IAU Symp. 242: Summary

- Progress since 2001 meeting in Brazil
- What do we think we understand?
- What don’t we understand?

Masers: Complexity

- Chemistry (Temp, dens, ionization, evaporation, dissociation, …)
- Amplification (limited by clumping or Vel/B-field gradients, saturation, beaming, pumping)

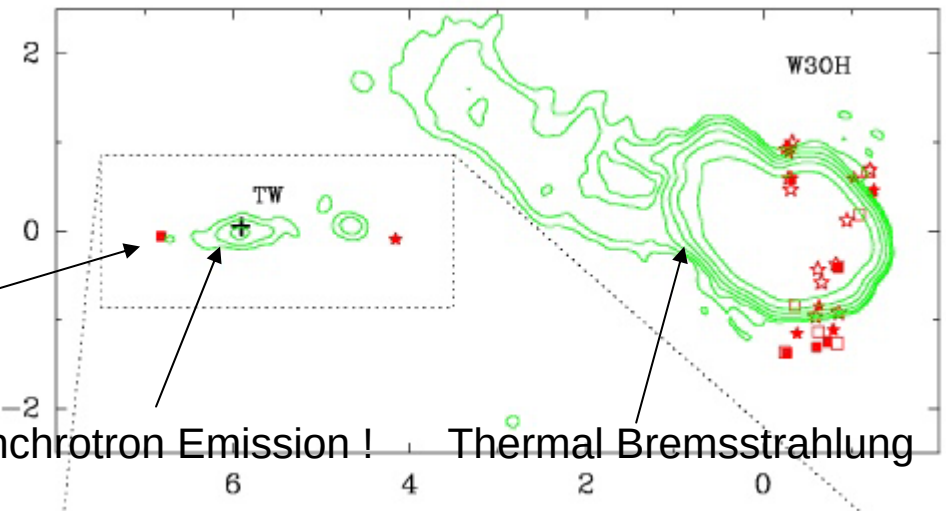
Pump: concept of single pump path naïve:10-100s routes contribute to OH

Ampl.: OH line wing variability ~10^3 s puzzling

Polarization: pure π components (100% linear) not seen! Why?

OH stimulation of σ by π radiation in aligned clouds

- Lifetimes (dynamic cloud formation)
- Projections (3-D observed as 2-D)
- Extinction (eg, visible, IR images)



OH masers in H2O outflow

Synchrotron Emission !

Thermal Bremsstrahlung

Interstellar Masers: Characteristics

- H_2O

  Power-law position correlations…no clustering scale…fractal/turbulence
  outer scale ~ injection of energy via jet wind (~10^{17} cm)
  inner scale ~ dissipation of energy at maser spot scale (~10^{13} cm)

- OH

  OH: strong clustering scale (not power-laws like H_2O) ~ 100 AU

  Both form lines/arcs on sky & worms in P-V space
  Are maser “worms” Strelnitski’s cascading vorticity?

- CH_3OH (unknown)

  Class II: expect similar to OH

  Class I: perhaps like H2O

Interstellar Masers: Variability

- CH_3OH Periodic Variability

  Clear quasi-sinusoidal variations in ~10% surveyed

  VLBA maps show spot “pulsation”, nothing else changing

  Periods between 133 to 504 days…similar to Miras

  While chance meeting of MSF cloud & Mira variable very low…
  embedded pulsating PMS star (eg, lower mass VY CMa) intriguing =>
  pulsation lifetime ~ 10% of maser lifetime

Masers Pumps

- SiO

  Collisions and/or radiation

- H_2O

  Collisional: doesn't correlate well with IR; but does with outflows/shocks

- CH_3OH

  Class-I collisional: shocks at interface of MC
  Class-II radiative: associated with IR dark clouds and hot molec cores of MSFRs

- OH

  Radiative: OH correlates well with MIR; not with fast outflow

- H_2CO

  Radio Continuum and IR pumps probably doesn't work;
  by default (possibly e^- if $n_H \sim 10^3$) collisions if $n_H \sim 10^6$

Does intrinsic complexity of the pumping or ignorance of atomic/molecular cross-sections dominate?

Mm/submm Masers

- Lots of new mm/submm masers,

  Even though (as Strelnitski pointed out at the last meeting),

  it is harder for Nature to invert populations at higher frequencies

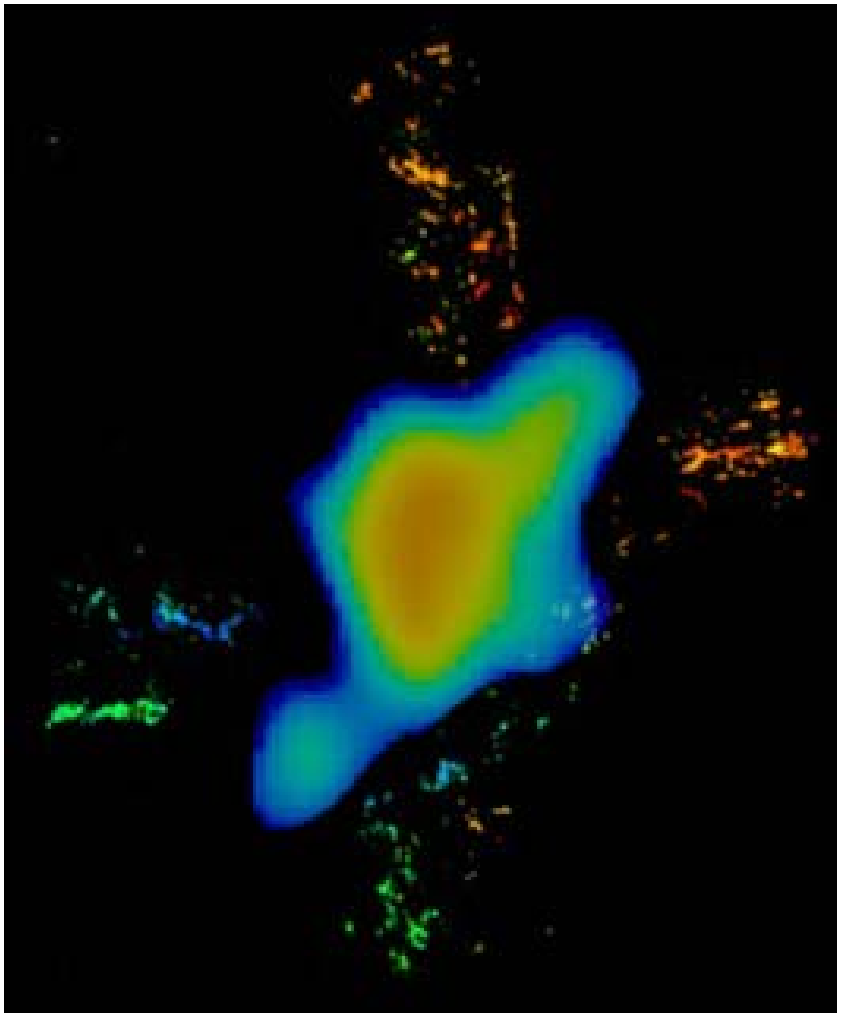
Interstellar Masers: YSO disk/jets

- Fast outflows: H_2O
- Slow outflows: H_2O, CH_3OH, SiO
- Disks: ? (H-recomb masers in MWC349)

  disk hard differentiate from bipolar jets

  often rely on other jet indicators:
  - H_2 2.1 um
  - thermal SiO
  - radio continuum, but not always…

- HII expansion: OH, CH_3OH Class II
- Shocks: CH_3OH Class I, OH/SNRs



Interstellar Masers: B-fields

- OH

  typically 1 – 10 mG…but up to 40 mG seen!

  Always ordered: either 0 or 1 reversal across source

- H_2O

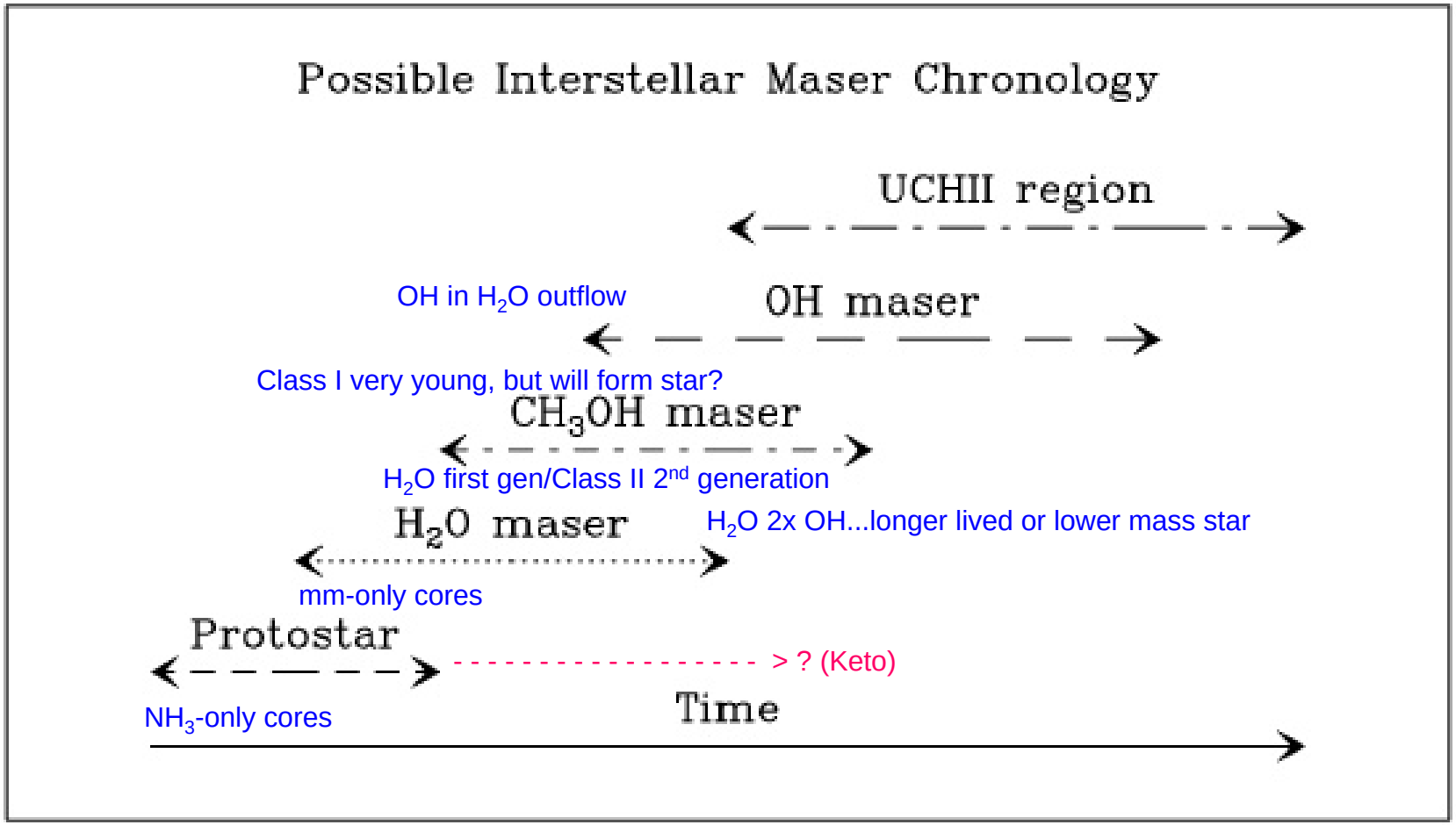
  typically 10 – 100 mG

- $B \sim n(H_2)^{0.5}$

  suggests $n(H_2O)$ only ~100 x n(OH)…

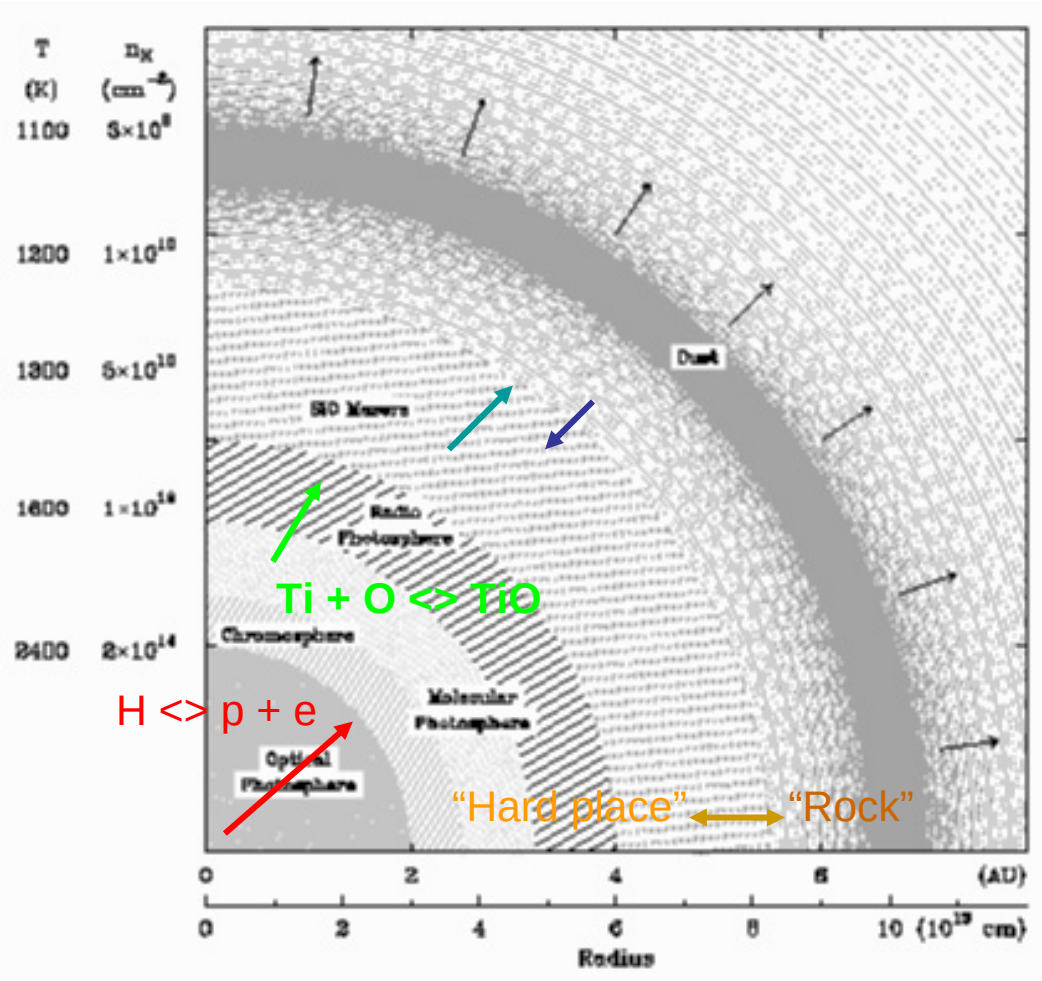
  but uncomfortable for $B(OH) > B(H_2O)$

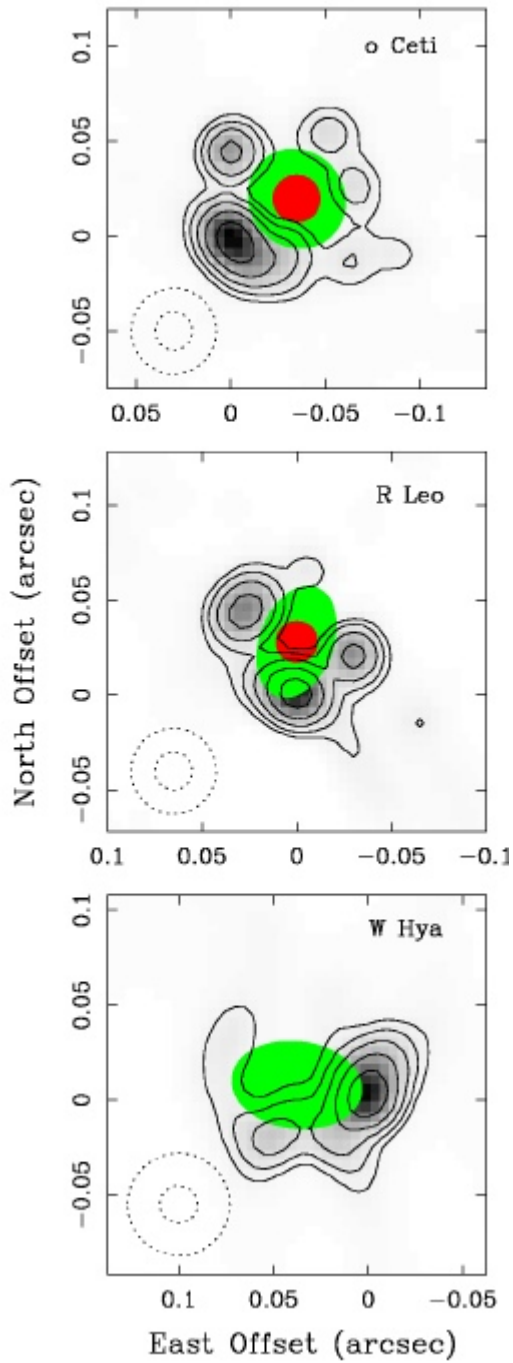
Interstellar Masers: Age Sequence



Other dimensions: stellar mass, external ionization & shocks, etc.

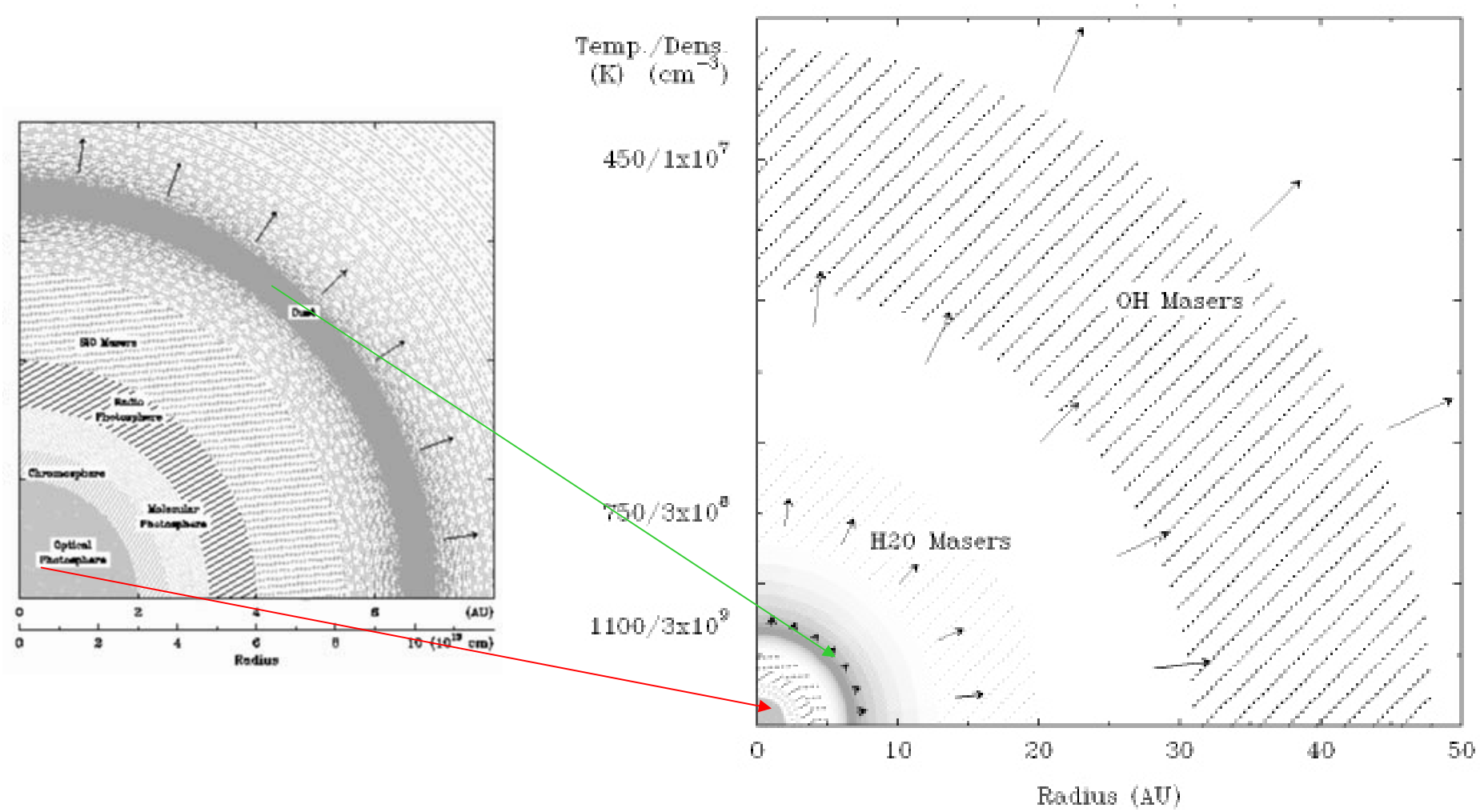
AGB Masers: Standard Model





Note: asymmetry in radio photospheres (green)

AGB Masers: Standard Model



Stellar Masers: Magnetic Fields

Maser	B(Zeeman) (G)	R (cm)	$B^2/8\pi$ --------	nkT dynes/cm^2	ρv^2 ------
OH	0.001	6×10^{14}	10^{-7}	4×10^{-7}	10^{-5}
H2O	0.1	3×10^{14}	10^{-3}	6×10^{-5}	10^{-3}
SiO	10.	5×10^{13}	10^{+1}	1×10^{-3}	10^{-2}

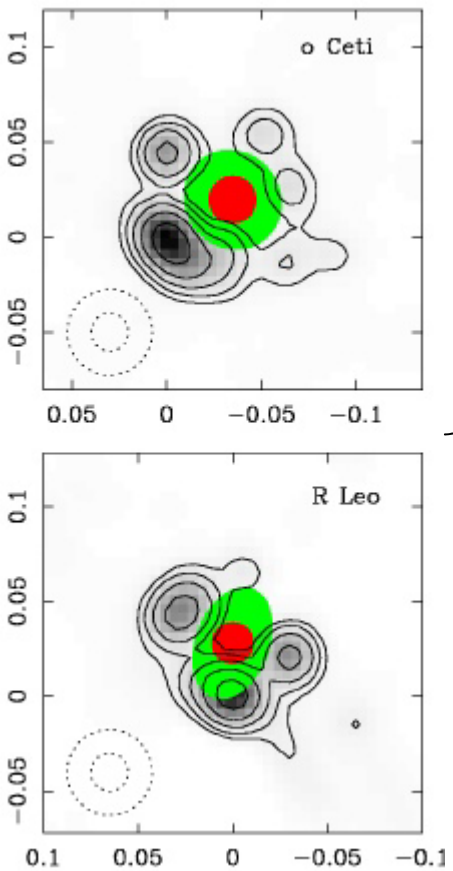
Stellar Masers: Magnetic Fields

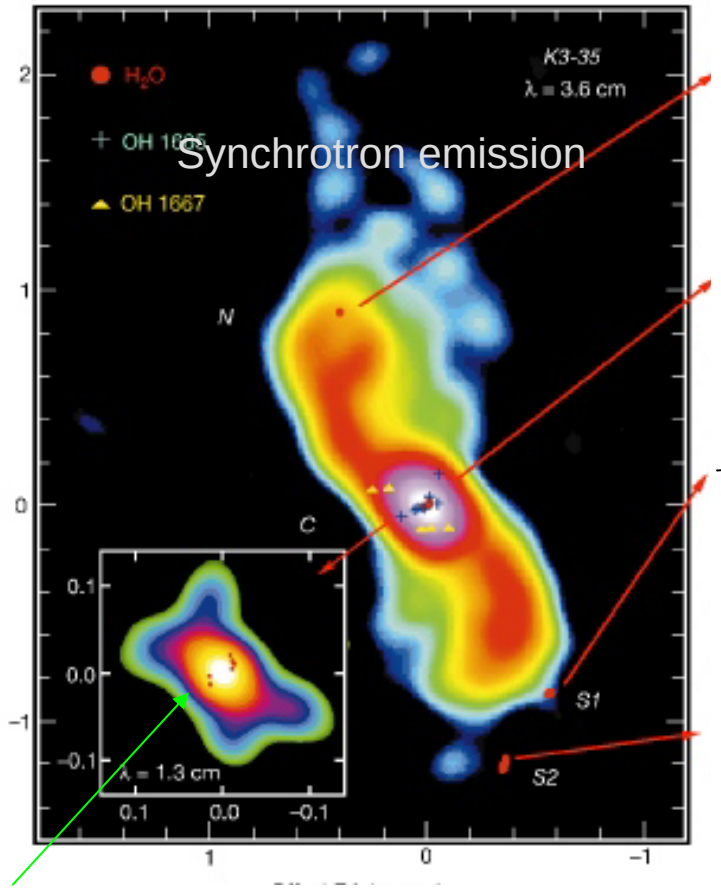
Maser	B(Zeeman) (G)	R (cm)	$B^2/8\pi$ --------	nkT dynes/cm^2	ρv^2 ------
OH	0.003	6×10^{14}	4×10^{-7}	4×10^{-7}	10^{-5}
H2O	0.03	2×10^{14}	4×10^{-5}	6×10^{-5}	10^{-3}
SiO	3.	6×10^{13}	4×10^{-1}	1×10^{-3}	10^{-2}
Radio/Molec	0.5	5×10^{13}	2×10^{-2}	3×10^{-1}	4×10^{-1}
Star	3 .	2×10^{13}	4×10^{-1}	5×10^{0}	$5\times10^{+1}$

Assume B ~ $1/R^2$

20 km/s shocks

Stellar Masers: Post AGB Stars





Cat's Eye PN (HST)

Eg, SiO "disk" + fast H2O "outflow"

Stellar Masers: Super & Hypergiant Stars

- VY CMa

  In SF region, but has no Li, so post-main-seq star

  $L \sim 5 \times 10^5\ L_{sun}\ (D/1.5\ kpc)^2$ ~ maximum allowed L
  parallax needed!

  Losing mass extremely rapidly over past 10^3 yr

  Complex asymmetric structures seen, but an axis at
  PA~50 deg seen in OH,H_2O,SiO,IR

- S Per

  H_2O projected to same R as main-line OH: problem.
  co-spatial or projection effect (H_2O f-b caps)?

  OH main-line Zeeman B-field 3 mG,
  H_2O B-field 150 mG suggests not co-spatial

  “Onion model dead” …too early to claim this.

Galactic Structure

- Spiral Structure

  Parallaxes are here, parallaxes are here!

  ~10 MSFRs &10 evolved stars
  (~25 Pulsars also)

  Large kinematic anomalies found

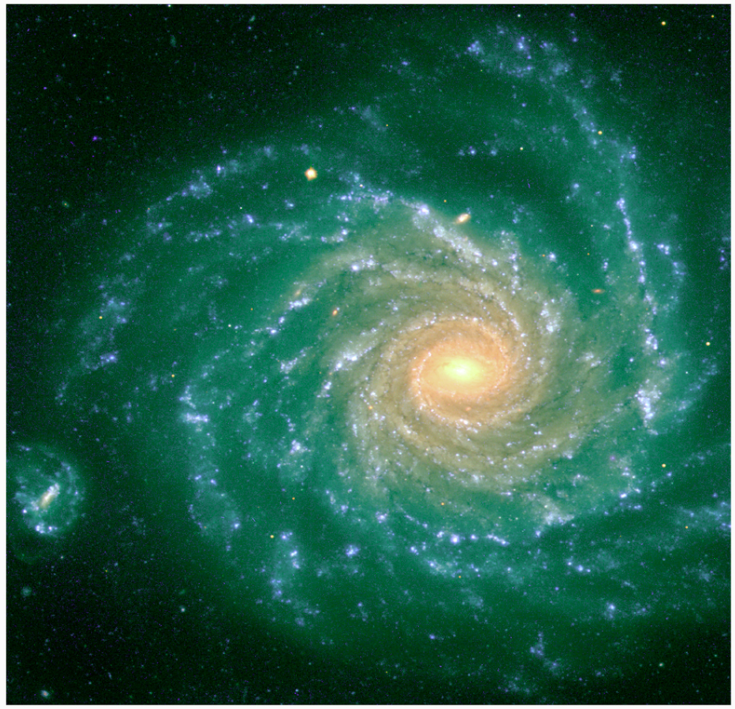
  VERA and VLBA will soon provide ~100
  mapping spiral arms (finally)
  determining (dark) mass distribution of M.W.
  measuring Θ_o & R_o (+/-few%)

- Inner Galaxy

  Surveys of evolved stars tracing the Bar

- Magnetic Field

  Some tantalizing correlations of Pulsar RM B-fields
  with OH maser B-field…definitive results must
  await many parallaxes



Spiral Galaxy NGC 1232 - VLT UT 1 + FORS1

ESO PR Photo 37d/98 (23 September 1998) ©European Southern Observatory

H_2O AGN Masers

- Sub-pc scale disks and jets

Clear understanding that masers populate both disk and jets

types: thin disks, thick disks, jets, winds

Learning details of accretion disks (warps, B-fields, n, T, $M_{BH,}$, spiral arms…)

NGC 4258: archetypal AGN maser

Thin, warped, accretion disk well established

Periodicity in high vel data real

disk thinness ~ 5 μas ~ ~10 AU measured => hydrostatic equil T=600 K

accel vs Vsys changes may be caused by spiral arms

H_2O AGN Masers

- Precision Cosmology

Maser Cosmology Project: GBT + VLBA

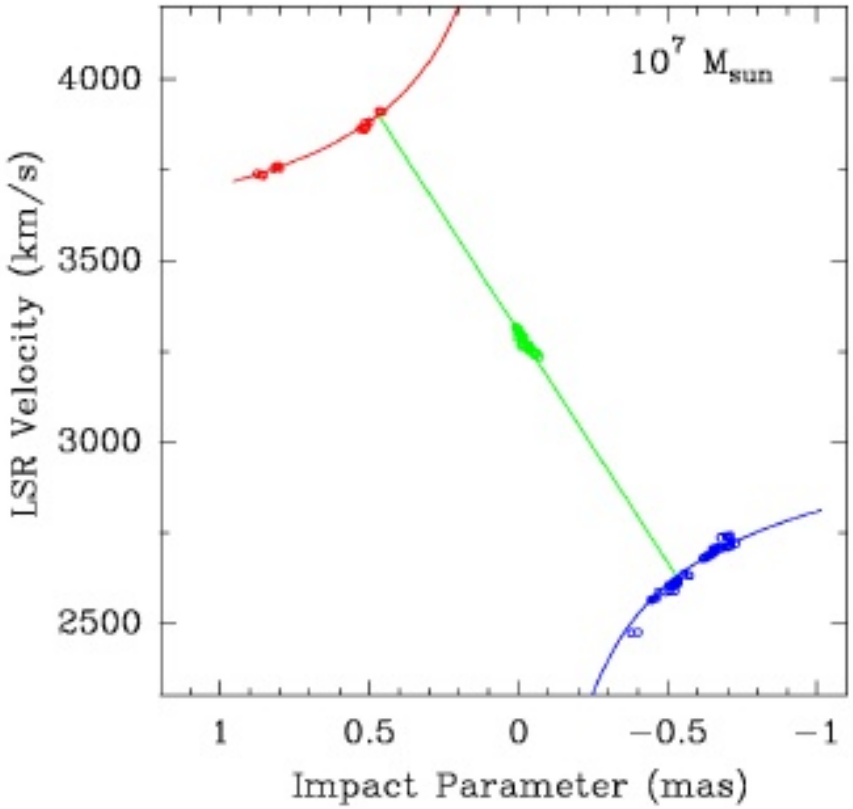
direct, geometric distance + redshift

goal: H_0 accurate to 3%

Eq. of state of dark energy …

Cosmological constant vs. quintessence

UGC3789 excellent “NGC4258-like” candidate



OH Megamasers

Associated with star bursts (result of major mergers)…

not associated with the AGNs, but…
183 GHz AGN H_2O masers found in Arp220 (which doesn't have 22 GHz!)

Very dense gas is key: specifically $n(H_2) \sim 10^{5.6}$ cm-3,

but if large B-fields measured are correct, might imply $n(H_2) > 10^{6-7}$

Associated, but weak, H_2CO and 1720 MHz OH "megamasers"

Why 1667 MHz compact & 1665 MHz extended?

Torus filled with clouds (each with low gain);

chance alignments (both along l.o.s. and in Vel) can give high gain spots

Aligned, well-separated clumps produces high beaming…unsaturated

Origin of arcs with V-gradients unclear: $M \sim r V^2 / G > 10^5 M_{sun}$ if gravitational

Next Meeting?

- H_o measured to 3% accuracy…w=1 (and the Universe will end)
- Constancy of Fundamental “Constants” further tested
- mm/submm maser observations will be as common as cm-wave masers
- Blind surveys (of at least the Plane) will be completed for all major classes of molecular masers
- Milky Way mapped with ~200 parallaxes/proper motions
- H-recombination line maser from EOR
- …

Where Should the Next Meeting be?

Washington DC (North America)

Rio de Janeiro (South America)

Alice Springs (Australia)

? (Europe, Asia, or Africa)

7’th meeting would logically be in the Antarctic in ~2030 !