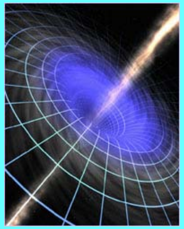
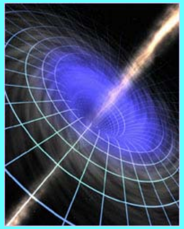
Astro-particle-physics



An operational definition:

Astro-particle-physics

The intersection of elementary particle physics (microprocesses) and astro-physical phenomena, including cosmology.

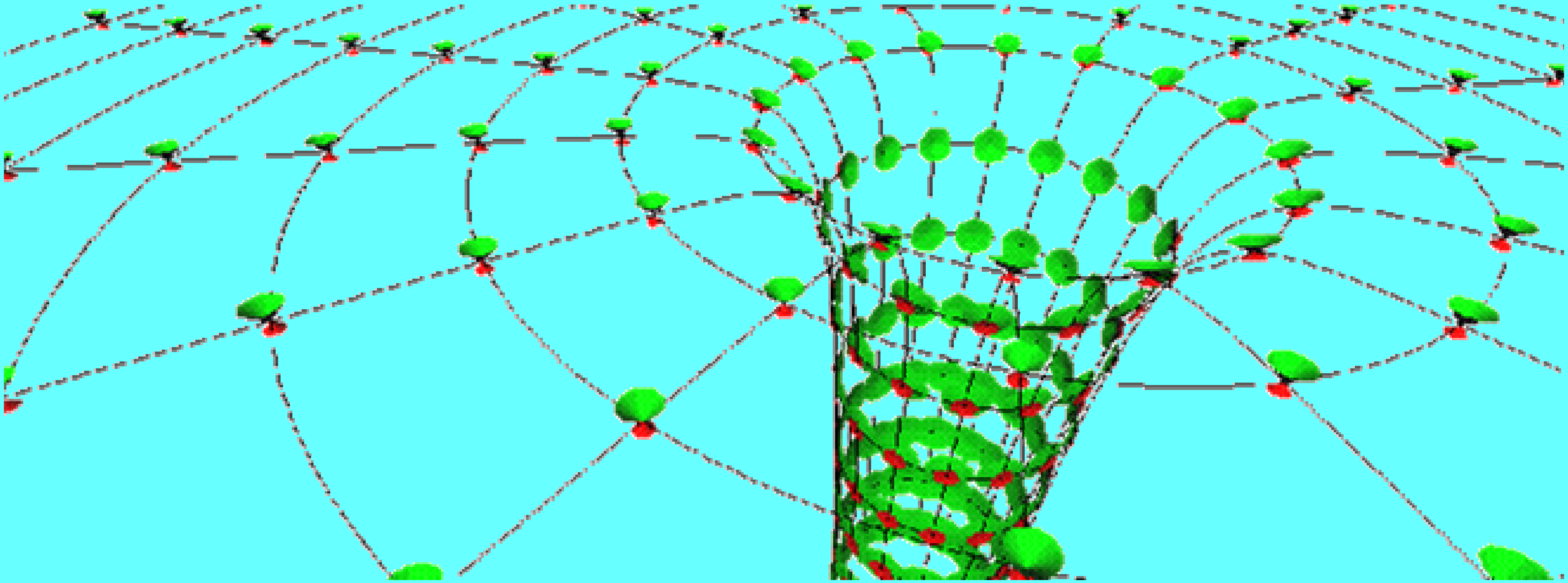


Outline of Lecture

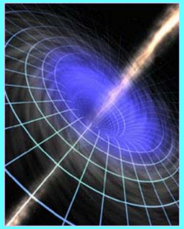
- Matter and curvature of space-time
- “Standard Cosmology”
- Observational data
- Inflation
- Evidence for dark matter
- Searching for dark matter

Curvature

CURVED SPACETIME

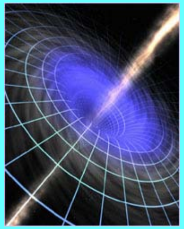


Comments



- Einstein field eqn's describe local effects of curvature (e.g. gravitational lensing, deflection of starlight)…*and* global structure of plausible (and implausible?) universes.
- Note: resemblance to e.g. Maxwell's equations with a "source" term (Stress-energy tensor) and a "field" term (Curvature)

Einstein Field Equation



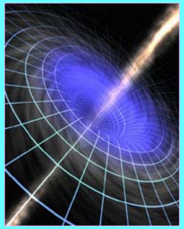
Cosmological constant

$$G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Curvature term

Stress-energy tensor

Stress Energy Tensor



$$T^{\alpha\beta}(x) = \sum_n p_n{}^{\alpha}(t)\frac{dx_n{}^{\beta}(t)}{dt}\delta^3(x - x_n(t))$$

Relativistic hydrodynamic
assumption

$$T^{\alpha\beta} = (\rho + p)U^{\alpha}U^{\beta} + pg^{\alpha\beta}$$

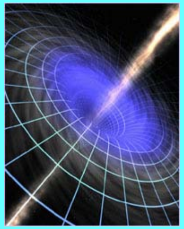
$$g_{\mu\nu} = \frac{\partial\xi^{\alpha}}{\partial x^{\mu}}\frac{\partial\xi^{\beta}}{\partial x^{\nu}}\eta_{\alpha\beta}$$

p pressure

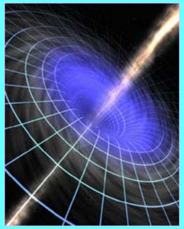
ρ density

U^{α} 4 velocity

Stress-Energy Tensor



- At first difficult to imagine objects (e.g. galaxies) as a hydrodynamic fluid, but this approximation is well merited.
- Components of vacuum energy, “normal” matter, photons, mysterious other terms.
- Work of cosmologists is to evaluate implication of “tweaking” of S-E tensor via introduction of new forms of matter



Curvature I

$$g_{\mu\nu} = \frac{\partial \xi^\alpha}{\partial x^\mu} \frac{\partial \xi^\beta}{\partial x^\nu} \eta_{\alpha\beta}$$

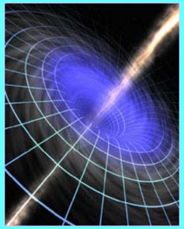
$$\Gamma^\lambda_{\mu\nu} = \frac{\partial x^\lambda}{\partial \xi^\alpha} \frac{\partial^2 \xi^\alpha}{\partial x^\mu \partial x^\nu}$$

$$\eta_{\alpha\beta} = diag(-1,1,1,1)$$

ξ^α Freely falling coord

x^μ Any coord

Curvature II



Curvature scalar

Ricci tensor

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$$

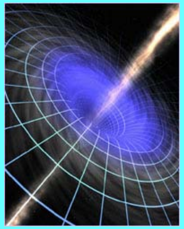
$$R_{\mu\nu} = R^{\lambda}{}_{\mu\lambda\kappa}$$

$$R = g^{\mu\kappa} R_{\mu\kappa}$$

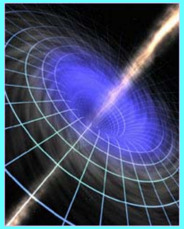
$$R^{\lambda}{}_{\mu\lambda\kappa} = \frac{\partial \Gamma^{\lambda}_{\mu\nu}}{\partial x^{\kappa}} - \frac{\partial \Gamma^{\lambda}_{\mu\kappa}}{\partial x^{\nu}} + \Gamma^{\eta}_{\mu\nu}\Gamma^{\lambda}_{\kappa\eta} - \Gamma^{\eta}_{\mu k}\Gamma^{\lambda}_{\nu\eta}$$

Curvature Tensor

Global Metrics



- Certain global metrics will describe a "cosmology" that will satisfies the Einstein-Field Equations.
- Many have odd features.
- The "standard cosmology" is the Robertson-Walker metric
  - Imbedded expanding 3-sphere – ("expanding balloon" analogy)

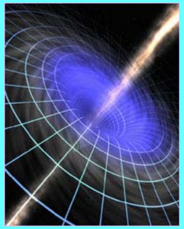


Robertson-Walker Metric

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

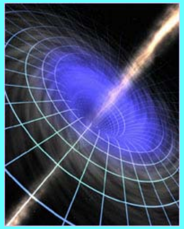
$d\tau$	**Proper time interval**
$R(t)$	**"Radius of Universe"**
k	**Sign of curvature (+1=closed, 0=flat, -1=open)**

FRW Model



- Describes observational data well
- No guarantees that the global topology is as simple as the FRW metric implies (e.g. toroidal universes…can you see the back of your head, multiply connected etc)
- Simple treatment of Stress-Energy tensor
- Concept of a “co-moving” inertial frame (e.g. w.r.t. cosmic microwave background)
- Regions can be out of causal contact

FRW Stress Energy Terms



$$T_{\nu}^{\mu} = diag(\rho, -p, -p, -p)$$

$$(p(t), \rho(t))$$

↓ **1st law of thermodynamics**

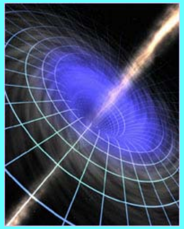
$$d(\rho R^3) = -p d(R^3)$$

↓

$$(p = \frac{1}{3}\rho) \Rightarrow \rho \propto R^{-4}$$ **Radiation**

$$(p = 0) \Rightarrow \rho \propto R^{-3}$$ **Matter**

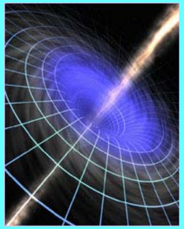
$$(p = -\rho) \Rightarrow \rho \propto (const.)$$ **Vacuum energy**



FRW Universe

- Early universe was radiation dominated
- With no vacuum energy, adolescent and late universe are matter dominated
- With "inflation" (see ahead) very early period where vacuum energy dominated the SE tensor

FRW Universe



G_{00}

$\downarrow$ **Use RW metric to solve Einstein field eqn.**

$$\frac{\dot{R}^2}{R^2} + \frac{k}{R^2} = \frac{8\pi G}{3}\rho$$

Friedmann Equation

$\downarrow$

$$\frac{\dot{R}}{R} \equiv H$$

Define Hubble parameter

$\downarrow$ **Recast Friedmann eqn.**

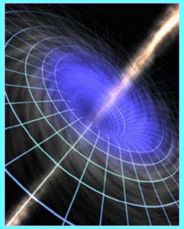
$$\frac{k}{H^2 R^2} = \frac{\rho}{3H^2/8\pi G} - 1 \equiv \Omega - 1$$

$$\Omega \equiv \frac{\rho}{\rho_c}$$

$$\rho_c \equiv 3H^2/8\pi G$$

Critical Density

Relation to curvature

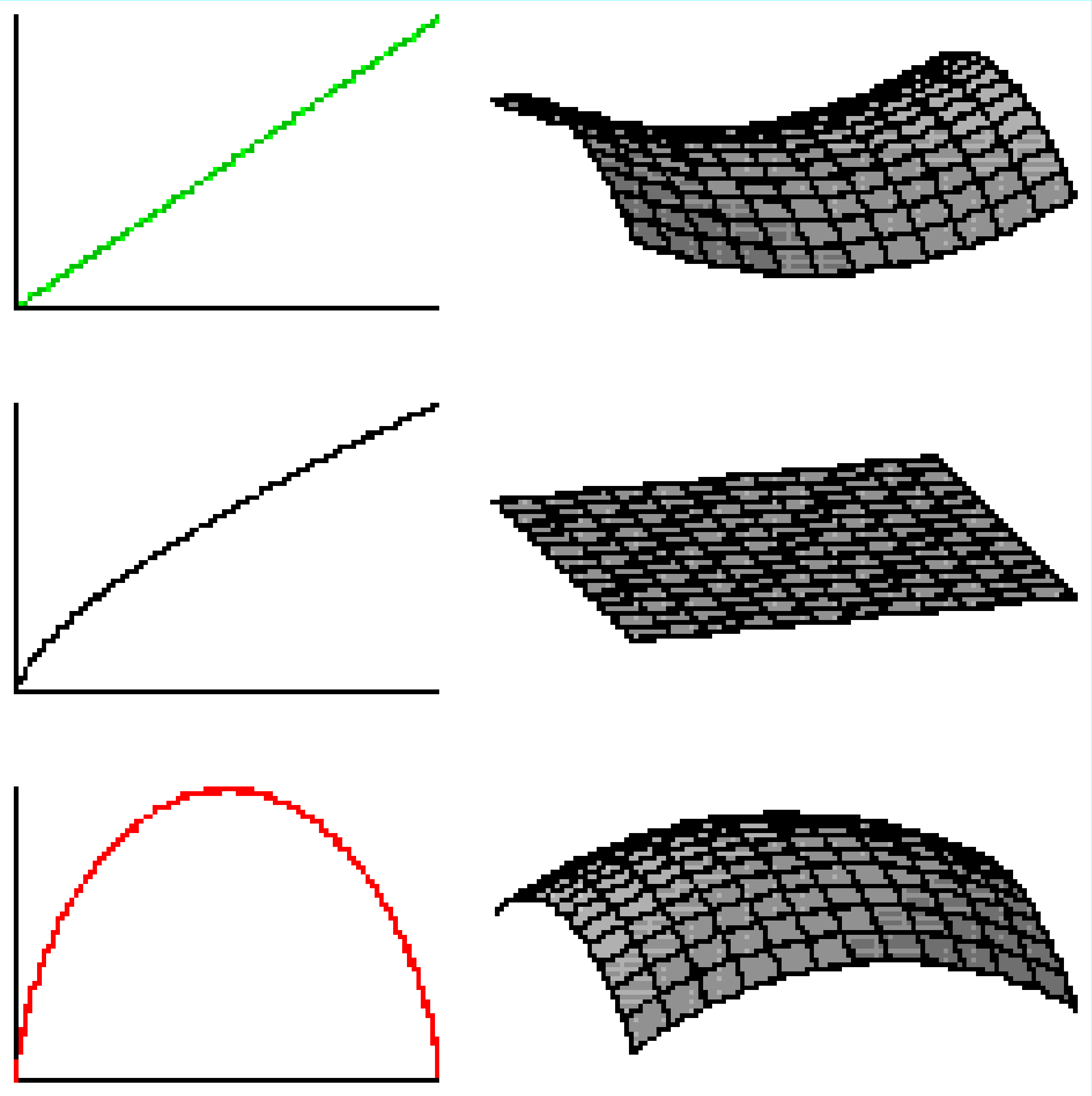


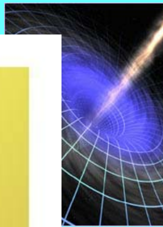
$\Omega > 1$ **Closed**

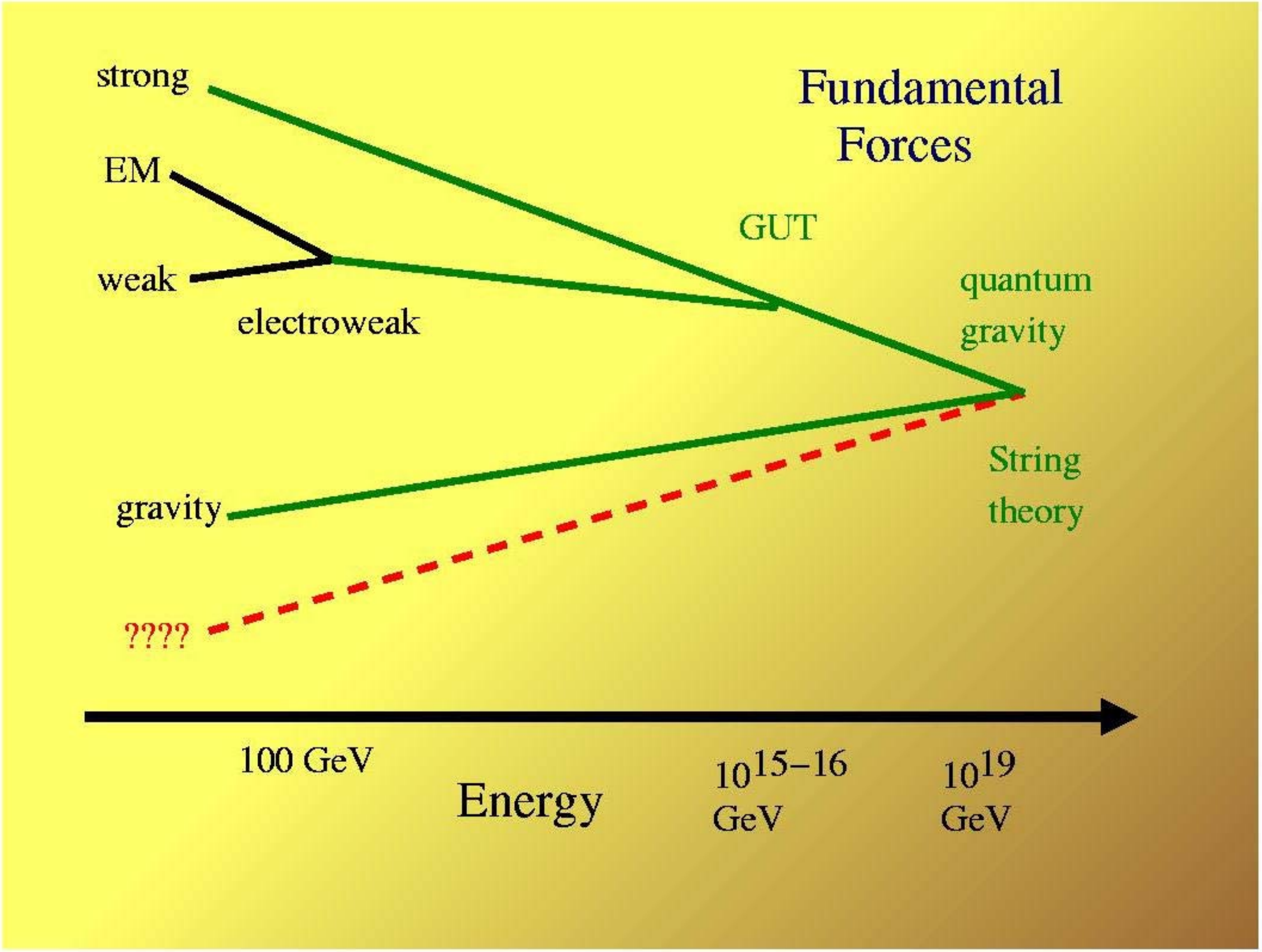
$\Omega = 1$ **Flat**

$\Omega < 1$ **Open**

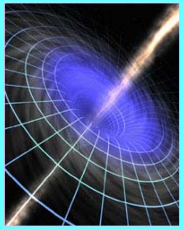
- Density of universe relative to critical density relates to curvature
- Universe is old, means that Ω cannot be too large or density was too high



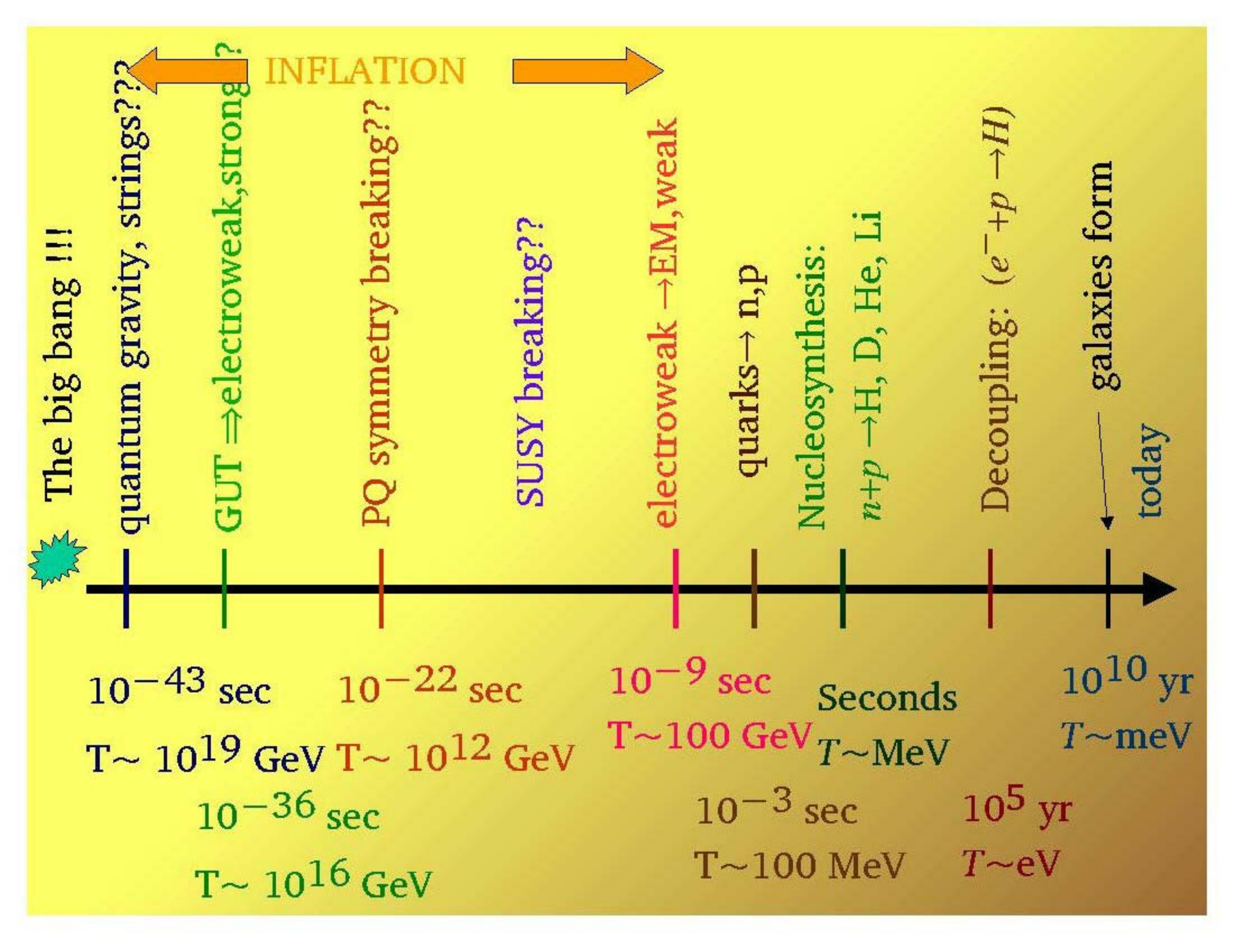



Fundamental
Forces
strong
EM
weak
electroweak
GUT
quantum
gravity
String
theory
gravity
????
100 GeV
Energy
10^15−16
GeV
10^19
GeV

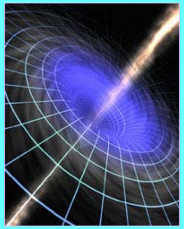
Epochs of FRW Universe



- Planck Era
  - Wave function of the universe(?)
- (Inflation – symmetry transition)
- Baryogenesis
- Nucleosynthesis
- Neutralization ("freeze out")
- Star/galaxy formation

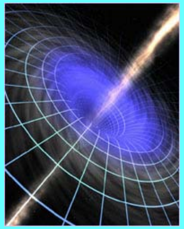

INFLATION
The big bang !!!
quantum gravity, strings???
GUT ⇒electroweak,strong?
PQ symmetry breaking??
SUSY breaking??
electroweak →EM,weak
quarks→ n,p
Nucleosynthesis:
$n+p \to$H, D, He, Li
Decoupling: $(e^- + p \to H)$
galaxies form
today
10^{-43} sec
T~ 10^{19} GeV
10^{-36} sec
T~ 10^{16} GeV
10^{-22} sec
T~ 10^{12} GeV
10^{-9} sec
T~100 GeV
10^{-3} sec
T~100 MeV
Seconds
T~MeV
10^5 yr
T~eV
10^{10} yr
T~meV

Particle Connections

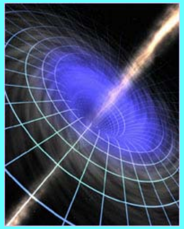


- The early universe is, in a sense, a laboratory for particle interactions
  - Baryogenesis – CP violation (GUT scale)
  - Inflation – symmetry breaking
  - Overall mass – supersymmetry (TeV scale)
  - Nuclear synthesis
  - Radiation - interaction with matter before freeze-out
  - Remaining vacuum energy (?) present

What can we observe?



- Red shift versus distance (R(t)-effectively)
  - Cepheids, SN, sizes, luminosity of galaxies
- Age of the universe
  - Radioactive clocks (U^{238} to U^{235} ratio)
  - Stellar populations
- Cosmic microwave background radiation
- Structure formation (distribution of mass)
- Nuclear abundances



Uranium Isotopic Content

$$\left[{}^{235}U/{}^{238}U\right] \cong 1.71$$

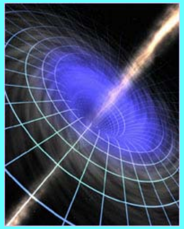
Production abundances

$$\left[{}^{235}U/{}^{238}U\right] \cong 0.00732$$

Observed abundances

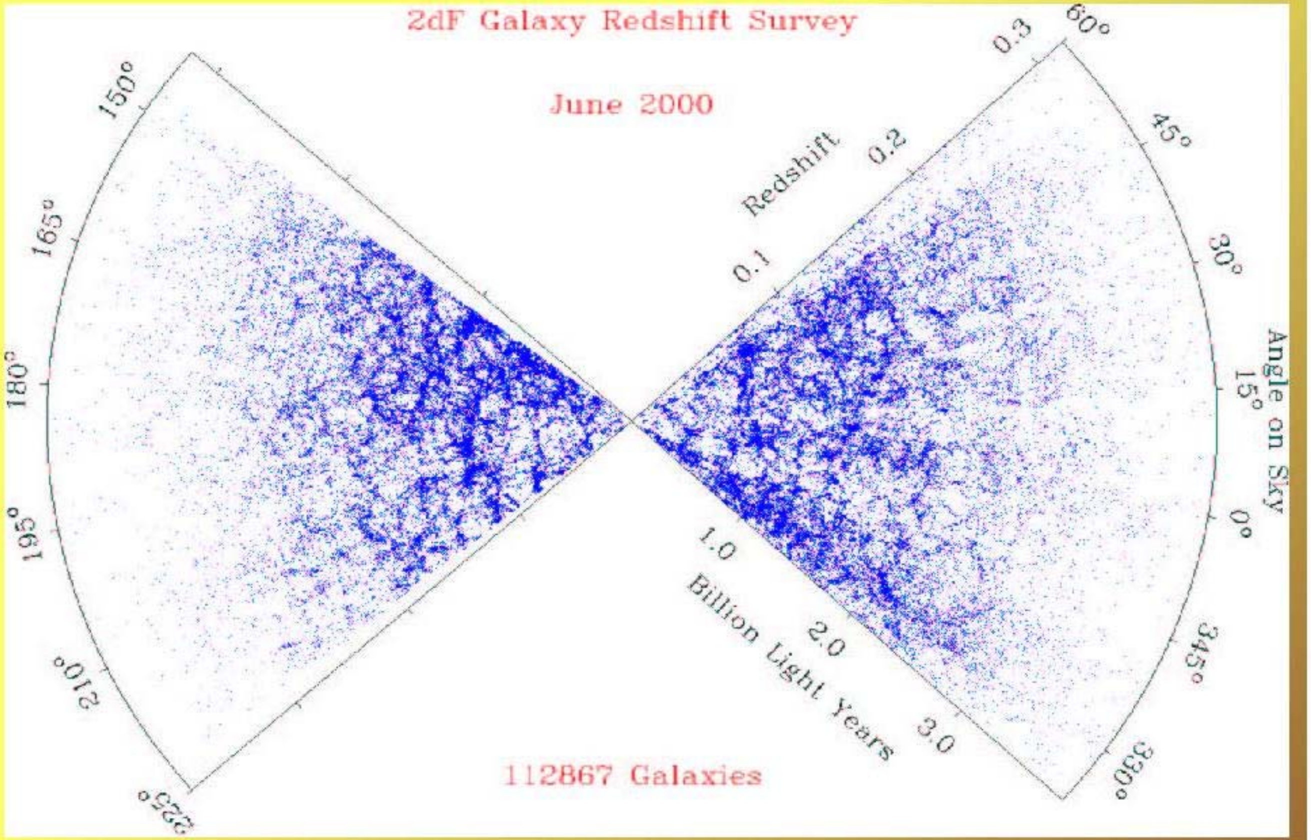
$$\Delta t = \frac{\ln\left[{}^{235}U/{}^{238}U\right]_P - \ln\left[{}^{235}U/{}^{238}U\right]_O}{\tau_{235}^{-1} - \tau_{238}^{-1}} \cong 6.6\,Gyr$$

Red Shift Versus Distance

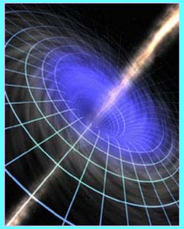


- The farther away you look, the more red-shift one sees.
- Effects of
  - Recessional velocity associated with expansion of universe
  - Looking "backward in time"

Galaxy megasurveys now mapping mass distribution over huge volumes (2dF and SDSS)

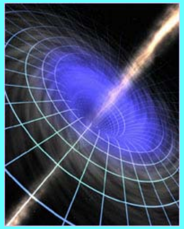


Age/Mass/Curvature



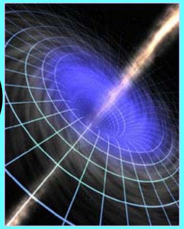
- Combination overconstrains FRW model
- Depending on test – 10-20 Gyr=age (14.37 Gyr?)
- Hubble constant measurements, Ω_o=1 (flat)
- Contributions to Ω
  - Luminous matter
  - Dark baryons (jupiters…)
  - Halos
  - Unclustered
  - Vacuum energy

Cosmic Distance Ladder



- Parallax – near star distances
- Kinds of stars, luminosity, spectrum
- Cepheids – variable stars with well defined periodicity/luminosity
- Supernovae – universal brightness curve
- SZE effect – using cosmic microwave background as “standard candle”

Mass Contributions(Circa 1989)



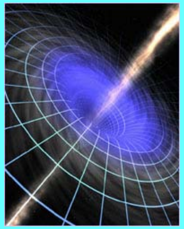
$$\Omega_{LUM} \approx 0.01$$ Luminous

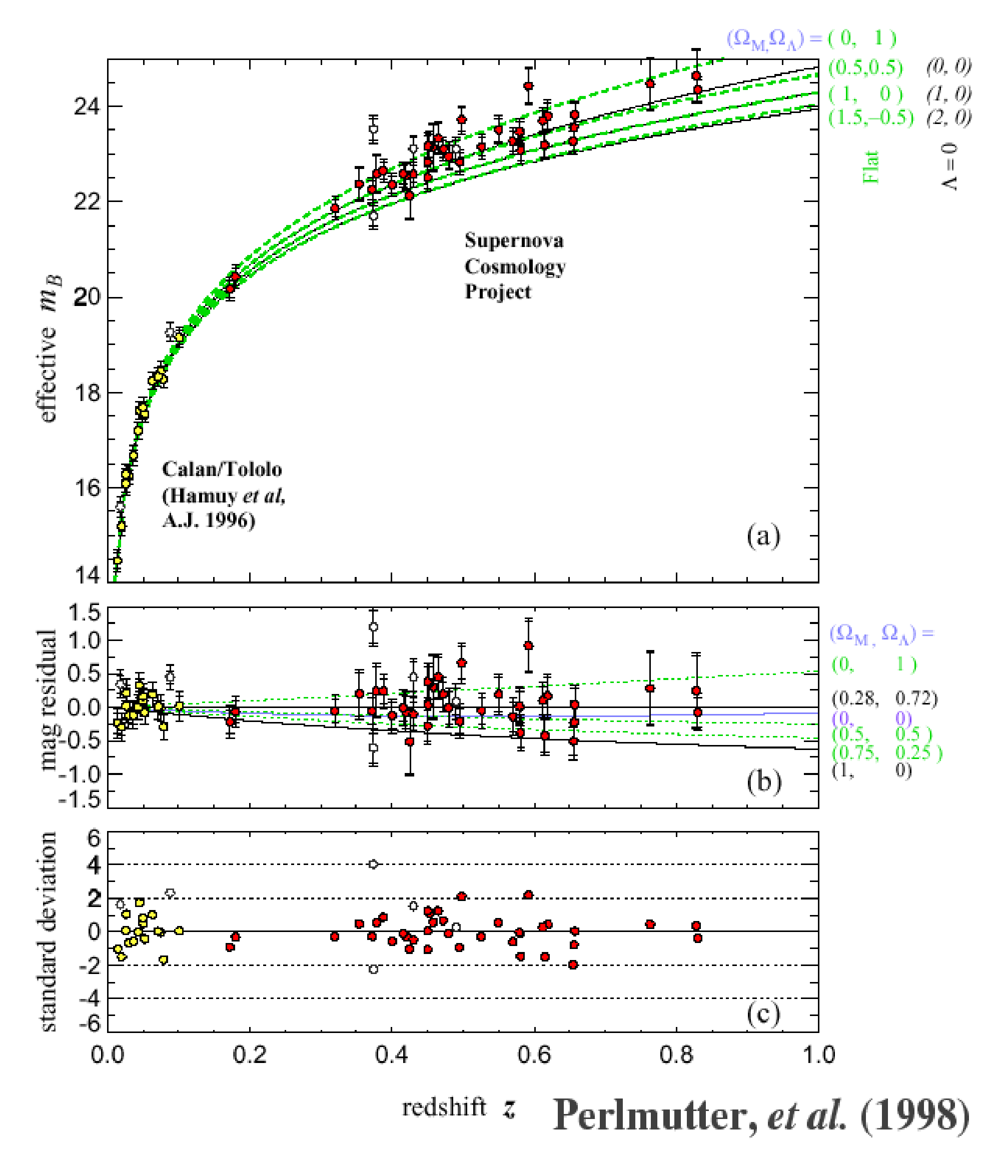
$$\Omega_{Halo} \geq 0.1 \approx 10\Omega_{LUM}$$ Halo

$$\Omega_{b} \geq 0.015$$ Baryonic

Assuming critical density

$$\Omega_{unclustered} = 0.8$$ Smooth at 10-30 Mpc distance scales



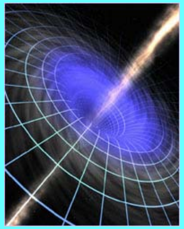


(ΩM,ΩΛ) = (0, 1)
(0.5,0.5) (0, 0)
(1, 0) (1, 0)
(1.5,–0.5) (2, 0)
Flat
Λ = 0
effective mB
Supernova Cosmology Project
Calan/Tololo (Hamuy et al, A.J. 1996)
(a)
mag residual
(ΩM , ΩΛ) =
(0, 1)
(0.28, 0.72)
(0, 0)
(0.5, 0.5)
(0.75, 0.25)
(1, 0)
(b)
standard deviation
(c)
redshift z
Perlmutter, et al. (1998)

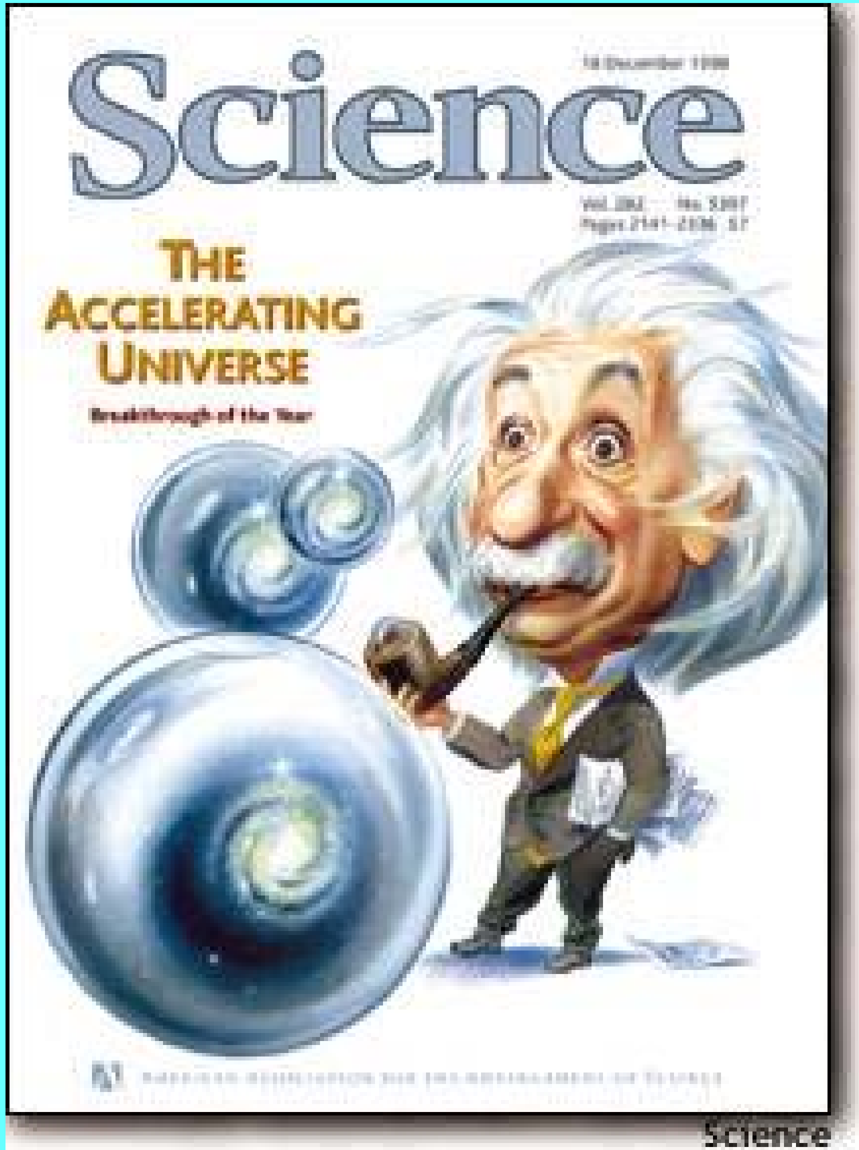
Recent Fits

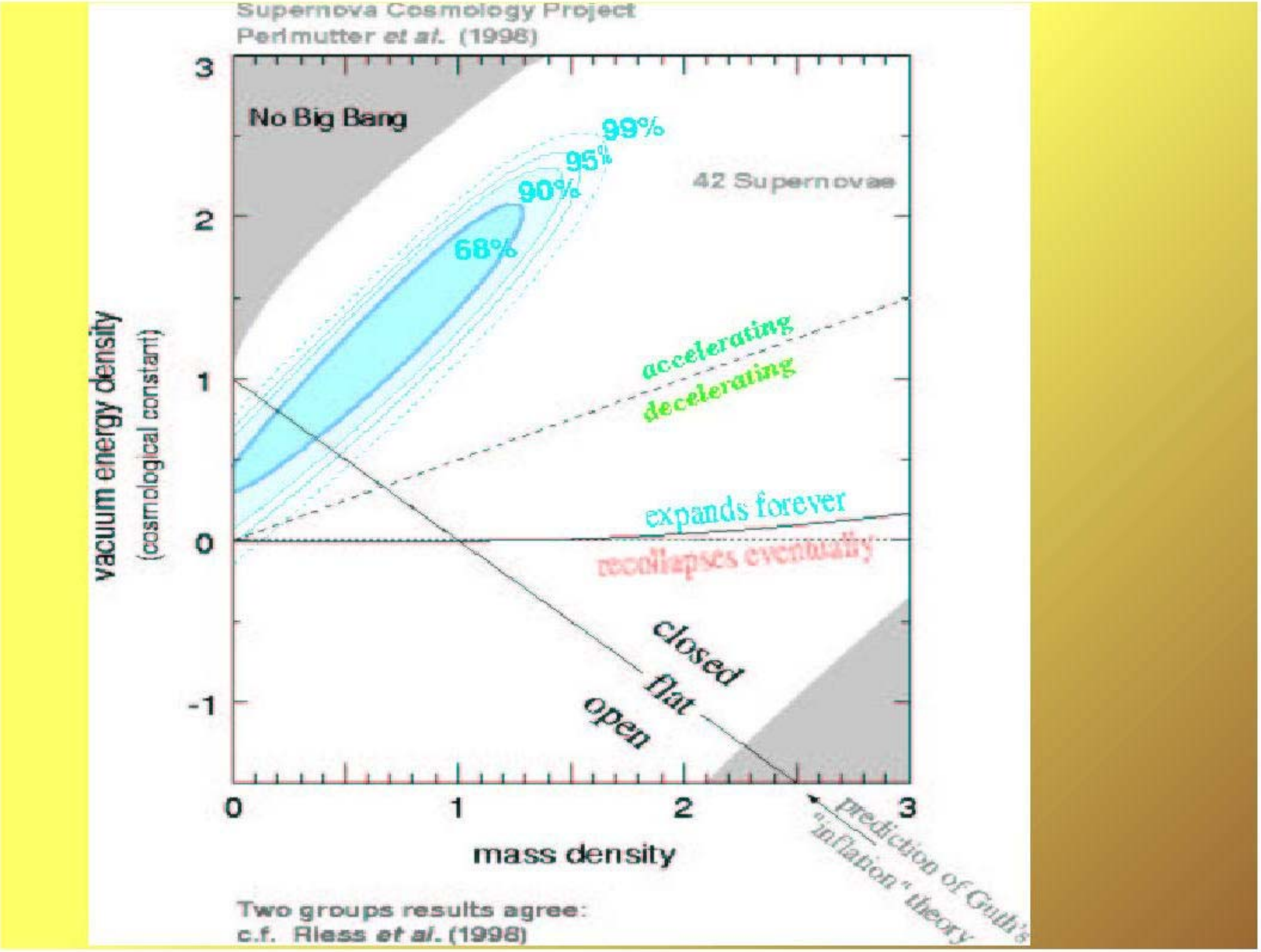
- 70% “dark energy”
- 24% “dark matter”
- 4% baryonic matter
- Mainly from Supernova survey (Perlmutter et al.)
- New projects will help elucidate this

Dark Energy

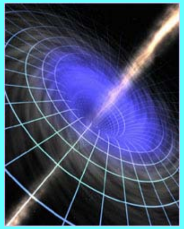


- Non-zero vacuum energy contributions to FRW universe can produce unusual effects
  - Inflation
  - “acceleration” of Hubble Expansion
- Recent surveys of redshift versus distance sets scale – is suggestive of a vacuum energy contribution (equivalent to Λ term in Einstein eqn)
- Ω_M versus Ω_Λ


Science
THE ACCELERATING UNIVERSE
Breakthrough of the Year
Science

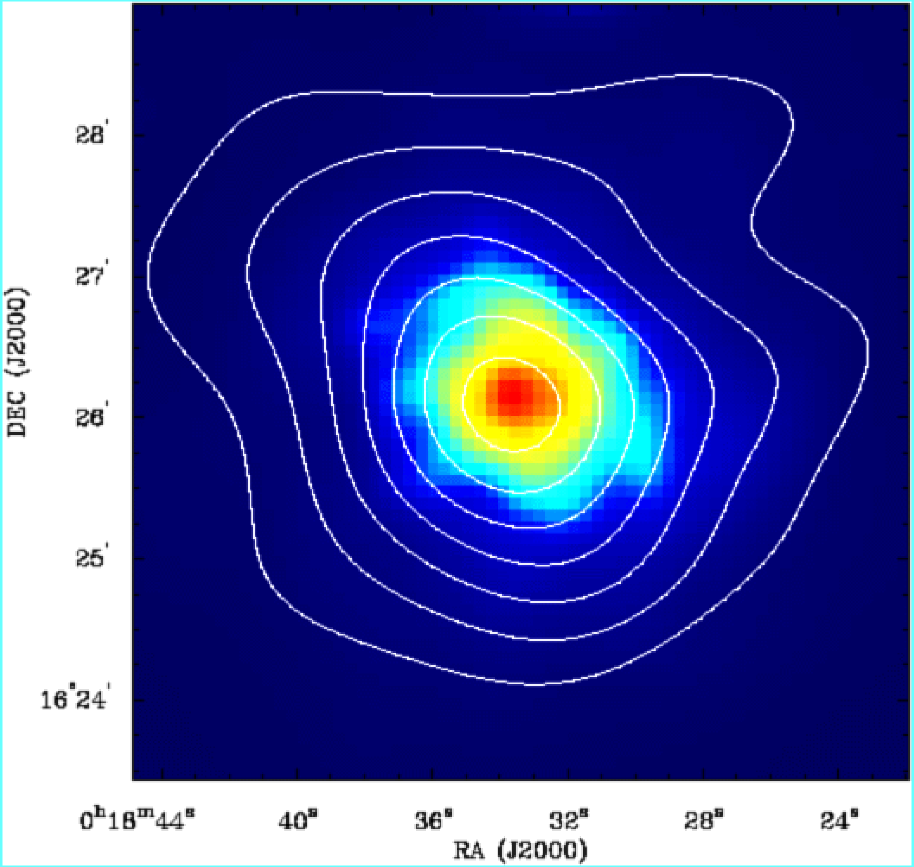

Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
accelerating
decelerating
expands forever
recollapses eventually
closed
flat
open
vacuum energy density
(cosmological constant)
mass density
prediction of Guth's "inflation" theory
Two groups results agree:
c.f. Riess et al. (1998)
3
2
1
0
-1
0
1
2
3

The Sunyaev-Zel'dovich Effect

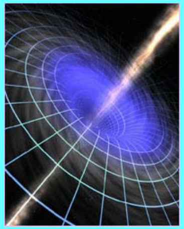


- Future path to elucidating the Hubble curve
- CMB photons scatter from ionized electrons in galaxy, giving a measure of temperature, and can be compared to redshift measurements to get larger distance measurements
- Existence proof by J. Carlstrom (U. Chicago)

SZE effect

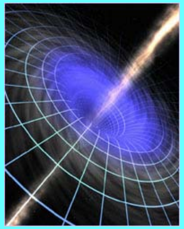


28'
27'
26'
25'
16°24'
DEC (J2000)
0h18m44s
40s
36s
32s
28s
24s
RA (J2000)



Isotropy Problem

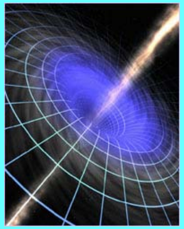
- At time of neutralization, 10^5 causally disconnected regions
- CMB uniform to about 1 part in 10^4 (most angular scales, subtracting out earth's motion wrt co-moving frame)
- Finite horizon makes it "impossible" to achieve this isotropy



Other unresolved issues

- From Grand-unification, theories predict a density of monopoles, cosmic strings, etc, which is not observed
- Flatness, $\Omega = 1$ (identically?)

Inflation



- After GUT symmetry breaking – a phase transition associated with a Higgs-like potential creates a very rapid expansion
  - Starts at 10^{-34} sec, lasts 10^{-32} sec
  - Spreads out universe by factor of 10^{-43}
- Preserves uniformity after causal disconnect
- Spreads out monopoloes
- Gives flat universe
- Variation: chaotic inflation

Higgs Potential

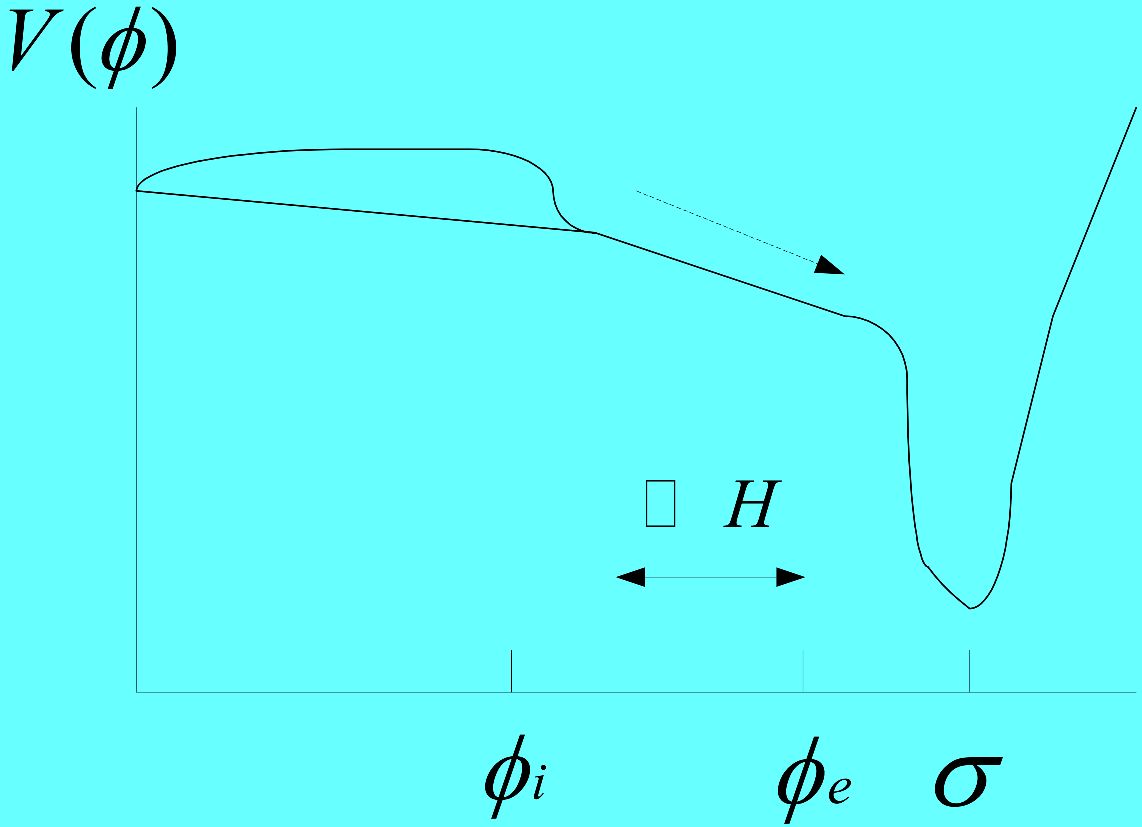
Higgs Potential

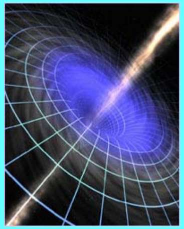
$$V(\phi) = -\frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

↓ Minima of Higgs potential

$$\sigma_{\pm} = \pm\sqrt{\frac{m^2}{\lambda}}$$

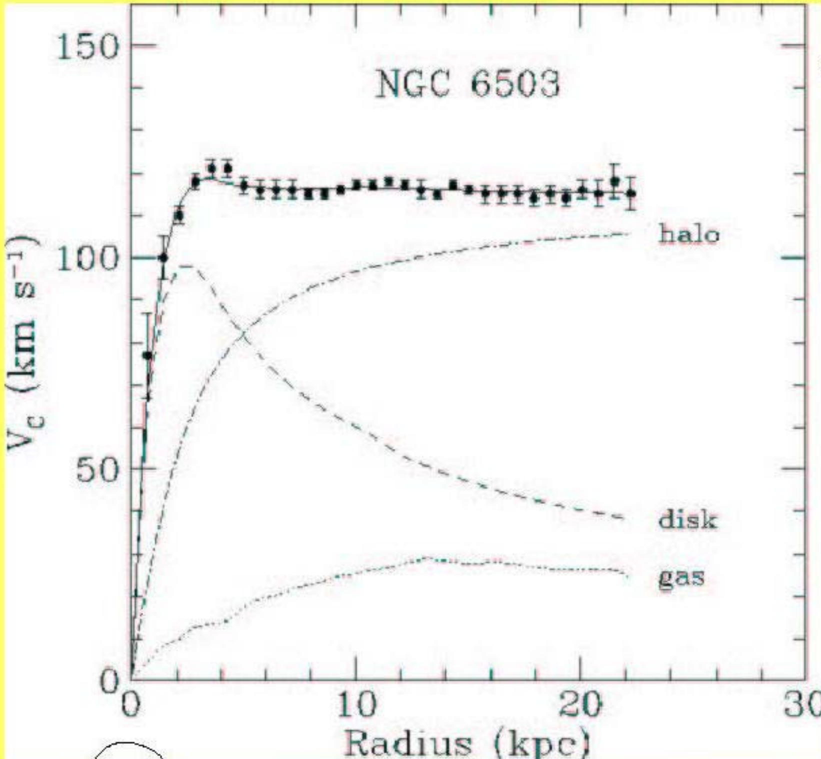
Inflationary potential





Dark Mass

- Evidence
  - Ω=1 discrepancy
  - Gravitational lensing
  - Supercluster velocities (Virgo infall)
  - Galactic rotation curves
- Origins
  - High velocity massive particles
  - Large population of “dark” galaxies
  - Significant vacuum energy contributions



density

core radius

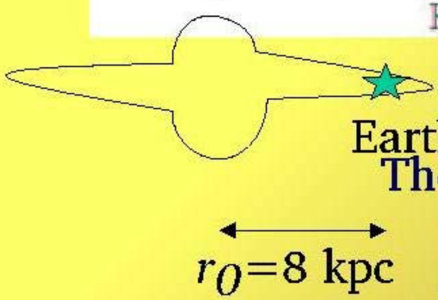
$$\rho(r) = \rho_0 \frac{r_0^2 + a^2}{r^2 + a^2}$$

spherical halo:

ρ_0=0.3–0.6 GeV/cm^3

If halo flattened,

$\rho_0 \uparrow$

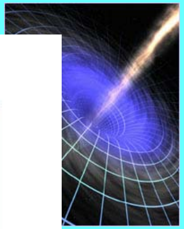


r →

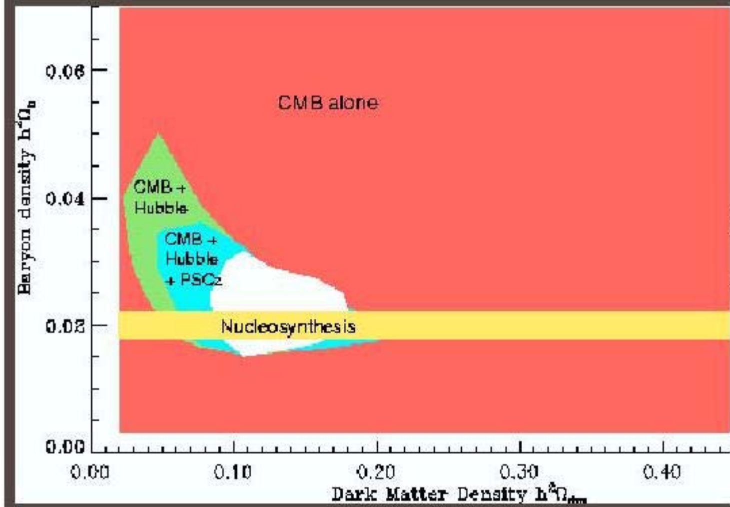
Velocity distribution ~ Maxwell–Boltzmann

With $\langle v^2 \rangle^{1/2}$~270 km/sec

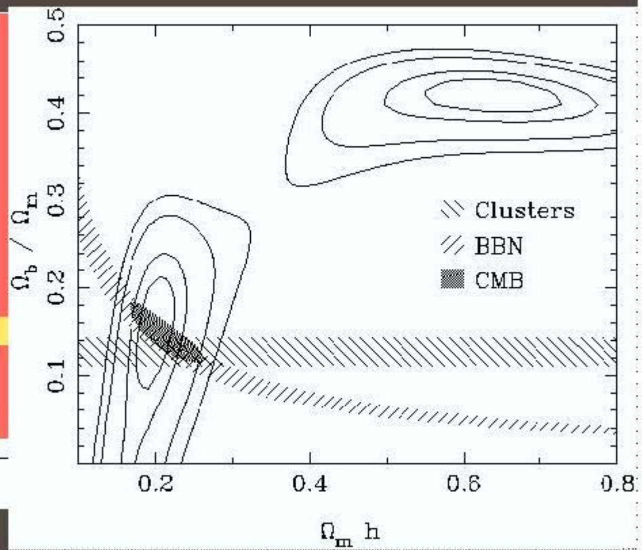
The standard smooth halo model



The matter budget



wang,tegmark,zaldarriaga,astro-ph/0105091



percival et al., ,astro-ph/0105252: likelihood surfaces for the best fit linear power spectrum

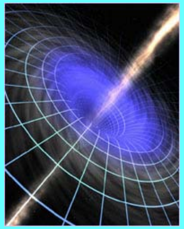
CMB
+ IRAS PCSz power spectrum
+ Hubble param. prior h=0.7

Ω_{dm} = 0.24+/-0.06
Ω_b = 0.04+/-0.02

Galaxy clustering: the 2dF galaxy redshift survey > 160 000 galaxies

Ω_m = 0.29 +/- 0.04
Ω_b = 0.04 +/- 0.02

Dark Mass Candidates



- Must be weakly interacting (broad distribution, no radiation damping)
- Neutrinos not favored
- Axions – associated with strong CP problem – perhaps
- Supersymmetric matter
  – Neutralinos

Favourite WIMP candidate: **neutralino**

if SUSY exists and R-parity $(-1)^{3(B-L)+2S}$ is conserved

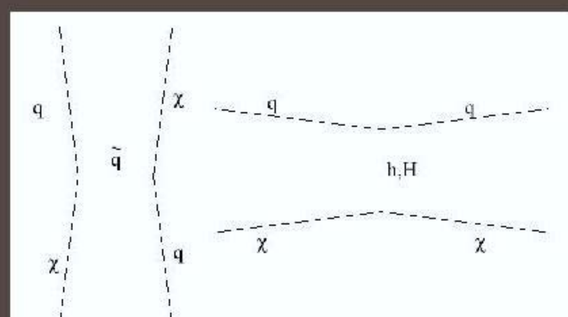
=> LSP is stable: potential DM candidate!

in general: mixture of photino, zino and higgsinos

$$\chi = \alpha\tilde{\gamma} + \beta\tilde{Z} + \gamma\tilde{H}_1^0 + \delta\tilde{H}_2^0$$

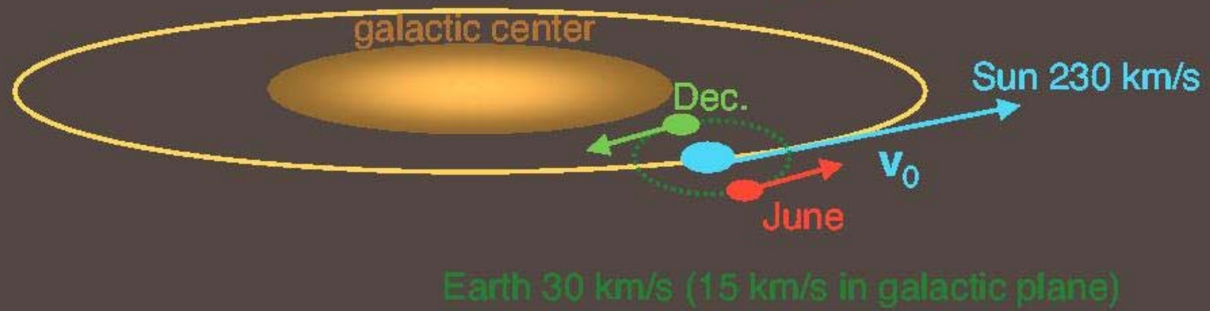
⇒prediction of masses, scattering cross sections

⇒elastic χ nucleus cross section dominated by SI part



Annual Modulation of Rate & Spectrum

WIMP Isothermal Halo (assume no co-rotation) v_0~ 230 km/s

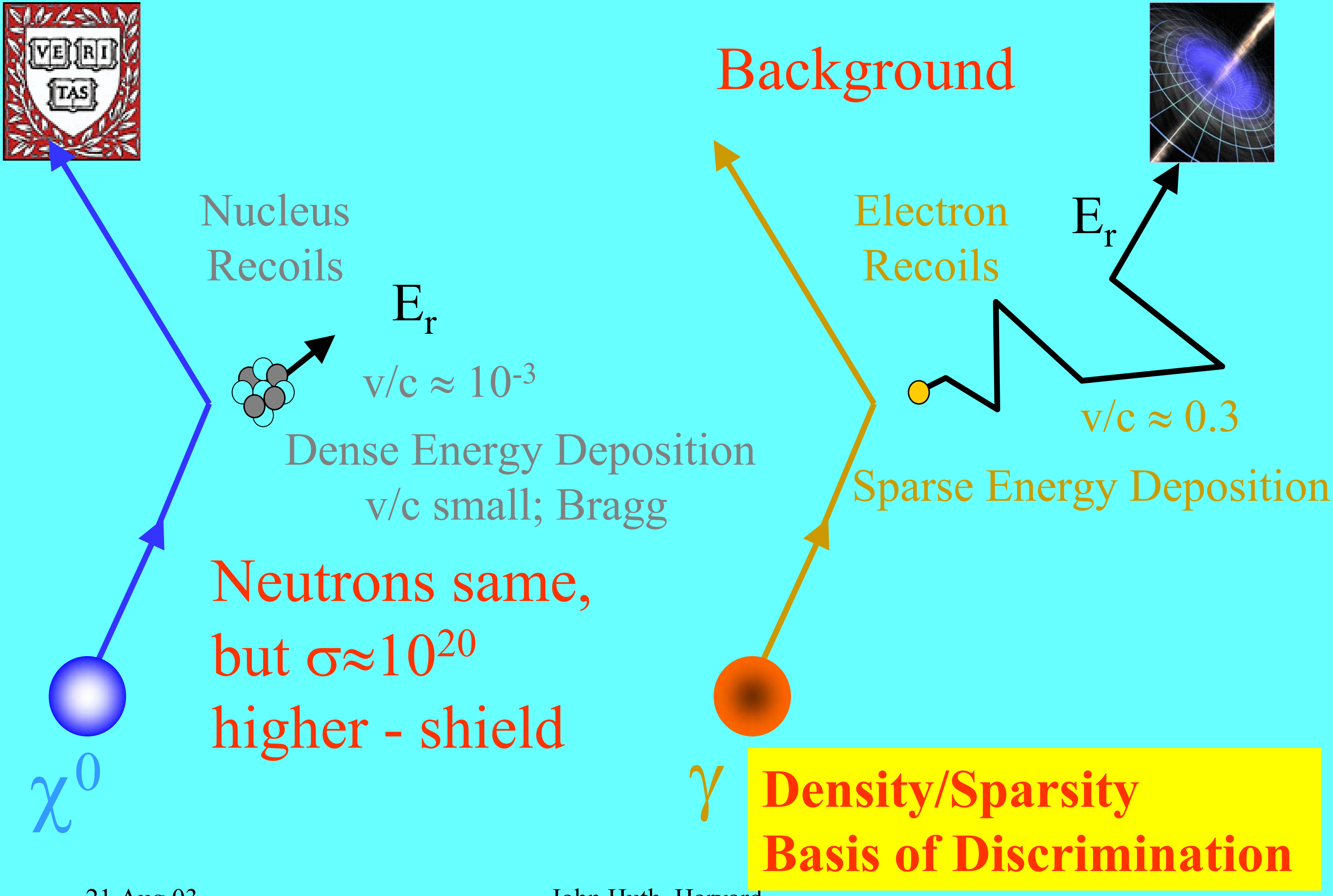


Combining earth and solar system motion around galaxy :

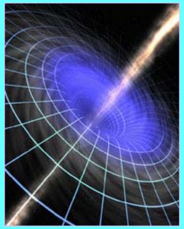
$$T(Q) = \frac{\sqrt{\pi}\, v_0}{4 v_e}\left[\mathrm{erf}\left(\frac{v_{\min} + v_e}{v_0}\right) - \mathrm{erf}\left(\frac{v_{\min} - v_e}{v_0}\right)\right]$$

where $v_e = v_0\left[1.05 + 0.07\cos\left(\frac{2\pi\left(t - t_p\right)}{1\ \mathrm{yr}}\right)\right]$

t_p = June 2 ± 1.3 days


Background
Nucleus
Recoils
E_r
$v/c \approx 10^{-3}$
Dense Energy Deposition
v/c small; Bragg
Neutrons same,
but $\sigma \approx 10^{20}$
higher - shield
χ^0
Electron
Recoils
E_r
$v/c \approx 0.3$
Sparse Energy Deposition
γ
Density/Sparsity
Basis of Discrimination

Dark Matter Detection



- Velocity of earth wrt WIMP cloud
  - Whatever that is!!! 300 km/sec minimum
  - 100 GeV scale – massive critters
- Backgrounds are the devil!!!
  - Cosmics
  - Residual radiation in materials
- CDMS (cryo dark matter search)
  - Solid state detectors – measure both phonons *and* ionization loss of recoil nuclei

WIMP nucleus cross section

Study the low energy SUSY theories which arise from GUT, supergravity or string theories, reduce > 100 MSSM parameters to 5-7...

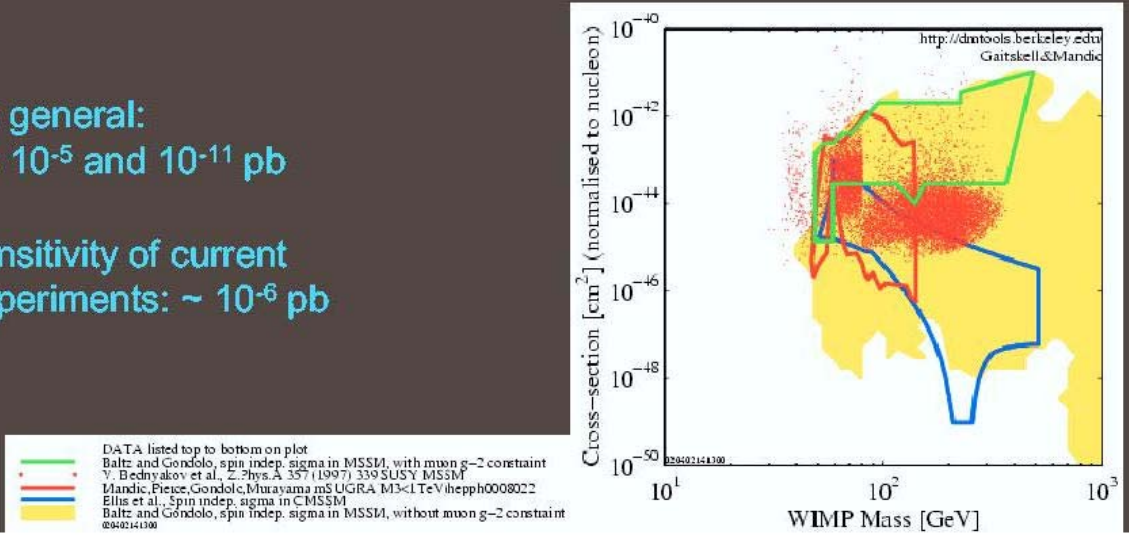
When masses and couplings fixed: calculate the WIMP-nucleus cross section (from χ-quark cross section, QCD, nuclear physics...)

Theorists survey a large set of models with masses and couplings within a plausible range; impose laboratory and relic density constraints

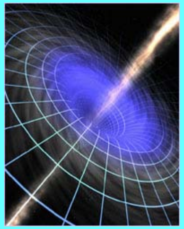
plots of elastic scattering cross sections versus neutralino mass

in general:
σ: 10^{-5} and 10^{-11} pb

sensitivity of current experiments: ~ 10^{-6} pb



The Experiments



CDMS - Ge/Si, measure ionization (Q) and heat/phonons (P)

Recoil/γ discrimination: Q/P

2 Detector Types, 2 sites! Updated Result

ZEPLIN 1 - Liq Xe, measure scintillation

Recoil/γ discrimination: Pulse Shape in Time

2 more ZEPLIN's - add ionization New Result

DRIFT - CS_2, measure ionization (Q)

Recoil/γ discrimination: Spatial Distribution of Q

Directionality

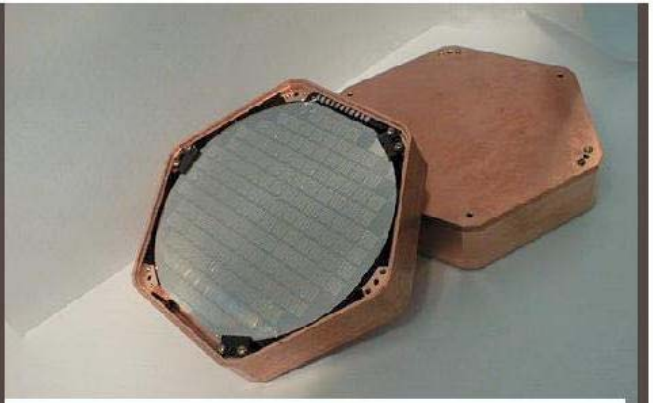
CDMS detectors

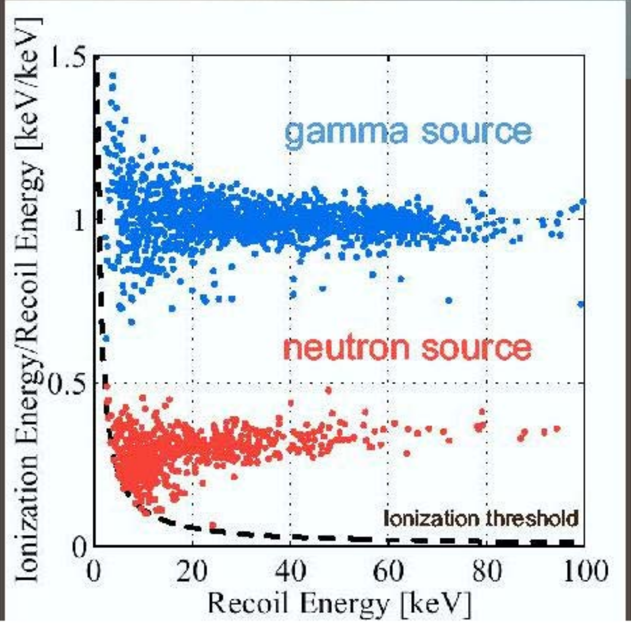
Ultra-pure Si and Ge crystals:
1cm thick; 7.5cm diameter.

measure phonons and ionization signals after an interaction

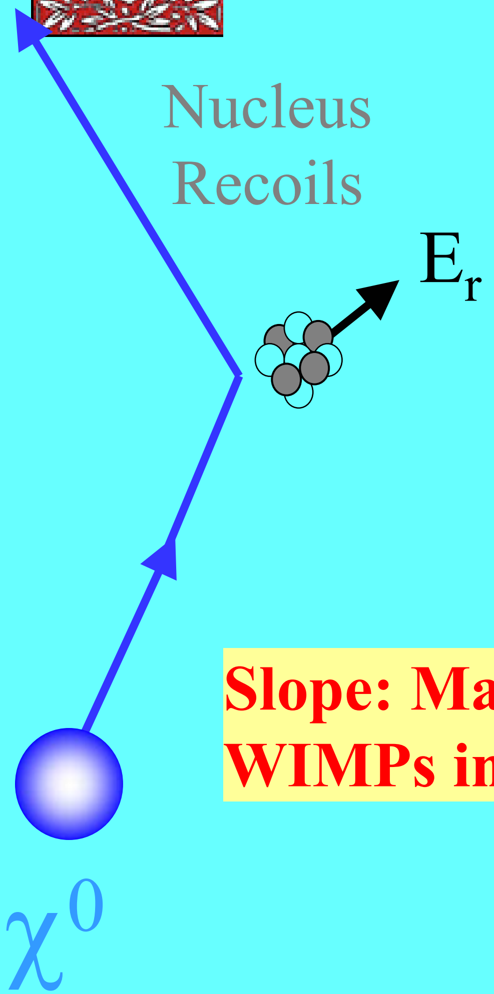
discrimination between nuclear and electron recoils

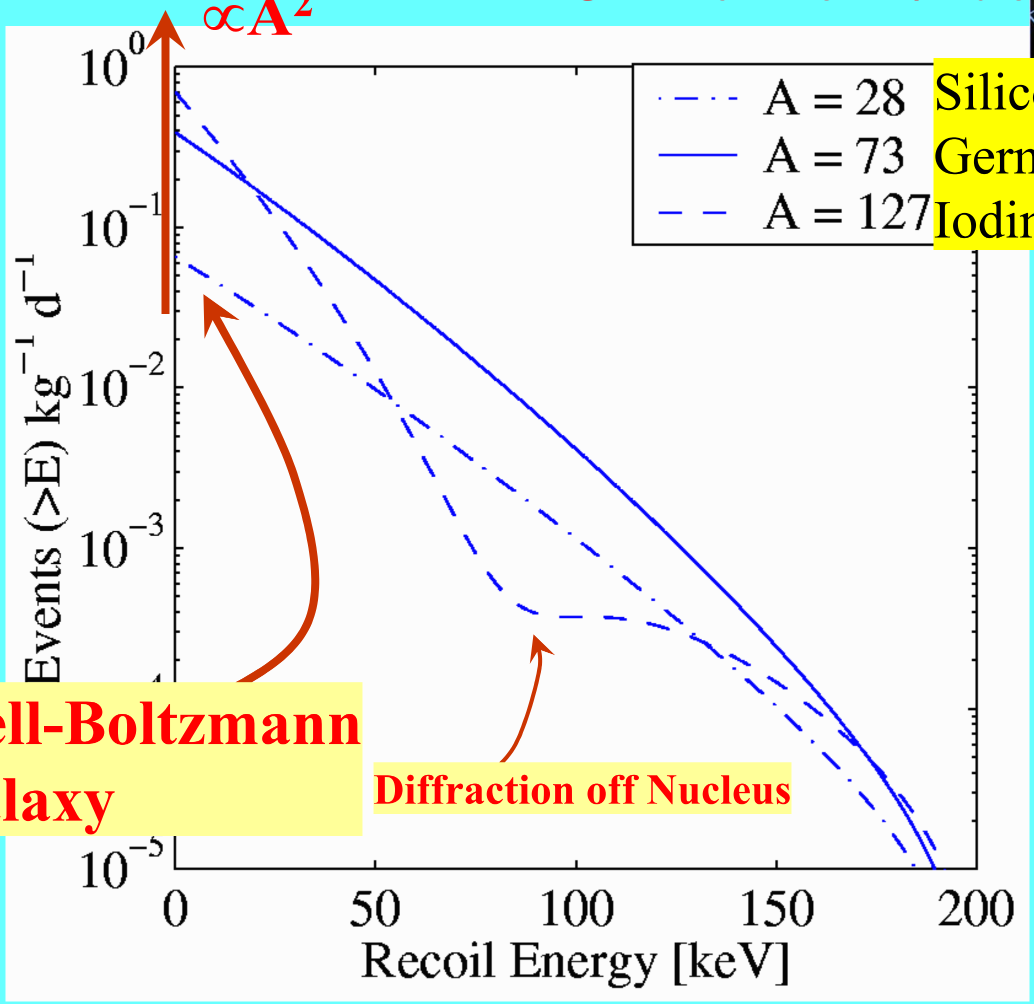
nuclear recoils: WIMPs, n
electron recoils: γ,e





M_{WIMP}=100 GeV
$\sigma = 10^{-42}$ cm²/nucleon



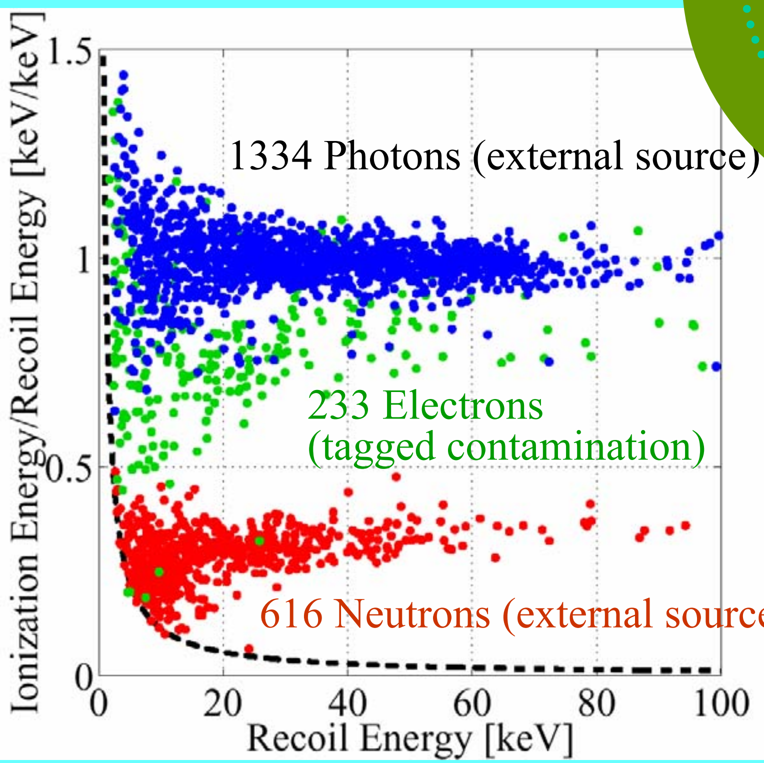


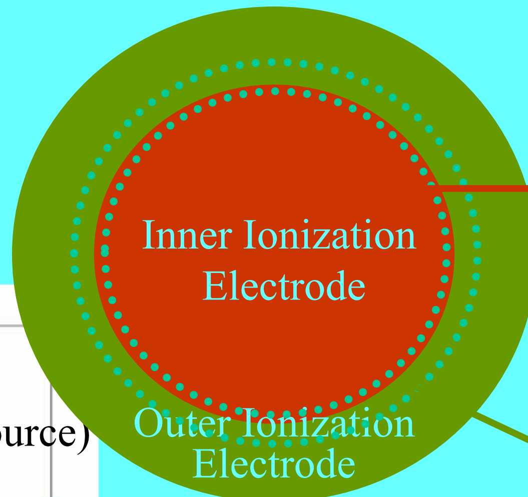
Slope: Maxwell-Boltzmann
WIMPs in Galaxy

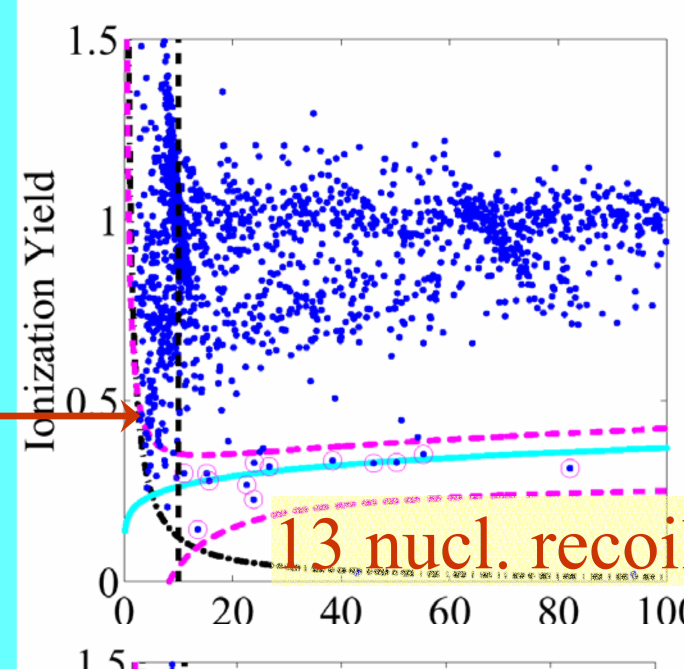
CDMS Data

Inner: 12 kg-d

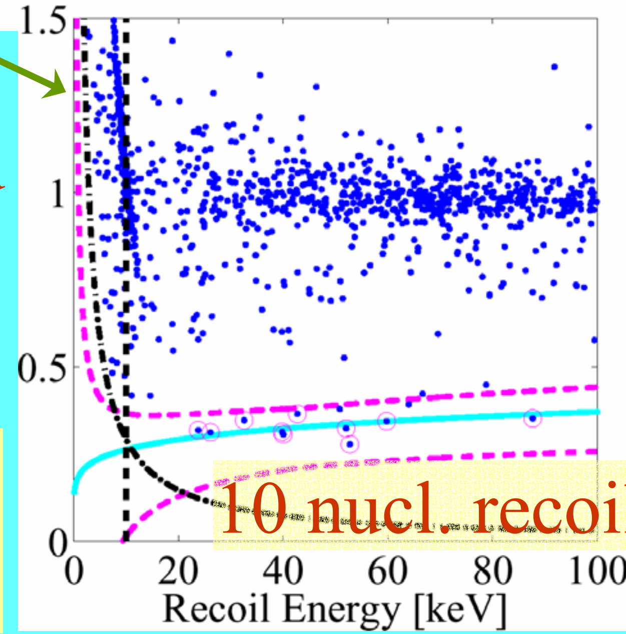
Calibration





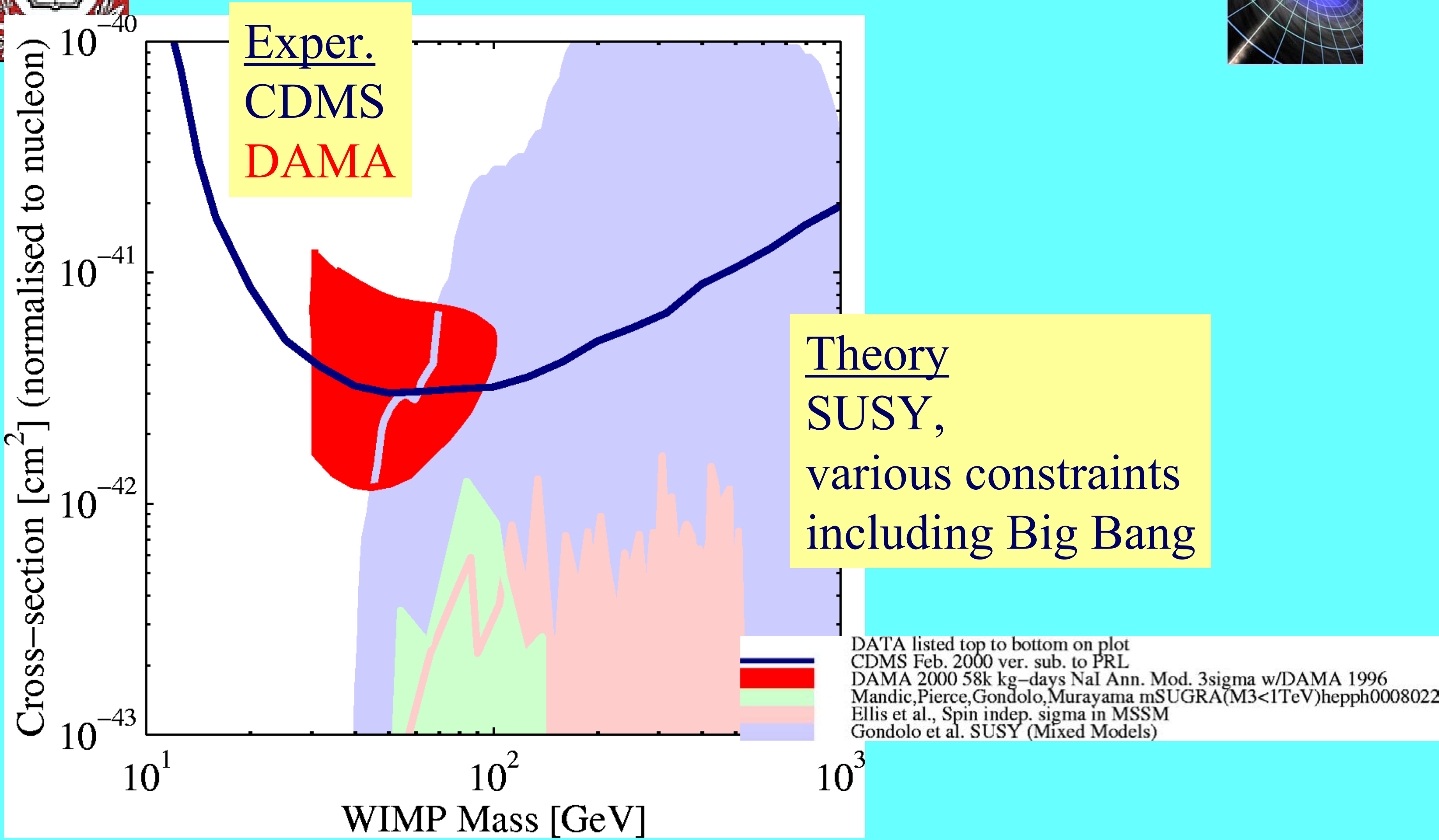


Shared: 4.4 kg-d



Shallow: Neutrons

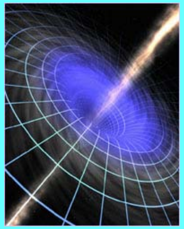
WIMP/nucleon $\sigma \approx 10^{-42}$ cm



Not covered here

- CMB (Scott)
- Nuclear abundances (Scott)
- CP violation, baryogenesis (Kate)

Conclusions/caveats



- It would be interesting to dig up this talk in 10 years and see how things stand up
  - Will Dark Energy Survive?
  - Will we find WIMP's or understand dark matter?
  - Will symmetry breaking shed light on inflation?
  - What does a TeV scale Planck scenario imply?
  - Will FRW models still be the standard?