

BEST CANDIDATE FOR EXTENDING STD COSMOLOGY

INFLATION

"LUMPINESS" ARISES FROM QUANTUM FLUCTUATIONS
ON SUB ATOMIC SCALES

COLD DARK MATTER

MOST OF MATTER IS
SLOWLY MOVING ("COLD")
ELEMENTARY PARTICLES LEFT OVER FROM EARLIEST
MOMENTS

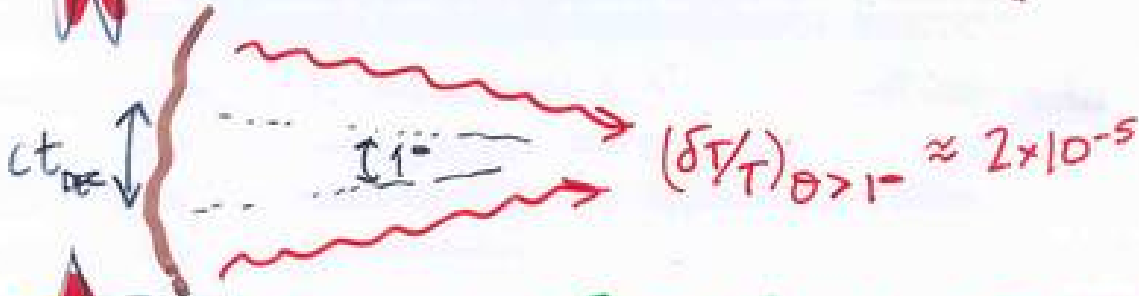
INFLATION

MOTIVATION:

STD COSMOLOGY IS VERY SUCCESSFUL, BUT...

HANDFUL OF SHORTCOMINGS:

★ "HORIZON PROBLEM": WHY SO SMOOTH



★ ORIGIN OF INHOMOGENEITY
WHERE 'SEEDS' FOR STRUCTURE COME FROM

★ FLATNESS: WHY IS $\Omega_0 \sim 0.3$



★ MONOPOLE PROBLEM: OVERPRODUCTION
(IPRIGUN problem again)

Promise of INFLATION:

★ TO LESSEN DEPENDENCE OF
PRESENT STATE UPON INITIAL STATE

★ "GRANDER" BIG BANG
MODEL -- FROM 10^{-2} sec \rightarrow 10^{-32} sec

Underlying Physics

★ SPECULATIVE --- BUT WELL
DEFINED (Classical field theory motivated
by grand unification, superstrings, supersymmetry)

COSMIC

Guth; Linde,
Albrecht-Spenberg

INFLATION

VACUUM ENERGY



SHORT PERIOD OF RAPID EXPANSION DRIVEN
BY "FALSE-VACUUM" ENERGY

★ MORE EXPANSION IN 10^{-32} SEC THAN NEXT 15 BYR

★ OBSERVED UNIVERSE BEGAN FROM INCREDIBLY

SMALL PATCH → FLAT & SMOOTH



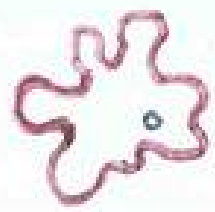
★ MICROSCOPIC PHENOMENA (QUANTUM FLUCTUATIONS)
CAN INFLUENCE MACROSCOPIC SCALES

→ QUANTUM ORIGIN OF "LUMPINESS"



ALL THAT WE CAN SEE TODAY

(STILL SMOOTH & FLAT)



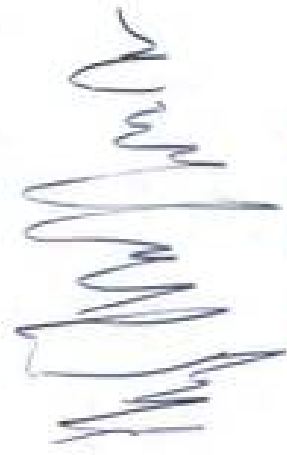
TINY ($\ll 1\text{cm}$) BIT OF UNIVERSE IS FLAT & SMOOTH (but too small to contain all we see today)



FLUCTUATIONS:

Burden, Steinhilber, MST, Guth-Pi;
Hawking, Starobinski, 1982

MICRO TO MACRO



←→ 10^{-8} cm

FLUCTUATIONS
DUE TO INTERACTION
OF PARTICLES

MORE
MATTER

LESS
MATTER

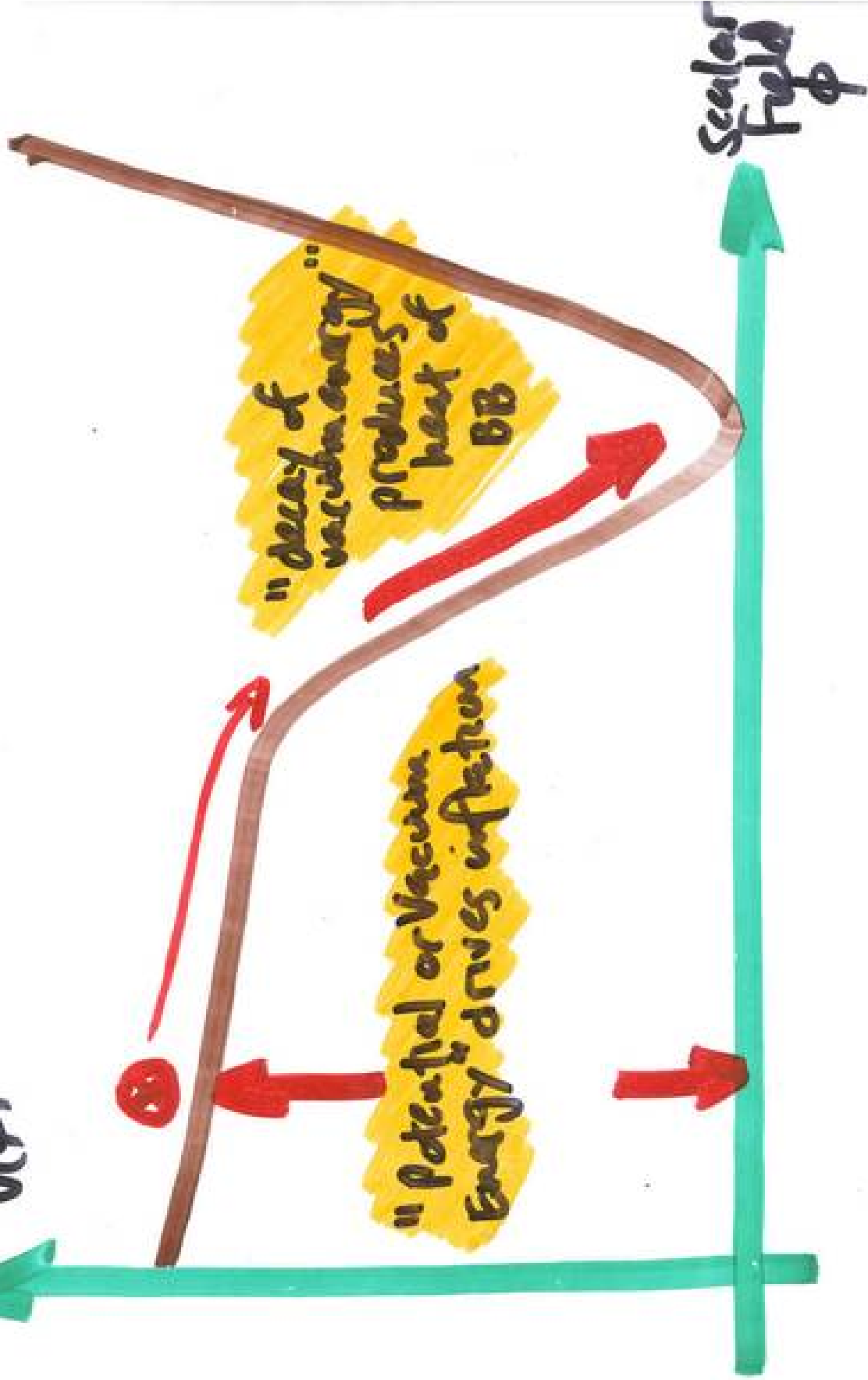
←→ LIGHT YAS

QUANTUM FLUCTUATIONS
ON SUBATOMIC SCALE

"LUMPY" DIS-
TRIBUTION OF
MATTER ON
MACRO SCALE

Potential Energy
of scalar field ϕ

$V(\phi)$



COLD DARK MATTER

'EQ':
 $R \sim 3 \times 10^5$
 $t \sim 100 \text{ yr}$
 $\delta p \sim 10^5$



$R \sim 1/3 - 1/2$
 $t \sim \text{few Gyr}$
GALAXIES FORM
Dark halos, baryons
dissipate



TODAY
formation of
larger structures (superclusters) continues...

INFLATION SCORECARD

FLAT UNIVERSE

$$\Omega_0 = 1.0 \pm 0.04$$



DENSITY PERTURBATIONS FROM QUANTUM FLUCTUATIONS



★ ADIABATIC

★ GAUSSIAN

★ NEARLY SCALE-INVARIANT

$$n = 1 \pm 0(0.1)$$

★ NEARLY POWER LAW

$$dn/d\ln k \sim 10^{-3}$$

3 ACOUSTIC PEAKS



NO EVIDENCE TO CONTRARY



$$n = 1.0 \pm 0.07$$



$$dn/d\ln k < 1/3$$



GRAVITY WAVES FROM QUANTUM METRIC FLUCT



$$\star T/S \approx 10^{-3} (?)$$

$$T/S < 1/2$$

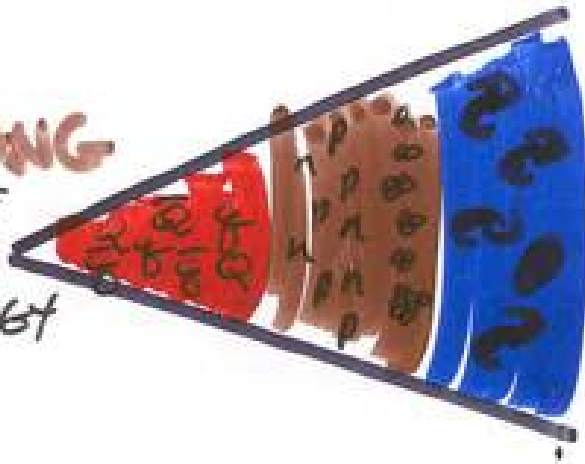
★ NEARLY SCALE-VARIANT

MAJOR GOAL FOR COSMOLOGY

B-MODE POLARIZATION
IN CMB ANISOTROPY
DIRECT DETECTION (SUPER-LSST)

THE BIG BANG

THE BIG BANG
CREATION OF
SPACE, TIME,
MATTER & ENERGY



NEAT & TIDY

satisfies St. Augustine
Principle

INFLATIONARY MULTIVERSE

INFINITY OF big bang's

NO BEGINNING
NO END

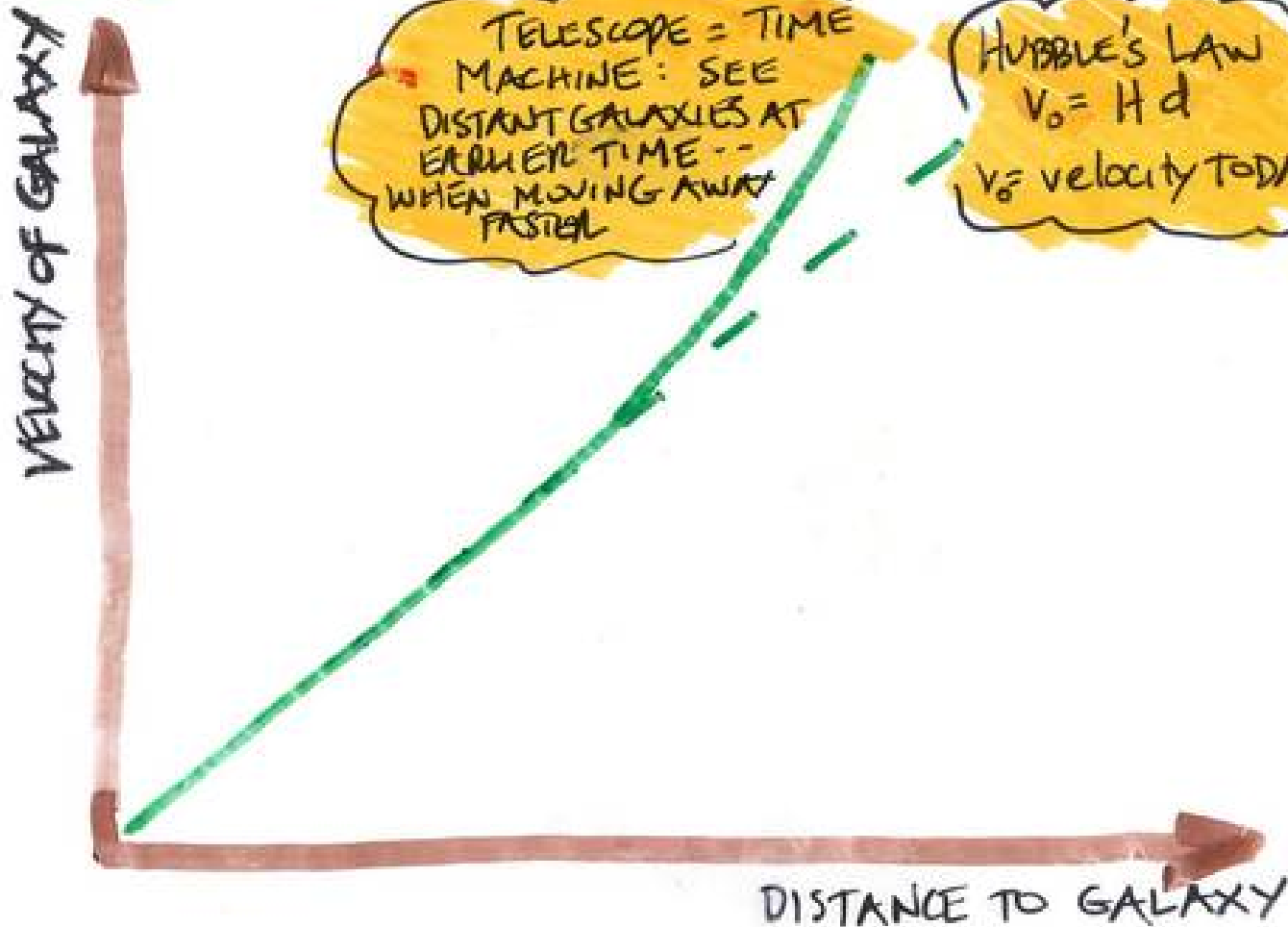


DARK ENERGY

7 LESSONS

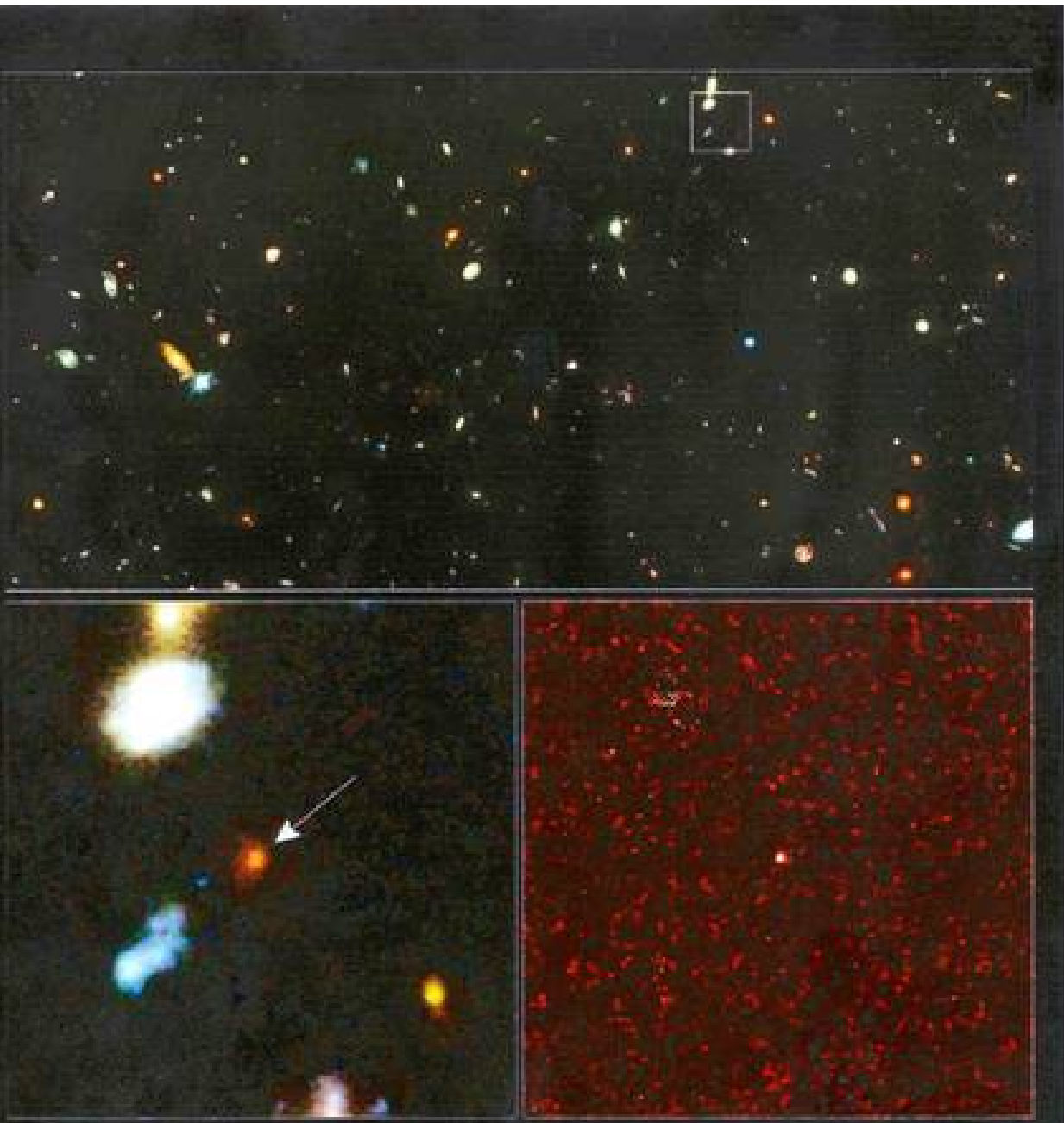
- ① UNIVERSE IS ACCELERATING: DIRECT EVIDENCE
SNe Ia
- ② INDIRECT EVIDENCE FOR SMOOTH COMP w/ $p < 0$
CMB + structure formation
- ③ REPULSIVE GRAVITY IS A FEATURE OF GR
(NOT A BUG) FLIP SIDE OF BHZ
- ④ WHAT ABOUT VACUUM ENERGY AKA EINSTEIN'S COSMOLOGICAL CONSTANT
- ⑤ CHARACTERIZING DARK ENERGY
"SMOOTH", LARGE NEGATIVE PRESSURE
- ⑥ PROBES OF DARK ENERGY
COSMOLOGY
- ⑦ DESTINY
OLD BEDTIME STORY IS WRONG

IS THE UNIVERSE SLOWING DOWN?



DATA SEE:
UNIVERSE IS
SPEEDING UP!

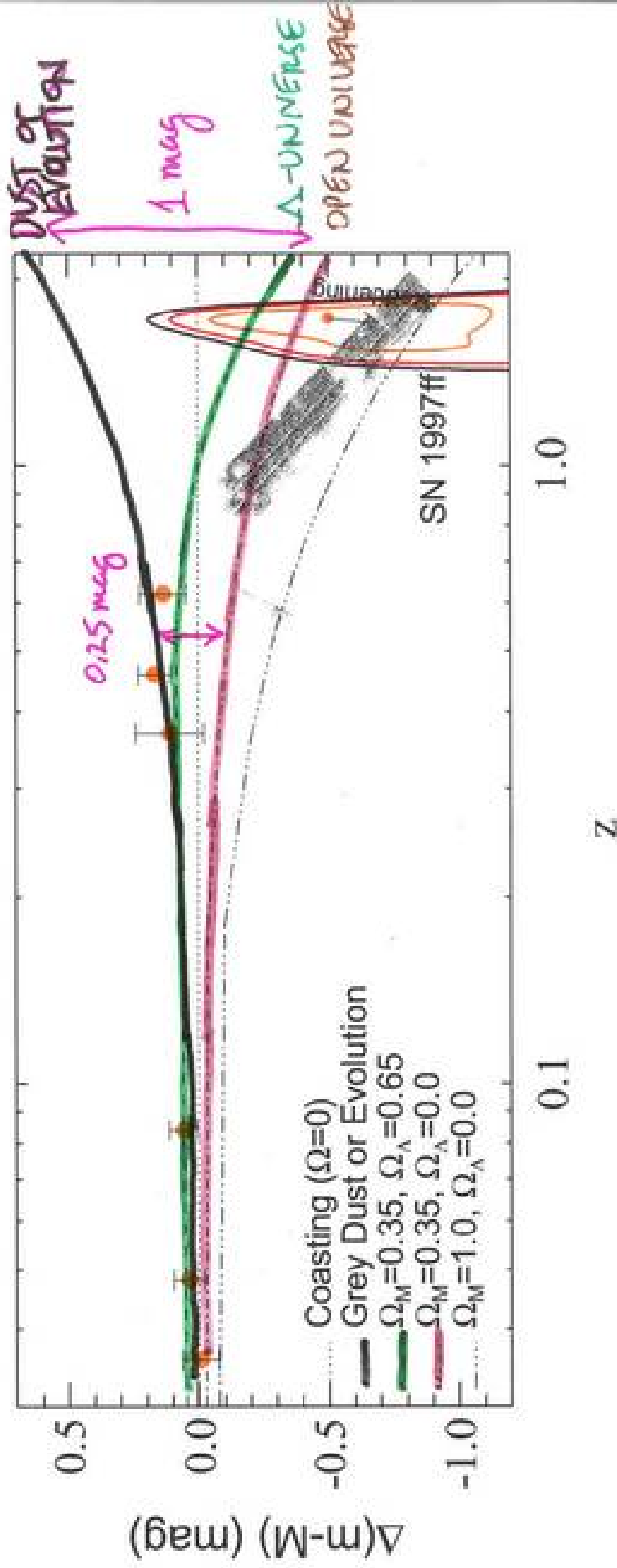
UNIVERSE IS
SPEEDING UP!?!# WHY?!



Distant Supernova in the Hubble Deep Field
Hubble Space Telescope • WFPC2

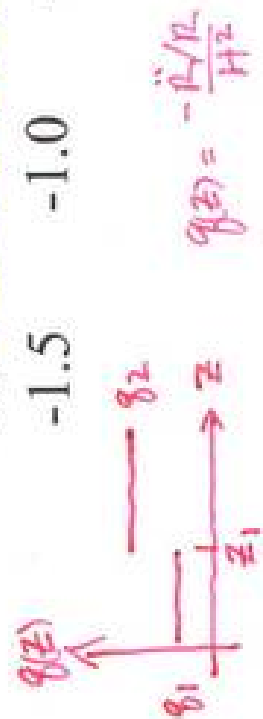
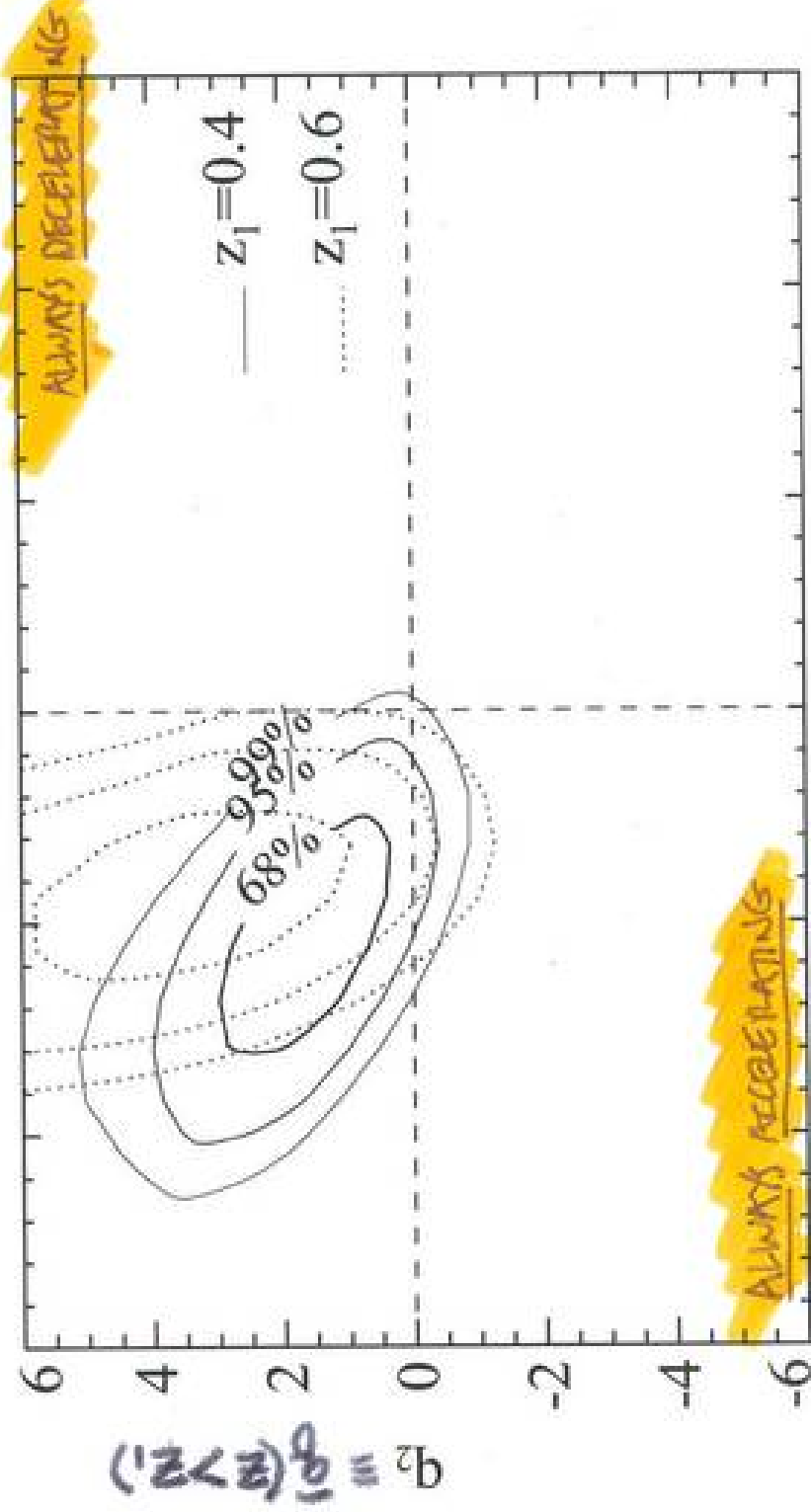
Differential Hubble Diagram

... relative to empty Universe ($\Omega_0=0$)



Riess et al. astro-ph/0104455

EVIDENCE FOR EARLY ($z > 1/2$) DECELERATING PHASE FROM SN 1997AF



$q_1 \equiv \bar{q}(z < z_1)$

MST-PRESS astro-ph/0105

GR ALLOWS FOR REPULSIVE GRAVITY:

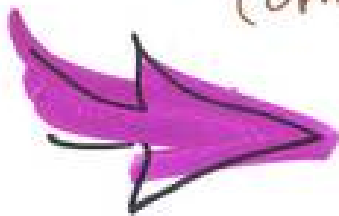
SOURCE OF GRAVITY

IN GR :

$$\rho + 3p$$

(SPHERICAL SYMMETRY)

FEATURE NOT A BUG!



BLACK HOLES WHEN $p \geq \rho/3$



REPULSIVE GRAVITY WHEN $p < -\rho/3$

QUANTUM VACUUM IS NOT EMPTY!

sea of virtual particles



whose existence has been detected
(shifting of atomic levels in H)

W. Lamb, ca 1950

Quantum vacuum is elastic ($p = -p$)
& its Gravity is Repulsive!

JUST WHAT IS NEEDED -- BUT...
THEORETICAL ESTIMATES OF AMOUNT

10^{55} x what is needed to
explain accelerating Universe

"Houston, we have a problem"

Comments About the Cosmological Constant Problem (Vacuum Energy)

Science Times, 30 November 1999 (J. Glanz)

S. Weinberg: "Right now, not only for cosmology but for elementary particle theory, this is the bone in our throat."

F. Wilczek: "...maybe the most fundamentally mysterious thing in all of basic science."

E. Witten: "... would be number 1 on my list of things to figure out."

And summarized by J. Harvey:

"Basically, people don't have a clue as to how to solve this problem."

WHAT IF

$\Lambda = 0$?

BE CAREFUL WHAT YOU
WISH FOR !!

FUNNY ENERGY

JANUARY 13 1957

in the UNIVERSE

THE UNIVERSE IS
EMPTY & REPulsive



I STEPPED
IN X-MATTER



QUINTESSENCE --- BETTER
THAN PERIER-LIGHT!



IT'S CRAZY! -
AND IT WAS MY IDEA!

THE MYSTERY OF DARK ENERGY

- SMOOTHLY SPREAD THRU UNIVERSE
- REPULSIVE GRAVITY
- DETERMINES DESTINY OF UNIVERSE
- DON'T HAVE A CLUE TO WHAT IT IS!

SOME POSSIBILITIES:

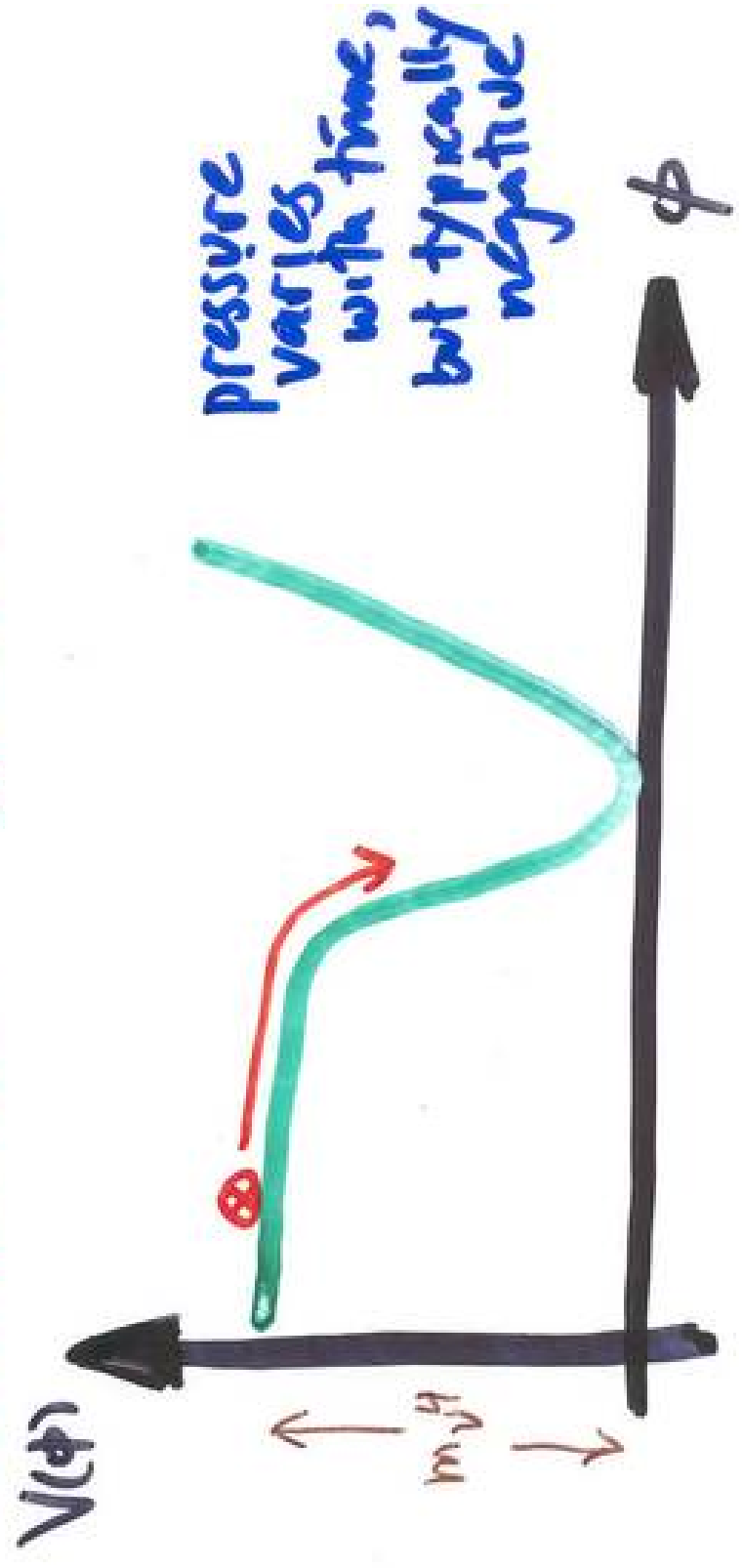
- ★ ENERGY OF NOTHING!
- ★ MILD INFLATION
- ★ INFLUENCE OF HIDDEN DIMENSIONS
- ★ BREAKDOWN OF EINSTEIN'S THEORY
- ★ "NEW VOICES"

A BRIEF EPISODE OF INFLATION

(aka. decaying cosmological constant, quintessence, rolling scalar field)

- ... mild episodes of inflation are unavoidable

A. GREEN SPAN



NETWORK OF (FRUSTRATED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Pen-Spangel '98



VERY ELASTIC: $\nu = -1/3$

IN GENERAL: $\nu = -N/3$



Weak Grav. Lensing:

Future 1000 sq deg survey

$$\sigma_w \approx 0.05$$

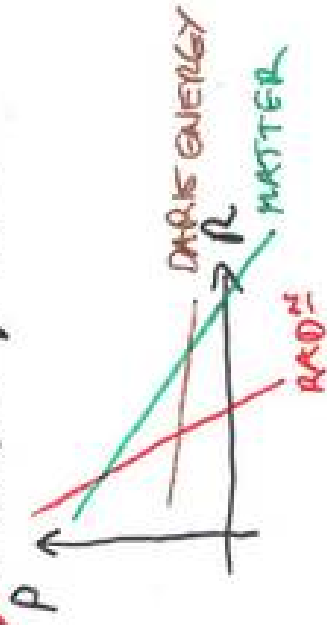
systematics not included

Other:

SEARCH FOR NEW, LONG-RANGE FORCES
STRONG GRAV LENSING OF QSOs, ...

6) NANCY KERHGAN PROBLEM

WHY ME?
WHY NOW?

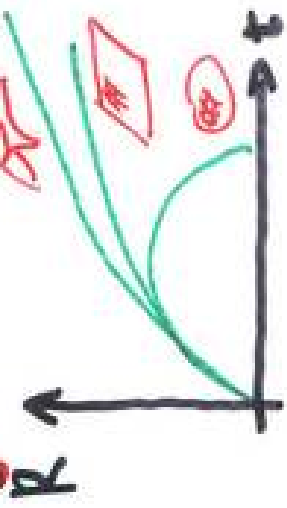


PAST: O.E. UNIMPACTANT
OTHERWISE WOULD INTERFERE w/ OBSERVABLE FORMATIONS

FUTURE: DOMINANT

TODAY: COMPARABLE TO MATTER

7) DESTINY!



IF MATTER ONLY
GEOMETRY & DESTINY LINKED



DESTINY LINKED TO DARK ENERGY

6 THINGS EVERYONE SHOULD KNOW ABOUT THE ^{UNIVERSE} EXCEPT IN KANSAS

- ★ IT ALL BEGAN WITH A BANG!
- ★ IN THE BEGINNING, THERE WAS QUARK SOUP ^{OR}
- ★ THE GREATEST DISCOVERY OF ALL TIME!
S.W. HAWKING
- ★ THE UNIVERSE IS SPEEDING UP, NOT SLOWING DOWN!
- ★ AND HELD TOGETHER BY DARK MATTER
- ★ LOOKING OUT TO SEE IN & LOOKING IN TO SEE OUT
INNER SPACE / OUTER SPACE

THE NEW COSMOLOGY

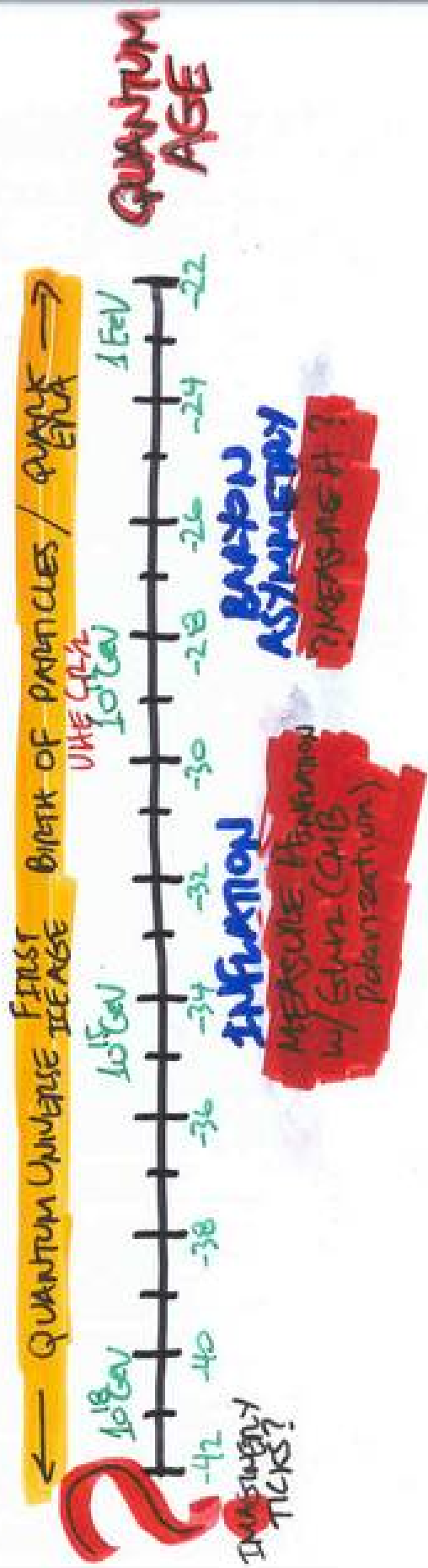
THE NEW, IMPROVED STD MODEL

$$T = 2.725 \pm 0.001 \text{ K} \quad h = 0.72 \pm 0.07 \quad \Omega_0 = 1.0 \pm 0.04 \quad \Omega_B = 0.039 \pm 0.0075$$
$$\Omega_M = 0.33 \pm 0.035 \quad \Omega_X = 0.67 \pm 0.06$$

- ➔ INCORPORATES STD HOT BIG BANG
 10^2 s ON: FROM QUARK SOUP \Rightarrow EXPANDING GRAVITIES
- ➔ EARLY EPOCH OF INFLATION
 $\sim 10^{-32}$ sec?
- ➔ STRUCTURE PRODUCED FROM QUANTUM FLUCTUATIONS
GAUSSIAN, ADIABATIC, NEARLY SCALE-INVARIANT
- ➔ FLAT, ACCELERATING UNIVERSE
- ➔ COLD DARK MATTER
AXIONS, NEUTRALINOS?

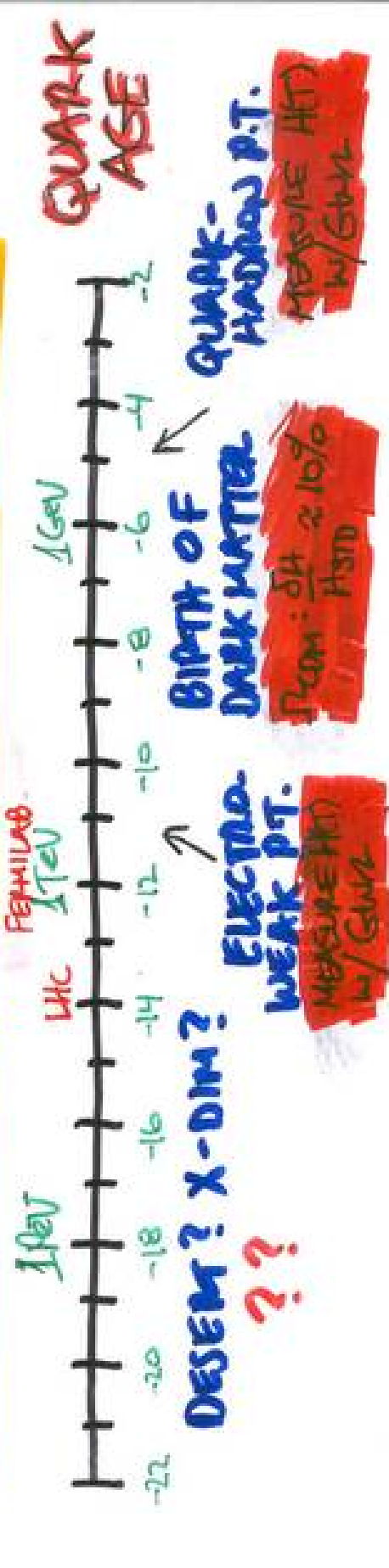
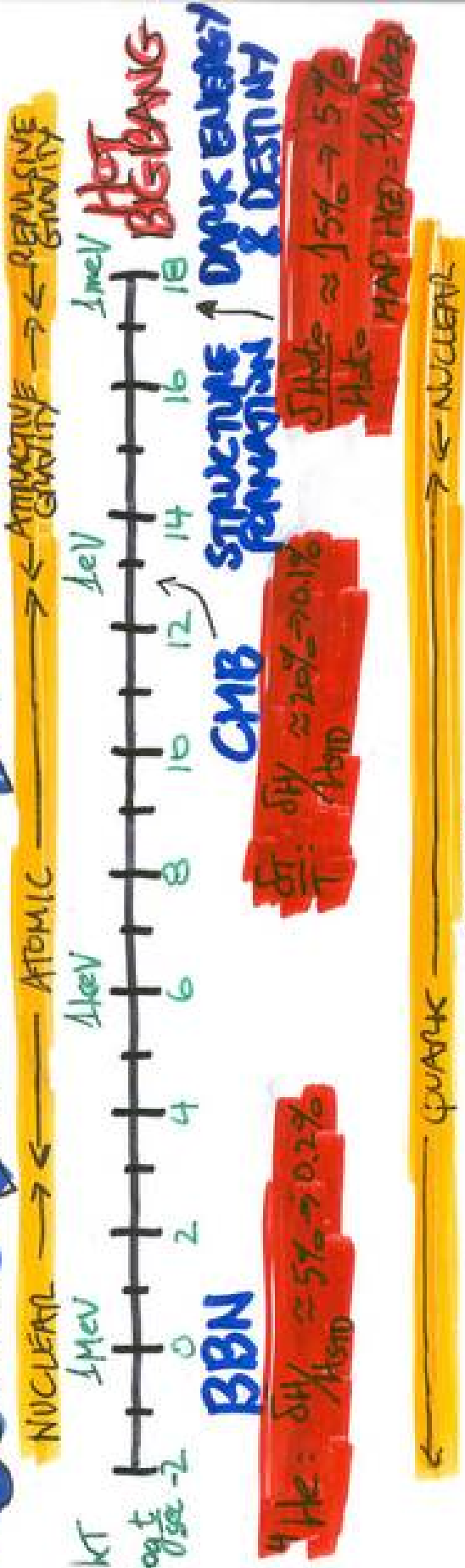
PASSED FIRST ROUND OF TESTS
PRECISION TESTING TO BEGIN

.... THERE WILL BE SURPRISES!



OPPORTUNITIES TO MEASURE MANY AGES

Cosmic Epochs Logarithmically



OUR ACCOMPLISHMENTS

OVER THE NEXT

TWENTY YEARS

**WILL DETERMINE IF
WE ARE IN A**

GOLDEN AGE