SPIRE-P Mapmaking, Data Processing and Future Developments

Matt Griffin

Broadband Photometer Flux Calibration

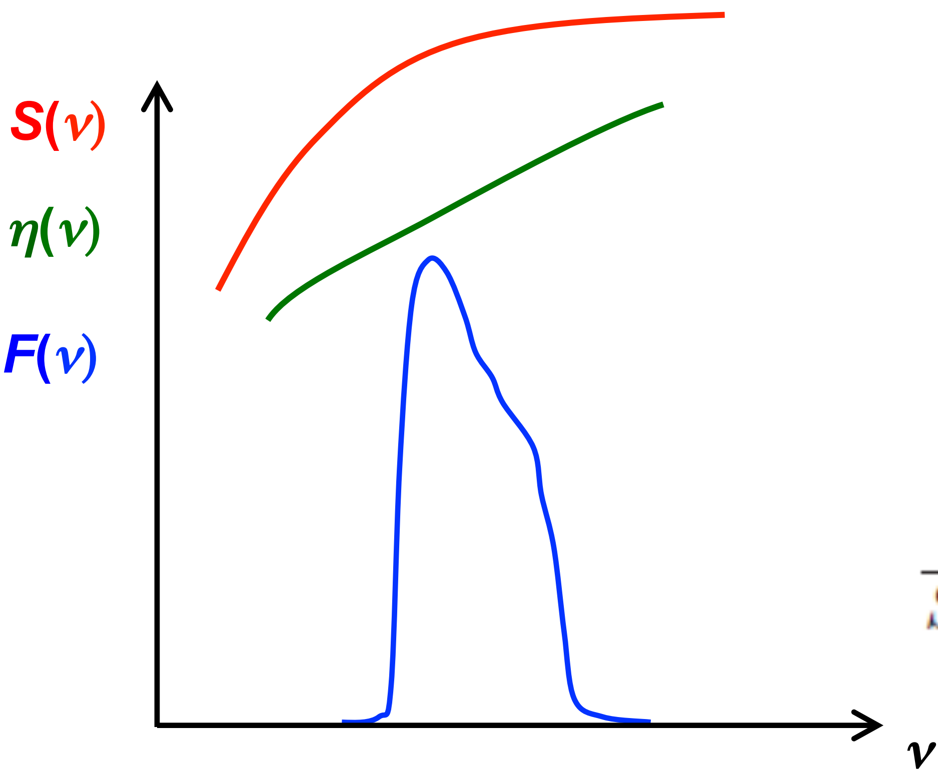
Matt Griffin

Chris North, Bernhard Schulz, Alex Amaral-Rogers, George Bendo, Jamie Bock, Alex Conley, Darren Dowell, Marc Ferlet, Jason Glenn, Tanya Lim, Chris Pearson, Michael Pohlen, Bruce Sibthorpe, Locke Spencer, Bruce Swinyard, IVan Valtchanov

Point Source Calibration

Measured Flux Density for a Point Source

- Detector absorbed power ∝ flux density, weighted by aperture efficiency and SRF, integrated across the band



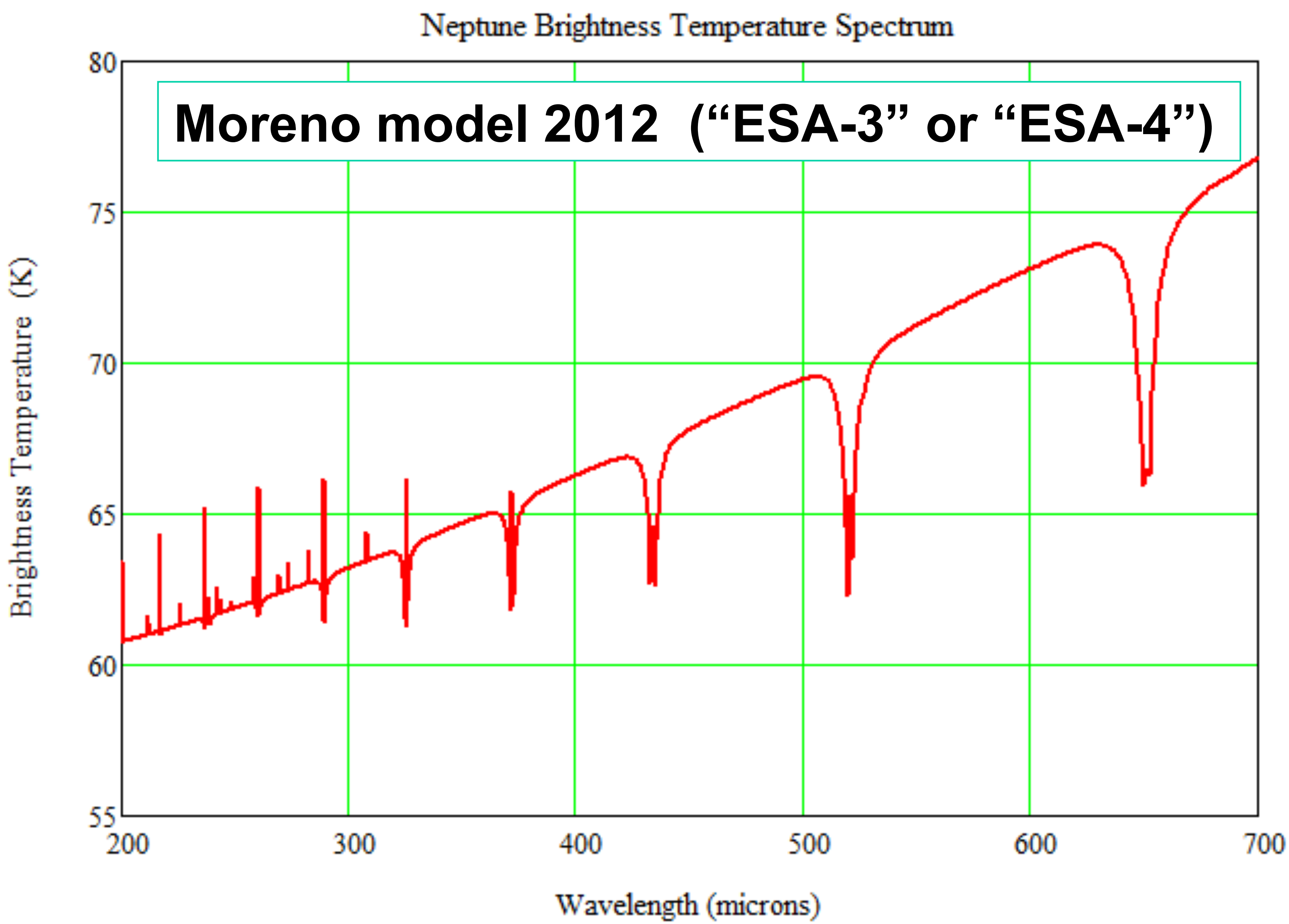
$S(\nu)$ = source spectrum

$F(\nu)$ = instrument SRF

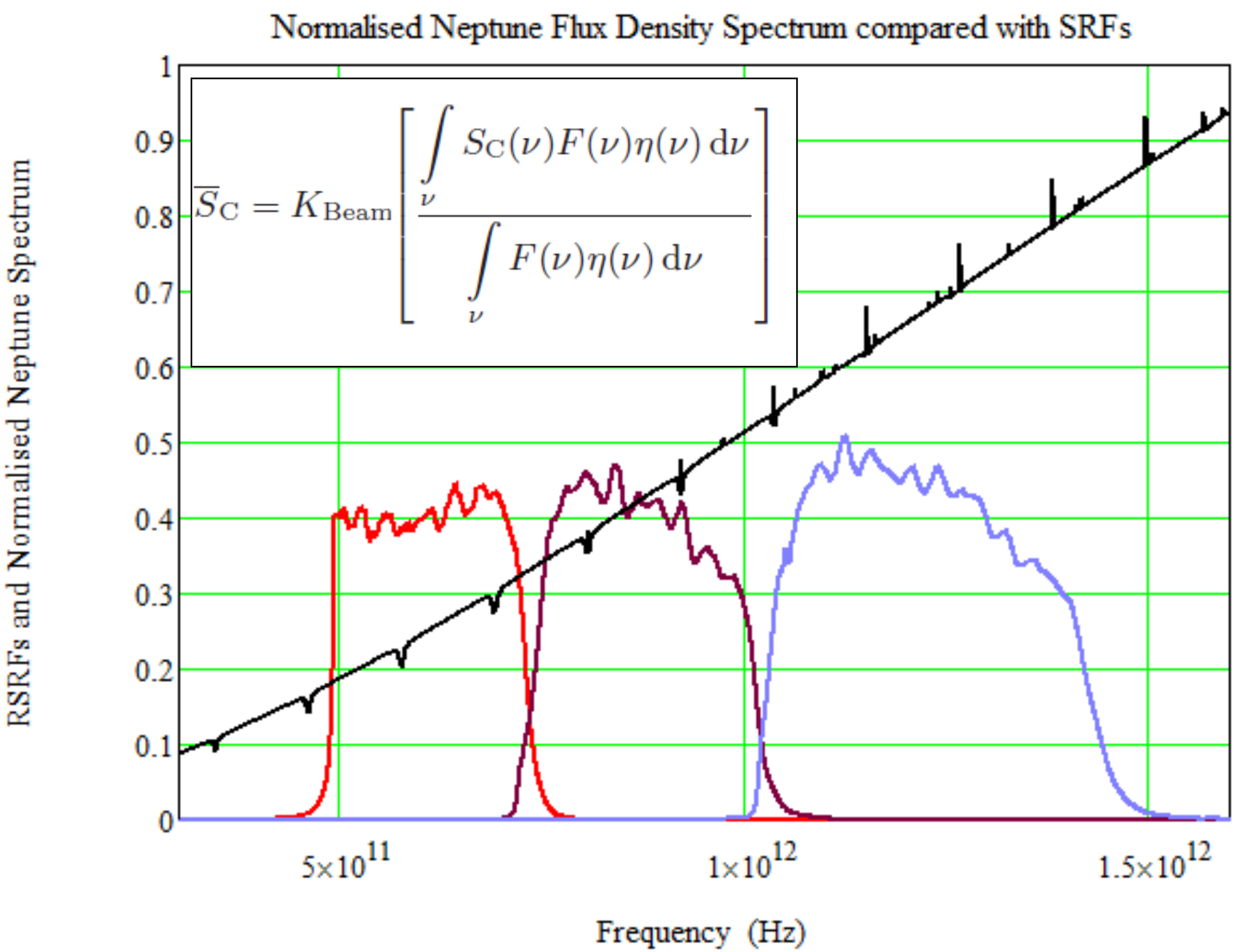
$\eta(\nu)$ = aperture efficiency

$$\overline{S}_{\mathrm{Meas}} = \frac{\int_{\nu} S(\nu)F(\nu)\eta(\nu)\,\mathrm{d}\nu}{\int_{\nu} F(\nu)\eta(\nu)\,\mathrm{d}\nu}$$

Primary Calibrator for SPIRE: Neptune
Brightness Temperature Spectrum



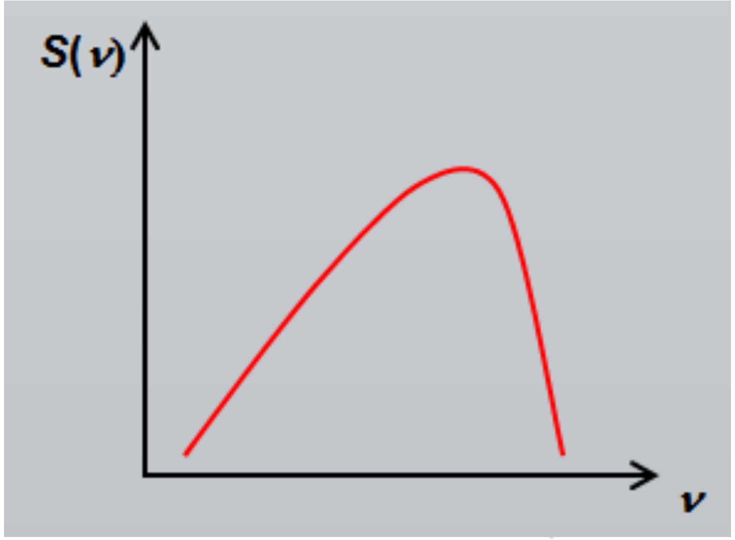
Neptune Spectrum and SPIRE Bands



Source Spectrum

- **Spectrum characterised by value at some frequency and a shape function**

$$S(\nu) = S(\nu_0) \cdot f(\nu, \nu_0)$$



- **Examples:**

Power law with index α :

$$f(\alpha, \nu, \nu_0) = \left(\frac{\nu}{\nu_0}\right)^{\alpha}$$

Grey body (*T*, β) :

$$f(T, \beta, \nu, \nu_0) = \frac{\mathcal{B}(\nu, T)}{\mathcal{B}(\nu_0, T)} \left(\frac{\nu}{\nu_0}\right)^{\beta}$$

Monochromatic Flux Density at ν_o

- **Measured SRF-weighted flux density is converted to monochromatic flux density at standard frequency ν_o**

$$S(\nu_0) = K_{\mathrm{MonP}}(f, \nu_0) \cdot \overline{S}_{\mathrm{Meas}}$$

- **A source spectrum must be assumed**

- **Power law case**

$$K_{\mathrm{MonP}}(\alpha, \nu_0) = \frac{\int_{\nu} F(\nu)\eta(\nu)\,\mathrm{d}\nu}{\int_{\nu} \left(\frac{\nu}{\nu_0}\right)^{\alpha} F(\nu)\eta(\nu)\,\mathrm{d}\nu}$$

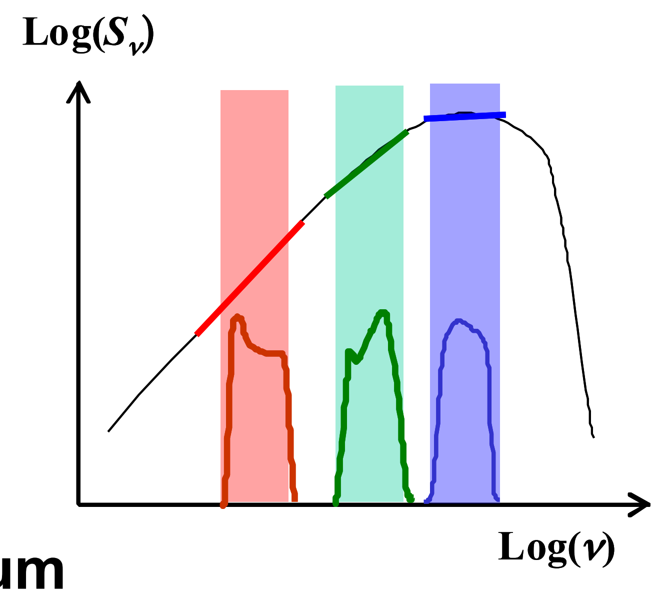
  - **Standard: adopt α_o = –1, i.e., ν *S*(ν) = constant**
  - **Pipeline produces**

$$S_{\mathrm{Pip}}(\alpha_0, \nu_0) = K_{\mathrm{MonP}}(\alpha_0, \nu_0) \cdot \overline{S}_{\mathrm{Meas}}$$

Colour Correction

- **Pipeline output = monochromatic flux density for α_s = –1**
- **Colour correction factor K_{ColP} must be applied**

$$S(\nu_0) = K_{\mathrm{ColP}}(f, \alpha_0, \nu_0) \cdot S_{\mathrm{Pip}}(\nu_0)$$



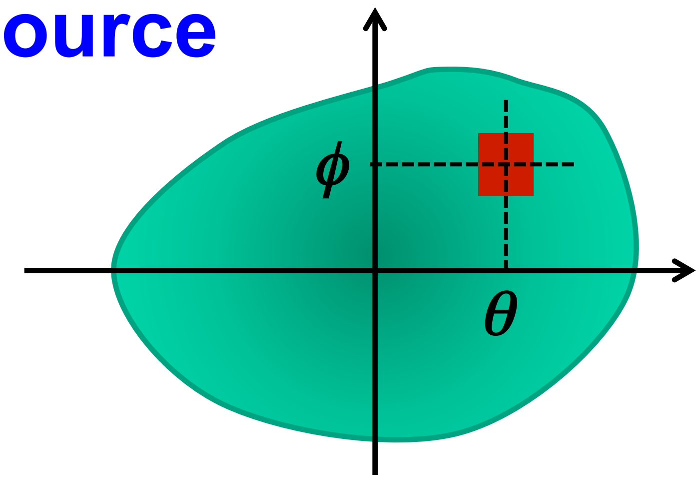
- **Depends on "actual" source spectrum**

E.g., for grey body assumption:

$$K_{\mathrm{ColP}}(T, \beta, \alpha_0, \nu_0) = \frac{\nu_0^{3+\beta-\alpha_0}}{e^{h\nu_0/k_BT} - 1} \left[\frac{\int\limits_\nu \nu^{\alpha_0} F(\nu)\eta(\nu)\,\mathrm{d}\nu}{\int\limits_\nu \left(\frac{\nu^{3+\beta}}{e^{h\nu/k_BT} - 1}\right) F(\nu)\eta(\nu)\,\mathrm{d}\nu} \right]$$

Extended Source Calibration

Extended Source



- **Small region at off-axis angles (θ, ϕ)**
  - **Brightness** $I(\nu, \theta, \phi)$
  - **Size** $\mathrm{d}\theta\,\mathrm{d}\phi$
  - **Flux density** $\mathrm{d}S(\nu, \theta, \phi) = I(\nu, \theta, \phi)\,\mathrm{d}\theta\,\mathrm{d}\phi$
  - **Normalised beam response** $B(\nu, \theta, \phi)$

- **Measured flux density for the small region:**

$$\mathrm{d}\overline{S}_{\mathrm{Meas}}(\theta, \phi) = \frac{\int\limits_{\nu} I(\nu, \theta, \phi) B(\nu, \theta, \phi)\,\mathrm{d}\theta\,\mathrm{d}\phi\, F(\nu)\eta(\nu)\,\mathrm{d}\nu}{\int\limits_{\nu} F(\nu)\eta(\nu)\,\mathrm{d}\nu}$$

Extended Source

- **Integrate over beam for total measured flux density**

$$\overline{S}_{\mathrm{Meas}} = \frac{\displaystyle\int_{\nu} y(\nu) F(\nu) \eta(\nu)\, \mathrm{d}\nu}{\displaystyle\int_{\nu} F(\nu) \eta(\nu)\, \mathrm{d}\nu}$$

$$y(\nu) = \iint_{\mathrm{Beam}} I(\nu, \theta, \phi) B(\nu, \theta, \phi)\, \mathrm{d}\theta\, \mathrm{d}\phi$$

- **Same as point source case except $S(\nu)$ replaced by sky intensity integrated over the beam**

Some Simplifying Assumptions

- Source characterised by spectral and spatial shape functions
- Spatial distribution is circularly symmetric

$$I(\nu,\theta) = I(\nu_0,0)\cdot f(\nu,\nu_0)\cdot g(\theta,\theta_0)$$

  - Spectral shape: e.g. power law, grey body . . .
  - Spatial shape: e.g., Gaussian, power law, uniform (*g* = 1) . . .
- Beam profile is also circularly symmetric: $P(\nu,\theta)$
- Deriving peak surface brightness from measured flux density:

$$I(\nu_0,0) = K_{\mathrm{MonE}}(f,g,\nu_0)\cdot \overline{S}_{\mathrm{Meas}}$$

- K_{MonE} converts flux density (Jy/beam) to surface brightness (Jy/pixel or MJy/sr)

Case of Uniform Extended Emission: $g(\theta, \theta_o) = 1$

- Integral over the beam ≡ frequency-dependent beam solid angle:

$\boxed{\text{Jy/beam} \rightarrow \text{surface brightness}}$

$$K_{\text{Uniform}}(f, \nu_0) = \frac{\int_\nu F(\nu)\eta(\nu)\,\mathrm{d}\nu}{\Omega(\nu_0)\int_\nu \Omega_{\text{norm}}(\nu,\nu_0) f(\nu,\nu_0) F(\nu)\eta(\nu)\,\mathrm{d}\nu}$$

$$\Omega_{\text{norm}}(\nu, \nu_0) = \Omega(\nu)/\Omega(\nu_0)$$

- This depends on how the beam solid angle varies across the band
  - Not measured directly
  - Must be modeled from band-averaged profile as measured on a point source with a known spectrum

Conversion from Point Source Pipeline to Extended Emission Pipeline

- **Extended pipeline surface brightness, which assumes a fully extended source with spectral index –1 :**

$$I_{\mathrm{PipE}}(\alpha_0, \nu_0, \theta = 0) = \left[\frac{K_{\mathrm{Uniform}}(\alpha_0, \nu_0)}{K_{\mathrm{MonP}}(\alpha_0, \nu_0)} \right] S_{\mathrm{Pip}}$$

- **Conversion to actual source peak intensity:**

$$I(\nu_0, 0) = K_{\mathrm{ColE}}(f, g, \alpha_0, \nu_0) \cdot I_{\mathrm{PipE}}(\alpha_0, \nu_0, \theta = 0)$$

$$K_{\mathrm{ColE}}(f, g, \alpha_0, \nu_0) = \frac{K_{\mathrm{MonE}}(f, g, \nu_0)}{K_{\mathrm{Uniform}}(\alpha_0, \nu_0)}$$

- **K_{ColE} converts to peak intensity of an extended source with brightness profile $g(\theta, \theta_o)$ and spectrum $f(\nu, \nu_o)$**

Beam Profile and Aperture Efficiency

Conversion from a Point Source Pipeline to Extended Emission Case

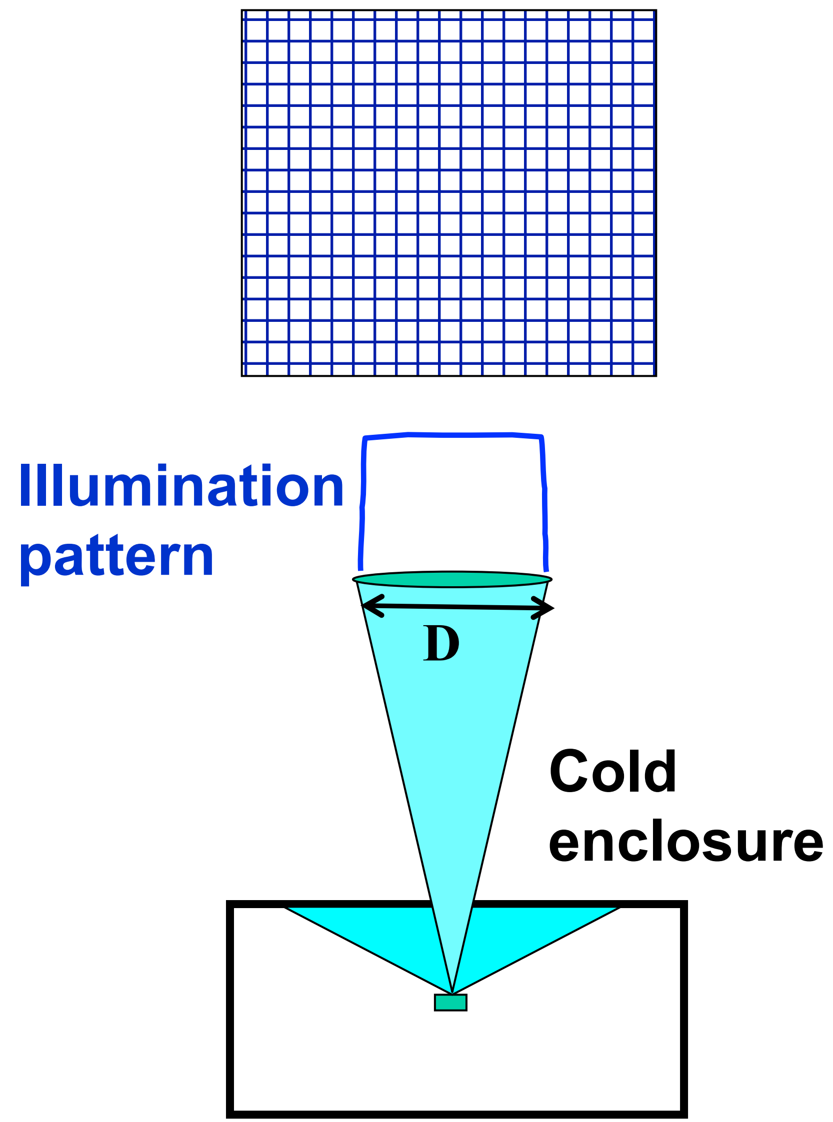
- Treatment above is very general
  - Beam properties (aperture efficiency and beam profile) are allowed to vary across the band
  - Source spectral and spatial distributions can also vary

- Details depend on detector and optical system architecture

- Two common cases
  - Absorber-coupling with $0.5\lambda/D$ square pixels
  - Antenna-coupling with $2\lambda/D$ circular feedhorns

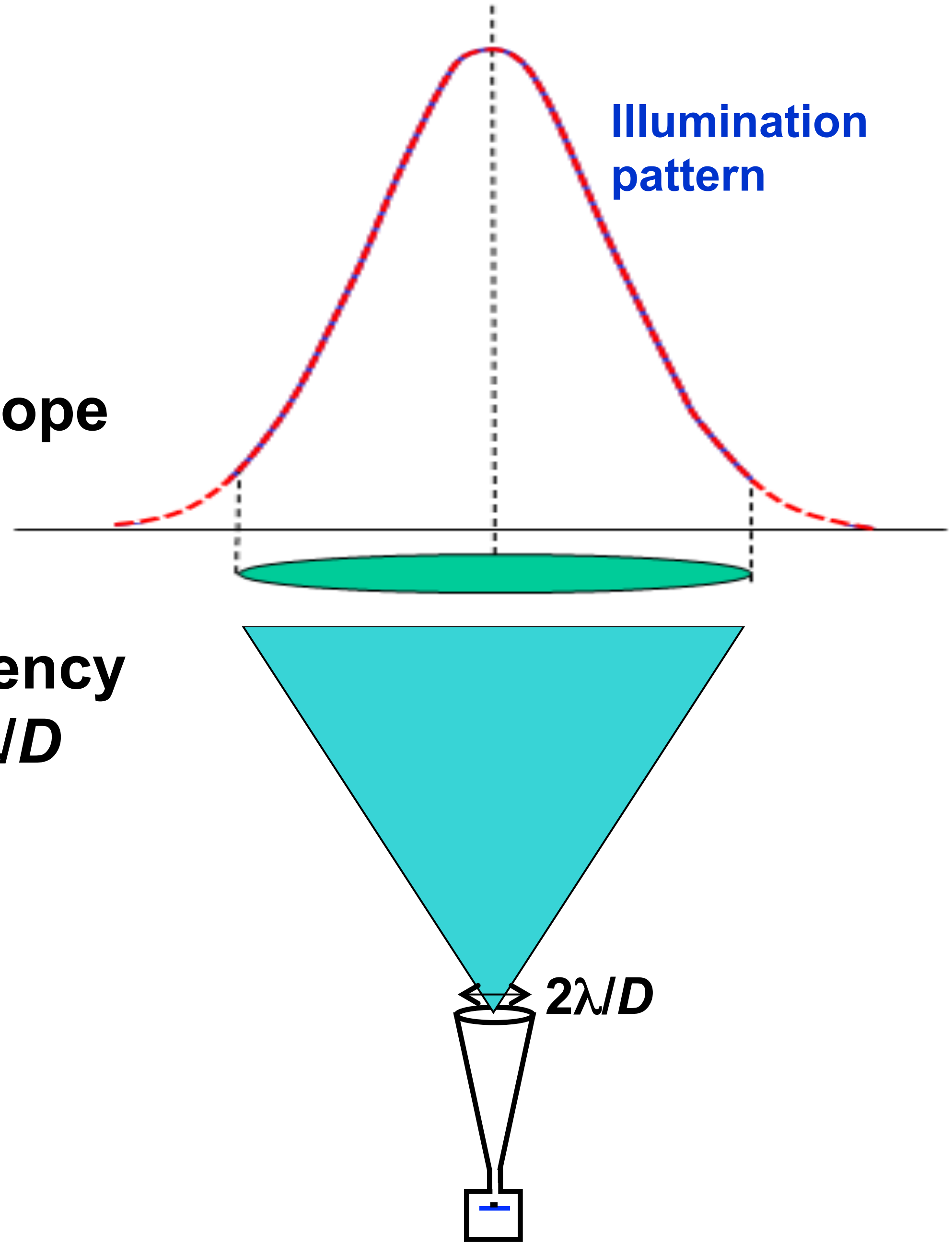
Absorber-Coupled Detectors

- Array of square pixels
- Pixel size ≡ $0.5\lambda/D$ for instantaneous full spatial sampling
- Wide pixel field of view (~ π sr)
- Cold stop limits field of view
- Near top-hat illumination of the telescope
- Pixel couples to Airy disk

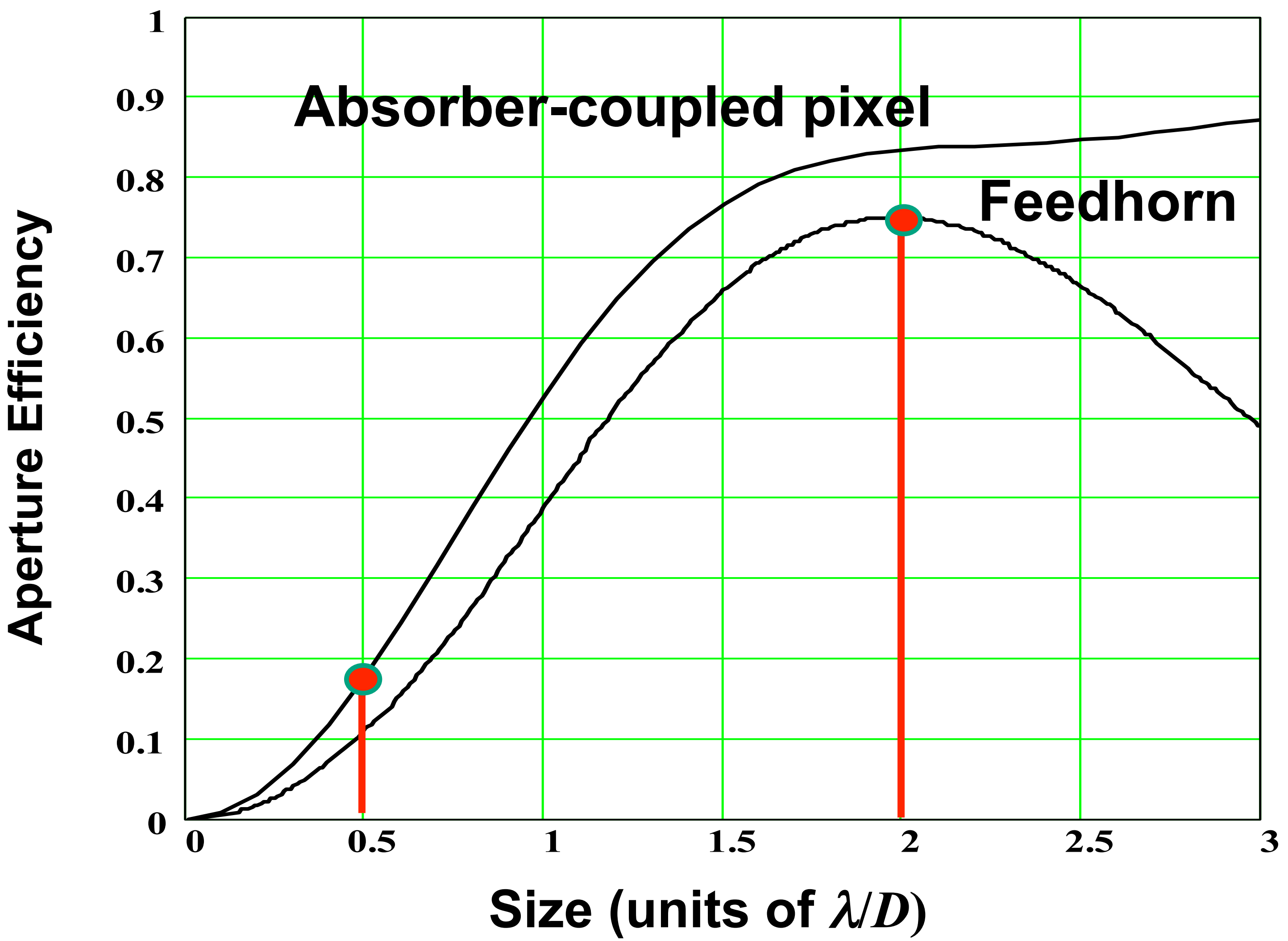


Feedhorn-Coupled Detectors

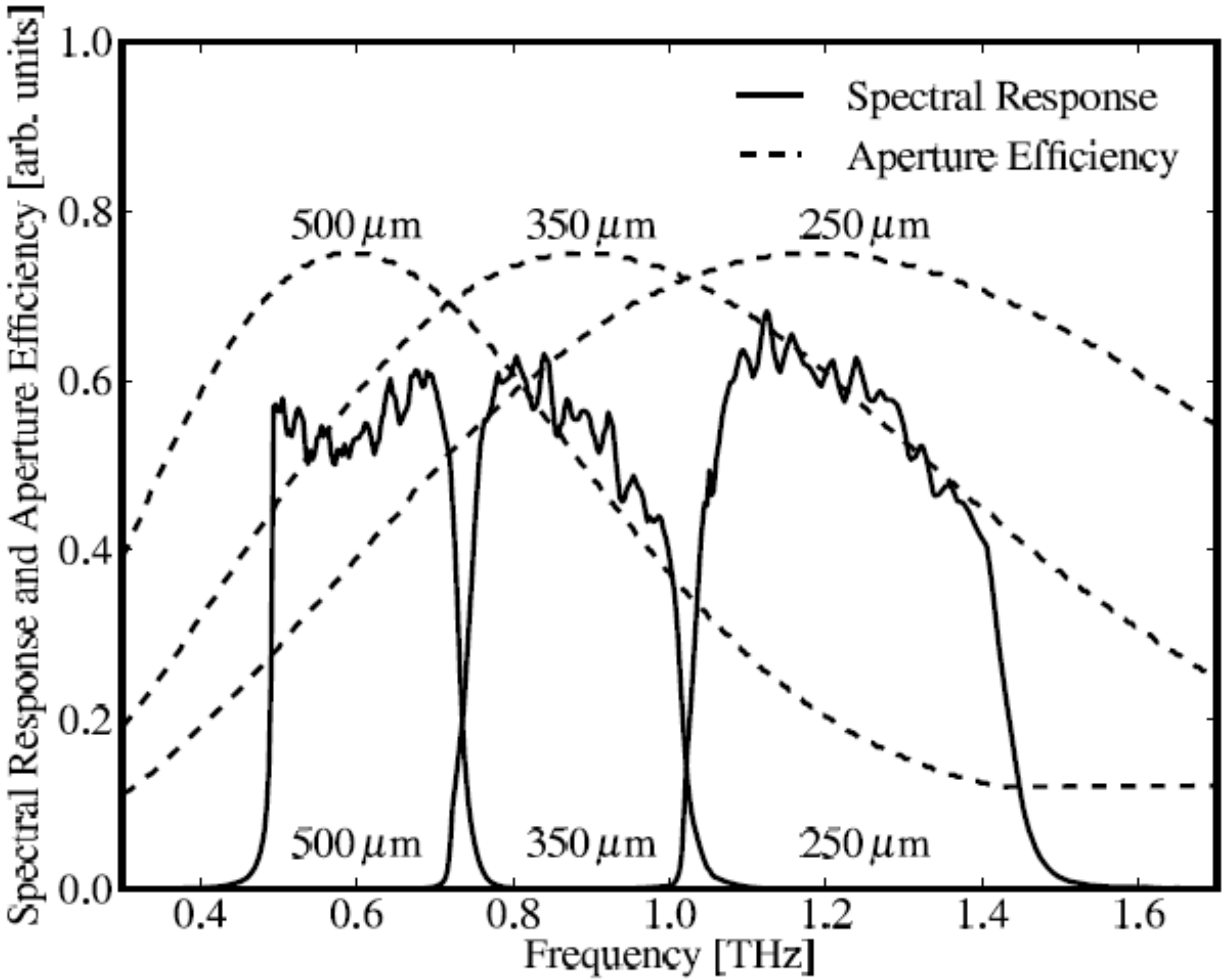
- **Single-mode feedhorns**
- **Tapered (~ Gaussian) illumination of the telescope**
- **Maximum aperture efficiency when horn diameter ≡ 2*λ*/*D***
- **Throughput is λ^2**



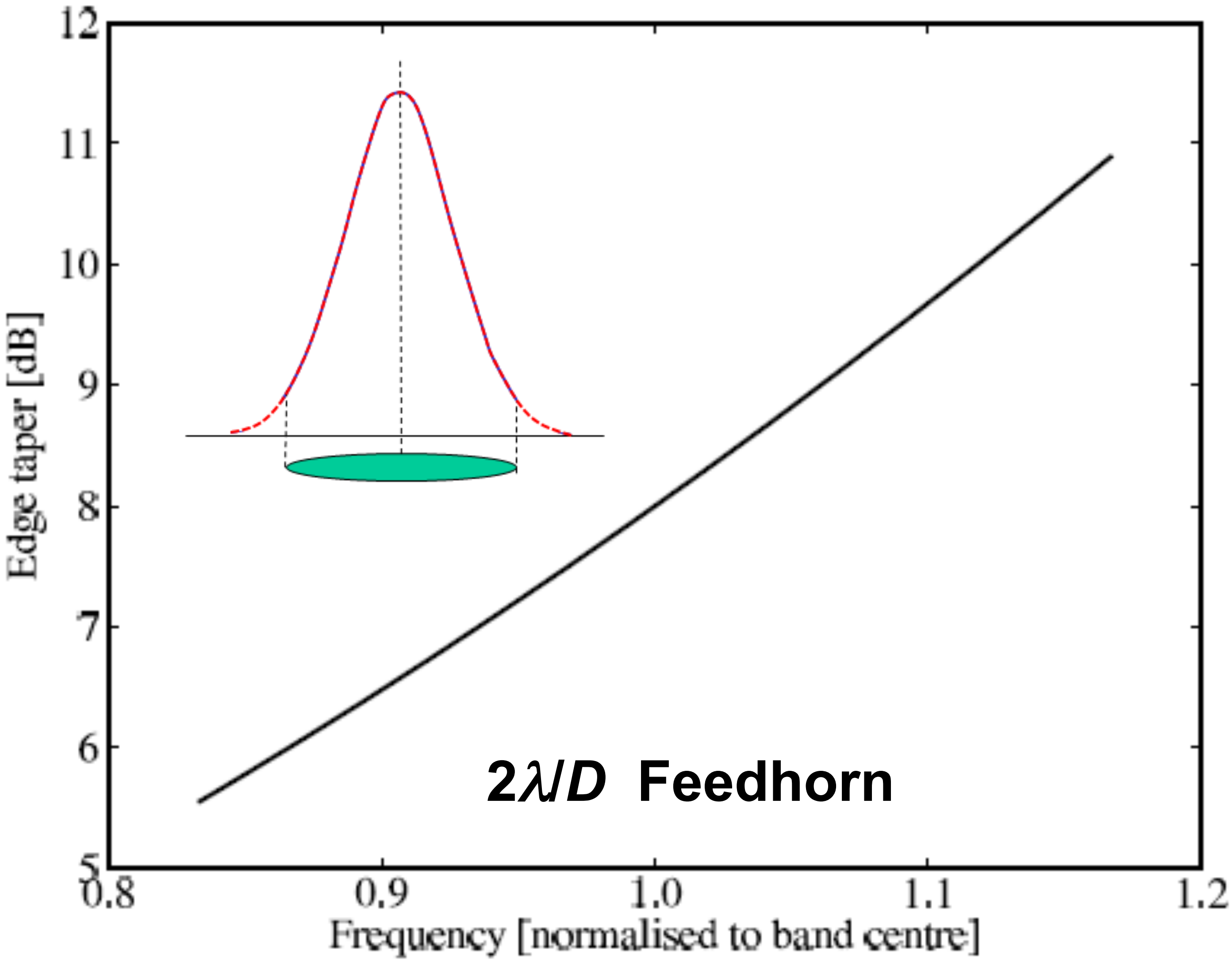
Aperture Efficiency vs. Detector Size



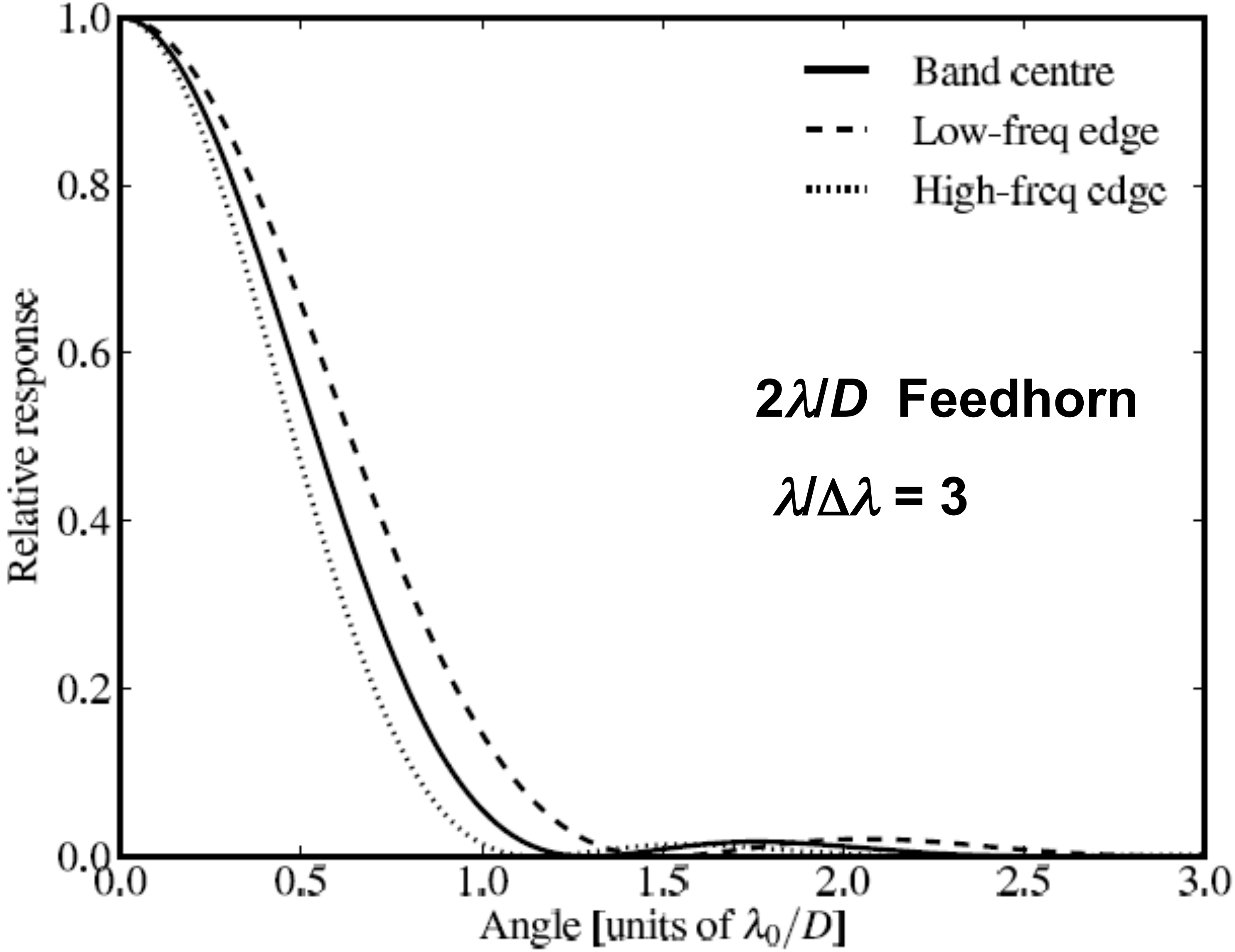
SPIRE SRFs and Aperture Efficiencies



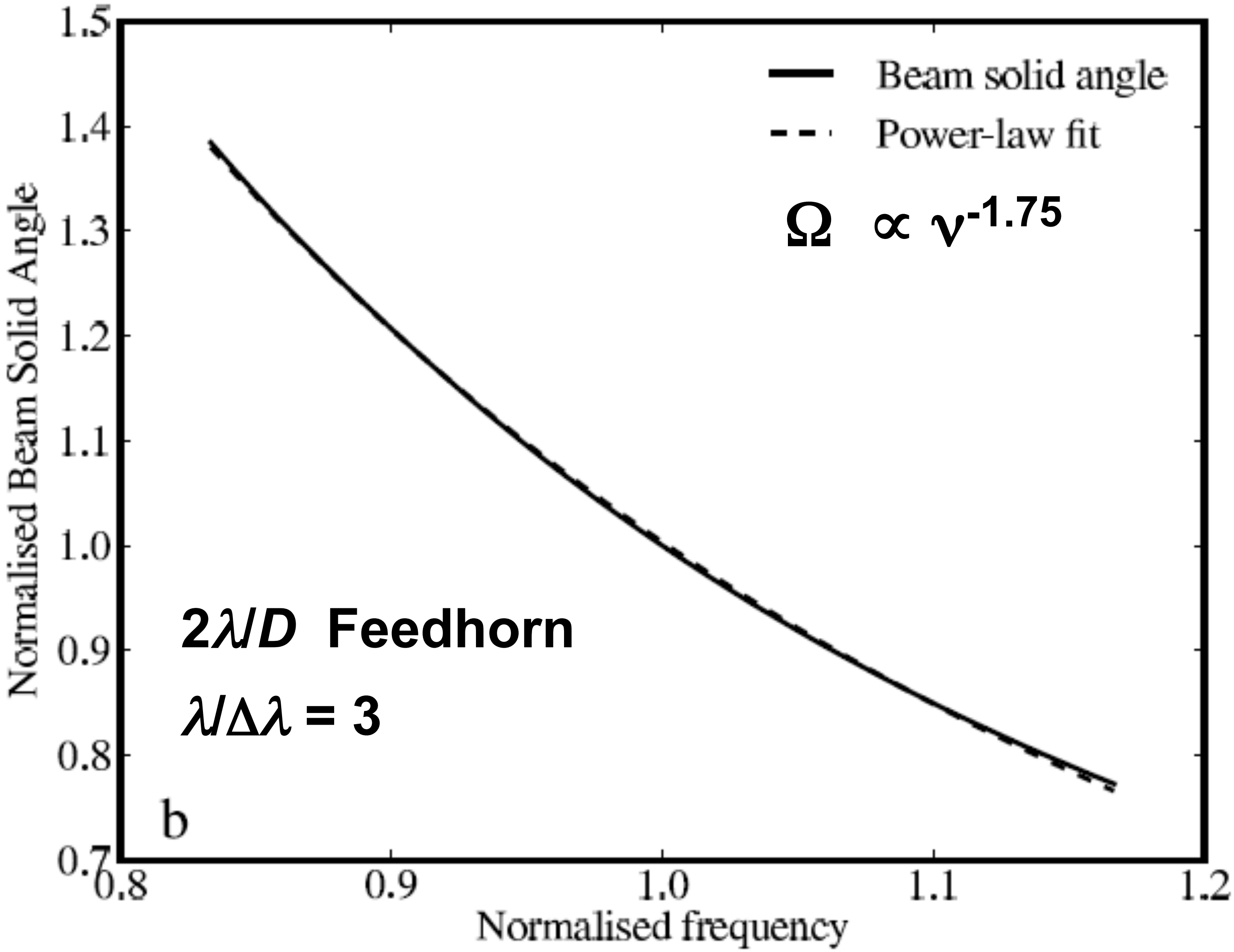
Primary Illumination Edge Taper Variation across the Band



Beam Profile for 2λ/D Feedhorn with $\lambda/\Delta\lambda = 3$



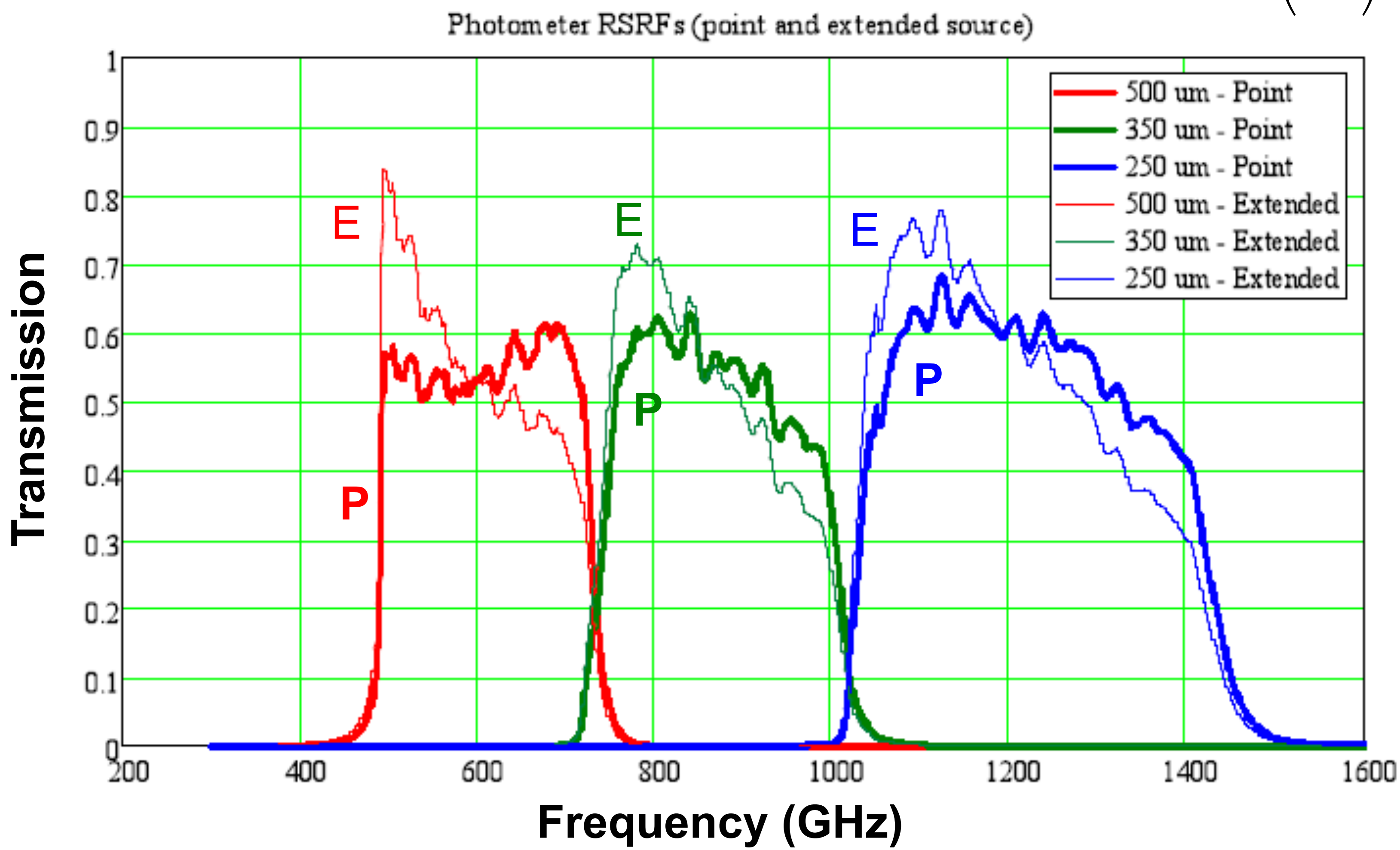
Corresponding Beam Solid Angle



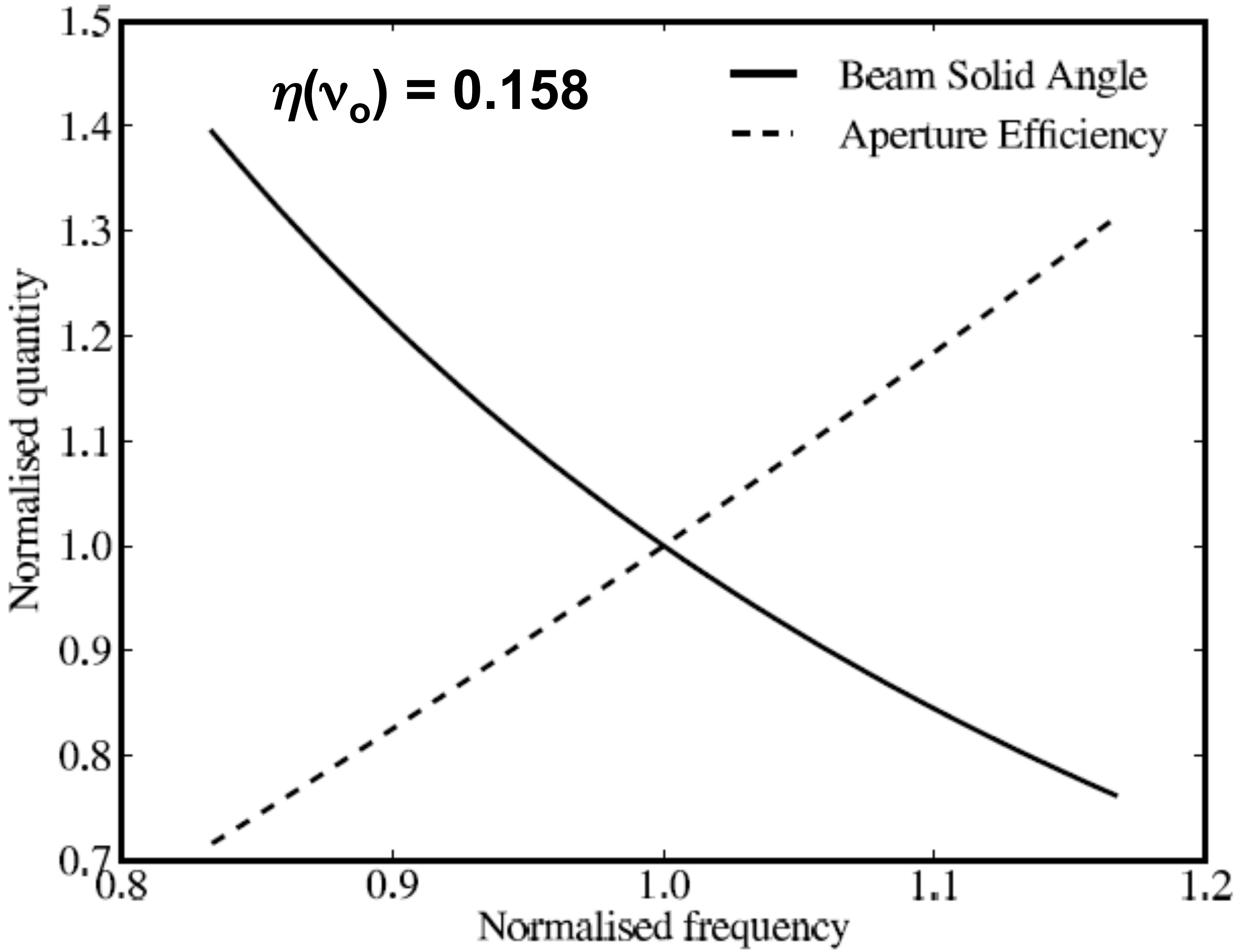
Earlier SPIRE Method of Dealing With This Effect: λ^2 Weighting of the SRF

P = Point source (no weighting)
E = Extended source (λ^2 weighting)

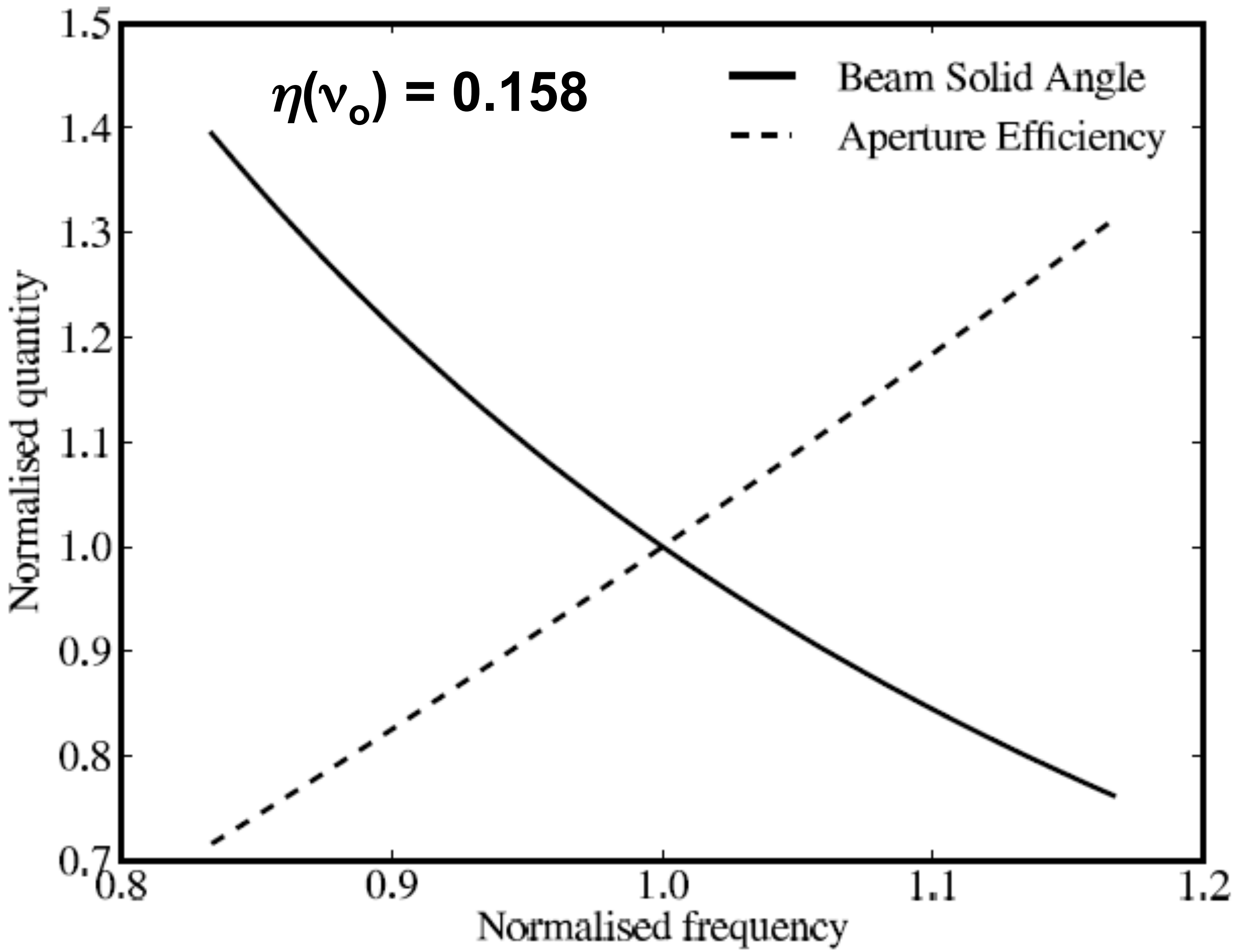
$$R(\nu) = R(\nu_0)\left(\frac{\nu_0}{\nu}\right)^2$$



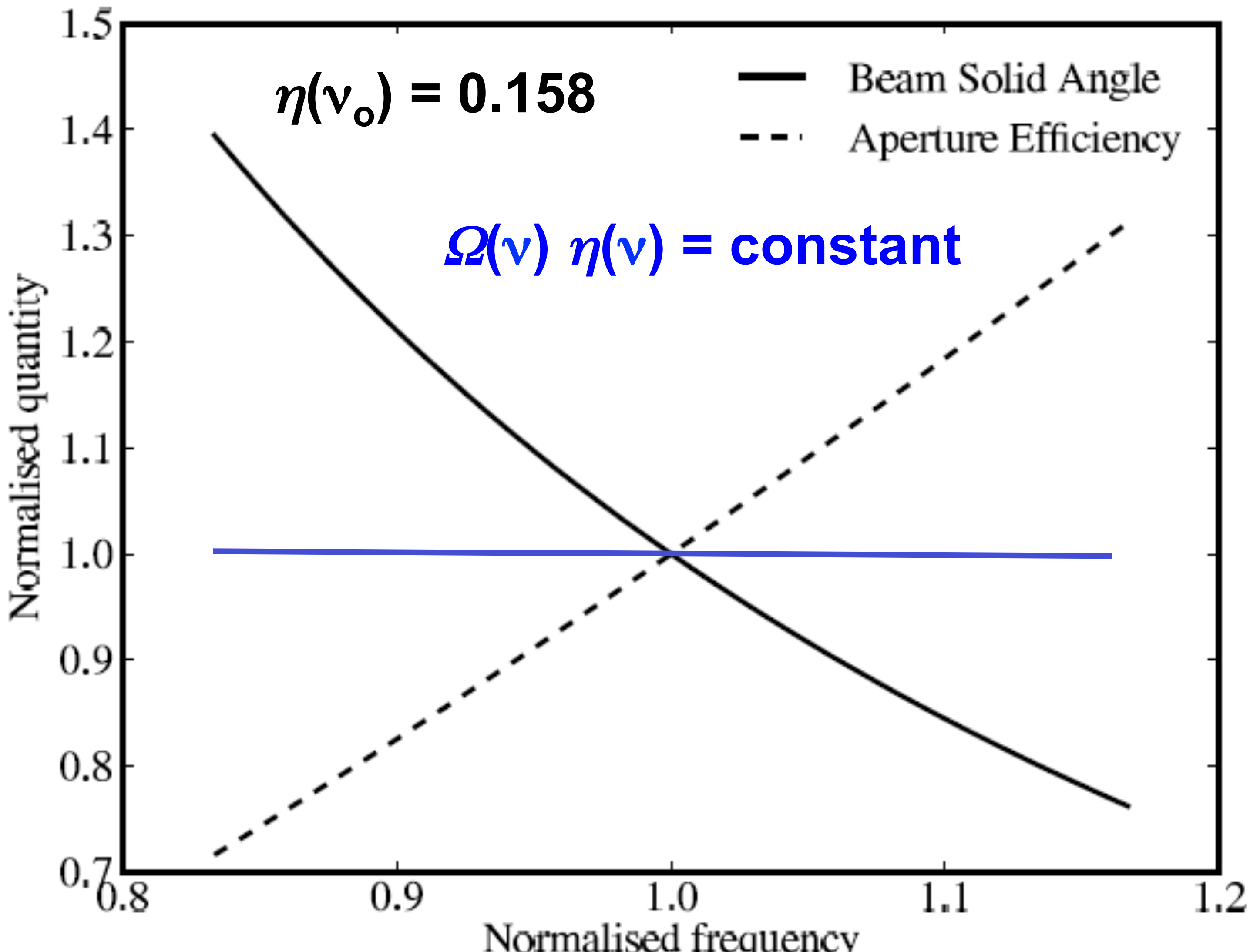
Beam Solid Angle and Aperture Efficiency for 0.5λ/D Pixel



$0.5\lambda/D$ Absorber-Coupled Pixel: Beam Solid Angle and Aperture Efficiency

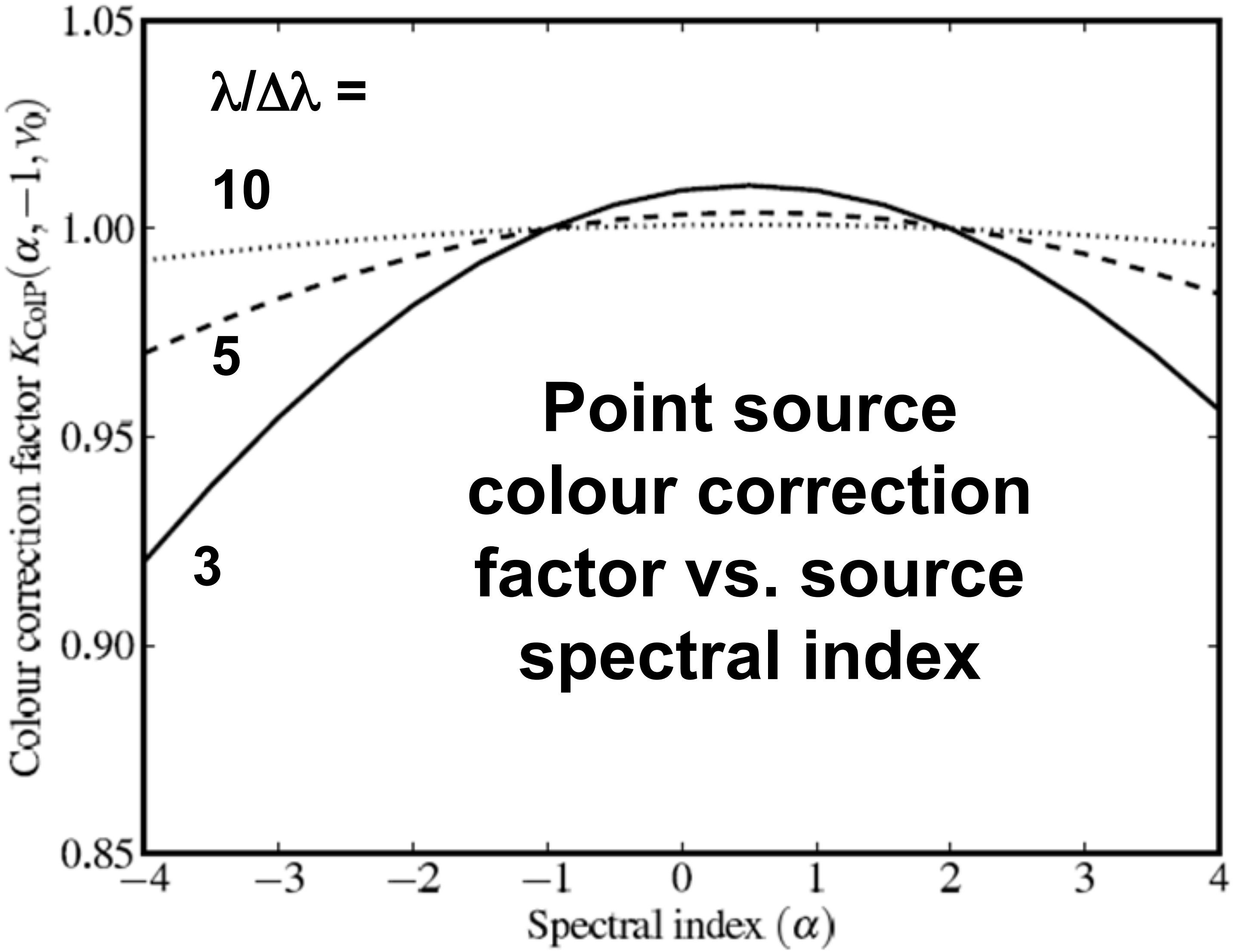


$0.5\lambda/D$ Absorber-Coupled Pixel: Beam Solid Angle and Aperture Efficiency

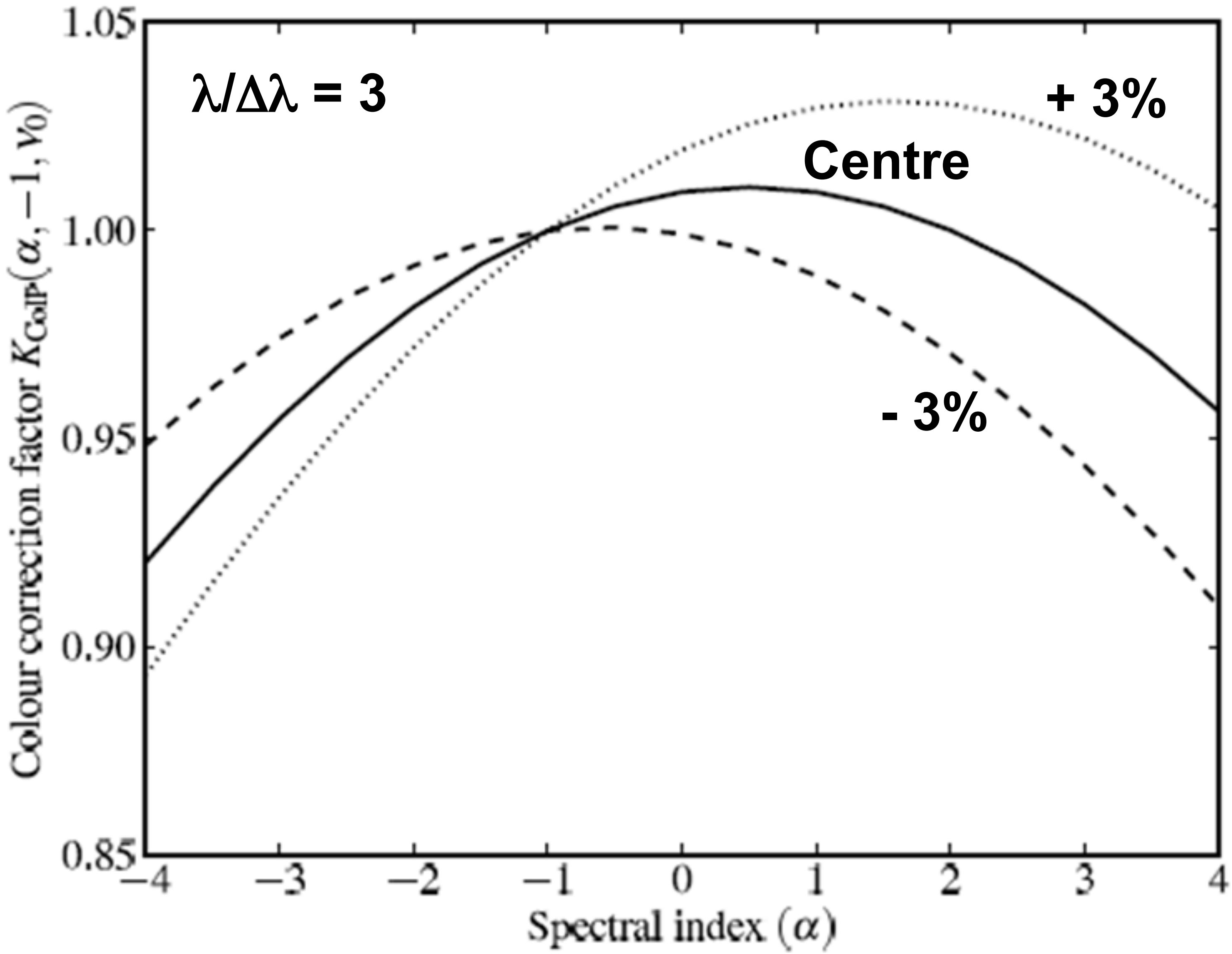


Examples

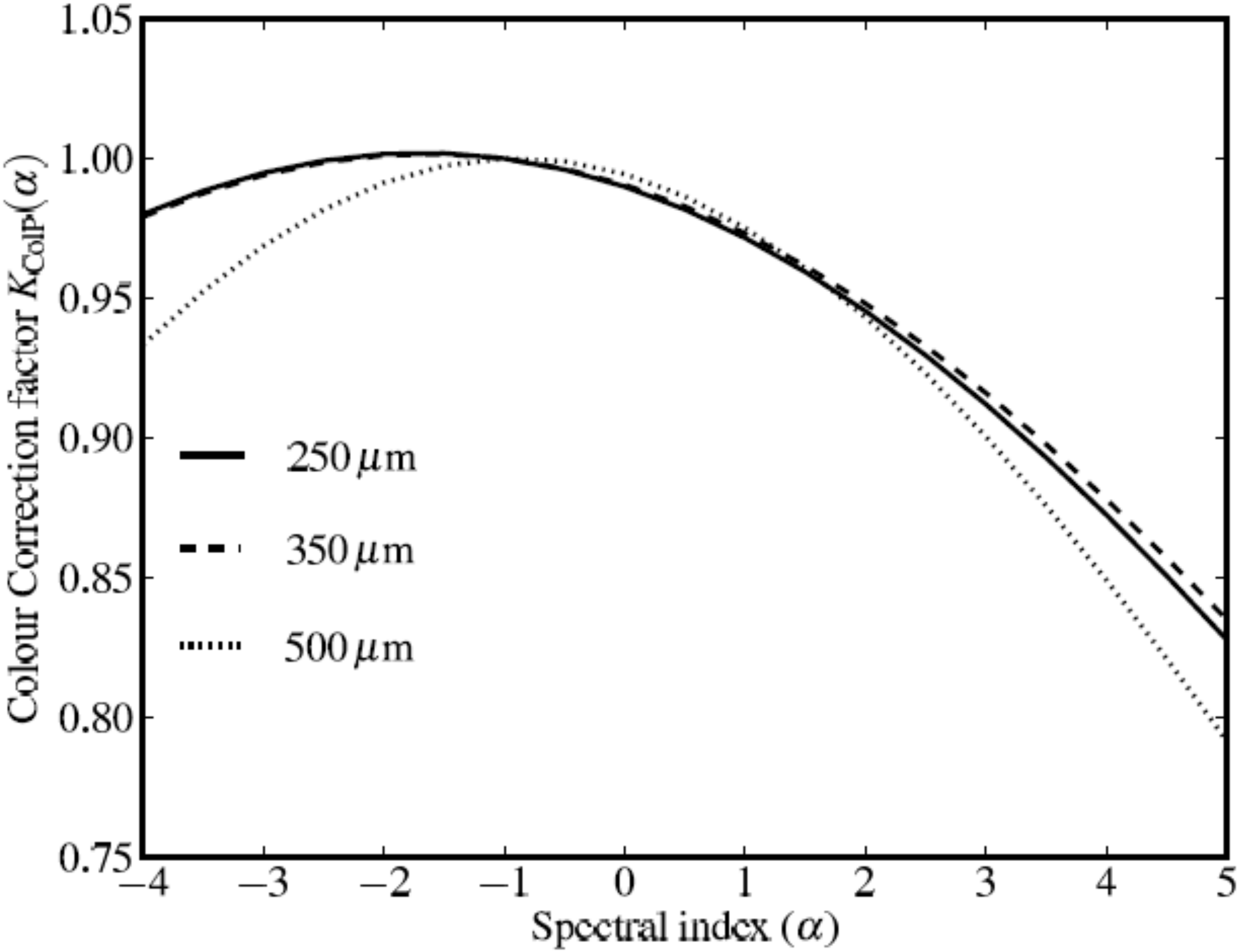
Feedhorn Coupling, Square Passband with ν_o at Centre



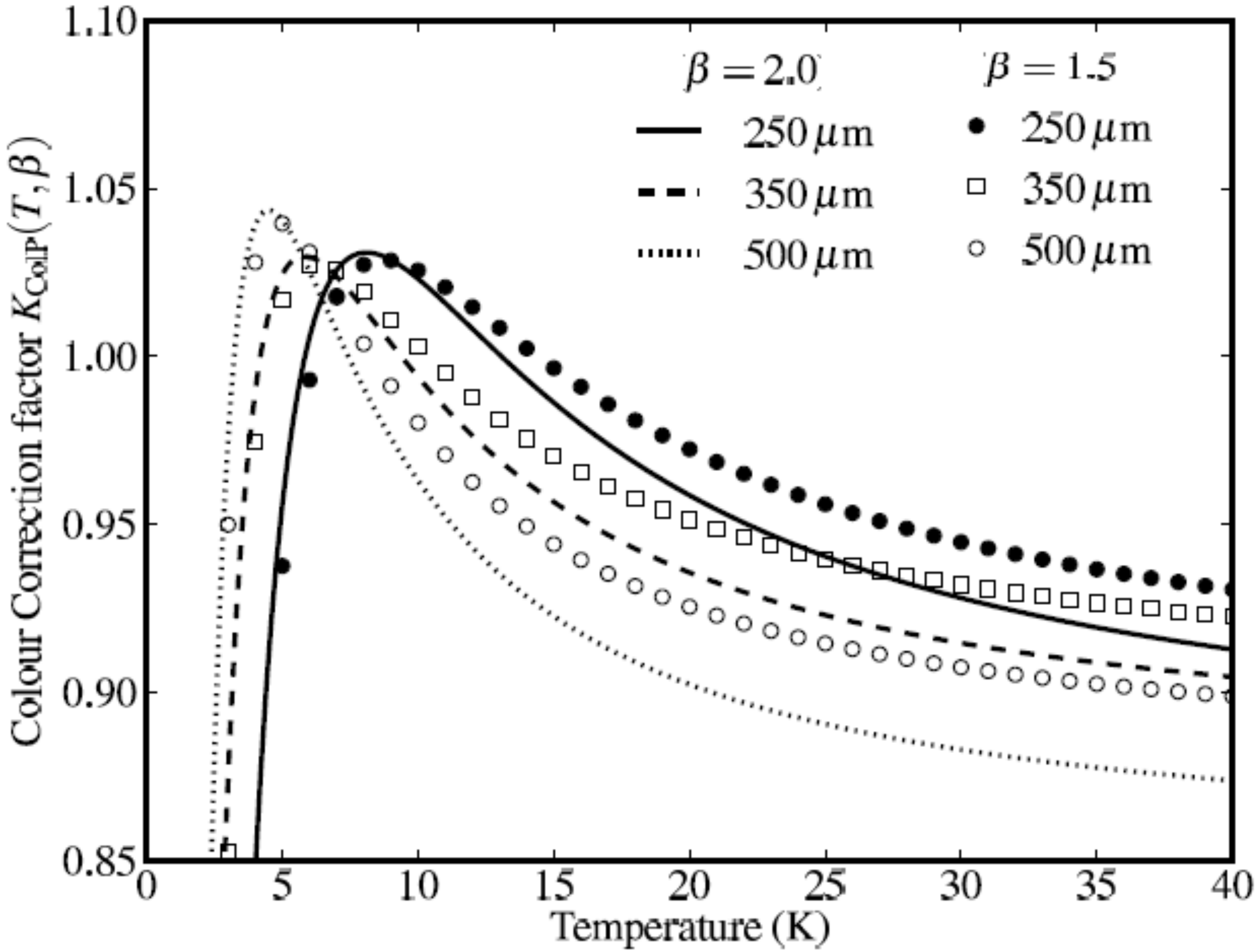
Different Choice of Nominal Frequency



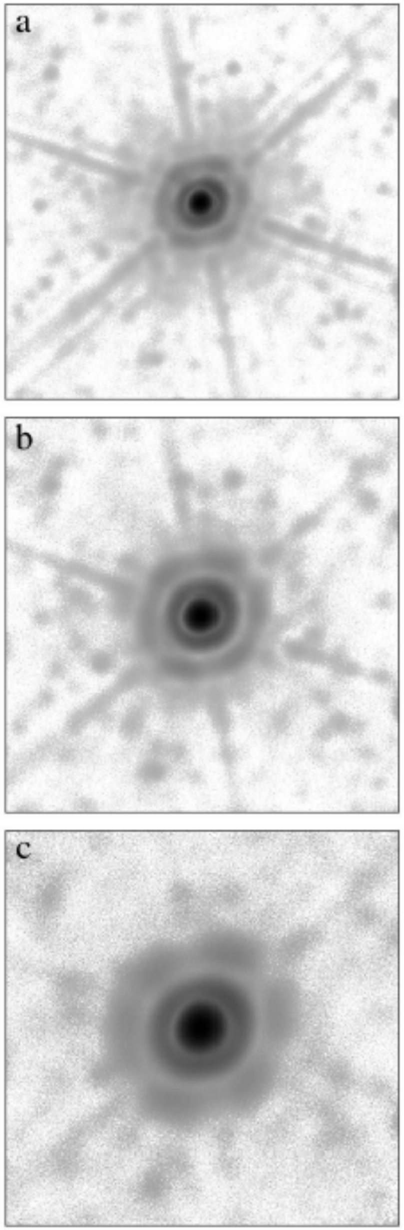
SPIRE Colour Correction (Power-Law SED)



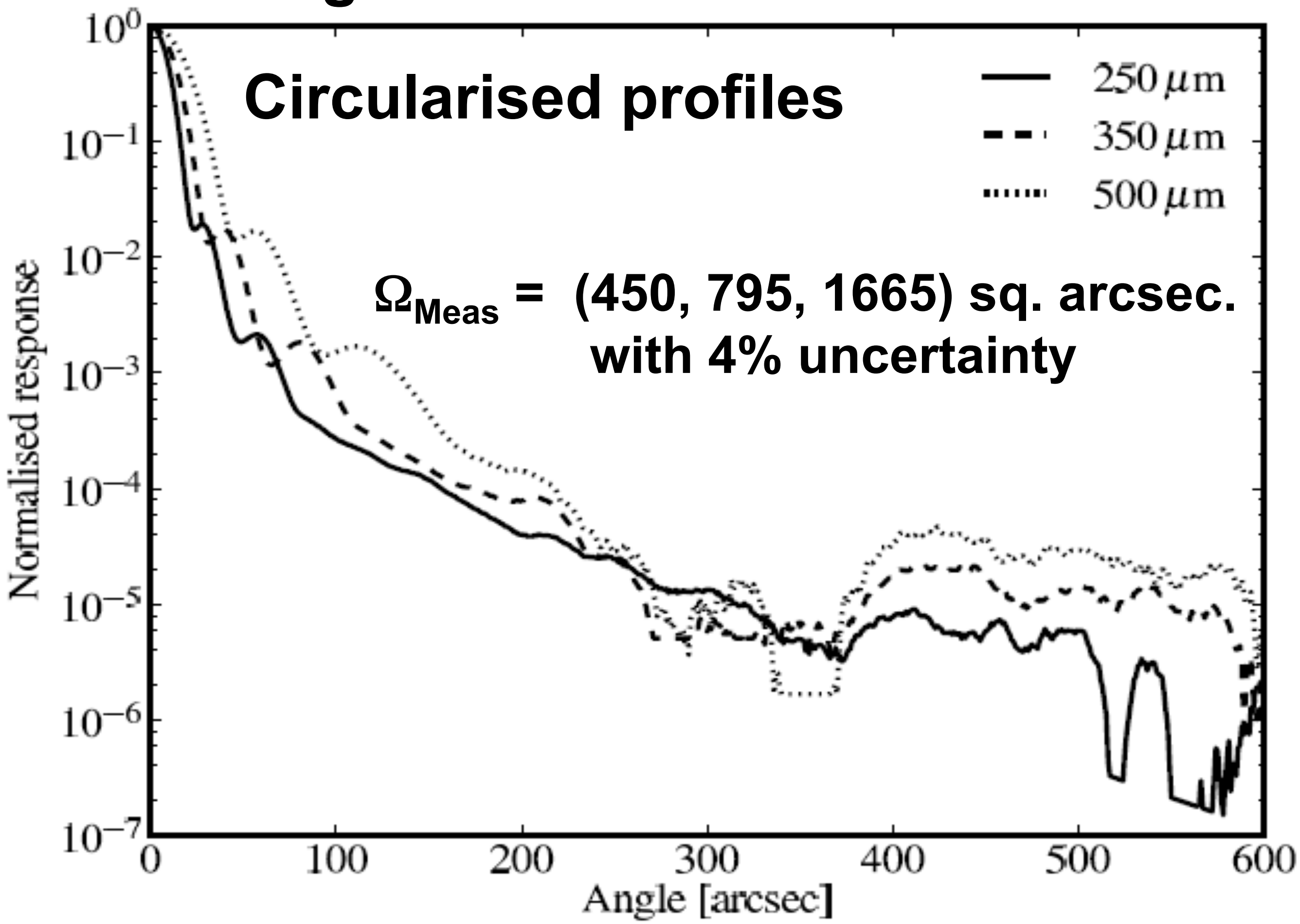
SPIRE Colour Correction (Grey Body SED)



SPIRE Beams

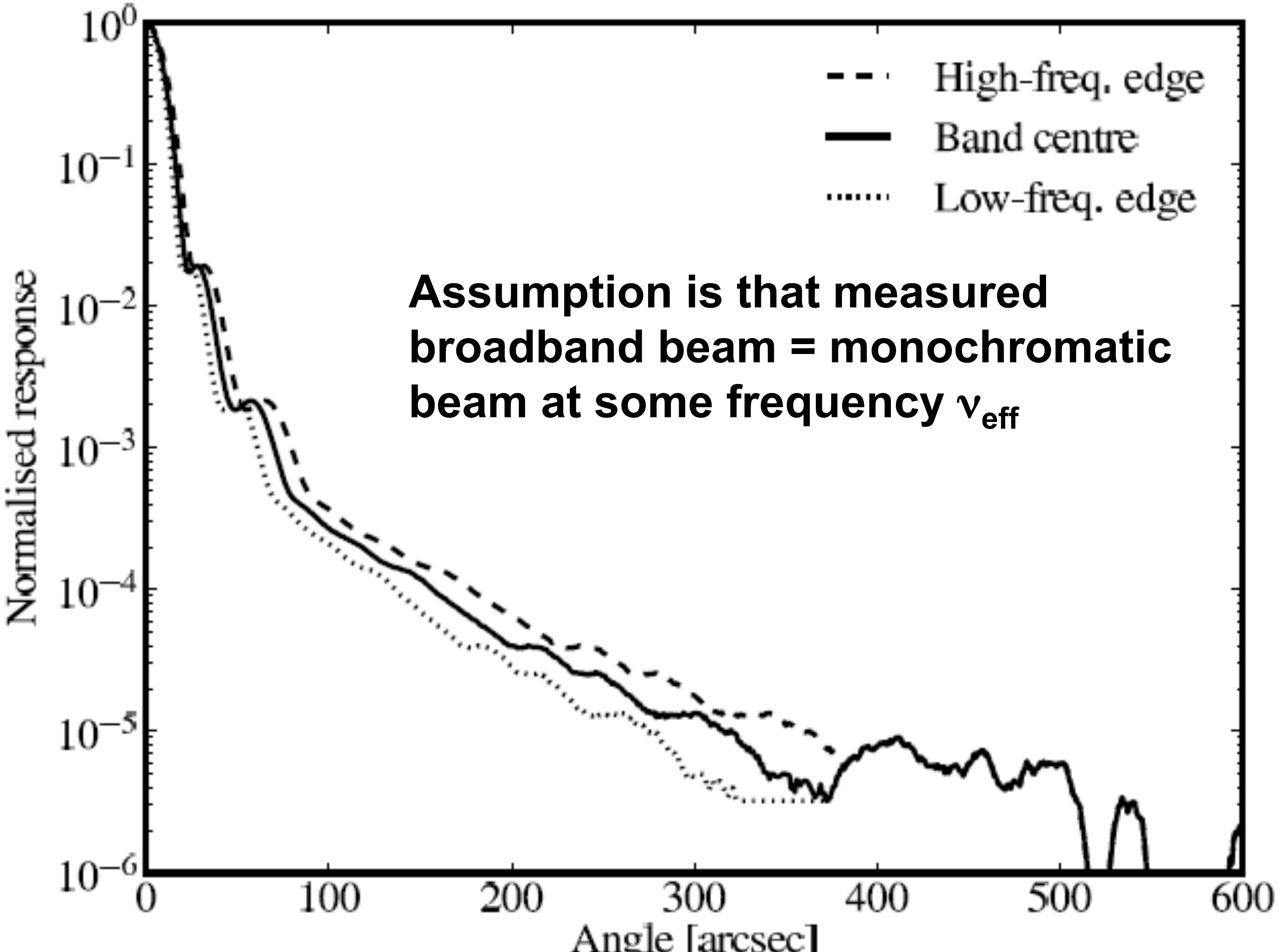


- **Broadband beams measured on Neptune (α = 1.3 – 1.5)**
- **Averaged over all detectors**



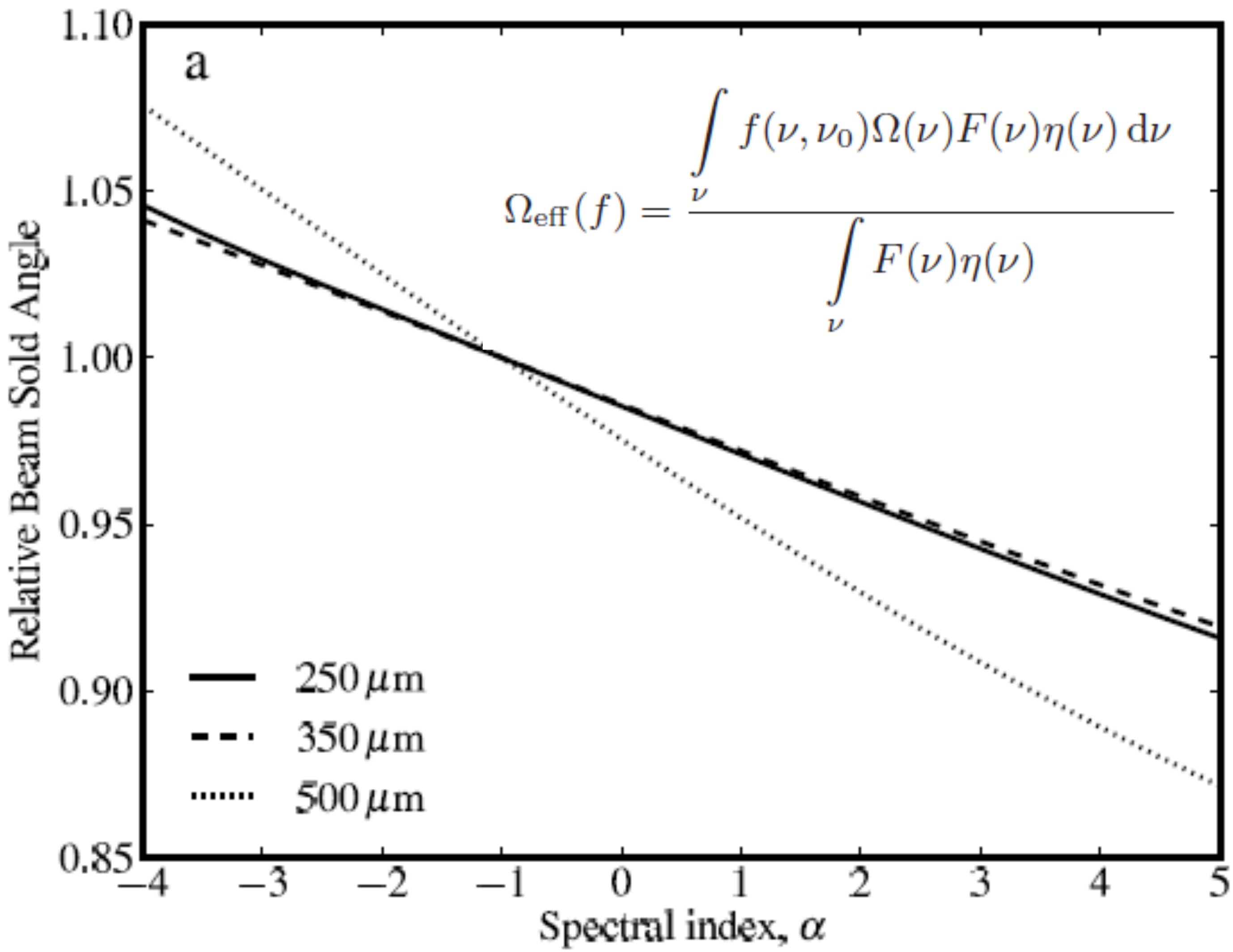
SPIRE Beams

- **Modelled 250-μm beam at ν_{eff} and band edges**



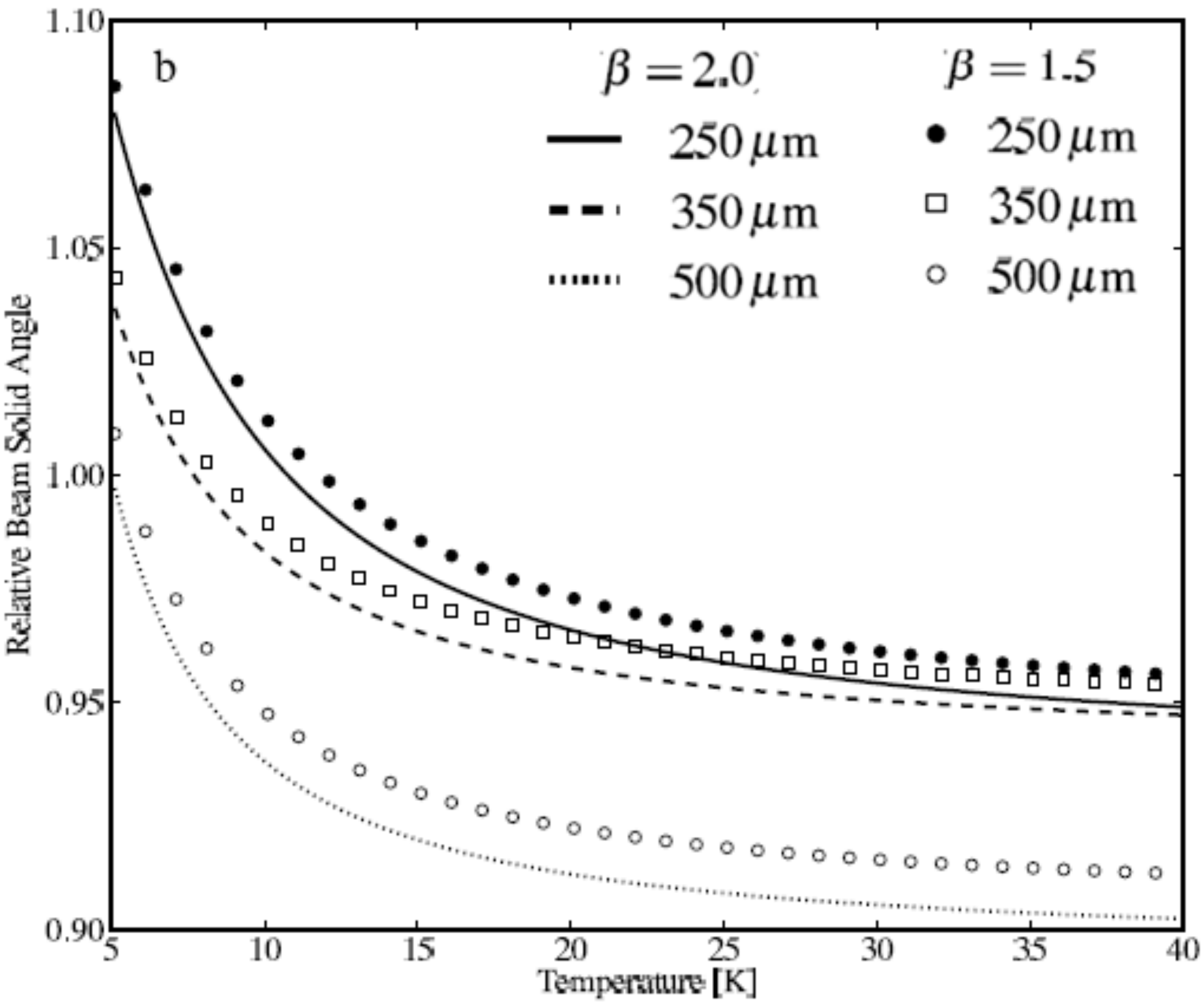
SPIRE Beams

- **Effective Beam Solid Angle vs. Source Spectral Index**

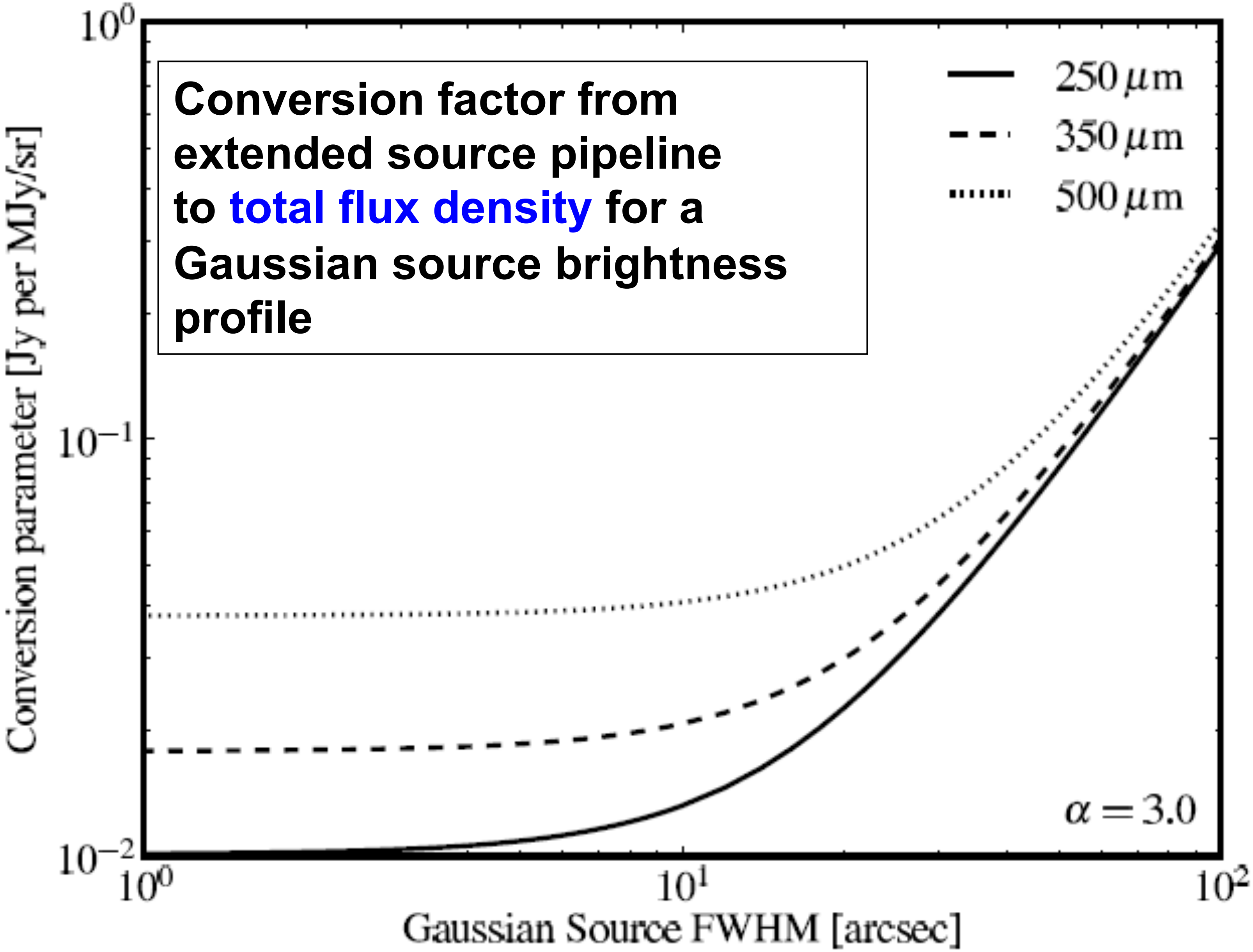


SPIRE Beams

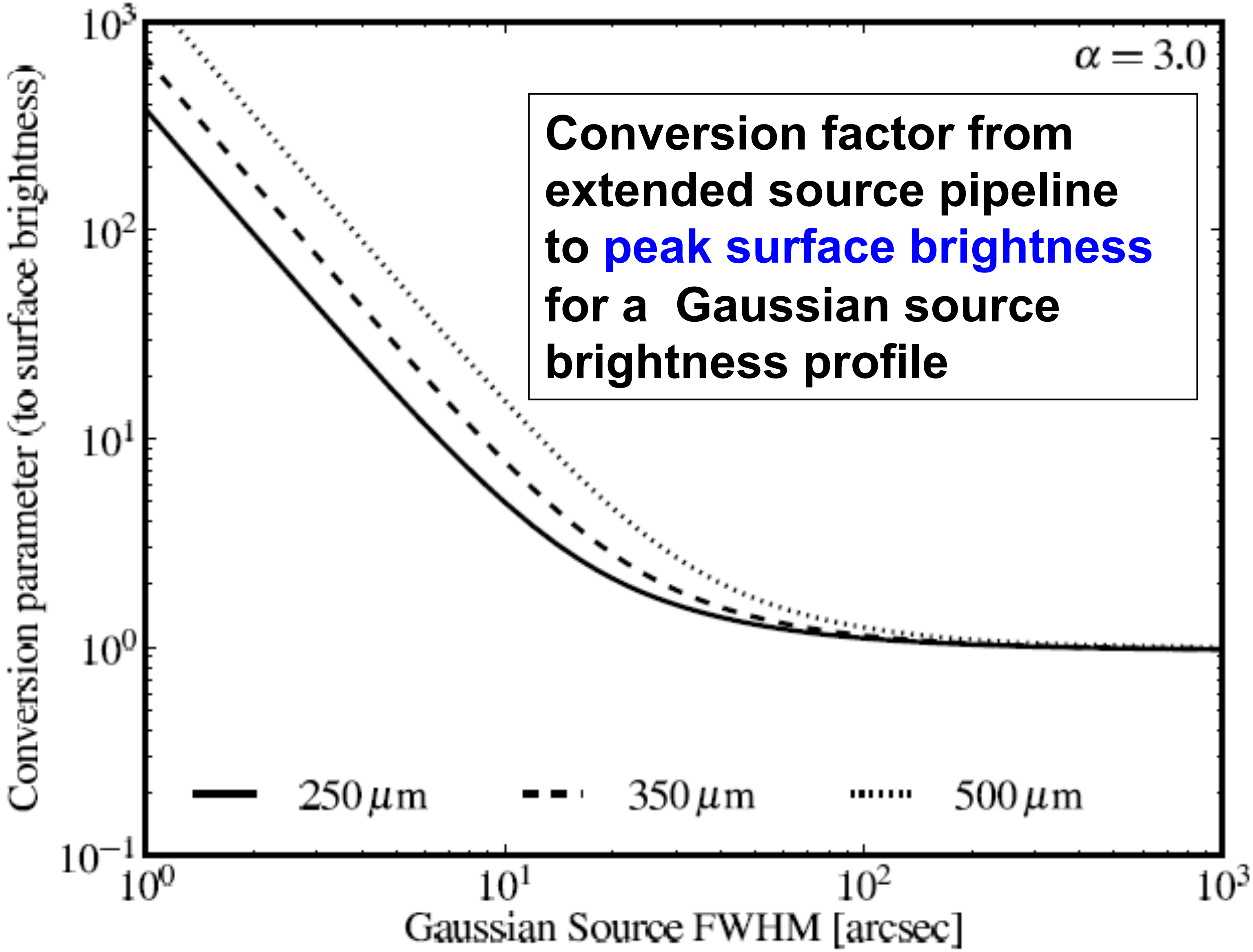
- **Effective Beam Solid Angle vs. Grey Body Temperature**



SPIRE Calibration of Partly Extended Emission



SPIRE Calibration of Partly Extended Emission



Conclusions

- General scheme for calibration of broadband photometric measurements of point-like, semi- or fully-extended emission
- Can be applied to absorber-coupled or antenna-coupled systems
- Calibration implementation for SPIRE: see
  - Talks by George Bendo and Bernhard Schulz
  - Poster by Chris North
  - Updated SPIRE Observers' Manual
- New method produces brightness values ~ (7, 7, 12)% lower than previous method for a ν^3 uniformly extended source
- Future work:
  - Develop practical scheme for dealing with semi-extended emission
  - Reduce beam solid angle Ω_{Meas} uncertainties using Neptune shadow map to remove zodiacal light and background point sources