Today:

Chapter 1.5,1.6 &1.7
Stochastic nature of radiation

Relation of 'special' functions to Gaussian and Poissonian distributions
OAF2 chapter 5.1 &
Num Res chapter 6.1 & 6.2

Error propagation
OAF2 chapter 5.2

What is the size of the fluctuations in the radiation field?

Bose-Einstein statistics

Particles are distributed in

h^3 momentum space boxes

there are $Z \propto 4\pi p^2 dp$ boxes

For each energy bin i there are n_i particles, Z_i boxes ≡ Z_i+1 boundaries of which Z_i-1 are "movable"

$$W(n_i) = \frac{(n_i + Z_i - 1)!}{n_i!(Z_i - 1)!}$$

this is also in chapter 6.2 of Lena

WHEN CONSIDERING ALL ENERGIES i

$$N = \sum_{i=1}^{\infty} n_i$$ TOTAL NUMBER OF PARTICLES

$$W = \Pi_{i=1}^{\infty} W(n_i)$$ TOTAL NUMBER OF POSSIBLE DISTRIBUTIONS

$$S \equiv k \ln(W)$$

MAXIMISE ENTROPY S

HENCE

$$\frac{d \ln W}{dn_i} = 0$$

Remember Taylor expansion:

$$W(x+\Delta x) = W(x) + \frac{dW(x)}{dx}\Delta x + \frac{1}{2}\frac{d^2W(x)}{d^2x}\Delta x^2$$

cf. equation 1.28 & 1.37 Lecture notes

Derivation of eq. 1.41 on black board

DEFINITIONS

n_i NUMBER OF PHOTONS WITH ENERGY i

n_{ν_k} OCCUPATION FRACTION

$N(\nu)$ VOLUME PHOTON DENSITY (PHOTONS PER SECOND PER HERTZ PER UNIT VOLUME)

$n(\nu)$ SPECIFIC PHOTON FLUX (PHOTONS PER SECOND PER HERTZ)

$\overline{P}(\nu)$ RADIATION POWER

$$\overline{P}(\nu) = h\nu\,\overline{n}(\nu)$$

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$n(\nu)$ SPECIFIC PHOTON FLUX (PHOTONS PER SECOND PER HERTZ) $\bar{n}(\nu) = 0.5\frac{c}{4\pi}\bar{N}(\nu)A_e\Omega$

$\overline{P}(\nu)$ RADIATION POWER $\overline{P}(\nu) = h\nu\,\overline{n}(\nu)$

Planck distribution for photons $\epsilon_i = h\nu$

Fluctuations in the number of photons per s per Hz

$$\Delta n^2(\nu) = n_\nu \left(1 + \frac{1}{exp(\frac{h\nu}{kT}) - 1}\right)$$

Power: $P(\nu) = h\nu \; n(\nu)$

Two limits:

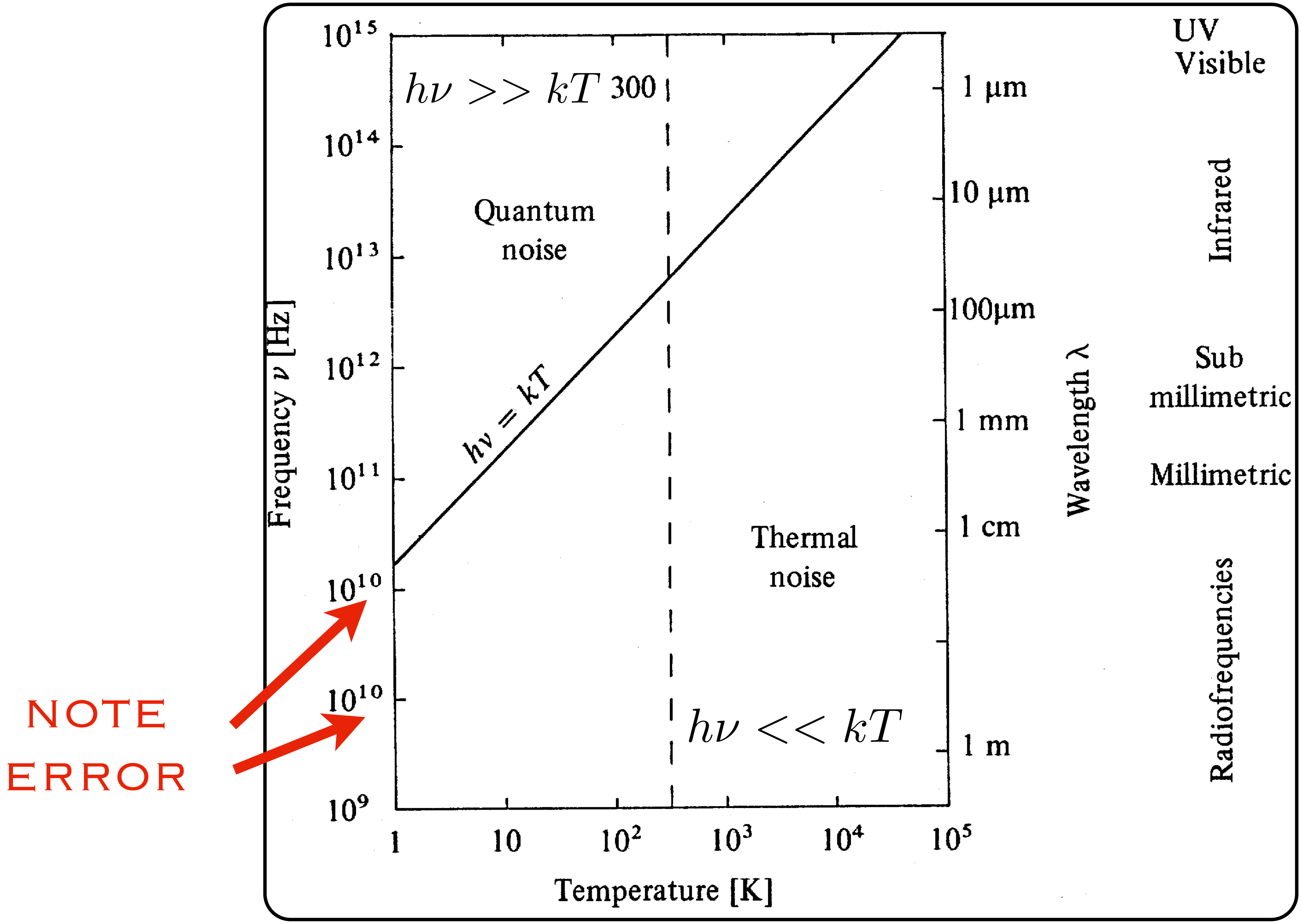
$h\nu >> kT$ Quantum limit

$$\frac{1}{e^\epsilon - 1} \rightarrow 0 \;\; \text{for}\, \epsilon >> 1 \qquad \overline{\Delta n^2}(\nu) = \bar{n}(\nu)$$

$h\nu << kT$ Thermal limit $\overline{\Delta P^2}(\nu) = \bar{P}^2(\nu)$

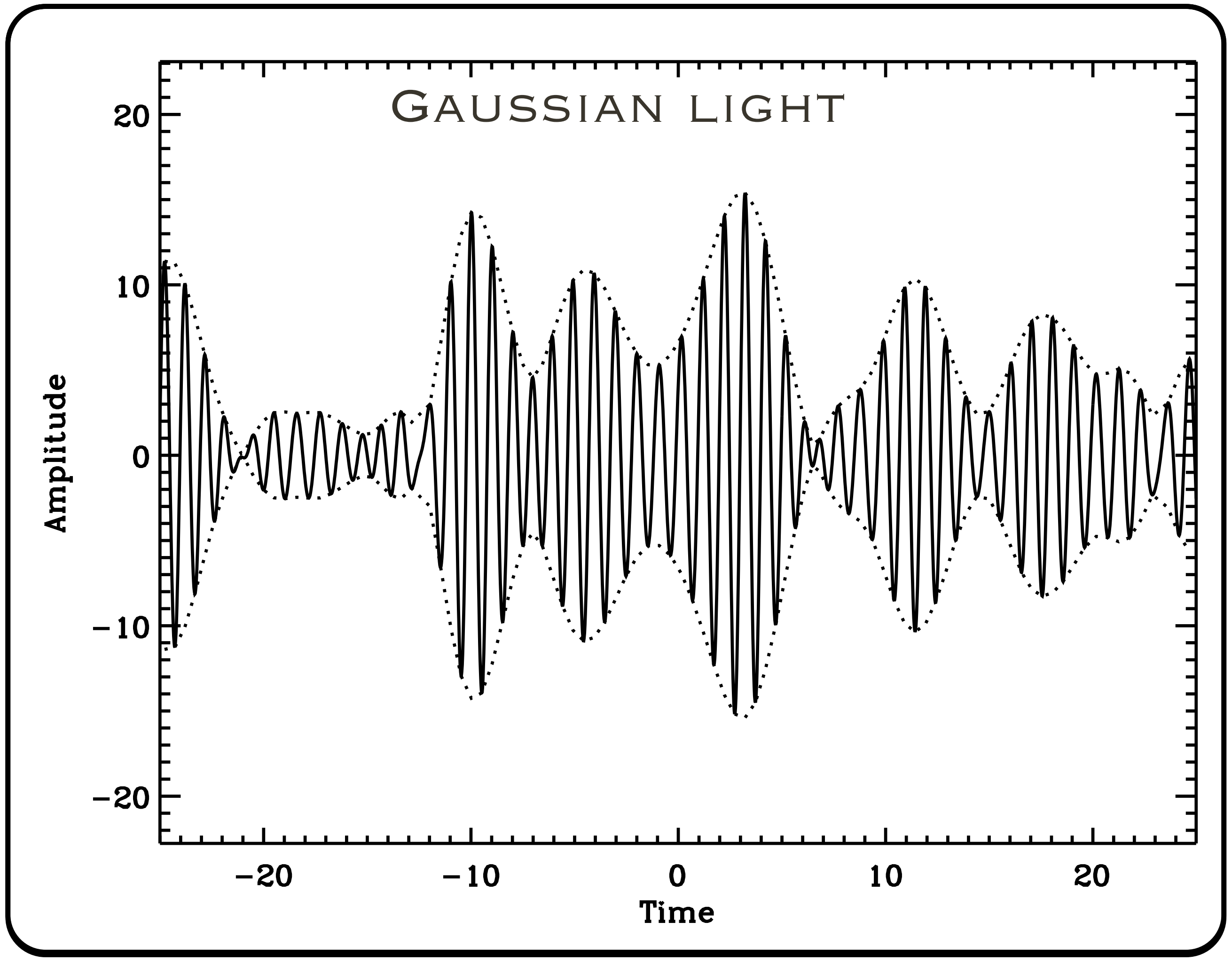
$$\frac{1}{e^\epsilon - 1} \rightarrow \epsilon \;\; \text{for}\, \epsilon << 1 \qquad \overline{P}(\nu) = kT$$

Difference between thermal and quantum limit explains the difference between the principles behind/limitations of radio and optical/X-ray observations



Stochastic description of radiation in the thermal limit

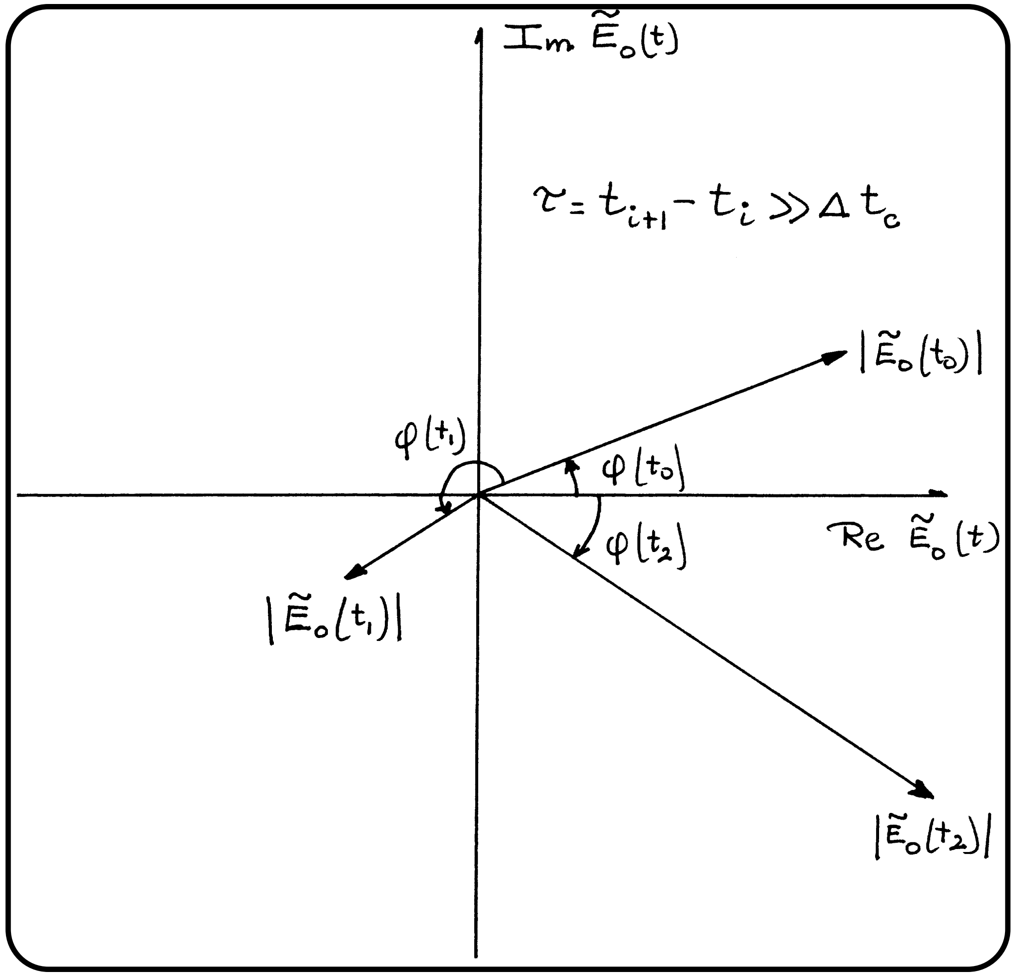
quasi-monochromatic radiation from a thermal source



Describe electric field by $\tilde{E}(t) = \tilde{E_0}(t)\ e^{2\pi i\bar{\nu}t}$

where $\tilde{E_0}(t)$ is the phasor

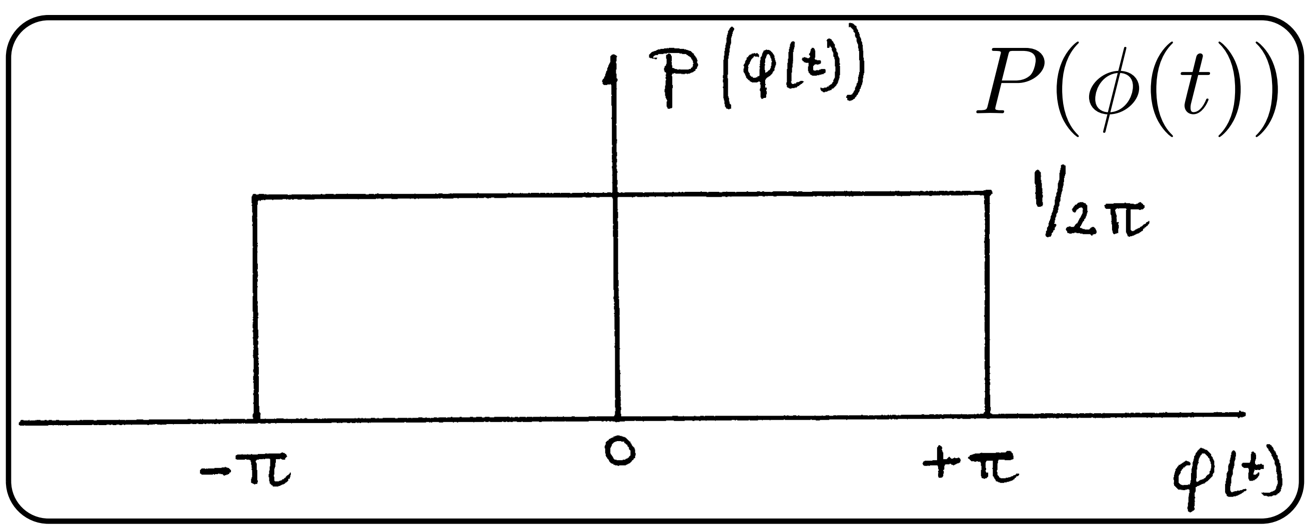
The phasor is described by amplitude $|\tilde{E_0}(t)|$ and phase $\phi(t)$



RANDOM VARIATIONS ON TIME SCALES >> THE COHERENCE TIME ASSOCIATED WITH (ATOMIC) TRANSITIONS

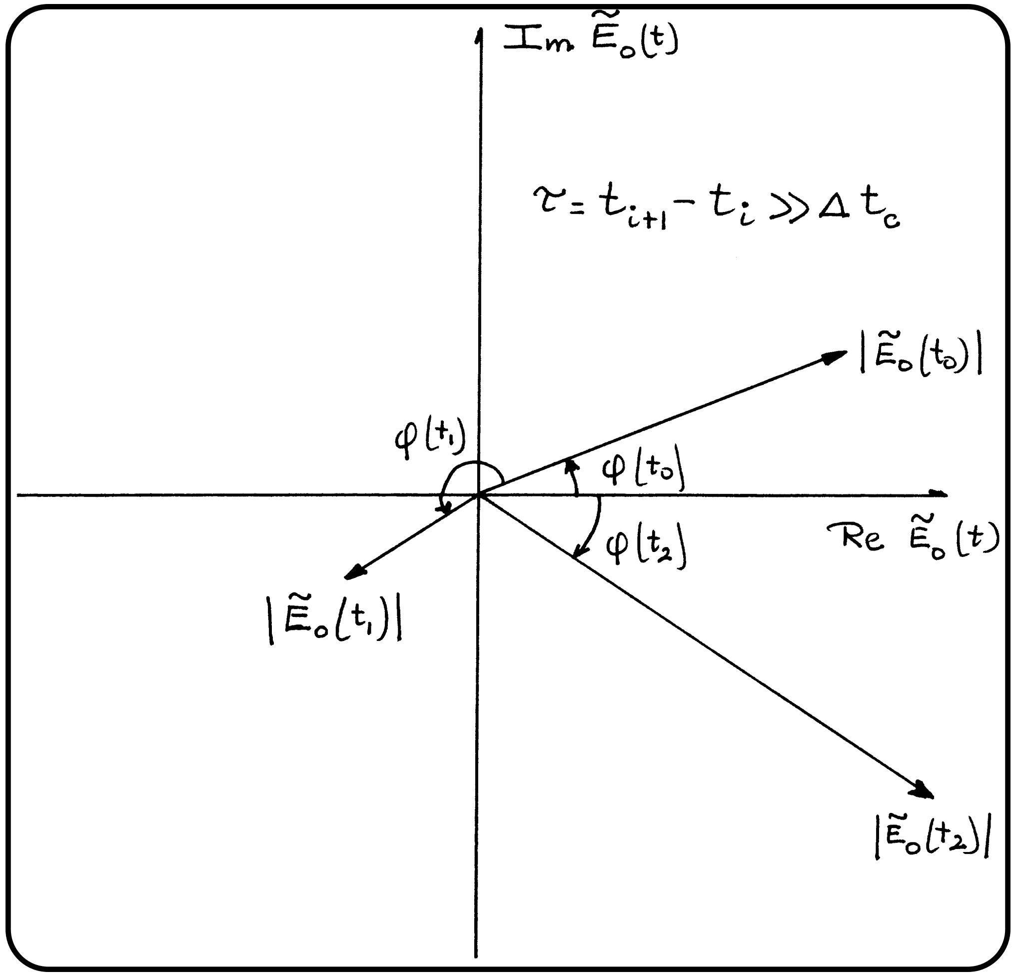
$$P(|E_0|(t), \phi(t))d|E_0|d\phi = \frac{E_0}{2\pi\sigma^2} e^{-\frac{E_0^2}{2\sigma^2}} d|E_0|d\phi$$

PROBABILITY DENSITY FOR:



AGAIN ONE FINDS THAT THE FLUCTUATIONS IN THE POWER FLUX DENSITY ARE:

$$\overline{\Delta I^2} = \bar{I}^2$$



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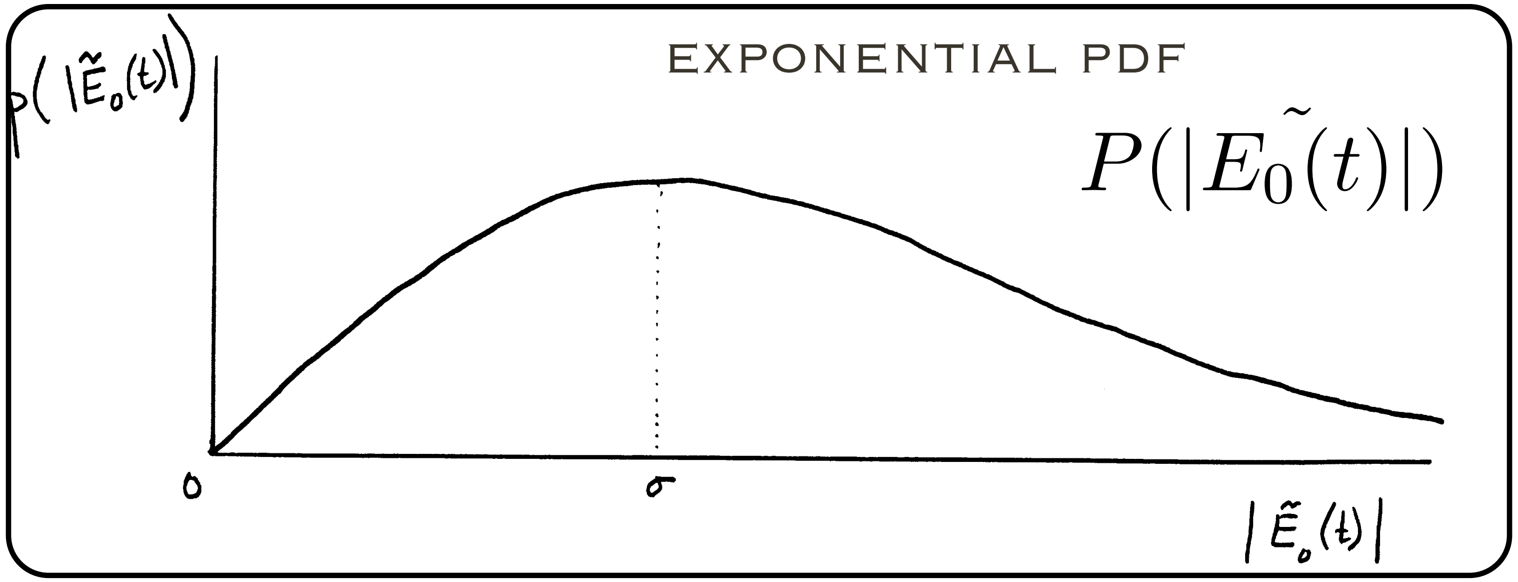


AGAIN ONE FINDS THAT THE FLUCTUATIONS IN THE POWER FLUX DENSITY ARE:

$$\overline{\Delta I^2} = \bar{I}^2$$

Alternative, thermodynamic view

connection via $S \equiv k \ln(W)$

→ define: $a(t) = (\epsilon_0 c\lambda^2)^{1/2} E(t)$

$$R(\tau) = \frac{1}{T}\int_0^T a(t)a^*(t+\tau)d\tau \quad [power][= \text{Watts}]$$

$$P(\nu) = R(\tau) \times \ time \quad [\text{Joule} \ = \ \text{Watts Hz}^{-1}]$$

$$P(\nu) = \frac{1}{2}u(\bar{\nu})\frac{\lambda^2}{4\pi}c = h\nu[exp\frac{h\nu}{kT} - 1]^{-1}$$

$$where \ u(\bar{\nu}) = \frac{8\pi h\nu^3}{c^3}[exp(\frac{h\nu}{kT}) - 1]^{-1}$$

=energy density photon field

→ thermodynamics (W here mean energy):

$$\langle \Delta W^2 \rangle = kT^2 \frac{d\langle W \rangle}{dT}$$

$$\langle \Delta P(\nu)^2 \rangle = kT^2 \frac{d\langle P(\nu) \rangle}{dT} = P(\nu)h\nu\{1 + [exp(\frac{h\nu}{kT}) - 1]^{-1}\}$$

Two limits again: quantum noise & thermal noise

QUANTUM NOISE LIMIT

$$h\nu >> kT \quad \rightarrow \langle[\Delta P(\nu)]^2\rangle \approx P(\nu)h\nu$$

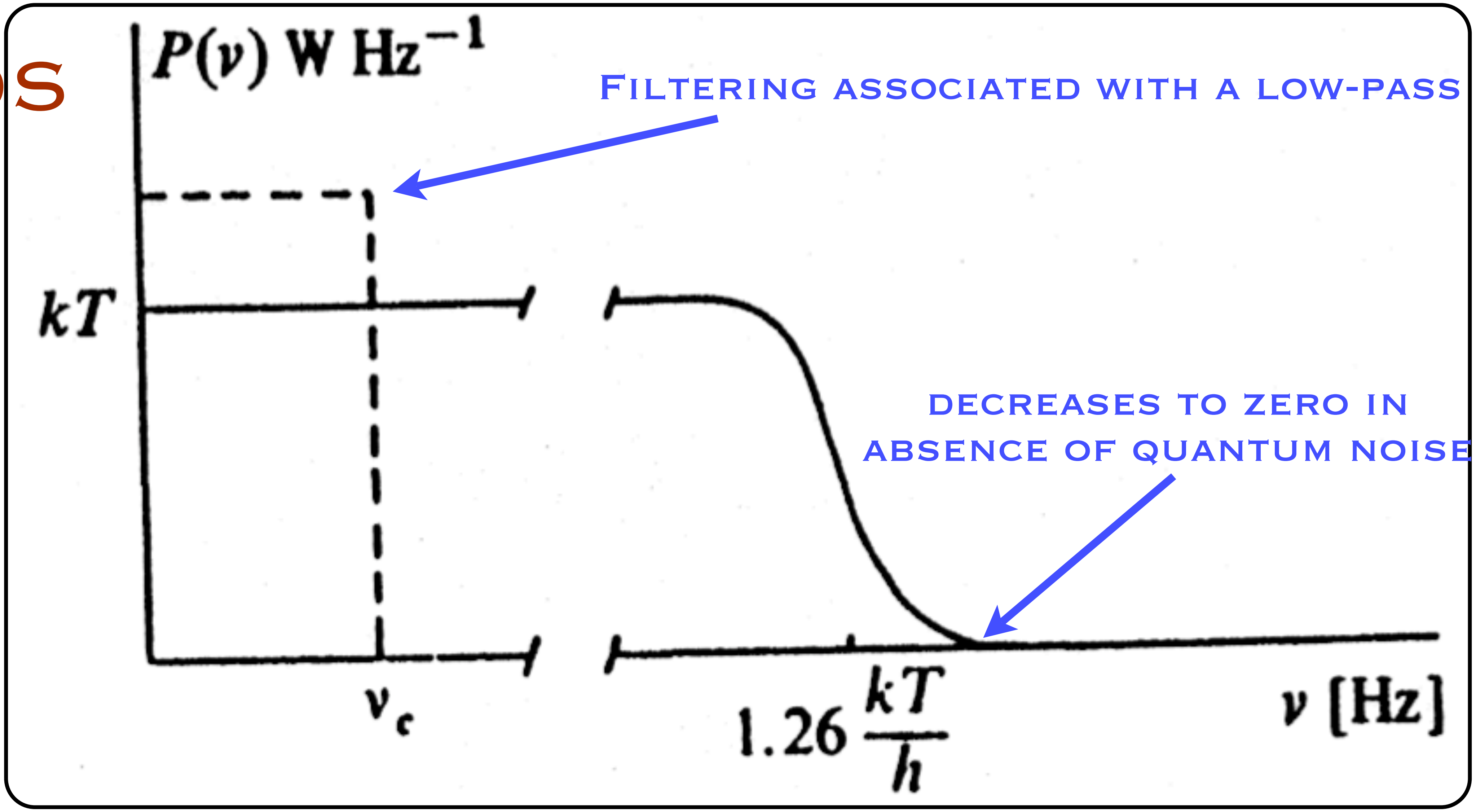
THERMAL NOISE LIMIT

$$h\nu << kT \quad \rightarrow \langle[\Delta P(\nu)]^2\rangle \approx P(\nu)h\nu[exp(\frac{h\nu}{kT}) - 1]^{-1}$$

$$\approx (kT)^2 \; since \; e^{\epsilon} - 1 = 1 + \epsilon - 1$$

$$and \; P(\nu) \approx kT$$

PDS



Three different ways to derive the size of the fluctuation in the thermal limit

- bose-Einstein
- Stochastic description E-M wave
- Thermodynamic

$$\overline{\Delta P^2}(\nu) = (kT)^2$$

Some (computational) math

stirling's approximation

$$\ln x! = x \ln x - x$$

in code use Gamma Function

$$\Gamma(z+1) = z!$$

$$\Gamma(z+1) = z\Gamma(z)$$

$$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$$

Gamma function has a computationally simple accurate approximation

Numerical Recipes Chap 6.1-6.2

INCOMPLETE GAMMA FUNCTIONS:

$$P(a,x) \equiv \frac{\gamma(a,x)}{\Gamma(a)} \equiv \frac{1}{\Gamma(a)} \int_0^x t^{a-1} e^{-t} dt$$

$$Q(a,x) \equiv 1 - P(a,x) = \frac{\gamma(a,x)}{\Gamma(a)} \equiv \frac{1}{\Gamma(a)} \int_x^\infty t^{a-1} e^{-t} dt$$

ERROR FUNCTIONS:

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \quad = P(\frac{1}{2}, x^2)$$

$$\mathrm{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt \quad = Q(\frac{1}{2}, x^2)$$

Cumulative Distribution function $F(x) = P\{x \leq y\}$

Probability density function $\frac{dF(x)}{dx} = f(x)$

$\hookrightarrow$ Gauss, Poisson, χ^2 etc

Gaussian or normal distribution and probability density function

$$F(x, \eta, \sigma) = 0.5 + erf\frac{x-\eta}{\sigma^2}$$

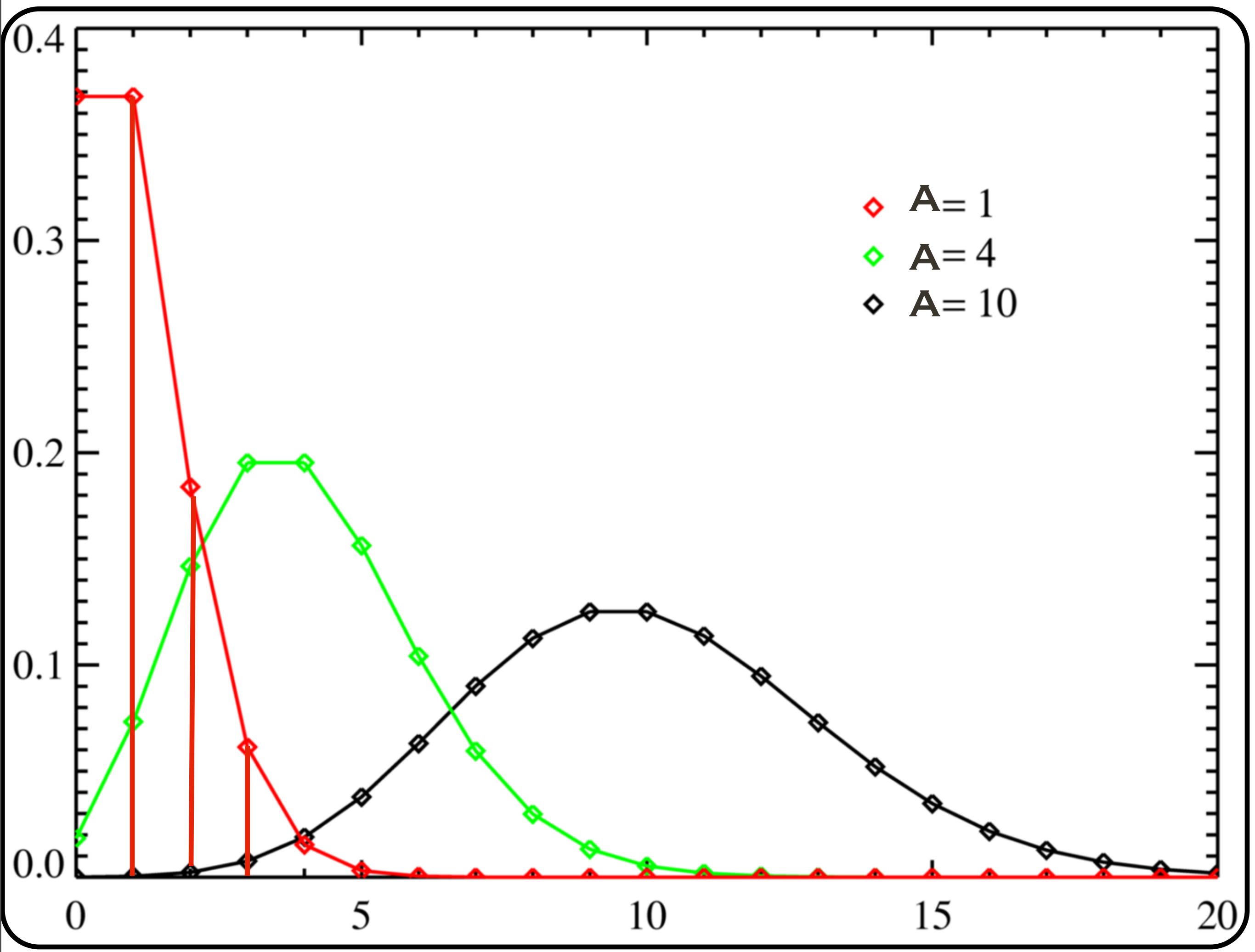
$$f(x) = \frac{1}{\sigma\sqrt{(2\pi)}}exp(-\frac{1}{2}\frac{(x-\eta)^2}{\sigma^2})$$

Poisson cumulative distribution and probability density function

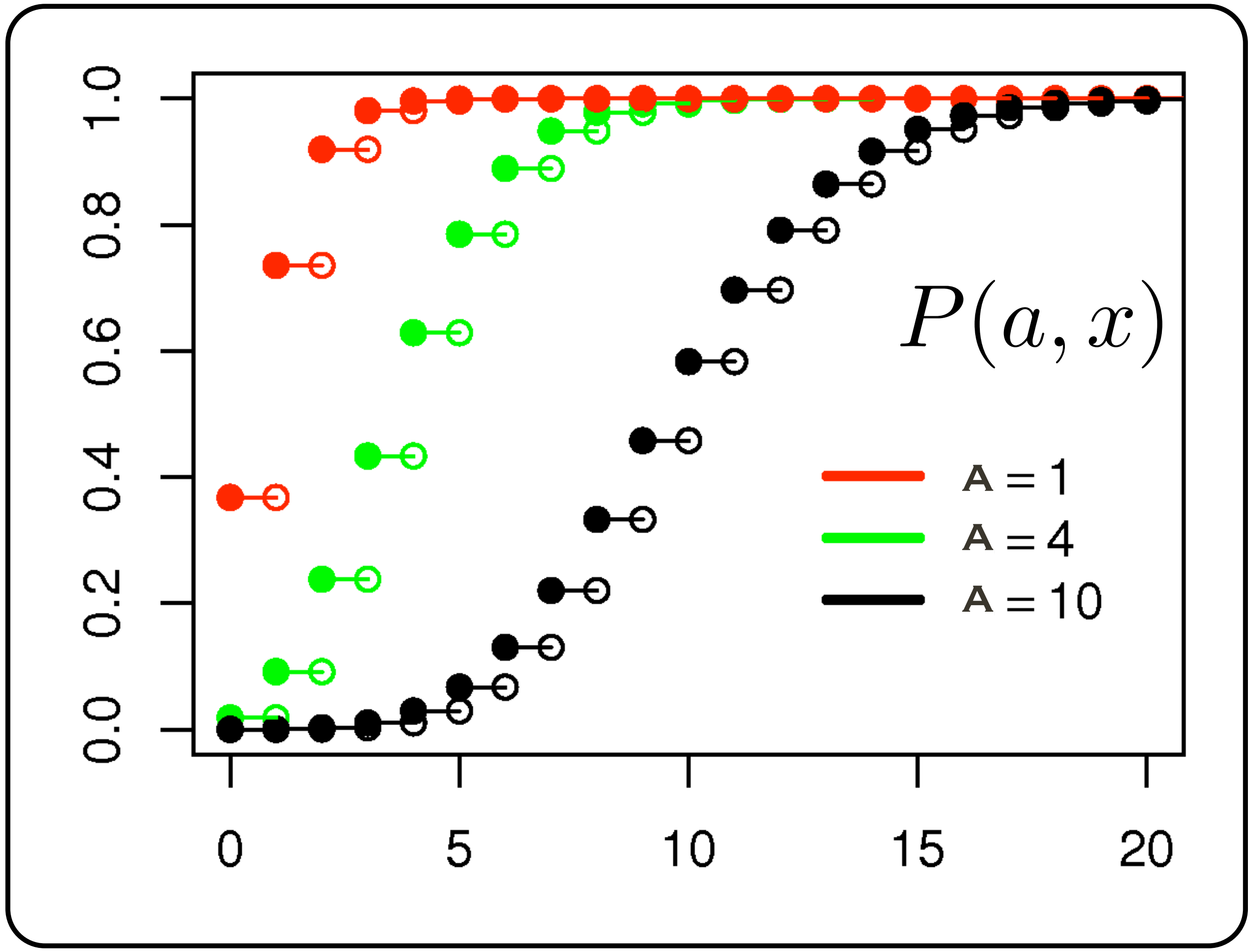
$$F(x) = 1 - P(a,x) \equiv \frac{1}{\Gamma(a)} \int_x^\infty e^{-t} t^{a-1} dt$$

$$f(x) = \frac{a^k}{k!} e^{-a} \rightarrow \ (discrete)\ e^{-a} \sum_{k=0}^{\infty} \frac{a^k}{k!} \delta(x-k)$$

Probability density



Cumulative distribution



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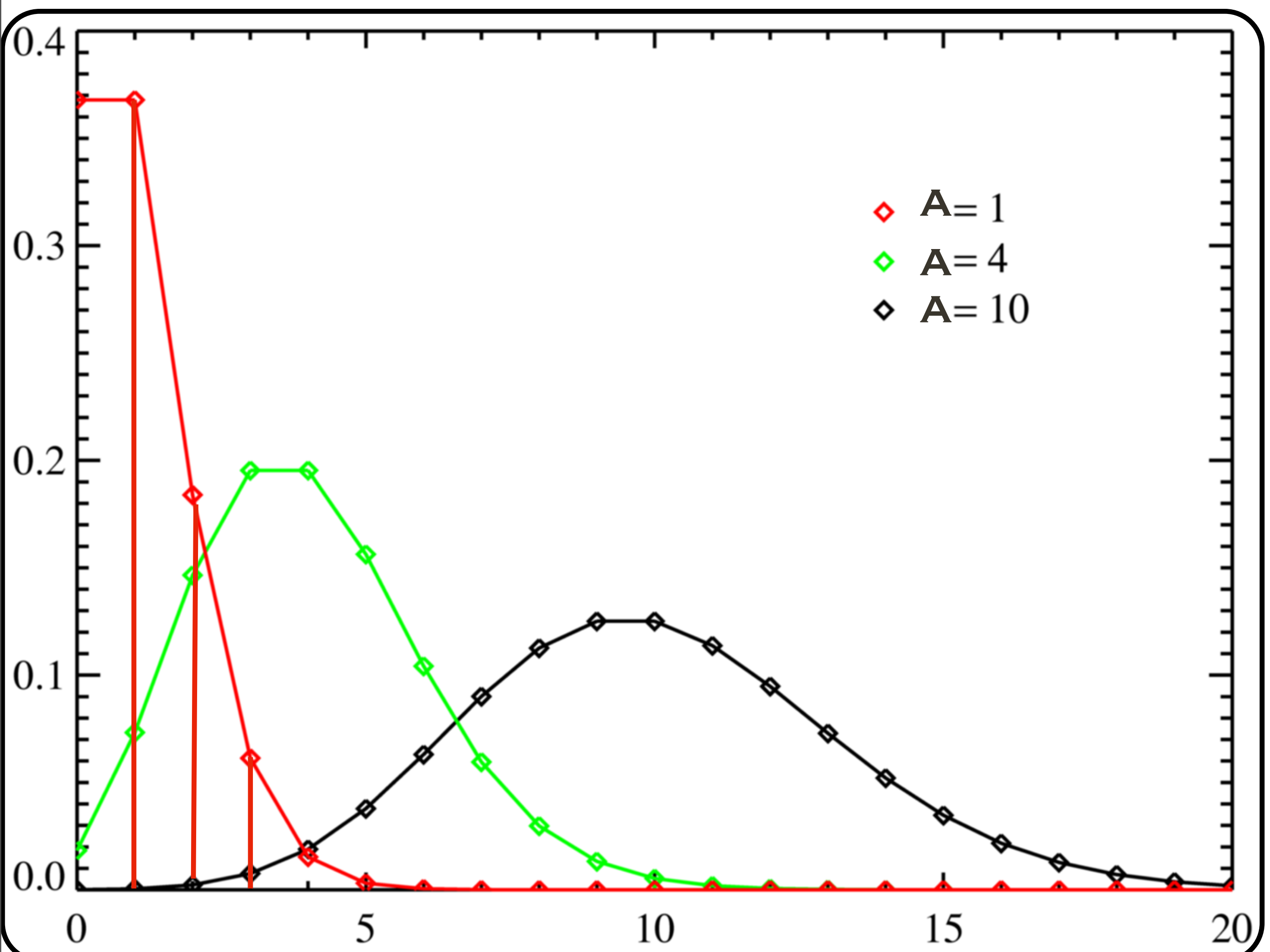
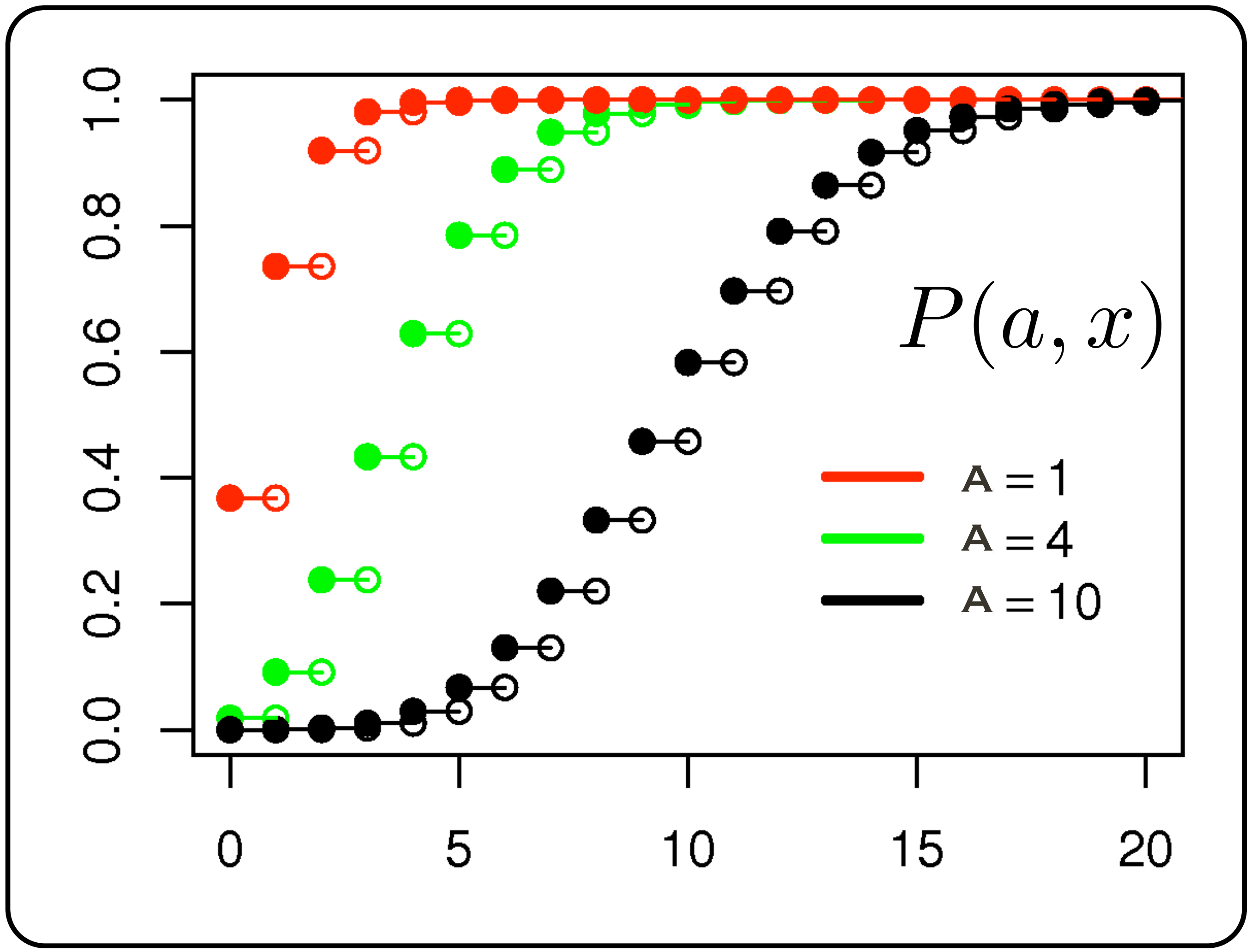
Incomplete Gamma Function

Probability density



Cumulative distribution



In computer codes dealing with Poisson and Gaussian distributions incomplete Gamma Functions are used

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Besides noise intrinsic to the s.p. noise is added due to the detector, background etc.

→ how to determine the resultant variance

Main assumption is that the average of the function f is well represented by the value for f at the averages for the variables

$$\bar{f} = f(\bar{u}, \bar{v}, ..)$$

Taylor expansion to first order around the average for each variable

$$f_i - \bar{f} \approx (u_i - \bar{u})\frac{\partial f}{\partial u} + (v_i - \bar{v})\frac{\partial f}{\partial v} + ...$$

Remember that the variance

$$\sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N}(f_i - \bar{f})^2$$

Fill-in the Taylor expansion here

Assume that the variables are independent such that their cross product cancel

$$\sigma_f^2 = \sigma_u^2(\frac{\partial f}{\partial u})^2 + \sigma_v^2(\frac{\partial f}{\partial v})^2 + ...$$