Sub-Kelvin Coolers for CMB Missions

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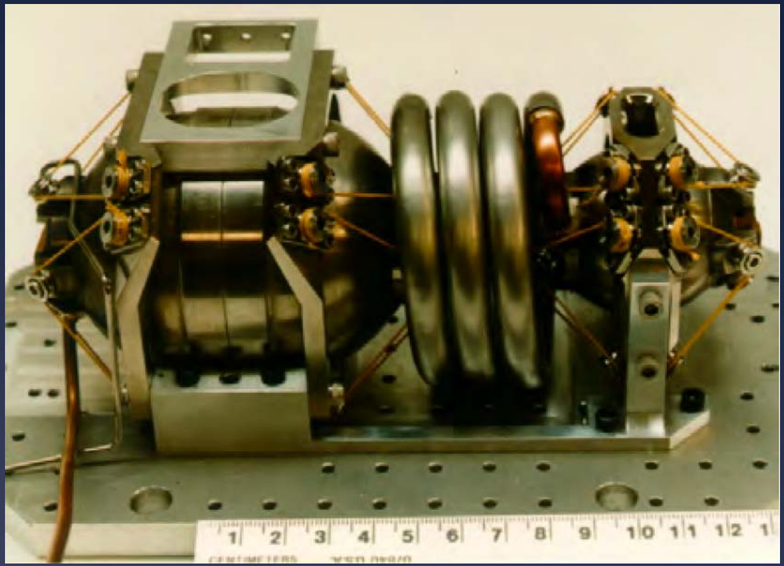
Top-Level Requirements

- Cooling in the 50-300 mK range
- Refrigeration techniques
  - Fluid-based
    - Sorption cooling
    - Dilution refrigeration
  - Solid state
    - Adiabatic demagnetization (ADR)
    - Tunnel-junction micro-coolers
- Heat sink temperature
  - Moving from superfluid helium dewars (1.5 K) to cryocoolers
    - Typically 4-5 K base temperature
    - JT can provide 2 K
  - Compatibility issues: peak heat rejection
    - Bias toward continuous systems, multi-stage architectures

3He Sorption Refrigerator

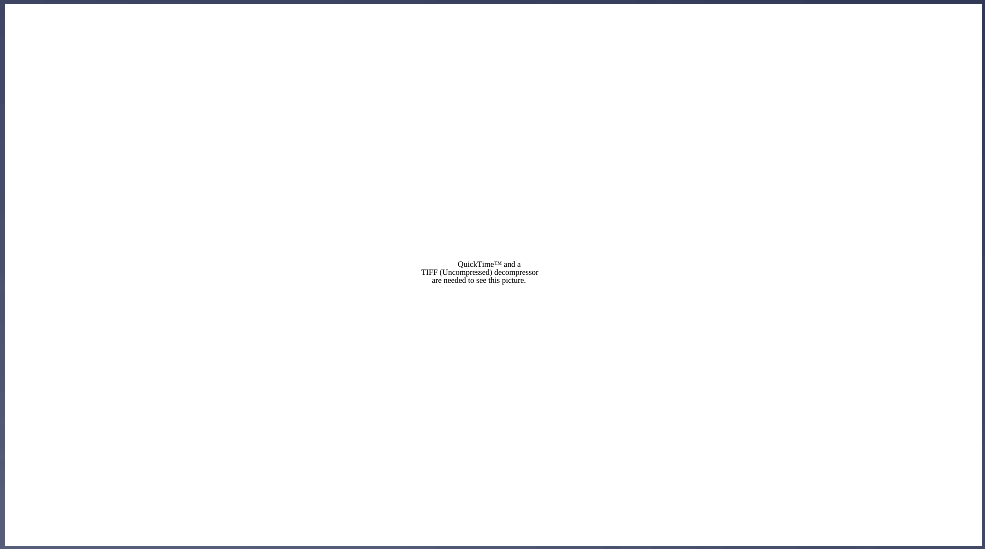
- Charcoal pumped pot
  - Inherently single-shot
  - Advantages: small, moderate cooling power (10 µW at 300 mK)
  - Disadvantages: inherently single-shot, low efficiency, ~200 mK limit



IRTS Cooler

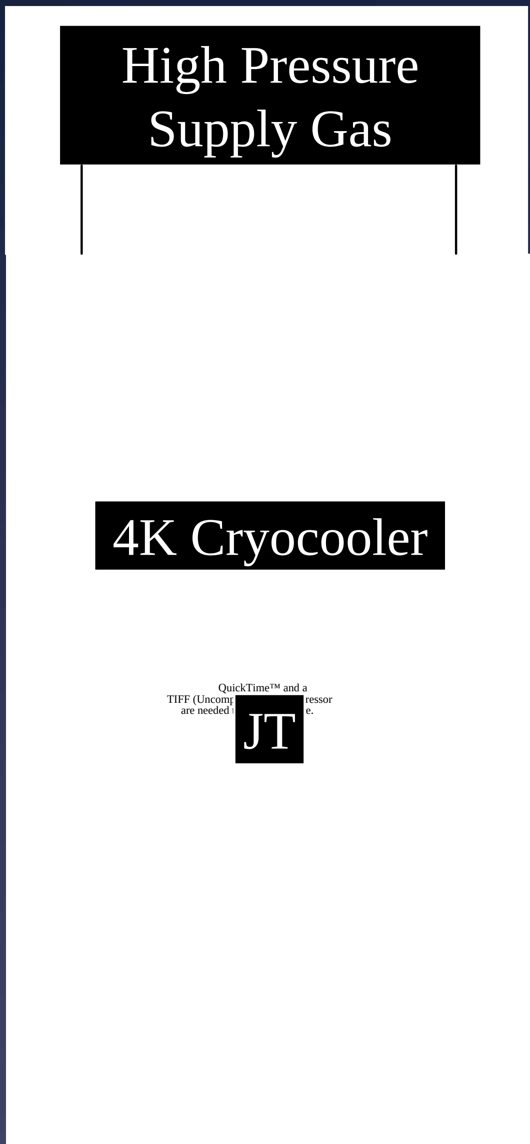
Courtesy Lionel Duband, CNES

SPUD 3-stage



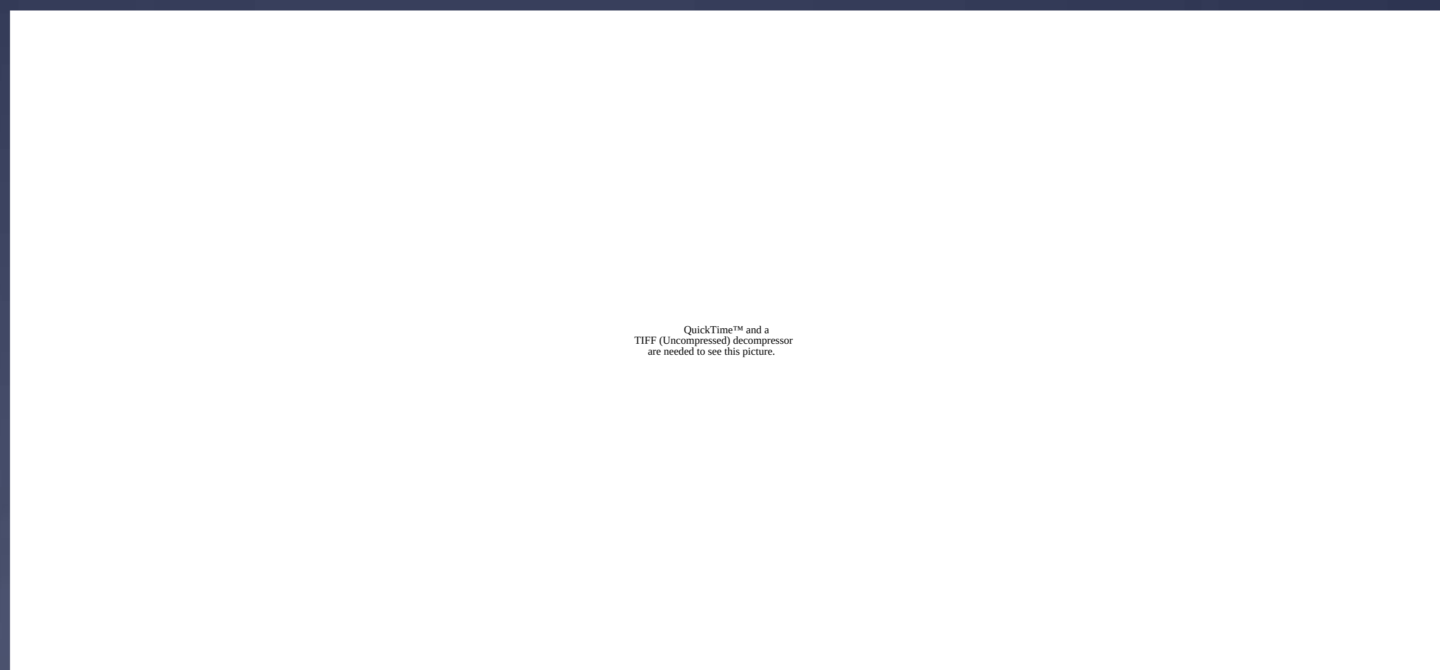
Herschel SPIRE Instrument

Dilution Refrigerator

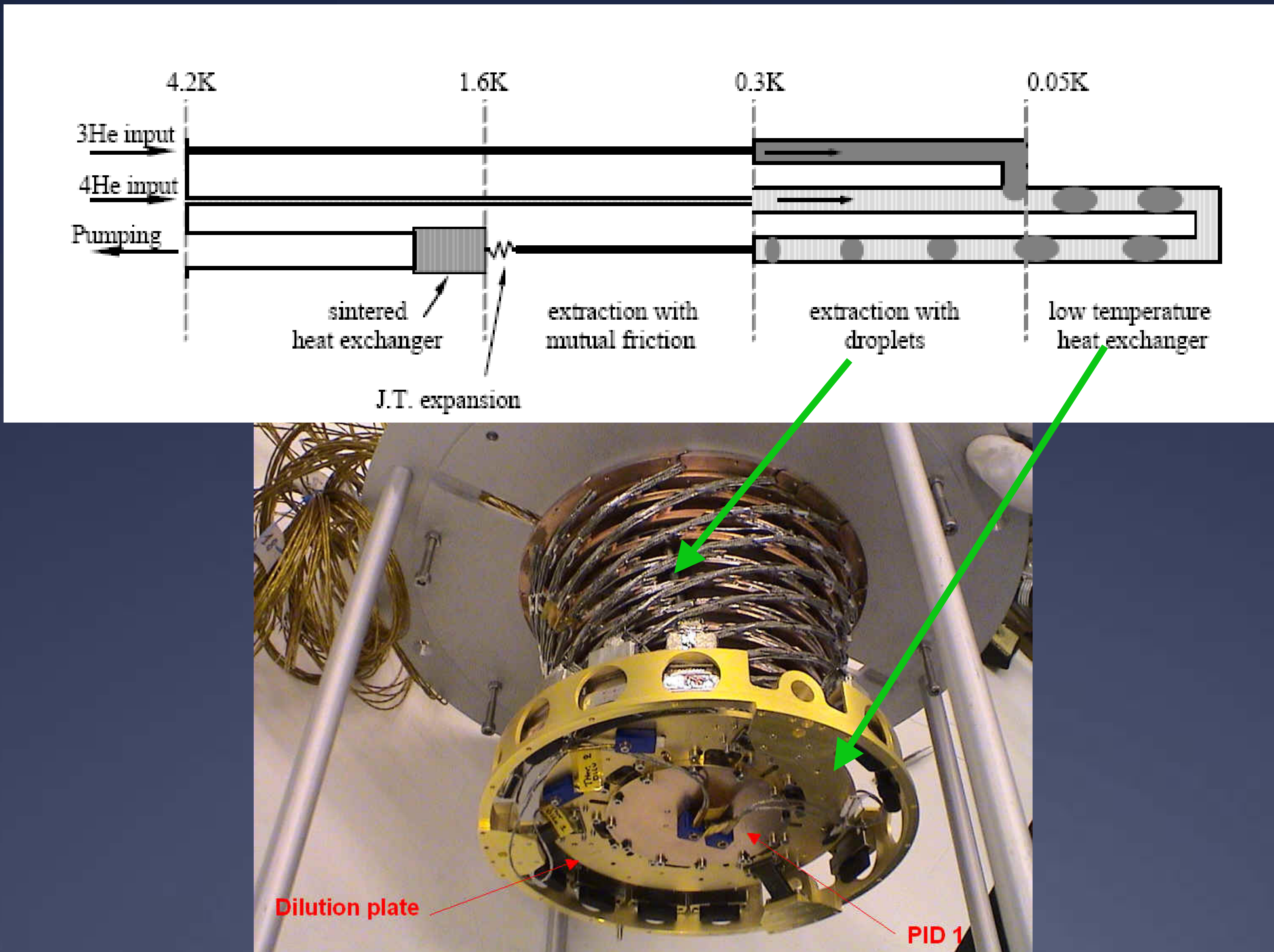


Courtesy Gerard Vermeulen

- Open cycle version is first to work in zero-g
  - Advantages: continuous, stable T, low cold mass
  - Disadvantages: low cooling power and efficiency (0.3 µW at 100 mK, <1%), large warm mass, limited lifetime
- Beginning work on closed cycle version
  - 50 mK, 1µW

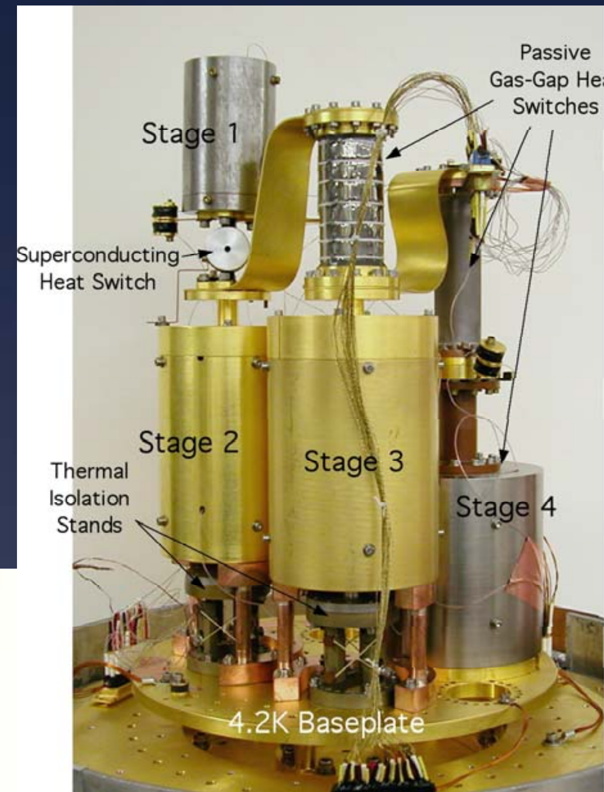


Planck Dilution Refrigerator

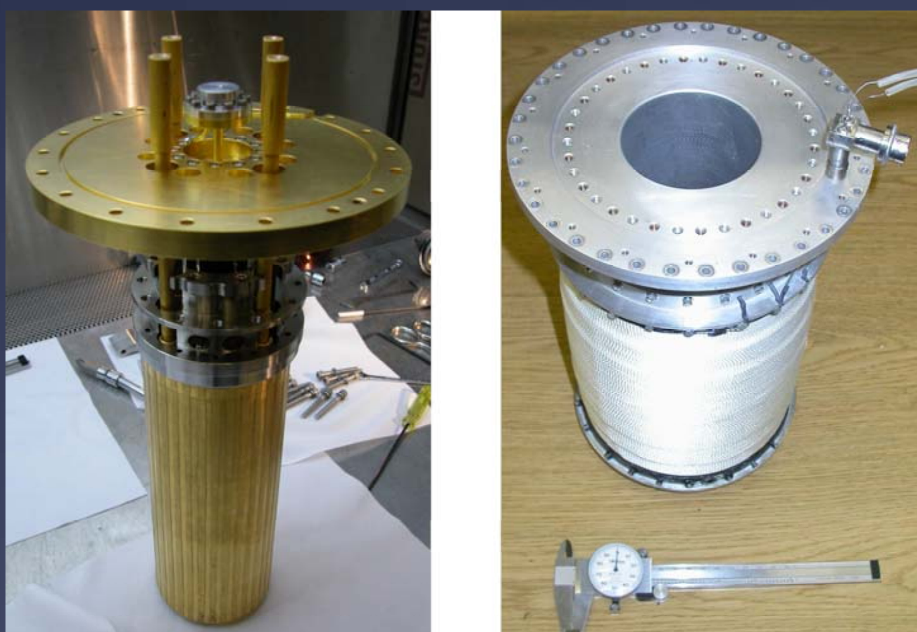


ADR

- Cycle based on magnetocaloric effect
  - Advantages: Very high efficiency, wide operating temperature range, dissipation-less temperature control
  - Disadvantages: inherently single-shot, magnetic fields, relatively large cold mass



Continuous 4-stage



XRS 1-stage ADR on Astro-E/2

2-stage breadboard for Astro-H

Tunnel Junction µ-Coolers

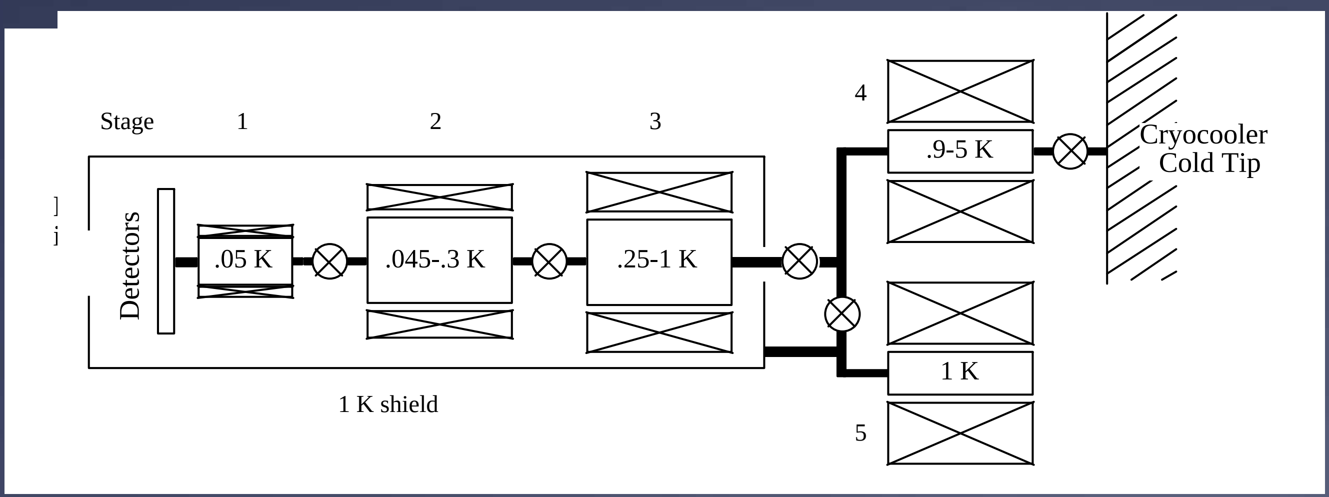
- Cooling produced by tunneling of hottest electrons in an NIS structure
  - Advantages: continuous, direct cooling of detector, potential cooling at 50 mK regime, low mass, simple control
  - Disadvantages: low starting temperature of 300 mK
- Demonstrated 190 mK from 300 mK

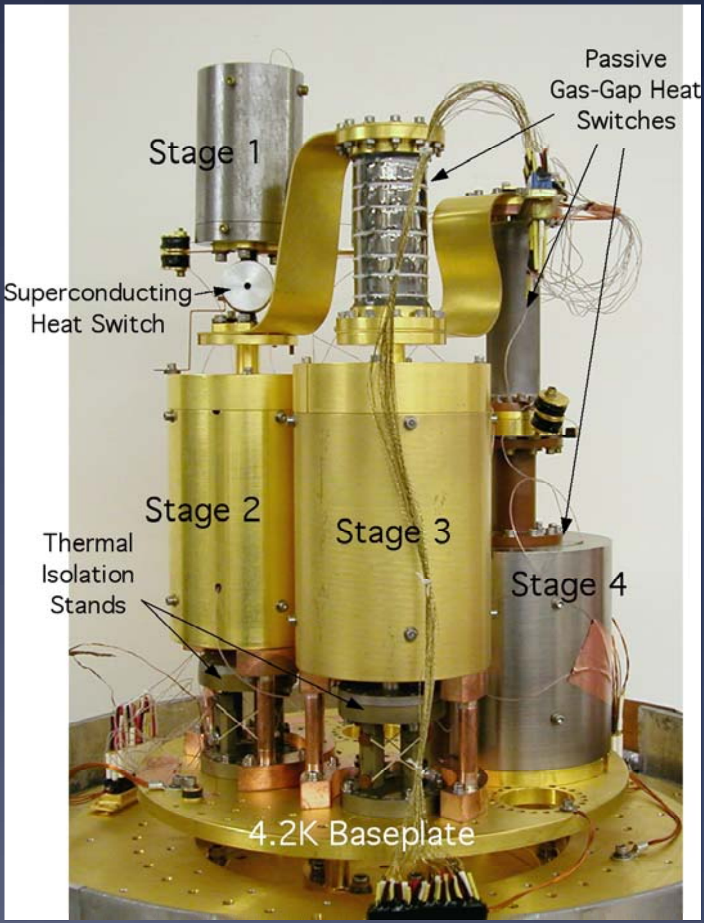
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Courtesy Joel Ullom, NIST

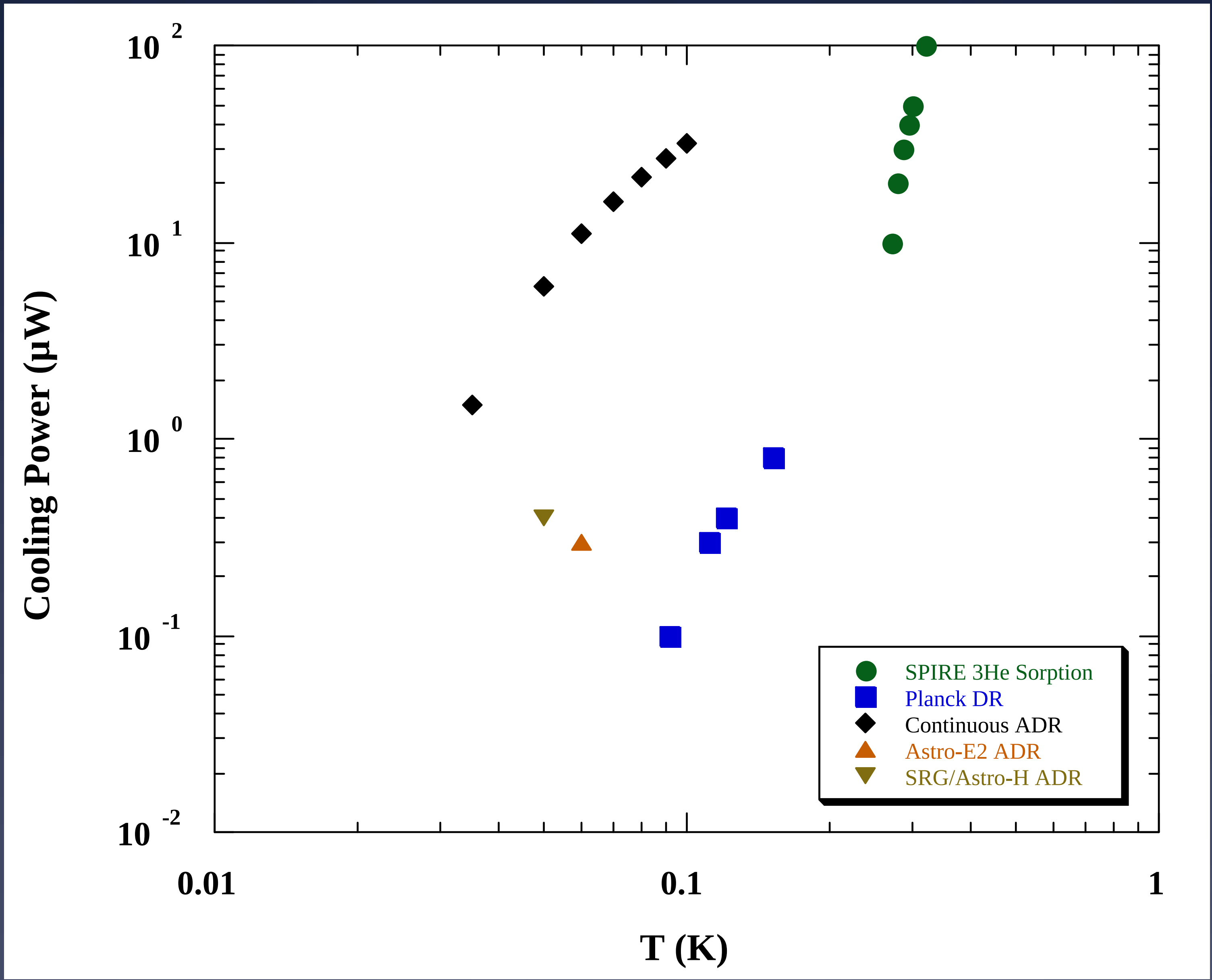
Multi-Stage Coolers

- Benefits of multi-staging
  - Reduce parasitic heat load on coldest stages
    - Reduce size, mass; increase efficiency
  - Extend operating temperature, lower or higher
  - Continuous operation
    - Low T and Intermediate T
    - Higher cooling power per mass
    - Reduce peak heat rejection
- ADR (as an example)
  - Complexity reduced by passive heat switches





Cooling Capabilities



Cooler Summary

Technology	Configuration	Operating Temperature	Cooling Power	Heat Sink	Avg. Heat Rejection	TRL	Heritage
Sorption Cooling	^{3}He, single-stage	300 mK	10 μW	1.5 K	3.7 mW	9	IRTS, Herschel
	^{3}He, two-stage	300 mK, 240 mK		2.5 K		6	
	^{3}He/^{4}He three-stage	2.5 K, 300 mK, 240 mK		5 K		6	
ADR	Single-stage	60 mK	0.3 μW	1.3 K	0.15mW	9	Astro-E2
	Two-stage	50 mK	0.4 μW	1.8 K	0.12 mW	5	SRG, Astro-H
	Continuous, Four-stage	50 mK	6 μW	5 K	3.0 mW	4+	
Dilution Refrigeration	Open-cycle	100 mK	0.1 μW	4.5 K	2.0 mW	7	Planck
NIS Coolers		190 mK		0.3 K			

Advantages/Disadvantages

	3He Sorption	Open Cycle DR	Closed-Cycle DR	1&2-stage ADR	Continuous ADR	NIS µcooler
Base T	-	-	+	+	++	
Heat sink T	-	+	+		++	-
Cooling Power		-	+		++	
Efficiency	-	-	?	+	++	
Continuous		+	+		+	+
Temperature Control				+	-	+
Magnetic Fields	+	+	+	-	-	+
Cold Mass	+	+	+		+	++
Warm Mass		-	?			
Maturity	+	+	-	+	+	-
Cryocooler Compatibility	-	+	?	-	+	-

Summary

- Several cooler options for 50-300 mK range
  - Considerable flight heritage
  - New technologies/architectures nearing TRL 5
- Multi-stage systems
  - Higher cooling power, efficiency
  - Continuous operation for ADR, sorption coolers
- System studies will depend on eventual cooling requirements
  - Detector dissipation
  - Wiring loads (mux'ing)
  - Intermediate temperature stages