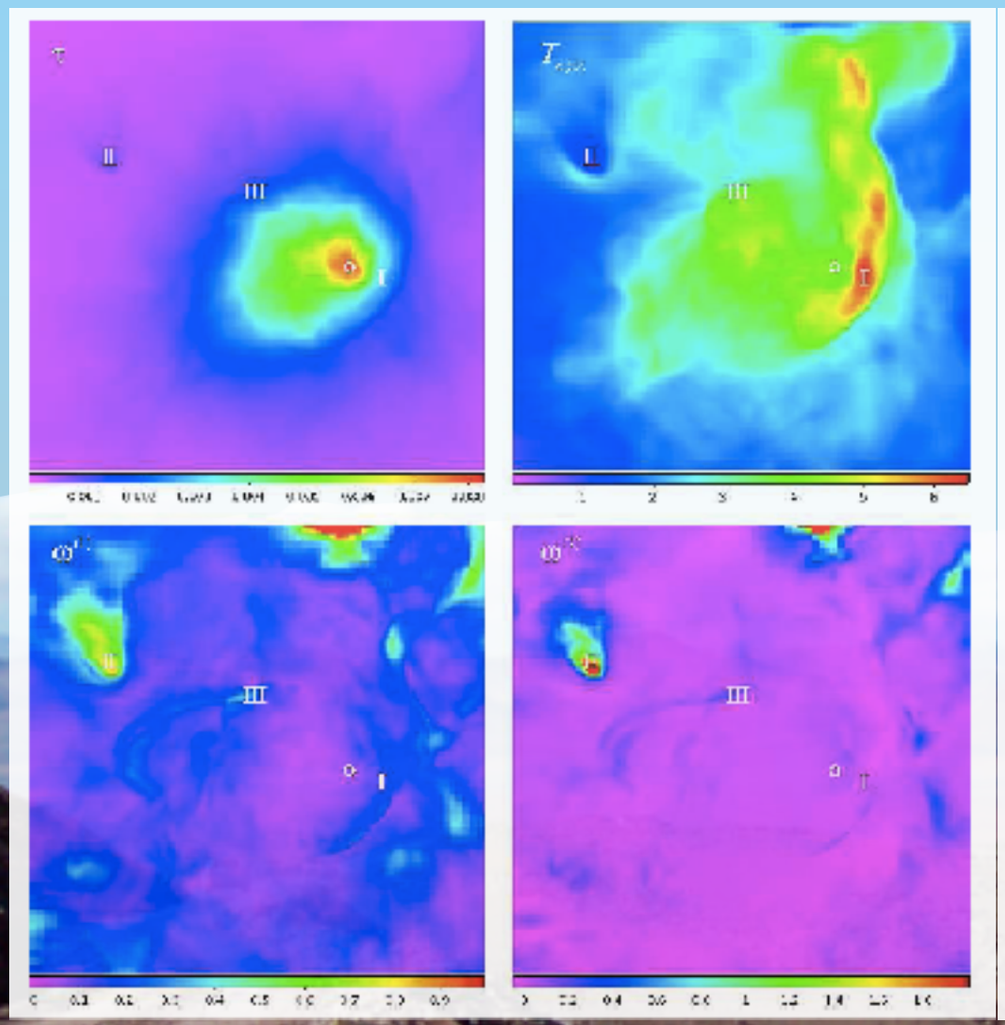
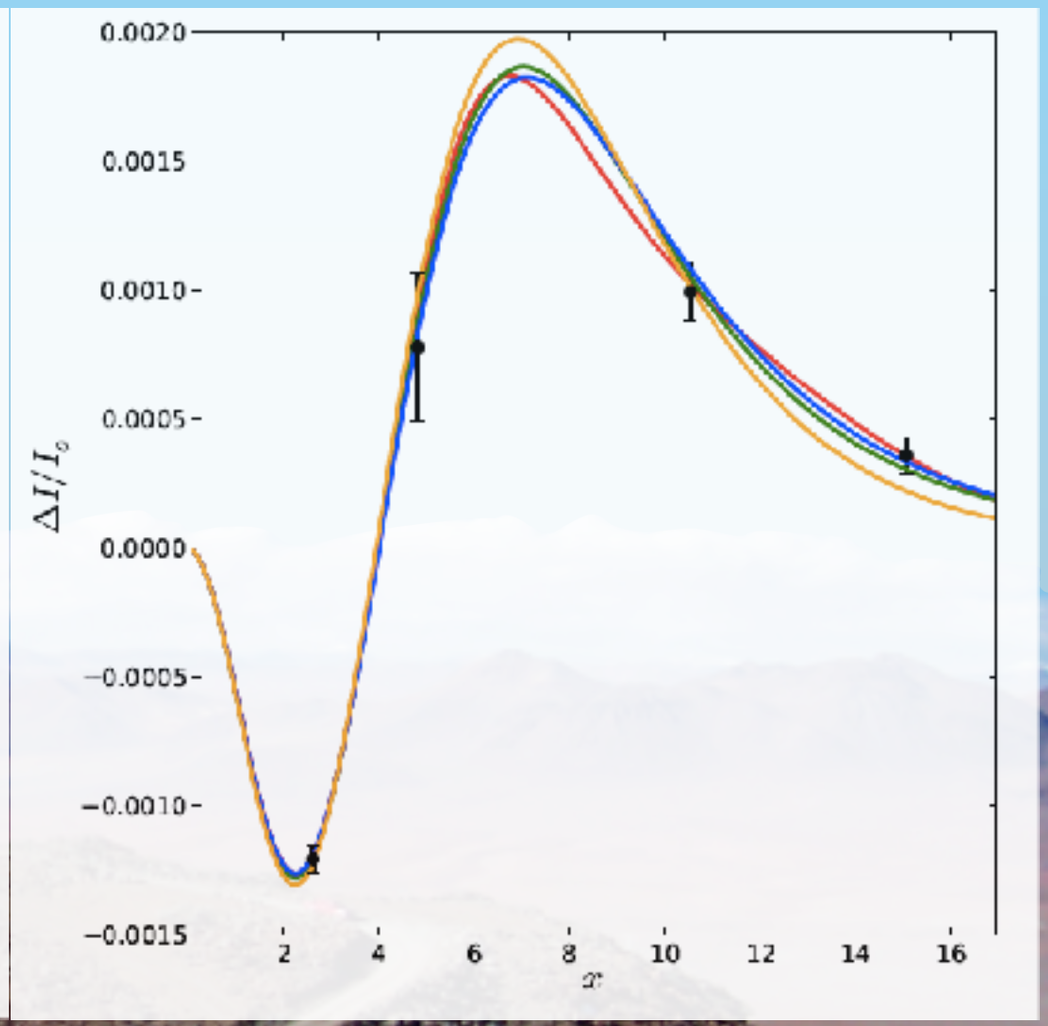
Efficient Computation of the SZ Signal Using Temperature and Velocity Moments





Jens Chluba

MANCHESTER 1824
The University of Manchester

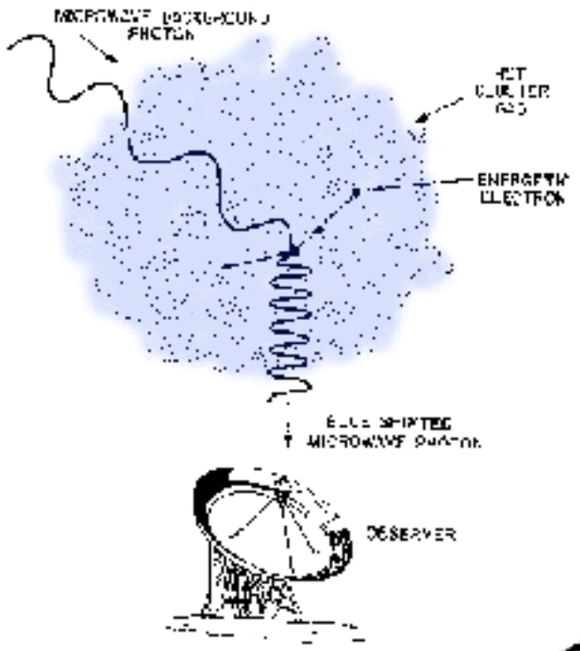
CMB in Germany - MPA

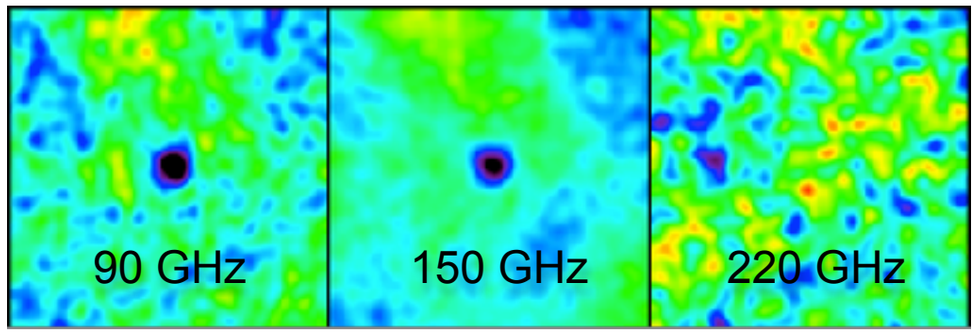
Garching, Germany, Jan 31st-Feb 1st, 2018

erc

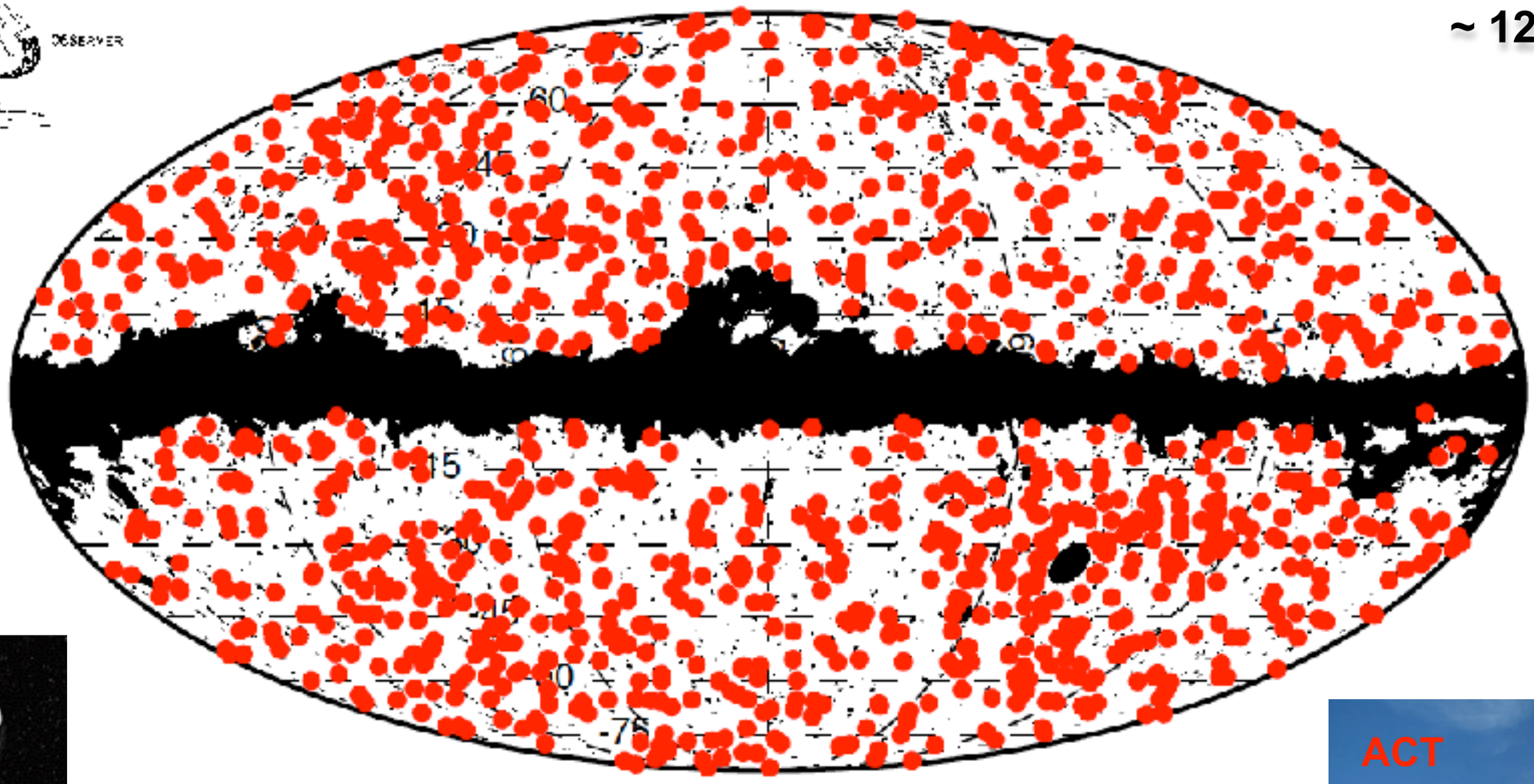
THE ROYAL SOCIETY

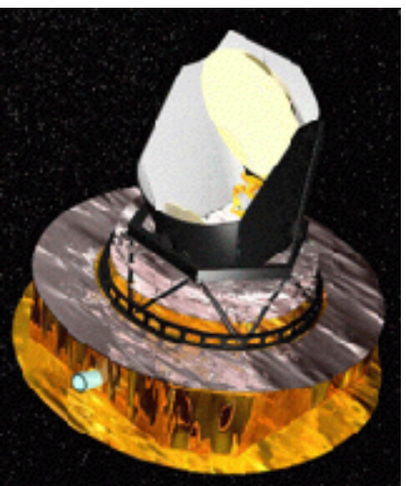
Thermal SZ effect is now routinely observed!





~ 1230 objects

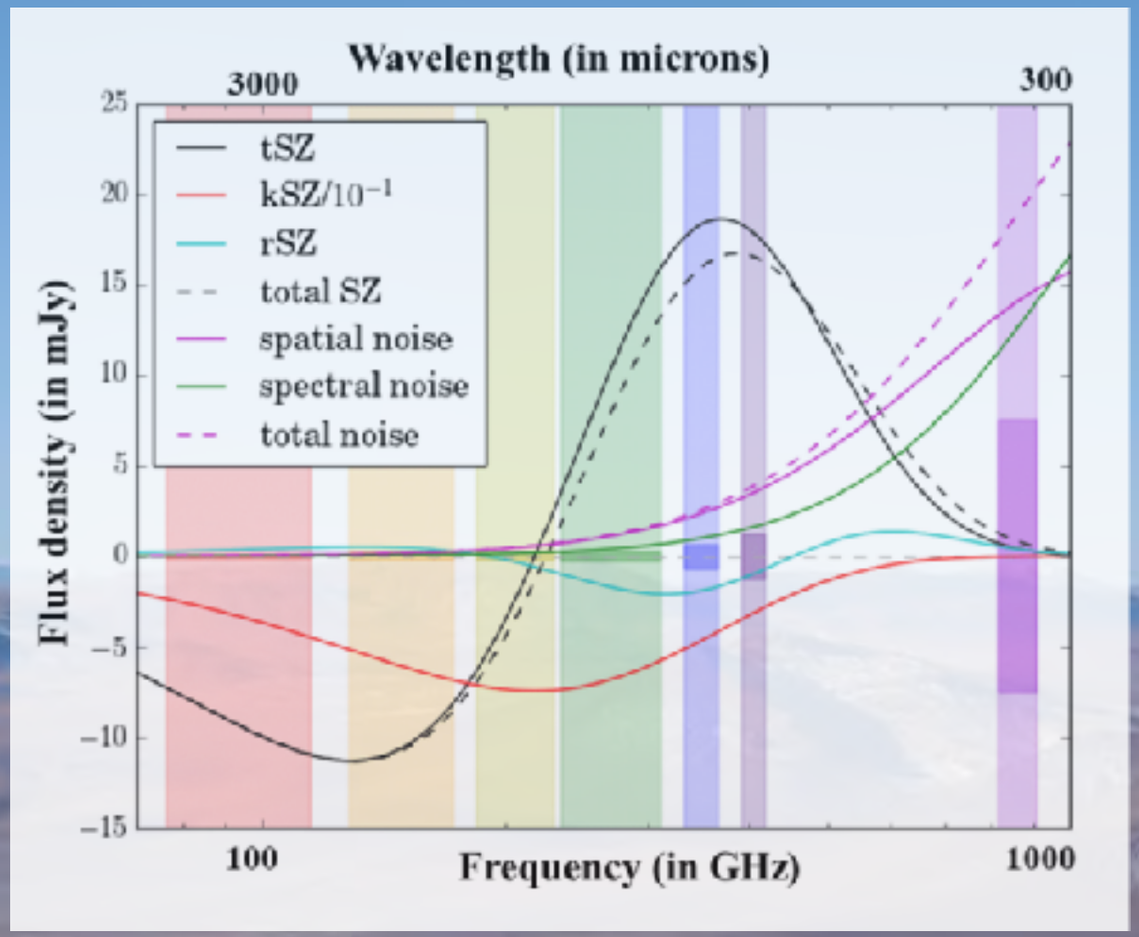




Planck Collaboration, 2013, paper XXIV

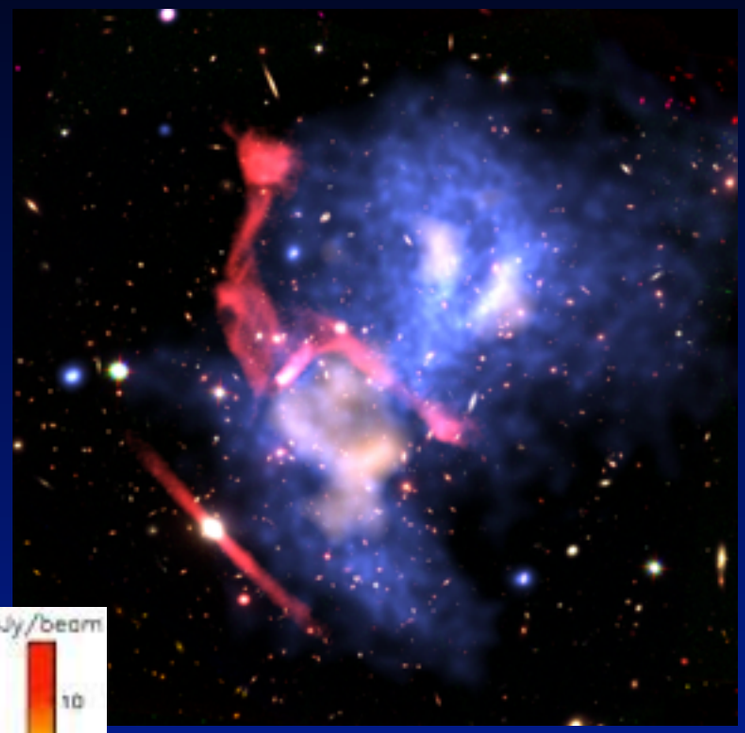
Planck Collaboration, 2015, papers

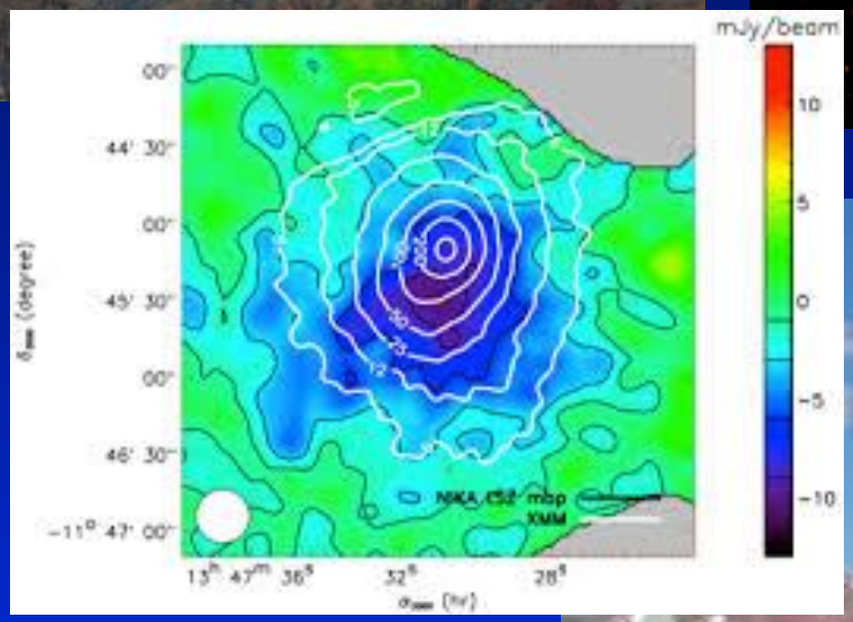
Frank's talk…


Wavelength (in microns)
3000
300
tSZ
kSZ/10⁻¹
rSZ
total SZ
spatial noise
spectral noise
total noise
Flux density (in mJy)
25
20
15
10
5
0
−5
−10
−15
100
Frequency (in GHz)
1000

Mustang 2

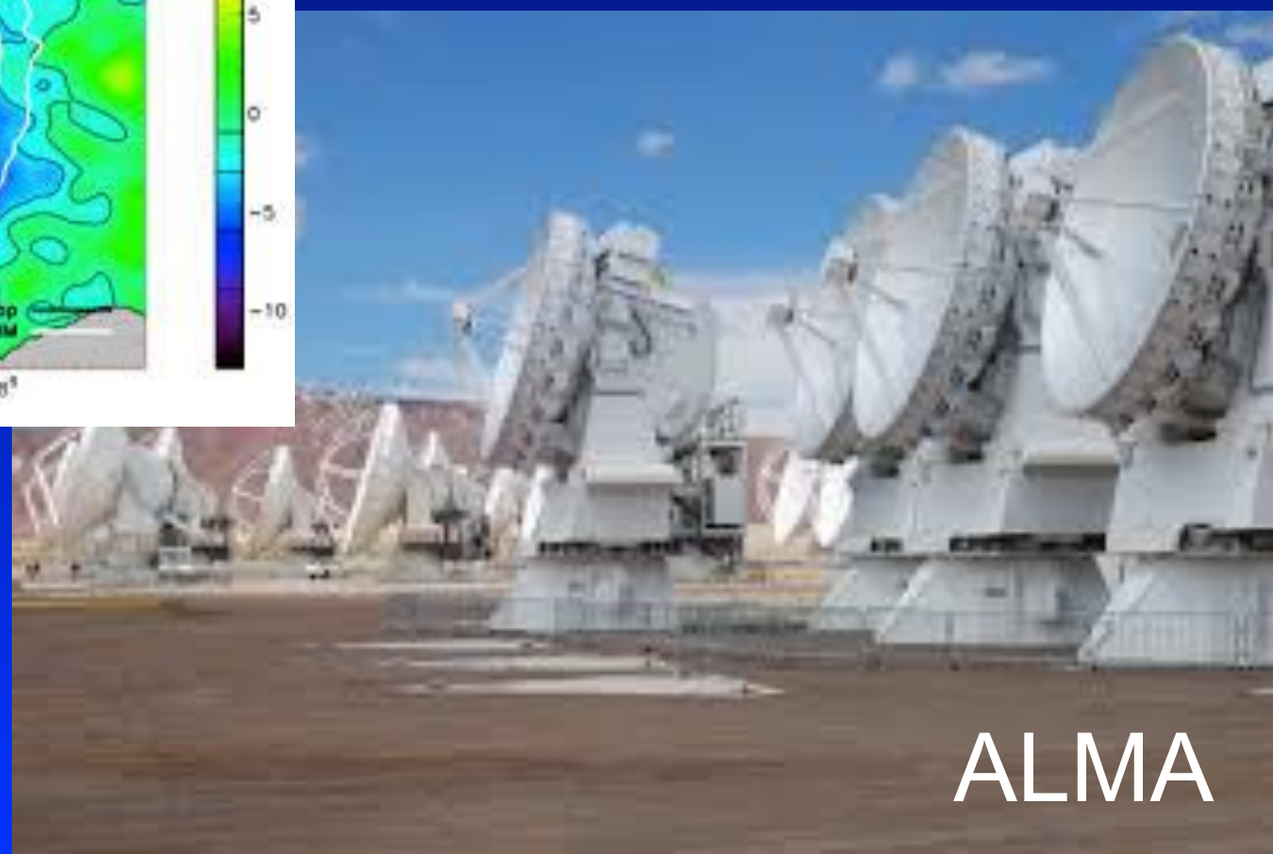
Tony's talk….





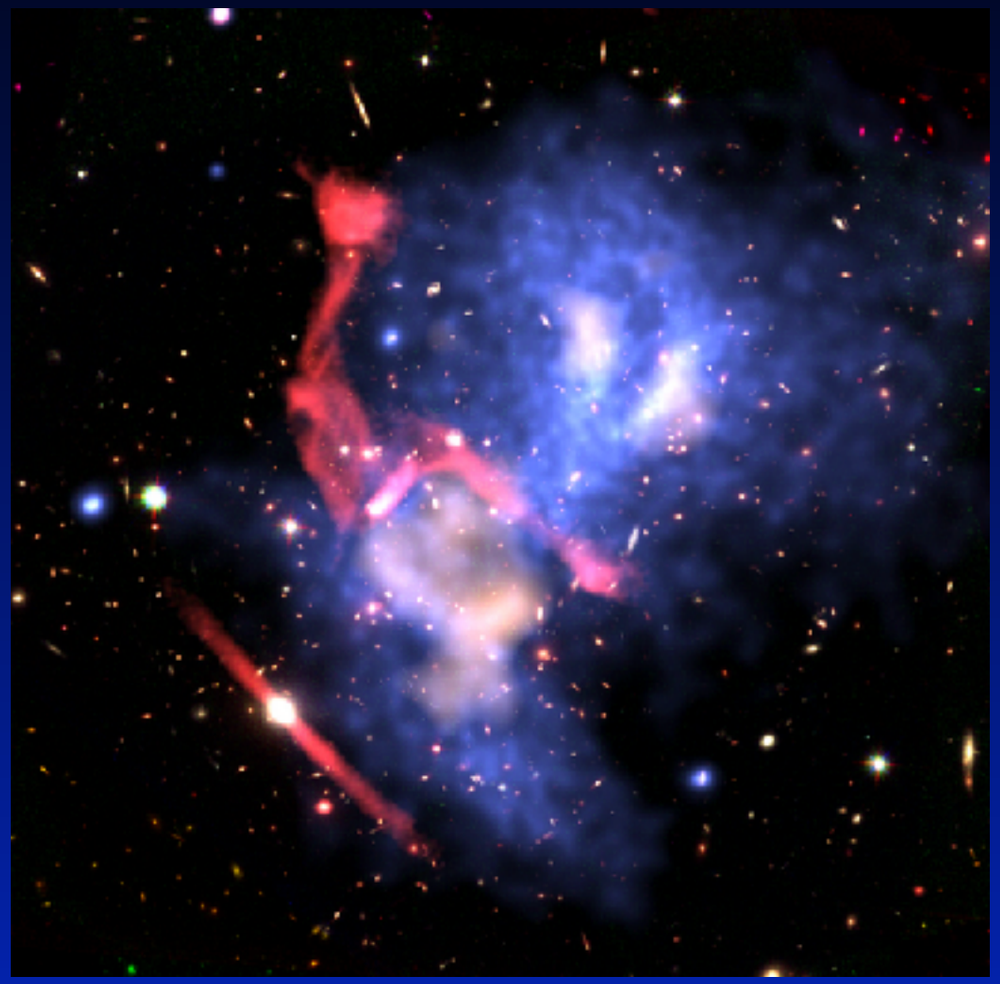
Millimetron?

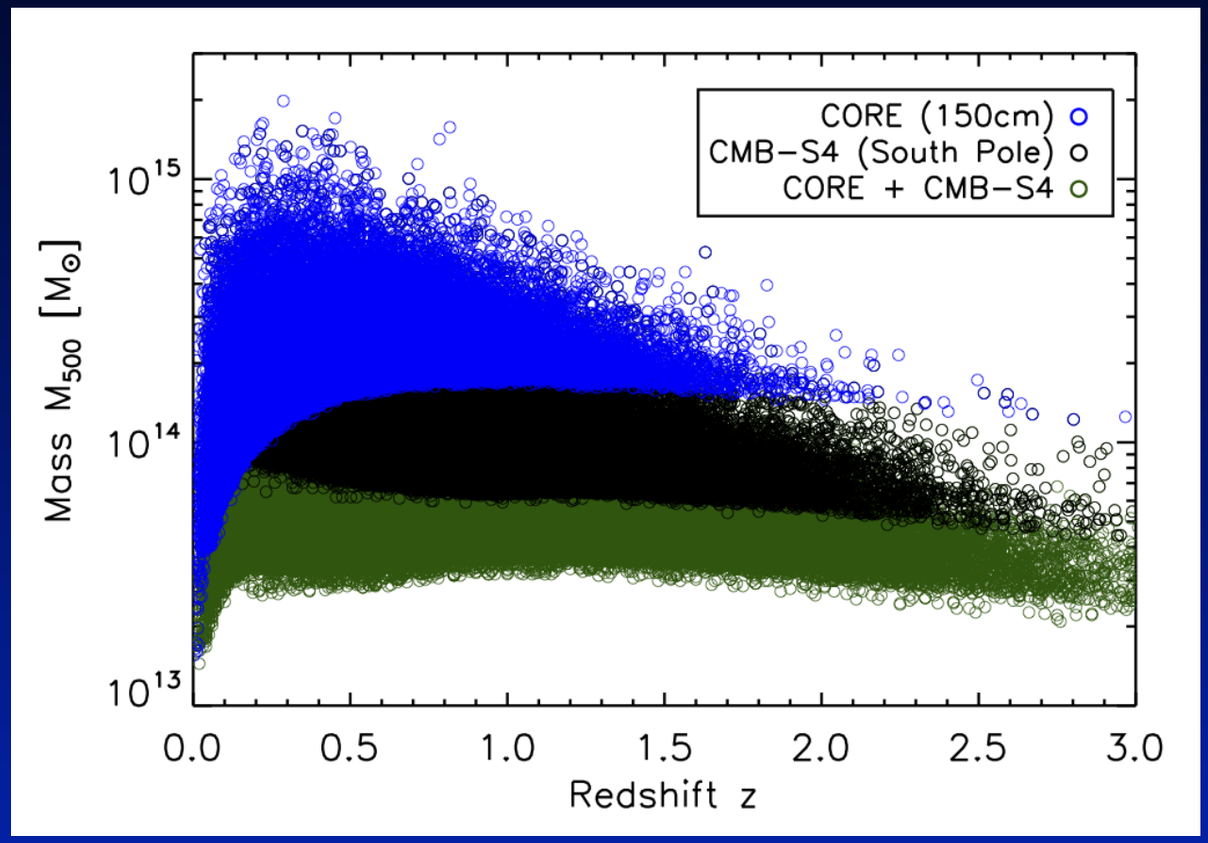
AtLAST



ALMA

Future SZ science opportunities





Individual cluster studies

⟷ ‘Gastrophysics’
⟷ state of the ICM, turbulence, profile reconstruction
⟷ feedback mechanisms and formation history

Cluster samples / stacking

⟷ still kind of ‘Blobology’
⟷ scaling relations
⟷ average properties
⟷ cosmology, lensing masses

What is the problem?

- Future high resolution & high sensitivity SZ observations

  → will allow us to address detailed questions about the state of the ICM

  → require accurate model for the SZ signal (e.g., *along different lines of sight...*)

  → which parameters actually determine the SZ signal?

SZpack available at: www.Chluba.de/SZpack

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- Computation of the SZ signal (*e.g., from a simulation or in stacking analysis*)

  → depends on the electron number density, temperature and velocity structure

  → *brute force* calculation pretty expensive & link to parameters complicated

  → previous analytic approximations have *limited applicability*

  → *variations* of the temperature and velocity structure not accounted for

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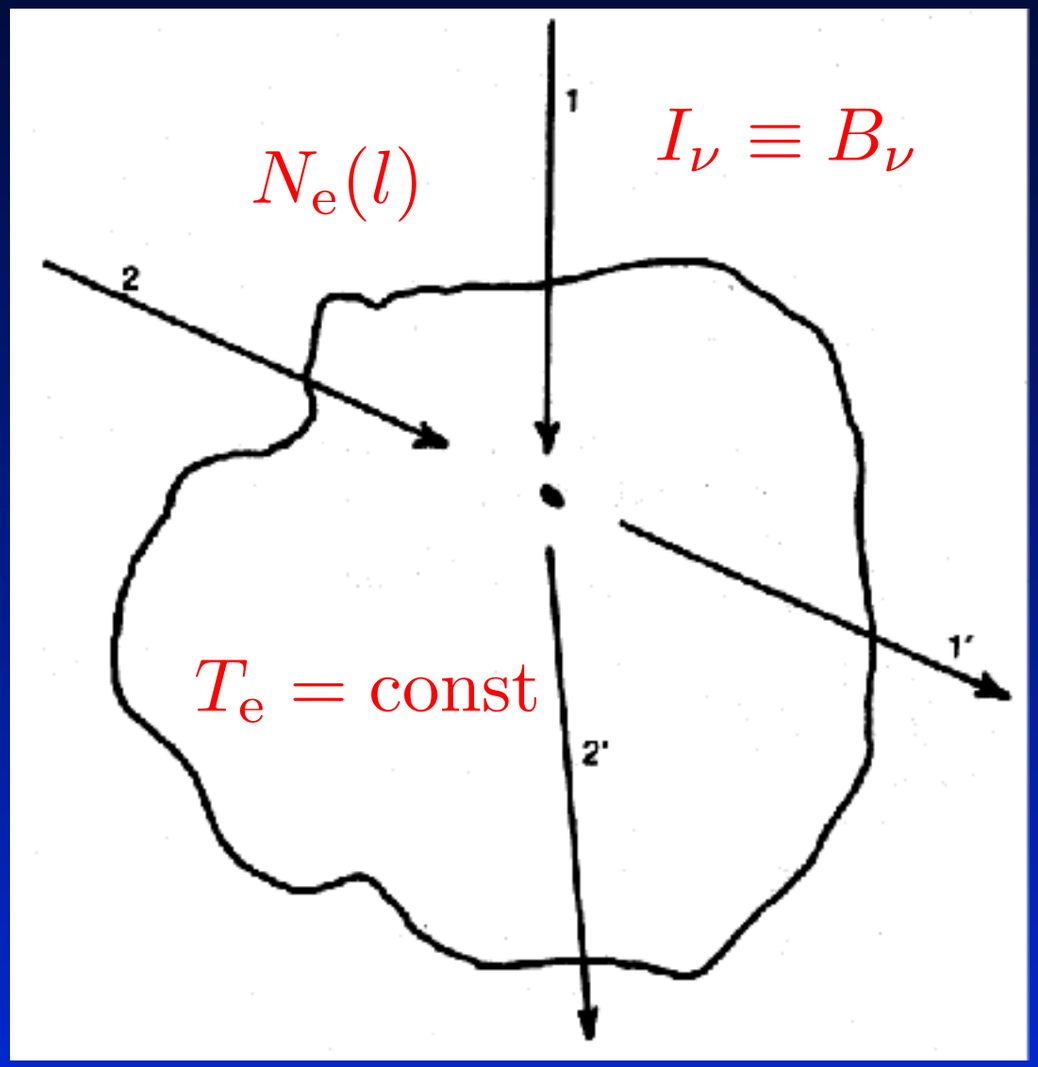
Thermal SZ effect for isothermal cluster



Scattering physics

- SZ signal depends on # of photons scattering *in* and *out* of the line-of-sight
- optically thin case $\Delta I_\nu \sim \tau\, S(\nu, T_{\rm e})$
- computation of $S(\nu, T_{\rm e})$ demanding

Sunyaev & Zeldovich, 1981

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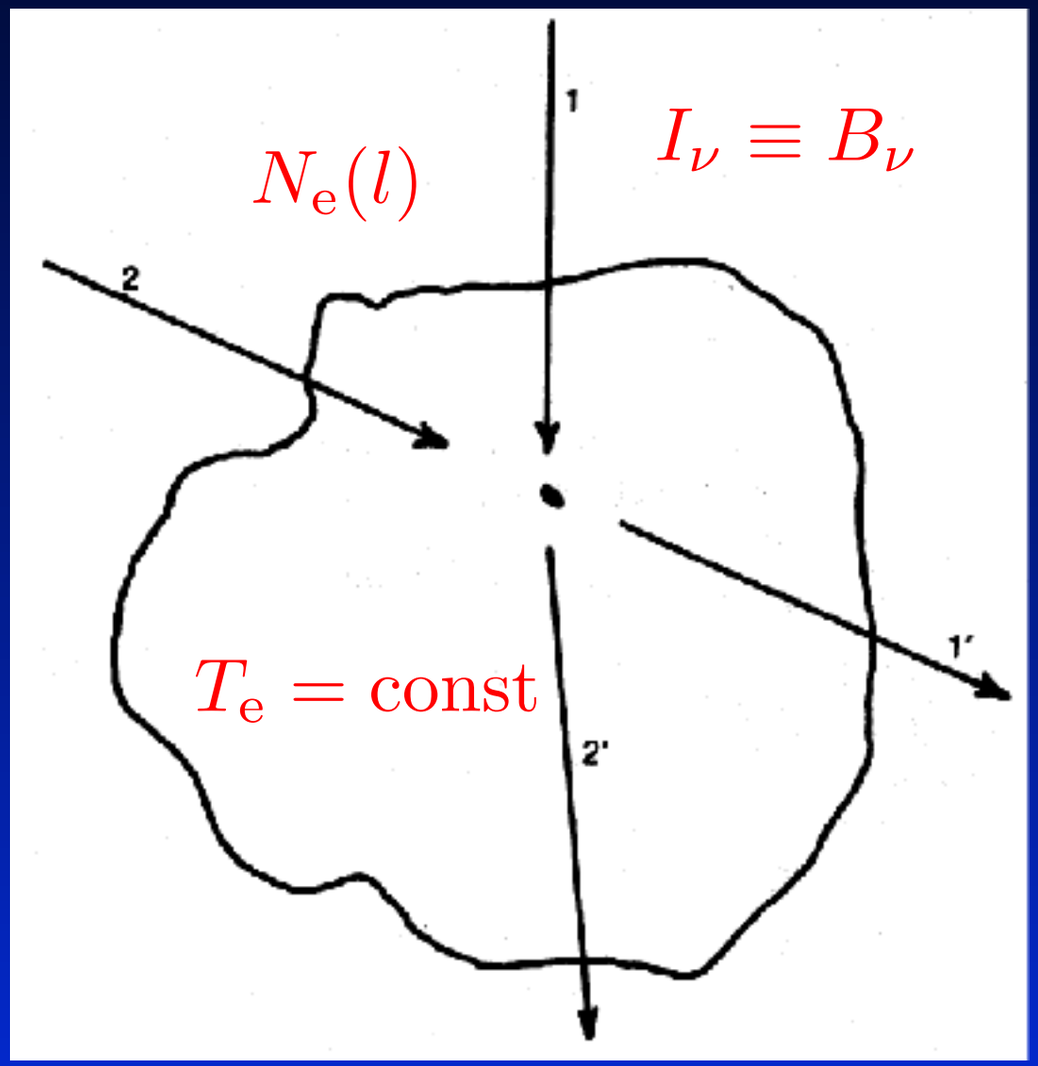

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Direct integration

- General for small # of scatterings
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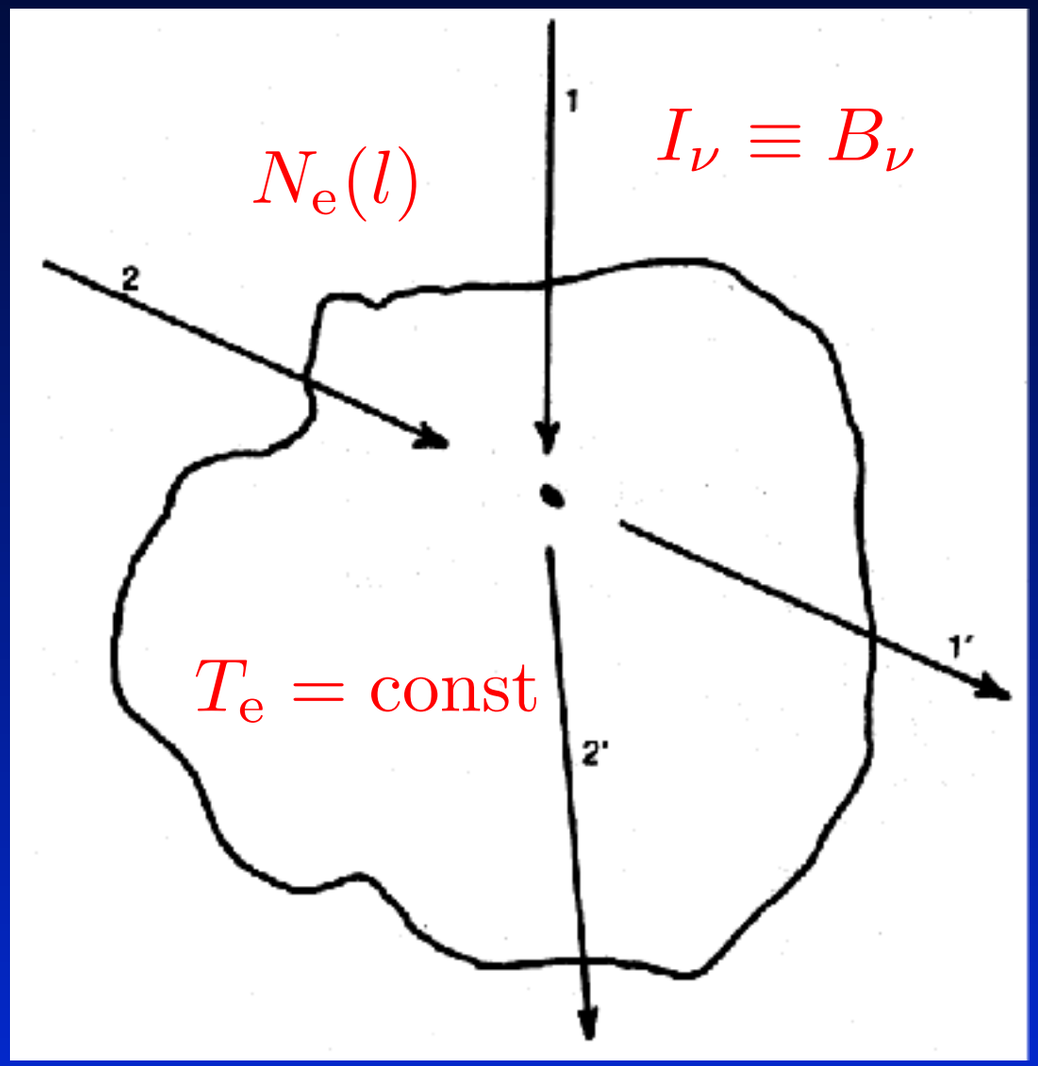

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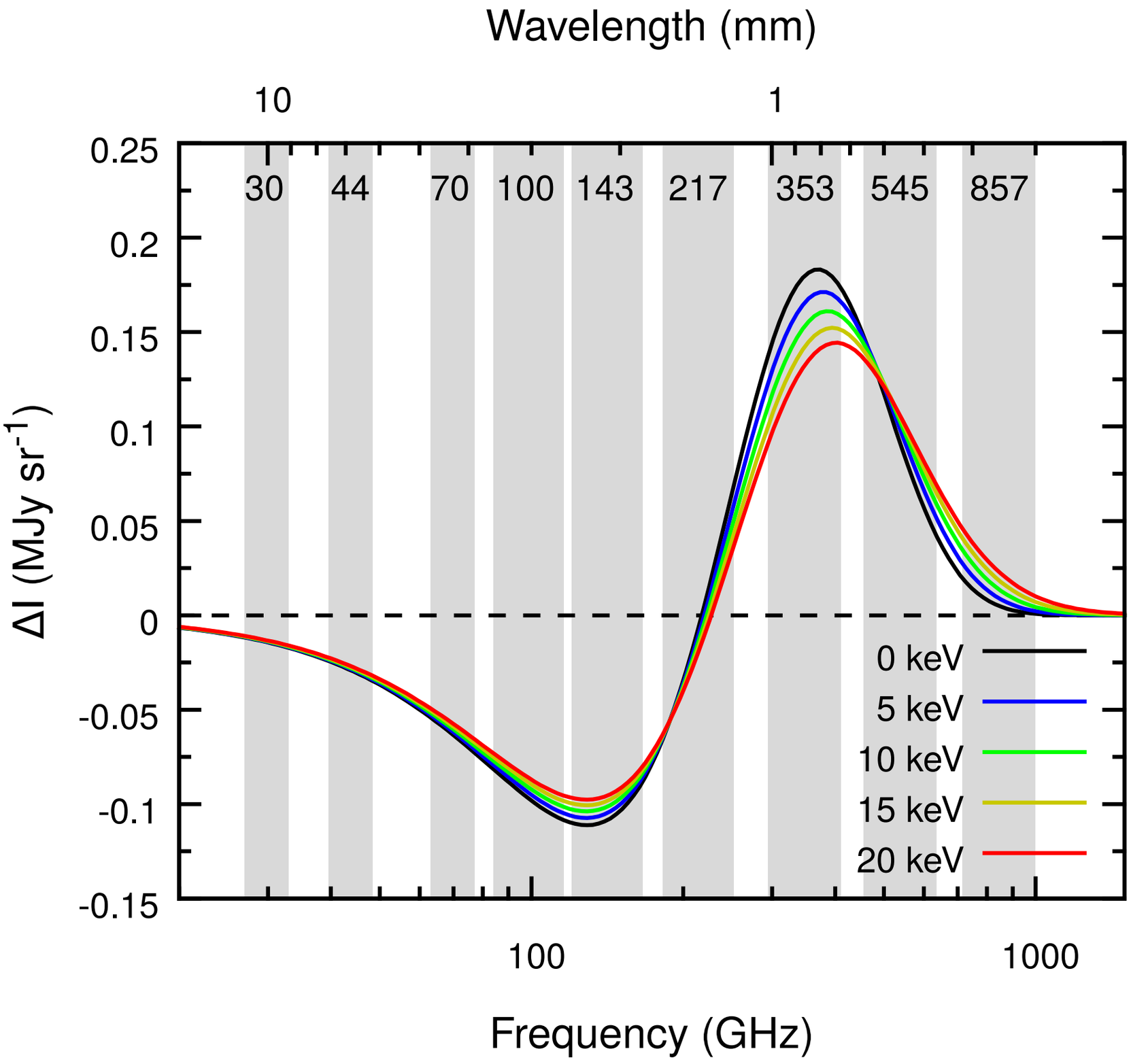
Approximate schemes

- Convergence issues
- Accuracy and user-interface
- flexibility

Effect of relativistic temperature corrections



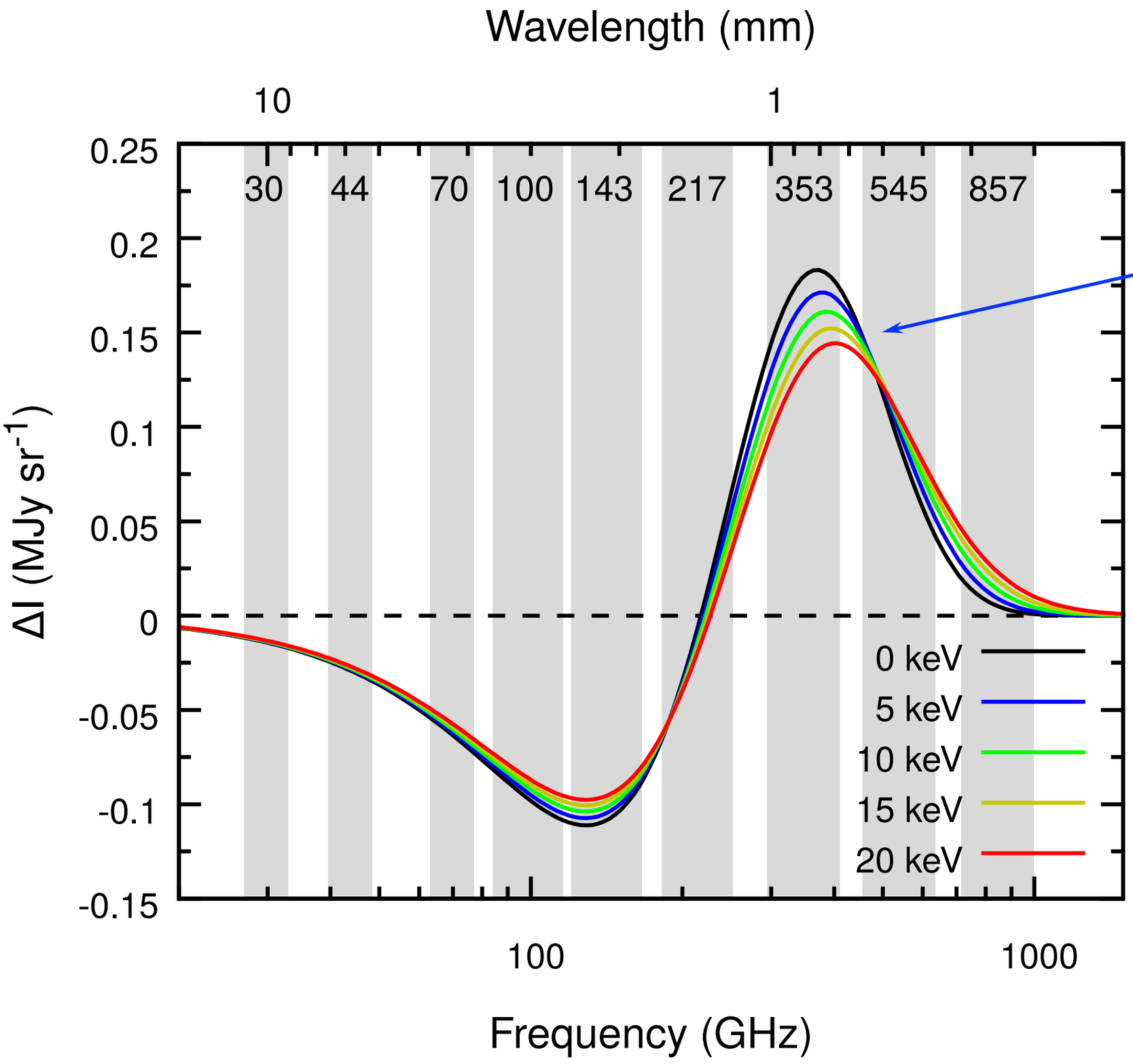
Relativistic velocities!

$$v_{\rm th} \simeq 0.1c$$

$$y = 10^{-4}$$

Erler et al, 2017, ArXiv:1709.01187

Effect of relativistic temperature corrections



A lot of information about rSZ from high frequency part

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RELATIVISTIC CORRECTIONS TO THE SUNYAEV-ZELDOVICH EFFECT FOR CLUSTERS OF GALAXIES

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$$\frac{\Delta n(X)}{n_0(X)} = \frac{y\theta_e X e^X}{e^X - 1}\,(Y_0 + \theta_e Y_1 + \theta_e^2 Y_2 + \theta_e^3 Y_3 + \theta_e^4 Y_4)\,,$$

$$Y_0 = -4 + \tilde{X}\,,$$

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Lots of terms just from nth derivative of Planckian…

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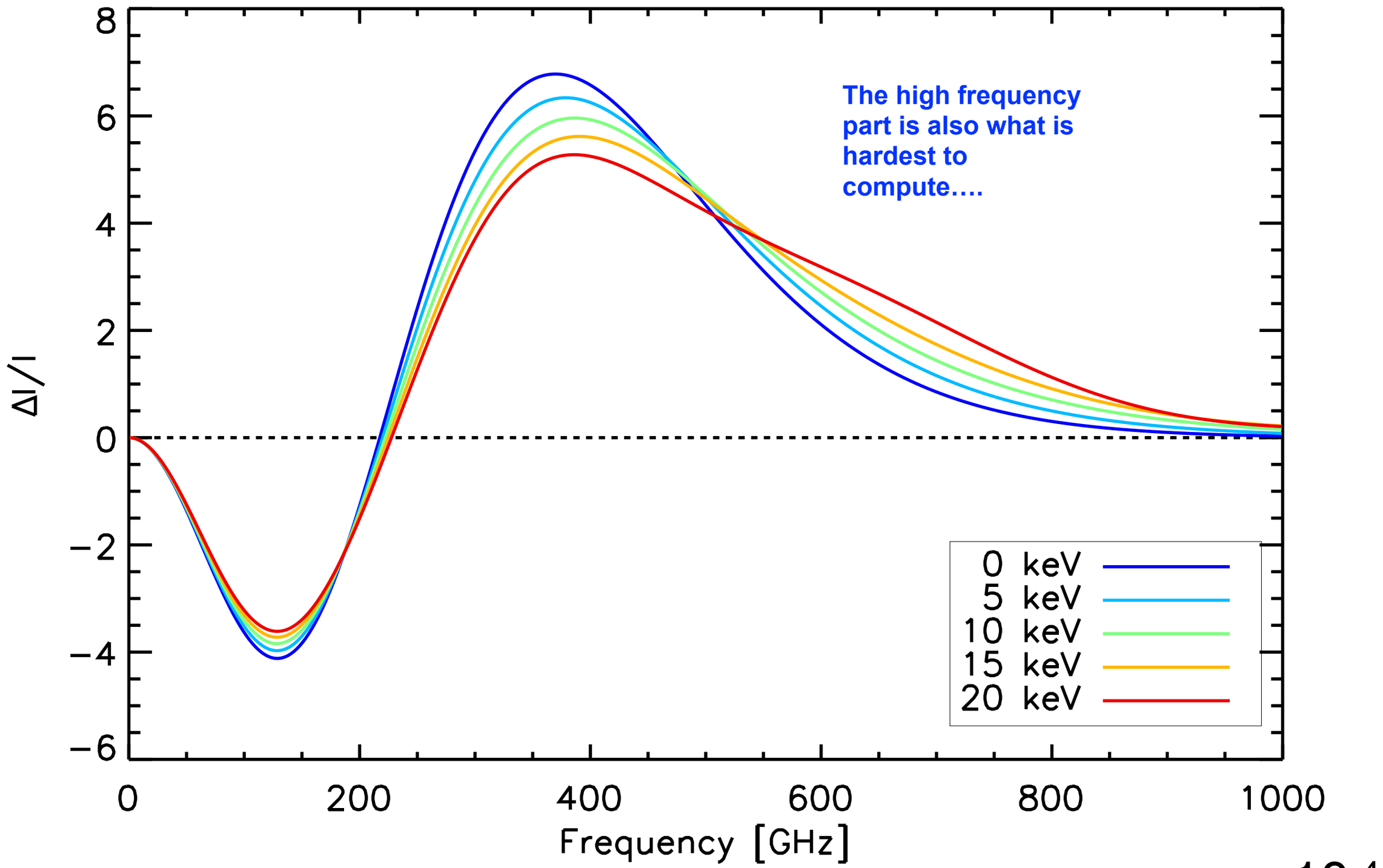

Hurier, 2017, ArXiv:1701.09020

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$$Y_0 = -4 + \tilde{X},$$

$$Y_1 = -10 + \frac{47}{2}\tilde{X} - \frac{42}{5}\tilde{X}^2 + \frac{7}{10}\tilde{X}^3 + \tilde{S}^2\left(-\frac{21}{5} + \frac{7}{5}\tilde{X}\right),$$

$$Y_2 = -\frac{15}{2} + \frac{1023}{8}\tilde{X} - \frac{868}{5}\tilde{X}^2 + \frac{329}{5}\tilde{X}^3 - \frac{44}{5}\tilde{X}^4 + \frac{11}{30}\tilde{X}^5 + \tilde{S}^2\left(-\frac{434}{5} + \frac{658}{5}\tilde{X} - \frac{242}{5}\tilde{X}^2 + \frac{143}{30}\tilde{X}^3\right) + \tilde{S}^4\left(-\frac{44}{5} + \frac{187}{60}\tilde{X}\right),$$

$$Y_3 = \frac{15}{2} + \frac{2505}{8}\tilde{X} - \frac{7098}{5}\tilde{X}^2 + \frac{14253}{10}\tilde{X}^3 - \frac{18594}{35}\tilde{X}^4 + \frac{12059}{140}\tilde{X}^5 - \frac{128}{21}\tilde{X}^6 + \frac{16}{105}\tilde{X}^7 + \tilde{S}^2\left(-\frac{7098}{10} + \frac{14253}{5}\tilde{X} - \frac{102267}{35}\tilde{X}^2 + \frac{156767}{140}\tilde{X}^3 - \frac{1216}{7}\tilde{X}^4 + \frac{64}{7}\tilde{X}^5\right) + \tilde{S}^4\left(-\frac{18594}{35} + \frac{205003}{280}\tilde{X} - \frac{1920}{7}\tilde{X}^2 + \frac{1024}{35}\tilde{X}^3\right) + \tilde{S}^6\left(-\frac{544}{21} + \frac{992}{105}\tilde{X}\right),$$

$$Y_4 = -\frac{135}{32} + \frac{30375}{128}\tilde{X} - \frac{62391}{10}\tilde{X}^2 + \frac{614727}{40}\tilde{X}^3 - \frac{124389}{10}\tilde{X}^4 + \frac{355703}{80}\tilde{X}^5 - \frac{16568}{21}\tilde{X}^6 + \frac{7516}{105}\tilde{X}^7 - \frac{22}{7}\tilde{X}^8 + \frac{11}{210}\tilde{X}^9 + \tilde{S}^2\left(-\frac{62391}{20} + \frac{614727}{20}\tilde{X} - \frac{1368279}{20}\tilde{X}^2 + \frac{4624139}{80}\tilde{X}^3 - \frac{157396}{7}\tilde{X}^4 + \frac{30064}{7}\tilde{X}^5 - \frac{2717}{7}\tilde{X}^6 + \frac{2761}{210}\tilde{X}^7\right) + \tilde{S}^4\left(-\frac{124389}{10} + \frac{6046951}{160}\tilde{X} - \frac{248520}{7}\tilde{X}^2 + \frac{481024}{35}\tilde{X}^3 - \frac{15972}{7}\tilde{X}^4 + \frac{18689}{140}\tilde{X}^5\right) + \tilde{S}^6\left(-\frac{70414}{21} + \frac{465992}{105}\tilde{X} - \frac{11792}{7}\tilde{X}^2 + \frac{19778}{105}\tilde{X}^3\right) + \tilde{S}^8\left(-\frac{682}{7} + \frac{7601}{210}\tilde{X}\right),$$

Lots of terms just from nth derivative of Planckian…

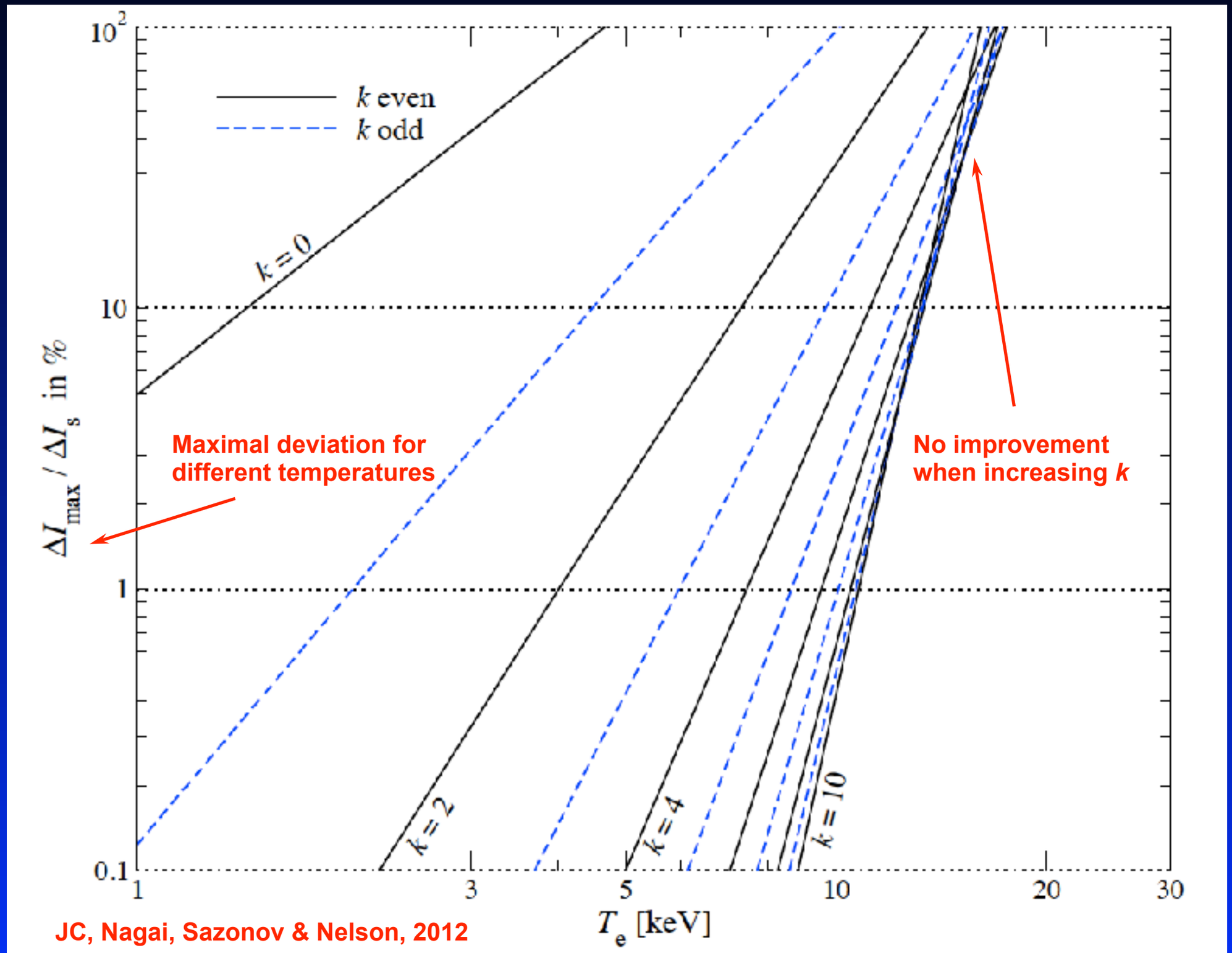
Asymptotic expansions

- Convergence slow at high-frequencies (Wien tail)
- Velocity terms add another dimension to the expansion
- All quite complicated and not very illuminating expressions

SZpack *(JC, Nagai, Sazonov & Nelson, 2012)*

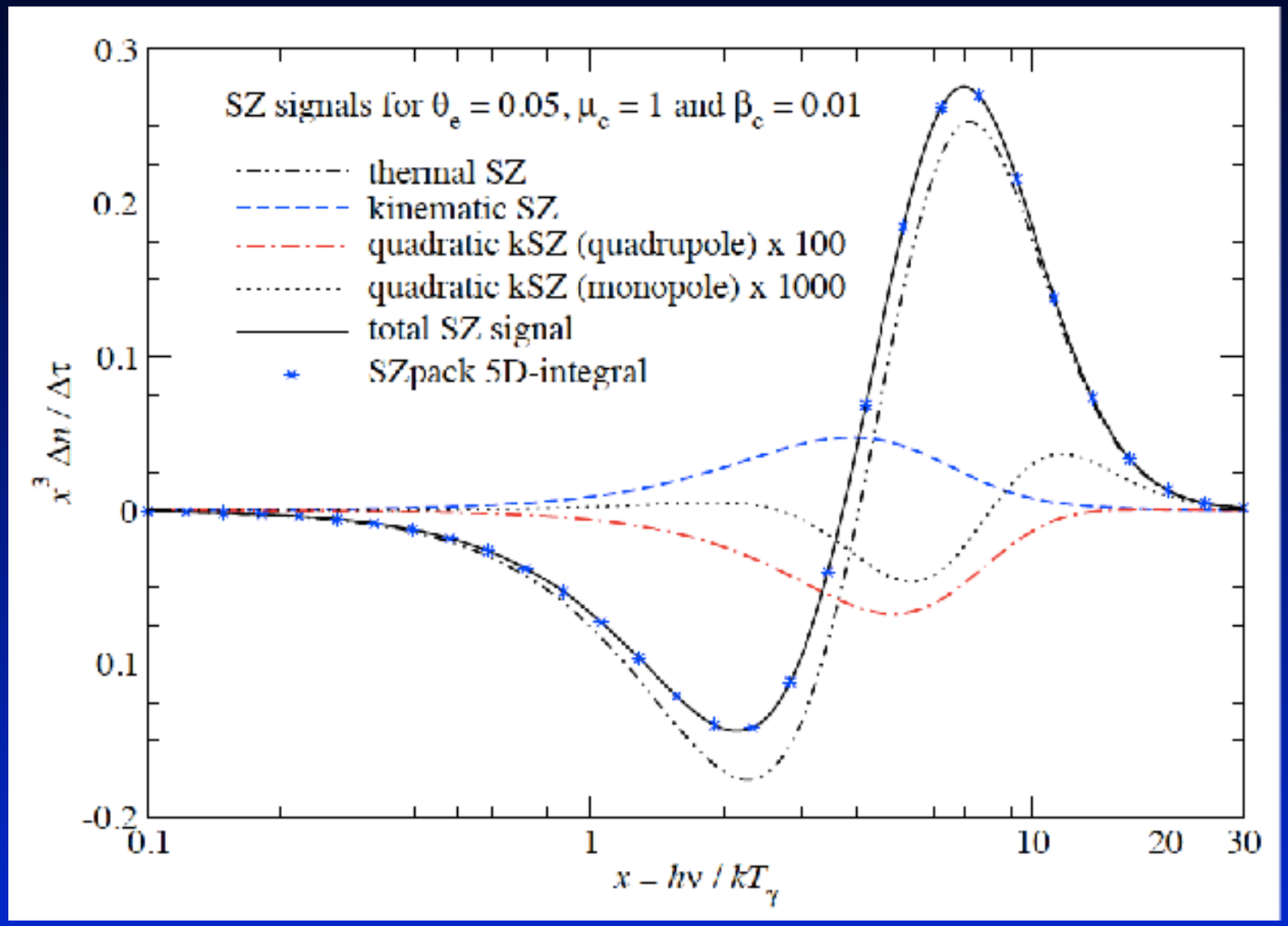
- Asymptotic expansions up to 10th order in T_e
- Motion of *cluster* and *observer* **(JC, Huetsi & Sunyaev, 2005)**
- Higher orders easy to add (but kind of pointless…)

Convergence of asymptotic expansion



JC, Nagai, Sazonov & Nelson, 2012

Thermal and kinematic SZ effect for isothermal cluster



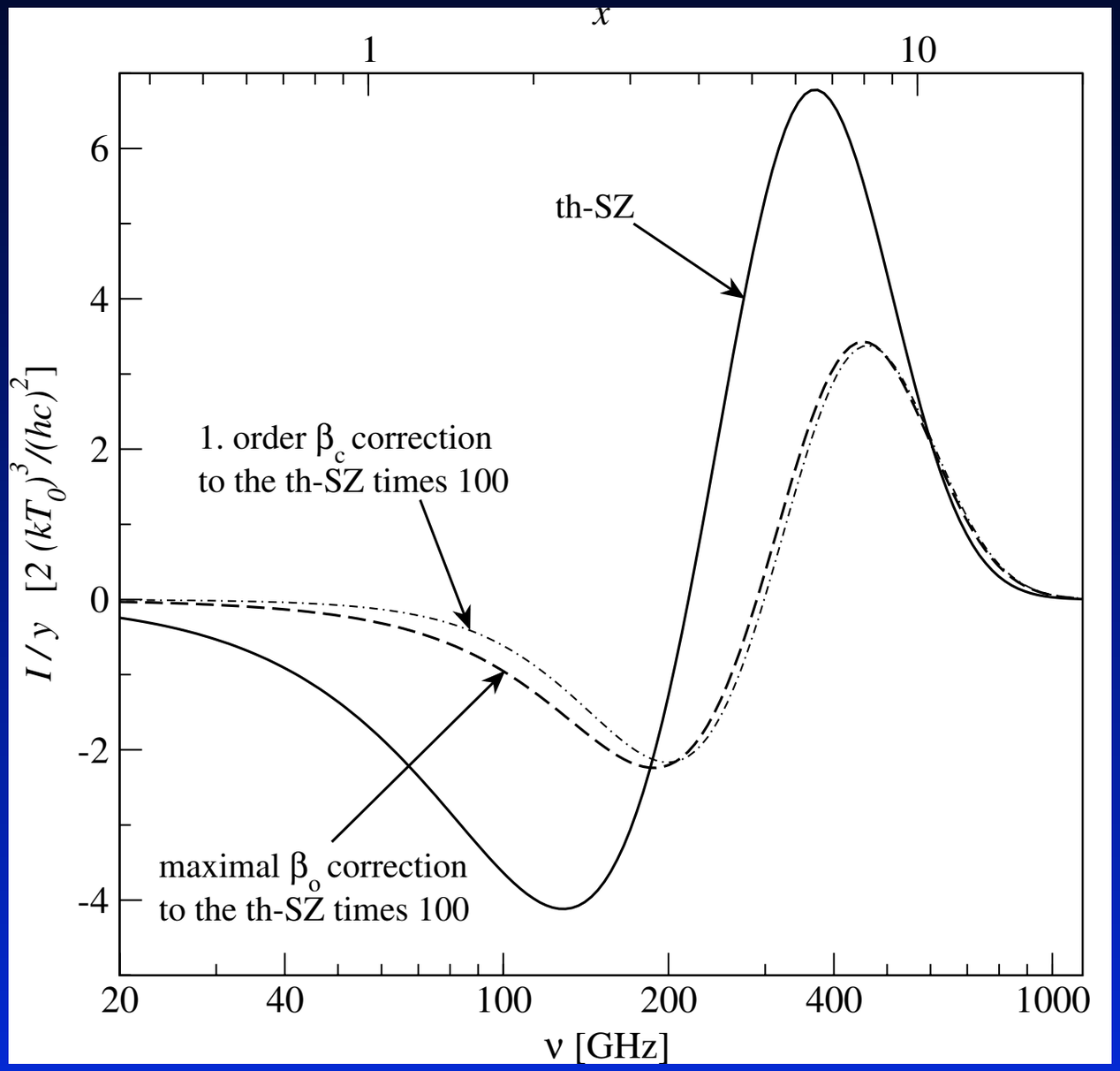
JC, Nagai, Sazonov & Nelson, 2012

New SZpack approach

- T_e derivatives analytically
- collision integral numerically for given reference temperature
- set of smooth basis functions that is motivated by scattering physics
- excellent convergence properties
- precise representation of SZ signal for $kT_e < 75$ keV and $x<30$

SZpack available at: www.Chluba.de/SZpack

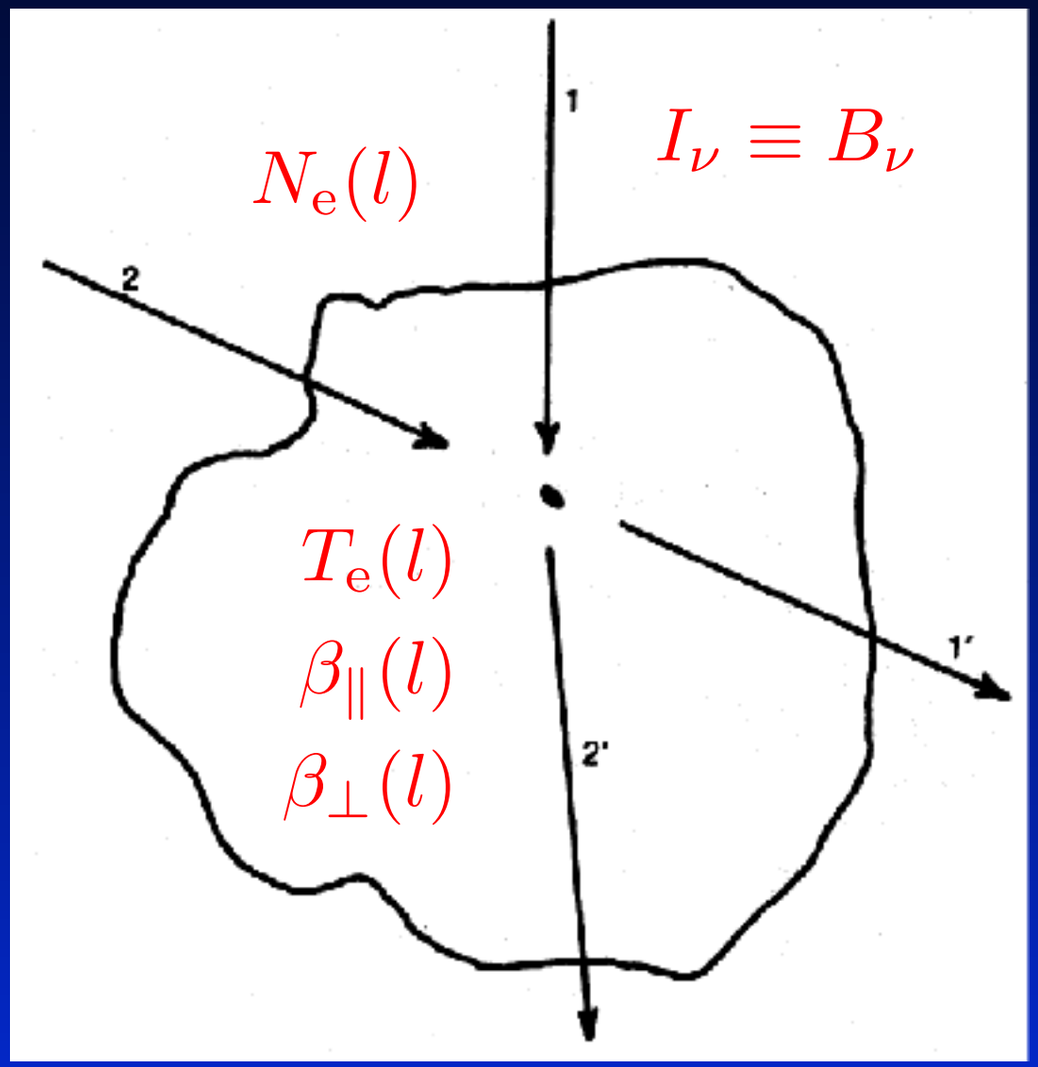
Motion of the observer



- Can be included by simple Lorentz-boost (SZpack)
- Well-known dependence on the sky
- Asymmetry in the cluster number counts
- Alternative way to constrain dipole
- Dominik's talk re systematic effects on observables

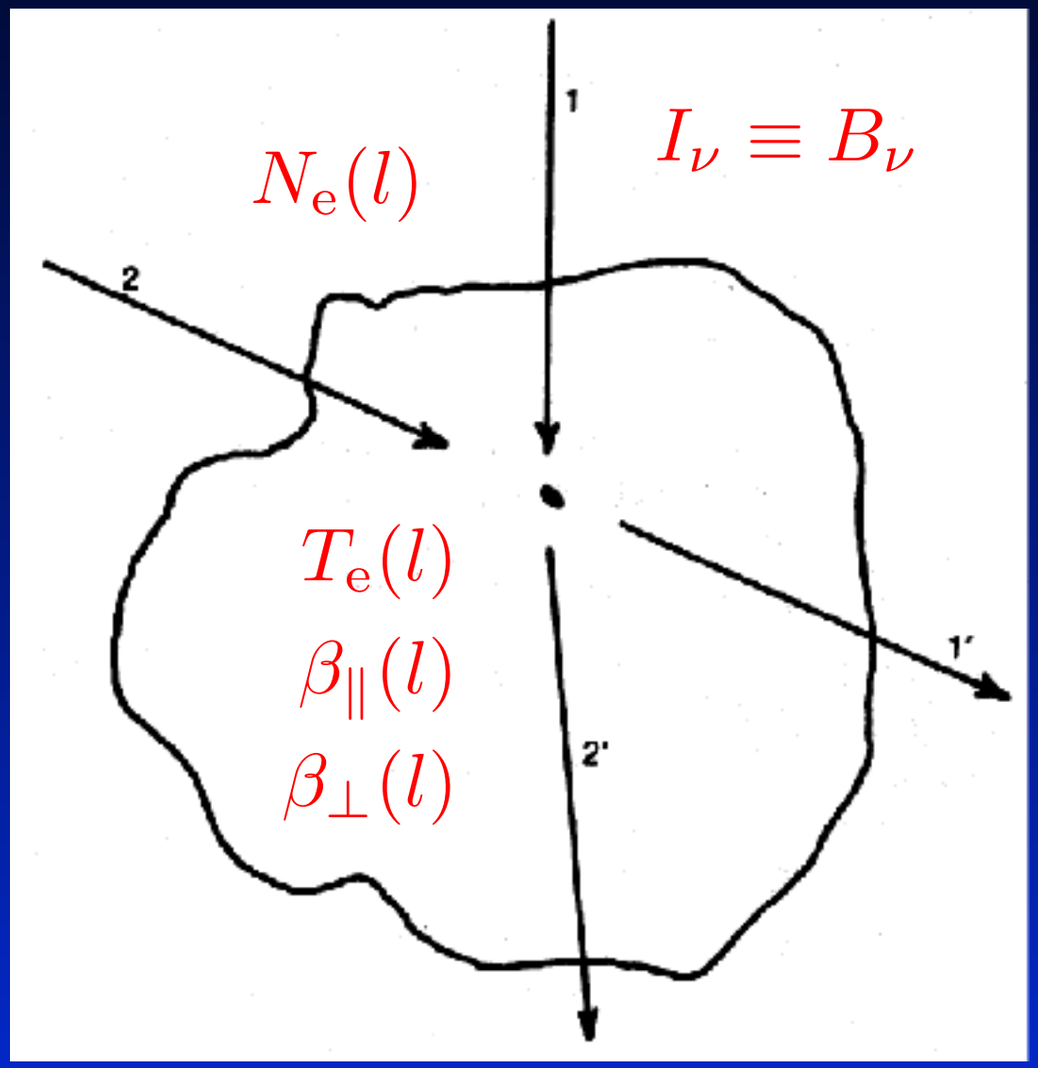
JC, Huetsi & Sunyaev, 2005

Non-isothermality and effect of internal motions



- SZ signal given by additional integral over line-of-sight
- problem becomes very demanding
- *Question*: what are the real parameters/observables?

Non-isothermality and effect of internal motions



- SZ signal given by additional integral over line-of-sight
- problem becomes very demanding
- *Question*: what are the real parameters/observables?

Simple Solution:

- perform expansion around mean values of main variables!
- *temperature-velocity moments* define new set of parameters:

$$p = \{\tau, T_{\rm e}, \omega^{(k)}, \sigma^{(k)}, \kappa^{(k)}, \beta_{\parallel}, \beta_{\perp}^2\}$$

$$S \approx S_{\rm iso}^{(0)} + S_{\rm iso}^{(2)}\,\omega^{(1)} + C_{\rm iso}^{(1)}\,\sigma^{(1)} + D_{\rm iso}^{(2)}\,\kappa^{(1)} + E_{\rm iso}^{(2)}\,\beta_{\rm c,\perp,SZ}^2 + \ldots,$$

all functions of $T_{\rm e}$, τ and $\beta_{\parallel}$

Average CMB spectral distortions in ΛCDM

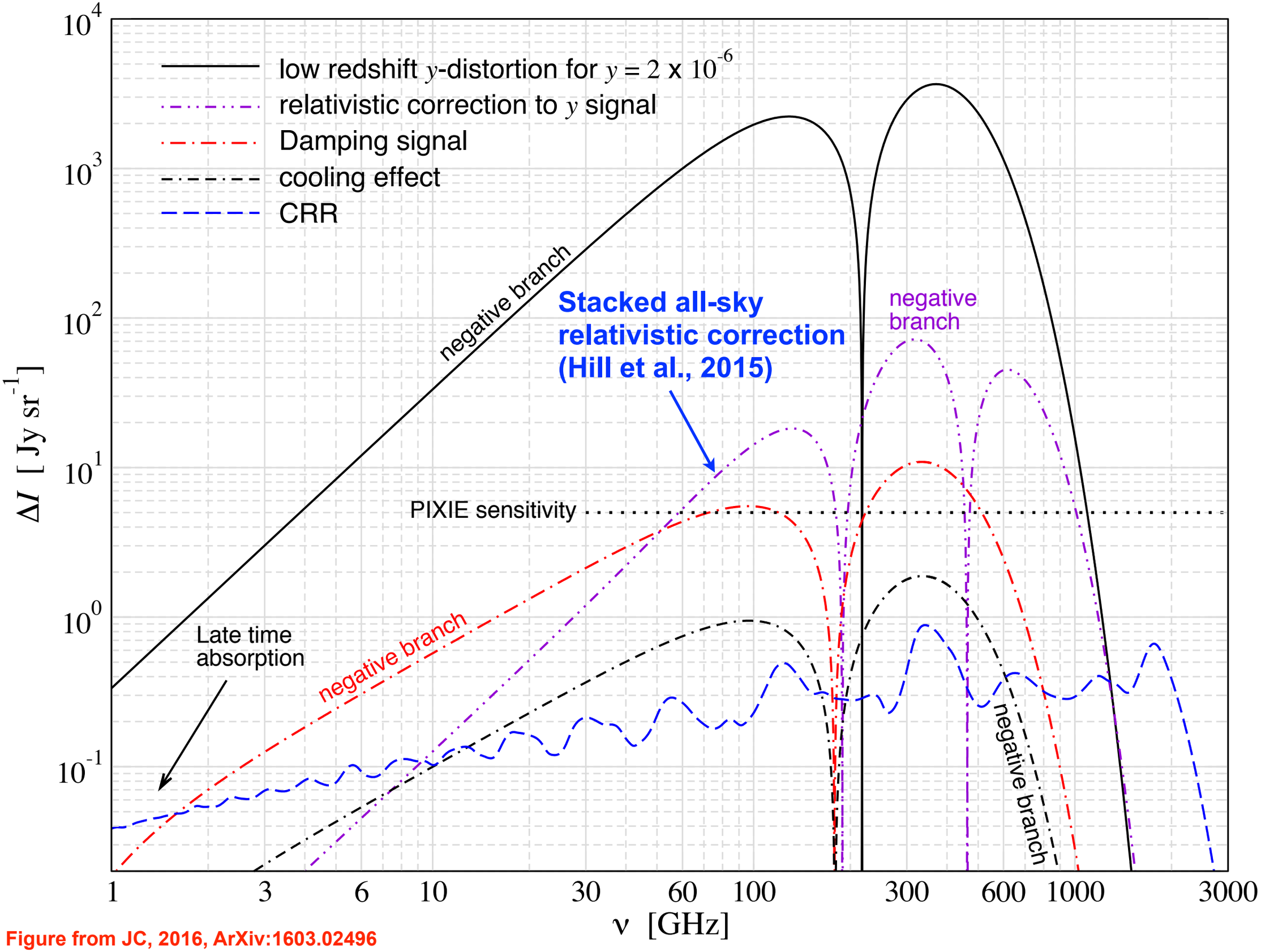
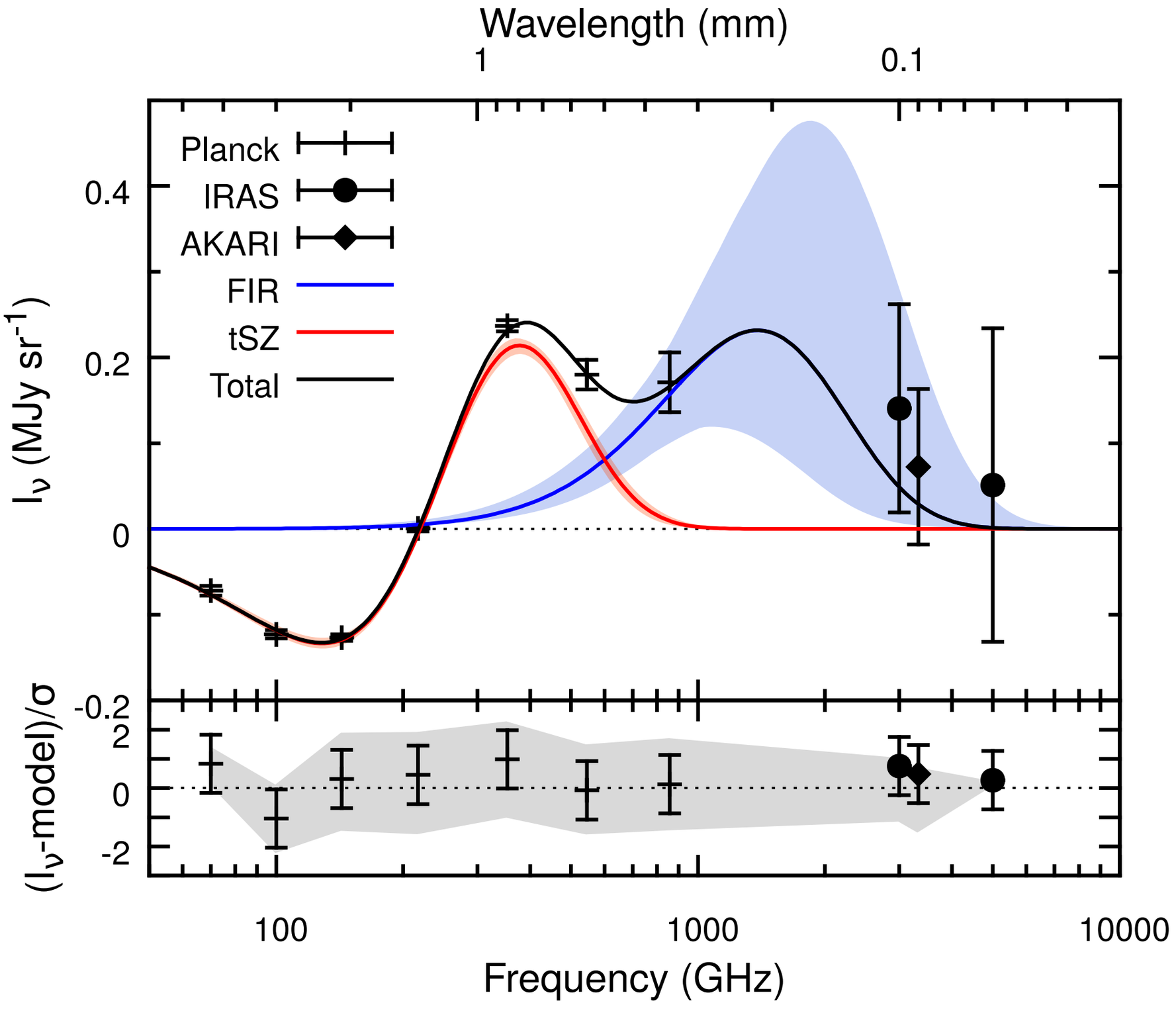


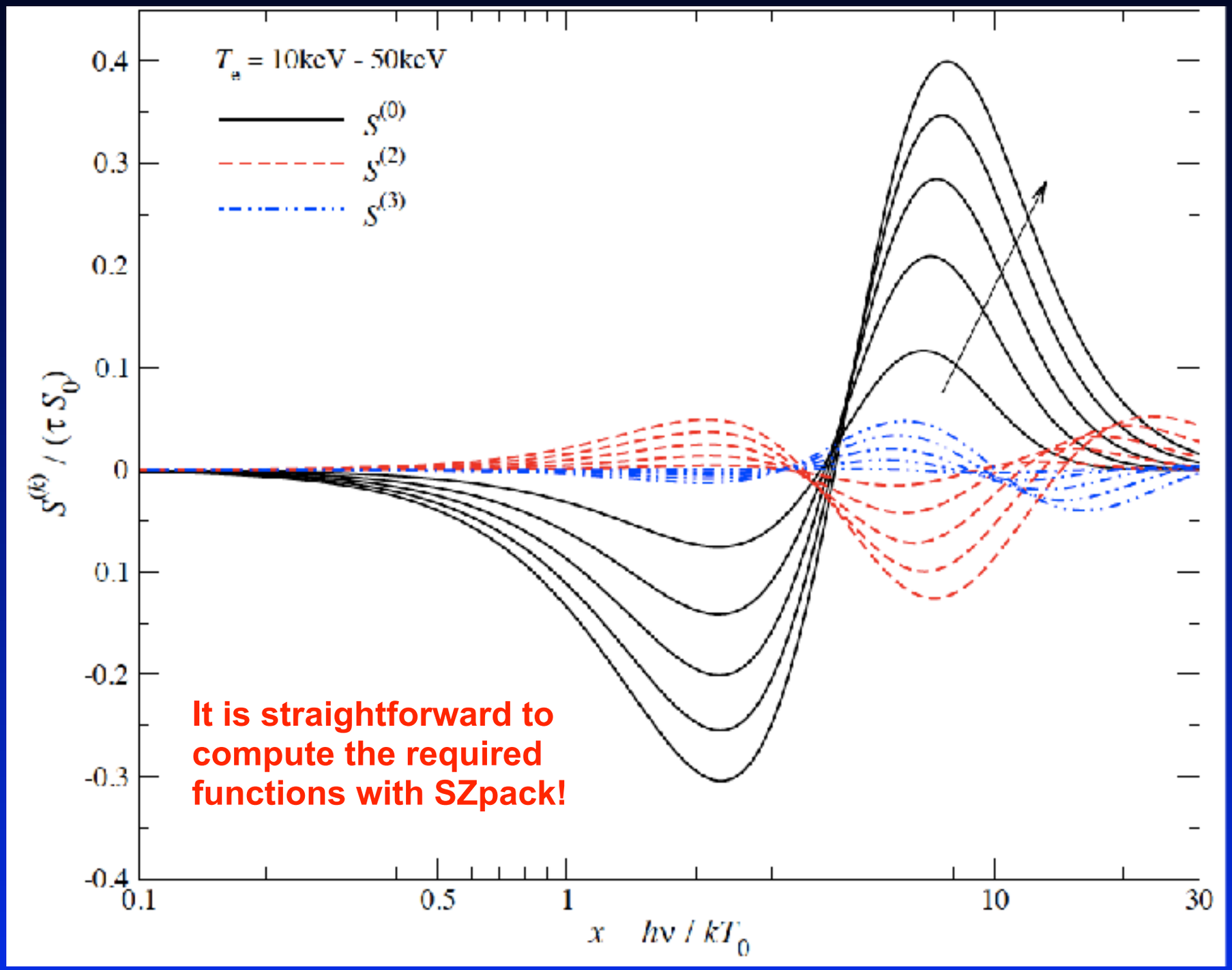
Figure from JC, 2016, ArXiv:1603.02496

Stacked SZ signal + foregrounds



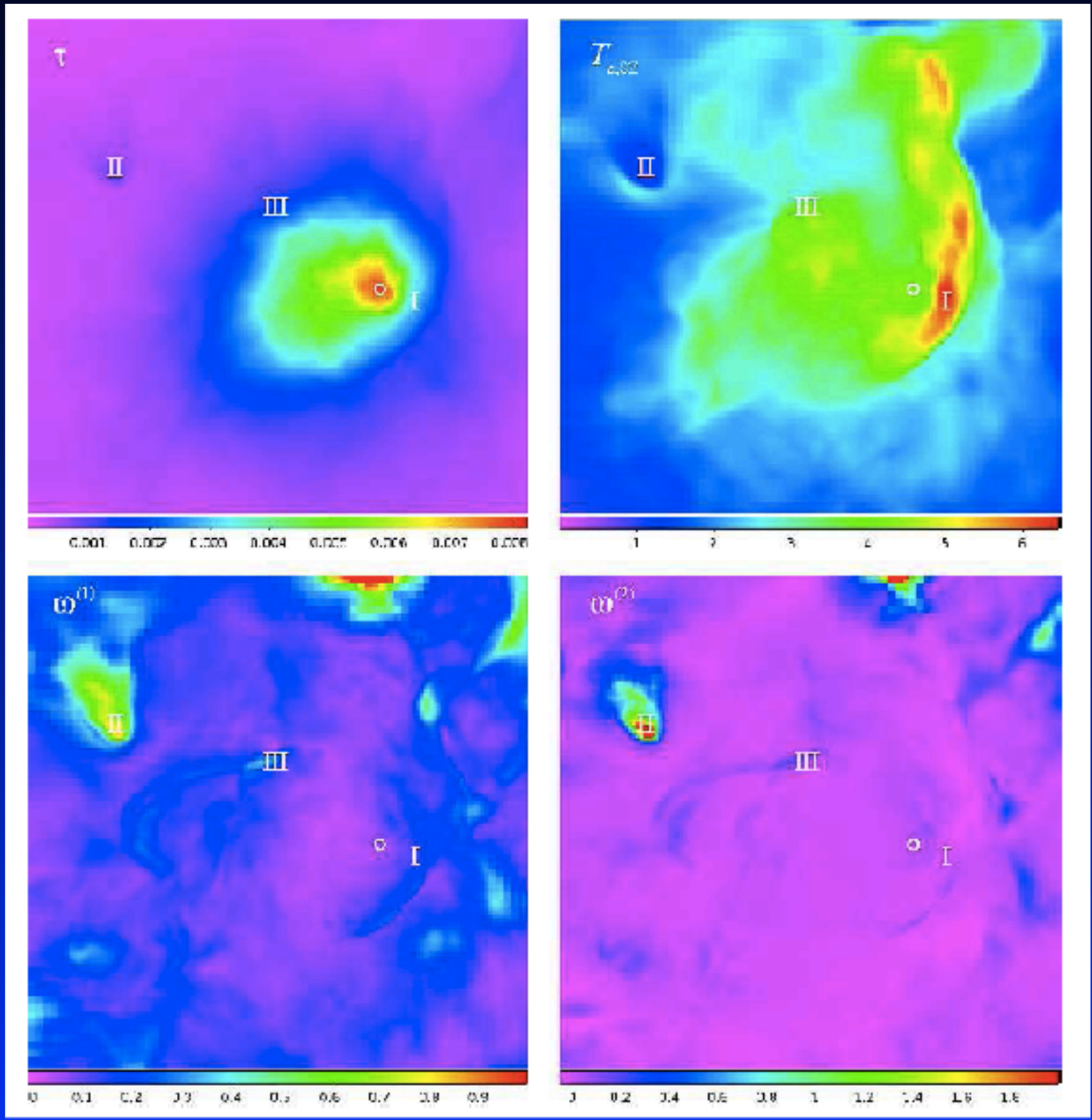
Erler et al, 2017, ArXiv:1709.01187

Basis functions to include non-isothermality



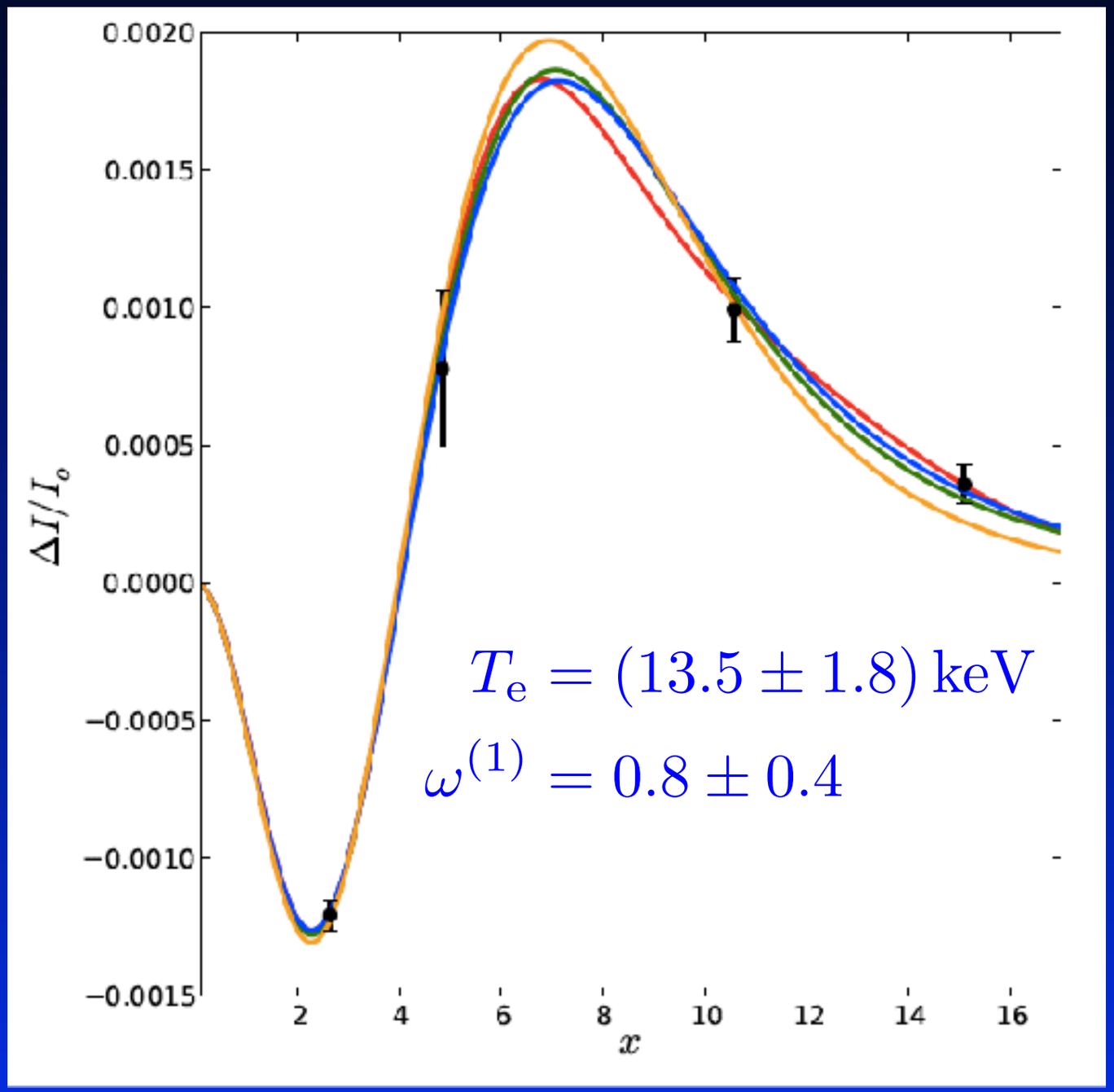
JC, Switzer, Nagai & Nelson, 2012

Can be directly used to compute signal morphologies



JC, Switzer, Nagai & Nelson, 2012

Analysis of Bullet cluster data (Prokhorov et al)

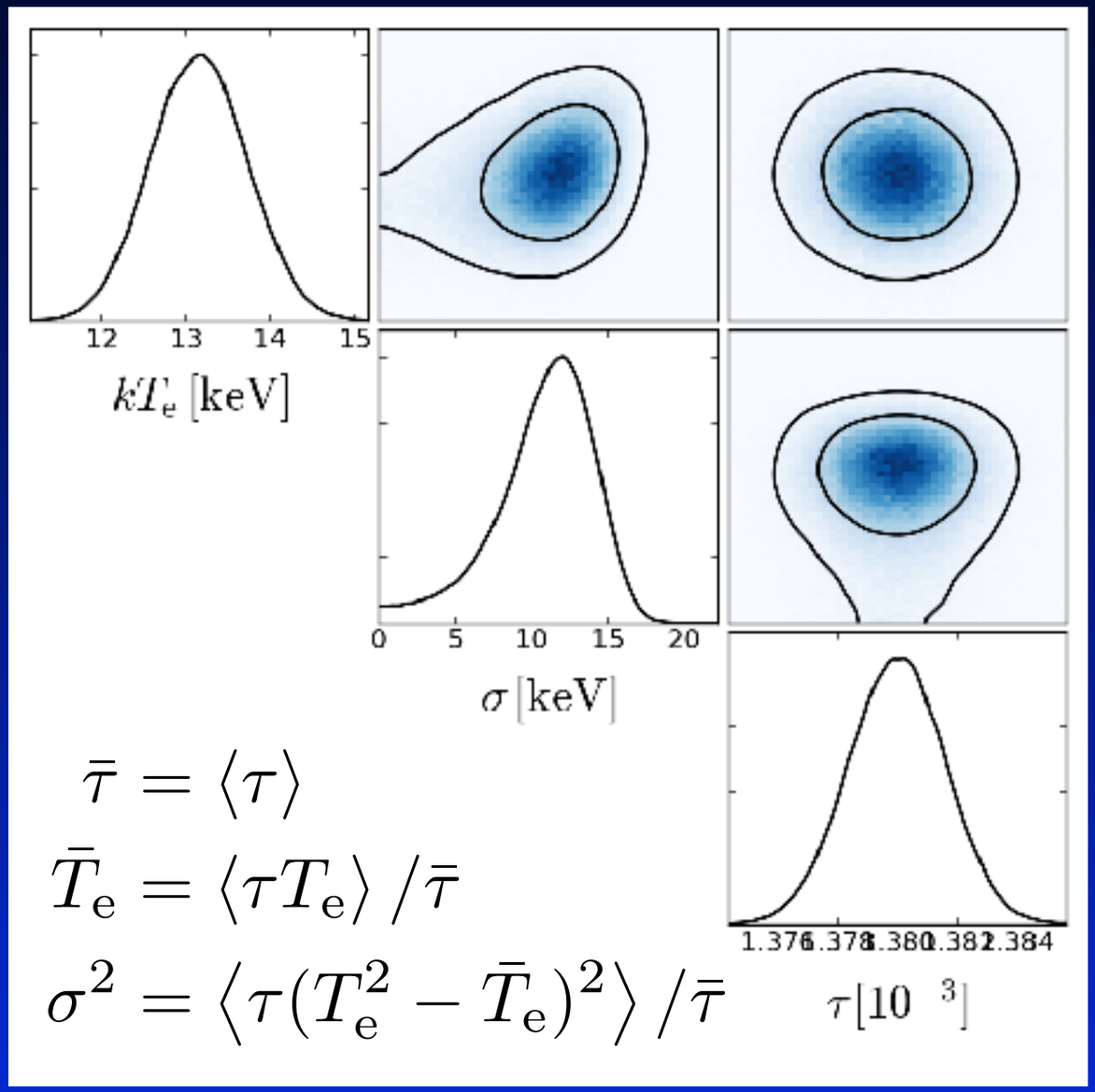


- MCMC analysis with *extended* set of parameters
- consistent analysis for mean and dispersion
- isothermal model in tension with data (orange)
- two-temperature (green) and simple dispersion (blue) models indistinguishable
- high frequency spectrum very important
- Itoh expansion (red) in this case not meaningful although at current level of precision consistent with data...

JC, Switzer, Nagai & Nelson, 2012

Dependence of weighting scheme (Bullet Cluster)

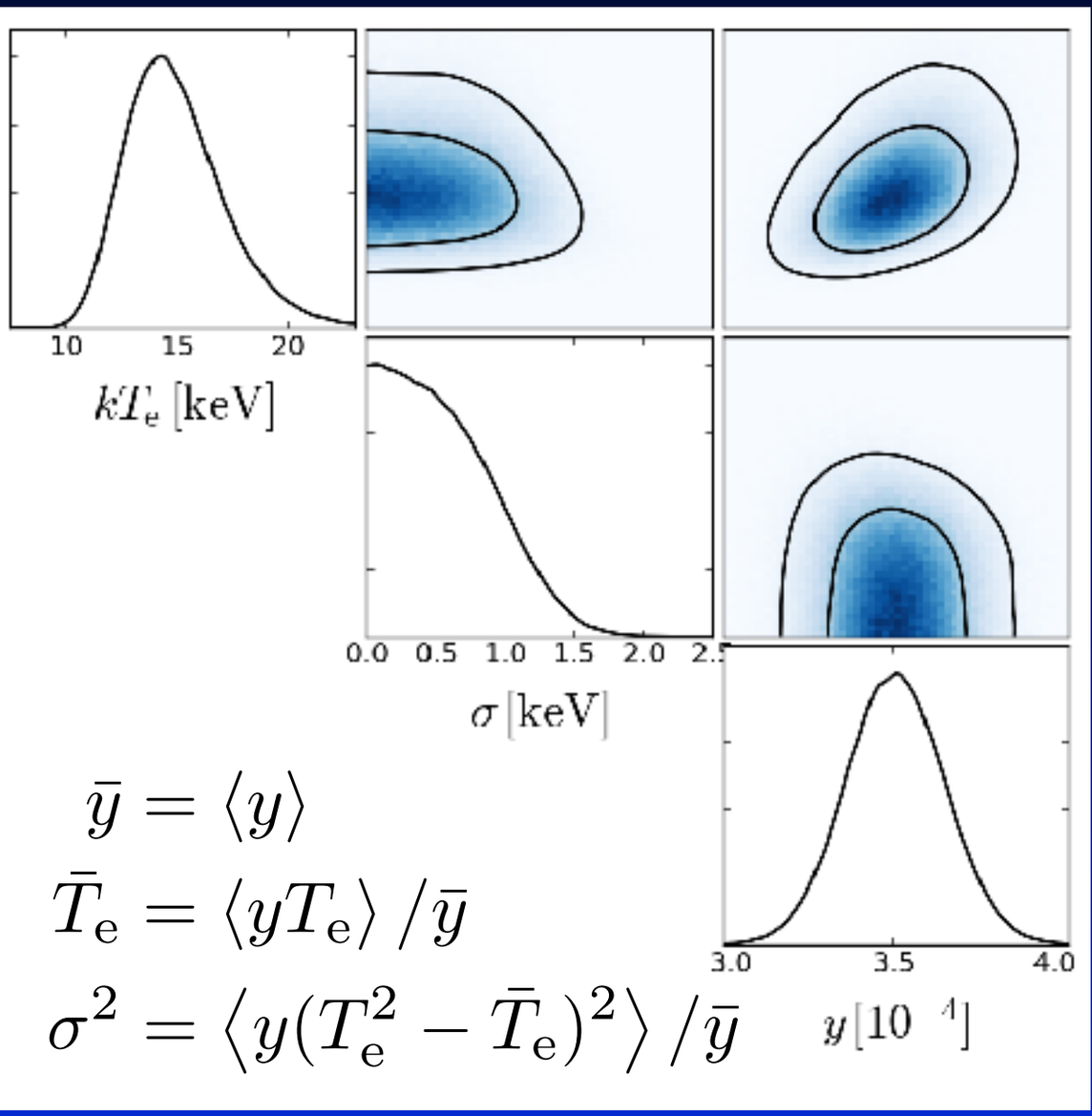
τ-weighted analysis



$$\bar{\tau} = \langle \tau \rangle$$
$$\bar{T}_\mathrm{e} = \langle \tau T_\mathrm{e} \rangle / \bar{\tau}$$
$$\sigma^2 = \langle \tau (T_\mathrm{e}^2 - \bar{T}_\mathrm{e})^2 \rangle / \bar{\tau}$$

- Prior on τ-needed (from X-ray)
- Indication for dispersion

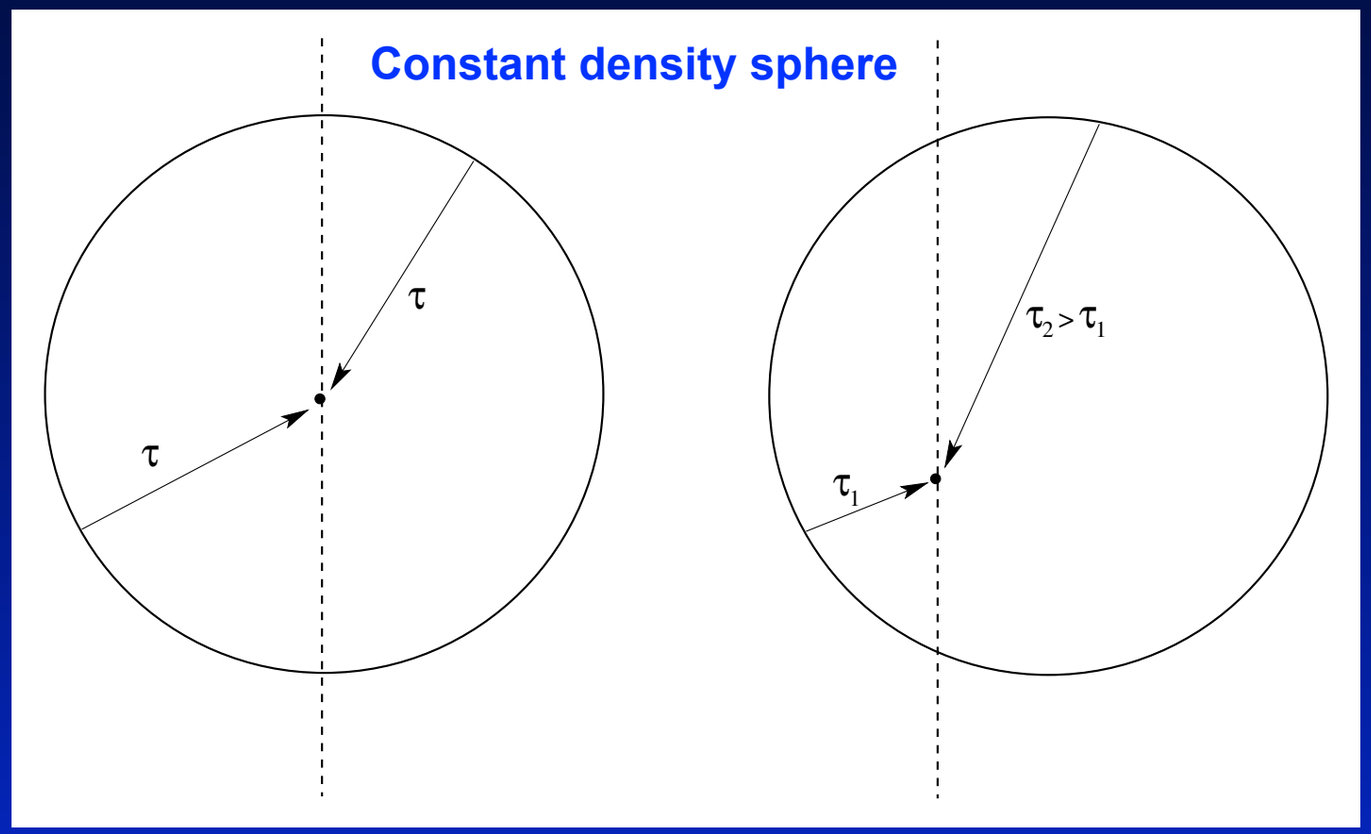
y-weighted analysis



$$\bar{y} = \langle y \rangle$$
$$\bar{T}_\mathrm{e} = \langle y T_\mathrm{e} \rangle / \bar{y}$$
$$\sigma^2 = \langle y (T_\mathrm{e}^2 - \bar{T}_\mathrm{e})^2 \rangle / \bar{y}$$

- No external prior
- upper limit on dispersion

Multiple-scattering SZ signal



- previous analysis neglected anisotropy of local radiation field
- even in simplest cases this is inconsistent
- treatment using *anisotropic scattering*
- local *monopole* through *octupole* relevant
- relevant correction remains very small….
- One could learn about the *local anisotropy* in the density of the medium

JC, Dai & Kamionkowski, 2013, ArXiv:1308.5969
JC & Dai, 2013, ArXiv:1309.3274

Conclusions/Question

- SZpack can deal with physically relevant cases
- what is the typical temperature dispersion etc?
  → use cosmological sims to estimate these effects
  → quantify possible biases to temperature measurements
- how feasible will it be to use *multiple scattering* correction to learn about structure of the ICM?
- combination with X-ray lines (*Athena*)?
- What does *polarization* tell us?
- add *non-thermal electron populations*
- *Extension* of method to X-rays
- Already applied to *CMB foregrounds* (see JC, Hill & Abitbol, 2017)

SZpack available at: www.Chluba.de/SZpack