Cryostat Options and Heat Loads

Astronomy 525

Lecture 25

Outline

- Temperature Requirements
- Cooling System Options
- Cryogenic Capacities
- Cryostat examples
- Heat Loads
  - Radiation
    - Shields
    - Window

Temperature Requirements

- Bolometers: minimize heat capacity and thermal conductance ⇒ smaller the better
- Photodetective devices: Dark current << photocurrent
  - The generation of dark current is an excitation process with

$$i_d \propto \exp\left(-\frac{\Delta E}{kT}\right)$$

Some rough operating temperatures for a selected sample of detectors are given on the right.

Material	λ_c(μm)	T(K)
Si CCD	1.0	120
HgCdTe	2.5	< 65
InSb	5.0	< 35
Si:As	26.	< 8
Ge:Ga	120	< 2

Temperature Reqm’ts (cont’d)

- Dewar photon power, or “background” << signal power, or photocurrent
  - The radiation from the structures and optics surrounding the detector should be much less than the signal.

$$N_B(ph/\sec) = \int_{\nu_{\min}}^{\nu_{\max}} \frac{\pi B_\nu(T) A_d}{h\nu}\, d\nu \ll N_S$$

N_S = signal photon rate on detector
A_d = detector area
ν_{min}, ν_{max} = limits of detector response

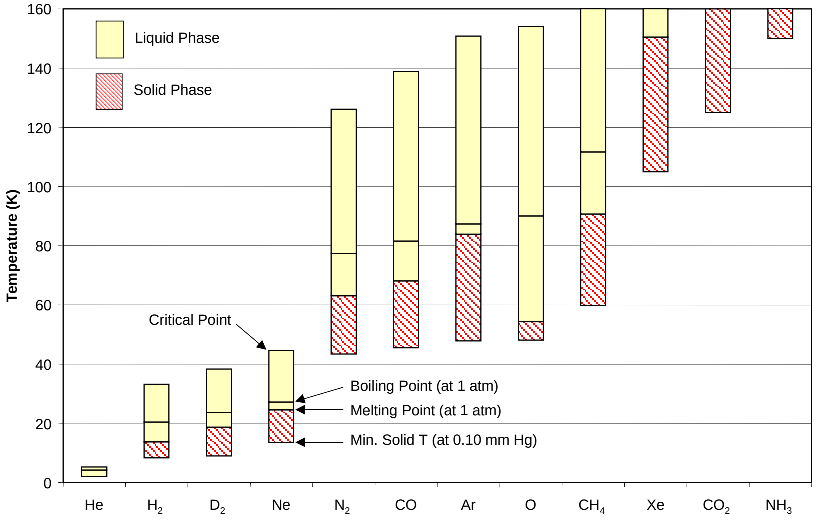
Cooling System Considerations

- Cooling capacity
- Operating temperature
- Desired “hold-time” (lifetime)
- Weight, volume, and power
- Device dimensions
- Cool down time
- Operating environment

Cooling System Options

	Range (K)	Capacity (W)
Open-cycle		
Liquid or solid cryogens	4.2 - 200	Unlimited
High pressure gas expansion	4.2 - 90	< 20
Closed-cycle system		
Mechanical refrigerators	4 - 77	< 15
^{3}He refrigerators	0.22 – 0.3	< 0.001
ADR		
Adiabatic Demag. Refrigerators	0.05	<0.000001
Thermoelectric coolers		
Single stage	230 - 300	0.1 - 100
Multi-stage	145 - 230	0.01 - 1.0
Passive radiators		
Space environments	35 - 200	1 to 10

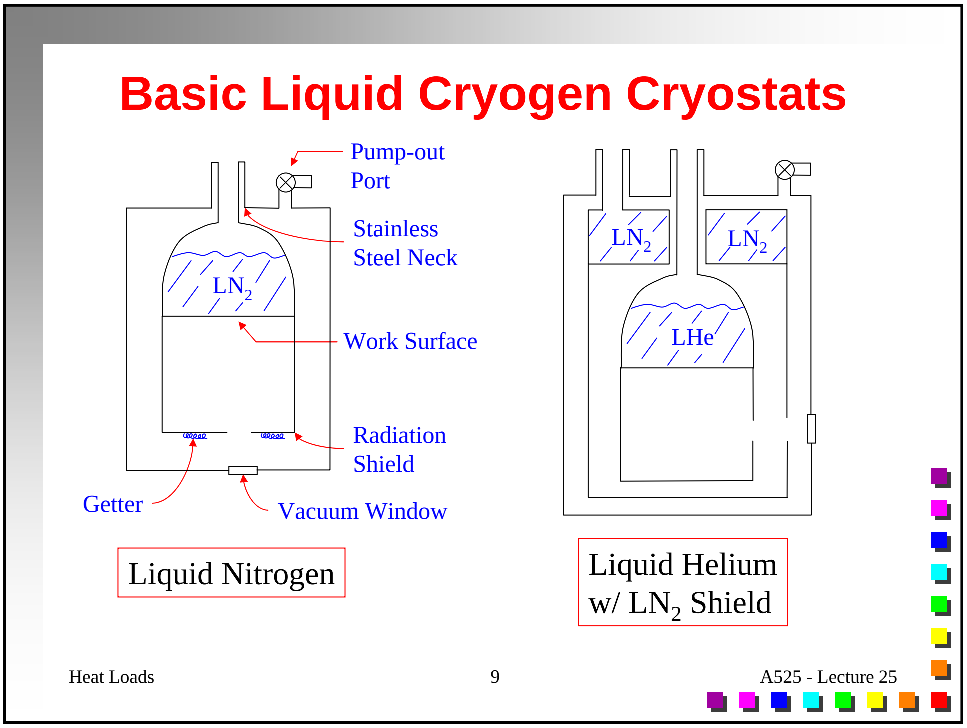
Expendable Coolant Operating Ranges



Cryogen Properties

Cyro-gen	Melting Point at 0.1mm Hg	Melting Point at 1 atm	Boiling Point at 1 atm	Critical Temp.	Critical Pressure	Liquid Density at bp	Vapor Pressure Solid at mp	Heat of Vapor at bp	Heat of Fusion at mp	Density of Solid	12 month holdtime for liquid with 100 mW load	
	(K)	(K)	(K)	(K)	(atm)	(kg/l)	(mm Hg)	(J/g)	(J/g)	(kg/l)	Mass(kg)	Vol. (l)
He	2.0	2.0	4.2	5.2	2.3	0.125	--	20.5	4.18	0.129	153.94	1231.52
H2	8.3	13.7	20.4	33.2	13.0	0.071	54	448.0	58.15	0.087	7.04	99.21
D2	9.0	18.7	23.6	38.3	16.2	0.173	12.8	286.0	50.00		11.03	63.78
Ne	13.5	24.5	27.2	44.5	26.8	1.200	323	87.0	16.72	1.490	36.27	30.23
N2	43.4	63.1	77.4	126.1	33.5	0.808	96.5	199.0	25.52	1.020	15.86	19.63
CO	45.5	68.1	81.6	138.8	35.0	0.812	--	213.0	29.27	1.030	14.82	18.25
Ar	47.8	83.9	87.4	150.8	48.0	1.391	516	162.7	28.05	1.670	19.40	13.94
O2	48.1	54.3	90.1	154.1	50.1	1.140	2	212.5	13.80	1.359	14.85	13.03
CH4	59.8	90.7	111.7	190.5	45.8	0.425	71	581.0	60.25	0.520	5.43	12.78
Xe	105.0	150.5	165.3	290.0	58.0	3.100	615	96.3	119.10	3.540	32.79	10.58
CO2	125.0	217.5	194.6	304.5	73.0	1.510	--	574.0	71.60	1.700	5.50	3.64
NH3	150.0	195.4	239.8	405.0	111.2	0.683	45	1363.0	--	0.800	2.32	3.39

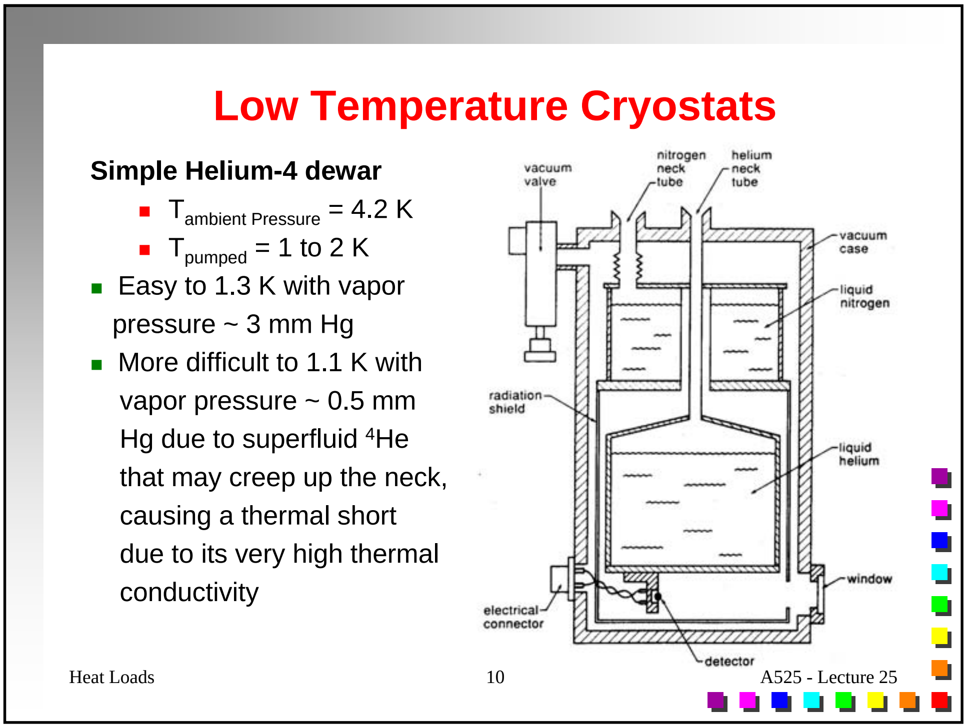
See Infrared & Electro-Optical Handbook, Volume 3, Chapter 6 for more details on cryogen properties, mechanical coolers, thermoelectric coolers, and radiative cooling.



Basic Liquid Cryogen Cryostats

Liquid Nitrogen

Liquid Helium w/ LN_2 Shield



Low Temperature Cryostats

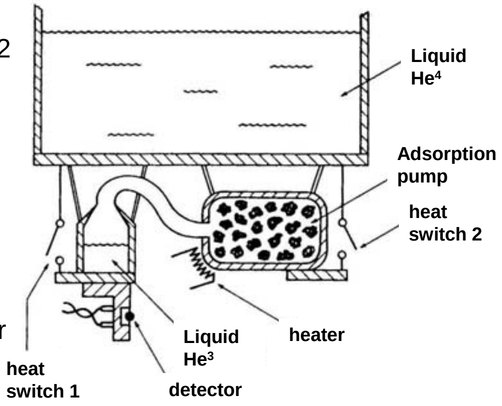
Simple Helium-4 dewar

- $T_{\text{ambient Pressure}} = 4.2$ K
- $T_{\text{pumped}} = 1$ to 2 K
- Easy to 1.3 K with vapor pressure ~ 3 mm Hg
- More difficult to 1.1 K with vapor pressure ~ 0.5 mm Hg due to superfluid ^{4}He that may creep up the neck, causing a thermal short due to its very high thermal conductivity

Low Temperature Cryostats

Helium-3 closed cycle refrigerator

- Heat switch1 closed, HS2 open, heater on:
  ⇒ condensed ^{3}He
- Heat switch 1 open, HS2 closed, heater off:
  ⇒ pumps ^{3}He
  ⇒ $T \rightarrow 0.3$ K
- The pumping mechanism is the affinity of carbon for ^{3}He



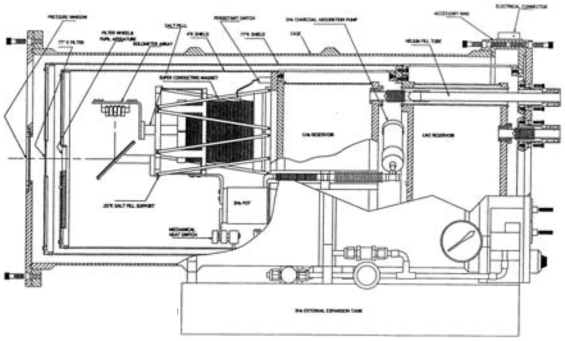
Dual Stage ^{3}He Refrigerator

- First stage acts as a thermal guard for the inner stage
- Temperatures as low as 220 mK attainable
- This model is used in ZEUS at Cornell
- Manufactured by Chase Instruments

Low Temperature Cryostats

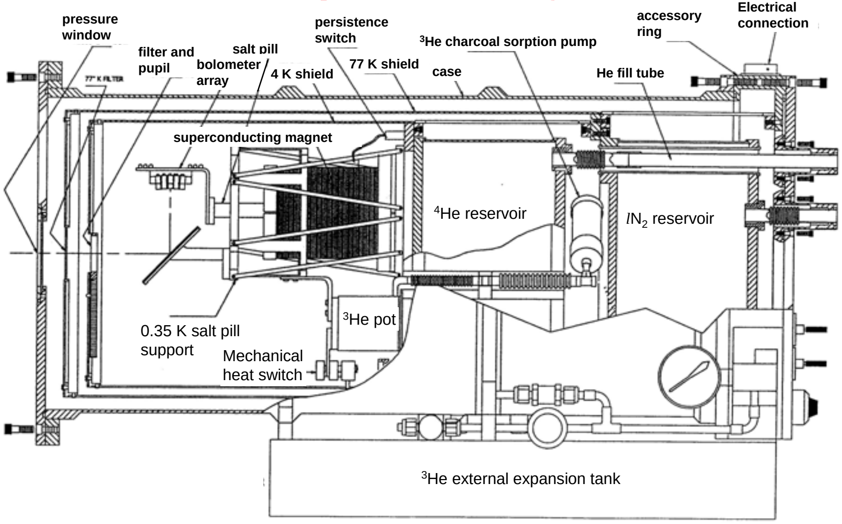
Adiabatic demagnetization refrigerator (ADR)

- Multistage system
- Salt pill holds > 40 hours
- Used in SPIFI

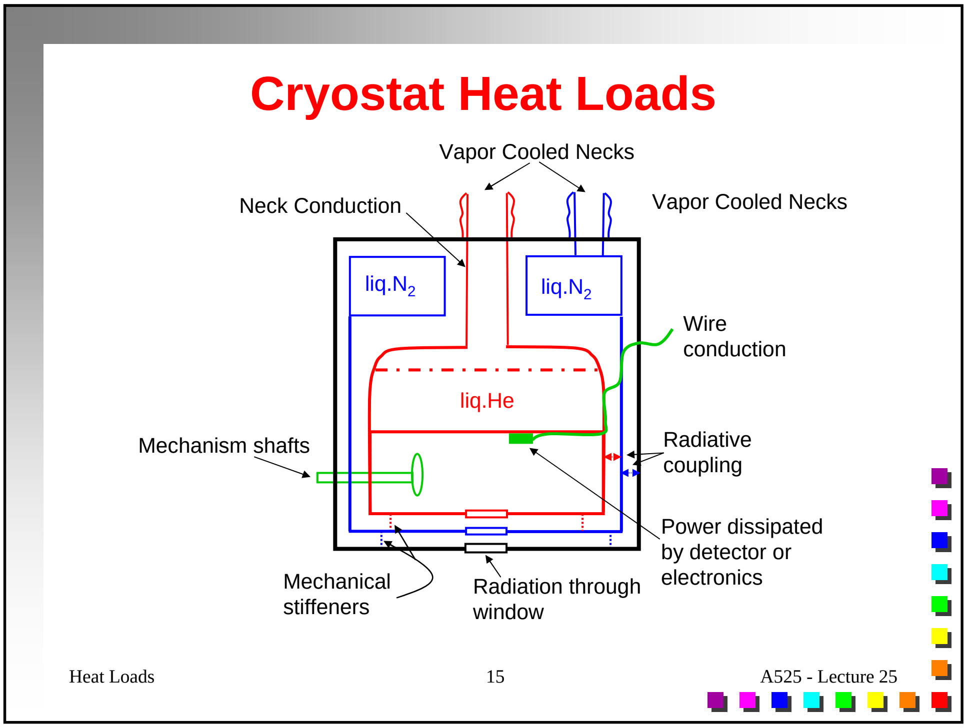


- Paramagnetic salt (ferric ammonium alum) cooled to 1.5 K with ^{4}He cryostat
- ^{3}He condenses, superconducting magnet energized to align magnetic domains, pill cooled again to 1.5 K (B fields are around 4 Tesla!)
- Heat switch between ^{4}He 1.5 K reservoir and ^{3}He pot and salt pill opened
- Current in magnet dissipated ⇒ salt pill domains randomize ⇒ T → 50 mK

Low Temperature Cryostats



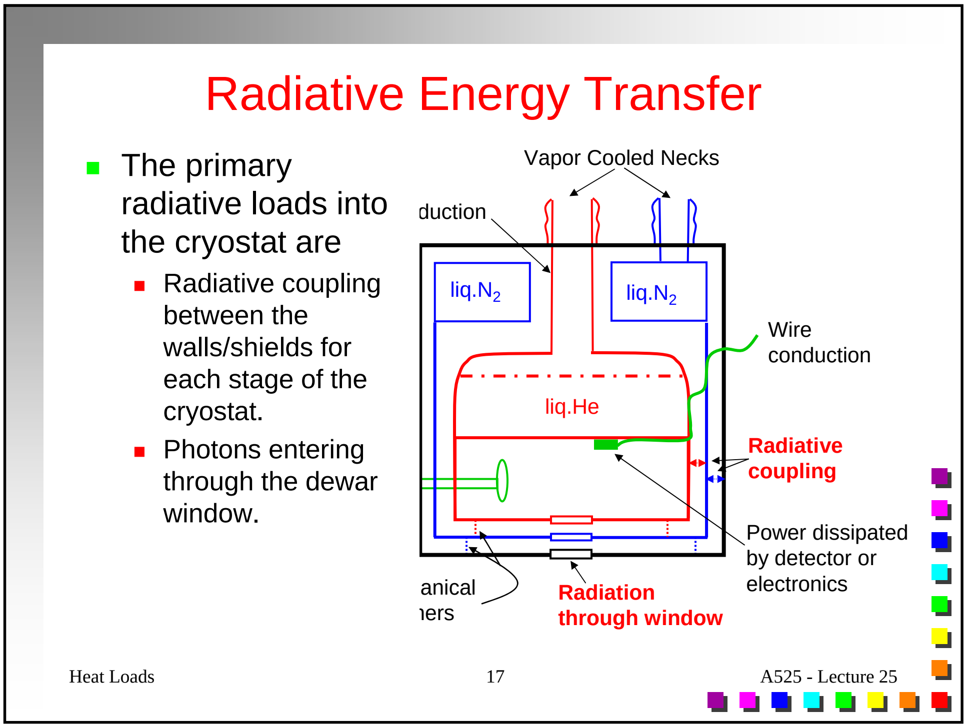
Cryostat Heat Loads



Cryogen Boil-off Rates

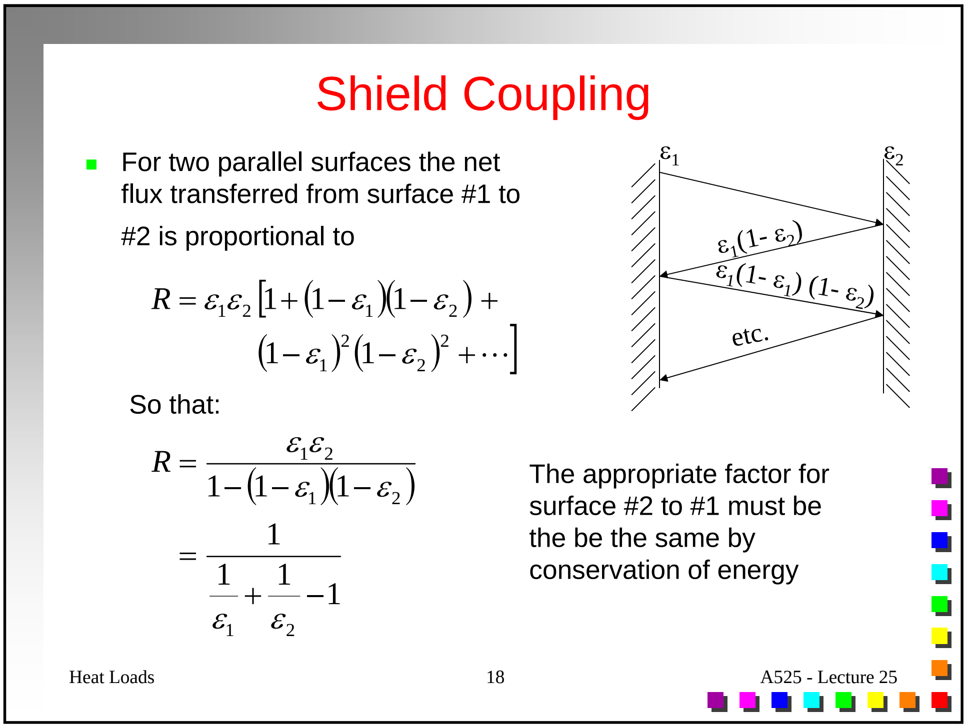
		Cryogen per Watt-Hour		
Cryogen	T	Mass	Volume	Power for 1 liter/day
	(K)	(g)	(liters)	(mW)
LHe	4	176	1.4	30
LH2	20	8	0.11	380
LN2	77	18	0.022	1900
SH2	7-10	7	0.079	530

- ❑ Per liter, liquid nitrogen has a very good cooling capacity – good for ground based systems
- ❑ Per gram, liquid and solid hydrogen are the best! – good for space based applications



Radiative Energy Transfer

- The primary radiative loads into the cryostat are
  - Radiative coupling between the walls/shields for each stage of the cryostat.
  - Photons entering through the dewar window.



Shield Coupling

- For two parallel surfaces the net flux transferred from surface #1 to #2 is proportional to

$$R = \varepsilon_1\varepsilon_2\left[1 + (1-\varepsilon_1)(1-\varepsilon_2) + (1-\varepsilon_1)^2(1-\varepsilon_2)^2 + \cdots\right]$$

So that:

$$R = \frac{\varepsilon_1\varepsilon_2}{1-(1-\varepsilon_1)(1-\varepsilon_2)} = \frac{1}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1}$$

The appropriate factor for surface #2 to #1 must be the be the same by conservation of energy

Shield Coupling (cont'd)

- The net transfer of energy between the two surfaces of area A is

$$Q_{rad} = \frac{A}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \sigma \left(T_1^4 - T_2^4 \right)$$

- Clearly Q_{rad} is smallest when $\varepsilon_1, \varepsilon_2 << 1$.
- How large is the radiative coupling? Taking $T_1 = 300$ K, $T_2 = 4.2$ K, and with $\sigma = 5.67\times10^{-8}$ W/m^2/K^4 gives:

$$Q_{rad} = \frac{459A}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \text{ W/m}^2 \xrightarrow[\varepsilon_1,\, \varepsilon_2 = \varepsilon << 1]{} 230A\varepsilon \text{ W/m}^2$$

Shield Coupling (cont'd)

- For a small dewar the surface area might be ~ 0.2 m^2. Then with $\varepsilon_1 = \varepsilon_2 = \varepsilon << 1$

$$Q_{rad} = 46\varepsilon \quad \text{Watts}$$

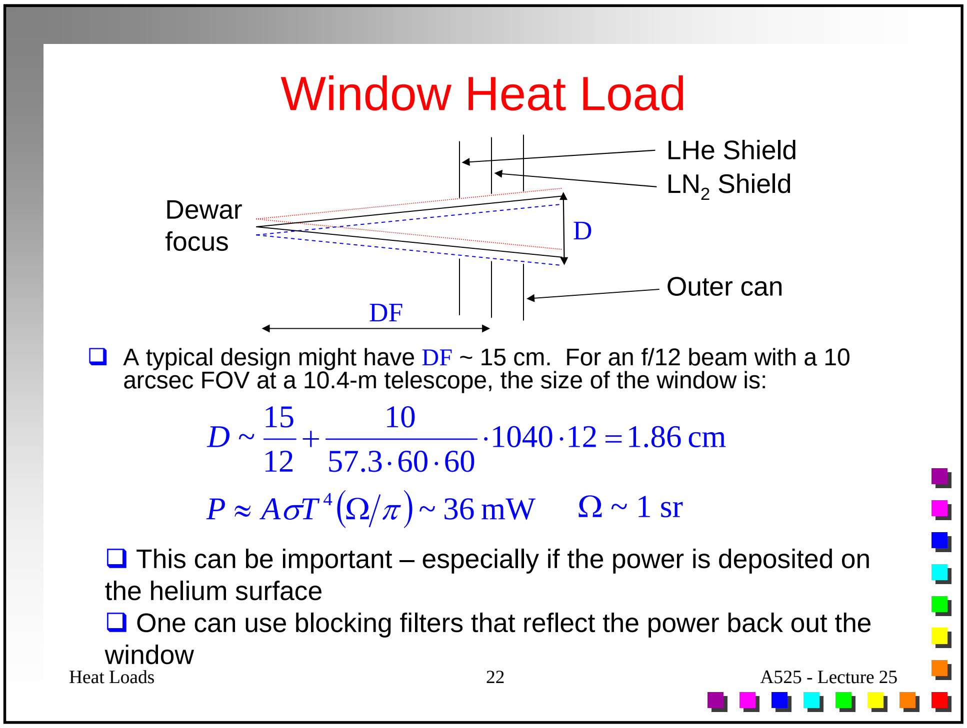
  - For $Q_{rad} \leq 30$ mW (one liter of LHe/day), $\varepsilon \leq 6.5\times10^{-4}$
  - This is extremely difficult, which is why a colder radiation shield is used around the LHe reservoir.
- If the coupling is between 300 K and 78 K (LN_2), the equation for Q_{rad} is essentially the same.
  - For $Q_{rad} \leq 1.9$ W (one liter of LN_2/day), $\varepsilon \leq 0.042$, which is much more reasonable.

Shield Coupling (cont'd)

- The radiative coupling between the LN_2 and LHe cans is

$$Q_{rad} = 0.21\varepsilon \quad \text{Watts}$$

  - For $Q_{rad} \le 30$ mW (one liter of LHe/day), $\varepsilon \le 0.14$
  - This contribution to the heat input to the LHe reservoir can be made small.



Window Heat Load

❑ A typical design might have DF ~ 15 cm. For an f/12 beam with a 10 arcsec FOV at a 10.4-m telescope, the size of the window is:

$$D \sim \frac{15}{12} + \frac{10}{57.3 \cdot 60 \cdot 60} \cdot 1040 \cdot 12 = 1.86 \text{ cm}$$

$$P \approx A\sigma T^4 (\Omega/\pi) \sim 36 \text{ mW} \qquad \Omega \sim 1 \text{ sr}$$

❑ This can be important – especially if the power is deposited on the helium surface

❑ One can use blocking filters that reflect the power back out the window