New Views of Cosmology and the Microworld

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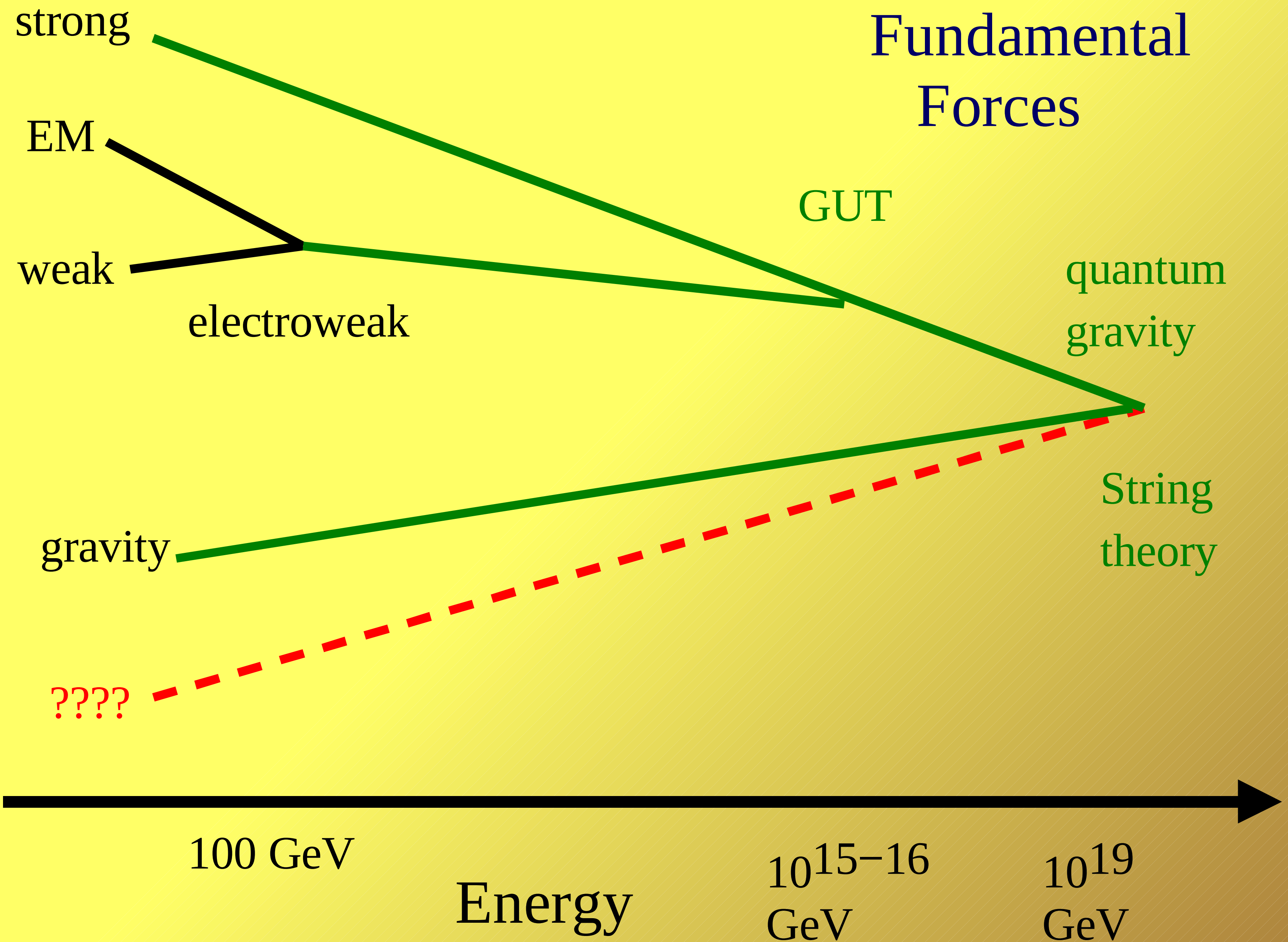
Topics in Particle Astrophysics and Cosmology:

I. Dark matter and relic particles
II. Gamma rays and x rays (GLAST, STACEE, VERITAS….)
III. The CMB and inflation
IV. Structure formation, cosmological parameters,
dark energy
V. Ultrahigh energy cosmic rays
VI. Gravitational radiation
VII. Neutrino astrophysics
VIII. Early universe and tests of fundamental physics
brane worlds and large extra dimensions

(see, e.g., Akerib, Carroll, MK, Ritz, summary of P4 Working Group at Snowmass 2002, hep−ph/0201178

Fundamental Forces



strong

EM

weak

electroweak

GUT

quantum gravity

gravity

String theory

????

100 GeV

Energy

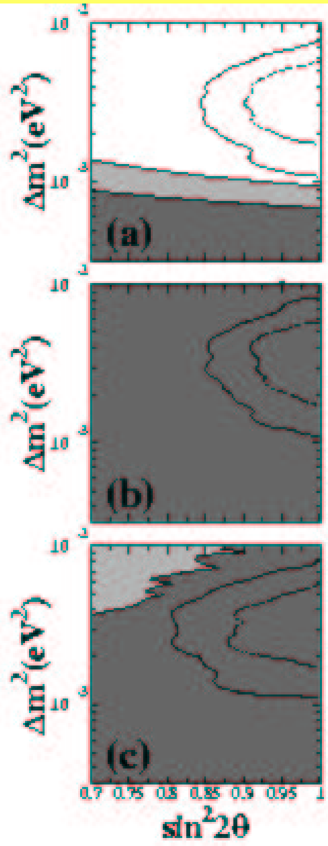
10^{15-16} GeV

10^{19} GeV

Astrophysics/cosmology and advances in fundamental physics; history:

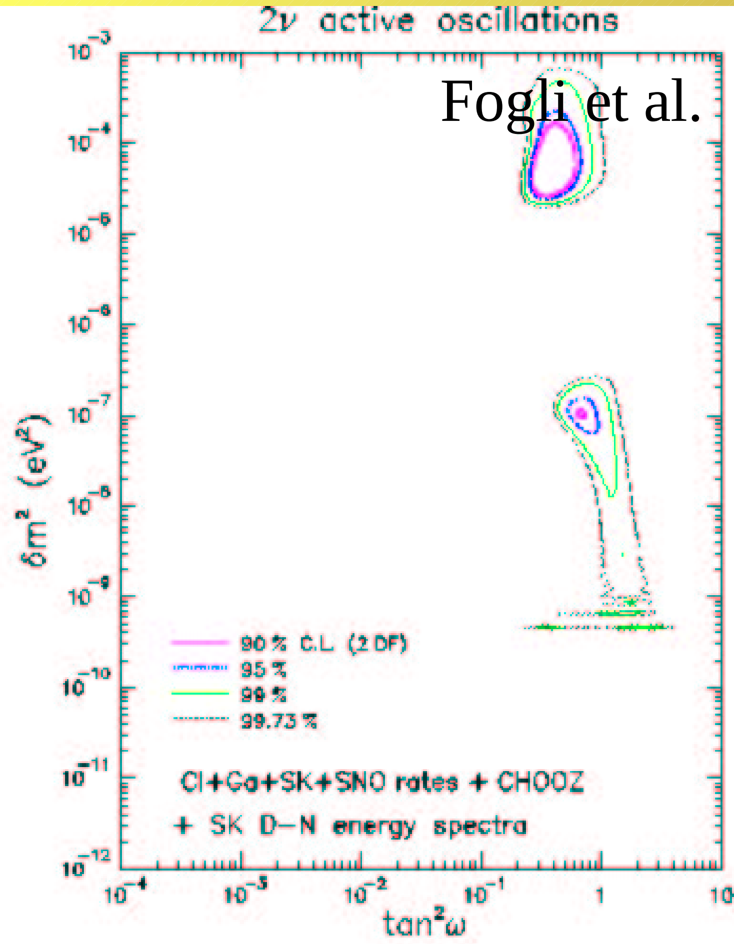
- Kepler's and Newton's laws
- Discovery of helium
- Serendipitous discovery of positrons, muons in cosmic rays
- Big bang nucleosynthesis and number of light neutrinos
- Cosmological constraints to stable neutrino masses
- Solar and atmospheric neutrinos and neutrino masses
- Astrophysical verifications of general relativity
  - Eddington and bending of light
  - expansion of Universe
  - pulsar timing and gravitational waves

Physics with astrophysical particles: neutrino masses and mixing from solar and atmospheric neutrinos



Super−K

FIG. 2. Excluded regions for three oscillation modes. (a) $\nu_\mu \leftrightarrow \nu_\tau$, $\nu_\mu \leftrightarrow \nu_s$ with (b) $\Delta m^2 > 0$ and (c) $\Delta m^2 <$ 0, the light(dark) gray region is excluded at 90(99)% C.L., Thin dotted(solid) line indicates the 90(99)% C.L. allowed regions from the analysis of FC single-ring events.



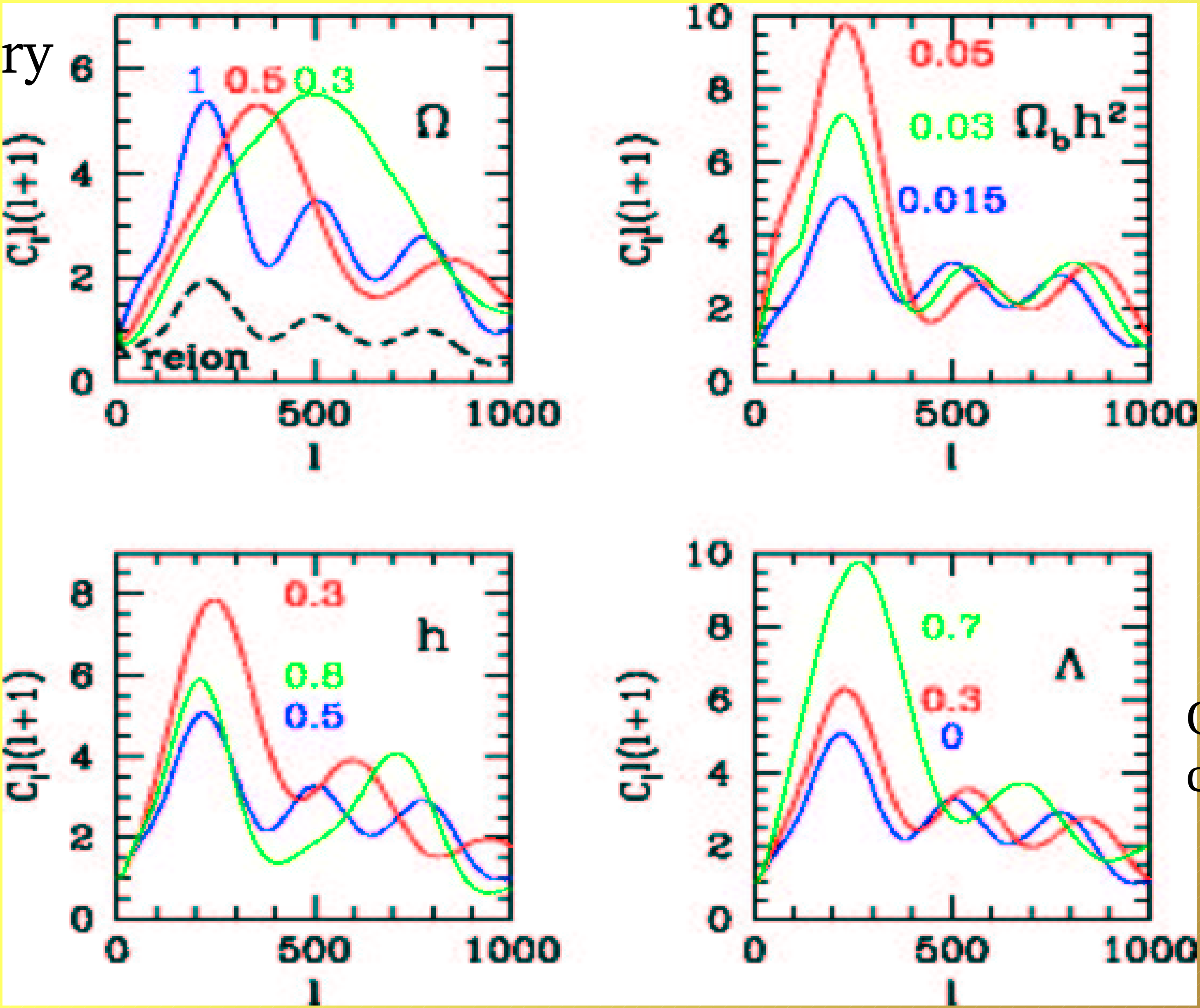
Fogli et al.

Fig. 7. Post-SNO 2ν oscillation analysis of total neutrino event rates and of SK day-night energy spectra. CHOOZ data included. Solutions at small mixing are highly disfavored. See the text for details.

I. The Cosmic Microwave Background and Inflation

Geometry

Baryon density



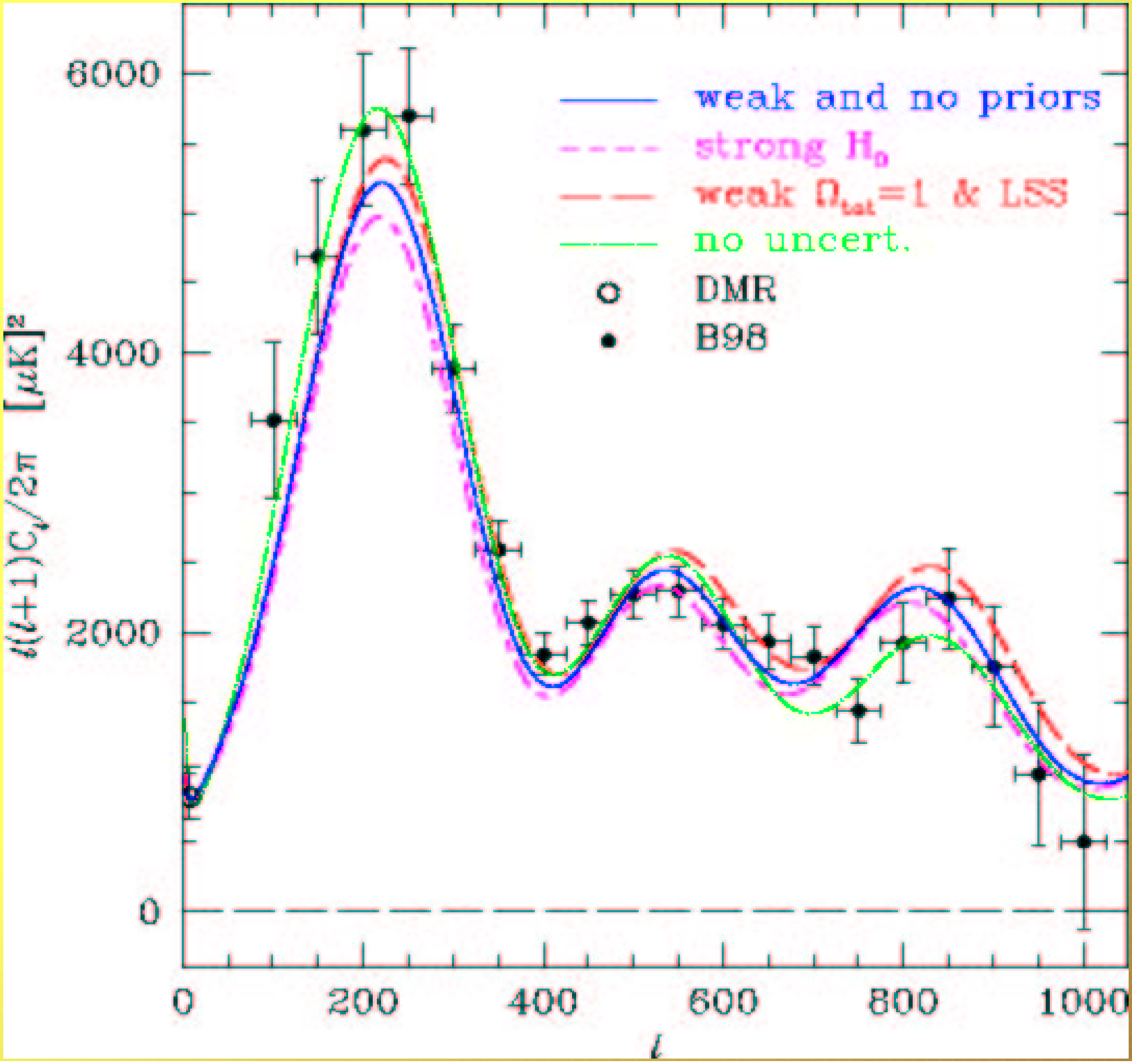
Hubble constant

Cosmological constant

Jungman, MK, Kosowsky, Spergel 1996

Results!!!

Netterfield et al. (BOOMERanG) astro−ph/0104460 (also from DASI/MAXIMA)



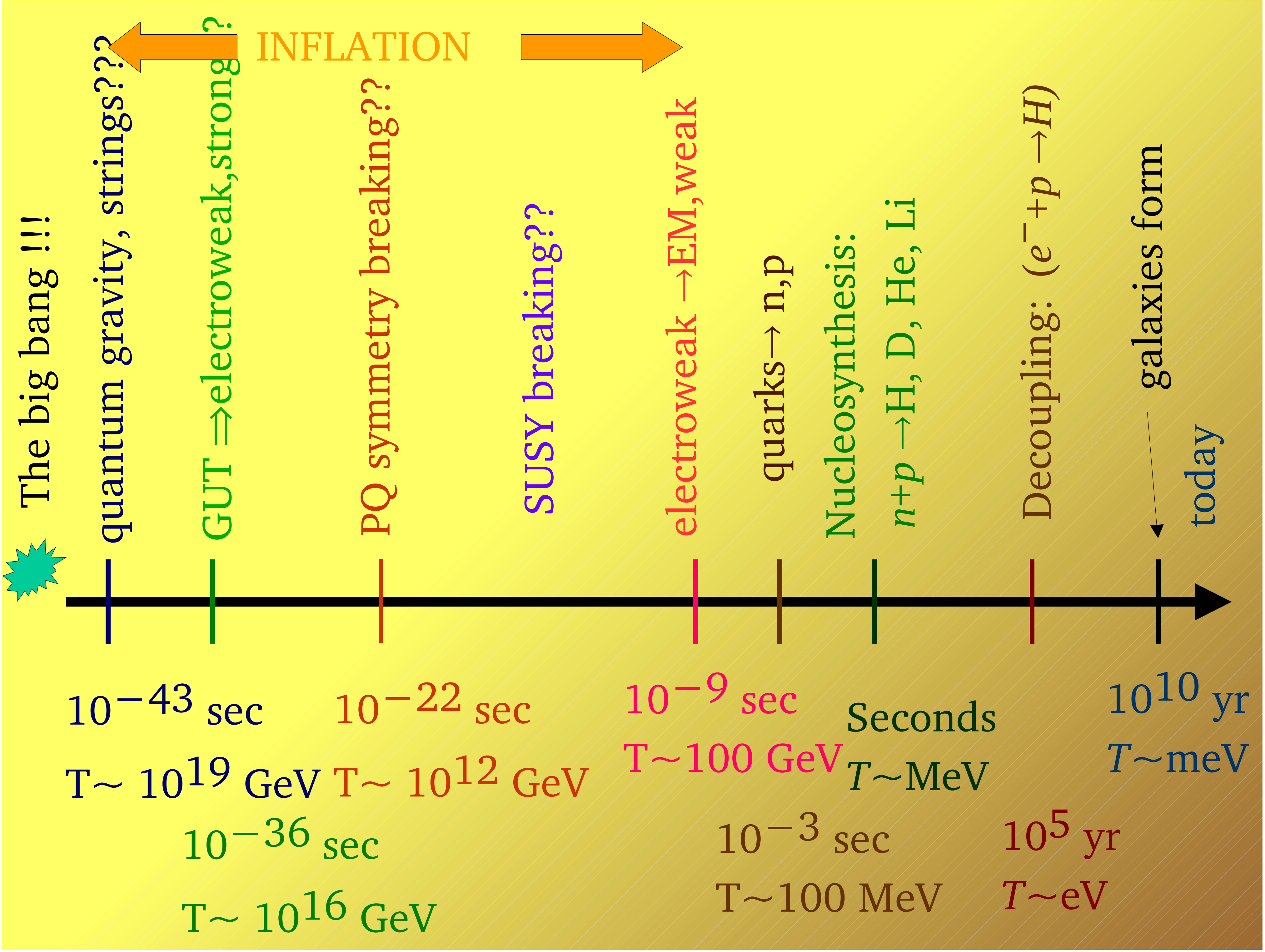
Current results:

Inflation!!

- show that Universe is flat
- determine primordial seeds for large scale structure
- independently verify big bang nucleosynthesis
- confirm existence of nonbaryonic dark matter
- suggest 70% of total energy density is some negative pressure dark energy (especially when combined with dynamical measurements indicating matter density of 30%)

Physics is simple and peak structure is distinctive, so most results (especially for geometry) are robust.

...show is not over!! What we have seen so far is just tip of the iceberg; MAP and Planck will improve precision of current measurements by order of magnitude.



INFLATION

The big bang !!!

quantum gravity, strings???

GUT ⇒electroweak,strong ?

PQ symmetry breaking??

SUSY breaking??

electroweak →EM,weak

quarks→ n,p

Nucleosynthesis:

n+p →H, D, He, Li

Decoupling: (e^-+p →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

CMB tests of inflation:

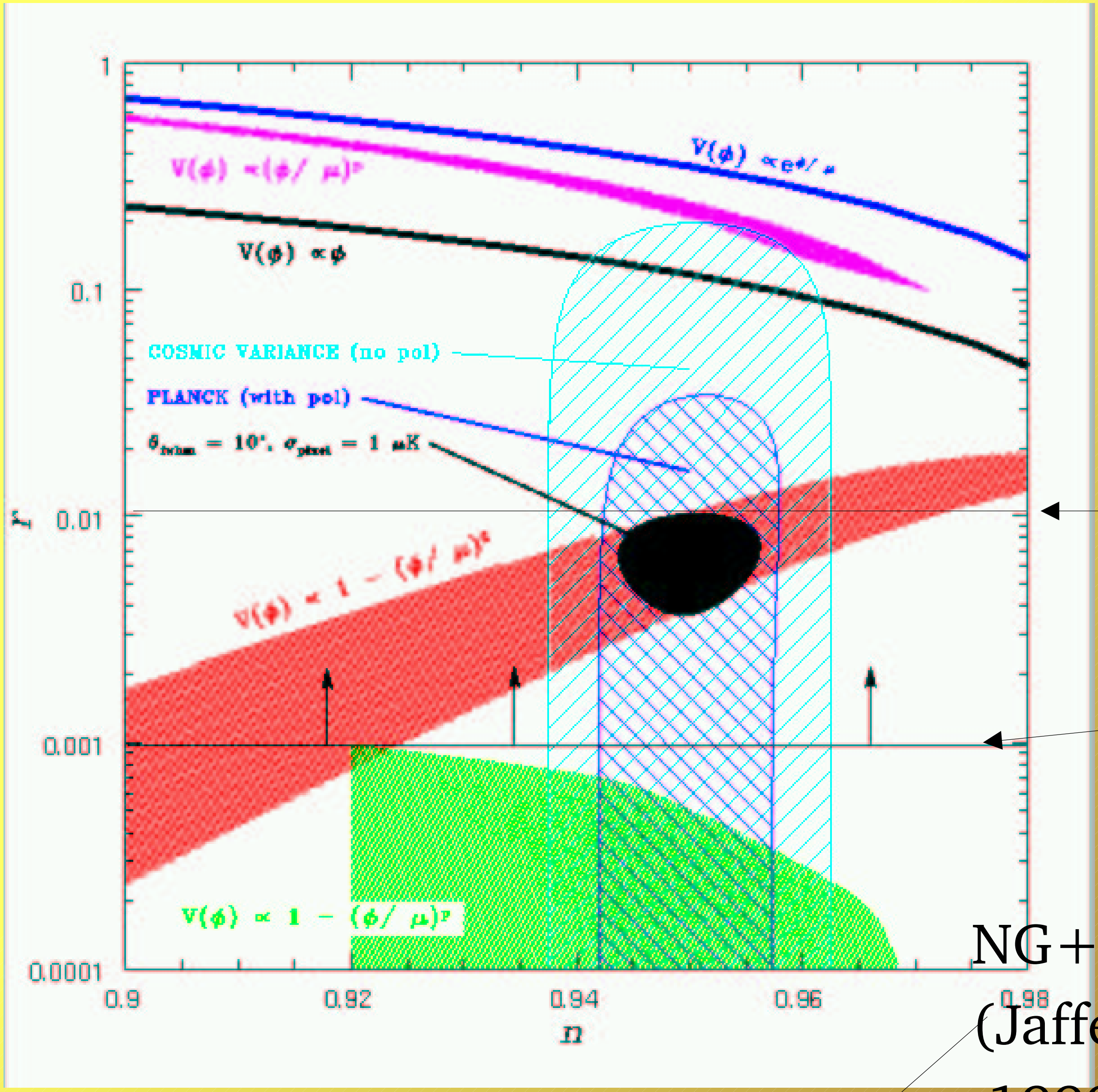
Recent CMB shows are on right track with inflation.
What next? Determine energy scale of inflation!!

Inflation robustly predicts gravitational−wave background with amplitude proportional to square of energy scale of inflation (Abbott&Wise 1984).

Detection of inflationary gravitational waves through CMB polarization can provide "smoking gun" for inflation at GUT scale.
(MK, Kosowsky, Stebbins 1997; Seljak,Zaldarriaga 1997)

Gravitational–Wave Amplitude

$(\text{Energy scale of inflation})^2$



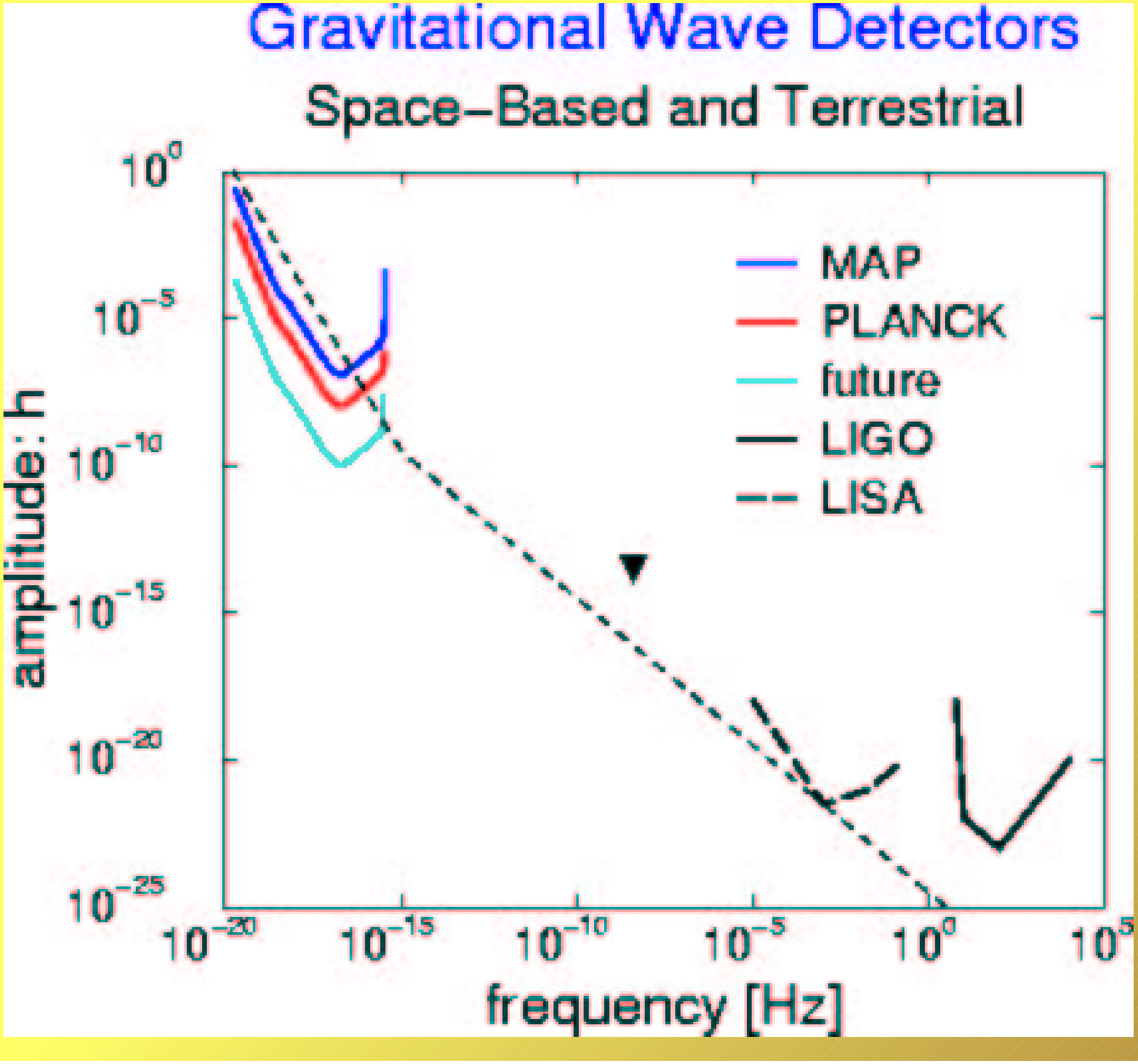
Planck

Next generation

NG+scan (Jaffe, Wang, MK 1999)

Gravitational waves: Another probe of the inflaton potential:

GW amplitude $h(\nu) \Leftrightarrow V(\phi)$



Caldwell, MK, Wadley

Brief aside: CMB detection of parity violation from Planck scale physics

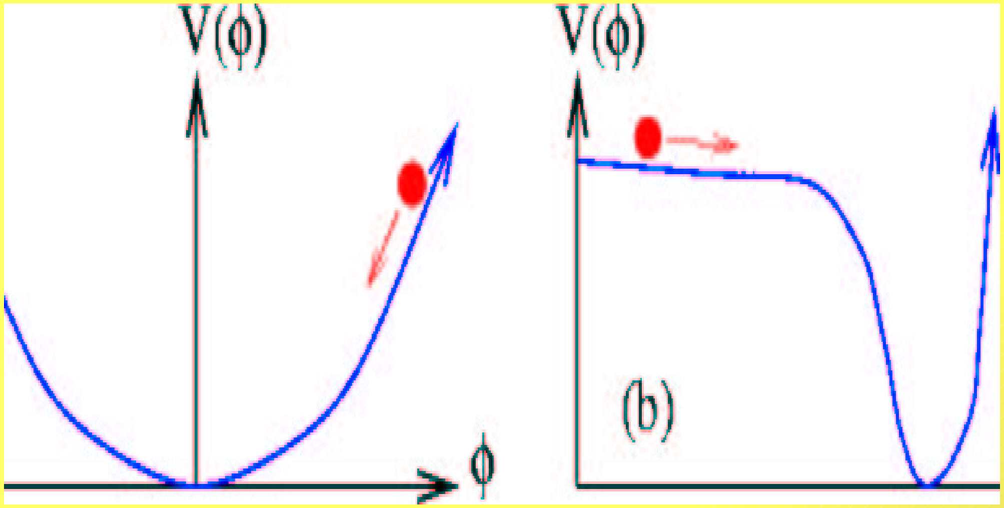
(Lue, Wang, MK, 1999)

Certain cross correlations between temperature and polarization components can arise only if parity is violated.

Two examples: $\phi F^{\mu\nu}\tilde{F}_{\mu\nu}$ Rolling scalar field with P,T violating coupling to EM

$\phi\varepsilon^{\mu\nu\rho\sigma}R_{\mu\nu\alpha\beta}R^{\alpha\beta}_{\rho\sigma}$ P,T violating coupling to gravity can produce preponderance of right versus left handed GWs during inflation

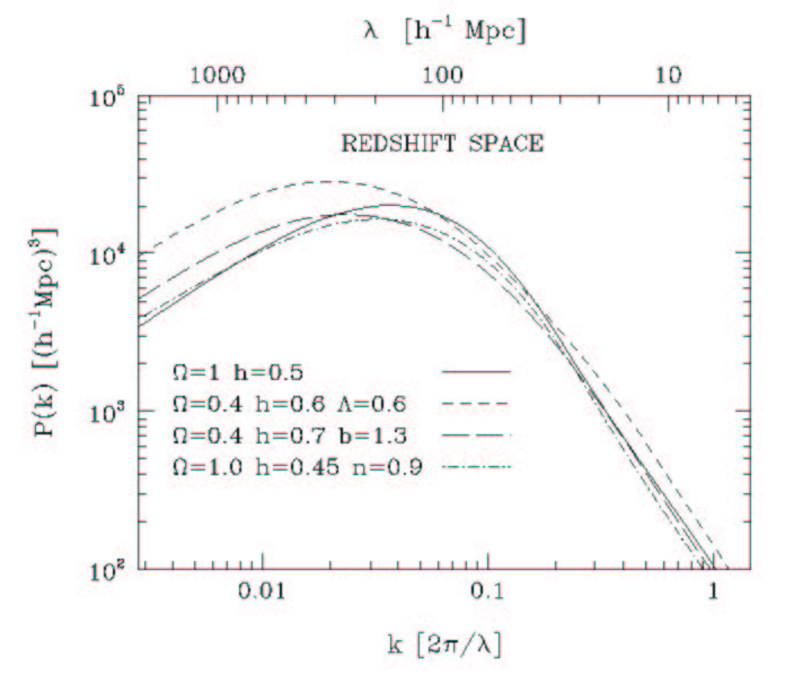
II. Large scale structure and inflation



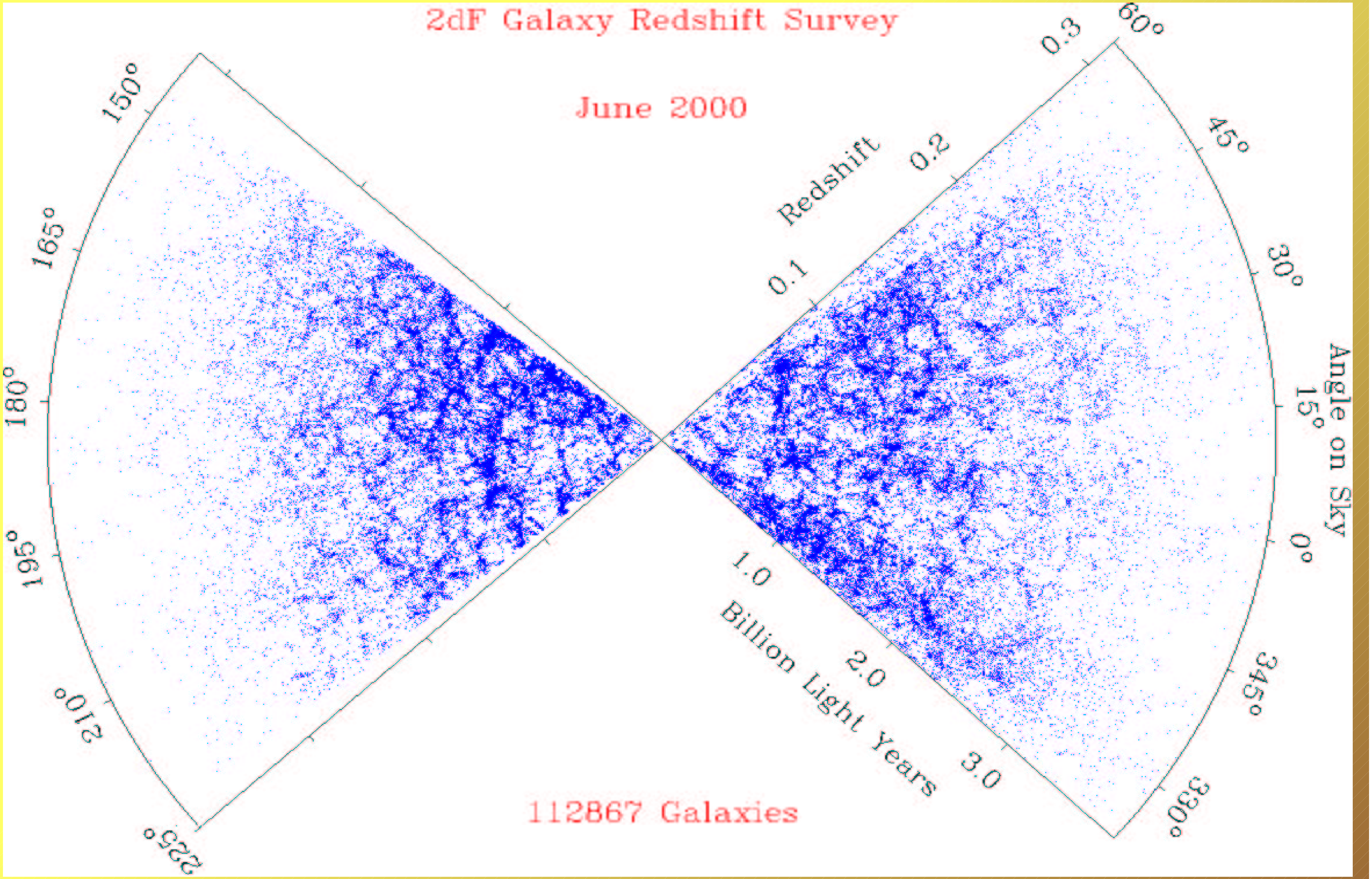
Inflaton potential

⤡

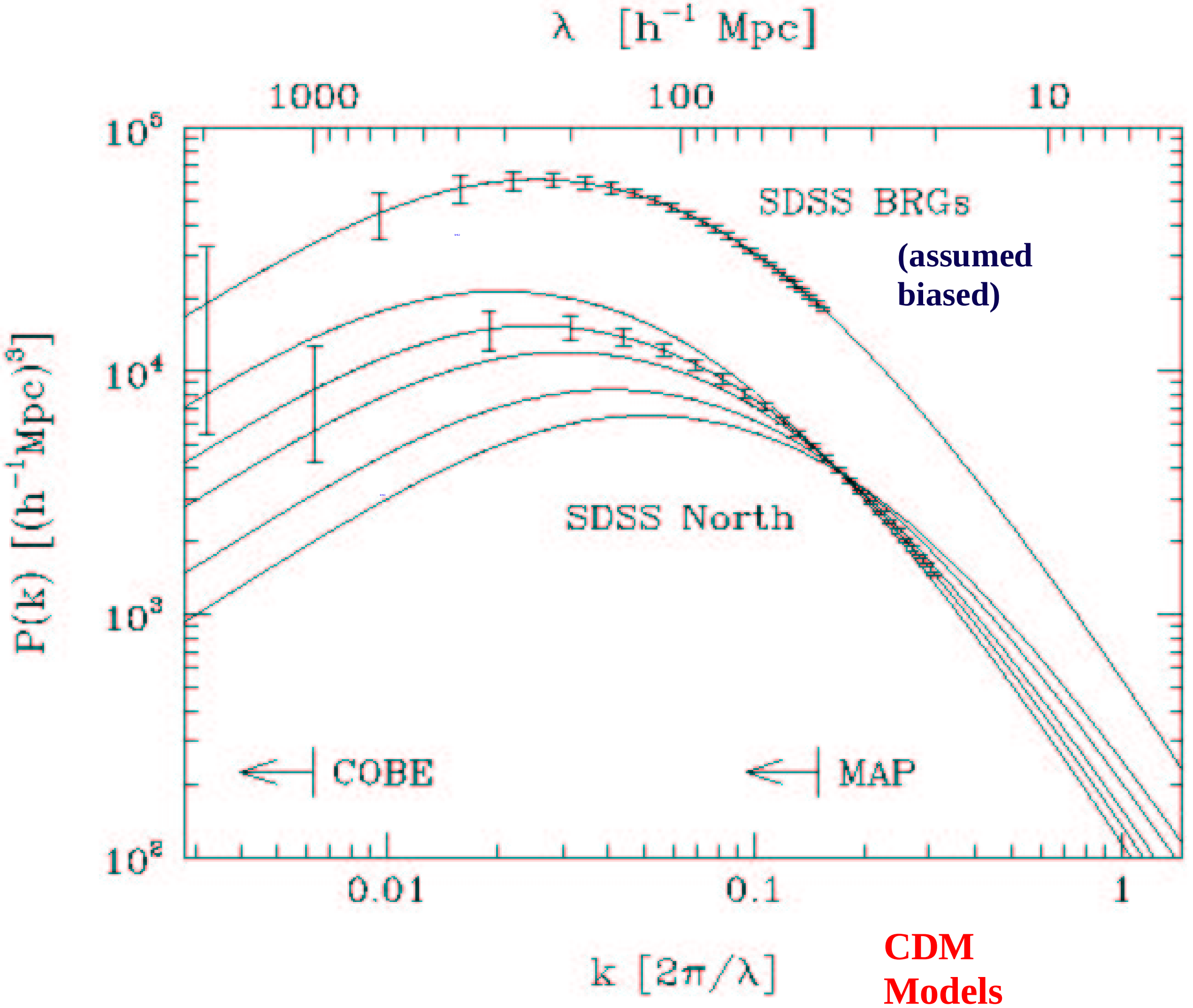
Matter power spectrum



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



Forecast SDSS Power Spectrum



(assumed biased)

CDM Models

Fig. 3.— Predicted uncertainties in the power spectrum estimated from a volume-limited ($R_{max} = 500h^{-1}$ Mpc) sample of SDSS North and for the Bright Red Galaxy sample (upper set of error bars). These errors assume that the true power spectrum is that of an $\Omega h = 0.25$ CDM model and that the BRGs are more clustered than normal galaxies. Plotted for comparison to the SDSS North errors are CDM power spectra (normalized to $\sigma_8 = 1$) for a range of Ωh from 0.2 (uppermost curve) to 0.5 (lowest curve) and indications of the range of comoving scales probed by the COBE and MAP CMB anisotropy experiments.

Dodelson et al. (SDSS Collaboration) ApJ (2001)

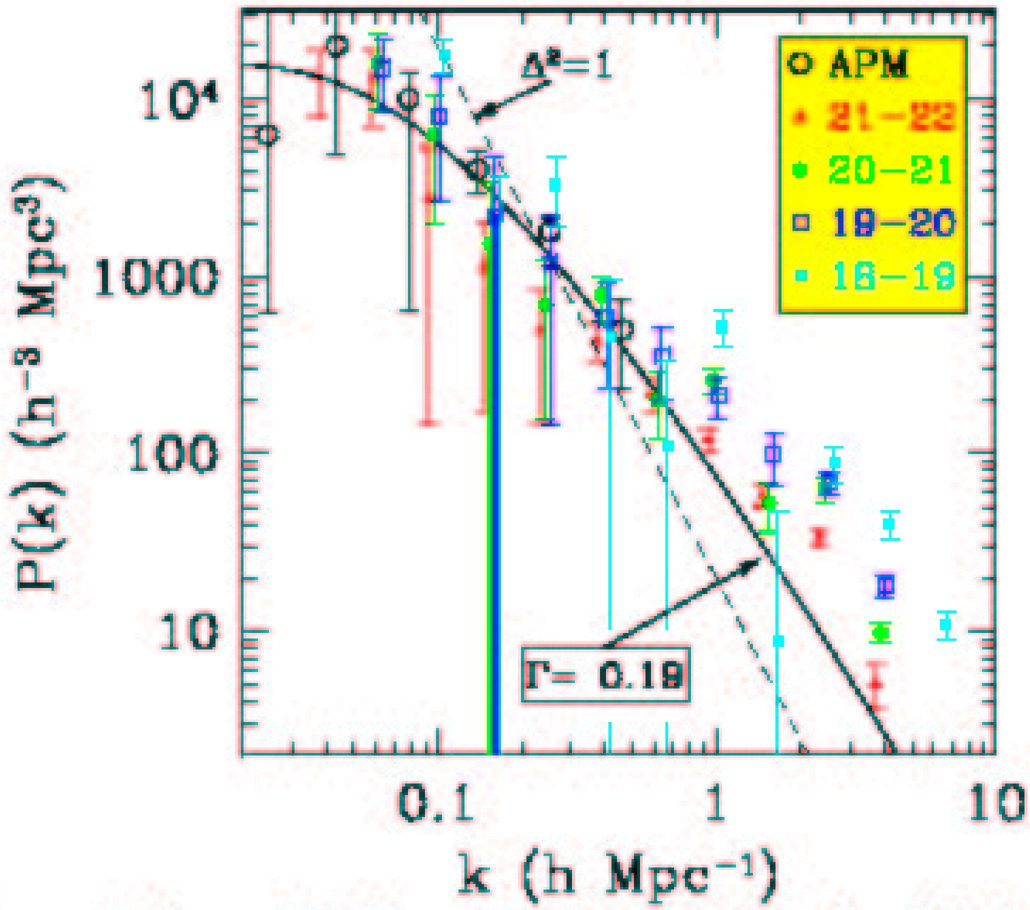


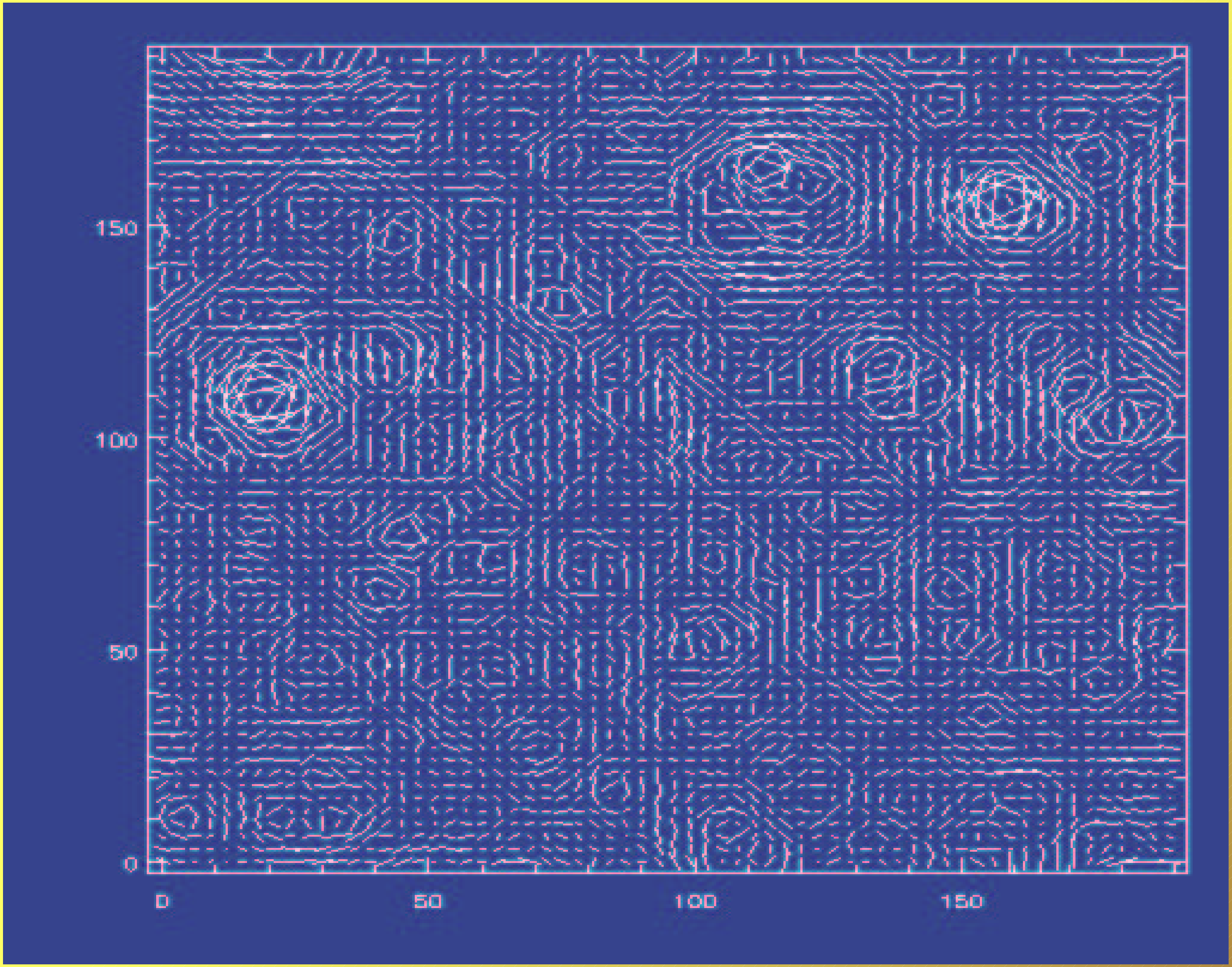
FIG. 12.— The 3D power spectrum from angular data in four magnitude bins. Also shown is the maximum likelihood power spectrum from the APM survey (Efstathiou & Moody 2000). The dashed line, defined by $\Delta^2 \equiv 4\pi k^3 P/(2\pi)^3 = 1$, delineates the linear from the non-linear regime, while the solid line is the best fit linear spectrum from Sz01. The parameter Γ, introduced by Bardeen et al. (1986) determines the shape of the power spectrum.

Cosmic Shear

First detection (by several independent groups) of "cosmic shear", weak gravitational lensing due to large scale mass inhomogeneities

Probes large–scale distribution of *mass* rather than of *galaxies.*

...and mapping of dark matter around clusters has become routine.



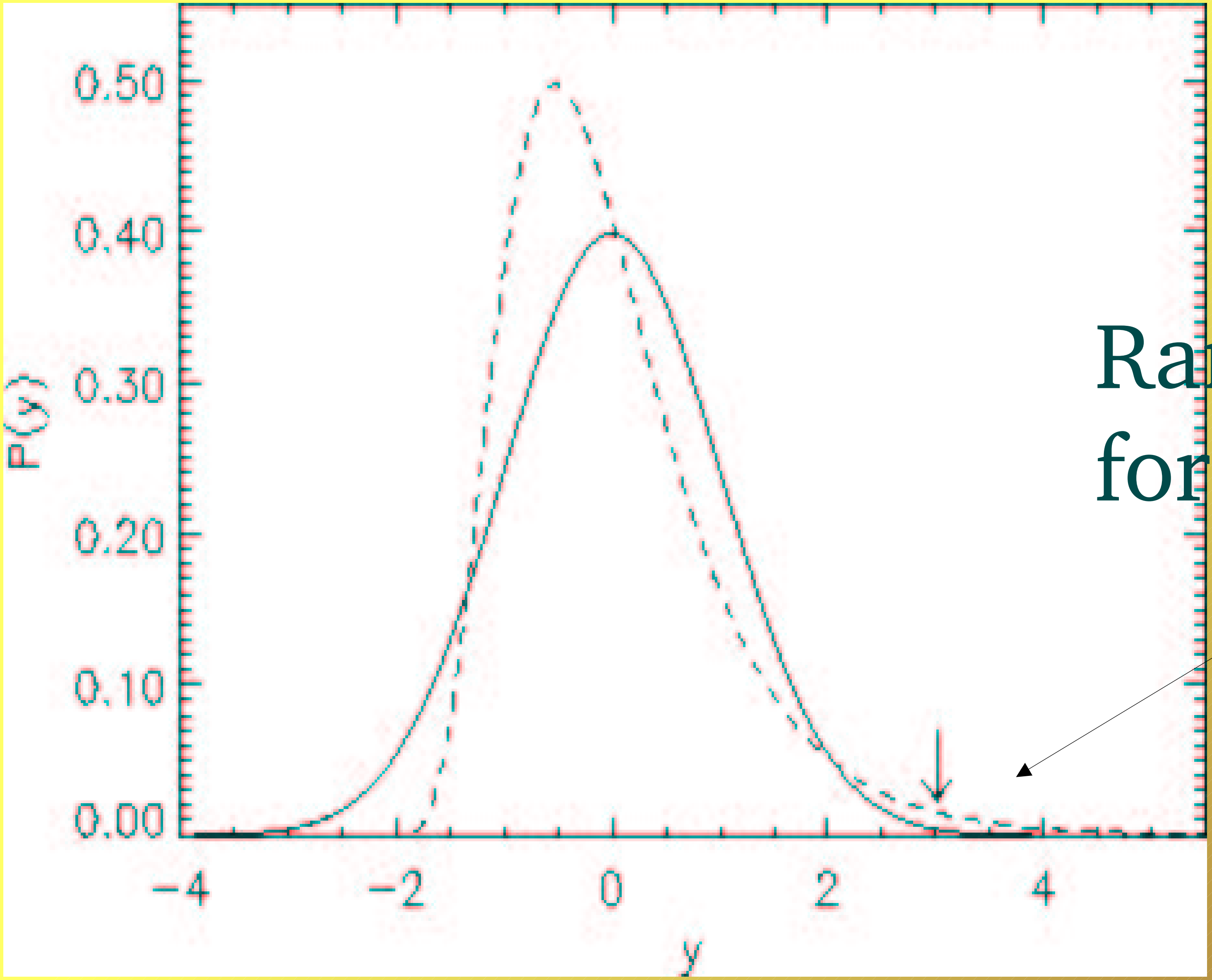
Possible, e.g., with SNAP

Inflation: What Else??

Inflation ⇒ distribution of primordial density perturbations is Gaussian.

Can be checked with CMB maps, galaxy surveys, weak lensing, cluster abundances, abundances of high−redshift objects, cluster properties....

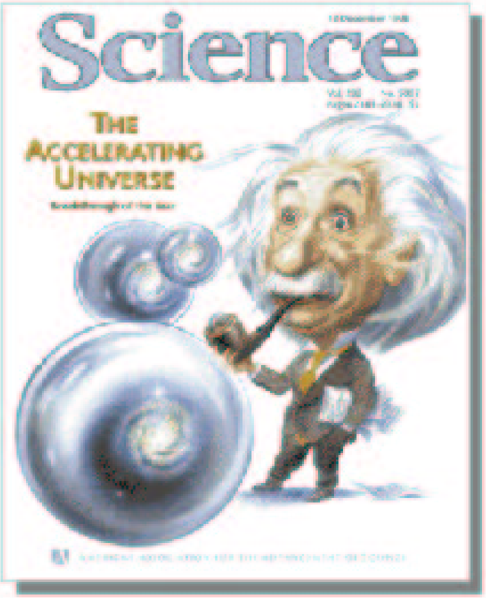
(e.g., Verde et al., 2000,2001)

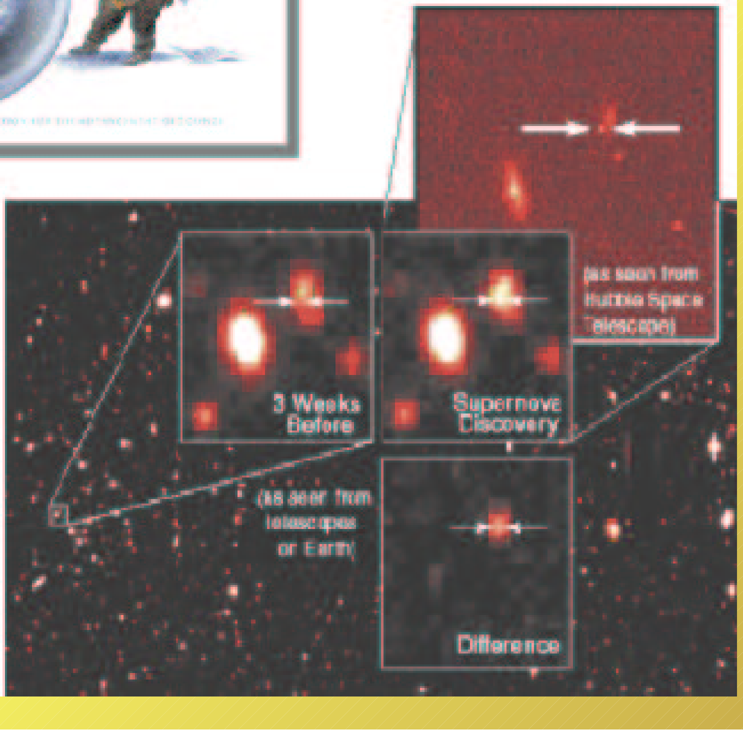


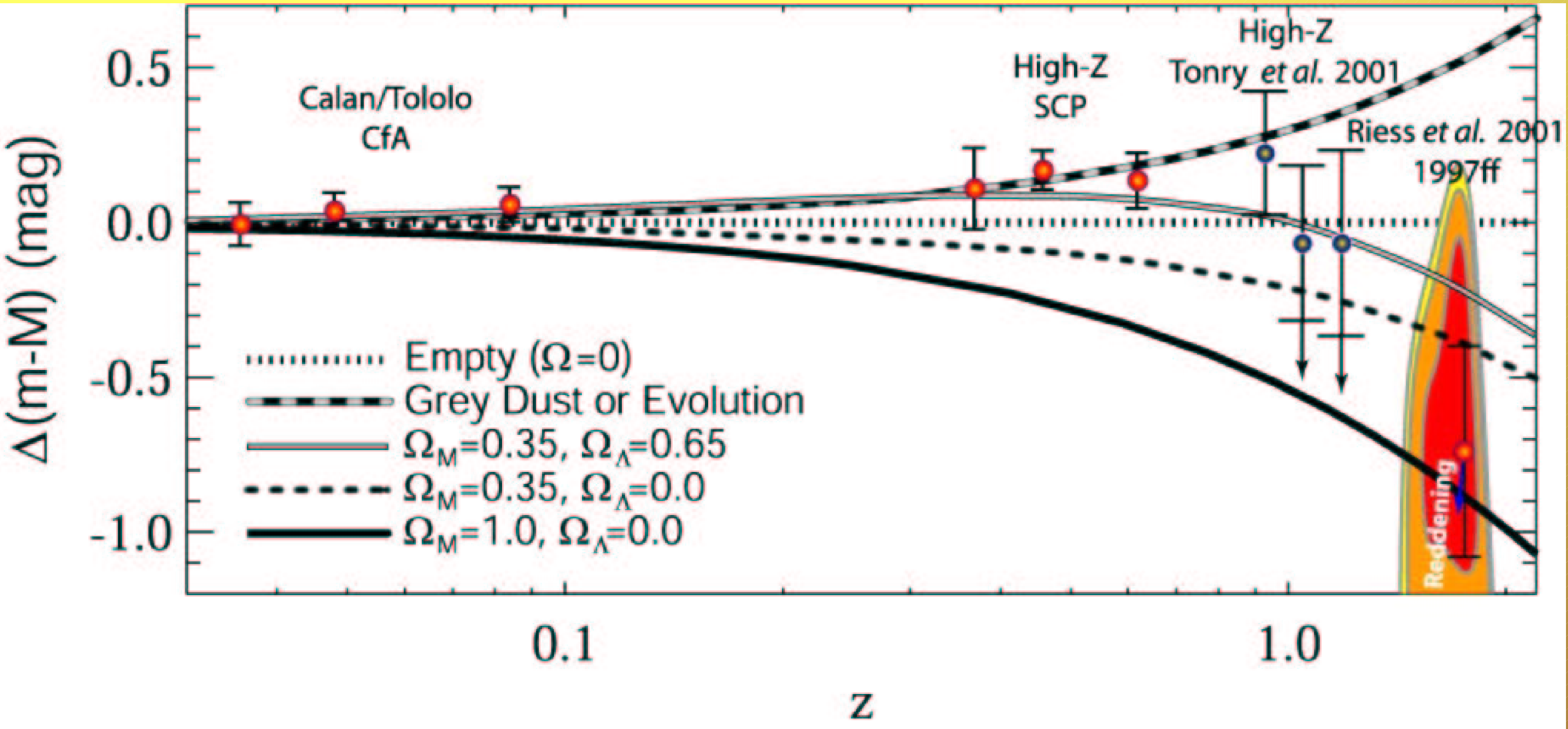
Rare objects form here

III. Supernovae, an accelerating Universe, and Dark Energy

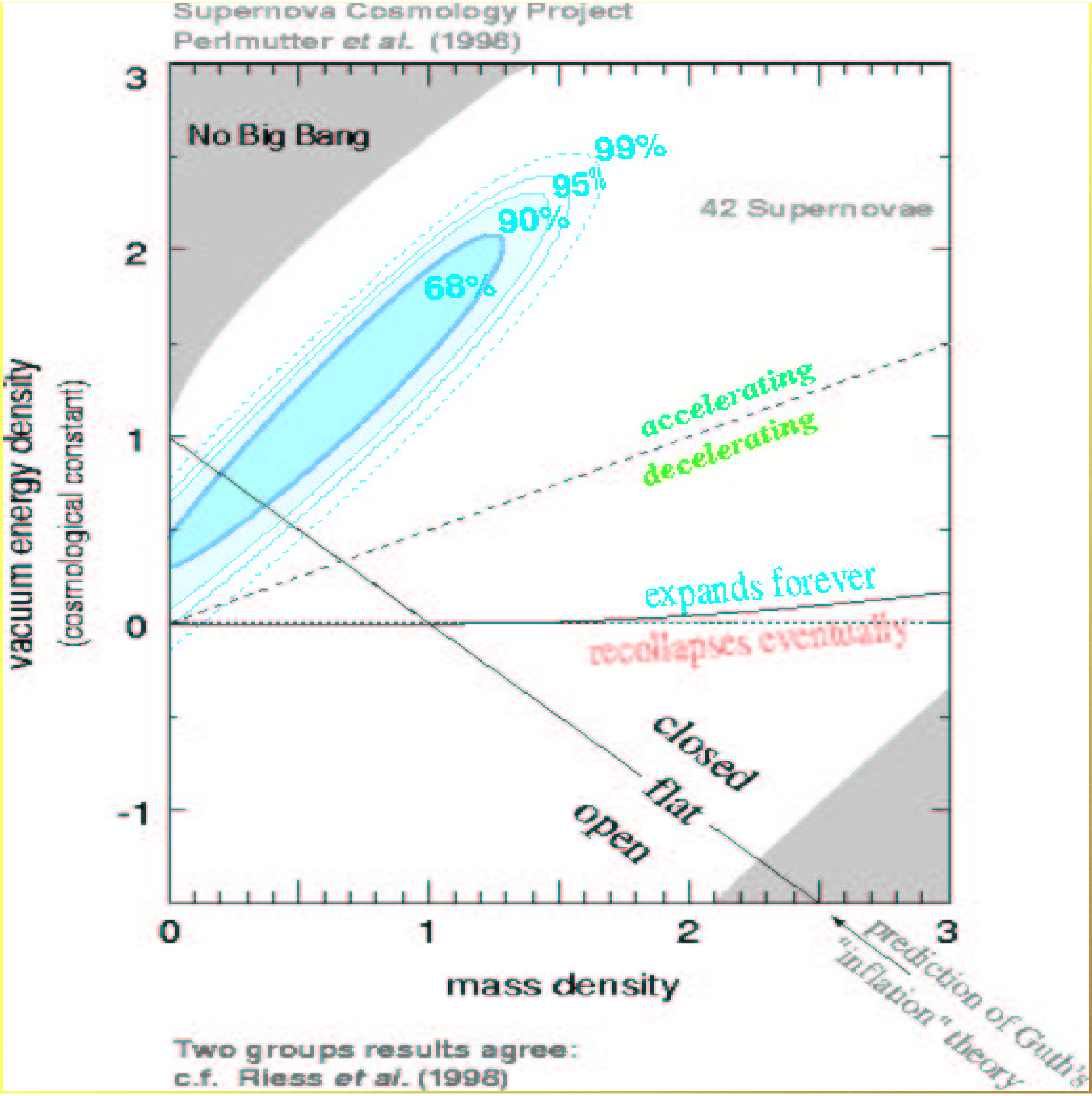
Science's Breakthrough of the Year: 1998
The Accelerating Universe



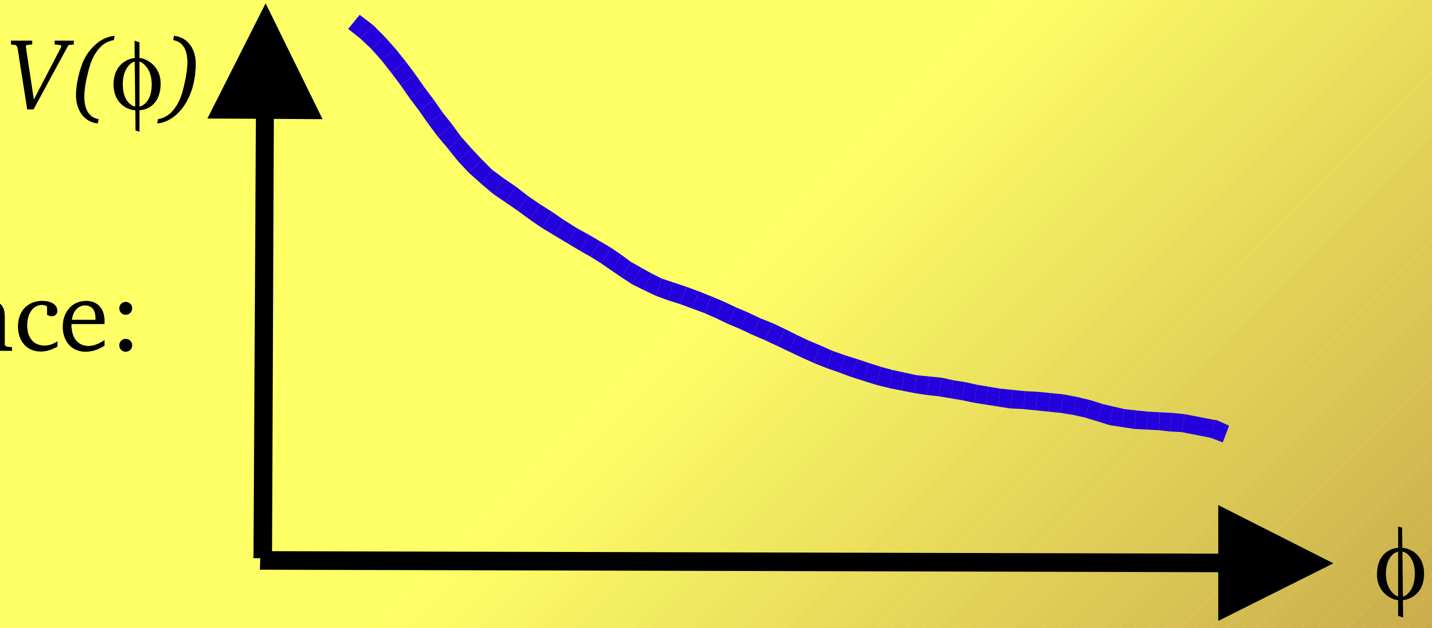




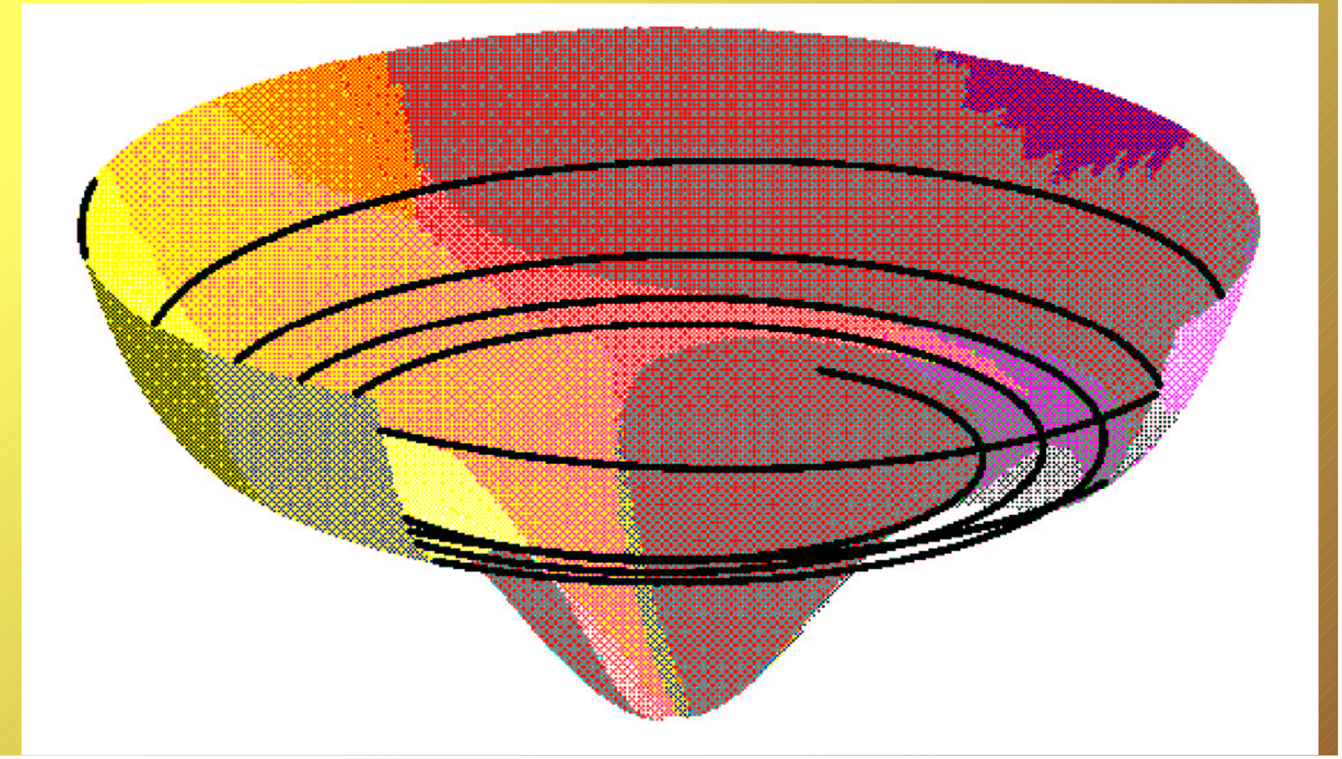
Courtesy P. Garnavich (High−z Supernova Search Team)
(results also from Supernova Cosmology Project)


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
prediction of Guth's "inflation" theory
vacuum energy density (cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3
Two groups results agree:
c.f. Riess *et al.* (1998)

Quintessence:

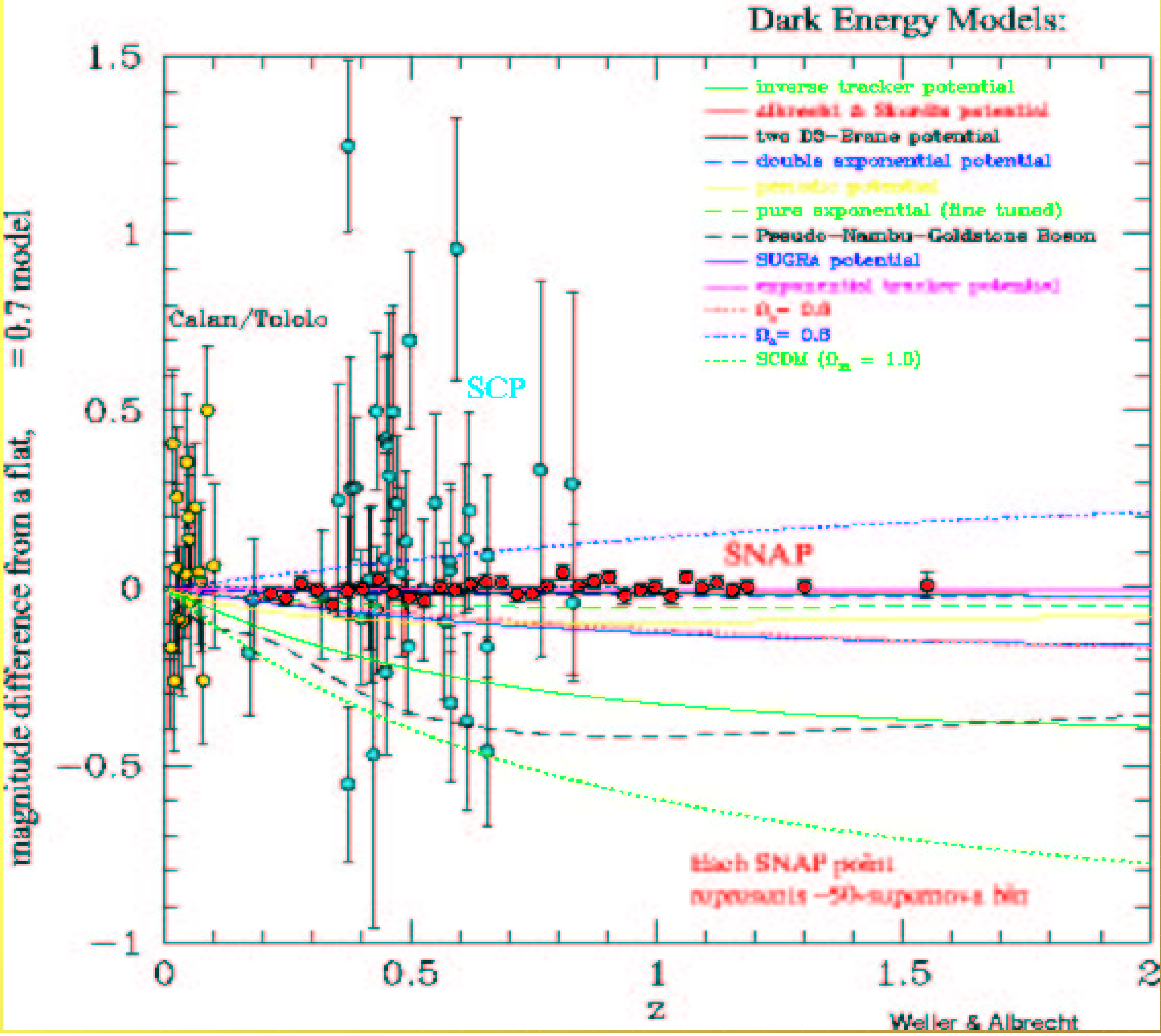


Spintessence:
(Boyle, MK,
Caldwell 2001)

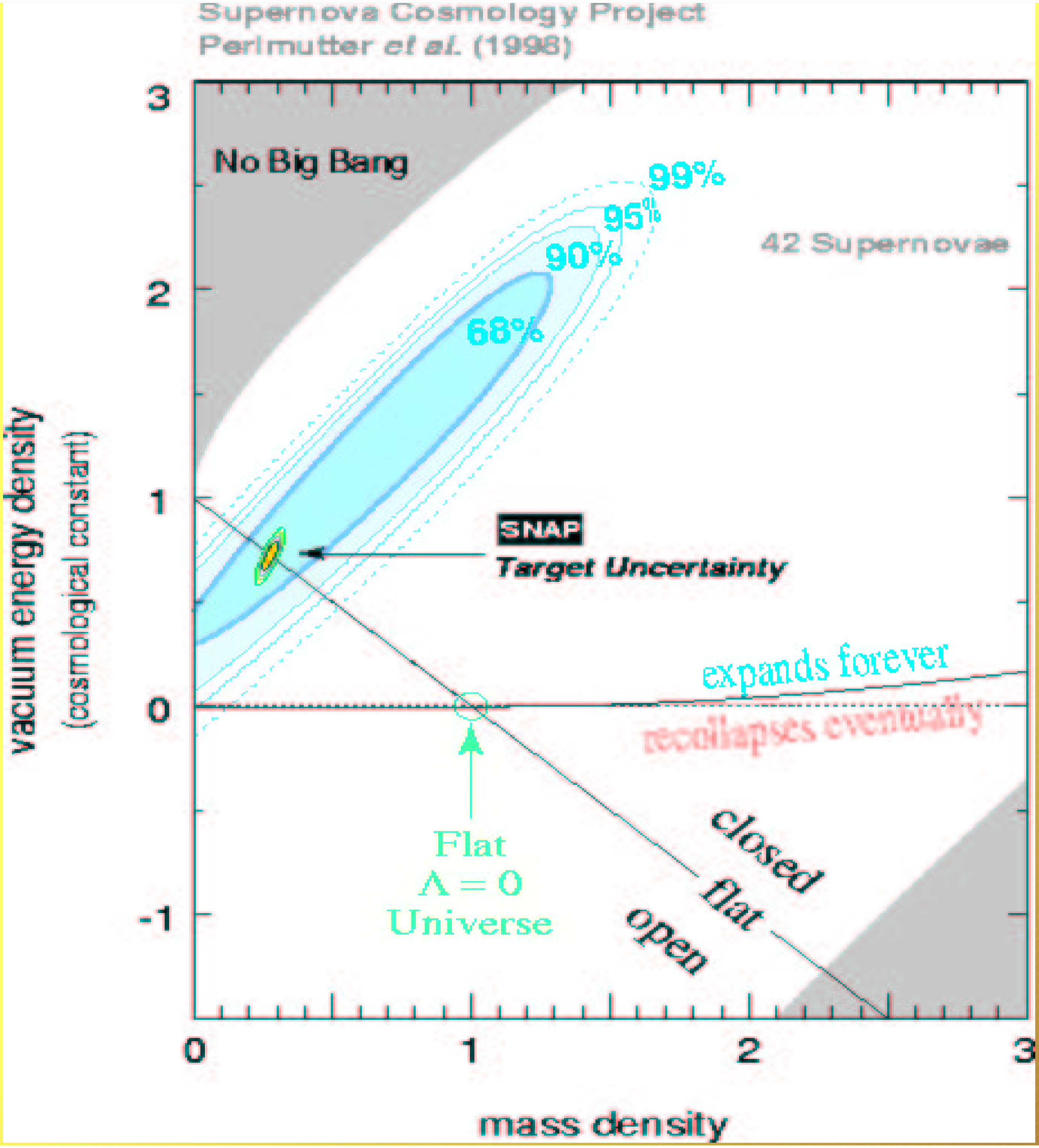


SNAP SuperNova Acceleration Probe

Current ground-based data
compared with binned simulated SNAP data.



Weller & Albrecht

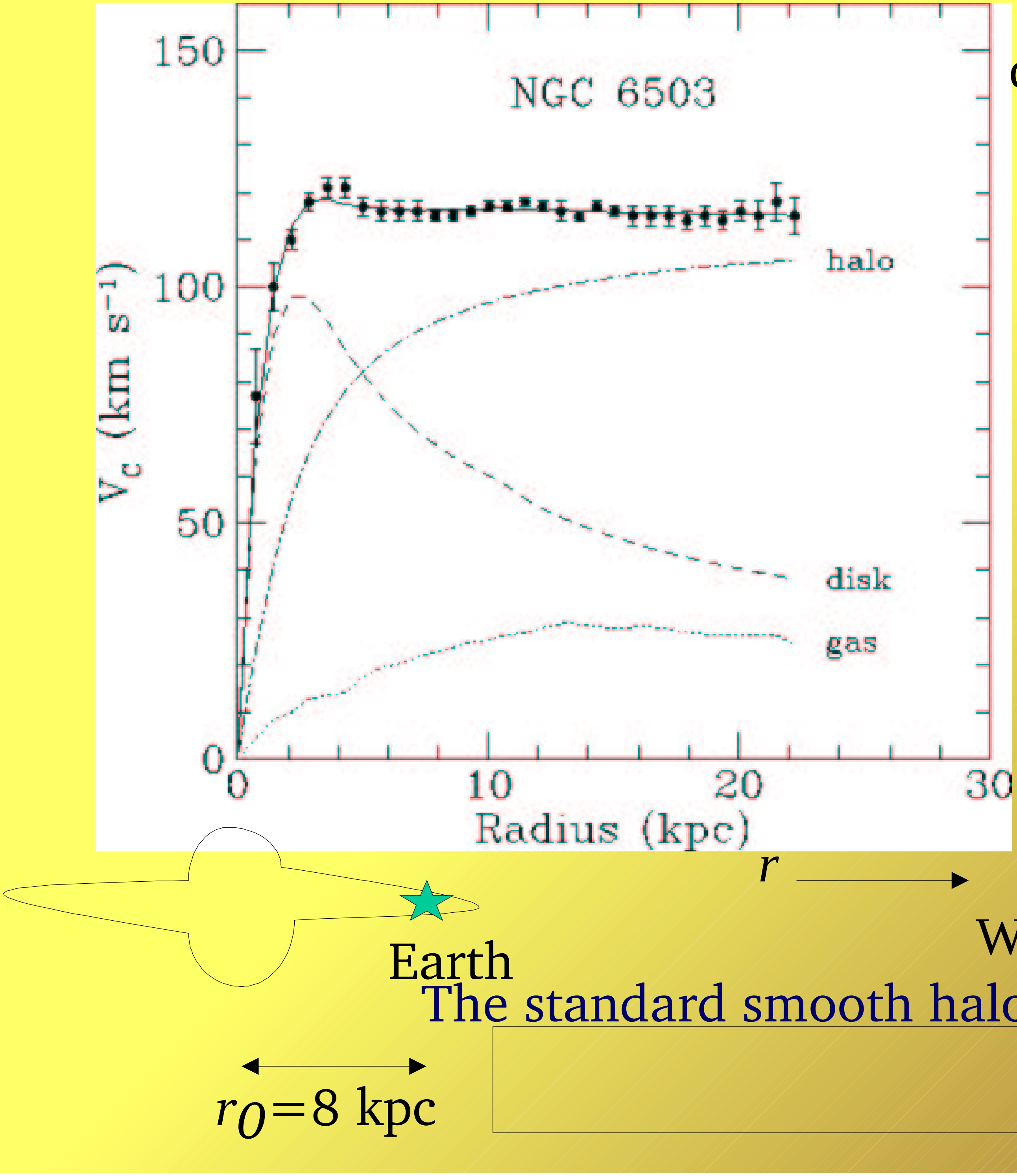

Supernova Cosmology Project
Perlmutter *et al.* (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAP
Target Uncertainty
expands forever
recollapses eventually
Flat
$\Lambda = 0$
Universe
closed
flat
open
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

Qu(sp)intessence! Other connections:

- "Vacuum" is CPT and Lorentz violating and may contain global charge
- May drive baryogenesis and/or hide antibaryons
- Could rotate polarization of distant radio sources if scalar field coupled to EM
- Can reproduce and generalize (e.g., to include quartic terms in potential) fuzzy cold dark matter

III. Particle Dark Matter Searches

The standard smooth halo model



density

core radius

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

spherical halo:

$\rho_0 = 0.3-0.6$ GeV/cm^3

If halo flattened,

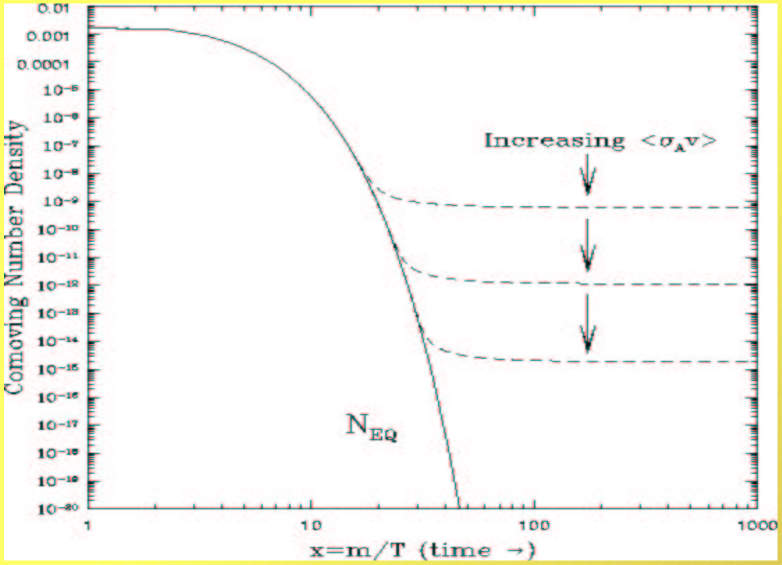
$\rho_0 \uparrow$

Velocity distribution ~ Maxwell−Boltzmann

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

Particle dark matter candidates

- Weakly Interacting Massive Particles (WIMPS). e.g.,neutralinos



$$\Omega_\chi h^2 \approx \frac{3\times10^{-27}\, cm^3/\sec}{\langle\sigma v\rangle}$$

- Axions

$$m_a \sim 10^{-4} - 10^{-6}\ \text{eV}$$

WIMPs

The relic density of a massive particle is about:

$$\Omega h^2 \approx \frac{3\cdot 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle v\sigma\rangle}$$

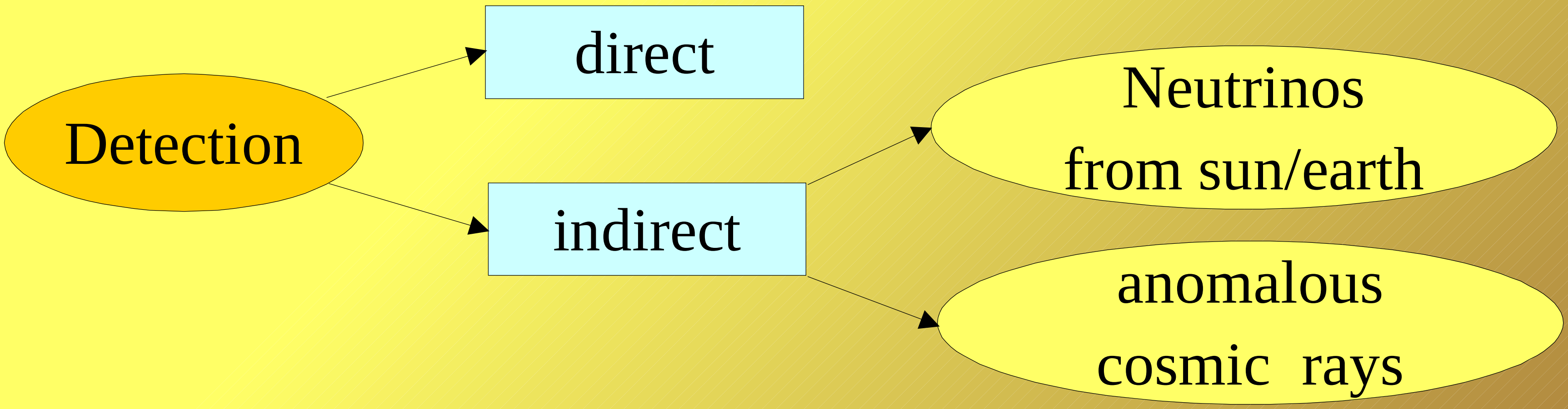
$\Downarrow$

$\langle v\sigma\rangle$ Of Weak Interaction strength

$\Downarrow$

the particle has to be coupled to SM particles

There is chance for detection:

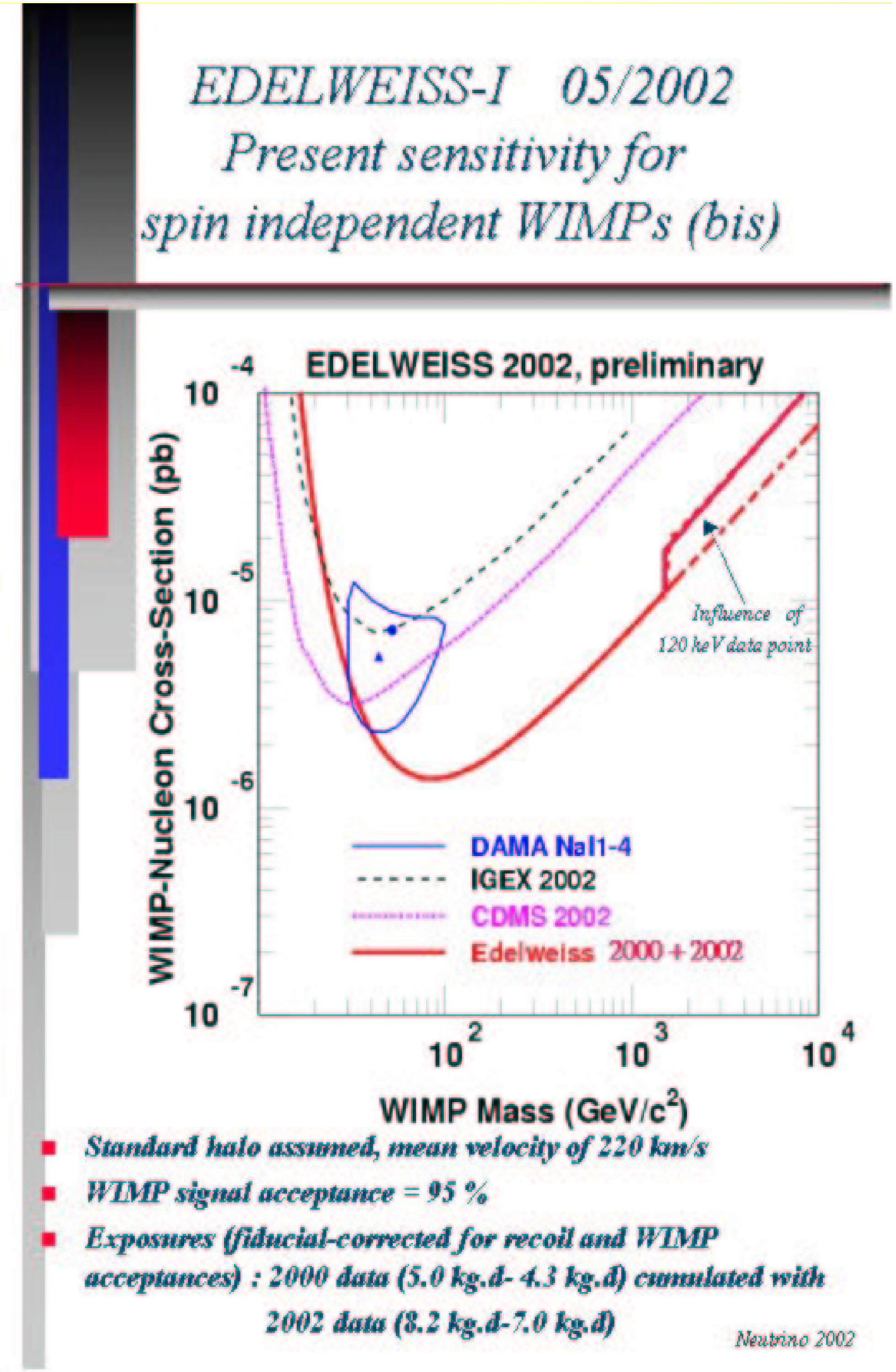


WIMP candidate motivated by SUSY:

Lightest Neutralino, LSP in MSSM

Particle dark matter searches (axions and SUSY particles)

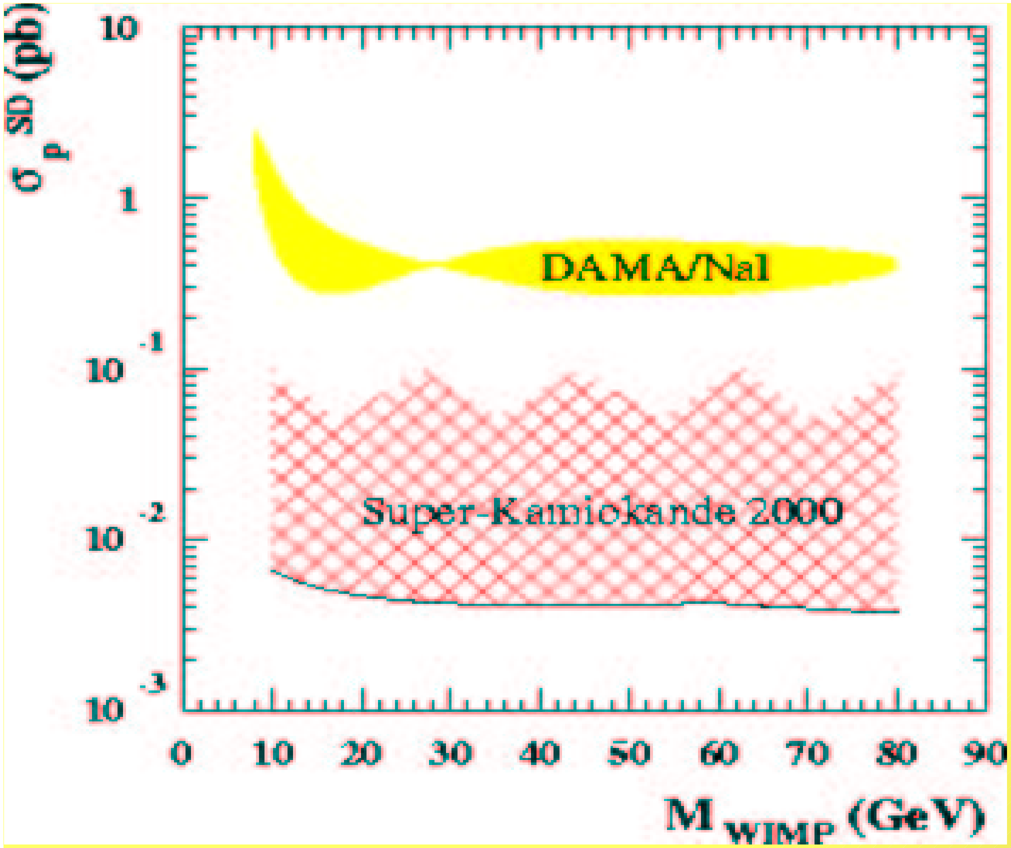
See dmtools.berkeley.edu



EDELWEISS-I 05/2002
Present sensitivity for
spin independent WIMPs (bis)

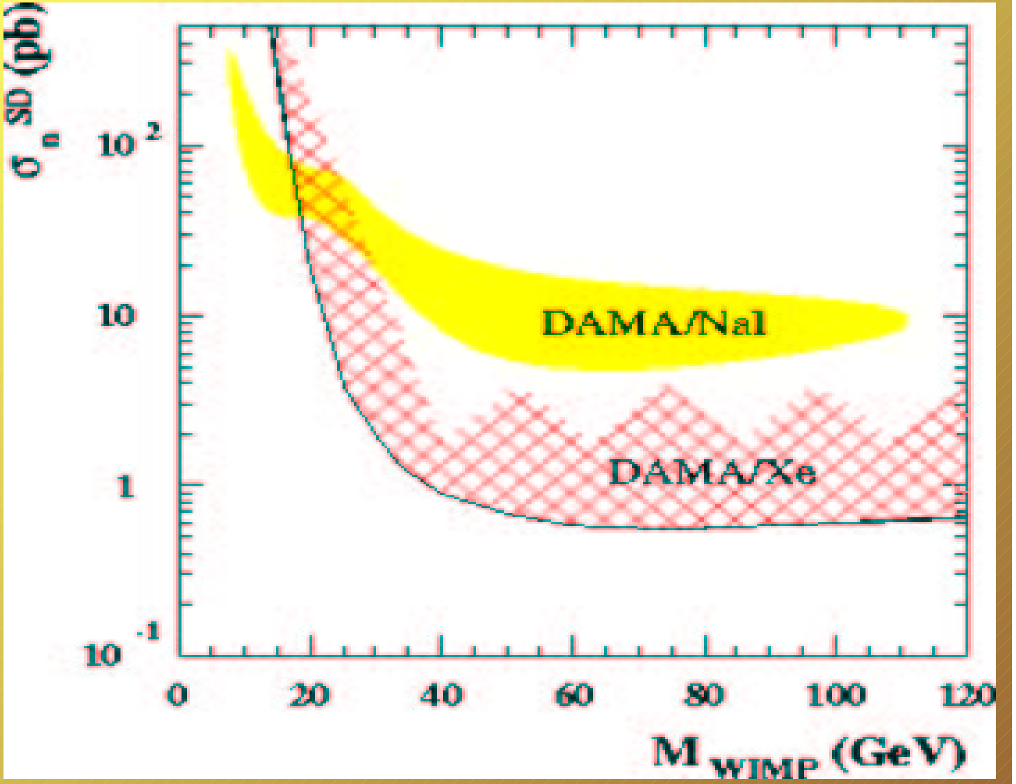
- *Standard halo assumed, mean velocity of 220 km/s*
- *WIMP signal acceptance = 95 %*
- *Exposures (fiducial-corrected for recoil and WIMP acceptances) : 2000 data (5.0 kg.d- 4.3 kg.d) cumulated with 2002 data (8.2 kg.d-7.0 kg.d)*

Neutrino 2002



Spin dependent WIMP−proton coupling

Ullio, MK, Vogel 2001

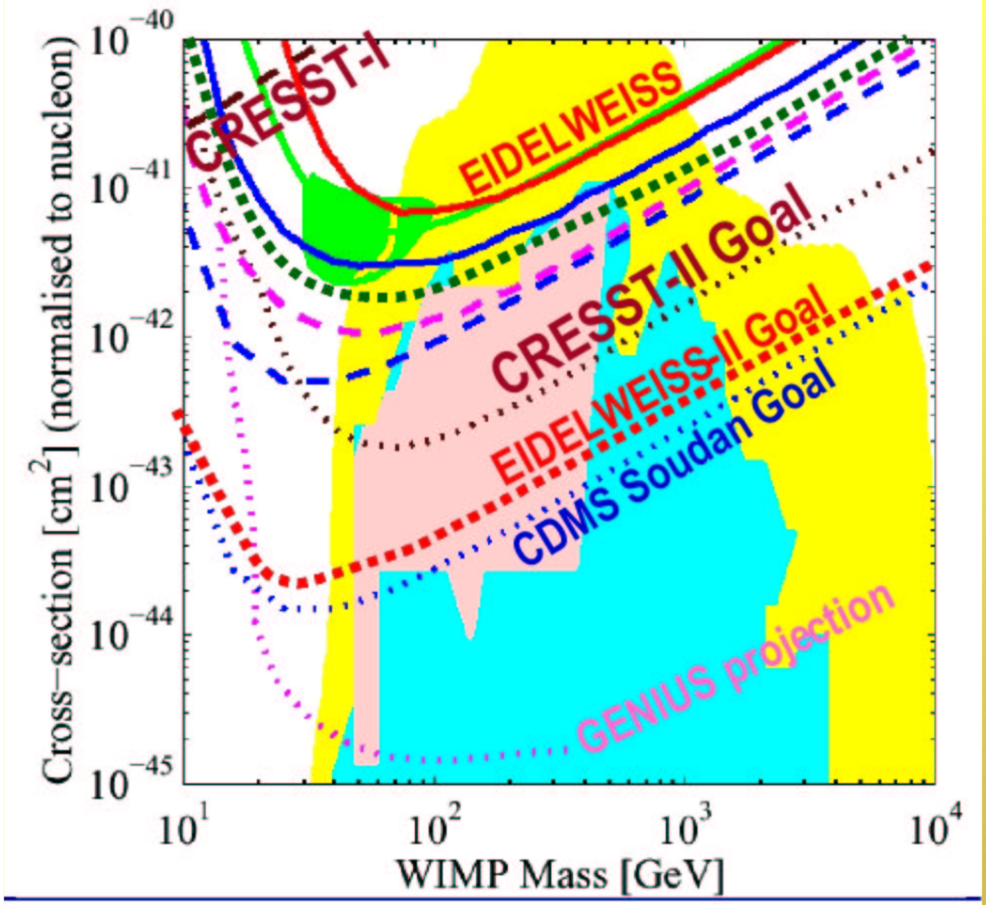


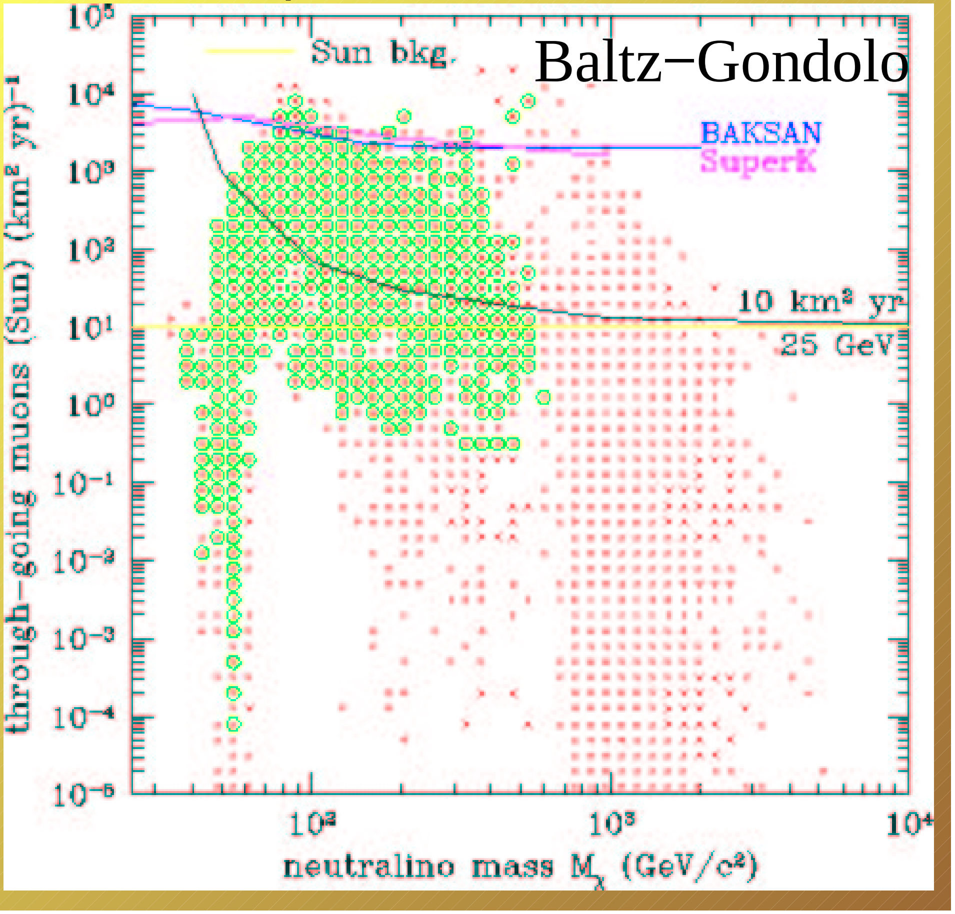
Spin dependent WIMP−neutron coupling

Searches for SUSY dark matter:

Direct detection in
low background detectors

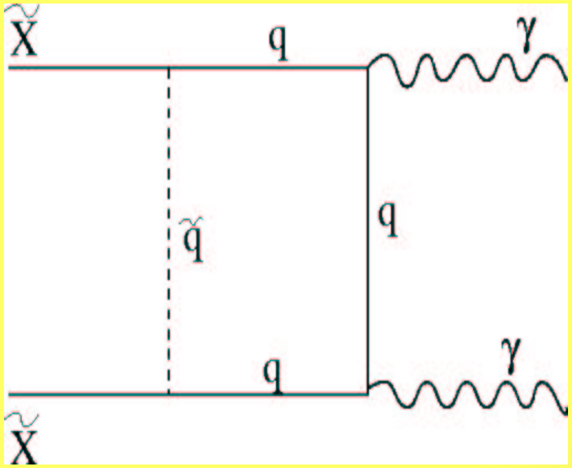
Indirect detection
via energetic neutrinos
from LSP annihilation
in Sun/Earth





Detection of SUSY dark matter:

Indirect detection via observation of cosmic gamma rays from LSP annihilation in halo

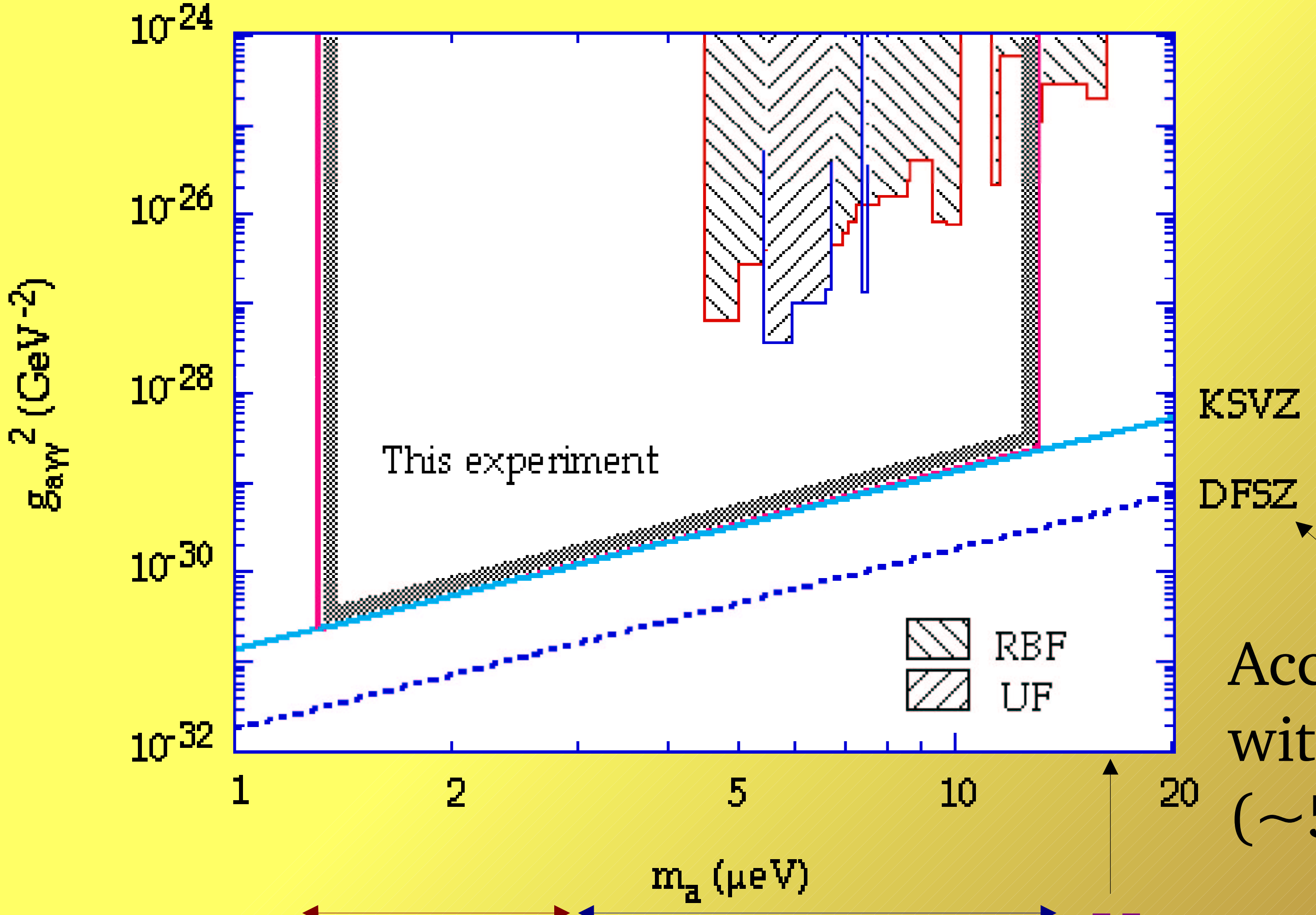


E.g., in GLAST, VERITAS, Whipple, CELESTE, STACEE…

Or via observation of exotic cosmic−ray positrons or antiprotons (e.g., in HEAT, PBAR, AMS….)

Axion–search (Livermore) update:

(courtesy of L. Rosenberg)



Accessible with upgrade (~5–yr timescale)

Scanned already

Next year

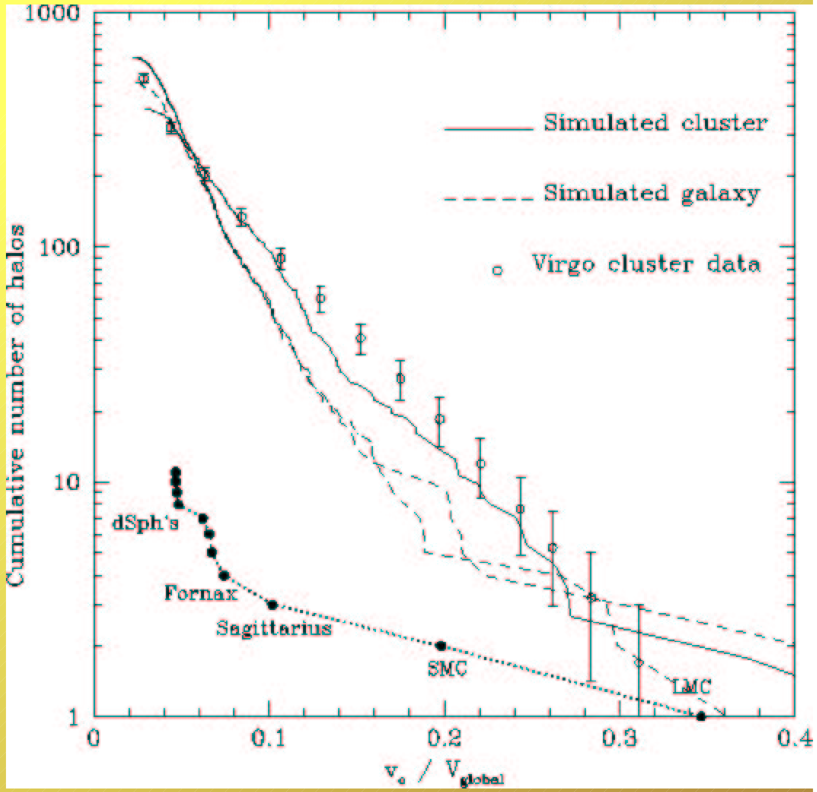
How can we get at these higher masses?

Self interacting dark matter?

Cluster

galactic
halo

300 kpc



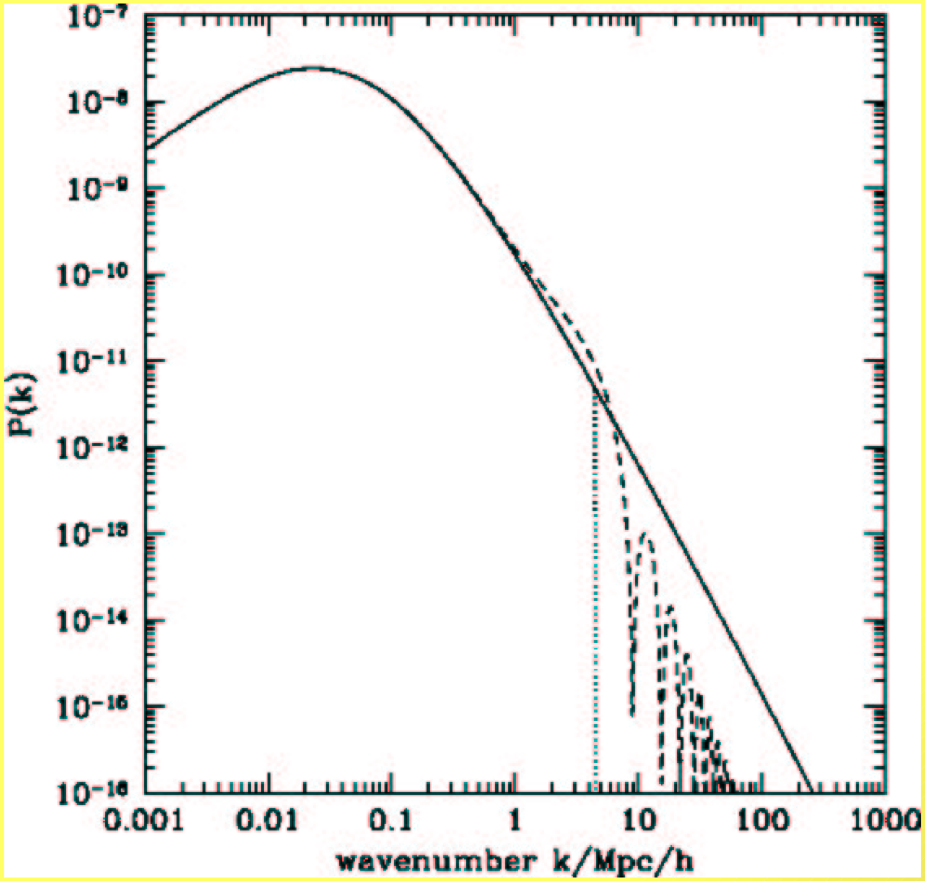
Moore et al., ApJL (1999)

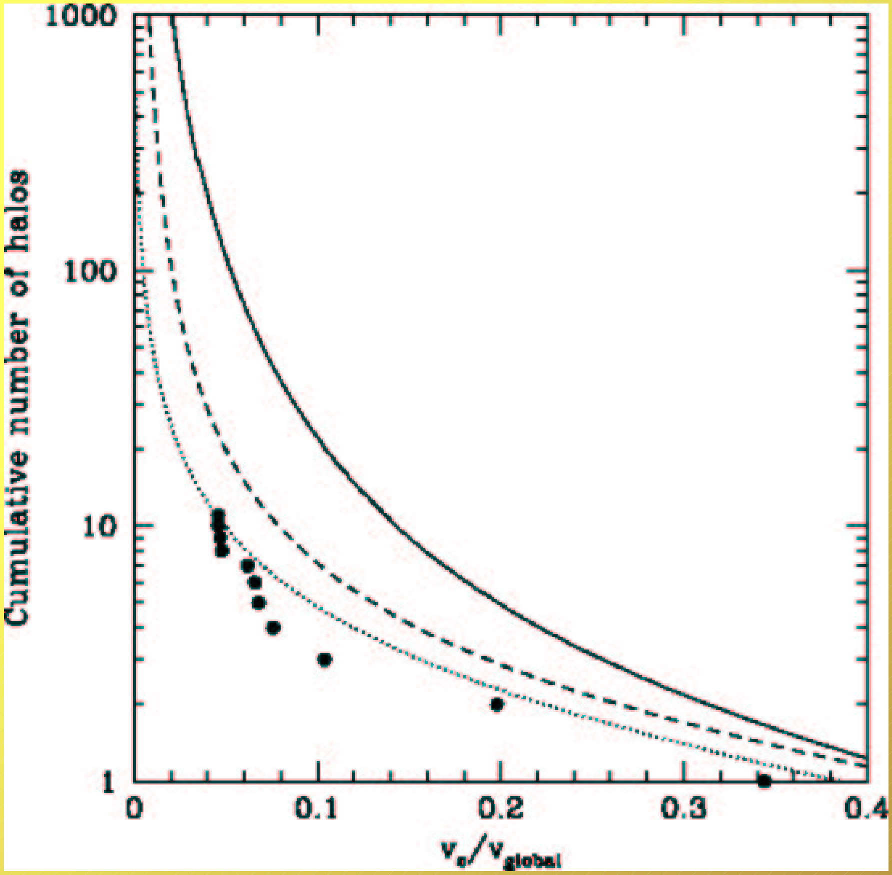
also Klypin et al, astro−ph/9901240;

Kaufmann, White, Guiderdoni, 1993

Probably don’t need self interacting DM:

- Requires very unusual particles (elastic scattering cross sections 13 order of magnitude bigger than annihilation
- Not really clear that self interaction improves agreement with observations
- May be due to other exotic process (e.g. Broken scale invariance in primordial power spectrum (MK, Liddle 2000))
- Absence of small scale structure in halo most likely due to prosaic astrophysical mechanism





MK,Liddle (2000)

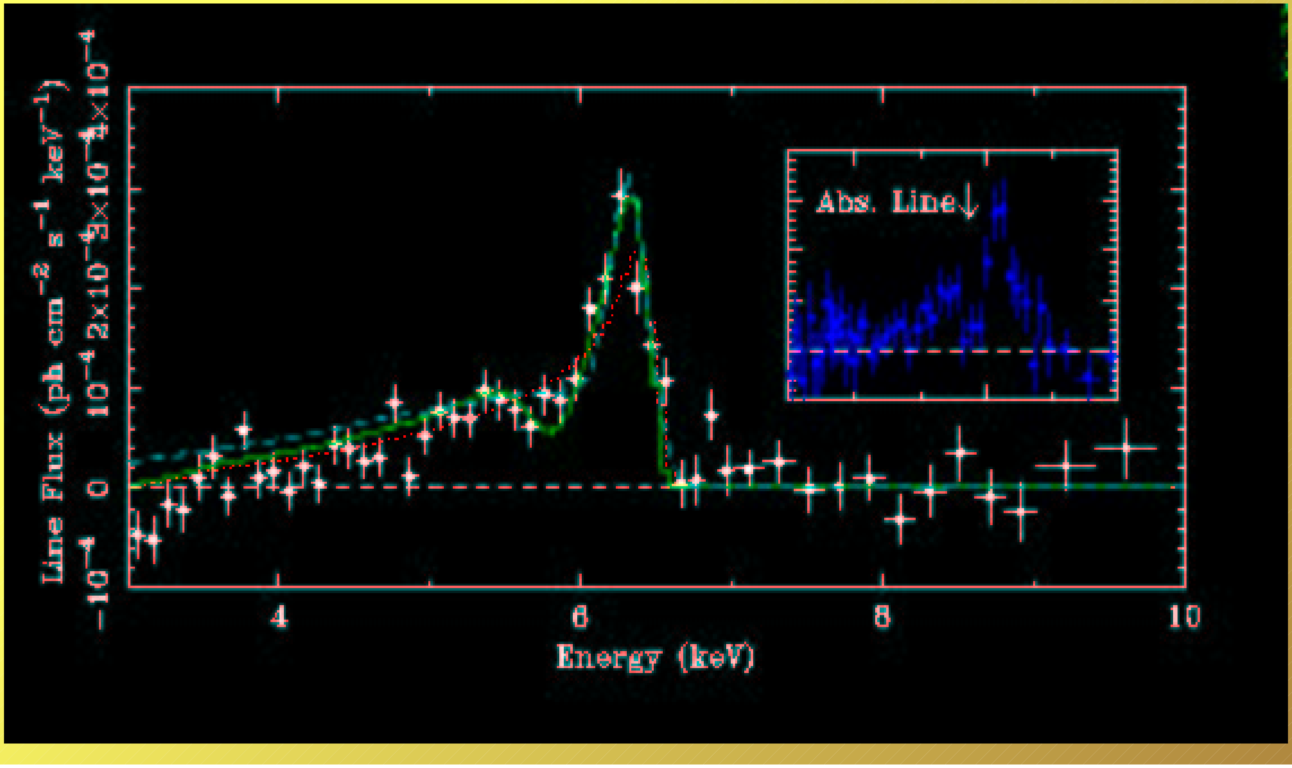
IV. Tests of strong−field gravity:

- Gravitational waves from stellar orbits around supermassive black holes (e.g., with LISA)
- X ray timing and spectroscopy from accretion disks around supermassive black hole (RXTE, Chandra, XMM, Con−X,GLAST...)

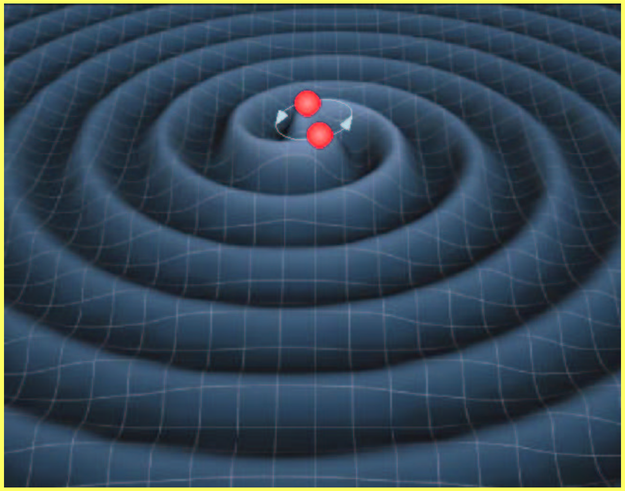
- other interesting tests with grav radiation; e.g., can test whether gravitational waves propagate at speed of light (extra dimensions says they might not!!)

Possible detection of effects of black hole spin on surrounding spacetime!!!

P. Nandra

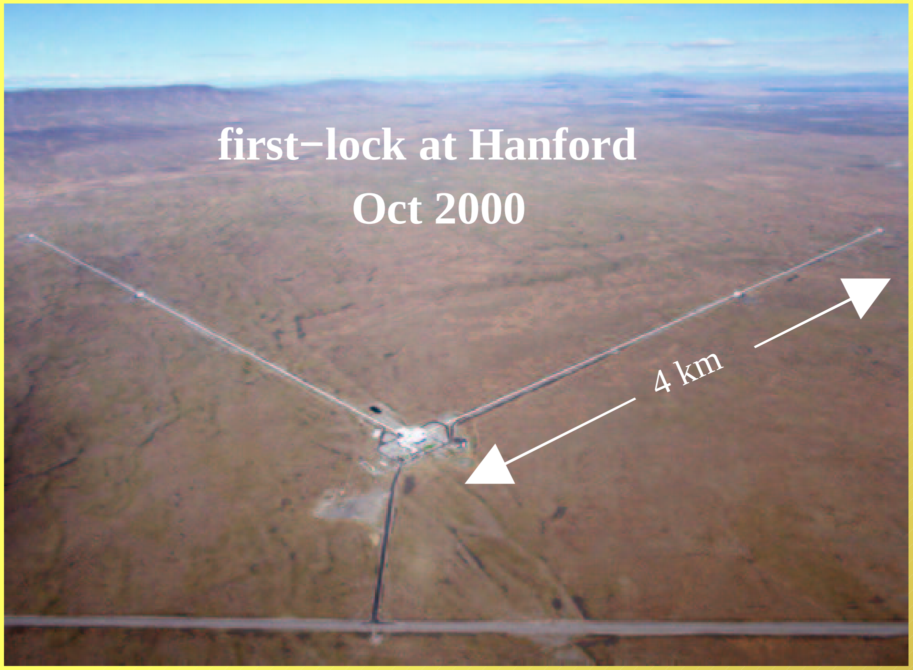


Gravitational Radiation

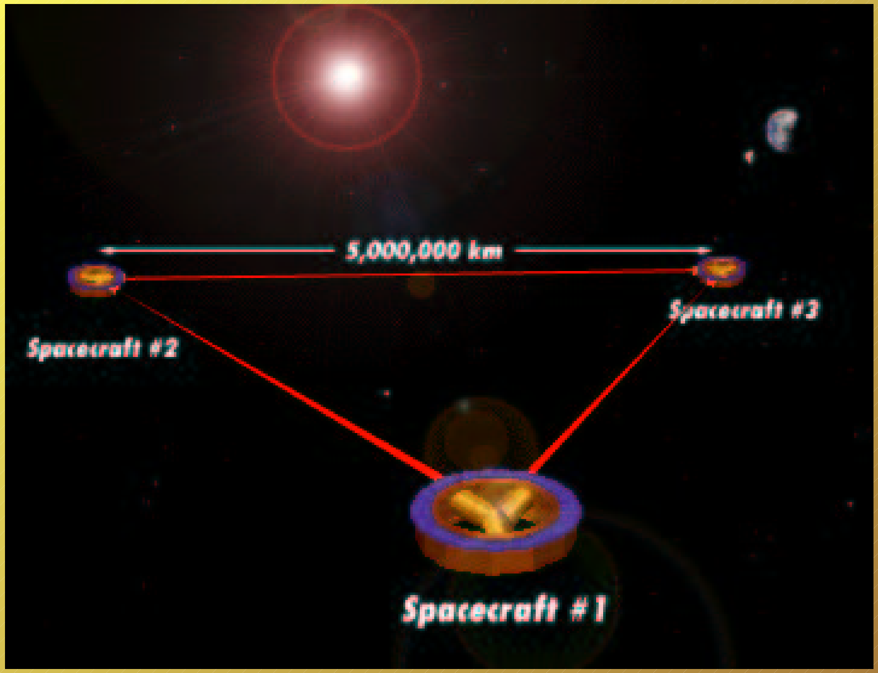


Orbiting and merging massive objects emit gravitational radiation

Two biggest experiments aiming to detect gravity waves:


first−lock at Hanford
Oct 2000

LIGO (ground−based, under construction)

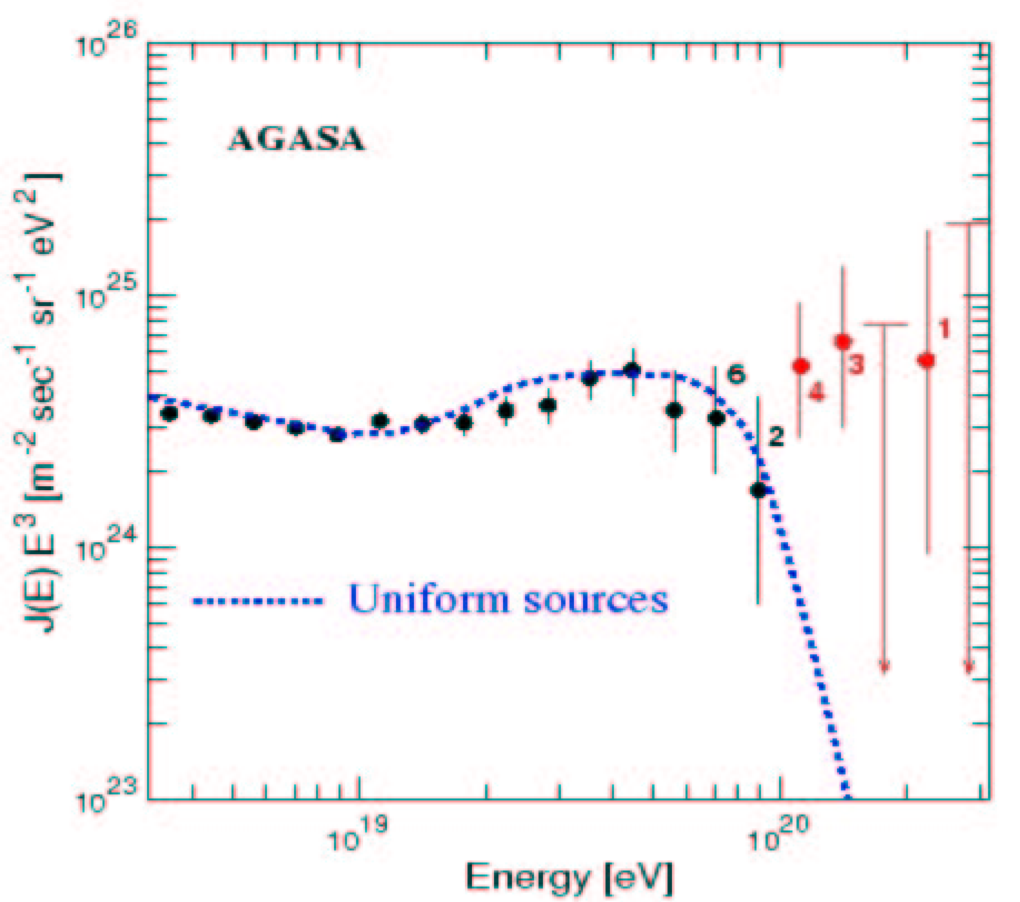


LISA (space−based, under development)

Possible detection of cosmic rays above GZK cutoff!!!

$\lambda(p + \gamma \rightarrow p + \pi) \leq 30$ Mpc for $E_p \geq 10^{20}$ eV,

but no obvious sources within ~30 Mpc also no dramatic cutoff in spectrum near 10^{20} eV.

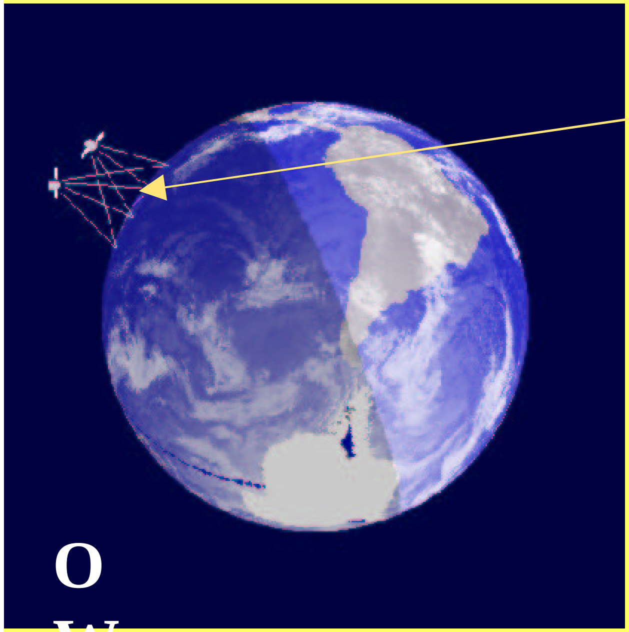


HiRes also seeing events

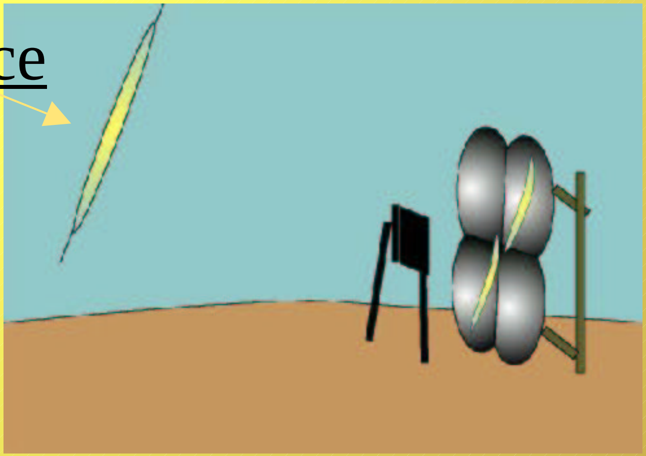
Ultra−high−energy cosmic rays:

Existence of cosmic rays above Greisen−Zatsepin−Kuzmin limit suggest possibly propagation of exotic particle and/or decays of topological defects or ultra−massive relic particles. Interactions in atmosphere may include interesting QCD.

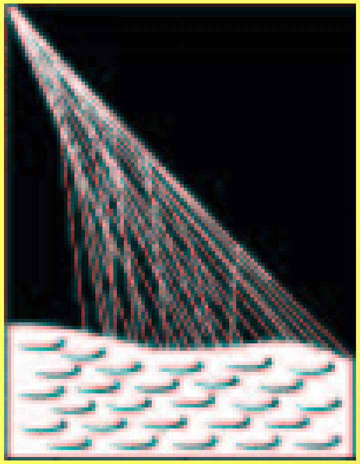
UHE Cosmic Ray Techniques

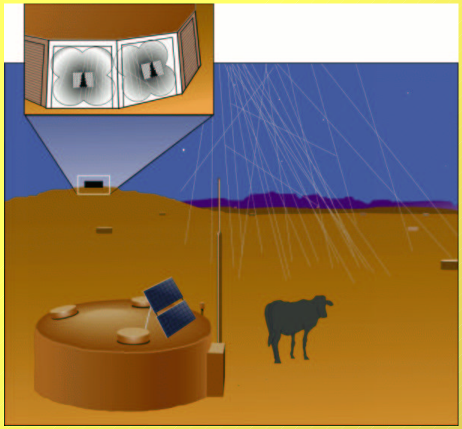


Nitrogen Fluorescence



Air Shower





Experiment	Technique	Eff. Aperture [1000xkm^2−sr]	Status
AGASA	Ground Array	~0.2	running
HiRes	Fluor.	~1	running
Auger	Ground Array + Fluor.	7 (x2)	building (prop)
Telescope Array	Fluor.	8	under study
OWL	Fluor.	~300	under study

More:

- Astrophysical probes of large extra dimensions, Lorentz/CPT violation...
- Astrophysical tests of general relativity (e.g., Shapiro time delay, radio deflection, lunar−laser ranging...
- Theoretical ultrahigh energy physics: the early Universe as a laboratory for string theory, PQ symmetry breaking, GUTs, SUSY breaking, extra dimensions....

Conclusions/Summary

Astrophysics and cosmology are often difficult and messy

BUT, can in some cases provide real opportunities to probe new physics not accessible with accelerators.

Its a good time for cosmology and particle astrophysics; plenty of exciting discoveries and breakthroughs; broad and rich frontier; healthy interplay between theory/experiment; prospects for rapid order of magnitude experimental advances in many areas.

Cosmology and particle astrophysics

August 16, 2002

QUIZ

1. CMB data suggests that the Universe is
   (a) flat
   (b) open
   (c) closed
   (c) It cannot be determined from the information given.

2. CMB data
   (a) rule out topological defects as the primary origin of large-scale structure
   (b) suggest primordial perturbations, like those from inflation, are responsible for large-scale structure
   (c) are beginning to provide independent constraints to several cosmological parameters
   (d) All of the above

3. The speaker
   (a) has an entirely irrational and purely religious belief in inflation.
   (b) thinks inflation is at best a bunch of hogwash.
   (c) finds inflationary predictions to be sufficiently consistent with recent CMB measurments to warrant further serious consideration.
   (d) It cannot be determined from the information given

4. Which of the following is *not* a prediction of inflation?
   (a) a flat Universe
   (b) primordial adiabatic perturbations
   (c) a nonzero cosmological constant today
   (d) a stochastic gravitational-wave background
   (e) Gaussian initial conditions

5. Rank the following in order of their likelihood, as you see it, for dark matter in the Galactic halo: with
   (a) the lightest supersymmetric particle
   (b) an axion
   (c) self-interacting dark matter
   (d) primordial black holes
   (e) none of the above

6. The existence of cosmic rays above the GZK bound is
   (a) an experimental artifact
   (b) due to some exotic new particle bringing signals from otherwise traditional (e.g., AGN) but distant astrophysical source
   (c) due to decay of topological decays or ultra-heavy relic particles
   (d) the result of traditional astrophysics, like shocks in the intergalactic medium

7. There is a direct and concrete connection between B physics and
   (a) measurements of the CMB power spectrum
   (b) searches for supersymmetric dark matter
   (c) theories of ultra-high-energy cosmic rays
   (d) measurements of the matter power spectrum with cosmic shear (i.e., weak gravitational lensing)