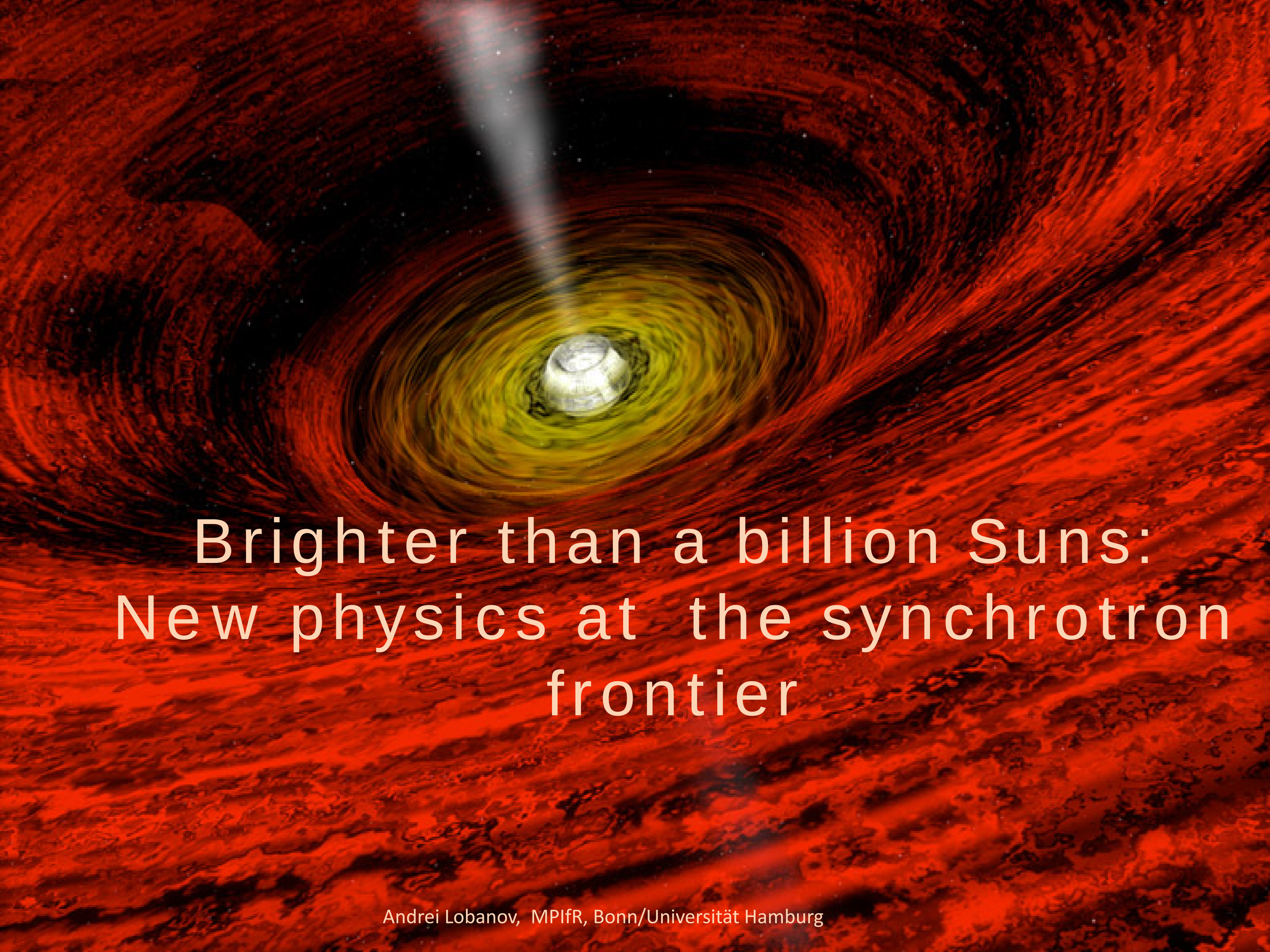


Brighter than a billion Suns: New physics at the synchrotron frontier

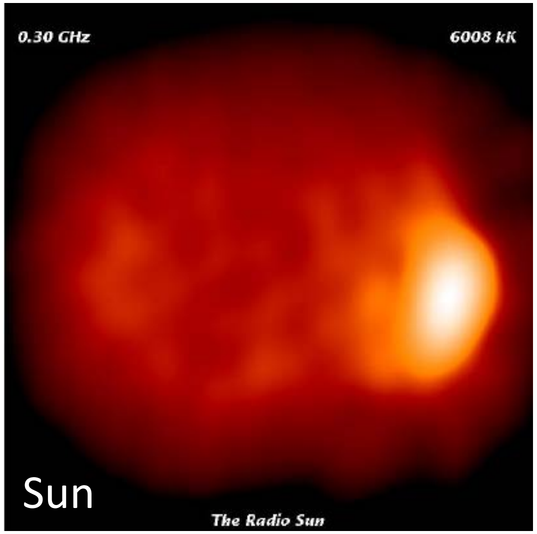
Andrei Lobanov, MPIfR, Bonn/Universität Hamburg

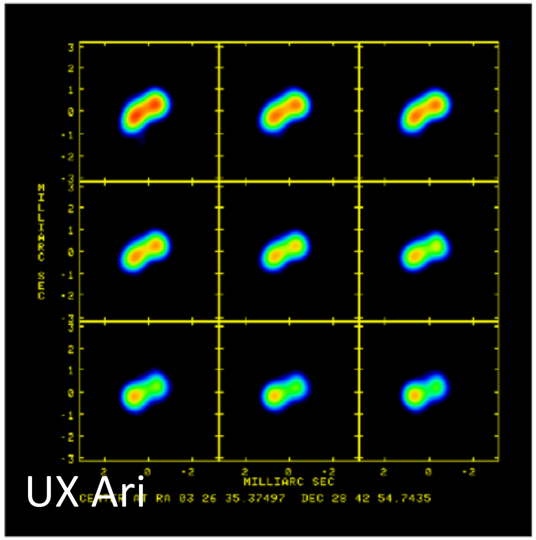
Synchrotron Era

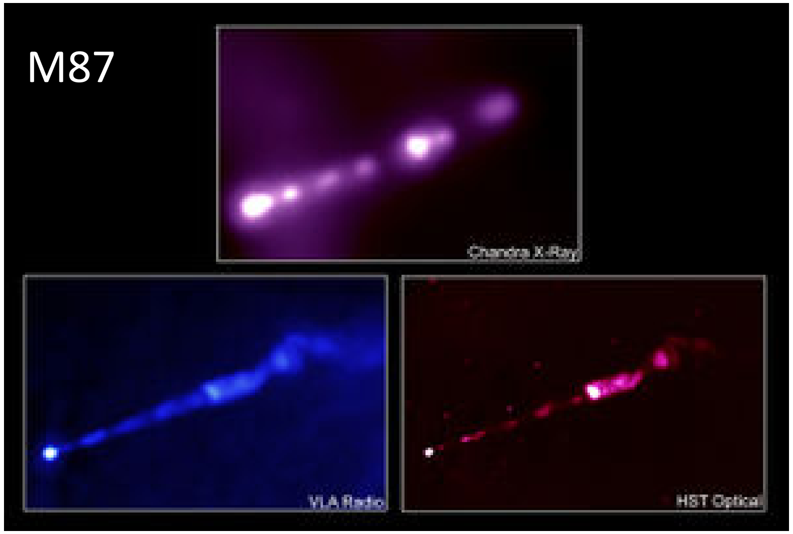
- 1944: predicted by Ivanenko and Pomeranchuk, Physical Reviews, v.65, p.343, 1944
- 1946: observed in the „Synchrotron“, an accelator built by General Electric in Schenectady, NY.
- 1950+: Relevance to cosmic objects recognized, and the era of cosmic synchrotron started.
- Synchrotron emission: nuisance in particle physics experiments while excellent light source for many other experiments; indispensable tool in astrophysics.

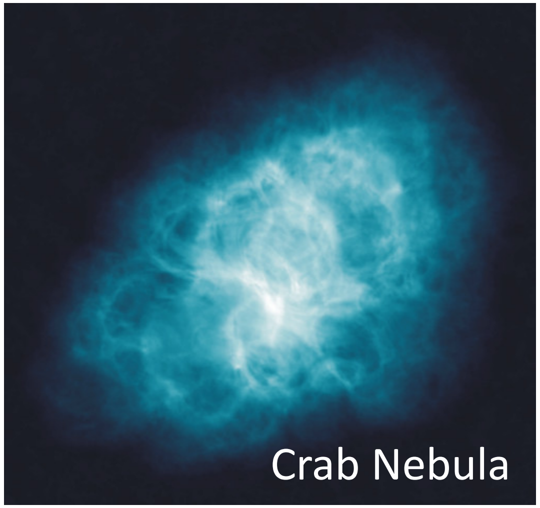
Cosmic Synchrotron

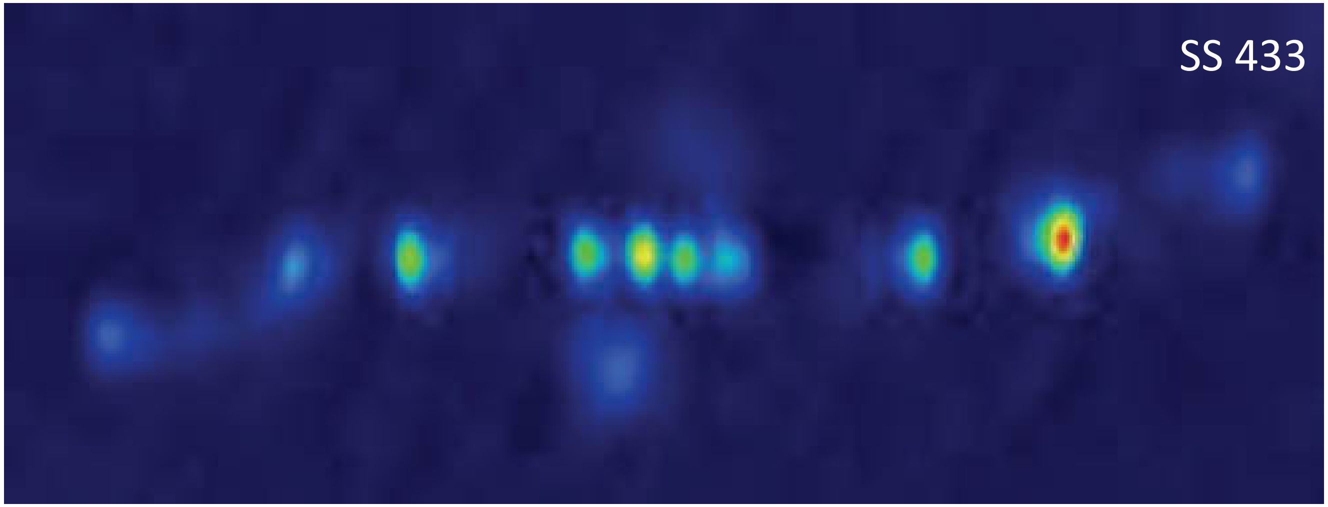
- Cosmic synchrotron sources come in an astounding variety



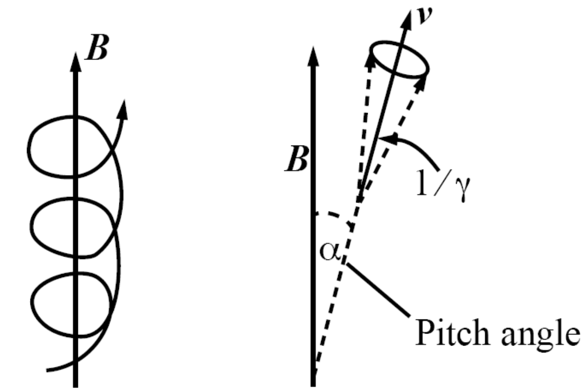








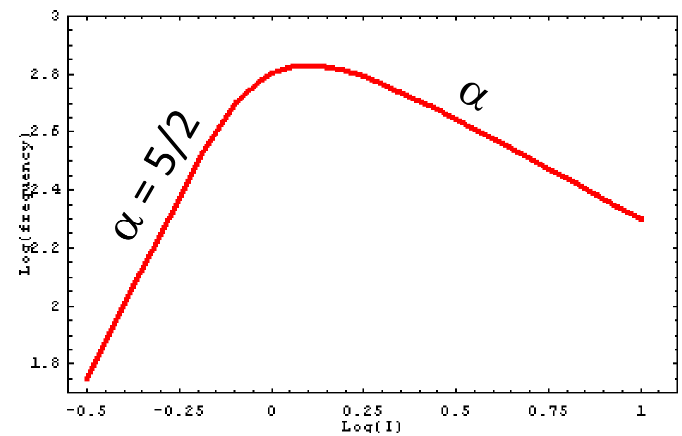
Diagnostics of Synchrotron



- Going from a single particle with

$$P(\omega) = \frac{\sqrt{3}}{8\pi^2\varepsilon_0 c}\frac{q^3 B\sin\alpha}{m}F(x)$$

to realistic plasma requires assuming distributions of particle energies N(γ) and pitch angles.



- Canonic assumptions: random pitch angle and a power law particle energy distribution $N(\gamma)\mathrm{d}\gamma = N(\gamma_0)\,\gamma^{-s}\mathrm{d}\gamma$
- Maximum brightness is then limited by the inverse-Compton losses to a brightness temperature $T_{b,\max} = \frac{I_{\nu,max}c^2}{2\,k\,\nu^2} \approx 10^{12}\mathrm{K}$, used as one of the prime diagnostics.

Getting to that I_ν

- You want to have I_ν, but really measure S over an area Ω.

$$I_\nu = S_\nu/\Omega = S_\nu/[2\pi(1-\cos\rho_d)] \approx S_\nu/(\pi\rho_\mathrm{d}^2)$$

- If you don't care about the extent of your region, you need to care about the resolution limit of your instrument. Then

$$I_\nu \geq 4S_\nu/(\pi\theta_\mathrm{lim}^2) \qquad T_\mathrm{b} \geq 2S_\nu c^2/(\pi k \nu^2 \theta_\mathrm{lim}^2)$$

- Otherwise, you need to image or model the structure of interest, before you can estimate T_b. Take, for instance (as everybody does) an elliptical gaussian:

$$I_\nu = (4\ \ln 2/\pi)\, S_\mathrm{g}/(\theta_\mathrm{maj}\,\theta_\mathrm{min})$$

$$T_\mathrm{b} = [2\ \ln 2/(\pi k)]\, S_\mathrm{g}\, c^2/(\nu^2\,\theta_\mathrm{maj}\,\theta_\mathrm{min})$$

Interferometric Measurements

- Interferometry: measuring visibility amplitude, *V*, at a spatial (Fourier) freuquency, *q*. Then for a source with

$$T_b = \frac{I_\nu c^2}{2k\,\nu^2} = \frac{S\,\lambda^2}{2k\,\Omega}.$$

-- and a single measurement of *V* on a baseline *B*,
-- with the proxies $S \rightarrow V$ and $\theta \rightarrow 1/q$ $(\Omega \rightarrow {}^{\pi}/_{q^2})$,
-- and recalling that $q = {}^{B}/_{\lambda}$,

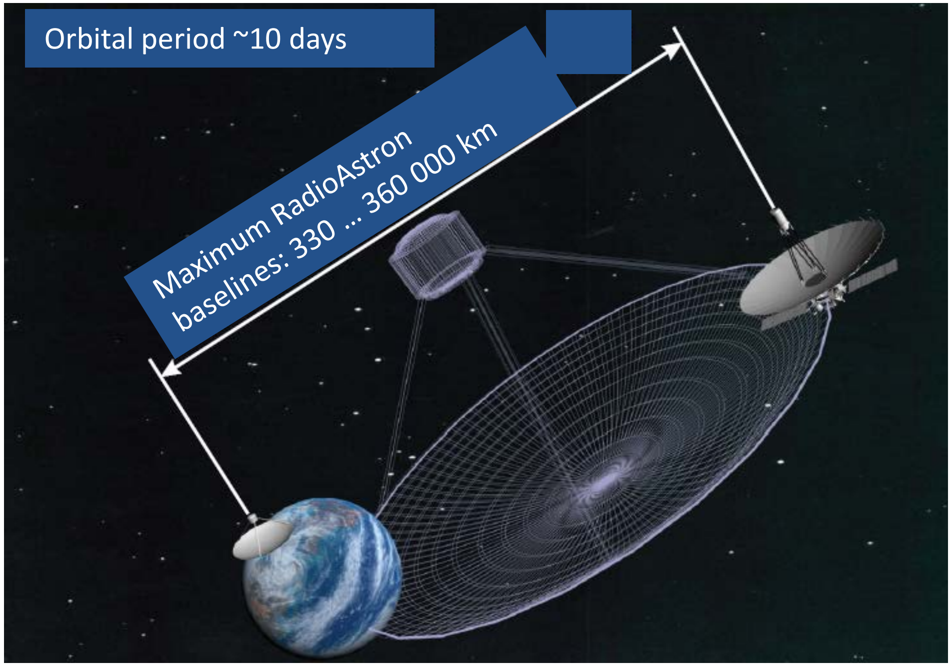
one gets

$$T_b = \frac{I_\nu c^2}{2k\,\nu^2} = \frac{V\,B^2}{2\pi\,k}$$

- That is: going to longer baselines is the best way to detect extreme brightness temperatures

RadioAstron's Quest for T_b

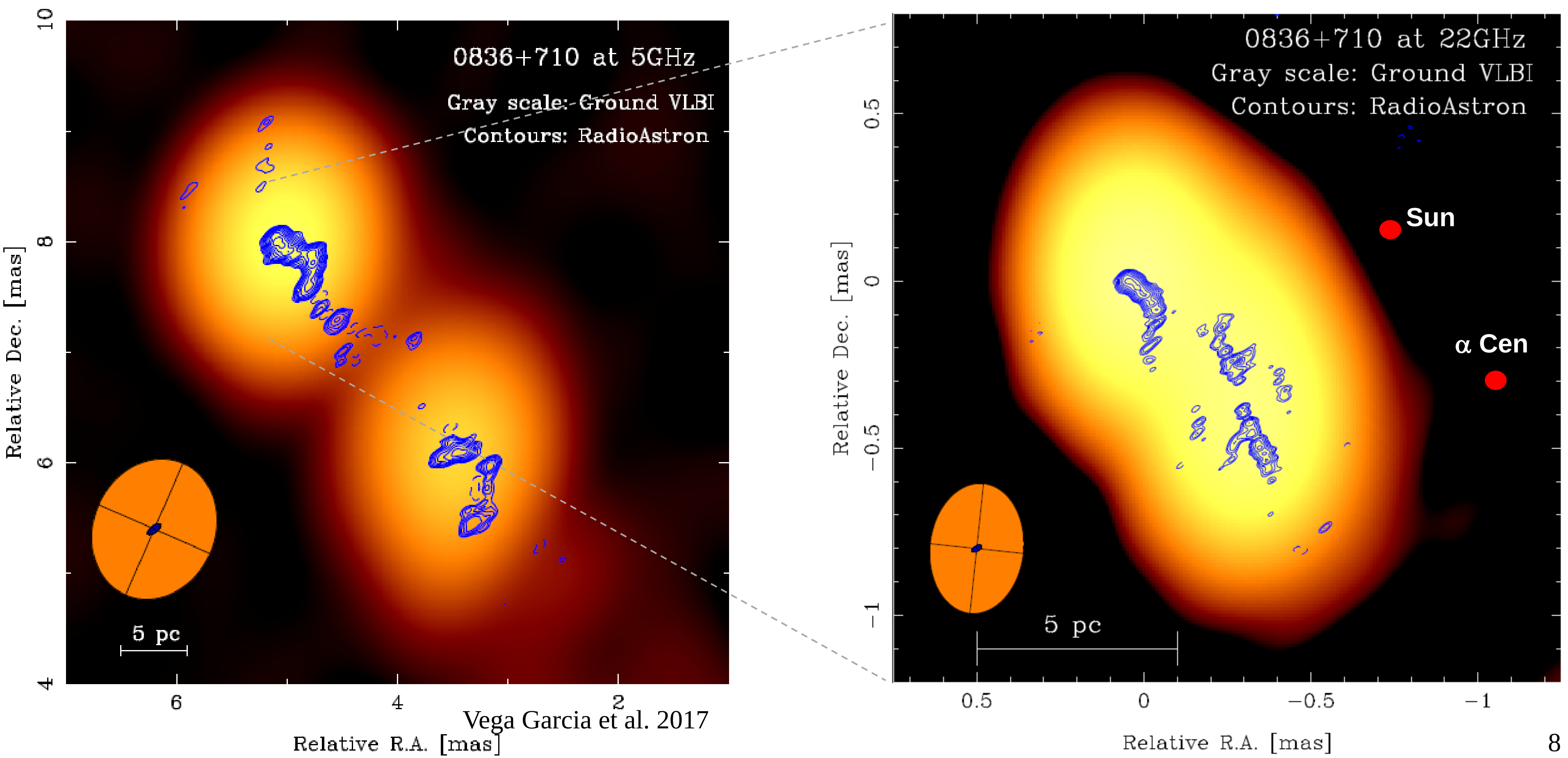
- Space VLBI mission: orbiting 10-m antenna and arrays of ground antennas
- Operates at 0.3, 1.6, 5, and 22 GHz.
- First SVLBI mission with imaging and polarization capabilities at 22 GHz.



- Elliptical orbit with perigee/apogee: ~ 10,000/360,000 km; smallest fringe spacing of 7 μas (22 GHz).
- Excellent tool for probing extreme brightness temperatures.

A Step Further with RadioAstron

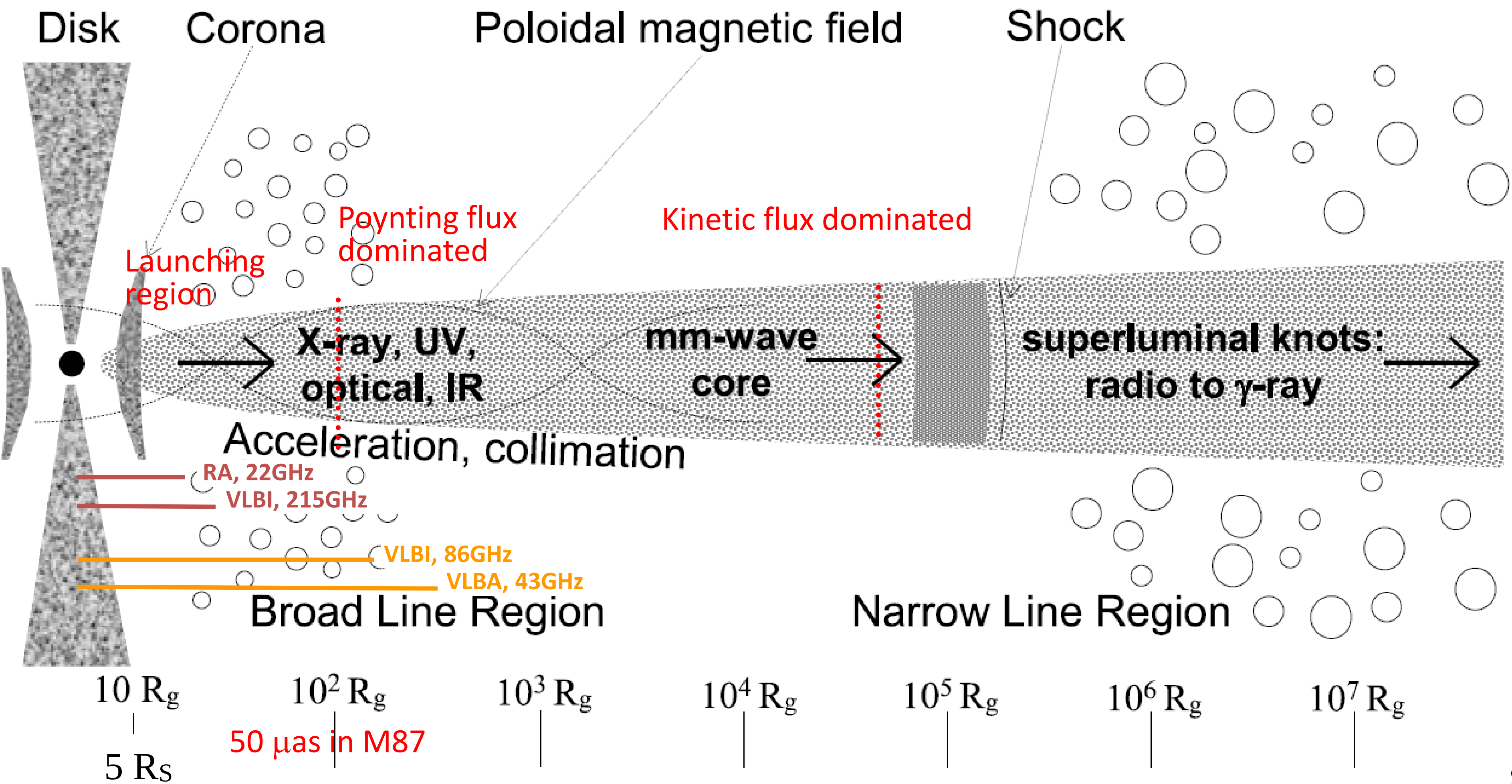
RadioAstron observations provide a factor of ~10 improvement in angular resolution, revealting the full wealth of structural detail down to the linear scales below 1000 R_g (and reaching ~10 R_g in nearby objects)



Vega Garcia et al. 2017

Space VLBI View of AGN Jets

- Space VLBI with RadioAstron directly probes of physics of the central engine in AGN: T_b, polarization, magnetic field.



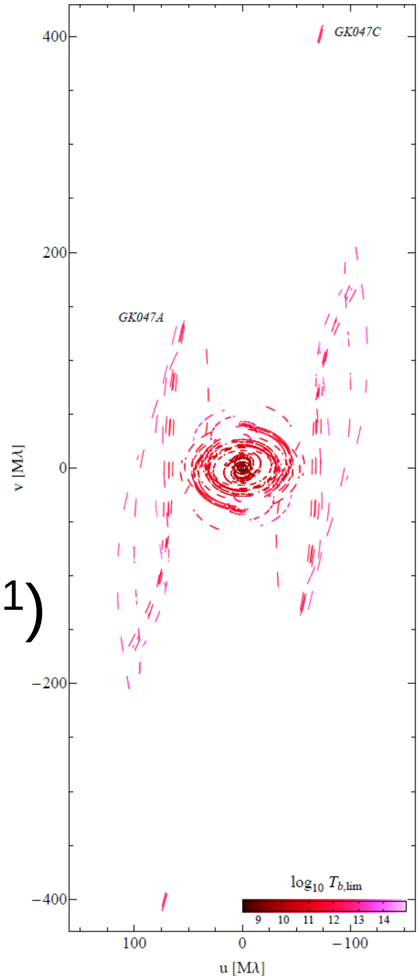
T_b Estimates from Visibilities

- RadioAstron has limited imaging capability -- hence need to be able to estimate T_b directly from the visibility amplitudes

- Interferometrist's luck: $V(q)$ = **F** $I(r)$

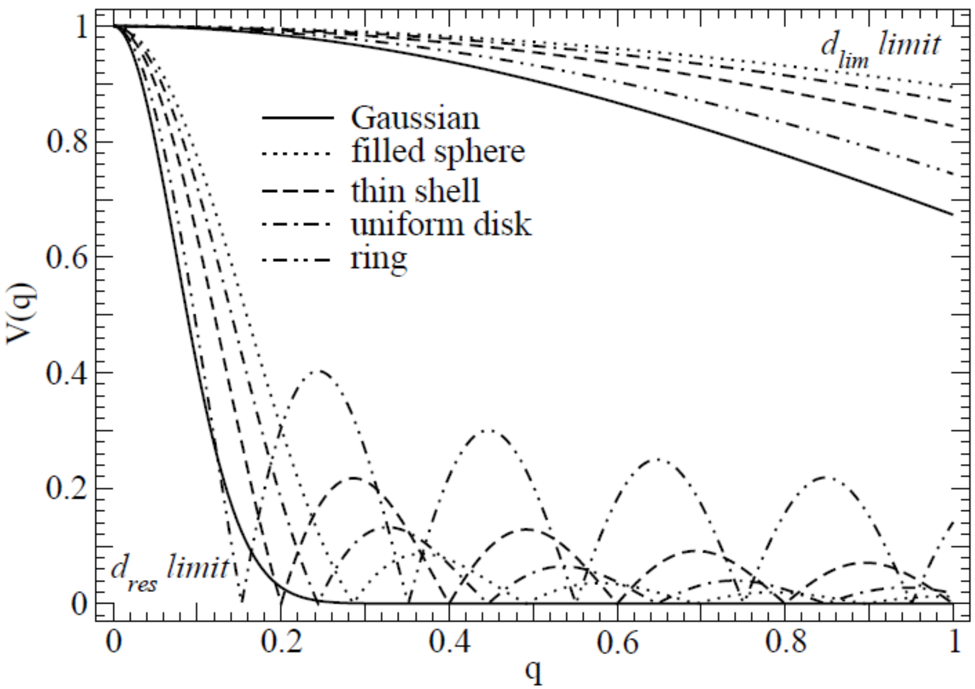
  Measure S (proxied by V) and θ (proxied by q^{-1}) with every single visibility.

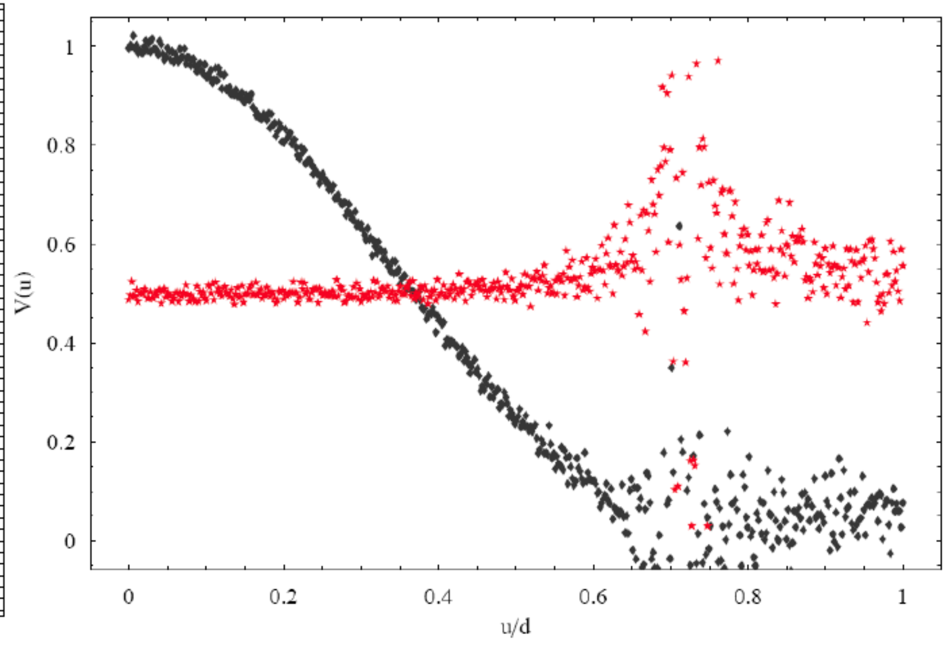
- Can then obtain robust limits on brightness temperature, if reasonable assumptions about zero spacing flux density, V_0, are made.



That Darn $V(q) = V_q \exp(-i\phi_q)$

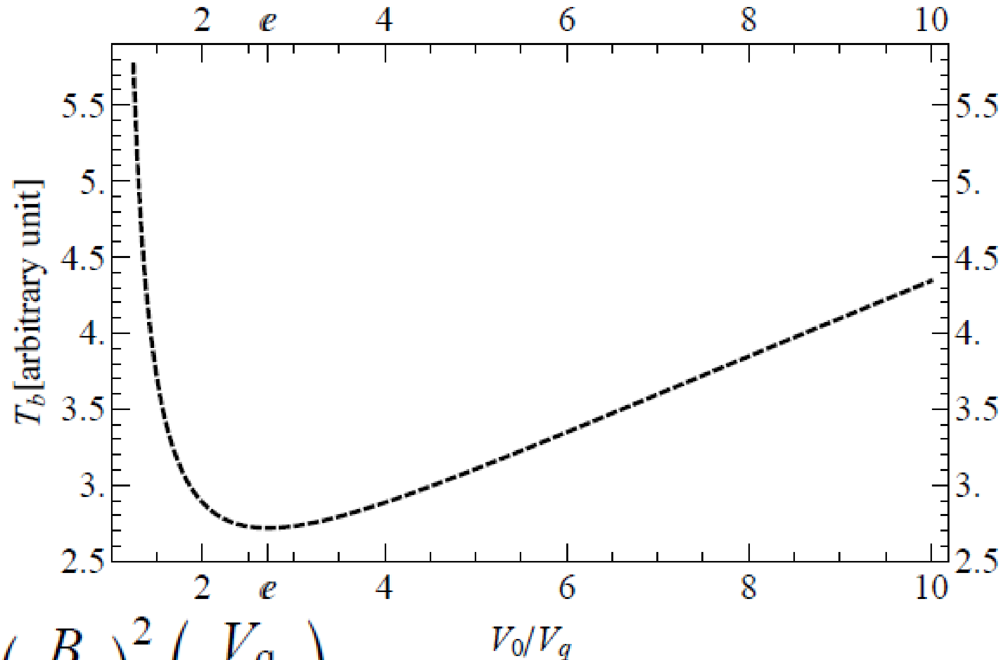
- ... comes in different shapes, and is also noisy (σ_q)
- Hence you need to know something about $V(q)$ at least at two different values of q. For instance, $V_0 = V(q)|_{q=0}$.
- Then you can use $V_q < V_0$ and $V_q + \sigma_q \le V_0$ to constrain T_b.





Minimum Brightness Temperature

- For a measured V_q, is there V_0 that minimizes T_b?
- Indeed, there is always a minimum of T_b, realized for some $V_0 > V_q$, since $T_b \to \infty$ for $V_0 \to V_q$ and $V_0 \to \infty$.
- It's at $V_0 = e\, V_q$ for the Gaussian.
- So, for a given V_q, you cannot get brightness temperature smaller than

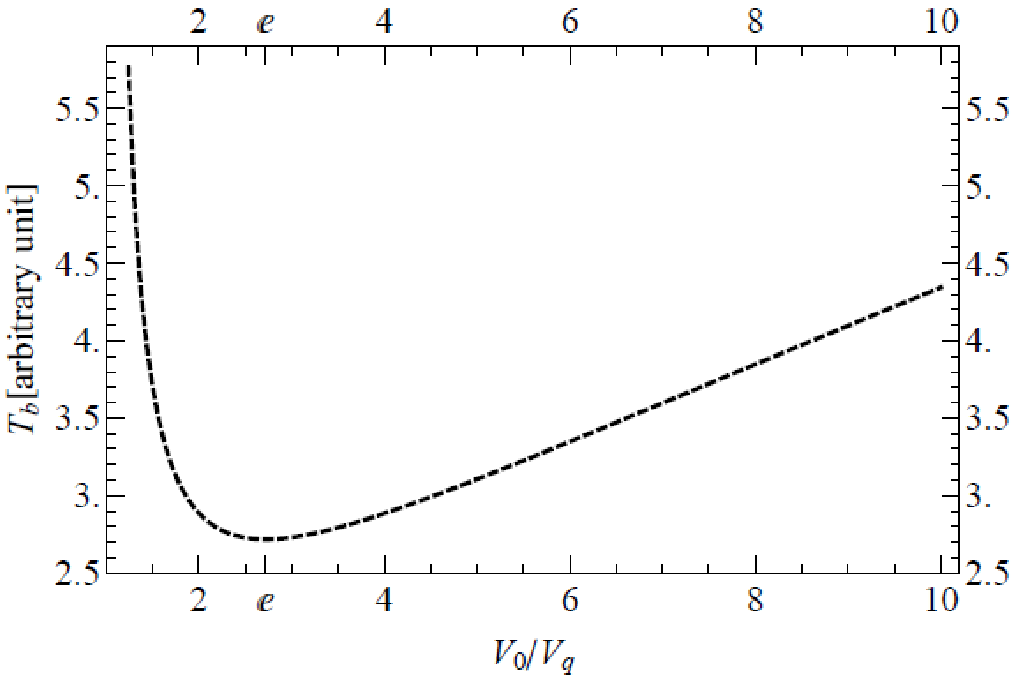


$$T_{\rm b,min} = \frac{\pi\, e}{2k} B^2\, V_{\rm q} \approx 3.09 \left(\frac{B}{\rm km}\right)^2 \left(\frac{V_{\rm q}}{\rm mJy}\right) [\rm K]$$

Maximum T_b for Resolved Emission

- Viable $T_{b,max}$ while going away from $V_0 = e\, V_q$?

- Possible answers:
  $V_0 \rightarrow \infty$ (unphysical)
  $V_0 = S_{tot}$ (not good)
  $V_0 = V_q + \sigma_q$ (perhaps, the better one)



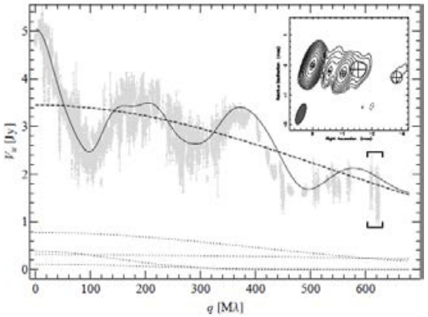
- Then, you'd get:

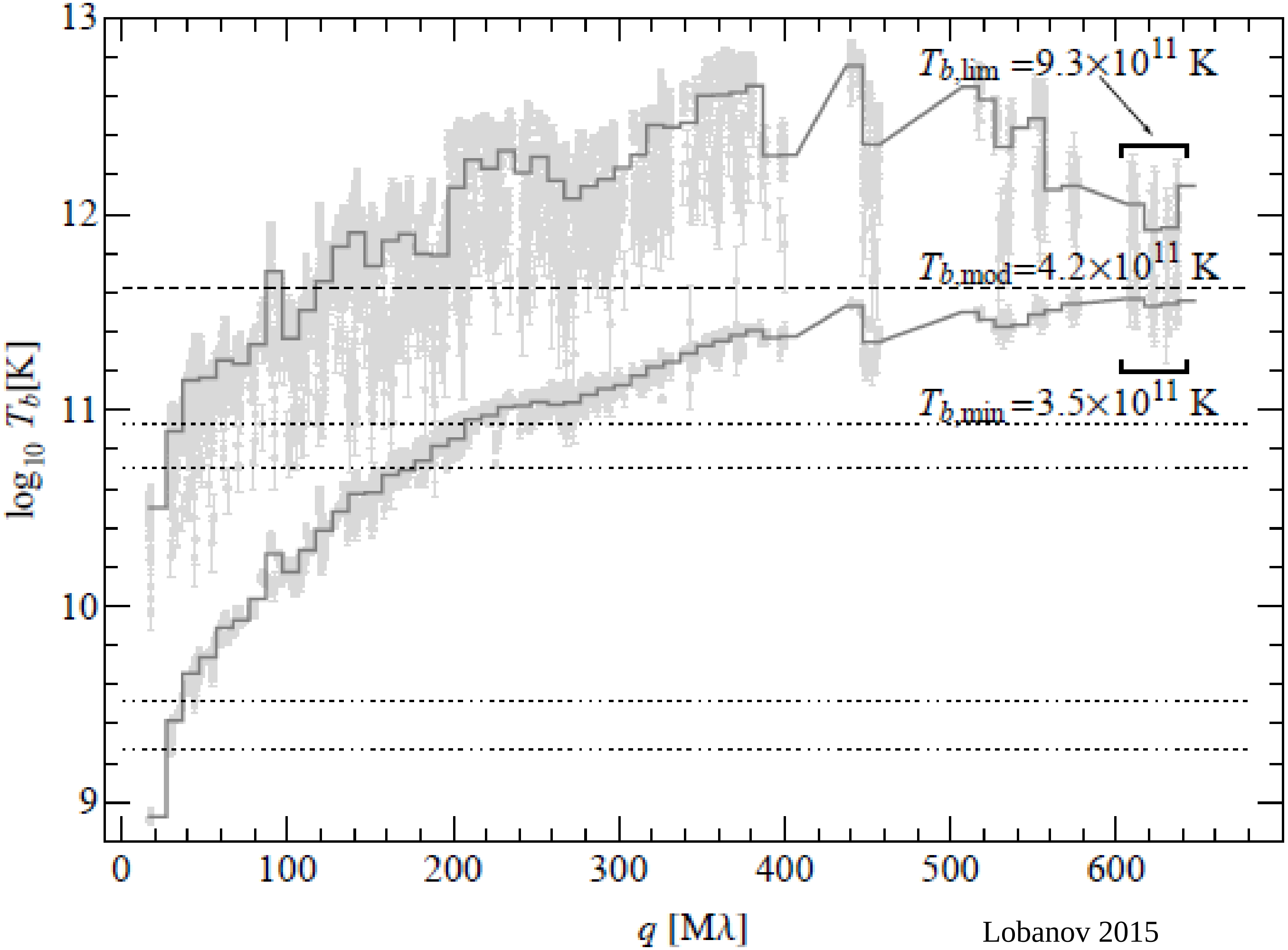
$$T_{\rm b,lim} = \frac{\pi B^2 (V_{\rm q} + \sigma_{\rm q})}{2k} \left[\ln \frac{V_{\rm q} + \sigma_{\rm q}}{V_{\rm q}} \right]^{-1}$$

$$= 1.14 \left(\frac{V_{\rm q} + \sigma_{\rm q}}{\rm mJy} \right) \left(\frac{B}{\rm km} \right)^2 \left(\ln \frac{V_{\rm q} + \sigma_{\rm q}}{V_{\rm q}} \right)^{-1} \ [{\rm K}]$$

Brightness Temperature Runs

- „True“ T_b is well within the ($T_{b,min}$,$T_{b,lim}$) bracket, at all q > 200Mλ. Hence a useful tool for the RA AGN survey.

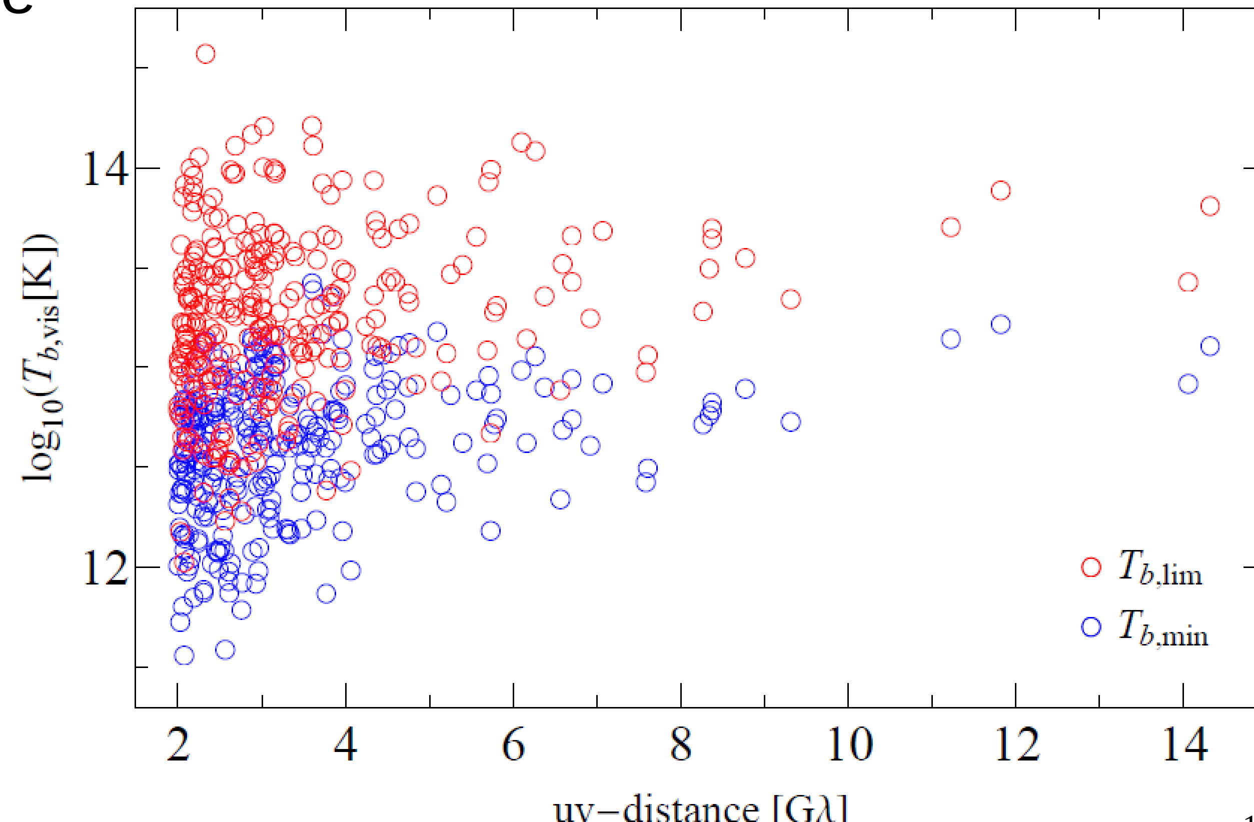




What Do We Get from RadioAstron?

- Most of the AGN imaged/modelfitted with RA show $T_{b,min} \geq 10^{13}$ K and $T_{b,lim} \geq 10^{14}$ K (cf., Kovalev+2016, Lobanov+2015, Gómez+ 2015)

- Similar results are coming from the visibility based estimates made from the RA survey data.



New Physics at the Brightness Limit?

- RadioAstron measurements indicate that violation of the IC limit on T_b may be rather common in AGN
- Let's see what can we do to get those high T_b values:

	$T_b \sim 10^{12}$ K	$T_b \gg 10^{12}$ K
Emitting particles:	$e^- e^+$	$e^- p^+$
Emission:	incoherent	coherent
Particle distribution:	power law	-> monoenergetic
Physical conditions:	~ equilibrium	continued injection
Geometrical conditions:	outside of jet cone	inside of jet cone

- The right column could very well describe... a pulsar (!) or, generically, a highly magnetized object. If so, we may expect high T_b to be accompanied by high magnetic field.

What if You Crank Up the *B*?

- Taking a look at a „normal“ IC-loss dominated plasma in a strong magnetic field gives:

$$T_{b,max} \sim 7 \times 10^9\ \mathrm{K}\ \left(\frac{B^{3/4}}{\mathrm{G}}\right)$$

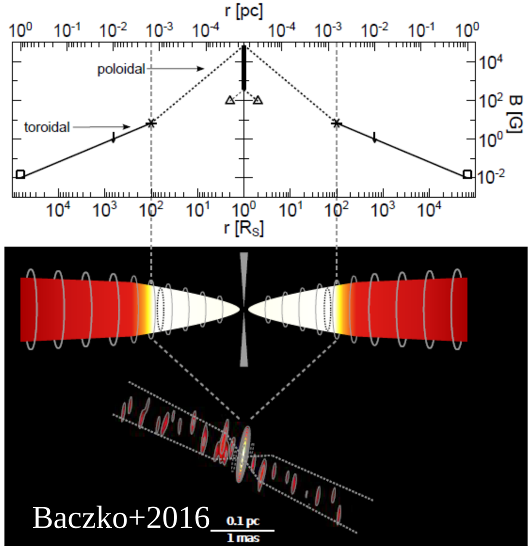
- This, of course, implies a sky-rocketing $\nu_m \propto B^{1/2}$.

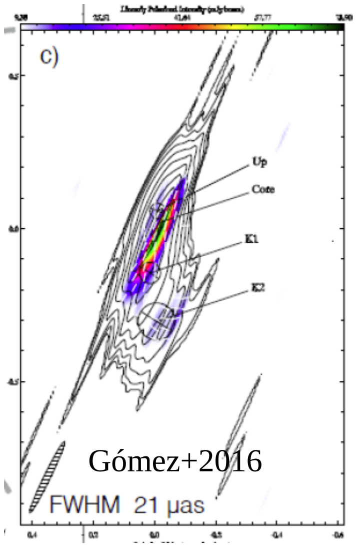
- However, the rogue ν_m can be kept low if the plasma particle density $N_0 \propto B^{-7/2}$.

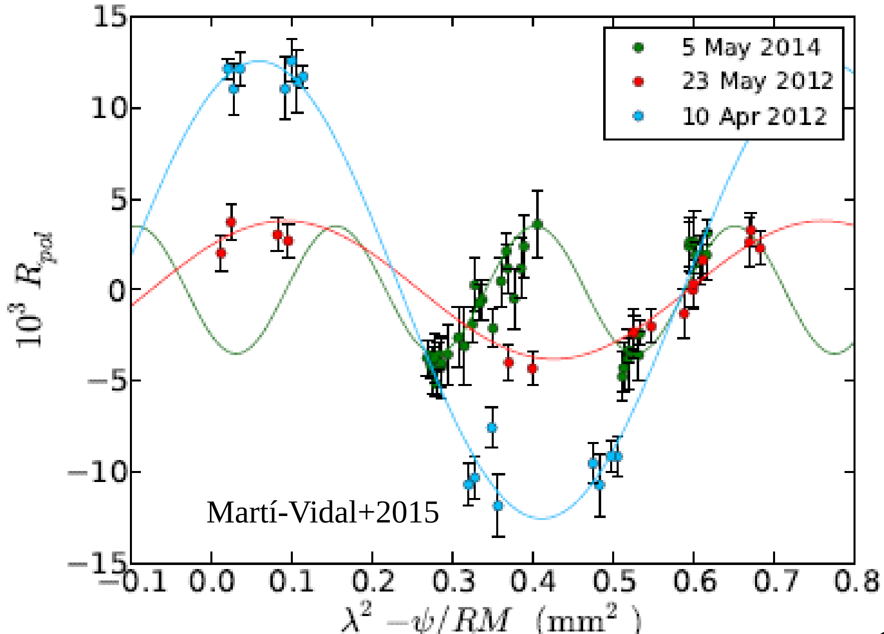
- This is actualy pretty feasible for:
  – a „runaway“ cell in a turbulent flow;
  – a BZ beam inside of BP jet;
  – a truly „indigenous“ pair creation (for $B > 10^{13}$ G)

Where Else Can Those B-fields Hide?

- In the collimation profiles of inner jet (NGC1052, Baczko+2016) $B > 10^4$ G
- In extremely well structured polarization (Gómez+2016), pointing towards a radial B-field.
- In extreme opacity profiles (e.g. IC 310, Schulz+2016), $B > 10^4$ G
- In extremely high rotation measures (Martí-Vidal+ 2015), RM > 10^8 rad/m^2

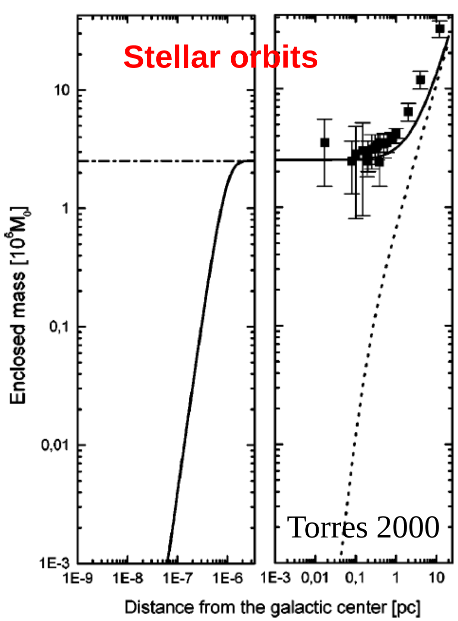


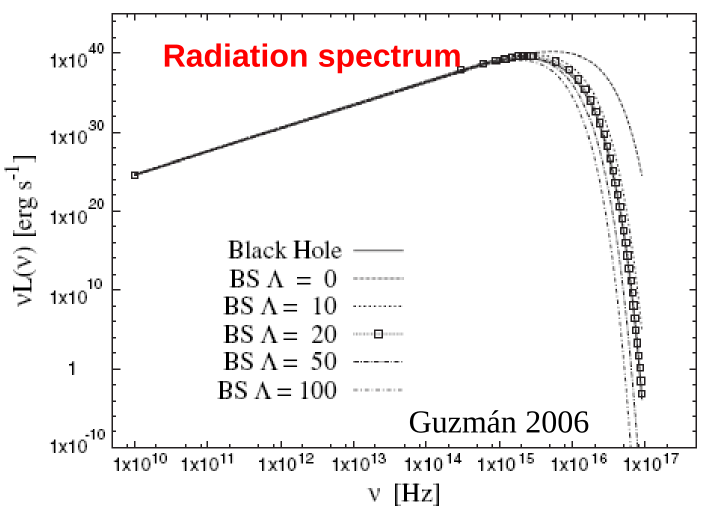


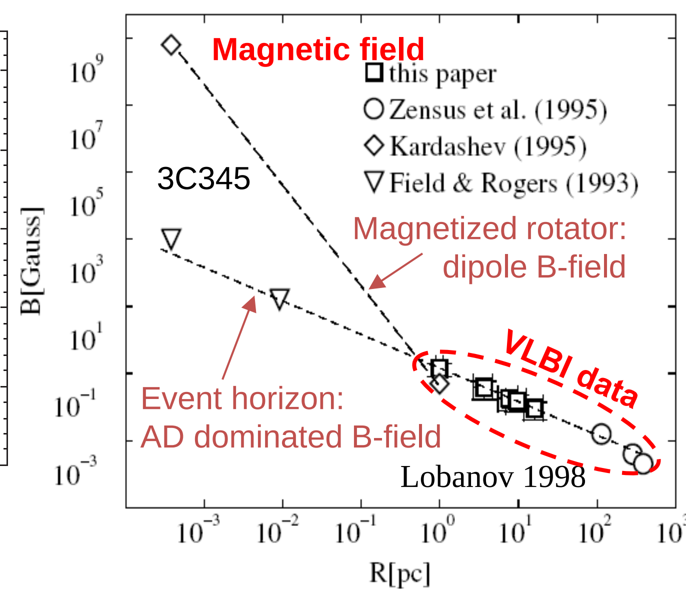


Fifty Shades of... Black?

- Present evidence does not strictly prove existence of BH.
- Need to devise instruments and experiments to distinguish effectively between BH and their alternatives (gravastars, wormholes, MECO):
  - **stellar orbits:** (S1, Sgr A*) good enough for BH vs. ν condensate tests
  - **radiation spectrum:** high energies (BH vs. BS), ELF (BH vs. MECO)
  - **gravitation waves:** BH vs. anything (but need accurate templates)
  - **VLBI:** 2D imaging (BH vs. BS/MECO?), B-field (BH vs MECO)







Summary: *B*s and T_bs in AGN

- The RA estimates of $T_{b,min}$ suggest B > 10^5 G.
- Good evidence for B~ 10^3—10^4 G in the nuclear region (Baczko+ 2016).
- Perhaps even stronger fields are implied by RM > 10^8 rad/m^2 measured with ALMA (Marti-Vidal+ 2015).
- Even higher magnetic fields can be expected for exotic objects such as magnetized rotators (Kardashev 1995), wormholes (Novikov, Kardashev, Shatskiy 2006), or gravastars (Mazur & Mottola 2001).
- The quest for understanding the high T_b -- and the actual physical conditions near the event horizon scales – must therefore continue!