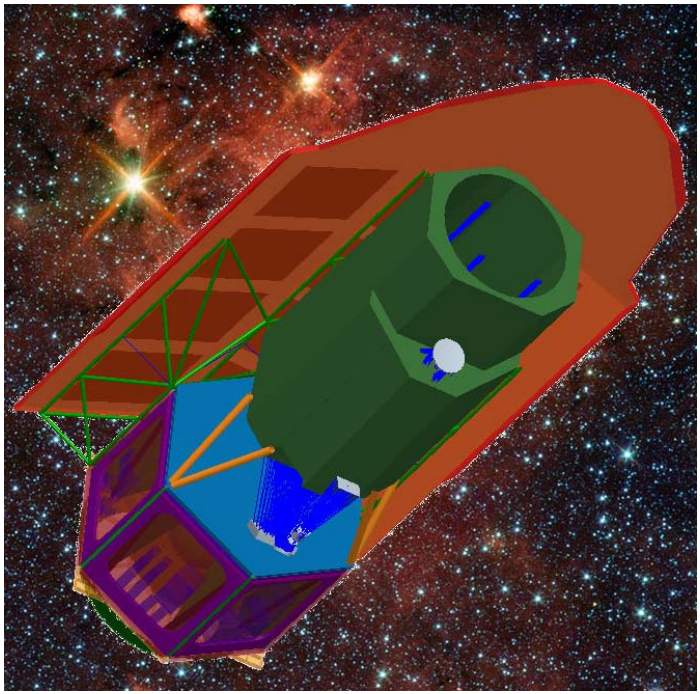
Space Telescopes, lightweight materials, & cryogenic operation

- Outline:
  - Problem statement
    - Why are we using glass mirrors?
    - Why are we heating the mirrors?
    - Do alternate choices help us save cost?
  - Materials trade space
    - Materials list
    - Metrics & Cryo properties
    - TRL comparison
    - What the usual textbook doesn't tell you
    - Suggested 'short list' of materials
    - Risk reduction activities required
  - Mass breakdown and status of fitting on Falcon9



Why are we using glass mirrors?

- HQ has consistently asked for low risk telescope approach for this mission
- 5-10 years ago only glass was TRL6
- Even now Be, SiC metering structures at sizes we need are NOT TRL6 in US
- Alternatives add risk without adding value – see following charts

PM History for US Dark Energy mission concepts

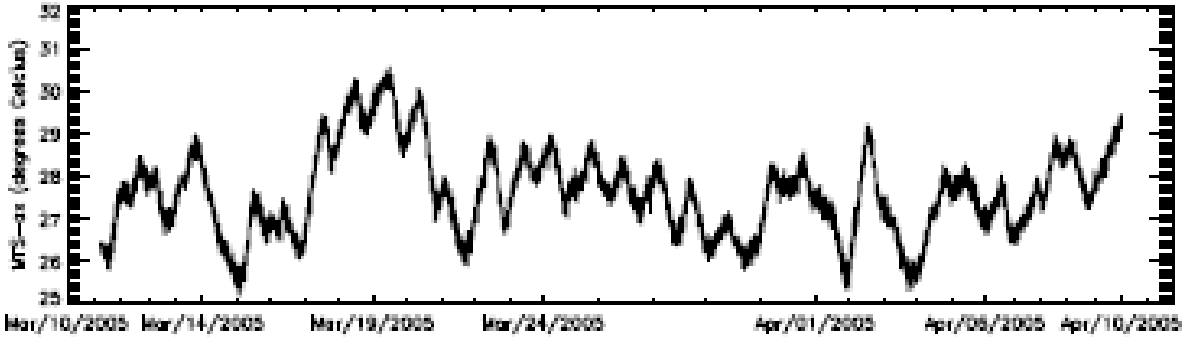
year	Mission Concept	D, m	λmax, um	material
2000	SNAP	2	1.7	Zerodur
2008	Destiny	1.6	1.7	ULE
2008	JDEM Yardstick	1.5	1.7	ULE
2008	ADEPT	1.3	2.0	ULE
2009	DECS	1.5	2	ULE/Zerodur
2009	Omega	1.5	2	ULE/Zerodur
2010	ProbeA	1.1	2	ULE/Zerodur
2011	IDRM1	1.3	2	ULE
2012	DRM 1,2	?	2.4?	?

Why are we heating the mirrors?

- Perception in the community, echoed by (e.g.) recent talks by Schechter, Hirata:
  - "WL is REALLY HARD"
- Solution is to engineer a very highly stable ImC optical path
- Requires low CTE, structural/mirror CTE matching, AND thermal control
- Thermal gradients and fluctuations are minimized through the flight proven, low risk approach of applying heater control to a cold biased system
- Point is to **eliminate thermoelastic changes as a source of wavefront error instability**
  - IF analysis shows this is overconservative, we will consider passive cooling without active control
- Figure shows HST thermal history – instability leads to systematic psf errors

5 °C thermal instability of PM-SM metering structure thermal gradient on HST; HST WL studies limited by systematic errors

DiNino, HST ISR TEL 2005-03



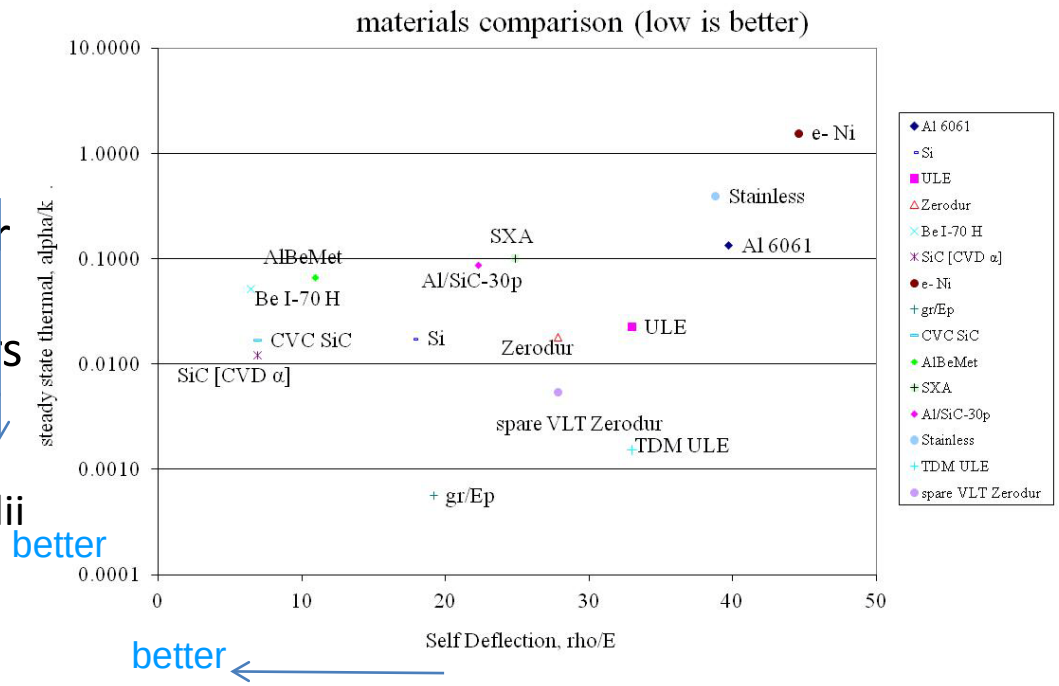
Single channel observatory mass breakdown

- Mirror and telescope structural mass are minor fraction of observatory
- This does NOT change with aperture
- Even more aggressive lightweighting does not changes mass story substantially
- Table gives IDRM1 payload mass breakdown; candidate DRM's are not very different

N. Armani 2/28/2012	IDRM 1.3m 3-Channel mass (kg)	%
Payload Mass Breakdown:		
OTA other (non Structural/non-optical mass)	174.7	0.207
OTA Structural	385.1	0.457
OTA Reflective Optics	105.3	0.125
OTA Transmissive Optics	27.8	0.033
OTA Optical Mounts, Ti	24.2	0.029
Instrument Structure	22.4	0.027
FGS	10.9	0.013
Instrument Radiator	34.2	0.041
Instrument FPA	27.5	0.033
Instrument Harness	19.8	0.023
FW/PW Mechanism	10.8	0.013
TOTAL	**842.7**	1.00

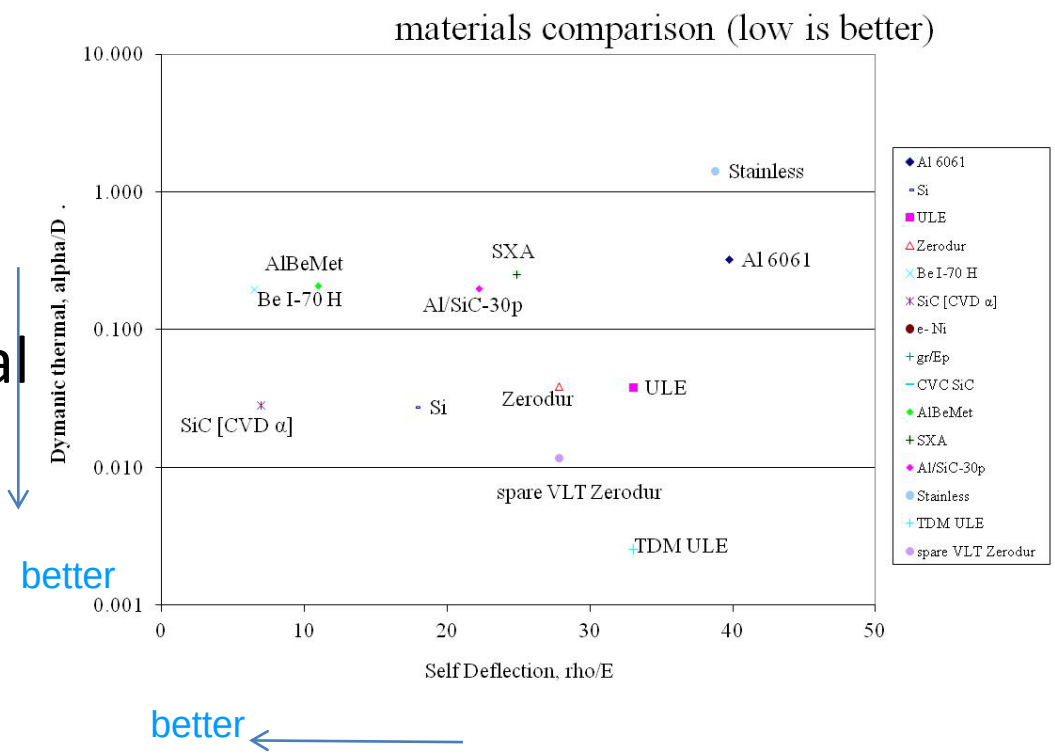
Materials trade space

- Usual metrics include:
  - Specific stiffness, E/ρ
    - E modulus, Gpa
    - ρ density, kg/m^3
  - Thermal static performance, α /k
    - α Coefficient of thermal expansion, ppm/K
    - k thermal conductivity, W/m.K
- Typical plot like this (ideal is lower left corner)
- Note – ideal is either make mirrors and structure of same material or match cte
  - With matched CTE, lengths and radii shrink together and <u>focus is maintained at lower temperature</u>



Materials trade space

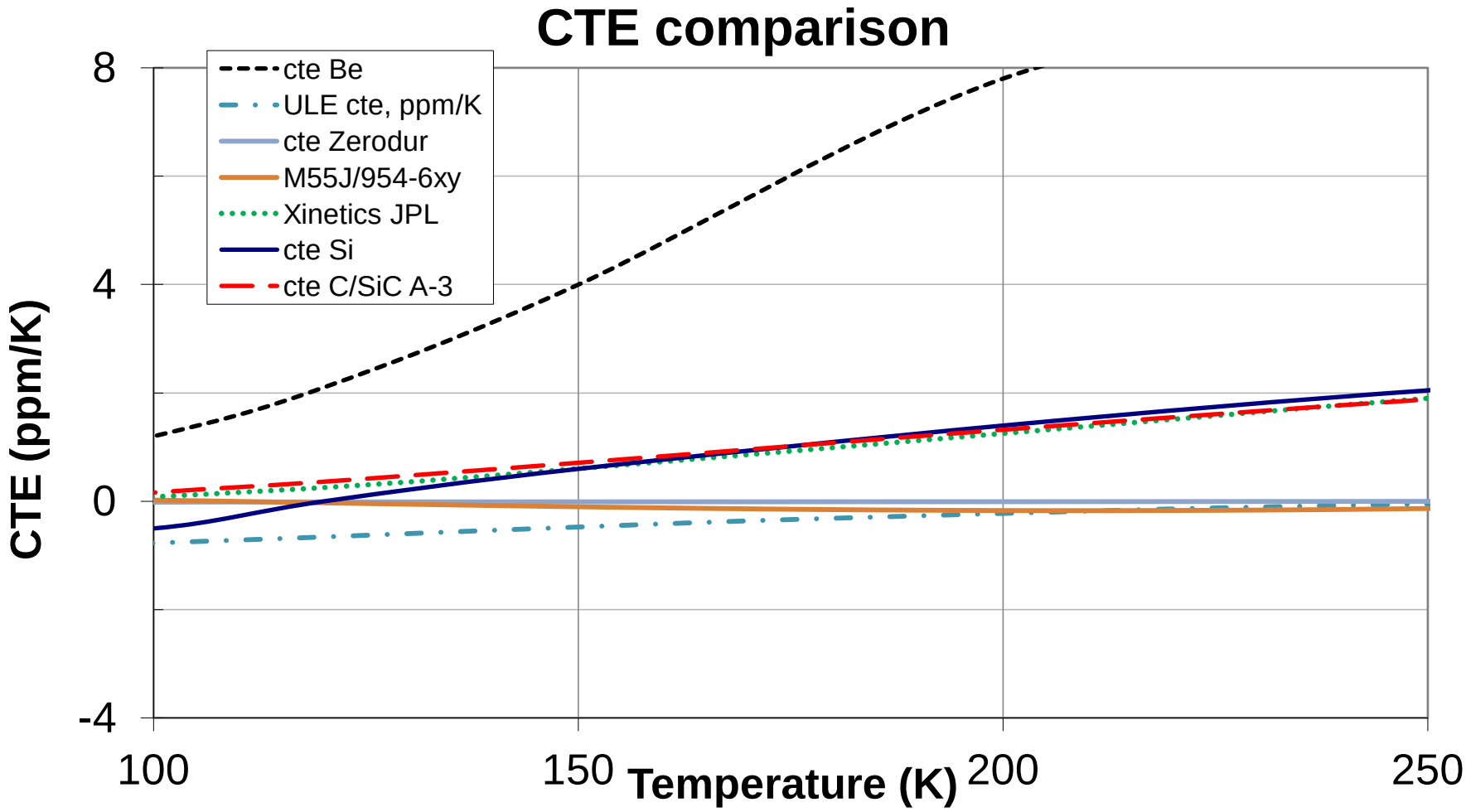
- Thermal dynamic performance:
  - α /D
    - α Coefficient of thermal expansion, ppm/K
    - D diffusivity W/m.K
- Typical plot like this (ideal is lower left corner)
- Al is ideal for low cost, particularly with Al structure; no experience at 1m scale



Cryo properties

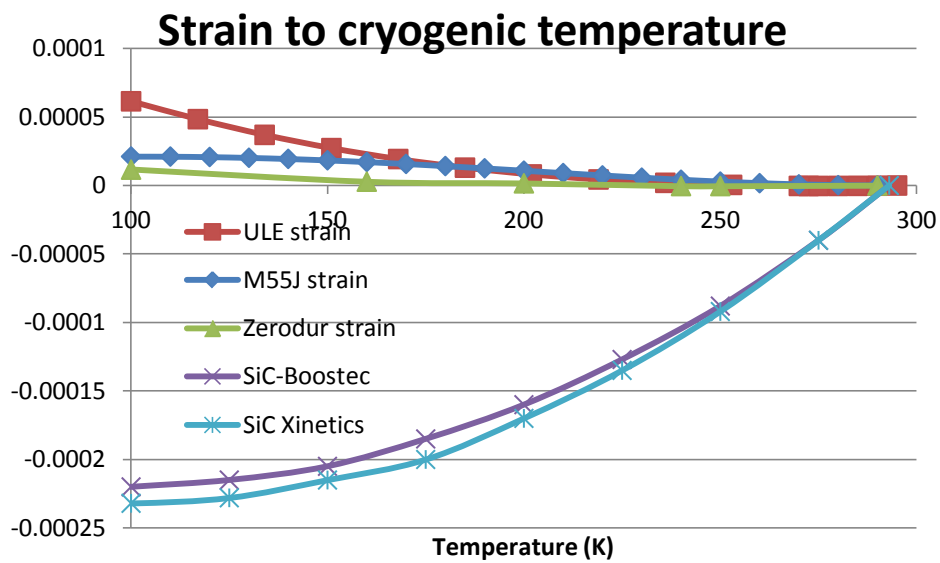
- Above charts are at room temperature
- CTE decreases with temperature, for most materials
- E increases
- Ideal case for stability is operating at cte=0 temperature
  - Driving reason for Be mirrors on JWST, 0 cte at 40K
- ULE/Zerodur/M55-J are all engineered materials for zero cte at room temperature
- What about in between?

CTEs at mild cryo



Integrated strain comparison

- Top shows strain from ambient for various materials
- ULE or Zerodur are low and well matched to M55J
- All SiC would be athermal also
- We have estimate of 2K control needed to limit thermoelastic strain to 2nm in wavefront error for IDRM1 ImC
  - To be confirmed through integrated modeling this spring
- Table scales this requirement by ratio of CTE at operating temperature for alternate materials
- **Average temperature and temperature gradients would need to be much more tightly controlled than with glass/composite for Be or SiC, to <0.1K**
  - **Eg Xinetics SiC at 150K would require 0.15K control; achievable but certainly more expensive**



Cryo CTE and scaled temperature control requirements						
ppm/K	ULE	Zerodur	SiC Xin.	SiC Boo.	Be	M55J
CTE 200	-0.044	-0.04	1.25	1.15	7.8	-0.172
CTE 150	-0.468	-0.04	0.58	0.58	4	-0.103
dT 200K	**2**	2.20	0.07	0.08	0.01	
dT 150K	0.19	2.20	0.15	0.15	0.02	

Why α/k is misleading for lightweight mirrors

- Textbooks and sales pitches often argue that SiC or Be are ideal mirror materials based on thermal stability
- However, for the case of very highly lightweighted mirrors, most of the material is removed
- Therefore actual conductivity is limited
- Thermal heat transfer is mostly radiative in this case
- Therefore CTE dominates, and α is the metric, not α/k, for thermal stability
- Example – switching from ULE to SiC on TPF-C primary mirror required much tighter [30x] thermal control [at room temperature]

Flight mirror table

flight lightweight mirror list

		m	m2	kg		kg/m^2			um		K
mission	launch yr	D	A	M	lin. Obs.	ρ_A	material	shape control	λ_{DL}	thermal control approach	temperature
HST	1991	2.4	4.03	1000	0.33	180	ULE	passive*	0.5	active	293
WMAP	2001	1.5	3.52	17	0	10	composite	passive	3200	passive, open	90
Spitzer	2003	0.85	0.54	15.3	*0.2*	28	Be	passive	6.5	cryogen	4
GeoEye	2008	1.1	0.85	34.7	*0.33*	41	ULE	passive	0.5	active	293
Herschel	2009	3.5	9.24	300	*0.2*	32	SiC	passive	80	passive, open	80
Kepler	2009	1.4	1.54	87	0	57	ULE	passive[1]	*1.7*	active	178
WISE	2009	0.4	0.11	9.3	*0.4*	88	Al	passive	*~12*	cryogen	10
GAIA	2013	1.5	0.86	38	*0*	22	SiC	passive	*1*	Passive	130
OPTIIX	2015	1.5	0.98	*19.9*	0.5	15	nlam/SiC	active	1?	active	293
IceSat-2	2016	0.8	0.47	*12.8*	0.25	27.1	Be	passive	*1.5*	active	
JWST	2018	6.5	32.06	*801.5*	0.184	25	Be	active	2	passive, open	40

* HST has actuators but they have not been used for image quality control

1. Kepler has a focus mechanism, but not shape control actuators

- Working limit on passive areal density is in range of 25 kg/m^2 independent of material for UV-NIR spectral range
- Broad consensus that minimum mirror diameter that justifies segmentation/active control is ≥3m
  - [radius control on ~1.5m JWST segments needed for phasing]

History of glass at cryo – usable to ~100K

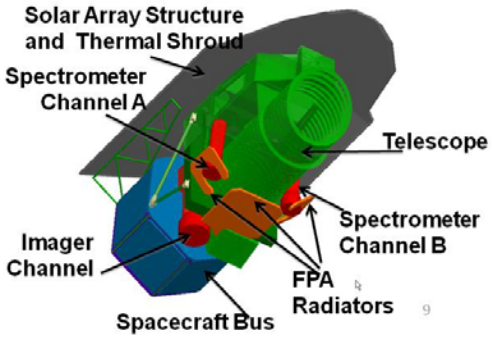
Kepler, passive spherical PM at ρ_A=40 kg/m2, 240 K, ~1.4m diameter

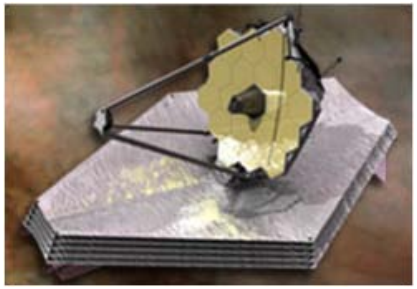
- ITT AMSD, off axis segments w/ actuators, ρ_A=25 kg/m^2, unstable wavefront at T<100 K, ~1.5m diameter
  - Would be usable for WFIRST
- Many room temperature mirrors to 2.4m
- No notable failures
- Composite benches do have finite moisture uptake and shrink on orbit
  - HST still shrinking 18 yrs after launch
  - Would be MUCH slower once composite structure freezes
- Glass is capable of being used colder than 200K
  - Some materials qualification may be needed
  - Mirror(s) may require "cool-null" figuring

- Cooling to 100K requires other trade-offs, e.g. stray light control

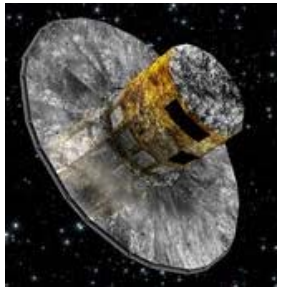
Why not run at 100K?

- If we chose 100K as an operating temperature, the instruments and focal planes are easier to cool
  - Could use SiC at/near its 0 CTE temperature
- Requires very open telescope architecture to get that cold [e.g. JWST/40K, WMAP/90K]
- Will require multiple layer to isolate payload from solar array and from room temperature spacecraft
  - Need to retain enough agility to carry out wide survey
- Ability to get this cold may be inconsistent with standard stray light control [telescope barrel]
  - JWST has spent many $M on stray light analysis for its open architecture needed to cool to ~40 K
- We want to cool enough to remove optics as noise source but still be able to use standard stray light control

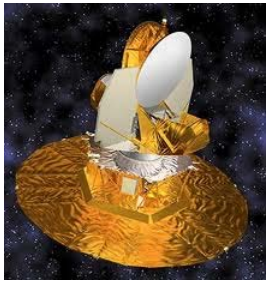




JWST 40K



GAIA 130K



WMAP 90K

Getting Cold Drives Mission Costs

- [Sun-Shadowed] Space is cold
- Observatories get integrated on a warm Earth
- It costs money & schedule to get colder on Earth
  - Schedule is a dominating mission cost driver
- Last spring the Project showed how detector cutoff (payload temperatures) drive costs
  - Payload temperatures lower than ~200K
    - Aspects of telescope and instrument require re-design
    - Components get more expensive
      - Filter wheel
      - Prism wheel
      - Spectroscopy materials challenges and limitations
    - Re-qualify some materials, parts and processes
    - Integration and test get more expensive
      - Drives test & metrology
      - Drives testing schedule
      - Cryo-figure process necessary to ensure figure accuracy operating at cold temperatures
    - Impact to payload critical path
      - Requires added staff, material and subassembly testing cycles
    - Increases cost, risk, schedule

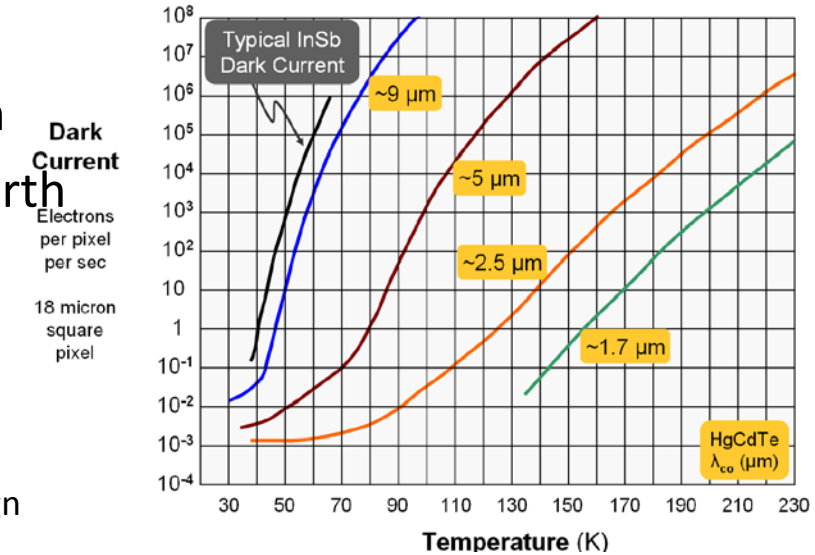


Fig. 8: The dark current of MBE grown HgCdTe detector material. The dark current is shown for an 18 µm pixel and can be scaled for smaller or larger pixel pitch. The cutoff wavelength (λ_{co}) is shown with the approximation symbol, since λ_{co} is a function of temperature and there will be slight variation in cutoff wavelength of a HgCdTe detector as it cools.

History of Be

- Many Lidar mirrors up to 1m, typically fast, ~1m metering to SM
- Interfaces can be an issue; flexures need significant attention
- Material can not be polished onsite but lots of heritage
- Have been issues:
  - “bent” spare SIRTF PM
  - ICESAT-2 currently reworking mounting concept for multipoint 0.8m LIDAR system due to mount induced wavefront errors
- >1.5m structures need new facilities
- Would need funding to bring to TRL6 at sizes of mirrors and structures for WFIRST

History of SiC

- Largest telescope mirror in space – ESA Herschel PM, 3.5m
- Seems to be working well for GAIA – ESA 1.5m astrometric mission, all SiC
- Small instruments successful
  - EO-1 [mirrors, SiC structure didn't work out, used Al]
  - LORRI {New Horizons, 130K, on its way to Pluto}
- LISA [US technology program portion] had notable failure –
  - Metering structure, to be used for testing picometer metrology, cracked on first cool down, total loss
- JWST/NIRSPEC is moving to spare SiC optical bench
  - Cracks at preload points
- Strongly prefer metering structure to match mirror CTE
  - >2m SiC structural elements may not be feasible in US
- 100K all SiC structure/mirror solution would be low CTE, well matched, highly conductive, and no CME issues
  - Potentially more stable than our baseline
  - Likely to require a more open structure than the baseline – potential stray light issue
    - JWST spent many $M examining stray light issues for their very open architecture

PROJECT: JWST

[Silicon Carbide, SiC] NIRSpec Bench Crack

Status as of: 1/31/12

G PROBLEMS/ISSUES	PROGRAMMATIC IMPACT	ACTION	DATE ESTAB.	DATE COMPL.
• Three cracks were discovered on the Optical Bench while performing final inspections of the chip repair	• Cracks could affect the structural integrity of the bench, leading to structural failure • Delayed flight instrument delivery	• Establish Failure Review Board and determine root cause of the cracks • Determine flight worthiness of the bench • Repair or replace the bench and complete environmental test program	7/11	12/11

CURRENT STATUS - CLOSED

- ETU bench inspected at GSFC and found to be free of cracks. The bench was shipped back to Astrium. The flight spare bench was also inspected and found to have no anomalies. FRB activities continue, are expected to conclude the end of September
- Repair of current bench is now in question. Changing over to the flight spare could delay the flight delivery several months. Working with ESA to turn up the gain on Astrium in order to avoid further schedule delays
- Decision has been made to move to the flight spare bench. Deintegration of the current flight bench is nearly complete, with no cracks found at primary interface joints
- Astrium is working double shifts and Saturdays in order to compress the rework schedule. FRB activities are continuing in parallel in order to determine root cause and corrective actions prior to retest at the instrument level
- Preliminary root causes established. Plans forward call for reduced preloads, and improved thermal compensation and tolerancing on secondary structure. Basically, handling these interfaces in the same manner as the primary interfaces were
- FRB is wrapping up, plan forward for NIRSpec has been established, implementing FRB (joint ESA/NASA) recommendations
  - Bench surface quality will be improved, bolt centering will be insured, and preloads will be reduced to required minimums
  - Environmental test program now includes a pre-vibe cryo to check for thermal stresses prior to vibe
- **NIRSpec delivery date now projected February 2013. ISIM schedule being revised to accommodate this without impacting delivery**

Considerations for various materials

- Be difficult to machine outside specialized facilities
  - Some people are allergic to Be dust
  - Special facilities, e.g. aqueous polishing
- ULE, Zerodur, composite all can have temp(CTE=0) adjusted

Risk reduction program required

- For new materials or larger sizes
  - Acoustic
  - Tensile including at cryo temperatures
  - Uniformity
  - CTE(T)
  - Qualification unit vibration testing
  - Joining and inserts [cause of NIRSPEC issues] can't be ignore
- Many $M, required early in program
  - Would compete with detector risk reduction
- JWST spent 10's of $M and >5 years on items such as this