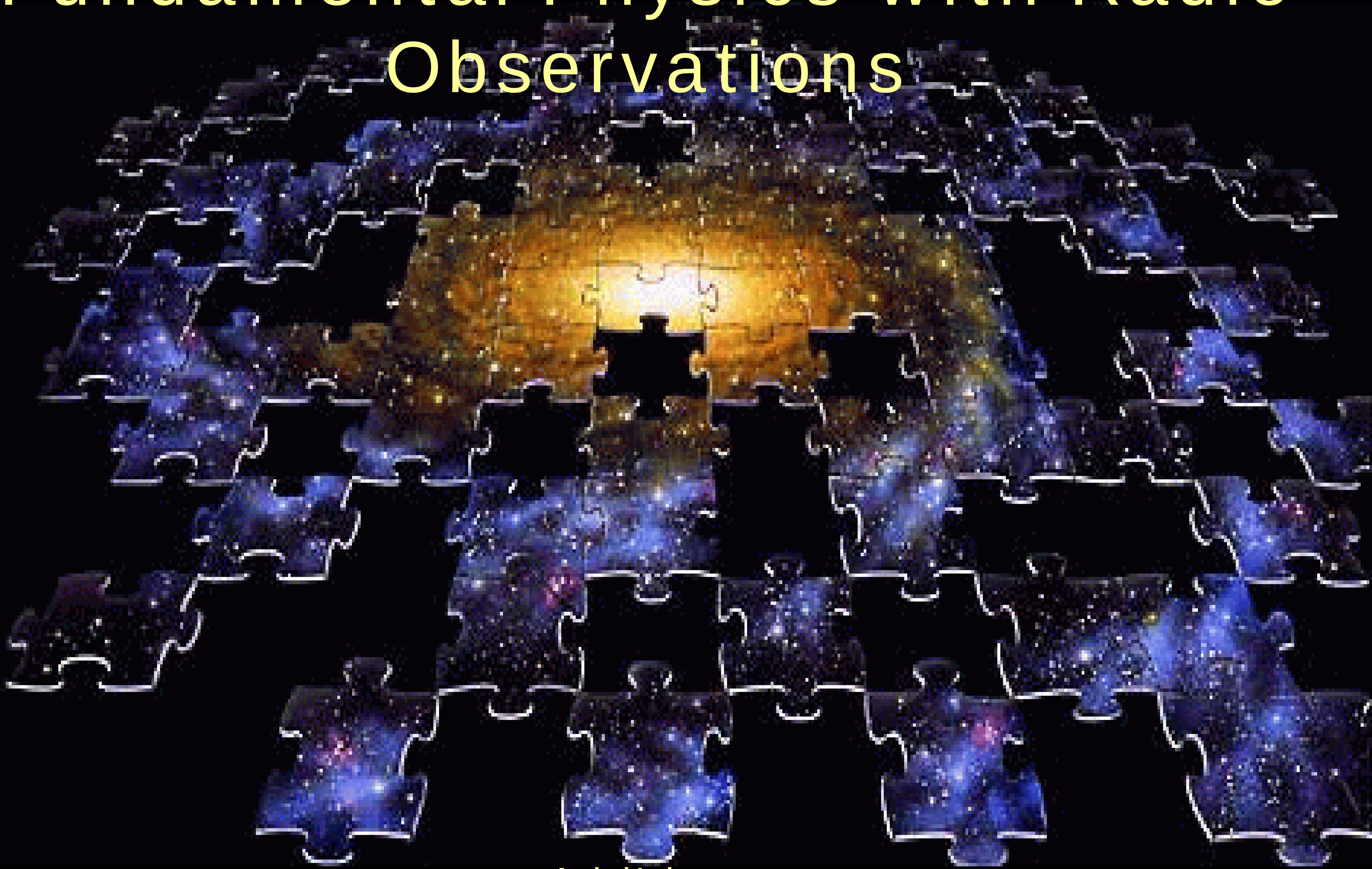
Fundamental Physics with Radio Observations



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Motivation

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- Using cosmos as a fundamental physics lab has its advantages... and its shortcomings as well.
- Astrophysical observations are highly complementary to laboratory experiments – as underlined by the continued success of astroparticle physics.
- New facilities in (radio) astronomy will further broaden the cross-section between studies of cosmos and research in fundamental physics.
- Examples of such „emerging“ areas of research which should blossom in the coming decade include:
  – detection of event horizon,
  – constraining the properties of dark matter, and
  – studies of weakly interacting particles

Nature as Physics Lab

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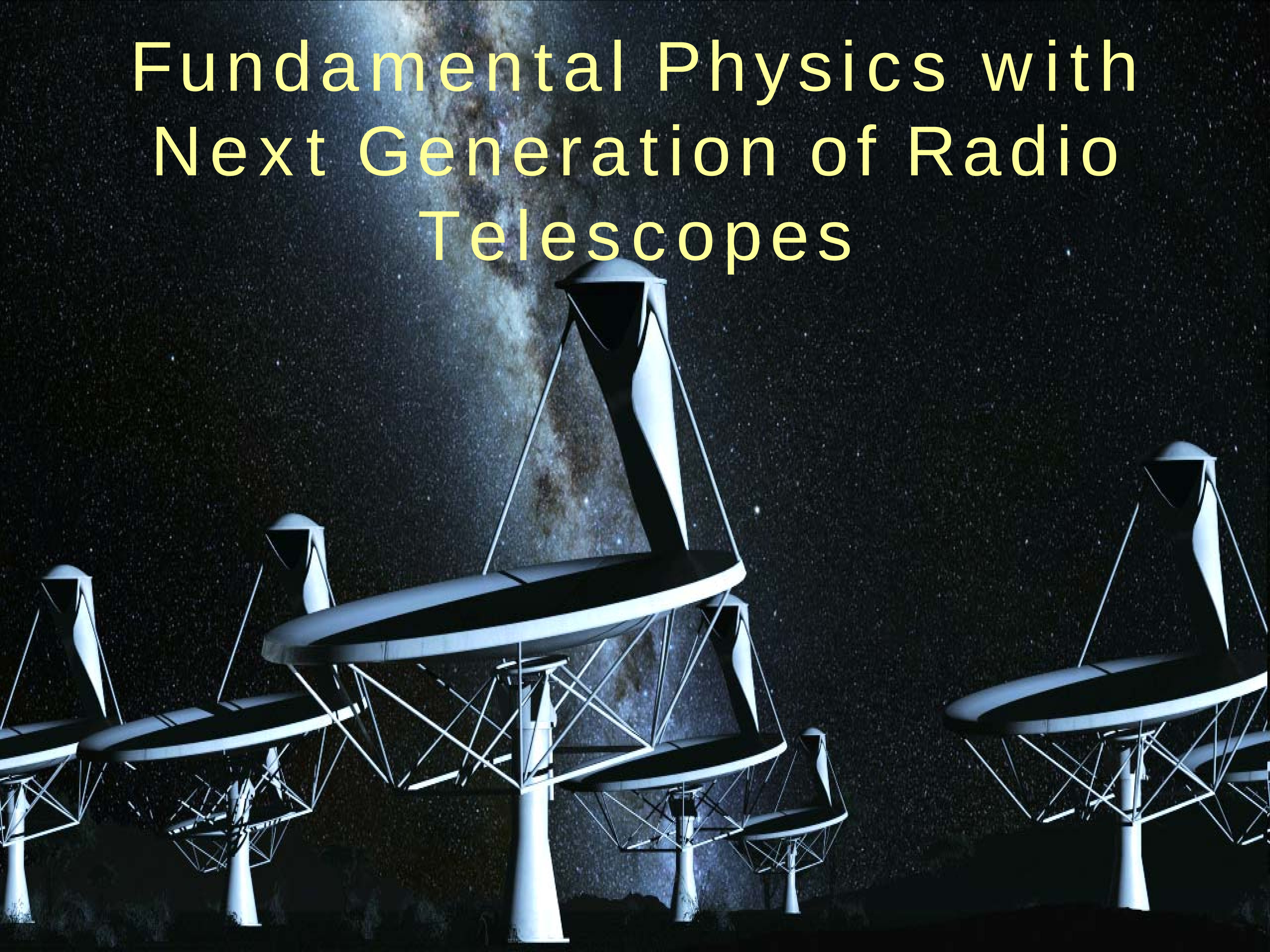
- Nature provides a „natural“ extension to laboratory, but leaves us virtually no opportunity to tweak the „experimental setup“.

Quantity	**Laboratory**	**Space**
Energy	100 GeV (electrons) 3.5 (7) TeV (hadrons)	10^8 TeV (cosmic rays)
Magnetic field	97.4 T (pulsed) 45 T (continuous)	10^8 T (pulsars) 10^{12} T (magnetars)
Vacuum	100 cm^{-3}	10^{-4} cm^{-3} (typical IGM)
Temperature	2×10^9 K	10^9 K (SN I) 10^{11} K (SN II)
Brightness	10^{12} K (average) 10^{20} K (peak)	10^{12} K (incoherent) 10^{21} K (coherent)
Dimensions	~10 km	~10^{19} km

Radio Goes Fundamental

- Fundamental physics is prime science for next generation instruments.
- Emerging fields in the radio: Dark matter annihilation and Hidden particles.
- Addressing supersymmetry and string extensions of the standard model via searches for weakly interacting particles.
- Targets: 1) WIMP neutralinos and gravitinos
  2) WISP hidden photons and (perhaps) axions.
- Strengths: 1) resolved DM annihilation signal only seen in radio
  2) unique range of axion/photon masses probed by radio.
- Status: 1) work started on DM in dSph galaxies and Fermi UFOs
  2) early results from hidden photon searches in SNR
  3) preparing for axion searches in radio regime

Fundamental Physics with Next Generation of Radio Telescopes



Key Science in Radio

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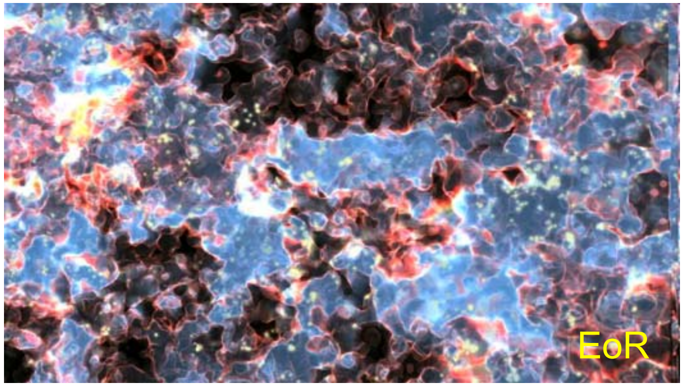
- Key Science Areas in radio include:
  - -- Epoch of reionisation (LOFAR/SKA)
  - -- Event horizon (VLBI)
  - -- Gravitational waves (SKA)
  - -- GR tests (SKA/LOFAR)
  - -- Dark matter & dark energy (SKA)

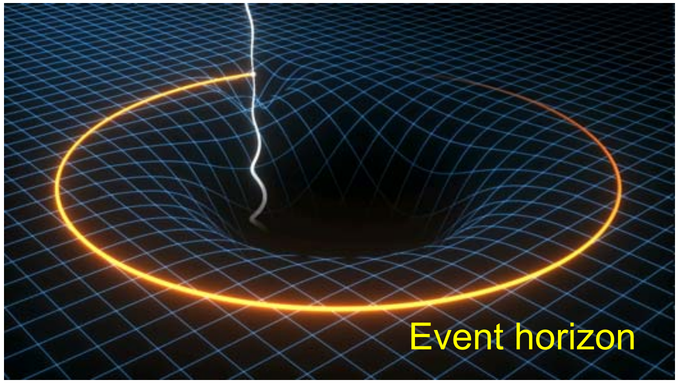


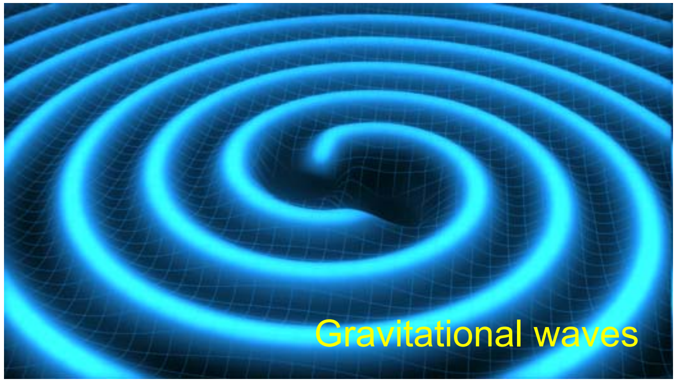
Emerging fields of study in the radio:

-- EM signals from DM annihilation

-- “hidden” particles.

Promoted as key science topics by the European SKA Science Working Group



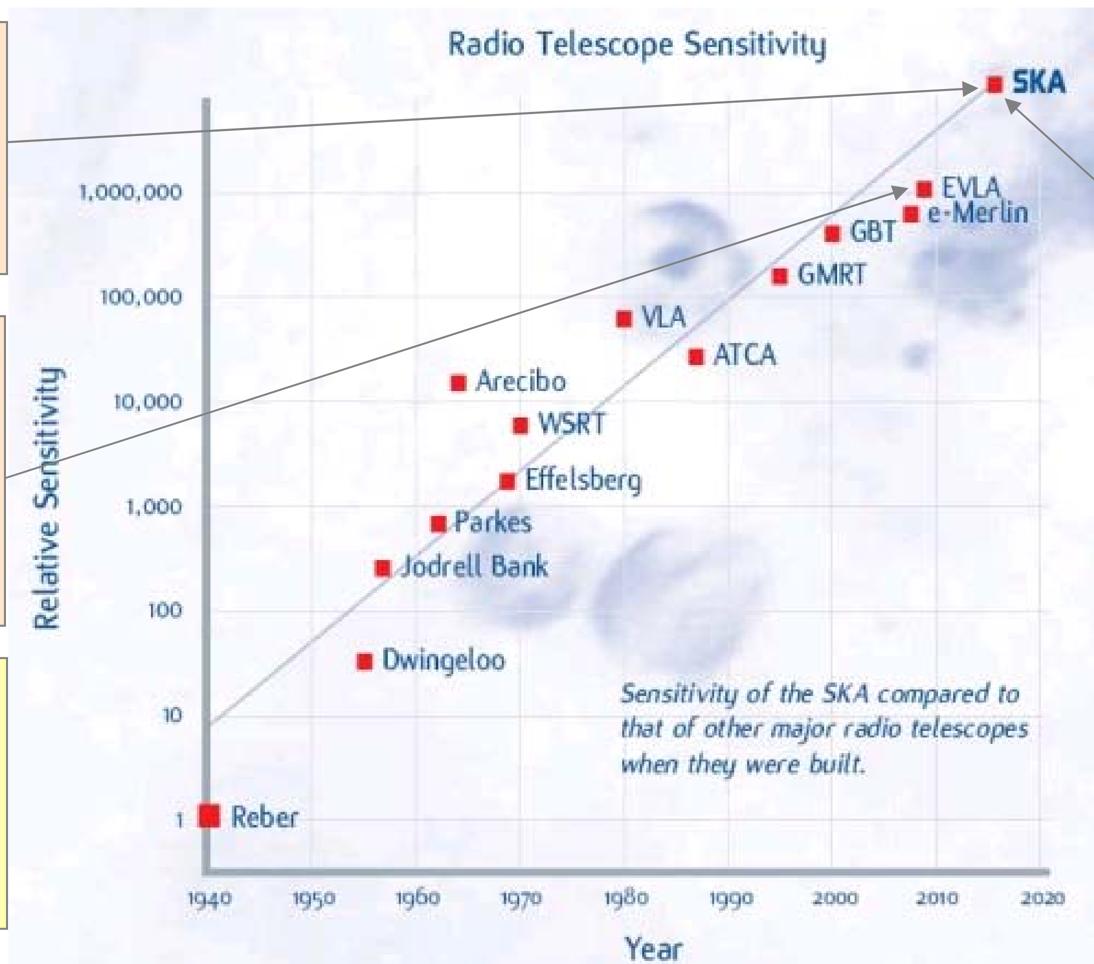


Quest of Radio Astronomy

- In the 0.03-1440 GHz range, LOFAR, EVLA, eMERLIN, ALMA,MeerKAT, ASKAP, and SKA push sensitivity,spectral resolution and survey speed by several orders of magnitude

Detecting transient events at a time resolution of 1 nanosecond

Reaching spectral resolution of 0.12 Hz (velocity resolution of ~1 cm/s)



Picking up an airport radar on a planet 50 light years away.

VHE:
1 OMG (10^{20} eV) particle ≈ a tennis ball at 100 km/h

Radio:
70 years of observations < a falling snowflake

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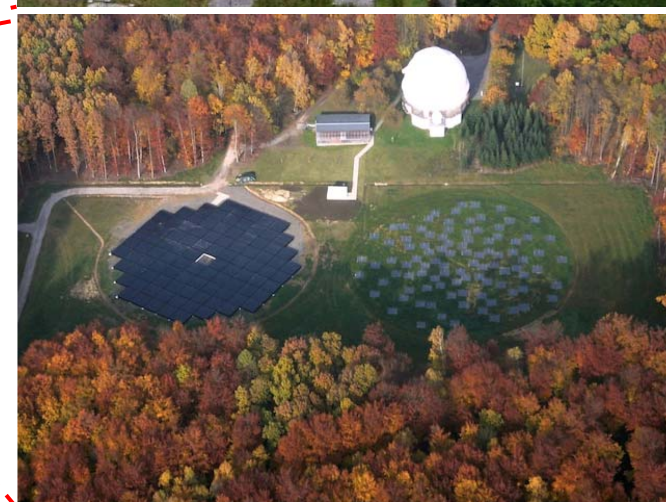
Expanding the Limits

- LOFAR expands the frequency coverage down to 30 MHz (λ=10 m), from ~300 MHz presently used at most radio interferometers.

German stations (and the planned station in Hamburg in particular) are important for increasing the resolution and improving the calibration and image quality of LOFAR observations.



Images from LOFAR

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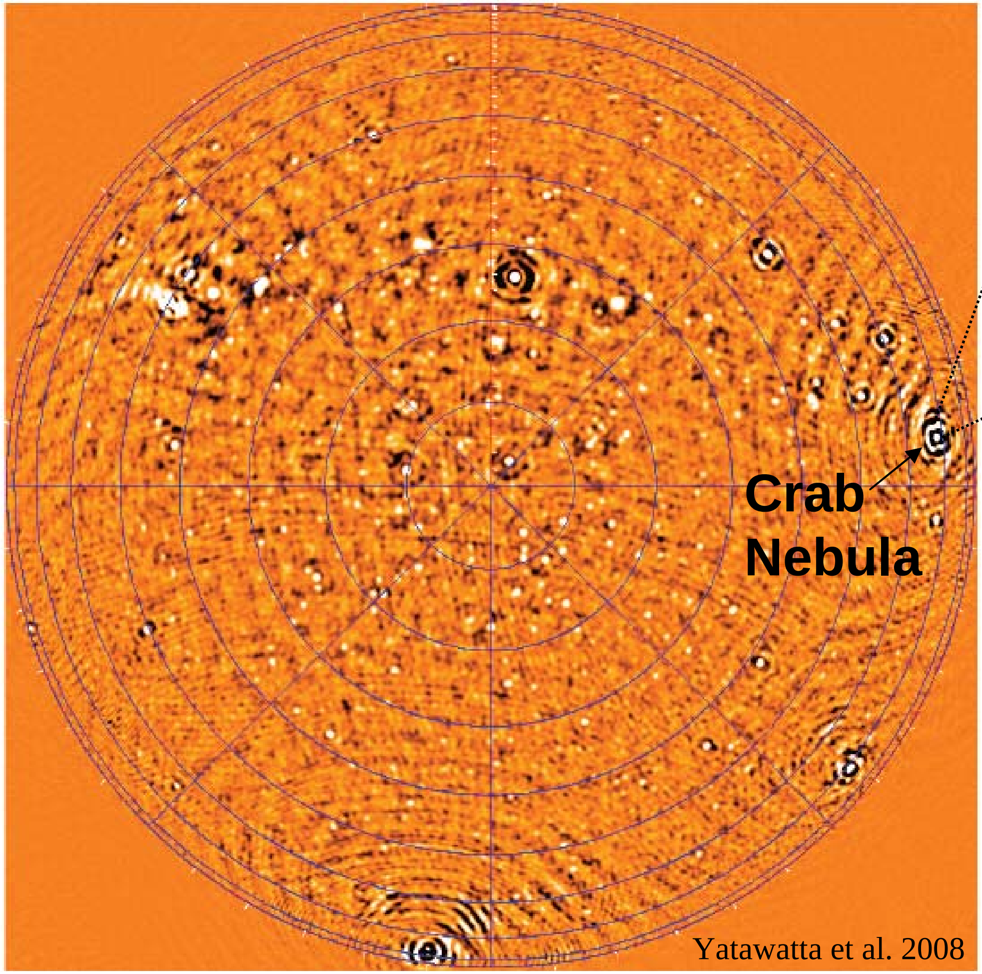
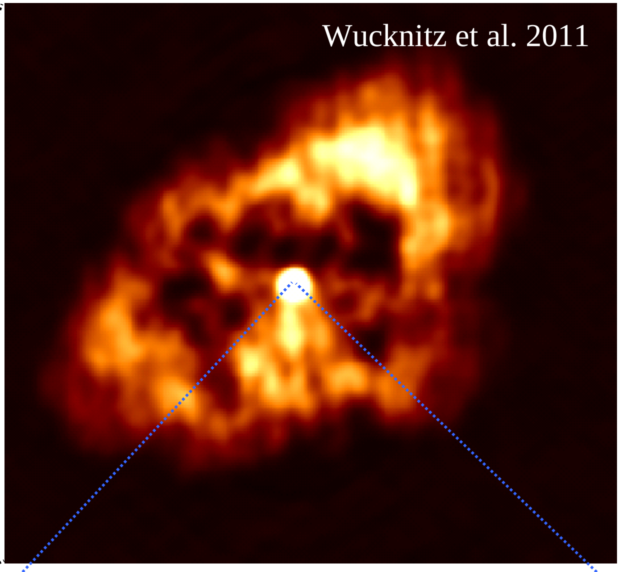
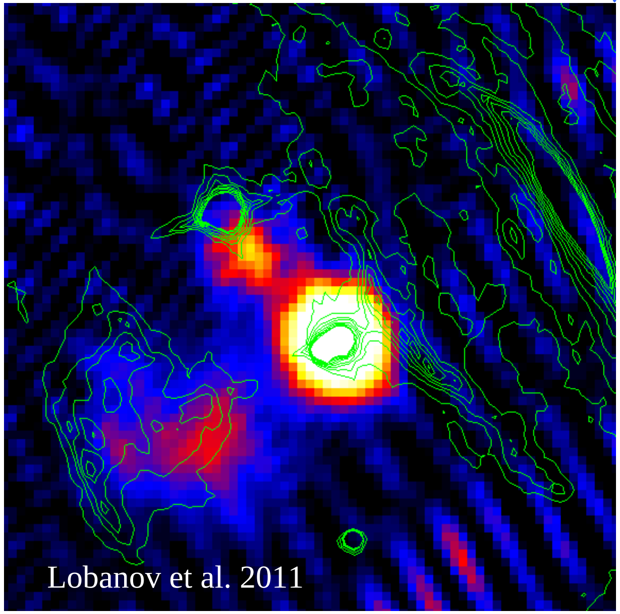
- LOFAR already delivers good images, with baselines to German stations being essential for achieving good image quality.



Yatawatta et al. 2008



Wucknitz et al. 2011



Lobanov et al. 2011

Radio Interferometry

- Reaching higher sensitivity and angular resolution of astronomical instruments are among the main technological drives in astronomy

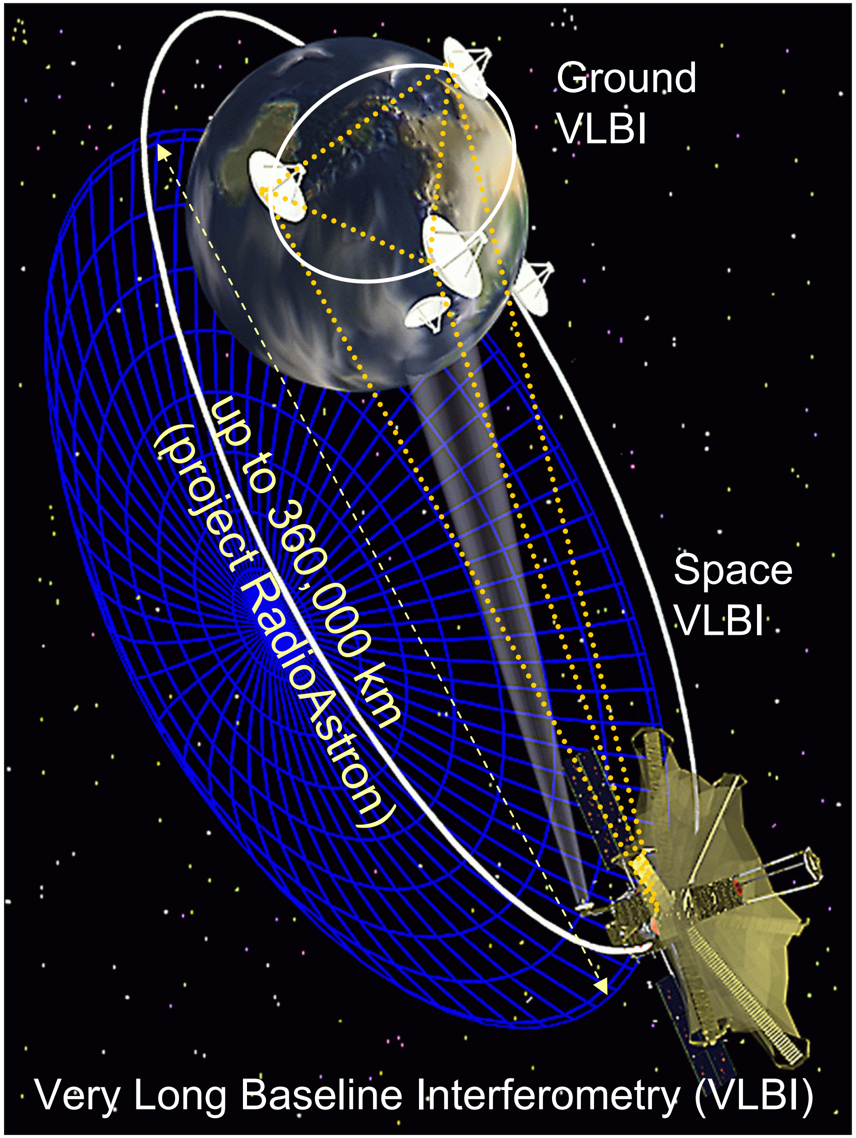
- **Modern radio interferometers** operate at wavelengths of 0.2–90 cm, combining antennas across the Earth and on board of spacecraft:

  Sensitivity is determined by sum of the areas of individual antennas.

$$\sigma_{im} \propto 1 / \sum D_i^2$$

  Resolution is driven by the largest separation between the antennas.

$$\theta_{im} \approx \lambda_{obs} / B_{\max}$$



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Angular Resolution

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Highest resolution is on highest demand.

Gravitational radius:

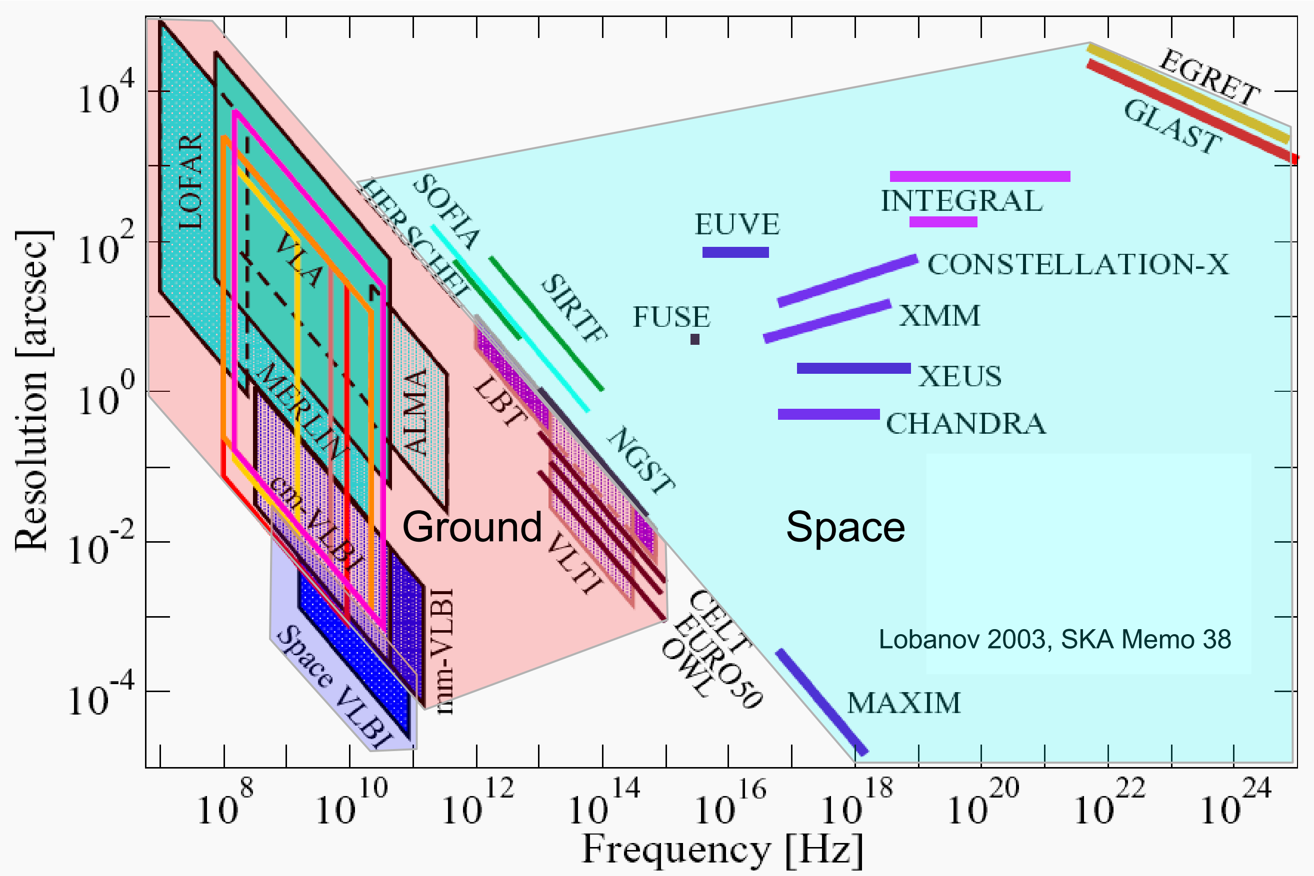
1 nas in AGN:
$M_{bh}=10^8\,M_{sun}$ at 1 Gpc

0.1 nas in XRB:

$M_{bh}=10\,M_{sun}$ at 1kpc

2 µas in M87

5 µas in Sgr A*

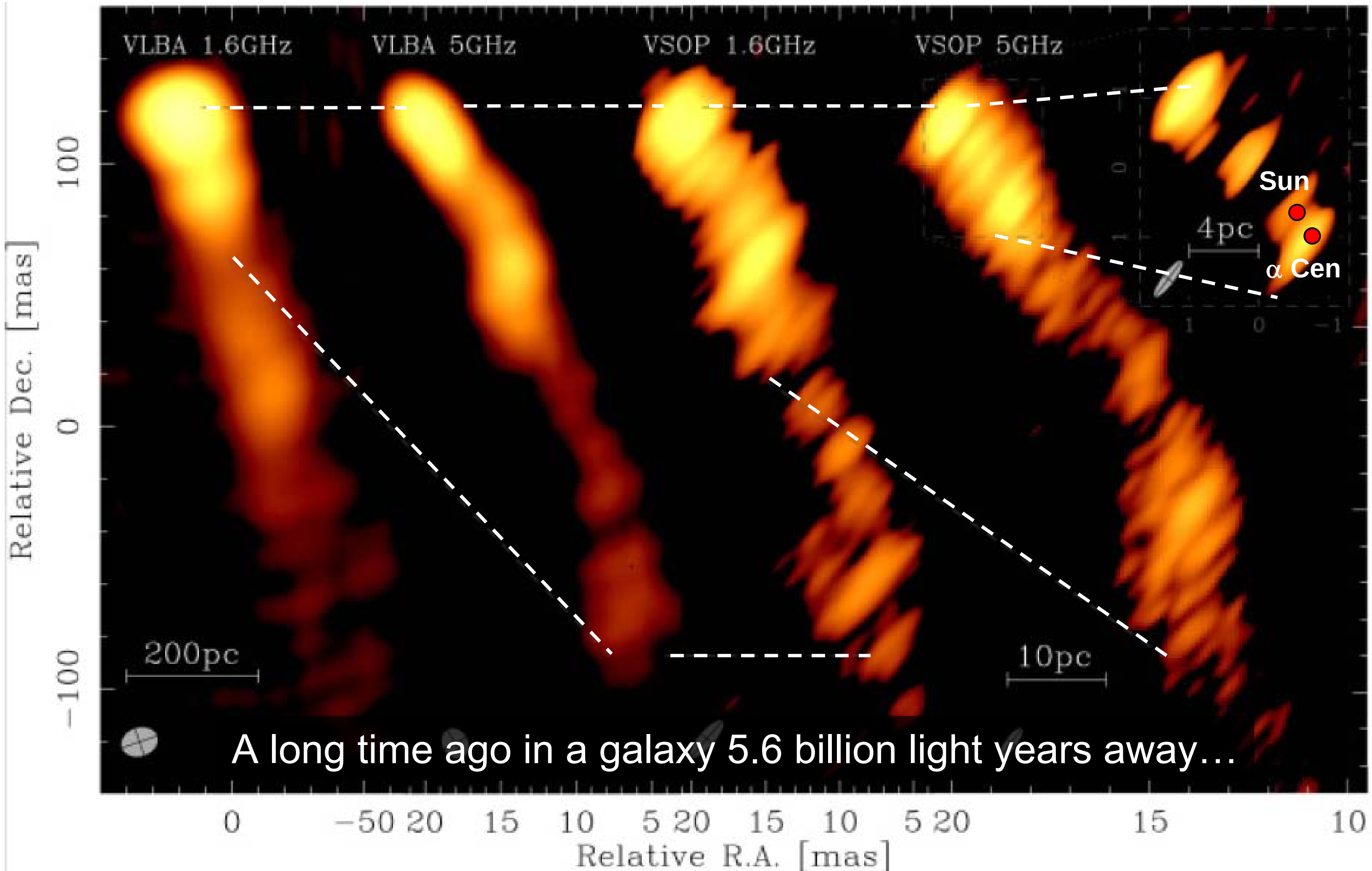


Radio interferometry: approaching 10 µas, aiming at 1 µas

1 milliarcsecond – a man on the Moon
1 microarcsecond – a child on the Sun
1 nanoarcsecond – a football field on... Alpha Centauri

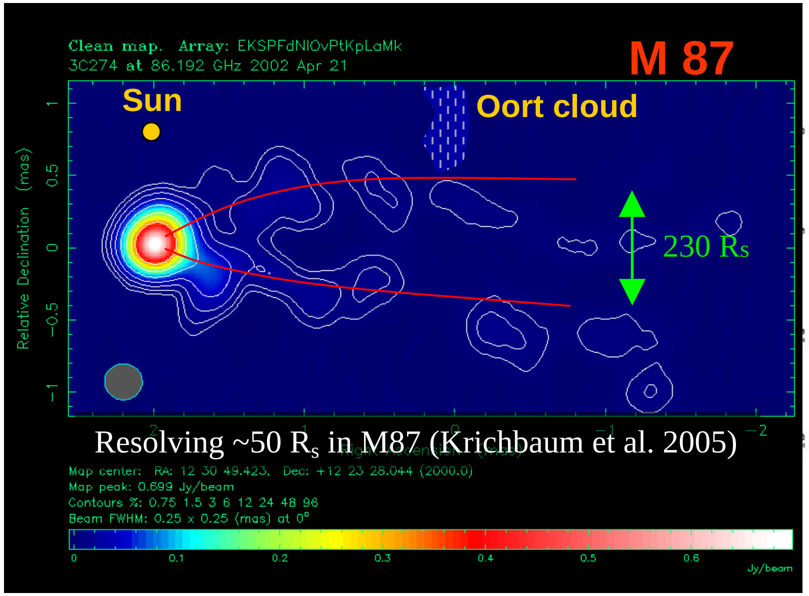
VLBI on Radio Jets

- VLBI observations probe a range of angular scales, enabling detailed studies of morphology, kinematics, and emission in extragalactic jets

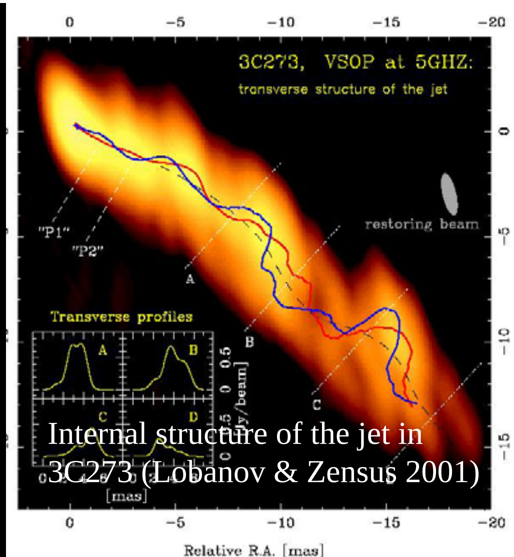


Radio Interferometry on AGN

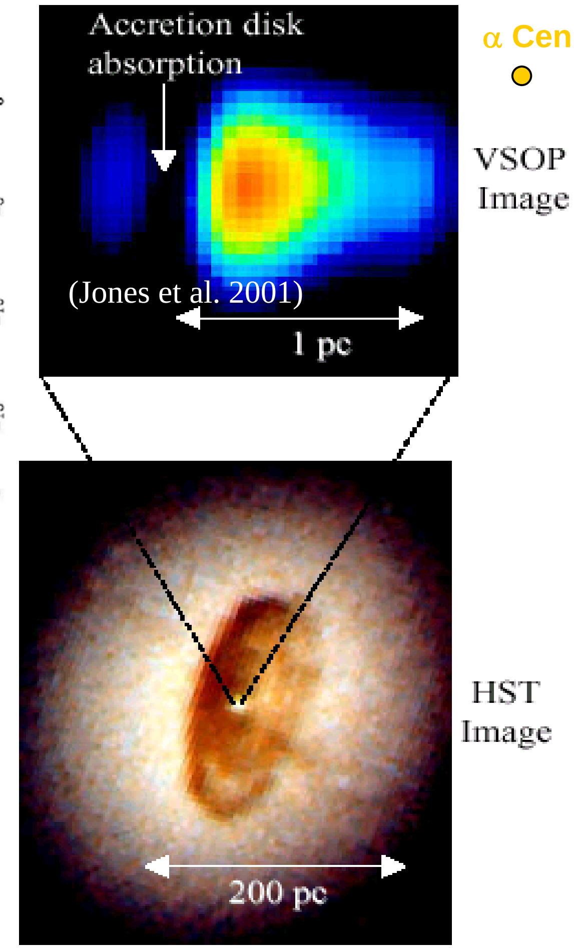
- ❑ Interferometry is a powerful tool for AGN studies on sub-pc and pc scales.



Resolving ~50 R_s in M87 (Krichbaum et al. 2005)

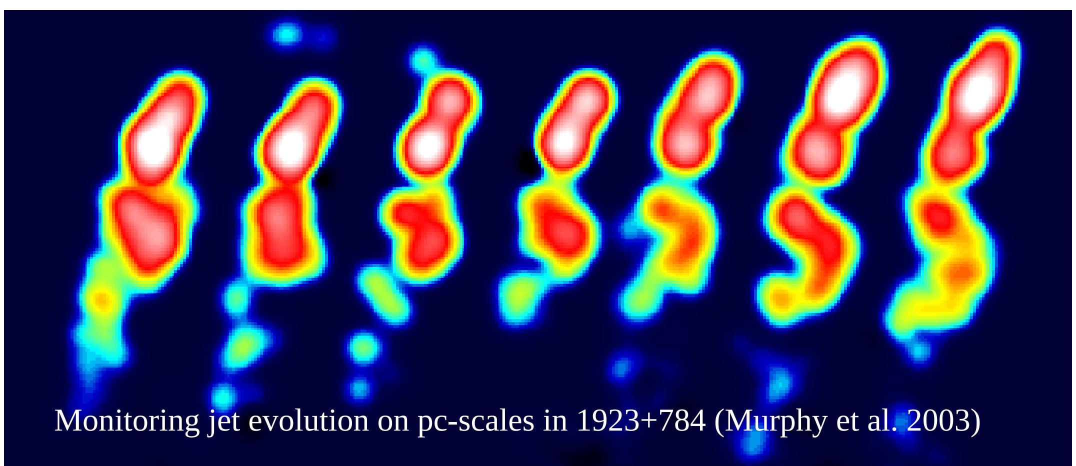


Internal structure of the jet in 3C273 (Lobanov & Zensus 2001)



(Jones et al. 2001)

Accretion Disk in NGC 4261



Monitoring jet evolution on pc-scales in 1923+784 (Murphy et al. 2003)


Towards the Event Horizon

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Vicinity of Black Holes

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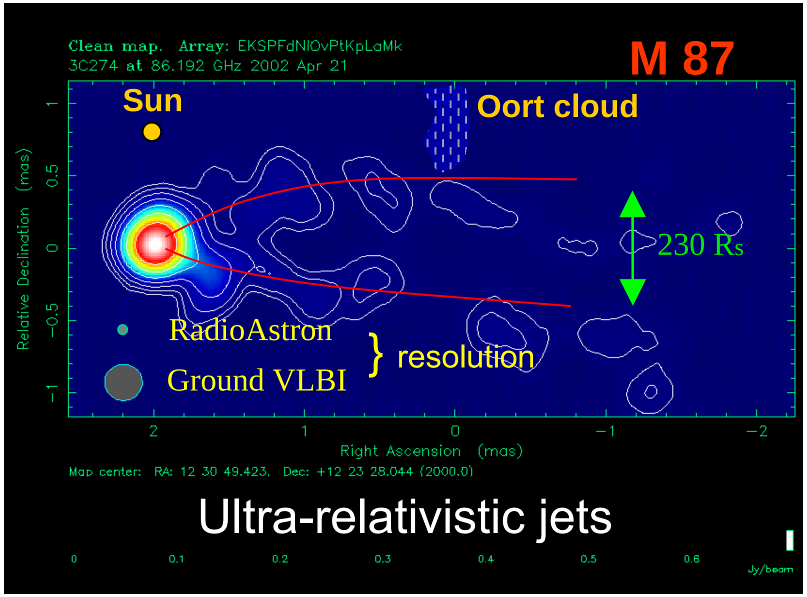
- Radio interferometry provides direct imaging of hot material in relativistic jets and accretion disks in the vicinity of SMBH: acceleration and collimation of jets; relativistic effects near the event horizon scale, R_S.

– **Sgr A***: R_S ~ 10 μas; **M87**: R_S ~ 4 μas; a BH "shadow" size ~30 μas.

– RadioAstron: ~10 μas at 22 GHz
– VSOP-2: ~40 μas at 43 GHz
– mm-VLBI: ~20 μas at 230 GHz

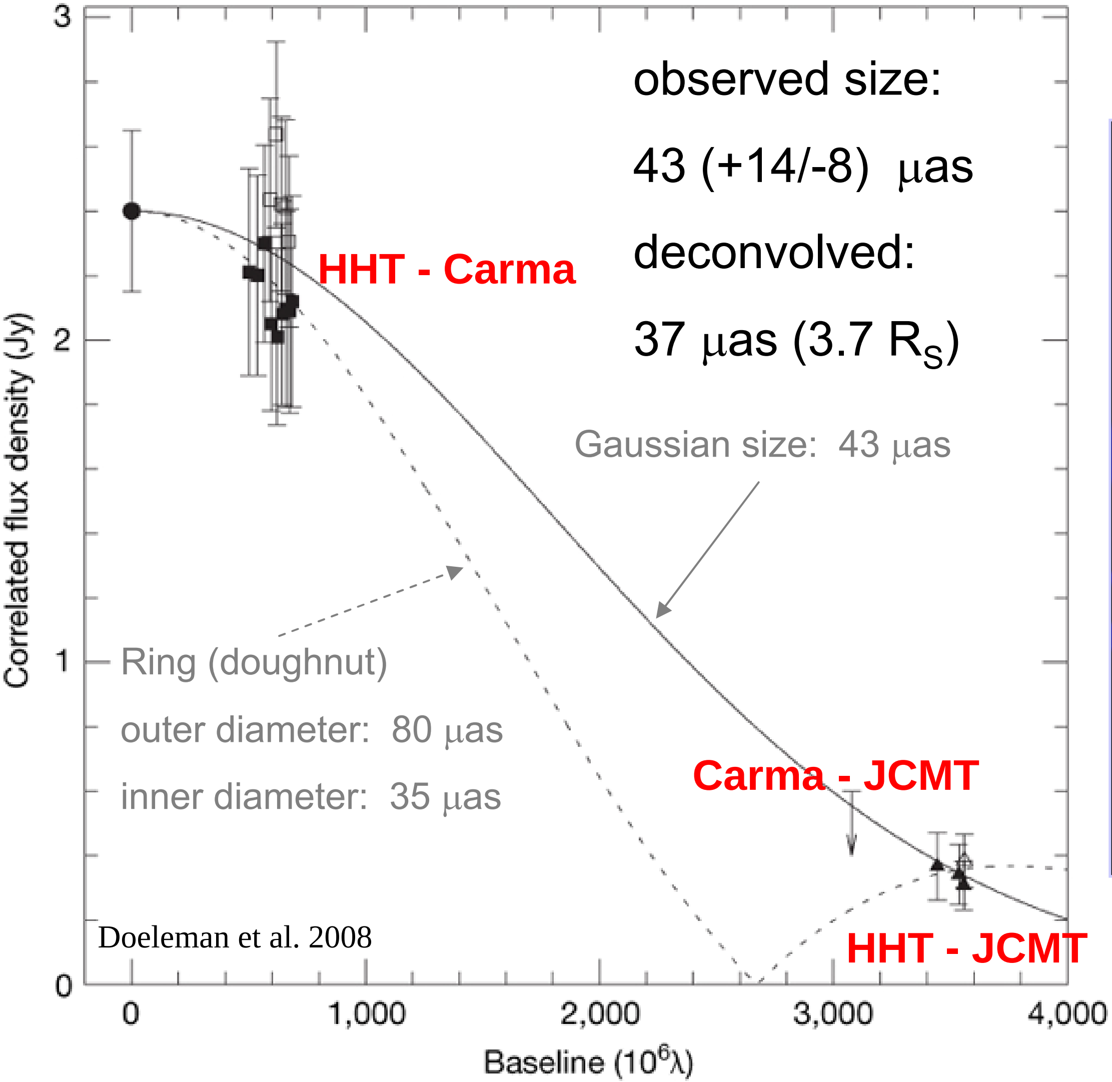

Extreme vicinity of supermassive black holes



Ultra-relativistic jets

Towards the Event Horizon

- VLBI observations at 230 GHz (1.3 mm) probe a $4R_S$ scale in Sgr A*



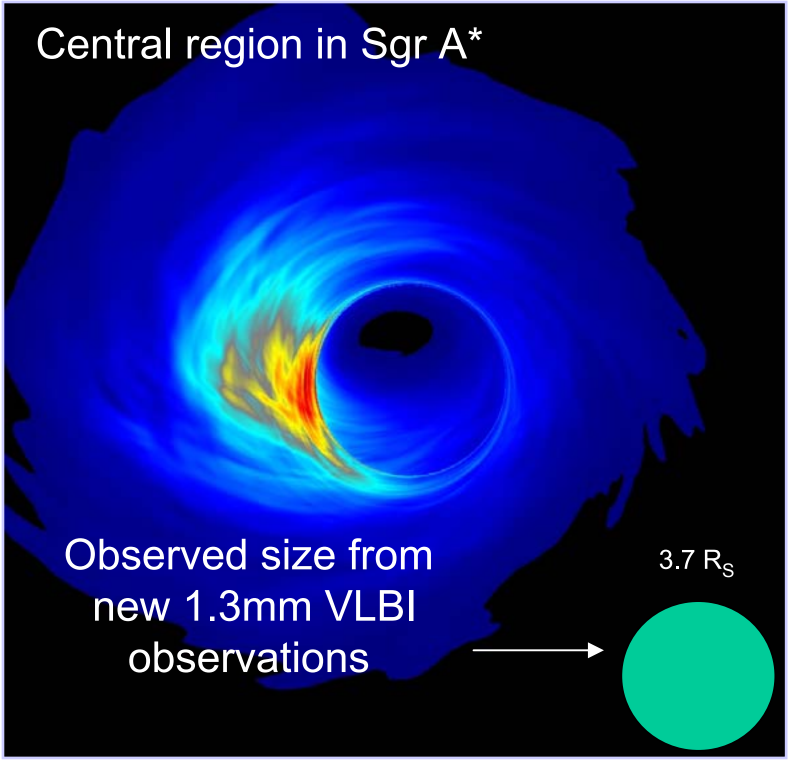


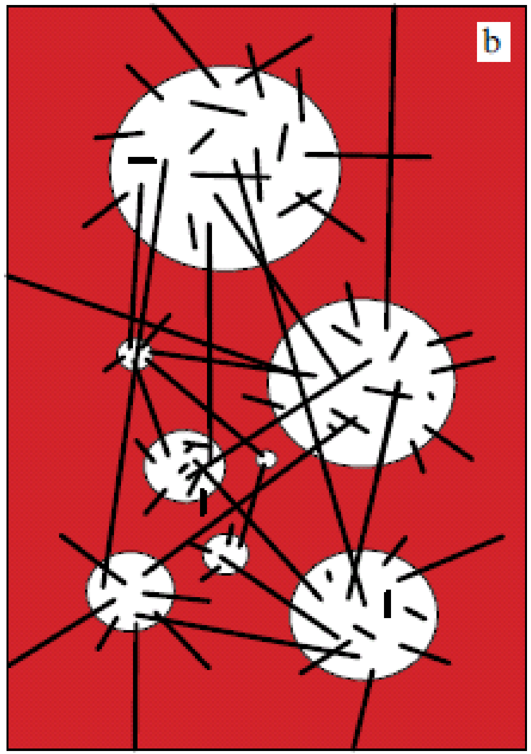
image credit: S. Noble (Johns Hopkins), C. Gammie (University of Illinois)

Horizon vs. Surface

- An object with a surface above R_g (*e.g.*, MECO): slow, steady collapse over times $\gg T_{\mathrm{Hubble}}$ (*e.g.*, Schild et al. 2008)
- To control the collapse, must radiate at Eddington rate but from highly redshifted surfaces.
- One of the tracers of such collapse: extremely high, dipole magnetic field, decreasing as $\sim r^{-3}$.
- The equatorial poloidal field of up to 10^{20} G, enough to create e^{+-} pairs out of vacuum.

Black Holes vs. Wormholes

- Wormholes may form at early stages of chaotic inflation (Novikov et al. 2007)
- They would be characterised by a strong, radial magnetic field, with $B \sim 10^9$ G near the „neck“ of a wormhole.
- The magnetic field decreases $\propto r^{-2}$
- No horizon is present; both receding and approaching motions can be detected wrt. the neck.

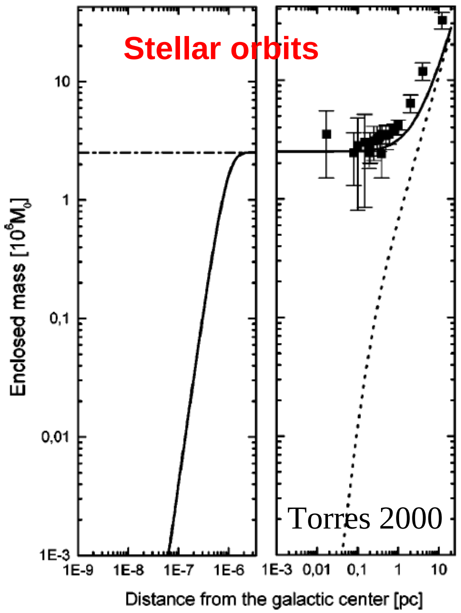


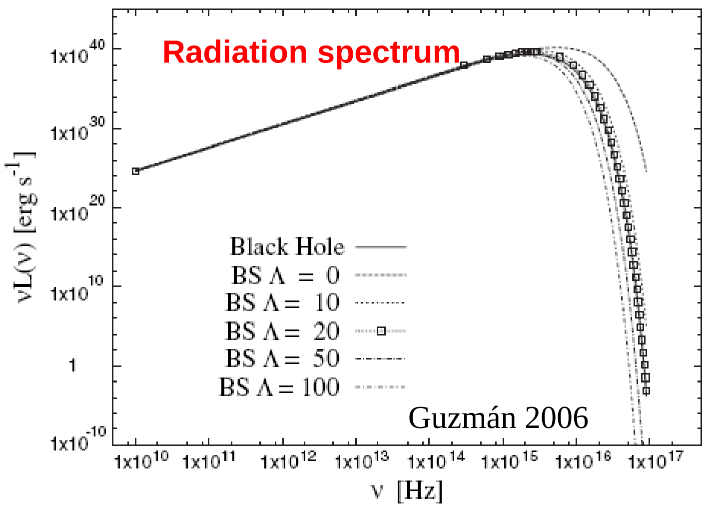
Novikov et al. 2007

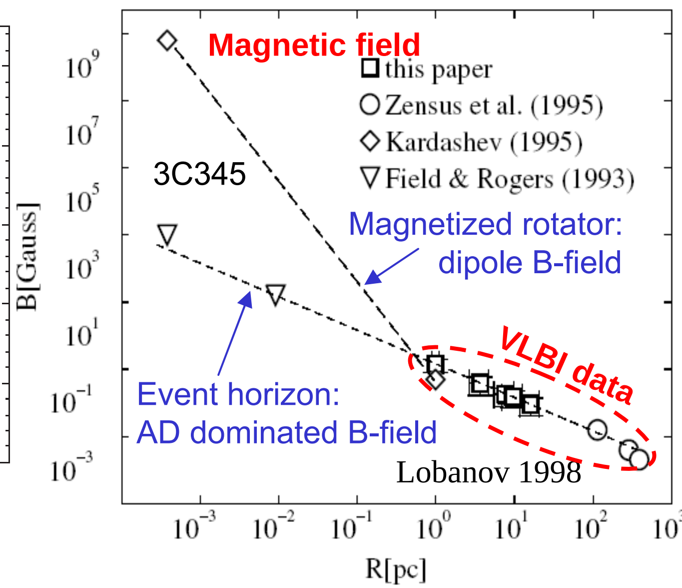
Wormholes and connecting tunnels in models with chaotic multicomponent inflation.

How Black is Black Hole?

- ❑ Present evidence does not strictly prove existence of black holes.
- ❑ Need to devise instruments and experiments to distinguish effectively between BH and their alternatives:
  - **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)





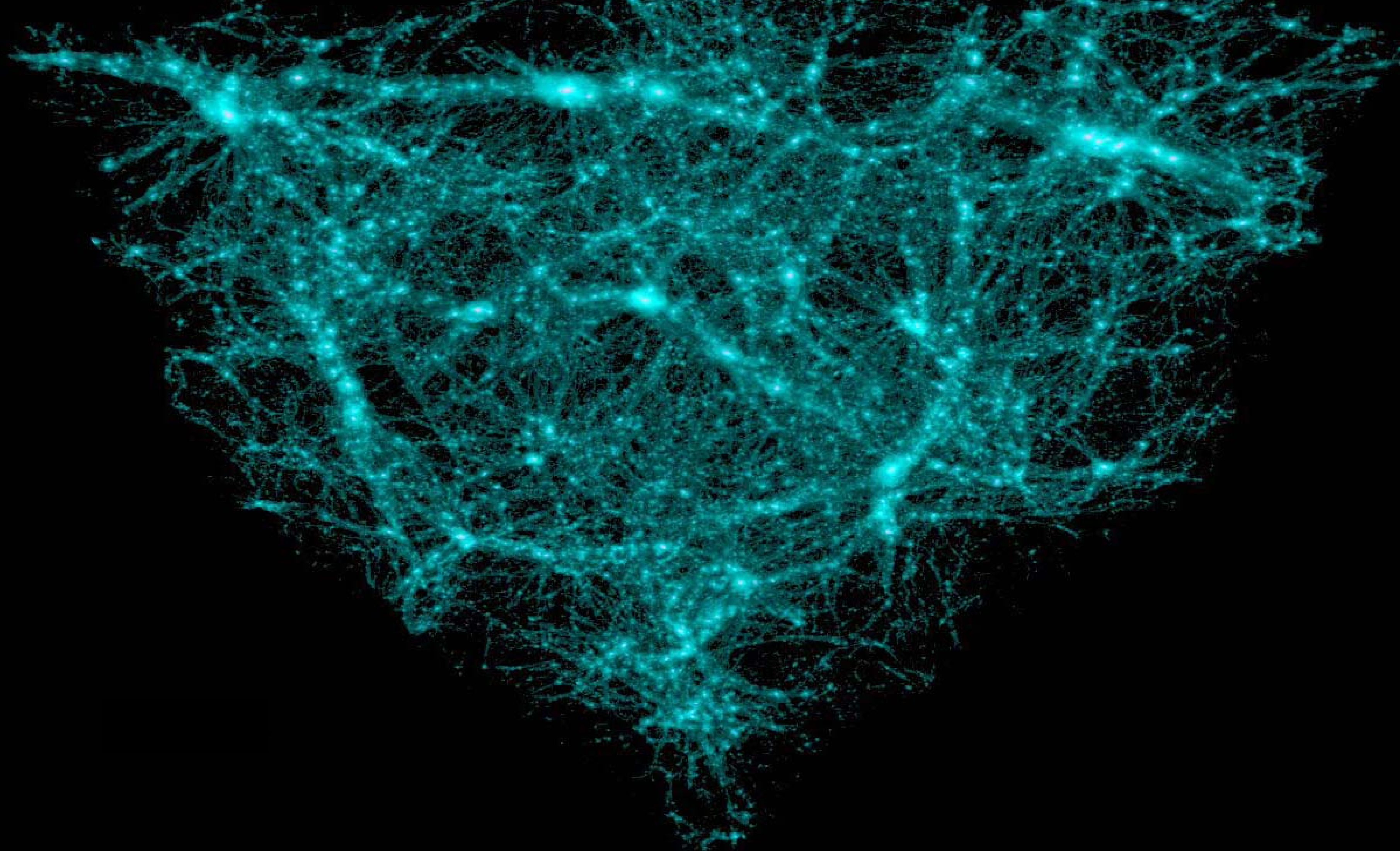


Can We See Them?

- **Direct detection methods:**
  – polarisation measurements – detection of a radial magnetic field (requiring high-fidelity polarimetric imaging at ~10R_g scales). One of the priority tasks for RadioAstron and 1-mm VLBI experiments.

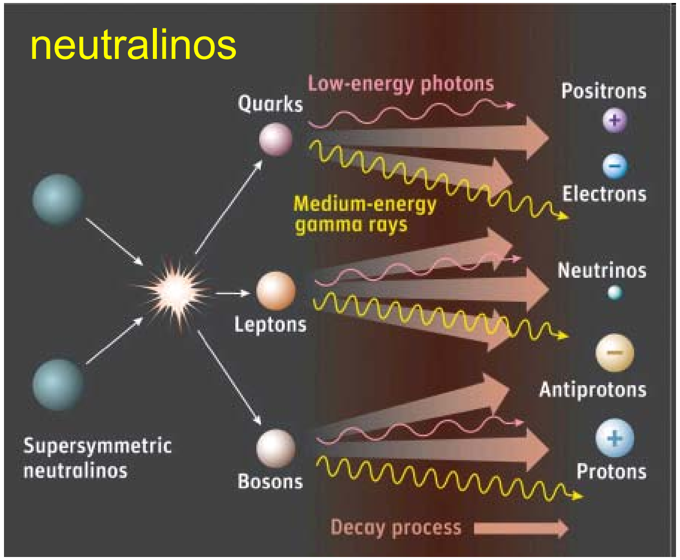
- **Indirect detection methods:**
  – spectral peak at 0.01 keV in MECO (due to finite redshift at the surface);
  – measurement of magnetic field in the region dominated by the field of the central object and showing a different radial dependence from the field dominated by the jet/accretion disk.

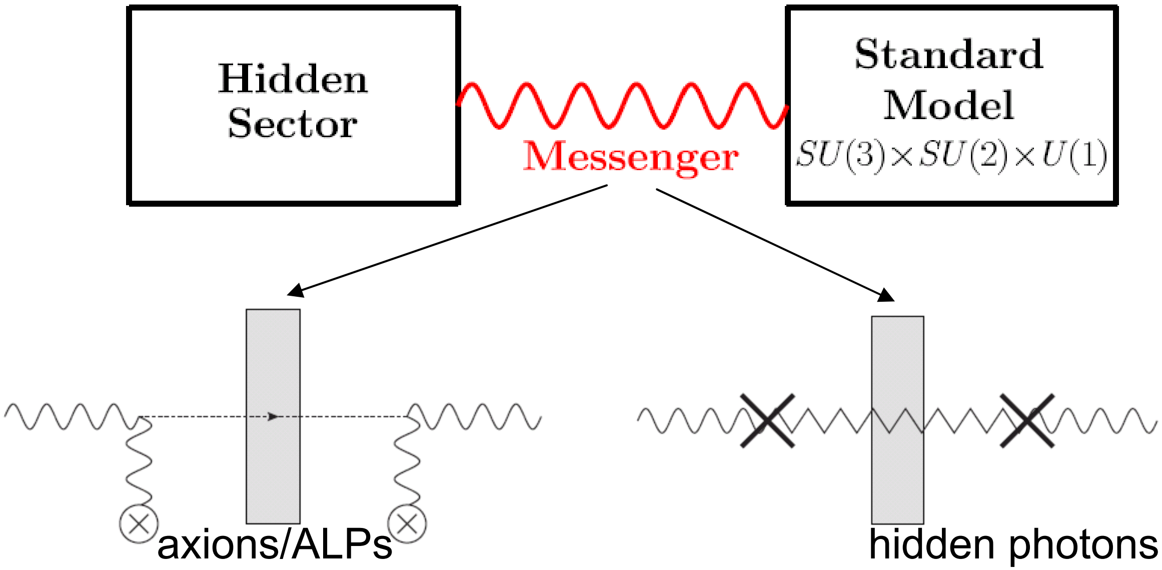
Signals from WIMP and WISP in the Radio Domain



Beyond the EW Scale

- SM extensions (going beyond the electroweak scale):
  – supersymmetry/supergravity: WIMP (neutralino, gravitinos) with m_χ >100 GeV; prime candidates for CDM.
  – string theory: WISP (axions, hidden photons) with m_γ <1 meV
- Direct detection of WIMP/WISP or putting bounds on their properties are of paramount importance for cosmology and particle physics.
- Astrophysical searches: EM signal from neutralino annihilation, axion-photon coupling and photon-photon oscillations.





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Dark Matter and Neutralinos

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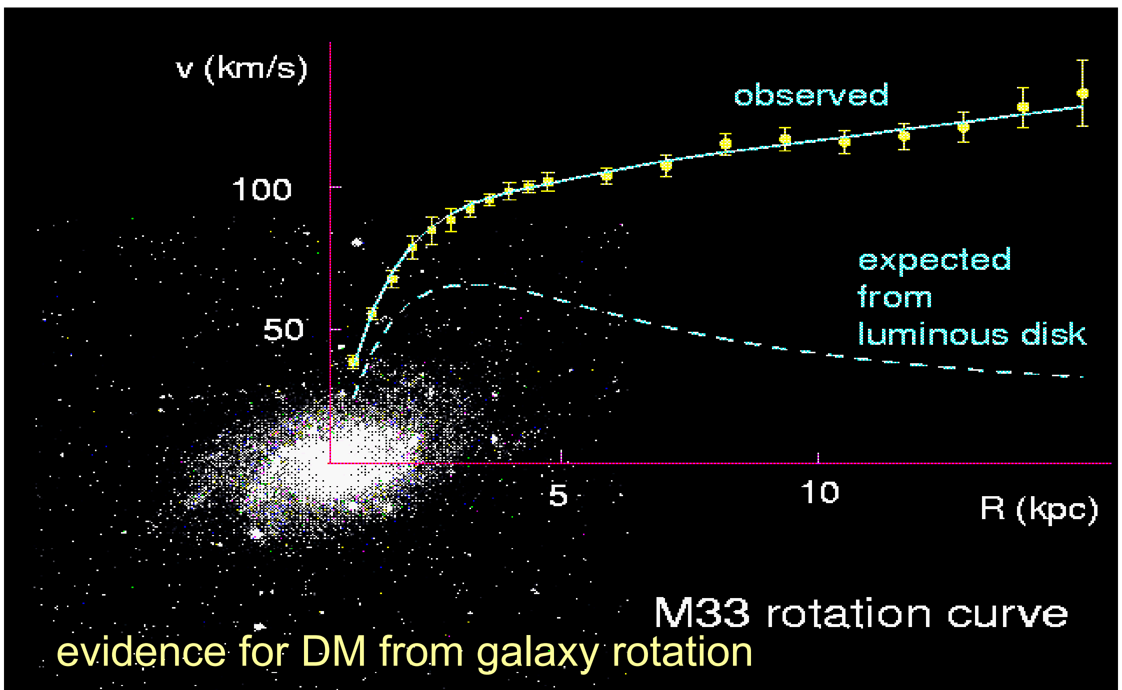
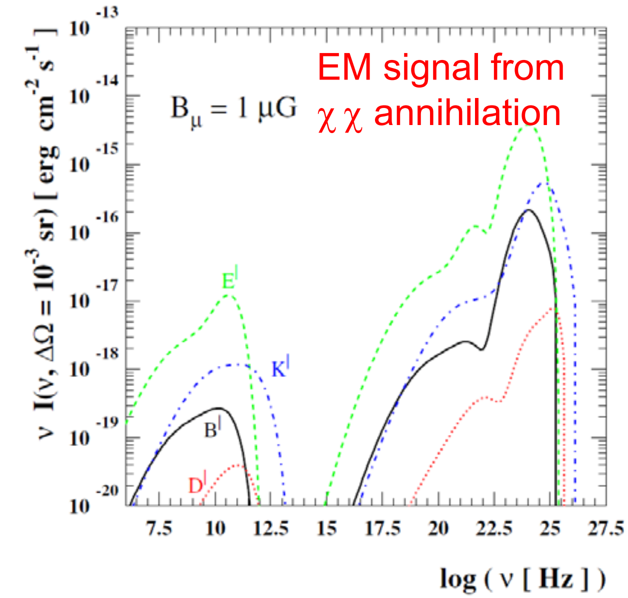
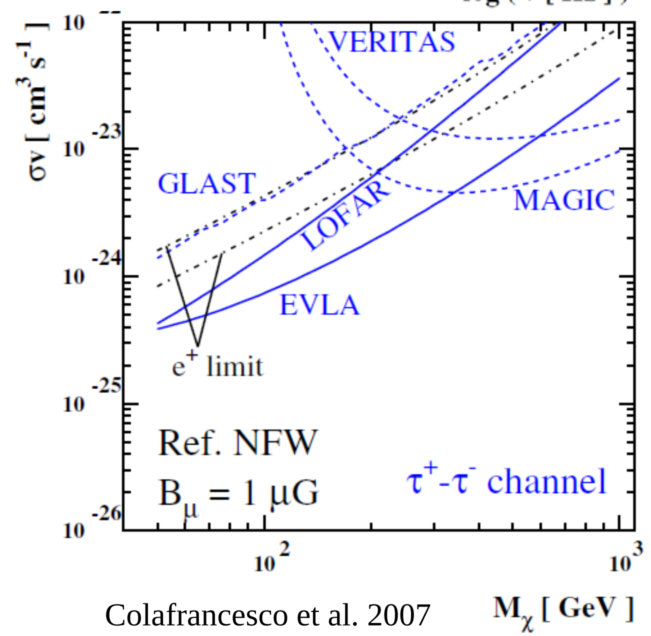
- Ample evidence for existence of dark matter; little knowledge about its physical nature.
- WIMP neutralinos (m_χ, $\langle\sigma v\rangle$) are among leading candidates for DM particles
- Indirect searches: EM signal from DM annihilation (radio and γ-ray regimes)







Colafrancesco et al. 2007

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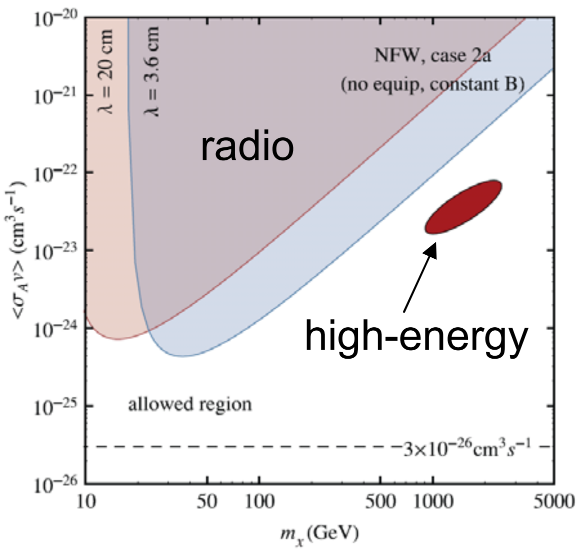
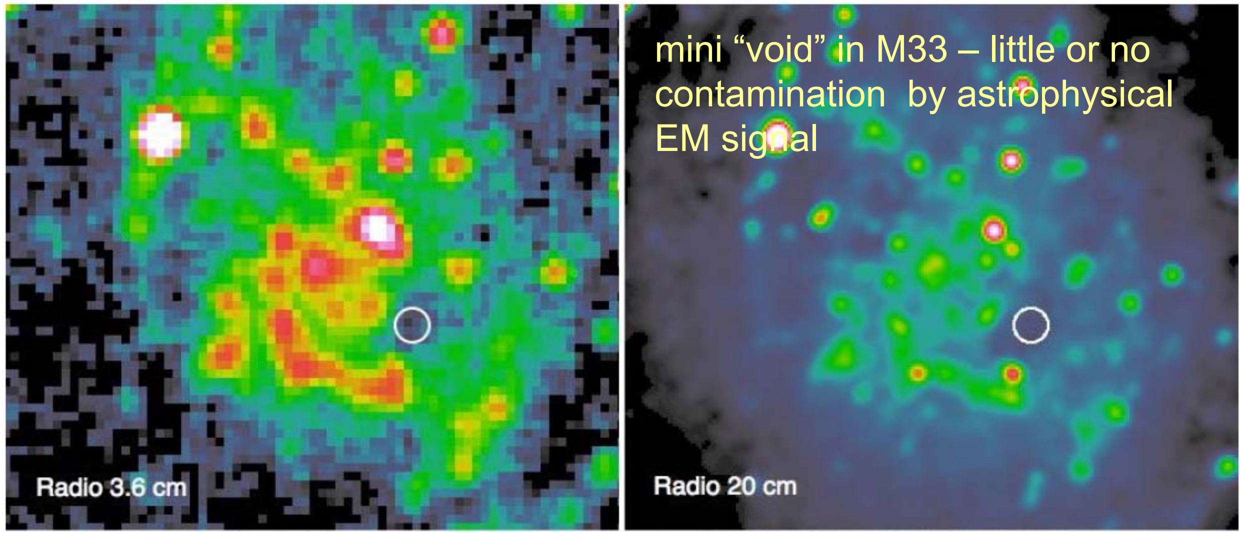
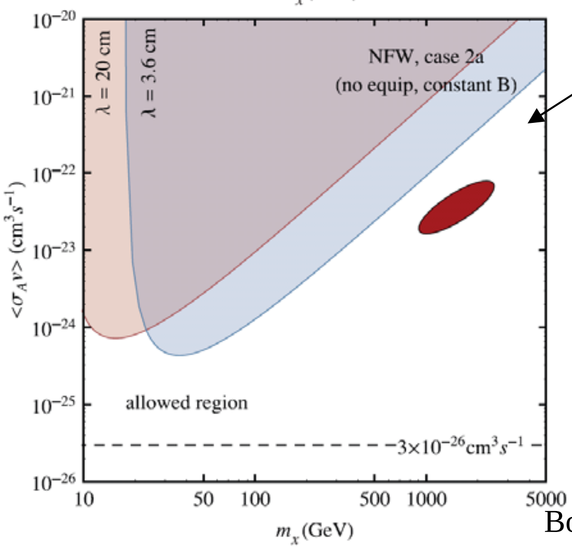
DM in M33

❑ Radio searches often set the most stringent limits on DM

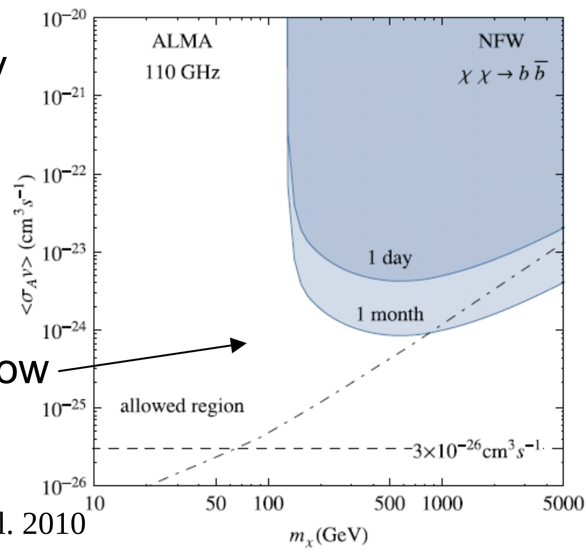


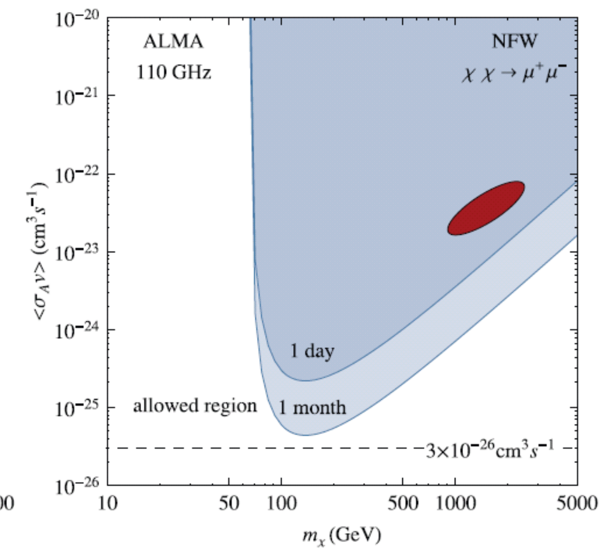




today

tomorrow

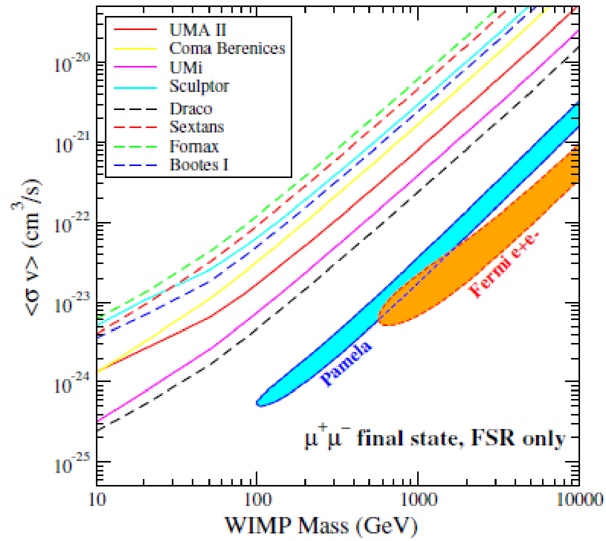




Borriello et al. 2010

DM in Dwarf Galaxies

- Astrophysical targets for DM searches: globular clusters, Galactic center, Milky Way, dwarf galaxies, field galaxies, galaxy clusters, CMB.
- Dwarf galaxies: smallest contamination by astrophysical EM signal; resolved DM signal.
- Radio searches are initiated.
- Working on detailed spatial diffusion models and extension of searches to globular clusters

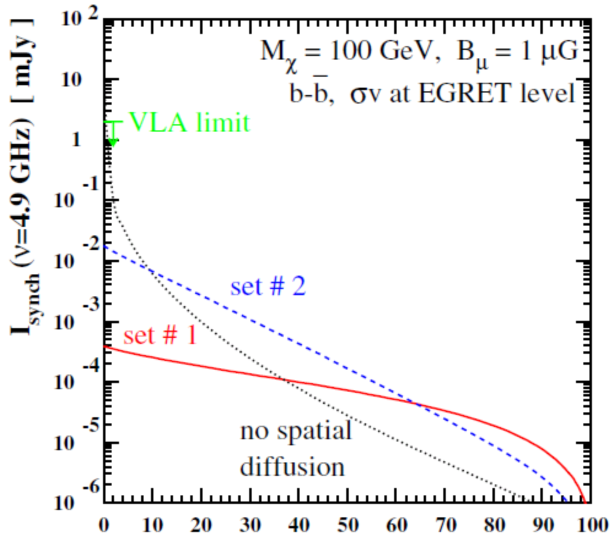


Abdo et al. 2010

Table 1: Dark matter annihilation signals from dSph galaxies in the radio band.

Name	R.A. [hh:mm:ss]	Dec. [dd:mm:ss]	D [kpc]	r_s [kpc]	M_{vir} [10^8 $M_\odot$]	θ_s [arcmin]	S_{tot} [Jy]	S_{peak} [mJy/beam]
UMa II	08:51:30	+63:07:48	30	0.17	0.6	19	0.022	1.8
Com	12:26:59	+23:55:09	44	0.16	0.4	13	0.005	1.0
Boo I	14:00:06	+14:30:00	62	0.27	1.5	15	0.008	1.0
UMi	15:09:08	+67:13:21	66	0.65	8.9	34	0.022	0.6
Scu	01:00:09	−33:42:33	79	0.95	9.4	41	0.007	0.1
Dra	17:20:12	+57:54:55	76	2.09	64.9	95	0.038	0.1
Sex	10:13:03	−01:36:53	86	0.37	1.4	15	0.002	0.2
For	02:39:59	−34:26.57	138	0.58	4.0	14	0.002	0.2

Zechlin et al. 2011



Colafrancesco et al. 2007

Fermi/NVSS for DM Searches

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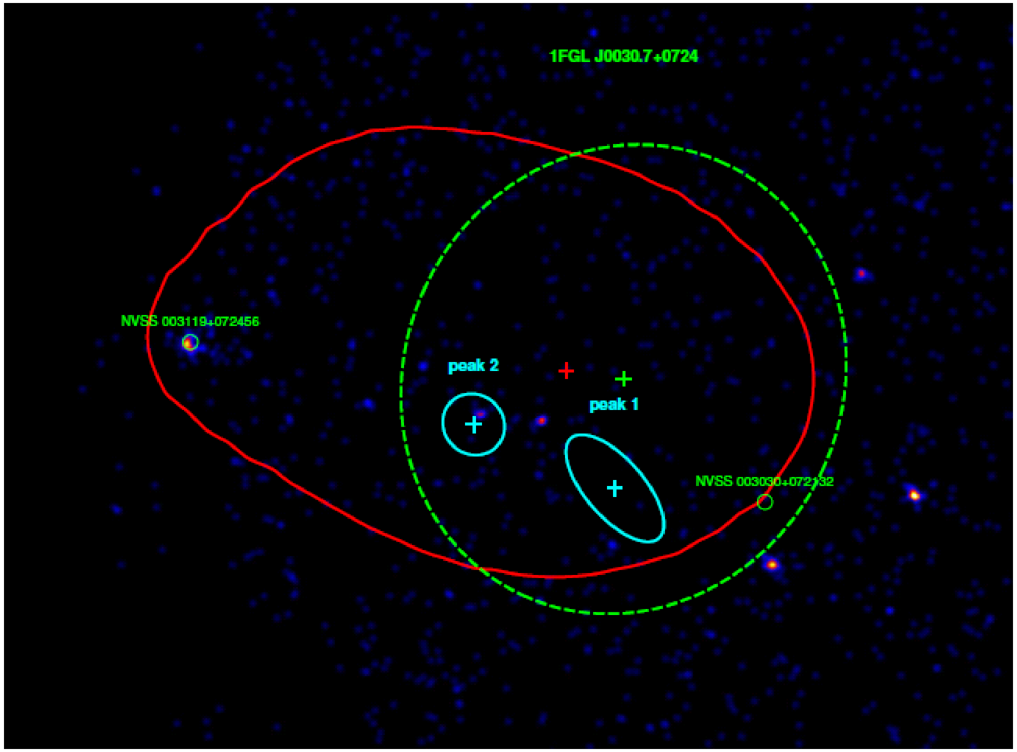
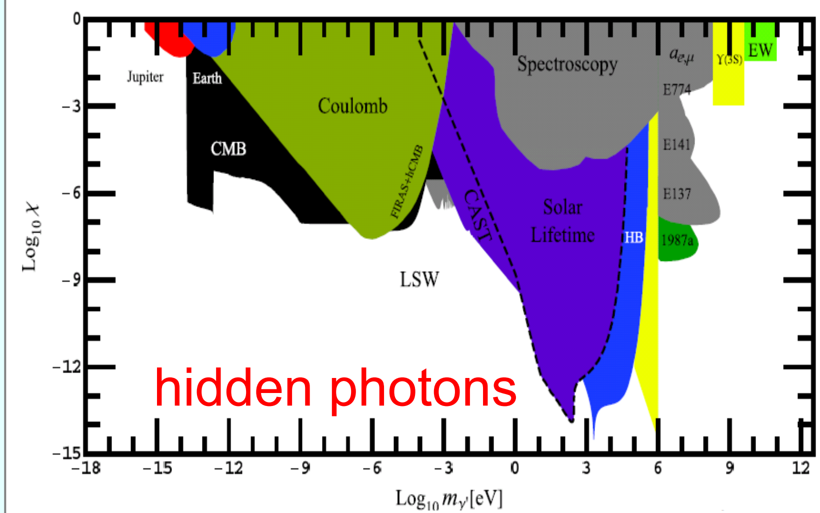
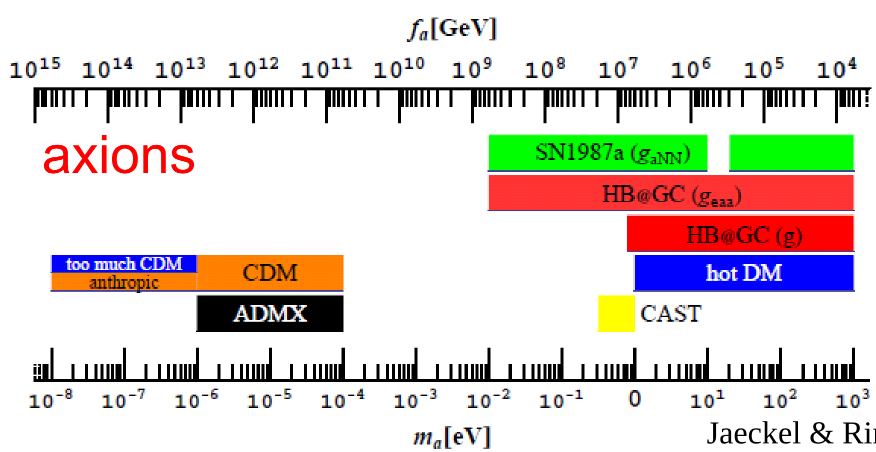
- Unidentified Fermi Objects (UFO) – γ-ray sources without detected counterparts in other regimes.
- Radio followups of selected UFO candidates are proposed.
- Joint Fermi/LAT and NVSS analysis: lowering detection thresholds to ~3.5σ for spatially coincident emission – strongest candidates for DM

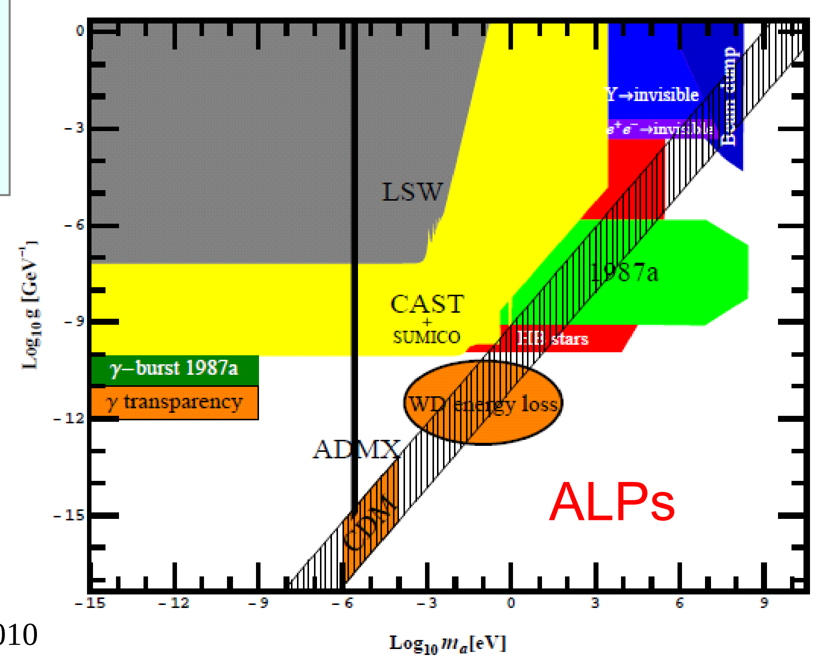


Axions and Hidden Photons

- Many laboratory and astrophysical constraints on axion mass and decay constant, ALPs mass and coupling constant, and hidden photon mass and kinetic mixing parameter.
- Effective detection of axion/ALPs requires strong magnetic fields – could potentially be probed with pulsars.
- Hidden photons: excellent potential for searches in broad-band radio spectra.







Jaeckel & Ringwald 2010

ALP and HP Searches

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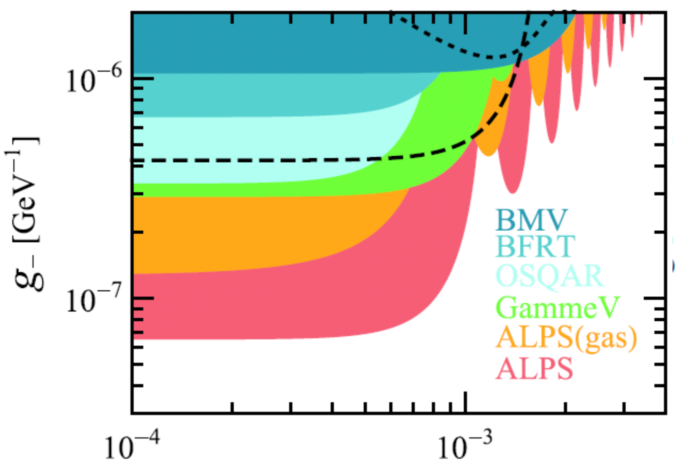
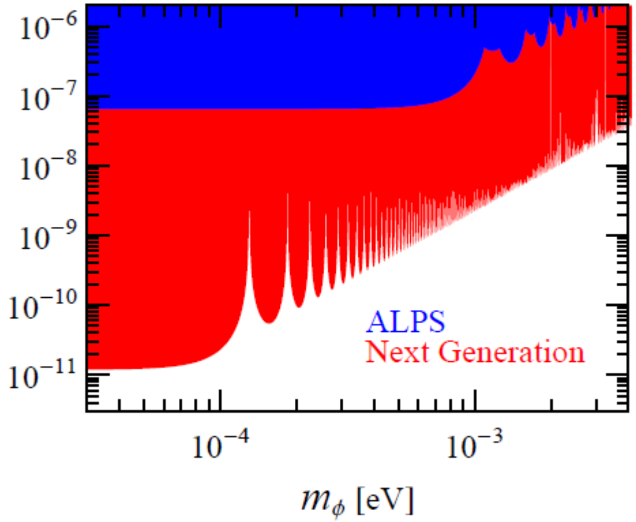
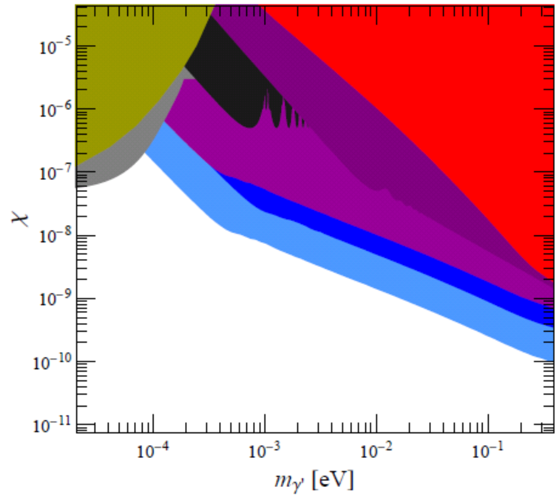
- DESY & University of Hamburg: ALP searches (ALPS, HIPS, microwave cavity); HP searches (CAST, SHIPS helisoscopes)





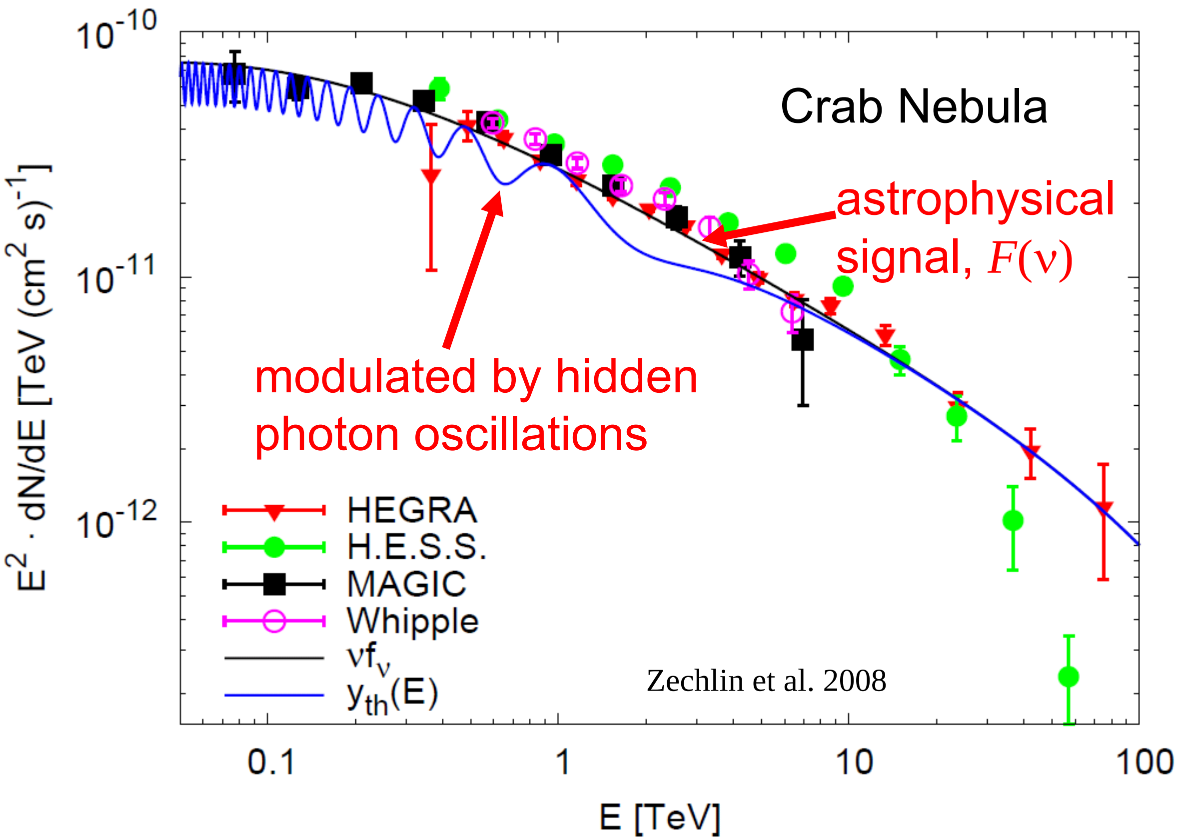
Ehret et al. 2010 (ALPS Collaboration)



Redondo et al. 2008, 2010

Astrophysical HP Searches

- ❑ Probability (and energy spectrum) of the oscillation depends on the mass μ and (coupling) kinetic mixing parameter χ of the hidden photons.
- ❑ Maximum distance at which oscillations can be detected depends on the emission process and environment conditions
- ❑ SNR in Galaxy and nearby galaxies are the best targets.



$$P_{\gamma\to\gamma_s}(L) = \sin^2(2\chi)\sin^2\left(\frac{\mu^2}{4E}L\right)$$

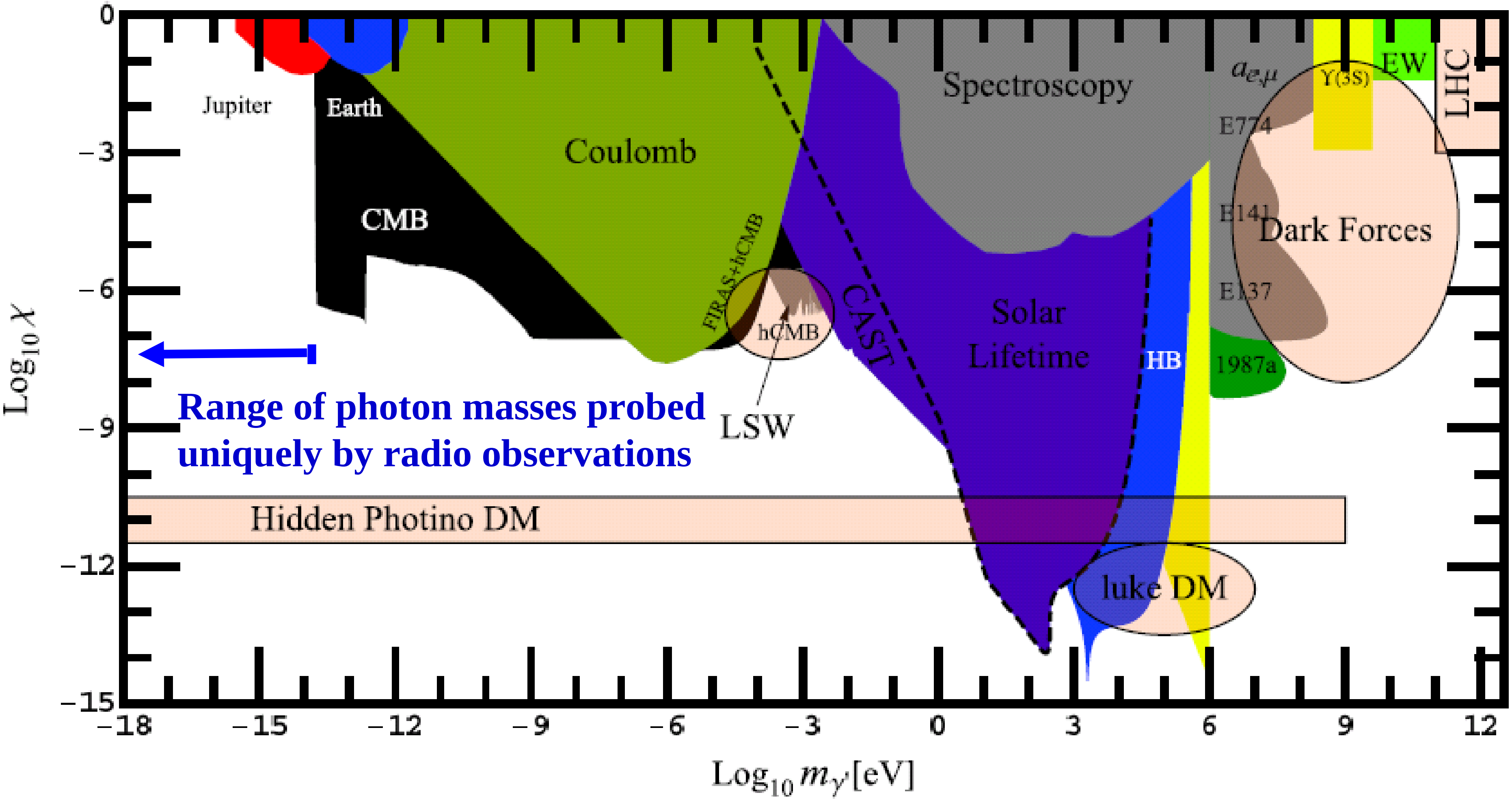
$$F_{\gamma'}(\nu) = F(\nu)\,(1 - P_{\gamma\to\gamma'})$$

Synchrotron emission: $d_{\max} \approx 20\,\mathrm{kpc}\,(B/[\mathrm{mG}])\,(\nu/[\mathrm{MHz}])^2\,(m_{\gamma'}/[10^{-15}\mathrm{eV}])^{-2}$

Bounds on Hidden Photons

A. Lobanov

- Radio is an excellent probe of hidden photons with $\mu < 10^{-14}$ eV

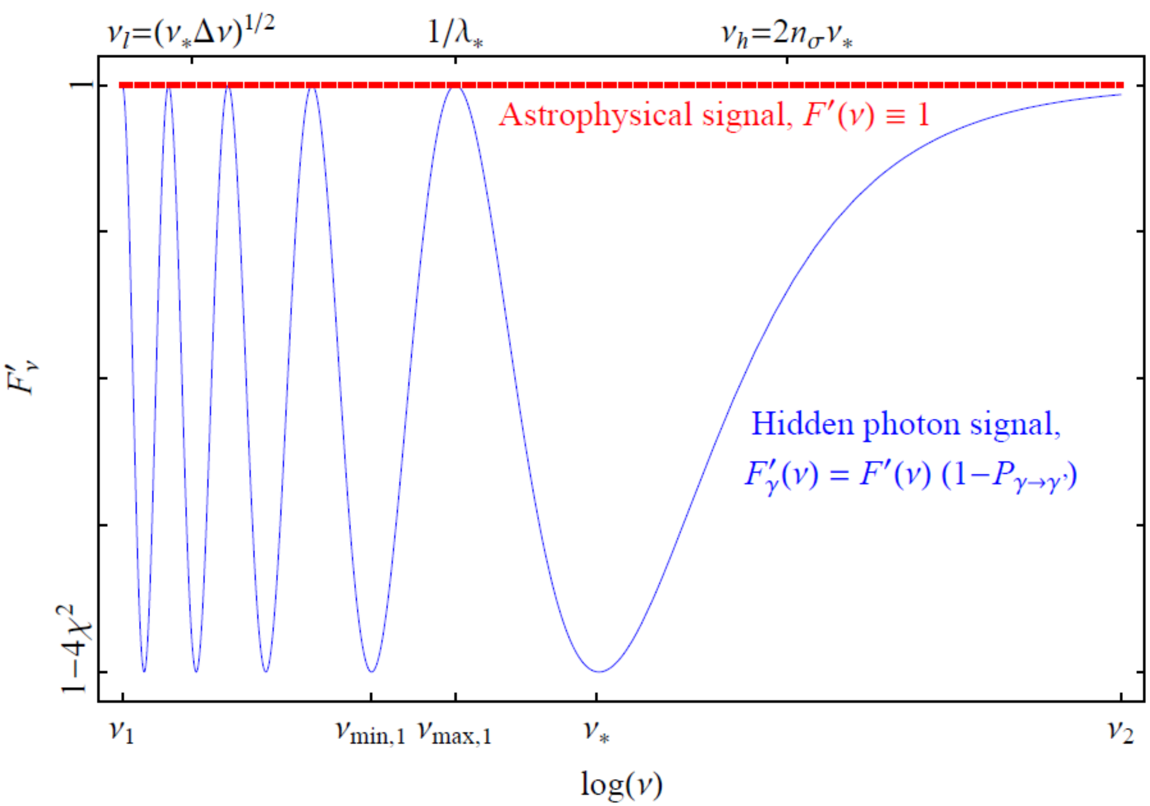


Jaeckel & Ringwald 2010

Photon-Photon Oscillations

A. Lobanov

- Oscillations can be detected around the primary frequency ν_*, within a „useful range" of frequencies (ν_l, ν_u).
- Can search for photon oscillations in galactic SNR and in AGN.
- Can stack multiple objects, substantially improving detection limits.



$$\nu_\star = \frac{m_{\gamma'}^2 L}{4\pi^2} = 6.0177 \times \left(\frac{m_{\gamma'}}{10^{-15}\,\mathrm{eV}}\right)^2 \left(\frac{L}{\mathrm{pc}}\right) \mathrm{MHz}$$

$$\lambda_\star = \frac{8\pi^2}{m_{\gamma'}^2 L} = 99.635 \left(\frac{m_{\gamma'}}{10^{-15}\,\mathrm{eV}}\right)^{-2} \left(\frac{L}{\mathrm{pc}}\right)^{-1} \mathrm{m}$$

$$\nu_1 = \sqrt{\nu_\star \Delta\nu + (\Delta\nu/4)^2} \approx \sqrt{\nu_\star \Delta\nu}$$

$$\nu_\mathrm{h} \approx 2\, n_\sigma\, \nu_\star$$

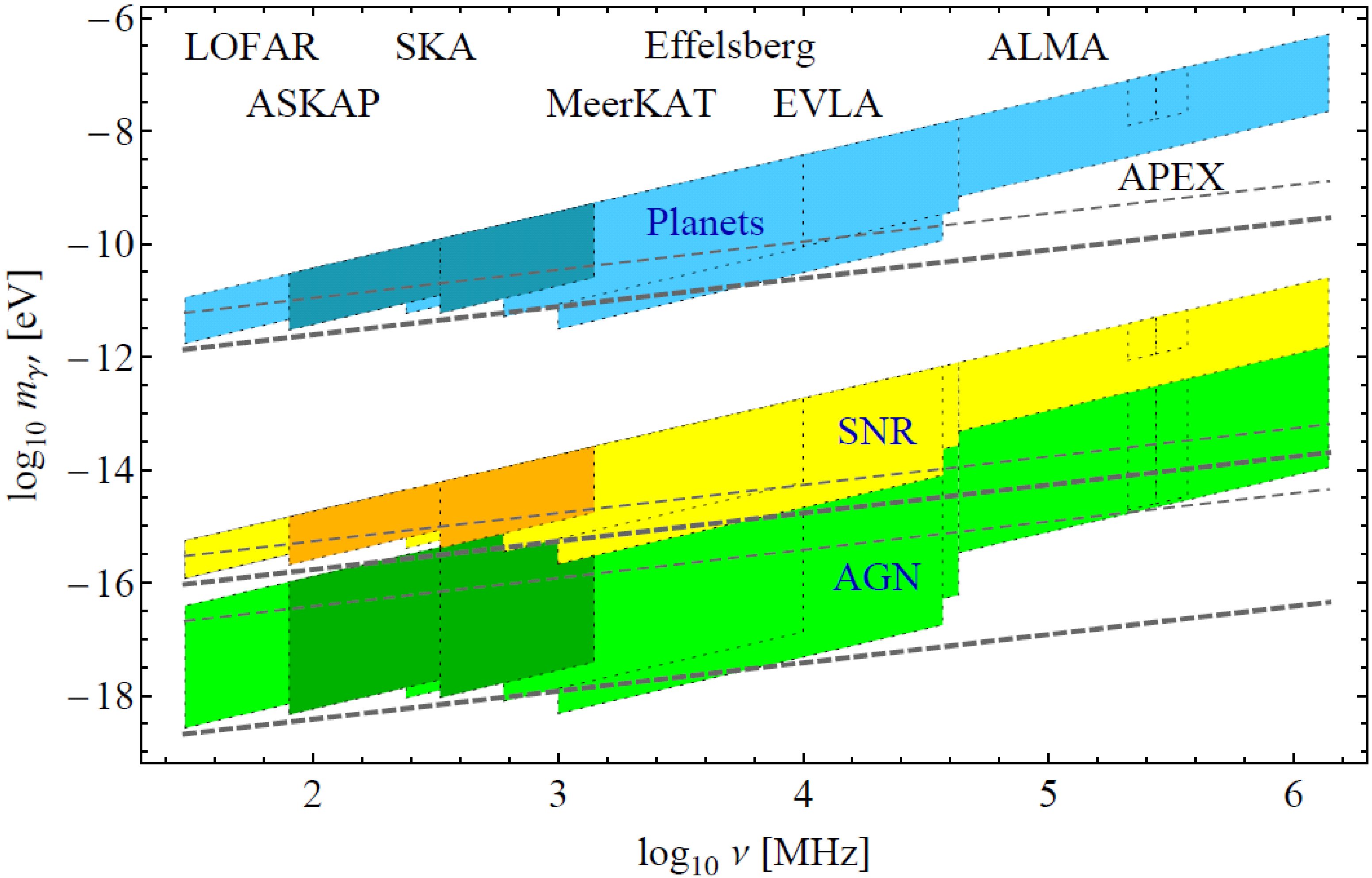
If detected, would provide exceptionally good distance measure (via λ_*)!

Lobanov et al. in prep.

Ranges of Photon Mass

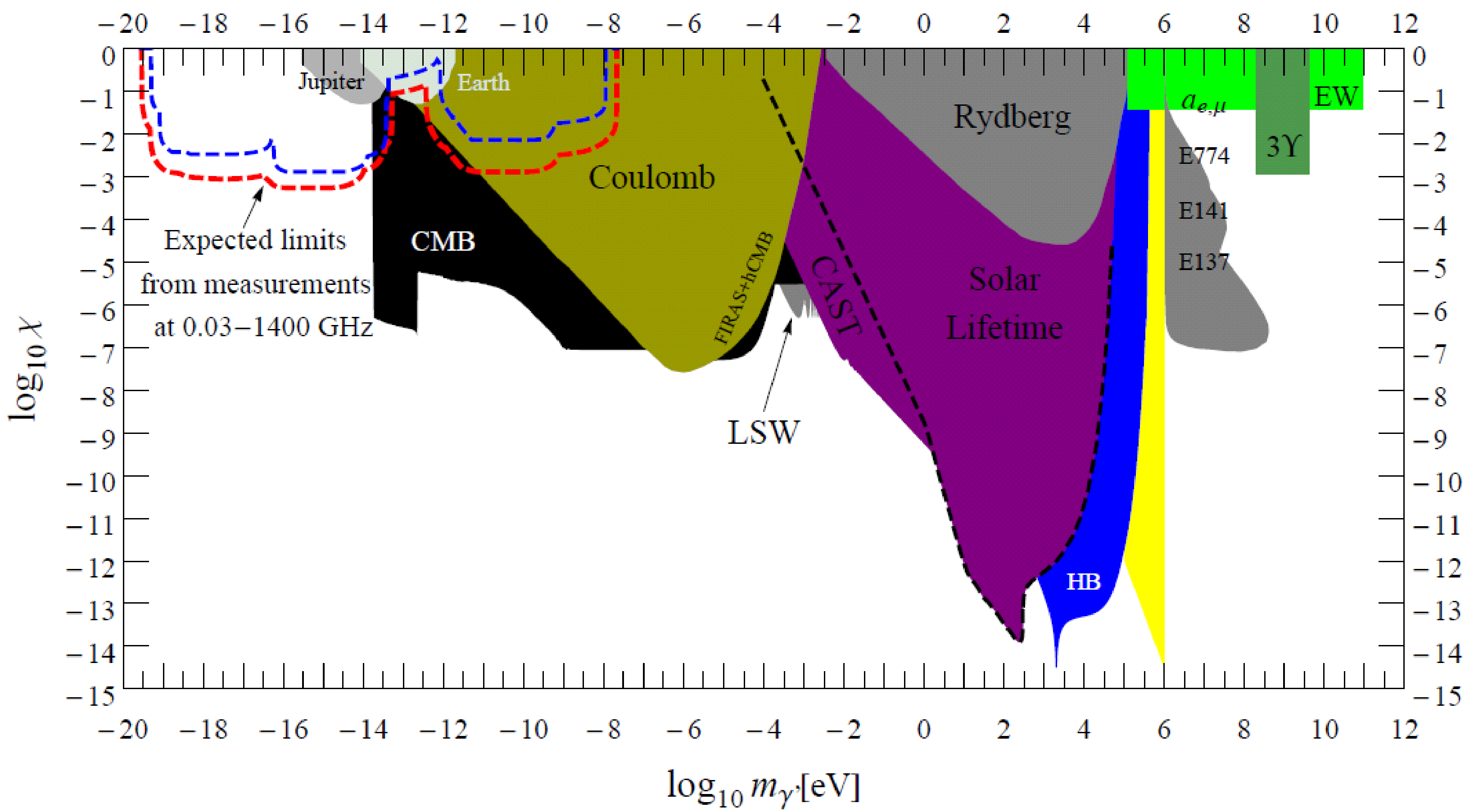
A. Lobanov

- Observations in 0.03-1400 GHz range probe a broad and partially unique range of hidden photon mass



Expected Impact

- Single source observations should provide $\chi<10^{-2}$ bounds; stacking of 10–100 objects would yield $\chi<10^{-3}$ bounds down to $m_\gamma = 10^{-19}$ eV
- SKA surveys: broad band measurements of 100000+ radio sources.



Hidden Photons in SNR

A. Lobanov

Max-Planck-Institut für Radioastronomie

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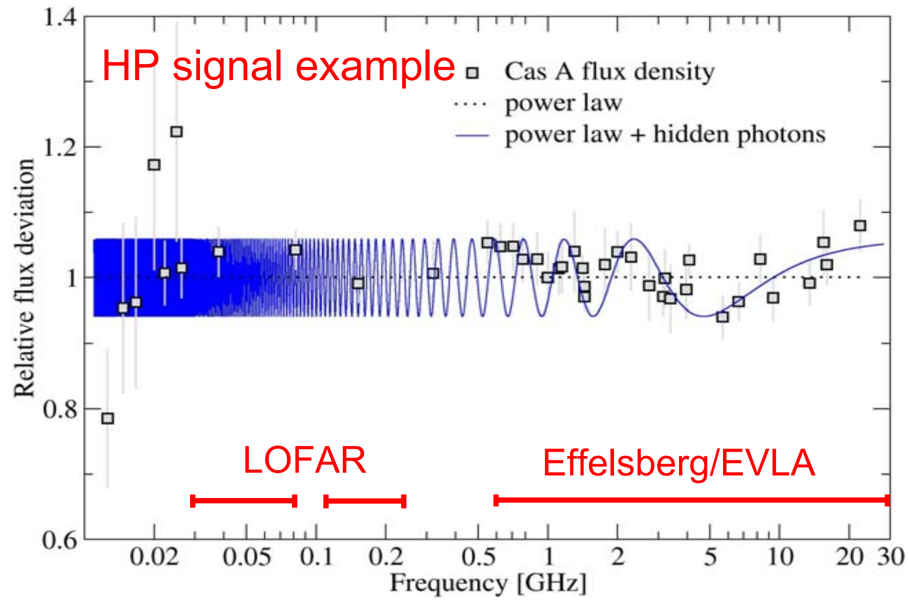
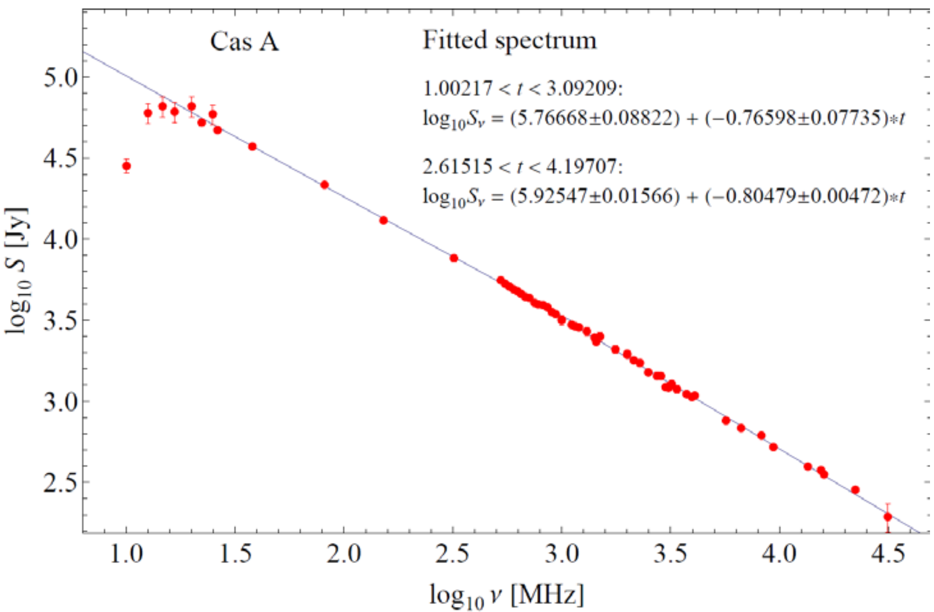
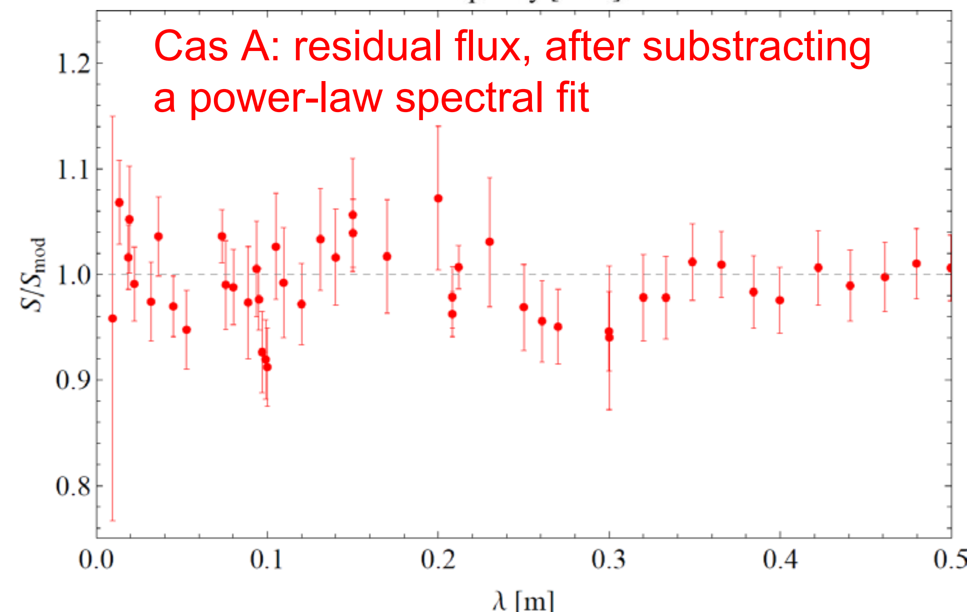
- ❑ Broad-band, absolute flux density measurements in Cas A, Tau A. Absolute calibration is an issue.
- ❑ In-band, relative measurements would be preferred (can be made now with LOFAR, EVLA, and Effelsberg).







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Periodic Oscillations

A. Lobanov

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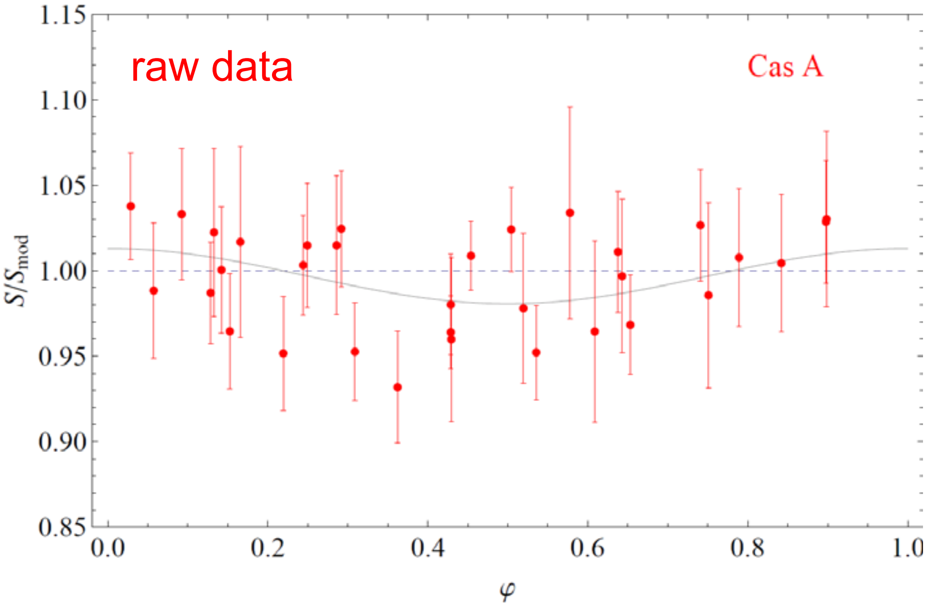
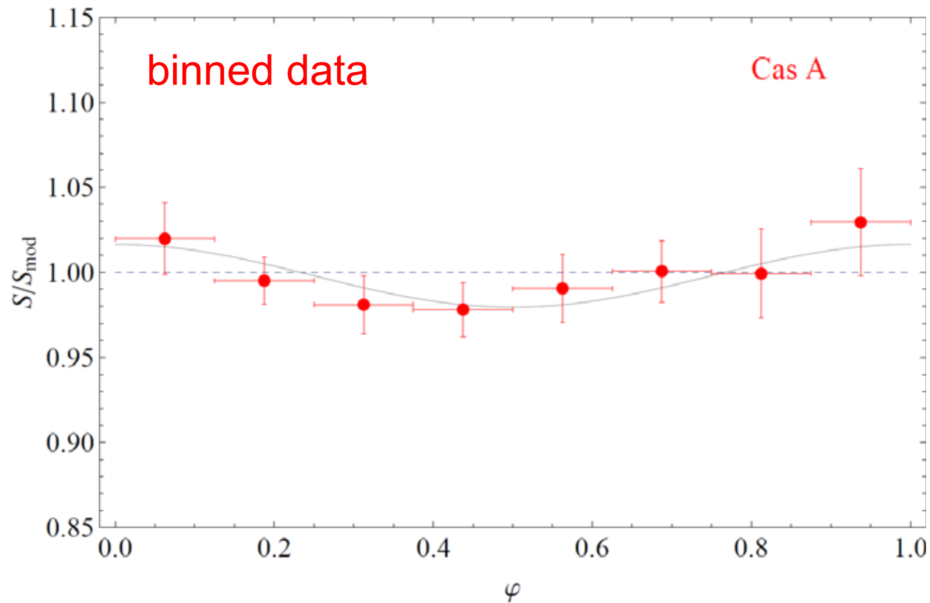
- Weak (<2σ) period detections in Cas A ($\lambda_* = 0.15$ m) and Tau A ($\lambda_* = 0.19$ m). Wavelength ratio (1.3±0.3) agrees well with the distance ratio of 1.4±0.5.
- Hence it could indeed be the same signal in both objects.
- Could try stacking all data together.



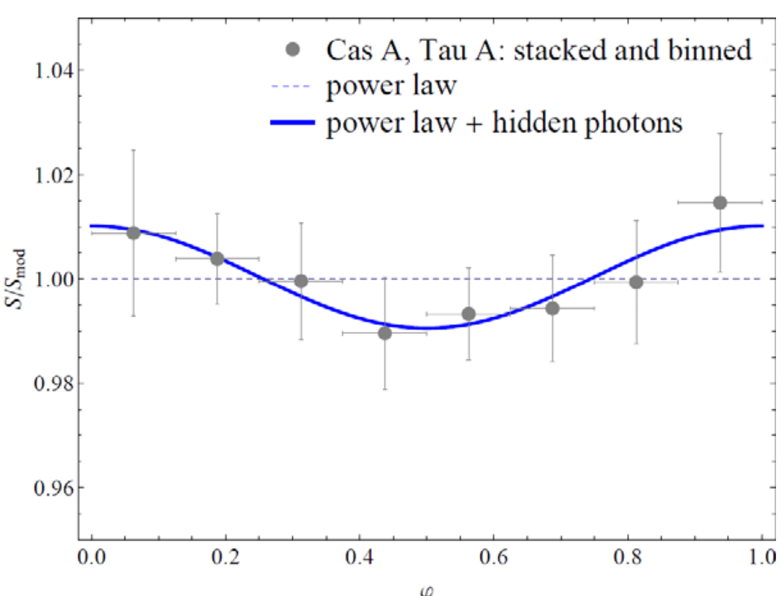


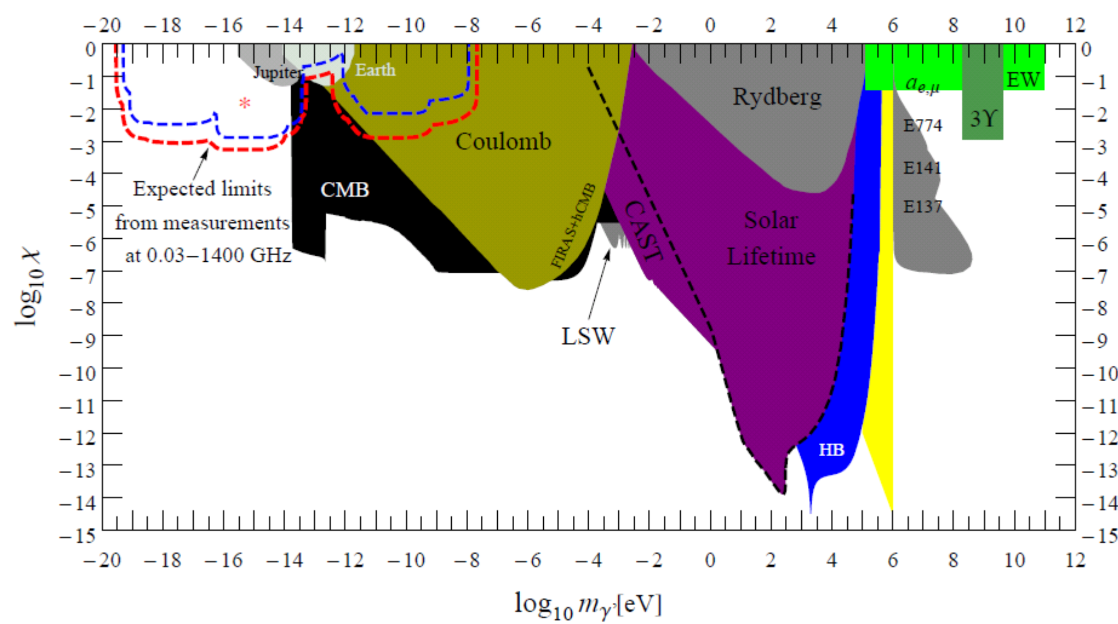
A. Lobanov

Results from Stacked Data

- Stacked data yield a ~2σ detection of a signal with
  $\lambda_* = 0.41 \pm 0.01$ m $[L/\mathrm{kpc}]^{-1}$
- This corresponds to a signal from hidden photons with
  $m_{\gamma'} = (4.9 \pm 0.5) \times 10^{-16}$ eV and $\chi = 0.02 \pm 0.01$

  and it is not excluded by existing measurements.





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In-band Measurements

A. Lobanov

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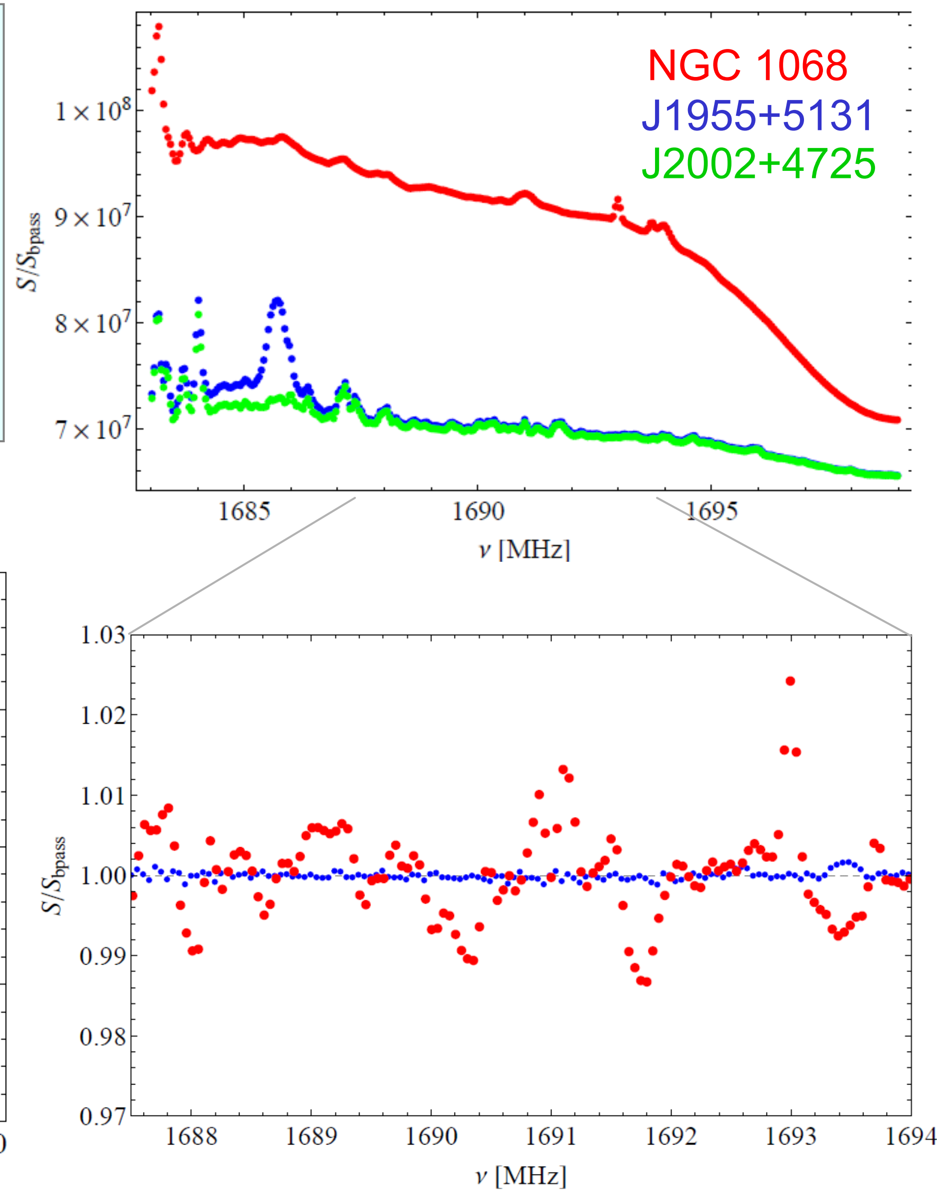
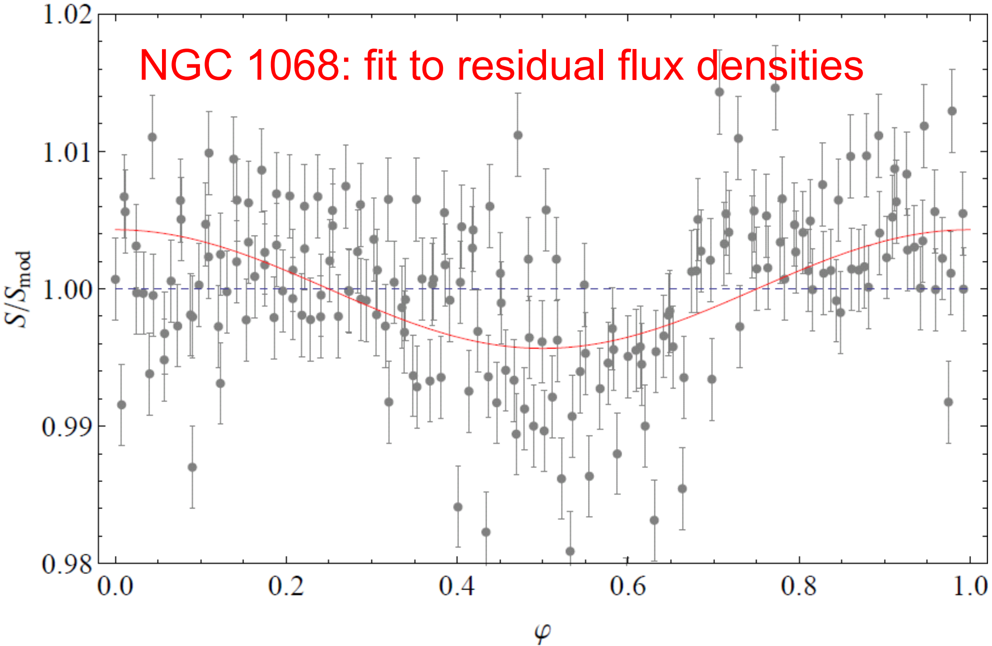
- In-band measurements: NGC 1068, with bandpass from J1955+5131 and J2002+4725.
- A fit to NGC 1068 corresponds to $m_{\gamma'} = (2.079 \pm 0.007) \times 10^{-16}$ eV $\chi = 0.008 \pm 0.001$





Further Plans

- Further joint analysis of existing absolute flux density measurements for Cas A, Tau A, NGC7027, and several well-studied SNR.
- Effelsberg and EVLA: In-band measurements of nearby radio sources, calibrated with bandpasses from high-redshift quasars.
- LOFAR/Eb: attempting to measure in-band flux density variations in a few pulsars and SNR – making assessments of calibration accuracy for relative flux density measurements and for axion searches in strong magnetic field environment
- Investigating the coherence properties of the photon oscillation signal from AGN (to check suitability of more distant objects for hidden photon searches) and pulsars (to investigate potentials for axion searches).

Summary

- Searches for WIMP and WISP is an emerging and highly promising field of study in the radio domain.
- Low cost / high yield research field, with a strong potential for new discoveries with Effelsberg, LOFAR, EVLA, and ALMA and excellent prospects with MeerKAT, ASKAP, and SKA.
- Radio observations and of dwarf galaxies and unidentified Fermi objects should provide robust and competitive limits on neutralino mass and annihilation cross-section.
- Measurements at 0.03-40 GHz offer an excellent probe of hidden photons with masses in the 10^{-19}–10^{-14} eV range. Verification of the tentative detections made is of paramount importance.
- Radio astronomical measurements offer set of tools for research in fundamanetal physics.

There is really a great and still largely unexplored potential here!