Particle Astrophysics and Cosmology

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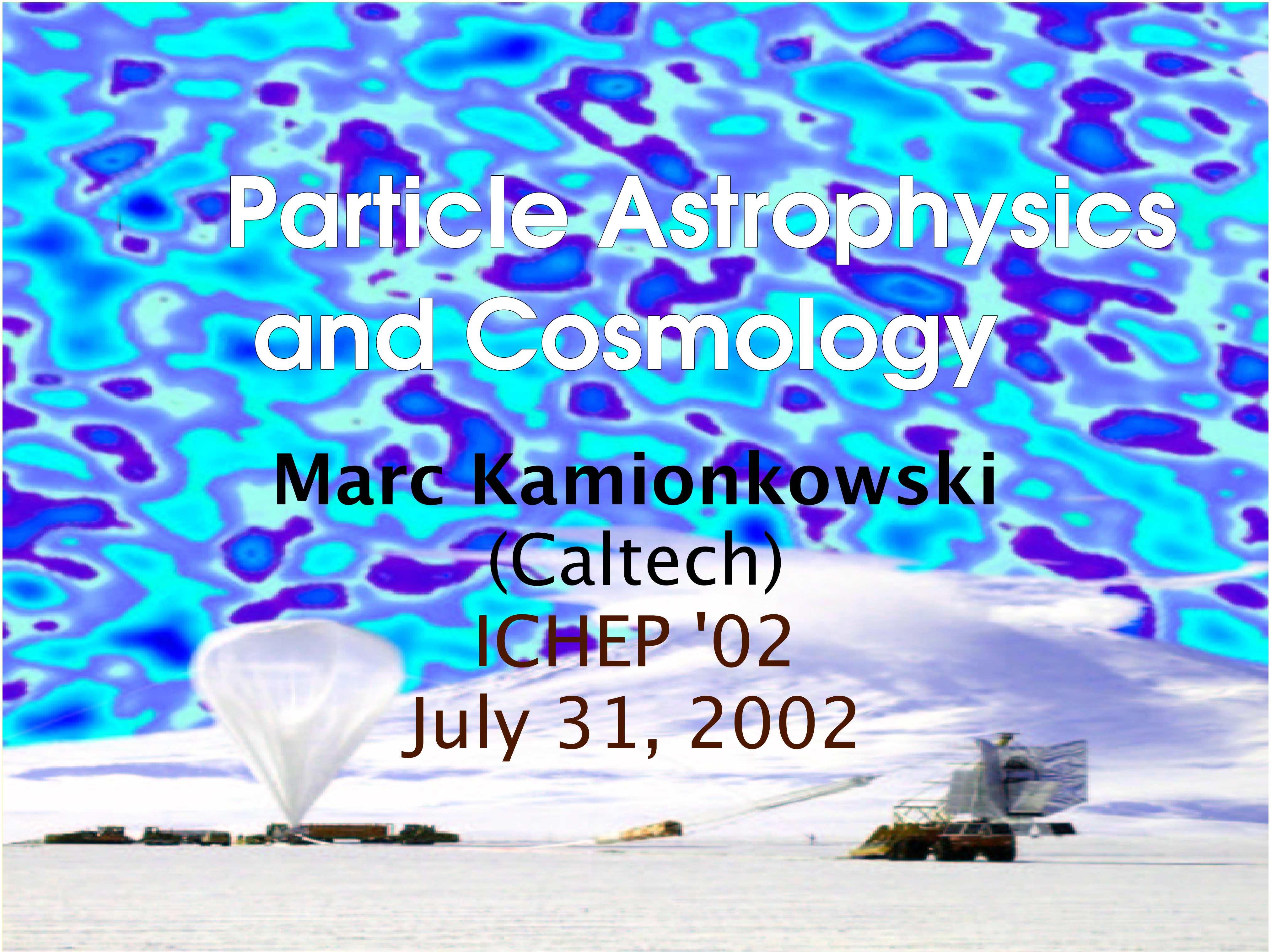
ICHEP '02
July 31, 2002



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

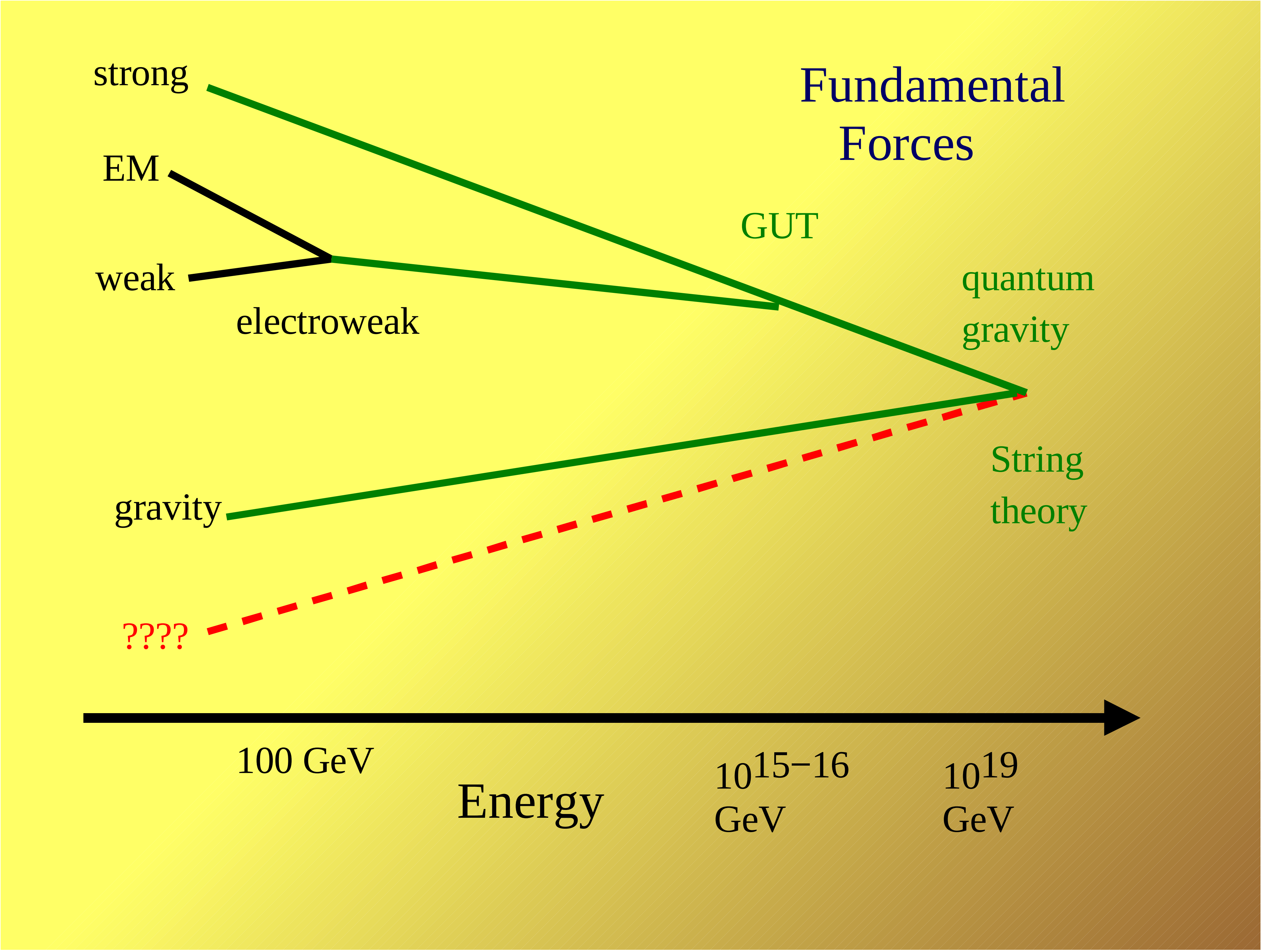
V. Ultrahigh energy cosmic rays

VI. Gravitational radiation

VII. Neutrino astrophysics

VIII. Early universe and tests of fundamental physics brane worlds and large extra dimensions

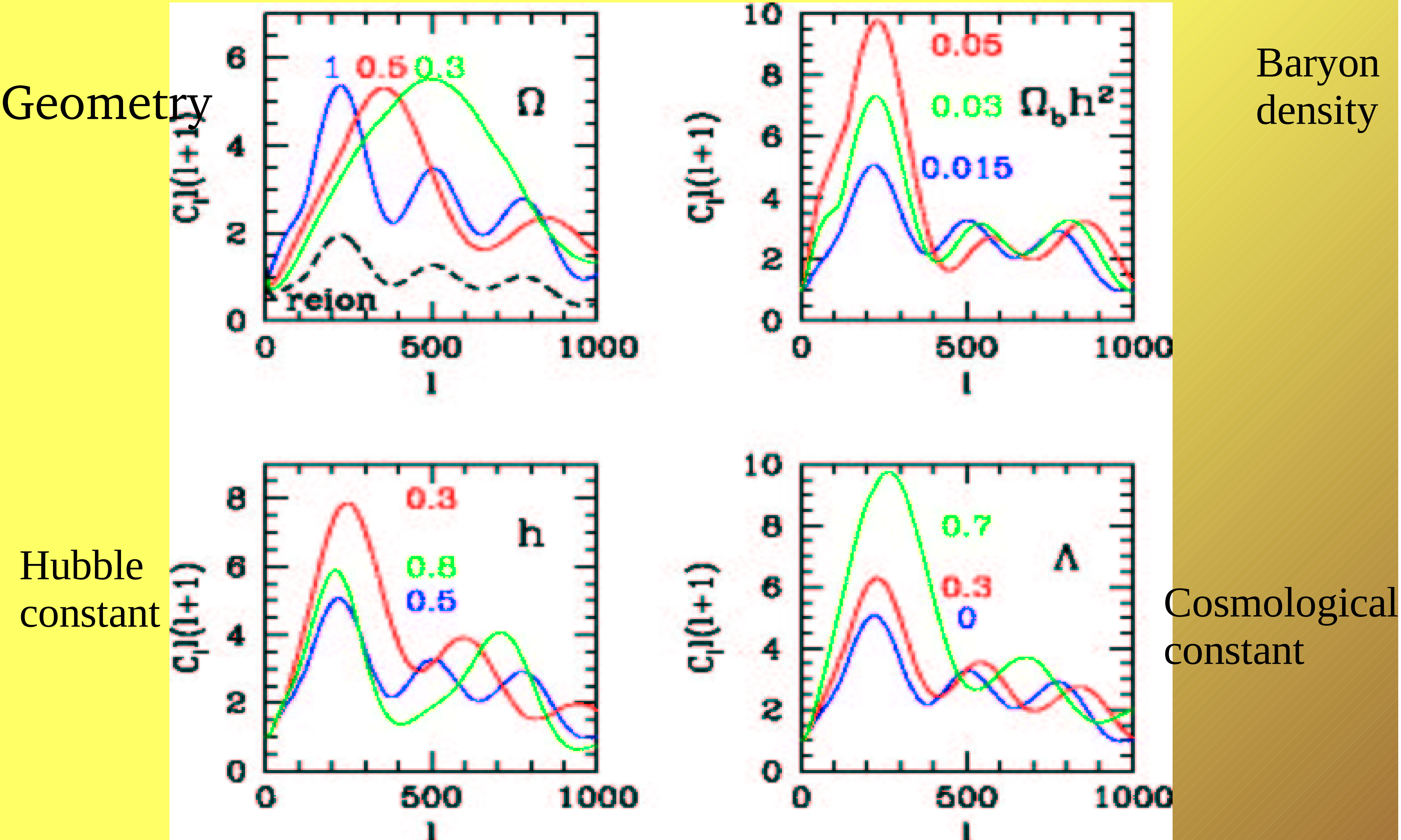
(see, e.g., Akerib, Carroll, MK, Ritz, summary of P4 Working Group at Snowmass 2002, hep−ph/0201178


Fundamental
Forces
strong
EM
weak
electroweak
GUT
quantum
gravity
String
theory
gravity
????
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

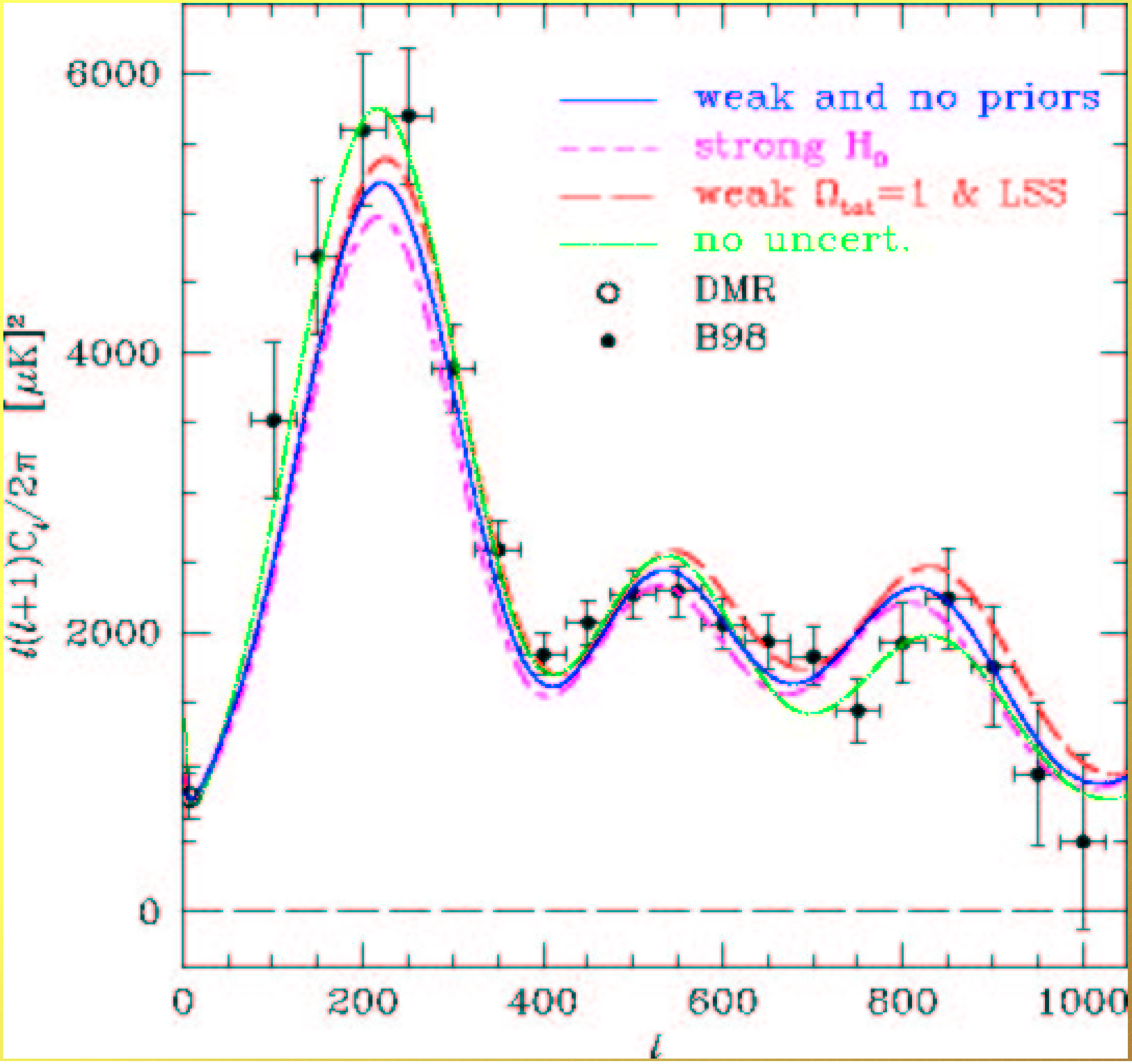
I. The Cosmic Microwave Background and Inflation



Jungman, MK, Kosowsky, Spergel 1996

Results!!!

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



Current results:

show that Universe is flat → ***Inflation!!***

determine primordial seeds for large scale structure → ***Inflation!!***

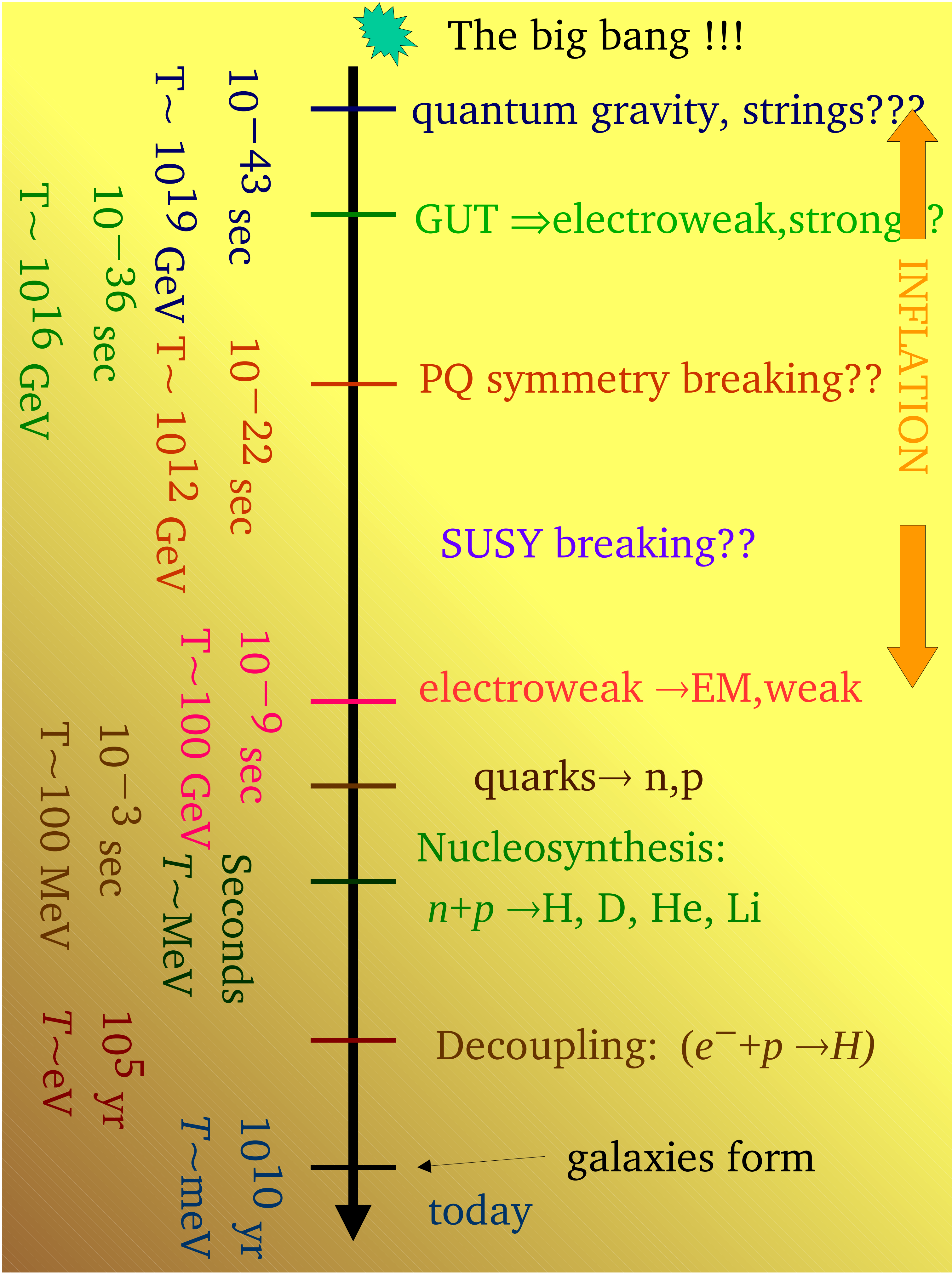
independently verify big bang nucleosynthesis

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.



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
INFLATION
10⁻⁴³ sec
T~ 10¹⁹ GeV
10⁻³⁶ sec
T~ 10¹⁶ GeV
10⁻²² sec
T~ 10¹² GeV
10⁻⁹ sec
T~100 GeV
10⁻³ sec
T~100 MeV
Seconds
T~MeV
10⁵ yr
T~eV
10¹⁰ yr
T~meV

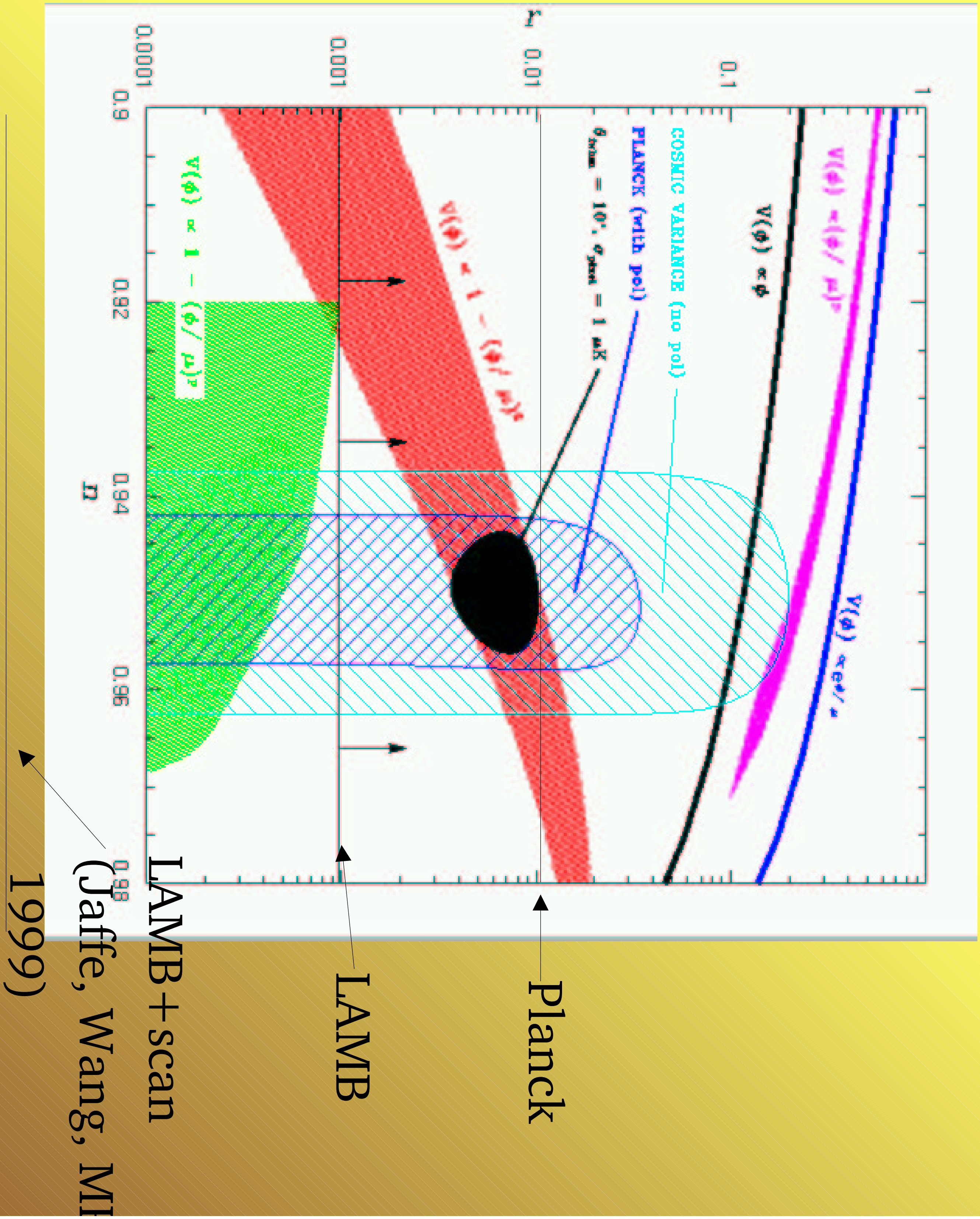
CMB tests of inflation:

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).

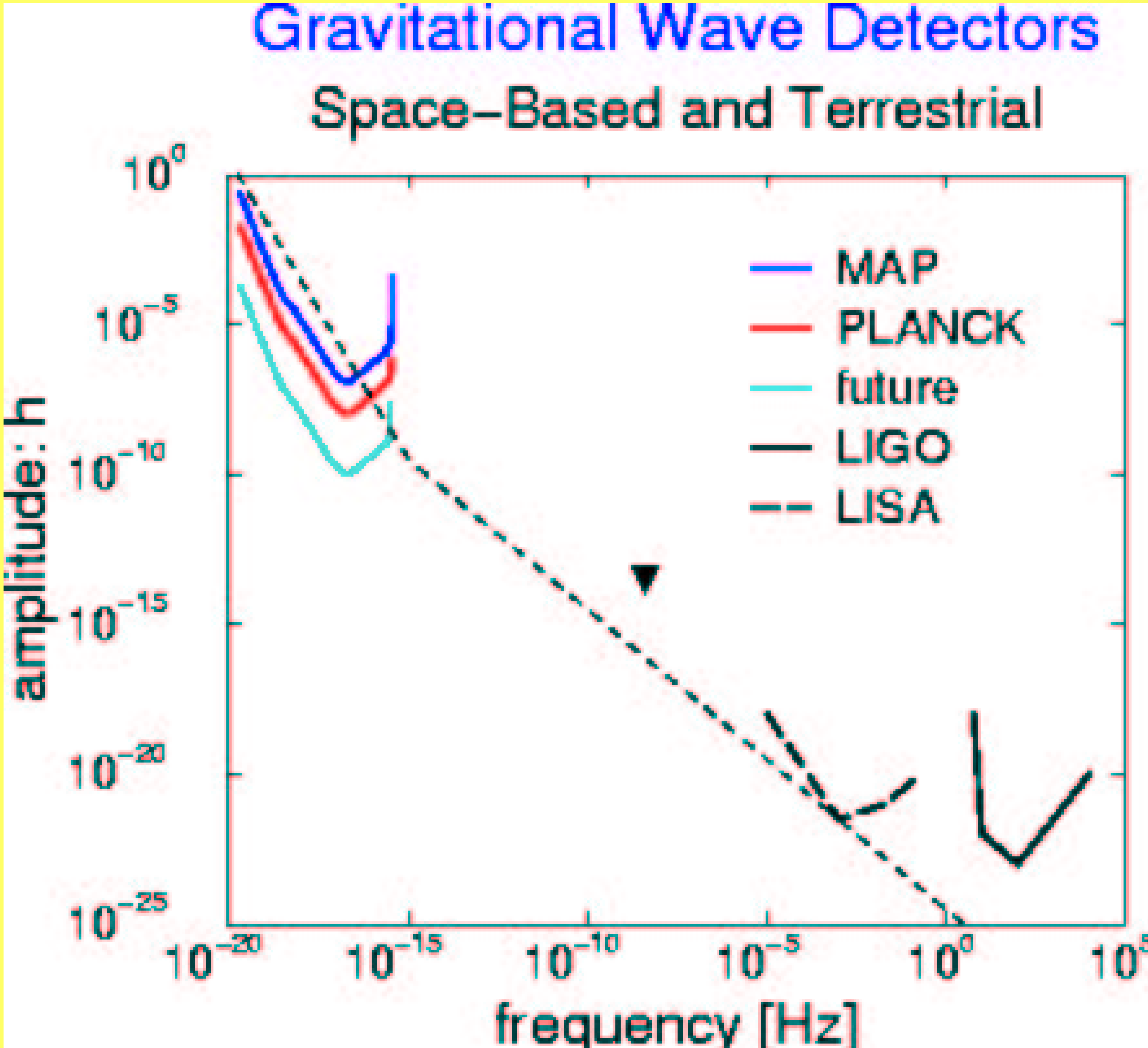
Detection of inflationary gravitational waves through CMB polarization can provide "smoking gun" for inflation at GUT scale.
(MK, Kosowsky, Stebbins 1997; Seljak,Zaldarriaga 1997)

Gravitational−Wave Amplitude
(Energy scale of inflation)^2



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

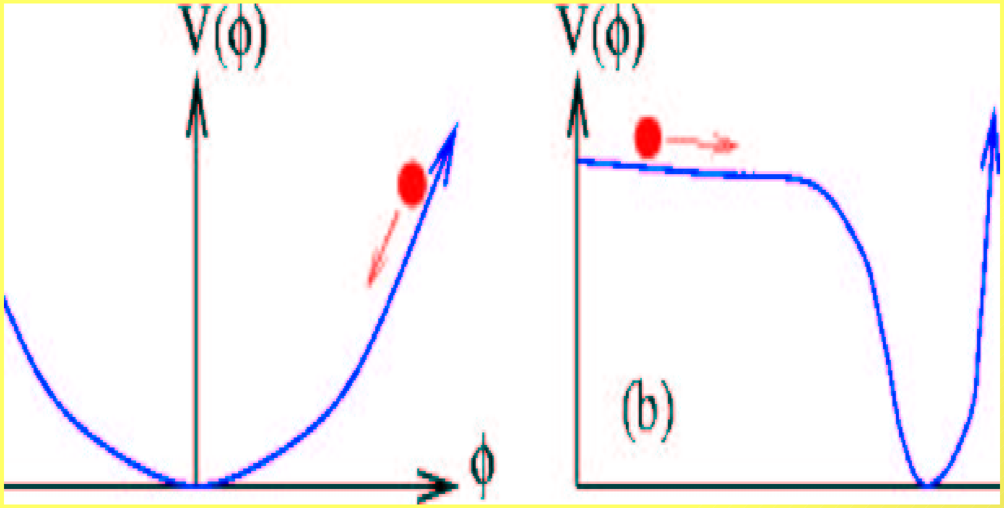
(Lue, Wang, MK, 1999)

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

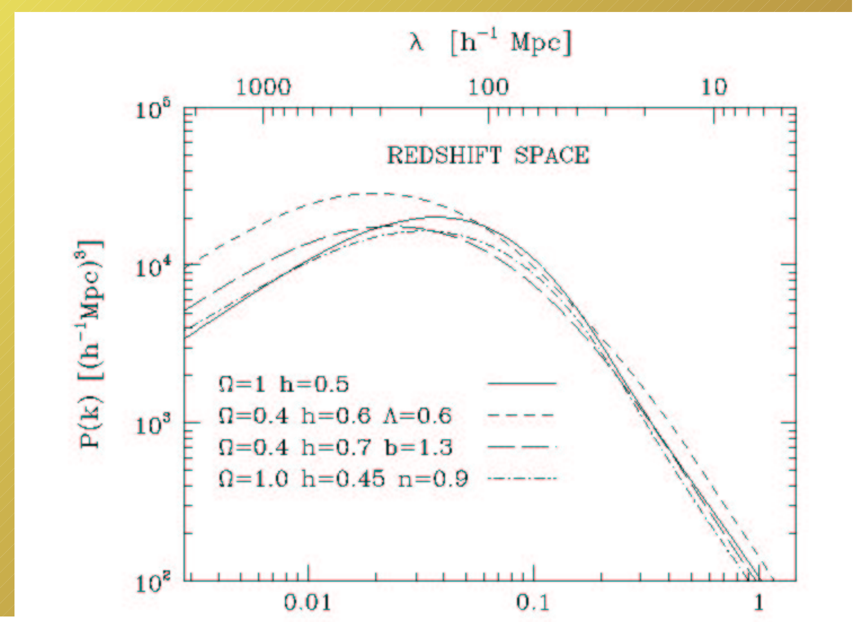
$\phi \varepsilon^{\mu\nu\rho\sigma} R_{\mu\nu\alpha\beta} R^{\alpha\beta}_{\rho\sigma}$ P,T violating coupling to gravity can produce preponderance of right versus left handed GWs during inflation

II. Large scale structure and inflation

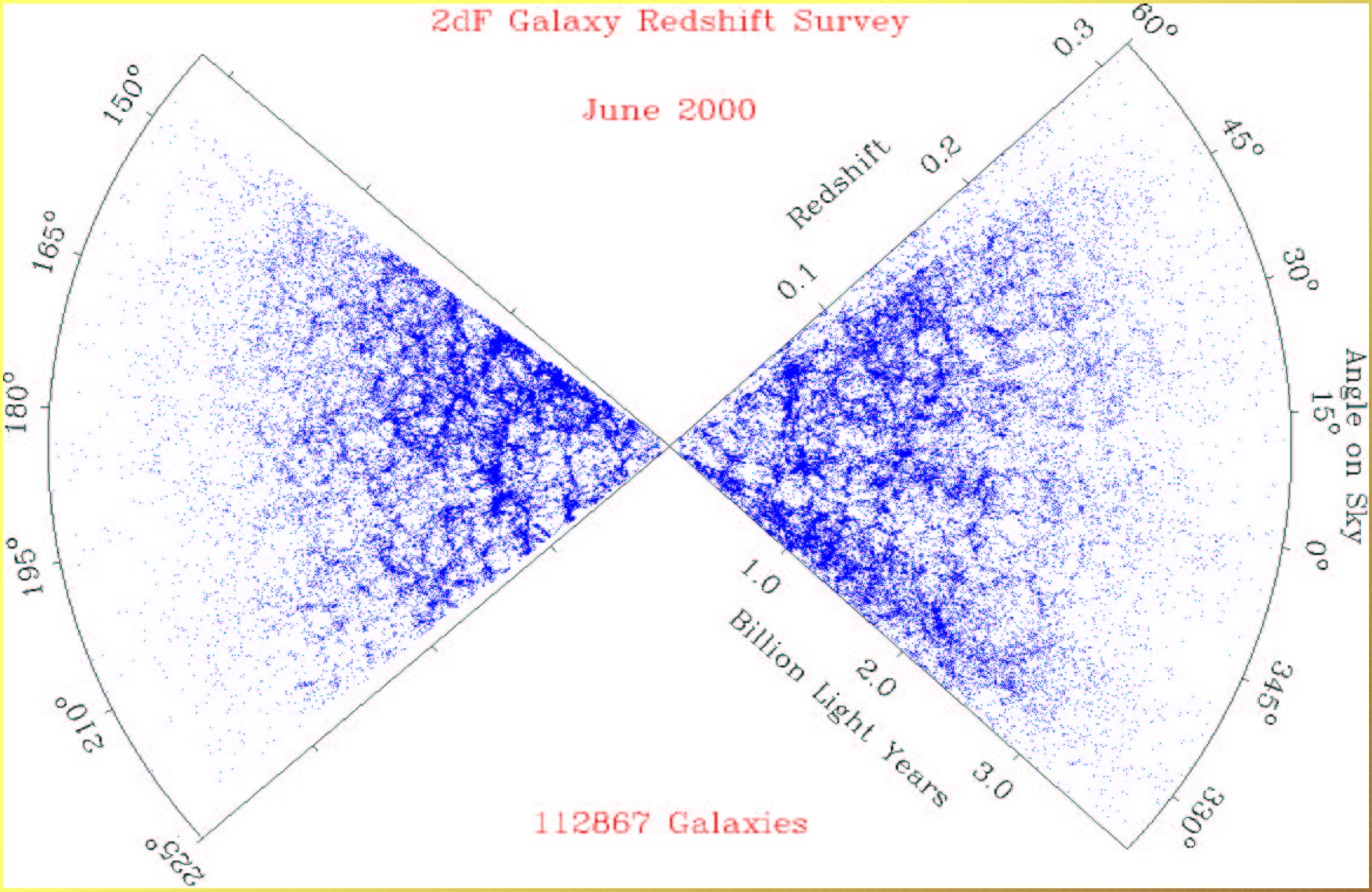


Inflaton potential

Matter power spectrum



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



Forecast SDSS Power Spectrum

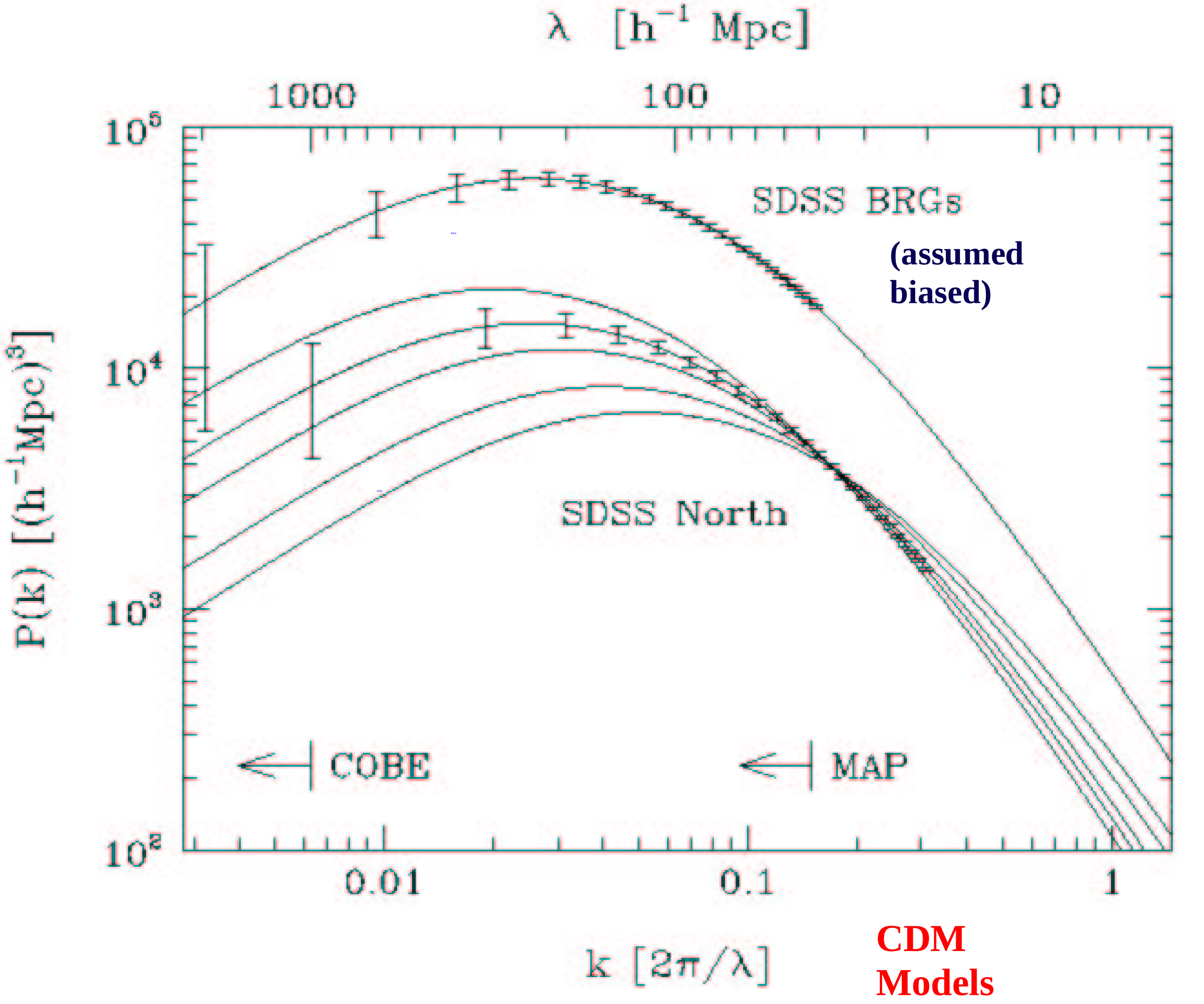


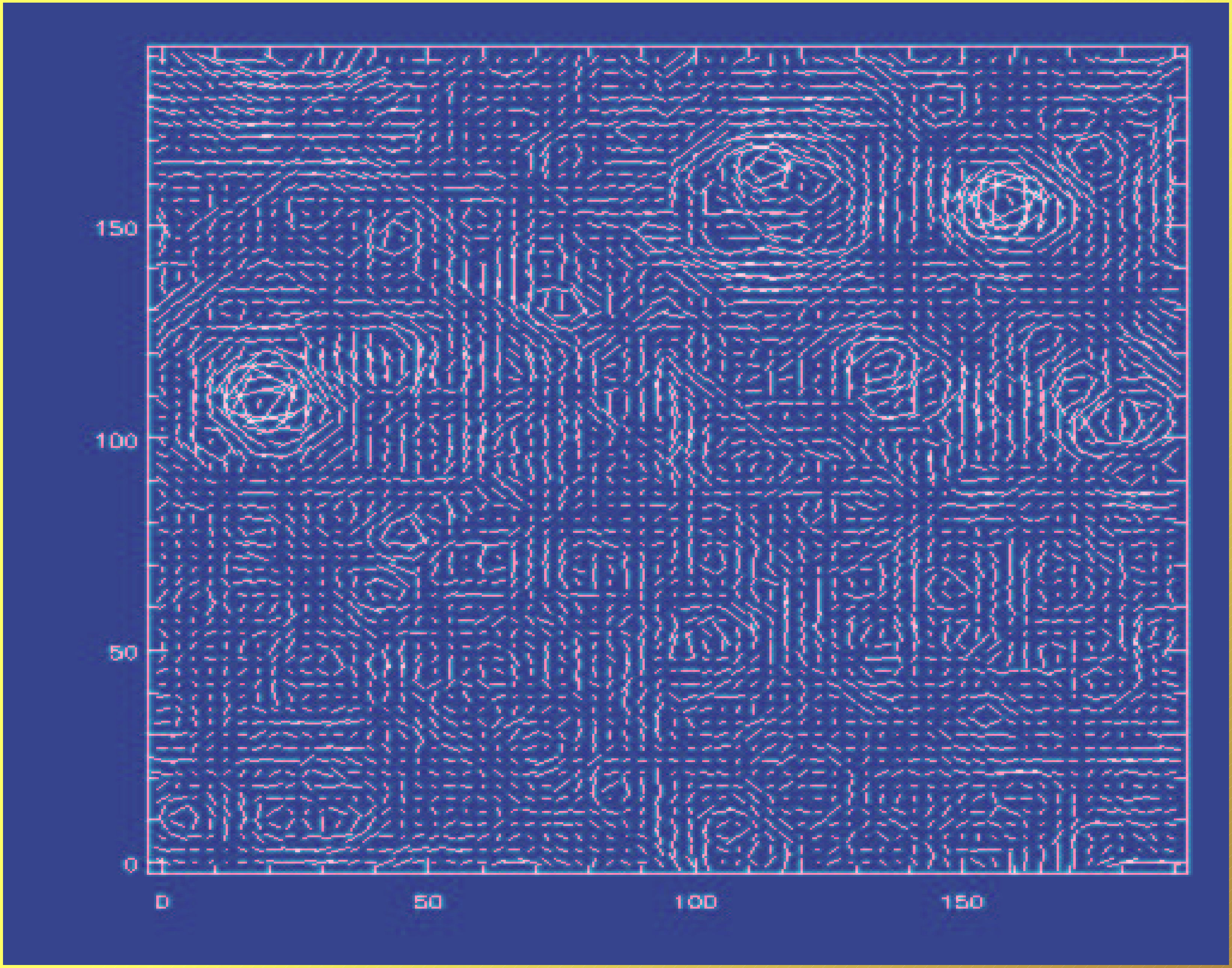
Fig. 3.— Predicted uncertainties in the power spectrum estimated from a volume-limited ($R_{max} = 500h^{-1}$ Mpc) sample of SDSS North and for the Bright Red Galaxy sample (upper set of error bars). These errors assume that the true power spectrum is that of an $\Omega h = 0.25$ CDM model and that the 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.

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

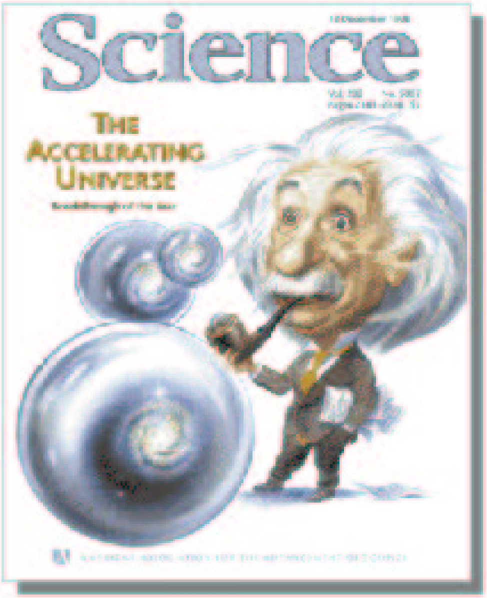
Inflation: What Else??

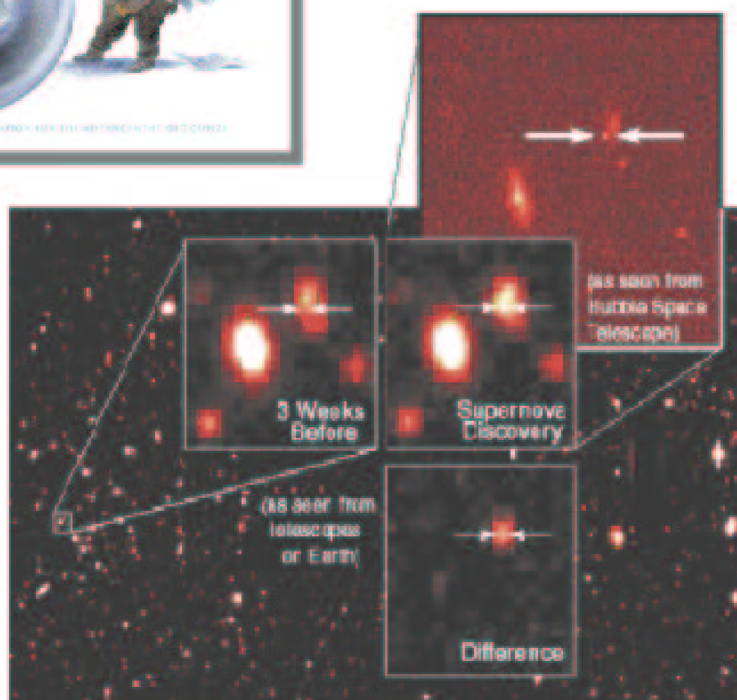
Inflation $\Rightarrow$ distribution of primordial density perturbations is Gaussian.

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

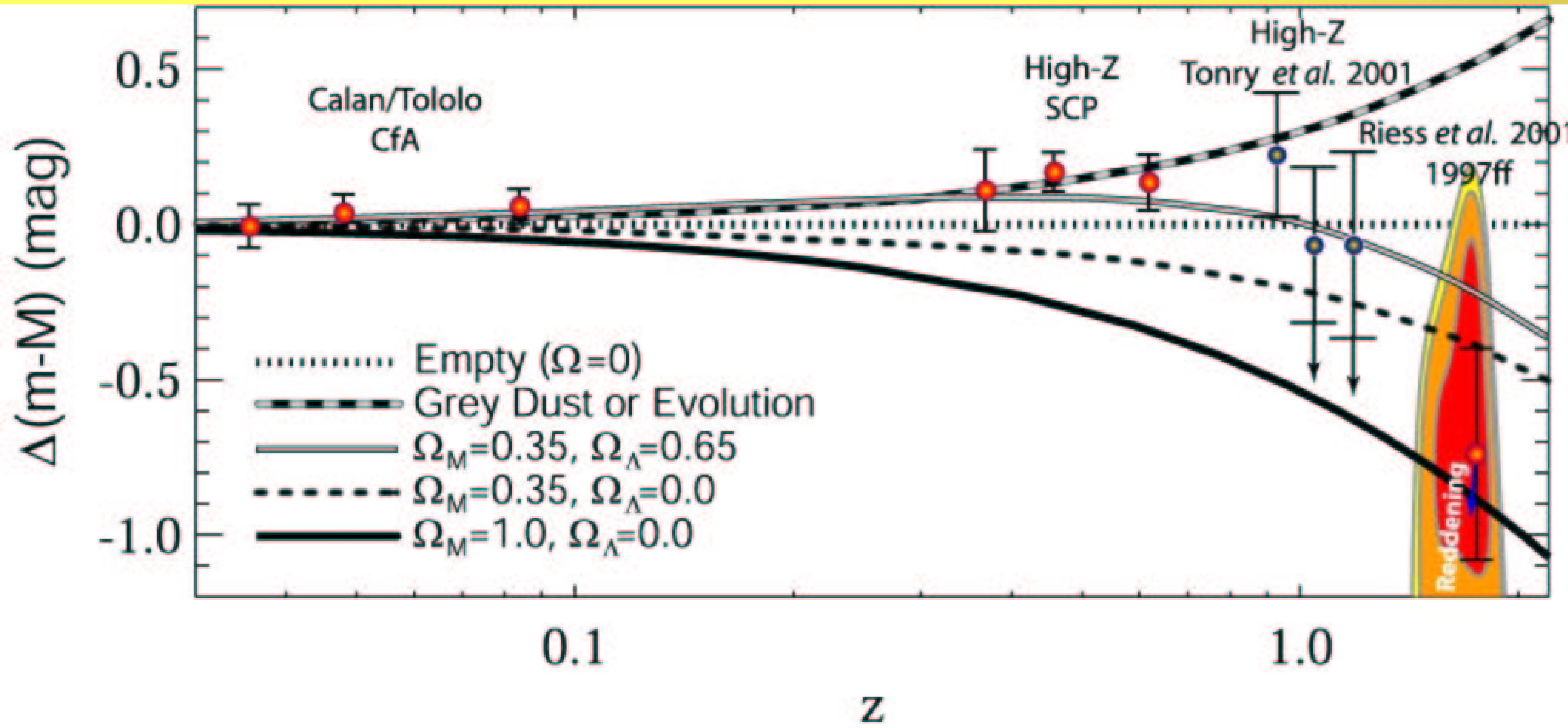
(e.g., Verde et al., 2000,2001)

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

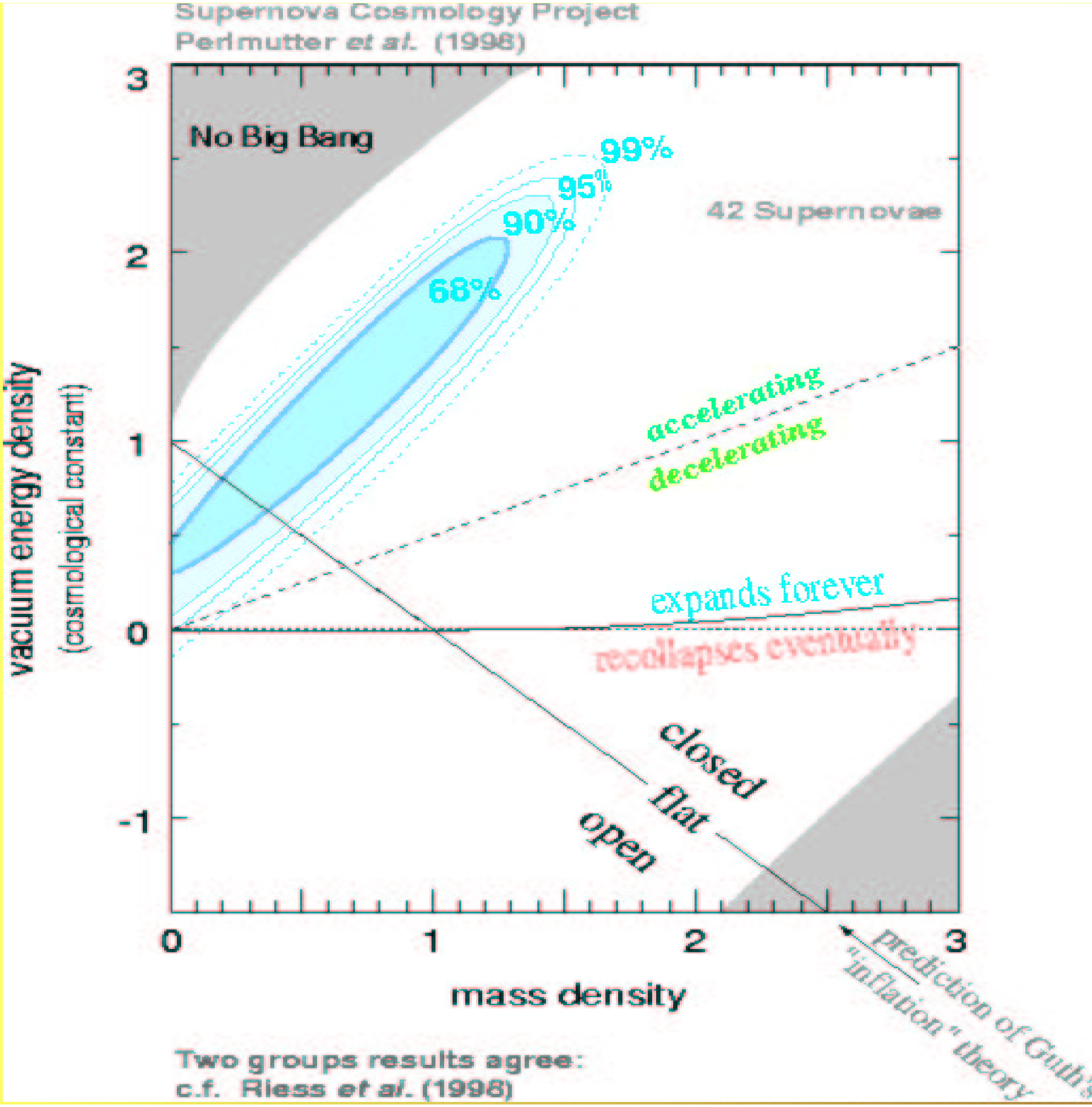




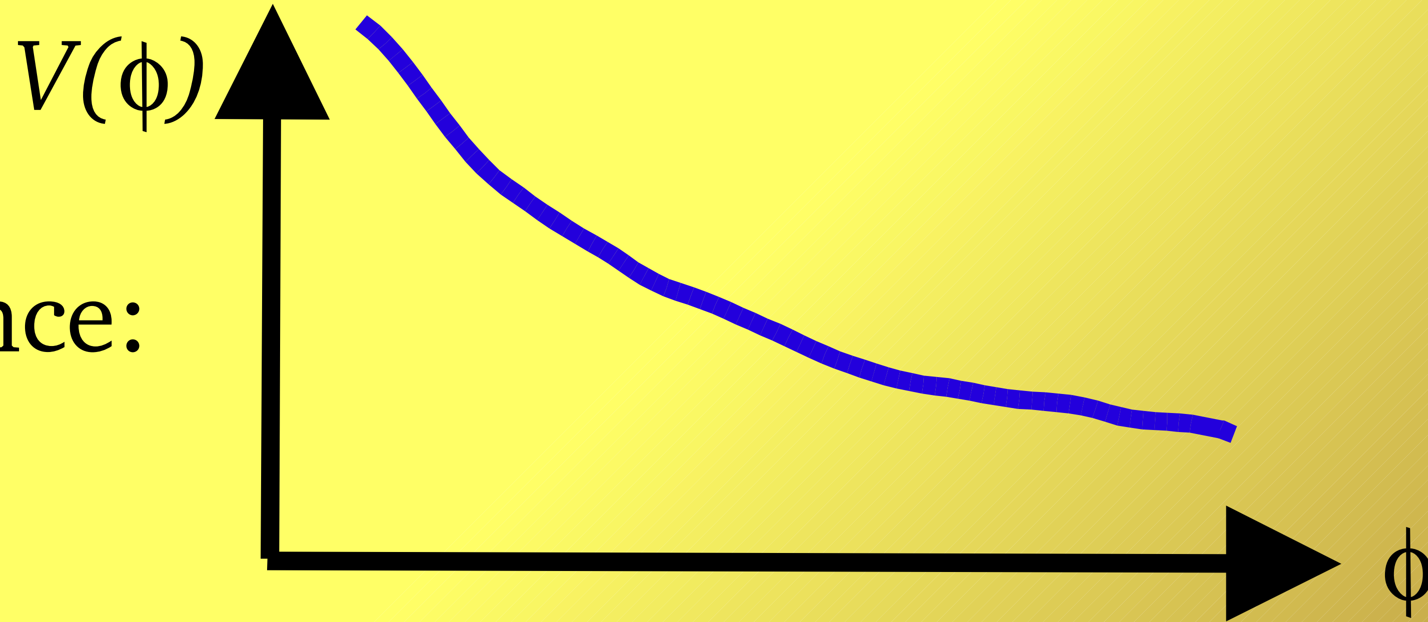
III. Supernovae, an accelerating Universe, and Dark Energy



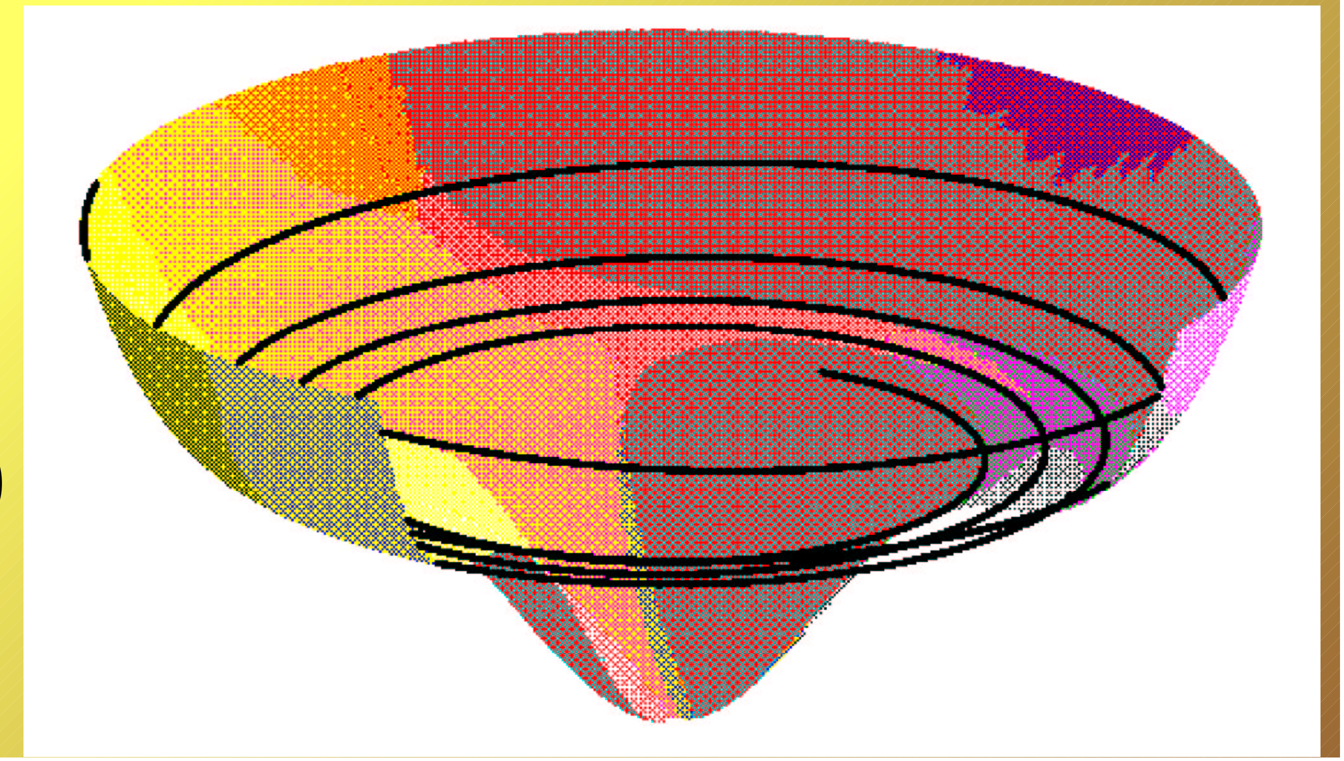
Courtesy P. Garnavich (High−z Supernova Search Team)
(results also from Supernova Cosmology Project)


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

Quintessence:

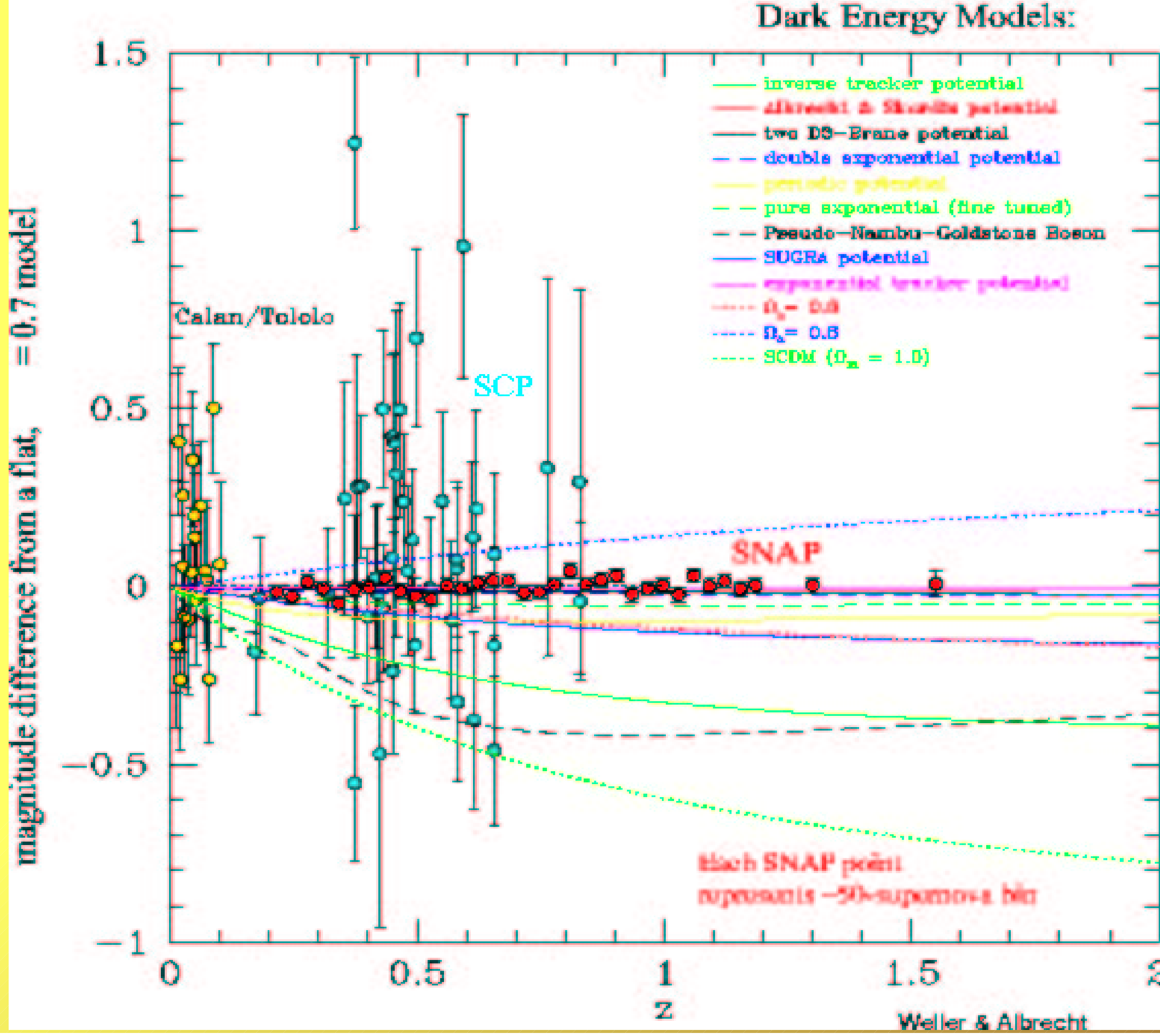


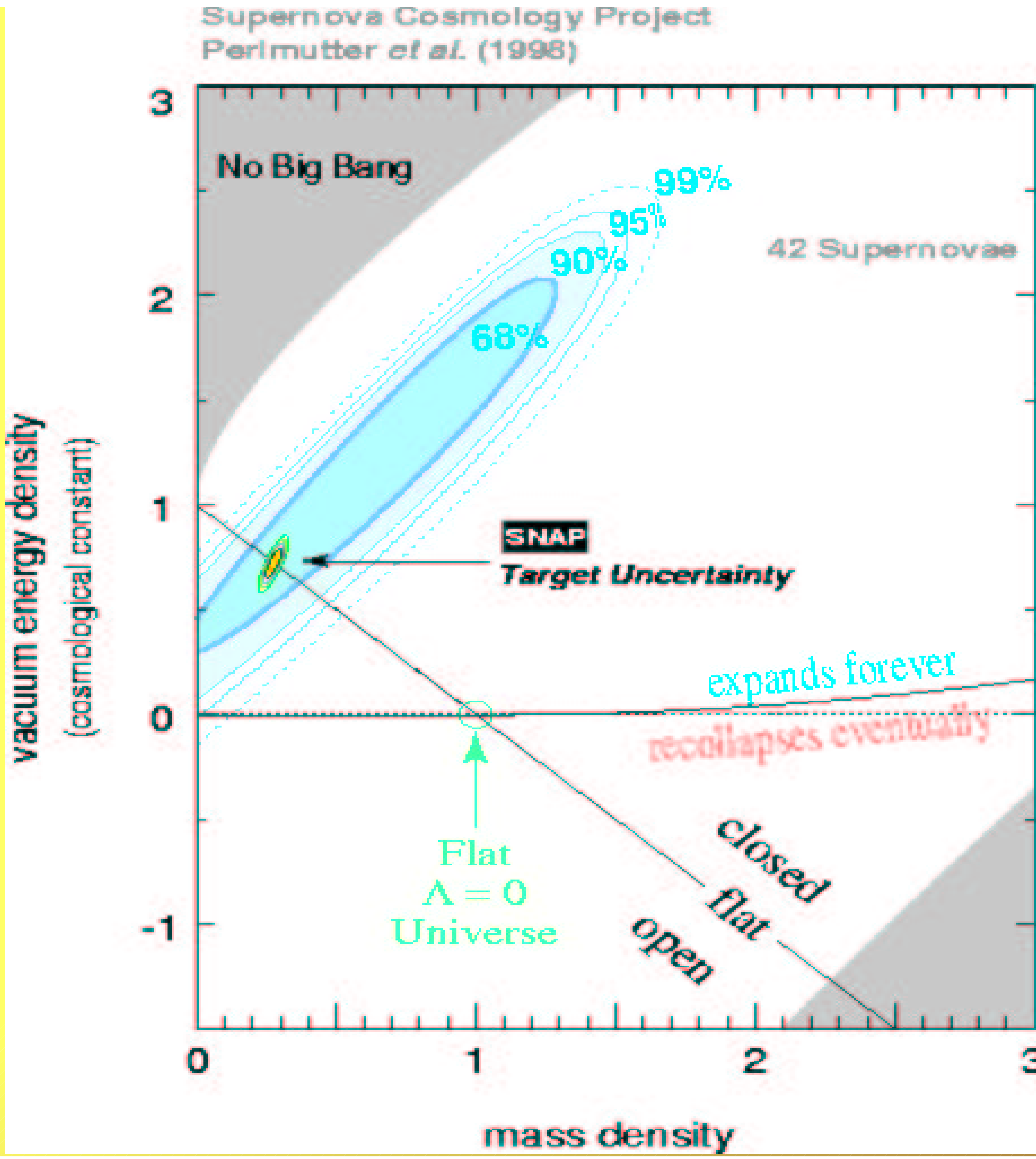
Spintessence:
(Boyle, MK,
Caldwell 2001)



SNAP SuperNova Acceleration Probe

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

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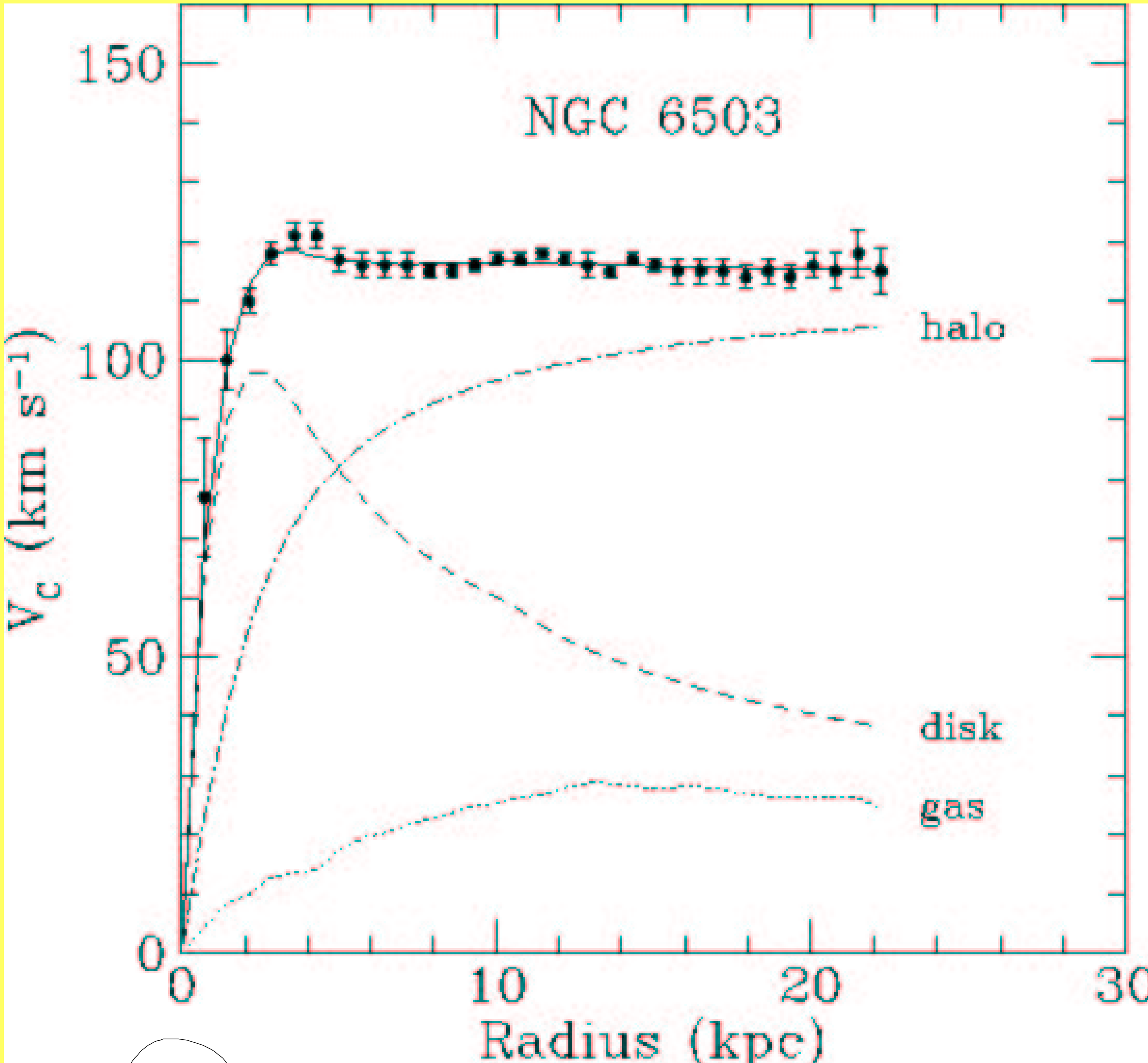
SNAP
Target Uncertainty
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

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:

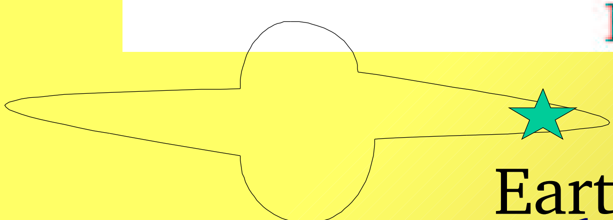
ρ_0=0.3−0.6 GeV/cm^3

If halo flattened,

$\rho_0 \uparrow$

Velocity distribution ~ Maxwell−Boltzmann

With $<v^2>^{1/2}$~270 km/sec



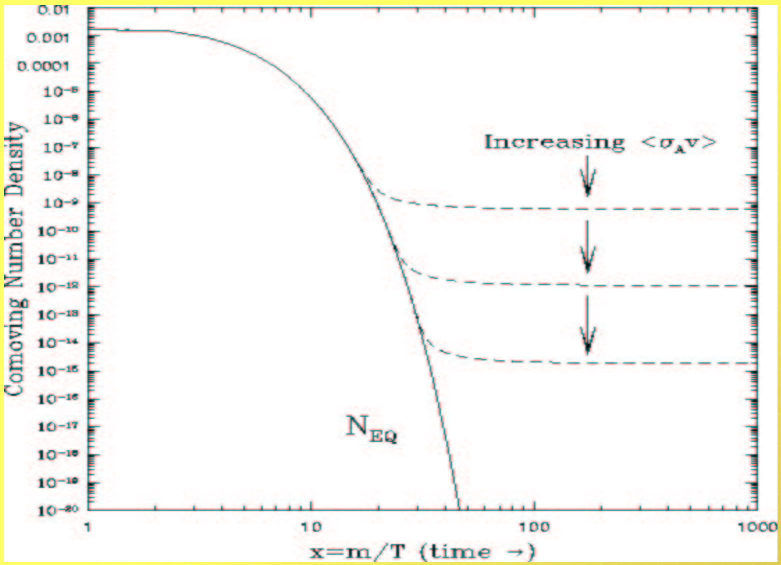
Earth

r →

r_0=8 kpc

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:

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

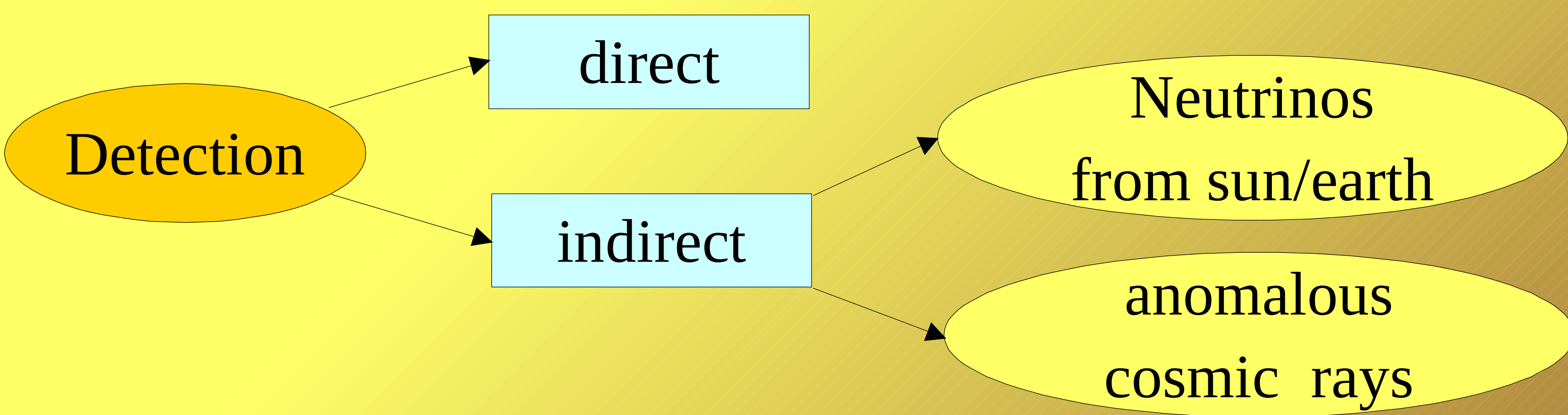
$\Downarrow$

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

$\Downarrow$

the particle has to be coupled to SM particles

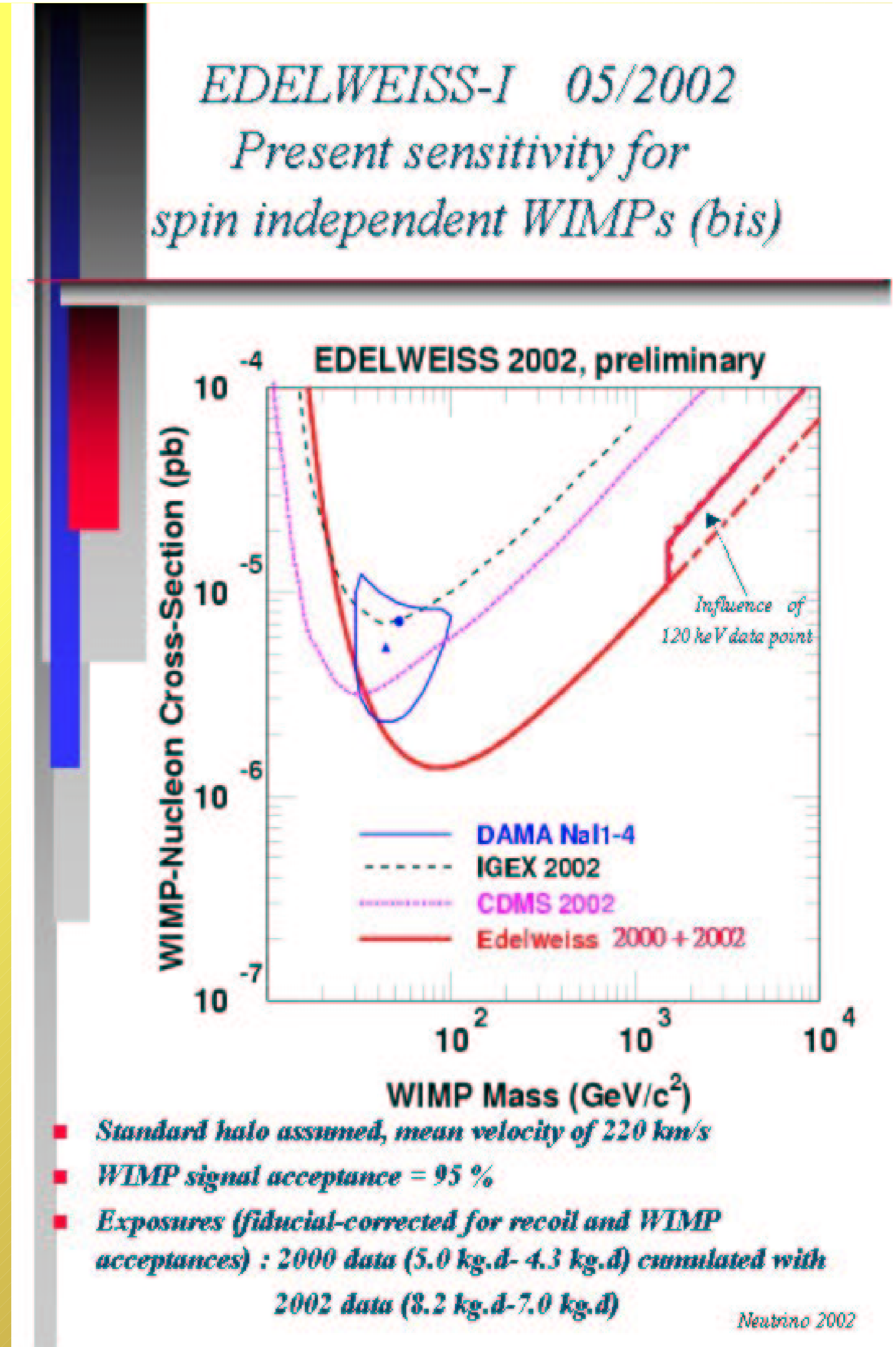
There is chance for detection:



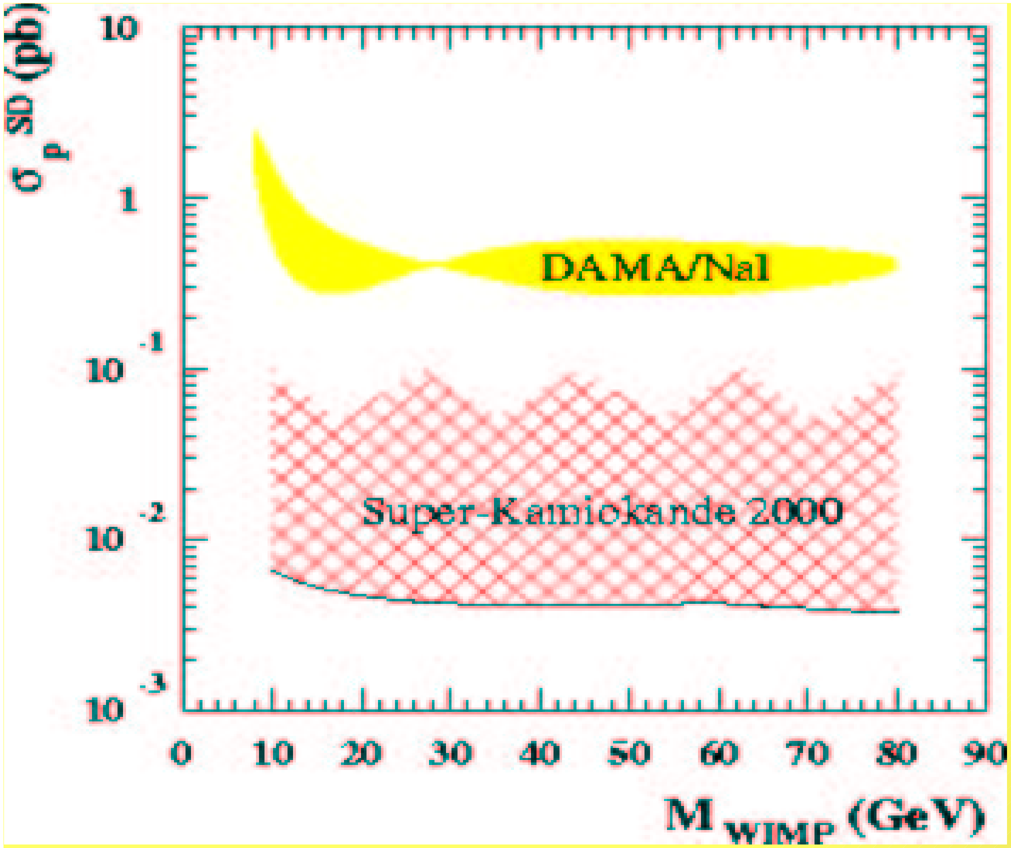
WIMP candidate motivated by SUSY:

Lightest Neutralino, LSP in MSSM

Particle dark matter searches (axions and SUSY particles)

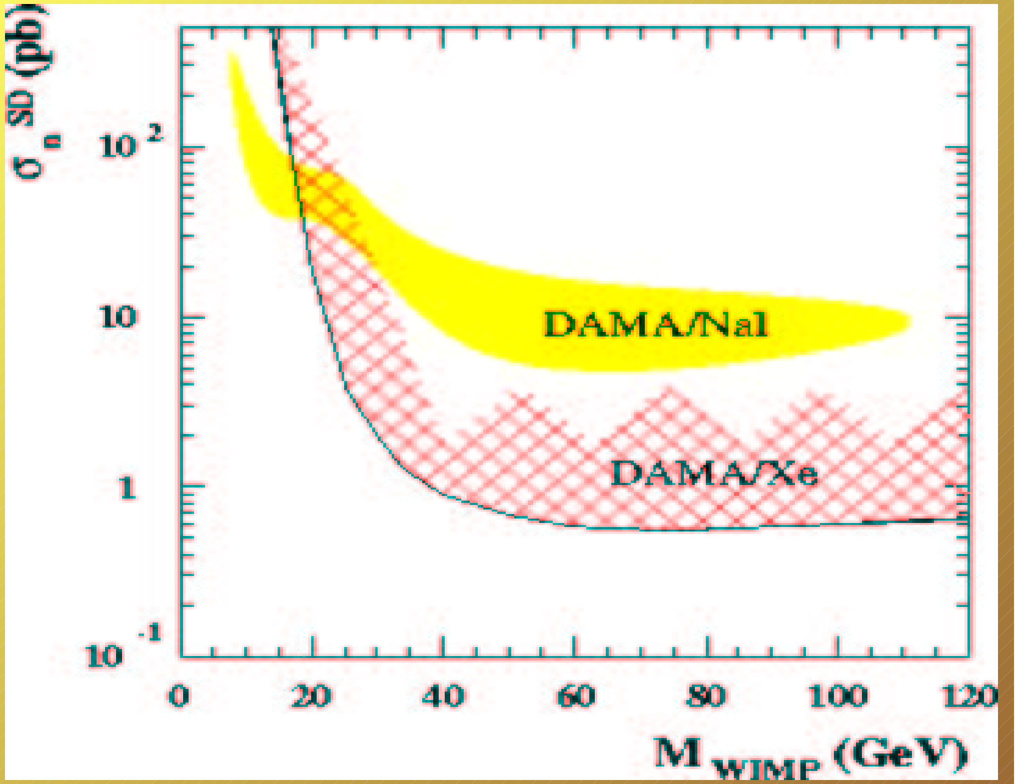


See dmtools.berkeley.edu



Spin dependent
WIMP–proton coupling

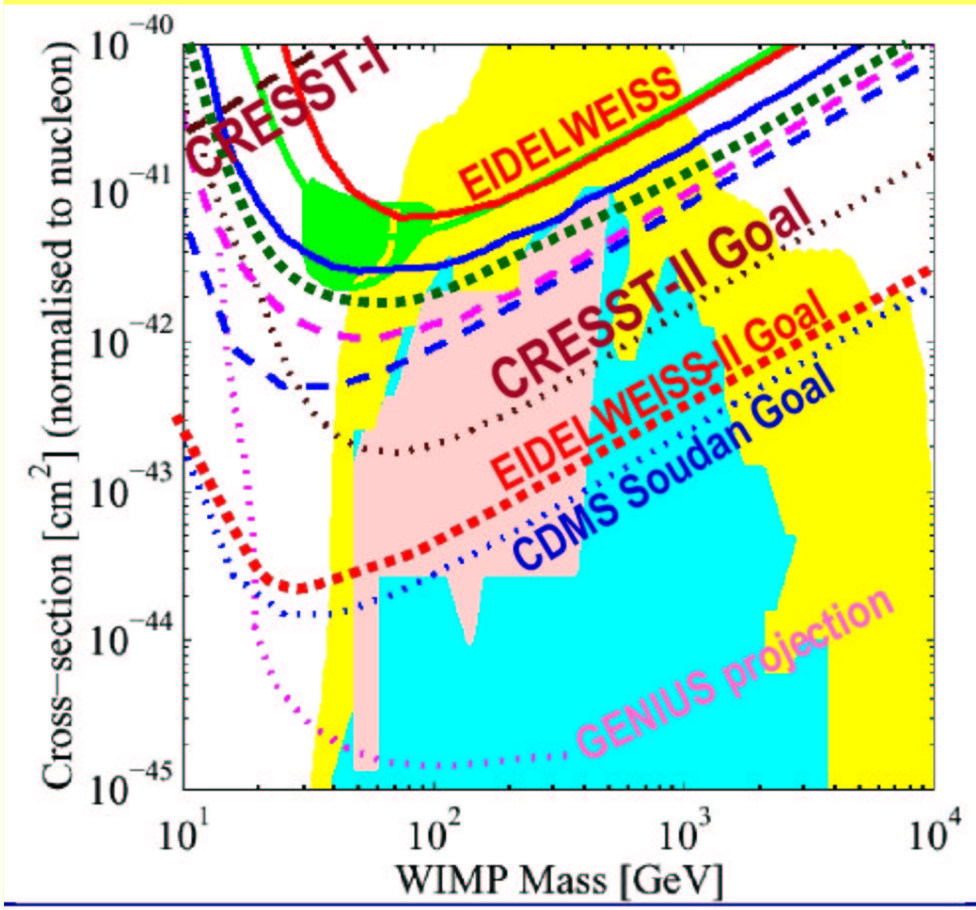
Ullio, MK, Vogel 2001



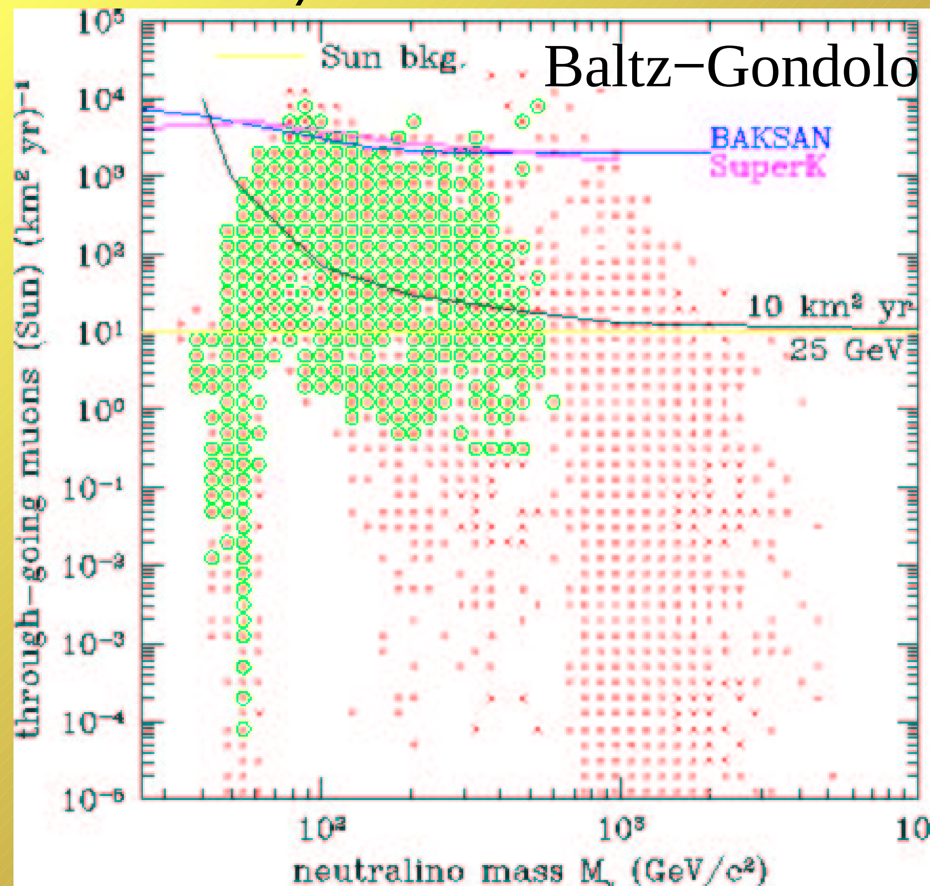
Spin dependent
WIMP–neutron coupling

Searches for SUSY dark matter:

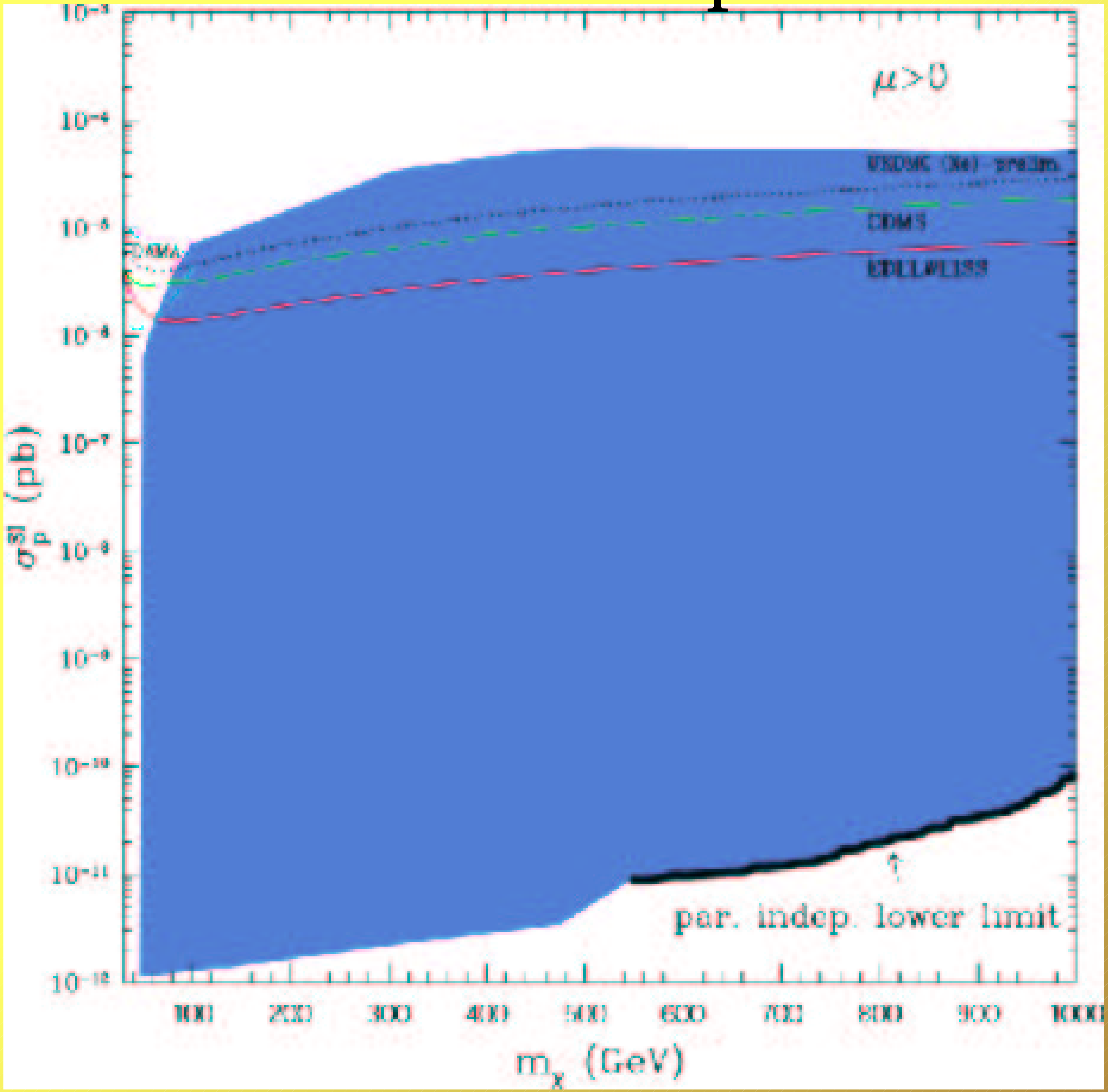
Direct detection in
low background detectors



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



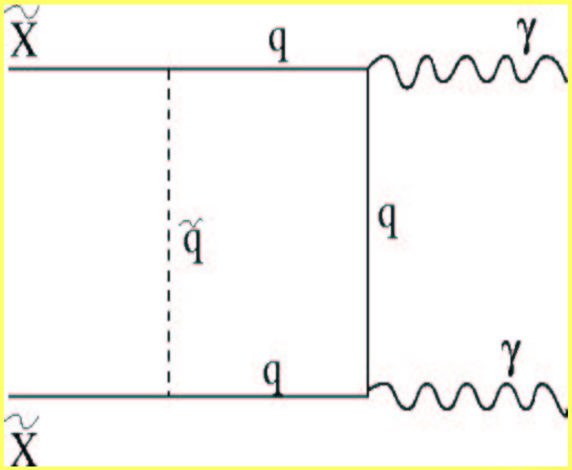
Another view of a SUSY parameter space:



Kim, Nihei, Roszkowski, de Autri, in preparation

Detection of SUSY dark matter:

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

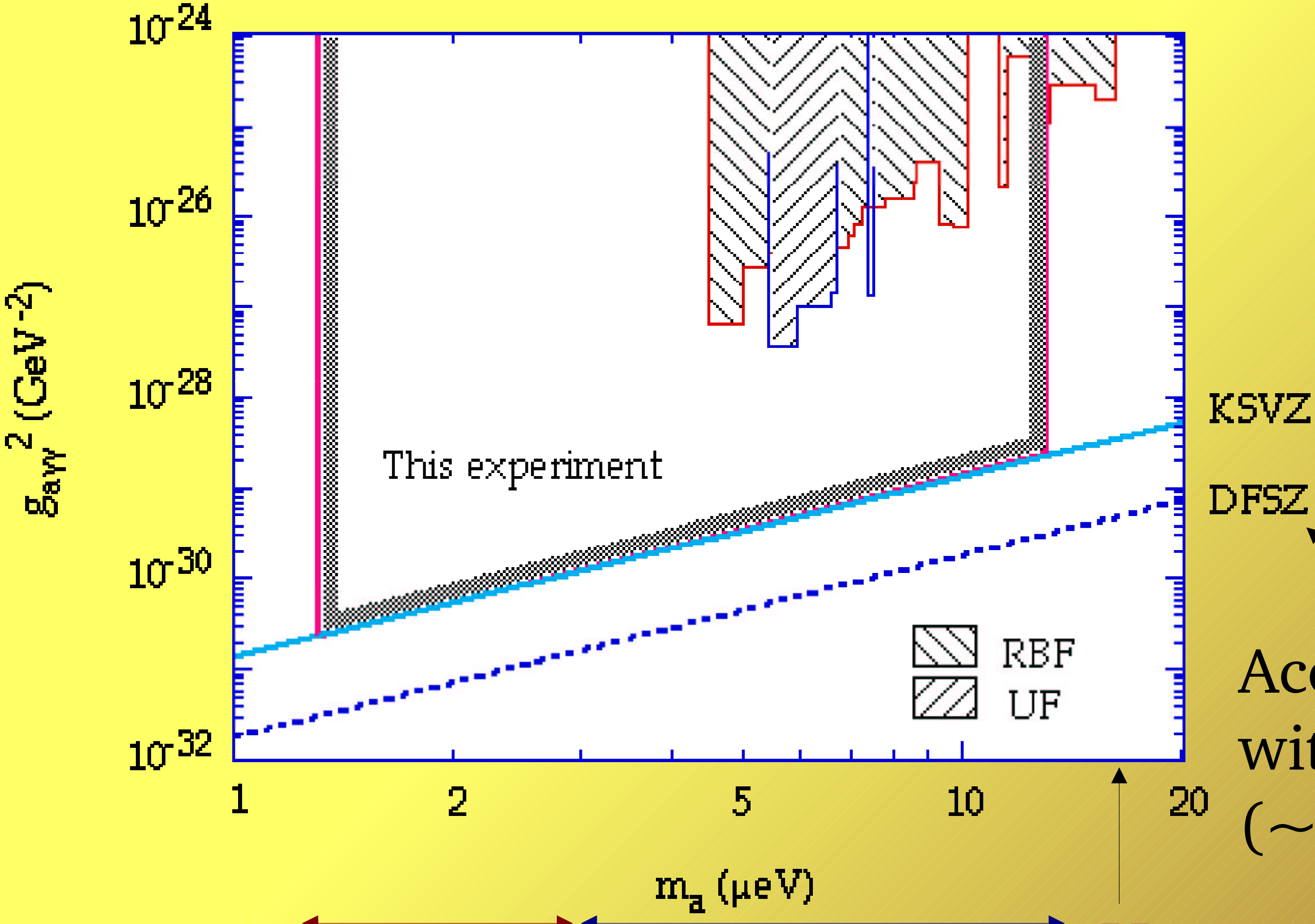


E.g., in GLAST, VERITAS, Whipple, CELESTE, STACEE...

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

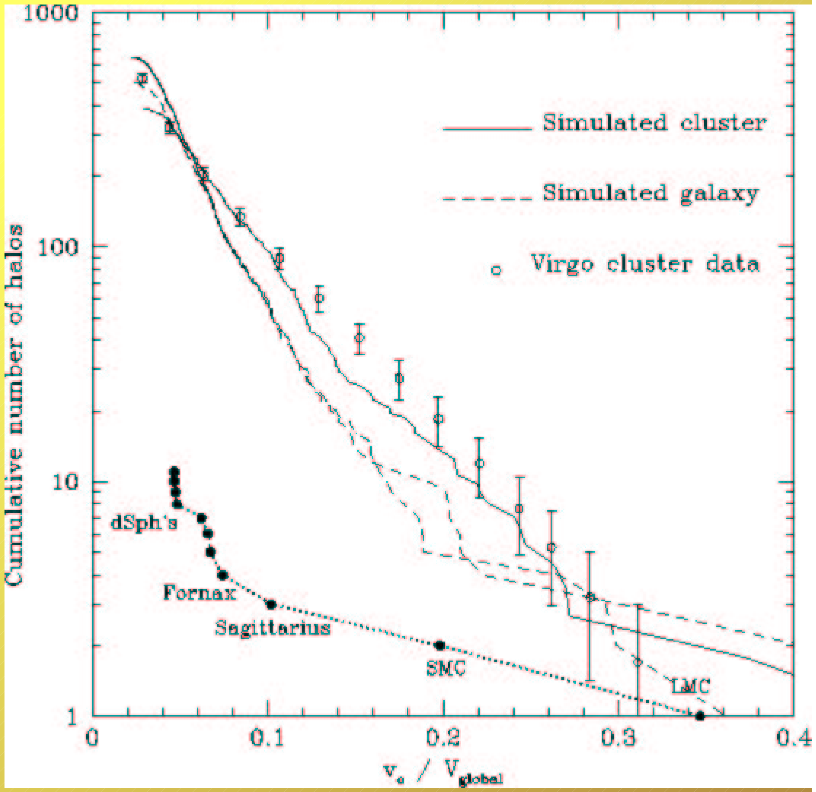
How can we get at these higher masses?

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

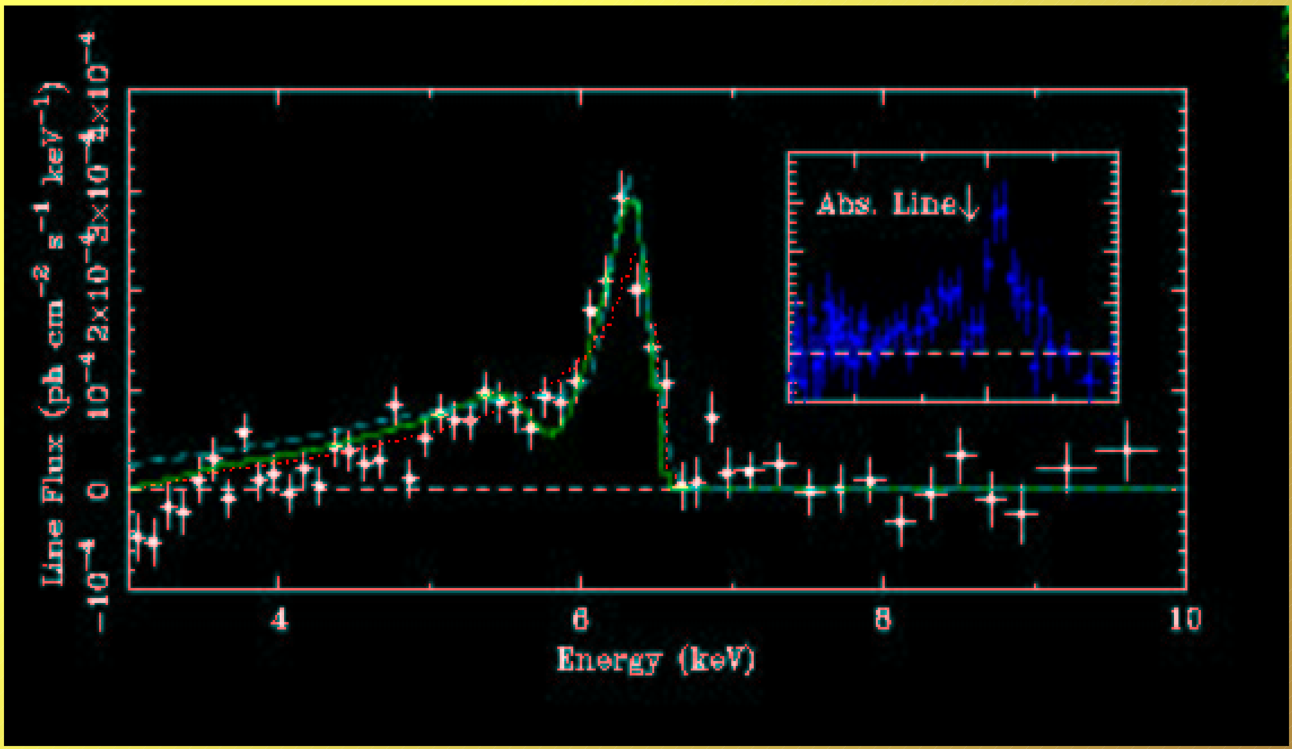
IV. Tests of strong−field gravity:

- 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…)

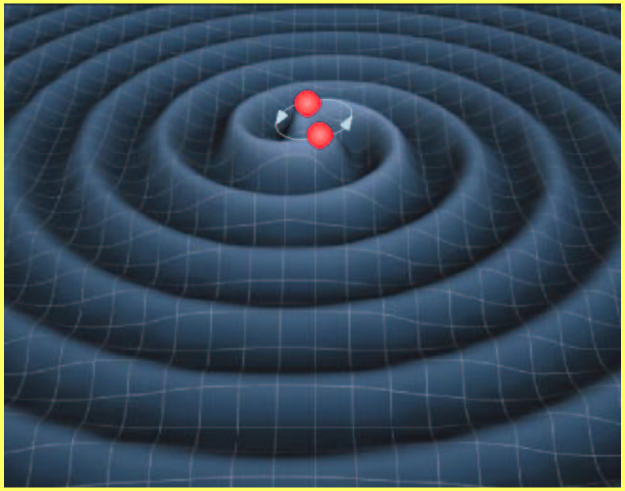
- other interesting tests with grav radiation; e.g., can test whether gravitational waves propagate at speed of light (extra dimensions says they might not!!)

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

P. Nandra

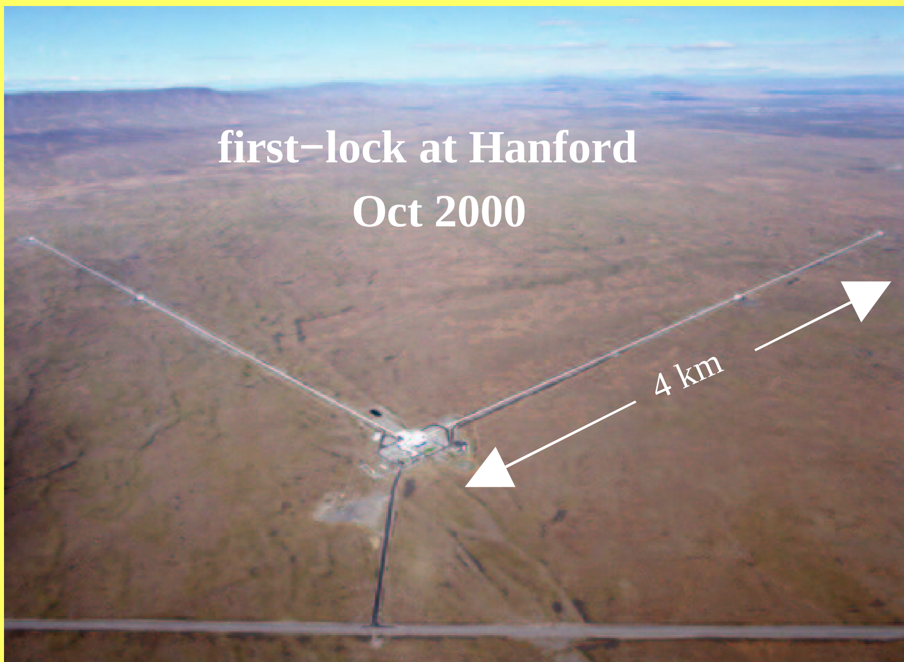


Gravitational Radiation

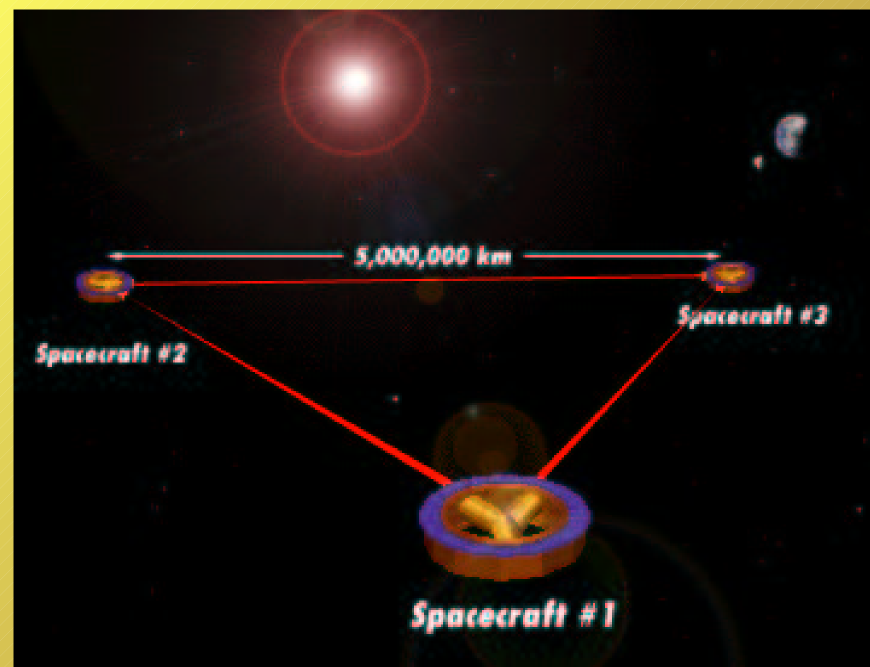


Orbiting and merging massive objects emit gravitational radiation

Two biggest experiments aiming to detect gravity waves:



LIGO (ground−based, under construction)



LISA (space−based, under development)

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 provide several opportunities for advances in fundamental physics that complement those from accelerator experiments.

Cosmology and particle astrophysics are in golden age; 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.