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

Courtesy Lionel Duband, CNES

SPUD 3-stage

IRTS Cooler

Herschel SPIRE Instrument
Dilution Refrigerator

- 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

Courtesy Gerard Vermeulen

Planck Cooling System
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

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

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

![Graph showing cooling power vs. temperature (T) for different cooling technologies: SPIRE 3He Sorption, Planck DR, Continuous ADR, Astro-E2 ADR, SRG/Astro-H ADR. The graph plots cooling power (µW) on a logarithmic scale against temperature (T) in Kelvin (K).]
## Cooler Summary

<table>
<thead>
<tr>
<th>Technology</th>
<th>Configuration</th>
<th>Operating Temperature</th>
<th>Cooling Power</th>
<th>Heat Sink</th>
<th>Avg. Heat Rejection</th>
<th>TRL</th>
<th>Heritage</th>
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</thead>
<tbody>
<tr>
<td>Sorption Cooling</td>
<td>$^3$He, single-stage</td>
<td>300 mK</td>
<td>10 µW</td>
<td>1.5 K</td>
<td>3.7 mW</td>
<td>9</td>
<td>IRTS, Herschel</td>
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<td>$^3$He, two-stage</td>
<td>300 mK, 240 mK</td>
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<td>$^3$He/$^4$He three-stage</td>
<td>2.5 K, 300 mK, 240 mK</td>
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<tr>
<td>ADR</td>
<td>Single-stage</td>
<td>60 mK</td>
<td>0.3 µW</td>
<td>1.3 K</td>
<td>0.15 mW</td>
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<td>Astro-E2</td>
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<td>Two-stage</td>
<td>50 mK</td>
<td>0.4 µW</td>
<td>1.8 K</td>
<td>0.12 mW</td>
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<td>SRG, Astro-H</td>
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<td>Continuous, Four-stage</td>
<td>50 mK</td>
<td>6 µW</td>
<td>5 K</td>
<td>3.0 mW</td>
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<tr>
<td>Dilution Refrigeration</td>
<td>Open-cycle</td>
<td>100 mK</td>
<td>0.1 µW</td>
<td>4.5 K</td>
<td>2.0 mW</td>
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<td>NIS Coolers</td>
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<td>190 mK</td>
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<td>0.3 K</td>
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<td>3He Sorption</td>
<td>Open Cycle DR</td>
<td>Closed-Cycle DR</td>
<td>1&amp;2-stage ADR</td>
<td>Continuous ADR</td>
<td>NIS µcooler</td>
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<td><strong>Base T</strong></td>
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<td><strong>Cooling Power</strong></td>
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<td><strong>Efficiency</strong></td>
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</table>
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