Radiative Processes F

High-energy radiative processes: Bremmstrahlung & Synchrotron

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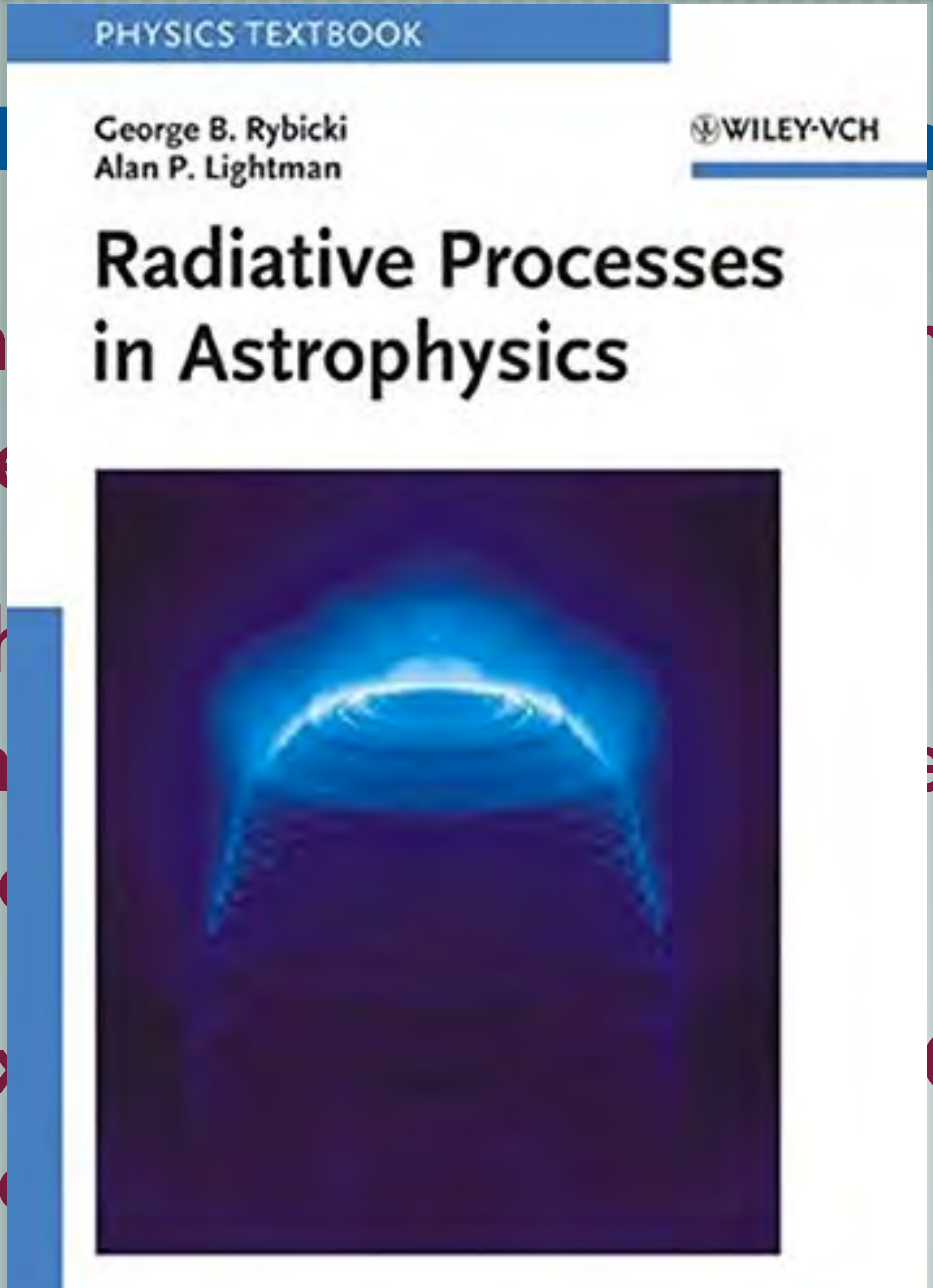
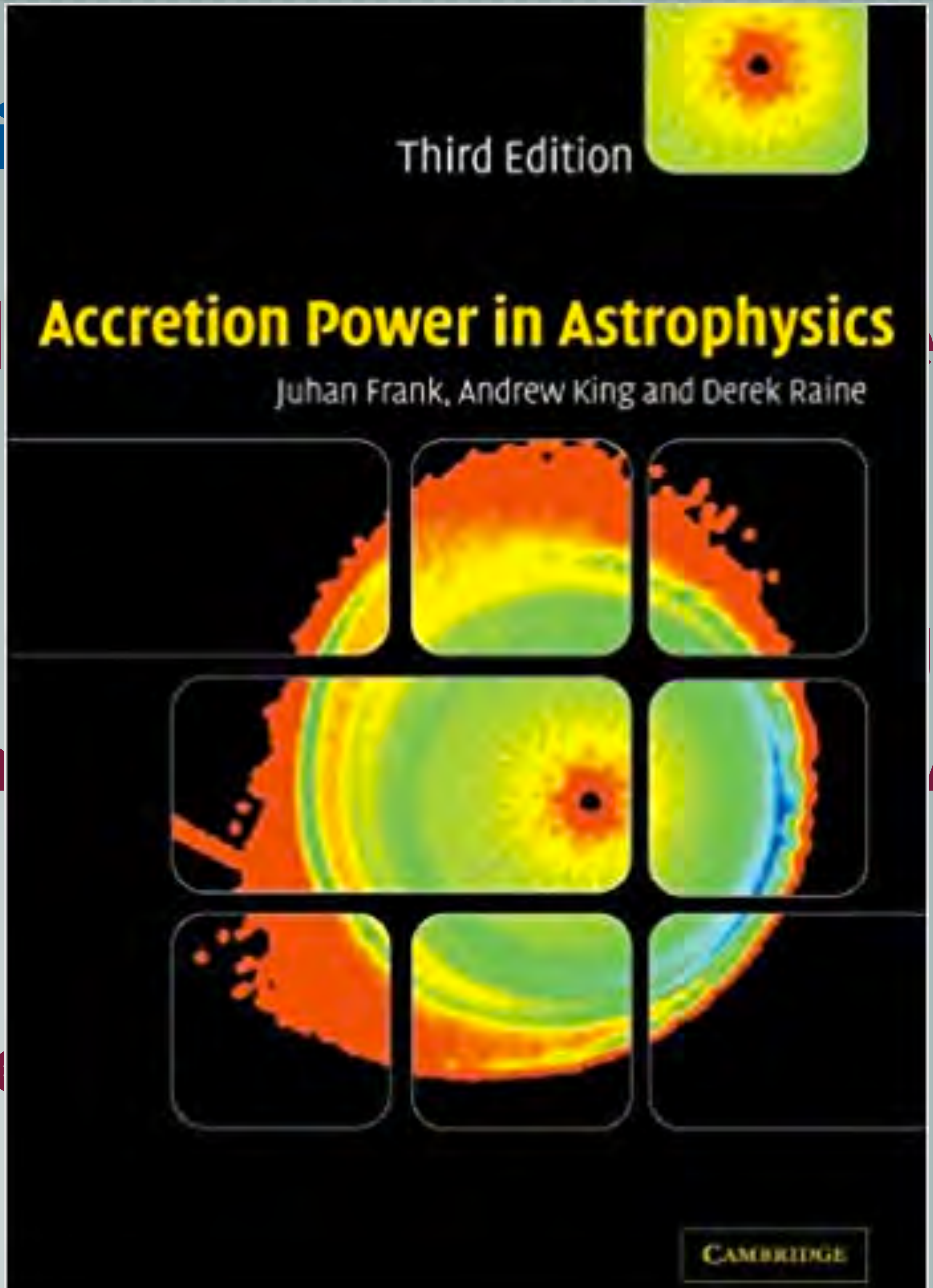
What Sebastian and I will try to cover in 4 hours (!?!)

High-energy electromagnetic radiation

- Introduction to nonthermal radiation and some of the theory behind it
- The basic concepts behind the three main high-energy radiation processes: bremsstrahlung, synchrotron, inverse Compton
- Experience with Monte Carlo technique for inverse Compton

What Sebastian and I will try to cover in 4 hours (!?!)





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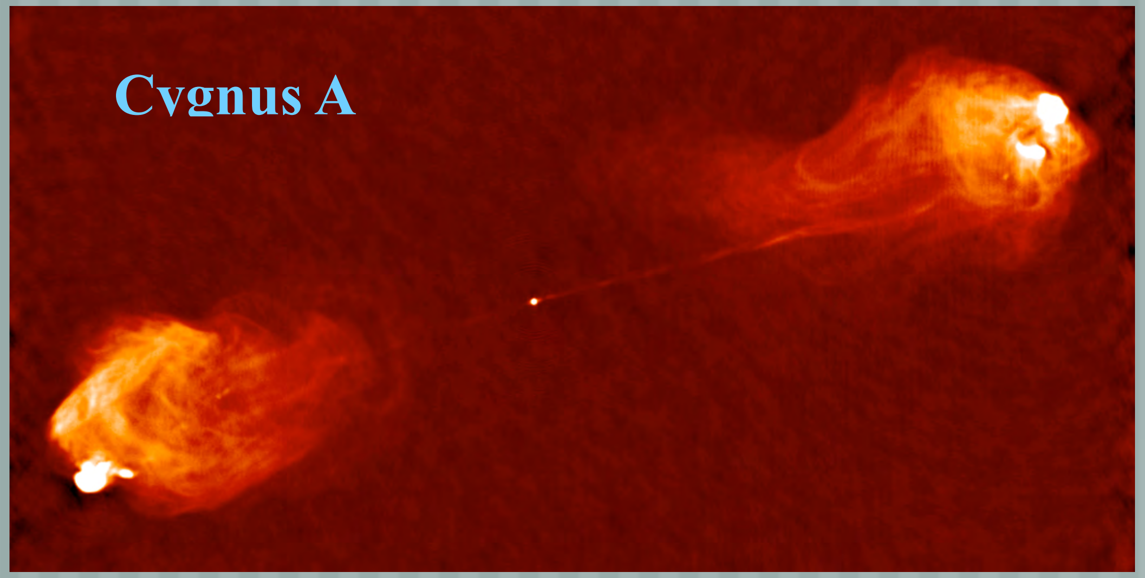
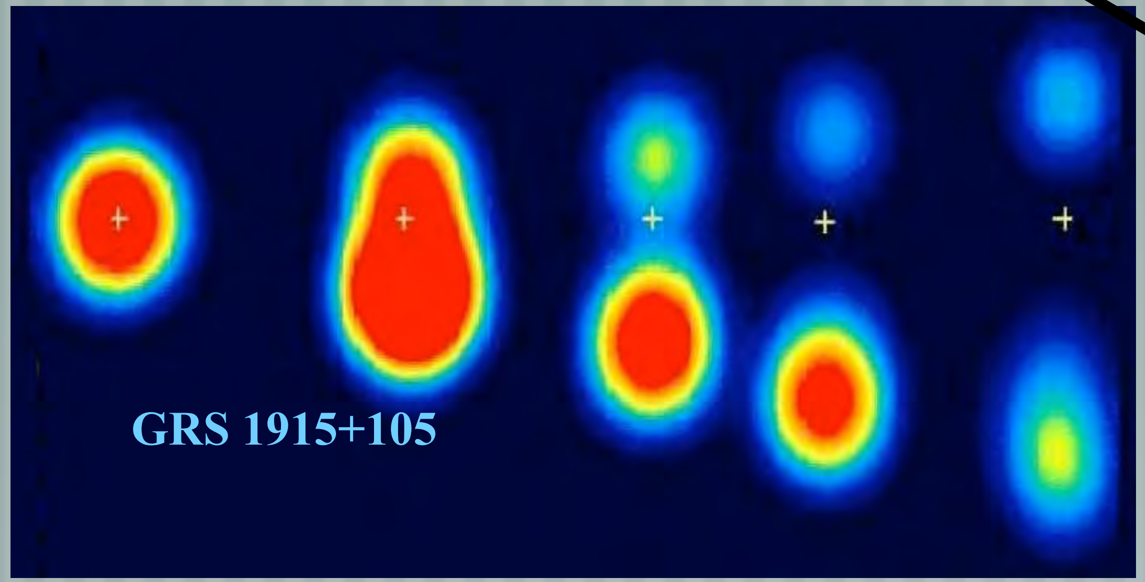
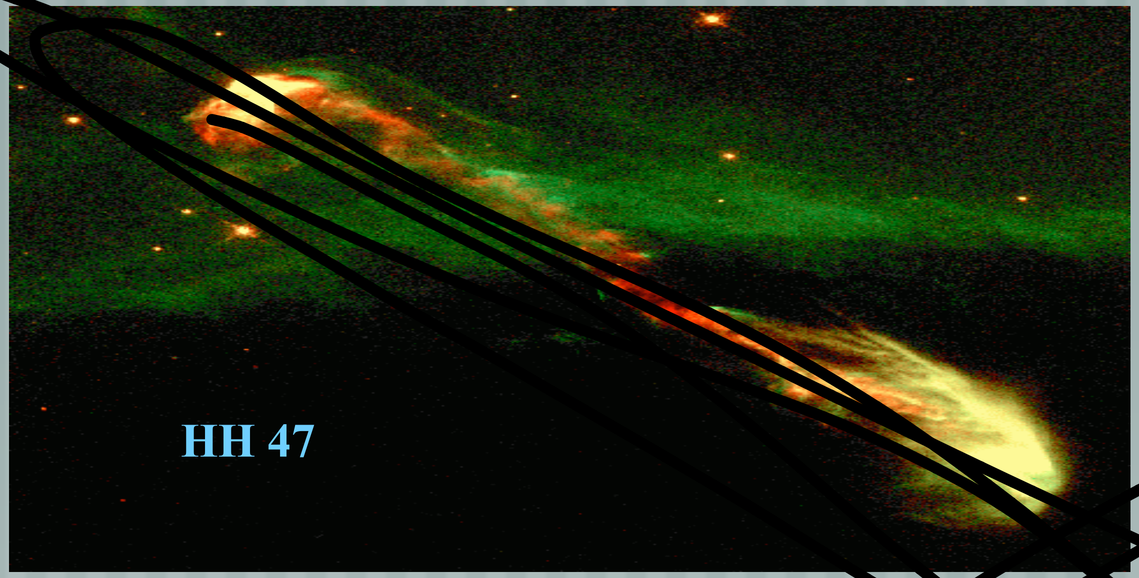
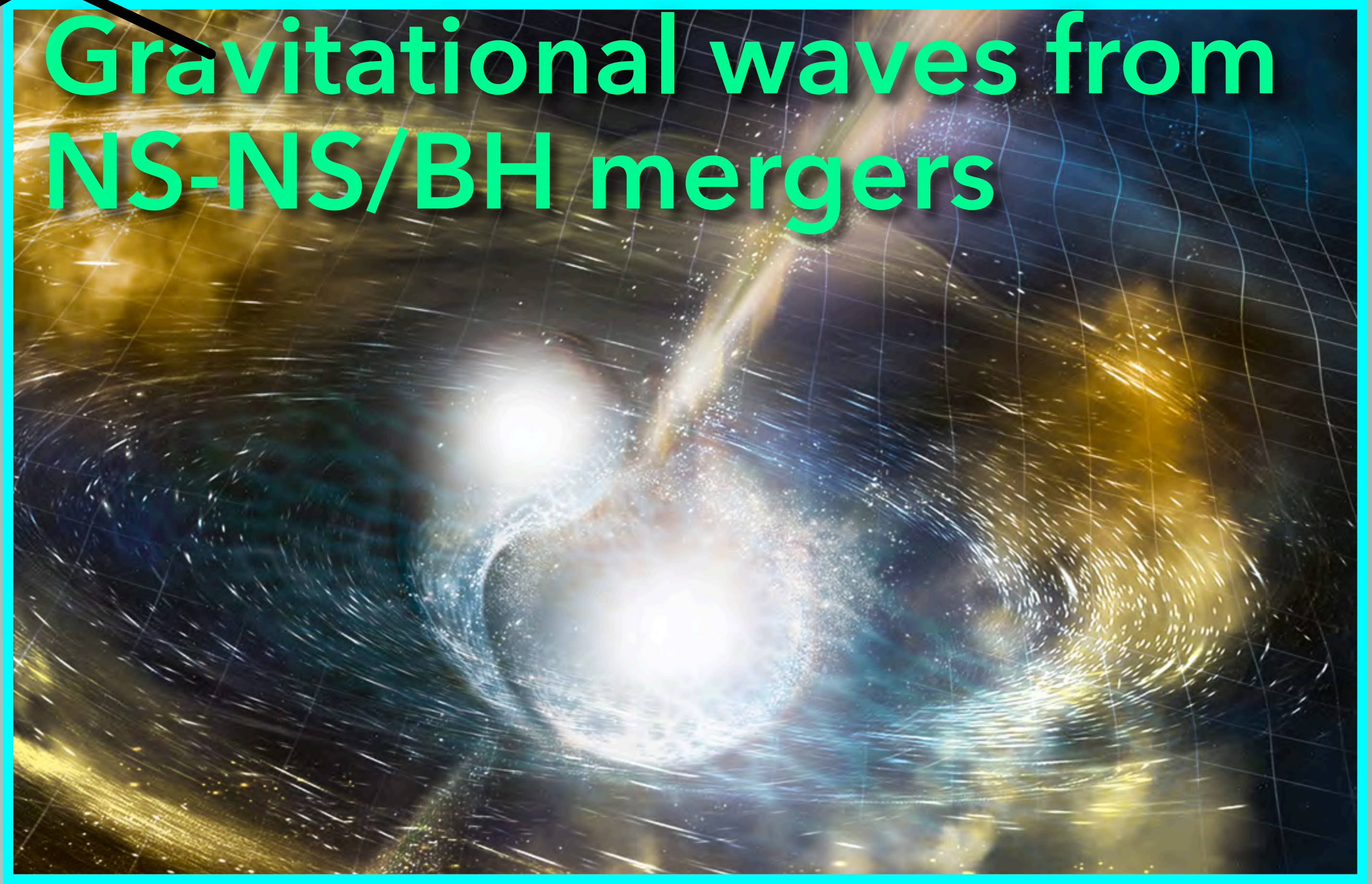
- Ex… Carlo te… C…

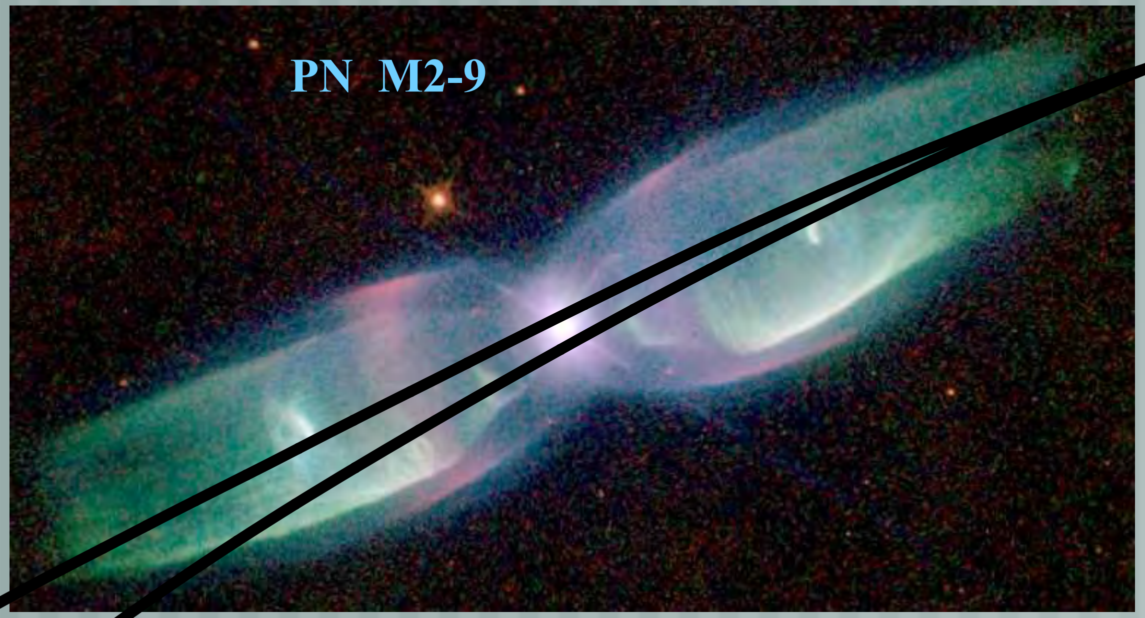
Cast of Characters

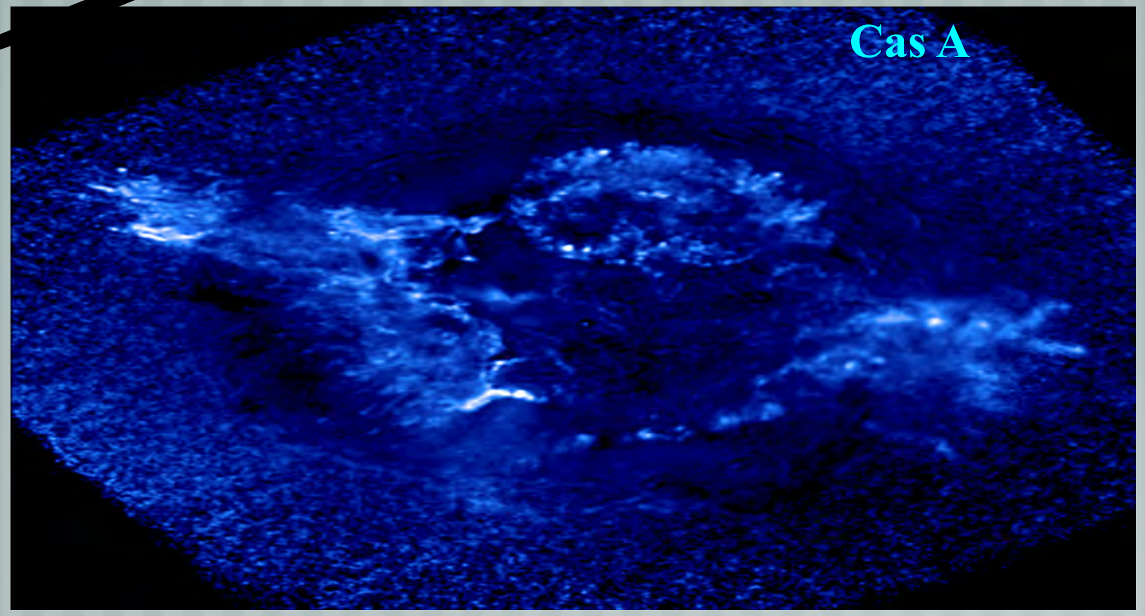


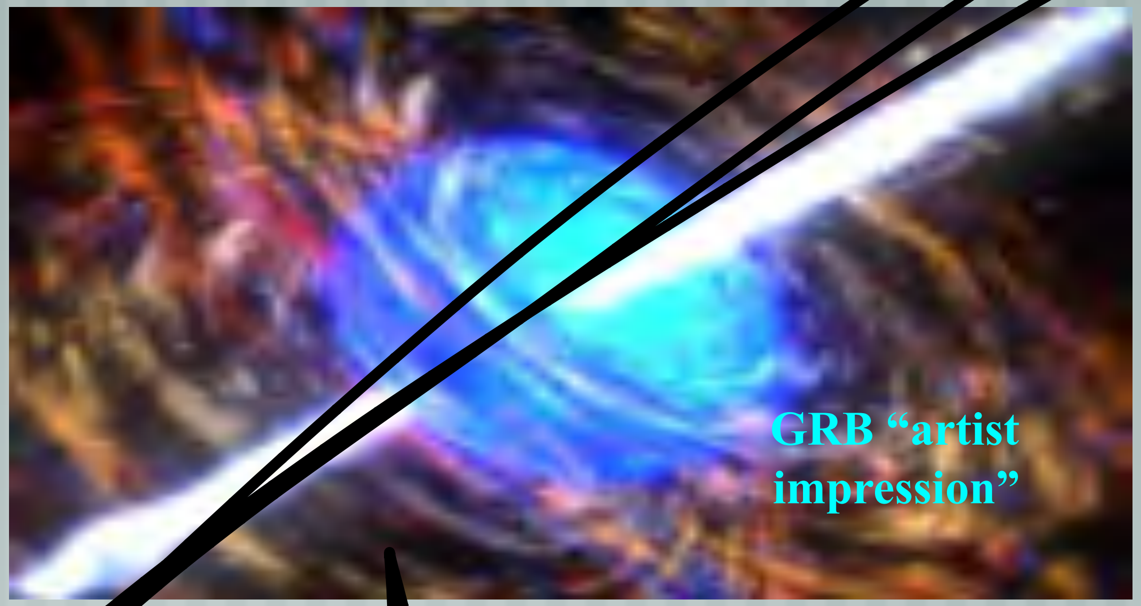


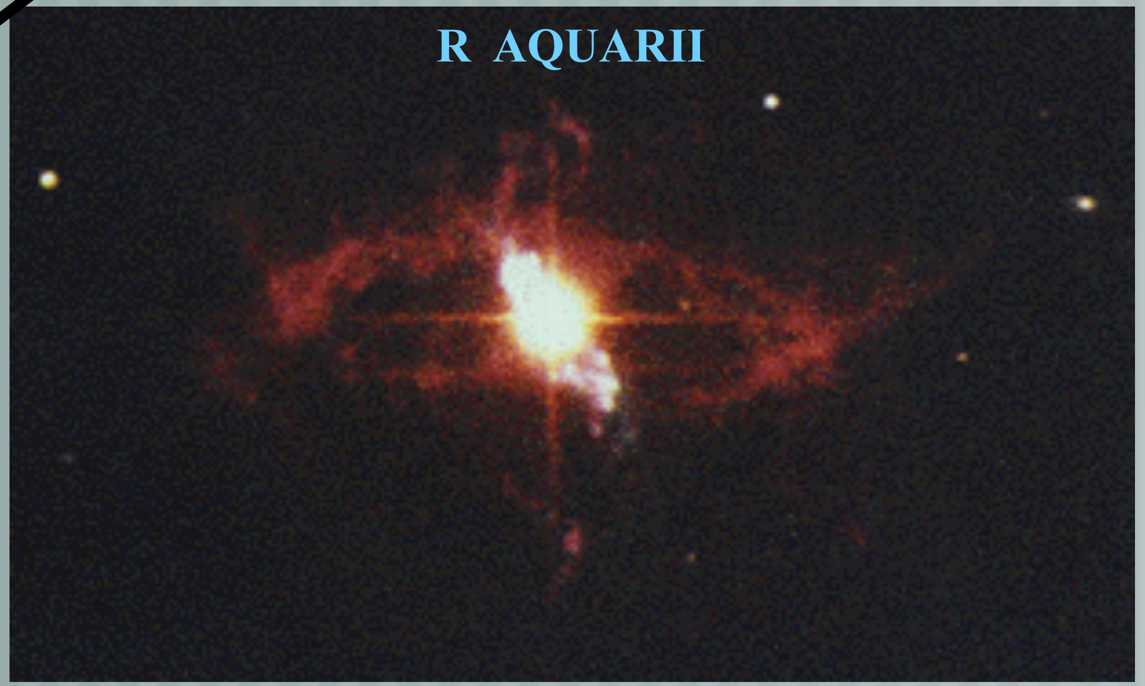


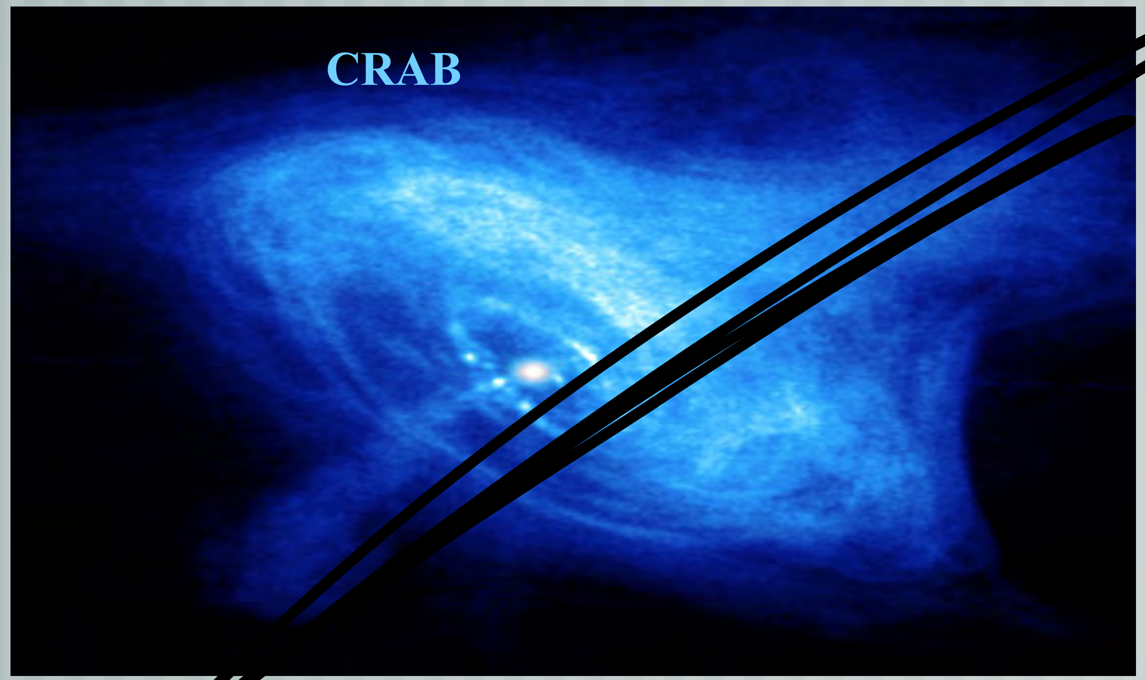












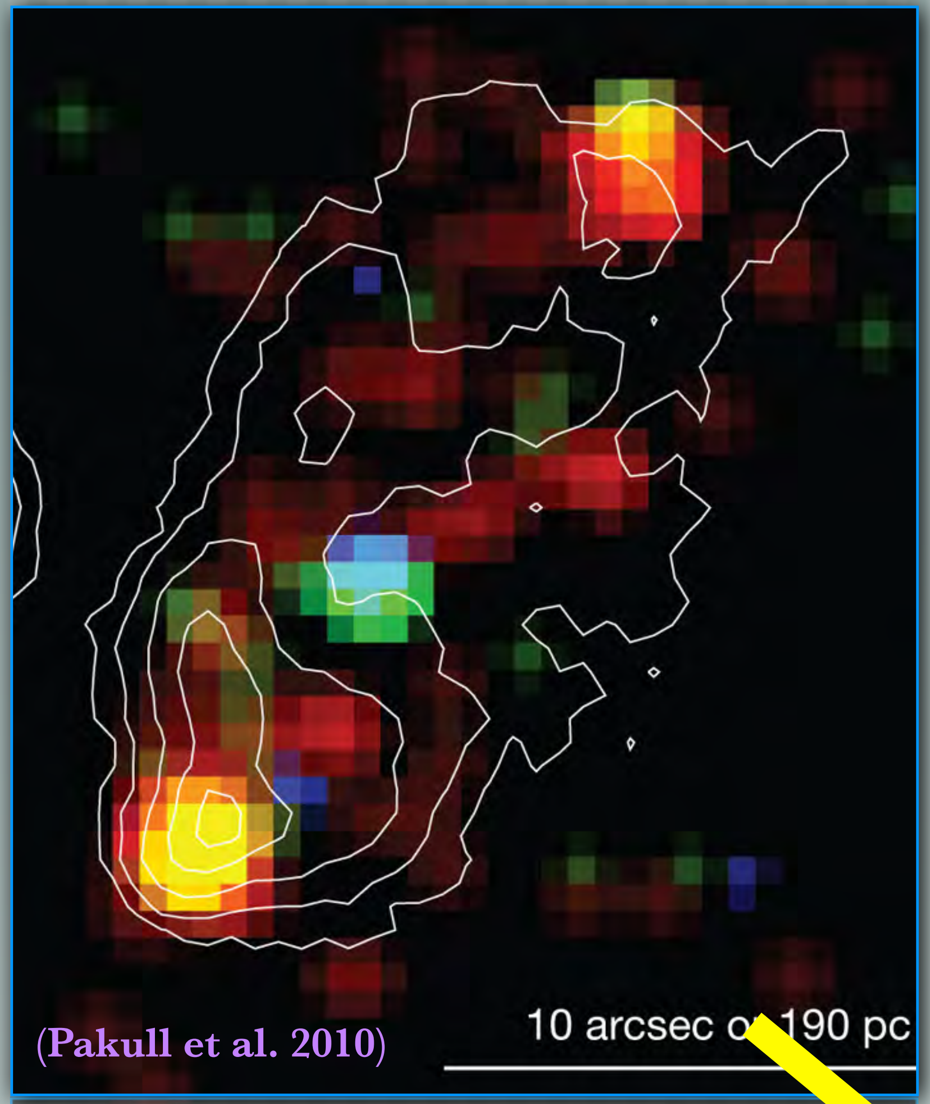
We need to understand how accretion works in order to understand...

Extra-Galactic Stellar mass BH

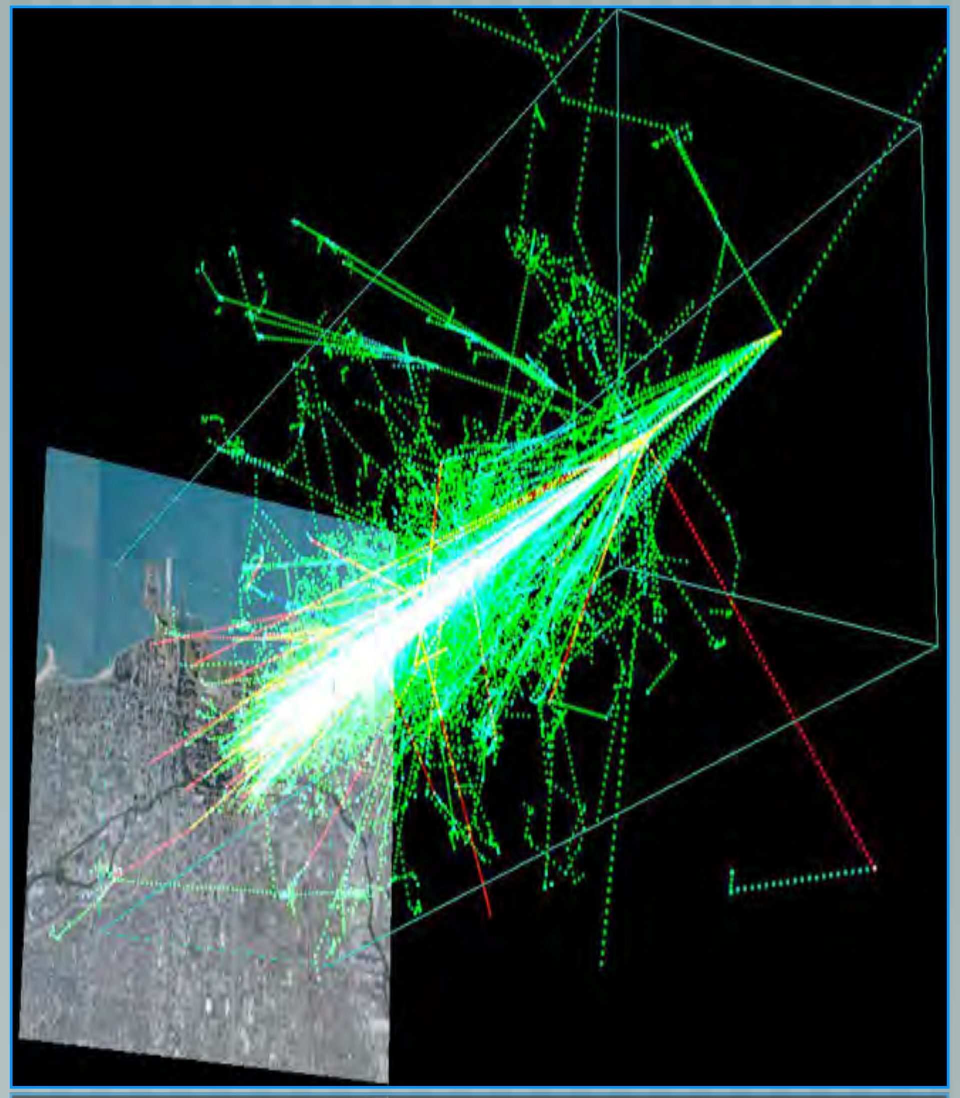
Active Jet

GALAXY EVOLUTION/ AGN FEEDBACK

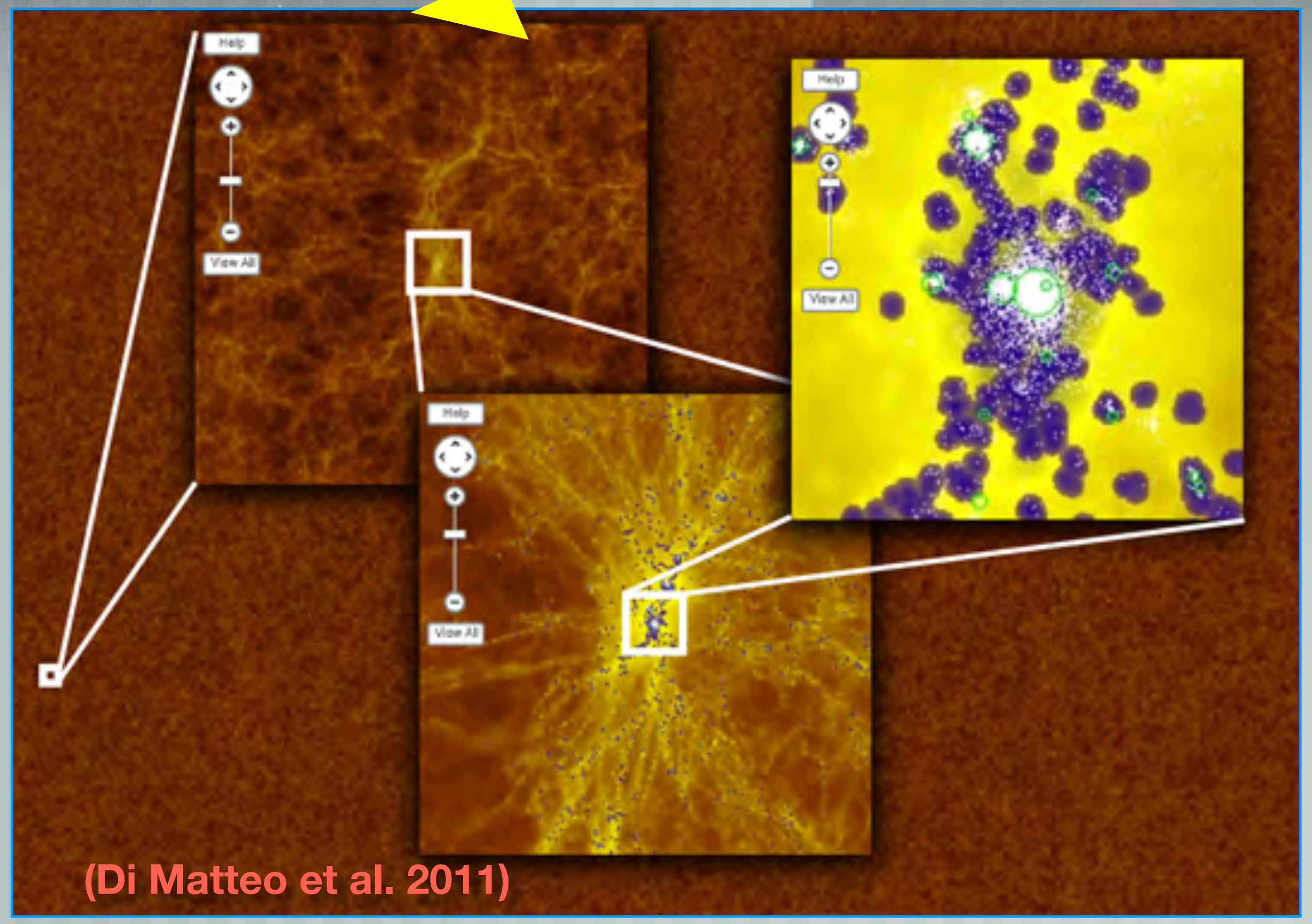
IONIZATION OF SURROUNDING GAS

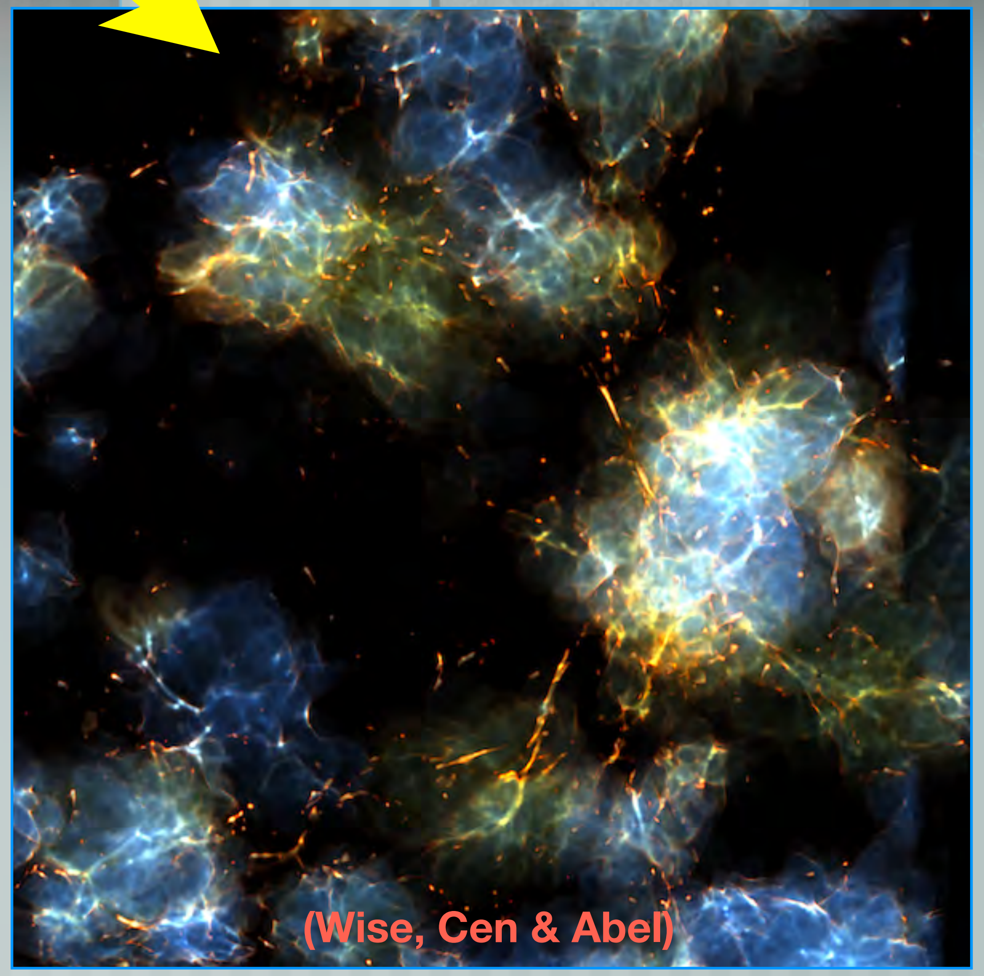


HIGH-ENERGY PARTICLE ACCELERATION



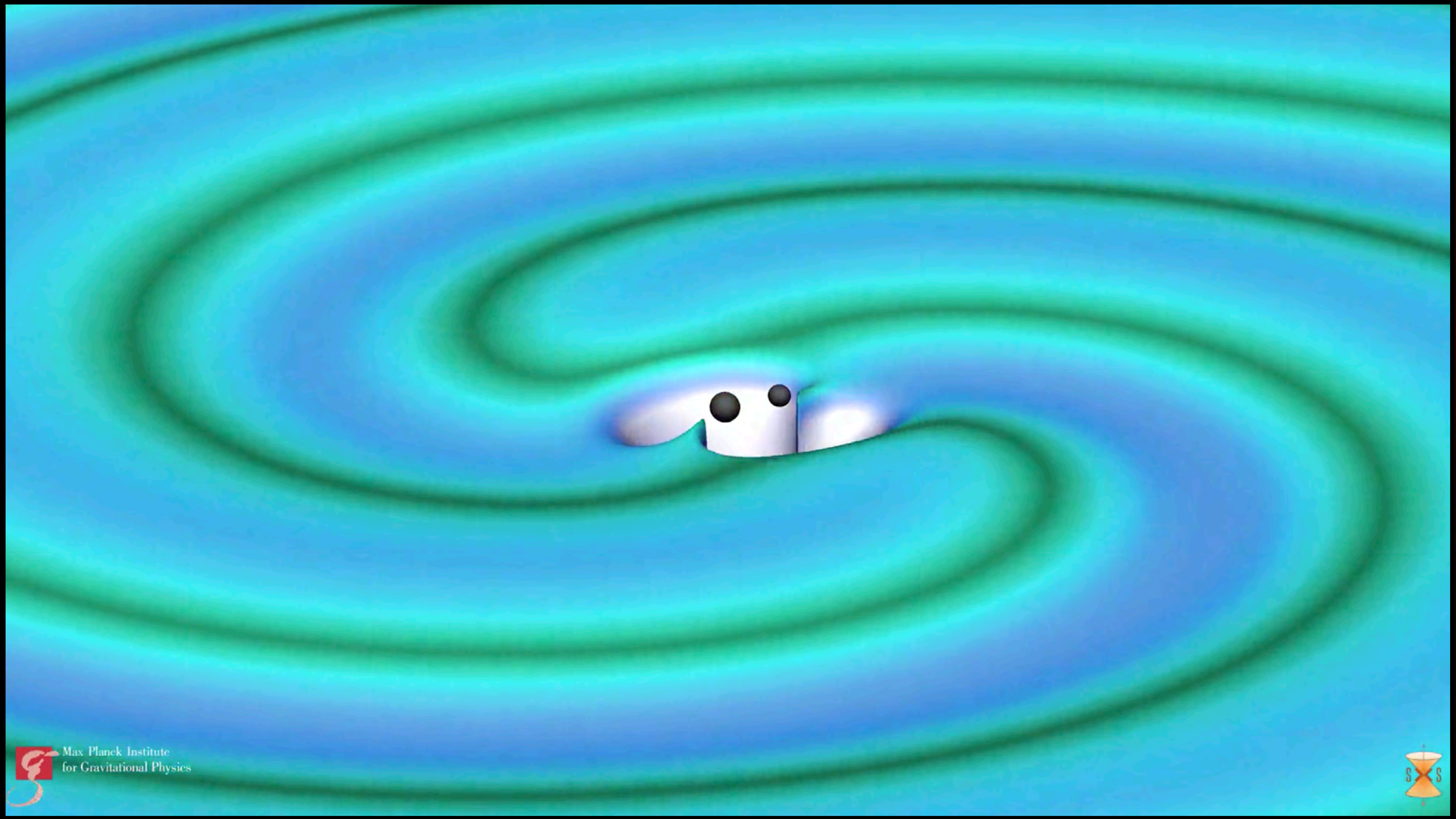
Cosmological Simulations:





The new revolution in (astro)physics: “seeing” black holes

2015: discovery of gravitational waves from merging black holes (*2017 Physics Nobel Prize*)

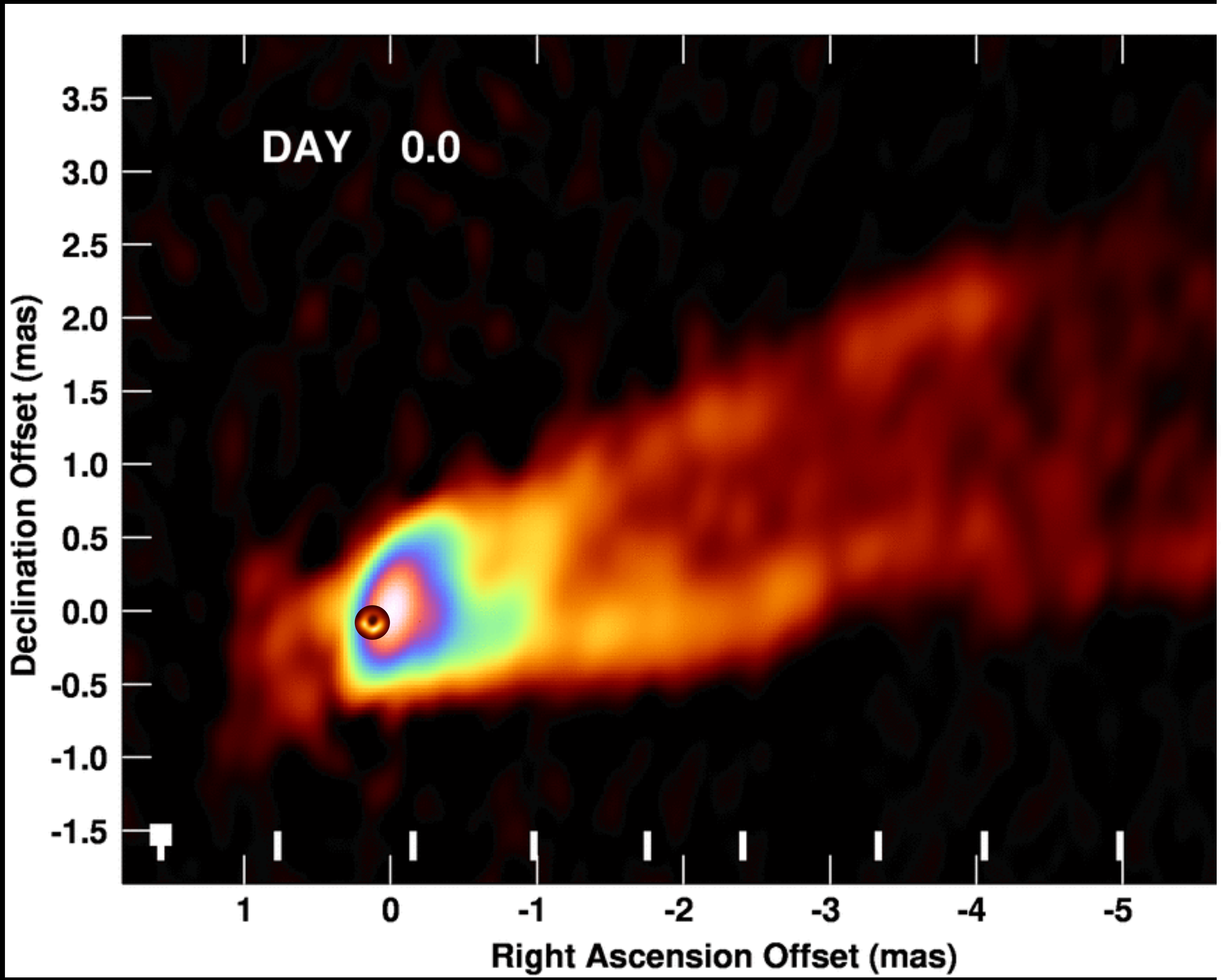


LIGO/VIRGO collaboration

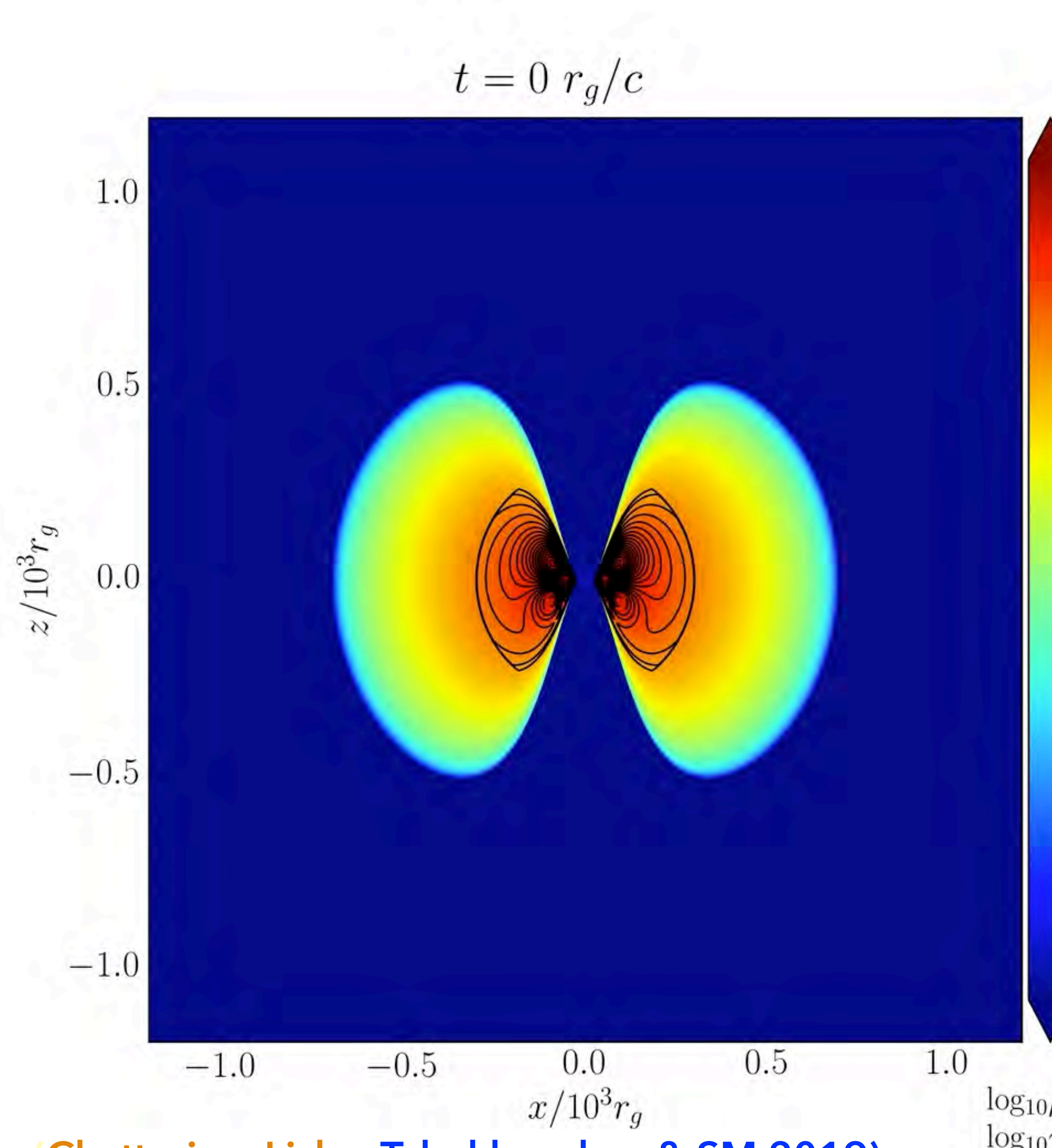
4/2019: first image of a supermassive black hole in the heart of a galaxy

Event Horizon Telescope Collaboration

Closing in on the dynamics, but lagging on microphysics of light

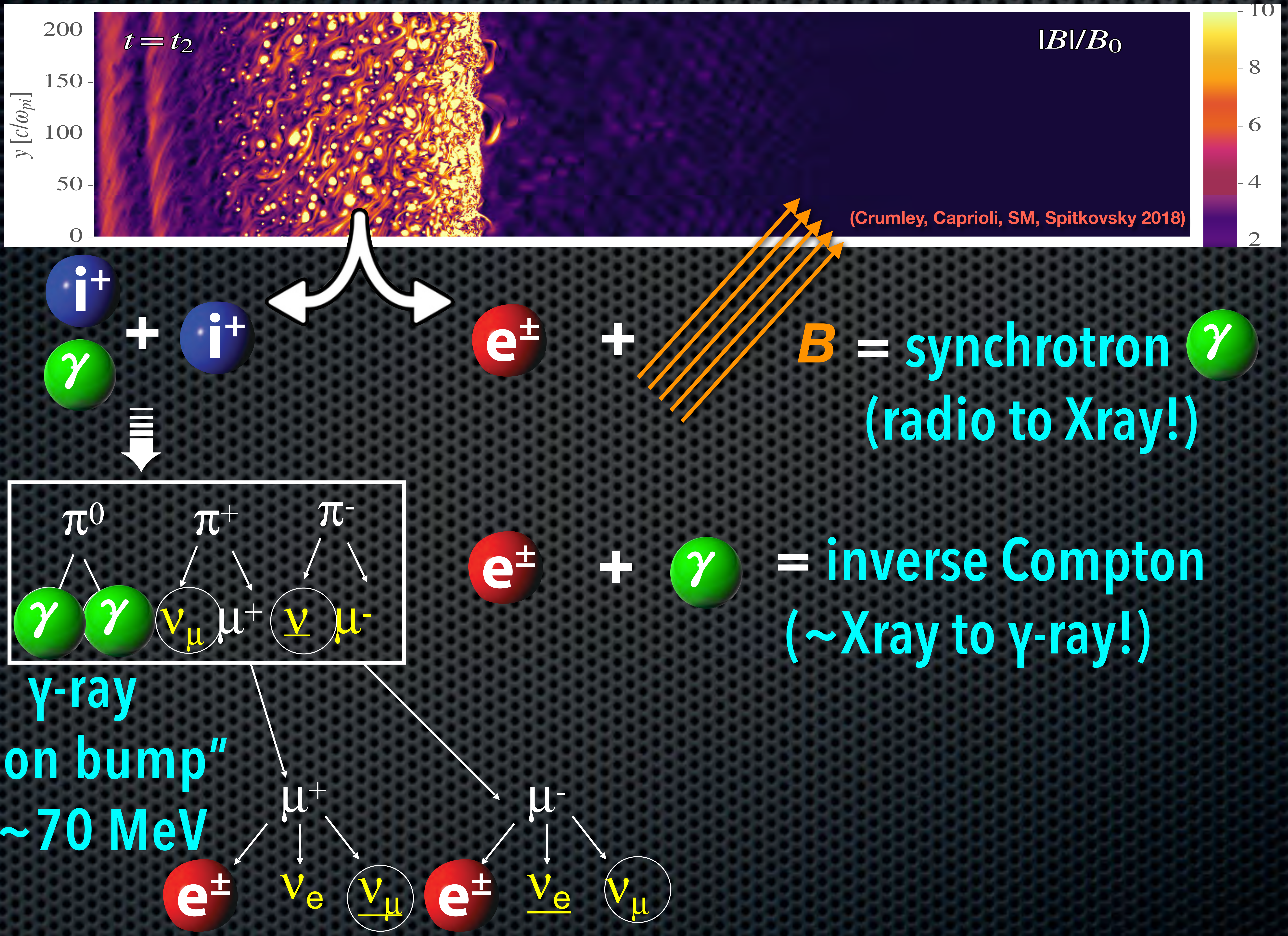


(M87 inner jet, Walker++2007/2008)

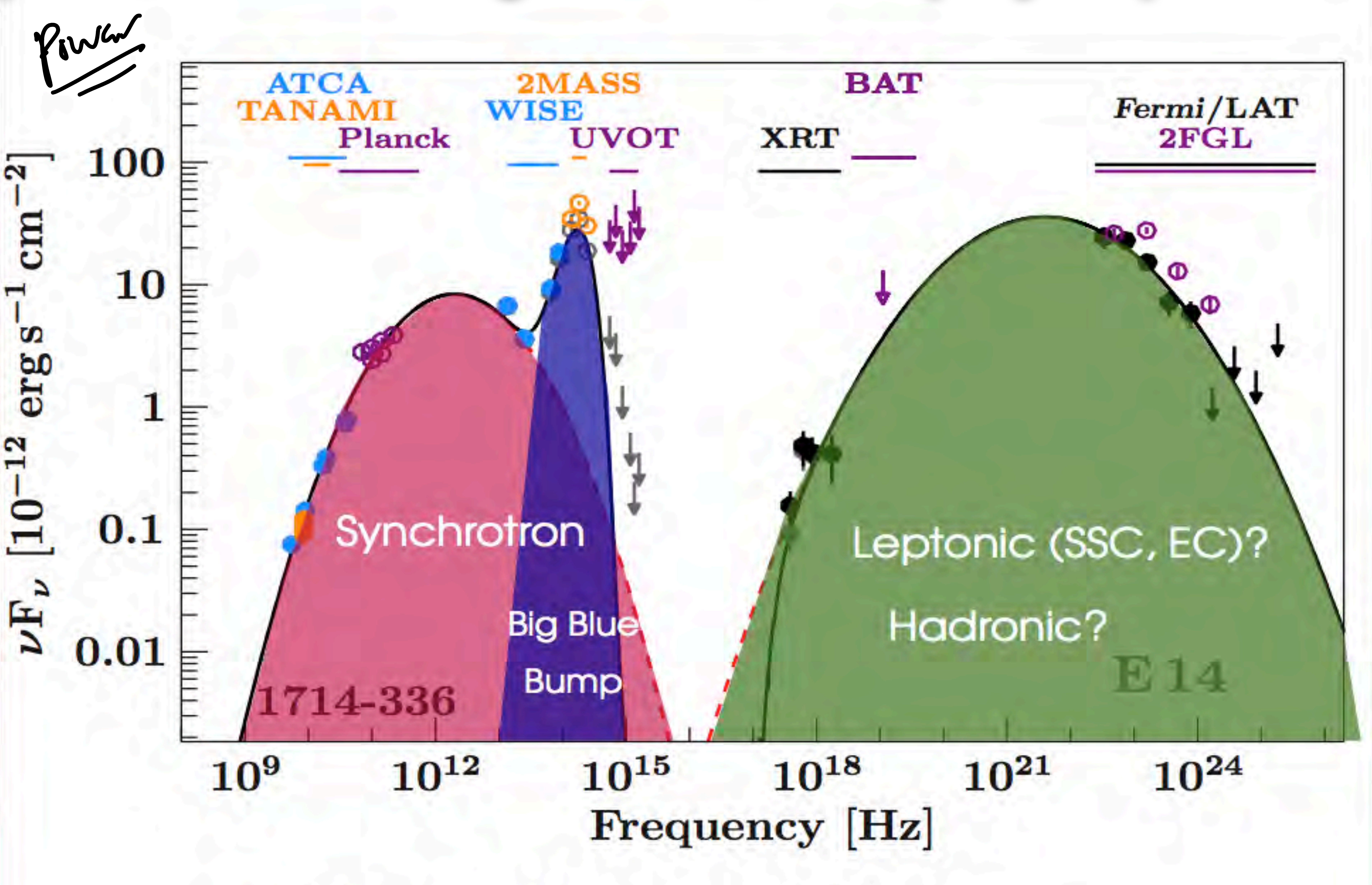


(Chatterjee, Liska, Tchekhovskoy & SM 2019)

'Nonthermal' emission traces particle acceleration



Complex (and thus degenerate) interplay of processes



Krauß F., Kadler M., et al., A&A, 2014, 556, L7

A quick primer on important properties of light

Radiative transfer: absorption/scattering & optical depth

- In target medium of particle density n (cm^{-3}), with cross section (absorption/scattering area) σ_ν (cm^2):

"absorption coefficient" $\alpha_\nu \equiv n\sigma_\nu$ $[\alpha_\nu] = \frac{1}{L}$ "skin depth"

τ = "optical depth" $\tau_\nu(s) = \int_0^s \alpha_\nu(s')\,ds' = \int n(s')\sigma_\nu\,ds'$

if homogeneous, $\tau \equiv n\sigma_\nu s = \alpha_\nu s$

In RT $e^{-\tau}$ | "e-folding" $\tau_\nu = 1 \Longrightarrow s = \frac{1}{\alpha_\nu} = \frac{1}{n\sigma_\nu}$ = mean free path!

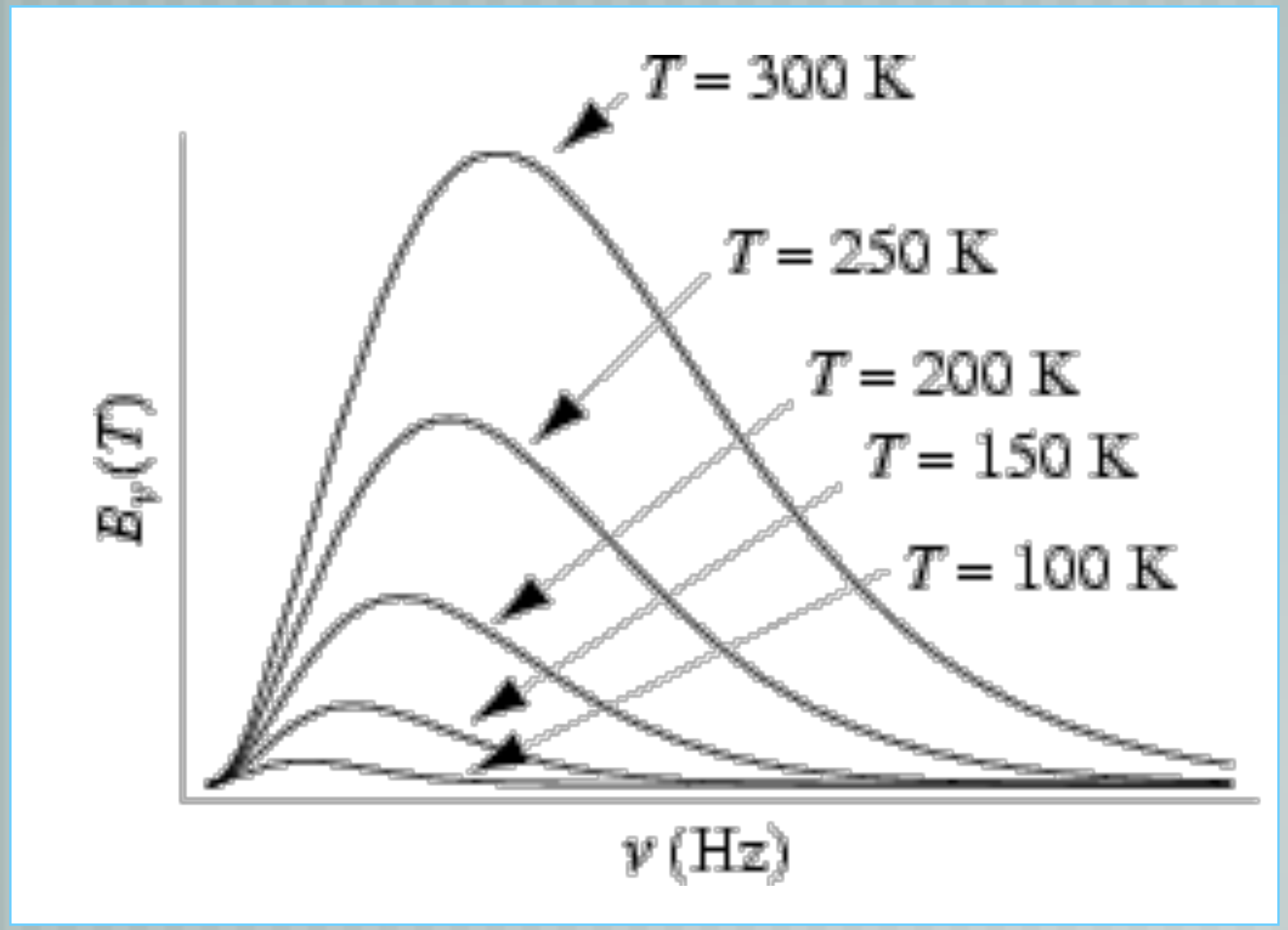
$\tau >> 1 \rightarrow$ opt. Thick $\tau \sim 1$

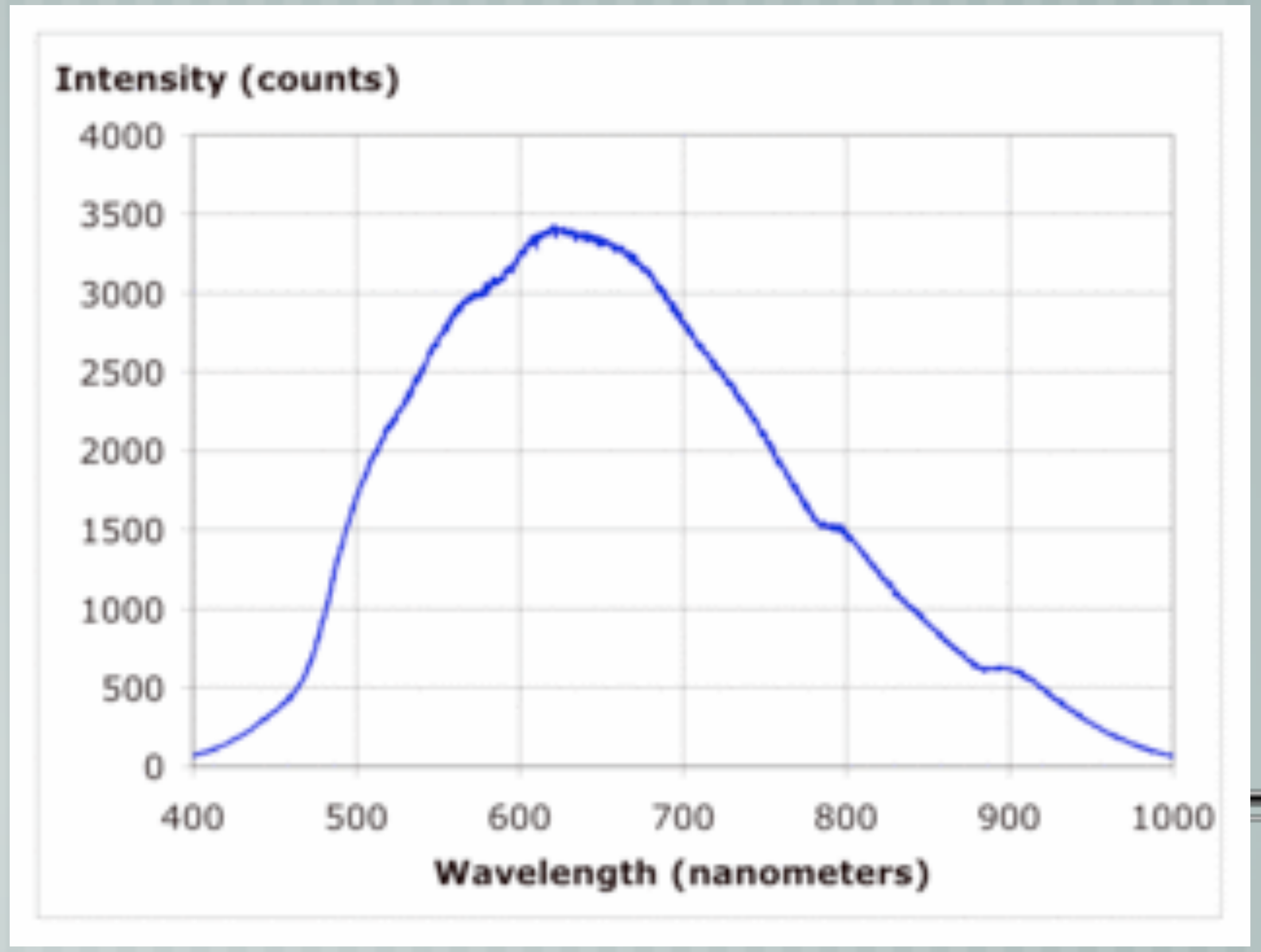
$\tau << 1 \Rightarrow$ opt. Thin

Thermal equilibrium + high opacity = Blackbody emission

- Plasma in 'causal contact', all global properties of photons depend only on T
  - Specific intensity given by the "blackbody" (Planck) formula:

$$I_\nu(T) \equiv B_\nu(T) = \frac{2h\nu^3/c^2}{\exp(h\nu/kT) - 1}$$





Blackbody emission II

Handy to know the essential characteristics like:

- Averaging over the total distribution gives a mean photon energy of $E_{mean}=h\nu_{mean}\approx 2.7kT$, close to the peak of the spectrum

- Integrating over frequency gives total energy density $\varepsilon_\gamma=aT^4$

- Total luminosity of a blackbody $L=(4\pi R^2)\sigma_B T^4$

Few E&M definitions (in vaccuum)

How particle moves

$$\vec{\nabla}\cdot\vec{E} = 4\pi\rho \qquad \vec{\nabla}\times\vec{E} = -\frac{1}{c}\frac{\partial\vec{B}}{\partial t}$$

$$\vec{\nabla}\cdot\vec{B} = 0 \qquad \vec{\nabla}\times\vec{B} = \frac{1}{c}\frac{\partial\vec{E}}{\partial t} + \frac{4\pi}{c}\vec{j}$$

$$\underbrace{\vec{j}\cdot\vec{E}}_{\frac{dU_{mech}}{dt}} + \underbrace{\frac{1}{8\pi}\frac{\partial}{\partial t}\left(E^2 + B^2\right)}_{U_B = \frac{B^2}{8\pi}} = -\underbrace{\vec{\nabla}\cdot\vec{S}}_{\text{loss term}}$$

→ +/- en. in particles

→ change in energy of field

loss term
transport of energy in fields away
"radiation"

$\vec{S}$ = poynting vector

$= \frac{c}{4\pi}\left(\vec{E}\times\vec{B}\right)$

EM ⇒ $\frac{c}{4\pi}|E|^2 = \frac{c}{4\pi}|B|^2$

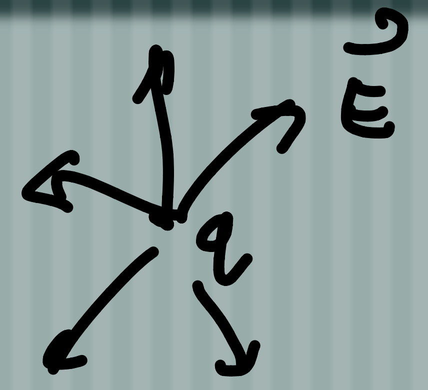
How is it we see things from so far away??
How can EM radiation travel without attenuation?

Need radiation field to somehow not decrease (much) with distance

- i.e., how do we maintain a signal over extremely long (astrophysical) distances?
- Typically static radial EM fields go as $1/R^2$ $\sim \frac{q}{R^2}$
- What is the scaling for energy transport (ie., radiation)?

$\sim 1/R^4$

Radiating charges



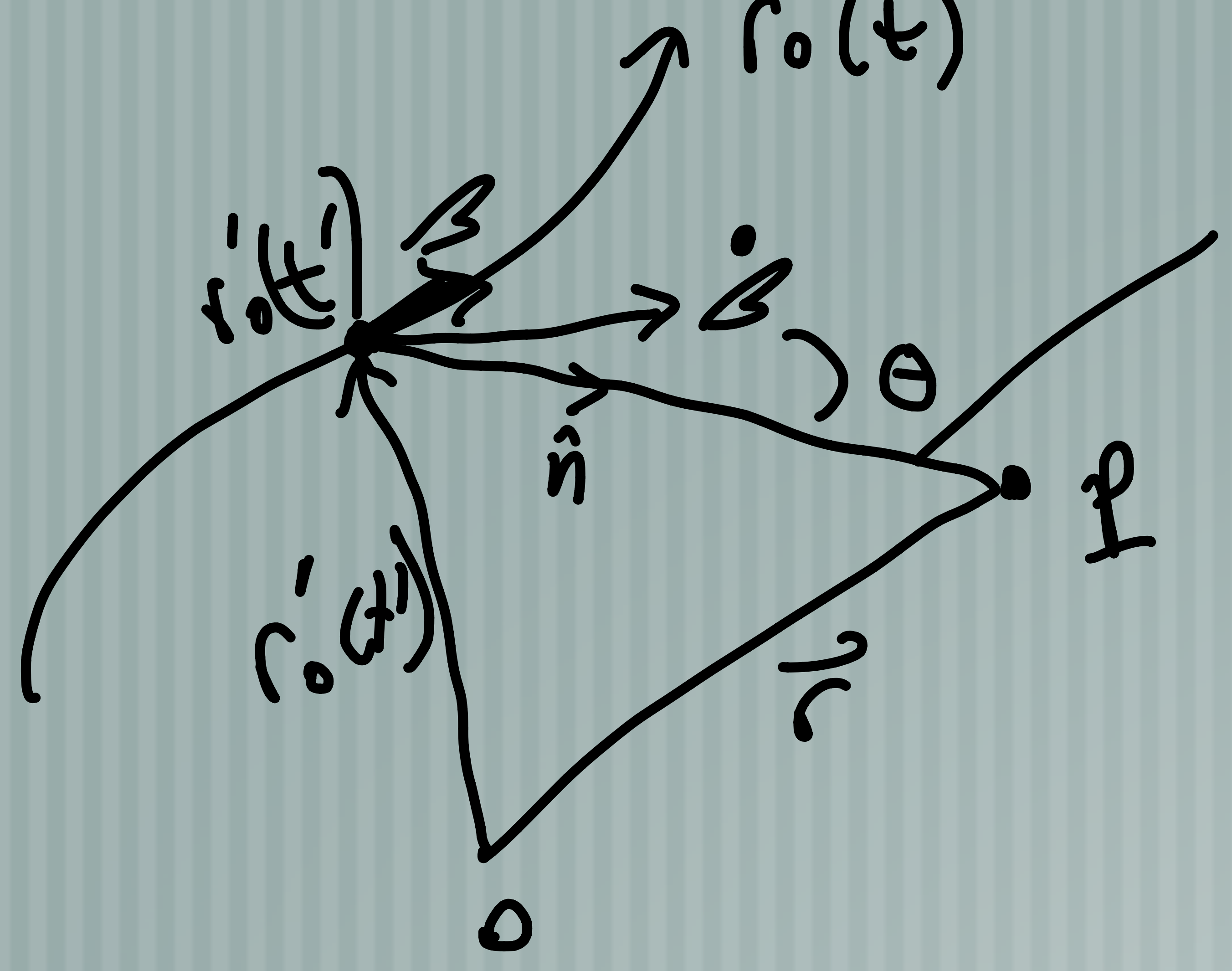
$\vec{E} \approx \frac{q}{R^2} \to \vec{S} \propto 1/R^4 \to$ no energy!

$\vec{E} \sim 1/R \to \vec{S} \propto 1/R^2 \to$ better

$\to$ ripple / pulse $\Rightarrow$ <u>acceleration</u>

Geometry with relativistic motion = retarded time

Coordinate system of observing rel. particle emitting light:



$R = |\vec r - r_0'(t')|$

"P" feels/sees EM radiation from same at

$$\boxed{t' \equiv t - R/c}$$

$\hat n \equiv \frac{\vec R}{R}$ at t'

$$\frac{dt'}{dt} \equiv \kappa = (1 - \hat n \cdot \vec\beta)$$

Electric field from Liénard-Wiechert Potential

$$\vec{E}_{\mathrm{rel}}(\vec{r},t) = \underbrace{q\left[\frac{(\hat{n}-\vec{\beta})(1-\beta^2)}{\kappa^3 R^2}\right]}_{\text{"velocity field"}} + \underbrace{\frac{q}{c}\left[\frac{\hat{n}}{\kappa^3 R}\times(\hat{n}-\dot{\vec{\beta}})\times\vec{\beta}\right]}_{\text{"acceleration field", "radiation field"}}$$

"velocity field"

$\beta \to 0$, reduces to q/R^2

$\kappa = 1$

not interesting

$(\vec{S} \sim 1/R^4)$

"acceleration field", "radiation field"

$\vec{S} \sim 1/R^2$

How you get a transverse/radial field from acceleration!

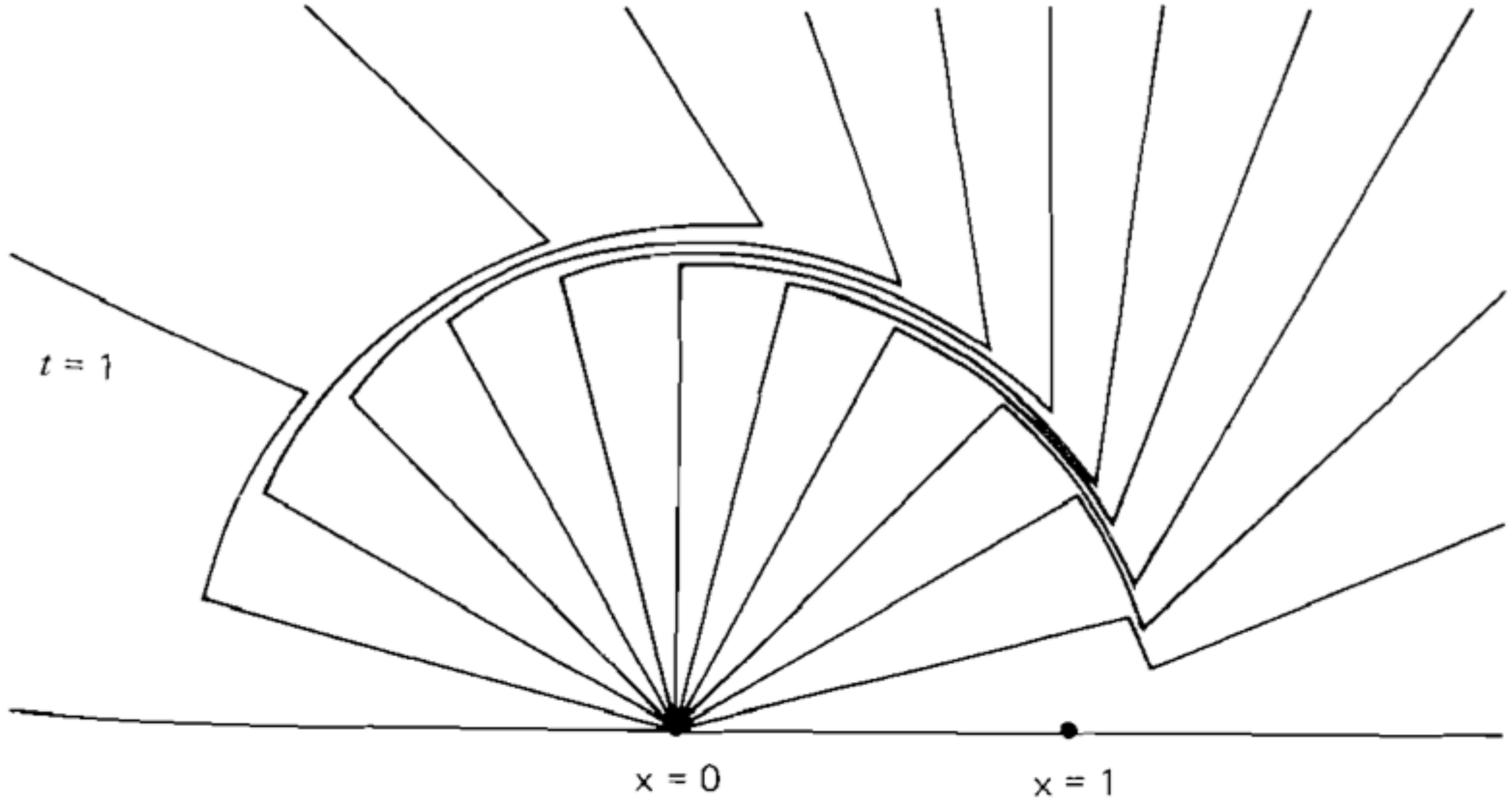


Figure 3.2 *Graphical demonstration of the $1/R$ acceleration field. Charged particle moving at uniform velocity in positive x direction is stopped at $x=0$ and $t=0$.*

How you get a transverse /radial field from acceleration!

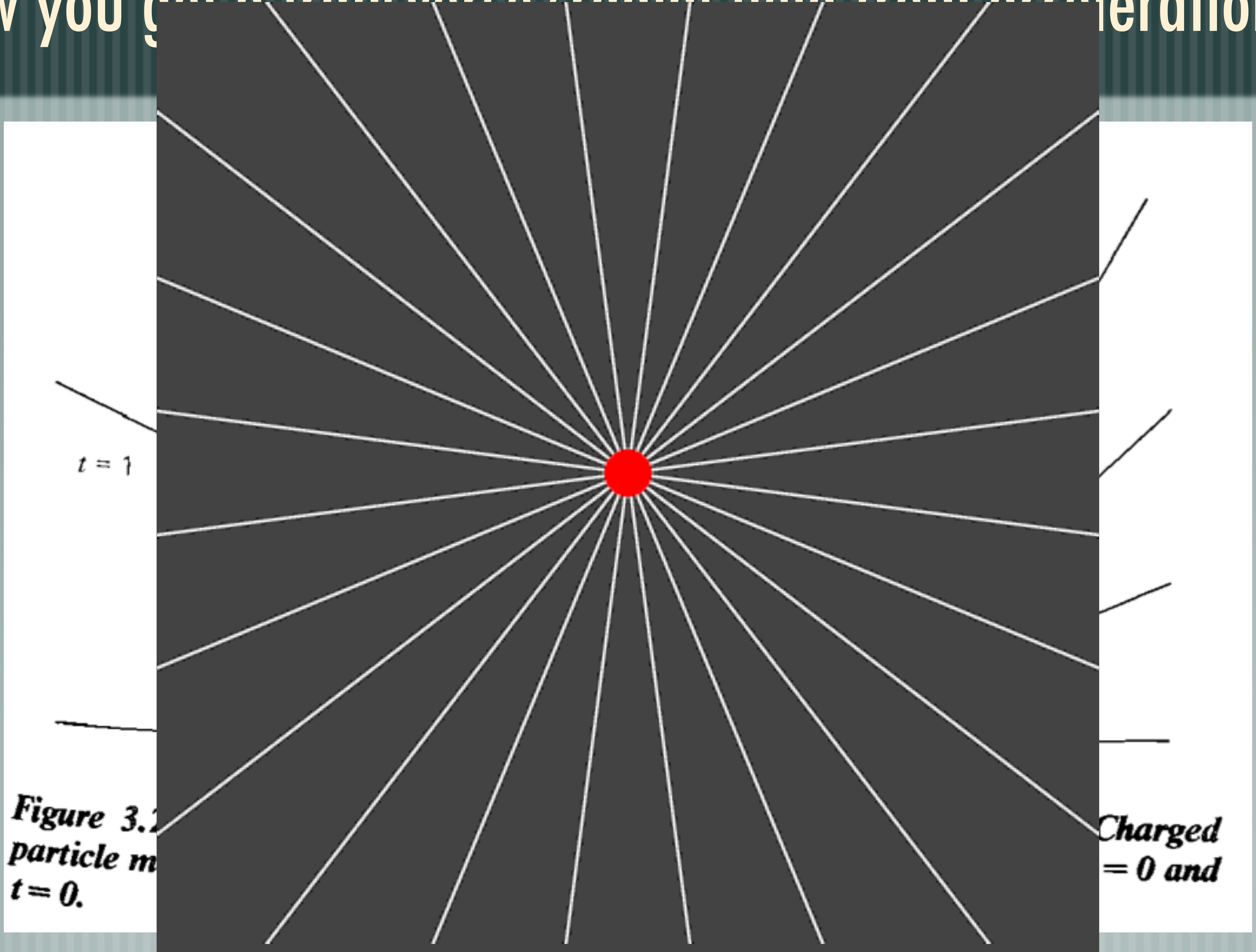
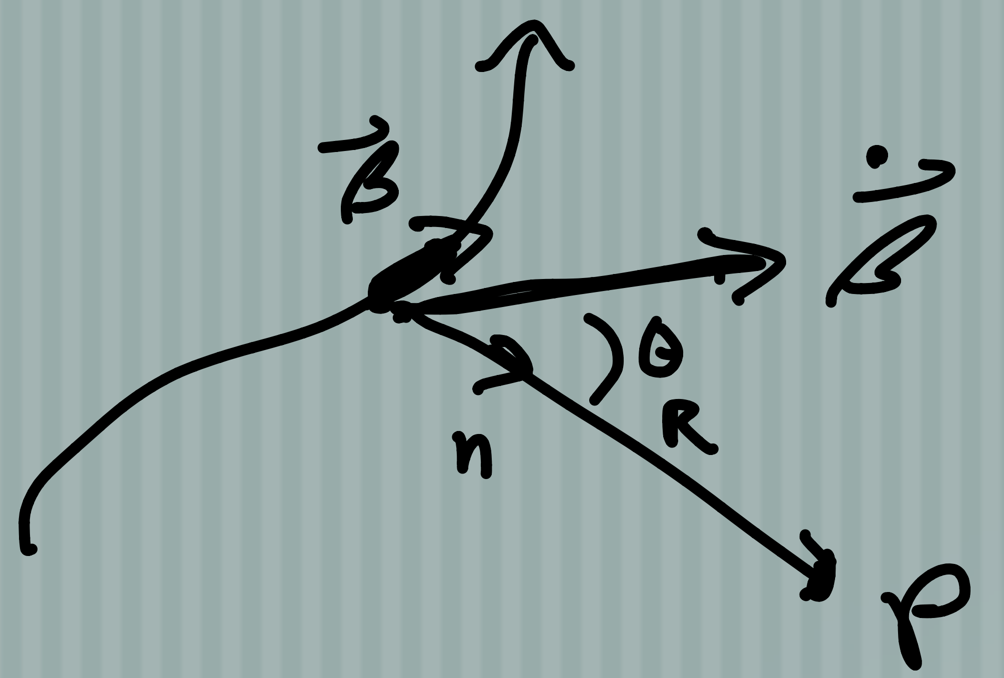


Figure 3.2 ... Charged particle m... = 0 and t = 0.

Radiation pattern & power from accelerating charges

Simplify & think non-relativistic $\beta \to 0$, $\kappa = 1$

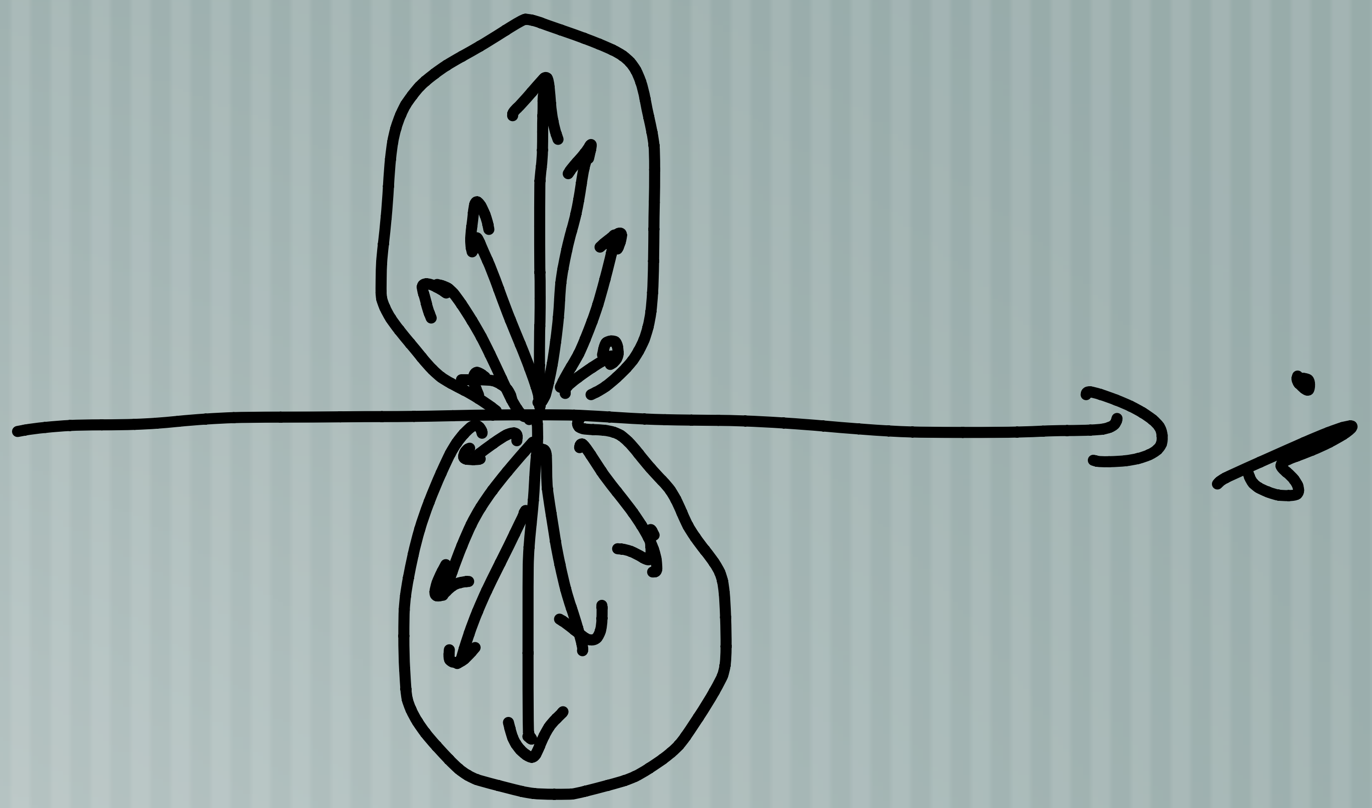


$$\vec E_{rad} = \frac{q}{cR}\left[\hat n \times \underbrace{(\hat n \times \dot{\vec\beta})}_{\dot\beta \sin\theta}\right]$$

$$|E_{rad}| = \frac{q}{cR}\,\dot\beta \sin\theta = |B_{rad}|$$

$$|S| = \frac{c}{4\pi}|E|^2 = \frac{q^2\dot\beta^2\sin^2\theta}{4\pi c R^2}$$

$$\frac{dP}{d\Omega} = \frac{dW}{dt\,d\Omega} = R^2|S| = \frac{q^2\dot\beta\sin^2\theta}{4\pi c}$$



Power from dipole radiation: Larmor's formula

$\vec{d} = q\vec{r}$

$\dot{\vec{d}} = q\vec{v}$

$\ddot{d} = q\dot{v} = q\dot{\beta}c$

$$\frac{dP}{d\Omega} = \frac{\ddot{d}^2 \sin^2\theta}{4\pi c^2} \qquad d\Omega = \sin\theta\, d\theta\, d\phi$$

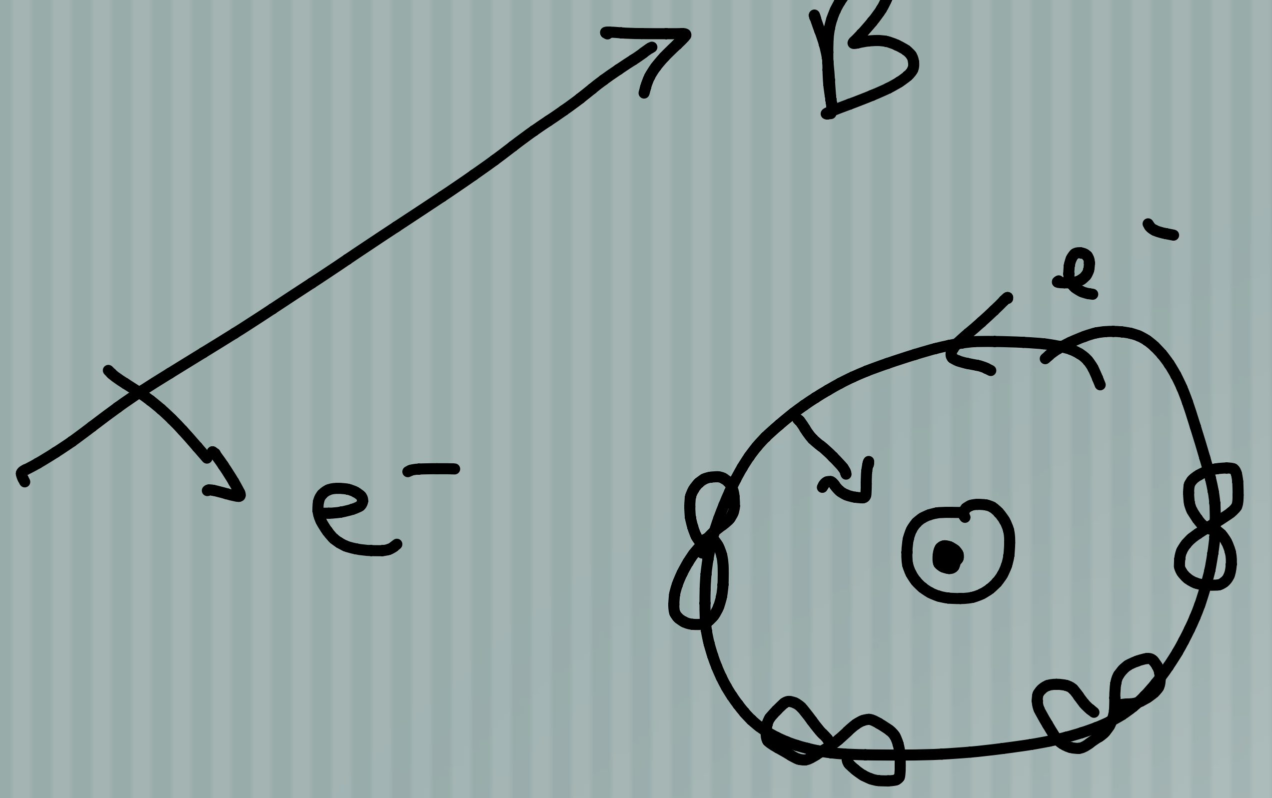
$$\int \frac{dP}{d\Omega} d\Omega = \left(\frac{8\pi}{3}\right)\frac{\ddot{d}^2}{4\pi c^2} \qquad \text{"Larmor's ="}$$

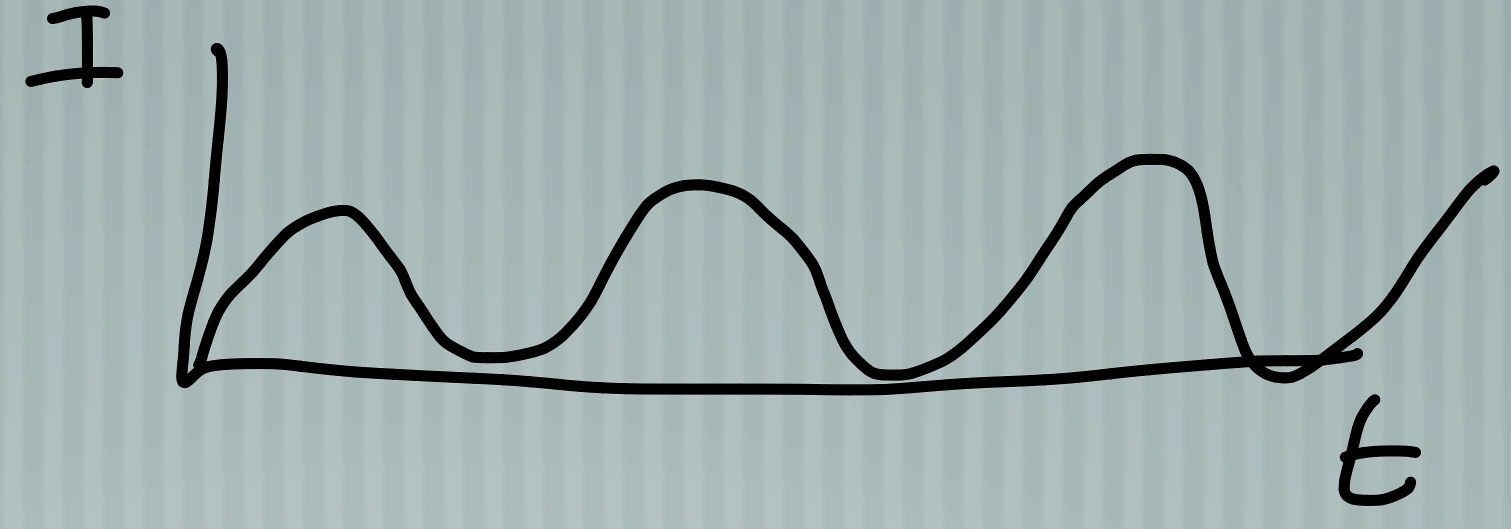
Takeaways: ★ accelerating charges radiate like dipole (if non-rel), can always transform to that frame

★ main effect of relativity (sp.) is beaming & angle aberration → math

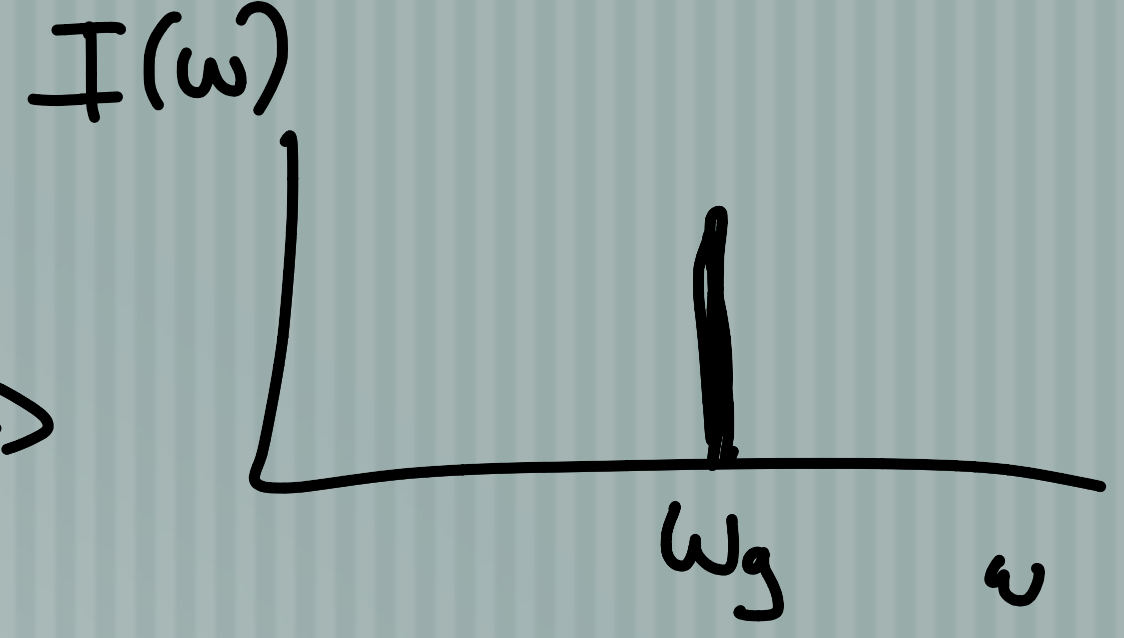
"Prelude" to cyclo-synchrotron

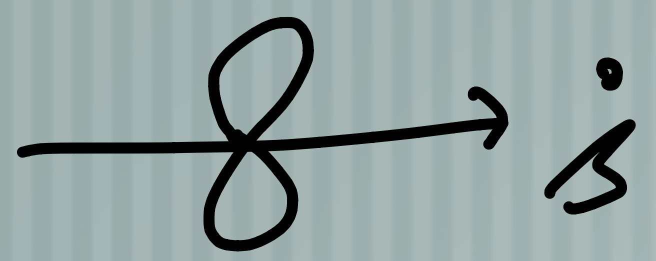
$F_L = -\frac{e}{c}(\vec{v} \times \vec{B})$



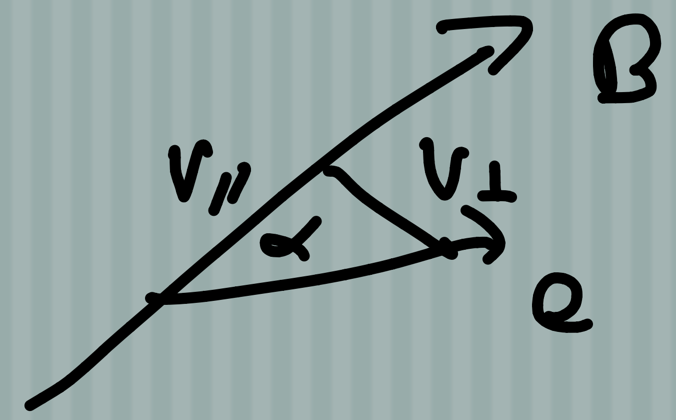


$\Longrightarrow$





Power from non-relativistic particle in a magnetic field (Cyclotron)



$V_{\parallel} \Rightarrow$ acceleration? No $\rightarrow$ no light

$V_{\perp} \Rightarrow V\sin\alpha$

$$\omega_g = \frac{V_\perp}{r} \Rightarrow \frac{eB}{mc} = \boxed{1.8\times 10^7 \, B_{gauss}}$$

want $\ddot{d} = -e\dot{v} = e v \sin\alpha \, \omega_g$

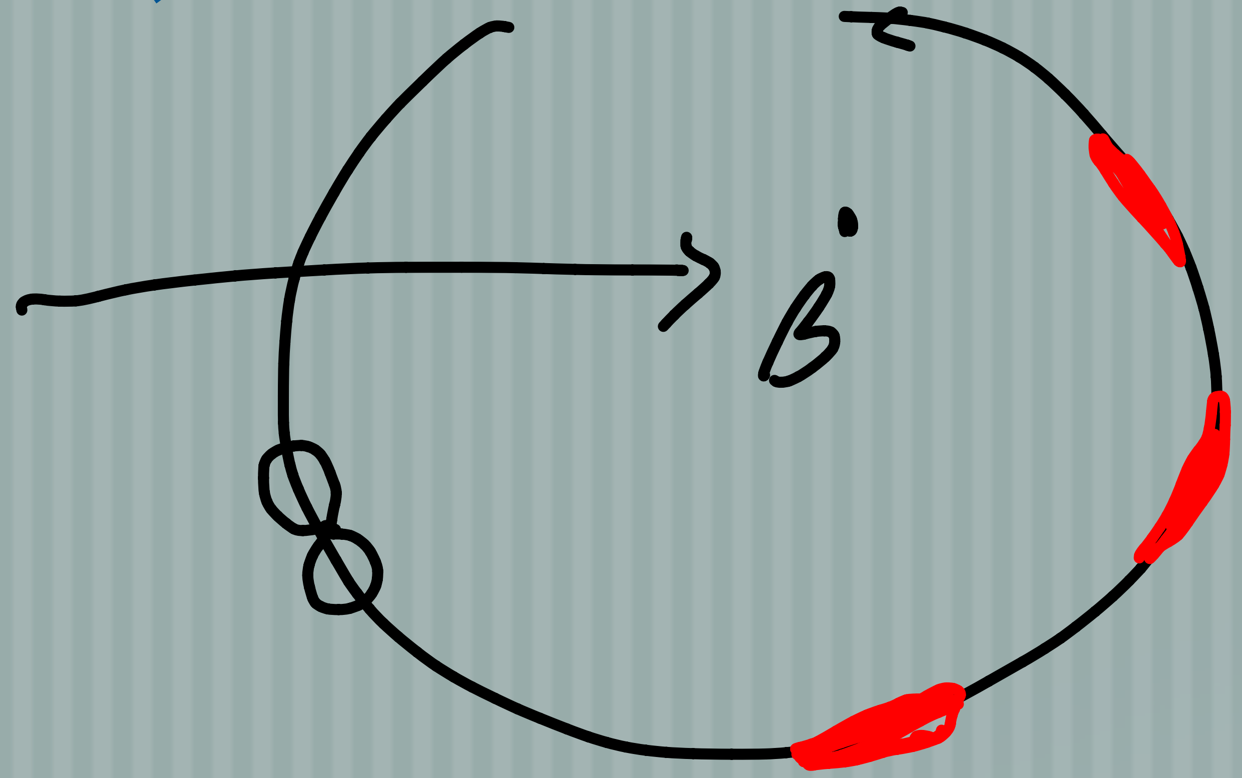
$F = ma$

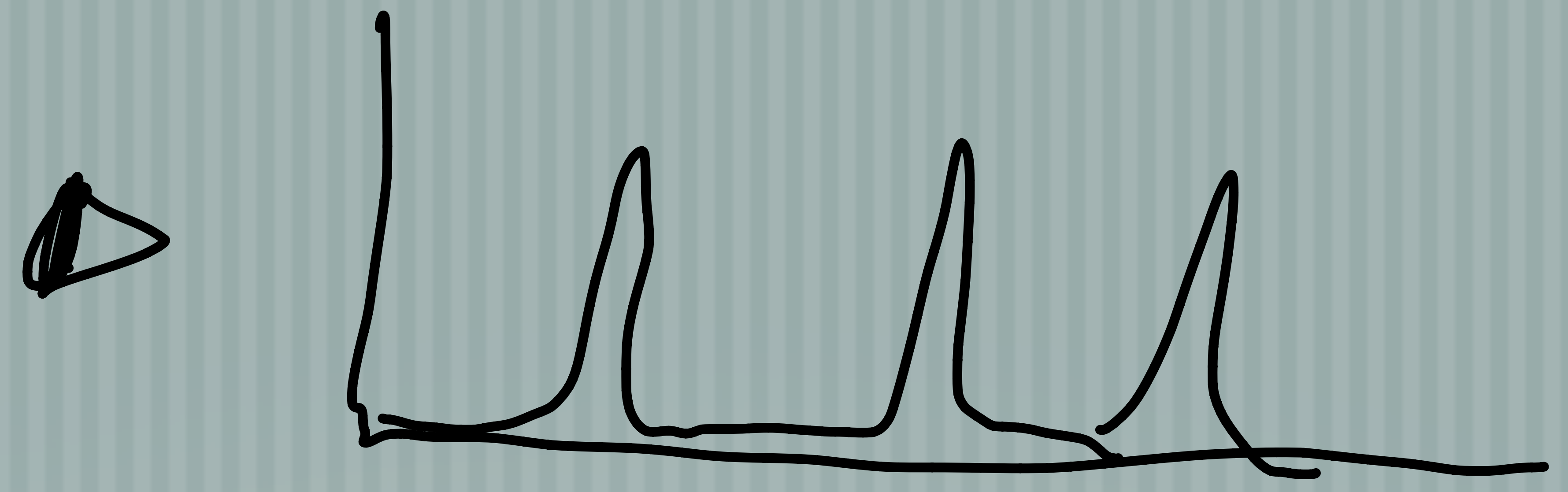
$-\frac{e}{c} v B \sin\alpha = m\dot{v}$

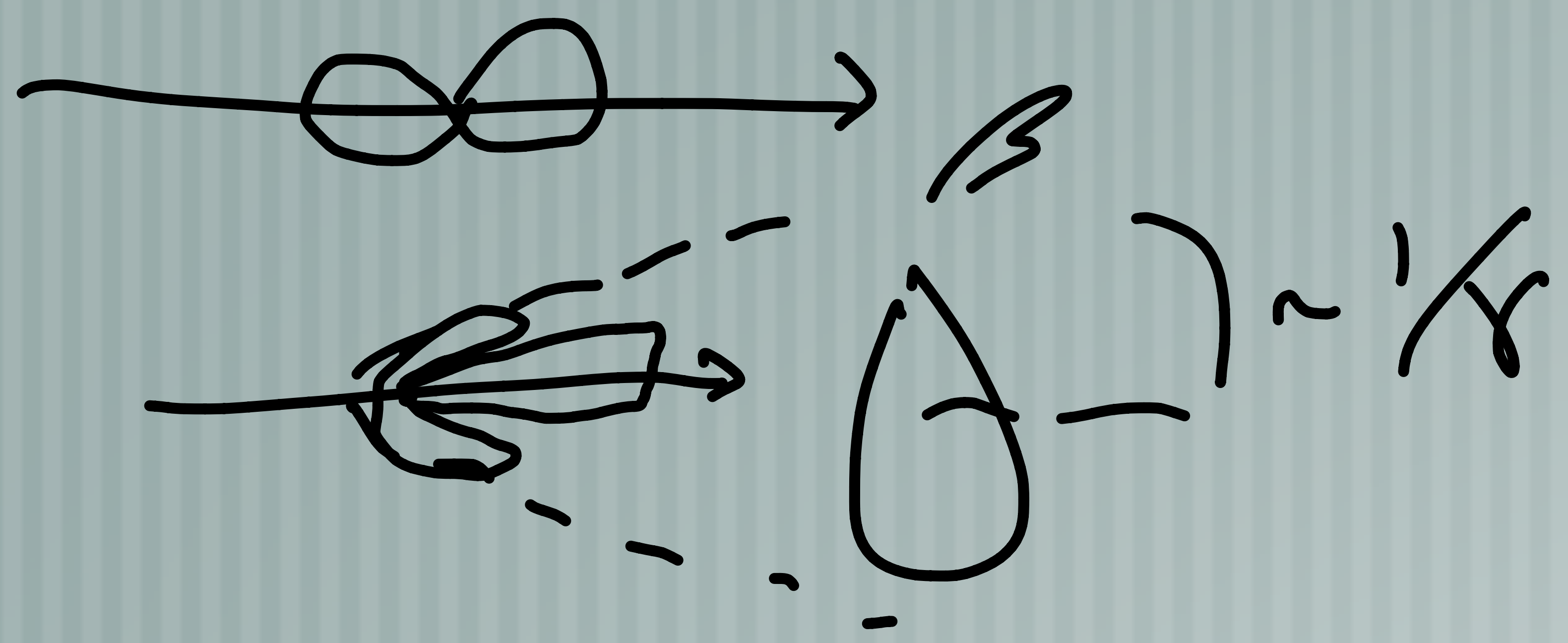
$$P_{cycl.} = \frac{2}{3}\frac{\ddot{d}^2}{c^3} = \frac{2}{3}\frac{e^2 v^2 \sin^2\alpha \, \omega_g^2}{c^3}$$

How does P depend on Energy $\propto v^2 = KE$

Qualitative extension to relativistic particle motion (synchrotron)







$$P_{larmor} = \frac{\frac{2}{3} e^2 v^2 \sin^2\alpha\, \omega_g}{c^3} \cdot \gamma^2$$

angle transfr

$$\beta = v/c$$

$$\frac{\int_\alpha P\, d\Omega}{\int_\alpha d\Omega} = \frac{1}{4\pi}\left(\frac{8\pi}{3}\right)\frac{2}{3}\frac{e^2}{c^3}\gamma^2\beta^2\omega_g^2$$

$$r_0 = \frac{e^2}{mc^2} \Rightarrow P_{synch,tot} = \frac{4}{3}\left(\frac{8\pi r_0^2}{3}\right)\left(\frac{B^2}{8\pi}\right)\gamma^2\beta^2 c$$

$$= \boxed{\frac{4}{3}\sigma_T U_B \gamma^2 \beta^2 c} \times n$$

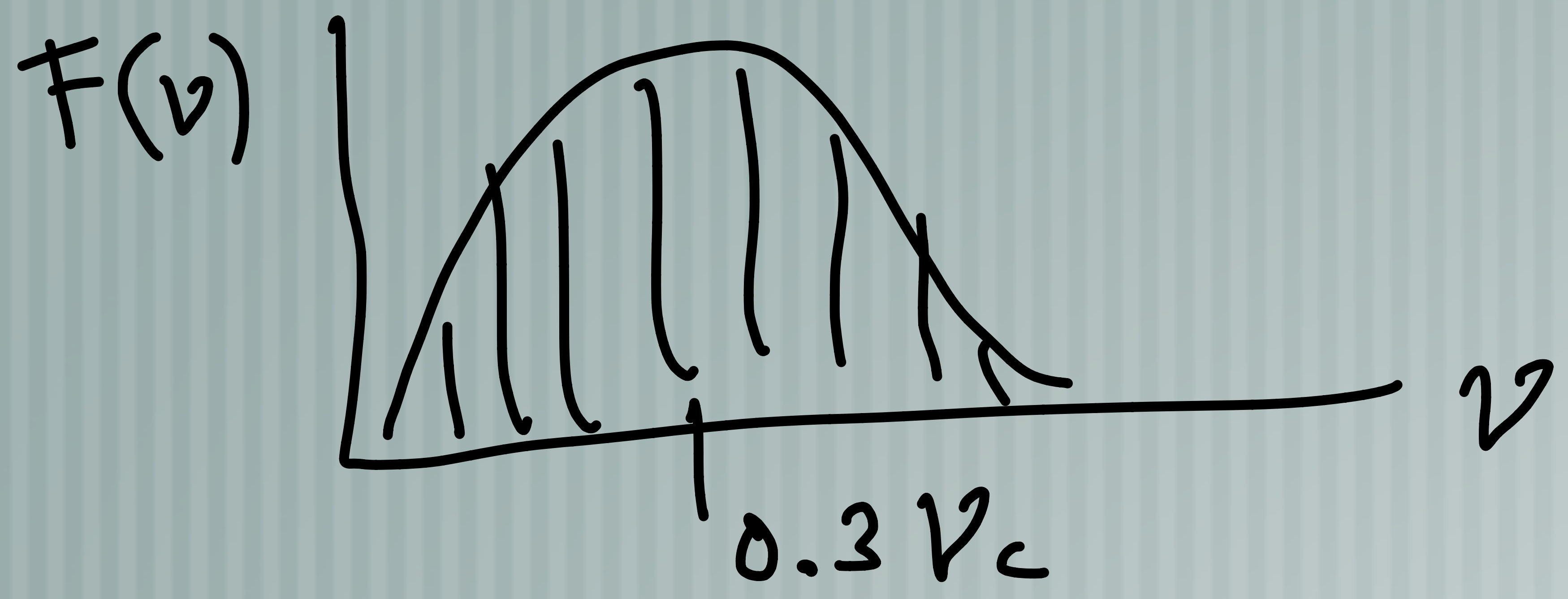
Dependance on energy? E^2

Form of frequency dependence dW/dω

Spectrum : $\frac{dP}{d\Omega\, d\omega} = \frac{dW}{dt\, d\Omega\, d\omega}$

$\frac{dW}{d\omega}$ = encodes the Fourier transform

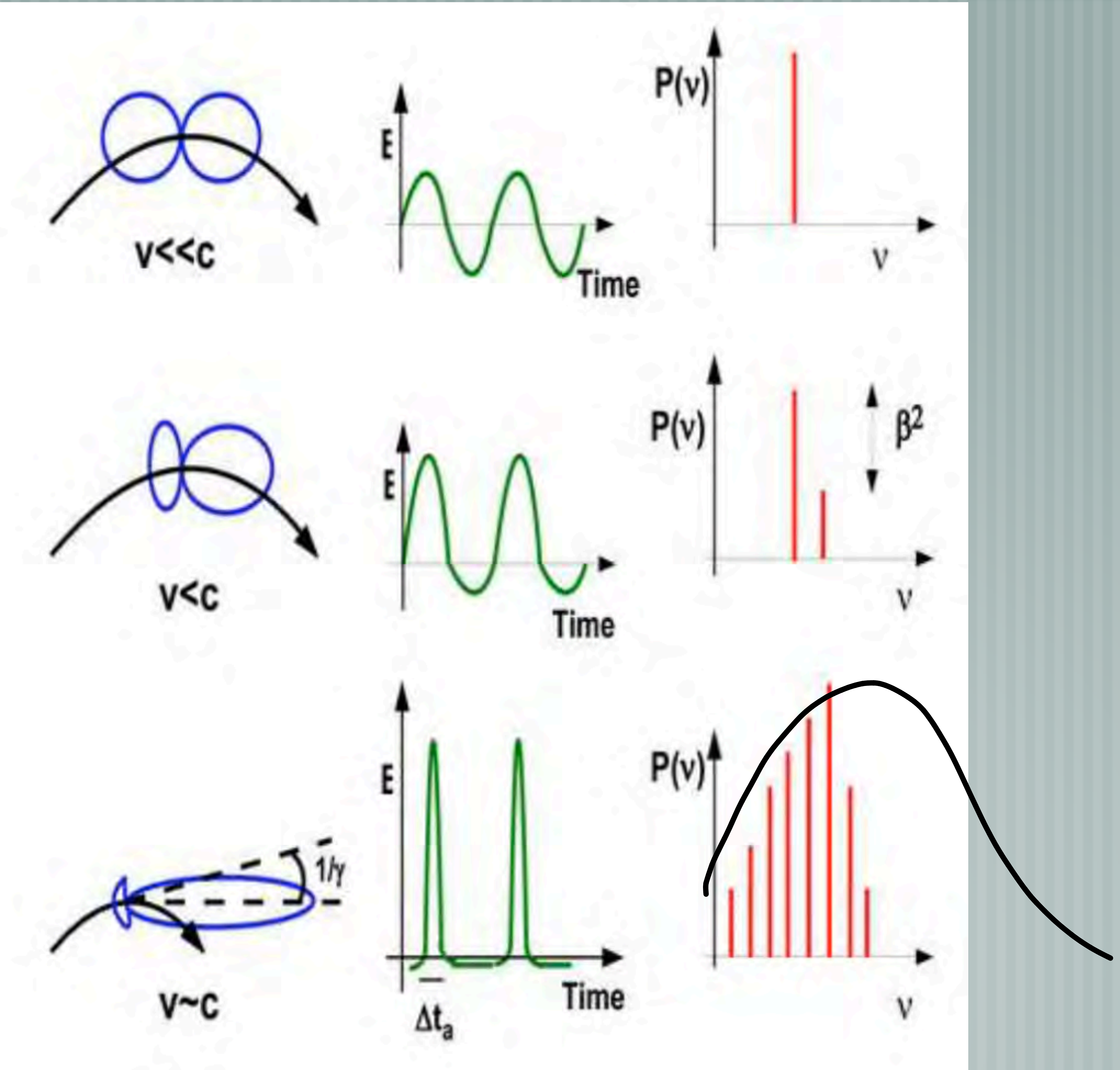
$$\frac{dW}{d\omega} = \frac{8\pi}{3} \frac{\omega^4}{c^3} \left| \tilde{d}(\omega) \right|^2$$



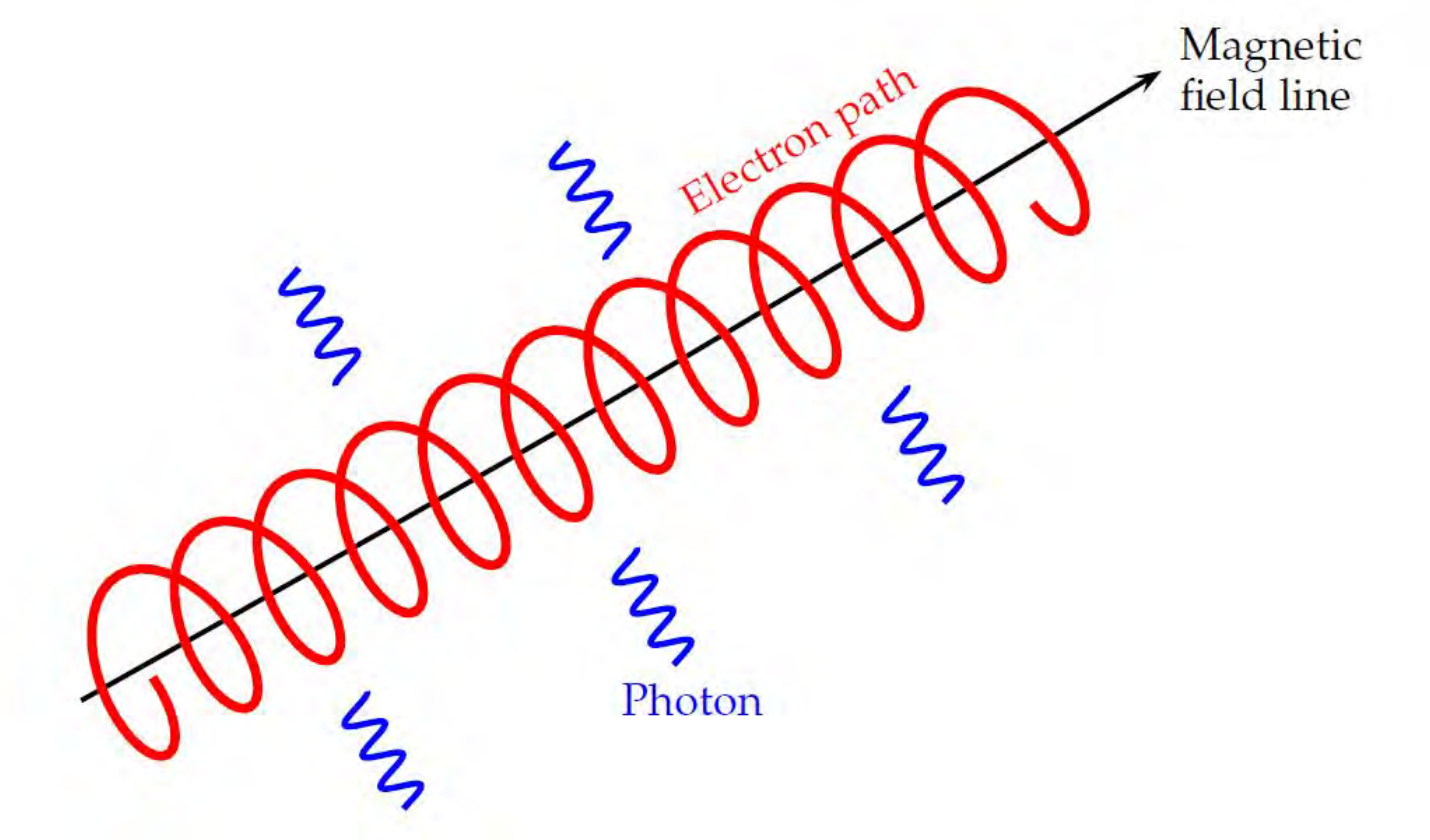
$$\nu_c \sim \frac{3}{4\pi} \gamma^2 \omega_g \cancel{\sin\alpha}^{\,1}$$

$$\sim \frac{3}{4\pi} \gamma^2 \frac{eB}{mc}$$

Relativistic motion/aberration effects spectrum



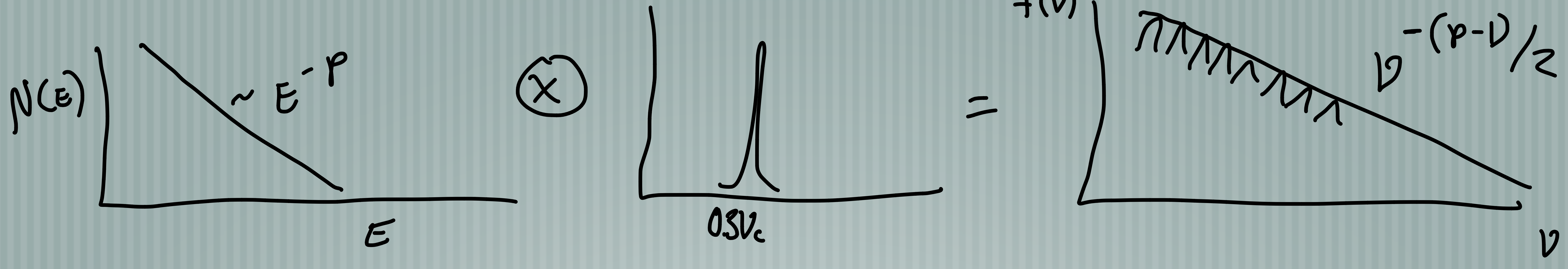
Synchrotron

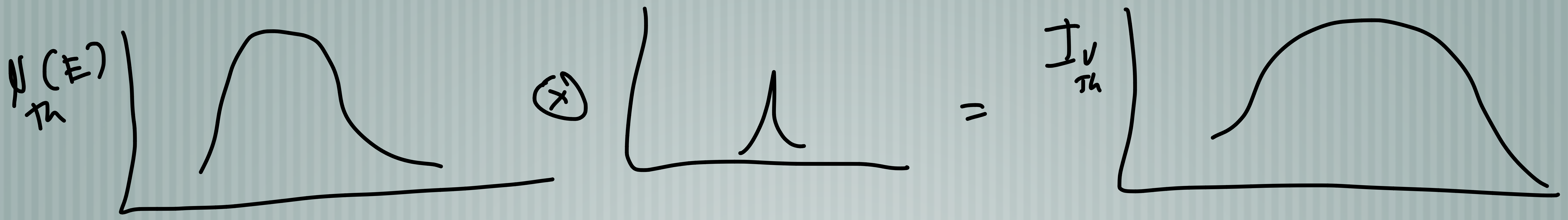


Synchrotron spectral form P(ν,E)

$$x = \nu/\nu_c$$

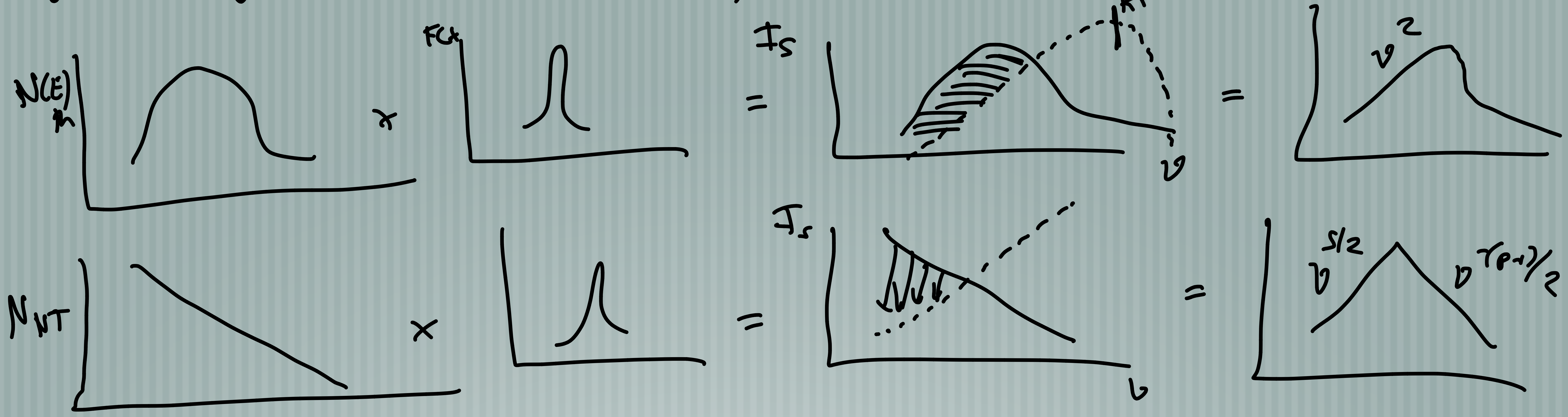
$$P(\nu, E_e) = \frac{\sqrt{3}\, e^3 B \sin\alpha}{mc^2} F(x)$$



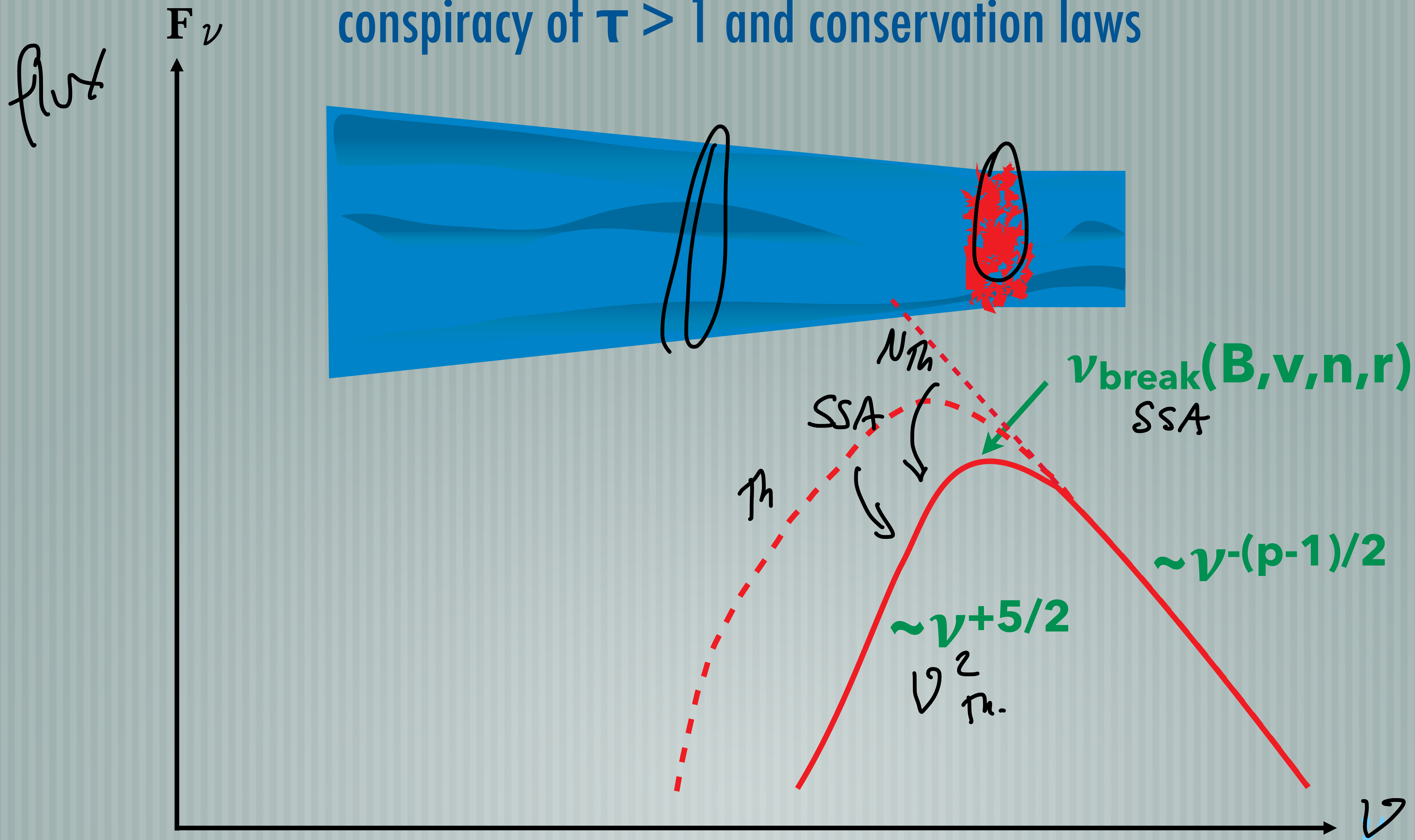


Synchrotron self-absorption

lower freq effect → Blackbody (th) wins, non-th.



"Signature" flat(ish) emission of compact jets ("cores") is a conspiracy of $\tau > 1$ and conservation laws



(Blandford & Königl 1979)

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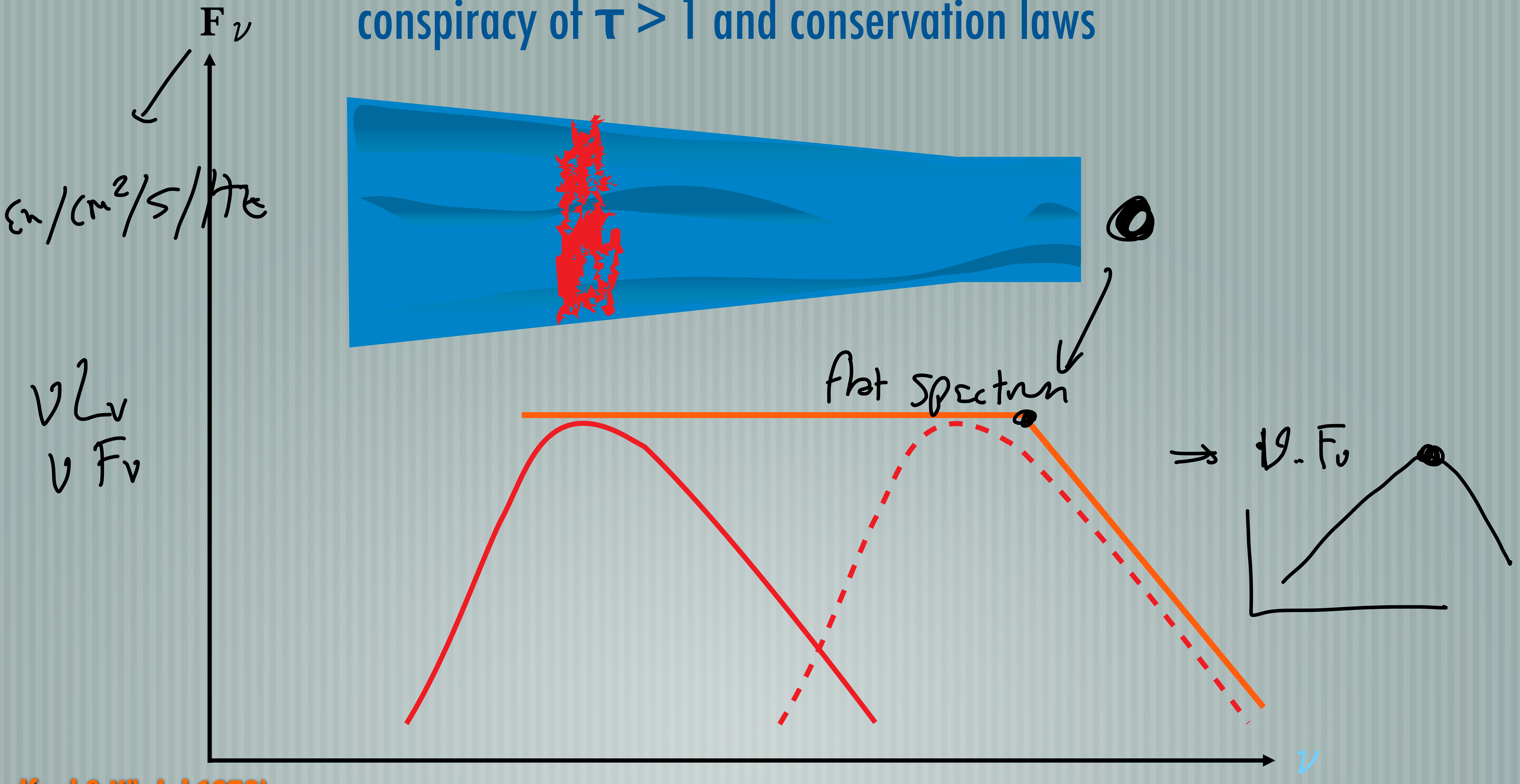


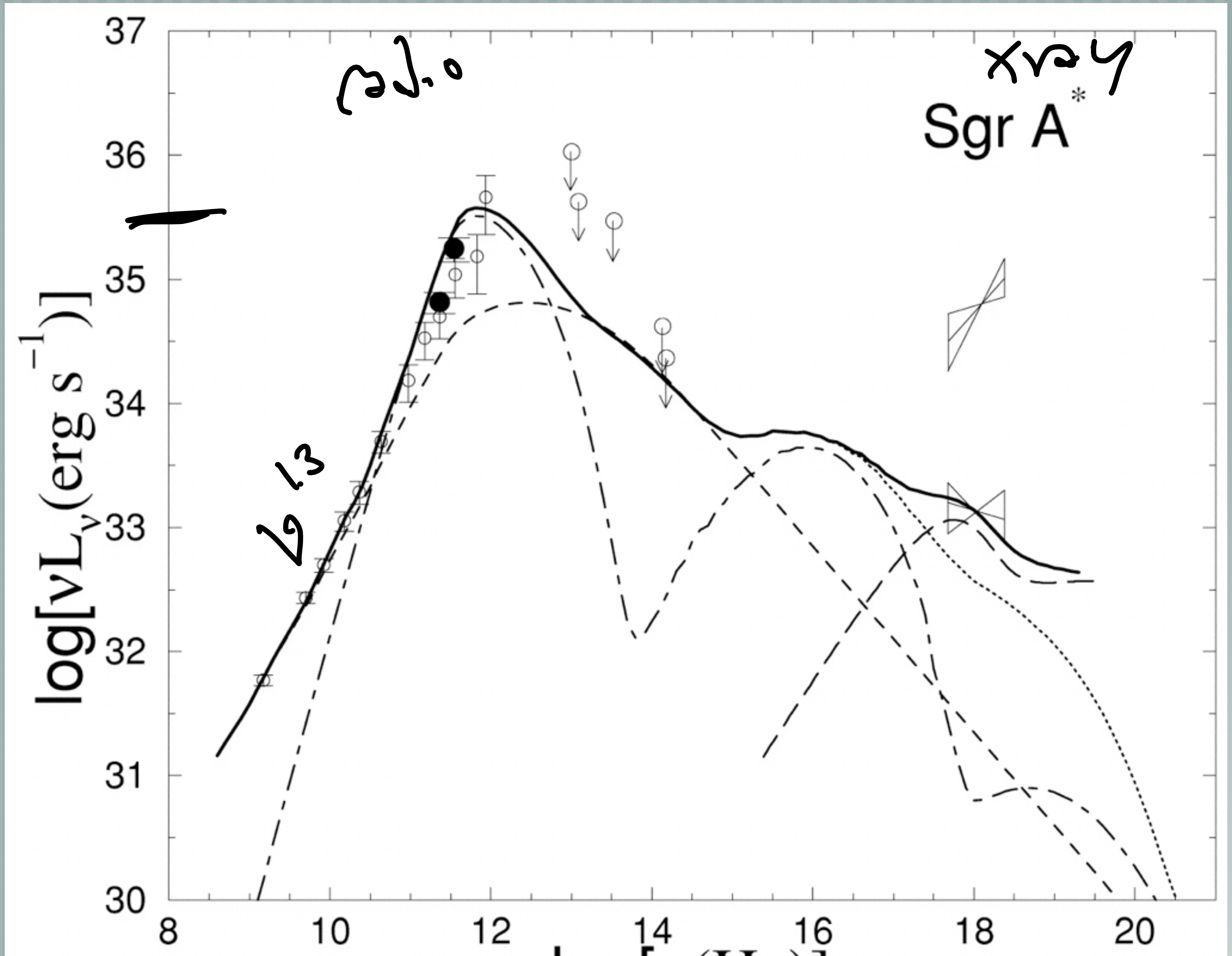
(Blandford & Königl 1979)

SSA in active galactic nuclei (AGN) jets

$$\nu_{SSA} = 100 \ \mathrm{MHz} \left(B_{mG} \right)^{4/3} \left(R_{kpc} \right)^{1/3}$$

Application to Sgr A* I: my favourite black hole!

F_ν



Yuan et al. 2003

$$R = 10\, r_g \qquad r_g \cong 10^5 \left(\frac{M}{M_\odot}\right) \text{cm}$$

$$M = 4\times10^6\, M_\odot = 10^{(6.6)}$$

$$\text{kpc} = 3\times10^{21}\,\text{cm} = 10^{21.5}$$

$$\nu_{SSA} \sim 100\,\text{MHz}\; B_{ma}^{4/5}\, R_{kpc}$$

$$r_g = 10^{(5+6.6)} = 10^{11.6}, \quad 10\, r_g = 10^{12.6}$$

$$10^{12}\,\text{Hz} \sim 10^{8}\,\text{Hz} \cdot B_{ma}^{4/3}\; R_{kpc}^{4/3}$$

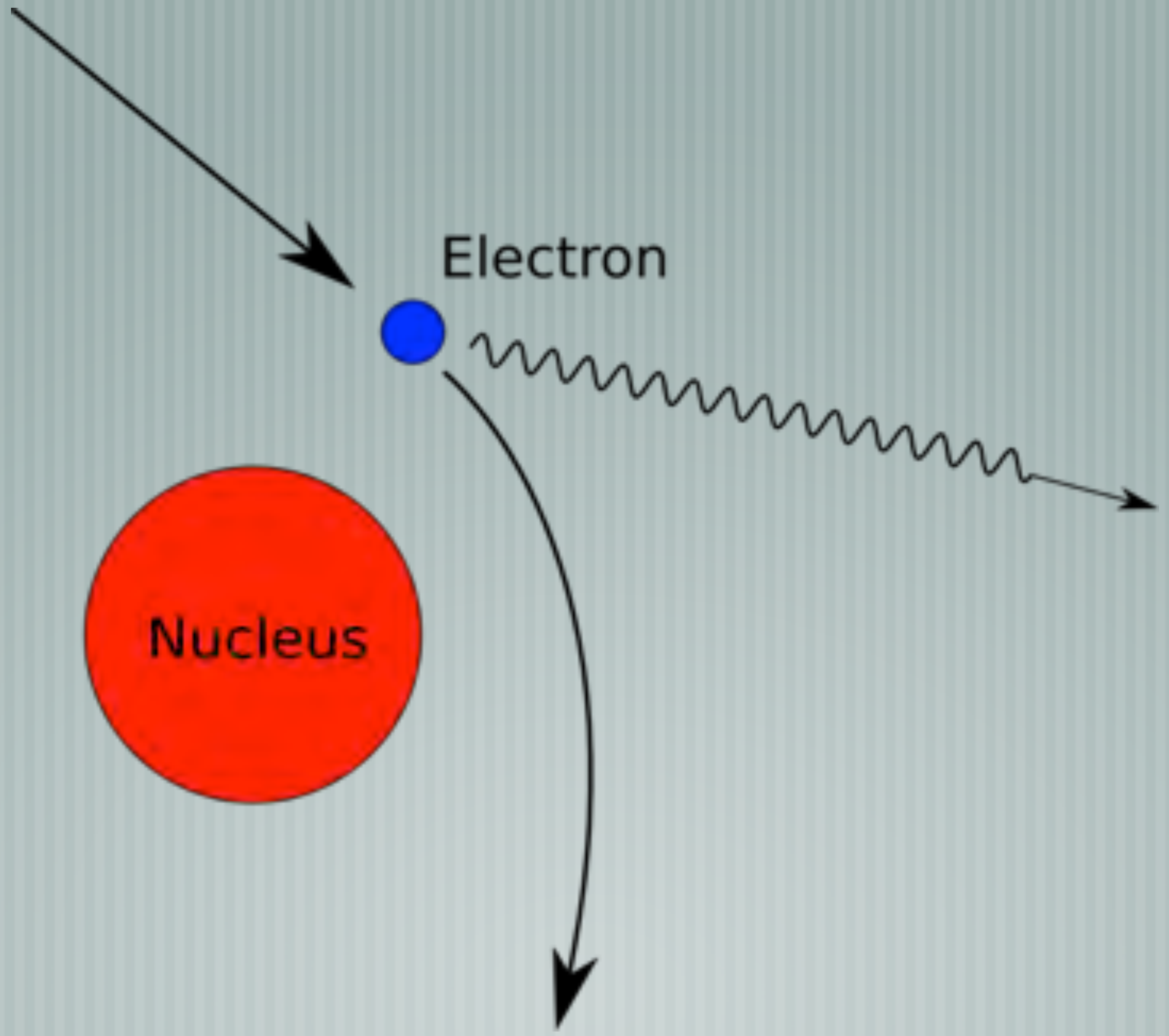
$$R_{kpc} \rightarrow 10^{12.6-21.5} \sim 10^{-9}$$

$$B_{ma}^{4/3} = 10^{12-8+3} = 10^{7}$$

$$B_{ma} = 10^{7\cdot3/4} \approx 10^{21/4} \sim 10^5\,\text{mG}$$

$$\boxed{\sim 100\,\text{G}}$$

Bremsstrahlung

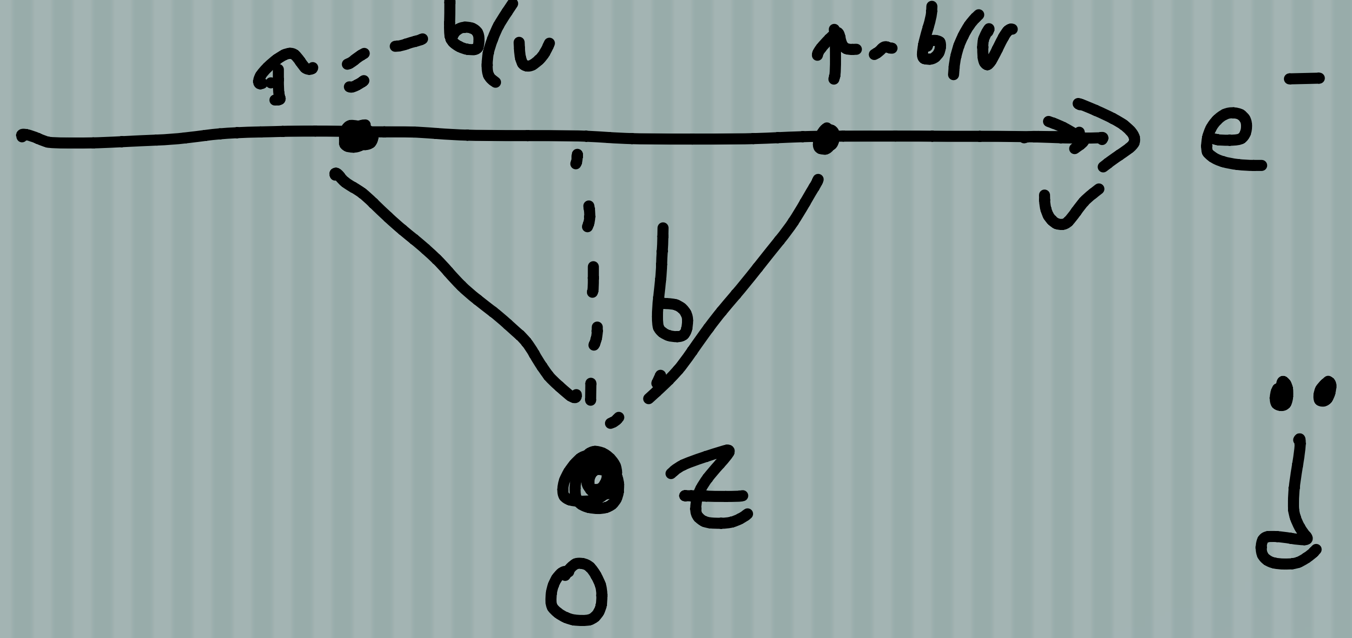


Bremsstrahlung

Radiation emitted as a particle de/accelerates in the Coulomb field of another charge

- “Braking radiation”, also called “free-free” emission
- QED process, but we can go pretty far with classical picture using dipole approximation for case of e-ion interactions
- If interested in seeing the full QM derivations:
  - e-p: Karzas & Latter 1961 ApJ Suppl., 6, 167
  - e-e+: Haug 1987, A&A, 178, 292
  - e-e: Haug 1989, A&A, 218, 330

Semi-classical "dipole" approximation for bremsstrahlung



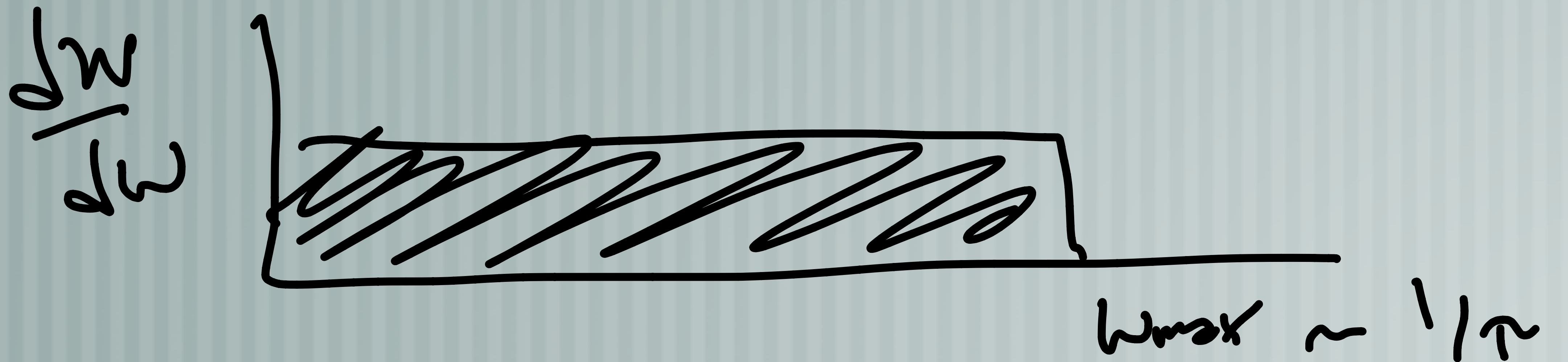
$$\vec{d} = e\,\vec{r}_e \quad \longrightarrow \quad \frac{dW}{d\omega} \sim f\,|\tilde{d}(\omega)|$$

$$\ddot{d}(t) = \int_{-\infty}^{\infty} (-\omega^2)\,\tilde{d}(\omega)\, e^{-i\omega t}\, d\omega$$

$$(-\omega^2)\,\tilde{d}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \ddot{d}(t')\, e^{i\omega t'}\, dt$$

assume $\tau \ll 1/\omega \Rightarrow \omega\tau \ll 1 \Rightarrow e^{i\omega t} \Rightarrow 1$ our accel. per.

$$-(\omega^2)\,\tilde{d}(\omega) = -\frac{e}{2\pi}\int_{-\tau}^{\tau} \dot{v}_e(t')\, dt \quad , \quad F = m\dot{v}_e = -\frac{Ze^2}{r^2}$$

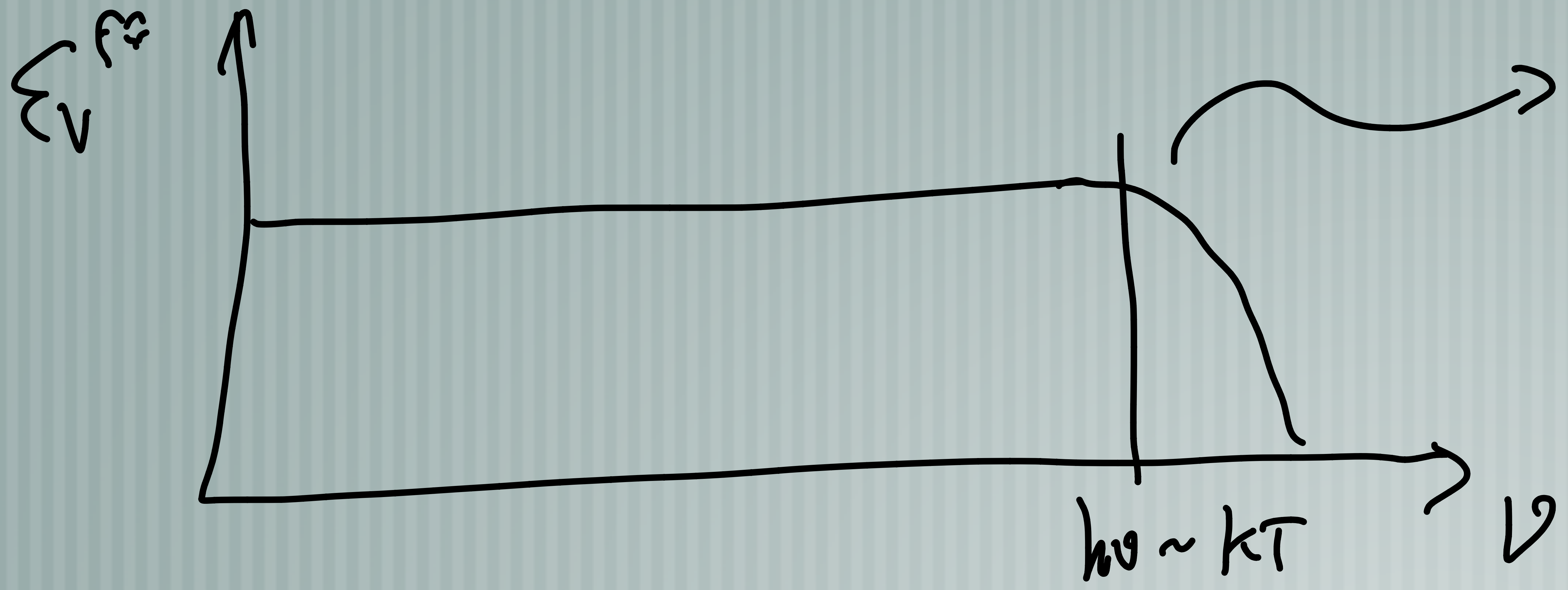


Application: astrophysical thermal plasma (relativistic:)

Thermal distribution in plasma, n_e, n_i, T

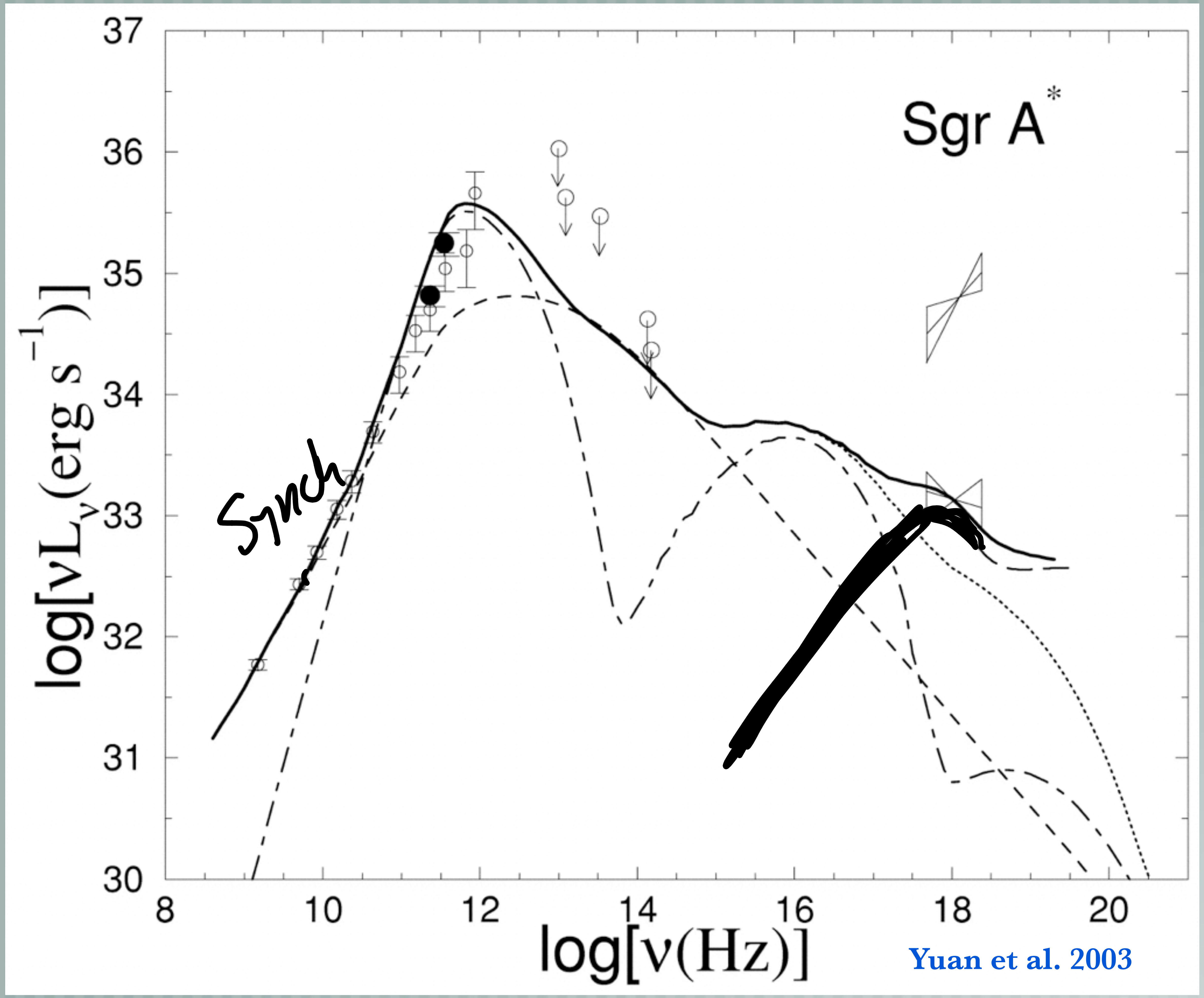
– average over M-B velocity distribution, incl. Gaunt (QM)

$$\varepsilon_\nu^{ff} = 7\times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT} \underbrace{\tilde{g}_{ff}}_{\sim 1} \quad \mathrm{erg/cm^3/s/Hz}$$



huge diagnostic

Sgr A*: What's the T?



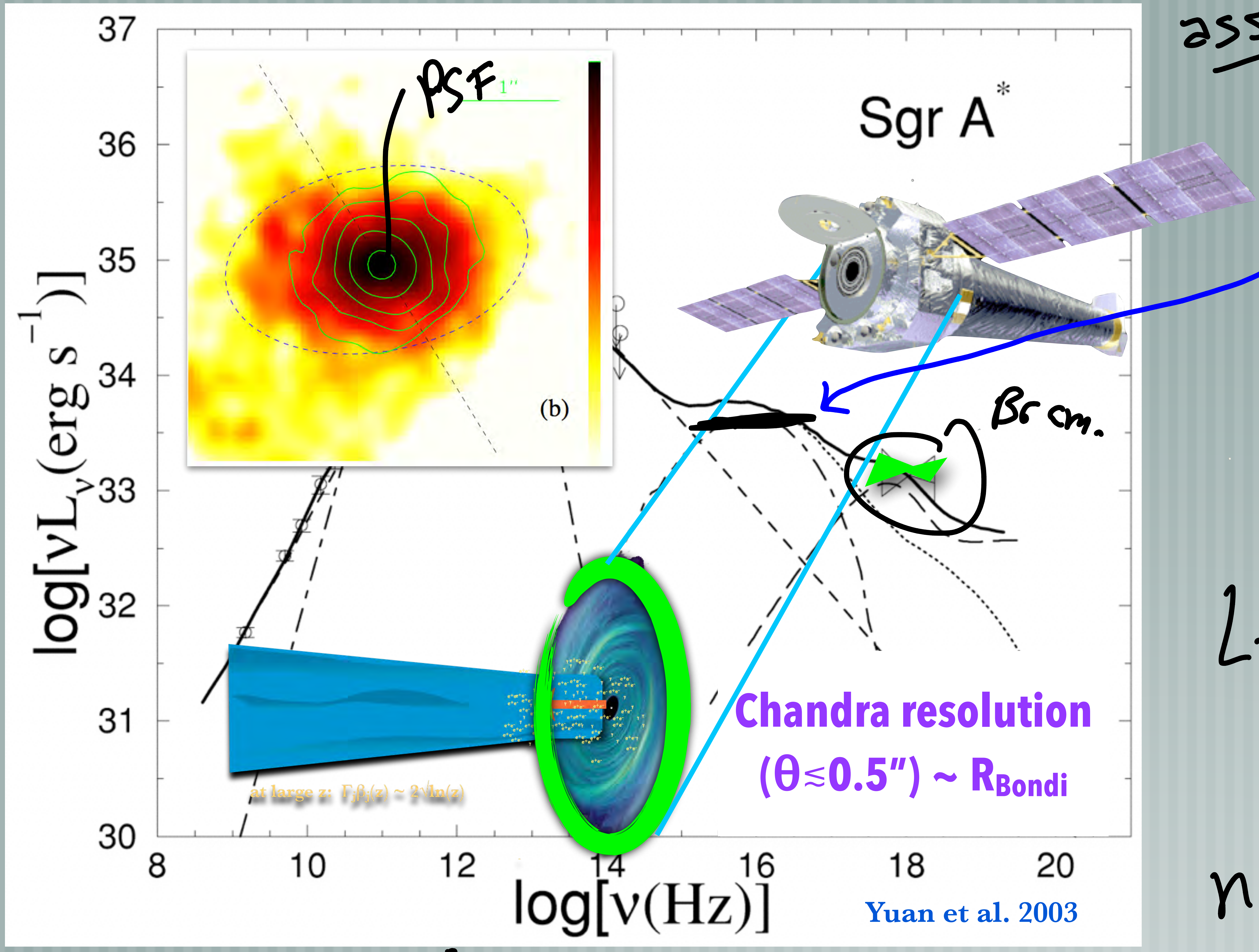
(K)T ~ 10^7 K ⇒ $10^{17\sim}$ Hz

$T = 4\times10^7$ K

At $r = 10^5 r_g$!

How do we know that size?

Sgr A*: What's Ṁ feeding the disk?



$T \sim 4\times 10^{7}$

assume: $n_e = n_i$ & $Z=1$

$10^{33.5}$ erg/s $= \varepsilon_\nu^{ff} \cdot \text{vol} \cdot \nu$

$\text{vol} \rightarrow \frac{4}{3}\pi r^3$, $\quad \nu \rightarrow 10^{18}$

Solve for n, using the formula:

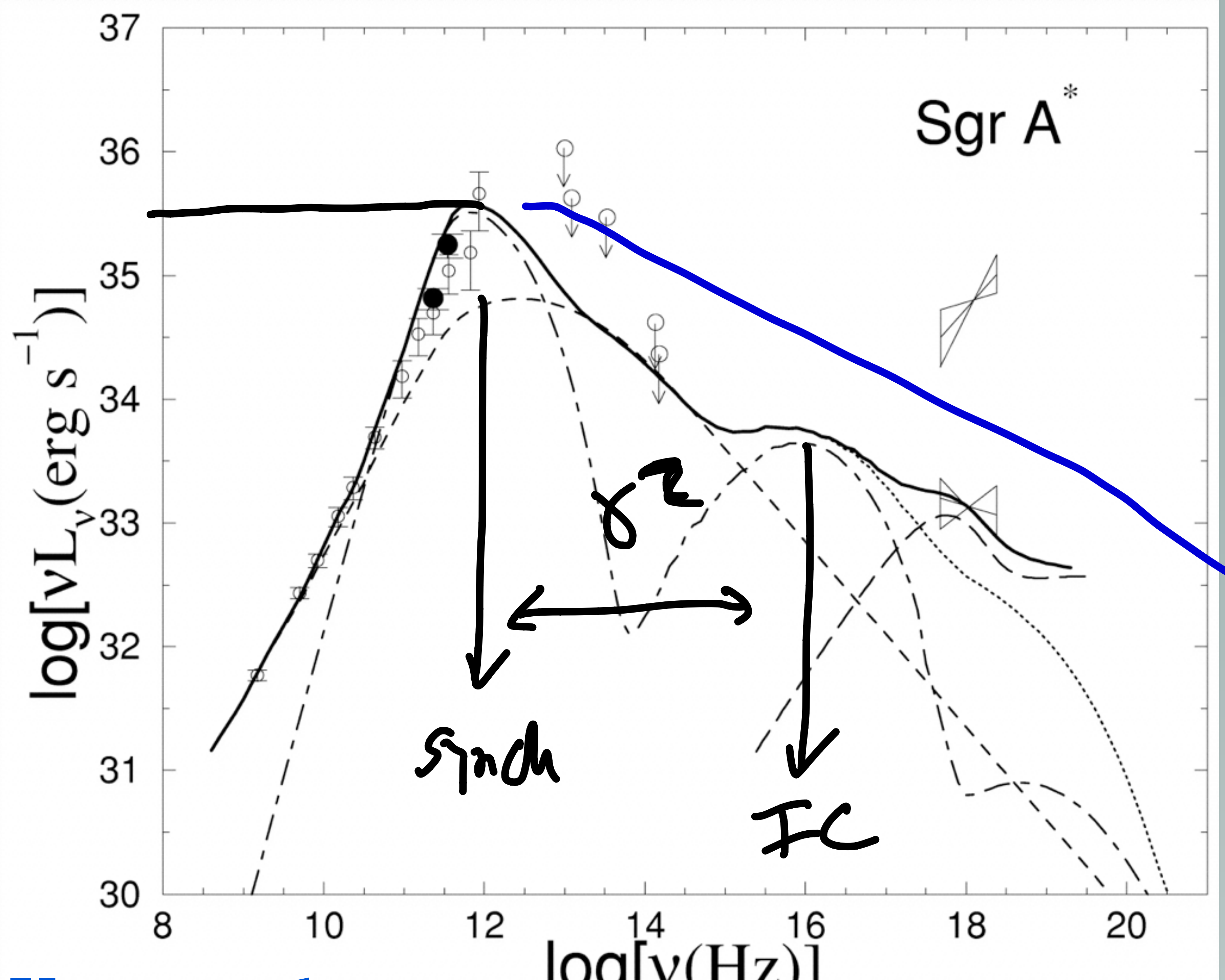
$$L_x \sim 10^{33} = 10^{0.85-38}\, n^2\, 10^{-7.6/2}\, 10^{18} \cdot \times 10^{17.5\cdot 3}$$

$$n = 10^{[33-0.85+38+3.8-18-52.5-0.6]/2} \sim 1.5/\text{cm}^3$$

$$n = \frac{\dot{M}}{4\pi r^2 c_s m_p} \Rightarrow \dot{M} \sim 5\times 10^{19}\ \text{gm/s} \sim 10^{-6}\ M_\odot/\text{yr}$$

$c_s \sim 10^{7}$ cm/s, local sound speed

Estimate temperature, return to synchrotron!



Yuan et al

Sgr A* is in low state, has hot, puffy disk but lets
just estimate the T of inflow using thin disk, $T \propto r^{-3/4}$

$$\frac{T_{in}}{T_{out}} \sim \left(\frac{r_{in}}{r_{out}}\right)^{-3/4} \sim \left(\frac{10 r_g}{10^5 r_g}\right)^{-3/4} \sim 10^{4 \cdot 3/4} = 10^3$$

So $T_{in} \sim 10^{7.6+3} = 10^{10.6}$ K, $\gamma_e = 1$ is $\sim 10^{9.6}$

So $\gamma_e \sim 10$ [This is about 10x too low but ok!] ...

$$L_{tot,synch} \simeq 10^{35.5} = \frac{4}{3}\sigma_T c \gamma^2 \beta^2 \frac{B^2}{8\pi} \cdot n \cdot vol \quad @\ 10\, r_g$$

$B = 100$ G, $\gamma = 10$:

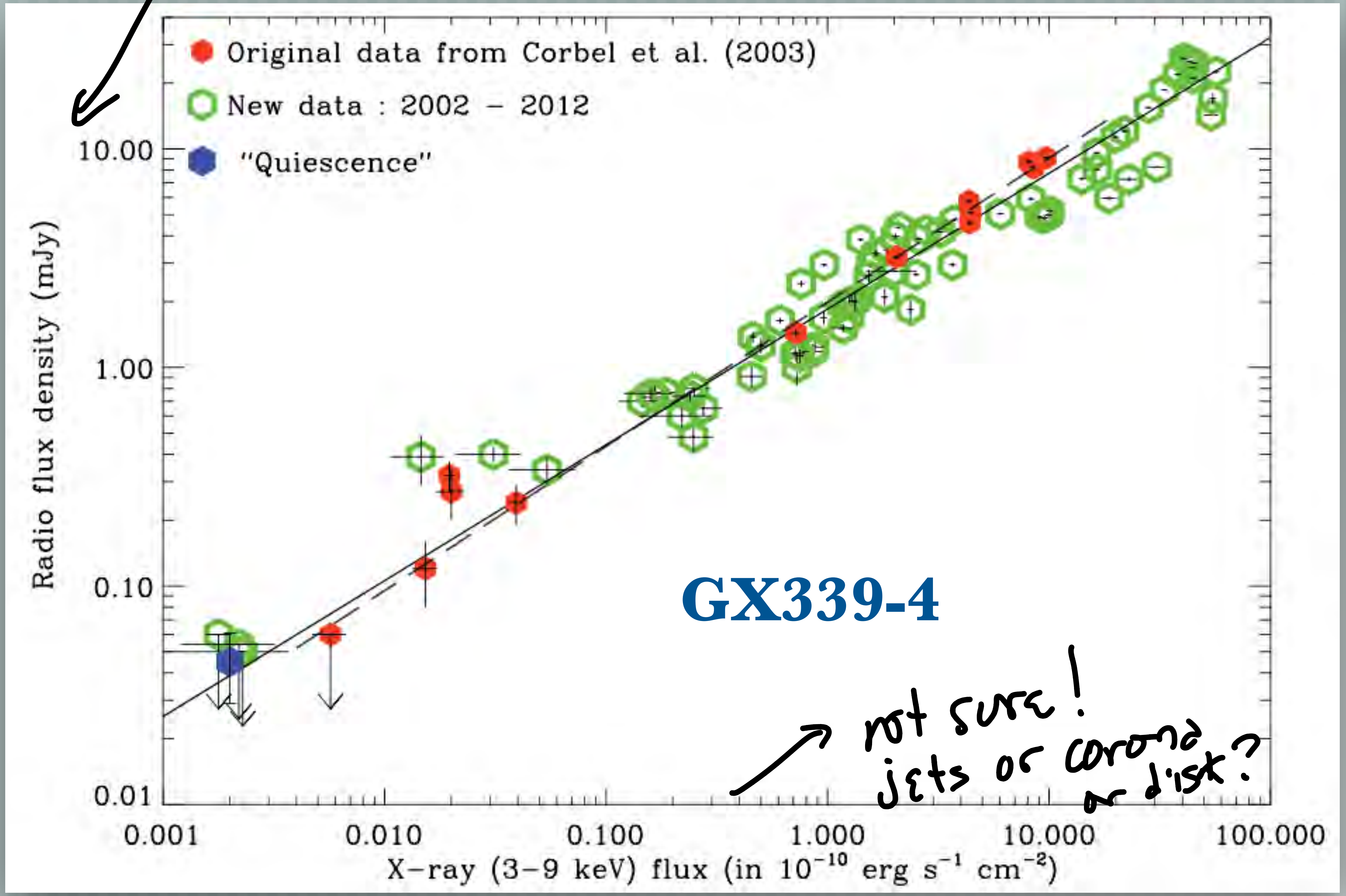
$$10^{35.5} = 10^{-24+10.5+2+4-1.4+0.5+3\times 12.6]} \cdot n$$

$n \sim 10^4\ cm^{-3}$ → bit low, but given θ magnitude not bad, w/in factor of 10!

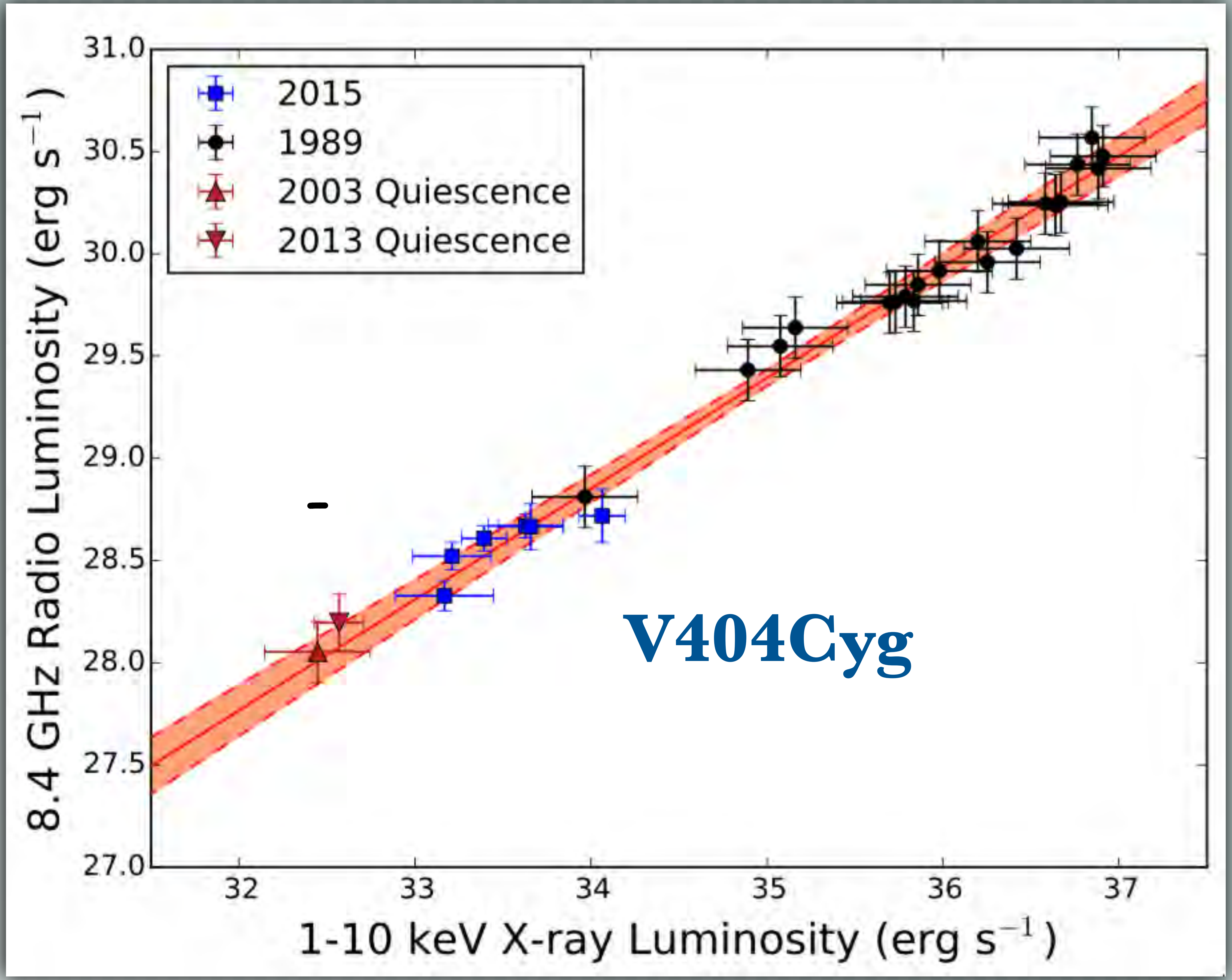
point: just from spectrum & simple power of 10 calculations, we got within a small factor of the physical conditions of a real black hole!!

Black hole XRBs have "built in" radio/Xray coupling

Synchrotron from jets



not sure!
jets or corona
or disk?



(SM++01,03,05; Corbel++2008; Hynes++2009; Corbel++2013; Rana++2016, Plotkin++2016)

Radio/Xray correlation = ratio of radiative efficiencies

$$L_R \sim L_X^{\underbrace{0.55-0.7}_{\text{range of observed slopes}}}$$

From synchrotron theory plus jet model conserving particle & magnetic energy:

$L_R \sim \dot{m}^{17/12}$ in optically thick (flat spectrum) regime

$L_X \sim \dot{m}^{q}$ $\Rightarrow$ we want to know q

$$\dot{m}^{17/12} \sim \dot{m}^{q\cdot(0.55-0.7)}$$

$$\Rightarrow q \sim \frac{17/12}{0.55-0.7} \sim \frac{1.4}{0.55-0.7} \sim 2-2.5$$

$\Longrightarrow$ has to be radiatively inefficient process!

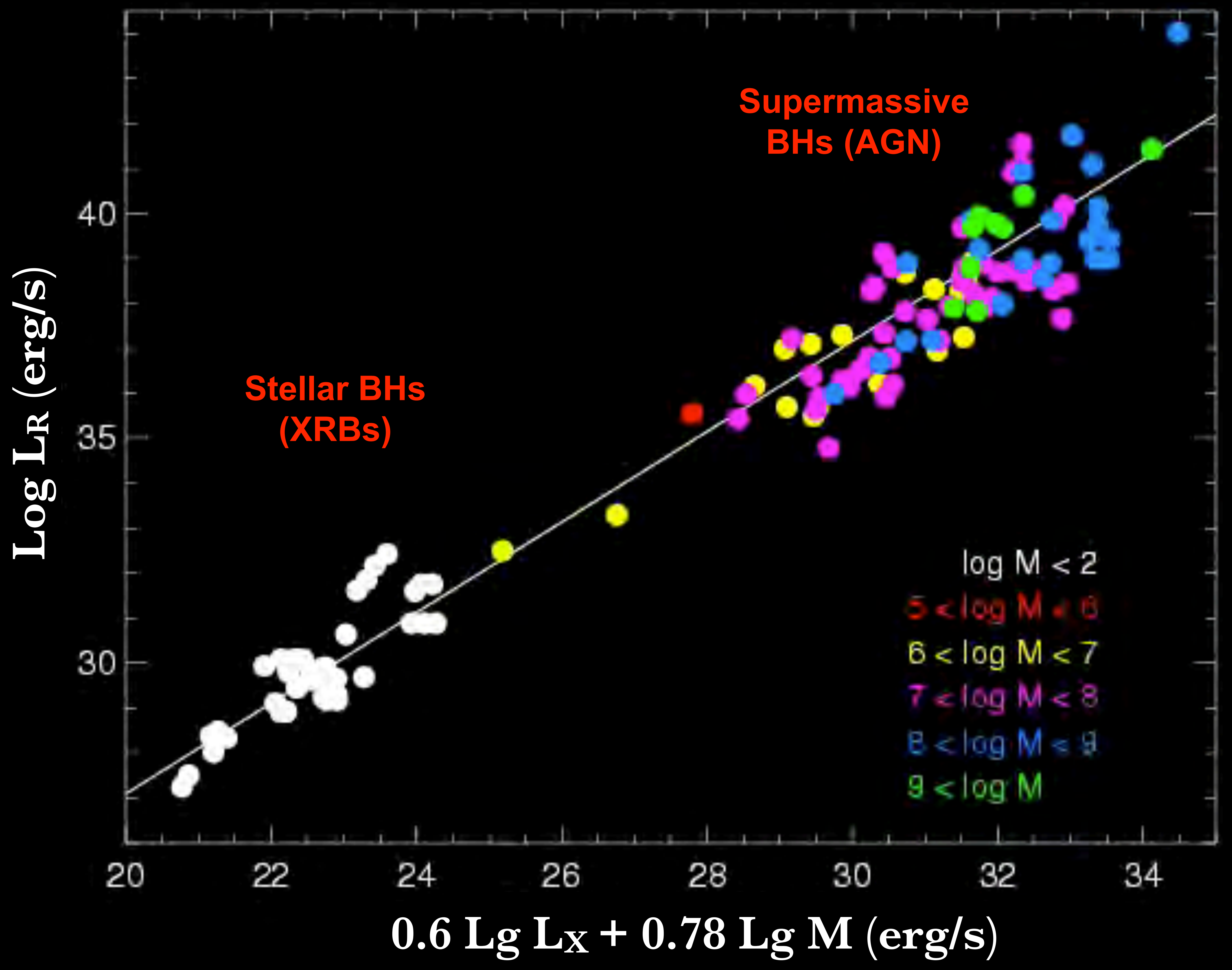
($L \sim \dot{m}$ is efficient)

- Synchrotron: $\propto n \cdot B^2$, both $\propto \dot{m}$ so $q = 2$
- SSC: $n \cdot n B^2 \Rightarrow q \leq 3$, since $\tau \leq 1$ will be $2-3$
- IC: $n \cdot \dot{m} \rightarrow q = 2$
- bremss: $n_e n_i$, both $\propto \dot{m}$ so $q = 2$

__But__ classic Shakura & Sunyaev disk $\propto \dot{m}$ won't work!

Fundamental Plane of Black Hole Accretion:

connecting (low $\dot{M}$) black holes of all masses



(SM et al. 2003; Merloni,Heinz & diMatteo 2003; Falcke, Körding & SM 2004; SM 2005; Merloni et al. 2006; Körding et al. 2006; Gültekin et al. 2009; Plotkin, SM et al. 2011)

(movie courtesy of S. Heinz)