Dark and Darker:
The Search for Dark Matter and Dark Energy

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Caltech Seminar Day

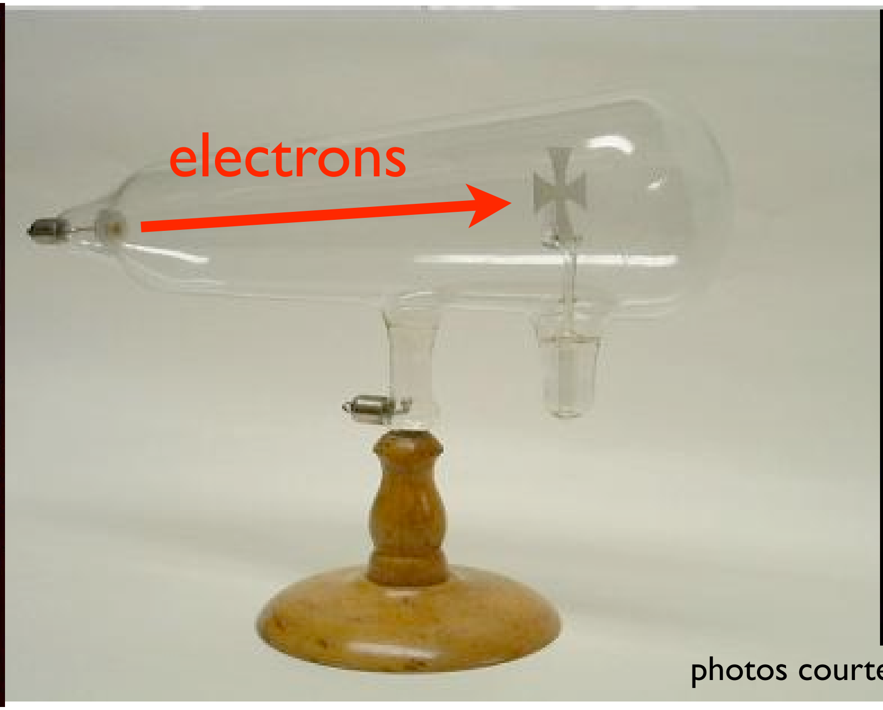
May 21, 2005

A Bit of History

- Physics has a history of happily invoking new, as-yet-unobserved physical *entities* to explain otherwise unexplainable phenomena

Roentgen and his X-rays

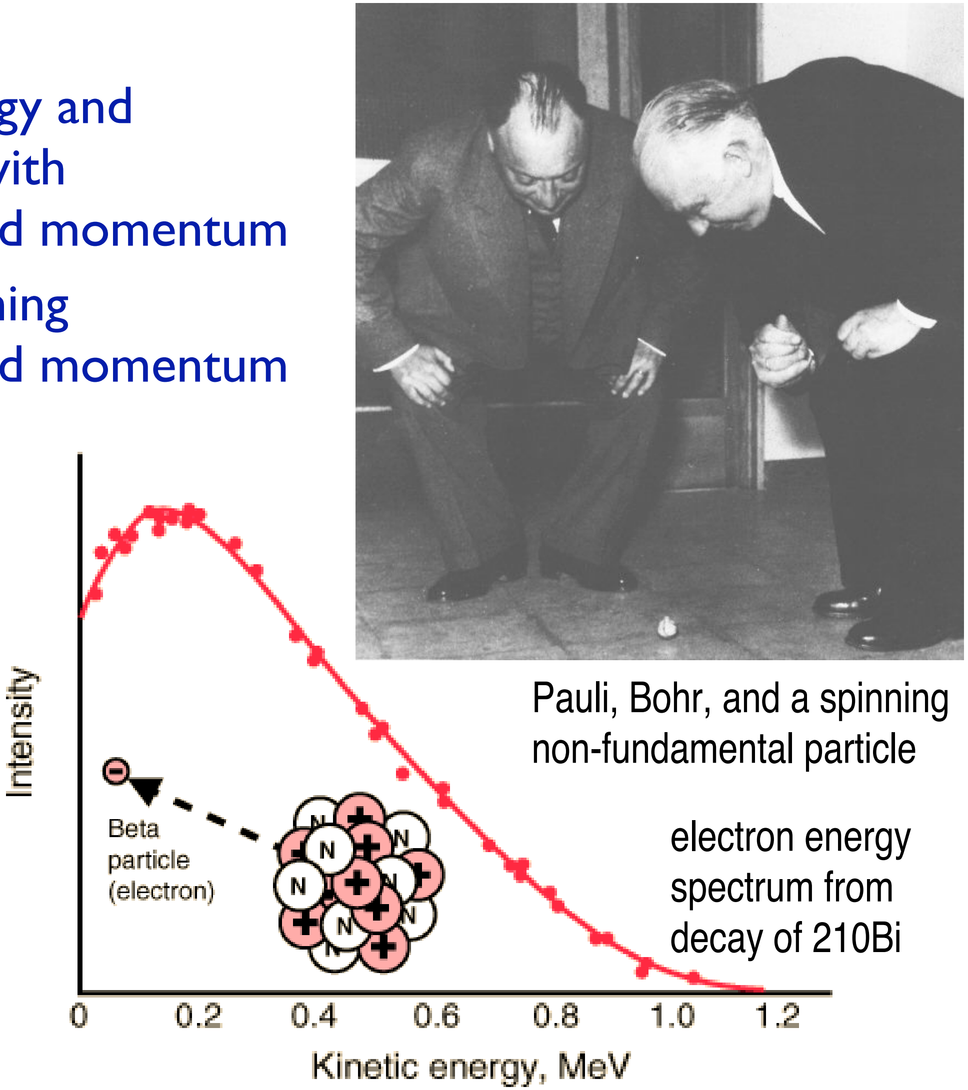
- William Roentgen was trying to determine whether cathode rays (electrons) could penetrate glass; his electron detector was a sheet impregnated with a barium solution, which would fluoresce when hit by electrons.
- While tuning up his cathode ray tube, his barium sheet all the way across the room began to glow...and it was already known that cathode rays could not travel that far. X-rays are discovered! X = "unknown"
- Produced by deexcitation after collisions of electrons with metal in anode.



photos courtesy Radiology Centennial, Inc

“Little Neutral Ones”

- Nuclear beta decay violates conservation of energy?
  - (Z, A) → (Z+1, A) + e^-
  - electron and nucleus energy and momentum inconsistent with conservation of energy and momentum
  - Niels Bohr favors abandoning conservation of energy and momentum
  - 1930: Wolfgang Pauli suggests that an as yet undetected particle carries away energy and momentum, saving the conservation laws
  - 1956: 26 years later, Reines and Cowan demonstrate directly the existence of the *neutrino*



Pauli, Bohr, and a spinning non-fundamental particle

electron energy spectrum from decay of 210Bi

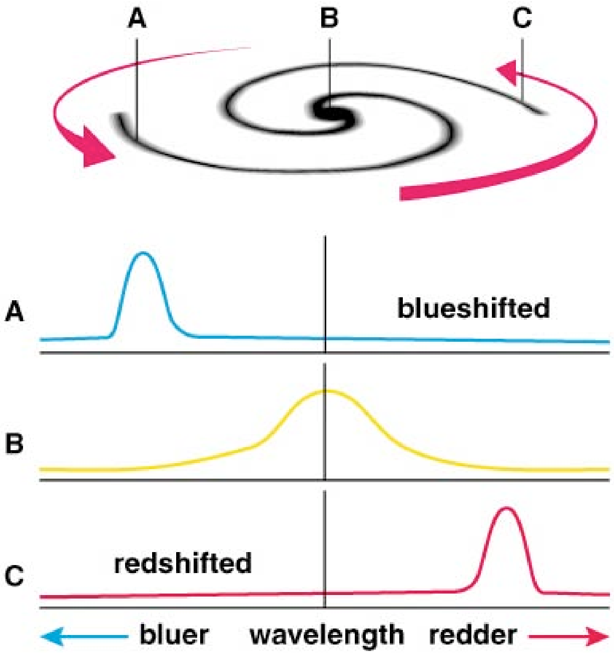
http://wwwlapp.in2p3.fr/neutrinos/anacteurs.html
http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/beta.html

Dark Matter and Dark Energy

- We again seem to need to invoke new entities
  - dark matter:
    - in galaxies and clusters of galaxies, the mass we see cannot provide the gravity needed to explain orbital motions
      - is our theory of gravity incorrect?
      - or, is there some *dark matter* that we cannot directly see?
  - dark energy:
    - the expansion of our universe seems to be accelerating, in violation of all standard expectations, which always predict deceleration
      - is our basic model for the universe incorrect?
      - or is there a new, invisible *dark energy* that has the appropriate properties to cause such an expansion
    - the universe is far more homogeneous than we expect given our model of the universe and how causality operates
      - again, is our basic model incorrect?
      - or, was there at one point an exponential expansion -- inflation -- driven by a dark energy?

Why Dark Matter?

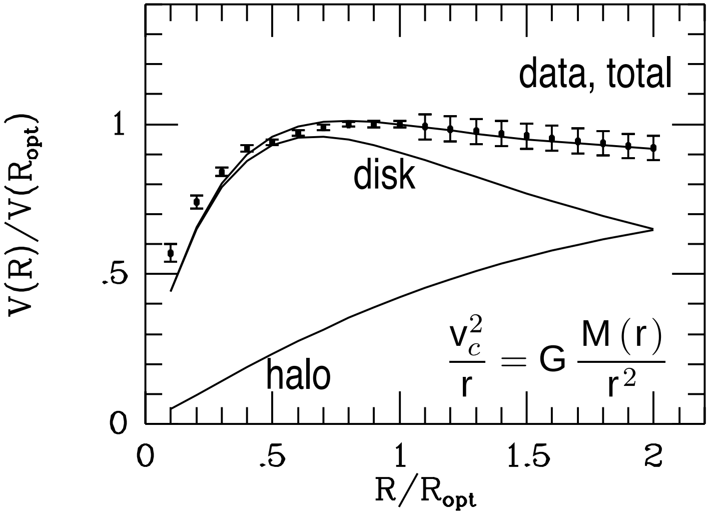
- Rotation curves of spiral galaxies
  - Measure the motion of stars and gas in galaxies (rotation velocity)



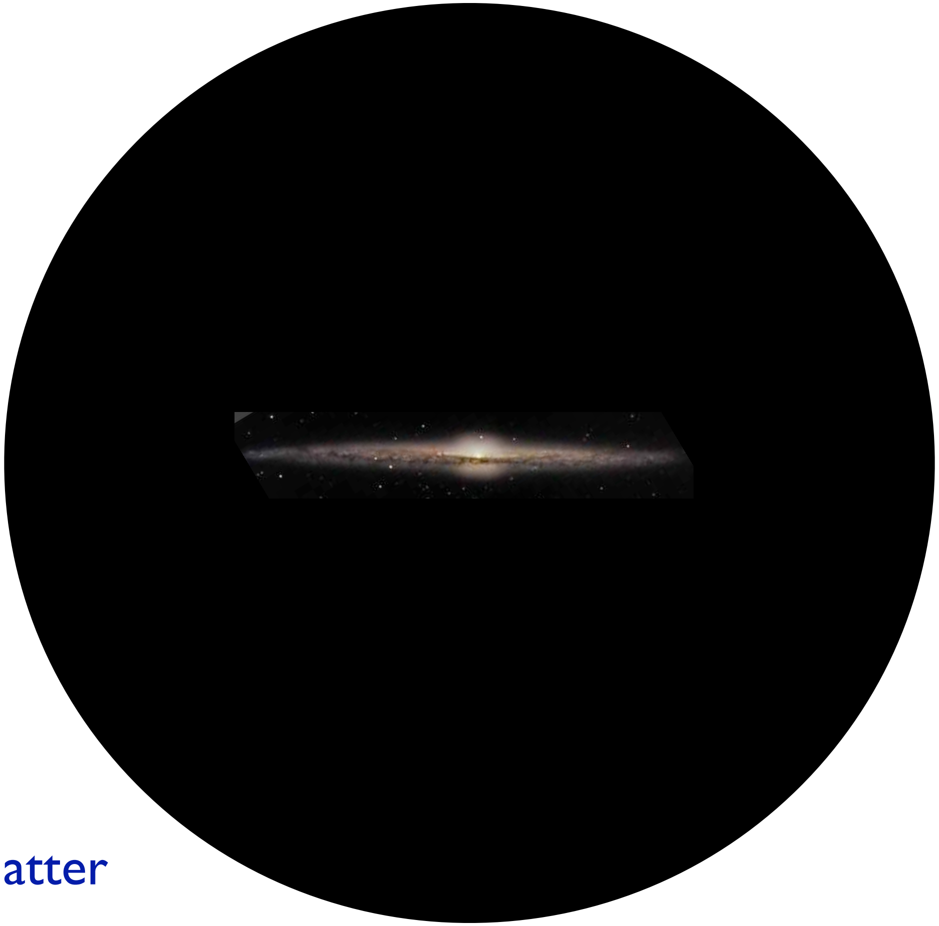
http://astrowww.astro.indiana.edu/~classweb/a105s4124_janet/notes/July30.pdf

Why Dark Matter?

- Rotation curves of spiral galaxies
  - Use Newton's laws to calculate how much mass must be enclosed to provide centripetal force that supports the rotation speed



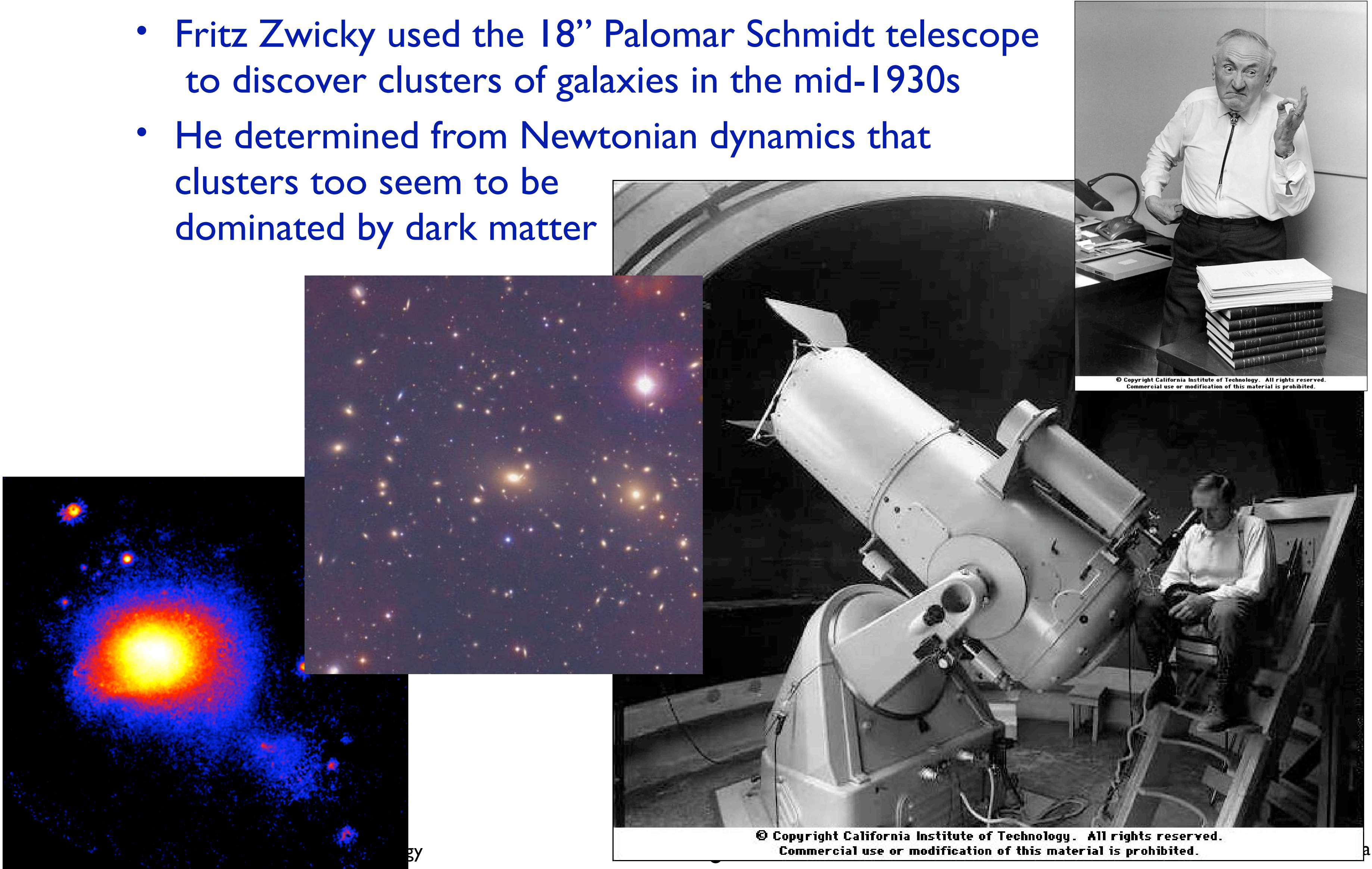
Persic and Salucci



  - v_c ~ 220 km/s typically
  - Measure mass in disk (stars, dust, gas)
  - Conclusion: not enough!
    Need spherical halo with ~10X
    as much dark matter as visible matter

Why Dark Matter?

- Clusters of galaxies
  - Fritz Zwicky used the 18” Palomar Schmidt telescope to discover clusters of galaxies in the mid-1930s
  - He determined from Newtonian dynamics that clusters too seem to be dominated by dark matter



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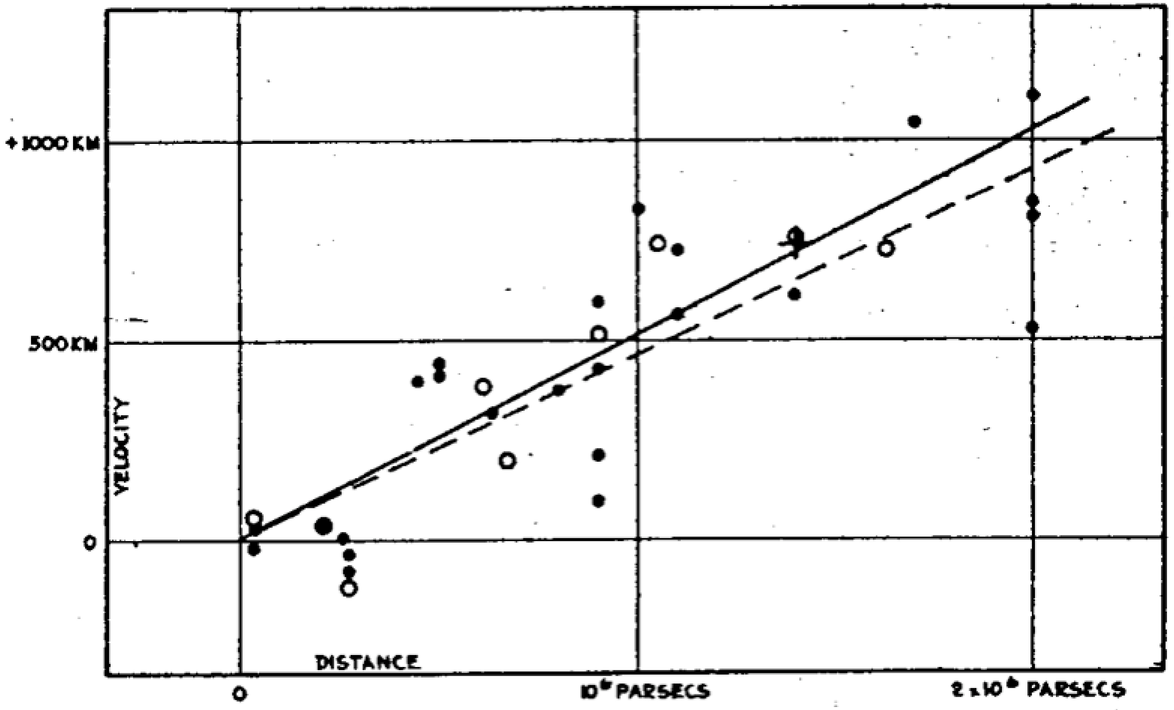
Why Dark Energy – The Expanding Universe

- Edwin Hubble first demonstrated that the universe is expanding, using the Mt. Wilson observatory above Pasadena
  - Distance measure from apparent brightness ($1/r^2$ law)
  - Recession speed measured by redshift

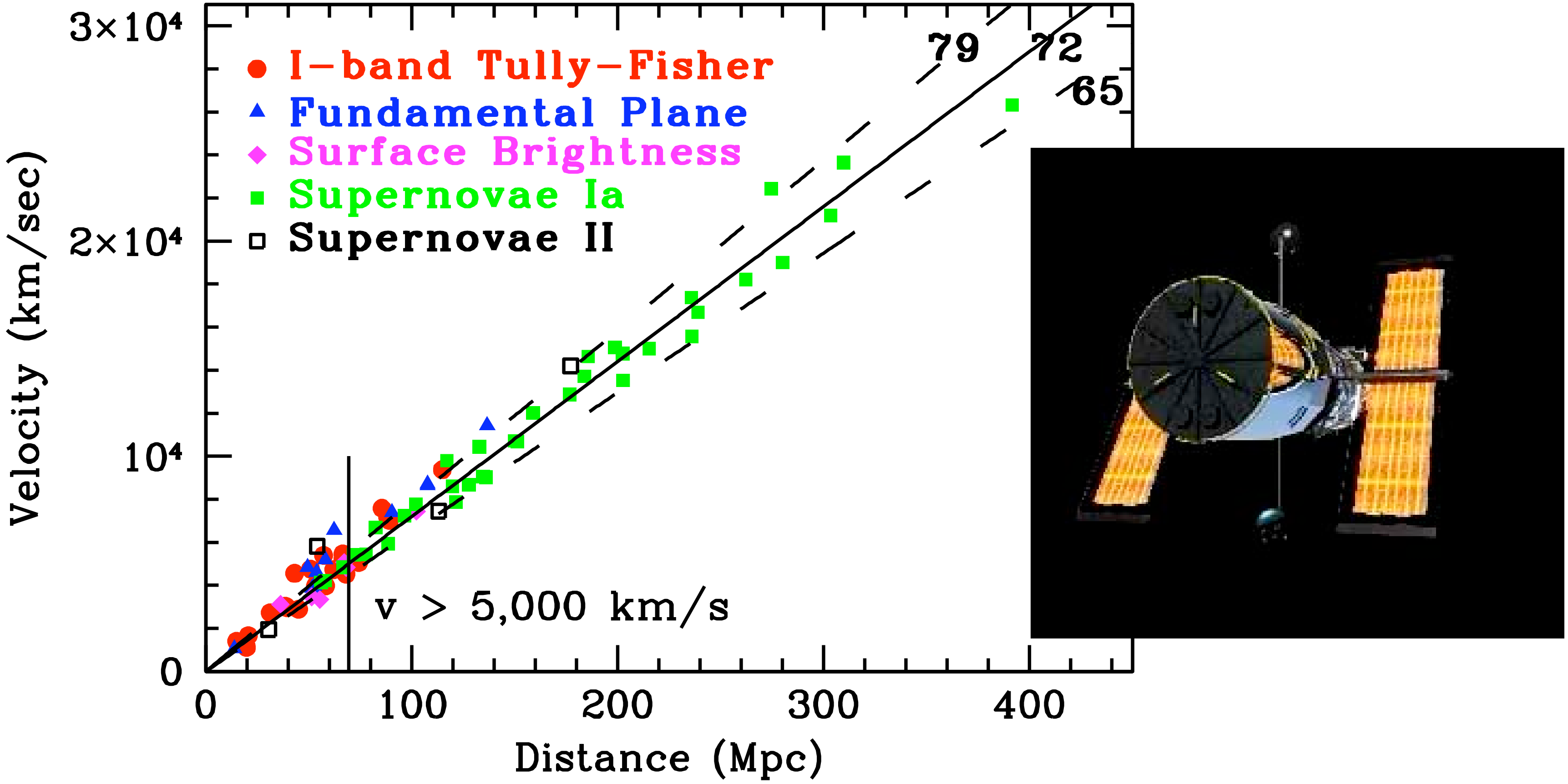


recession speed from redshift

distance from apparent brightness

Why Dark Energy – The Expanding Universe

- The Hubble space telescope has precisely measured the current expansion rate



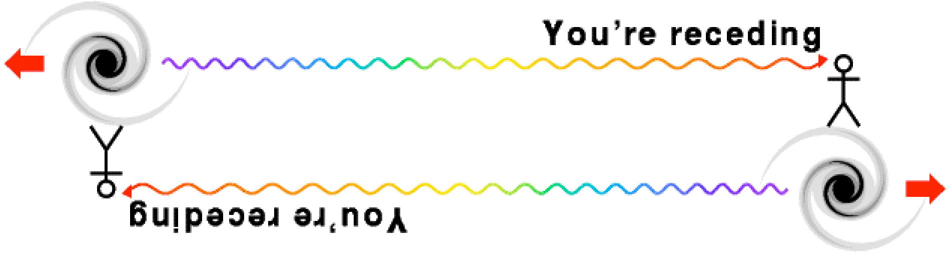
recession speed from redshift

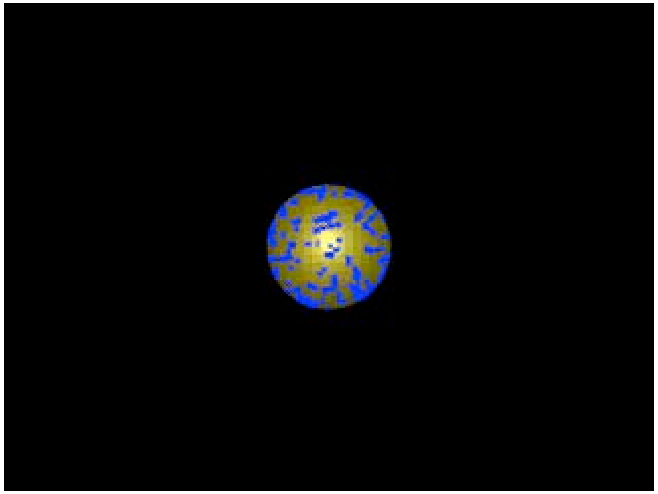
distance from apparent brightness

Freedman and Turner, RMP (2003)

Why Dark Energy – The Expanding Universe

- Assuming we do not live in a special place in the universe -- the Copernican principle -- we must live in a universe whose space itself is expanding.
- Analogy: the surface of a sphere

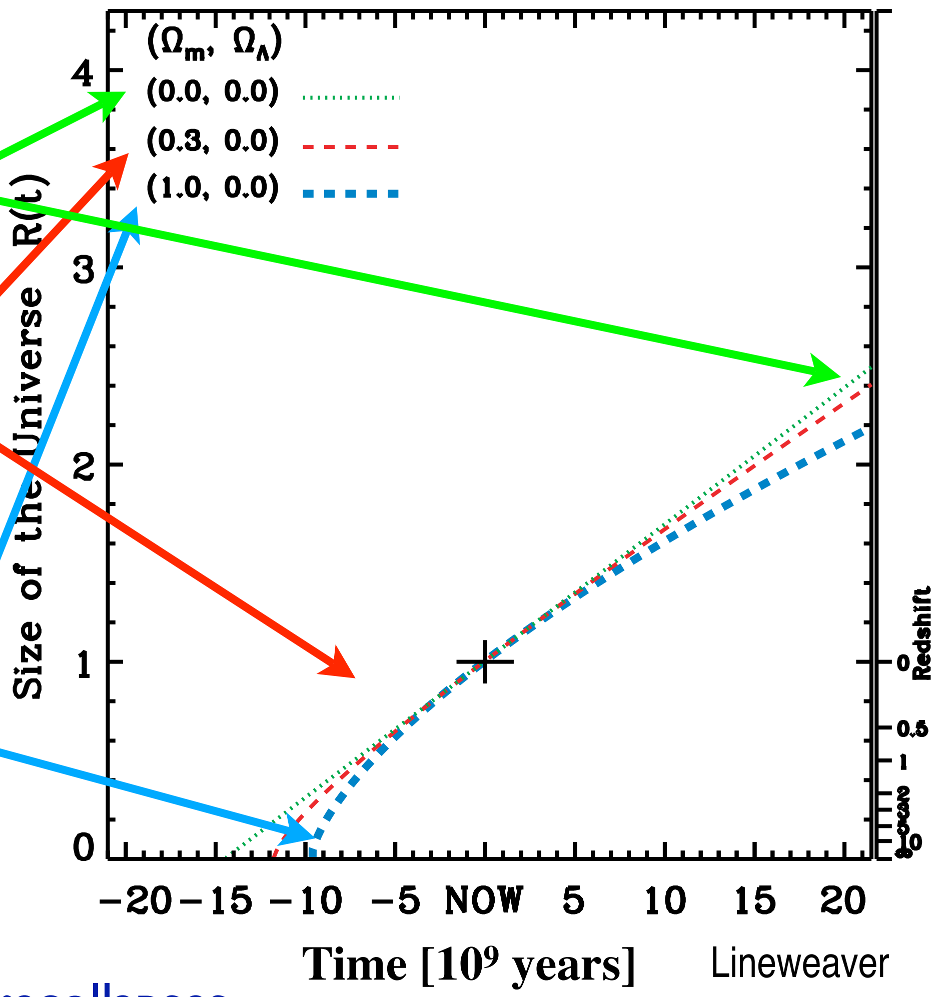




- Recession speed related to (nonlinearly) to distance
- Relation between recession speed and distance measures history of expansion rate

Why Dark Energy – The Expanding Universe

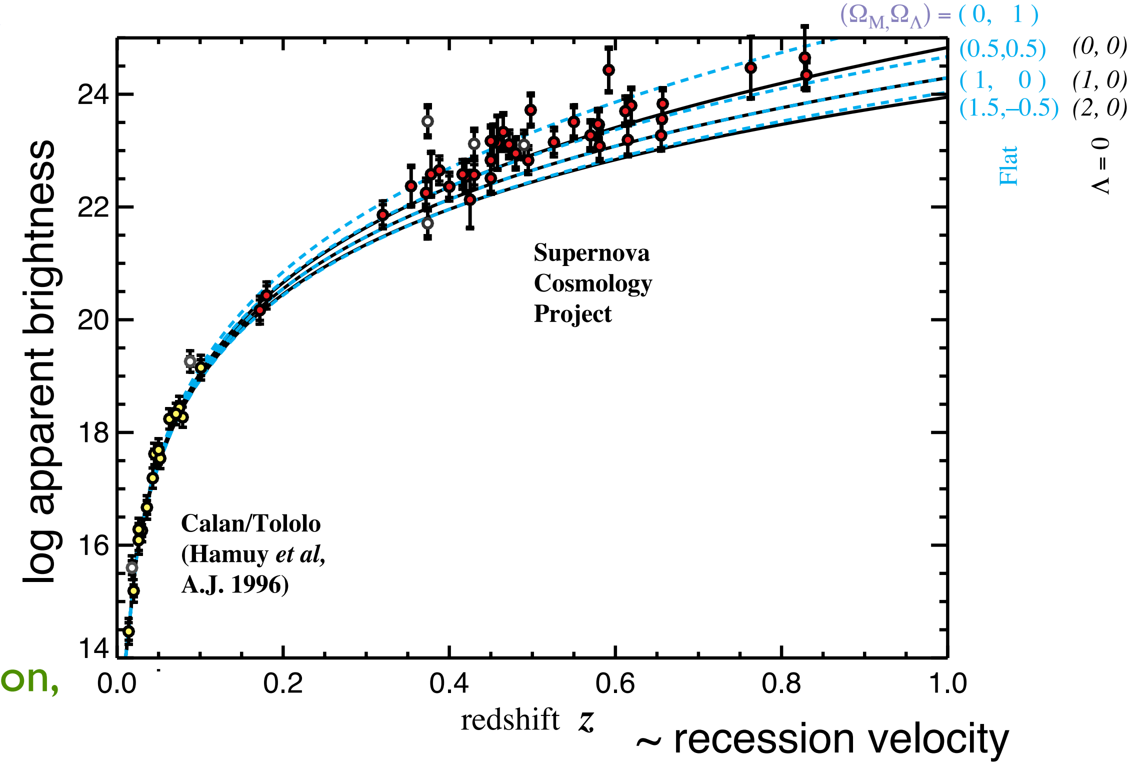
- The gravity of the energy and matter should cause the expansion to decelerate
  - An empty universe will expand at a constant rate forever: no gravity to stop expansion.
  - Universes with nonzero energy density will have decelerating expansion -- the expansion rate is slowed by gravity.
  - At the *critical density*, the expansion rate vanishes as t → ∞: just enough gravity to stop the expansion.
  - For larger densities, the universe stops expanding and recollapses.



Lineweaver

Why Dark Energy – The Accelerating Universe

- The gravity of the energy and matter should cause the expansion to decelerate
  - two groups tried to measure the current deceleration of the expansion rate by looking at the history of the expansion rate
  - they found acceleration:
    - Recession velocity from redshift
    - Distance from apparent brightness of Type Ia supernovae, a "standard candle", using 1/r^2 law
    - Observed that distant SN are dimmer even than in an empty universe (no deceleration, max velocity)
    - Implication: distant supernovae are farther away than they ought to be, expansion is accelerating



Why Dark Energy – The Accelerating Universe

- An accelerating expansion. How?
  - General relativity tells us

accel-
eration
of size

$$\frac{\ddot{a}}{a} = -\frac{4\,\pi\,G}{3}\left(\rho + 3p\right)$$

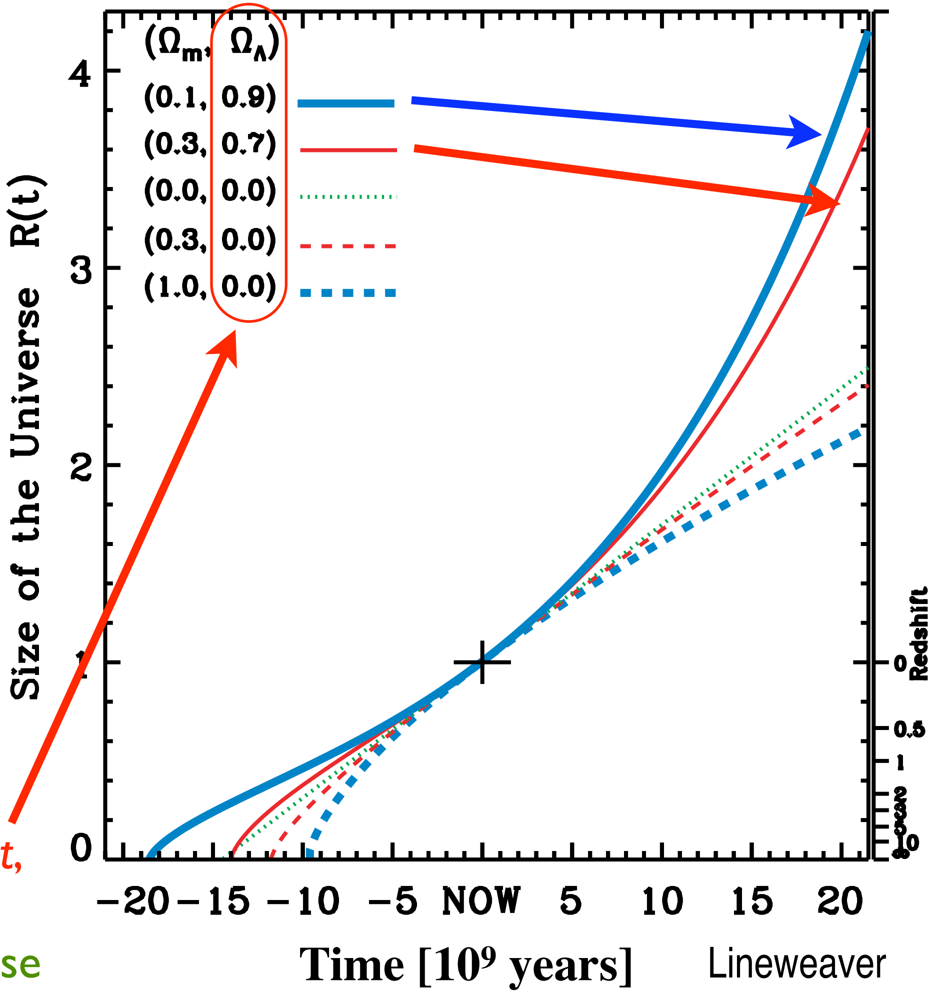
size of
universe

energy
density

pressure

A component with *negative pressure* is needed.

  - General relativity allows the vacuum to have an energy density, which, depending on its sign, can provide negative pressure.
    - This is the *cosmological constant*, originally discussed by Einstein to *prevent* an expanding universe
  - More on this later



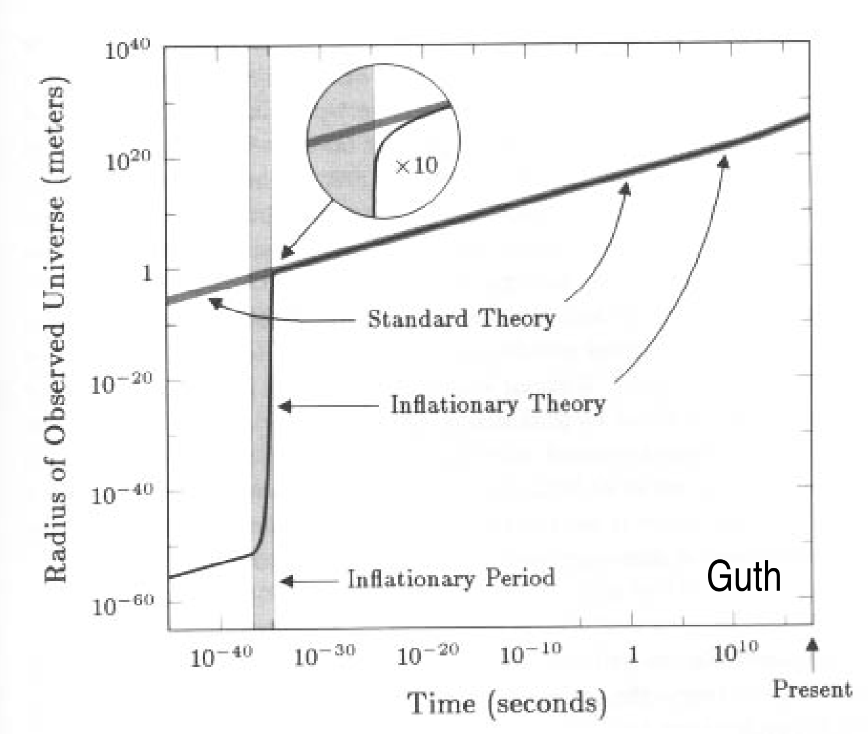
Lineweaver

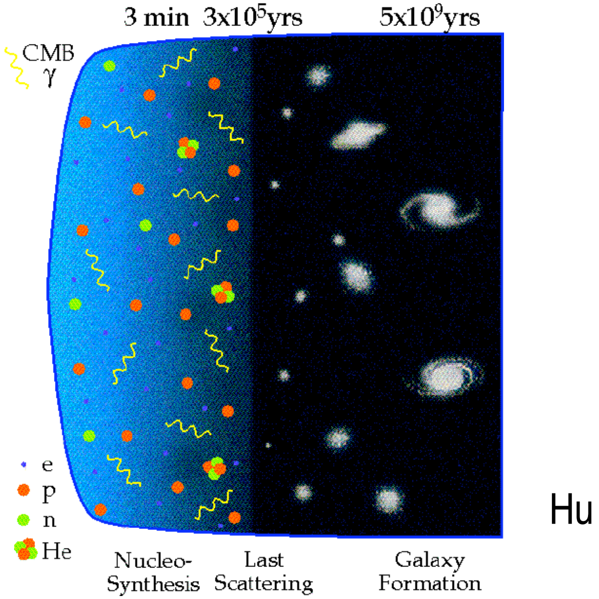
Why Dark Energy – The Smoothness Problem

- The smoothness problem
  - Our universe is extremely homogeneous on large scales
    - The *cosmic microwave background radiation* (CMBR) – light coming to us from all directions from when the universe was 380,000 years old (t = 13.7 billion years now) – is homogeneous to 1 part in 100,000.
    - Even today, the universe is smooth on scales large compared to galaxies.
  - But, when the CMBR was released, the universe we see today was composed of 10^{13} different causally connected regions
    - A "causally connected region" is one that light has had enough time to travel across, so that information can be exchanged. At *t* = 380,000 yrs, that was ~ 380,000 light-years. Also know as the "horizon" – as far as one can see.
    - Today, at *t* = 13.7 billion years, we can see a region 13.7 billion light years in diameter.
  - This is the "smoothness" or "horizon" problem: how did the universe get so smooth if it is composed of so many distinct causally connected regions?

Why Dark Energy – The Smoothness Problem

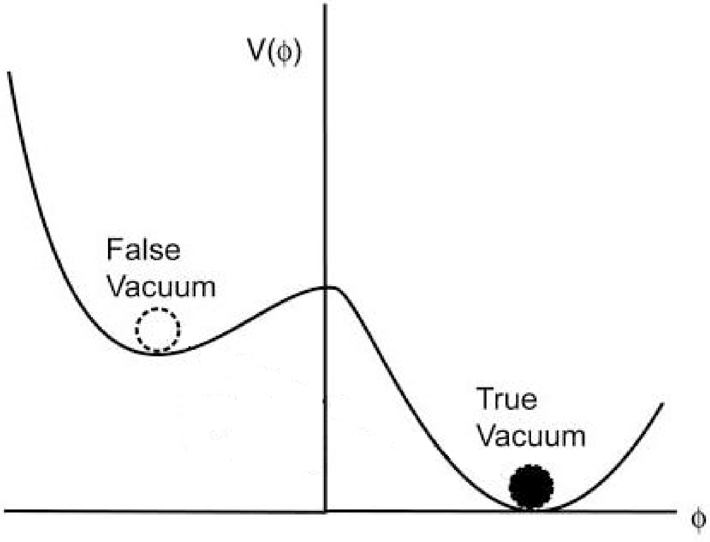
- Solvable with negative pressure
  - If negative pressure dominated during the very early universe and the universe expanded at an exponential rate, the relation between the age and the horizon distance falls apart.
    - Nonintuitive – the universe can expand faster than the speed of light.
  - Expansion factor needed: 10^{26}
  - This phenomenon is termed *inflation* and was driven by physics similar to that causing the current accelarating expansion.
- Has to turn off at appropriate time to get the universe we see.





What is Dark Energy?

- These constituents of the universe with negative pressure are termed *dark energy*. How could they arise? One possibility is *false vacuum*.
  - Suppose the universe is permeated by a field (like the electromagnetic field), but there is some potential energy function for the field.
  - Suppose the function has a true minimum – *true vacuum* – and a false minimum – *false vacuum*.
  - True vacuum has zero energy and pressure.
  - False vacuum regions eventually become true vacuum regions.
  - Therefore, false vacuum has negative pressure – true vacuum with negative pressure wants to expand into it.



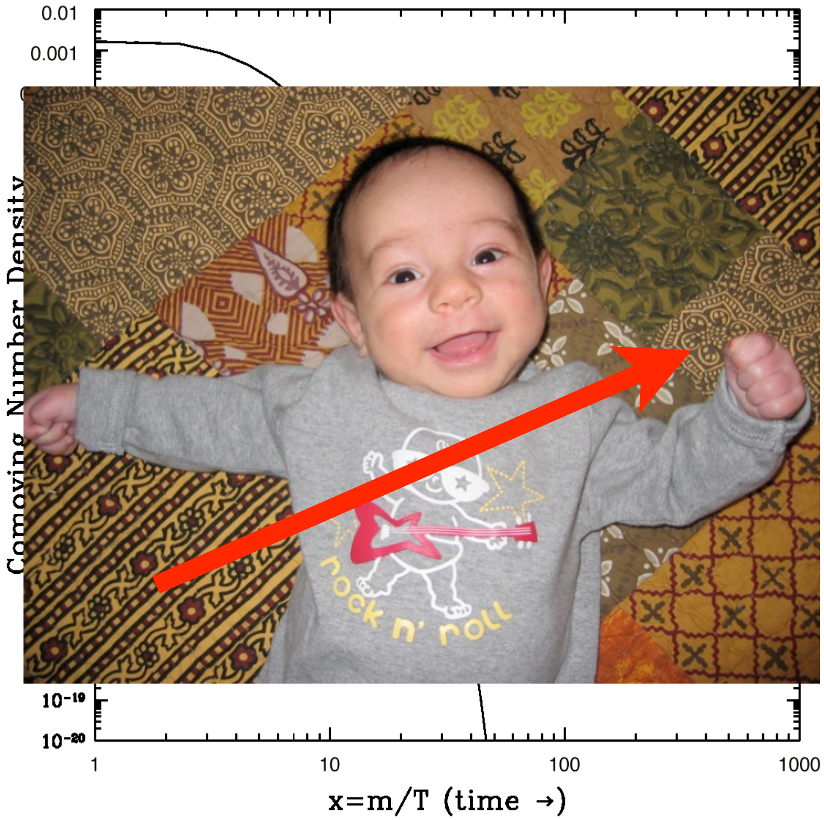
  - Einstein's vacuum energy density is the potential energy of the false vacuum state.

Detecting Dark Matter and Dark Energy

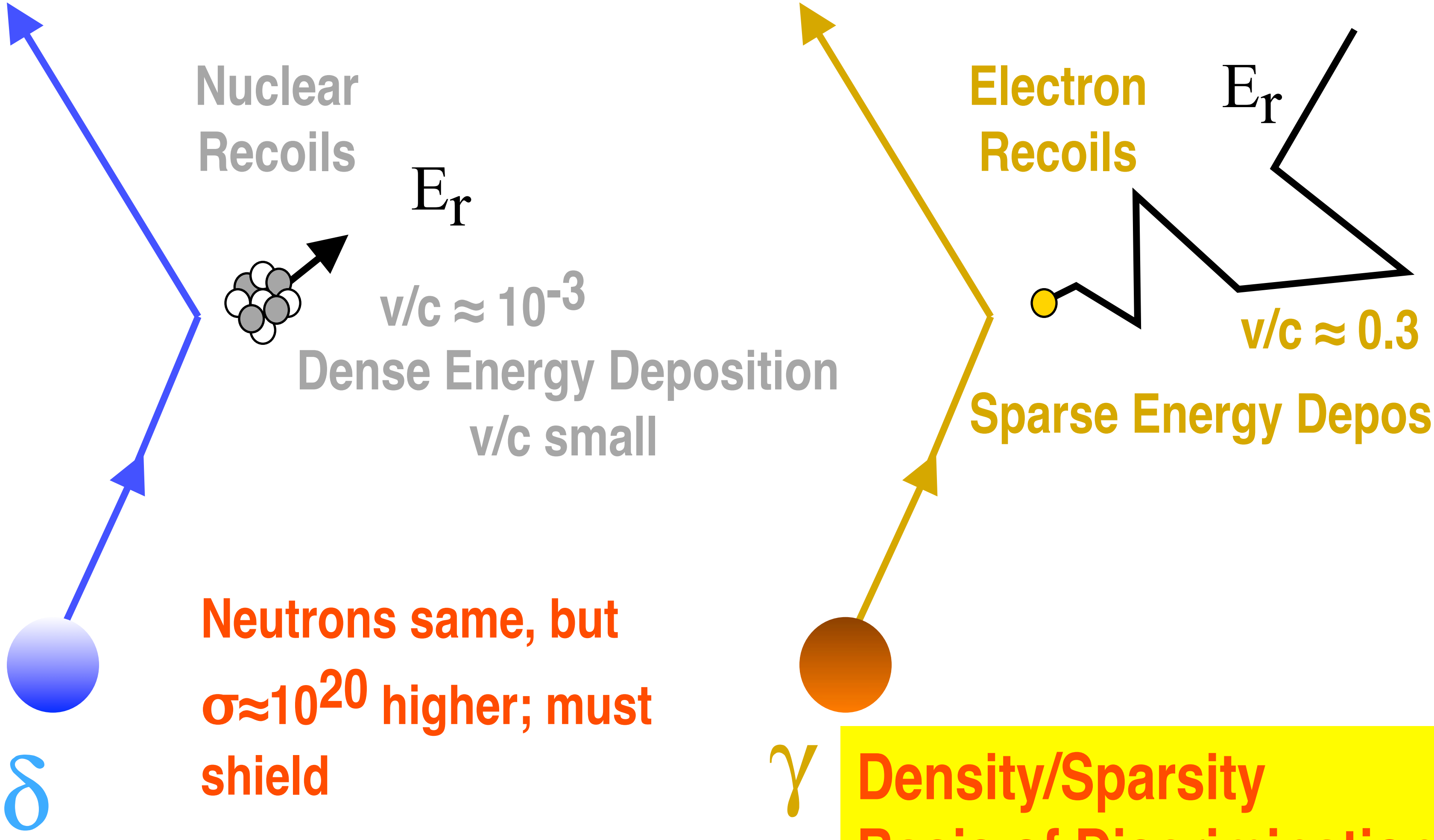
- We have invoked two new physical entities. How do we directly demonstrate their existence?
  - dark matter:
    - Direct detection of subatomic particles that may make up the dark matter
  - dark energy:
    - Contemporary dark energy:
      - Difficult to probe directly, to do more than just measure its effects.
      - Some possibilities exist for measuring its ability to collapse under its own gravity.
    - Inflationary dark energy: look for relic gravity waves produced when inflation ended
      - Specific signatures in the cosmic microwave background radiation
      - Direct detection of gravitational waves (LIGO and LISA, gravitational wave observatories with significant Caltech involvement – will not discuss)
- A common theme – the importance of development of new technology to tackle these difficult experimental challenges.

WIMPs – A Particle Dark Matter Candidate

- WIMP – Weakly Interacting Massive Particle
- Produced when $k_B T >> mc^2$ in early universe
- As T decreases, abundance drops as $\exp(-mc^2/k_B T)$
- But, weakly interacting → may "freeze out" and leave relics
- If particles are "just beyond the Standard Model", relics would be the dark matter
- Orbiting in our galaxy, passing through us all the time (10 million/cm^2/sec)
- Interact very rarely, < 1/kg/day
- Will interact primarily with nuclei, depositing energy ~ tens of keV (like one medical X-ray photon)



Nuclear Recoil Discrimination



Signal

Nuclear Recoils

E_r

$v/c \approx 10^{-3}$

Dense Energy Deposition

v/c small

δ

Neutrons same, but $\sigma \approx 10^{20}$ higher; must shield

Background

Electron Recoils

E_r

$v/c \approx 0.3$

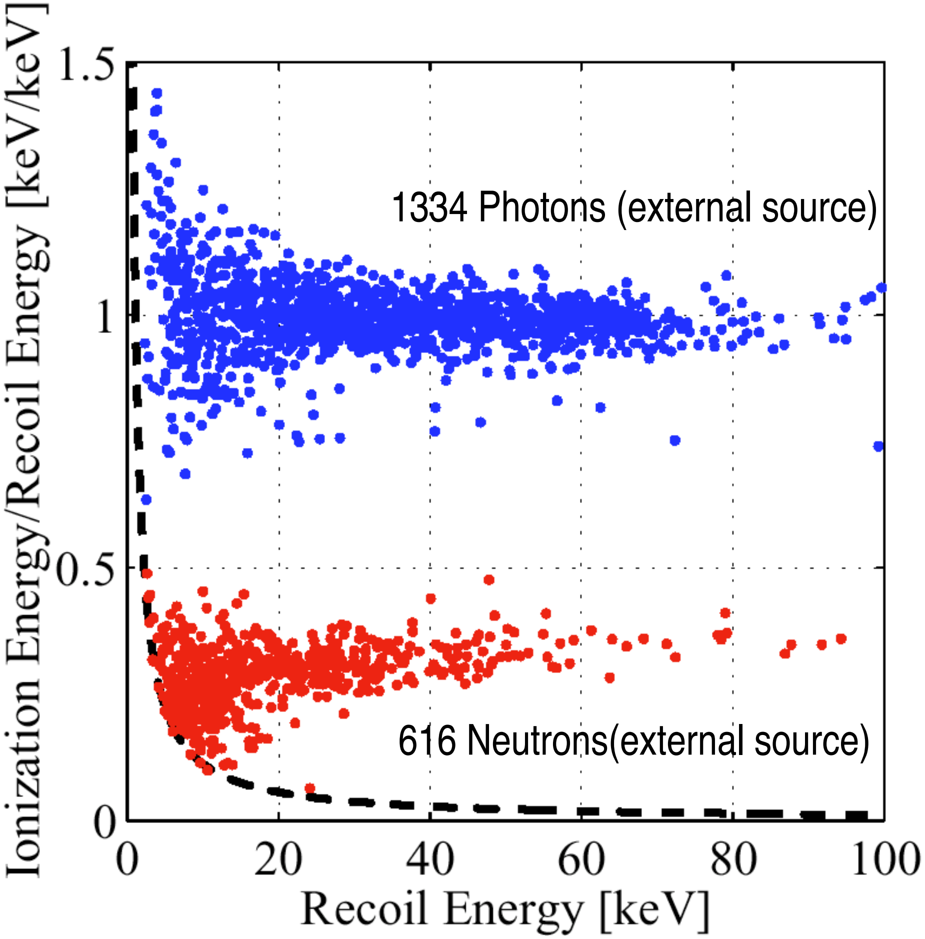
Sparse Energy Deposition

γ

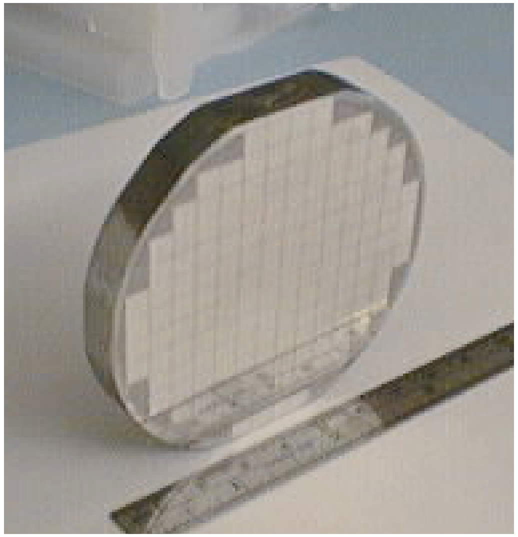
Density/Sparsity Basis of Discrimination

Nuclear Recoil Discrimination

- Nuclear recoils arise from
  - WIMPs
  - Neutrons
- Electron recoils dominate and arise from
  - photons
  - electrons
  - alphas
- Ionization yield
  - ionization/recoil energy strongly dependent on type of recoil
- Recoil energy
  - Phonon measurement gives full recoil energy



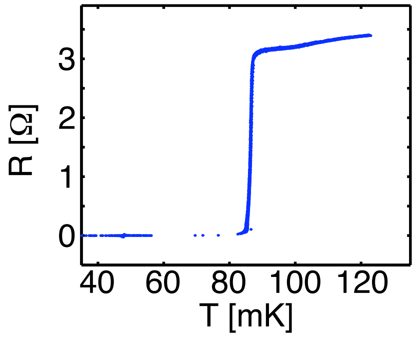
- Event-by-event discrimination of nuclear recoils from electron recoils

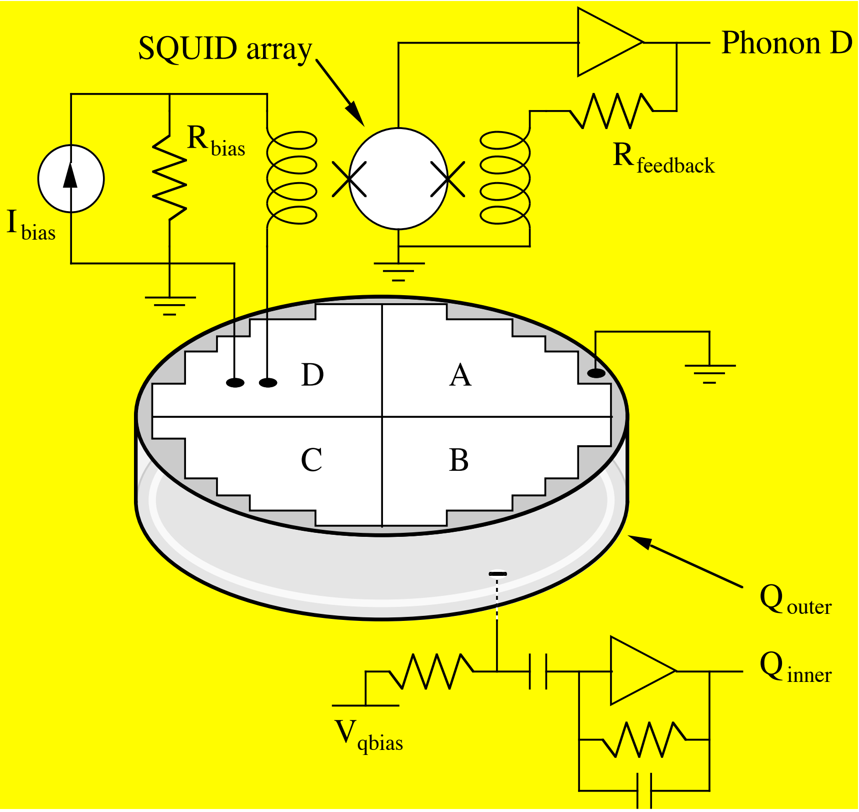


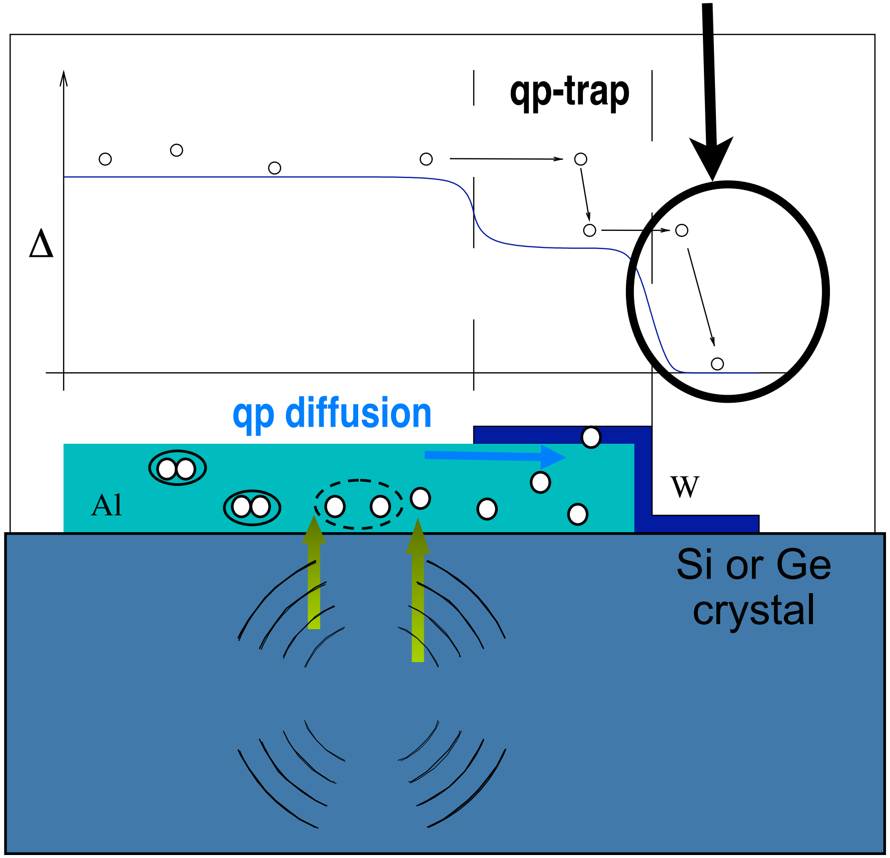
ZIP Detectors

Z-sensitive Ionization- and Phonon-mediated detectors:

Phonon signal measured using photolithographed superconducting sensors.

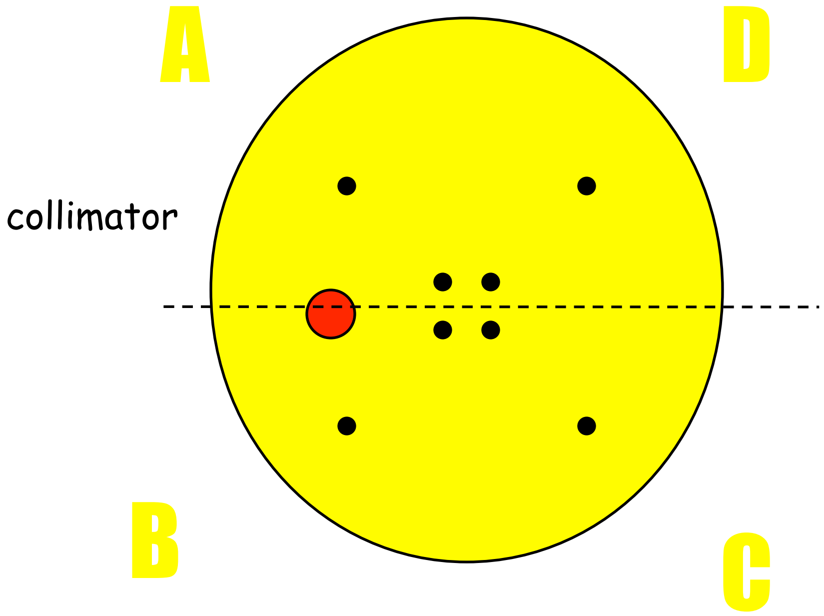


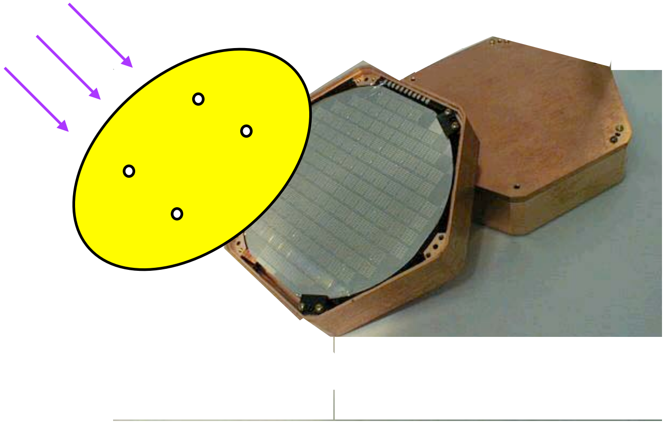




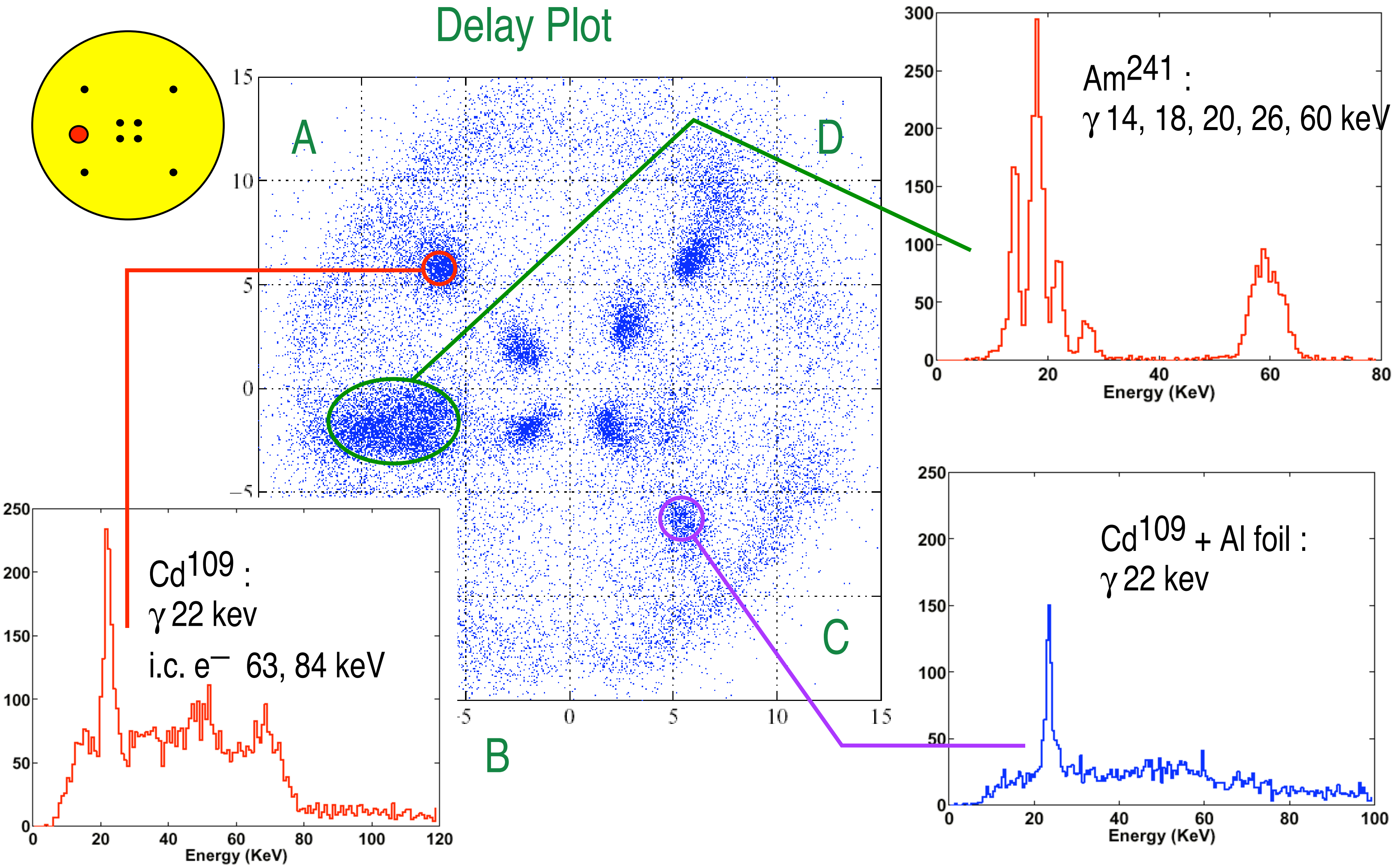
ZIP xy Position Sensitivity

- Phonon sensors provide measurement of xy position of interaction
  - Speed of sound in Si (Ge) crystal of ~ 1 (0.5) cm/ms results in measurable delays between the pulses of the 4 phonon channels
  - Able to measure x,y coordinates of interaction
  - Demonstrate by shining sources through a collimator
  - (Some z sensitivity in phonon signal also)



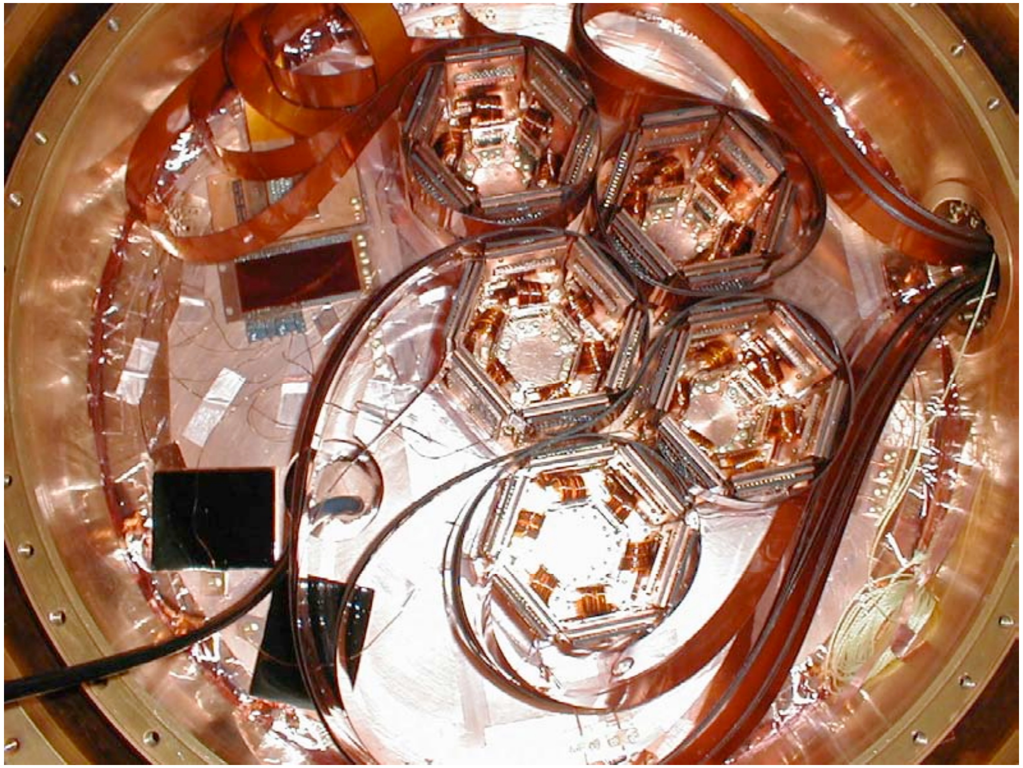


ZIP xy Position Sensitivity



The Cryogenic Dark Matter Search

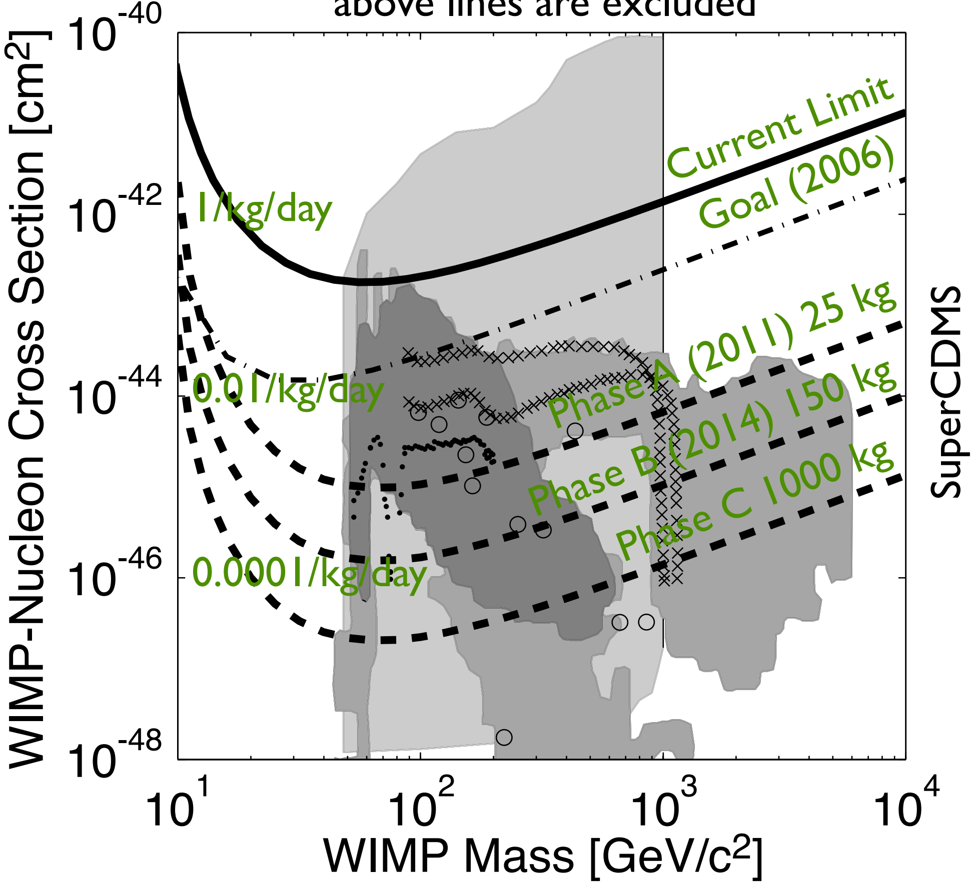
- Employs 5 kg of ZIP detectors in shielded environment to search for WIMPs



CDMS Current Status

- Currently has world's best limits by factor of 10 (0.1/kg/day)
  - Beginning to probe some particle physics models that predict WIMP dark matter
  - More sensitive than experiments with 20x mass
  - Technology development has been essential, but is always under pressure from agencies (NSF, DOE): they want projects with clear schedules and results; development projects make them uncomfortable
- Starting final run soon, proposing major upgrade: SuperCDMS (Phases A, B, C)
- R&D at Caltech
  - New detector for screening for radioactive contamination
  - New kinds of dark matter detectors with J. Zmuidzinas, F. Harrison

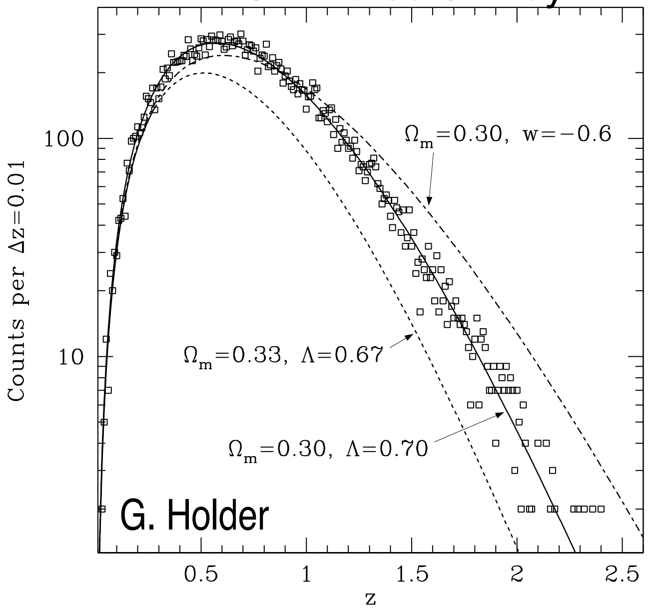
Exclusion Limit Plot: Cross sections above lines are excluded



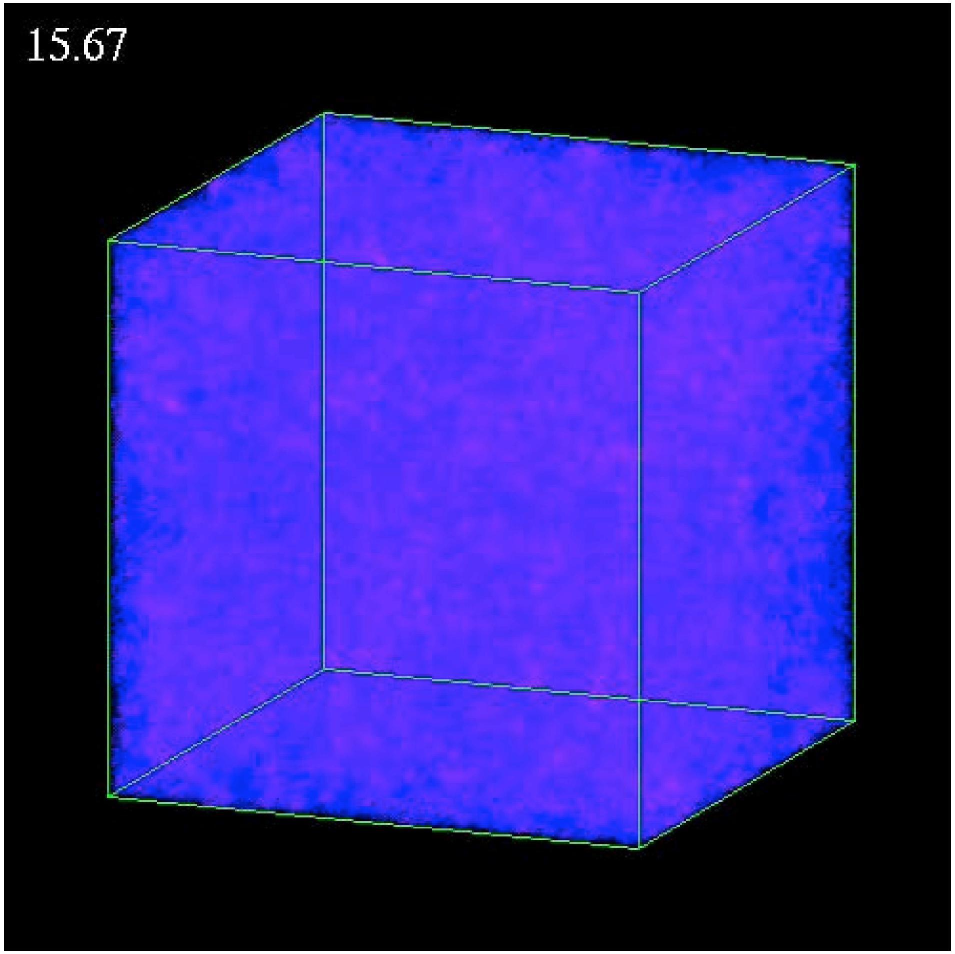
Studying Dark Energy

- One method is to measure the growth of structure in the universe
- The abundance of high-contrast objects is quite sensitive to matter density and dark energy effects on expansion history

Number of clusters per redshift bin above 3.5×10^{14} M_{Sun} in 4000 deg^2, with simulated survey



G. Holder

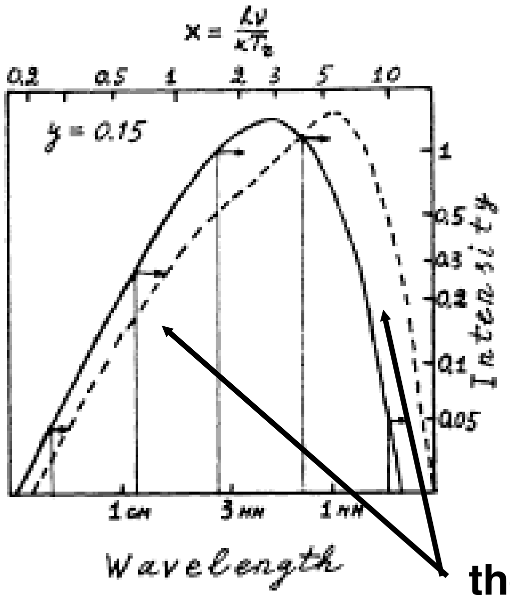


Virgo Consortium
http://www.icc.dur.ac.uk/Outreach/Movies.html

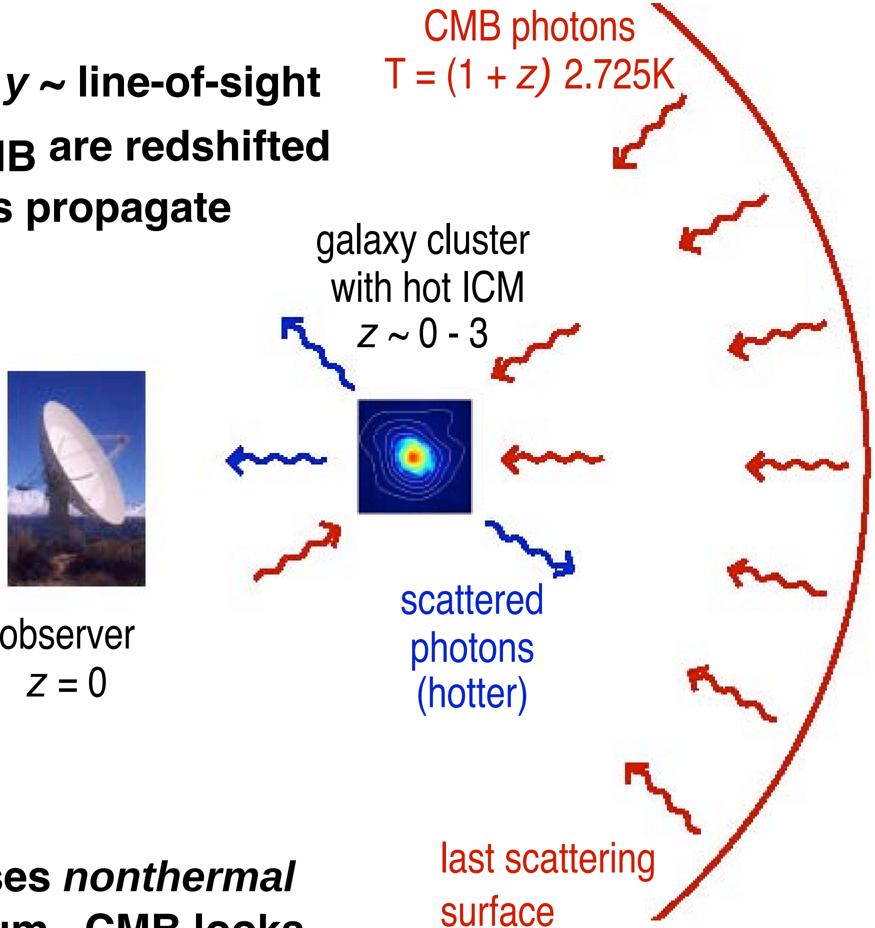
The Sunyaev-Zeldovich Effect in Galaxy Clusters

Thermal SZE is the Compton up-scattering of CMB photons by electrons in hot, intracluster plasma

$\Delta T_{CMB}/T_{CMB}$ depends only on cluster y ~ line-of-sight integral of $n_e T_e$. Both ΔT_{CMB} and T_{CMB} are redshifted similarly → ratio unchanged as photons propagate and independent of cluster distance



thermal SZE causes *nonthermal* change in spectrum. CMB looks colder to left of peak, hotter to right



CMB photons
T = (1 + z) 2.725K

galaxy cluster
with hot ICM
z ~ 0 - 3

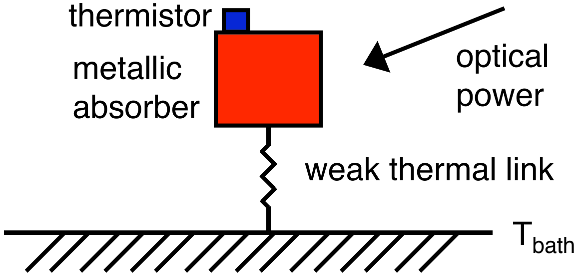
observer
z = 0

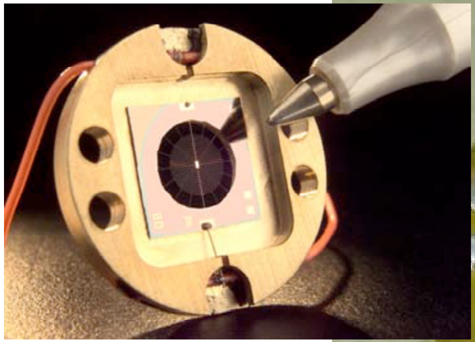
scattered
photons
(hotter)

last scattering
surface
z ~ 1100

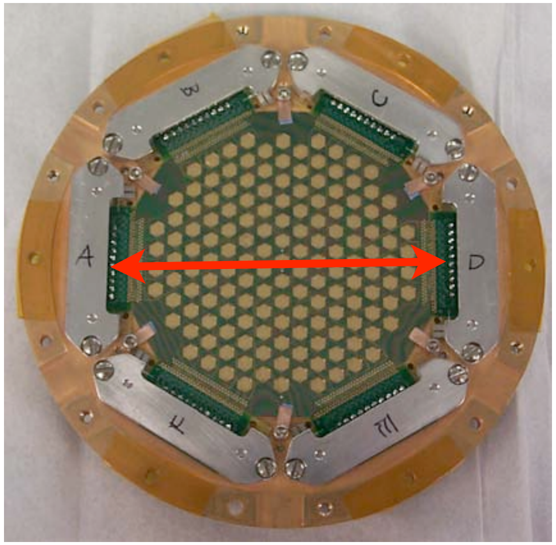
Bolocam

- 2-mm wavelength camera with 144 pixels observing with Caltech Submillimeter Observatory



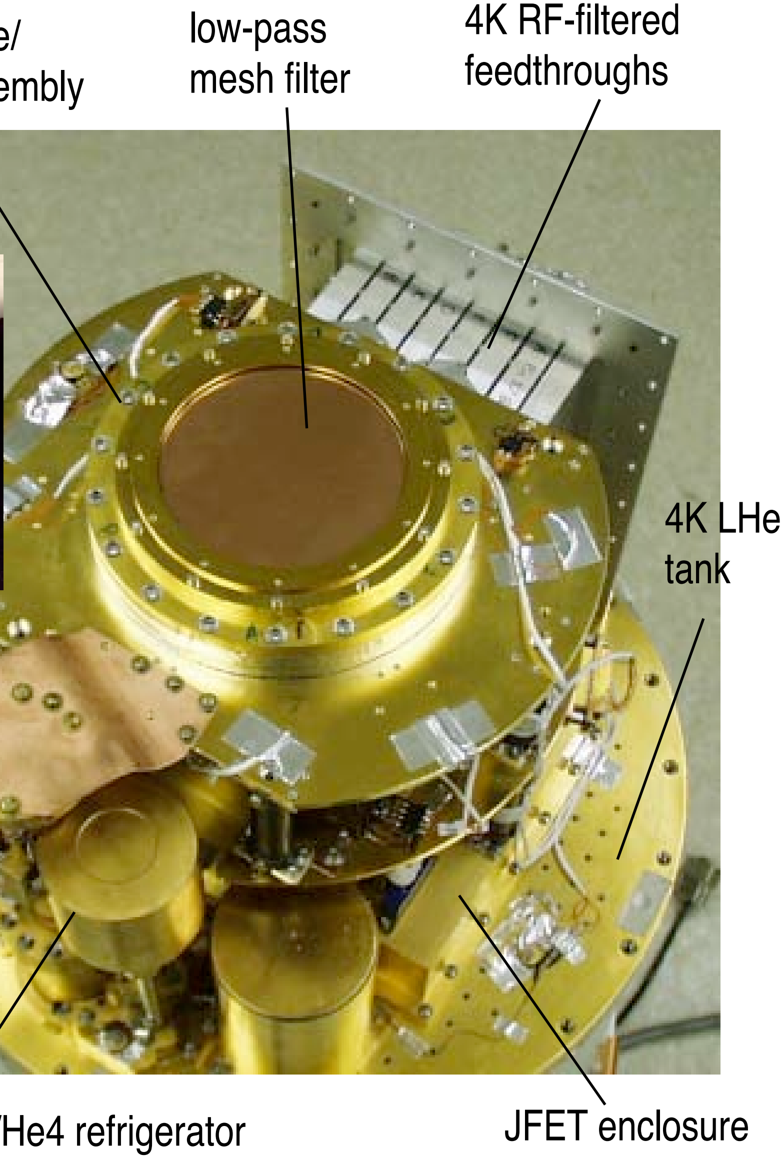


3 inch wafer



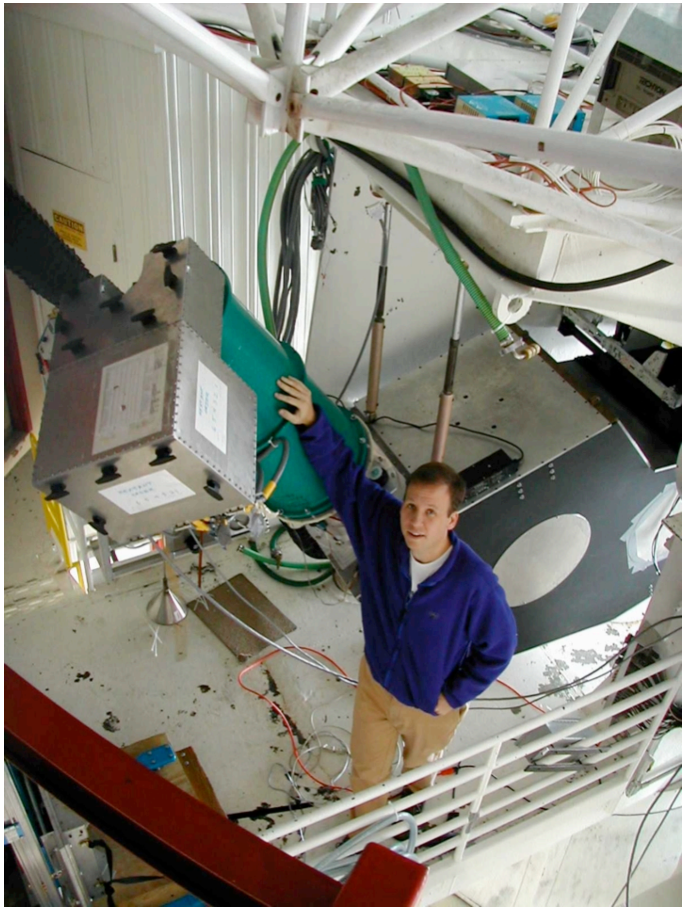
first monolithic bolometer array

important precursor to instruments on Herschel Space Observatory



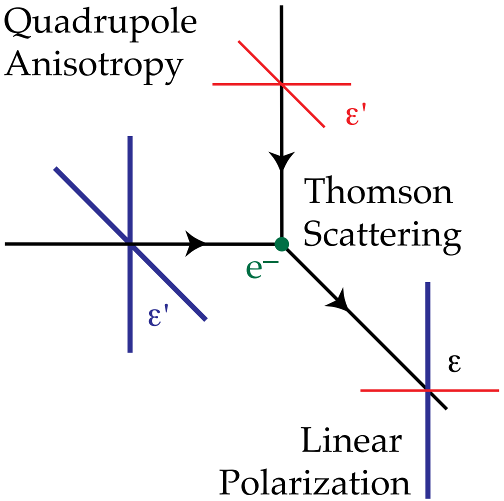
Bolocam at the CSO

- Have undertaken survey for galaxy clusters using SZ effect
- Expect ~few detections in 1 sq deg – data currently being analyzed at Caltech
- “First try” – pathfinder for a number of new instruments coming online soon
- esp. important as precursor to cameras for Caltech-Cornell Atacama Telescope – 25m submillimeter/millimeter-wave telescope under study, to be sited in Chile

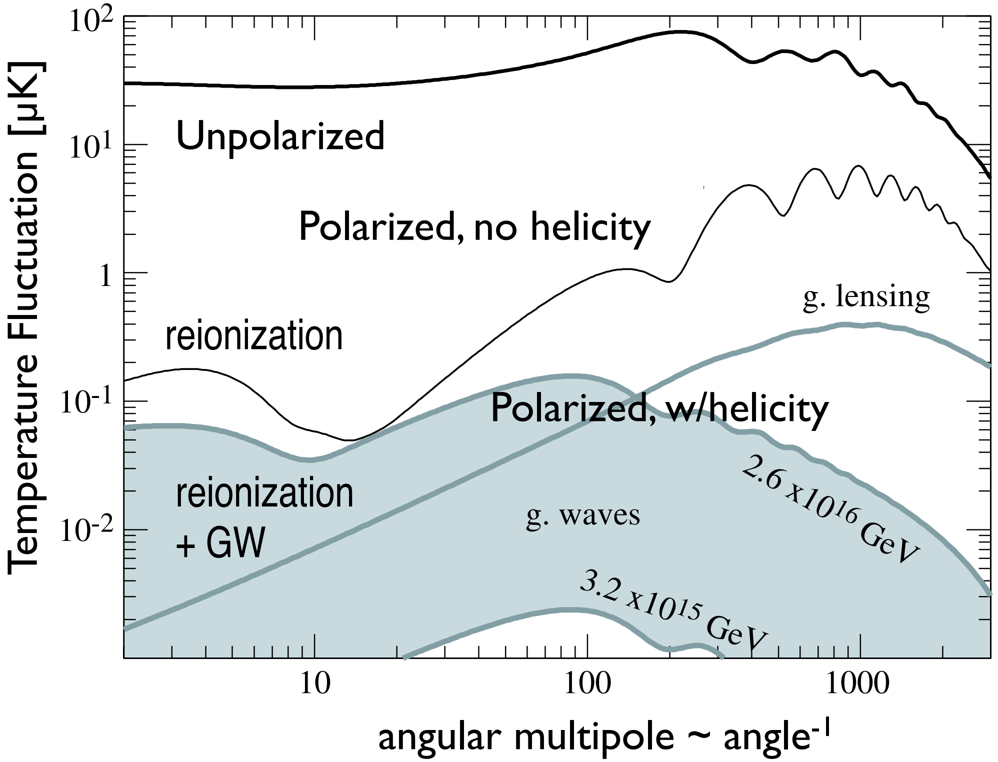


Inflationary Dark Energy and Relic Gravity Waves

- The cosmic microwave background radiation has fluctuations; these grew into the structure (galaxies, clusters of galaxies) we see today
- There are also fluctuations in polarization of the CMBR due to local anisotropy in the CMBR at the time it was released
- If inflation happened, then gravity waves were generated and they imprinted *helicity* on the CMBR that could not arise in any other way:
  a "smoking gun" for inflationary dark energy in the early universe.
- Likely will be the goal of a satellite mission late 2010s

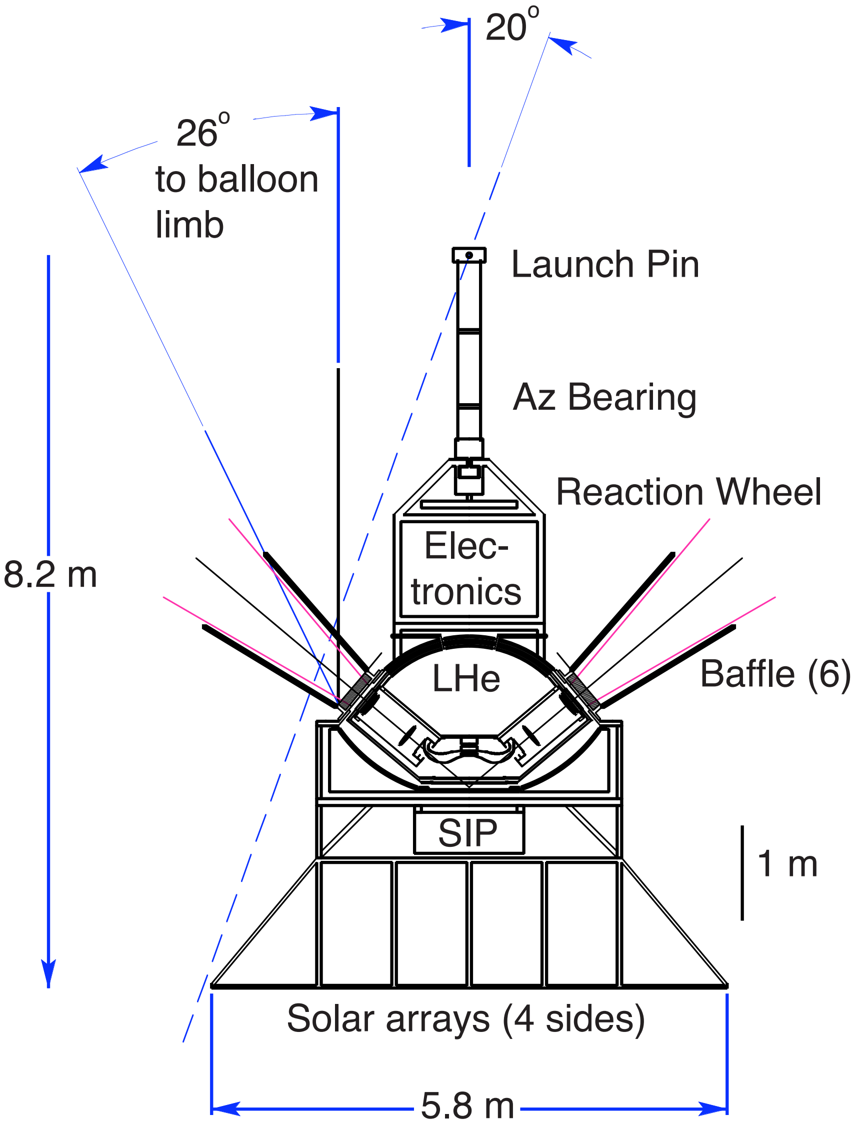


W. Hu



Hu, Hedman, Zaldarriaga

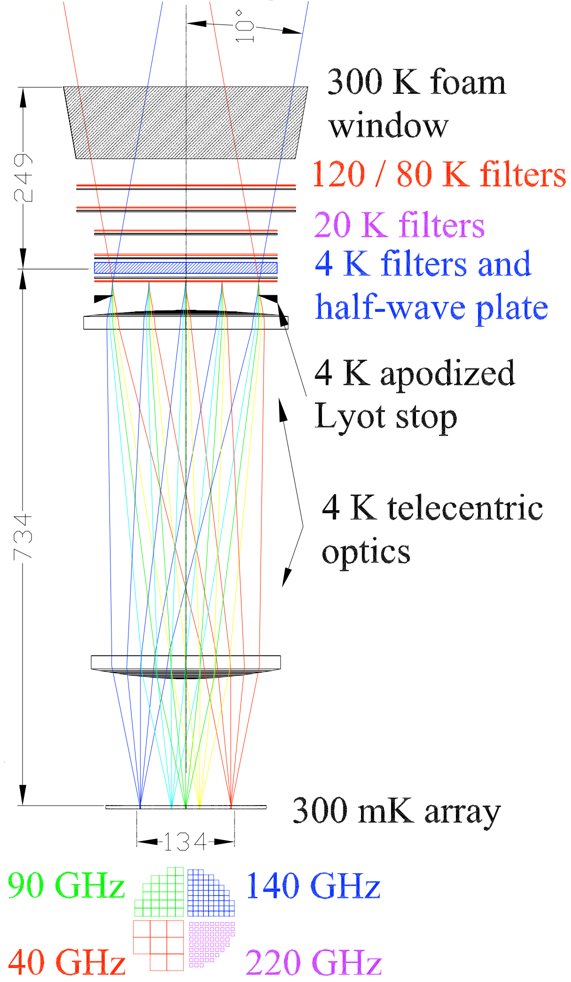
Looking for Relic Gravity Waves with SPIDER

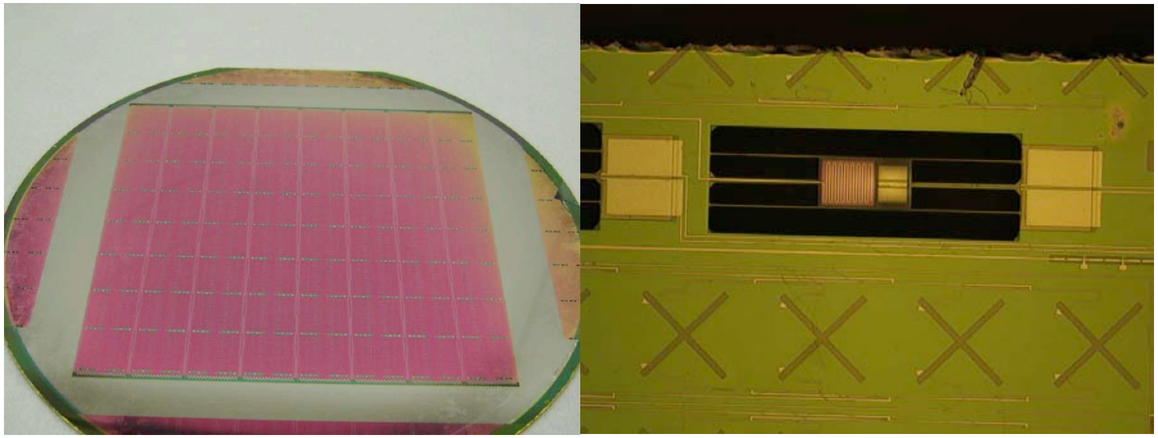


Angular Resolution	1 deg at 90 GHz
Sky coverage	50%, constant elev. scans
Platform	20-day flight, from Australia
Frequencies	40, 3x90, 150, 220 GHz (6 telescopes)
# of detectors	1856
Cryogenics	LHe cryostat + 3He fridge (300 mK)
Schedule	Fall 2008: test flight Dec, 2009: science flight

Optics and Detectors

- 6 receivers, identical up to detectors and antireflection tuning of optics
- It's a polarimeter: pol-sensitive detectors, low-pol optics, rotating half-wave plate, no reflections, almost all optical elements are unmodulated



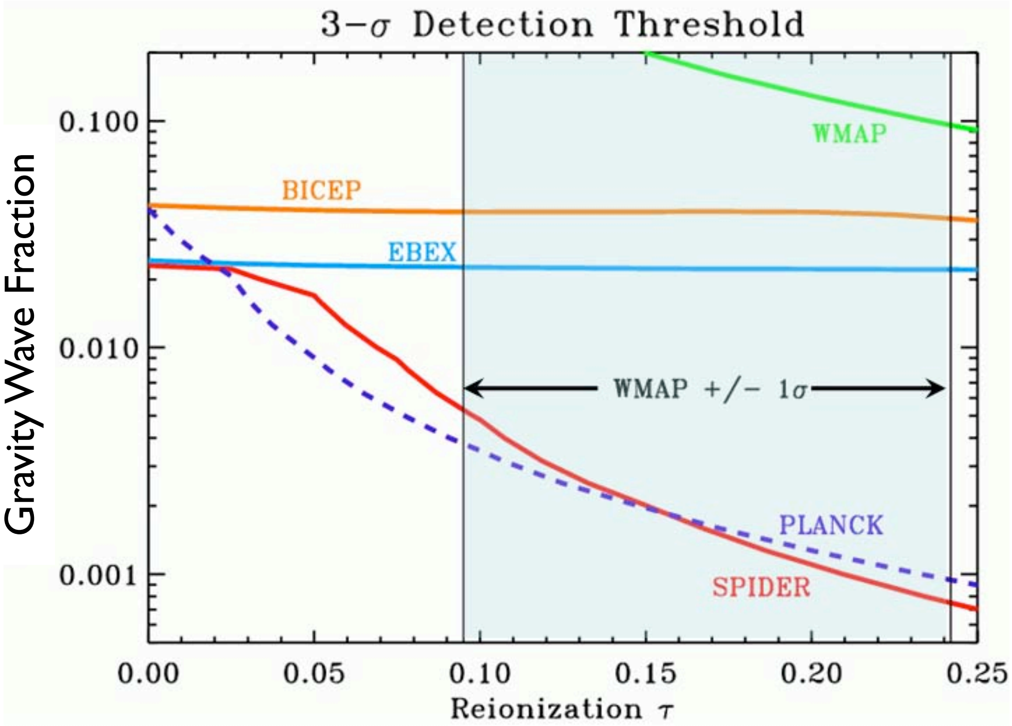


Observing Band (GHz)	Bandwidth (GHz)	Beam FWHM (arcmin)	Number of Spatial Pixels	Number of Detectors	Single-Detector Sensitivity ($\mu K_{\rm CMB}$ $s^{1/2}$)	Instrument Sensitivity ($\mu K_{\rm CMB}$ $s^{1/2}$)
40	10	145	32	64	130	16.3
84	33	69	128	256	60	3.8
92		63	128	256		
100		58	128	256		
145	32	40	256	512	80	3.5
220	40	26	256	512	150	6.6

Table 1: Observing bands, pixel and detector counts, and single-detector and instrument sensitivities. The latter is obtained by dividing the single-detector sensitivity by $\sqrt{N_{\rm det}}$. A total of 1856 detectors are distributed between the six telescopes.

Gravity Waves and Reionization

- SPIDER will have the best sensitivity to gravity waves experiment of its epoch
- Enabled by detector development
  - development of photolithographic means for producing hundreds of pixels and integration of polarization-pure elements
  - well ahead of the competition
  - farsighted approach at Caltech/JPL – use what is ready, but invest in the future
    - Enabled by internal R&D funds and high-quality JPL fab facilities and staff
    - All CMB results of last 5 years > 100 GHz have used JPL detectors
    - Next two submm/CMB missions (Herschel, Planck) will have JPL focal planes
  - But current climate at NASA is making this more difficult
    - Internal JPL funds and facilities under financial pressure
    - Code R (technology dev't) canceled, Office of Space Science under pressure



Conclusion

- Dark matter and dark energy are two groundbreaking propositions, but with a strong intellectual heritage in physics
- The hunt is extremely exciting, with a great deal of Caltech activity
  - Have not mentioned significant contributions from optical astronomers and instrumentalists at Caltech (Richard Ellis, Caltech Optical Observatories, Alan Weinstein) and JPL
- On the experimental side, the *science* is only possible with significant technology investment
  - Recent invitation by administration to submit $10M Moore Foundation proposal to support detector development work (A. Lange, PI)

CDMS II Collaboration

- Brown University: M.J. Attisha, R.J. Gaitskell, J-P. F. Thompson
- California Institute of Technology: S. Golwala, G. Wang
- Case Western Reserve University: D.S. Akerib, C. Bailey, P. Brusov, M.R. Dragowsky, D.D.Driscoll, D. Grant, R. Hennings-Yeomans, S.Kamat, T.A. Perera, R.W.Schnee
- Fermi National Accelerator Laboratory: D.A. Bauer, M.B. Crisler, R. Dixon, D. Holmgren, E.Ramberg, J. Yoo
- Lawrence Berkeley National Laboratory: R. McDonald, R.R. Ross, A. Smith
- National Institute for Standards and Technology: K. Irwin
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- University of Colorado at Denver and Health Sciences Center: M. E. Huber
- University of Florida: L. Baudis, S. LeClercq
- University of Minnesota: P. Cushman, L. Duong, A. Reisetter

Bolocam Instrument Team

- Caltech
  - (Mihail Amarie), (Samantha Edgington), Sunil Golwala, Andrew Lange, Philippe Rossinot, Jack Sayers
- JPL
  - Jamie Bock, Alexey Goldin, Hien Nguyen, Fab team at MDL
- University of Colorado, Boulder
  - James Aguirre, Jason Glenn, Glenn Laurent, Phil Maloney, Patrick Stover
- University of Wales, Cardiff
  - Peter Ade, Douglas Haig, Phil Mauskopf, Rob Tucker

PhD thesis, has done bulk of analysis work

SPIDER Collaboration

Institution	Responsibilities
Caltech-JPL (Bock, Lange, Golwala)	Detectors, optics, single-receiver assembly and testing, data analysis
Cardiff University (Ade)	filters, optics
Case Western Reserve University (Ruhl)	rotating half-wave plate, data analysis
CEA Grenoble (Duband)	3He refrigerator
Imperial College (Contaldi)	data analysis, theory
NIST (Irwin)	multiplexed cold SQUID electronics
University of Toronto/CITA (Netterfield, Bond)	gondola, pointing, data analysis
University of British Columbia (Halpern)	warm SQUID electronics, data analysis