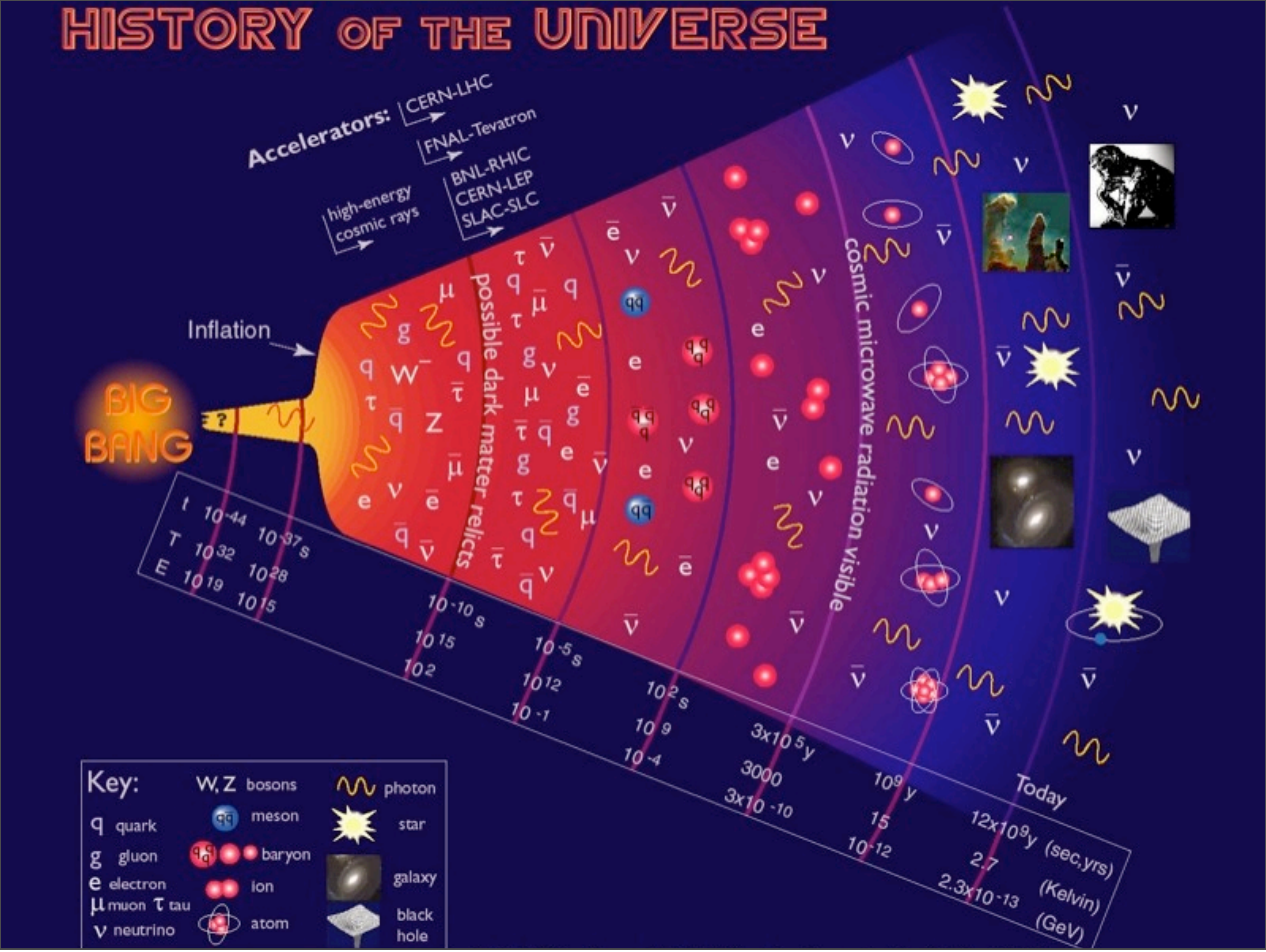

HISTORY OF THE UNIVERSE
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole

Friedmann-Robertson-Walker metric

$$ds^2 = dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right)$$

R(t) is the scale factor

k is curvature constant :

k = -1, 0, +1 for spatially open, flat or closed Universes

with perfect-fluid source

$$T^{\mu\nu} = -pg^{\mu\nu} + (\rho + p)u^\mu u^\nu$$

and solve Einstein's equations

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

The (00) component gives:

$$H^2 \equiv \frac{\dot{R}^2}{R^2} = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3}$$

The (ii) components give:

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N(\rho + 3p)}{3}$$

In addition $T^{\mu\nu}{}_{;\nu} = 0$ gives:

$$\dot{\rho} = -3H(\rho + p)$$

Consider $k = \Lambda = 0$

$$\frac{\dot{R}^2}{R^2} = \frac{8\pi G_N \rho}{3} \qquad \dot{\rho} = -3H(\rho + p)$$

i) Radiation dominated Universe: $p = \rho/3$

$\rho \sim R^{-4}$ and $R \sim t^{1/2}$

ii) Matter dominated Universe: $p = 0$

$\rho \sim R^{-3}$ and $R \sim t^{2/3}$

Inflation- Cosmological Problems

Flatness Problem

$$\frac{k}{R^2} = H^2(\Omega - 1) \qquad (\Lambda = 0)$$

Divide by T^2 and evaluate today:

$$\hat{k} = \frac{k}{R_0^2 T_0^2} = H_0^2(\Omega_0 - 1)/T_0^2 \qquad < 2 \times 10^{-58}$$

Represents an initial condition on the Universe

Inflation

- Standard cosmology assumes an adiabatically expanding Universe, $R \sim 1/T$
- Phase transitions can violate this condition

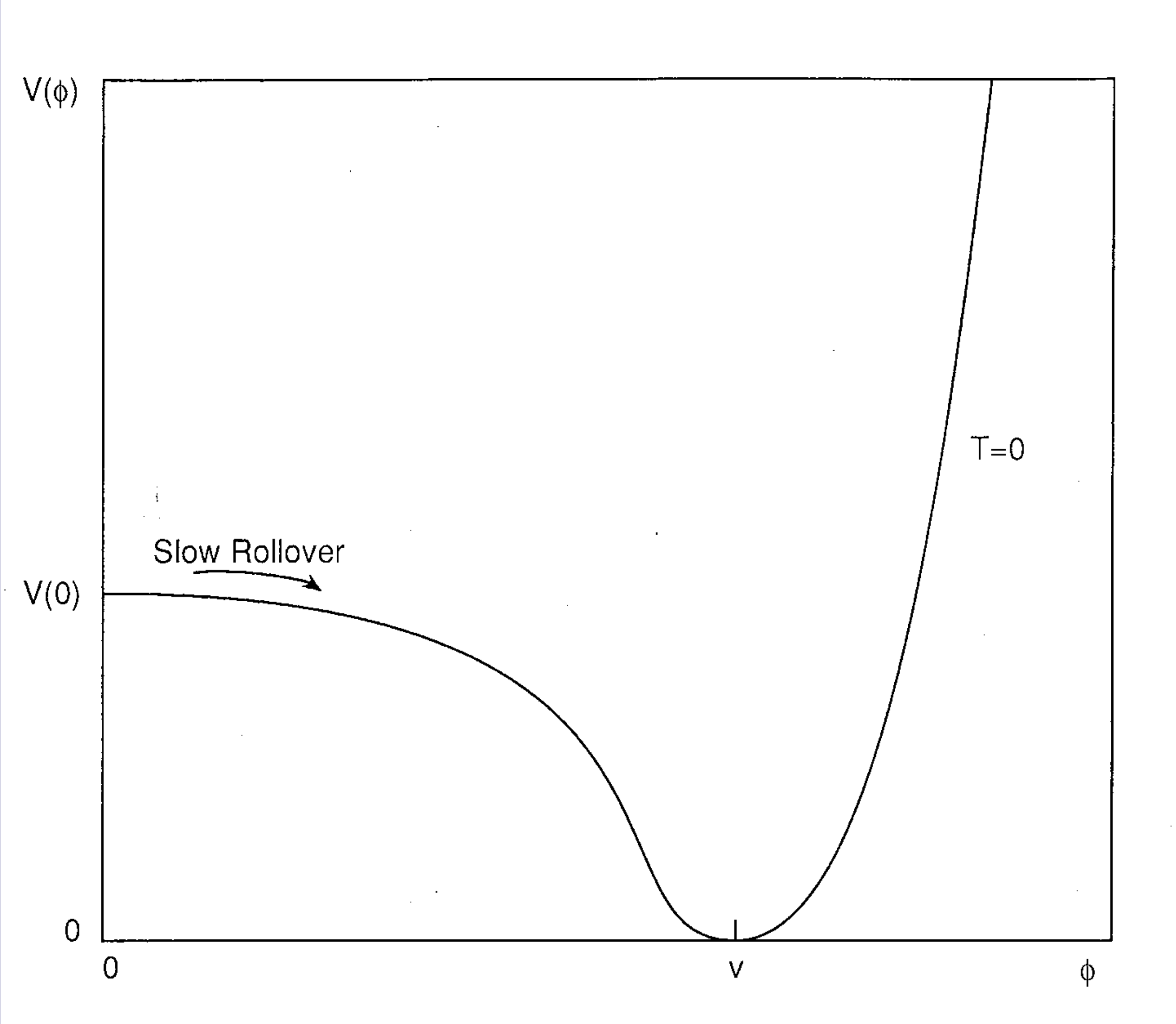
Phase Transitions

- Expect several phase transitions in the Early Universe
  - GUTS: SU5 → SU(3) x SU(2) x U(1)
  - SM: SU(2) x U(1) → U(1)
  - possibly other non-gauged symmetry breakings

- Entropy production common result

- Type of inflation will depend on the order of the phase transition

New Inflation



Inflation

$$\Lambda = 8\pi G_N V_0$$

For $\varrho << V_0$,

$$H^2 = \frac{\dot{R}^2}{R^2} \approx \frac{8\pi G_N V_0}{3} = \frac{\Lambda}{3}$$

or

$$\frac{\dot{R}}{R} \approx \sqrt{\frac{\Lambda}{3}}\,; \qquad R \sim e^{Ht}$$

For $H\tau > 65$, curvature problem solved

When the transition is over, the Universe reheats to $T < V_0^{1/4} \sim T_i$, but $R >> R_i$

Anti-matter in the Universe

- On Earth?
- On the Moon?
- In the Solar System?
- In the Galaxy?
  - in cosmic rays antimatter is secondary
  - antiHelium - never observed

$$\bar{He} = \bar{p}\bar{p}\bar{n}\bar{n}$$

- Anywhere?

Baryogenesis

The Baryon asymmetry

- Goal: To calculate η from microphysics

- Problem: In baryon symmetric universe the baryon density is determined by freeze-out of annihilations

$$\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma}$$

For T >> m_N, $$\frac{n_B}{n_\gamma} \sim O(1)$$

For T < m_N, $$\frac{n_B}{n_\gamma} \sim \left(\frac{m_N}{T}\right)^{3/2} e^{-m_N/T}$$

The Sakharov Conditions

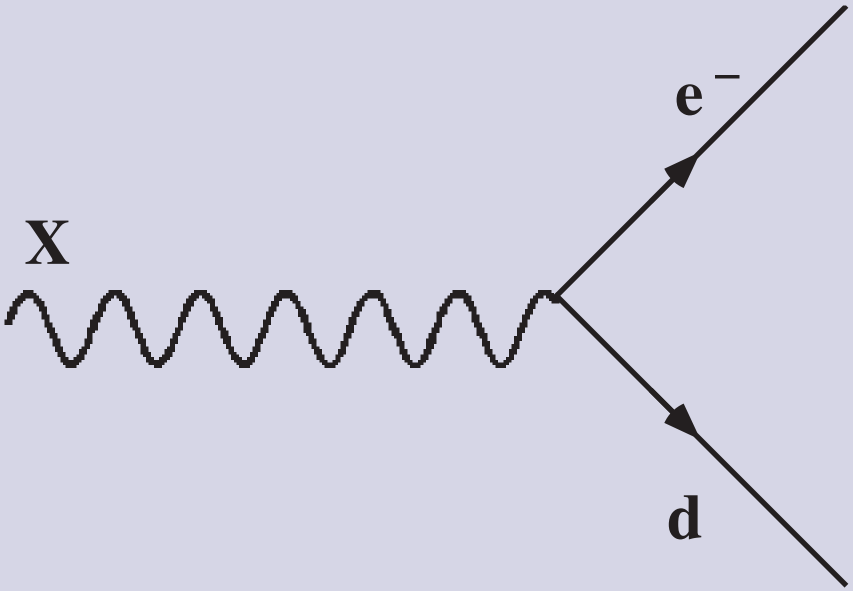
To generate an asymmetry:

1. Baryon Number Violating Interactions
2. C and CP Violation
3. Departure from Thermal equilibrium

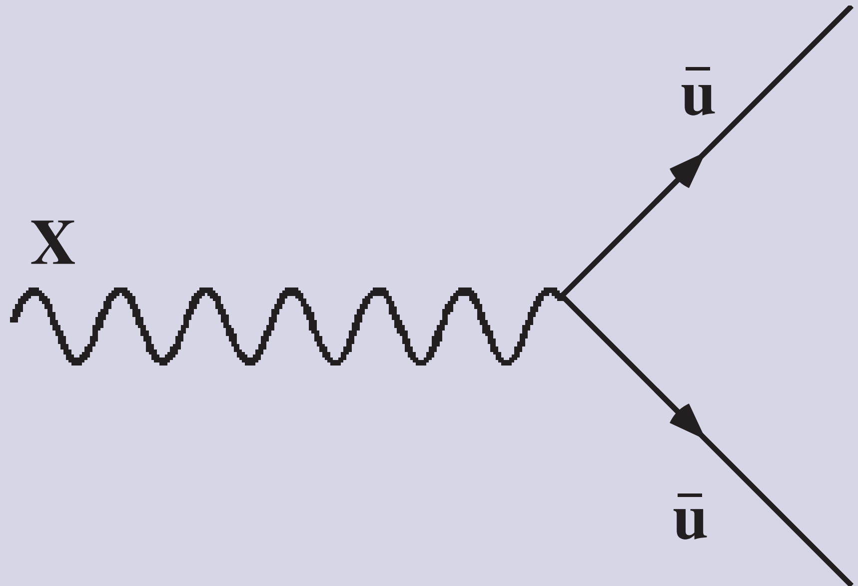
1. and 2. are contained in GUTs
3. is obtained in an expanding Universe

Grand Unified Theories

In SU(5), there are gauge (and Higgs) bosons which mediate baryon number violation. Eg.,



$\Delta B = +1/3$



$\Delta B = -2/3$

Conditions in the Early Universe:

$$T \gtrsim 1 \text{ MeV}$$

$$\rho = \frac{\pi^2}{30}(2 + \frac{7}{2} + \frac{7}{4}N_\nu)T^4$$

$$\eta = n_B/n_\gamma \sim 10^{-10}$$

β-Equilibrium maintained by weak interactions

Freeze-out at ~ 1 MeV determined by the competition of expansion rate $H \sim T^2/M_p$ and the weak interaction rate $\Gamma \sim G_F^2 T^5$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

$$n + \nu_e \leftrightarrow p + e^-$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

At freezeout n/p fixed modulo free neutron decay, $(n/p) \simeq 1/6 \rightarrow 1/7$

Nucleosynthesis Delayed (Deuterium Bottleneck)

$p + n \rightarrow \mathbf{D} + \gamma$ $\qquad \Gamma_p \sim n_B \sigma$

$p + n \leftarrow \mathbf{D} + \gamma$ $\qquad \Gamma_d \sim n_\gamma \sigma e^{-E_B/T}$

Nucleosynthesis begins when $\Gamma_p \sim \Gamma_d$

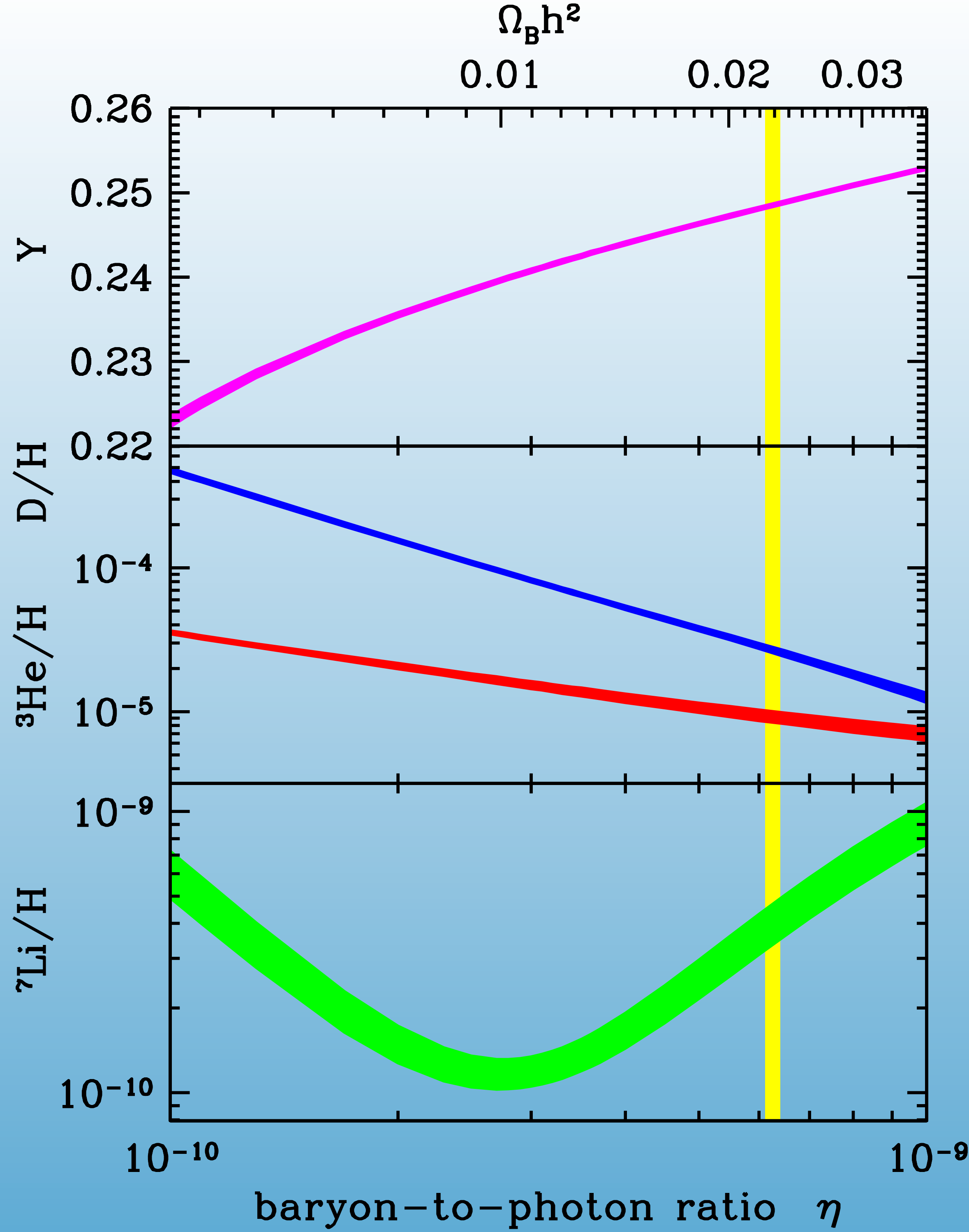
$\frac{n_\gamma}{n_B} e^{-E_B/T} \sim 1$ $\qquad$ **@** $T \sim 0.1$ **MeV**

All neutrons $\rightarrow$ ^{4}He

$$Y_p = \frac{2(n/p)}{1 + (n/p)} \simeq 25\%$$

Remainder:

D, ^{3}He $\sim 10^{-5}$ and ^{7}Li $\sim 10^{-10}$ by number



$\Omega_B h^2$
0.01
0.02
0.03
0.26
0.25
0.24
0.23
0.22
Y
D/H
^{3}He/H
10^{-4}
10^{-5}
^{7}Li/H
10^{-9}
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio η

Historical Perspective

Intimate connection with CMB

Alpher
Herman
Gamow

Conditions for BBN:

Require T > 100 keV $\Rightarrow$ t < 200 s

$$\sigma v(p + n \rightarrow D + \gamma) \approx 5 \times 10^{-20}\ cm^3/s$$

$$\Rightarrow n_B \sim 1/\sigma v t \sim 10^{17}\ cm^{-3}$$

Today:

$$n_{Bo} \sim 10^{-7}\ cm^{-3}$$

and

$$n_B \sim R^{-3} \sim T^3$$

Predicts the CMB temperature

$$T_o = (n_{Bo} / n_B)^{1/3}\, T_{BBN} \sim 10\ K$$

Some History:

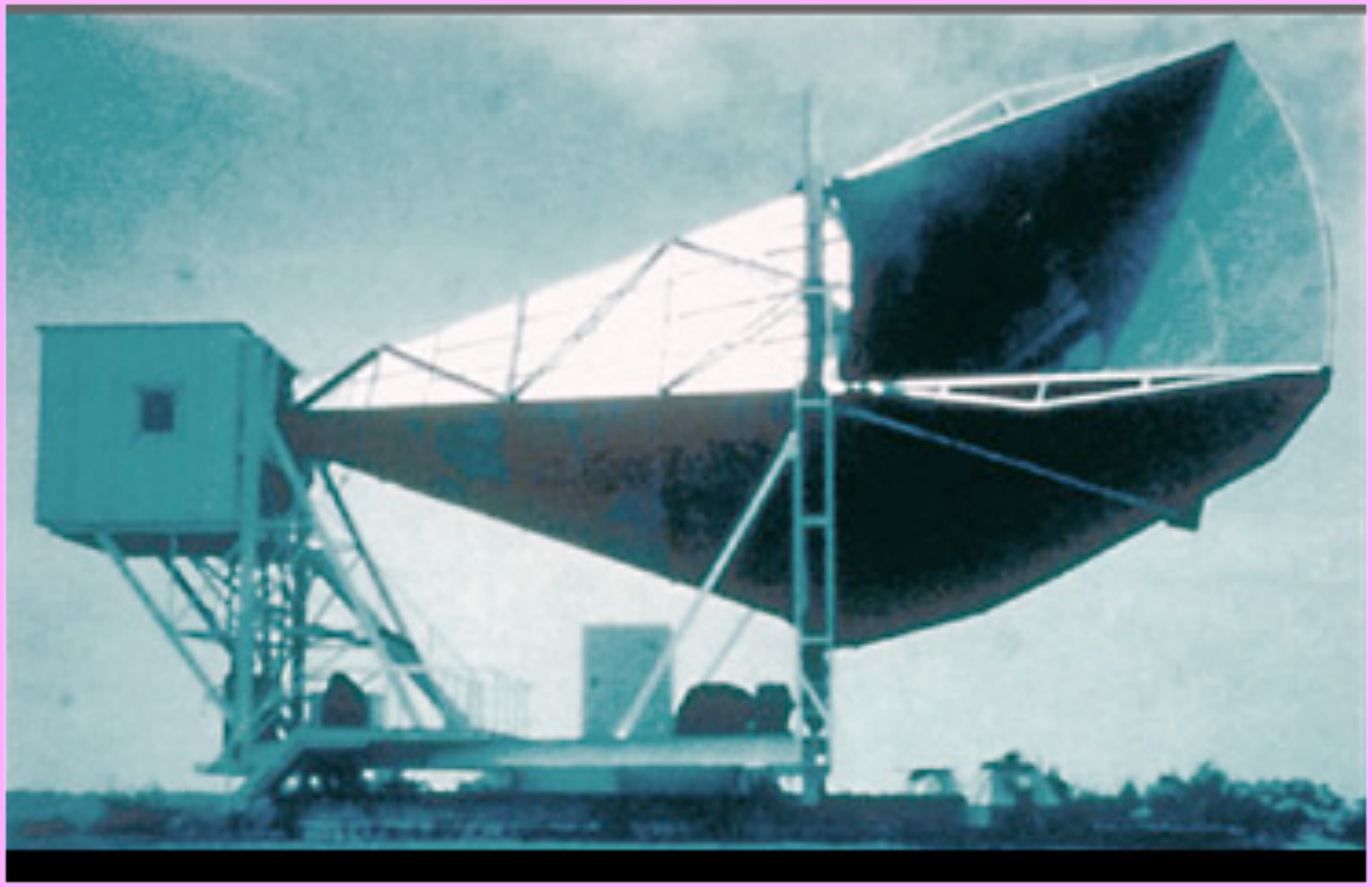
Penzias and Wilson:
Perfecting a radio antenna to track the Echo satellite
found background noise which could not be eliminated.

Corresponding temperature:

$T = 3.5 \pm 1\ K$

Published in
"A Measurement of Excess Antenna Temperature at 4080 Mc/s"

Followed by an explanation by Dicke, Peebles Roll, & Wilkenson



Subsequently, many measurements (ground and balloon based) showed that:

$$T = 2.7 - 3\ K$$

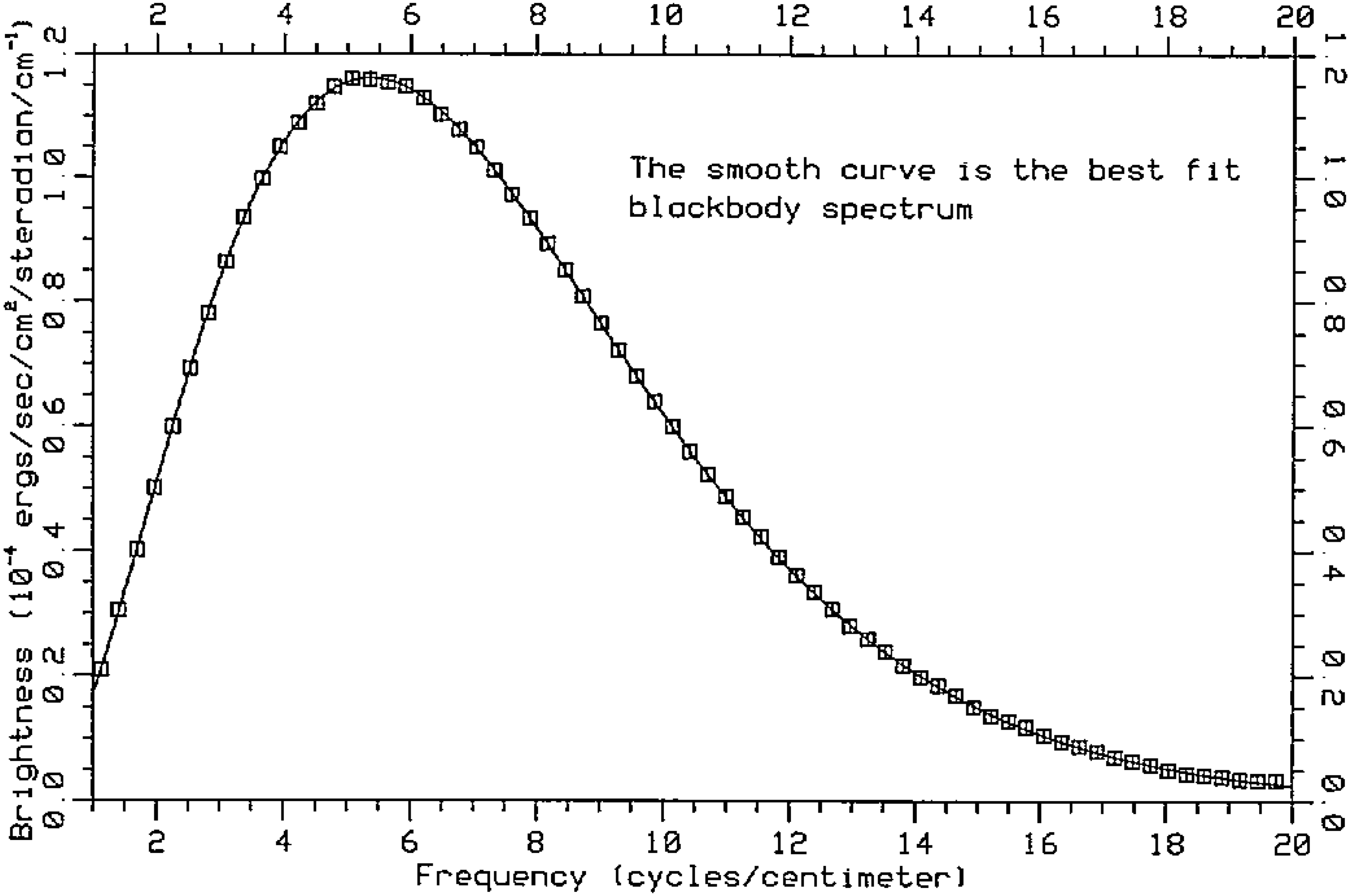
Enter COBE.

Lingering doubts regarding distortions and aniotropies set aside.

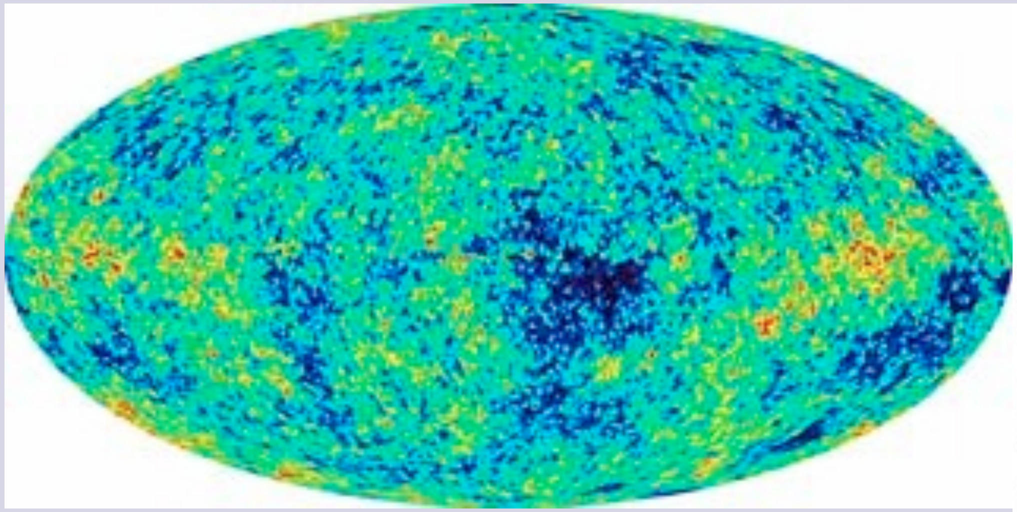
$$T = 2.73 \pm 0.01\ K$$

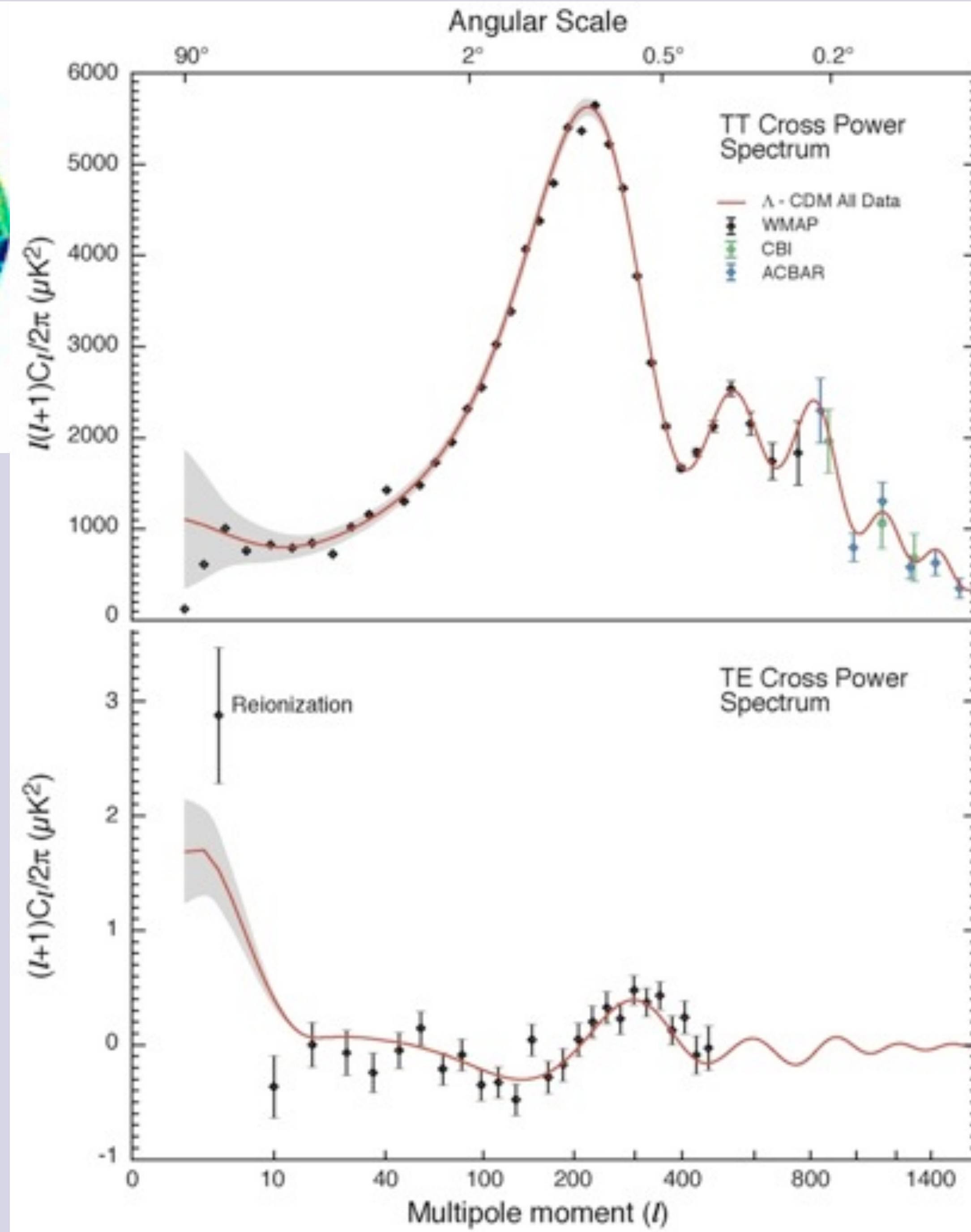
$$n_\gamma \sim T^3 = 411\ cm^{-3}$$

$$\varrho_\gamma \sim T^4 \leq 10^{-4}\ \varrho_c$$


Brightness (10^{-4} ergs/sec/cm^2/steradian/cm^{-1})
Frequency (cycles/centimeter)
The smooth curve is the best fit
blackbody spectrum

WMAP



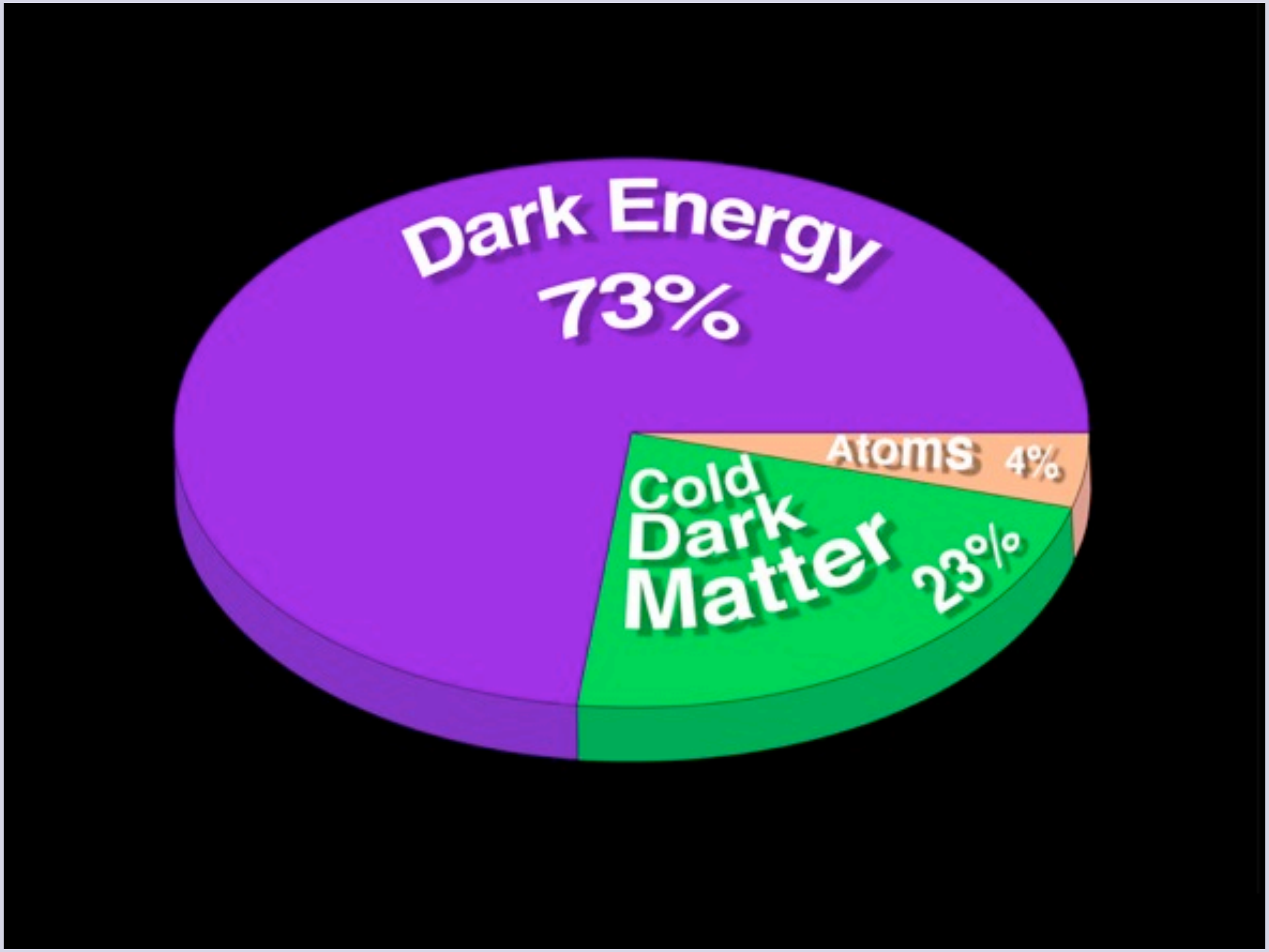


Position of 1st peak

$\Rightarrow \quad \Omega = 1$

Cosmological Parameters:

$$\Omega = 1.006 \pm 0.006$$



Galactic Rotation Curves

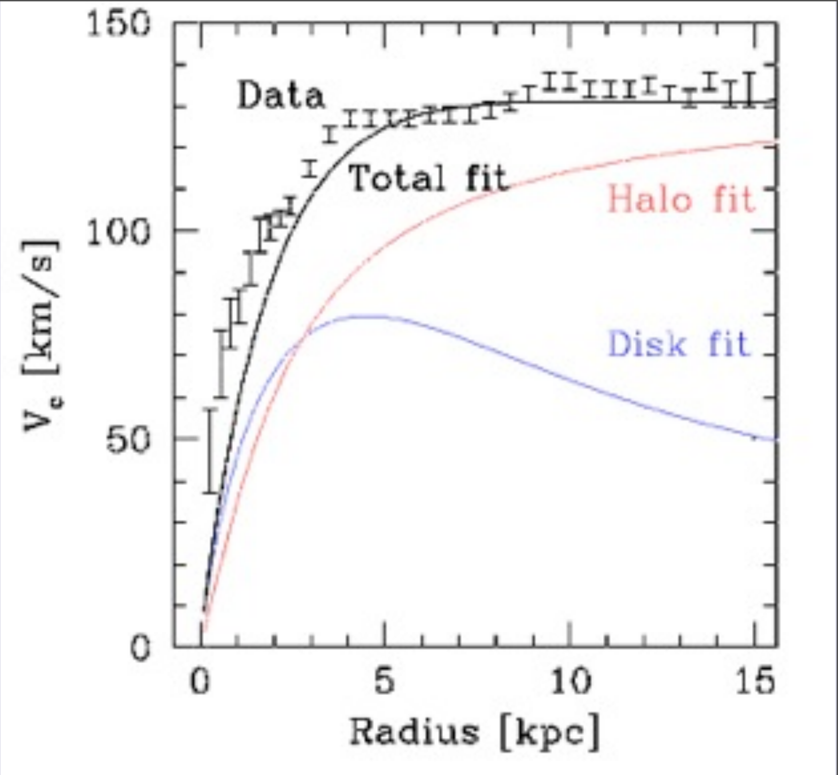
Doppler measurements in spiral galaxies

Observe: $v(r)$

Expect: $$\frac{GM^2}{r^2} = \frac{KMv^2}{r}$$

or $$M(<r) = \frac{Kv^2 r}{G}$$

if M is constant $$v^2 \sim 1/r$$



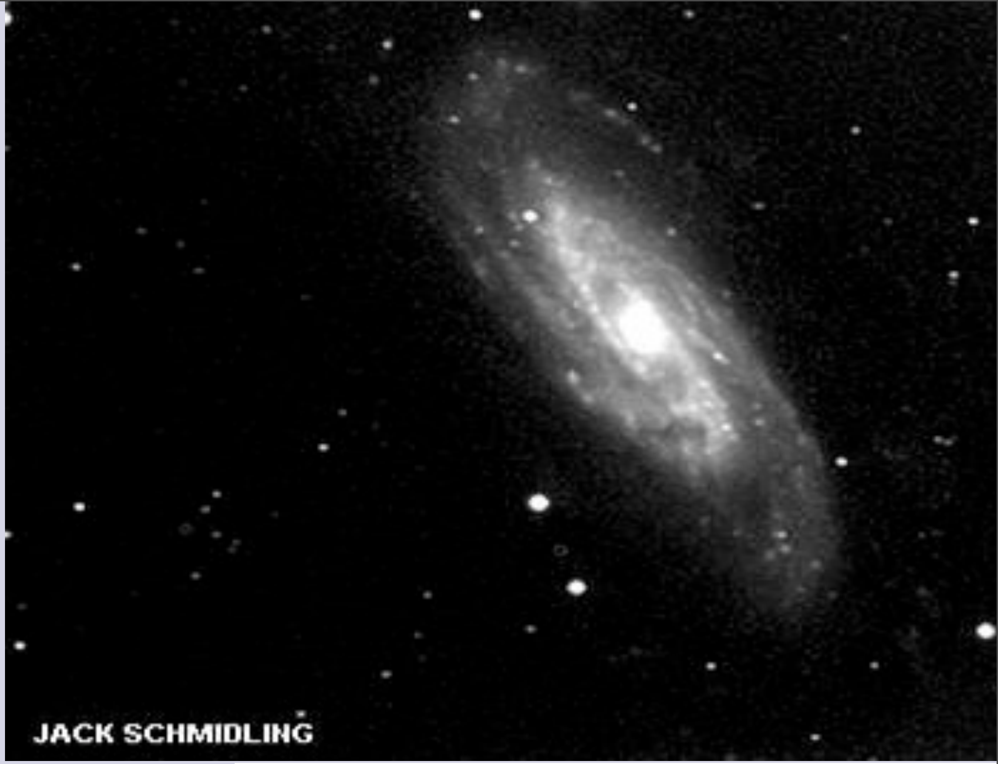
NGC 2403

Expect: $\frac{GM^2}{r^2} = \frac{KMv^2}{r}$

or $M(< r) = \frac{Kv^2 r}{G}$

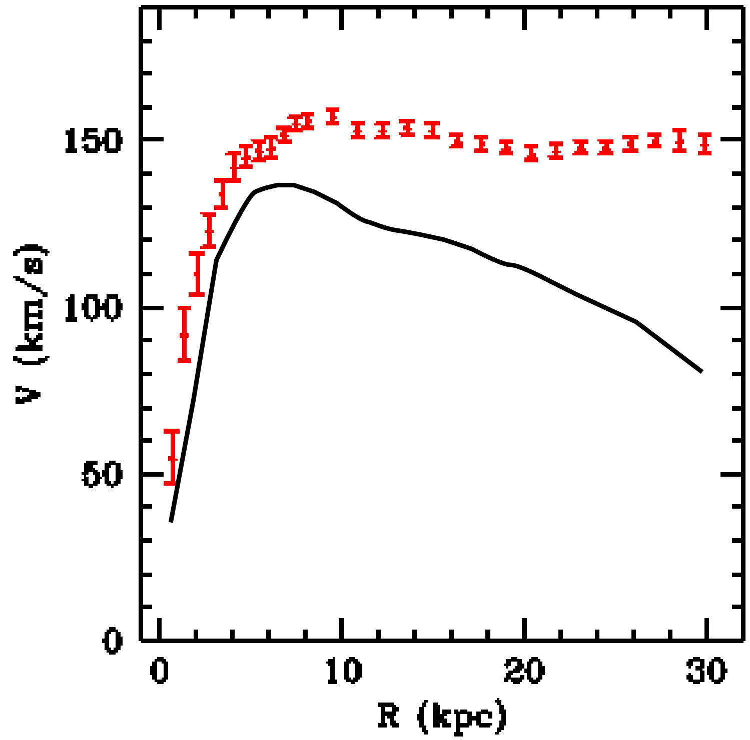
if M is constant $v^2 \sim 1/r$

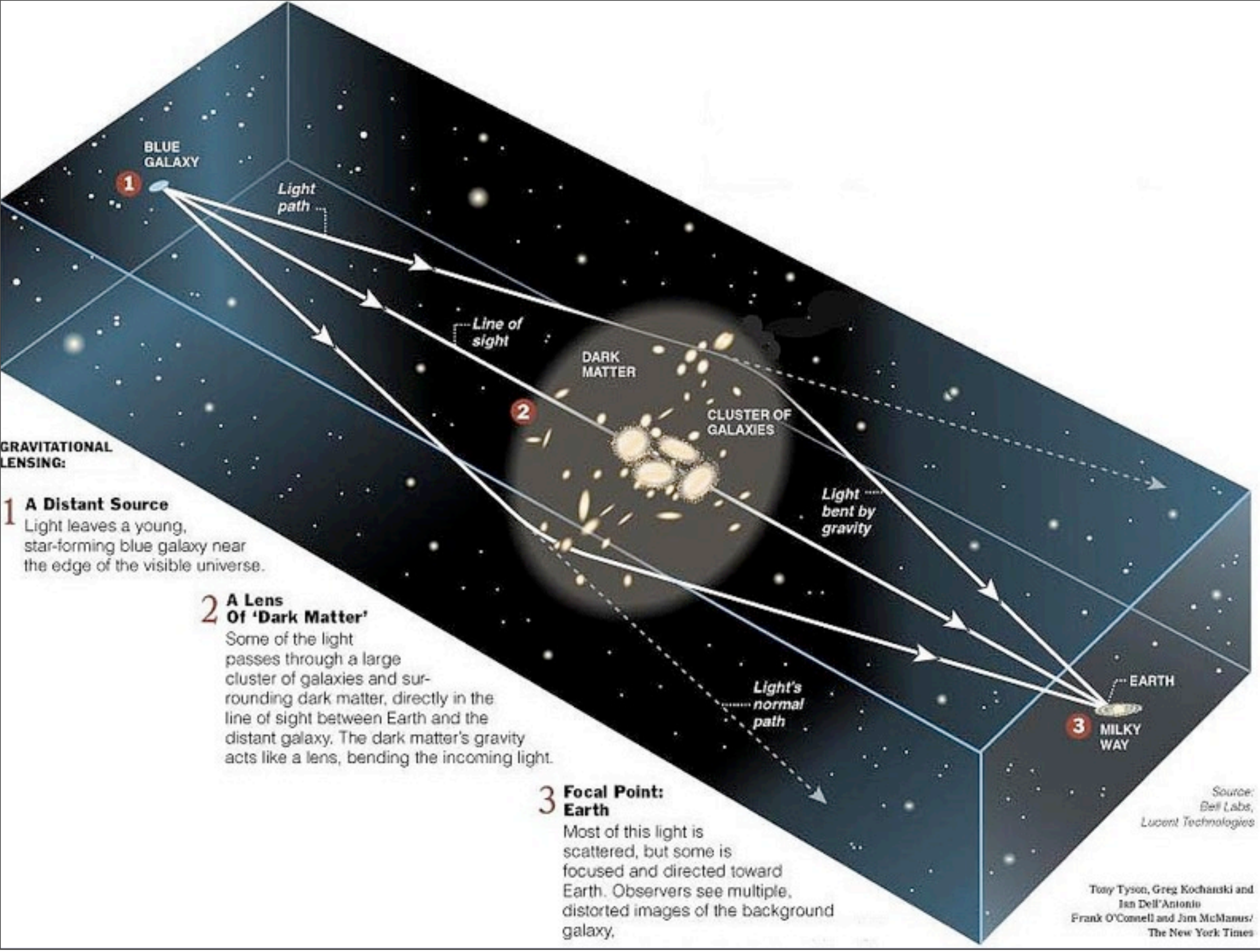
if v is constant $M \sim r$



$\Rightarrow$ Existence of Dark Matter

NGC 3198





Friday, July 13, 12

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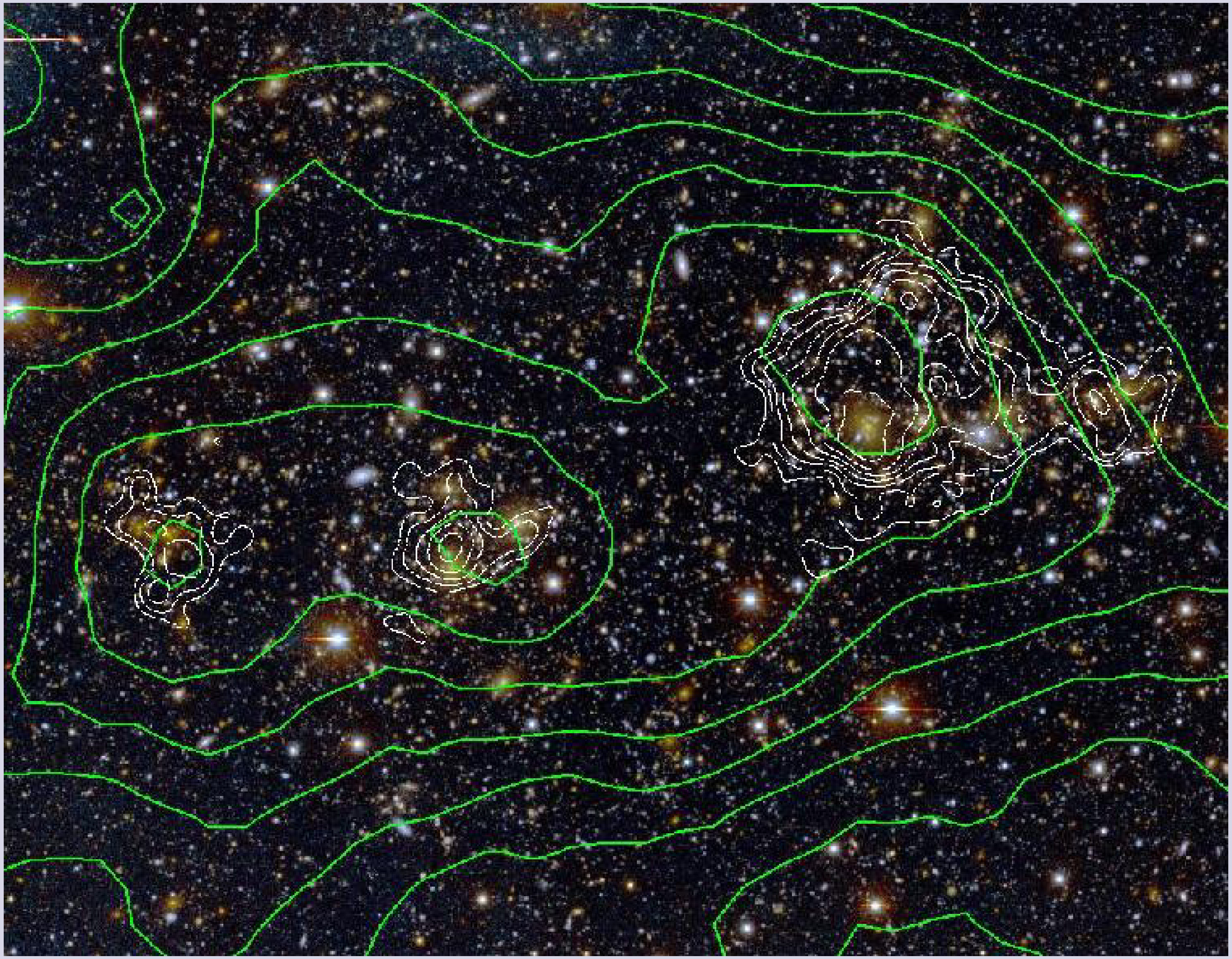


Abell 781 Wittman et al.

The Bullet Cluster

How Much Dark Matter

WMAP 7

Komatsu etal

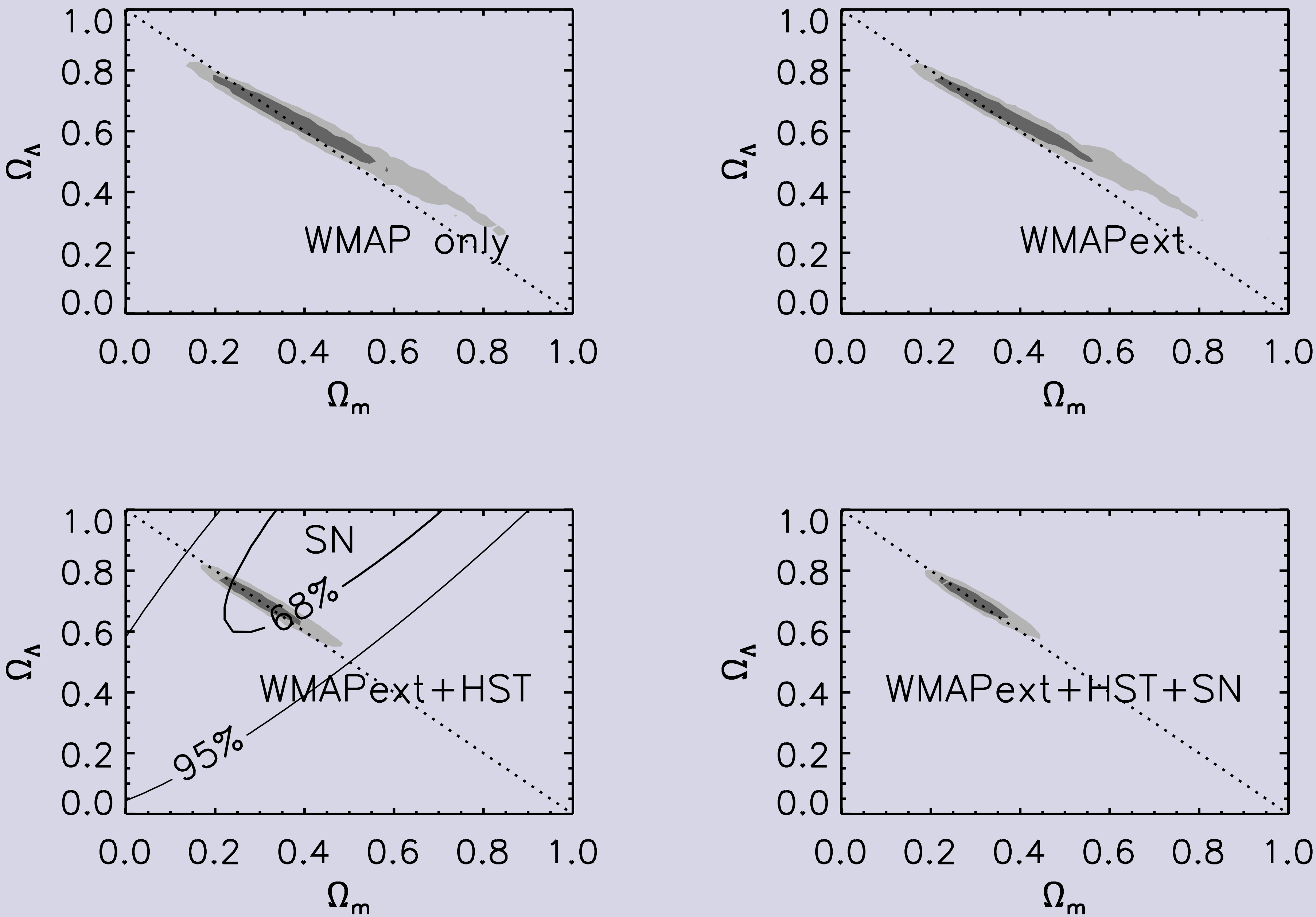
Precise bounds on matter content

$\Omega_m h^2 = 0.1334 \pm 0.0056$ $\Omega_b h^2 = 0.0226 \pm 0.0006$

$$\Omega_{cdm} h^2 = 0.1109 \pm 0.0056$$

or

$$\Omega_{cdm}\, h^2 = 0.0997 - 0.1221 \quad (2\,\sigma)$$



WMAP only
WMAPext
SN
68%
95%
WMAPext+HST
WMAPext+HST+SN
Ω_Λ
Ω_m

Candidates

- Baryons
  - Cluster, produce heavy elements, …$\Omega_B h^2 = 0.0224$
- Neutrinos
  - We know too much ($0.0005 < \Omega_\nu h^2 < 0.0076$)
- Axions
  - Solve the strong CP problem, scale is not well motivated
- LSP
  - Natural stable dark matter candidate with good relic density
- …

Gauge Hierarchy Problem

$M_P \approx 10^{19}$ GeV

$M_X \approx 10^{15}$ GeV

$M_W \approx 10^{2}$ GeV

Why are these scales different?
Do they stay different?

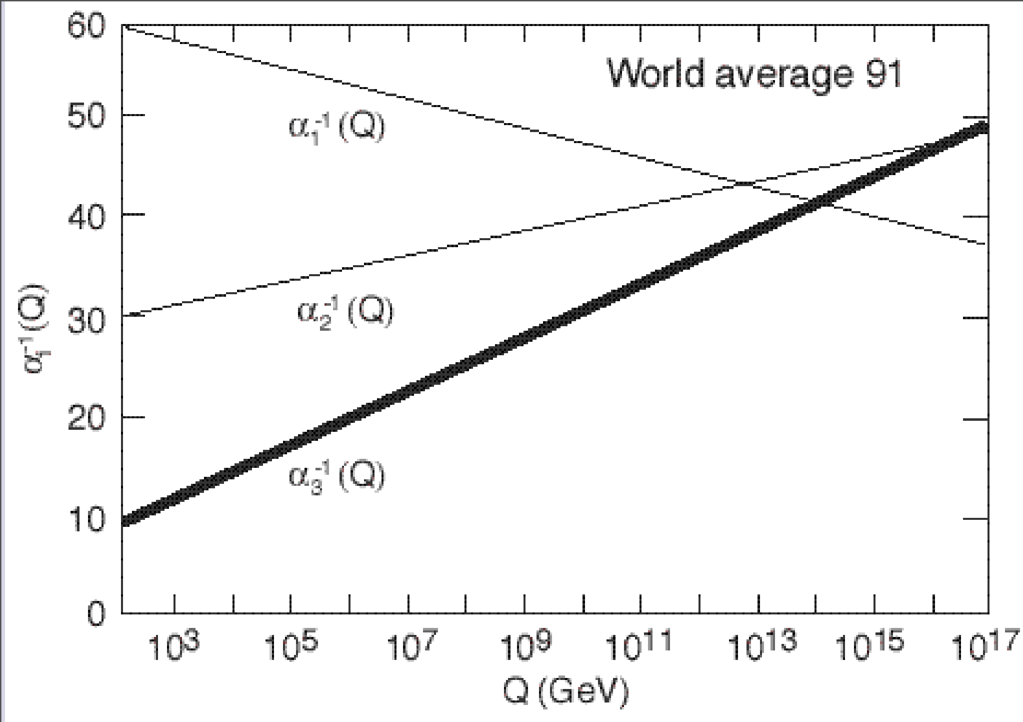
What is supersymmetry?

$$Q|Boson\rangle = |Fermion\rangle$$
$$Q|Fermion\rangle = |Boson\rangle$$

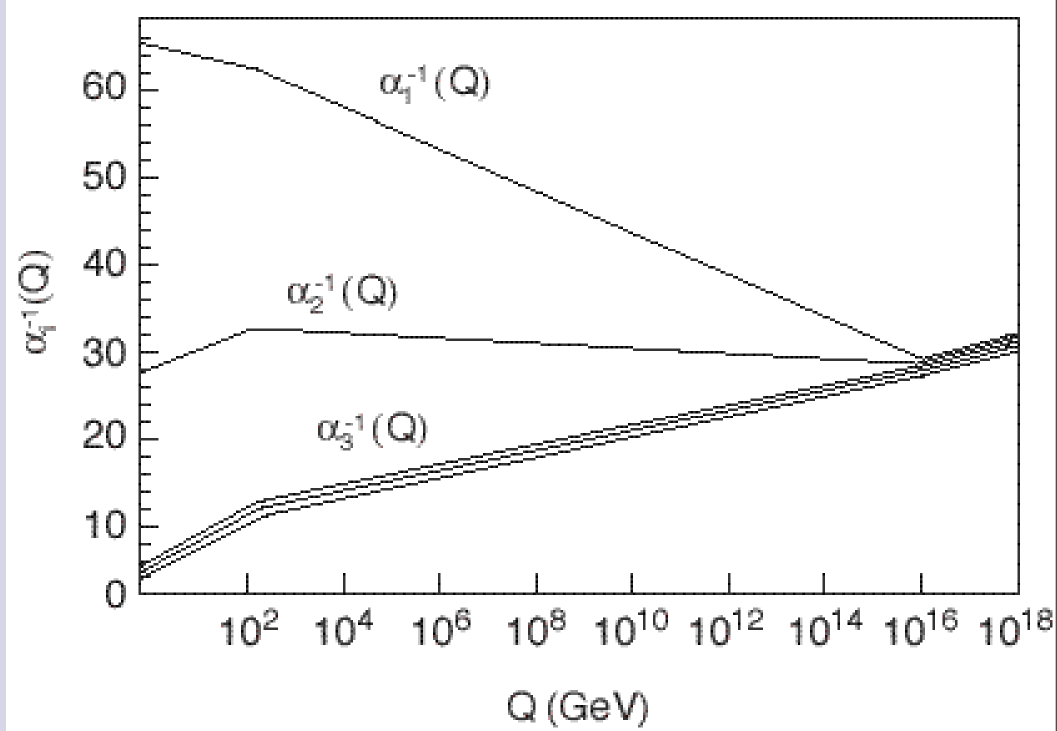
Chiral multiplet $\begin{pmatrix} \tilde{e} \\ e \end{pmatrix}$ $\begin{pmatrix} \text{scalar} - \text{spin } 0 \\ \text{fermion} - \text{spin } 1/2 \end{pmatrix}$

Vector multiplet $\begin{pmatrix} \tilde{\gamma} \\ \gamma \end{pmatrix}$ $\begin{pmatrix} \text{fermion} - \text{spin } 1/2 \\ \text{vector} - \text{spin } 1 \end{pmatrix}$

(also gravitational multiplet with
gravitino (spin 3/2) and graviton (spin 2).



Running of the Gauge couplings in the standard model



Running of the Gauge couplings in the supersymmetric standard model

What is the MSSM

1) Add minimal number of new particles:
Partners for all SM particles + 1 extra Higgs EW doublet.

2) Add minimal number of new interactions:
Impose R-parity to eliminate many UNWANTED interactions.

$$R = (-1)^{3B+L+2S}$$

Particle Content of the MSSM

Gauge					
γ		B	$\Rightarrow$	$\tilde{B}$	neutralinos
Z	or	W^3		$\tilde{W}^3$	
$W^\pm$		W^i		$\tilde{W}^\pm$	charginos

Higgs			
H_1	$\Rightarrow$	$\tilde{H}_{1,2}$	neutralinos
H_2		$\tilde{H}^\pm$	charginos

Matter			
q	$\Rightarrow$	$\tilde{q}_{L,R}$	squarks
l		$\tilde{l}_{L,R}$	sleptons

All New particles have R = -1

E.g.:

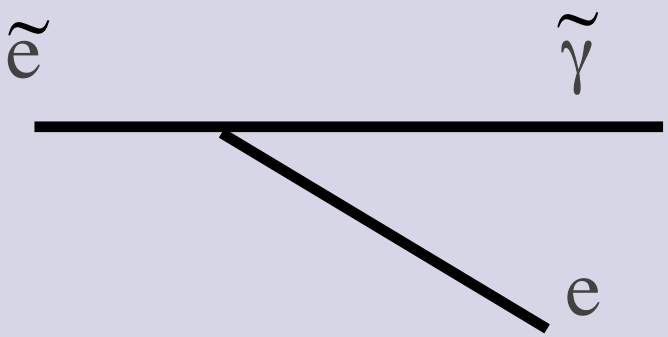
γ: S=1/2; B=L=0; $R=(-1)^{1}$ = -1

e: S=0; B=0; L= -1; $R=(-1)^{-1}$ = -1

u: S=0; B=1/3; L=0; $R=(-1)^{1}$ = -1

R-Parity Conservation ⇒

The Lightest Supersymmetric Particle (LSP) is stable



SUSY Dark Matter

MSSM and R-Parity ⟹ Stable DM candidate

1) Neutralinos

$$\chi_i = \alpha_i \widetilde{B} + \beta_i \widetilde{W} + \gamma_i \widetilde{H}_1 + \delta_i \widetilde{H}_2$$

2) Sneutrino

Excluded (unless add L-violating terms)

3) Other:

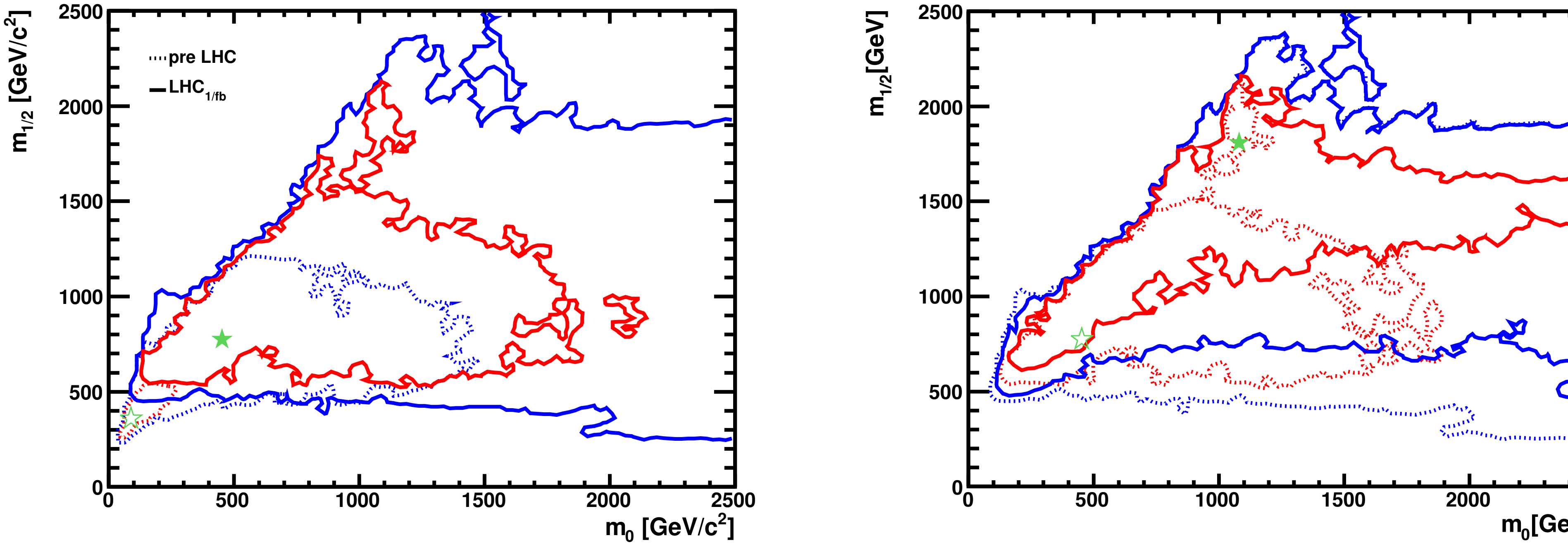
Axinos, Gravitinos, etc

The Search:

- Colliders:
  - Supersymmetry
  - Missing energy
  - Rare Processes
- Direct Detection
- Indirect Detection

$\Delta\chi^2$ map of m_0 - $m_{1/2}$ plane

Mastercode



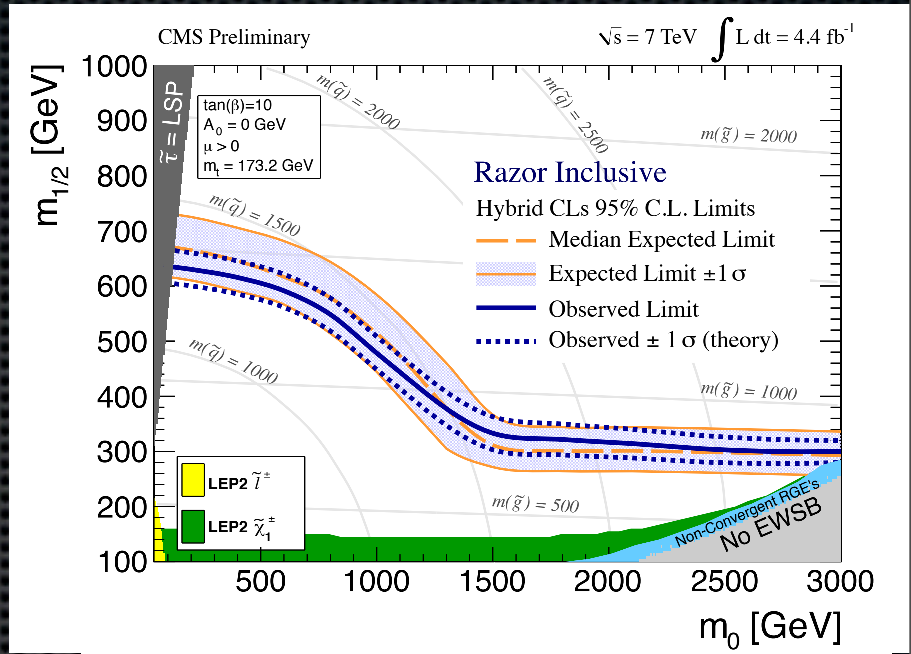
- CMSSM

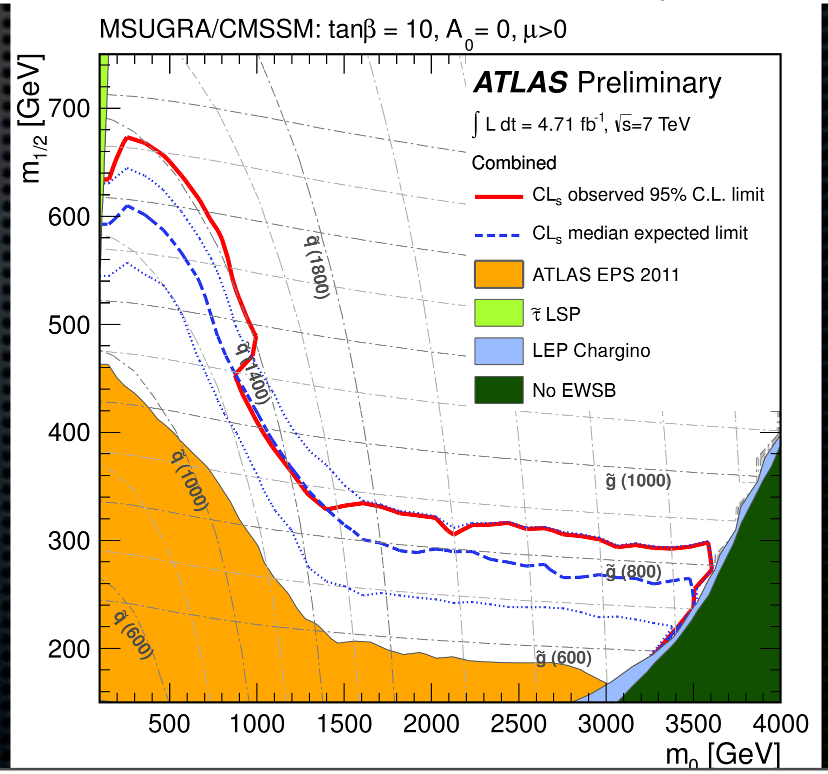
Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer
Isidori, Olive, Ronga, Weiglein

Effect of Results from LHC

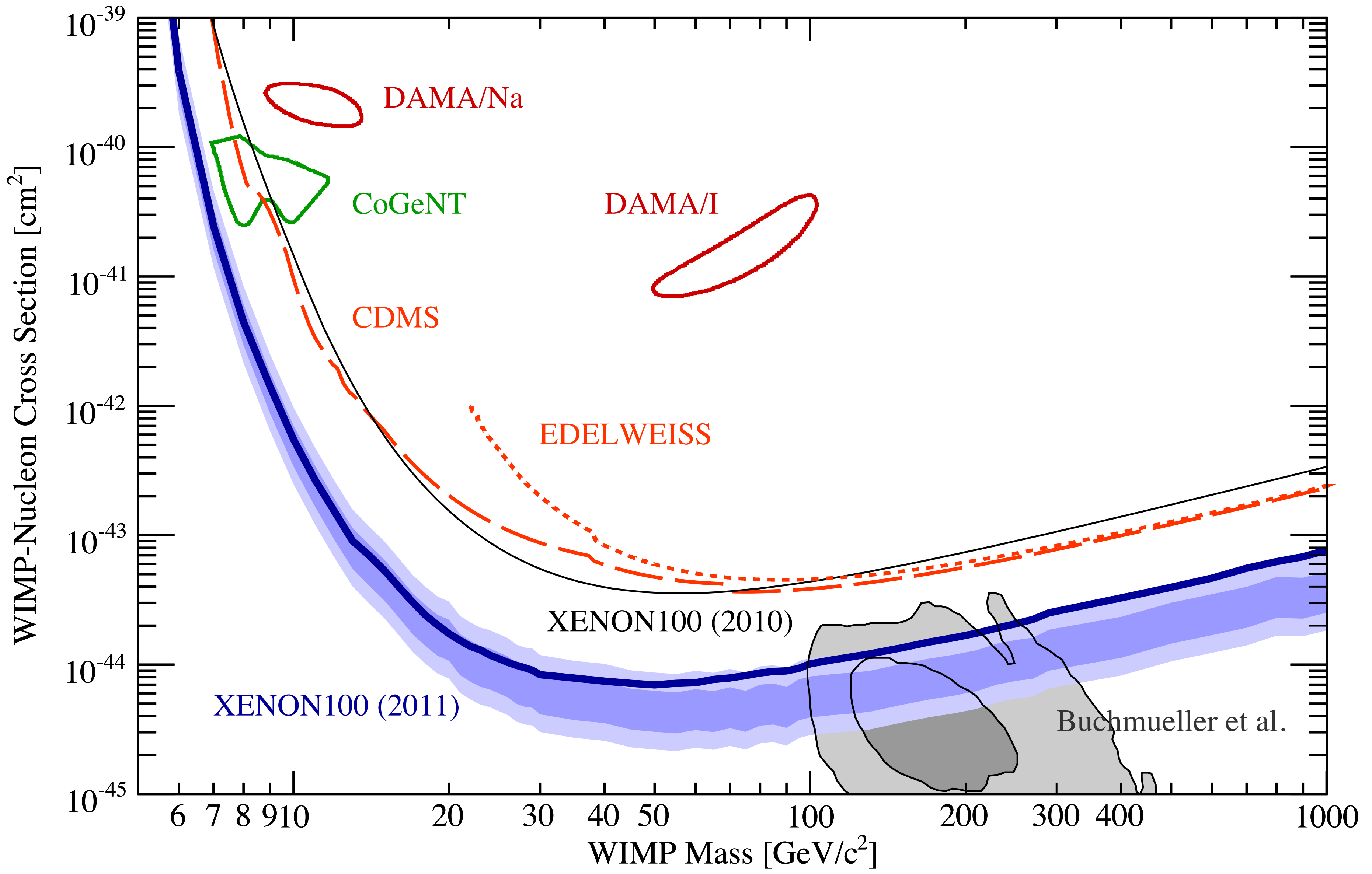
~5fb^{-1} @ 7 TeV

- jets + missing E_T with/without leptons
- Heavy Higgs to $\tau\tau$
- B to $\mu\mu$



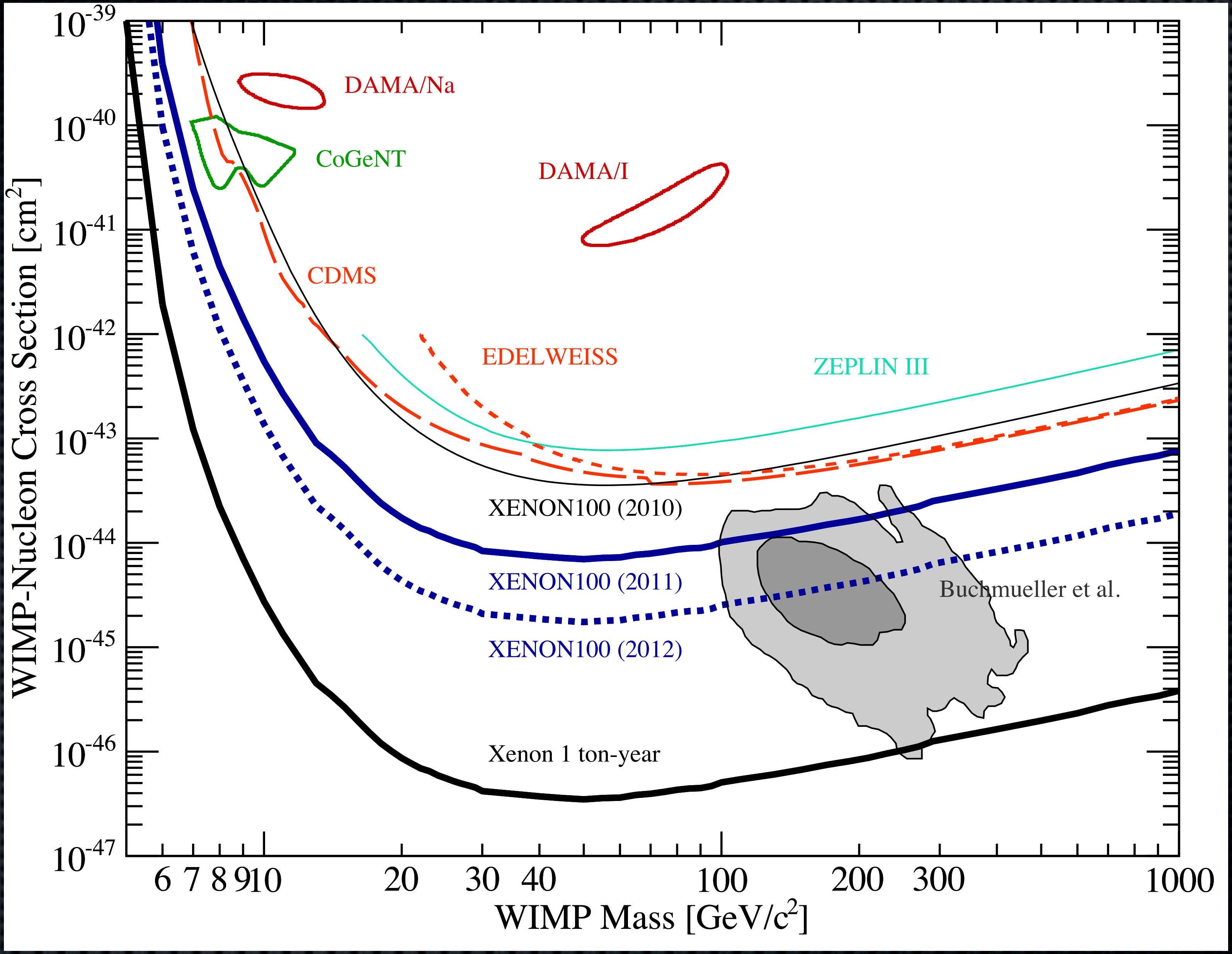


Most recent result from Xenon100



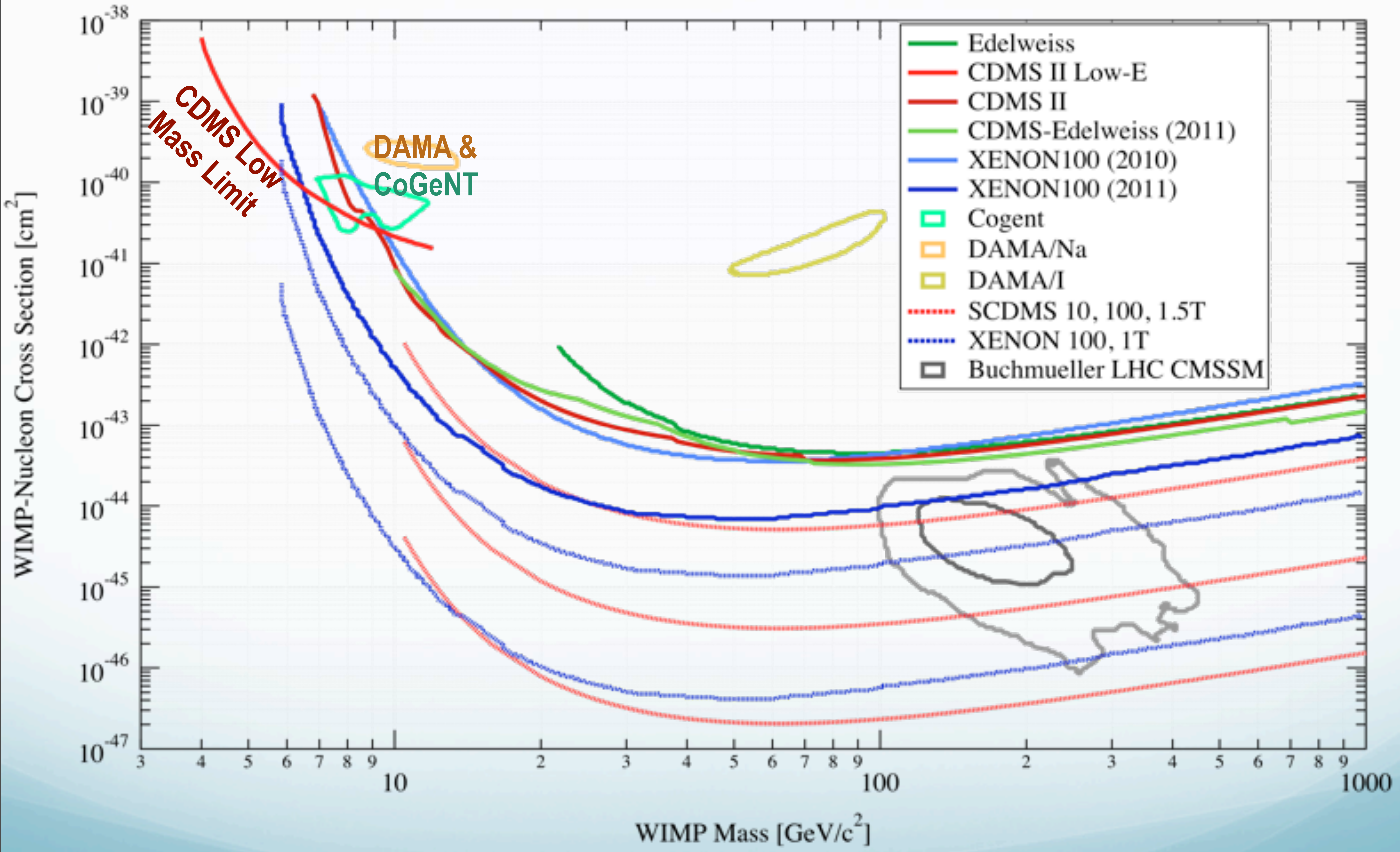
Aprile et al.

Most recent result from Xenon100



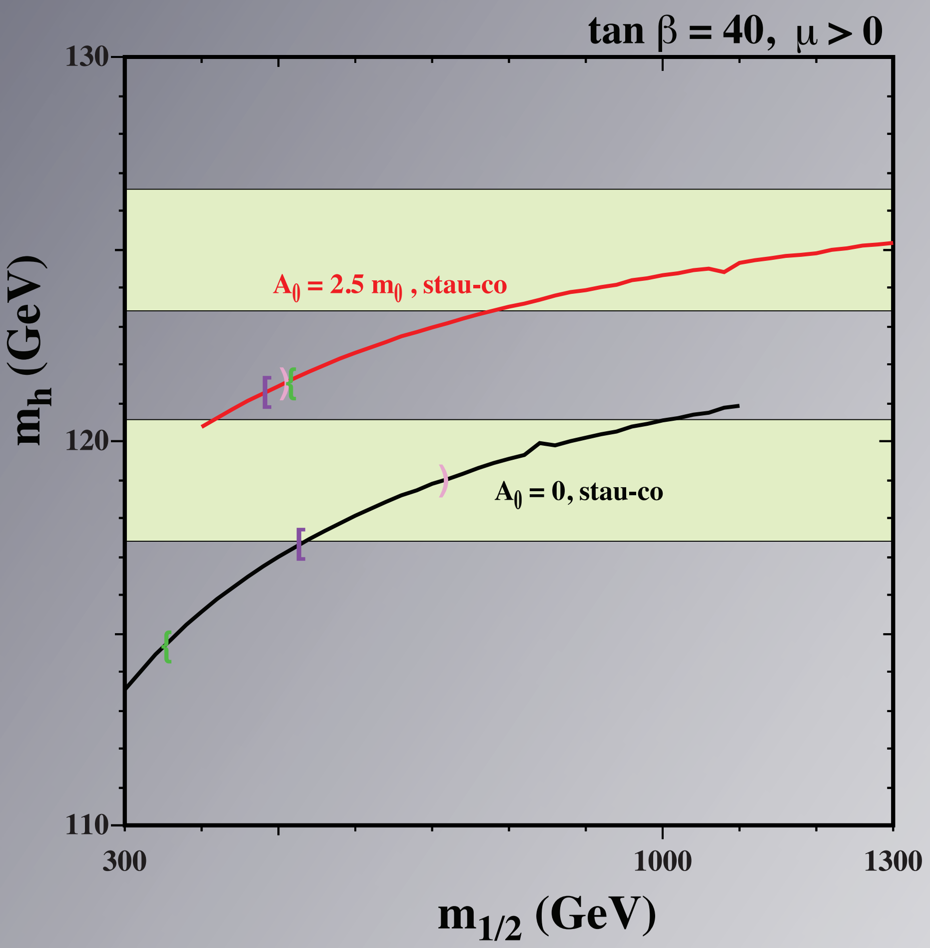
Aprile

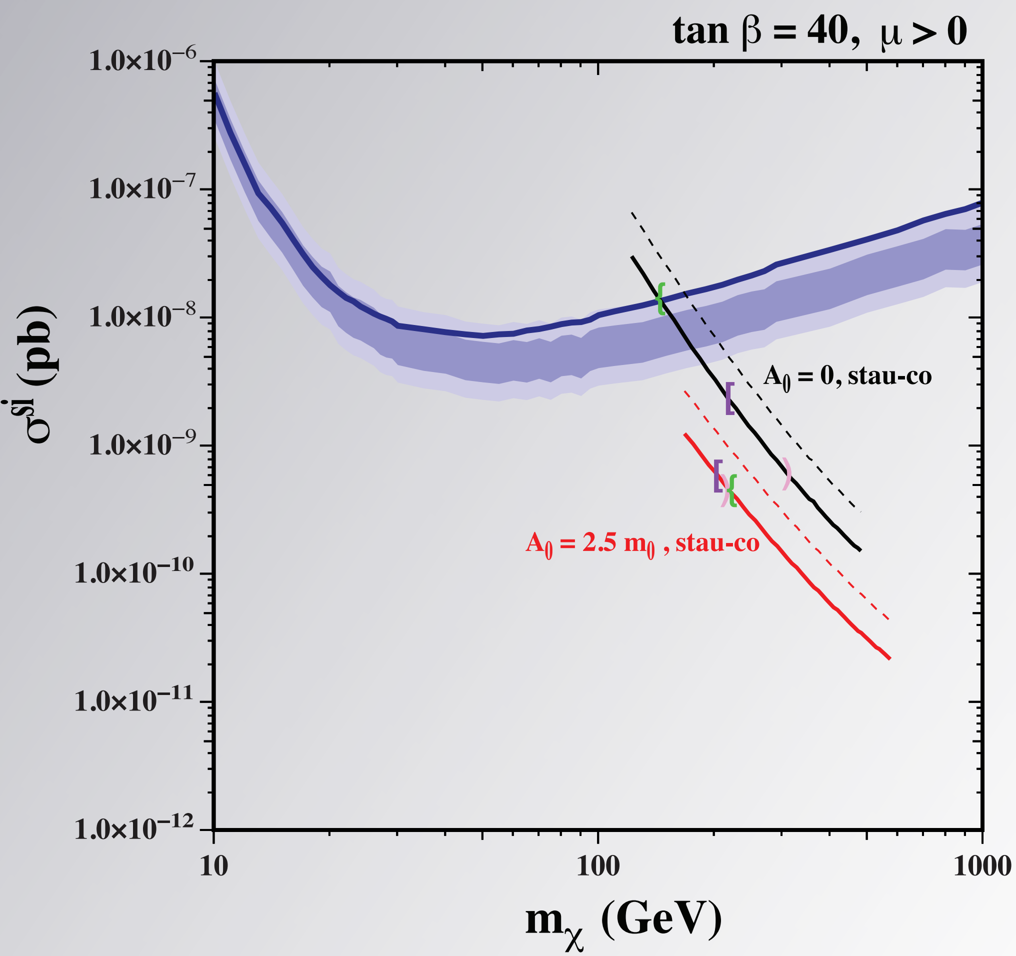
Red is CDMS **Blue is Xenon** **Green is Edelweiss**



P. Cushman

Higgs masses vs elastic cross sections





Higgs masses vs elastic cross sections