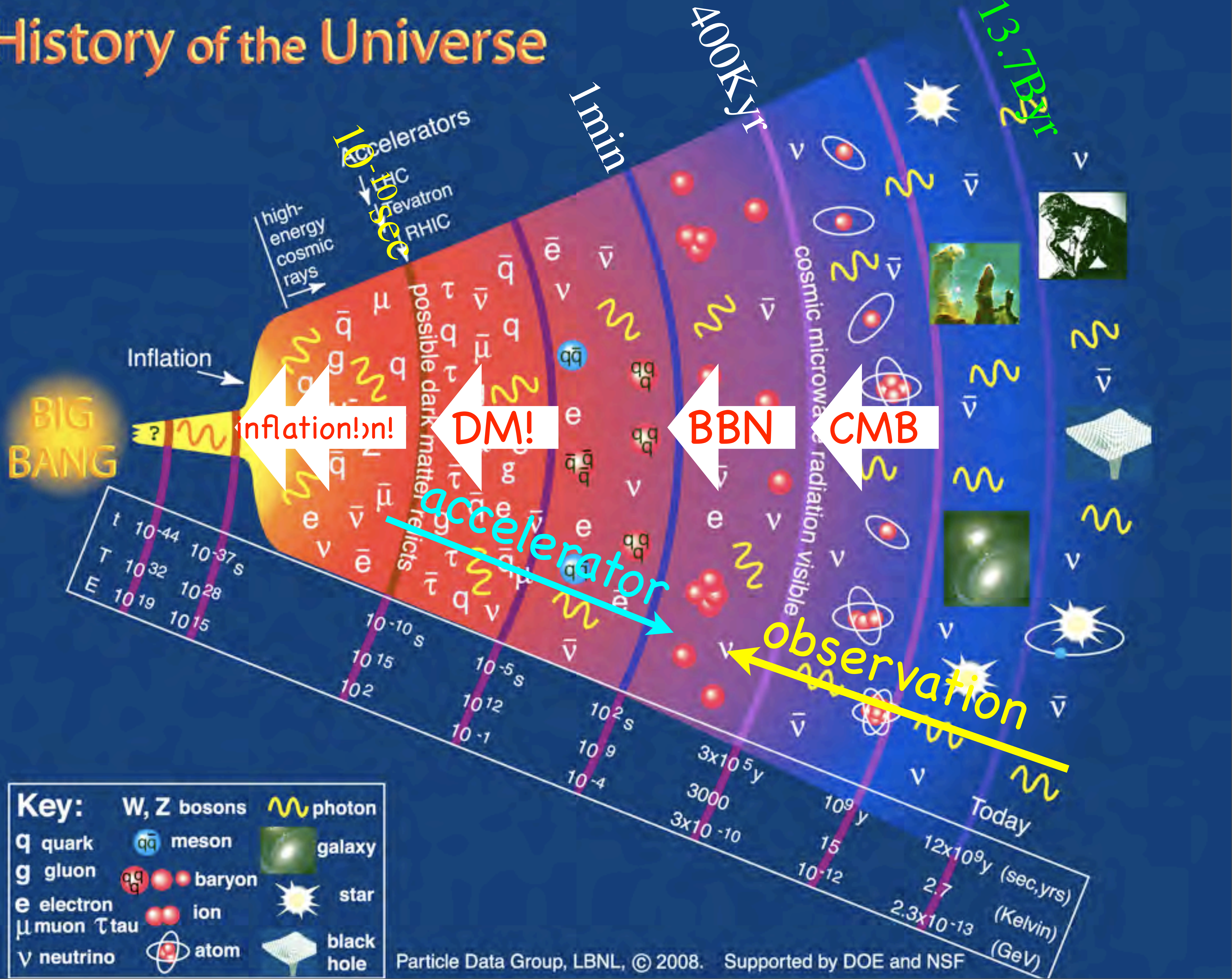
H. Murayama et al, PRL 70, 1912

Origin of the Universe

- Right-handed scalar neutrino: V=$m^2\phi^2$
- n_s~0.96
- r~0.16
- Need m~10^{13}GeV
- Still consistent with latest WMAP
- But V=$\lambda\phi^4$ is excluded
- Verification possible in the near future



History of the Universe



Conclusions

- Consistent picture of the universe emerged
- Yet, unknown components: Dark matter, Dark Energy
- where did the anti-matter go?
- What is Dark Field? Why is it there?
- Universe emerged from quantum physics
- New experiments gearing up to solve these puzzles

TeV: rich energy scale?

- *Dark Matter*

$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(\mathrm{TeV})^2}{\sigma_{ann}}$$

- *Fermi (Higgs) scale*

  $G_F^{-1/2}$=0.3TeV

- *Dark Energy*

  ρ_Λ~(2meV)^4 *vs* (TeV)$^2/M_{Pl}$~0.5meV

- *Neutrino*

  $(\Delta m^2_{LMA})^{1/2}$~7meV *vs* (TeV)$^2/M_{Pl}$~0.5meV

TeV-scale physics likely to be rich

We are now getting there!

IPMU

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

- 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
- $\approx$20 now, $\approx$40 in fall
- excellent new faculty hires, young and dynamic!
- will hire about 30 more scientists
- support visitors!
- new building in 2009
- intl guest house in 2009
- wkshp about a month


INSTITUTE FO
MATHEMATIC



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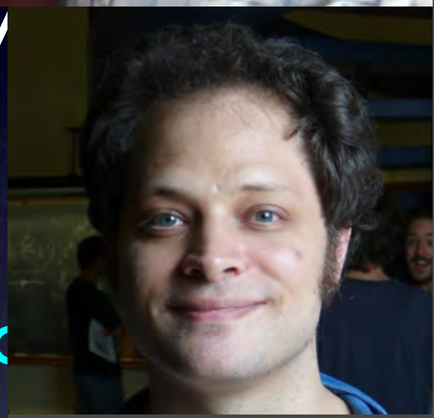


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Astronomer

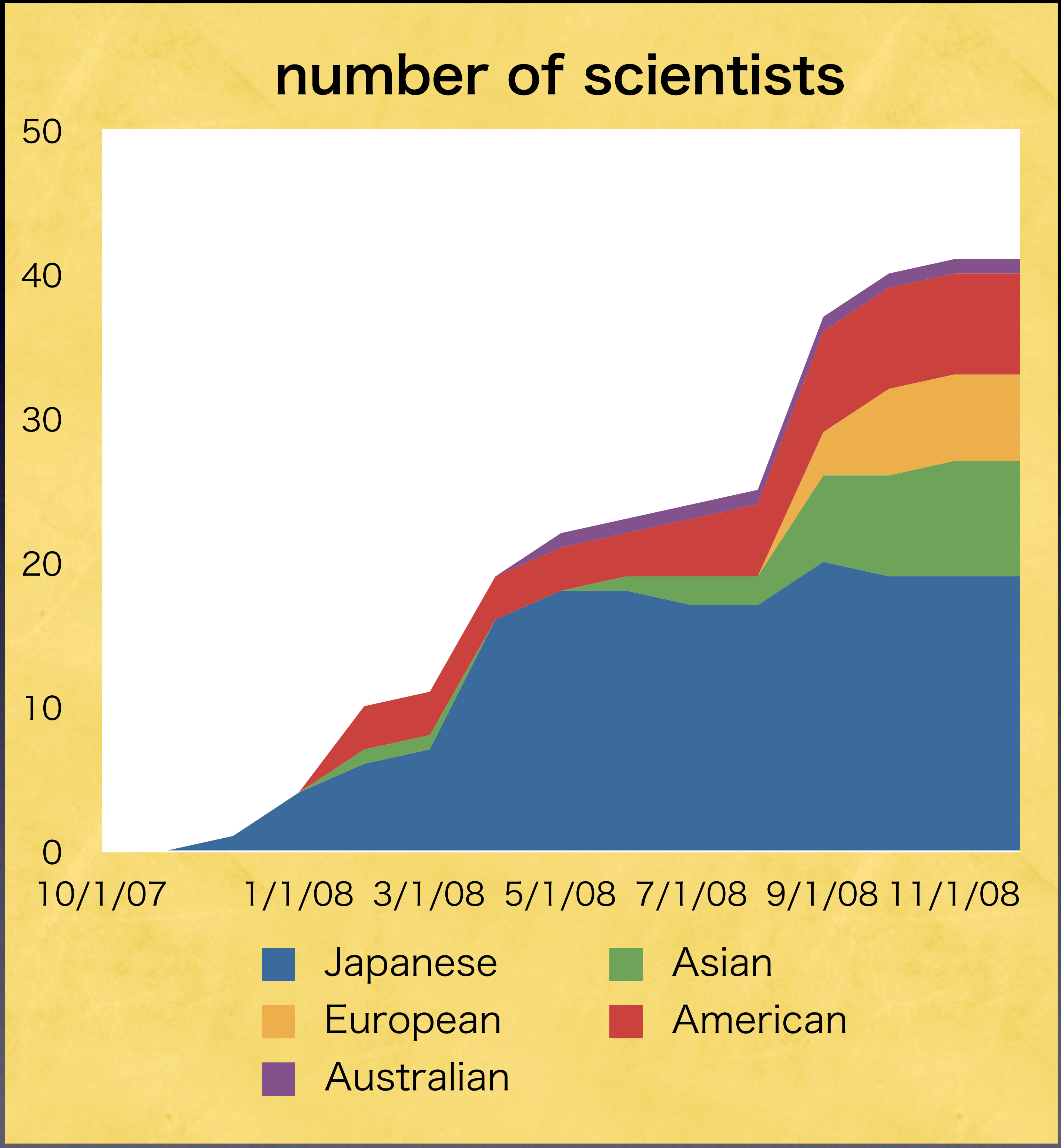
14 PIs in
40s & 50s


Winter 2009 occupancy
~5900m²

emphasis on large interaction area

"like a European town square" ~400 m^2

On Site Scientists



non-Japanese 50%