NBI 2018

Lec 1

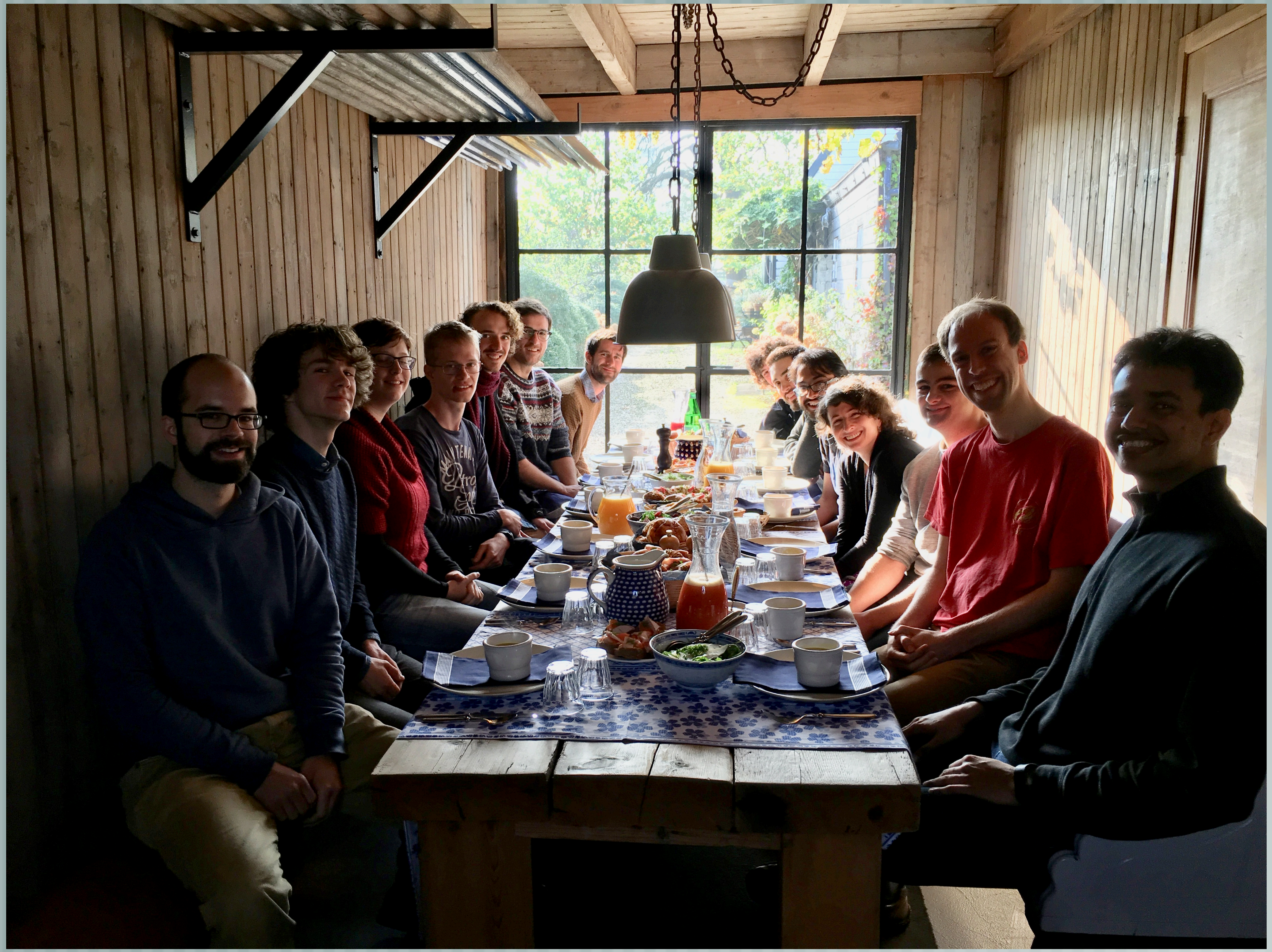
High-Energy Radiative Processes and Jets

Lecture 1

Sera Markoff (API/GRAPPA, U Amsterdam)

Brief introduction

My group @ U Amsterdam:



- All education in the US (PhD 2000)
- First postdoc: Humboldt Fellow @ MPIfR, Bonn, Germany
- Second postdoc: NSF A&A fellowship @ MIT, USA
- Faculty @ Amsterdam since 2006
- Field: High-energy astrophysics, particle astrophysics. In particular: accretion processes around compact objects, jets ⇔ particle acceleration

What Sebastian and I will try to cover in 6 hours (!?!)

High-energy electromagnetic radiation

* Introduction to the relevant sources and some interesting problems/state of the art (why we care)
* Introduction to particle acceleration and “multi-messenger”
* Introduction to nonthermal radiation and some of the theory behind it
* Some problems to get you started

What Sebastian and I will try to cover in 6 hours (!?!)

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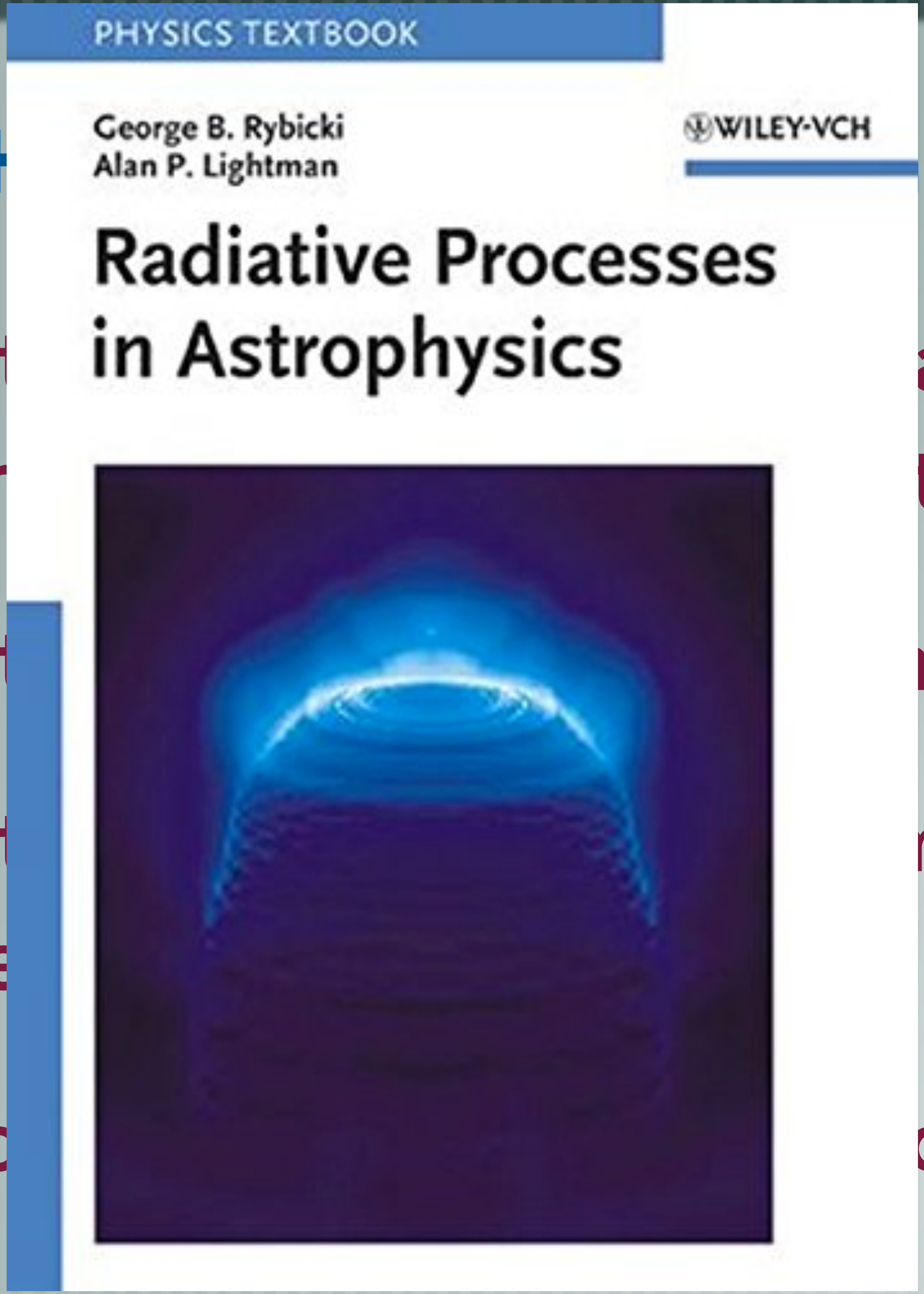
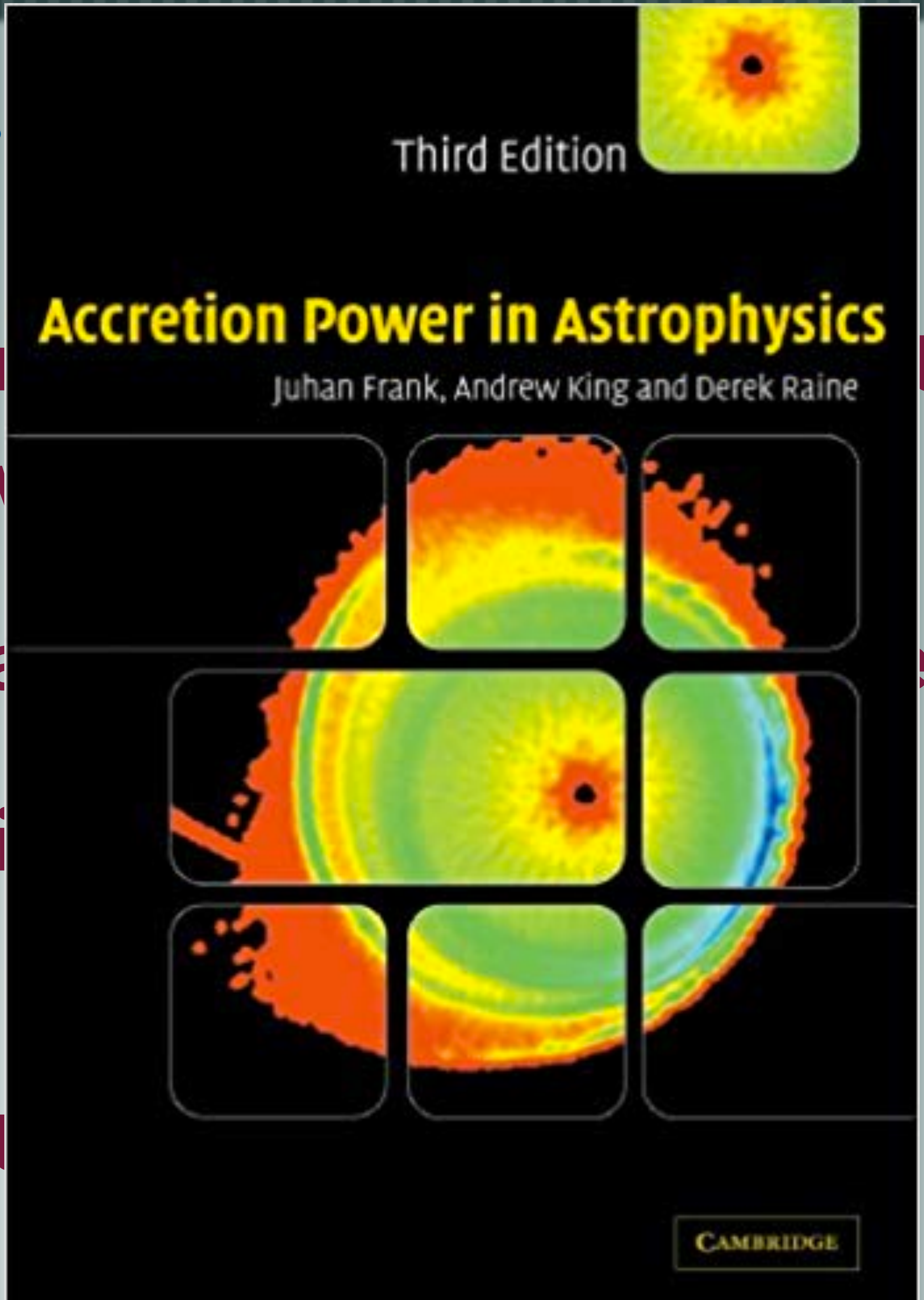
- So… ou start…





Cast of Characters

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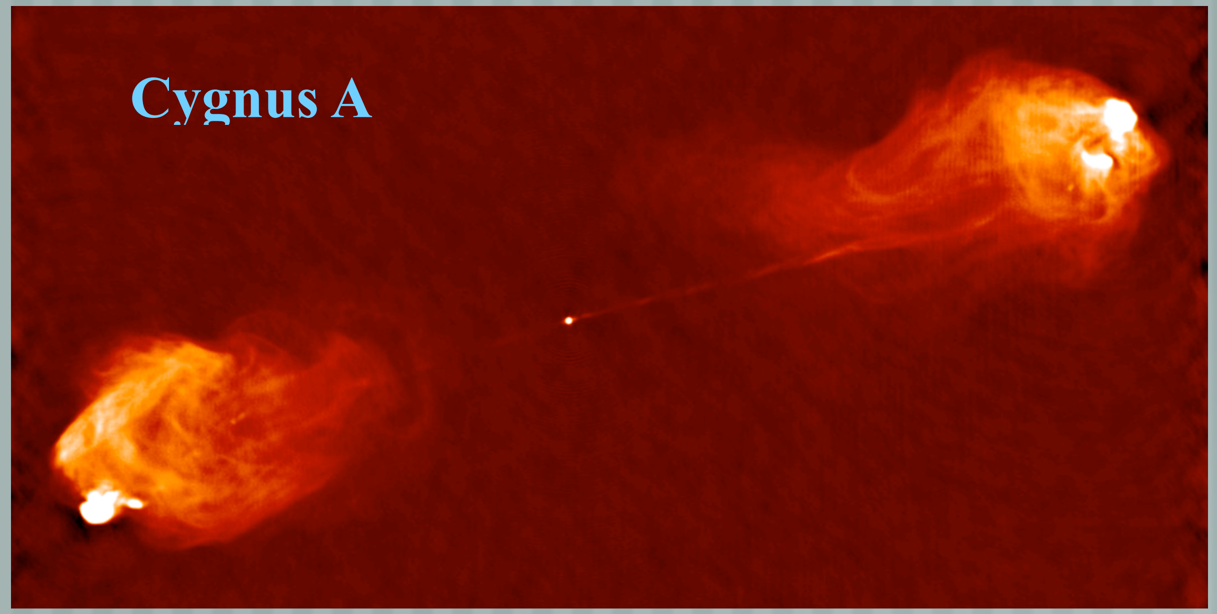

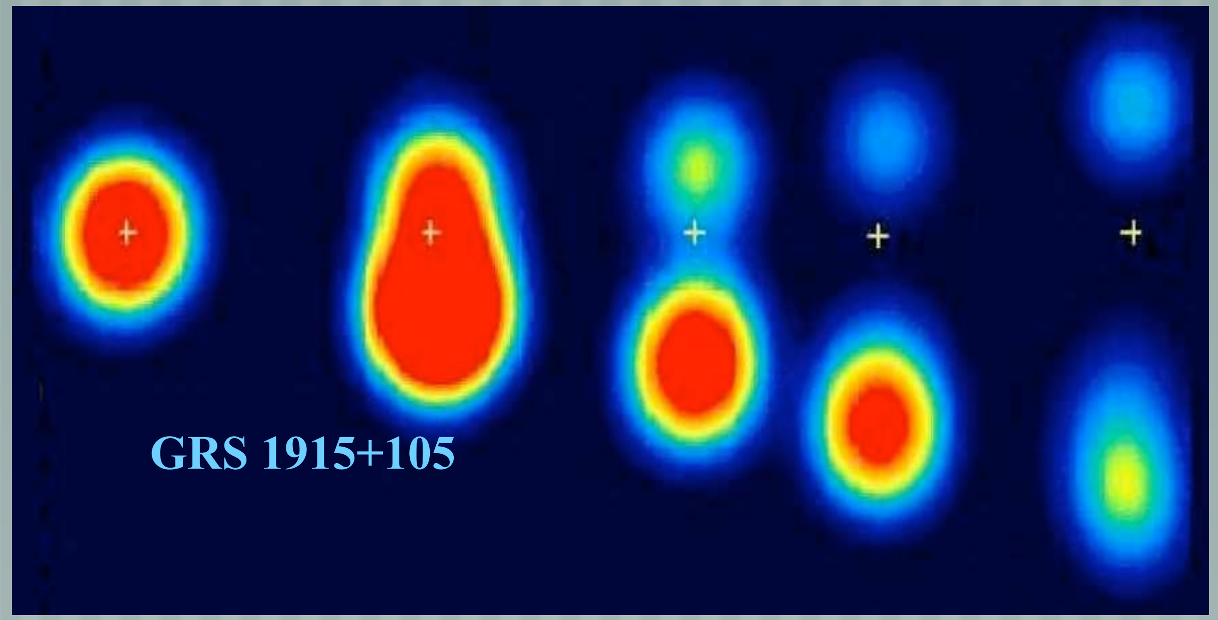

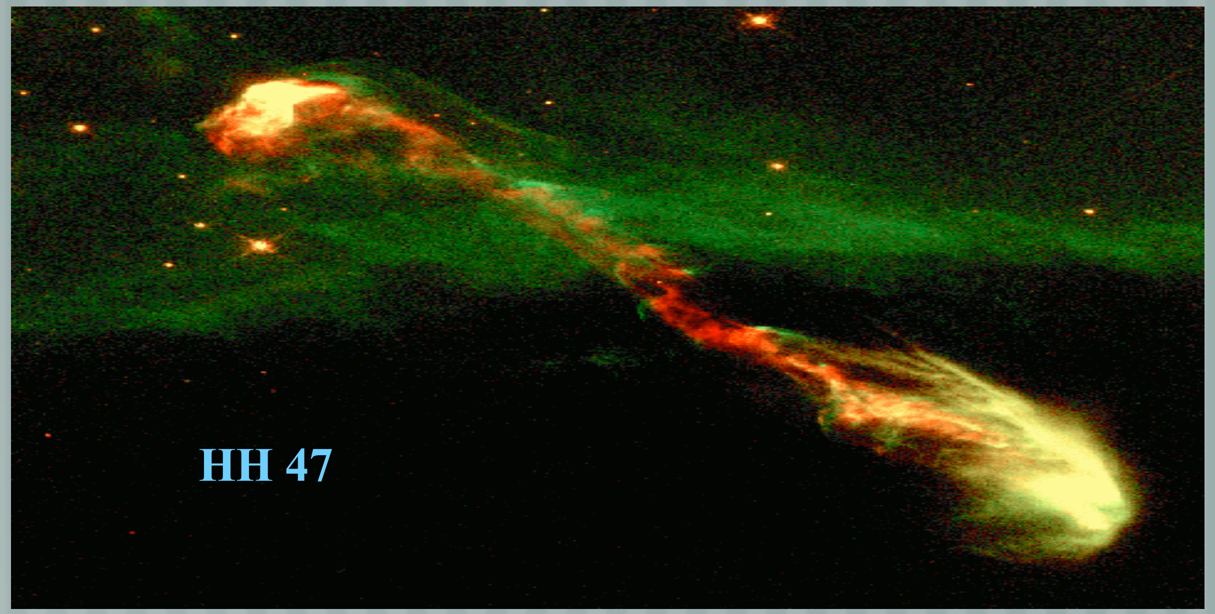

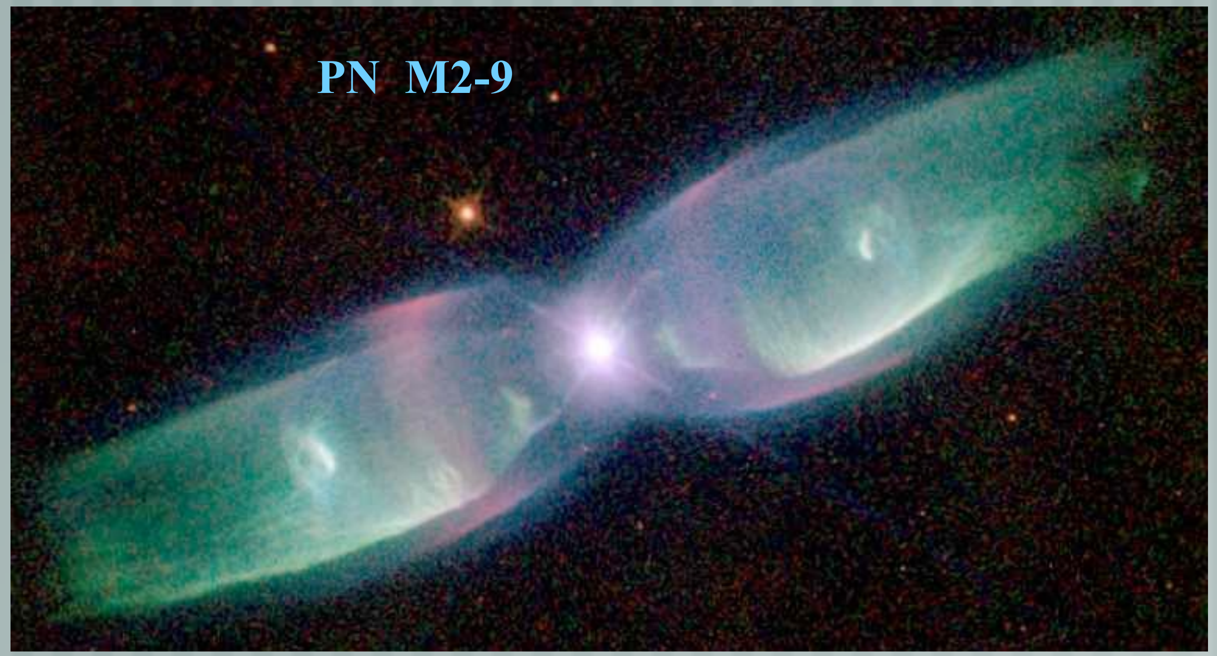

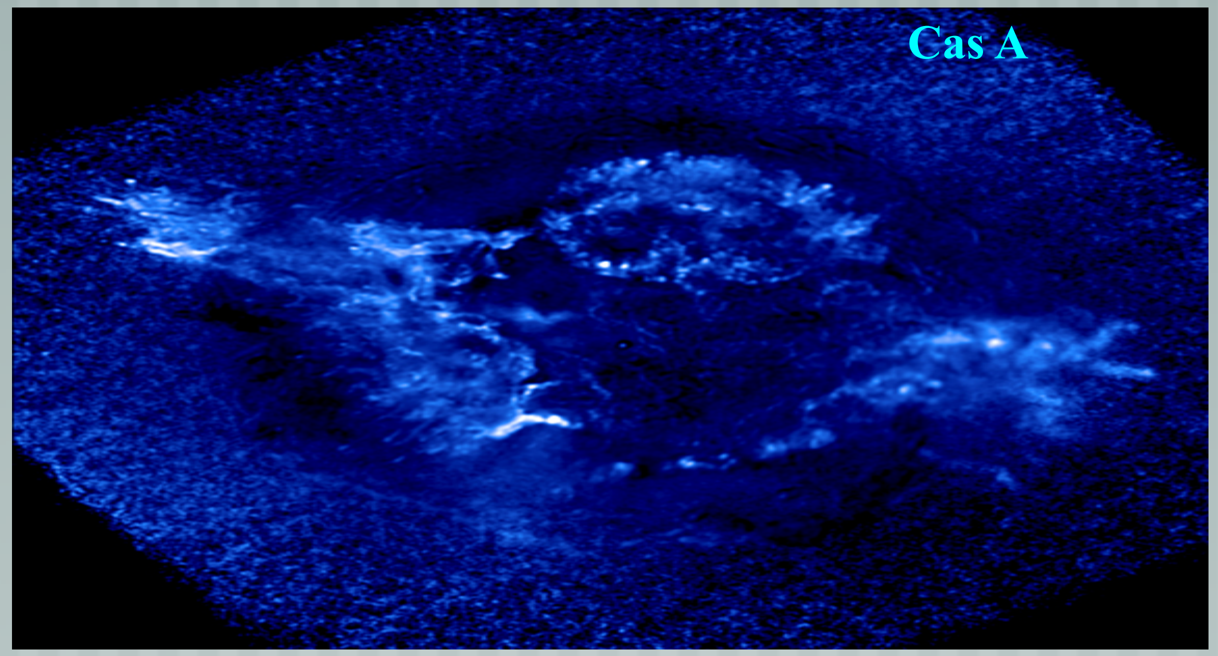

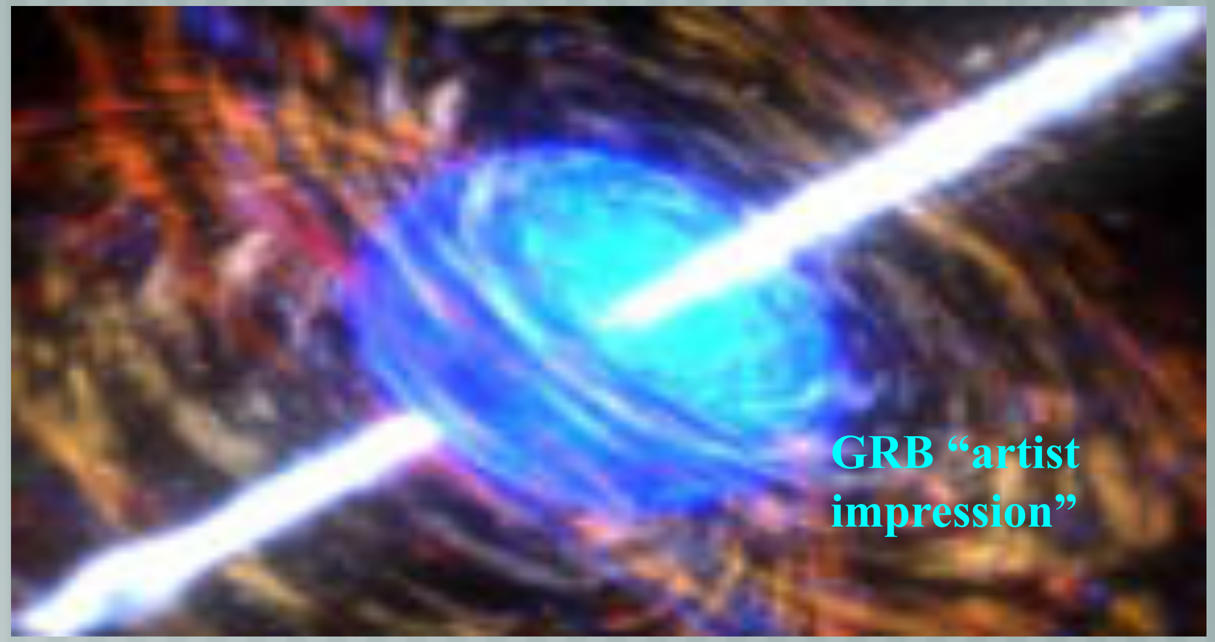

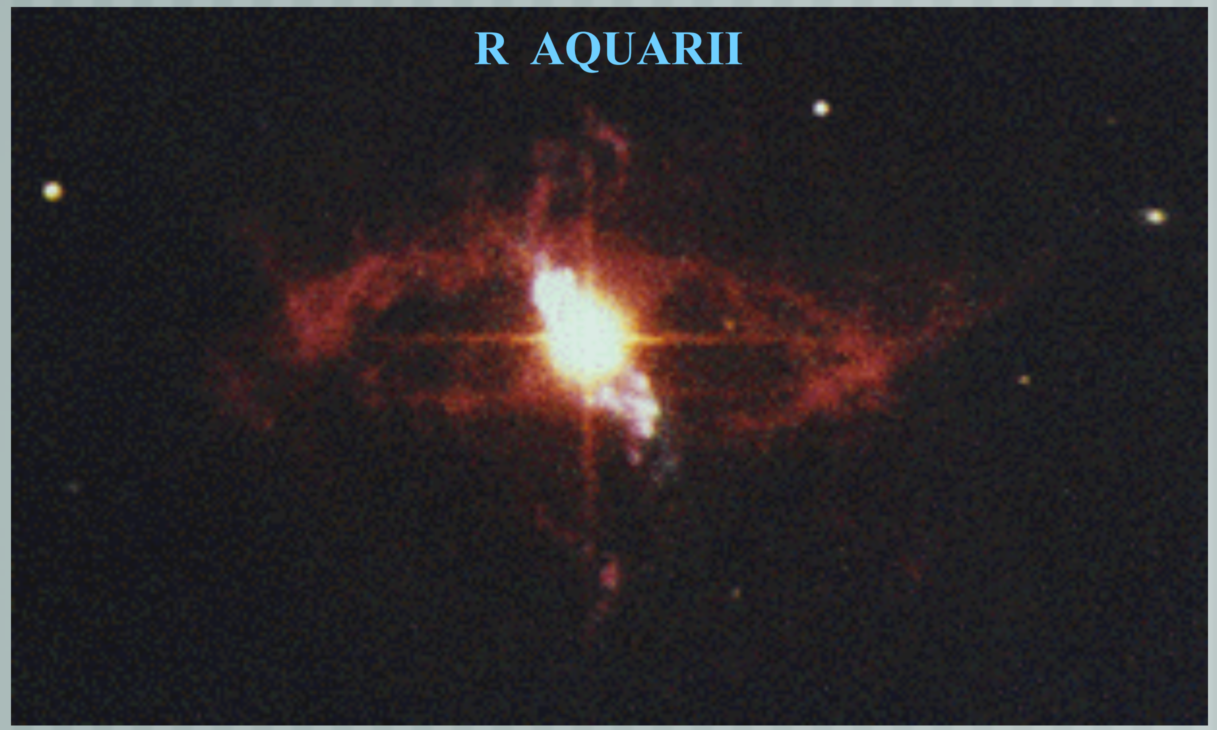

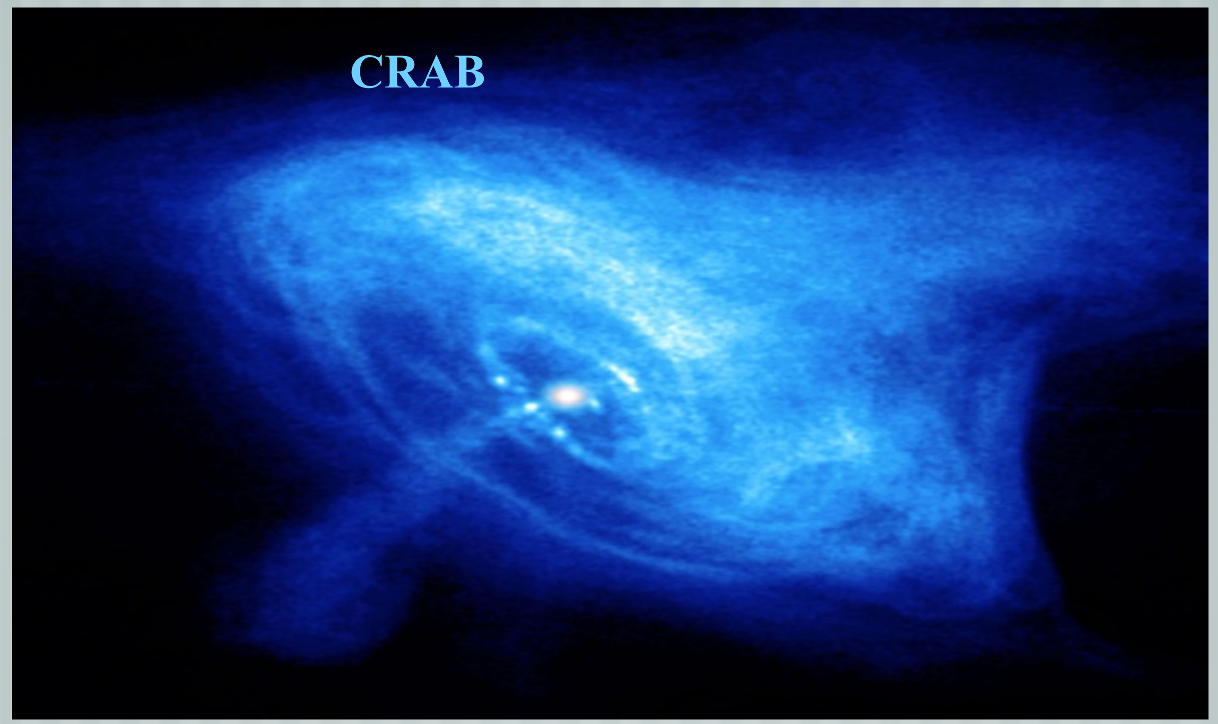

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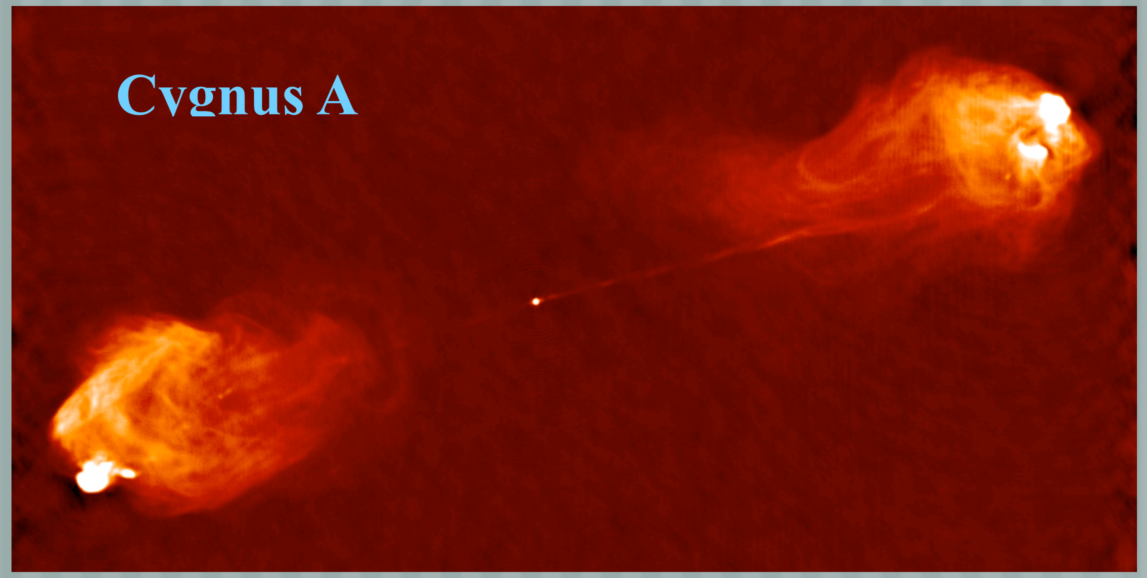
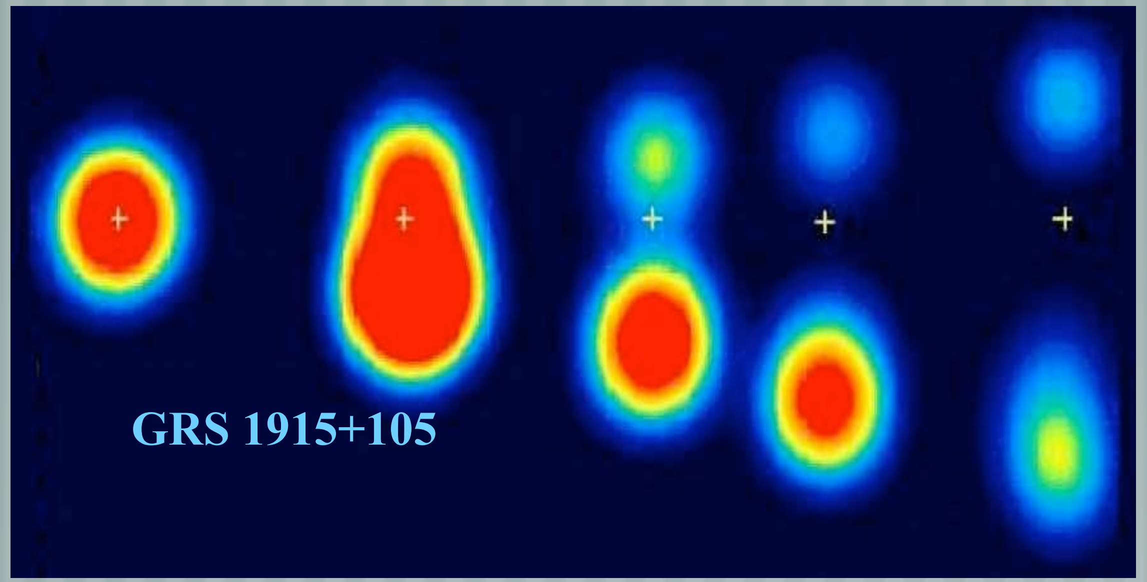
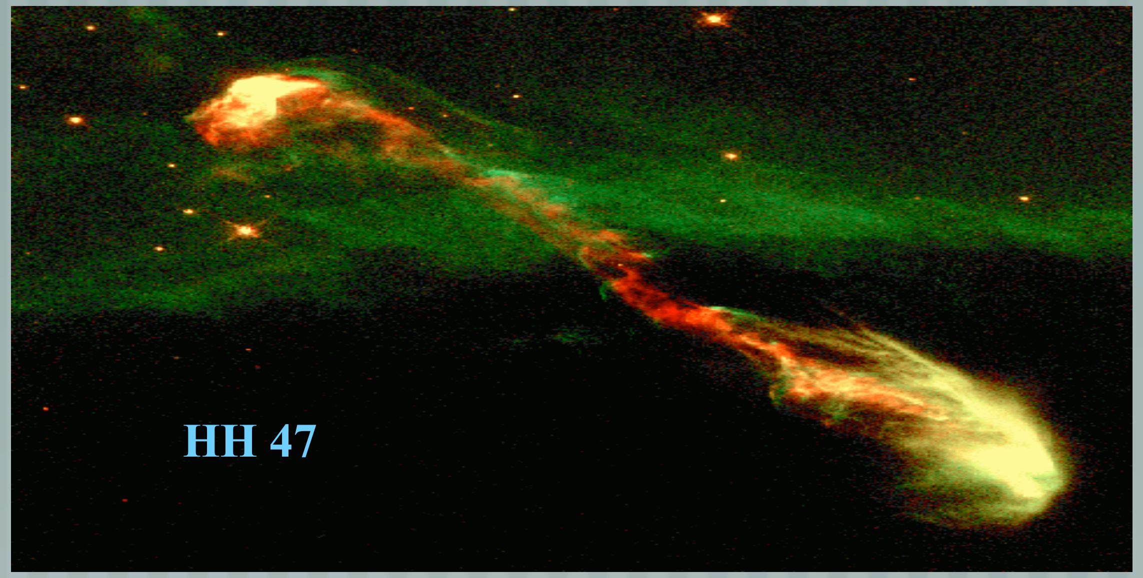
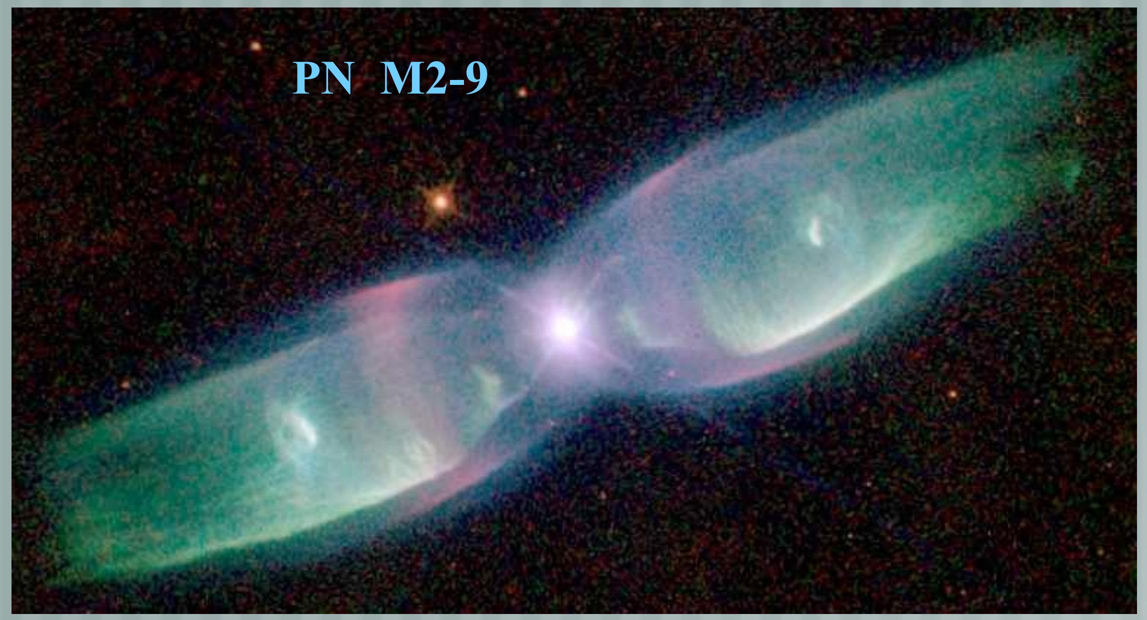
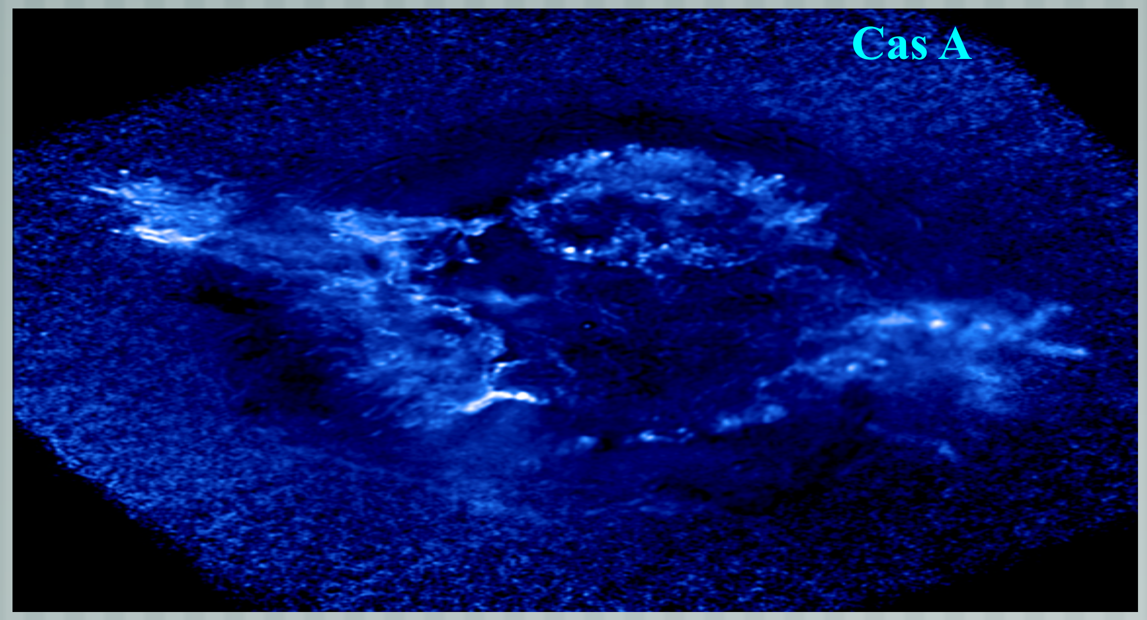
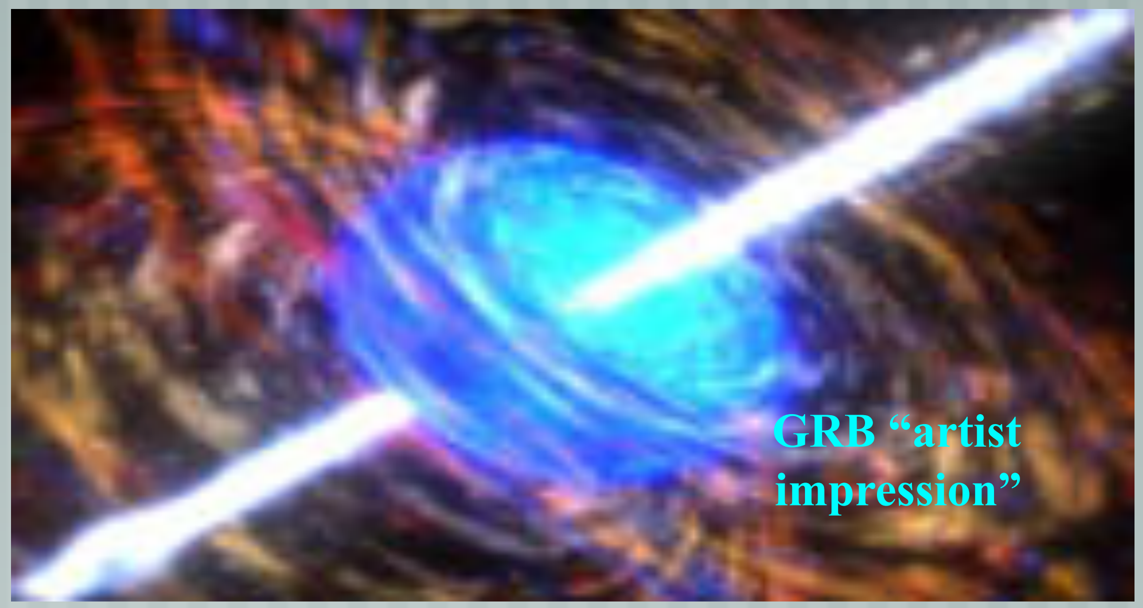


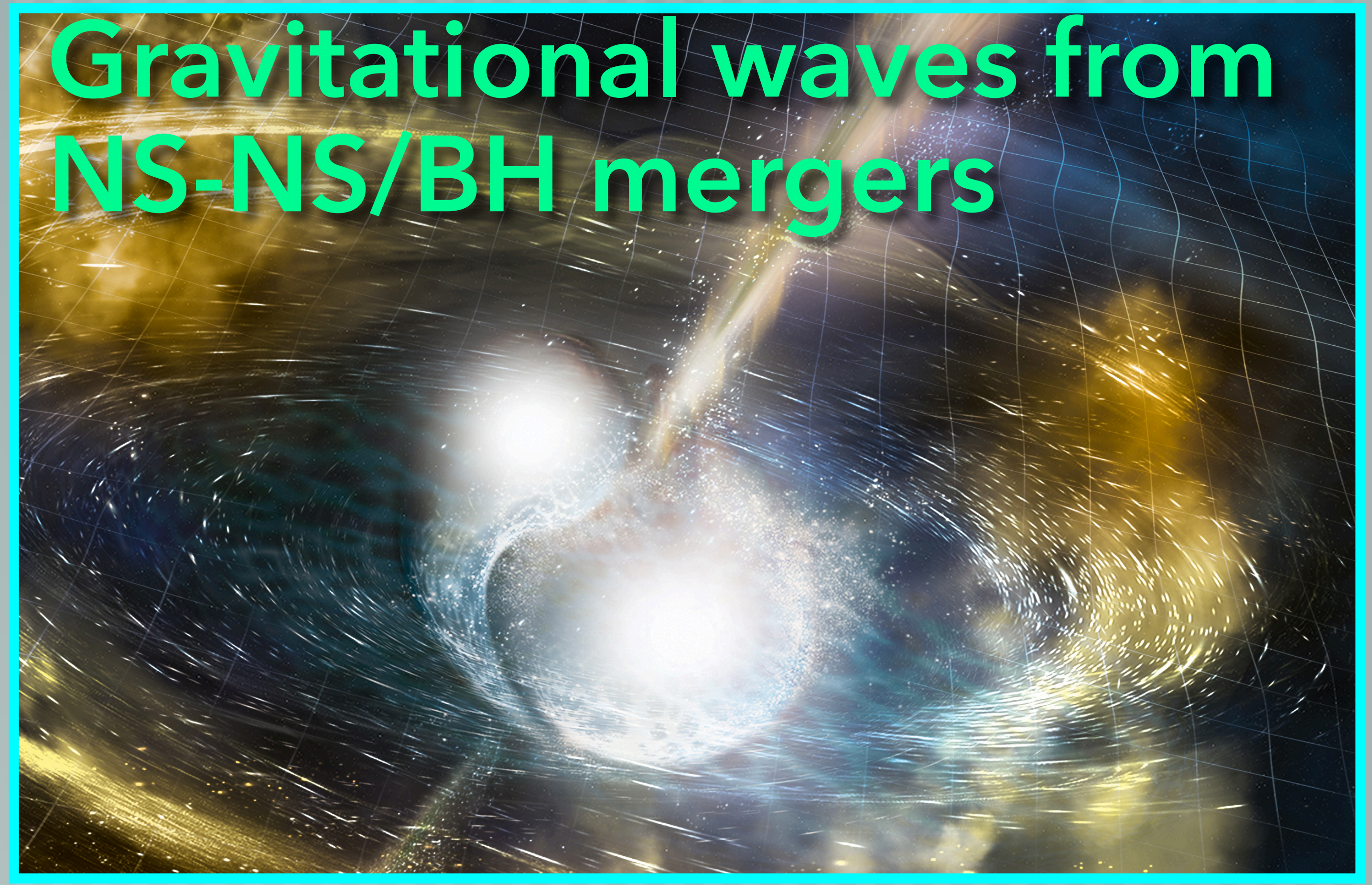


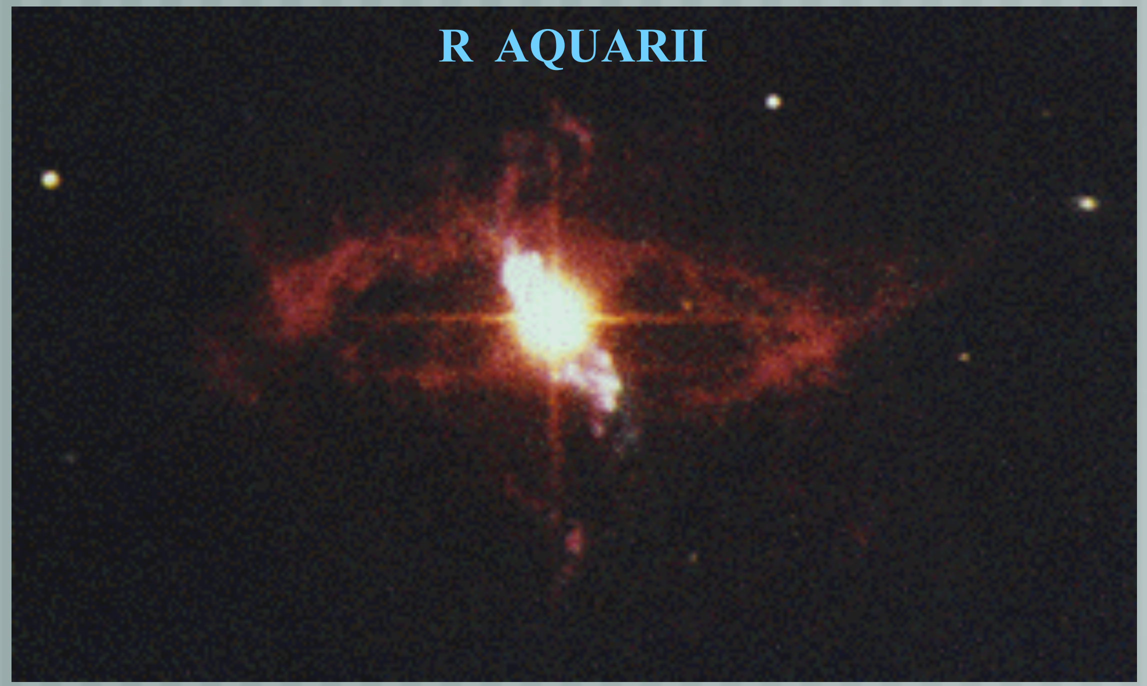


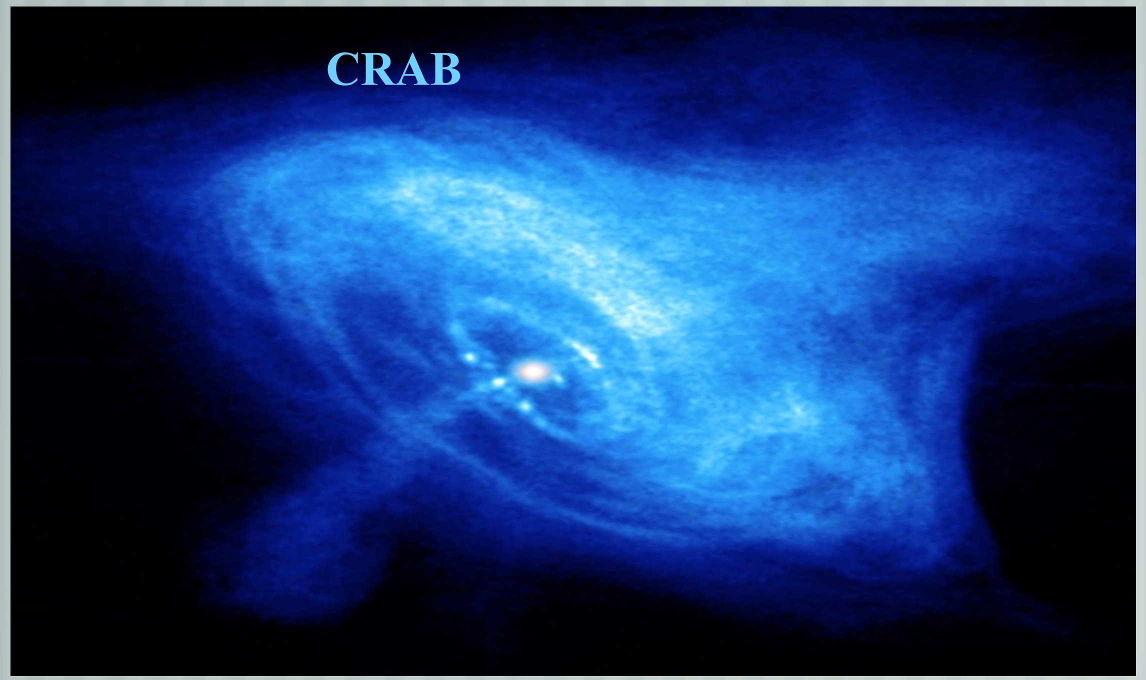






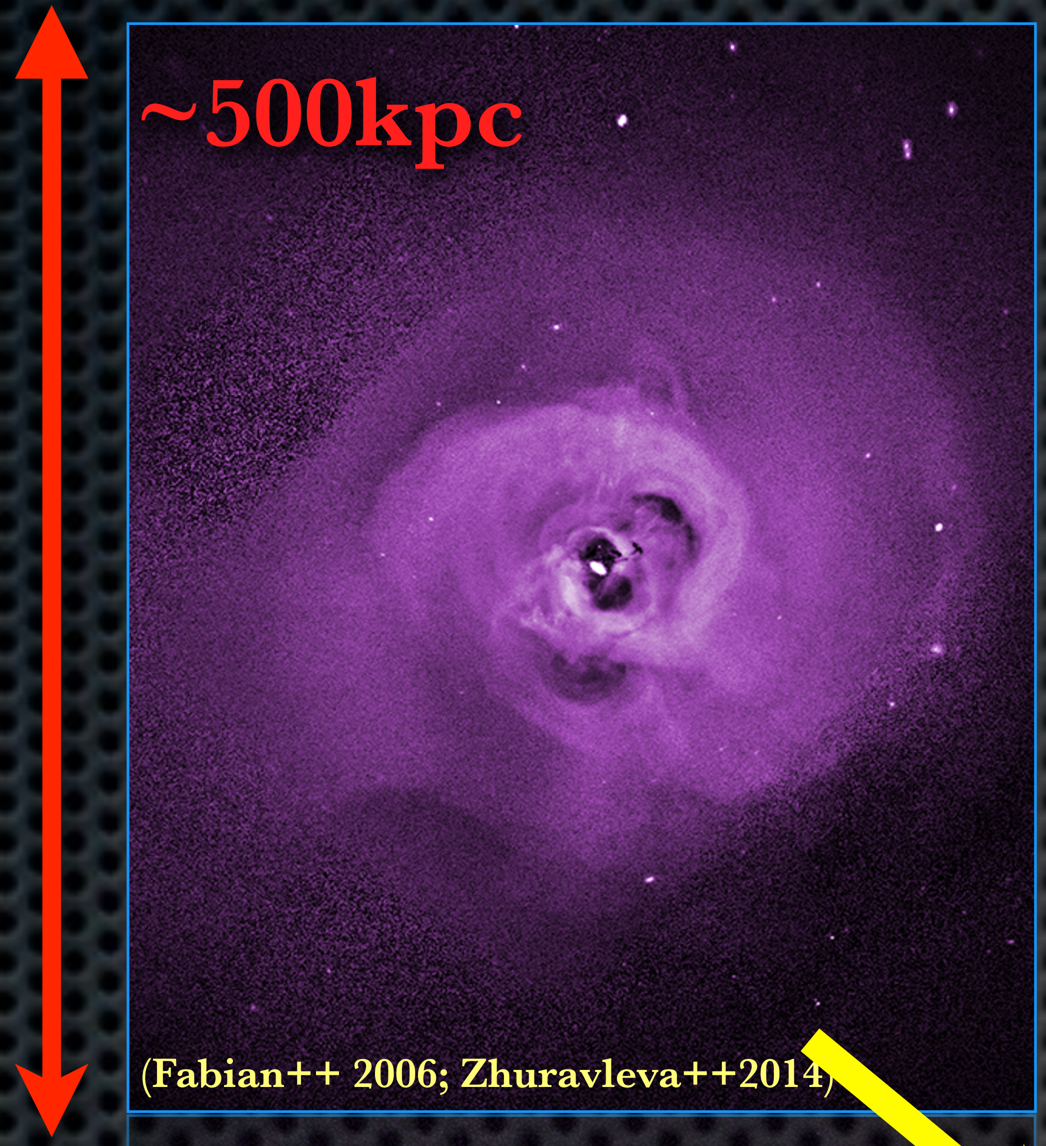






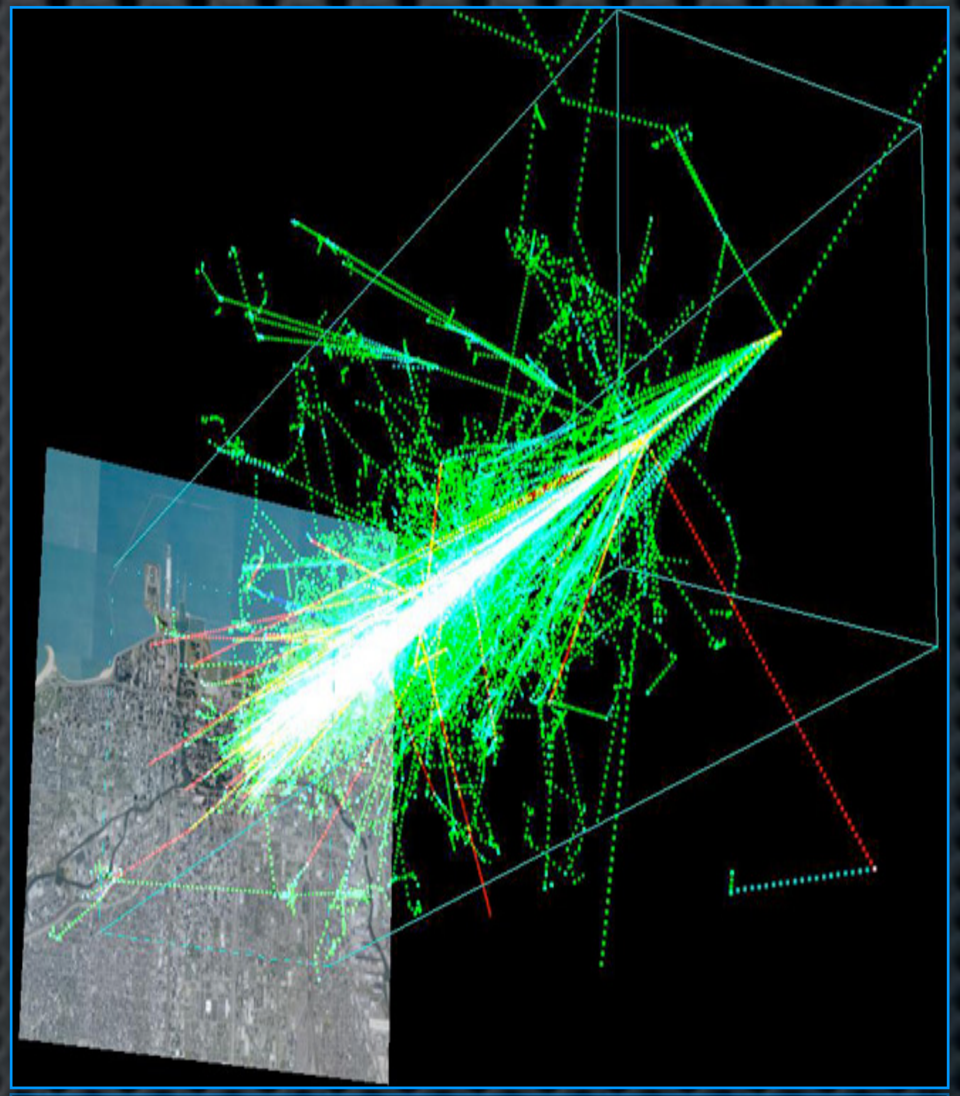
We need to understand how black hole accretion works in order to understand...

GALAXY EVOLUTION/ AGN FEEDBACK

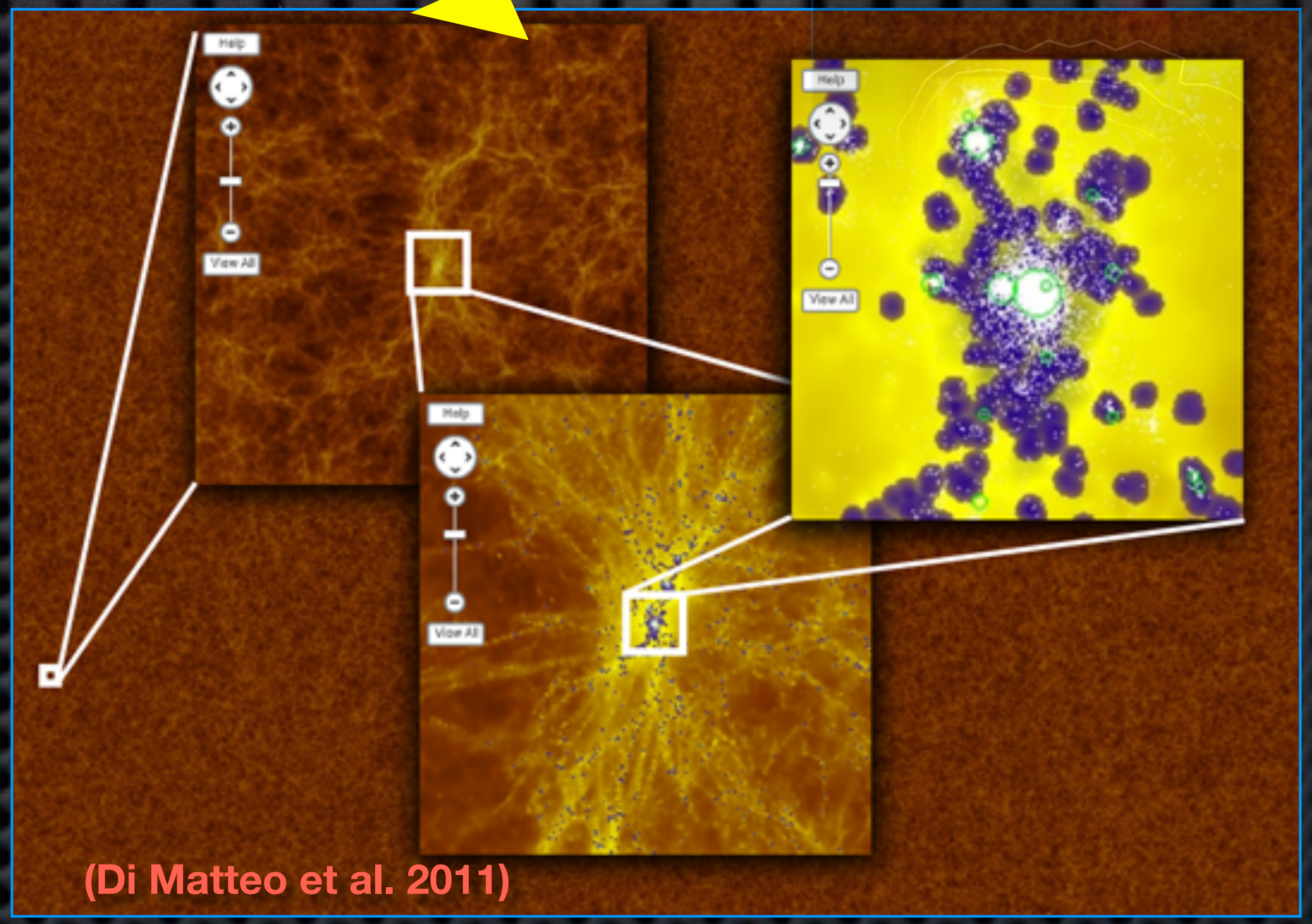


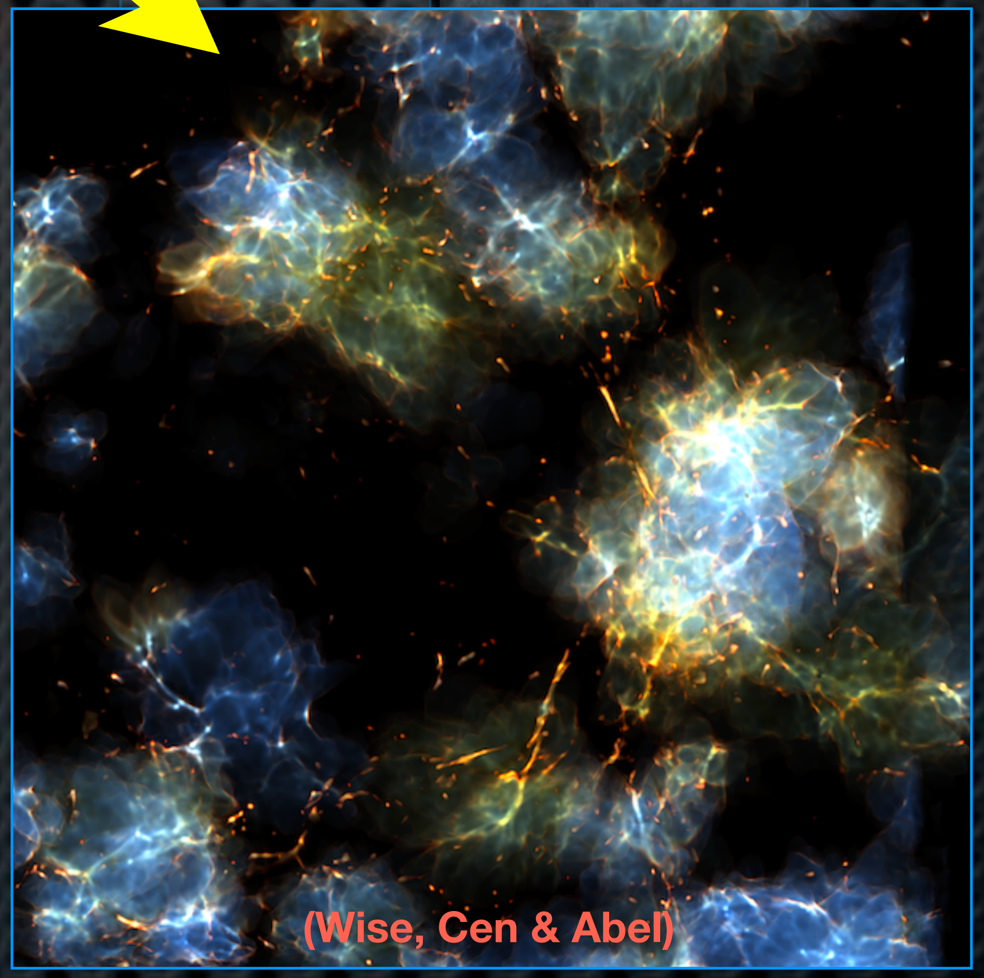
IONIZATION OF SURROUNDING GAS

HIGH-ENERGY PARTICLE ACCELERATION



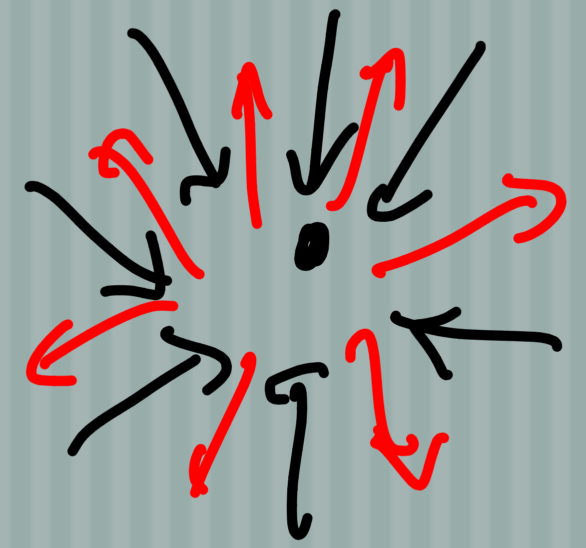
Cosmological Simulations:





Maximum energy budget?

Is there a characteristic maximum accretion rate possible?



Dimensional analysis

$$P \sim F/A \sim \frac{dp/dt}{A} \sim \frac{dE}{dt\,A\,c} \quad \text{photons} \quad p \sim \frac{E}{c}$$

$$\sim \frac{f}{c}$$

$$F_{rad} \sim P \cdot A \sim \frac{f}{c} \cdot A \sim \frac{L}{4\pi r^2 c} \cdot \sigma_T$$

$$F_g = F_{rad} \implies L_{edd} = \frac{4\pi r^2 c}{\sigma_T} \cdot \frac{GMm_p}{r^2}$$

$$L_{edd} \sim 1.25 \times 10^{38} \text{ erg/s } (M/M_\odot)$$

Eddington luminosity

"canonical" maximum luminosity, the Eddington luminosity:

$$L_{\rm Edd} \equiv \frac{4\pi c G M m_p}{\sigma_T} \sim 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right) \rm erg/s$$

Source	Energy output= minimum budget	L_{Edd} = max budget
XRBs/ULX	10^{33-39} erg/s, <10^{41} erg/s	10^{38-39} erg/s
AGN/TDE	10^{35-48} erg/s	10^{44-48} erg/s
PWN	Crab = 5x10^{38} erg/s	~10^{38} erg/s
SNR	10^{51} ergs initial explosion	~10^{38} erg/s
GRB	10^{51-54} ergs!	10^{38-39} erg/s

Timescales

What sorts of timescales are relevant?

- freefall
- viscous ⇒ dynamical
- diffusion
- cooling/radiation
- heating/acceleration
- adiabatic or expansion
- interactions/collision

$t_{dyn} \gtrless$ other stuff

(bulk properties) (particle)

"Slow" system

$t_{dyn} \gg t_i$ i = stuff

steady state $\Longleftrightarrow$ Equilibrium, "time to communicate"

specifically for accretion, $t_{collisions}$ is longer than cooling...

$\Rightarrow$ thermal equilibrium $\rightarrow$ bulk properties & T

$\Longrightarrow$ Maxwell - Boltzmann

$\Rightarrow$ Maxwellian distribution

Thermal equilibrium + high opacity = Blackbody emission

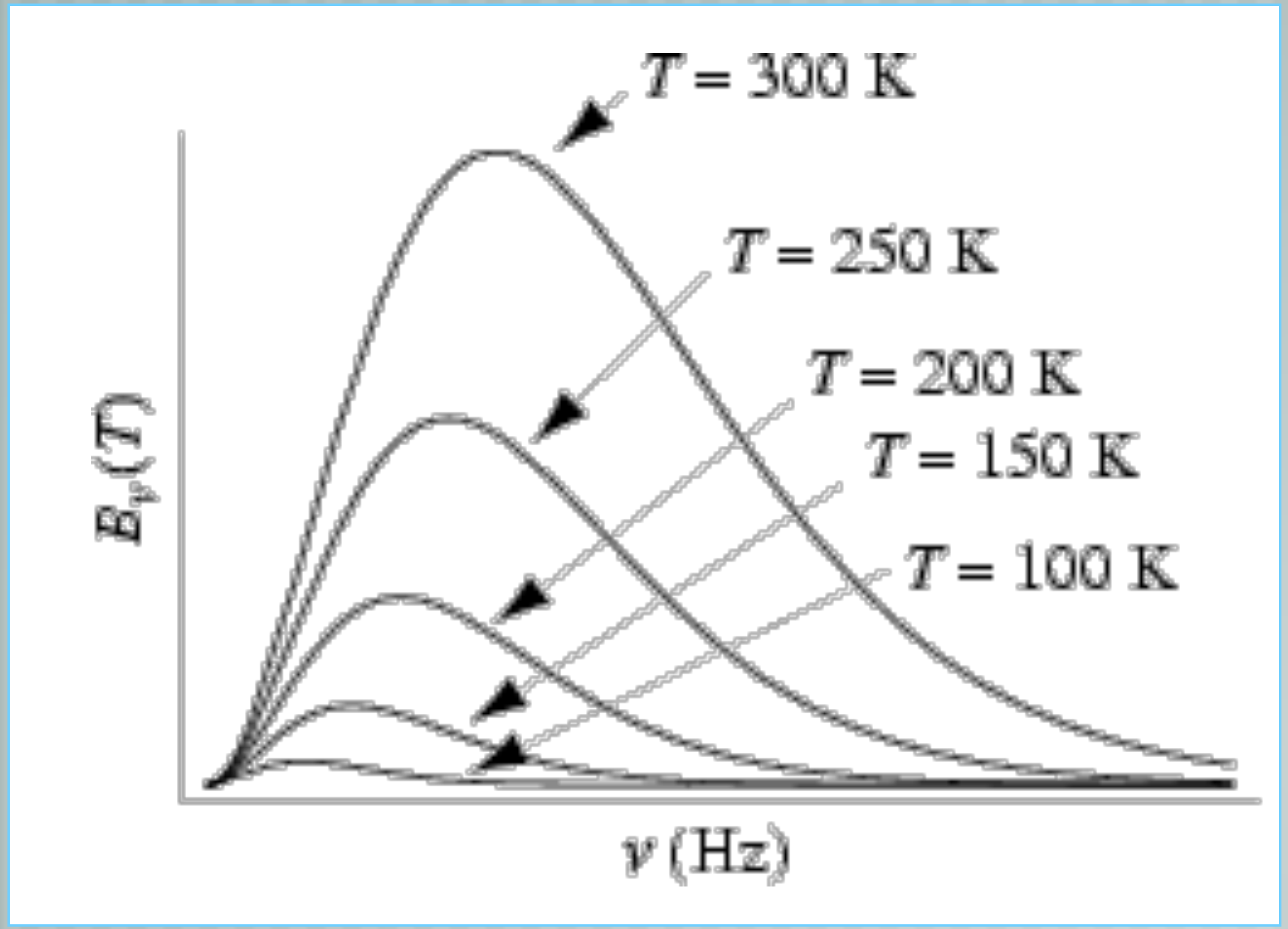
- Plasma in 'causal contact', all global properties of photons depend only on T
  - ➠ Specific intensity given by the "blackbody" (Planck) formula:

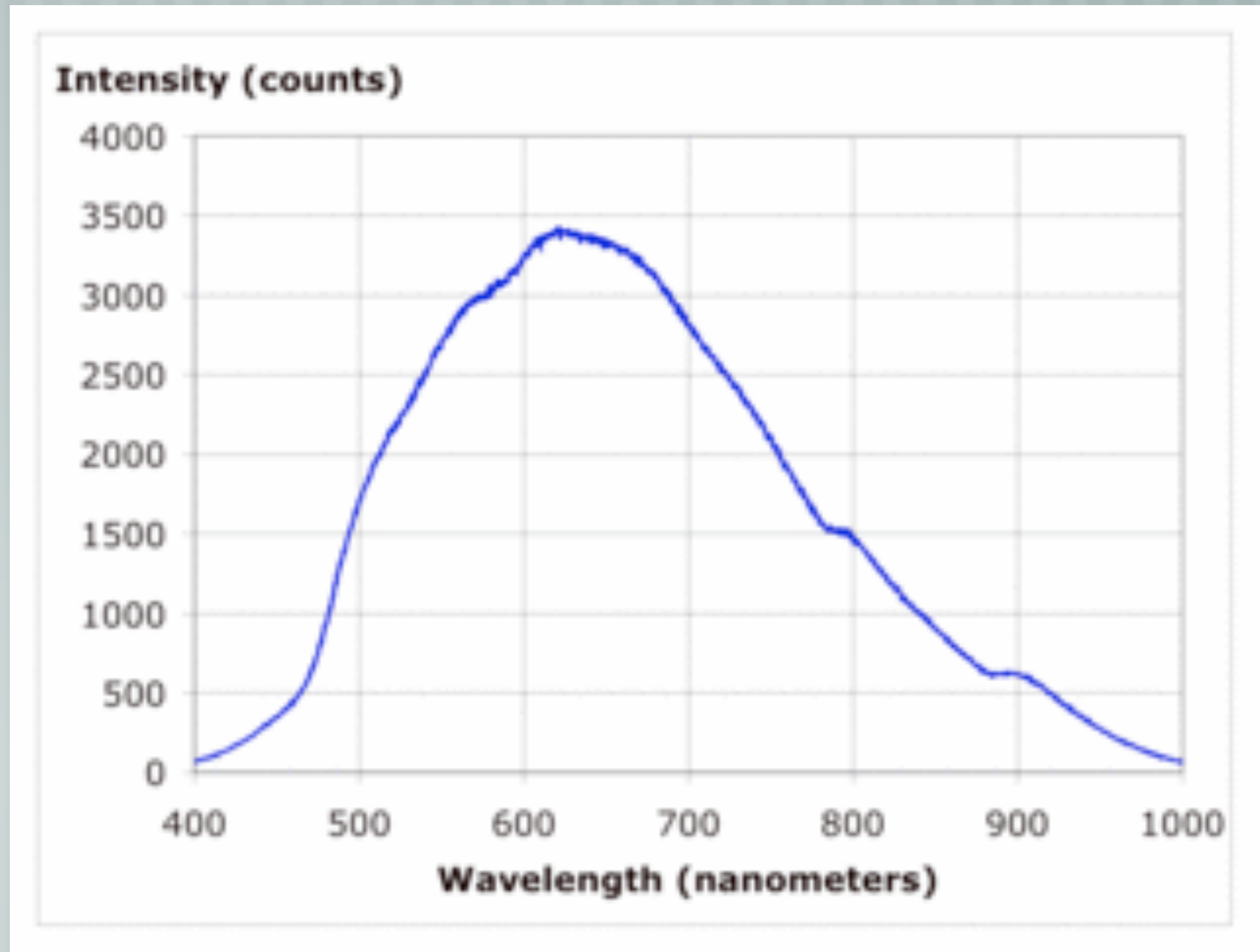
$$I_\nu(T) \equiv B_\nu(T) = \frac{2h\nu^3/c^2}{\exp(h\nu/kT) - 1}$$

"classic accretion disk"

Shakura & Sunyaev 1973

$T \propto r^{-3/4}$





"multicolor BB"

$T_{max} \sim r_{min}$

Blackbody emission II

Useful to remember essential characteristics like:

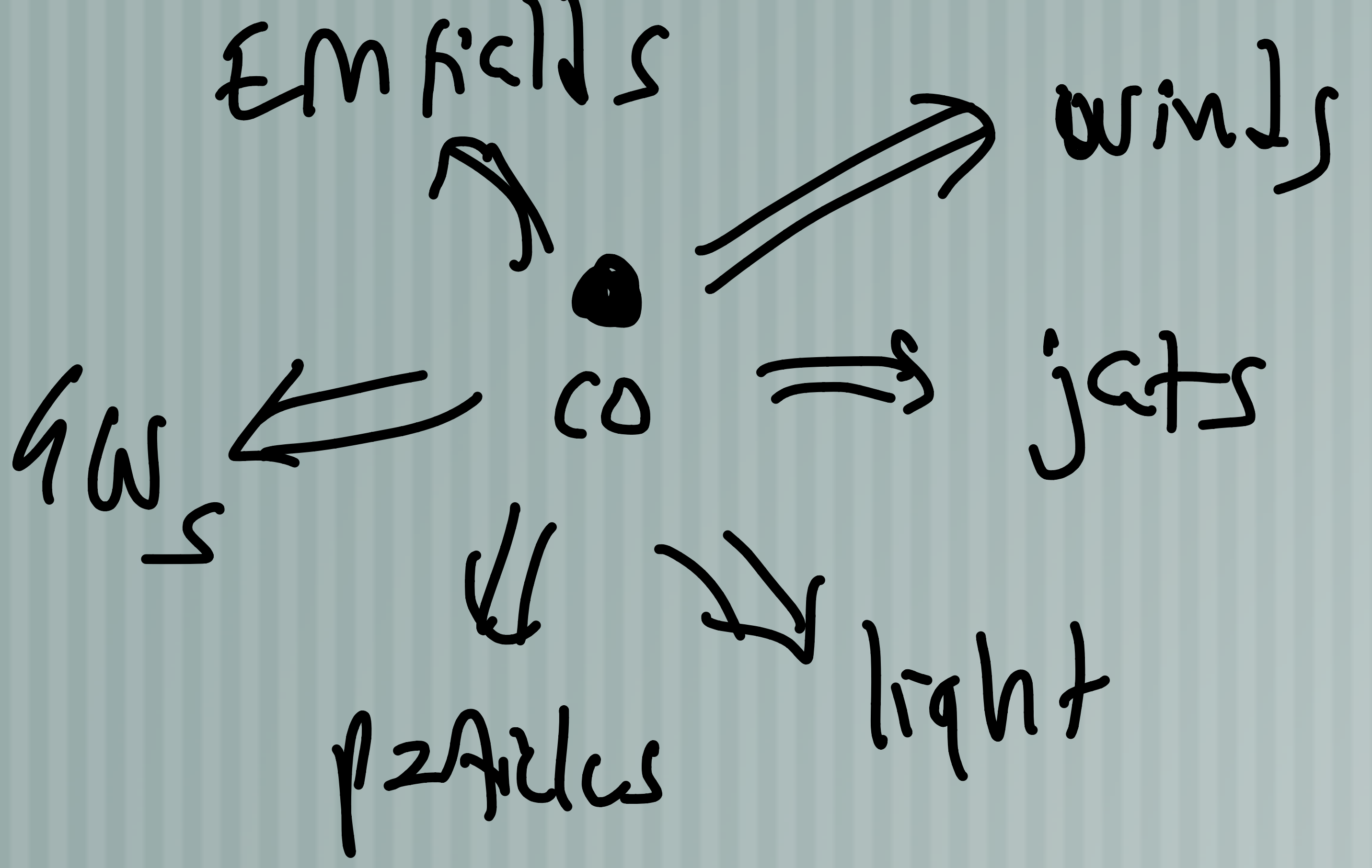
- Averaging over the total distribution gives a mean photon energy of $E_{mean}=h\nu_{mean}\approx 2.7kT$, close to the peak of the spectrum
- Integrating over frequency gives total energy density $\varepsilon_\gamma=aT^4$
- Total luminosity of a blackbody $L=(4\pi R^2)\sigma_B T^4$

"Fast" systems = nonthermal processes

$t_{dyn} << t_{other\ stuff}$!

interesting interplays btw different processes

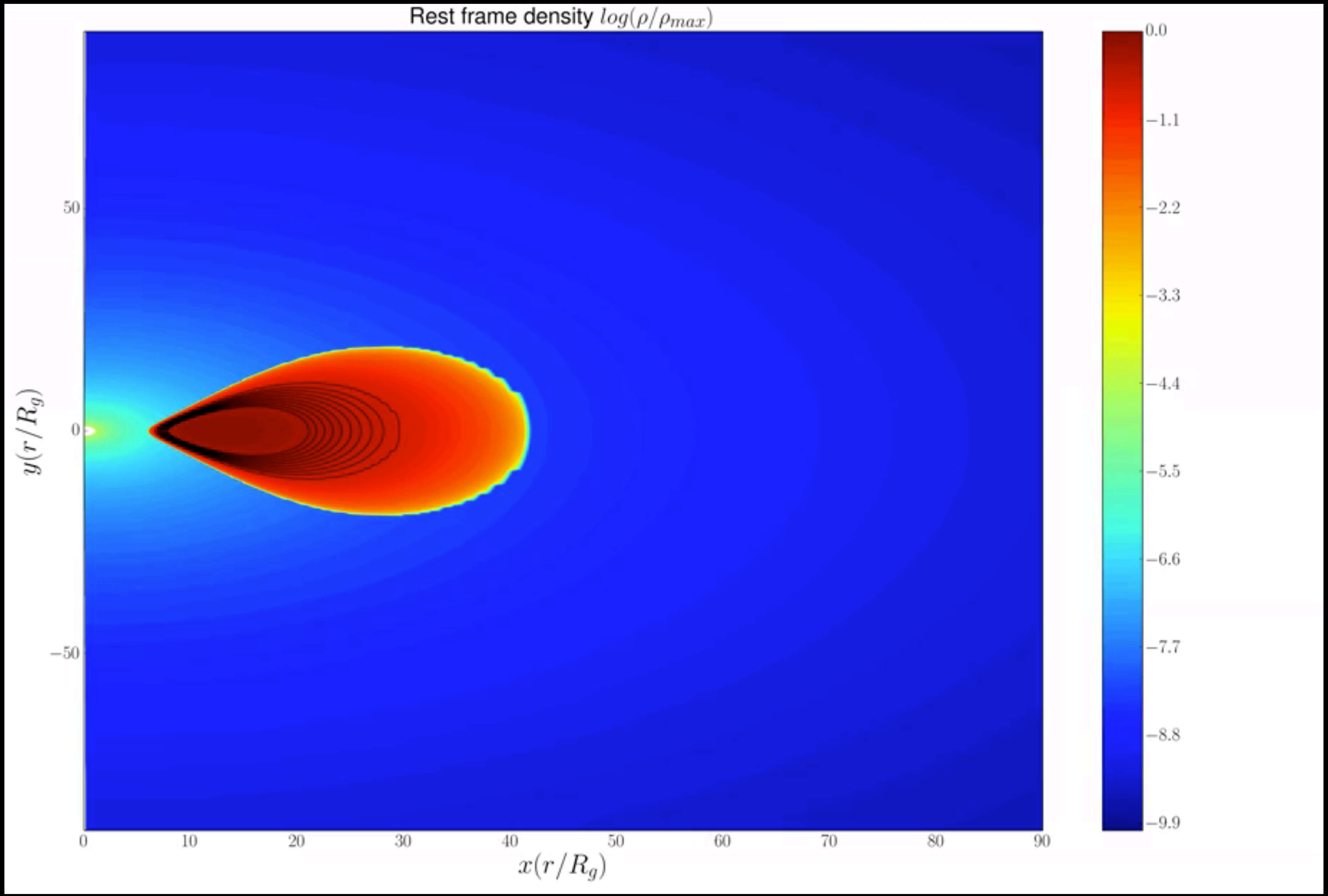
↳ stochastic / probability ⟹ power laws ⟹ energization prob + escape prob/cooling



mechanisms : - bremsstrahlung
- synchrotron
- inverse Compton (IC, EC)
- synchrotron self Compton (SSC)
- hadronic processes

A few examples where radiative processes play a key role (that we still don't fully understand)

Simulations: *"a priori"* physics but which physics is correct?



(Dibi, Drappeau, Fragile, SM & Dexter 2012; Drappeau, Dibi, Dexter, SM & Fragile 2013; Chatterjee, Liska, Tchekhovskoy, SM,++ in prep.,…plus many other groups!)

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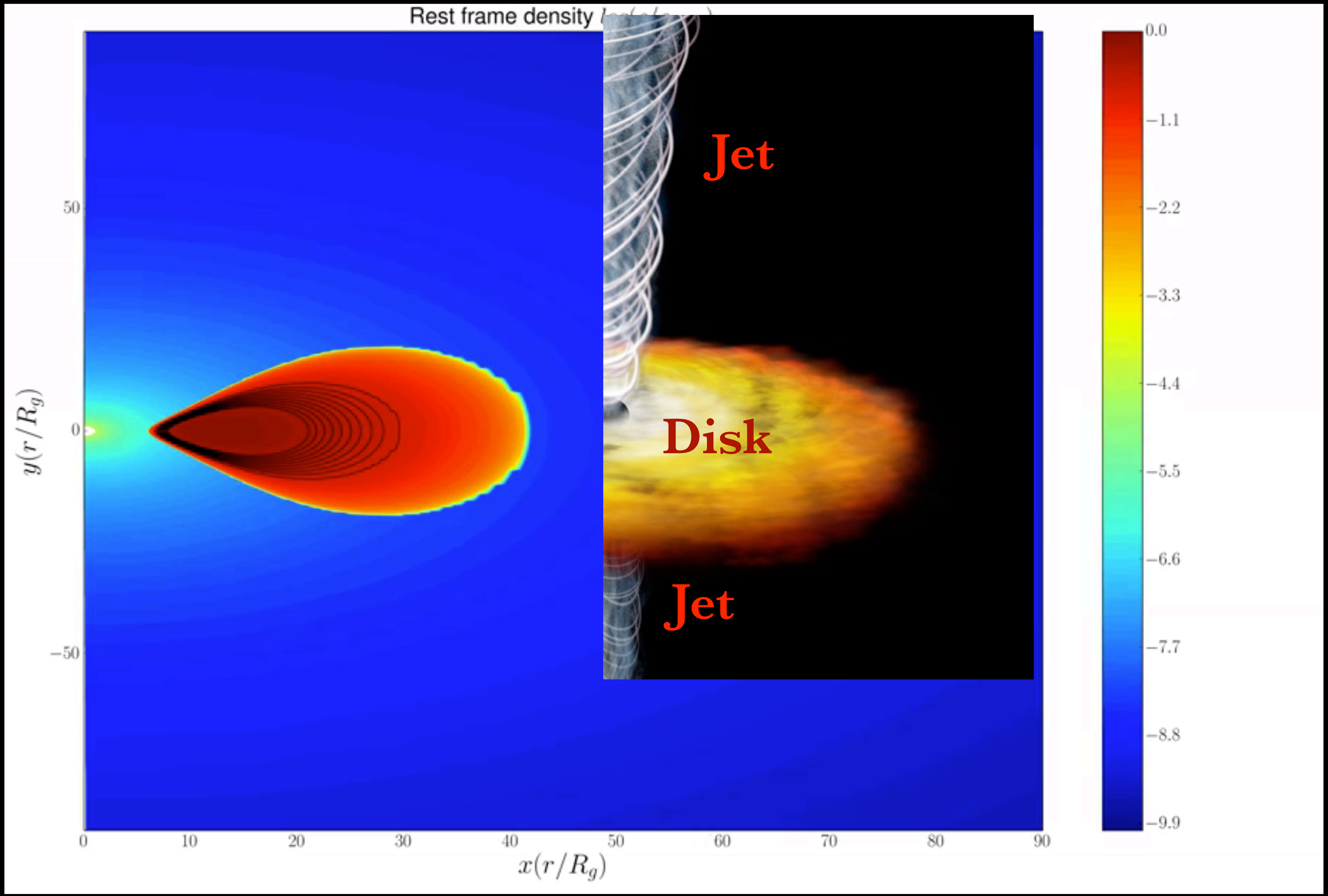

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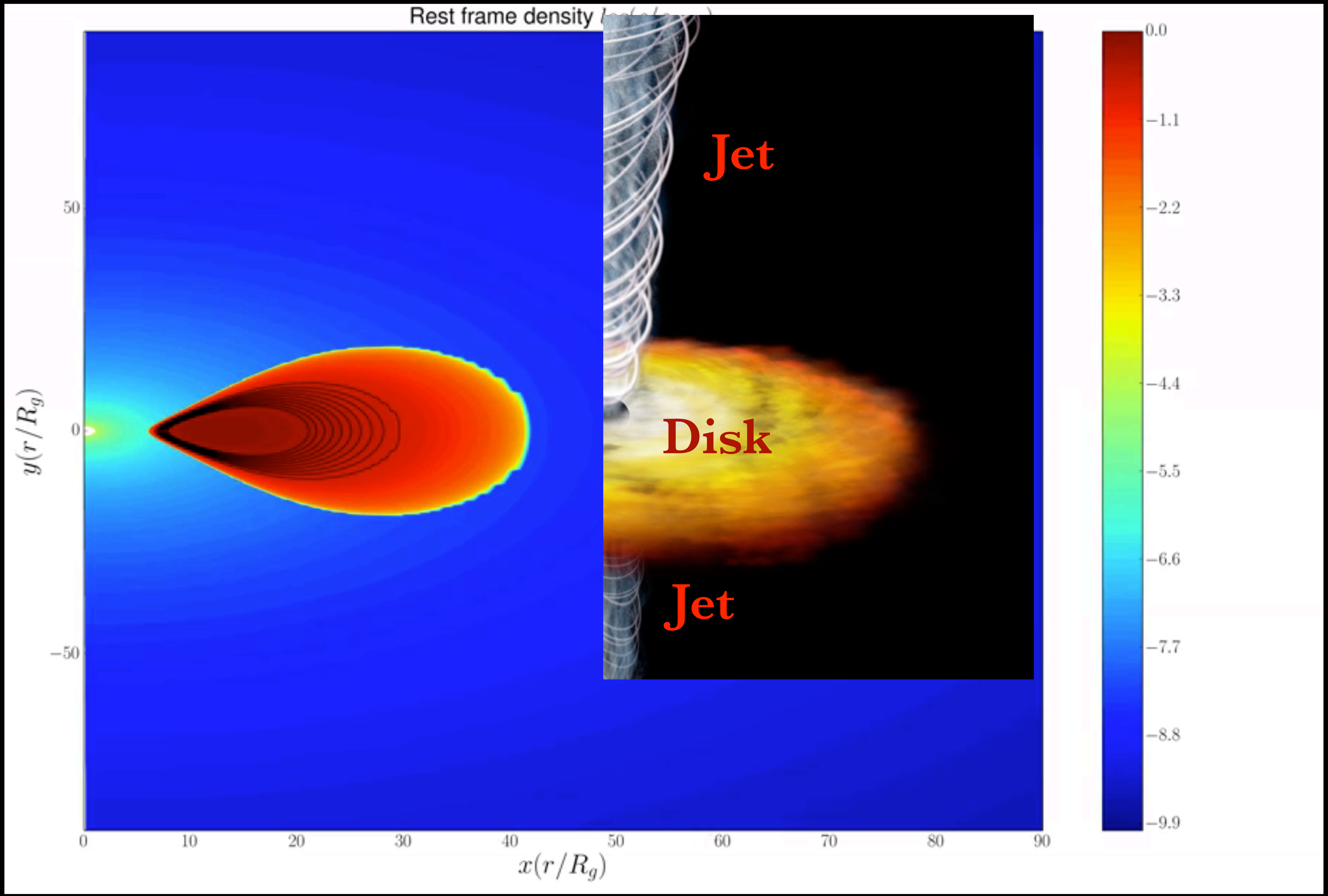

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- ★ Unrealistic/limited geometry, resolution

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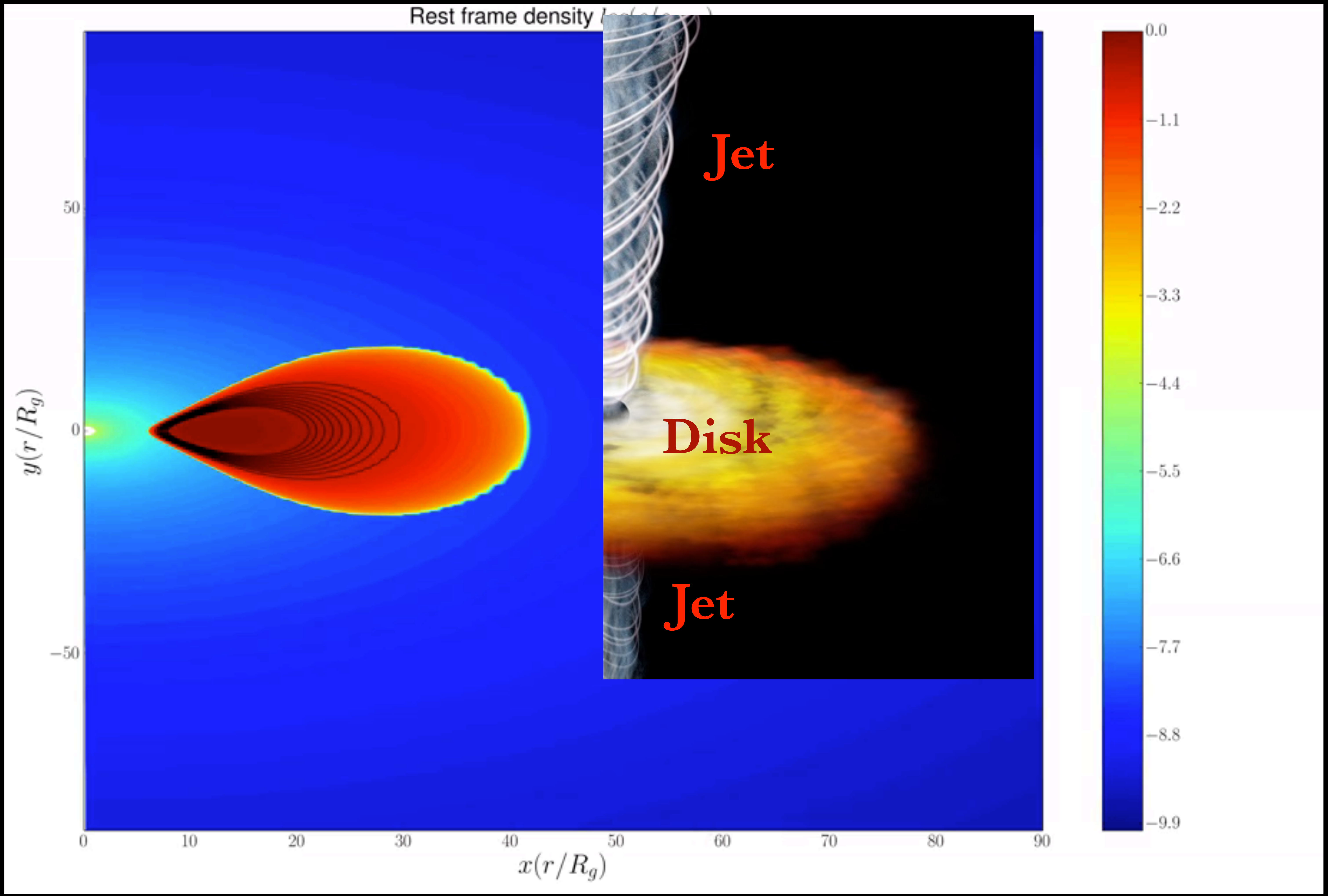

- ⭐ Unrealistic/limited geometry, resolution
- ⭐ Degeneracy in plasma initial conditions ($\dot{m}$, β, σ, μ, B field config.)

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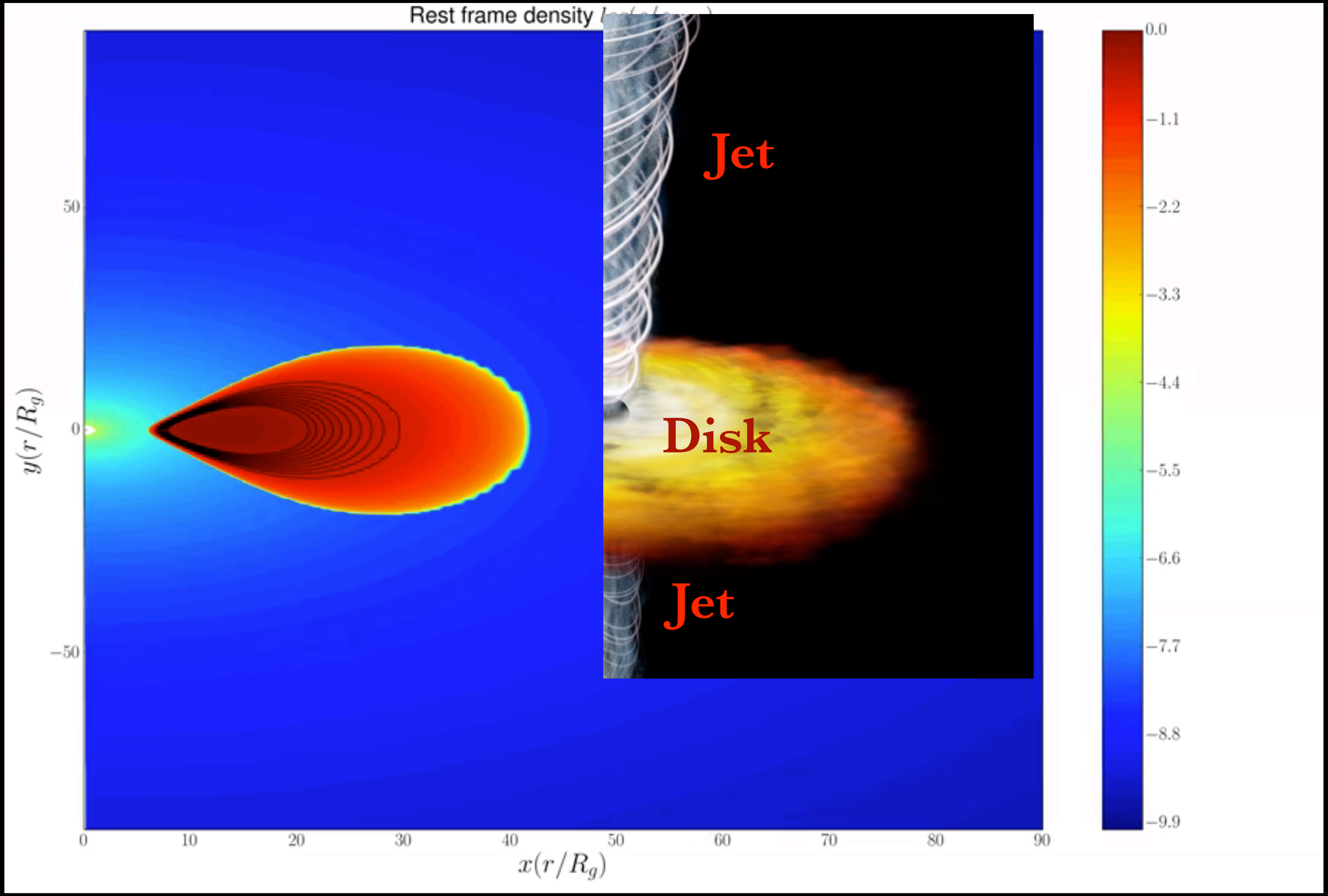

- ⭐ Unrealistic/limited geometry, resolution
- ⭐ Degeneracy in plasma initial conditions ($\dot{m}$, β, σ, μ, B field config.)
- ⭐ Ideal MHD: Empty jets *(=density floors)*, no dissipation

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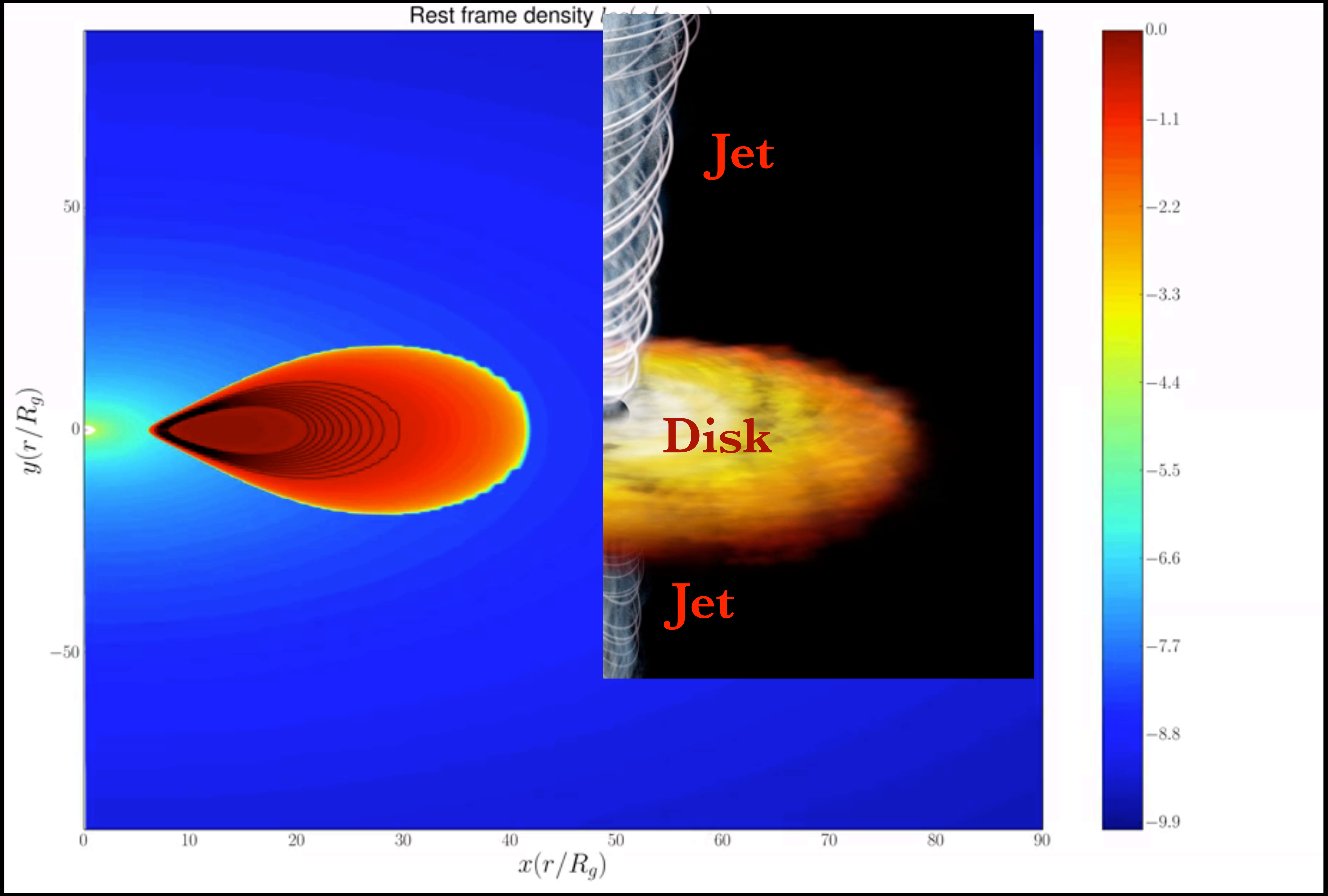

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- 1-fluid (no e-ion TD)

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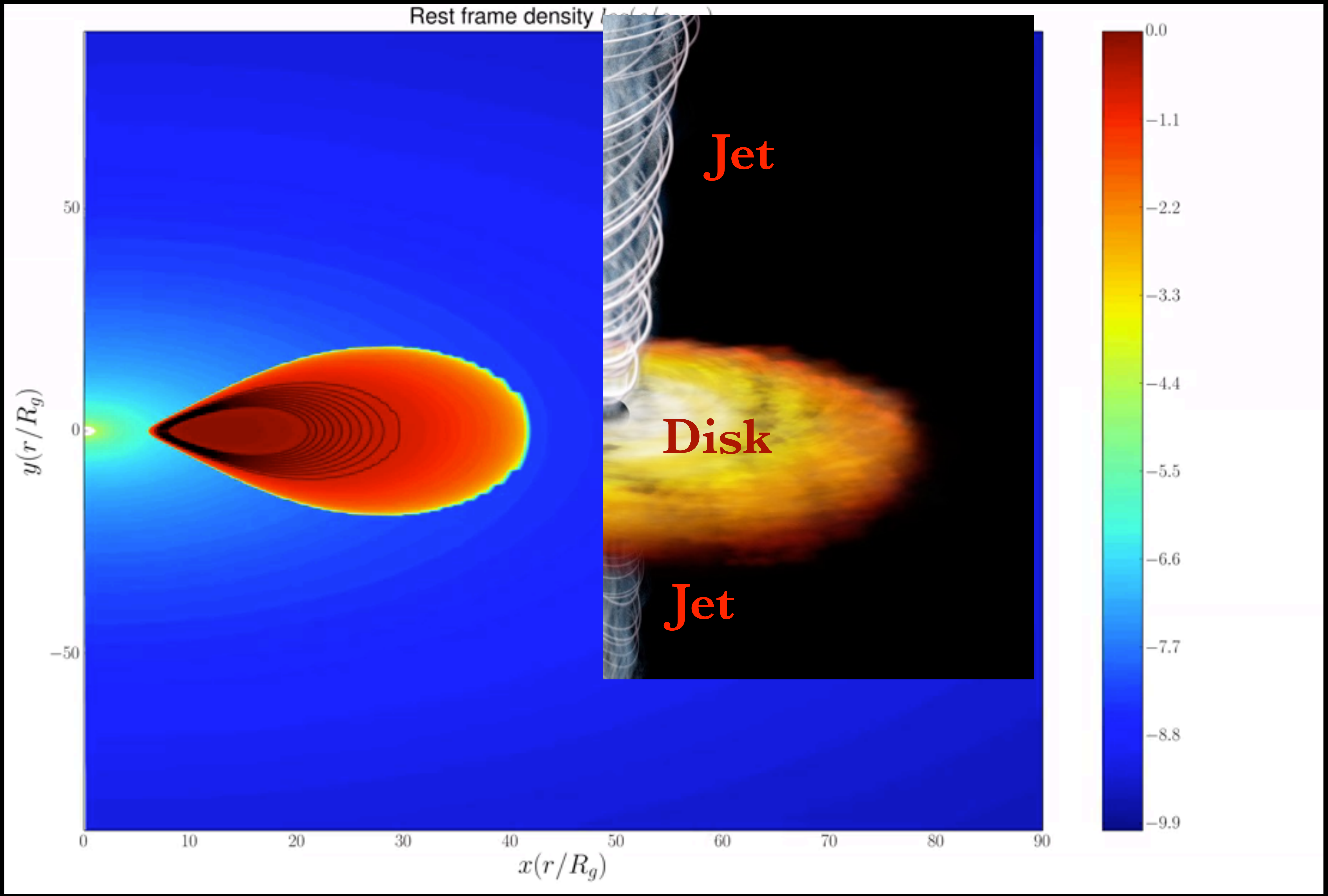

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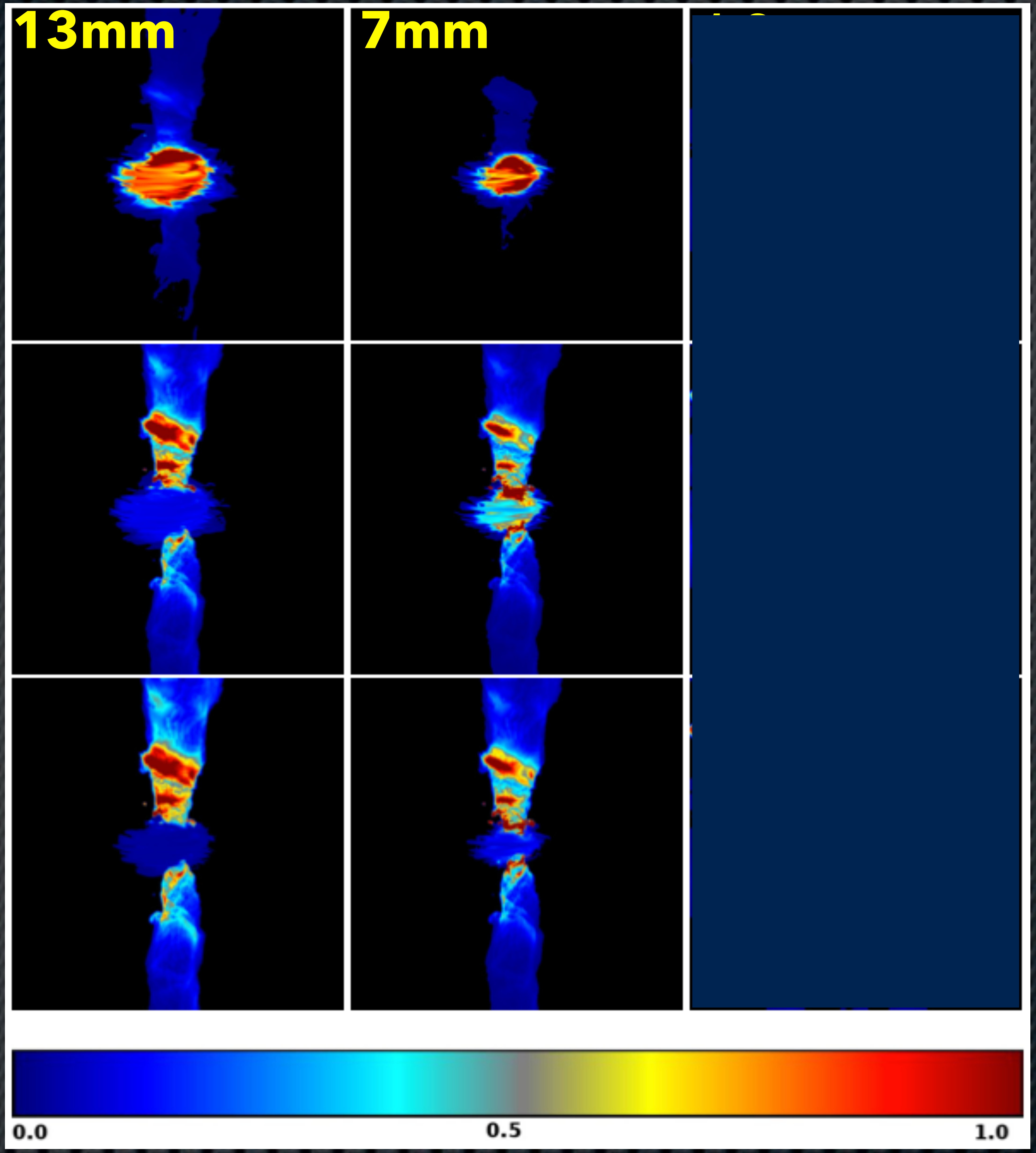
- ★ Unrealistic/limited geometry, resolution
- ★ Degeneracy in plasma initial conditions ($\dot{m}$, β, σ, μ, B field config.)
- ★ Ideal MHD: Empty jets *(=density floors),* no dissipation
- ★ 1-fluid (no e-ion TD)
- ★ no microphysics = no light!

Illustration of "Macro/microphysics + radiation problem"

$T_p/T_e=5$

$T_p/T_e=15$

$T_p/T_e=25$



(Moscibrodzka, Falcke, Shiokawa & Gammie 2014)

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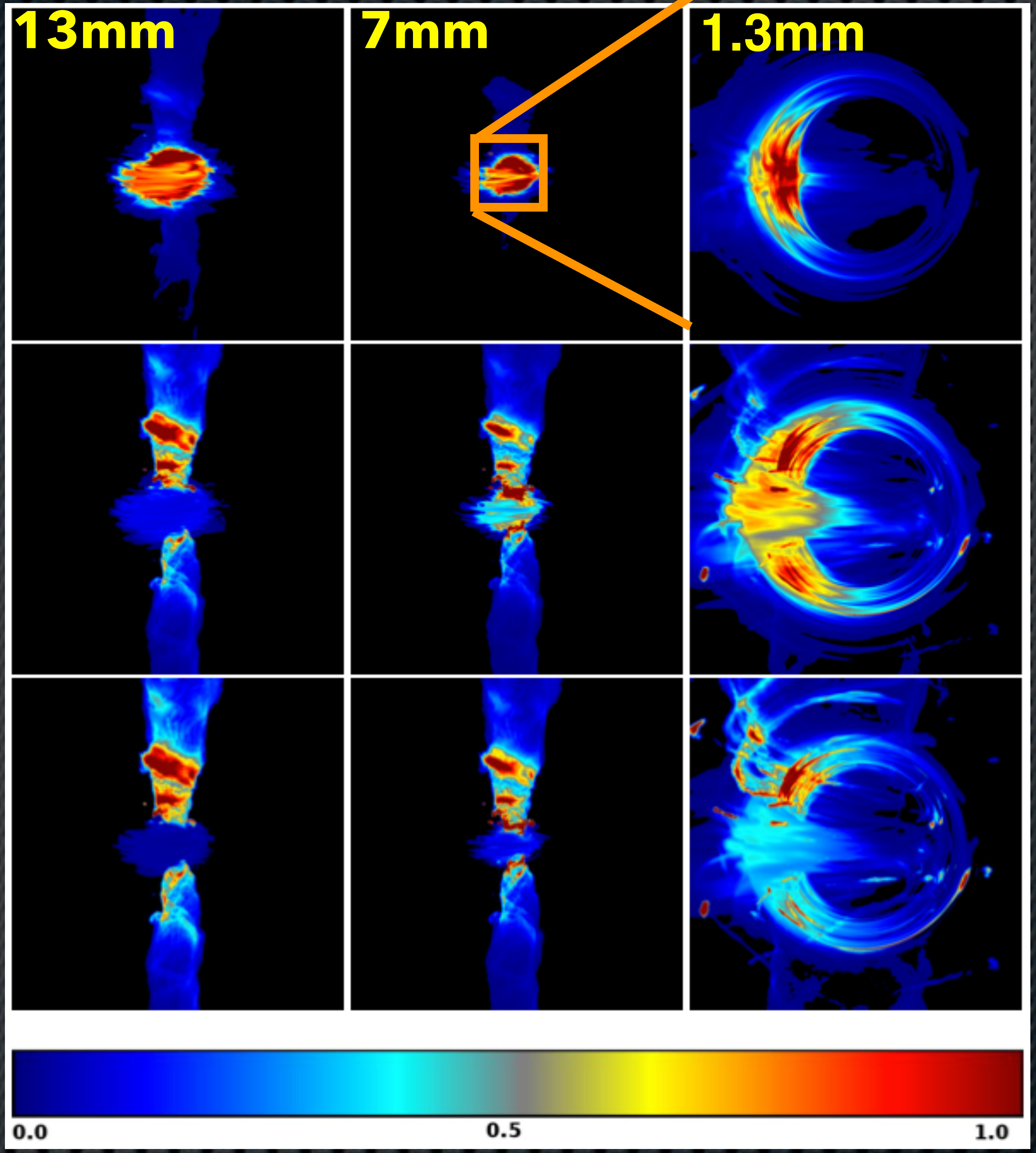

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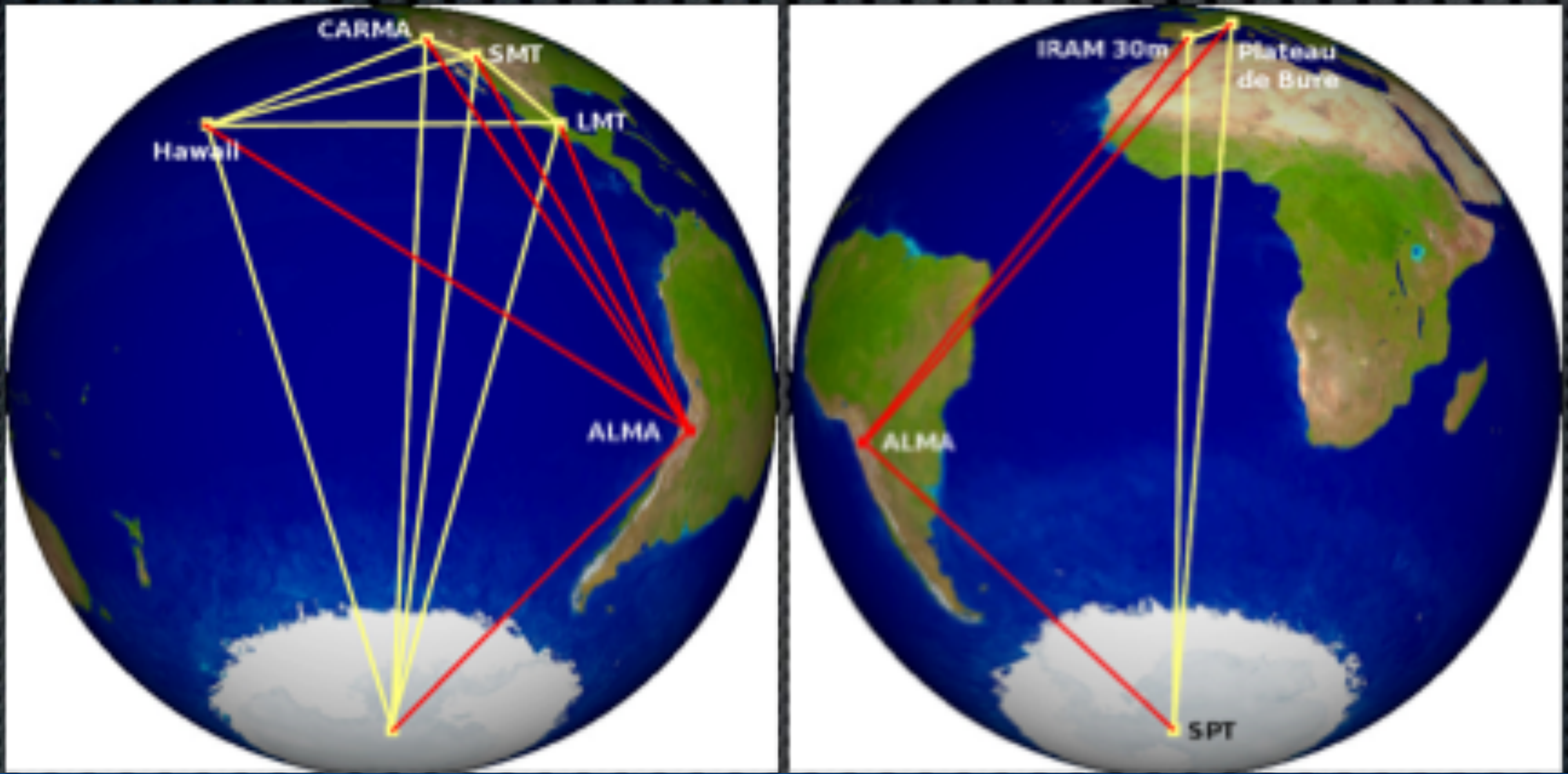
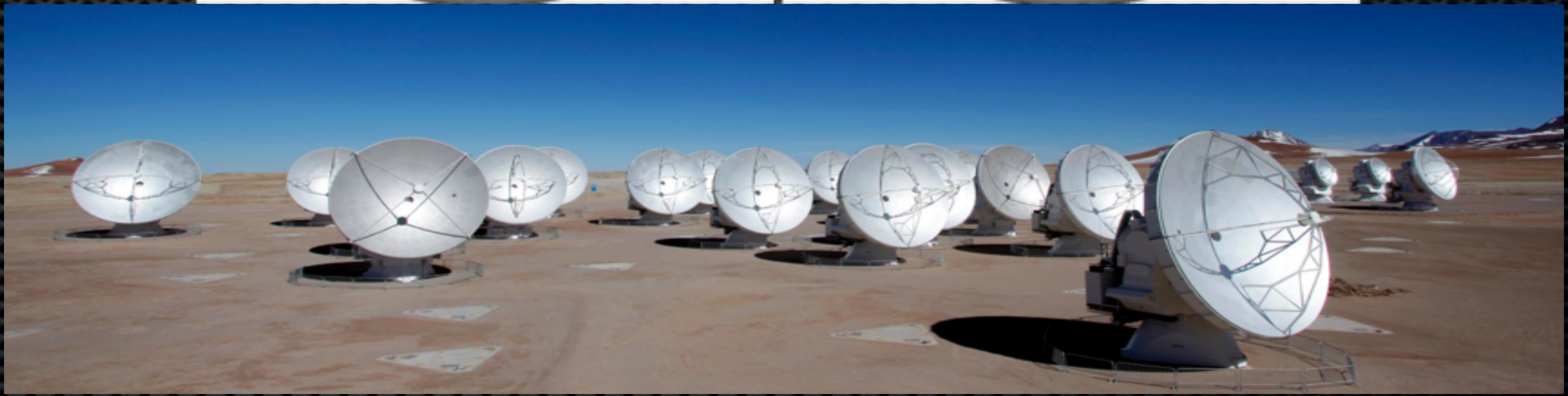
The Event Horizon Telescope





The Event Horizon Telescope

10 μas resolution, first full run with phased ALMA core in April 2017!

Targets: SgrA*, M87, CenA, OJ287, 3C279, NGC1052

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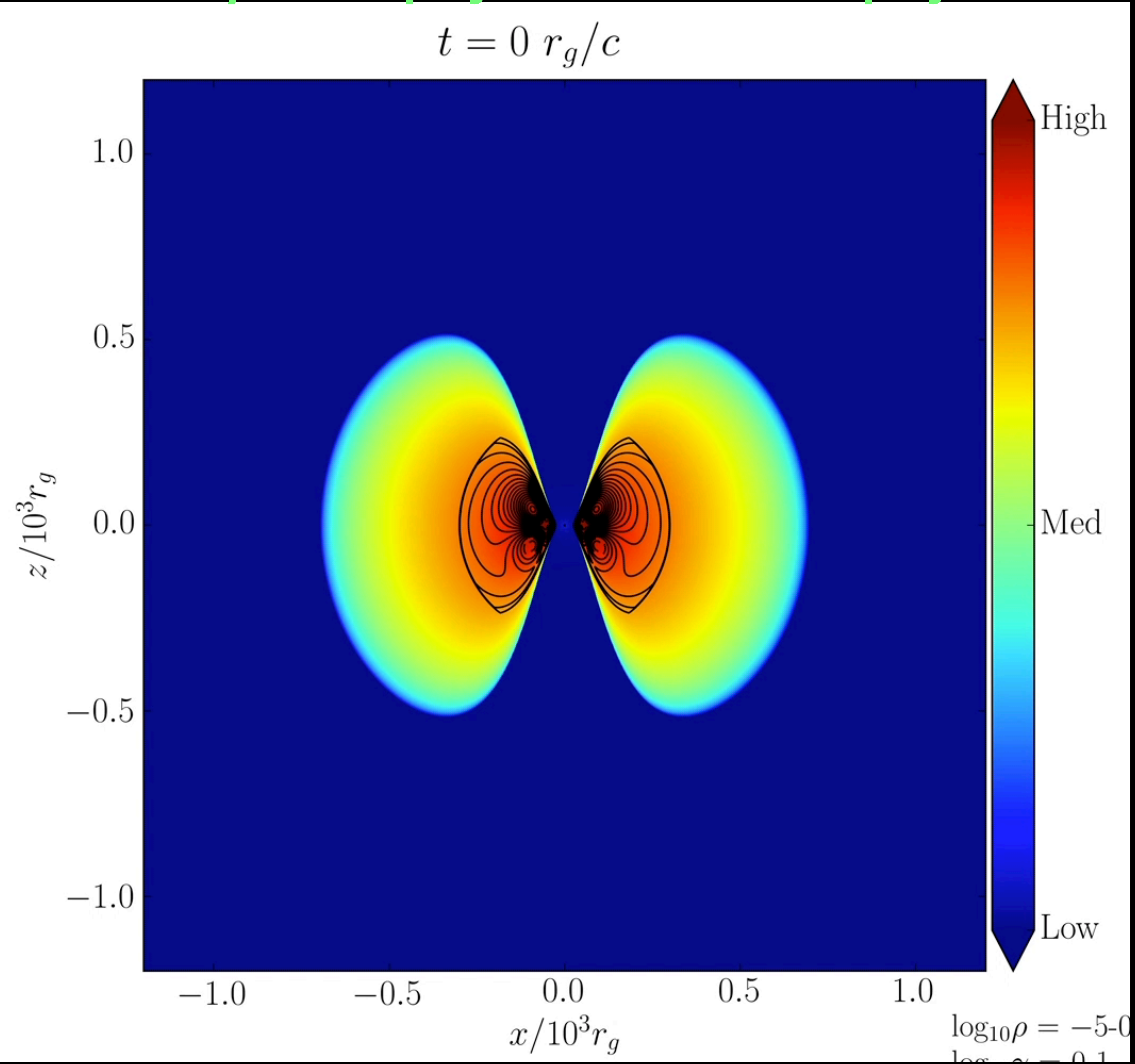
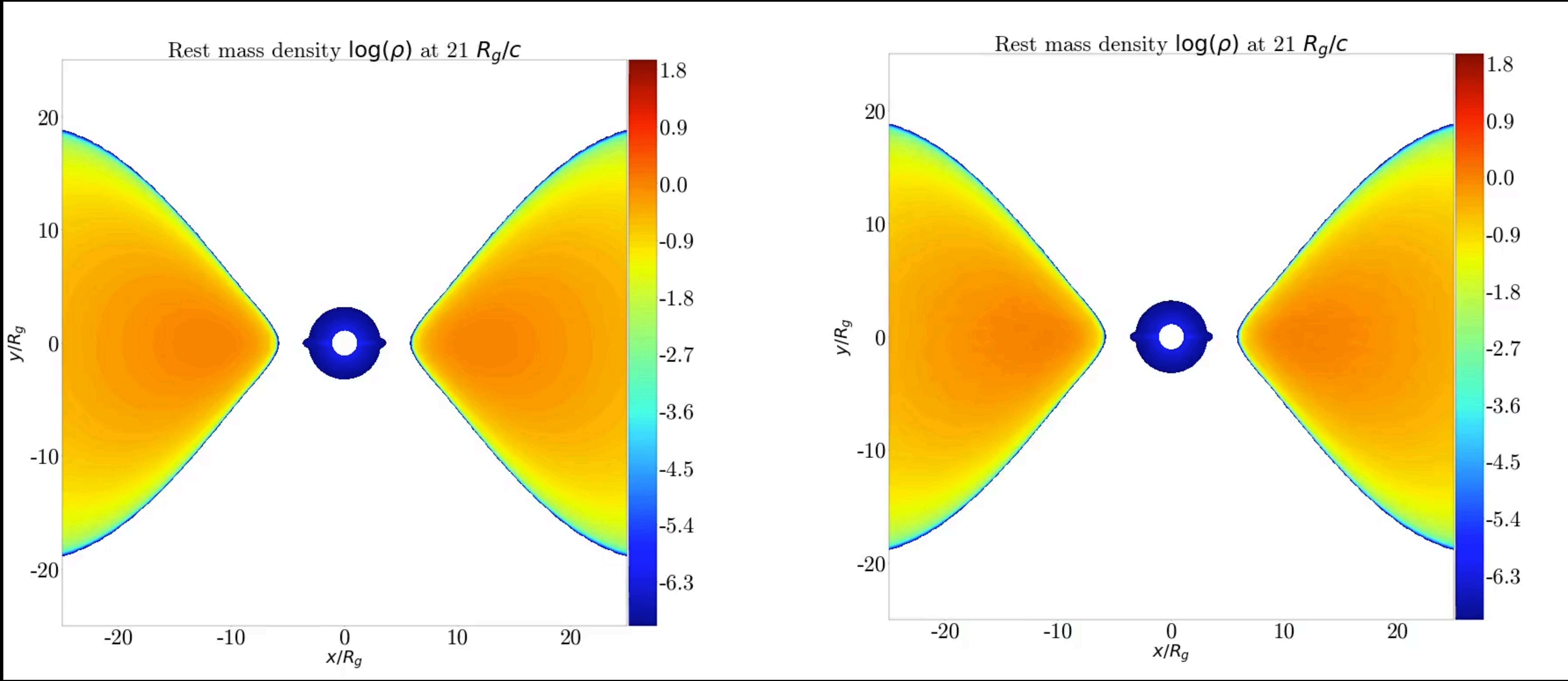


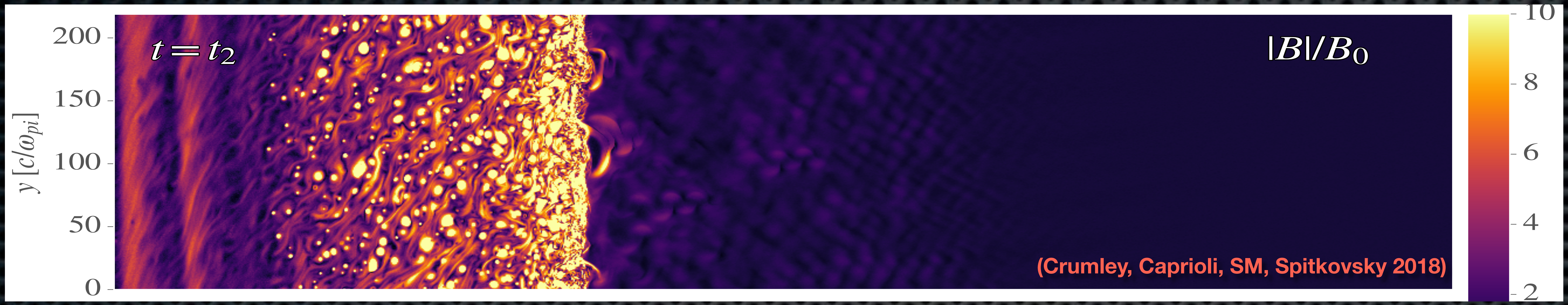
(Chatterjee, Liska, Tchekhovskoy, SM++ in prep)

Effects of including radiative cooling



(van Eijnatten, Chatterjee, SM, Liska, Tchekhovskoy+, in prep.)

‘Nonthermal’ emission traces particle acceleration



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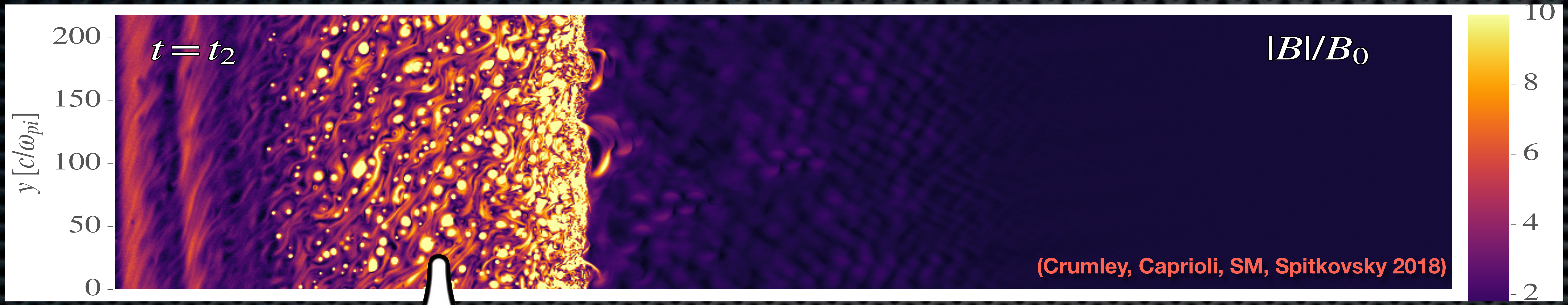

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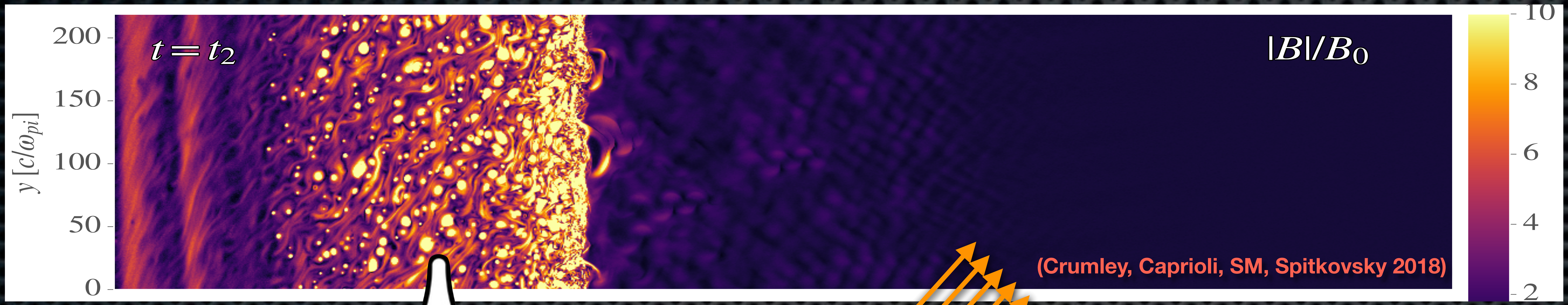
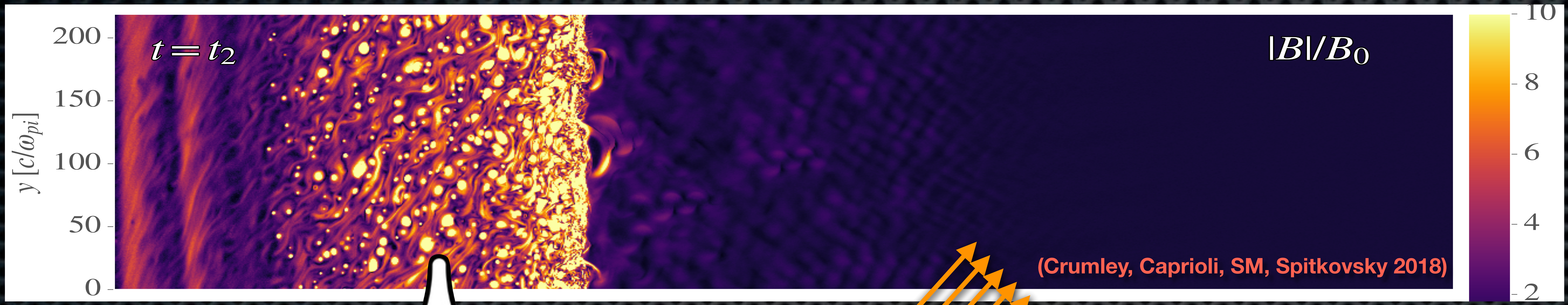


B = synchrotron γ
(radio to Xray!)

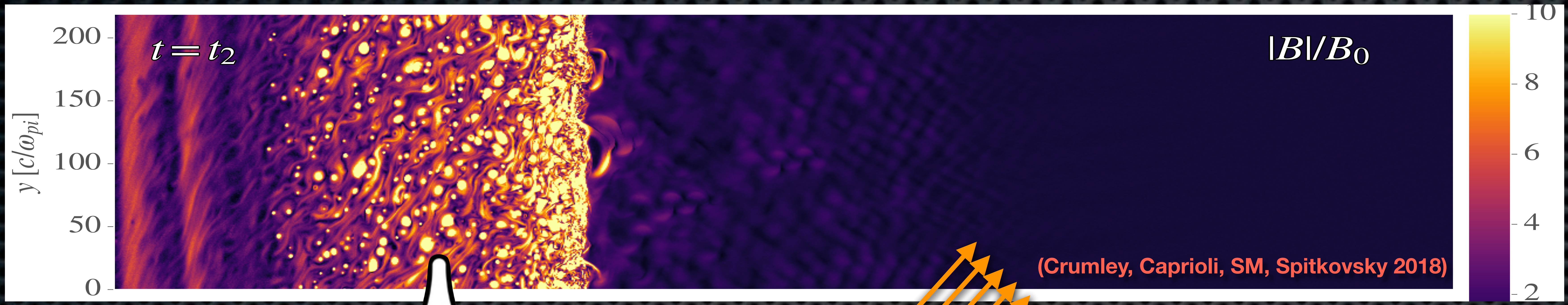
'Nonthermal' emission traces particle acceleration



i^+ $e^\pm$ + **B** = synchrotron γ
(radio to Xray!)

$e^\pm$ + γ = inverse Compton
(~Xray to γ-ray!)

‘Nonthermal’ emission traces particle acceleration



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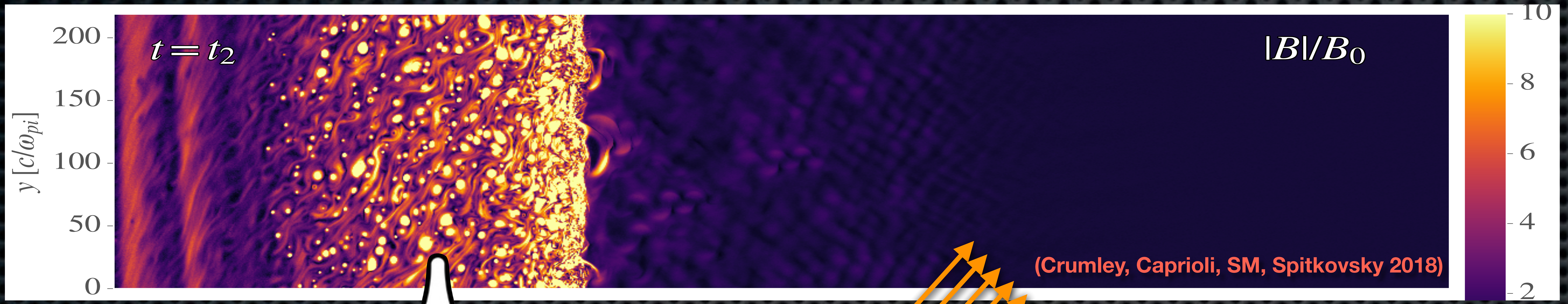
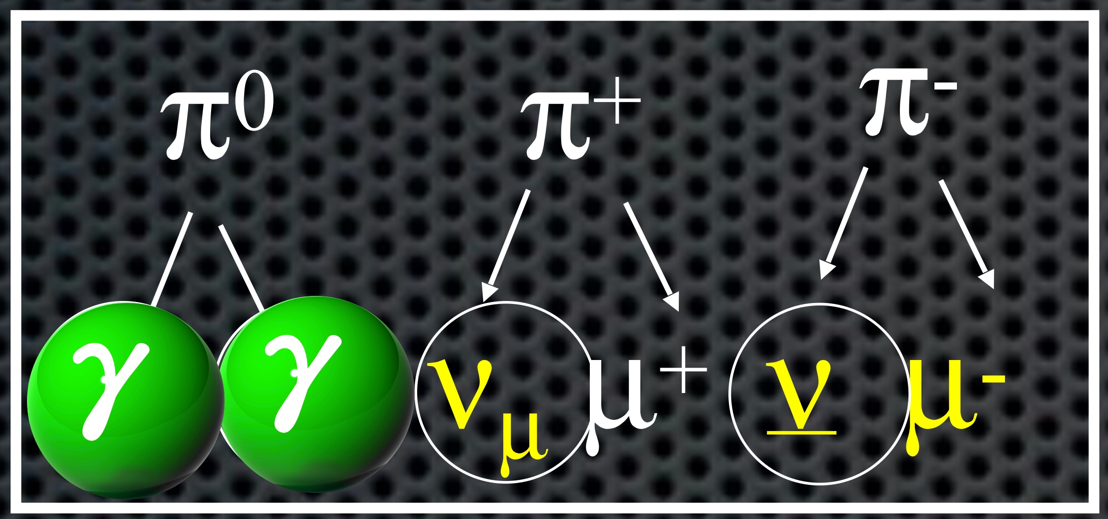


i^+ + i^+

γ

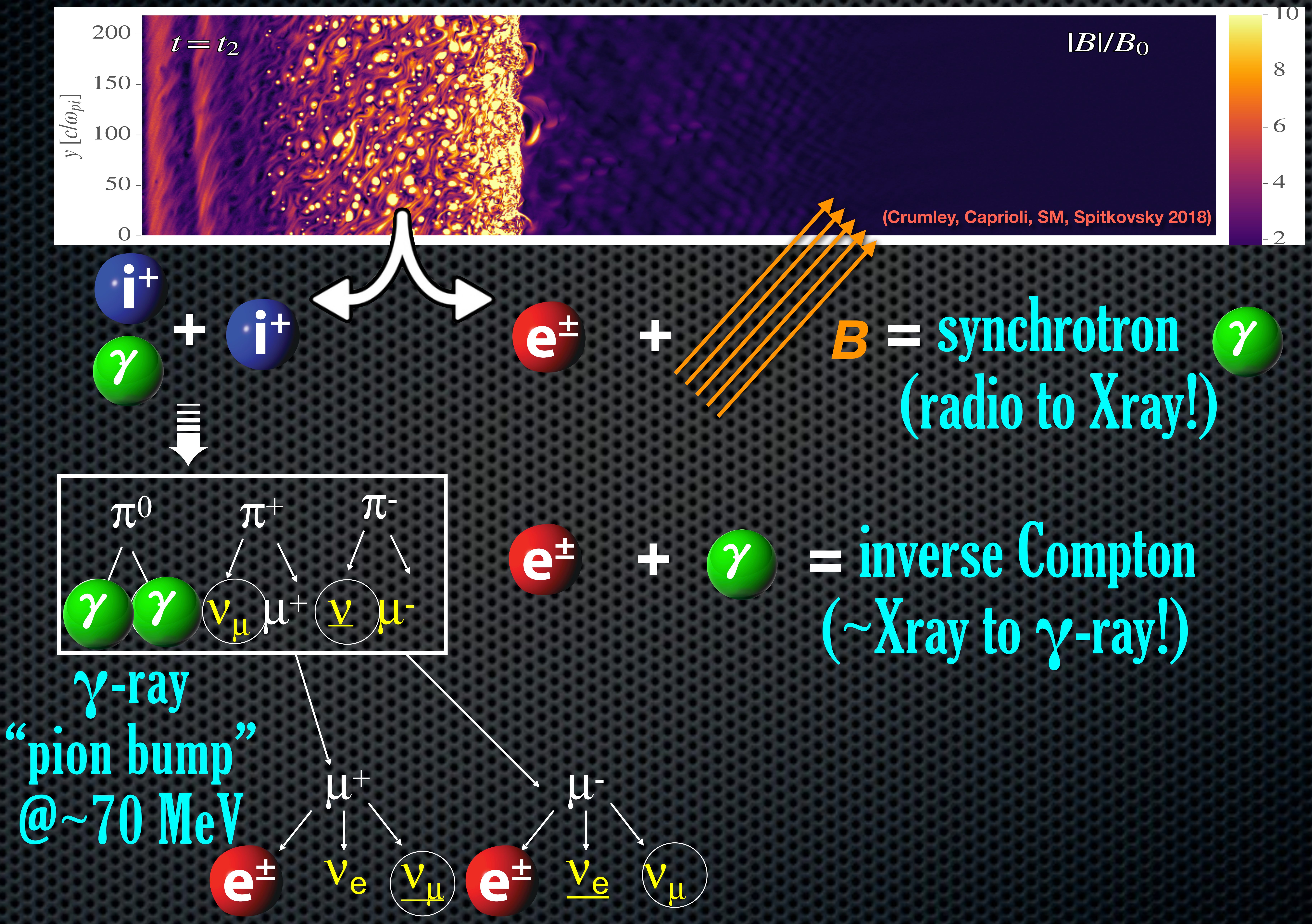


γ-ray
“pion bump”
@~70 MeV

$e^\pm$ + *B* = synchrotron γ
(radio to Xray!)

$e^\pm$ + γ = inverse Compton
(~Xray to γ-ray!)

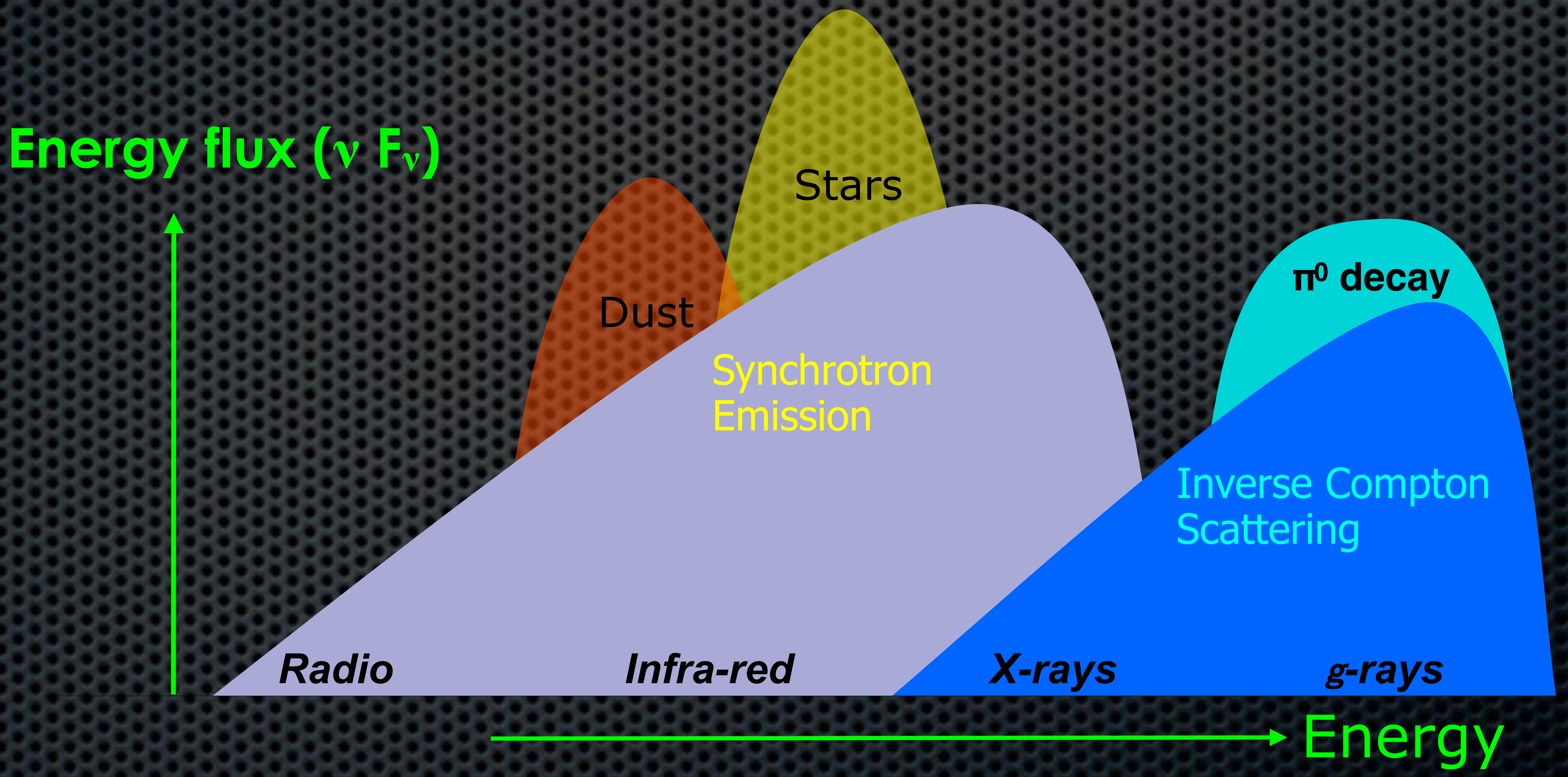
‘Nonthermal’ emission traces particle acceleration



Complex (and thus degenerate) interplay of processes

Particles (e+e- pairs and/or e-p/ions) **+** B field (or ∇V) **+** shock (or turbulence, reconnection, waves)

= accelerated particles (CRs: e+e-,p's, ions) **+** secondary (higher energy) leptons



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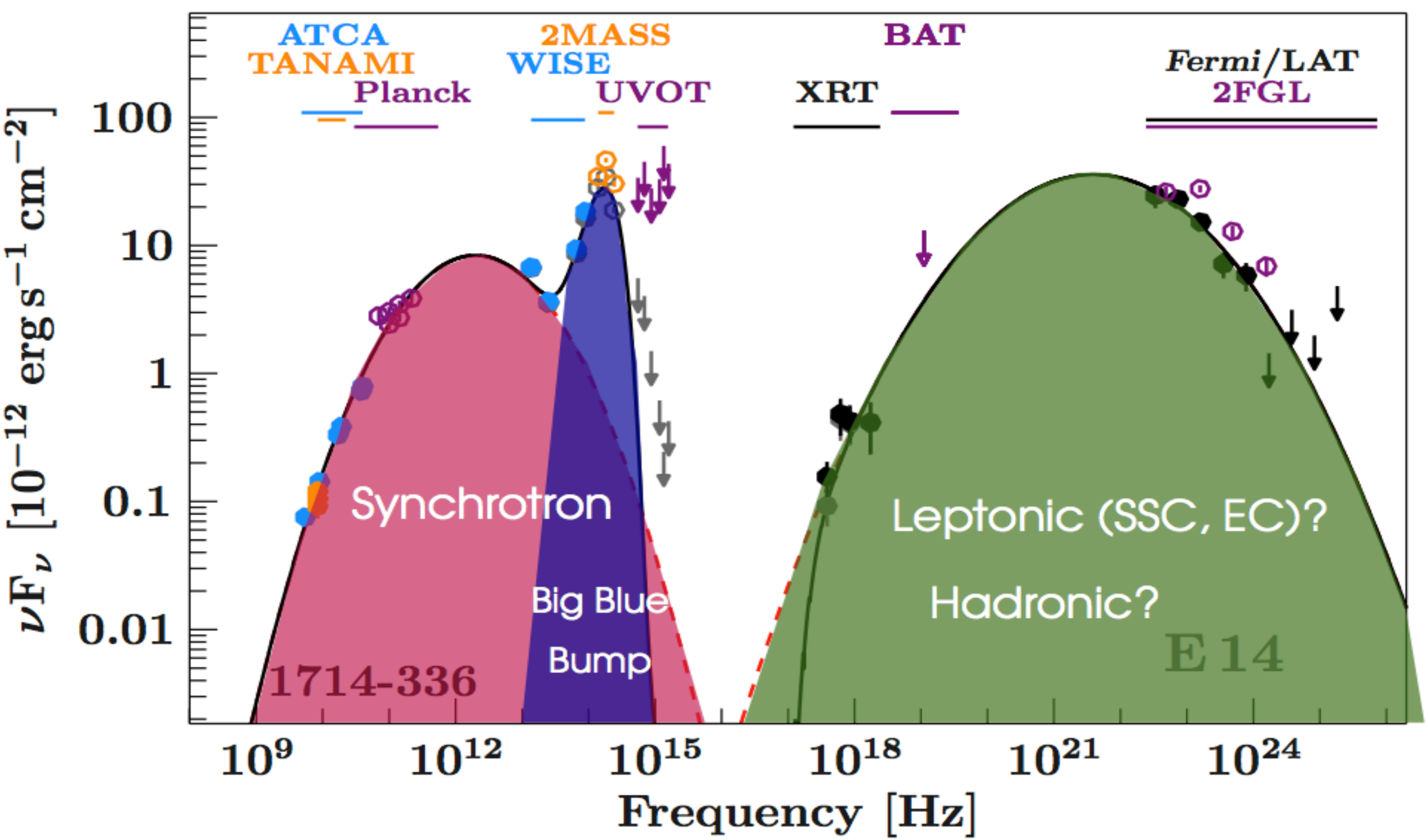
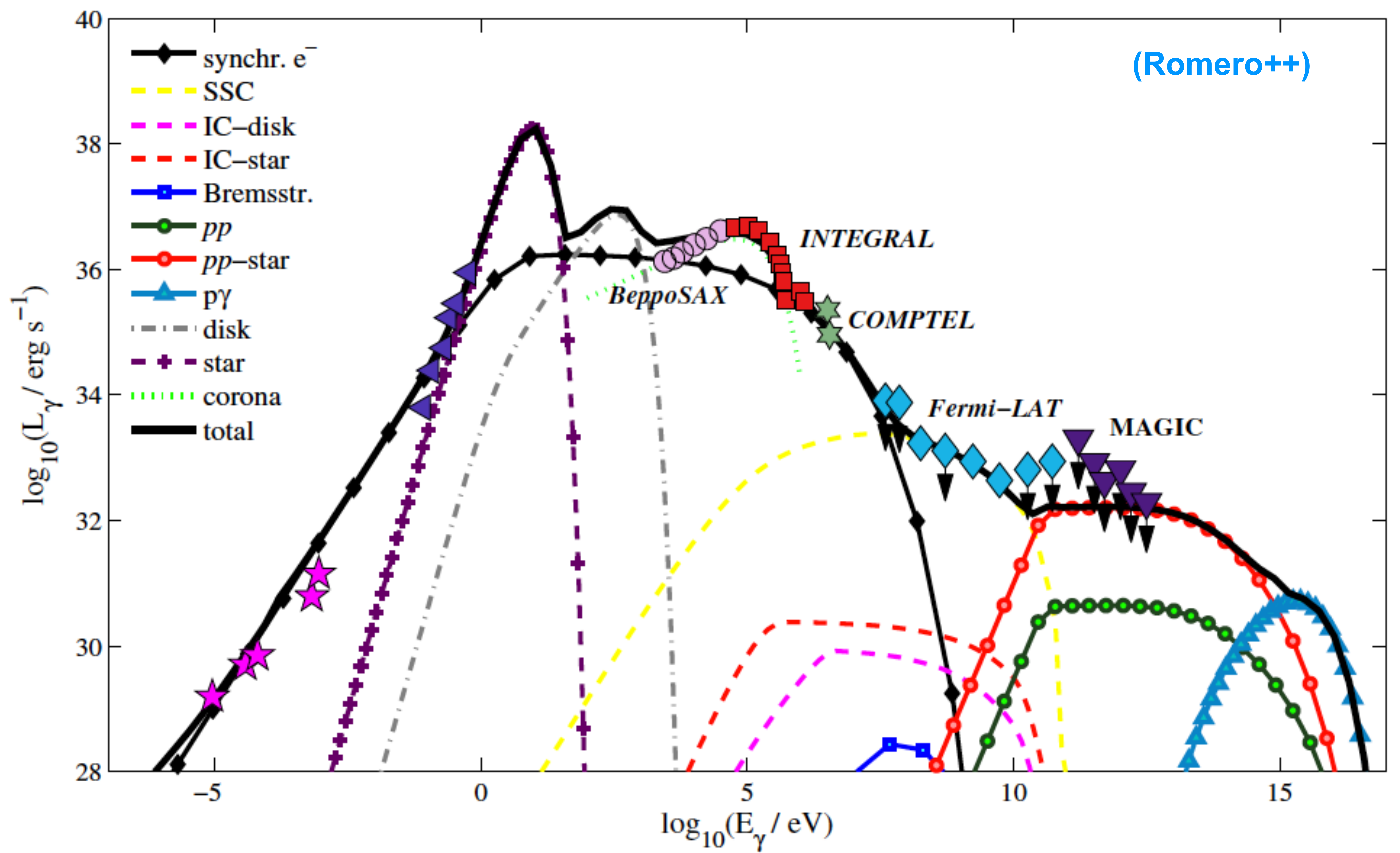


Krauß F., Kadler M., et al., A&A, 2014, 556, L7

Complex (and thus degenerate) interplay of processes



The kinetic equation approach

Protons:

$$\frac{\partial n_p}{\partial t} + L_p^{BH} + L_p^{photopion} + L_p^{psyn} + L_p^{pp} + \frac{n_p}{t_{p,esc}} = Q_p^{inj} + Q_p^{photopion}$$

Electrons:

$$\frac{\partial n_e}{\partial t} + L_e^{syn} + L_e^{ics} + L_e^{ann} + L_e^{tpp} + \frac{n_e}{t_{e,esc}} = Q_e^{ext} + Q_e^{BH} + Q_e^{\gamma\gamma} + Q_e^{photopion} + Q_e^{tpp} + Q_e^{pp}$$

Photons:

$$\frac{\partial n_\gamma}{\partial t} + \frac{n_\gamma}{t_{\gamma,esc}} + L_\gamma^{\gamma\gamma} + L_\gamma^{ssa} = Q_\gamma^{syn} + Q_\gamma^{psyn} + Q_\gamma^{ics} + Q_\gamma^{ann} + Q_\gamma^{photopion} + Q_\gamma^{pp}$$

Neutrinos:

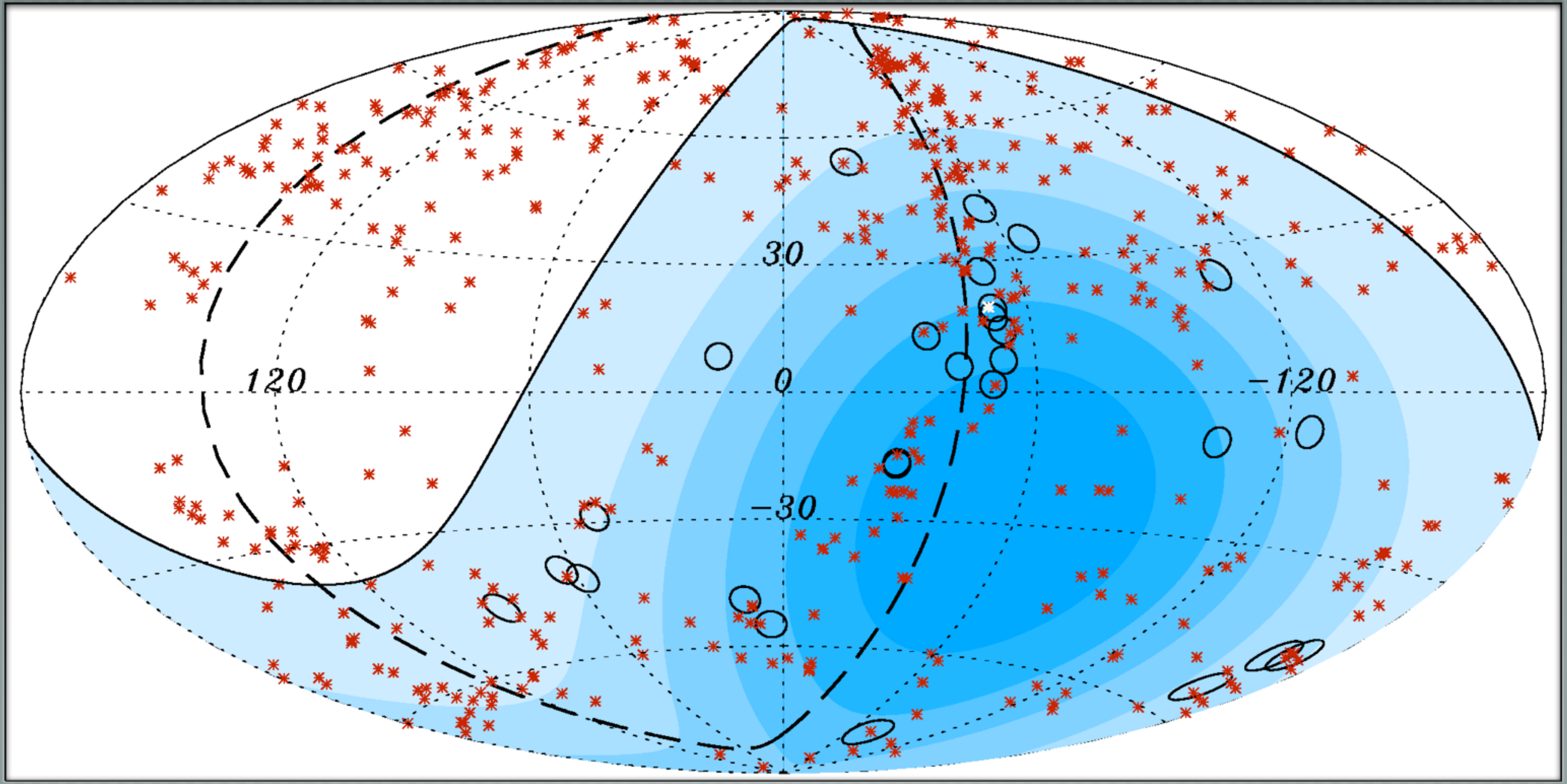
$$\frac{\partial n_\nu}{\partial t} + \frac{n_\nu}{t_{esc}} = Q_\nu^{photopion} + Q_\nu^{pp}$$

Neutrons:

$$\frac{\partial n_n}{\partial t} + L_n^{photopion} + \frac{n_n}{t_{esc}} = Q_n^{photopion} + Q_n^{pp}$$

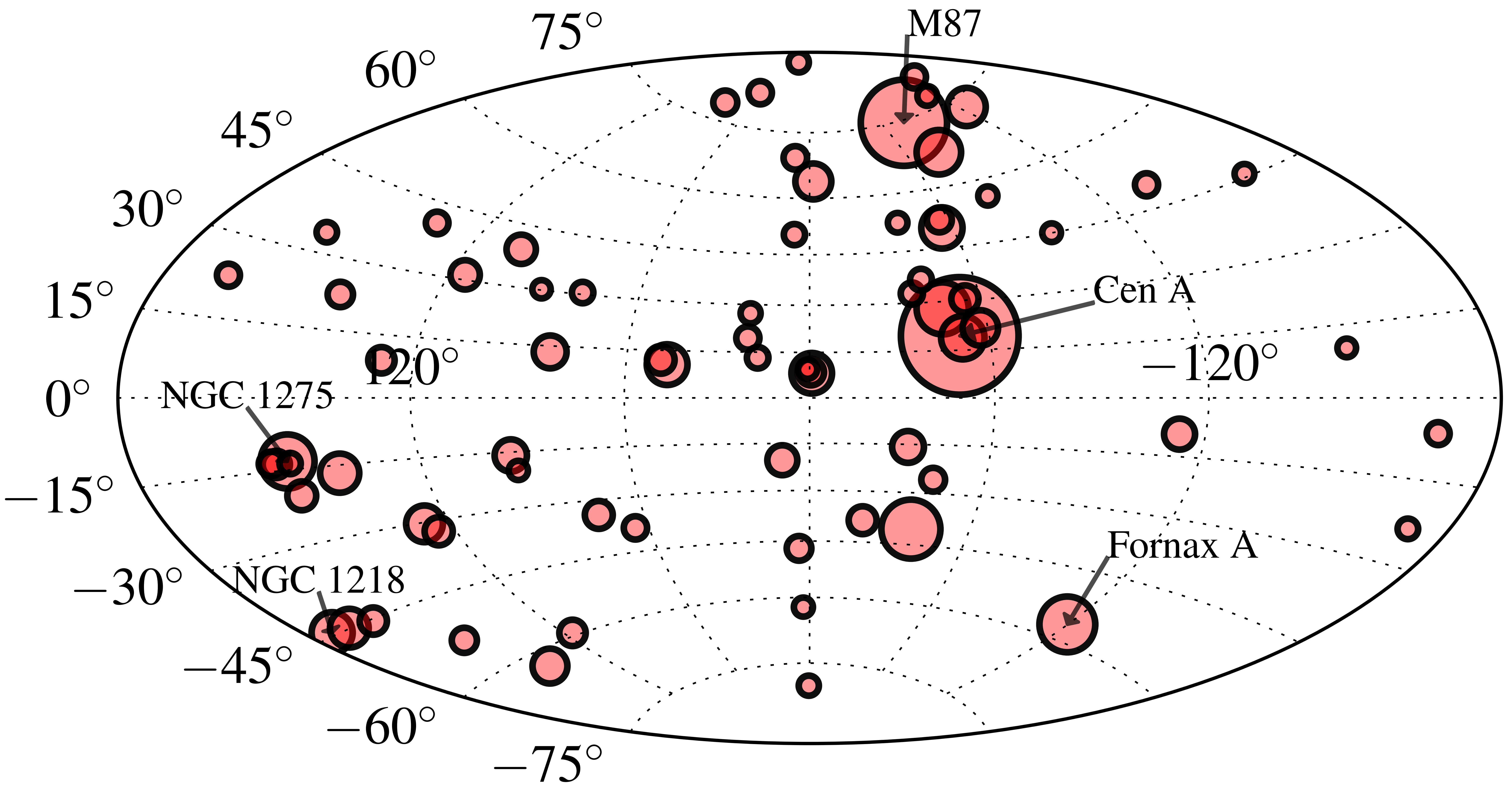
- injection
- pp
- Bethe-Heitler
- ssa
- proton synchrotron
- γγ
- synchrotron
- photopion
- annihilation
- triplet pair production

AUGER: evidence for AGN UHECRs?



van Velzen et al. 2012

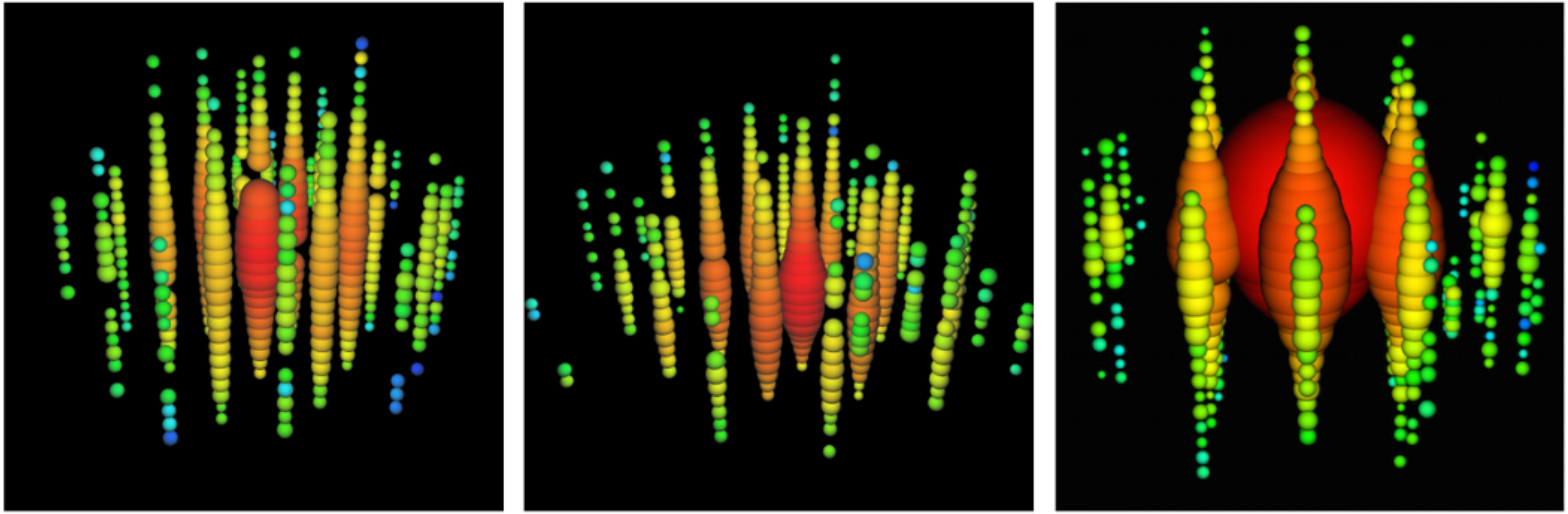
Map of radio galaxies within 100 Mpc



AUGER (2017 ICRC), 2-3sigma anisotropy?

Figure 1: Left: Correlation of events with Cen A as a function of the angular distance ψ and the energy threshold Eth. Right: Scan in (Eth, ψ) for the cross-correlation of events with the most luminous AGNs of the Swift-BAT catalog within 130 Mpc and brighter than 1044 erg/s.

IceCube sees PeV neutrinos in 2010-2013 data



IceCube has detected the highest energy neutrinos ever recorded, with energies reaching above 2 PeV. From left to right, Bert, Ernie and Big Bird, with energies of 1.0, 1.1 and 2.2 PeV.

Requires 40 PeV (4×10^{16} eV) CRs

Constraints on source localisation

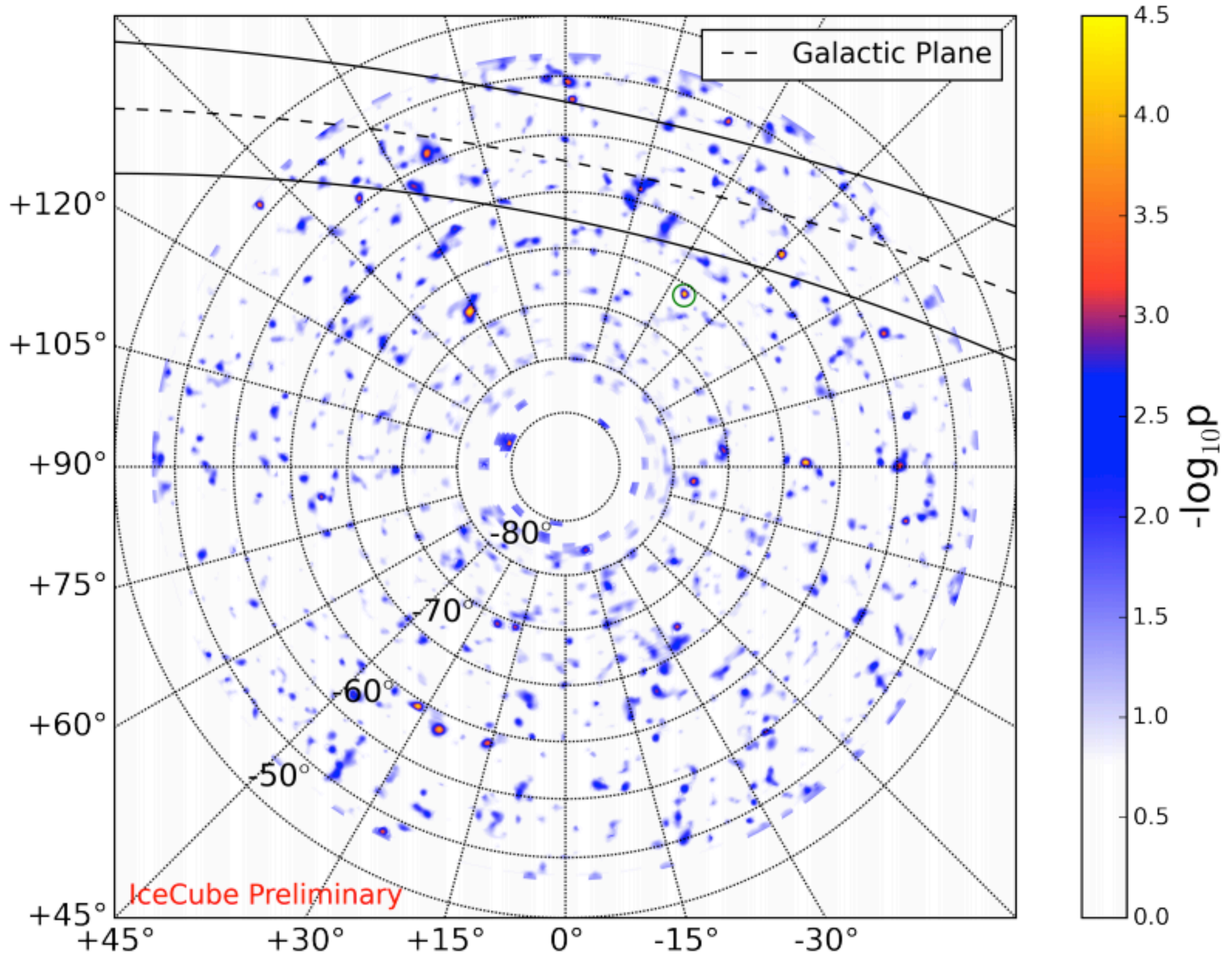
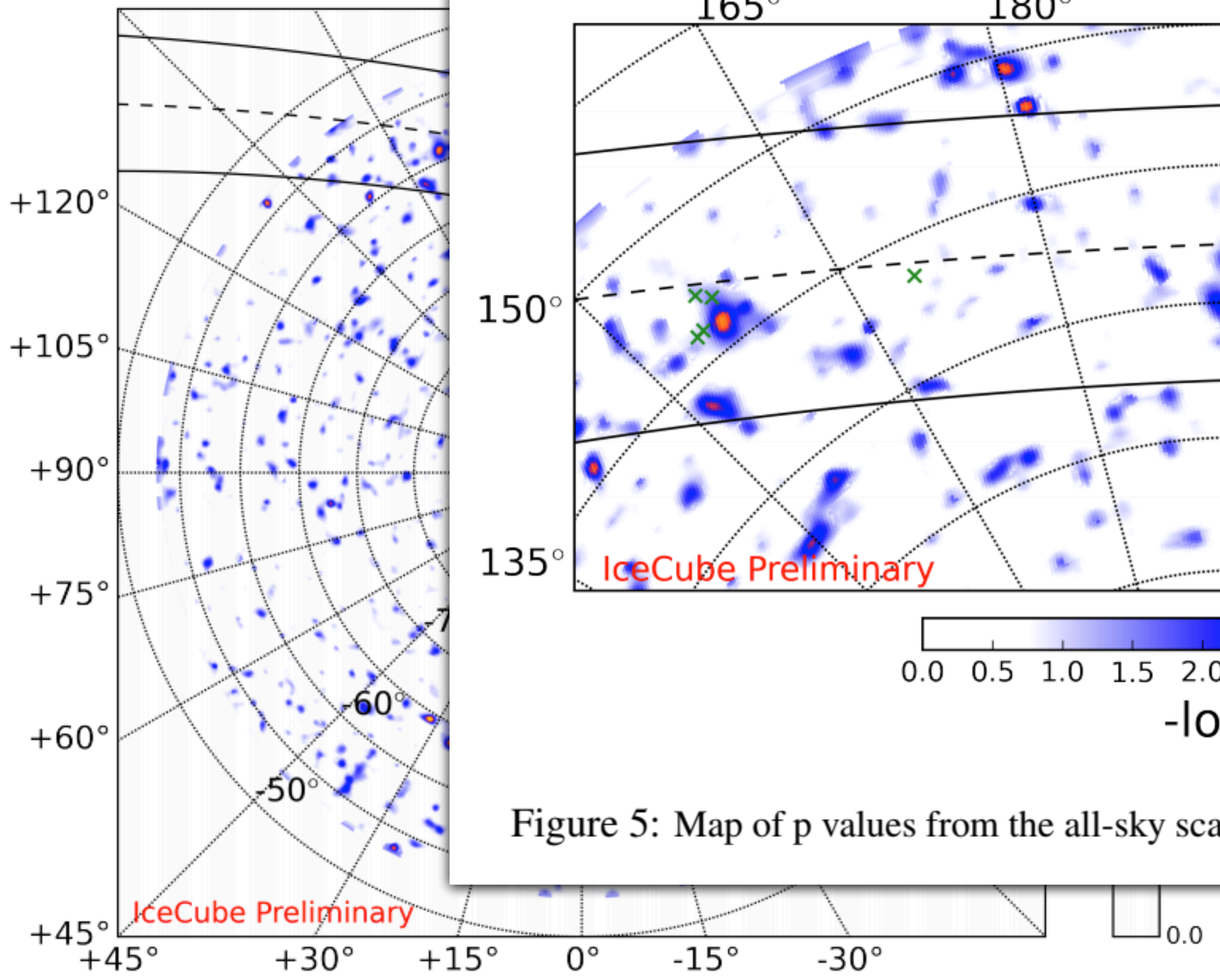


Figure 2: An equatorial polar map of the all-sky scan pre-trial p-values. The solid and dashed black line represents the Galactic plane region ±10°. The location of the lowest p-value is circled in green.

(IceCube collaboration, 2017, ICRC)

Constraints on source localisation



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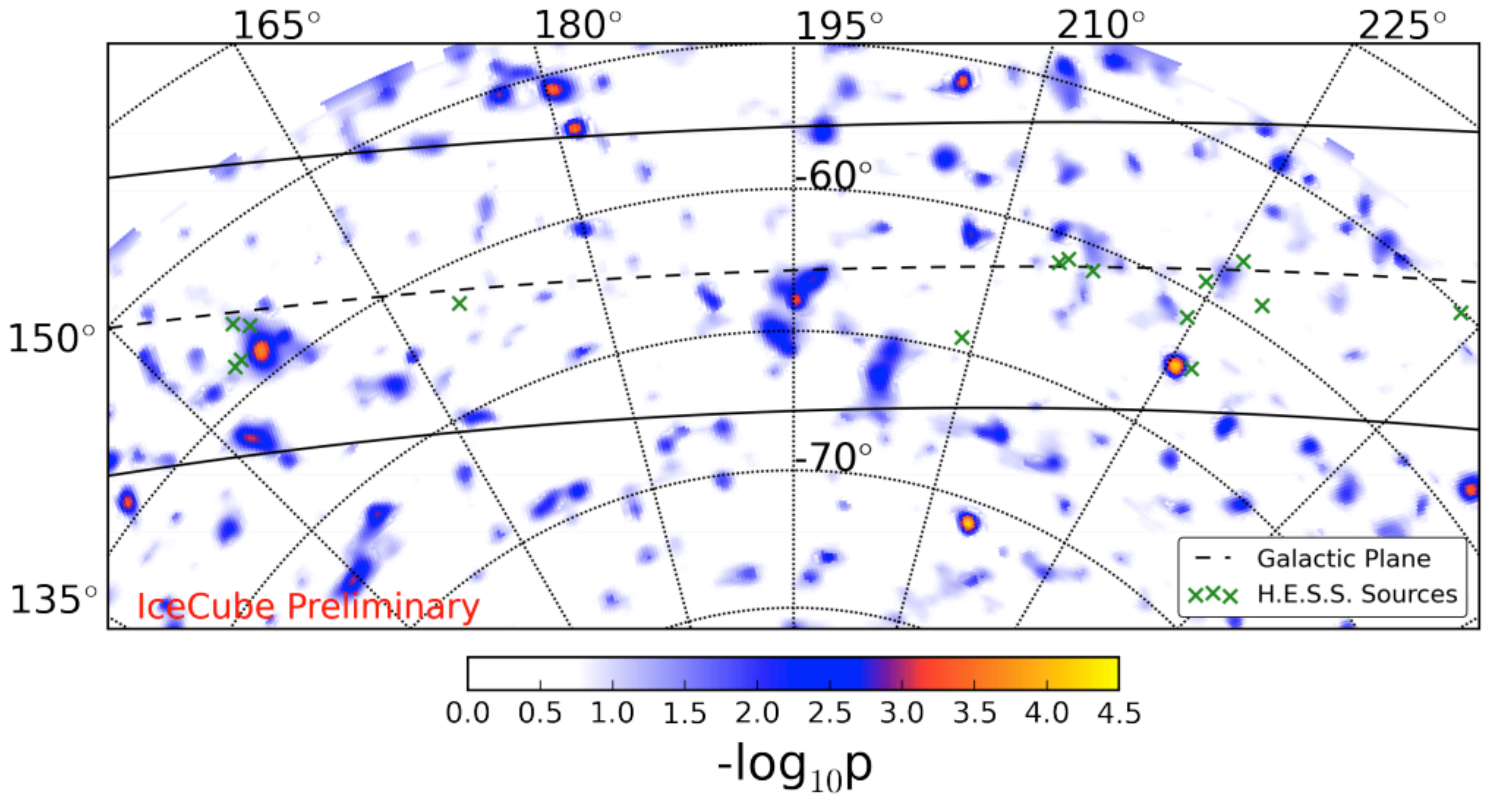
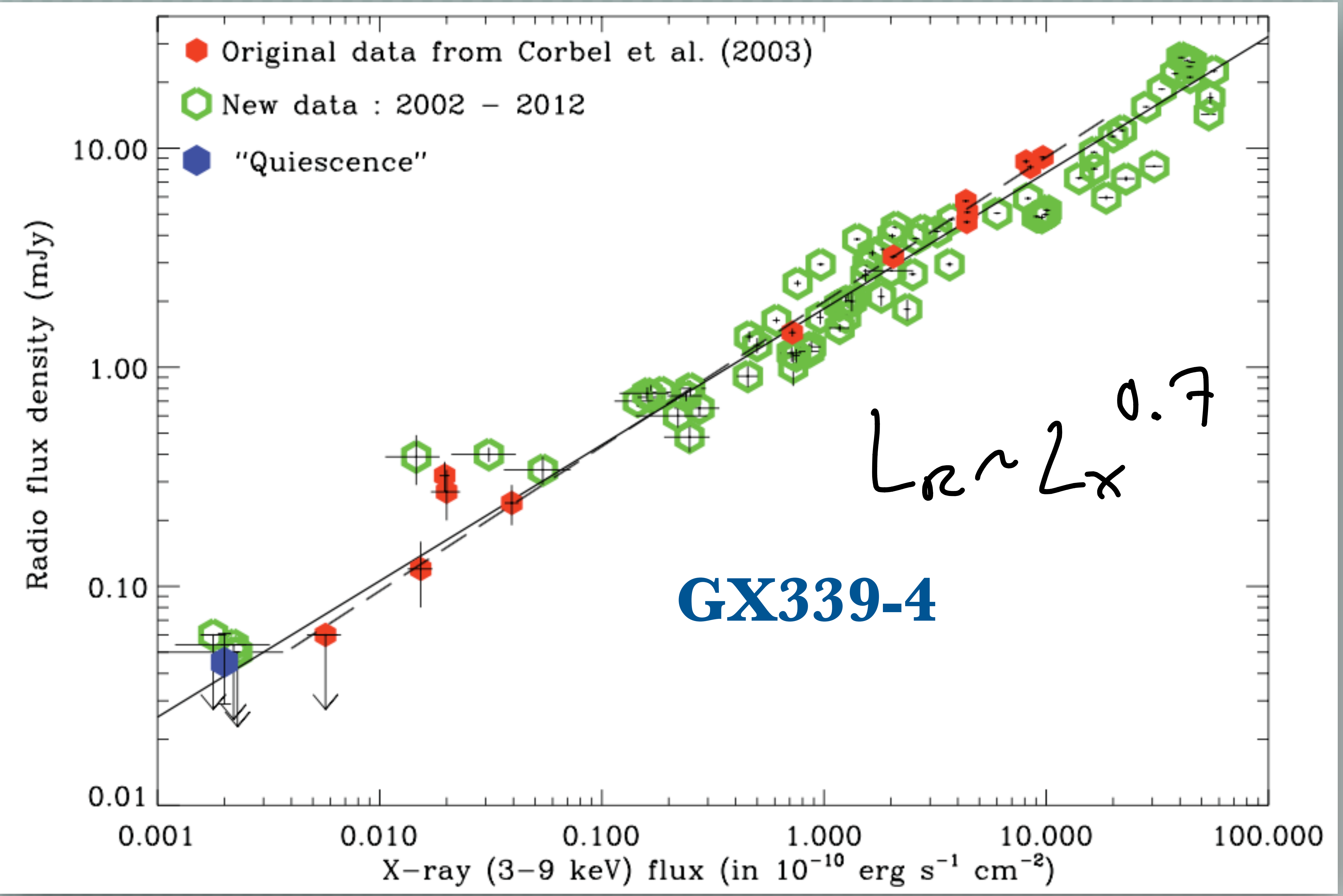
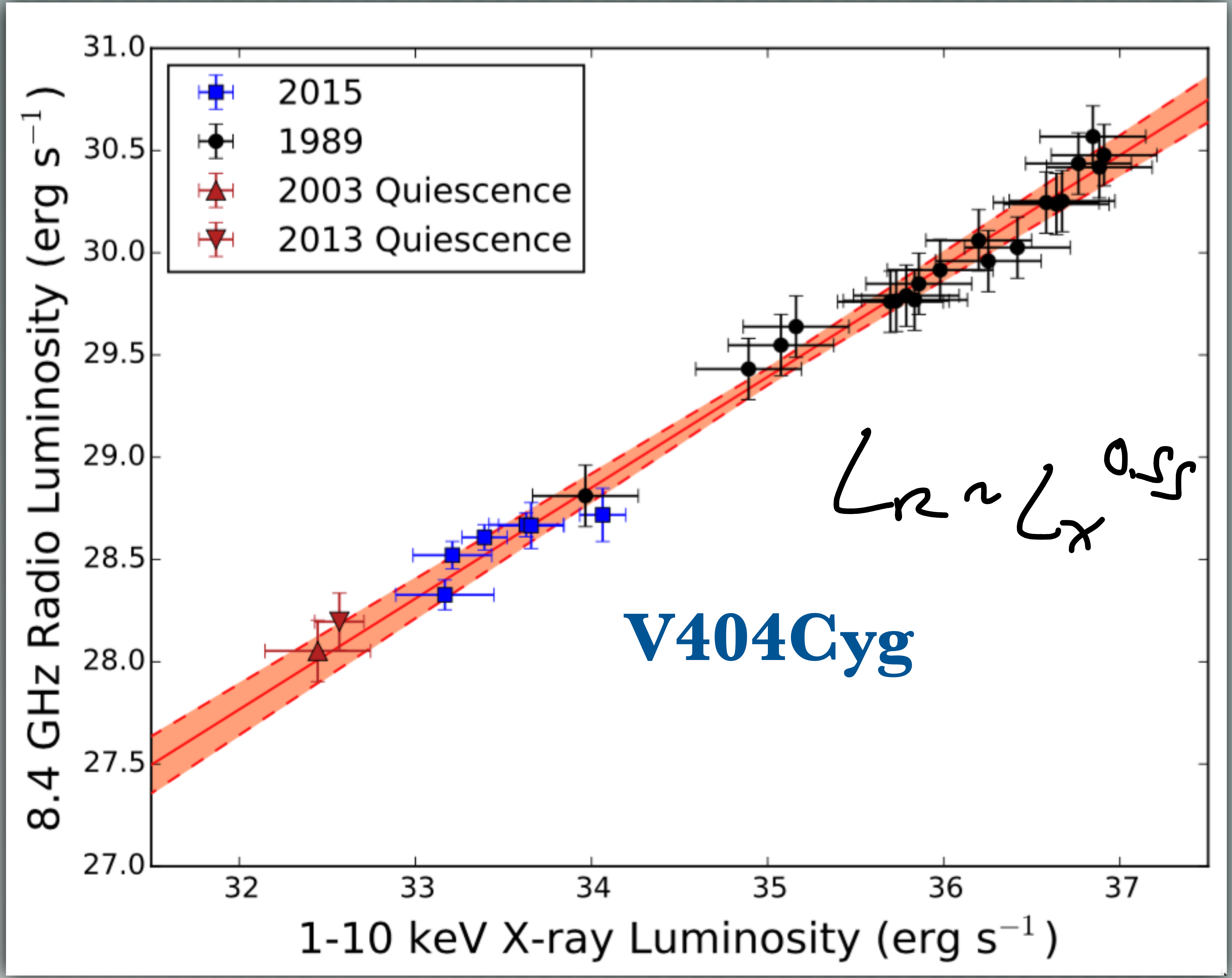


Figure 5: Map of p values from the all-sky scan with H.E.S.S. source directions overlaid.

(IceCube collaboration, 2017, ICRC)

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





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

Radio/Xray correlation = ratio of radiative efficiencies

$L_R \sim \dot{m}^{17/12}$

$L_X \sim \dot{m}^{q}$

$L_R \sim L_X^{0.55-0.7}$

take log both sides

$\frac{17}{12} \sim (0.55-0.7)q$

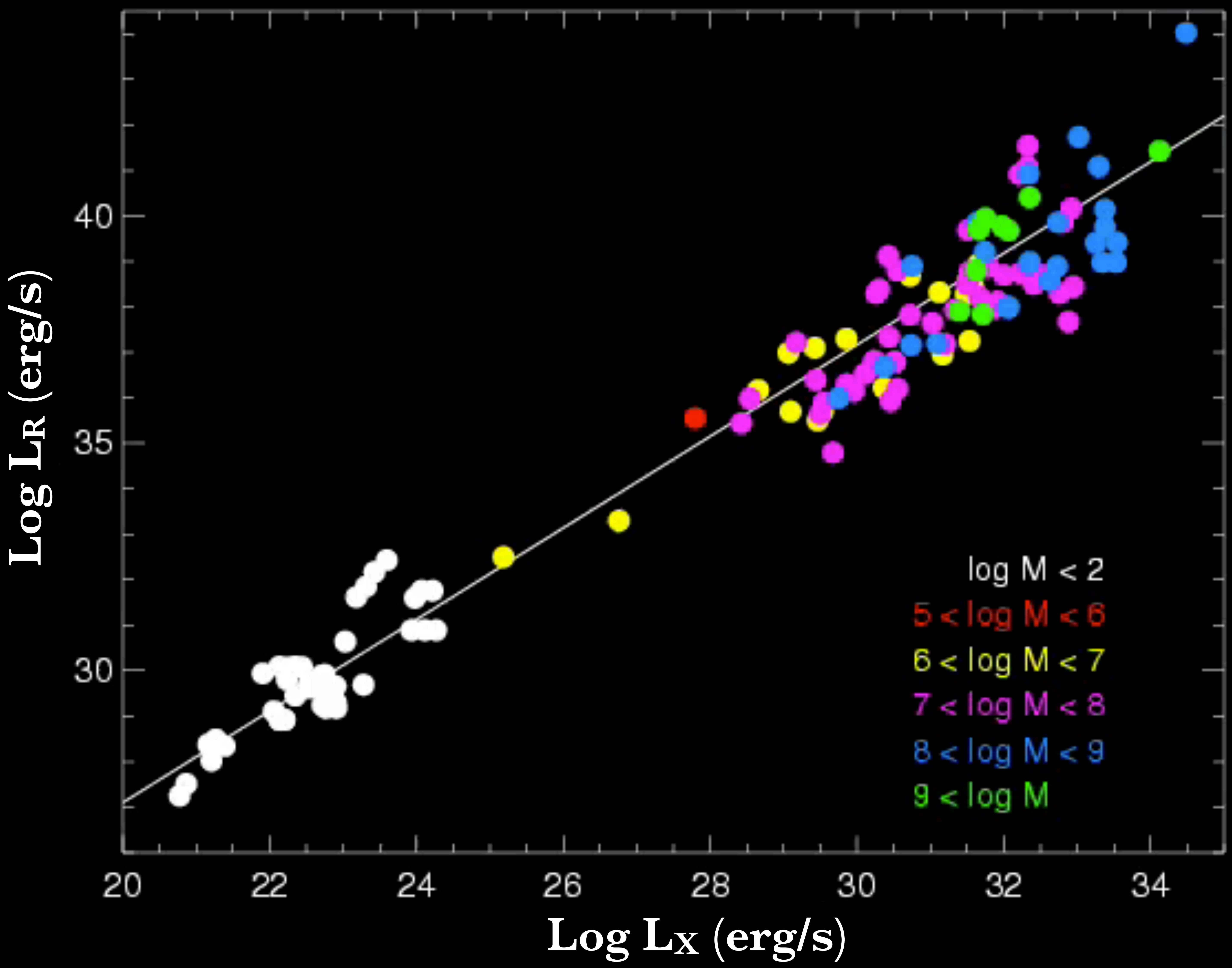
$q \to 2-2.5$

$q > 1 \Rightarrow$ radiatively inefficient

[Shakura Sunyaev $\propto \dot{m}$]

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)

Some (too) quick fundamentals about light and radiative transfer

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

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 $1/R^2$
- What is the relevant quantity to tell us about energy transport (ie., radiation)?

Few E&M definitions (in vaccuum)

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

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

$$\vec{J} \cdot \vec{E} + \frac{1}{8\pi}\frac{\partial}{\partial t}\left[E^2 + B^2\right] = -\vec{\nabla} \cdot \vec{S}$$

$\vec{J} \cdot \vec{E} = \frac{dU_{mech}}{dt}$ → +/- particles

$\frac{B^2}{8\pi} = U_B$ ⇒ change in energy in EM fields

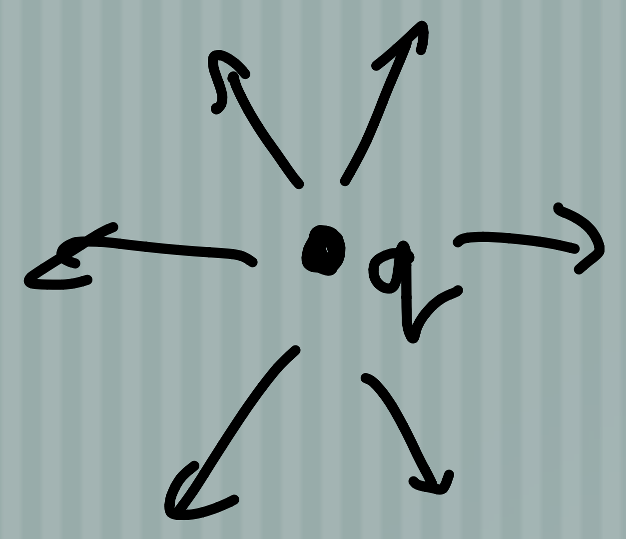
$-\vec{\nabla} \cdot \vec{S}$: energy carried away (loss) by EM fields → LIGHT

⇒ quantity of interest = Poynting Flux

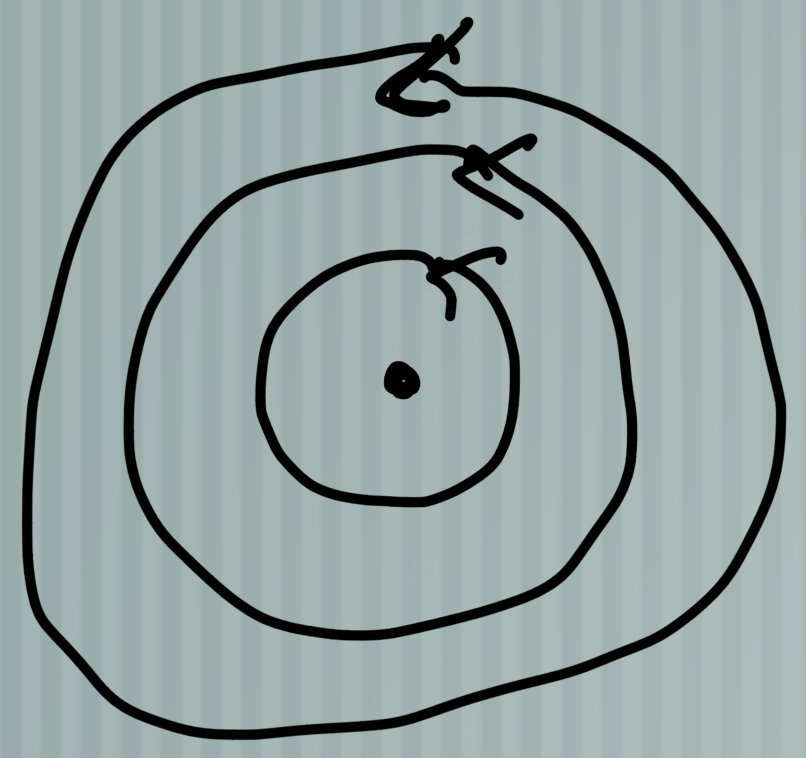
$$\vec{S} \equiv \frac{c}{4\pi}\left(\vec{E} \times \vec{B}\right)$$

Radiating charges

Static EM



$\vec{E} \sim \frac{q}{r^2}$ $|E| = |B|$ $\Rightarrow$ $\vec{S} = \frac{c}{4\pi}|E|^2 = \frac{c}{4\pi}|B|^2$ ~~$\propto 1/r^4$~~



→ ripple, pulse ⇒ moving / accelerating ?

$\vec{E} \sim \frac{q}{r} \longrightarrow \vec{S} \propto 1/r^2$

⇒ every EM related HE radiation process

→ transverse wave

Vector/scalar potentials

relativistic E&M ⟹ instead of $\vec{E}$ + $\vec{B}$ ⟹ $\vec{A}$ (vector potential)

ϕ (scalar potential)

why?

1) vector + scalar = easier than two vector esp. in SR
2) you can write $A^\mu = (\vec{A}, i\phi)$ ⟹ $A^\mu A_\mu$ → Lorentz invariant
3) D'Alembertian $\Box^2 = \vec{\nabla}^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}$ ⟶ solution

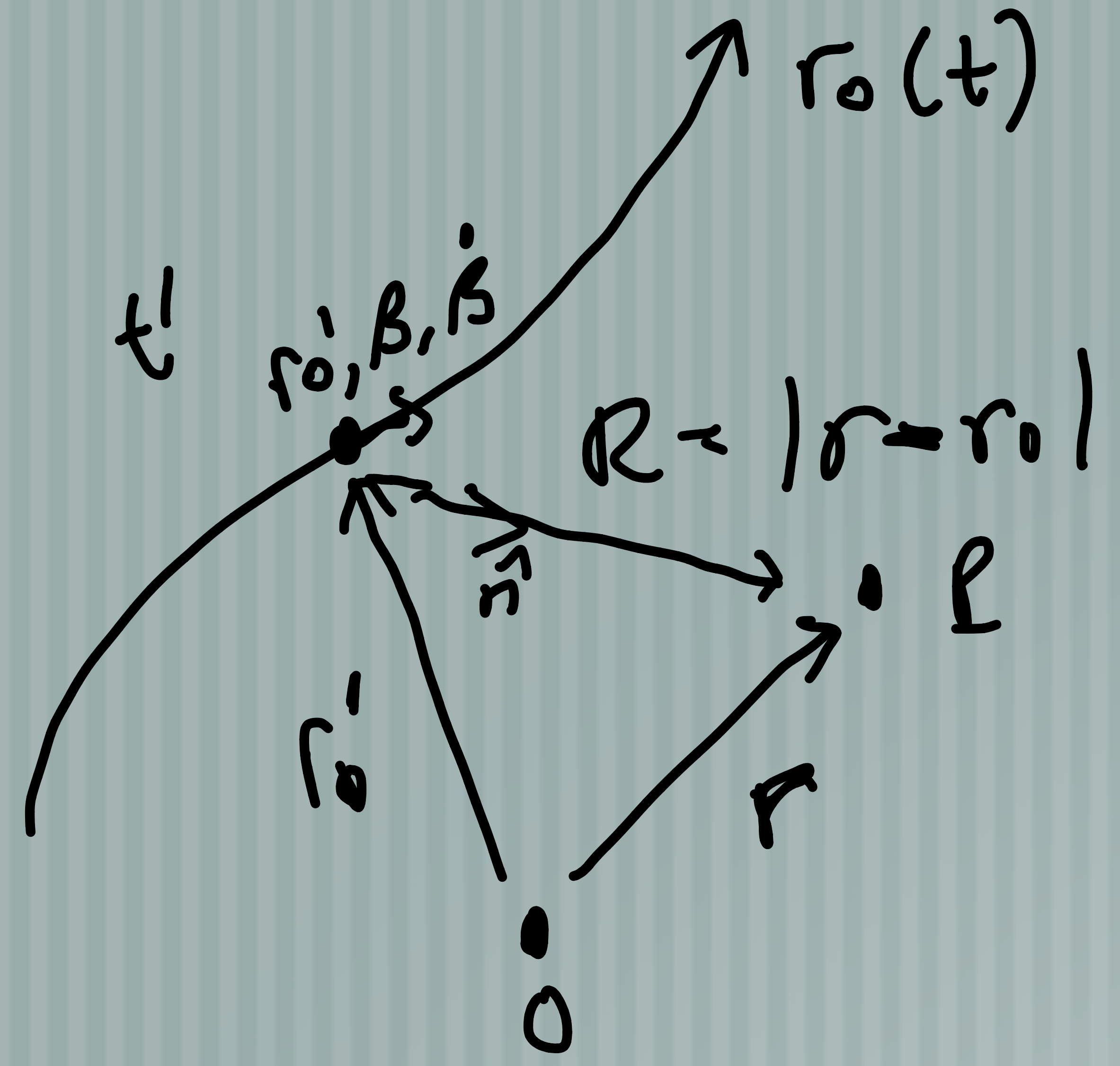
rewrite MW ⟹ $\Box^2 \begin{pmatrix}\vec{A}\\ \phi\end{pmatrix} = -4\pi \begin{pmatrix}\vec{J}/c\\ \rho\end{pmatrix}$

$\phi(t) \approx \frac{q}{r}(t - r/c)$

q ~ r ~ R (obs)

→ retarded time

Vector/scalar potentials and retarded time (SR)



Potential that P "feels" is at retarded time

$$t' \equiv t - R/c$$

$$\hat{n} \equiv \frac{R}{r}$$

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

~~Liénard-Wiechert Potentials~~

→ out comes of

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

nonrelativ. limit

$\beta \ll 1$, $\kappa = 1$

$\rightarrow q/R^2$

"velocity field"

$S \propto 1/R^4$

⇒ acceleration field

$S \sim 1/R^2$

→ accelerating charge to get transverse wave

How you get a transverse/radial field from acceleration!

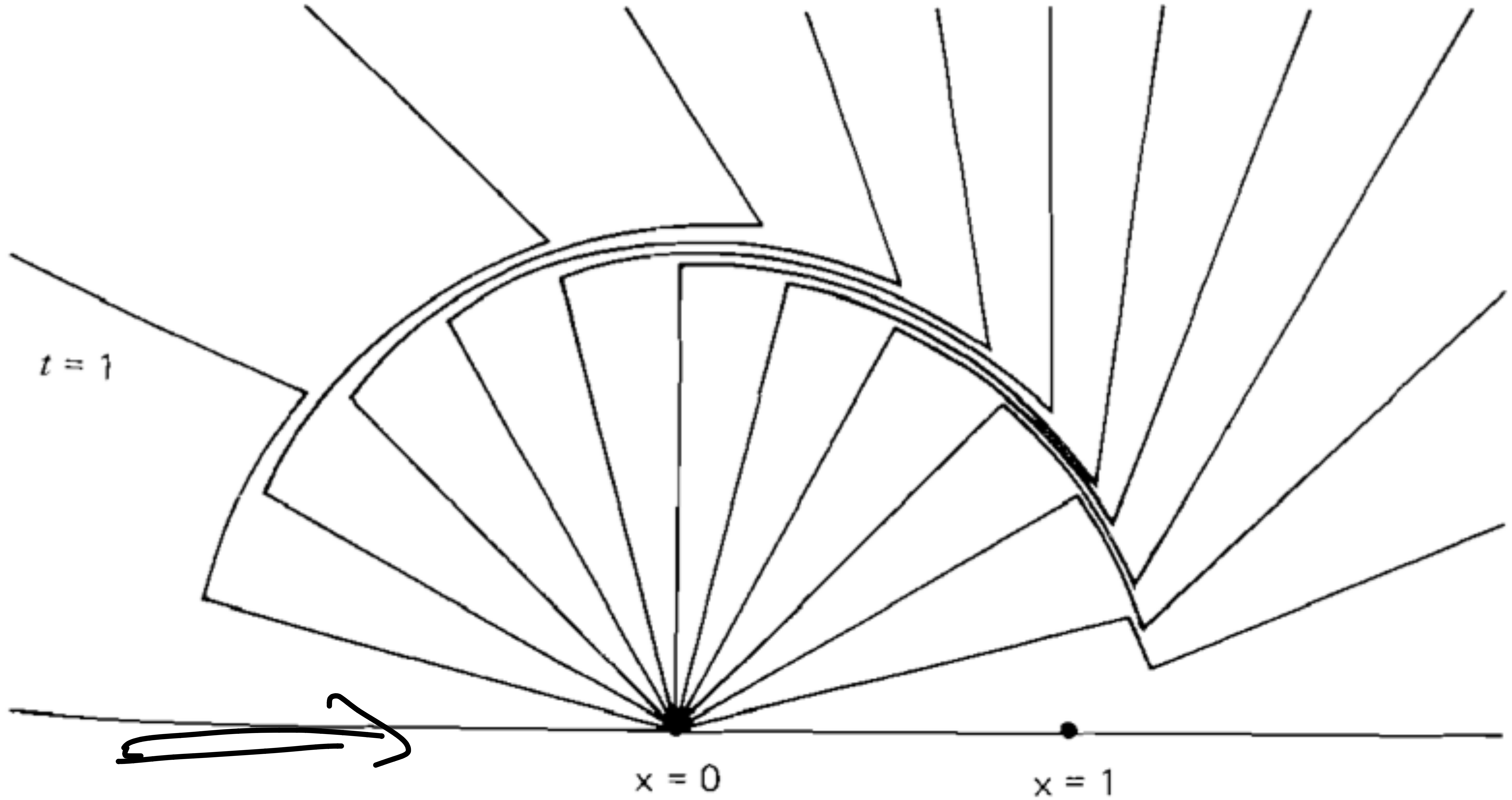


Figure 3.2 Graphical demonstration of the 1/R acceleration field. Charged particle moving at uniform velocity in positive x direction is stopped at x = 0 and t = 0.

How you get a transverse /radial field from acceleration!

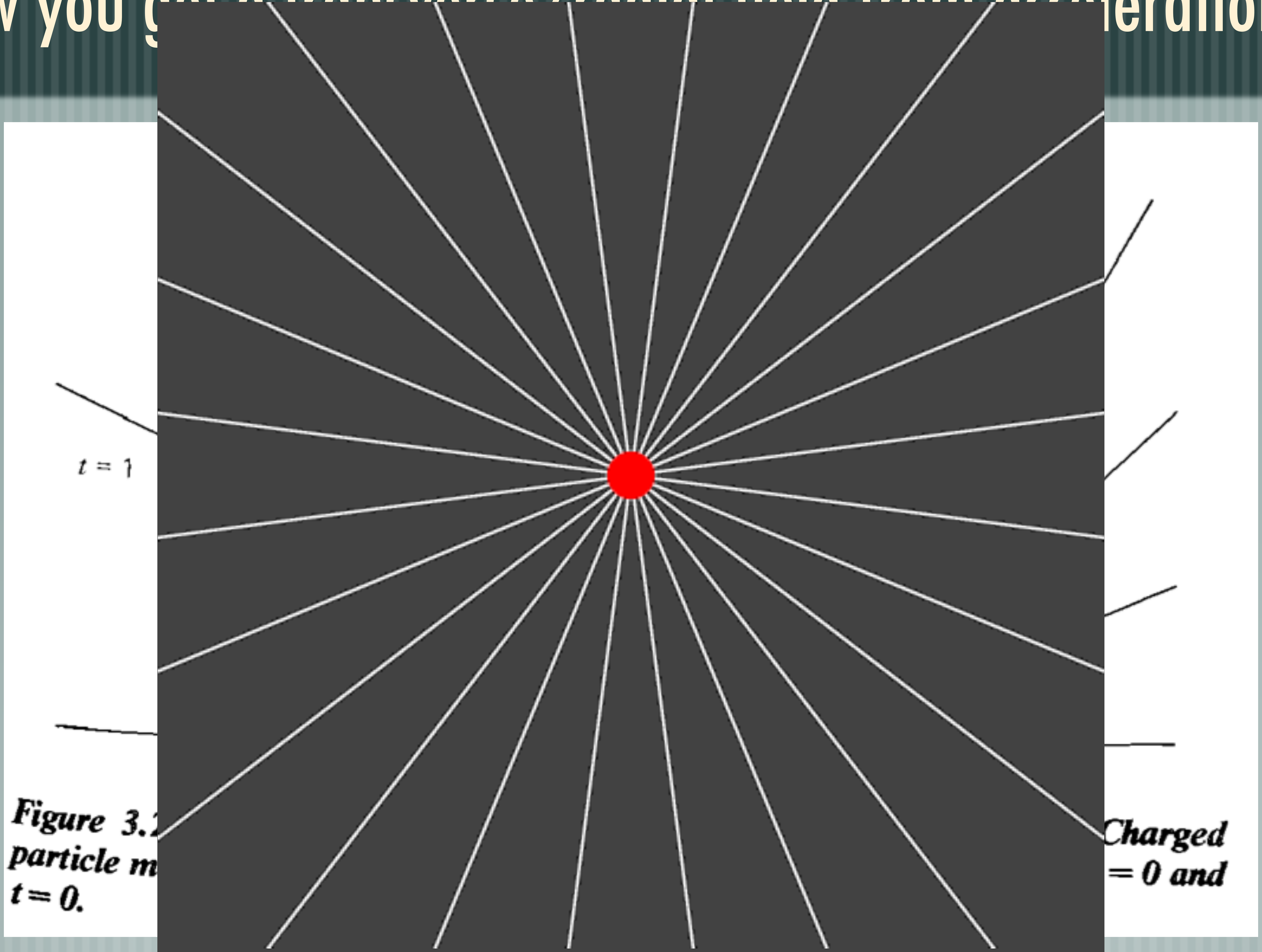
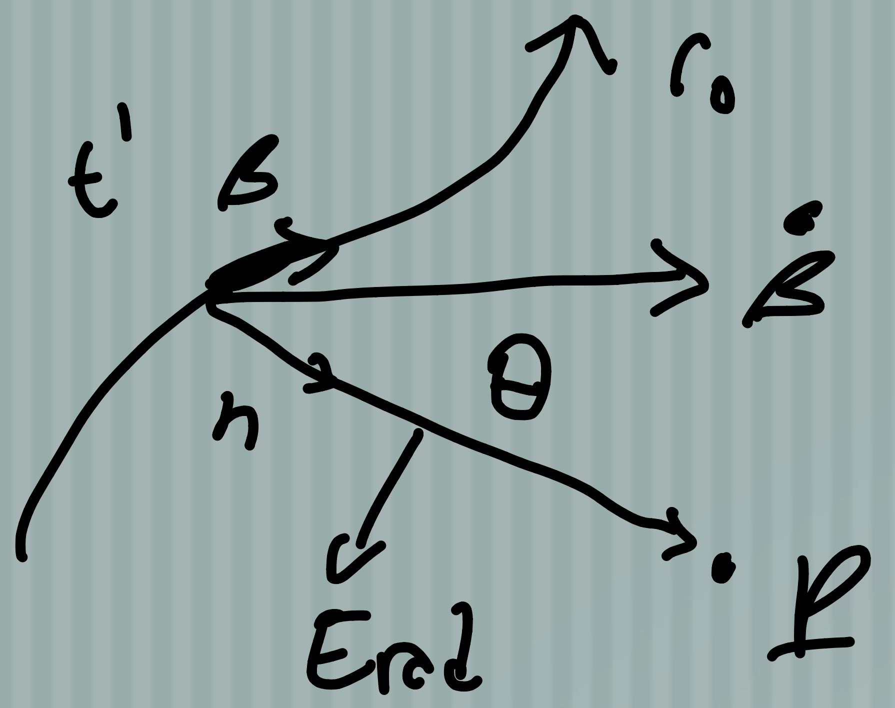


Figure 3.2 ... *Charged particle m* ... *= 0 and t = 0.*

Power from accelerating charges I

Start w/ nonrelativistic case (Why? Easier to work in e^- inst. rest frame)

$\beta \ll 1$, $\gamma \sim 1$



$$\vec{E}_{rad} \simeq \frac{q}{cR}\left[\hat{n} \times (\hat{n} \times \dot{\vec{\beta}})\right]$$

$$\hat{n} \times \dot{\vec{\beta}} = \dot{\beta} \sin\theta \quad \odot$$

$$\hat{n} \times (\hat{n} \times \dot{\vec{\beta}}) = \dot{\beta} \sin\theta \quad \Rightarrow \quad E_{rad} = \frac{q}{cR} \dot{\beta} \sin\theta$$

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

$$\frac{dP}{d\Omega} = R^2 |S| = \frac{q^2}{4\pi c} \dot{\beta}^2 \sin^2\theta \longleftarrow \quad \text{"Larmor's"}$$

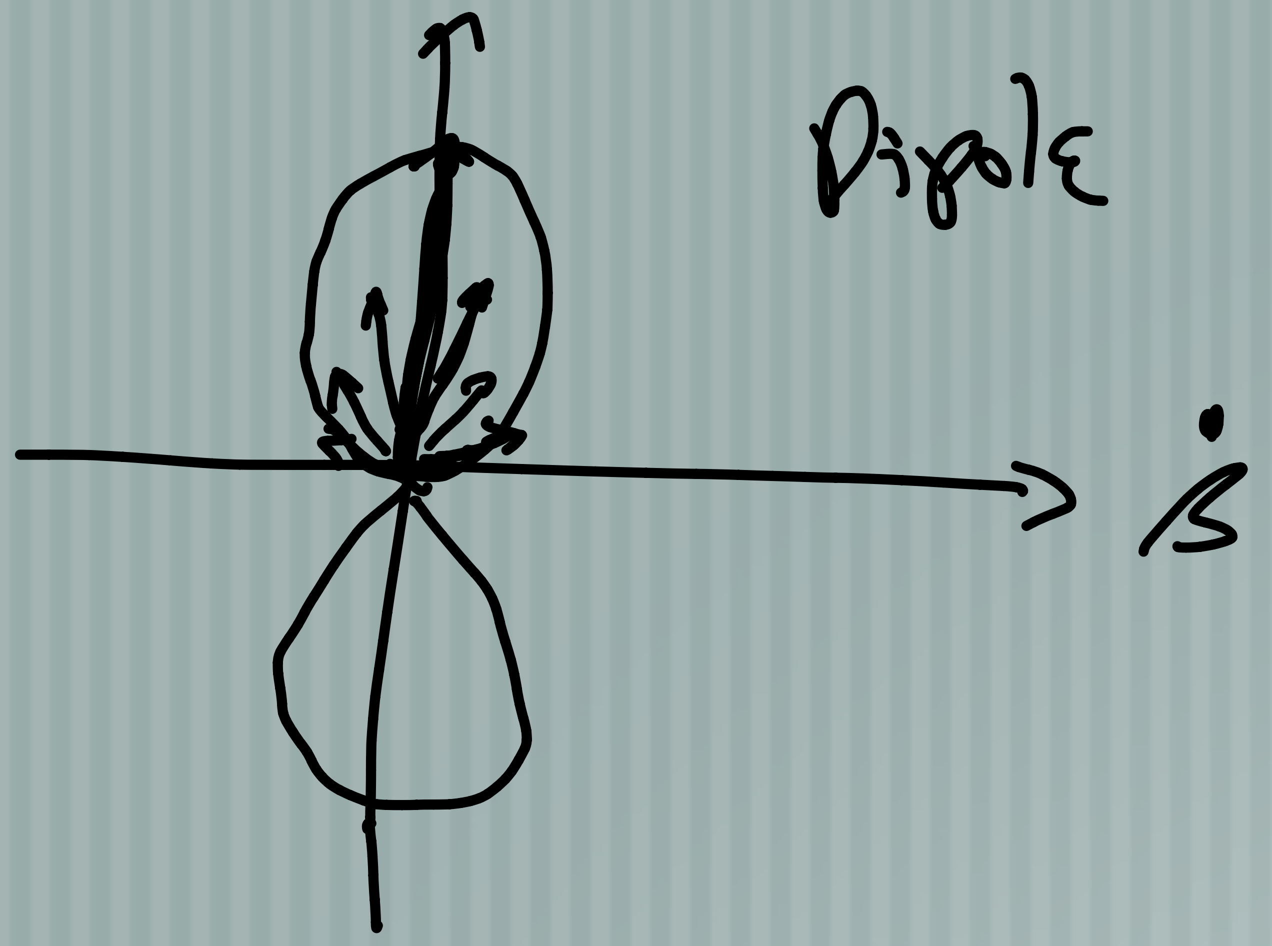
$(d\Omega = \sin\theta \, d\theta \, d\phi)$

$$P_{tot} = \iint \frac{dP}{d\Omega} d\Omega = \left(\frac{8\pi}{3}\right) \frac{q^2}{4\pi c} \dot{\beta}^2$$

Power from accelerating charges II : radiation pattern

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

"Larmor dipole approx"



Dipole

Single particle dipole w/ orig

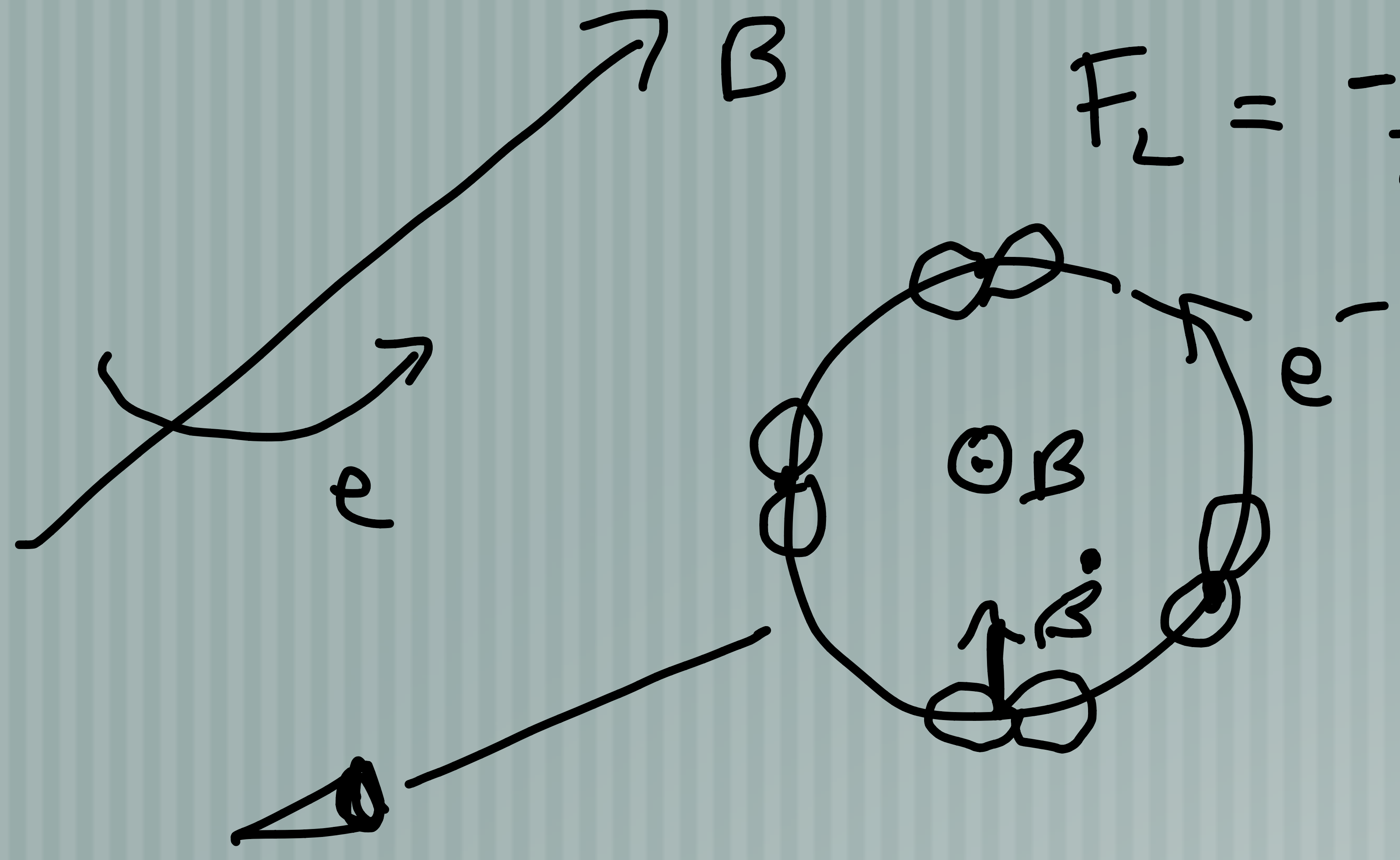
$$\vec{d} = q\vec{r}$$

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

$$\ddot{\vec{d}} = q\dot{\vec{v}} = qc\dot{\vec{\beta}}$$

$$\frac{dP}{d\Omega} = \frac{\ddot{d}^2 \sin^2\theta}{4\pi c^3}, \quad P = \frac{2}{3}\frac{\ddot{d}^2}{c^3}$$

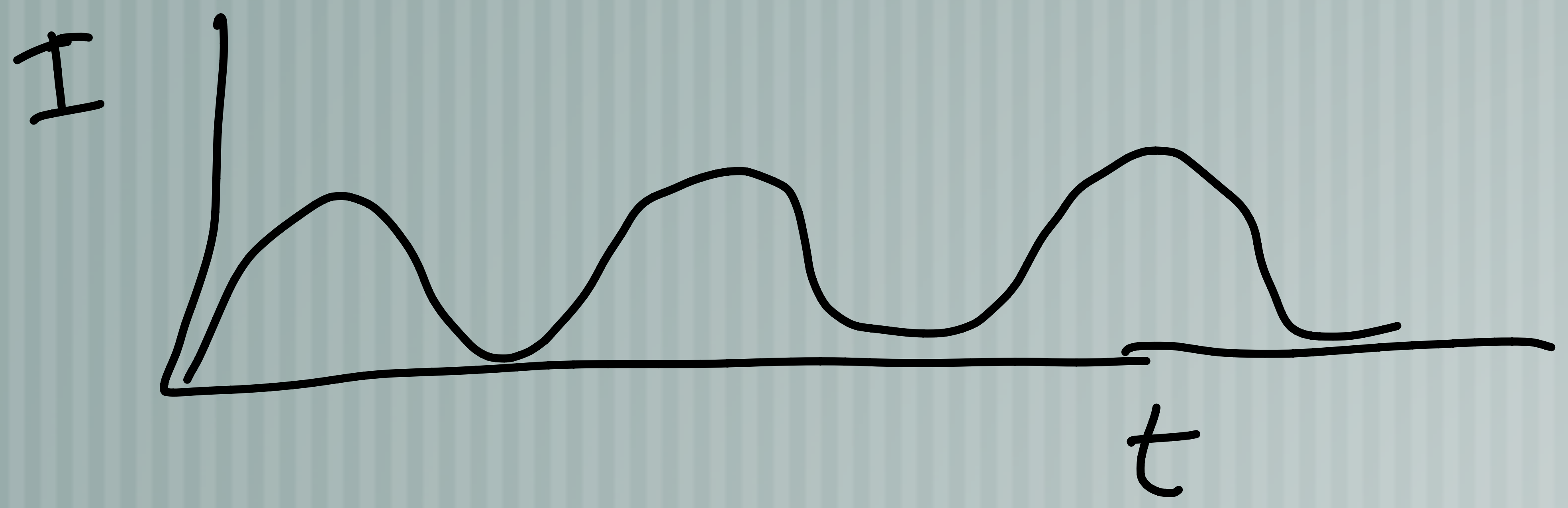
“prelude” to cyclo-synchrotron



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

→ gyration = circular

→



⟹

“prelude” to cyclo-synchrotron II