Cosmic (Particle) Accelerators II

- Sources & **Mechanisms** -

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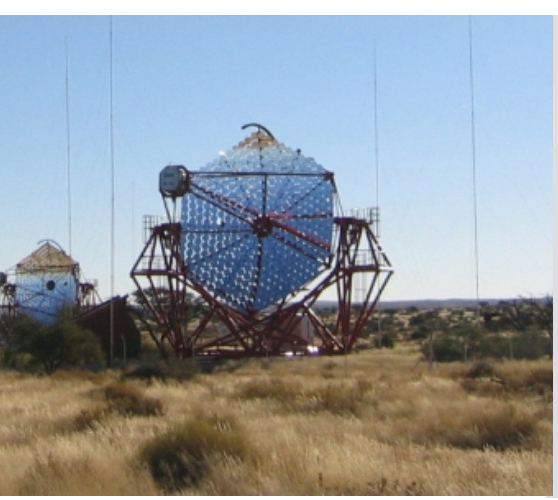
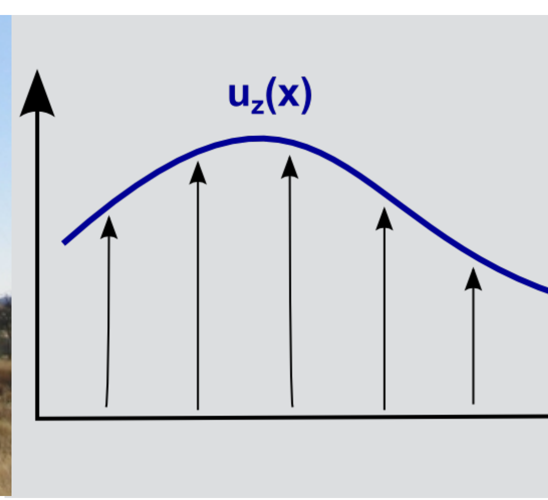
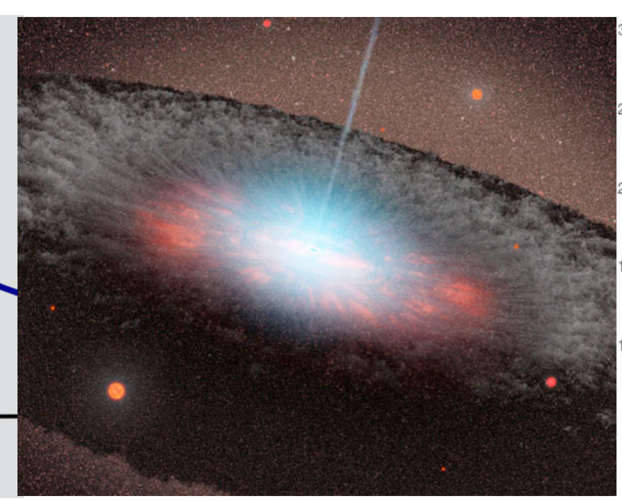
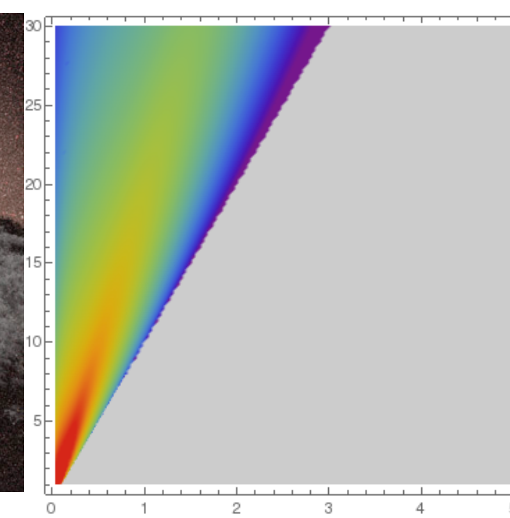
ISAPP School

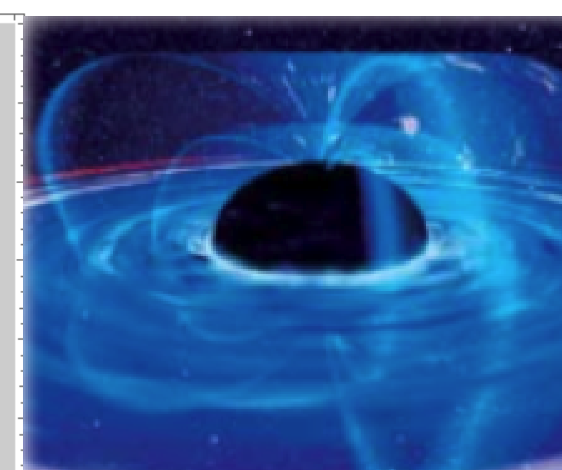
Heidelberg, May 28, 2019











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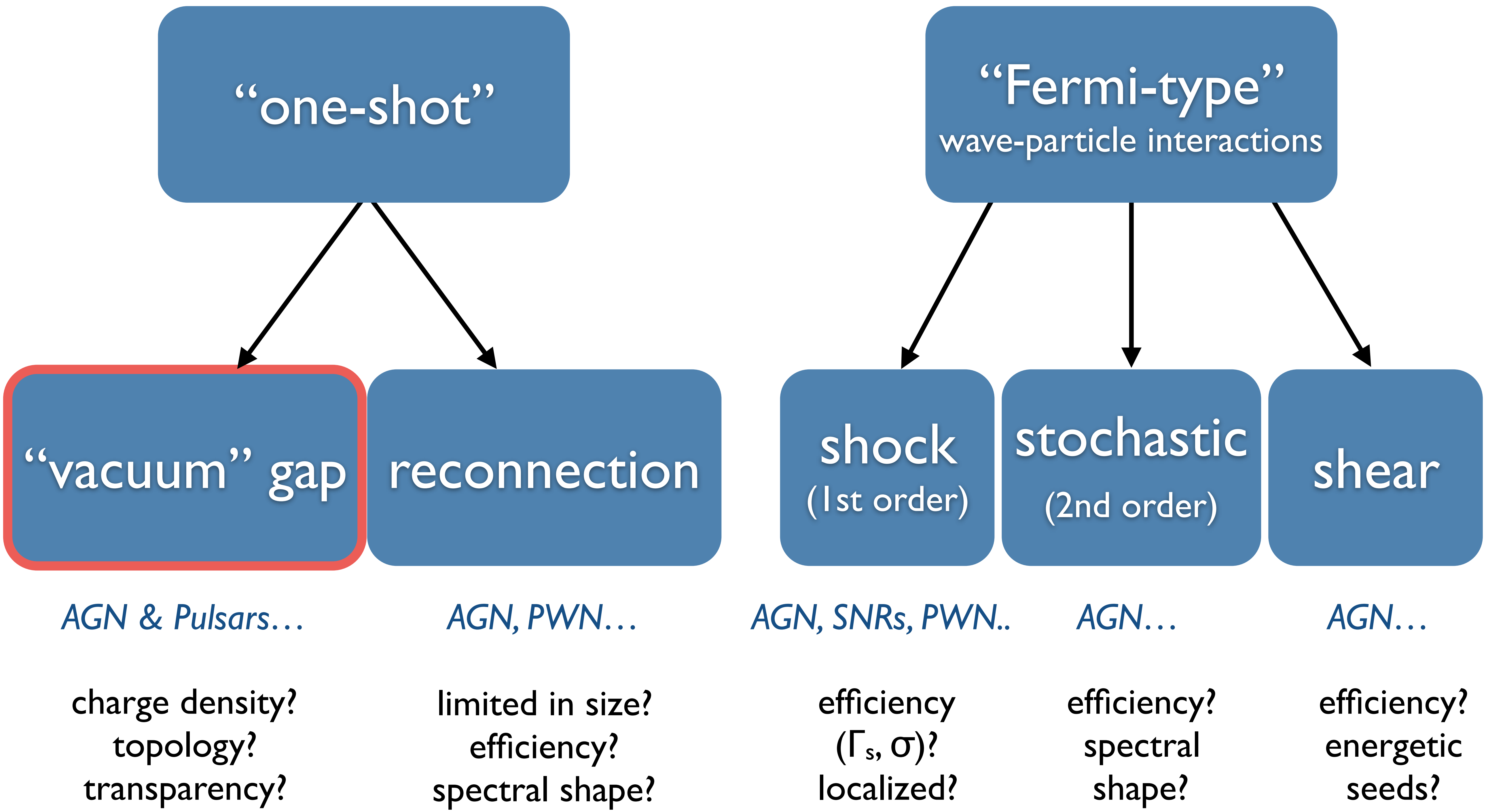
Outline

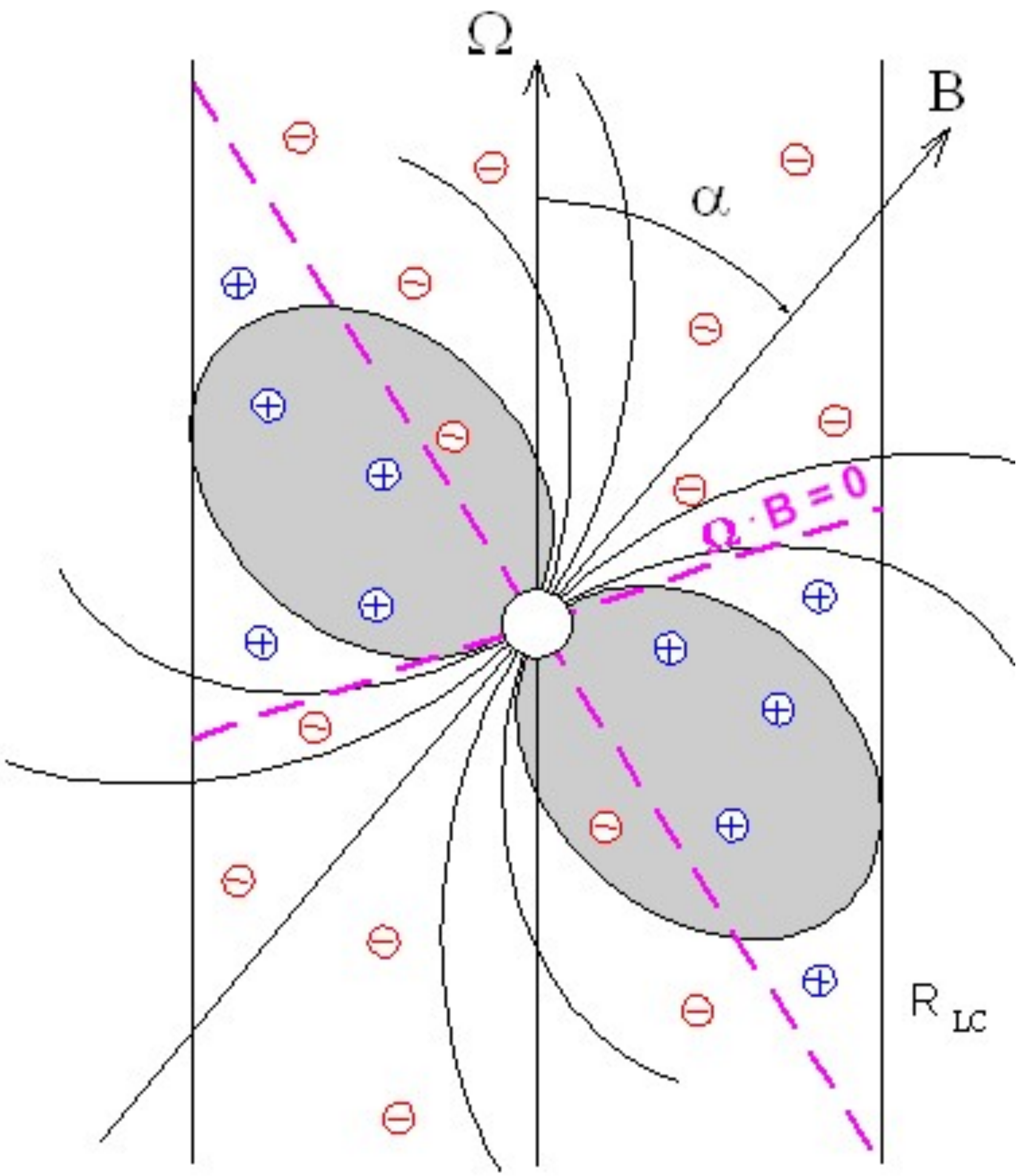
- Particle Acceleration Mechanisms
- *Gap-type particle acceleration* (pulsars, black holes)
  - concept & relevance
- *Fermi-type particle acceleration*
  - stochastic 2nd order Fermi
  - shock acceleration - 1st order Fermi (SNR)
  - shear acceleration (AGN)
- Conclusions

Possible Acceleration Processes & Sites (*not exhaustive*)



The Occurrence of Gaps in Pulsar Magnetospheres I

Goldreich & Julian 1969



$R_{LC}=c/\Omega$

- in vacuum: e $E_{||}$ >> F_{grav} at surface
  - vacuum conditions cannot exist
- if enough charges, force-free conditions possible:

$$\vec{E} = -(\vec{v} \times \vec{B})/c = -([\vec{\Omega} \times \vec{r}] \times \vec{B})/c$$

- Goldreich-Julian charge density:

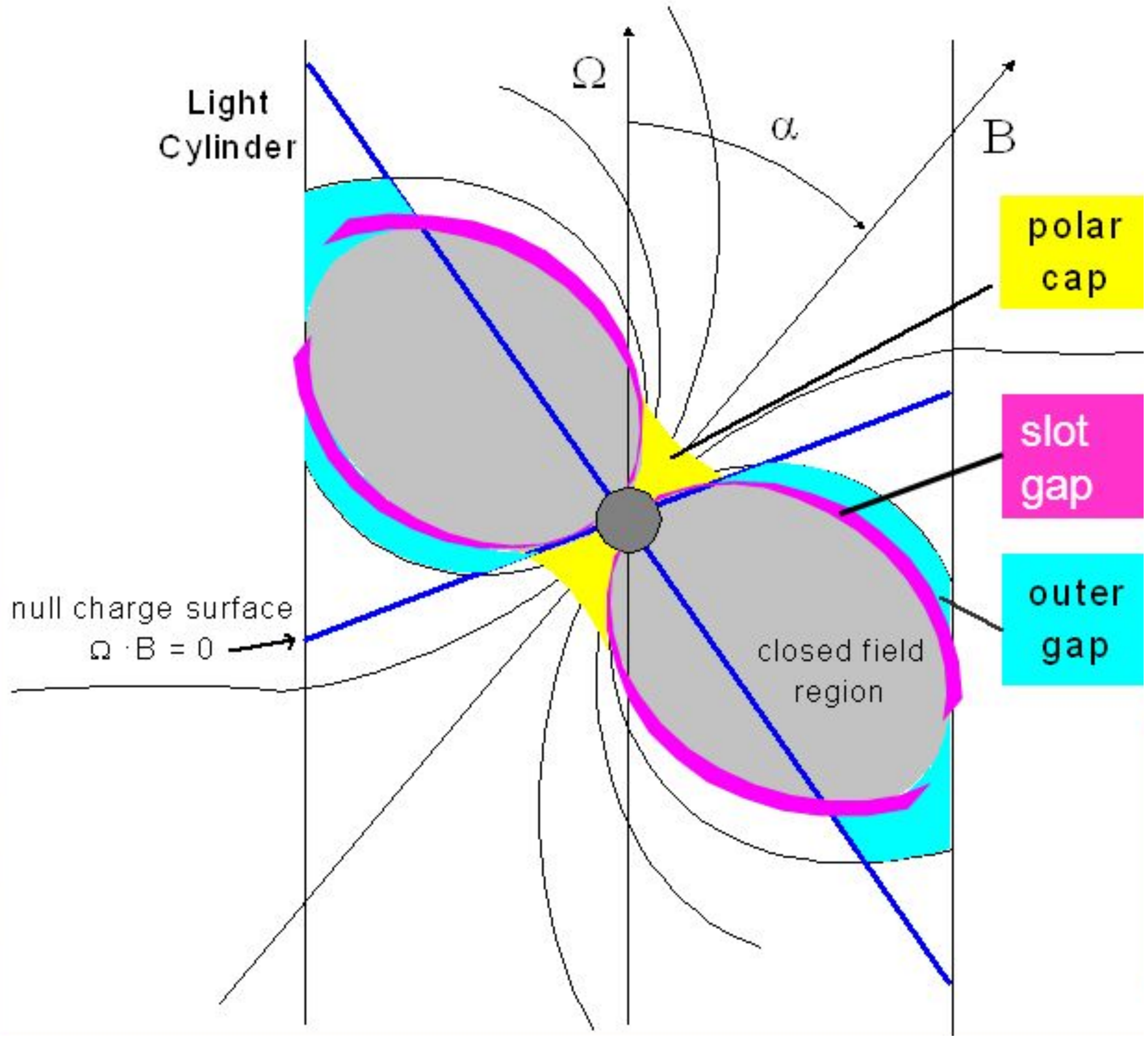
$$\rho_{GJ} = \frac{\vec{\nabla} \cdot \vec{E}}{4\pi} \simeq -\frac{\vec{\Omega} \cdot \vec{B}}{2\pi c}$$

- co-rotating dipole magnetic field defines null charge surface

$$\vec{B} \propto (2\cos\theta\,\vec{e}_r + \sin\theta\,\vec{e_\theta})/r^3$$
$$\Rightarrow \rho_{GJ}(r) \propto (\sin^2\theta - 2\cos^2\theta)/r^3$$

- no particle acceleration ($E_{||}$ =0)

Possible sites of particle acceleration



(Credits: A. Harding)

- ideal MHD in most of magneto-sphere: $\vec{E} \cdot \vec{B} = 0$
- deficient charge supply:

$$\vec{E} \cdot \vec{B} \neq 0$$

$\Rightarrow$ particle acceleration

- Solve Gauss' law:

$$\vec{\nabla} \cdot \vec{E} = 4\pi\,(\rho - \rho_{GJ})$$

(e.g., Ruderman & Sutherland 1975; Cheng et al. 1985; Muslimov & Harding 2003)

The Occurrence of Gaps in BH Magnetospheres

- ***Null surface* in Kerr Geometry ($r \sim r_g \equiv GM/c^2$)**

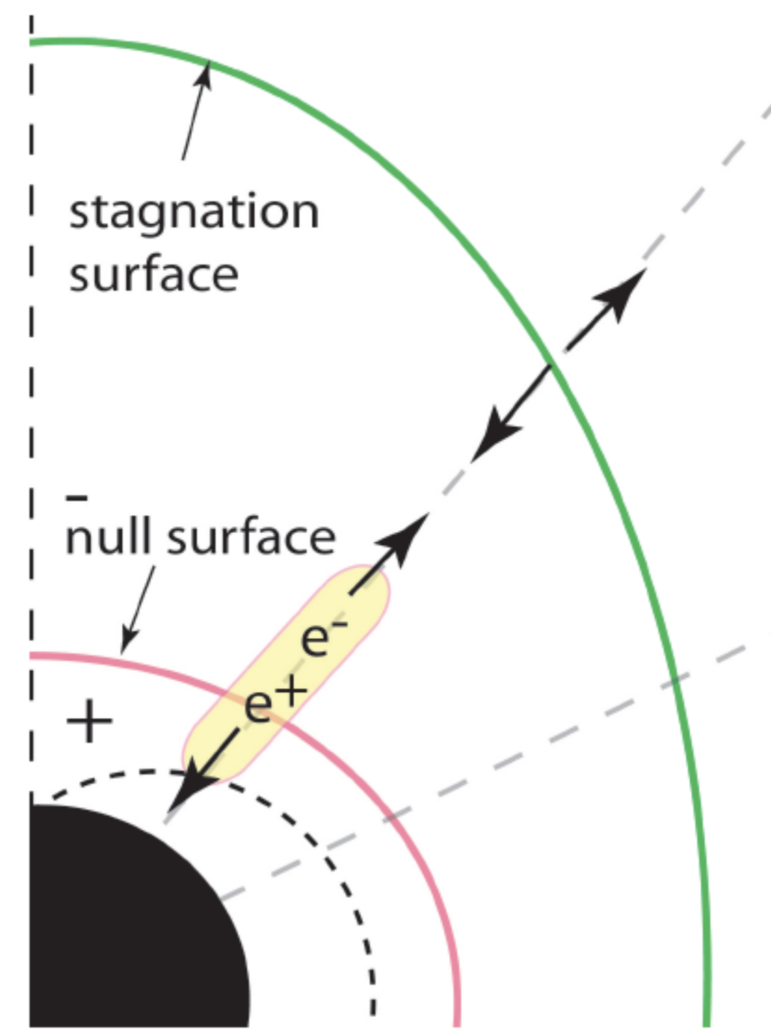
  for force-free magnetosphere, vanishing of poloidal electric field $\mathbf{E}_p \propto (\Omega^F - \omega) \nabla\Psi = 0$, ω =Lense-Thirring

  $\Rightarrow$ ρ_{GJ} changes sign, "gap" may easily develop

- ***Stagnation surface* ($r \sim$ few r_g)**

  Inward flow of plasma below due to gravitation field outward motion above

  $\Rightarrow$ charges need to be continuously replenished

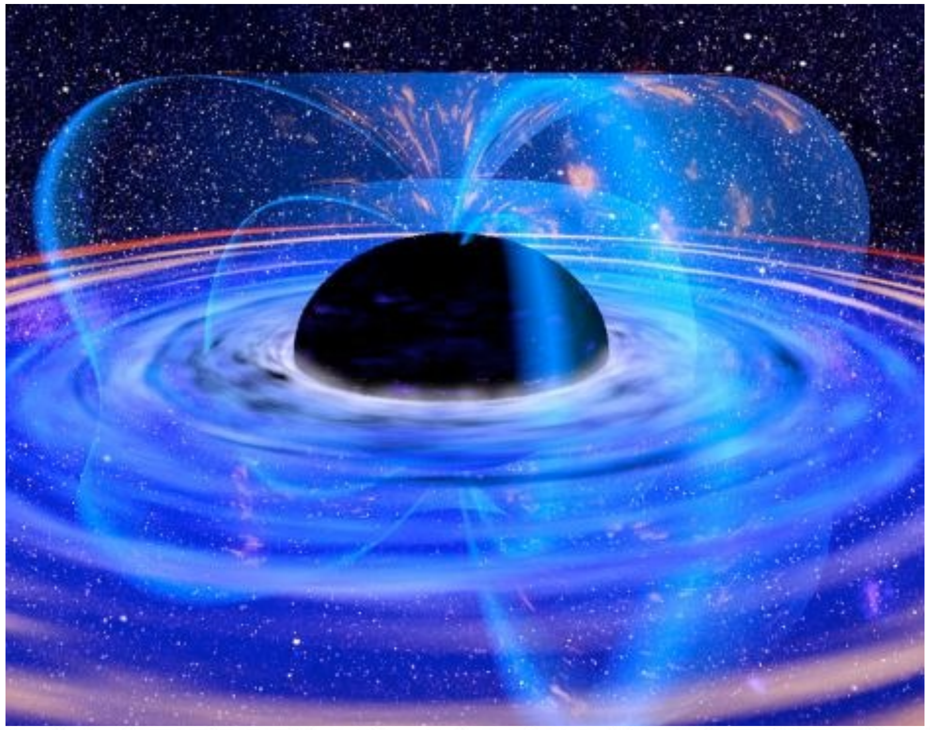


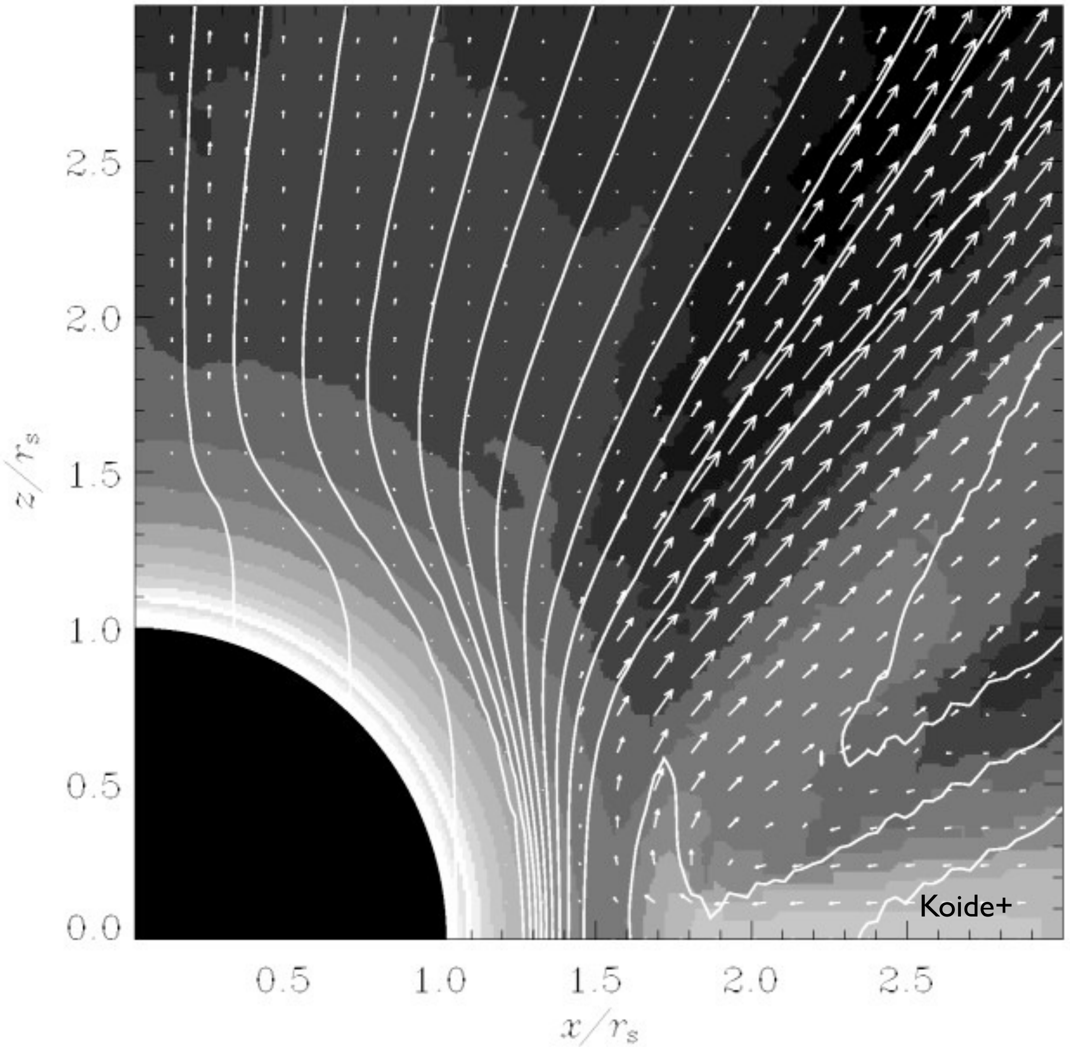
Levinson & Segev 2017

(e.g., Blandford & Znajek 1977; Beskin et al. 1992, Hirotani & Okamoto 1998)

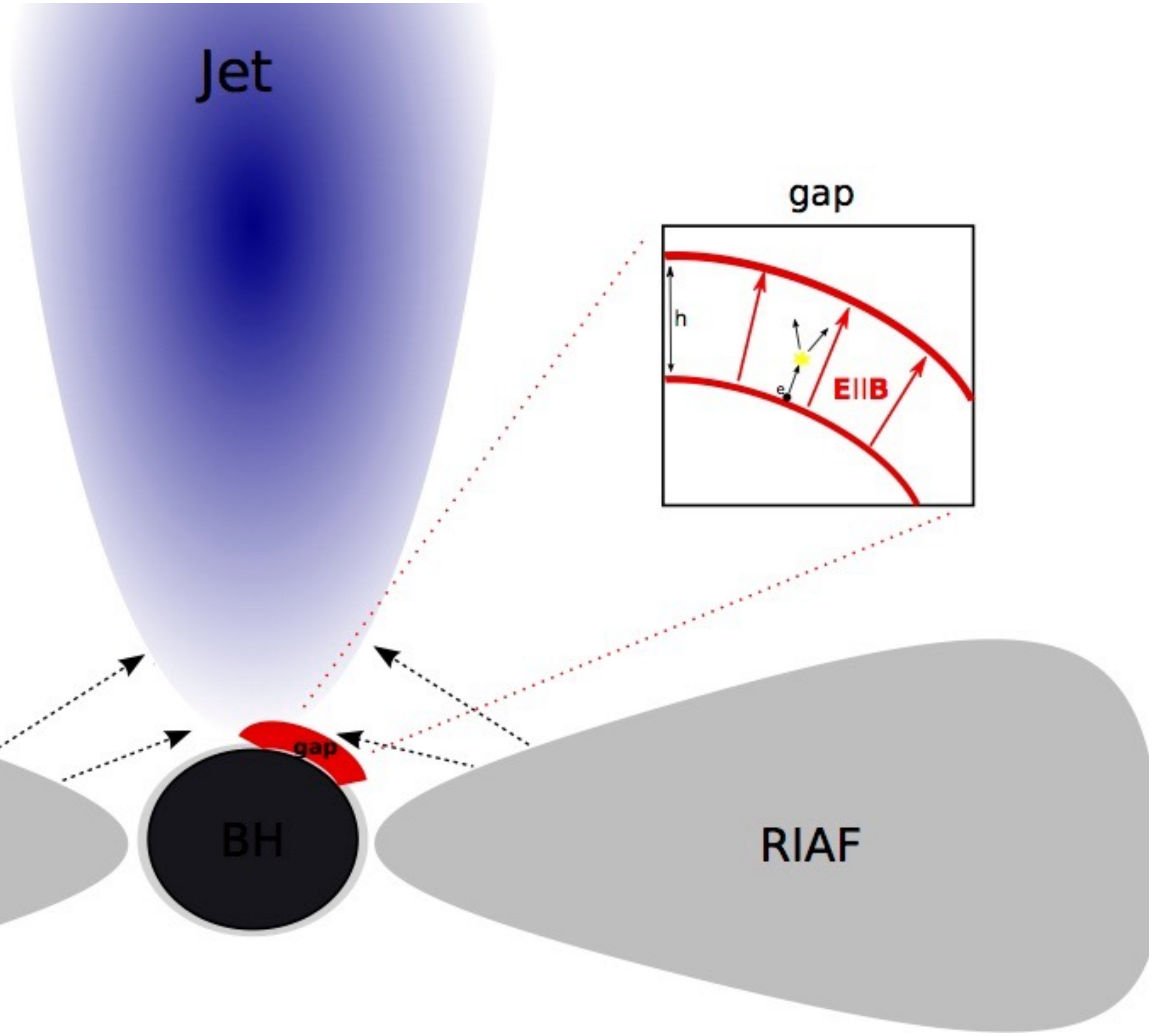
The Conceptual Relevance of BH Gaps

- ***BH-driven jets (Blandford-Znajek)***
  - *Self-consistency:* Plasma source needed to ensure force-free MHD
- ***Non-thermal Particle Acceleration***
  - *Implication:* efficient (direct) acceleration of electrons & positrons
- ***Radiation & Pair Cascade…..***
  - *Features:* expect ɣ-ray production,
    - ɣɣ-absorption triggers pair cascade
    - generating charge multiplicity
    - ensuring electric field screening (closure)





Gamma-Ray Emission from AGN Magnetospheres



- *Direct electric field acceleration:*

  Rate of energy gain for electron:

  $d\gamma/dt \propto e\,\Delta\phi_{gap} \cdot (c/h)$

- *Curvature & Inverse Compton:*

  HE γ-rays via curvature: $\nu \sim (0.2c)\,(\gamma^3/R_c)$

  VHE γ-rays via IC: $h\nu \lesssim \gamma\, m_e\, c^2$

- *Accretion environment (RIAF):*

  Radiatively inefficient needed to facilitate escape of VHE photons

- *Maximum Gap luminosity:*

  $L_{gap} \propto n_{GJ}$ (Volume) $(d\gamma/dt)$

Characterizing the Magnetospheric Potential

$$\frac{dE_{||}}{dh} = 4\pi\left(\rho_e - \rho_{GJ}\right) \quad \text{"Gauss' law"}$$

Possible boundary conditions in the pulsar case :

- "*non-free escape*" *(Ruderman)*: $E_{||}(h=0) \neq 0$, $E_{||}(h=H)=0$, $\rho_e << \rho_{GJ}$:

- "*free escape*" (*Arons*): $E_{||}(h=0)=0$, $E_{||}(h=H)=0$, $\rho_e \sim \rho_{GJ}$ ($\rho_e \neq \rho_{GJ} \equiv \Omega B \cos\theta_b$) :

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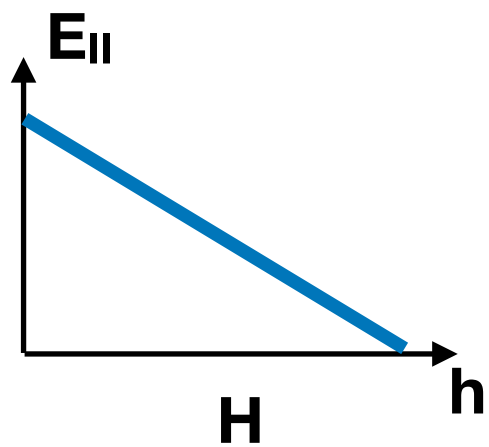

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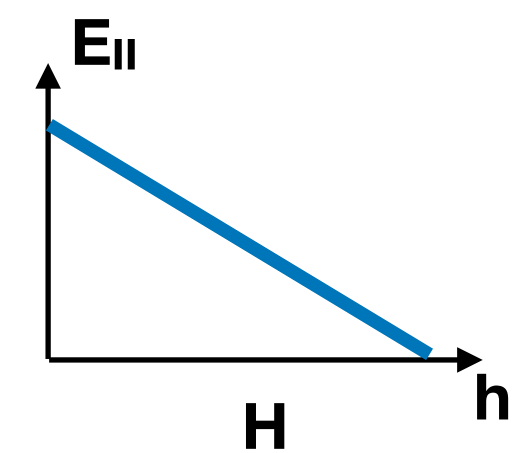
$$\frac{dE_{||}}{dh} \simeq -4\pi\,\rho_{GJ} \Rightarrow E_{||}(h) = -4\pi\,\rho_{GJ} h + \text{const}$$

$$E_{||}(h=H) = 0 \Rightarrow \text{const} = 4\pi\rho_{GJ} H$$

$$\text{Thus :} \quad E_{||}(h) = E_0 \frac{(H-h)}{H}, \text{ where} \quad \mathbf{E_0 = 4\pi\rho_{GJ} H}$$



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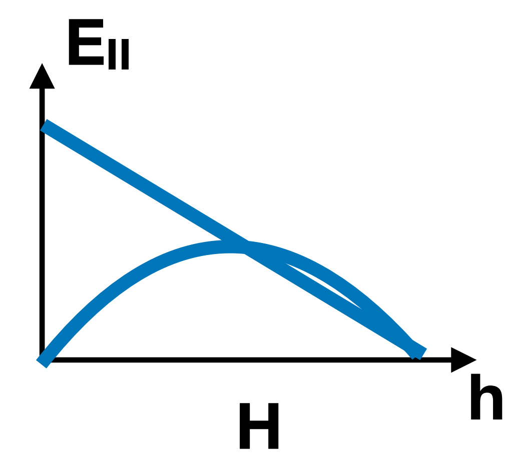

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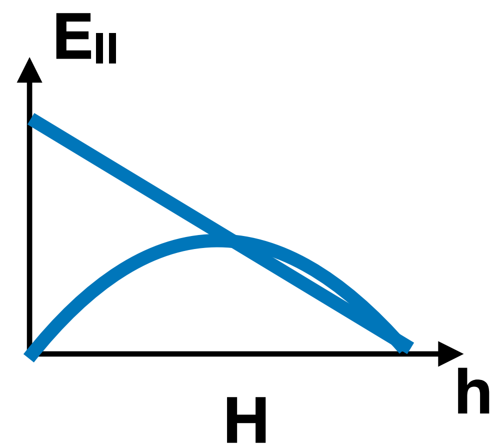

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$$\frac{dE_{||}}{dh} \simeq 4\pi\,\frac{d(\rho-\rho_{GJ})}{dh}\,\Big|_{h=H/2}\;(h-H/2)$$

$$\Rightarrow E_{||}(h) = -E_A\,\frac{h(H-h)}{H^2} \quad \text{with} \quad \mathbf{E_A} = 2\pi\,\frac{d(\rho-\rho_{GJ})}{dh}\,\mathbf{H^2}$$

Magnetospheric Potential & Jet Power in AGN - *Differences*

Solving Gauss' laws depending on different boundaries

$$\frac{dE_{||}}{dh} = 4\pi\left(\rho_e - \rho_{GJ}\right) \quad \text{"Gauss' law"}$$

highly under-dense: $\rho_e \ll \rho_{GJ}$

- Gap potential:
  - $\Delta\phi_{gap} \sim a_{spin}\, r_g\, B\, \mathbf{(H/r_g)^2}$
- Constraining losses:
  - Curvature, IC…
- Jet power:
  - $L_{VHE} \sim L_{jet} \times \mathbf{(H/r_g)^2}$ …

e.g., Blandford & Znajek 1982,
Levinson 2000
Levinson & FR 2011

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e.g., Hirotani & Pu 2016
Katsoulakos & FR 2018

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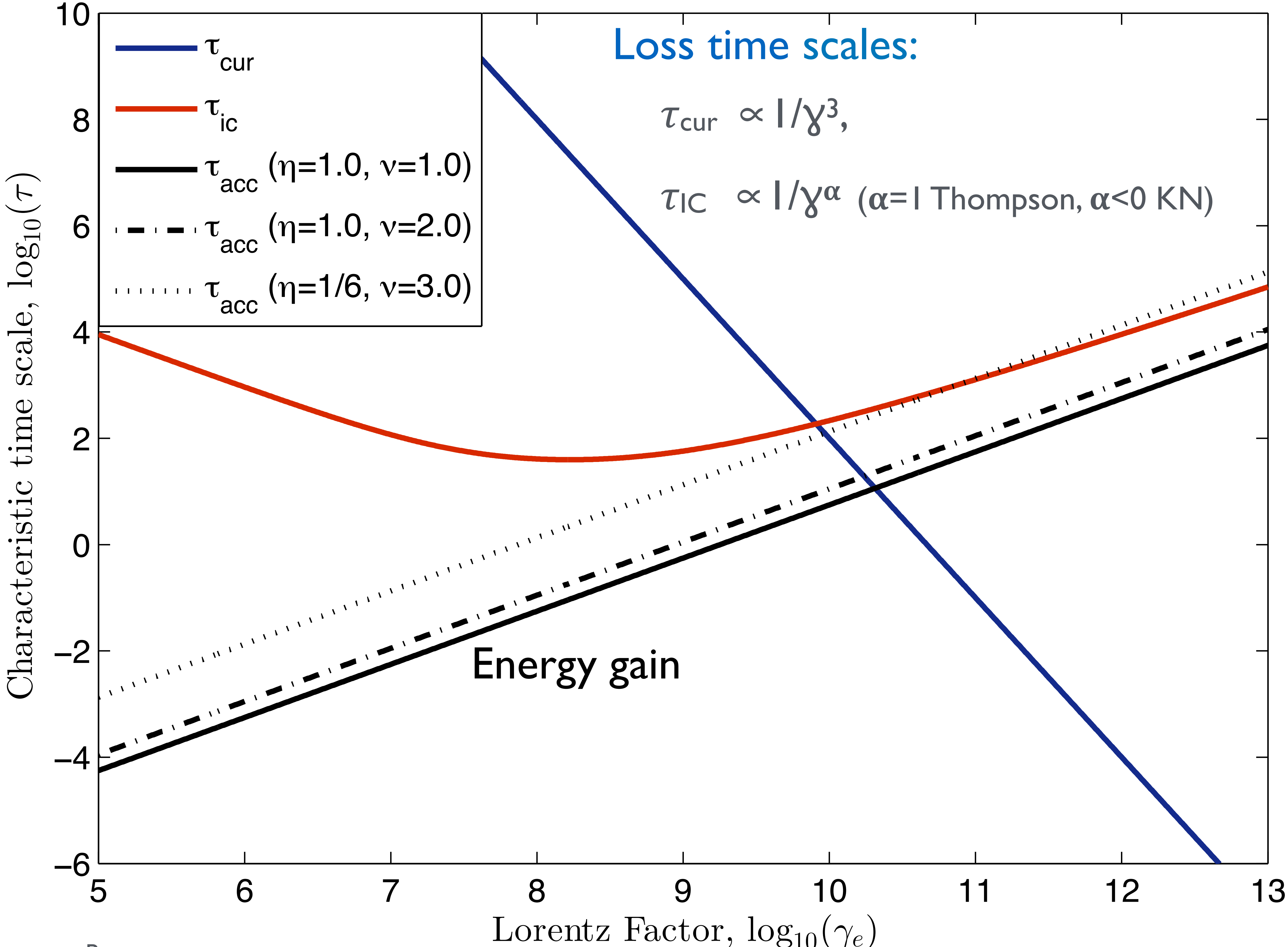
e.g., Hirotani & Pu 2016
Katsoulakos & FR 2018

Jet power constraints can become relevant

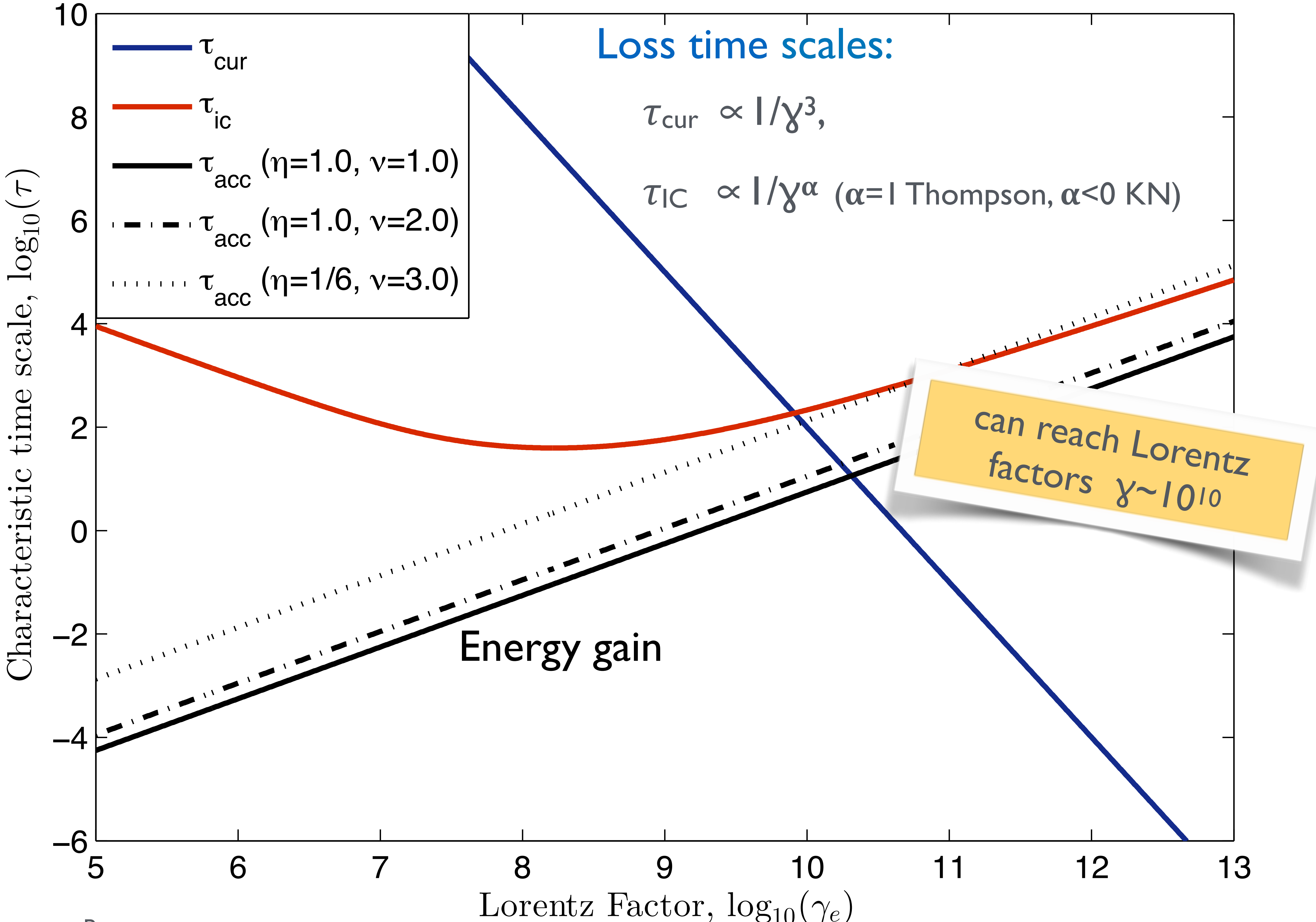
Timescales (example)



Parameters:
$M_9=5$, $\dot{m}=10^{-4}$ (ADAF), $h/r_g=0.5$

Katsoulakos & FR 2018

Timescales (example)



Parameters:
M_9=5, $\dot{m}$=10^{-4} (ADAF), h/r_g=0.5

Katsoulakos & FR 2018

Example: Phenomenological Relevance of Gaps in AGN

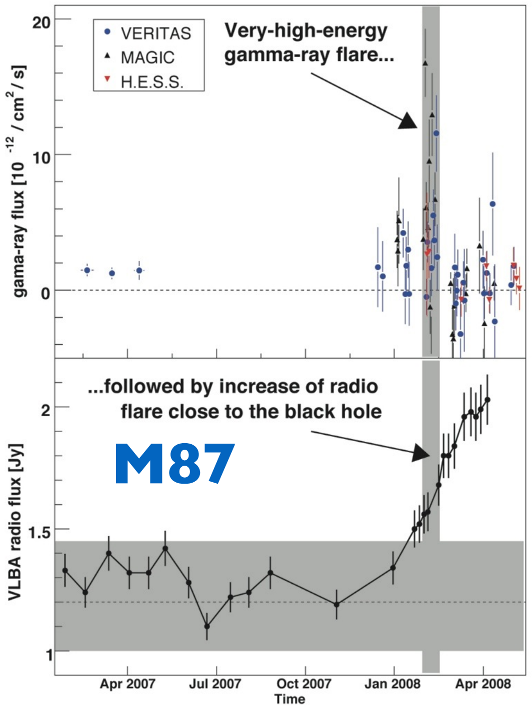
- *Gamma-Ray Emission from Radio Galaxies:*

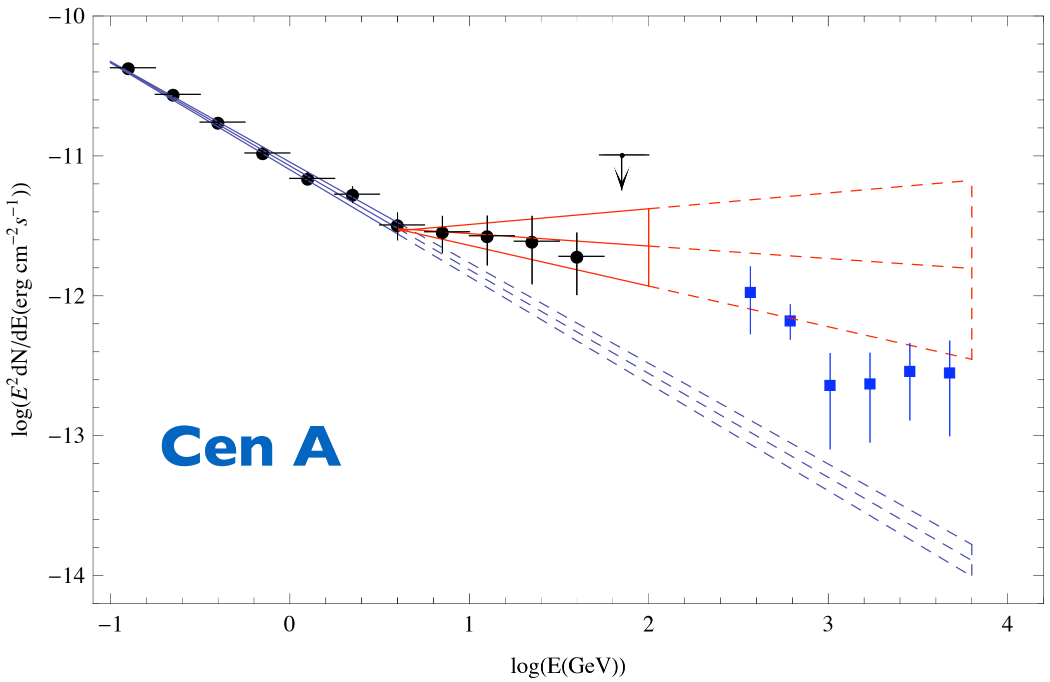
  misaligned jets: moderate Doppler boosting of jet emission only

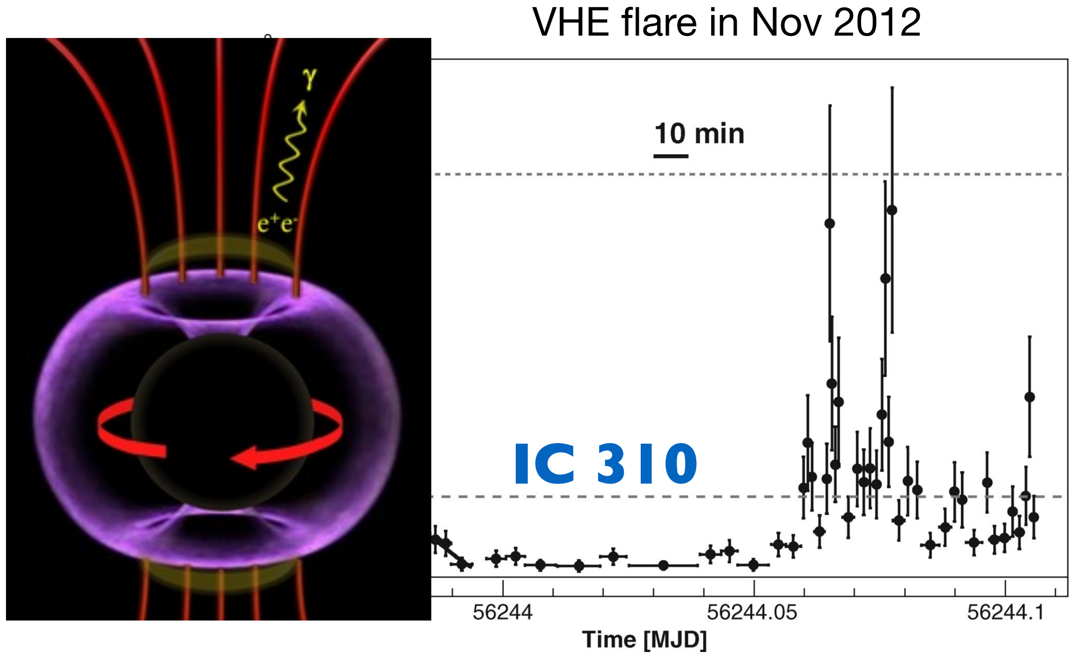
  ⇒ *gap IC & curvature emission may show up at hard HE-VHE gamma-rays*

- *Possibly related to observable AGN features in:*

  - **M87** (d ~17 Mpc): day-scale VHE variability, radio-VHE outburst correlation…
  - **Cen A** (d ~ 4 Mpc): spectral hardening of core emission above ~5 GeV…
  - **IC 310** (d ~ 80 Mpc): rapid (5 min) VHE variability, huge power ($L_\gamma \sim 10^{44}$ erg/sec)

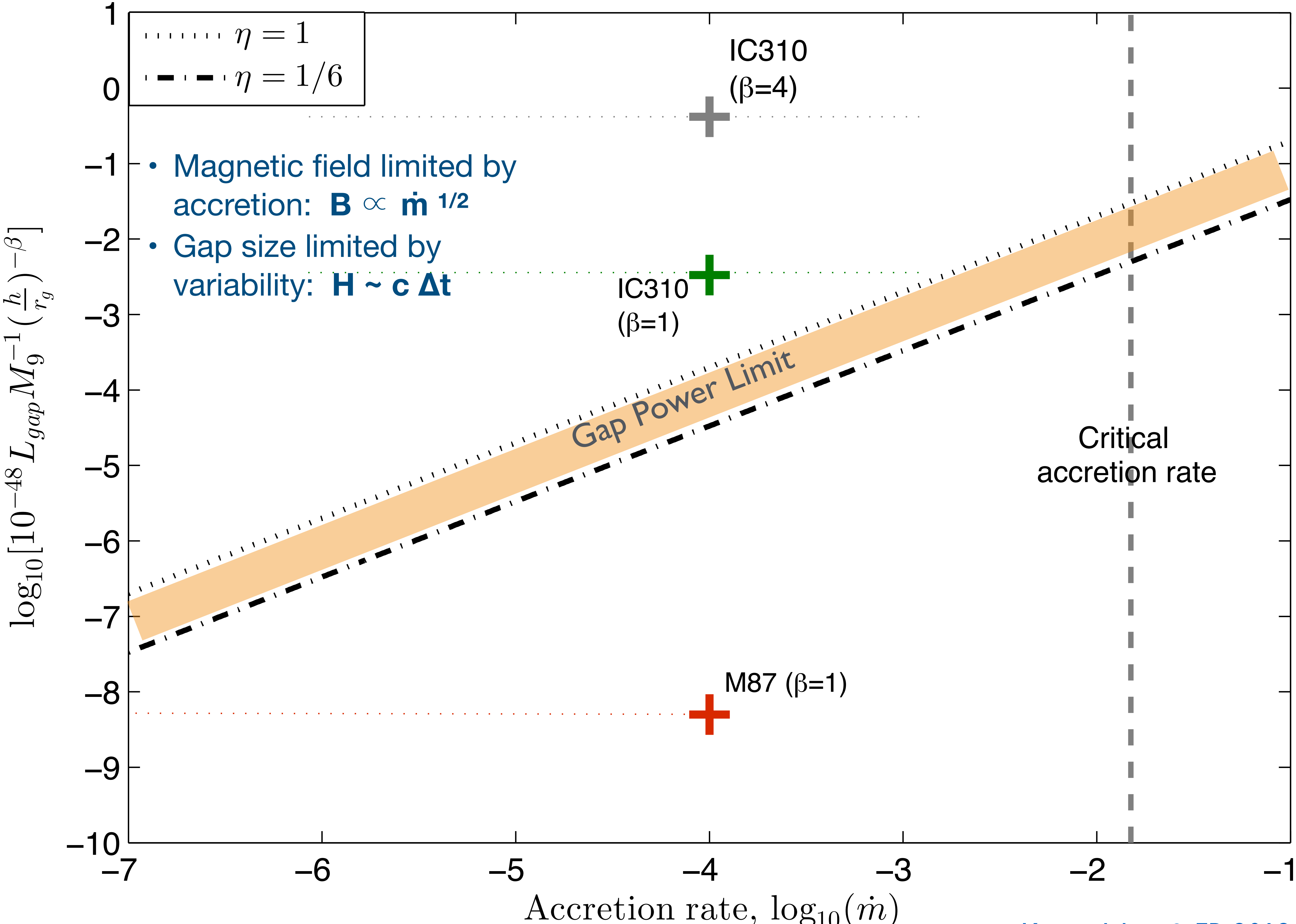






(cf. FR & Levinson 2018 for review and references)

Example: Maximum Gap Power Constraints



Katsoulakos & FR 2018

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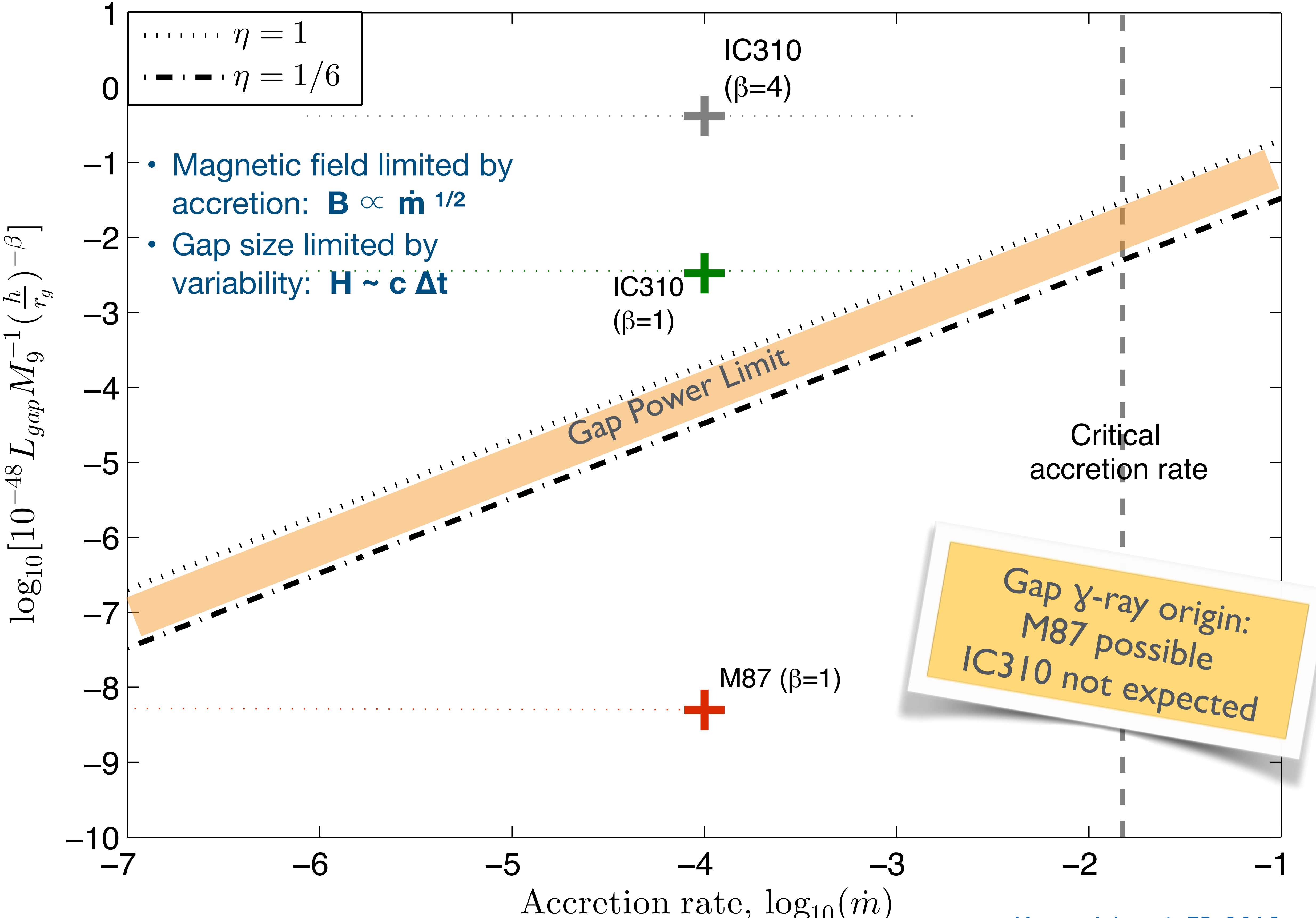
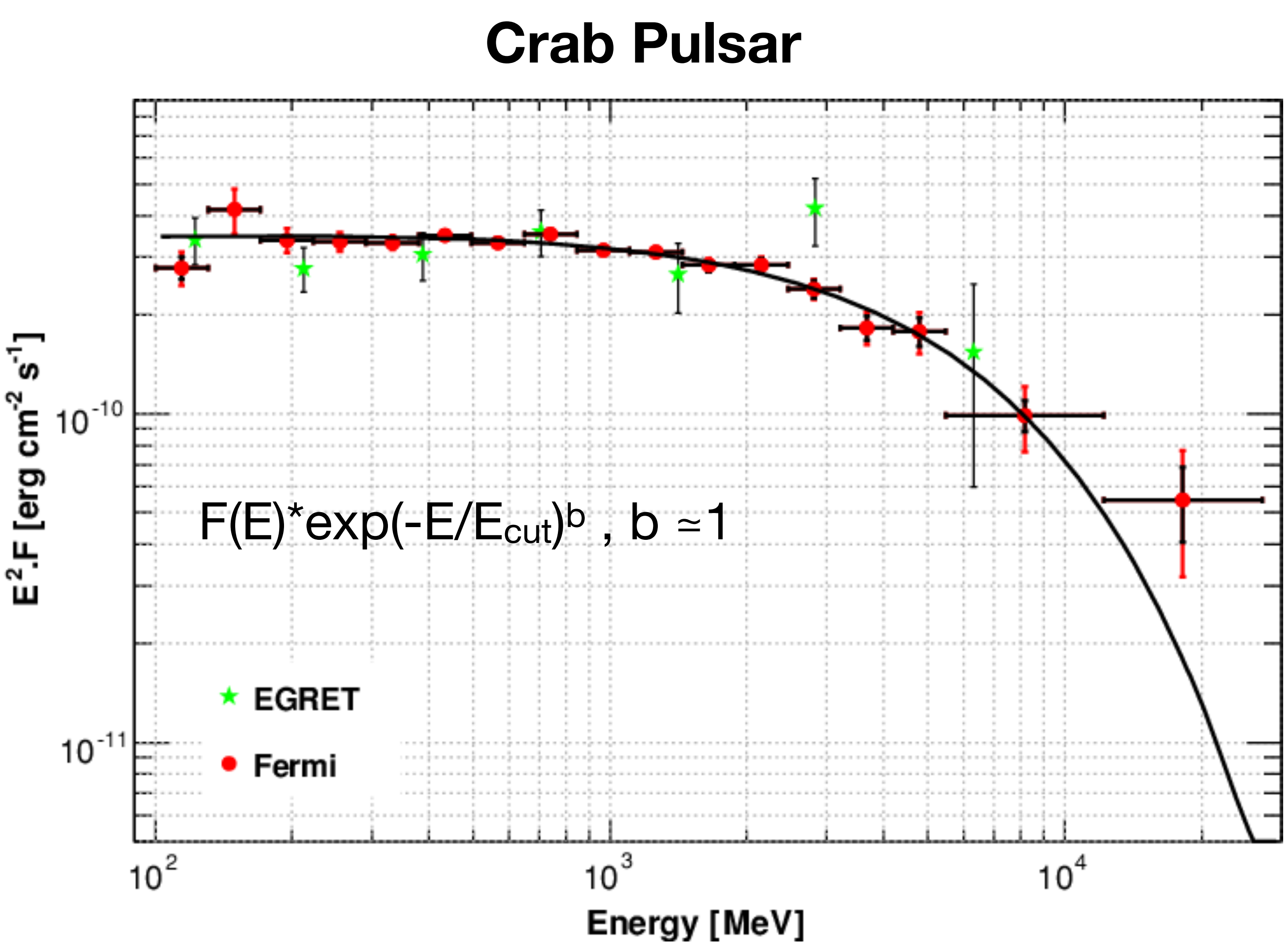


Katsoulakos & FR 2018

Preference for Outer Gap Acceleration in Pulsars ?

- ***Polar Cap Acceleration:***
  - absorption via magnetic pair creation, super-exponential cut-off in gamma-ray emission
- ***Outer Gap Acceleration:***
  - curvature radiation, exponential cut-off in gamma-ray emission
- Fermi-LAT HE observations:
  - super-exponential cutoff excluded
  - brightest pulsars (Crab, Vela) : even show sub-exponential cut-off
    - ➡ superposition (states & sites) ?
  - cut-offs in narrow band E_{cut} ~1-5 GeV
  - compatible with curvature radiation
- origin of TeV (IC)?



Phase-averaged spectrum, E_{cut}~ 5 GeV

Fermi LAT Collab. 2009

Gap-type Particle Acceleration - Summary

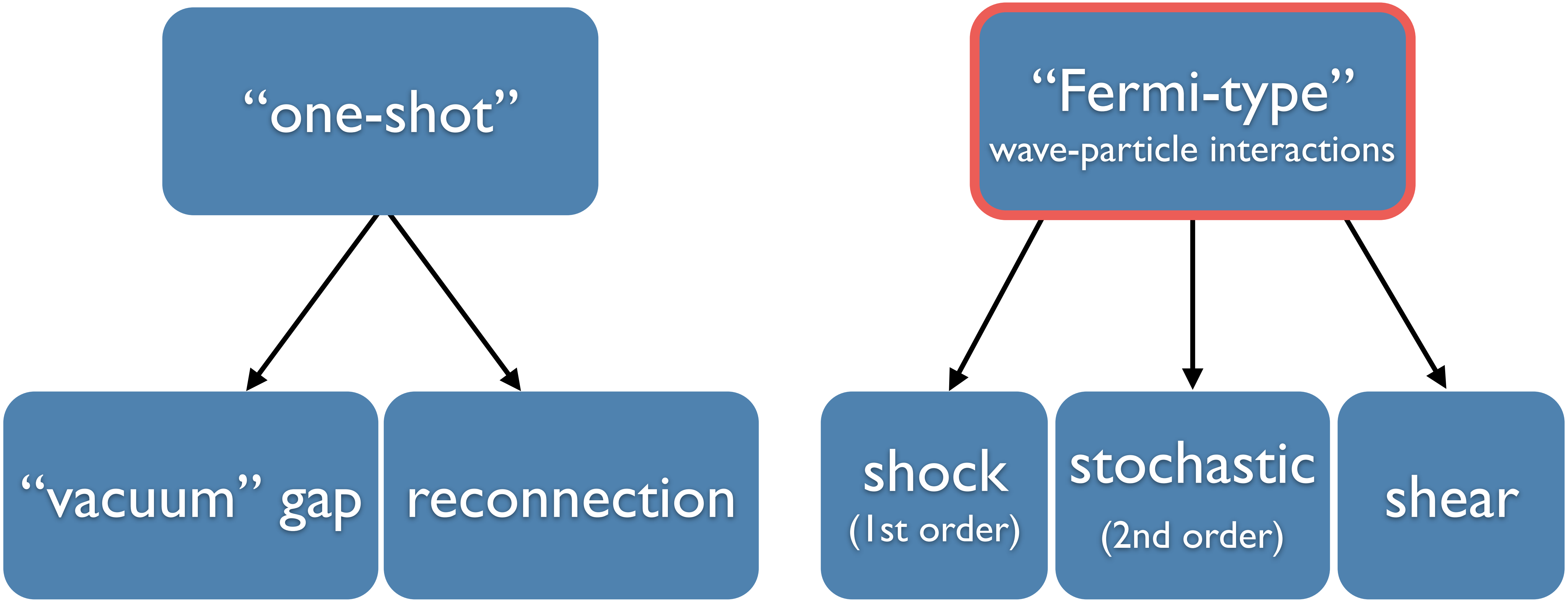
- *gaps ("unscreened parallel electric fields") are to be expected in the magnetospheres of pulsars, and may occur around supermassive black holes*

- *most efficient ("direct - one-shot") particle acceleration mechanism*
  - energy gain $dE/dt \simeq e\,\phi\,(c/H)$
  - acceleration timescales can be as short as $t_{acc} \sim \gamma\, m\, c\, /\, (eB)$

- unavoidable max. cutoff due to curvature radiation
  - *pulsars :* $\gamma_{max} \sim 10^{7\text{-}8}$ (e^+e^-)
  - *AGN :* $\gamma_{max} \sim 10^{10}$ (e, p)

- Development of pair cascade may limit size of gap & lead to closure

Possible Acceleration Processes & Sites (*not exhaustive*)



"vacuum" gap	reconnection	shock	stochastic	shear
AGN & Pulsars…	*AGN, PWN…*	*AGN, SNRs, PWN..*	*AGN…*	*AGN…*
charge density? topology? transparency?	limited in size? efficiency? spectral shape?	efficiency (Γ_s, σ)? localized?	efficiency? spectral shape?	efficiency? energetic seeds?

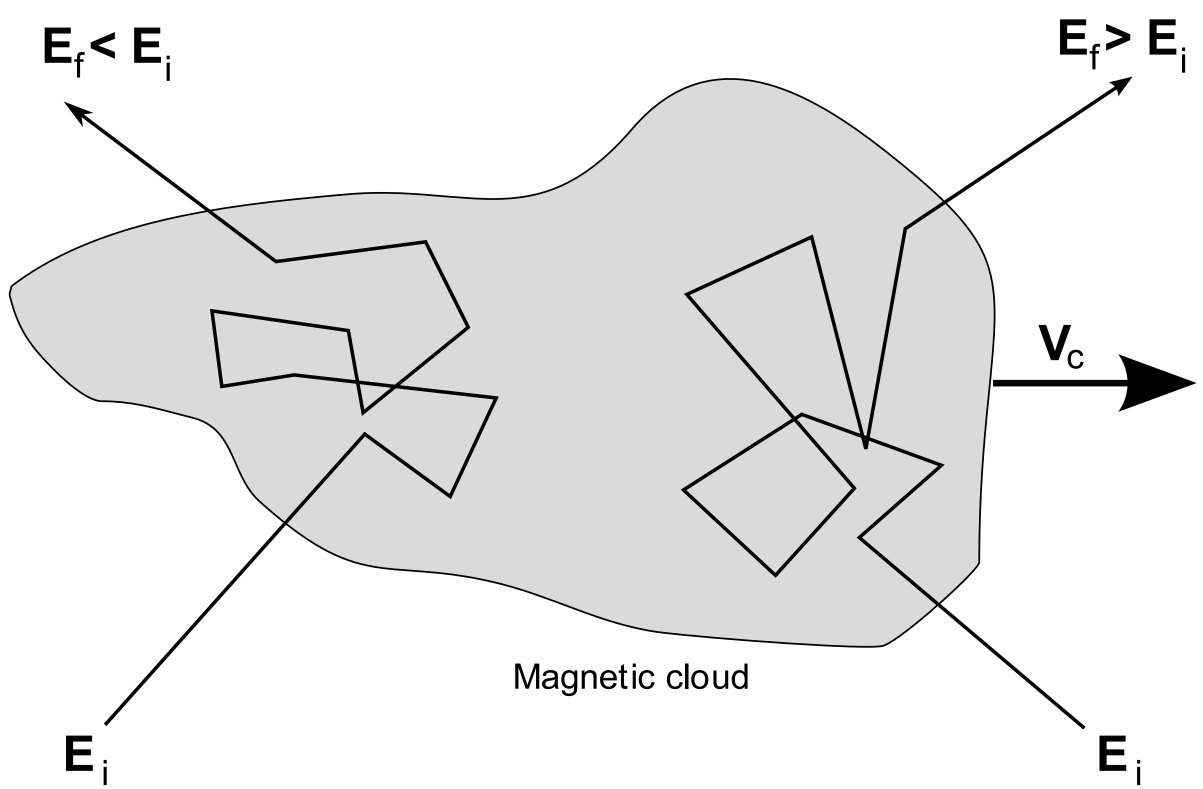
Fermi-type Particle Acceleration

Kinematic effect resulting from *scattering off magnetic inhomogeneities*
Fermi, Phys. Rev. 75, 578 [1949]

⇒ energy gain as results of multiple scatterings (stochastic process)

_Ingredients: in frame of scattering centre

- momentum magnitude conserved
- particle direction randomised



Fermi Acceleration - energy change in elastic scattering event I

Energy change ΔE for particle with initial E_i and $\vec{p}_i$ interacting with massive cloud of speed $\vec{V}_c$:

- Elastic Scattering: In cloud frame K', particle energy is conserved, momentum direction parallel to $\vec{V}_c$ reversed (noting $p_{\|} = \vec{p}\vec{V}_c/V_c = p\cos\theta \simeq \frac{E}{c^2}v\cos\theta$)
- Lorentz-Transformation to cloud frame K' (cf. time and space trafo):

$$\begin{aligned} E'_i &= \gamma_c(E_i - \vec{p}_i\vec{V}_c) = \gamma_c(E_i - p_{i,\|}V_c) \\ p'_{i,\|} &= \gamma_c\left(p_{i,\|} - \frac{V_c}{c^2}E_i\right) \end{aligned}$$

- Elastic scattering in frame K' implies:

$$E'_f = E'_i$$

$$p'_{f,\|} = -p'_{i,\|}$$

- Transforming back to lab. frame K:

$$\begin{aligned} E_f &= \gamma_c(E'_f + p'_{f,\|}V_c) = \gamma_c(E'_i - p'_{i,\|}V_c) \\ &= \gamma_c^2\left([E_i - p_{i,\|}V_c] - \left[p_{i,\|} - \frac{V_c}{c^2}E_i\right]V_c\right) = \gamma_c^2\left(\left[1 + \frac{V_c^2}{c^2}\right]E_i - 2p_{i,\|}V_c\right) \end{aligned}$$

Fermi Acceleration - energy change in elastic scattering event II

- Energy change ΔE:

$$
\begin{aligned}
\Delta E &= E_f - E_i = \gamma_c^2 \left(\left[1 + \frac{V_c^2}{c^2} \right] E_i - 2 p_{i,\parallel} V_c \right) - E_i \\
&= (\gamma_c^2 - 1) E_i + \gamma_c^2 \left(\frac{V_c^2}{c^2} E_i - 2 p_{i,\parallel} V_c \right) \\
&= 2\gamma_c^2 \left(\frac{V_c^2}{c^2} E_i - p_{i,\parallel} V_c \right)
\end{aligned}
$$

noting that $(\gamma_c^2 - 1) = \gamma_c^2 \beta_c^2$.

_Characteristic energy change per scattering (non-relativistic V_c):

$$\Delta E = E_f - E_i = 2\,(E_i\, V_c^2/c^2 - \vec{p}_i \cdot \vec{V}_c)$$

➡ *energy gain for head-on ($\mathbf{p}\ \mathbf{V_c} < 0$), loss for following collision ($\mathbf{p}\ \mathbf{V_c} > 0$)*

- **stochastic:** average energy gain 2nd order: $< \Delta E > \sim (V_c / c)^2\ E$

Fermi Acceleration - energy change in elastic scattering event II

- Energy change ΔE:

$$\Delta E = E_f - E_i = \gamma_c^2 \left(\left[1 + \frac{V_c^2}{c^2} \right] E_i - 2p_{i,\parallel} V_c \right) - E_i$$

$$= (\gamma_c^2 - 1) E_i + \gamma_c^2 \left(\frac{V_c^2}{c^2} E_i - 2p_{i,\parallel} V_c \right)$$

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can we do better?

- **stochastic:** average energy gain 2nd order: $< \Delta E > \sim (V_c / c)^2 E$

Fermi Acceleration @ shocks

Shock=discontinuity moving through medium at speed larger than speed of sound (upstream)"

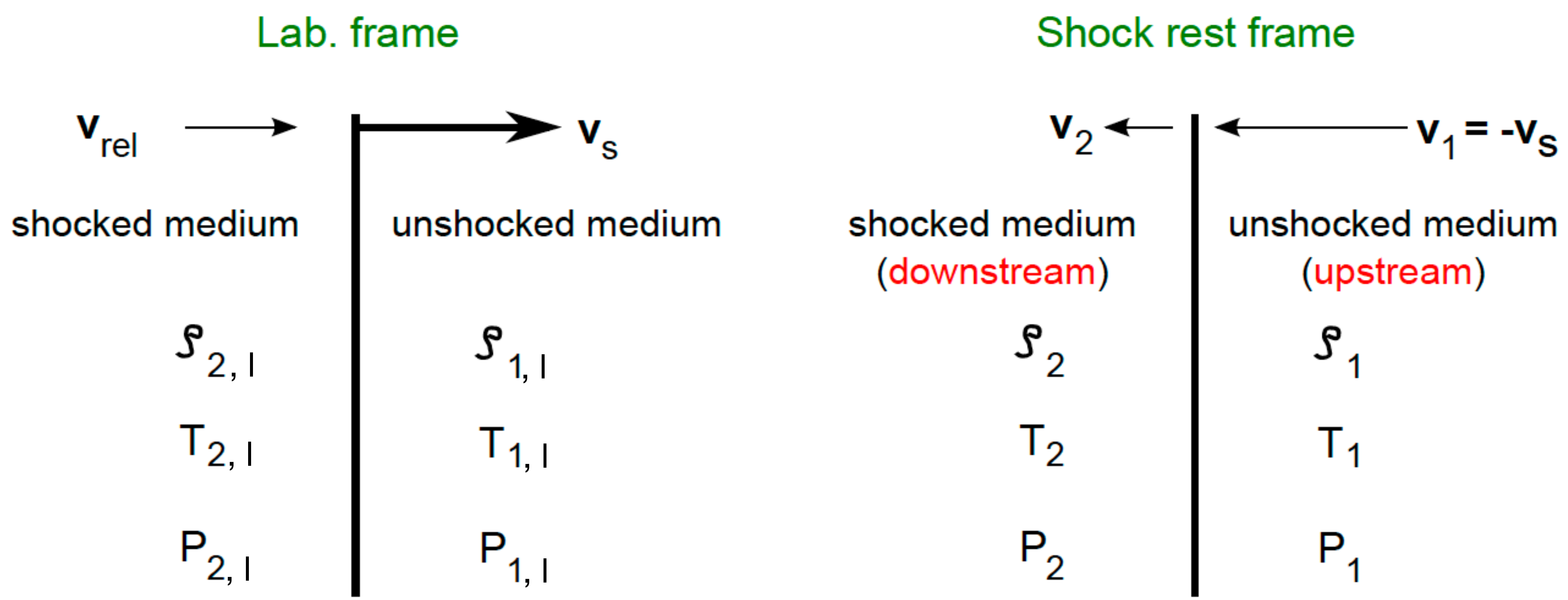

Figure 5: Non-relativistic shock wave in the reference frame of the un-shocked medium, $v_1 = 0$ (lab.frame, left) and in reference frame where the surface of the discontinuity is at rest, $v_s = 0$ (shock rest frame, right). The shock advances into the un-shocked medium at speed v_s. In rest frame of the shock, upstream medium approaches it at speed $v_1 = -v_s$. The shocked fluid moves away from the shock front at speed $v_2 = \rho_1 v_1/\rho_2$. The shocked fluid thus approaches the un-shocked fluid at speed $v_{rel} = v_1 - v_2$.

_For particles crossing the shock, scattering is always head-on:

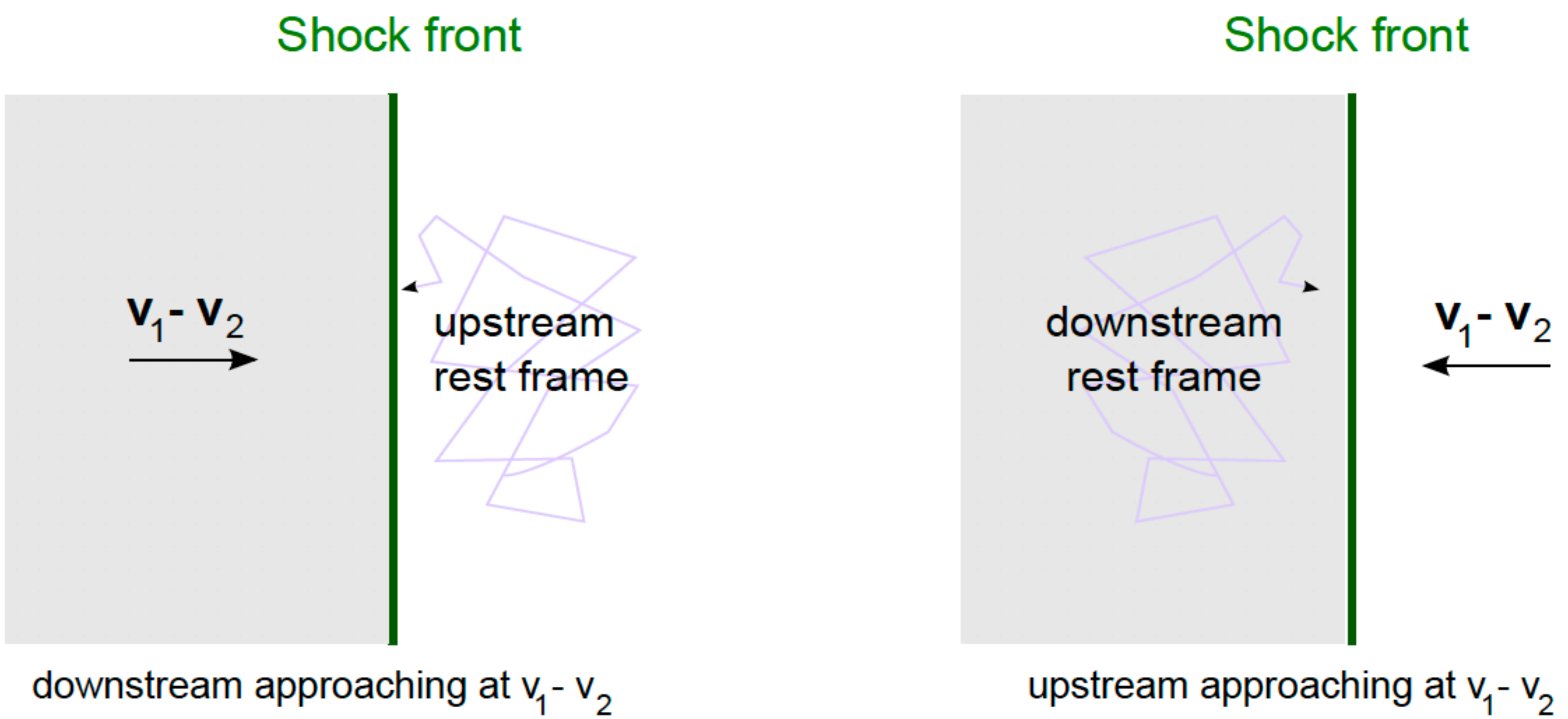

Figure 6: Diffusive shock acceleration: Energetic particles get isotropized in the downstream and upstream rest frame, respectively, by scattering off waves quasi-embedded in the background plasma (2nd order Fermi effects assumed being negligible). The situation is symmetrical: On each crossing of the shock front, they essentially experience head-on collisions with $\delta v = |v_1 - v_2|$, leading to 1st order Fermi acceleration.

- **shock:** spatial diffusion, gain on crossing is 1st order: $< \Delta E > \sim (\Delta v / c)\ E$

Fermi Acceleration Timescales

_Acceleration timescale ~ particle energy / (rate of energy change):

$$t_{\rm acc} = \frac{E}{(dE/dt)} \simeq \frac{E}{\Delta E} \times \tau$$

- **stochastic:** τ = λ / c "mean scattering time" (λ = mean free path):

$$t_{\rm acc} = \frac{E}{(dE/dt)} \simeq \frac{E}{\Delta E} \times \tau \sim \left(\frac{c}{V_A}\right)^2 \frac{\lambda}{c} \propto \frac{\lambda}{V_A^2}$$

- **shock:** *spatial* diffusion process $\tau = t_c \sim \kappa / (V_s\, c)$ "crossing time"

(residence time t_c = diffusion length / c , with diffusion length $l \sim \sqrt{\kappa\, t}$, and $t \sim l / V_s$)

$$t_{\rm acc} = \frac{E}{(dE/dt)} \simeq \frac{E}{\Delta E} \times t_c \sim \left(\frac{c}{V_s}\right) \frac{\kappa}{V_s\, c} \sim \frac{\kappa}{V_s^2} \propto \frac{\lambda}{V_s^2}$$

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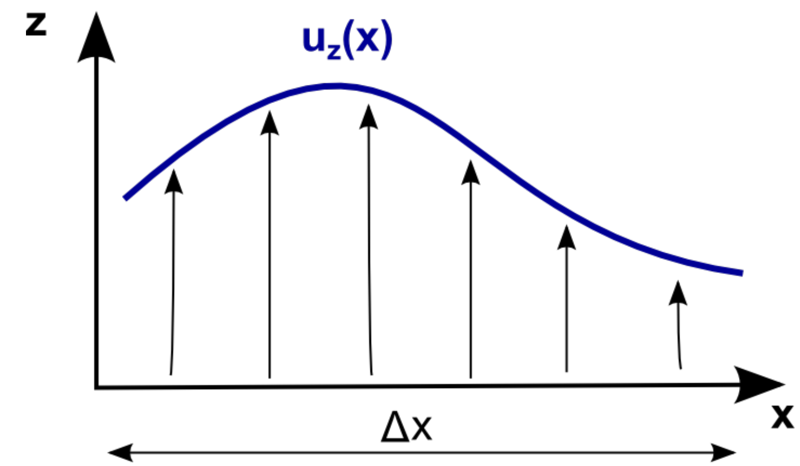
also second order in shock speed !

Fermi Acceleration @ shear flows

non-relativistic

_**Gradual shear flow** with frozen-in scattering centres: $\vec{u} = u_z(x)\ \vec{e}_z$

- like 2nd Fermi, stochastic process with average gain:



$$\frac{<\Delta E>}{E} \propto \left(\frac{V}{c}\right)^2 = \frac{1}{c^2}\left(\frac{\partial u_x}{\partial x}\right)^2 \lambda^2$$

using *characteristic effective velocity*:

$$V = \Delta u = \left(\frac{\partial u_z}{\partial x}\right) \lambda$$, where λ = *particle mean free path*

- leads to

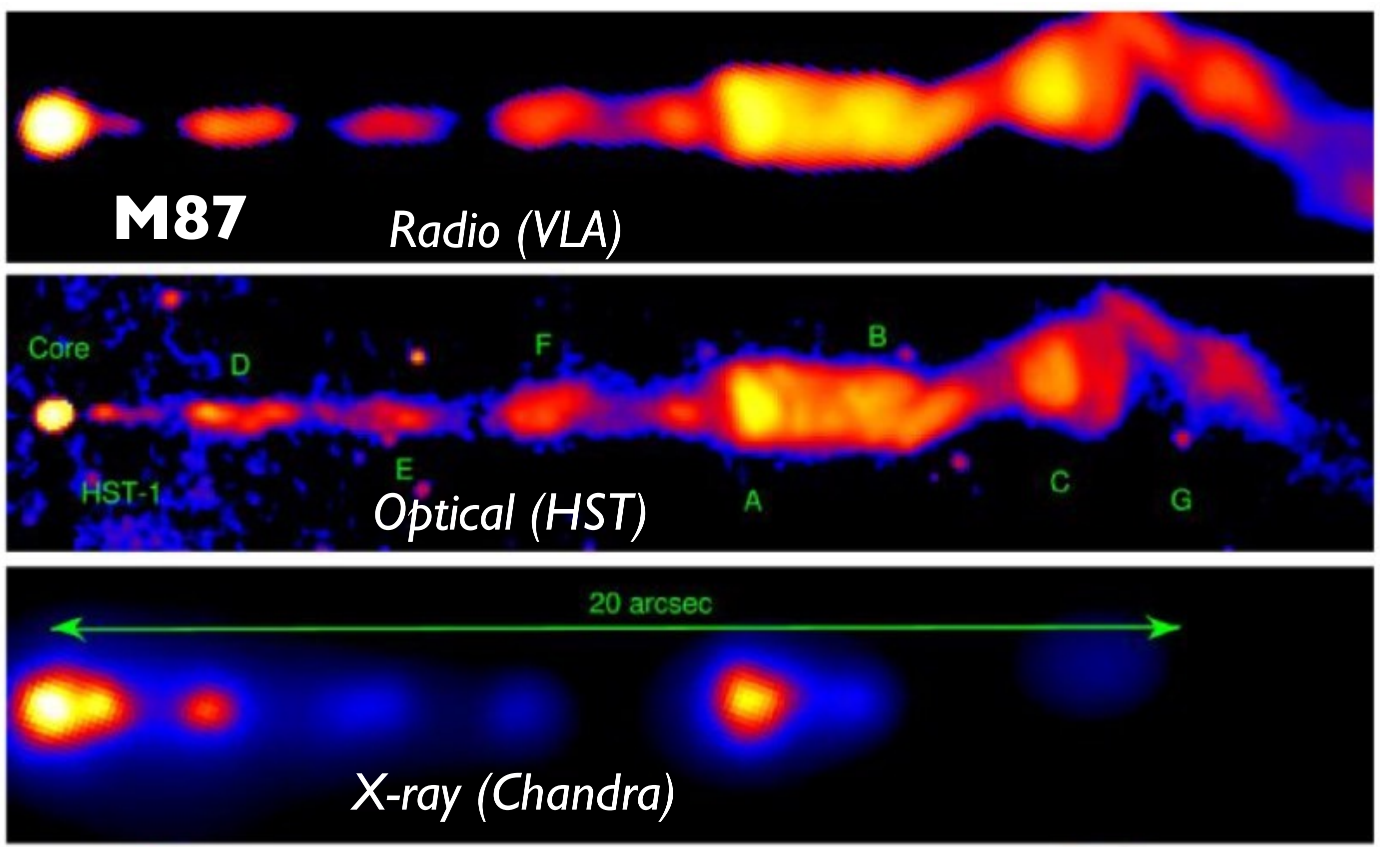
$$t_{\mathrm{acc}} = \frac{E}{(dE/dt)} \simeq \frac{E}{\Delta E} \times \tau \sim \left(\frac{c}{[\partial u_z/\partial x]\ \lambda}\right)^2 \frac{\lambda}{c} \propto \frac{1}{\lambda}$$

  - seed from acceleration @ shock or stochastic….
  - easier for protons….

_Emission from large-scale jets

- extended X-ray electron synchrotron emission
- electron Lorentz factors $\gamma \sim 10^8$
- short cooling timescale $t_{cool} \propto 1/\gamma$; cooling length $c\, t_{cool} \ll$ kpc
- distributed acceleration mechanism required (Sun, Yang, FR+ 2018 for M87)

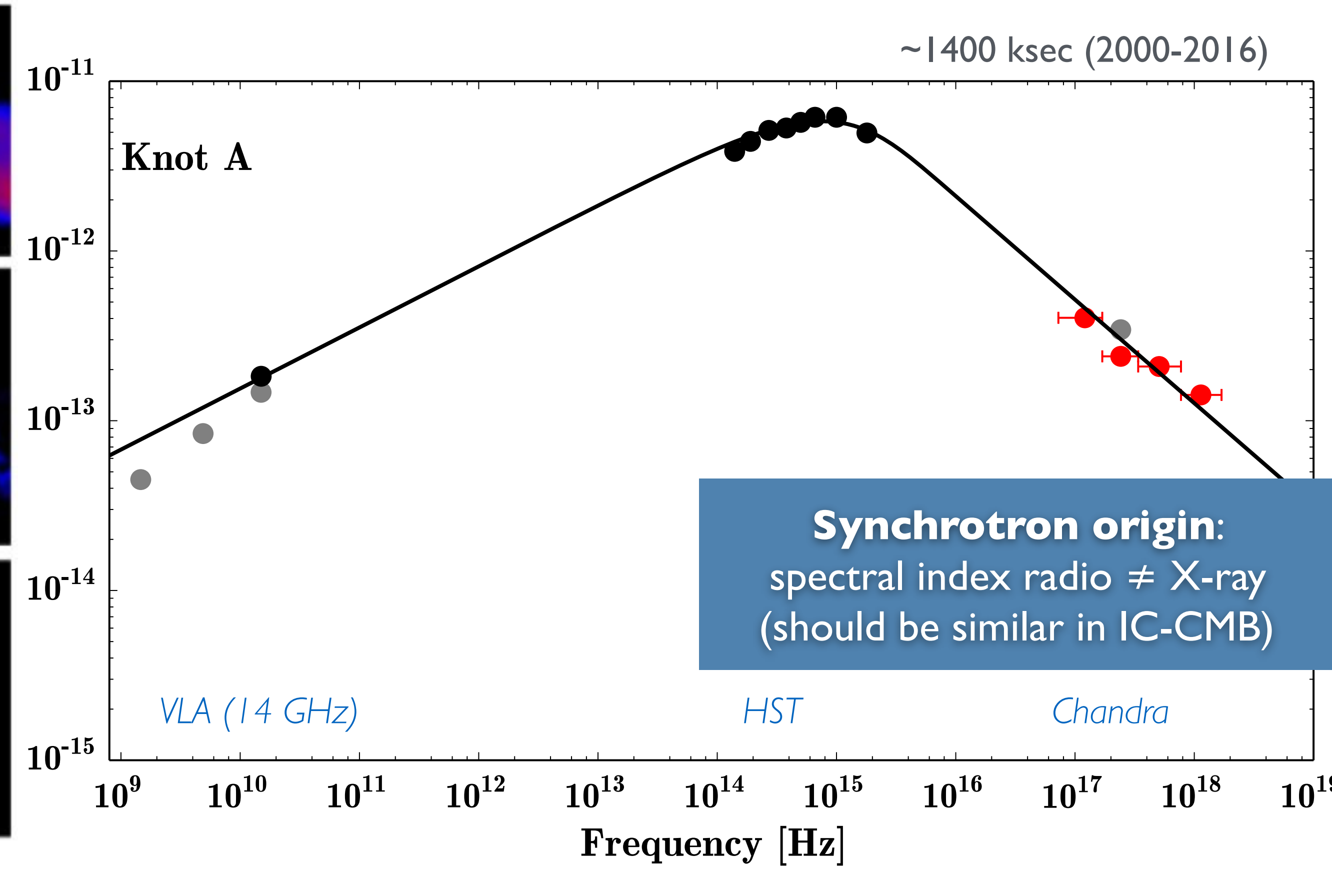
$$\nu \propto \gamma^2 B$$



1 arcsec ~ 0.1 kpc (0.081 kpc)

Marshall+ 2002

Relativistic particles throughout whole jet

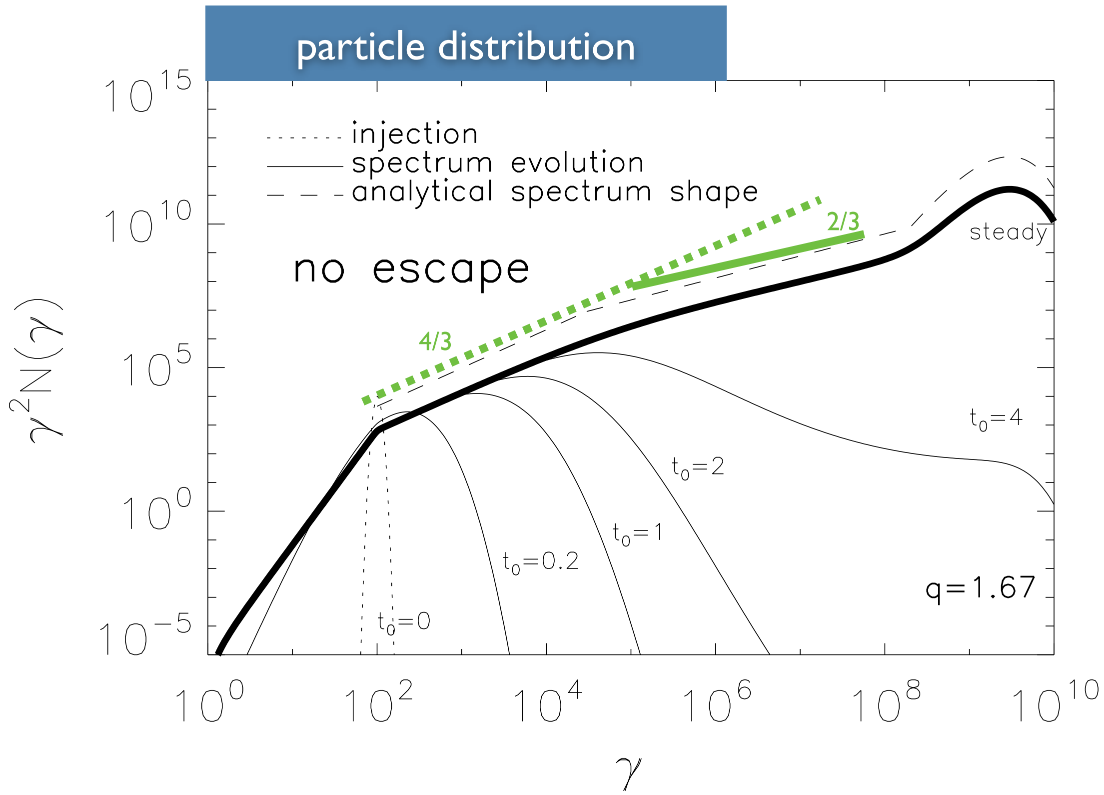


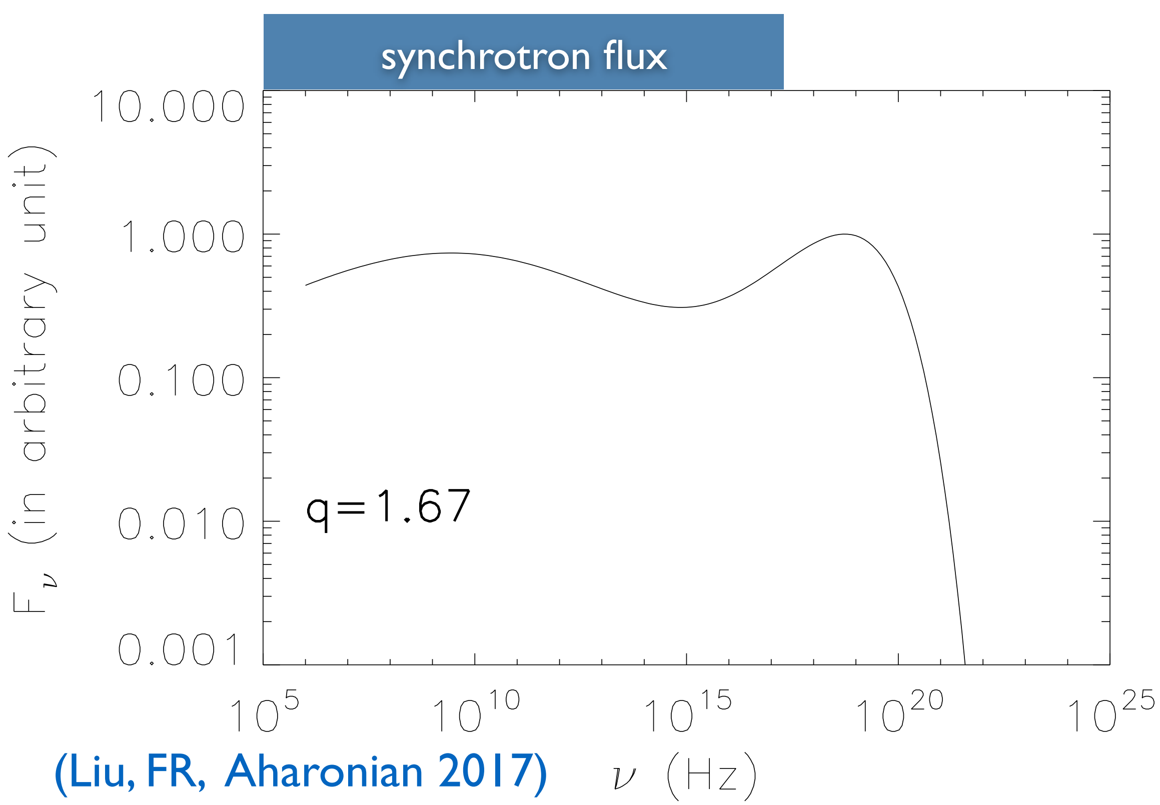
SED can be fitted by broken power-law

($B = 3\times10^{-4}$ G, $\gamma_b \sim 10^6$, $\gamma_{max} \sim 10^8$, $P_{jet} \sim 10^{43}$ erg/s, $\Delta\alpha \sim 2$)

Example: Stochastic & shear acceleration in large-scale AGN jets II

Radiative-loss-limited acceleration in mildly relativistic flows





(Liu, FR, Aharonian 2017)

Ansatz: Fokker-Planck equation for f(t,p) including stochastic, shear and synchrotron for cylindrical jet.

- from 2nd Fermi ($t_{acc} \propto \lambda$) to shear ($t_{acc} \propto 1 / \lambda$)…
- electron acceleration up to $\gamma \sim 10^9$ possible
- formation of multi-component particle distribution

Parameters: B = 3μG, $v_{j,max} \sim 0.4c$, $r_j \sim 30$ pc, $\beta_A \sim 0.007$, $\Delta r \sim r_j/10$, mean free path $\lambda = \xi^{-1} r_g (r_g/\Lambda_{max})^{1-q} \propto \gamma^{2-q}$, q=5/3 (Kolmogorov), ξ=0.1

Fermi Acceleration Timescales - Summary

_"1st order" Fermi - standard shock (non-relativistic):

with shock crossing time $t_c \sim \kappa/(u_s\, c)$, where $\kappa \sim \lambda\, c$

$$t_{\rm acc} \sim \left(\frac{c}{V_s}\right)\frac{\kappa}{V_s\, c} \sim \frac{\kappa}{V_s^2} \propto \frac{\lambda}{V_s^2}$$

_"2nd order" Fermi (stochastic):

with scattering time $\tau \sim \lambda/c$

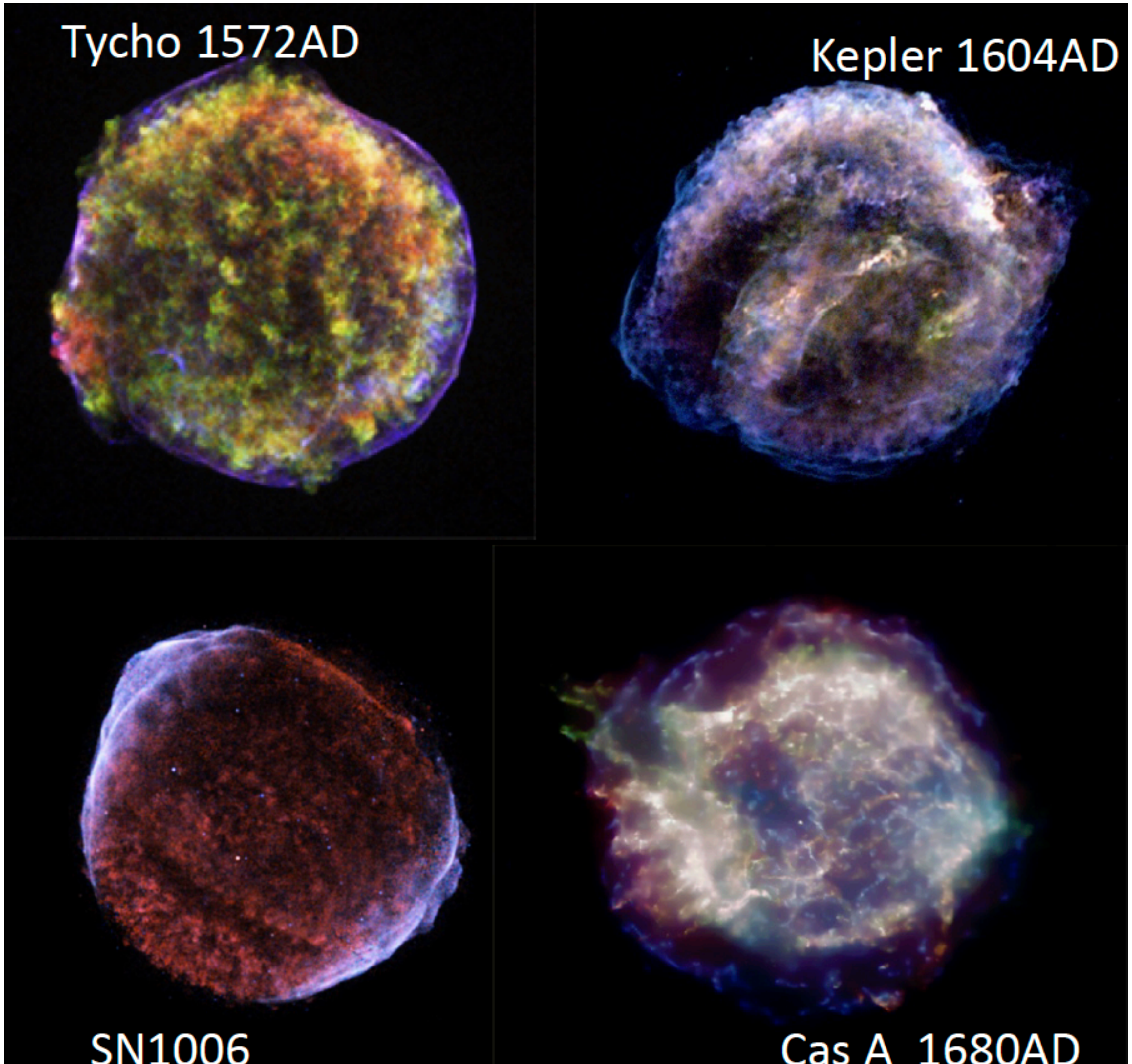
$$t_{\rm acc} \sim \left(\frac{c}{V_A}\right)^2 \frac{\lambda}{c} \propto \frac{\lambda}{V_A^2}$$

_Shear - **gradual** (non-relativistic):

$$t_{\rm acc} \sim \left(\frac{c}{[\partial u_z/\partial x]\,\lambda}\right)^2 \frac{\lambda}{c} \propto \frac{1}{\lambda}$$

(e.g., Drury 1983; Kirk 1994; Duffy & Blundell 2005; FR+ 2007)

Example: Shocks in SNRs - historical shell SNR



Chandra X-ray emission (Credits: NASA+)

Mixture of line radiation (hot plasma) & synchrotron continuum (relativistic electrons).

For electron synchrotron in (amplified) magnetic field of ~ 0.1-1 mG:

- radio (GHz): $\gamma_e \sim 10^{3-4}$
- X-rays (keV): $\gamma_e \sim 10^{7-8}$

(but: *degeneracy in B & γ*)

Example: Efficient Cosmic Ray (PeV) Acceleration @ SNR shocks ?

- Acceleration timescale:

$$t_{\rm acc} \simeq \frac{8\,\kappa}{V_s^2} = \frac{8}{3}\frac{\lambda\, c}{V_s^2}$$

- with spatial diffusion coefficient:

$$\kappa = \lambda\, c\, /\, 3$$

SNR radius

$t_{acc} \leq t_{age} \simeq R\,/V_s$ implies: $\lambda \leq \frac{3}{8}\frac{V_s}{c} R$

- smallest possible mean free path: $\lambda \approx r_{gyro} = E\,/\,(e\,B)$

⇒ Limit on maximum CR energy: $E_{\rm max} \leq \frac{3}{8}\frac{V_s}{c} R\, e\, B$

- typical for young SNR:

ISM mag field: few μG

$V_s = c\,/\,50$

$R \sim 10^{19}$ cm

$$E_{\rm max} \lesssim 10^{14}\,(B\,/\,5\mu{\rm G})\ {\rm eV}$$

(Lagage & Cesarsky 1983)

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but limitations due to self-regulated CR escape implying E_{max} < 1 PeV for Tycho, Cas A, Kepler (e.g., Bell+ 2013)

(Lagage & Cesarsky 1983)

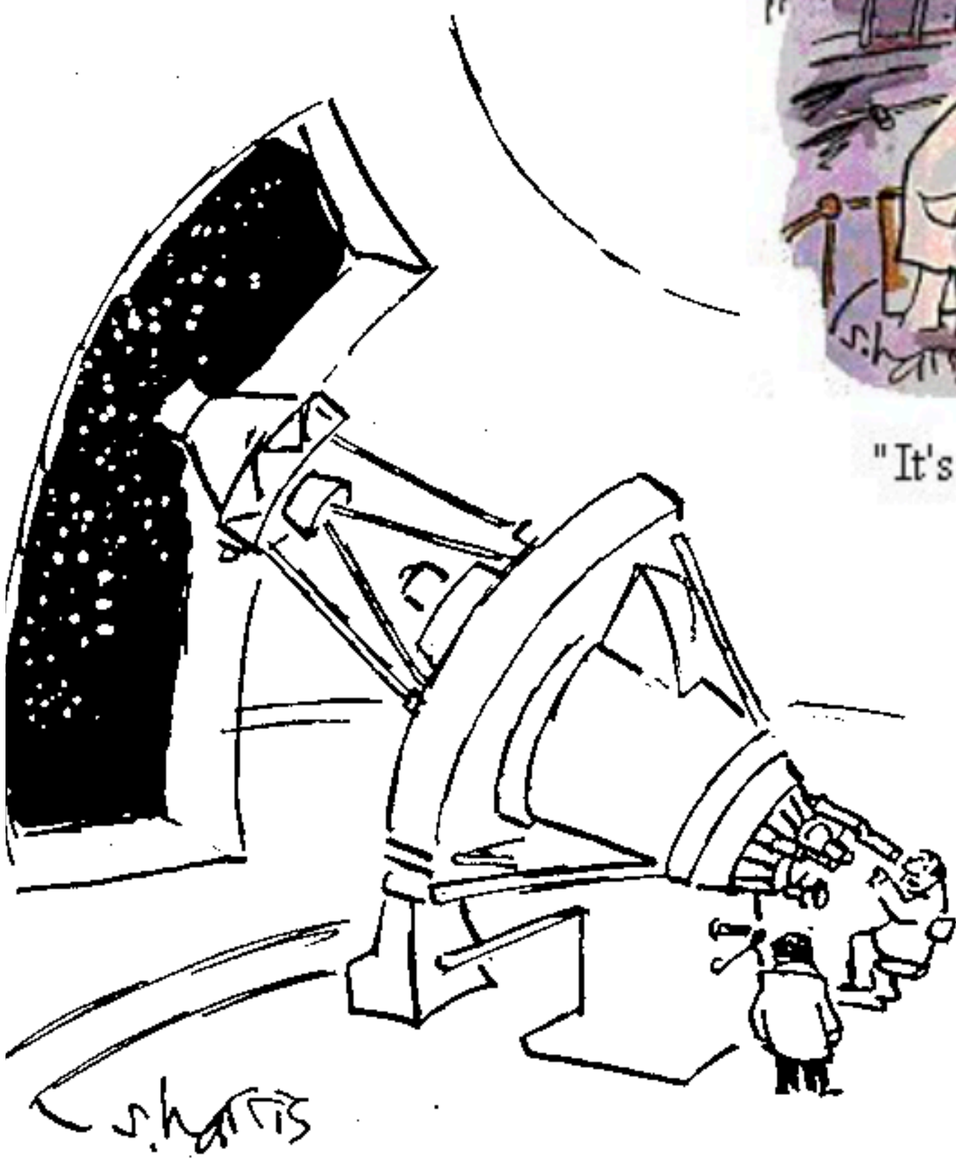
Some Issues Concerning Fermi-type Particle Acceleration

- ***Stochastic particle acceleration:***
  - generates no unique power-law particle distribution, e.g., index depends on ratio of t_{acc}/t_{escape}; if synchrotron-loss limited, relativistic Maxwellian distributions may occur…
  - slow process unless the scattering center speed is high (Alfven speed; AGN jets)…
- ***Shock acceleration:***
  - highly relativistic shocks (PWN, GRBs etc) are not expected to be efficient accelerators (e.g., isotropization upstream not guaranteed; relativistic shocks are generically quasi-perpendicular as $B_\perp = 3\,\Gamma_s\,B_\perp'$…)
  - no longer a unique power law…
- ***Shear acceleration:***
  - only efficient in relativistic shear flows
  - particle transport across flow still to be understood
  - destruction of flow (KH/shear instabilities)?

(e.g., Sironi+ 2013, Lemoine & Pelletier 2017; Bell+ 2018, Webb+ 2018, FR 2019)

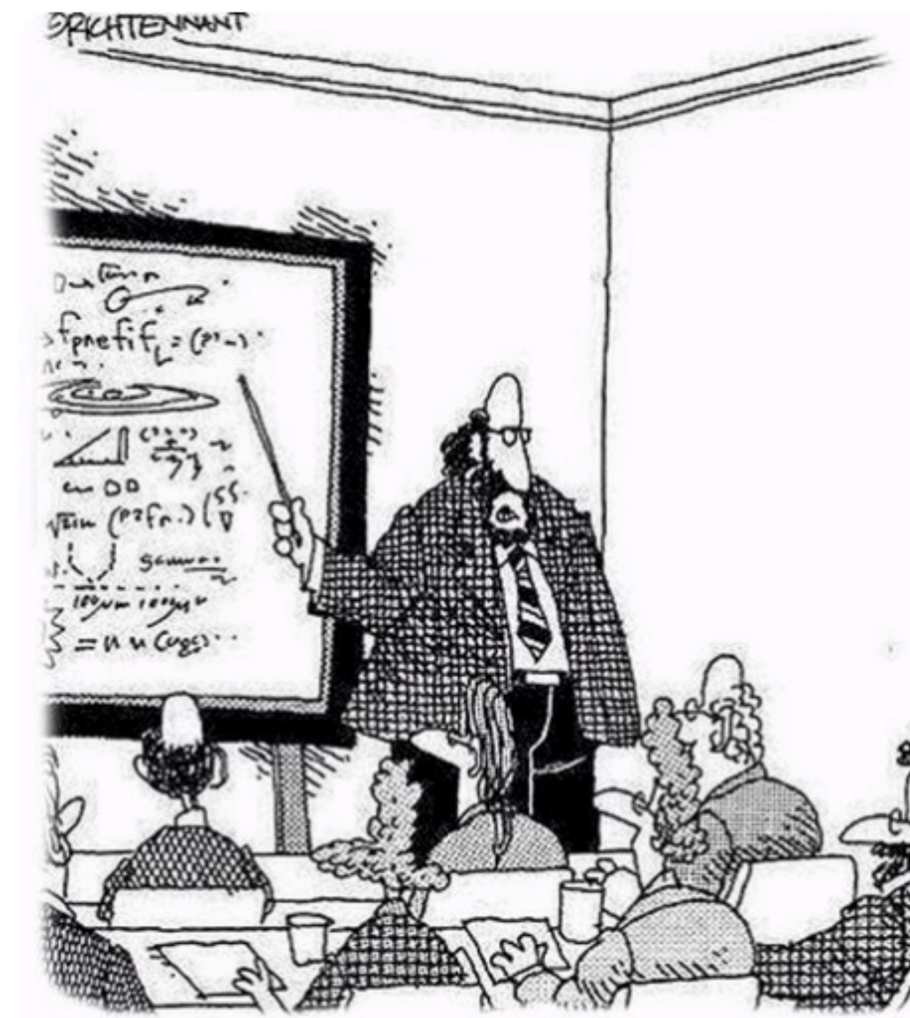
The END

"It's black, and it looks like a hole. I'd say it's a black hole."



"Actually they all look alike to me."

Thank you!



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."