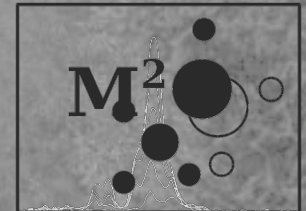
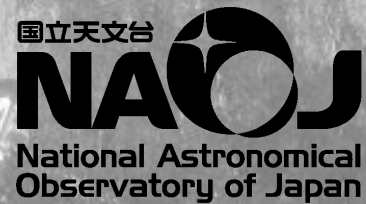


Masers

Ross Burns
DARA training, May 2021



A large, circular radio telescope dish antenna structure, likely the Arecibo radio telescope, is shown in a grayscale image. The dish is supported by a complex metal framework and is surrounded by dense trees. The text "What is a maser?" is overlaid in the center of the image.

What is a maser?

What is a maser?

Essentially, a cloud of molecular gas

With "population inversion"

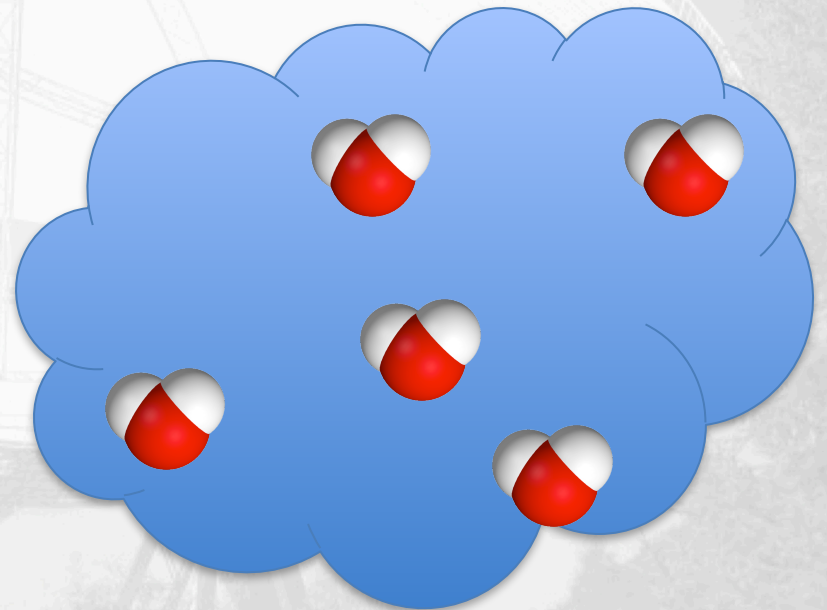
Full list of known astrophysical masers (from Wikipedia)

But many are quite rare and not discussed further

OH	CH ₃ OH	³⁰ SiO
CH	HNCNH	HCN,
H ₂ CO	SiS	H ¹³ CN
H ₂ O	HC ₃ N	H
NH ₃ ,	SiO,	CS
¹⁵ NH ₃	²⁹ SiO,	

Molecules that **commonly** produce masers (in astrophysical contexts):

OH, **CH₃OH**, **H₂O**, SiO



~1-100 AU

Excited molecules

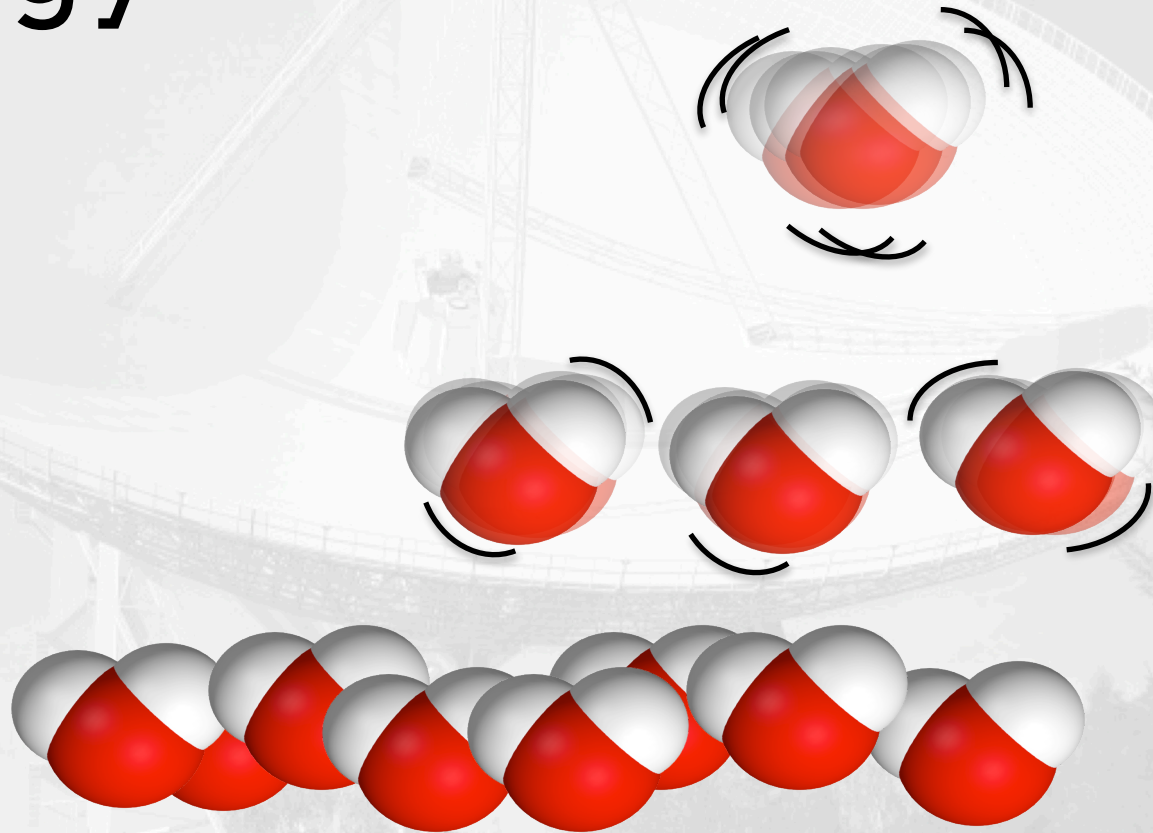
Boltzmann "Thermal" distribution

Energy

E_2

E_1

E_0

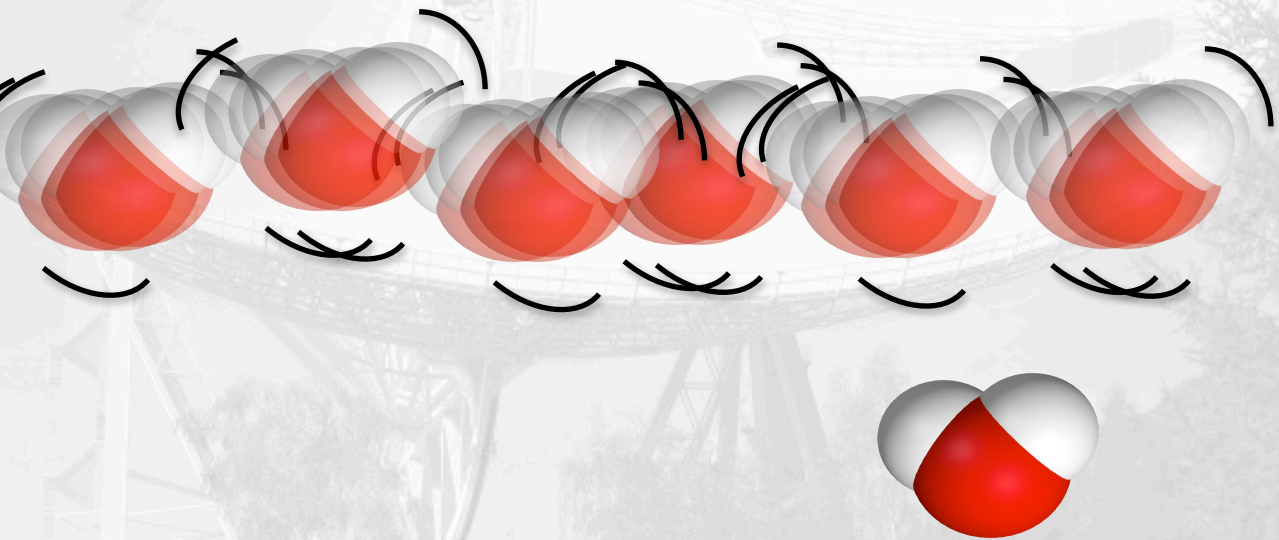


Excited molecules

Energy

E_2
 E_1
 E_0

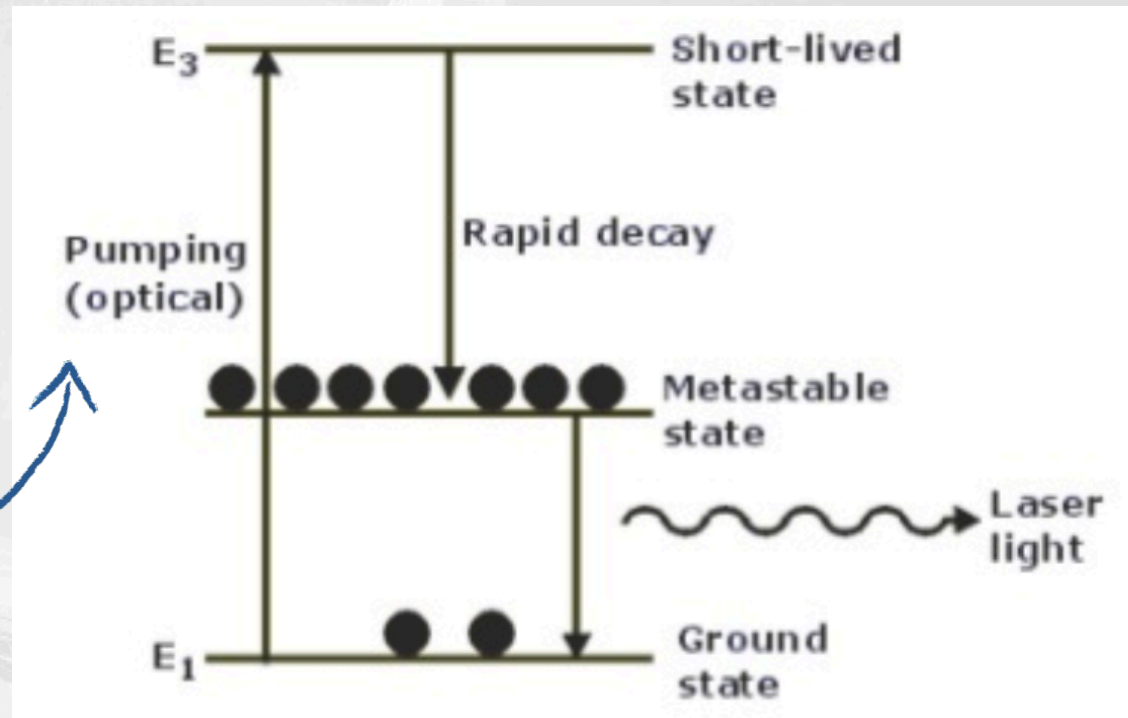
“Population inversion”



Population inversion, how?

Energy input:

- Radiation
- Collisions



Very important: Incoming photon of $E=h\nu$ will stimulate emission of a photon of $h\nu$ – production of many photons of the same frequency.

- Need velocity coherence for ampl. Turbulent cloud is no good
- Spectrum is a bright, narrow spike

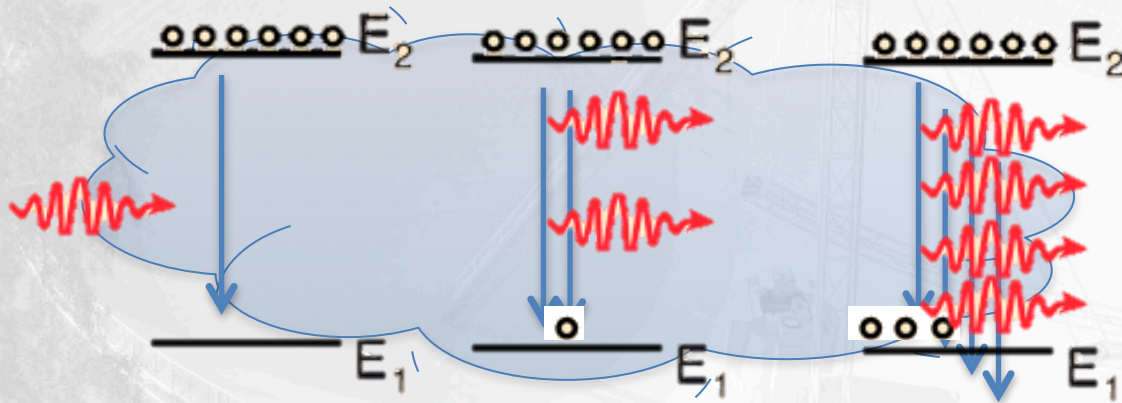
What determines maser brightness?

1.1 Path length



Masers in space

Population
inversion

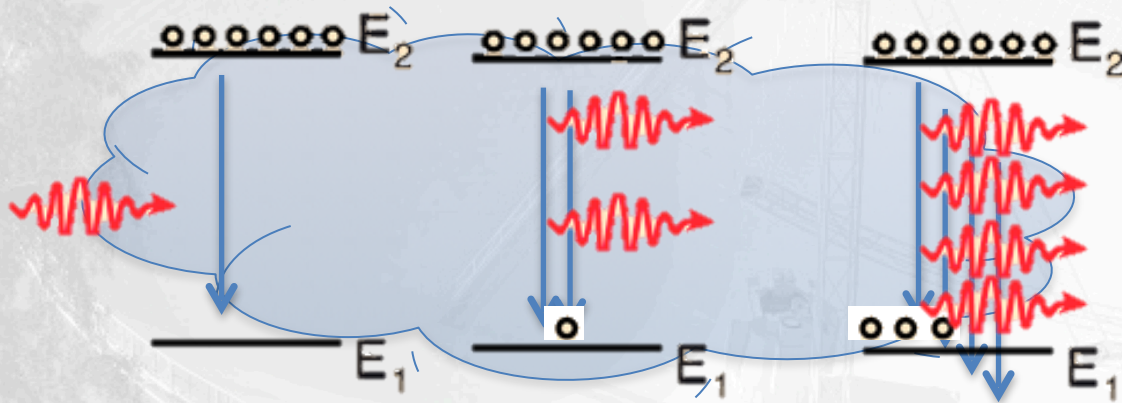


Common masers:

OH, CH₃OH, H₂O, SiO

Masers in space

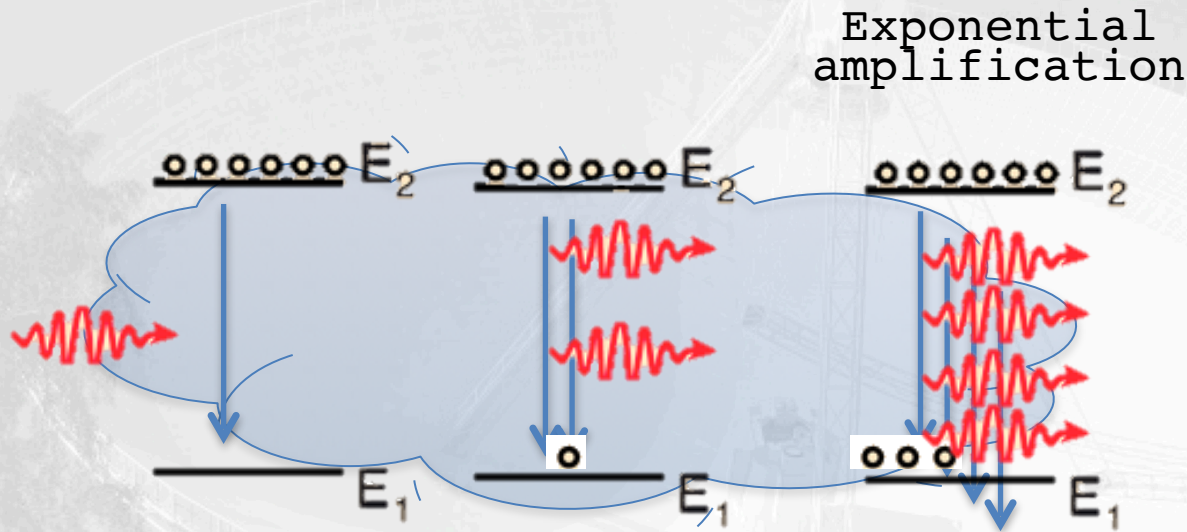
Stimulated emission



Common masers:

OH, CH₃OH, H₂O, SiO

Masers in space

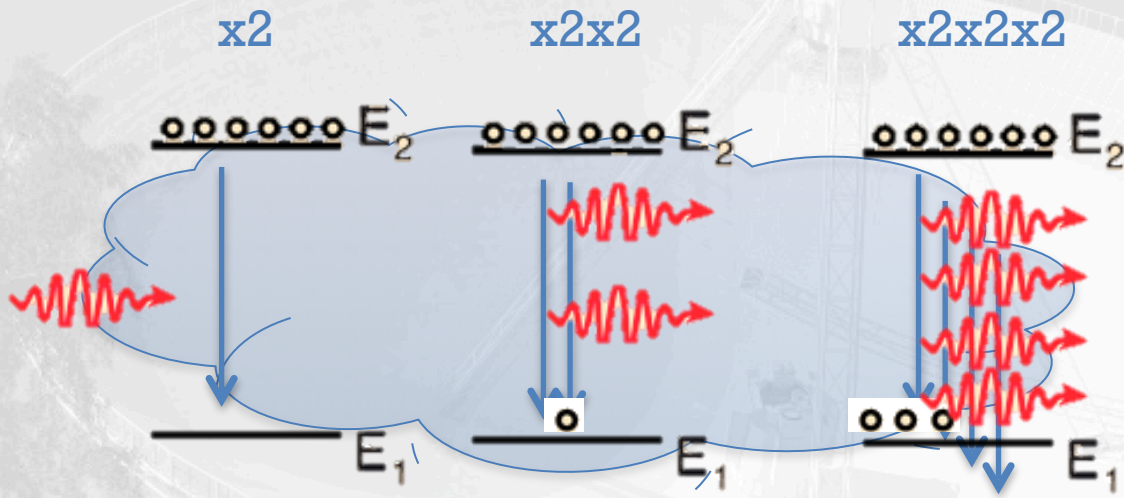


Common masers:

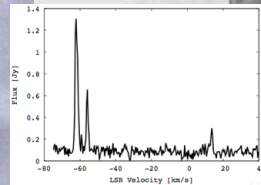
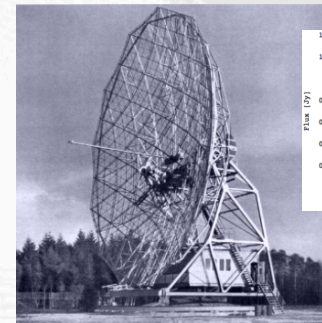
OH, CH₃OH, H₂O, SiO

- Amplification $\propto e^{\text{path length}}$

Masers in space



Observer



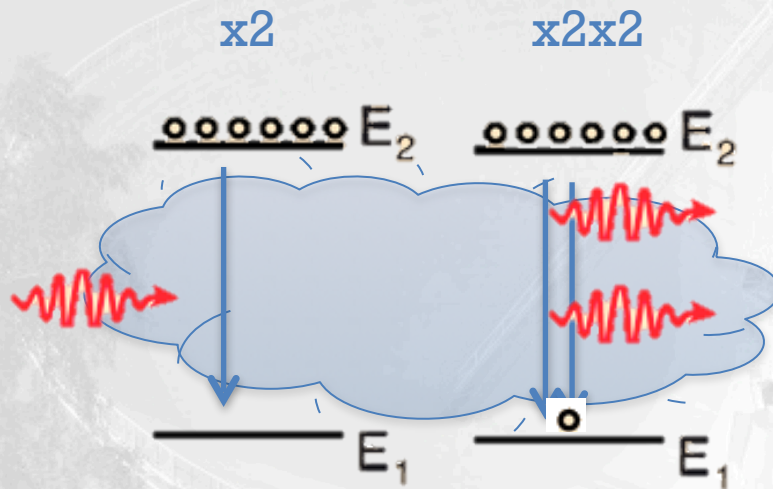
If the orientation of the maser is **long** in the line-of-sight of the observer then there will be **many** instances of stimulated emission and **exponential amplification**

Common masers:
OH, CH₃OH, H₂O, SiO

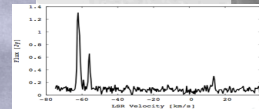
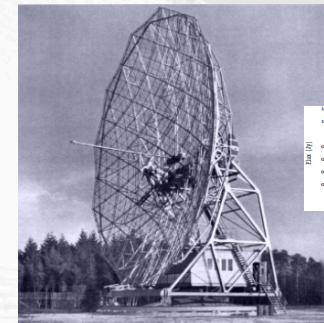
Therefore a **bright** maser will be observed

- Amplification $\propto e^{\text{path length}}$

Masers in space



Observer



If the orientation of the maser is **short** in the line-of-sight of the observer then there will be **few** instances of stimulated emission and **exponential amplification**

Common masers:

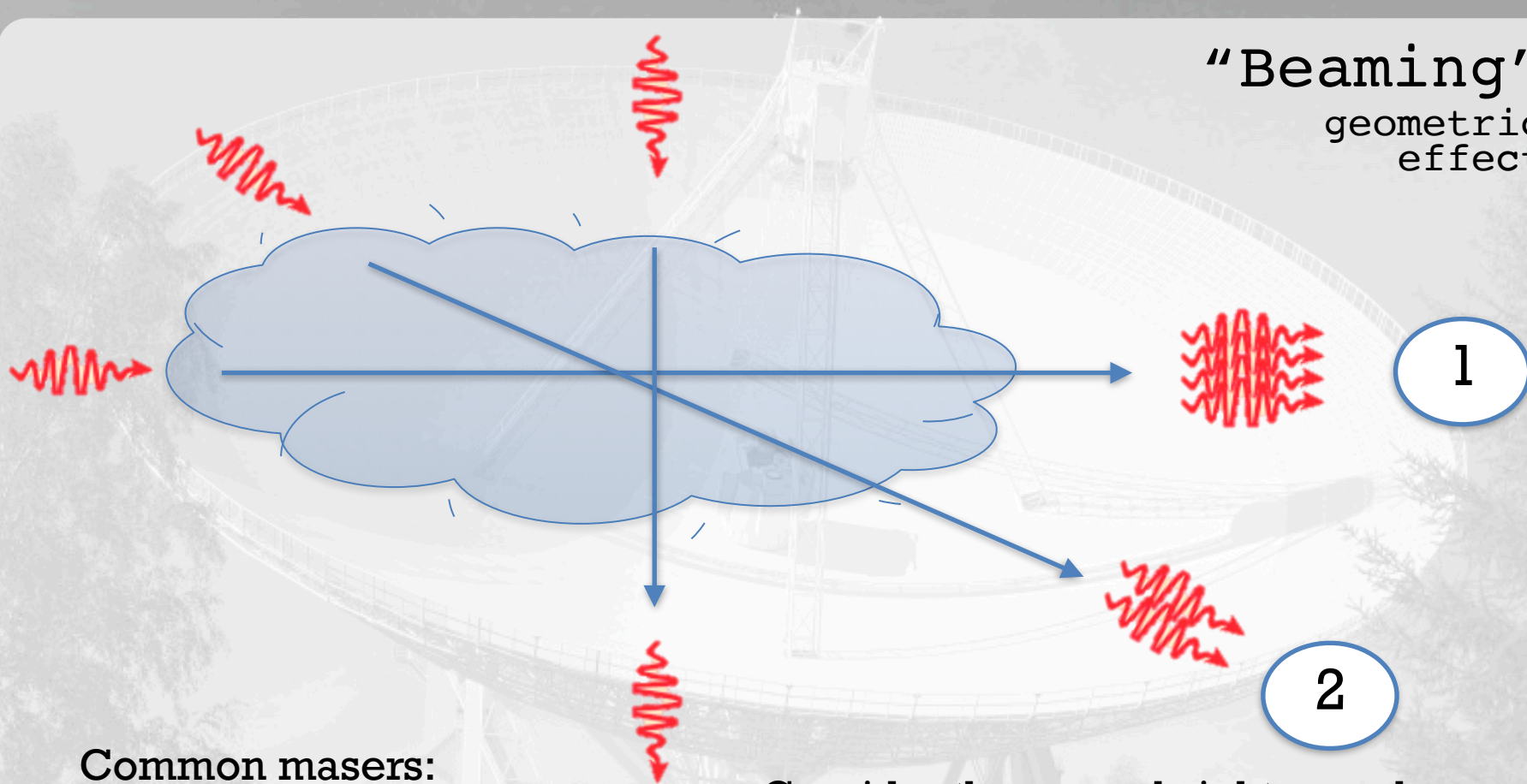
OH, CH₃OH, H₂O, SiO

Therefore a **weak** maser will be observed

- Amplification $\propto e^{\text{path length}}$

Viewing angles

“Beaming”
geometric
effect



Common masers:

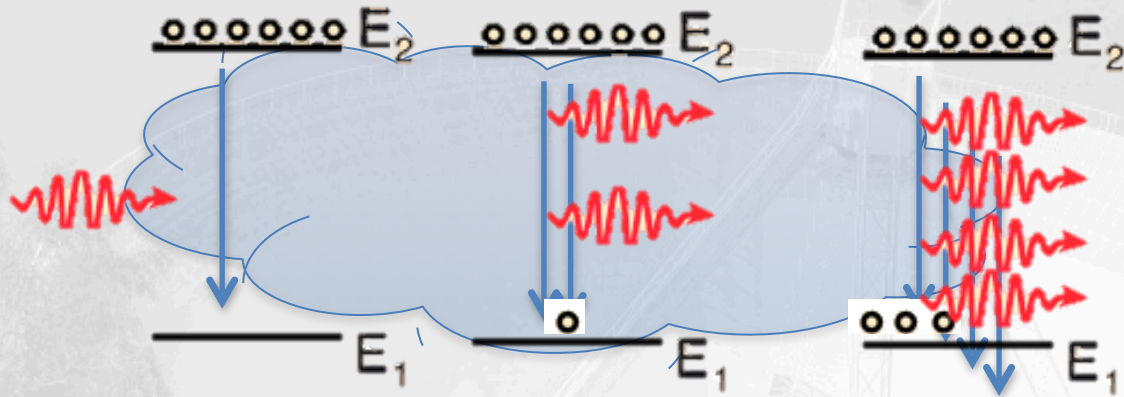
OH, CH₃OH, H₂O, SiO

- Amplification $\propto e^{\text{path length}}$

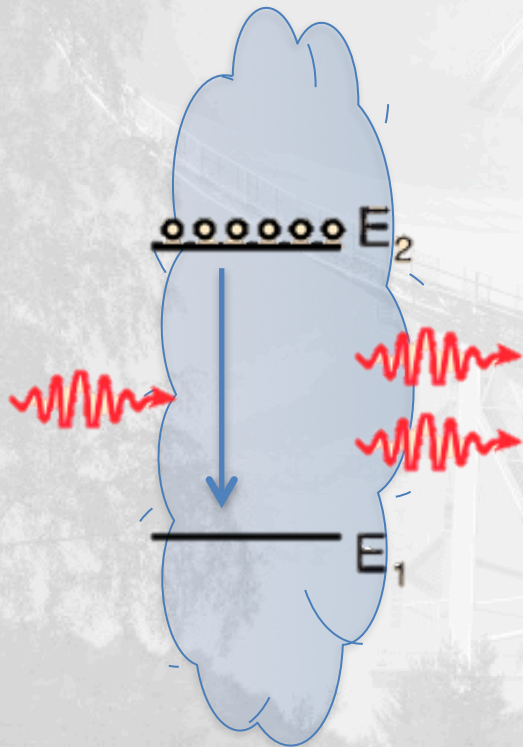
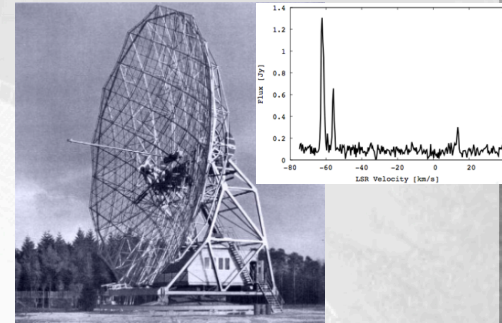
Consider the maser brightness observed from the following perspectives:

- 1 - bright
- 2 - moderate
- 3 - weak

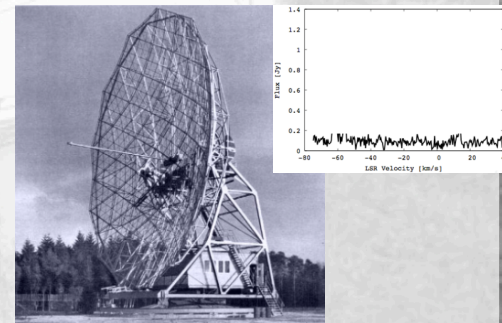
Another example



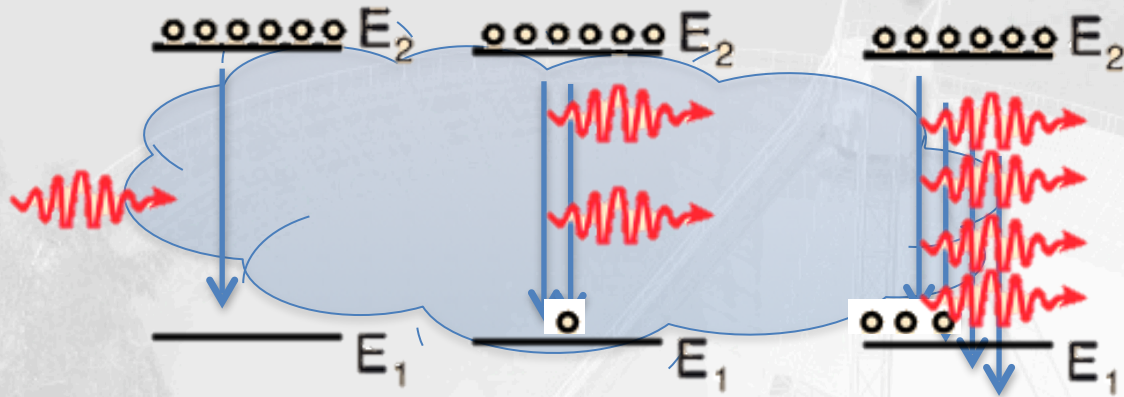
Observer 1



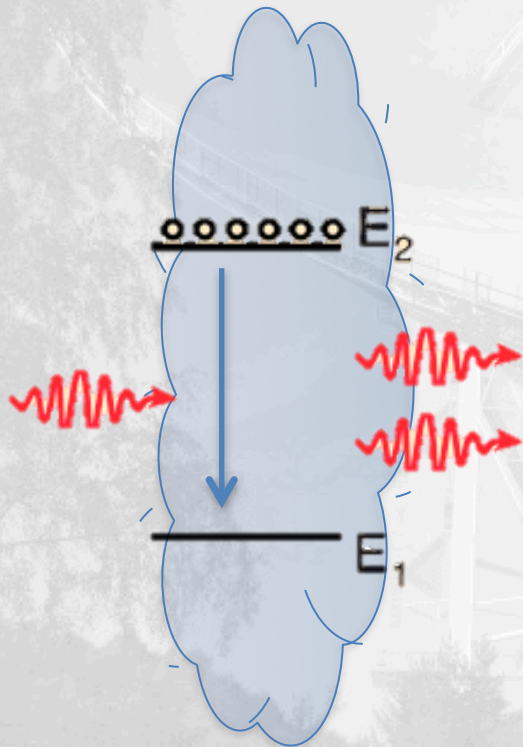
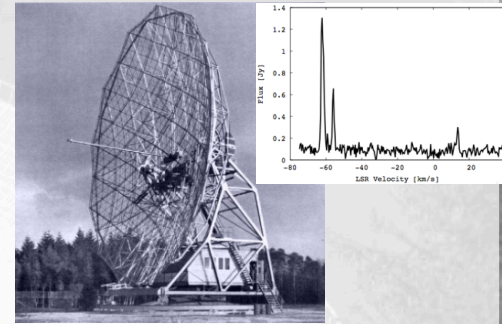
Observer 2



Another example

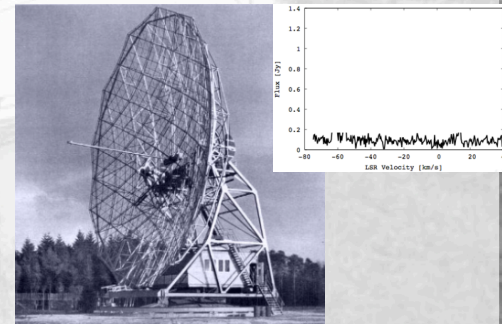


Observer 1



Despite the two masers being the same length Observer 1 sees much brighter maser emission than Observer 2

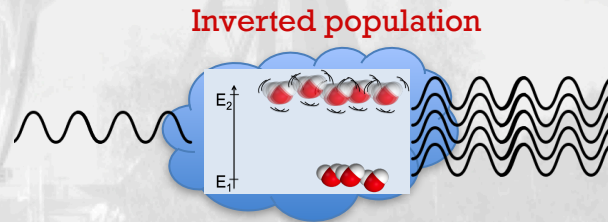
Observer 2



Longer path length leads to brighter masers

Discuss: LASERS

- What is the acronym for LASER?
 - How does a LASER work?
 - What is its energy source?
 - What determines its colour?
-
- What is the difference between a LASER and a MASER?
(size / natural or manmade / wavelength)



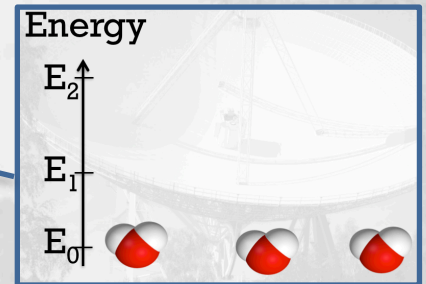
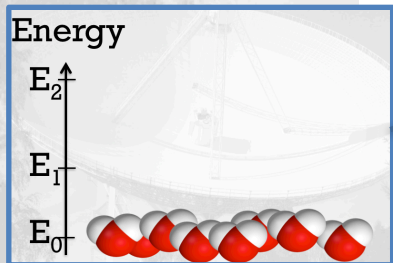
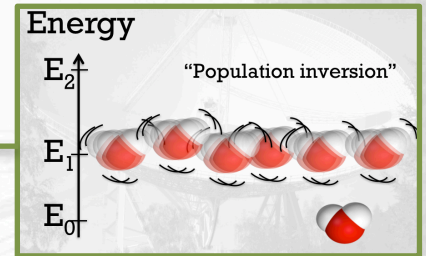
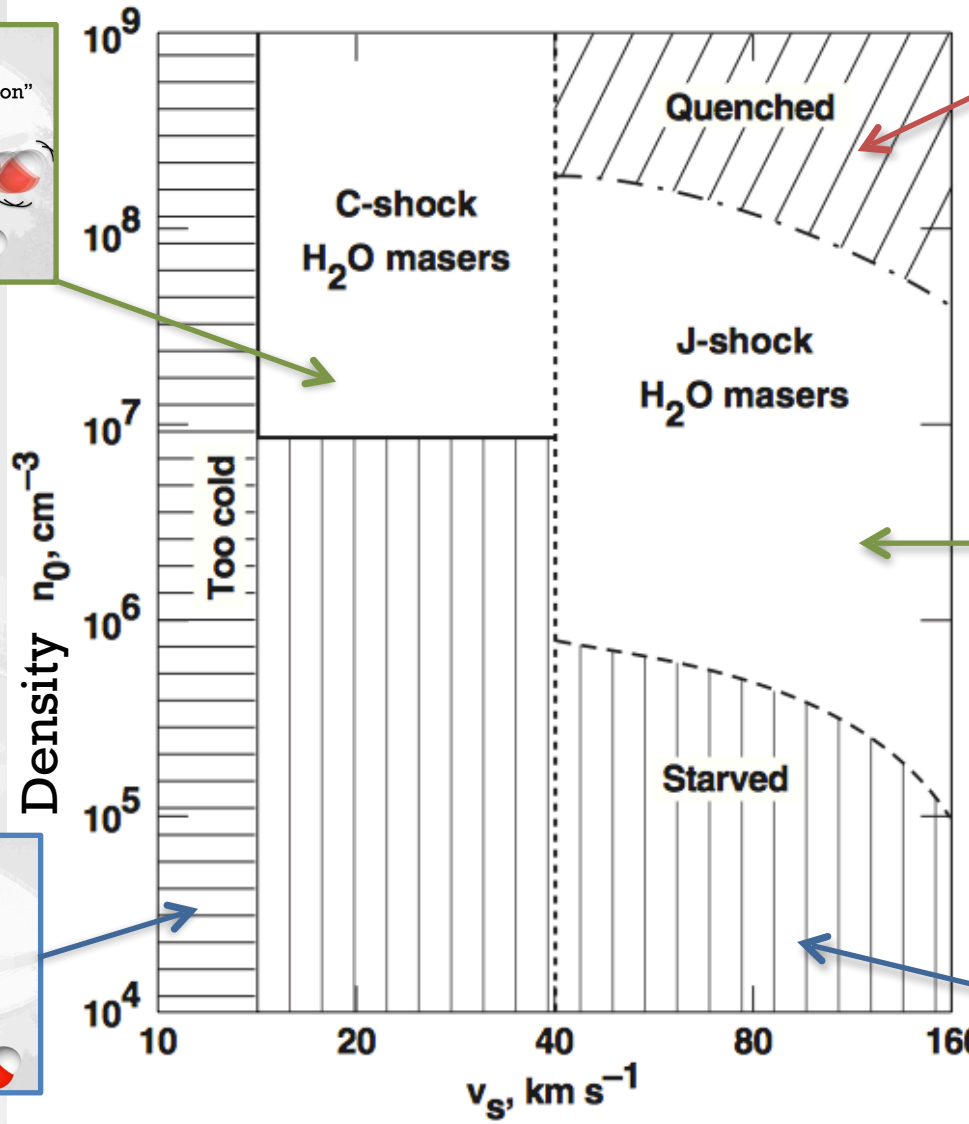
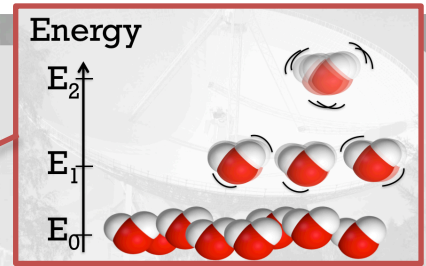
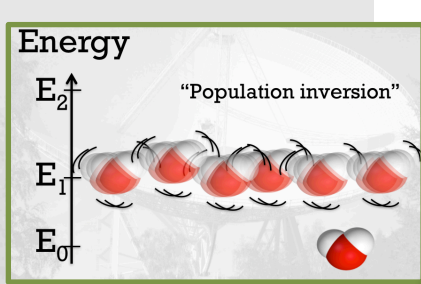
What determines maser brightness?



1.2 Pumping conditions

Pumping conditions

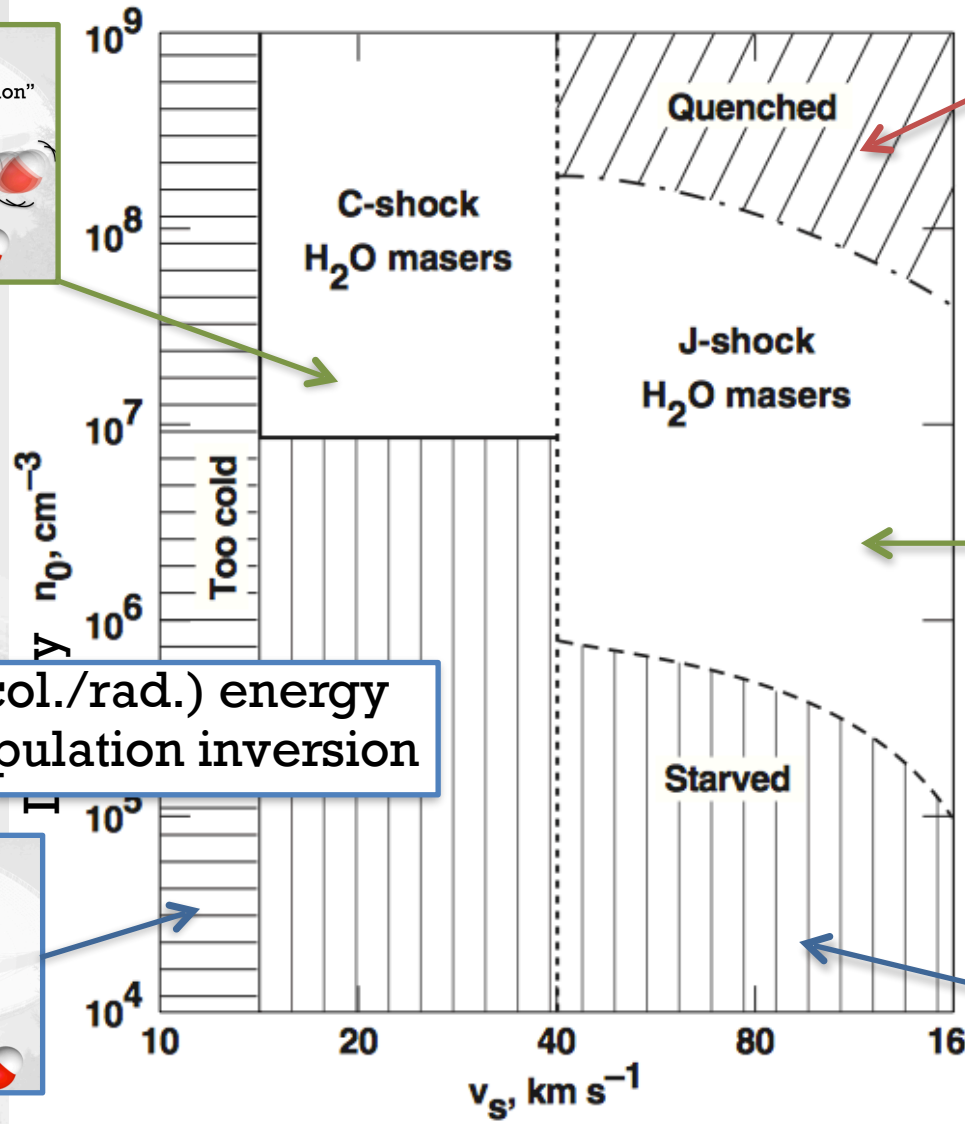
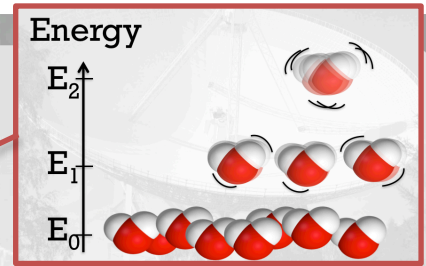
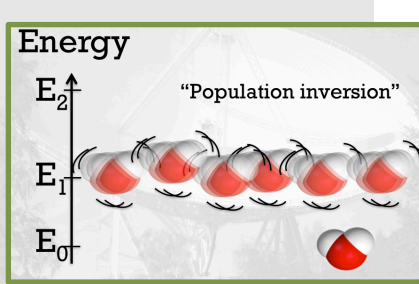
Hollenbach et al. 2013, ApJ, 773, 70



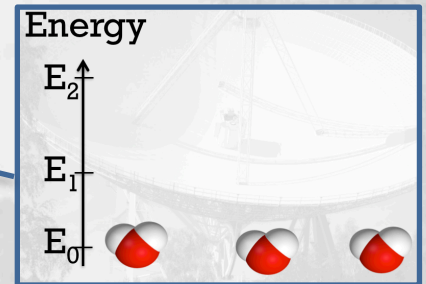
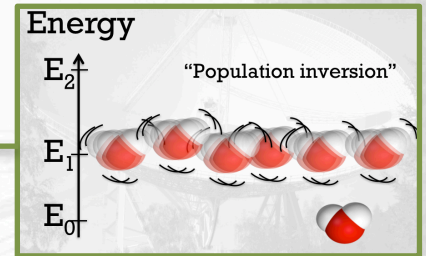
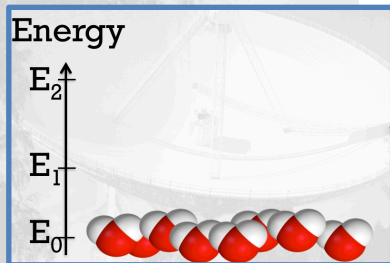
Shock speed (collisional energy)

Pumping conditions

Hollenbach et al. 2013, ApJ, 773, 70



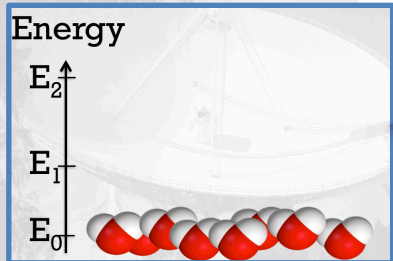
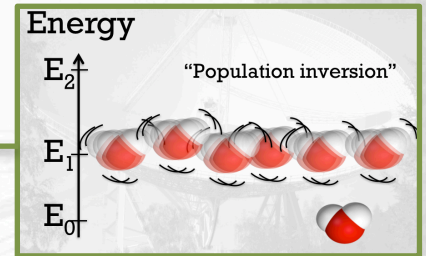
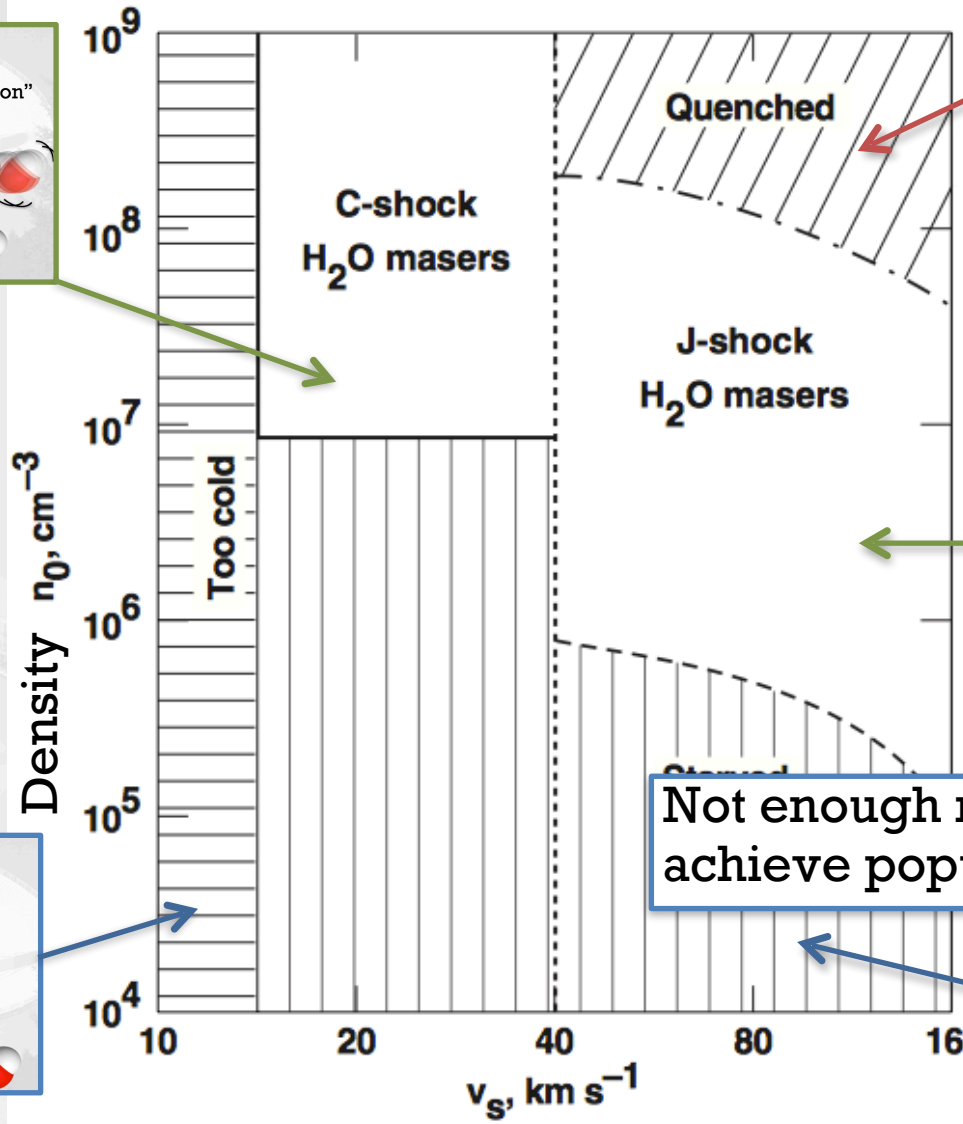
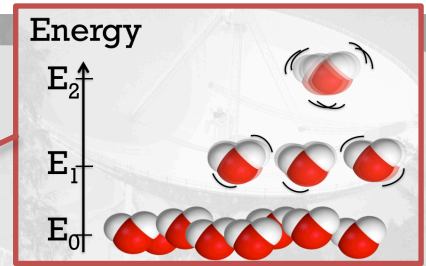
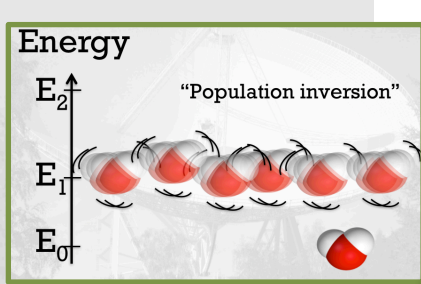
Not enough (col./rad.) energy to achieve population inversion



Shock speed (collisional energy)

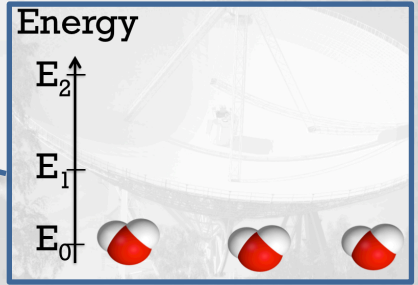
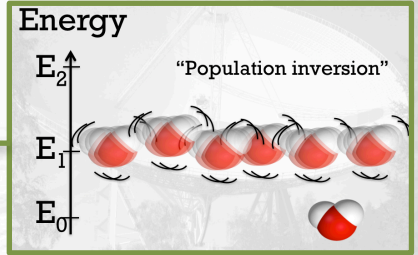
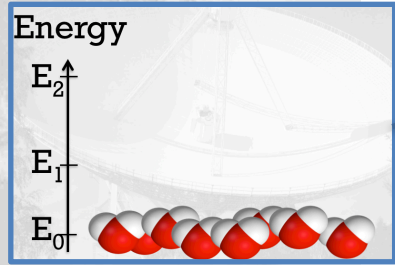
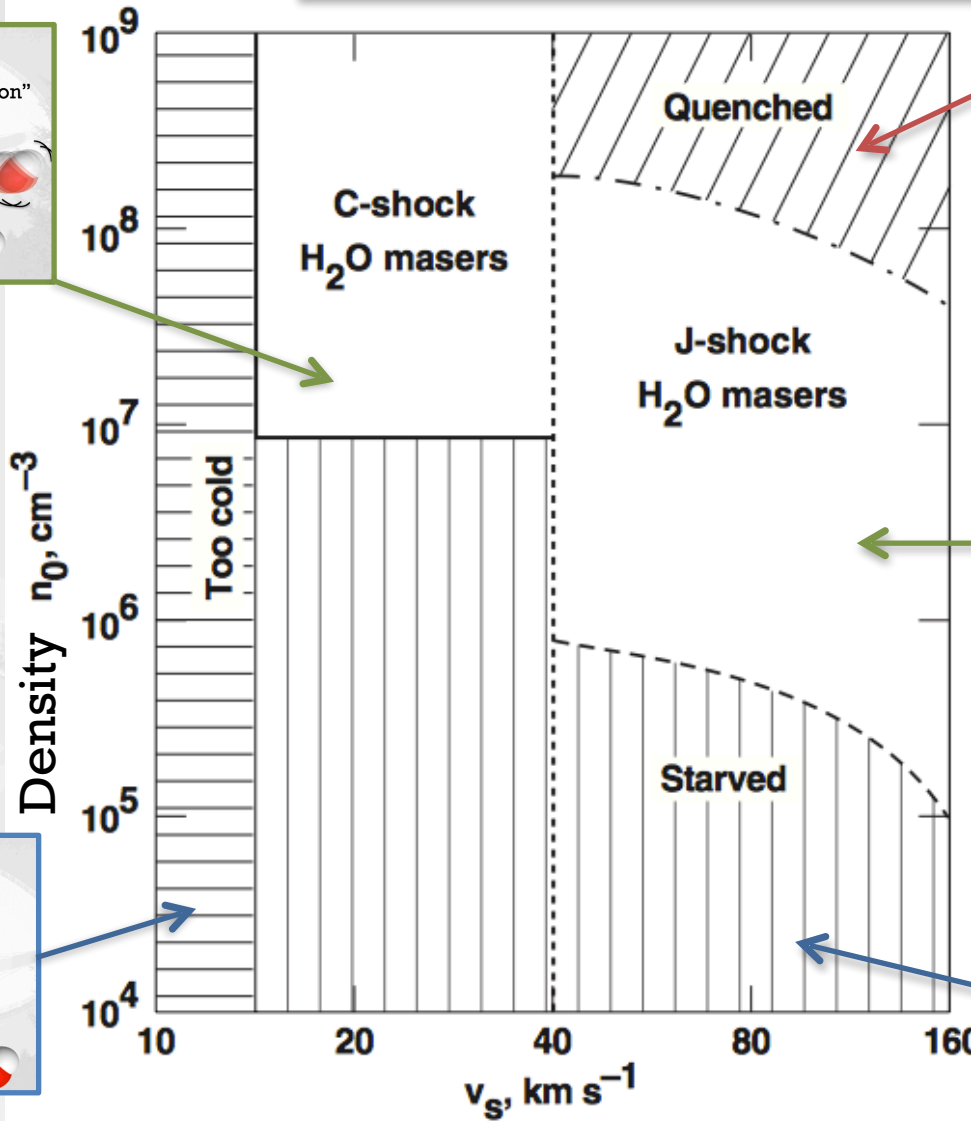
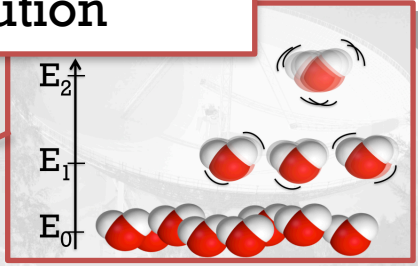
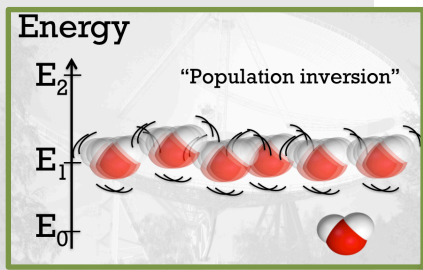
Pumping conditions

Hollenbach et al. 2013, ApJ, 773, 70



Shock speed (collisional energy)

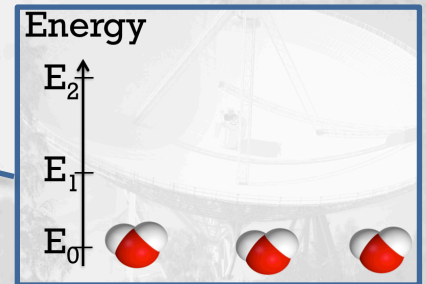
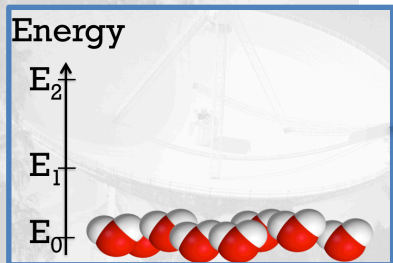
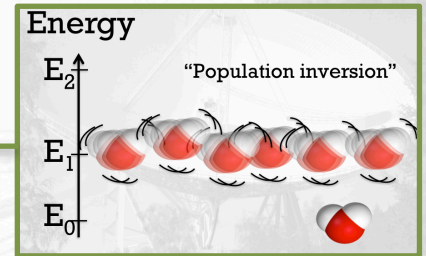
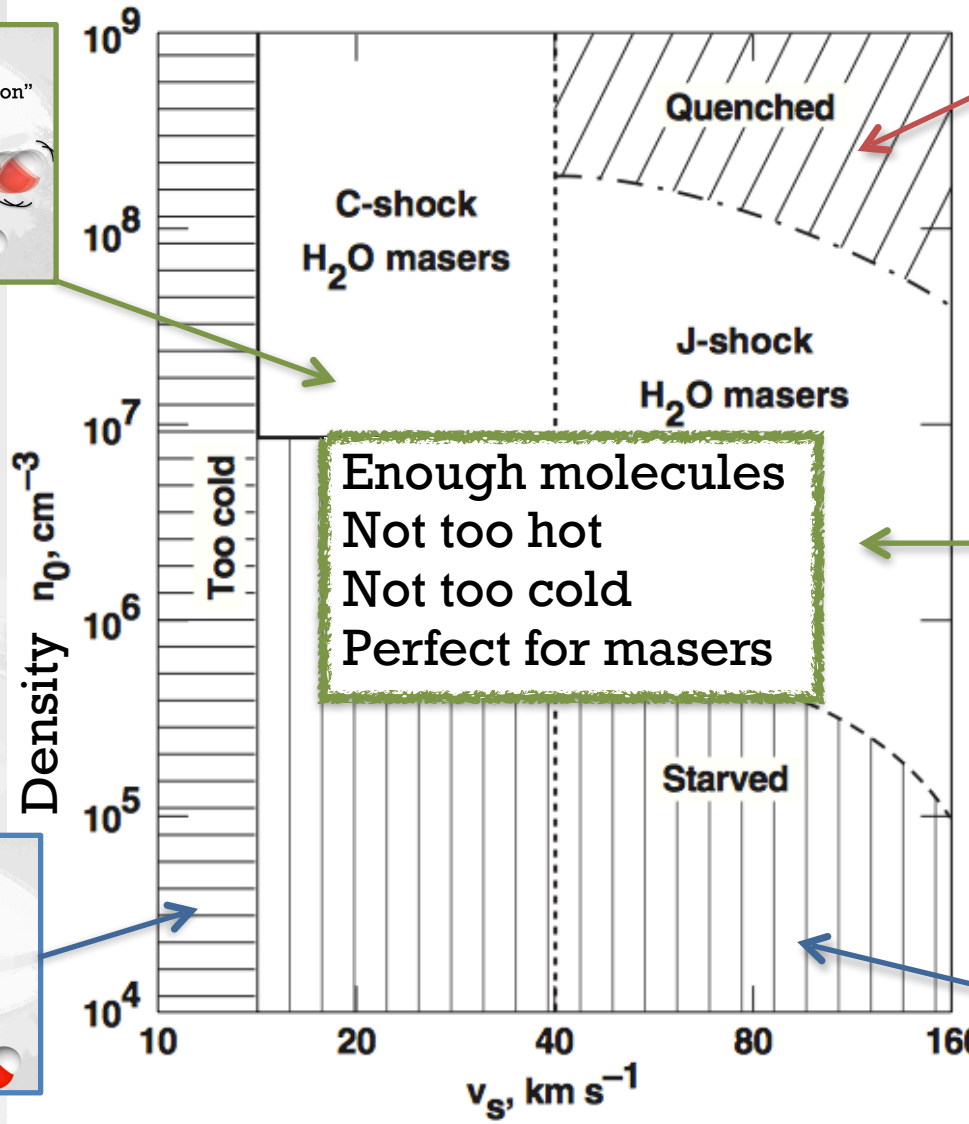
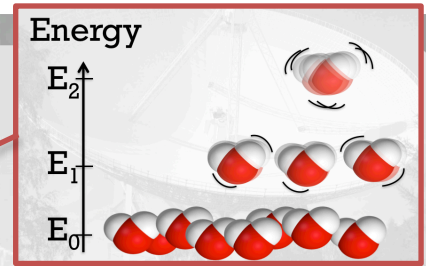
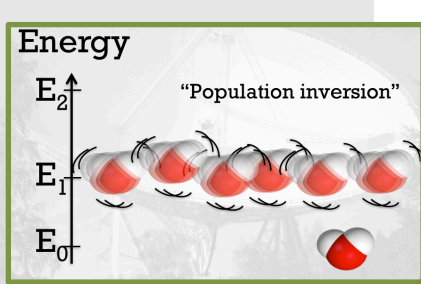
Too much (col./rad.) energy, molecules become 'thermal' (Boltzmann) distribution



Shock speed (collisional energy)

Pumping conditions

Hollenbach et al. 2013, ApJ, 773, 70



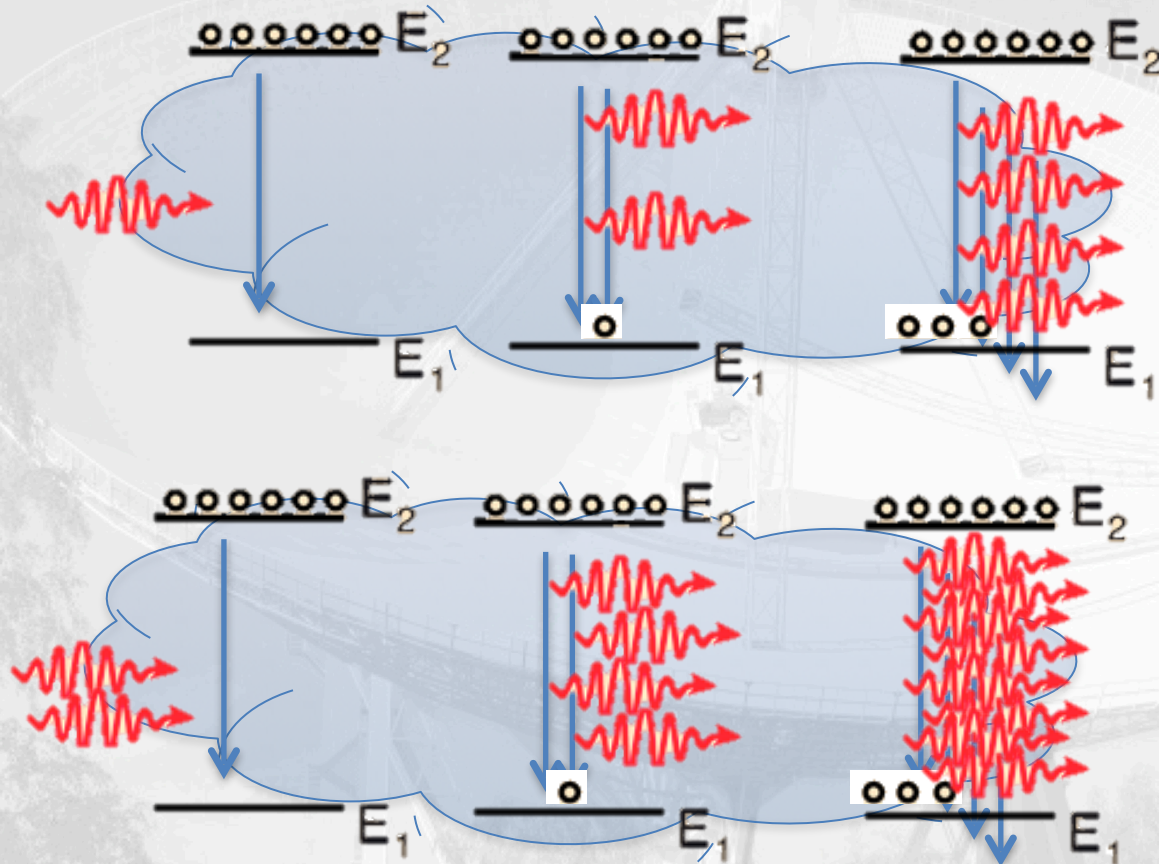
Shock speed (collisional energy)

What determines maser brightness?



1.3 Input "Seed" photons

Input "seed" photons



More input "seed" photons leads to more output photons

A large radio telescope dish is shown in a forest setting. The dish is a large, curved structure made of metal panels, supported by a complex network of steel beams and cables. It is positioned on a hillside, and the surrounding area is filled with trees and foliage. The image is in grayscale and has a slightly faded, artistic quality.

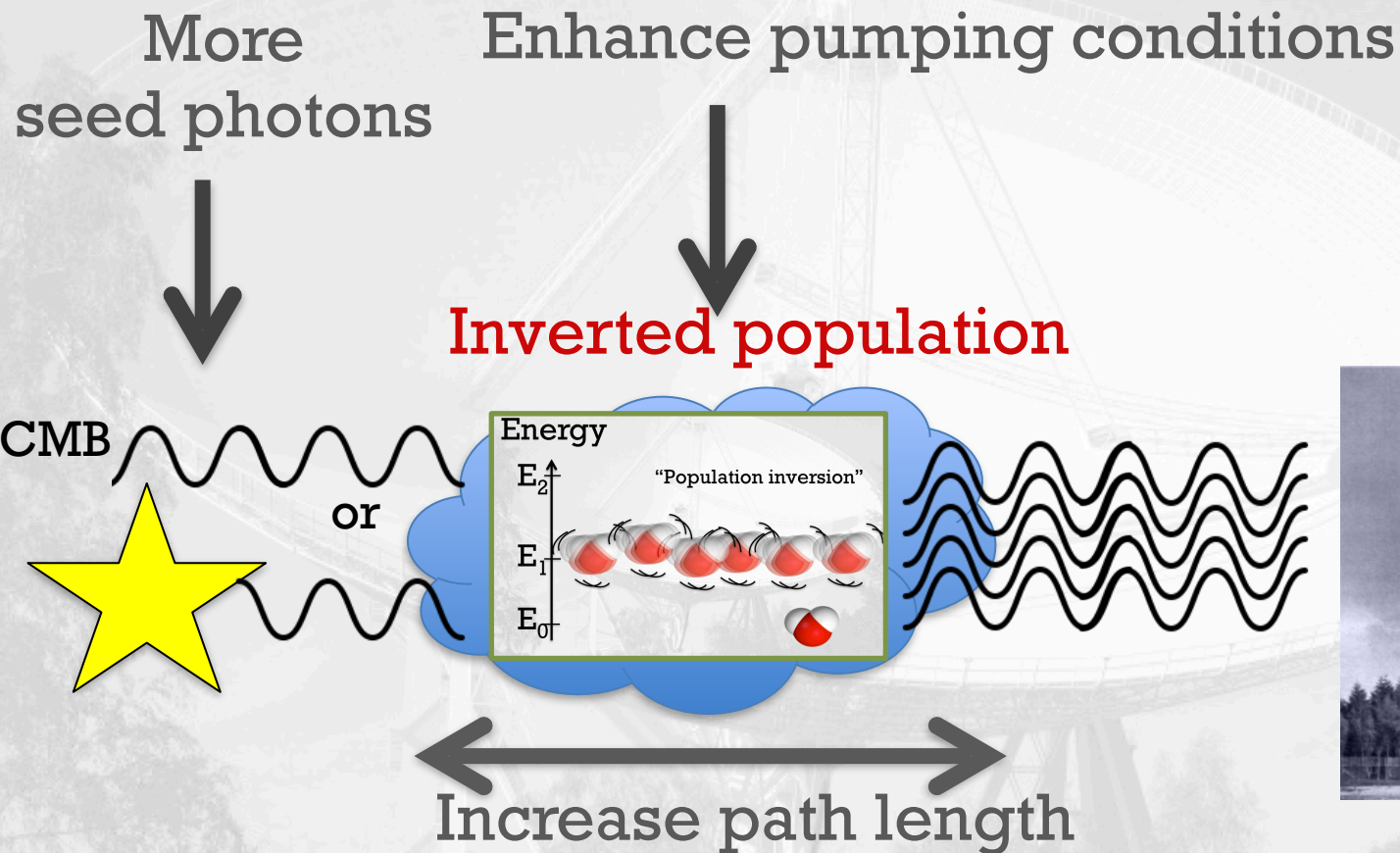
What determines maser brightness?

1.1 Path length

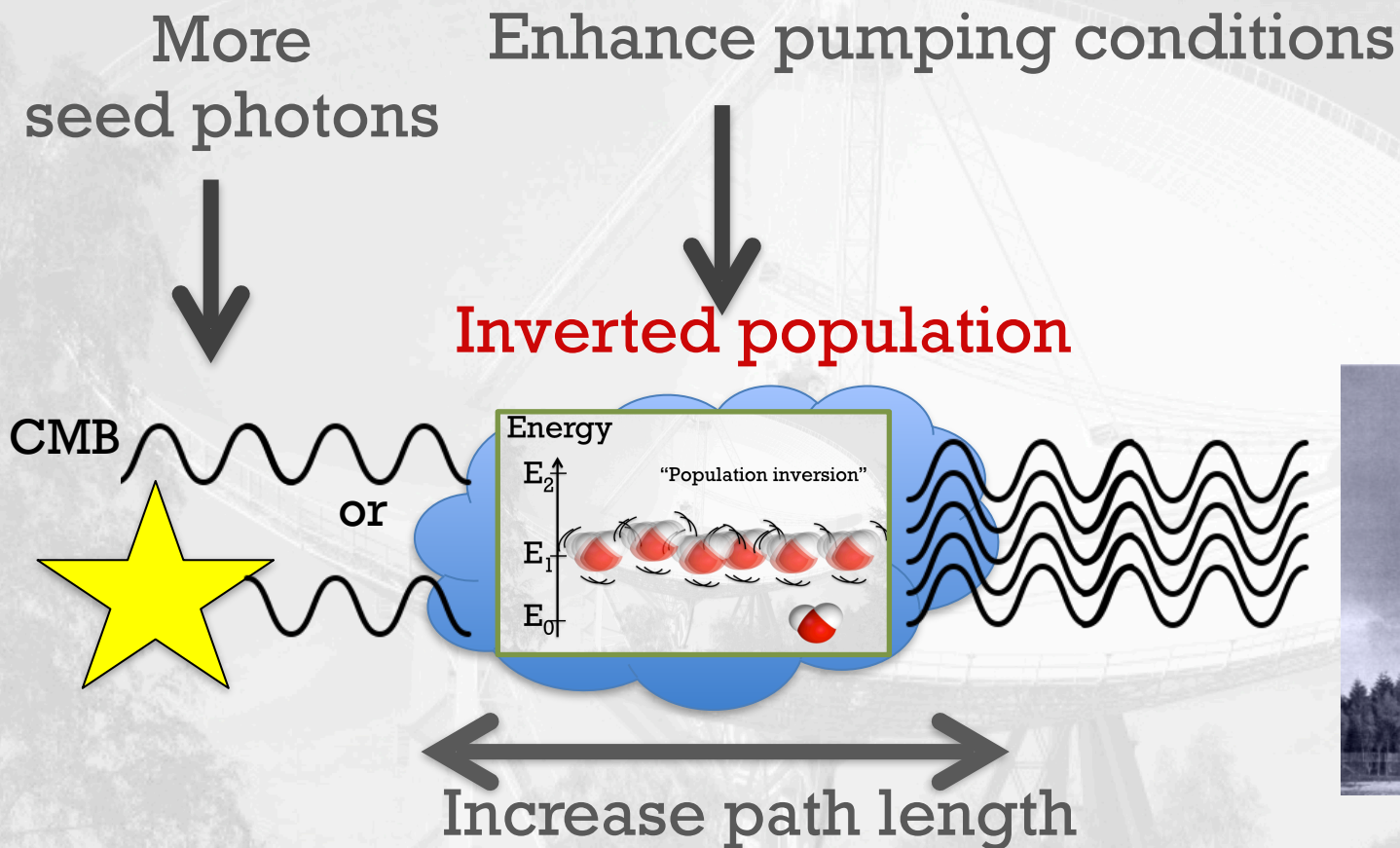
1.2 Pumping conditions

1.3 Seed photons

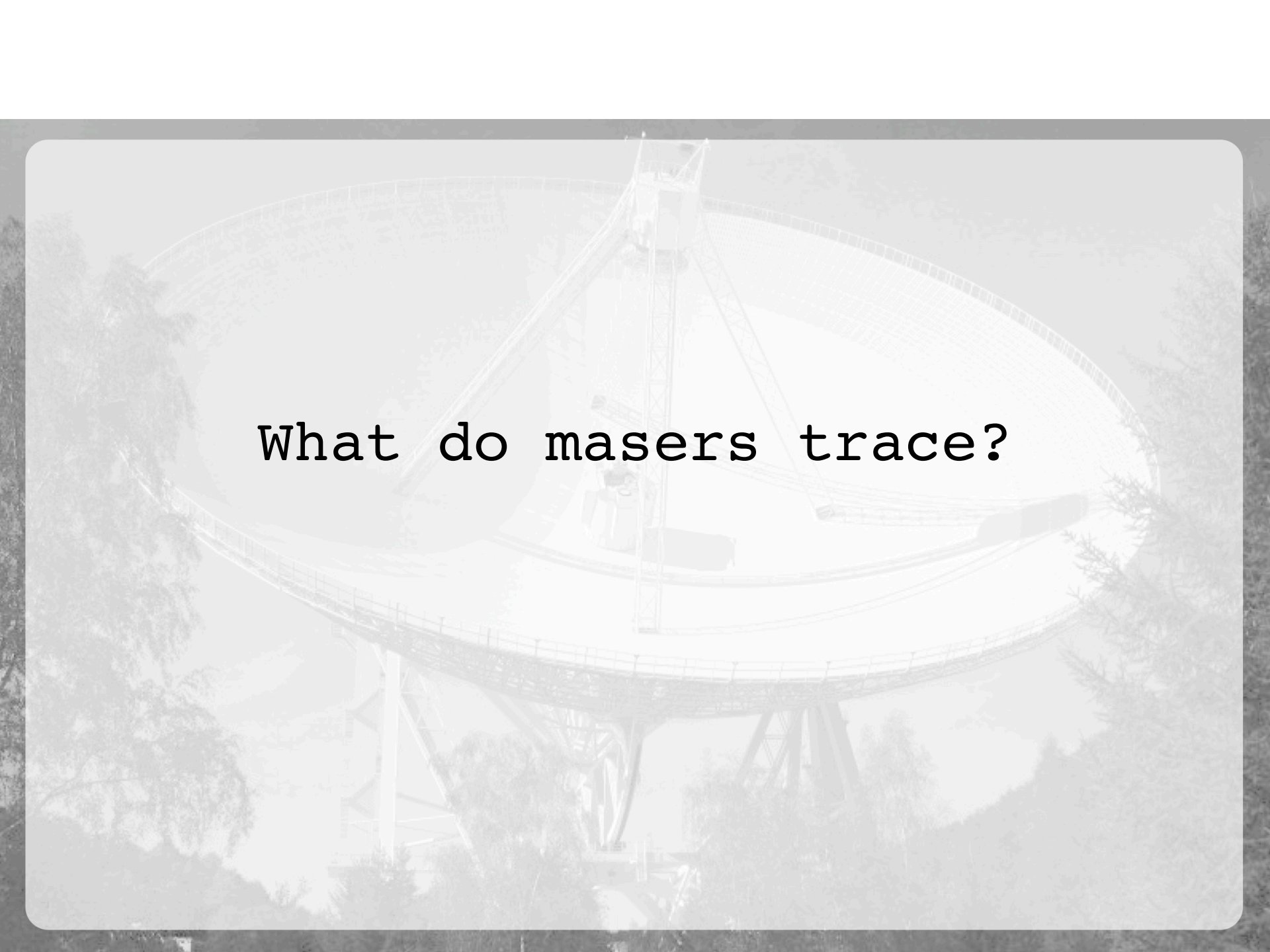
What determines the maser brightness?



What determines the maser brightness?



Discuss each of these for a minute with your colleagues to check your understanding

A large, white, parabolic radio telescope dish is the central focus of the image. It is supported by a complex metal structure and is situated in a dense forest of tall evergreen trees. The dish is oriented towards the sky. The entire image has a light gray overlay, and the text is centered in a black, monospaced font.

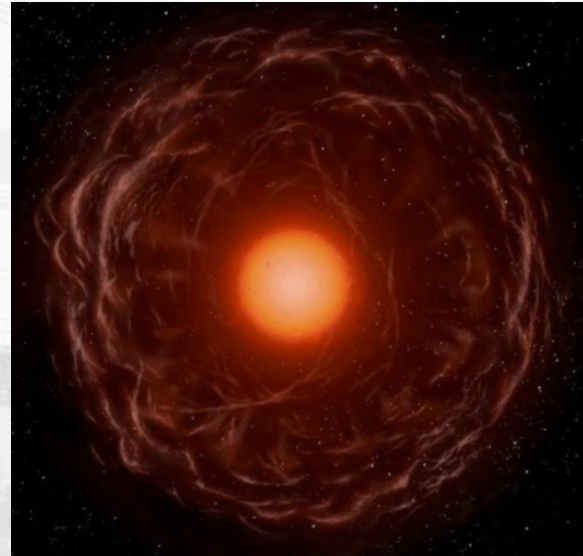
What do masers trace?

Typical environments

Evolved stars



Protostars



Also: comets, planetary atmospheres, supernova, extragalactic disks

Typical environments

Evolved stars

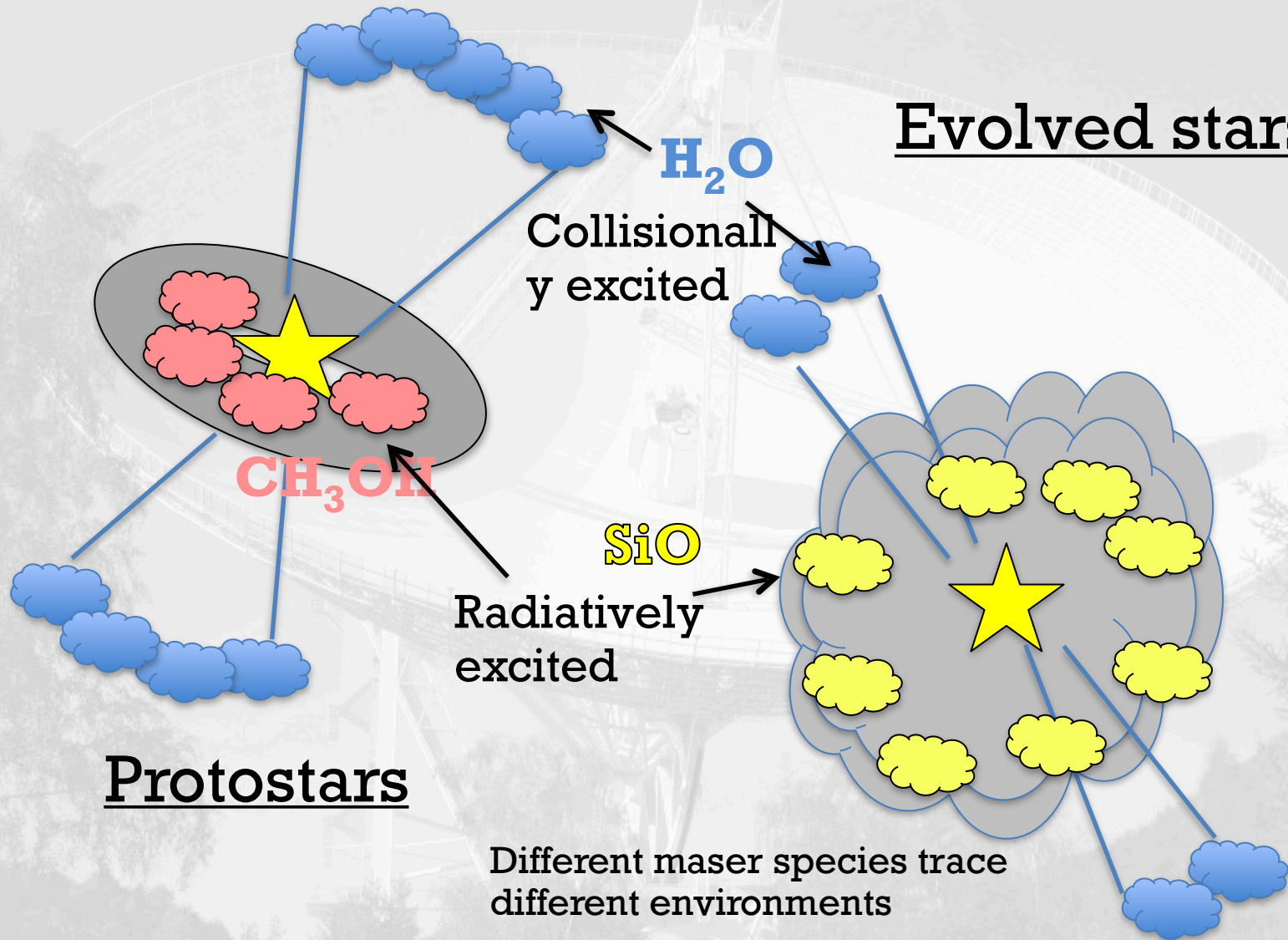
H_2O
Collisionally excited

SiO
Radiatively excited

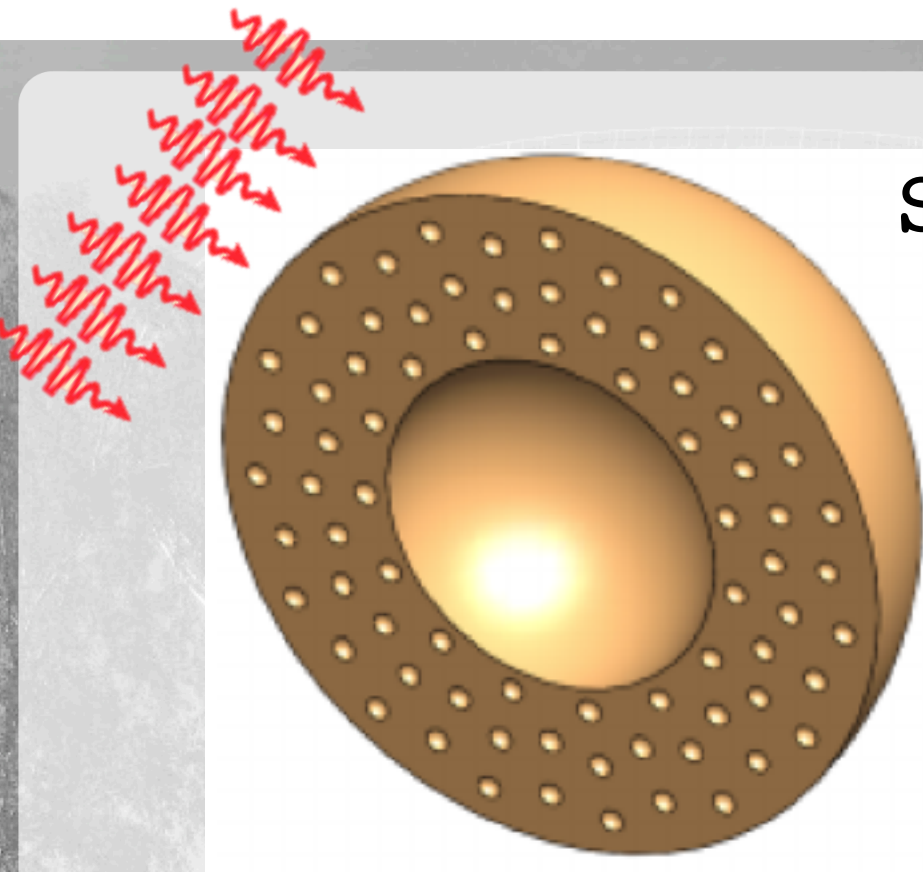
CH_3OH

Protostars

Different maser species trace different environments



Masers in evolved star shells

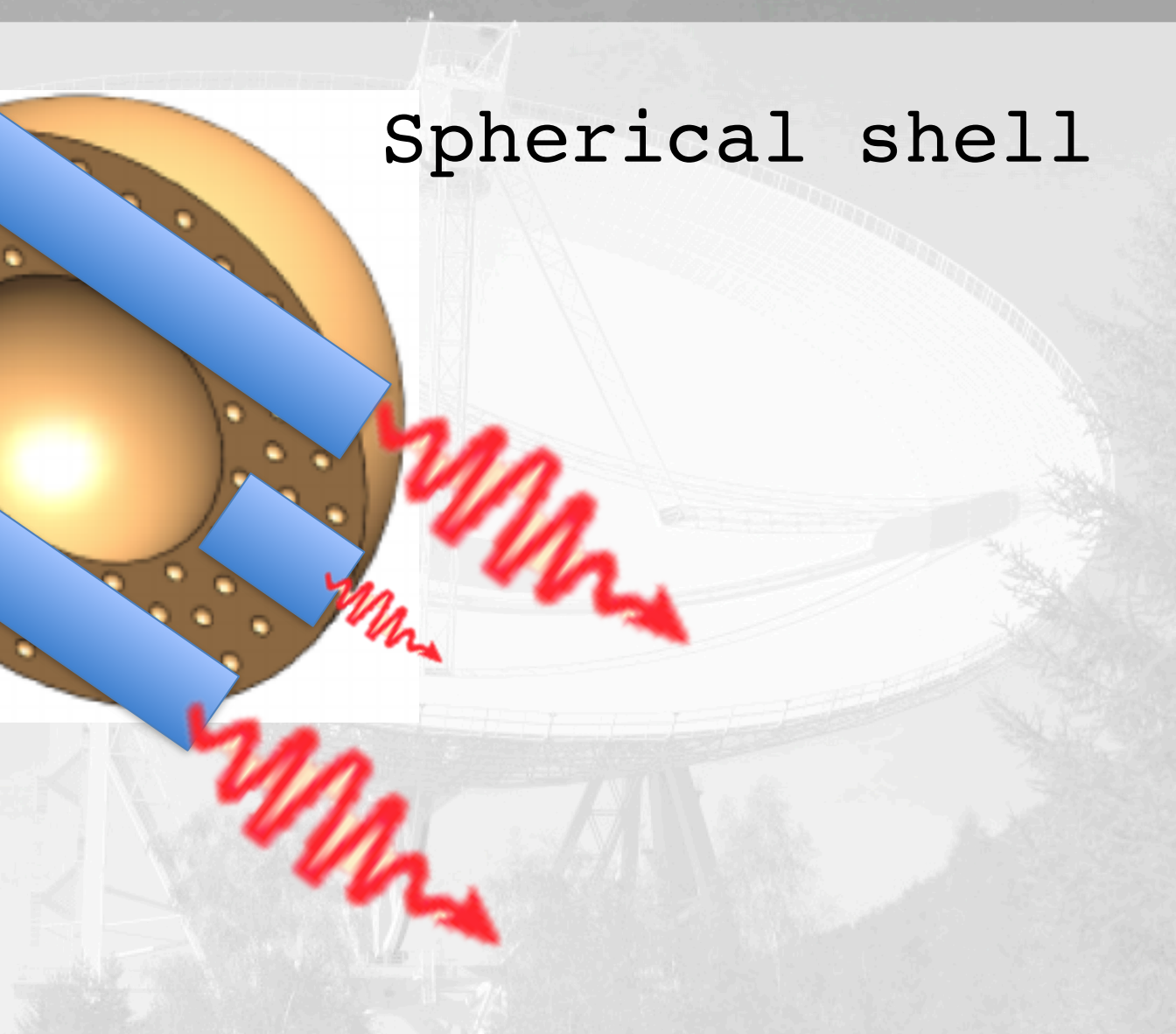
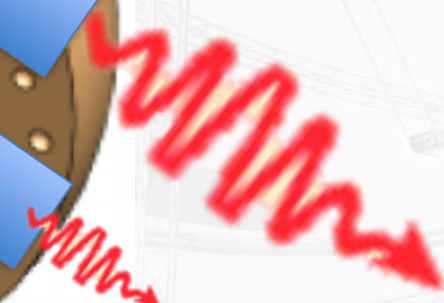
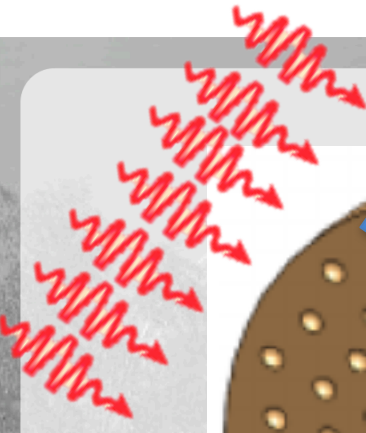
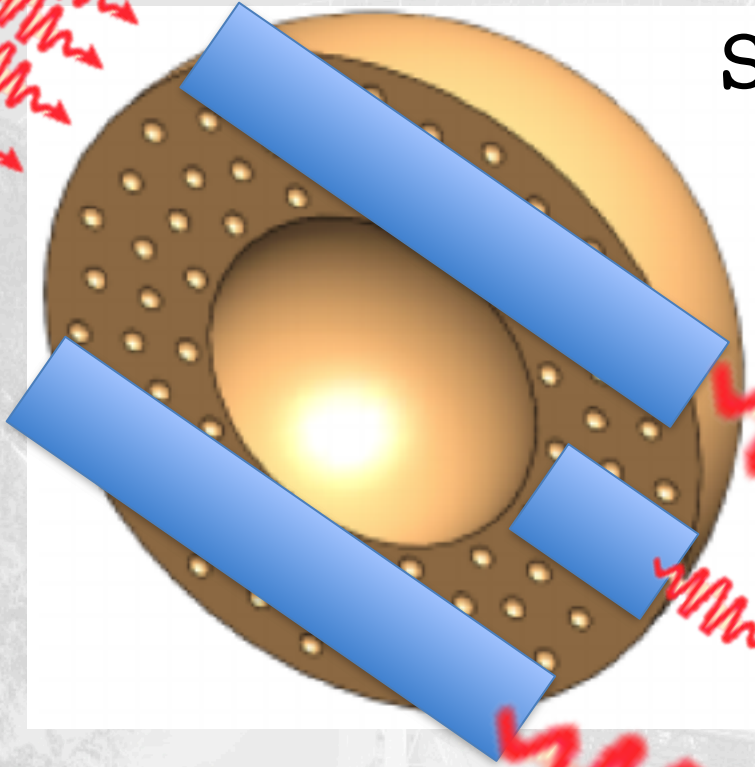


Spherical shell



Masers in evolved star shells

Spherical shell



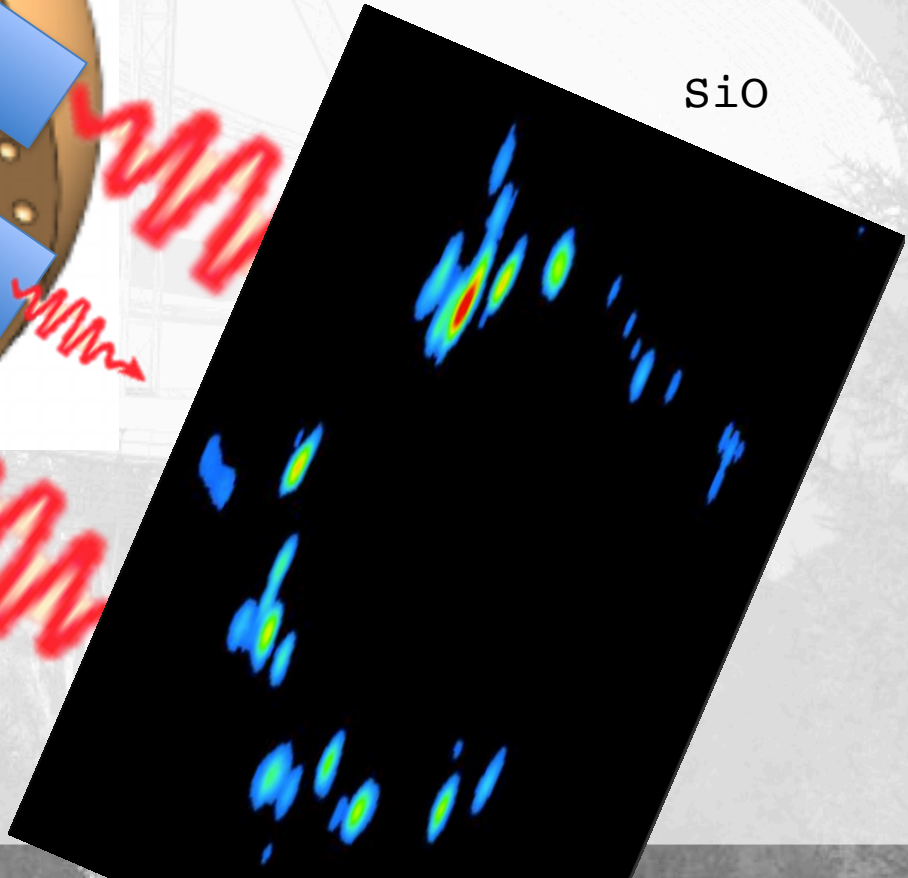
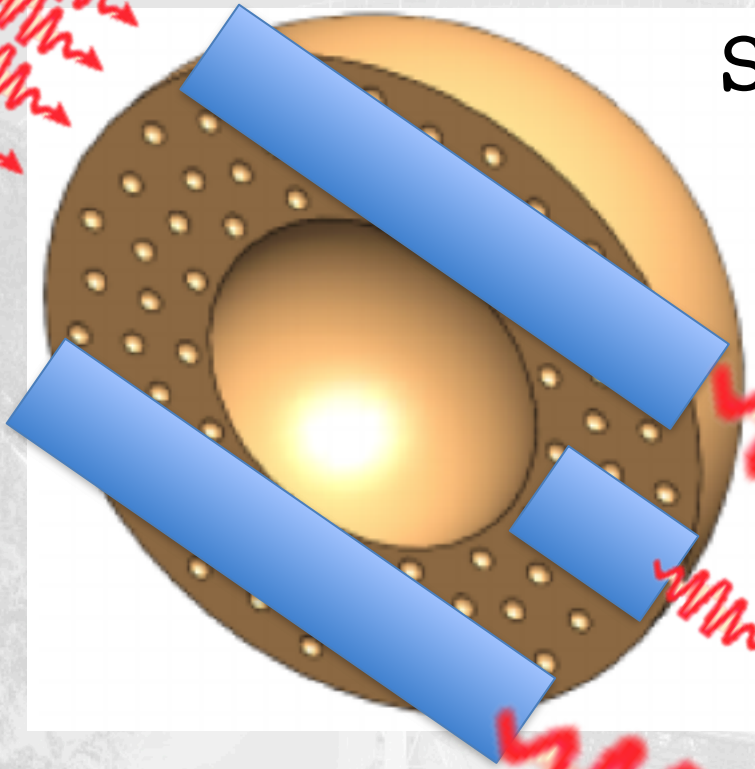
Masers in evolved star shells

Spherical shell

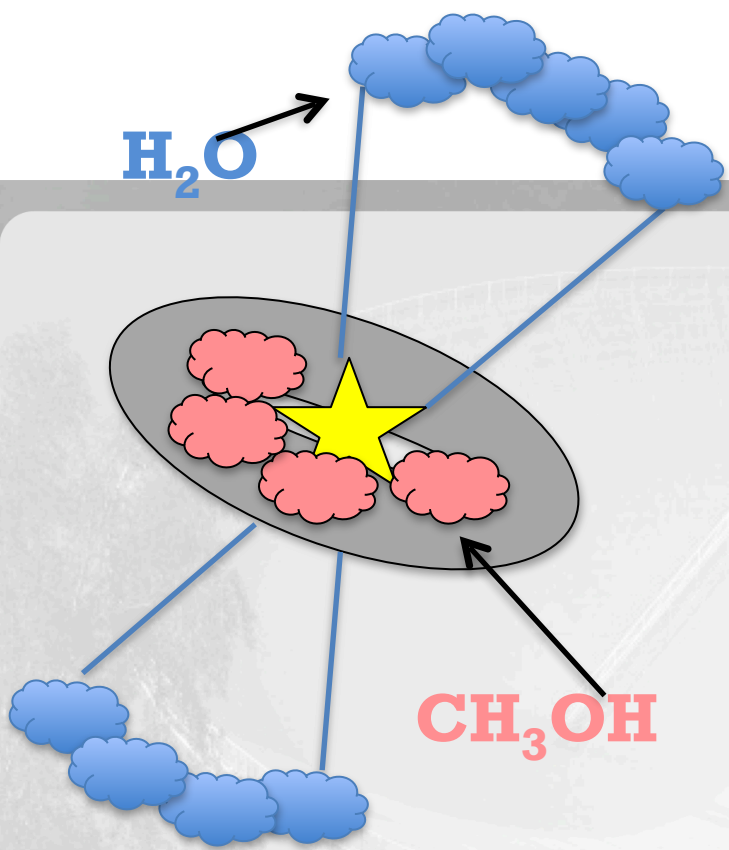
Masers only seen when the path-length is long and velocity coherent

SiO

Circular image



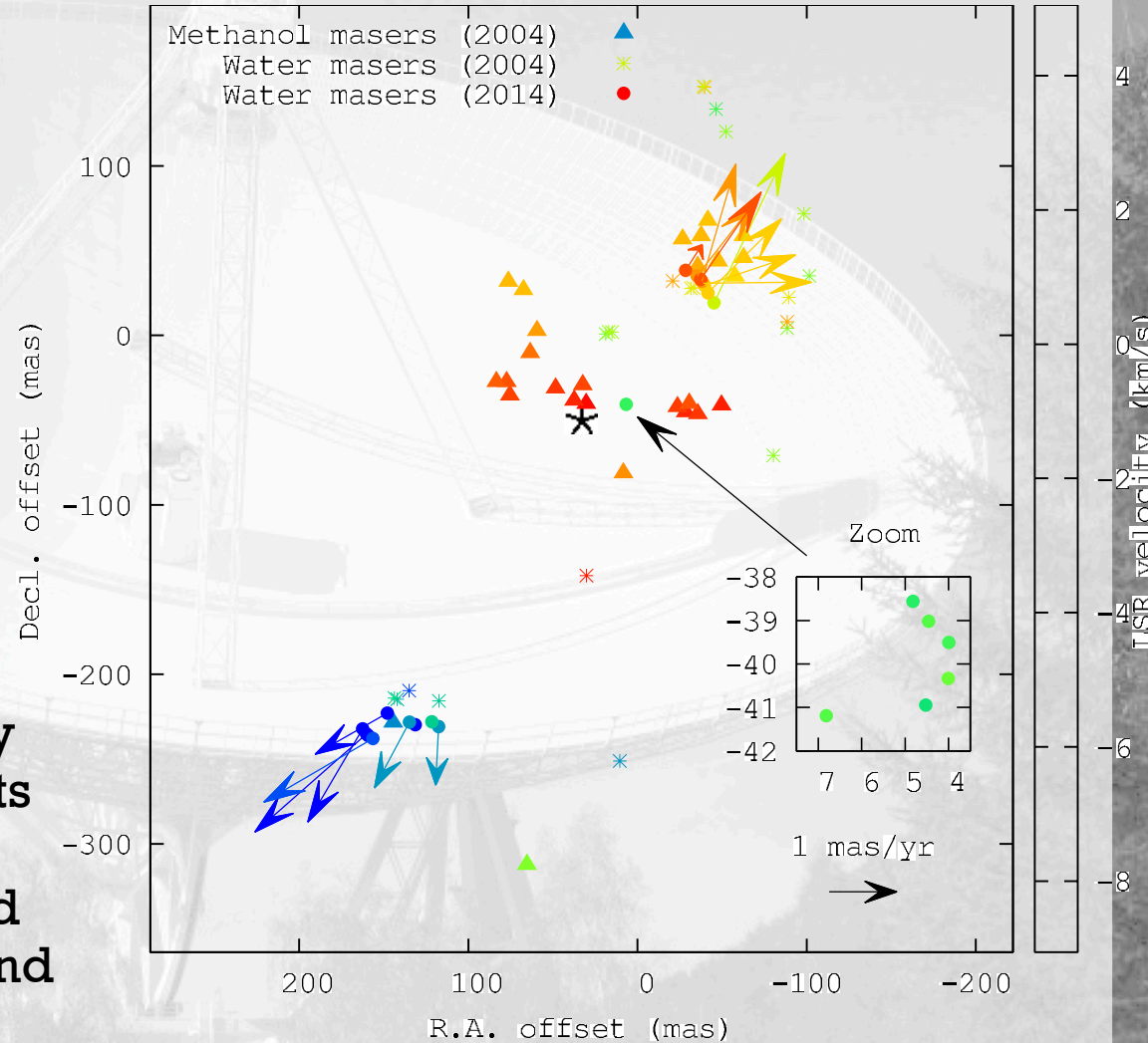
High-mass protostars



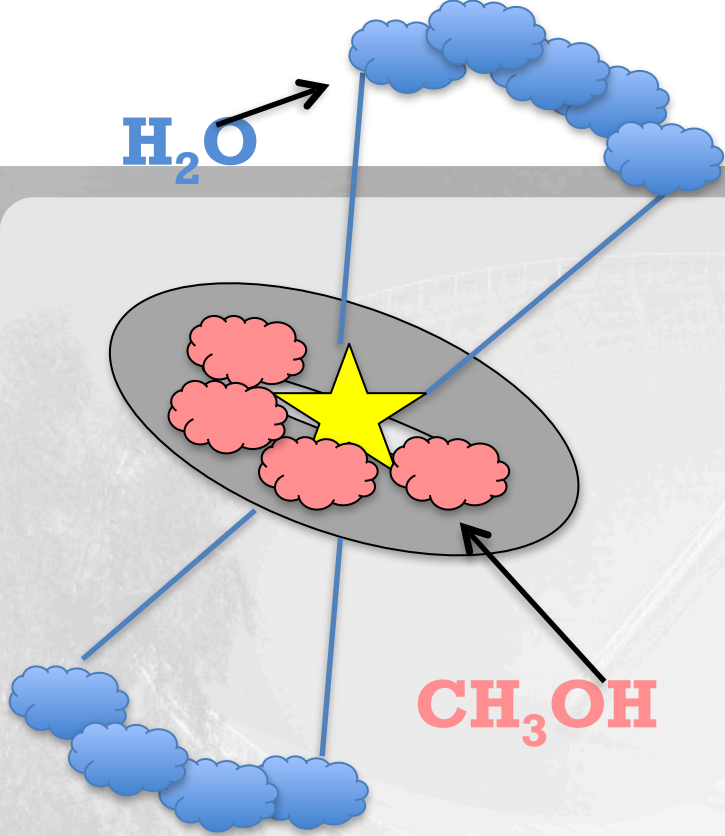
Water masers are pumped by collisions and are found in jets

Methanol masers are pumped by warm infrared radiation and are found in disks

Burns et al. 2017, MNRAS, 467, 2367



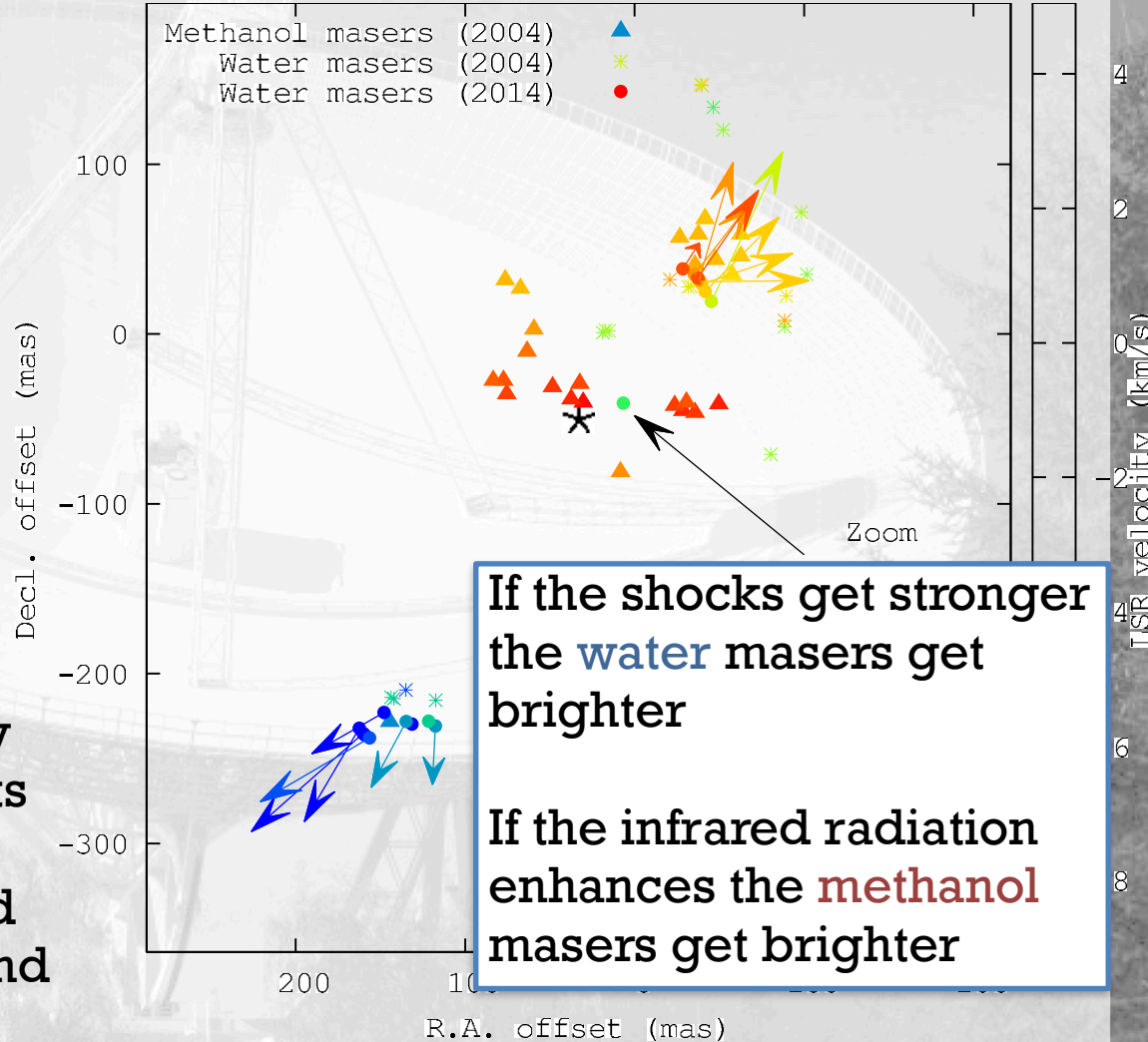
High-mass protostars



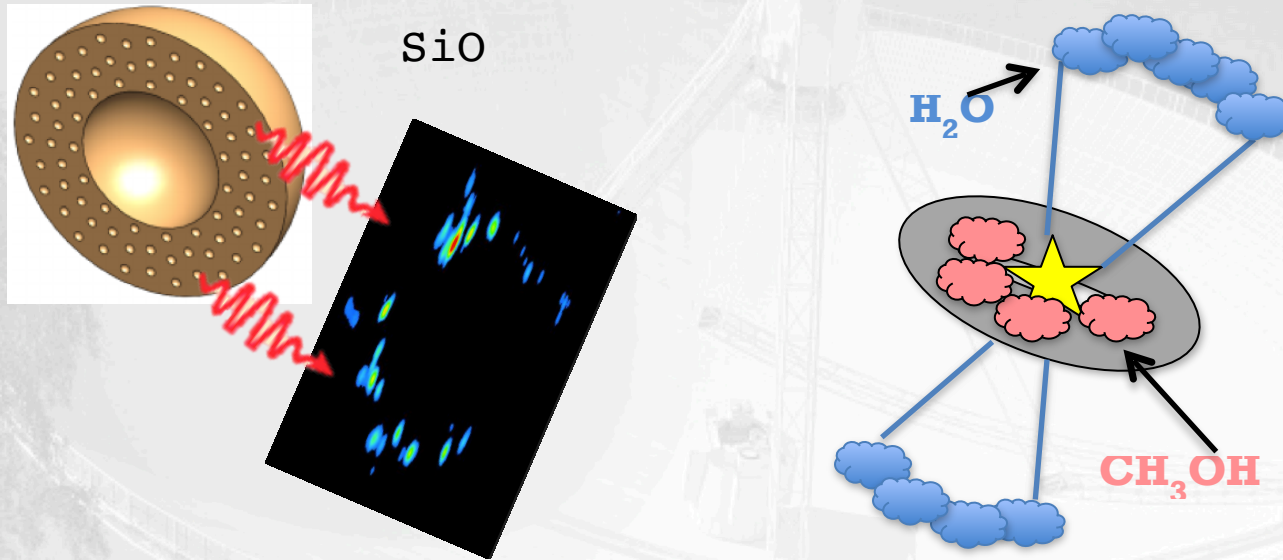
Water masers are pumped by collisions and are found in jets

Methanol masers are pumped by warm infrared radiation and are found in disks

Burns et al. 2017, MNRAS, 467, 2367



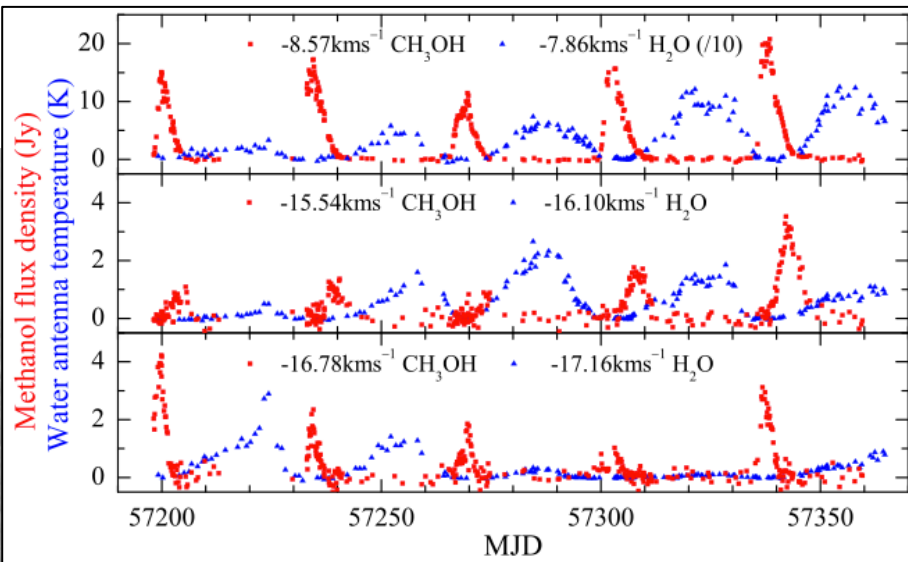
Shocks and shells



Conclusion 1: maser detections are strongly biased to regions that have a long path-length along the observer's line-of-sight; you almost always see a cross-section of your target.

Conclusion 2: Amplification is sensitive to changes in path length / radiation / collisions → maser variability

Variability

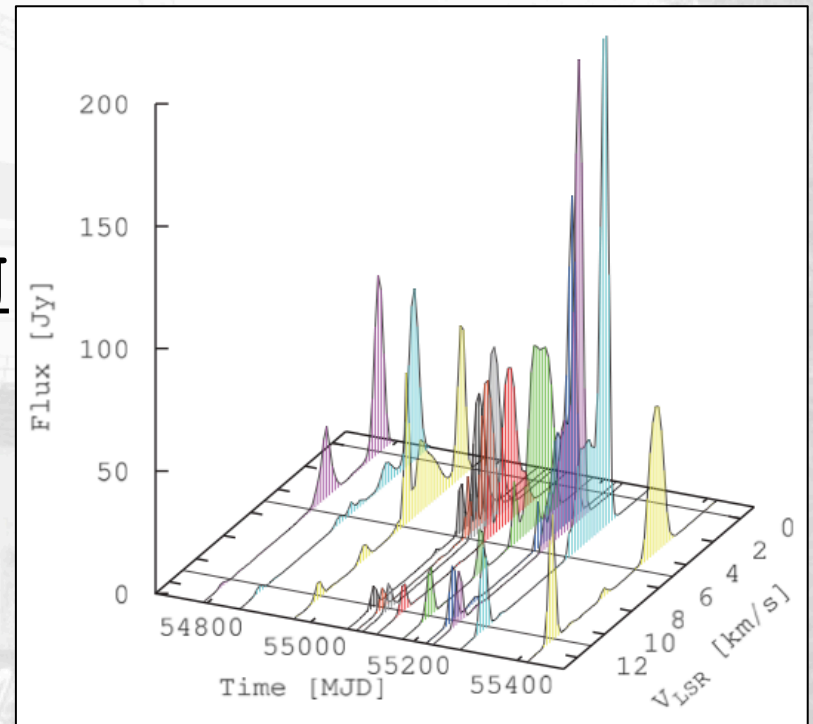


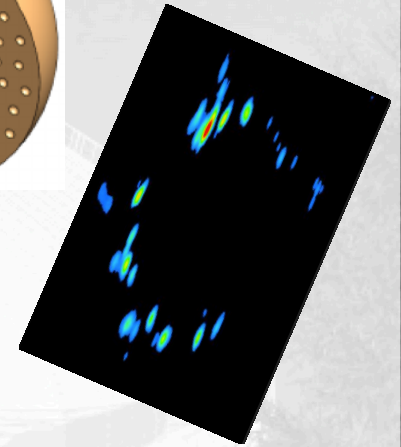
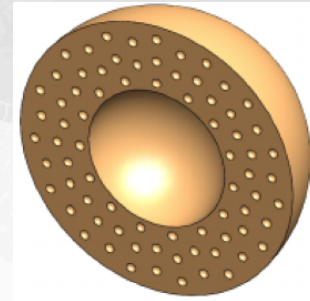
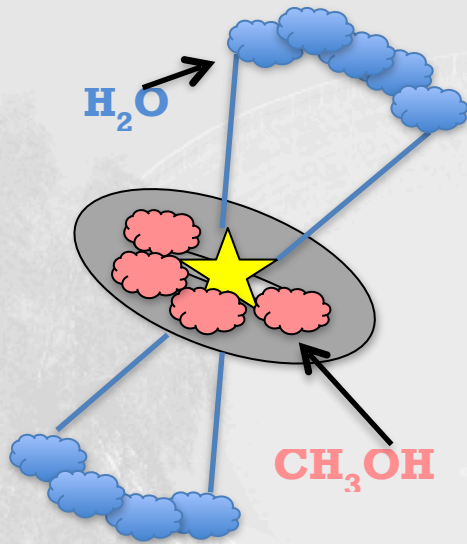
Periodic

Gradual brightening

Gradual dimming

Bursts





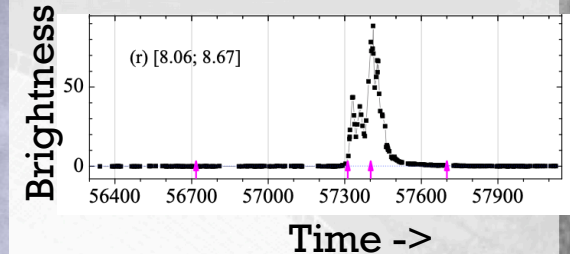
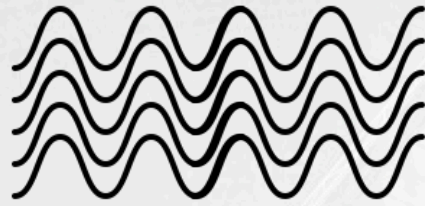
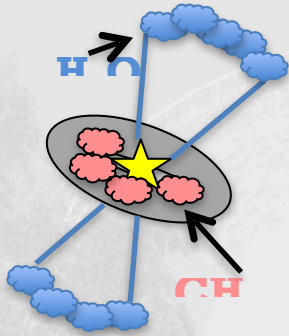
Discuss

- What is the pumping energy source for **water** masers?
- Where are **water** masers often found?
- What is the pumping energy source for **methanol** masers?
- Where are **methanol** masers often found?
- What is the pumping energy source for **SiO** masers?
- Where are **SiO** masers often found?

A large radio telescope dish, likely the Arecibo radio telescope, is shown in a grayscale image. The dish is a massive, curved structure supported by a complex metal framework. In the center, a receiver structure is visible. The dish is surrounded by dense trees, and the sky is visible in the background. The text "Maser Monitoring" is overlaid on the image in a black, monospace-style font.

Maser Monitoring

Maser Monitoring



We already learned that the maser brightness can depend on Path length, pumping conditions, and input seed photons. Therefore, by monitoring the brightness of masers using a radio telescope we can interpret any changes in the maser brightness as physical changes in the maser region.

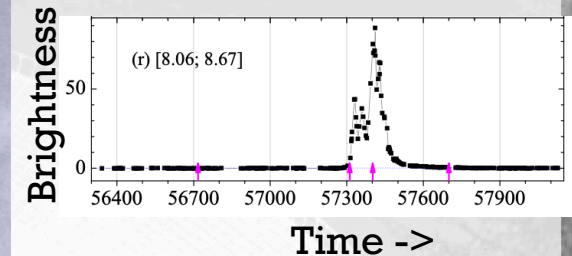
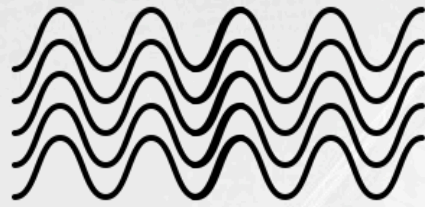
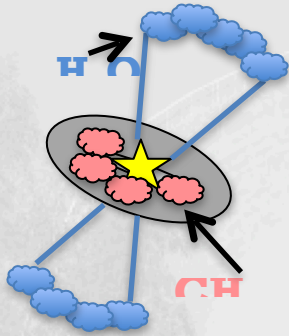
For this reason there are many radio telescopes monitoring many astrophysical maser sources. Examples of what they have found:

- Newly launched protostellar jets

- Pulsating evolved star shells

- Brightening of infrared sources due to protostellar accretion

Maser Monitoring



We already learned that the maser brightness depends on the path length, pumping conditions, and input seed. Therefore, by monitoring the brightness of masers using a radio telescope we can interpret any changes in the maser brightness as physical changes in the maser region.

For this reason there are many radio telescopes monitoring many astrophysical maser sources. Examples of what they have found:

Newly launched protostellar jets

Pulsating evolved star shells

Brightening of infrared sources due to protostellar accretion

Can you say which maser molecule was used for each of these findings?

A large radio telescope dish, likely the Green Bank Telescope, is shown in a grayscale image. The dish is a large, curved structure supported by a complex metal framework. A central receiver structure is mounted on the dish. The background consists of a dense forest of trees and a clear sky. The text "Maser imaging observations" is overlaid on the image in a black, monospace-style font.

Maser imaging observations

Maser imaging observations



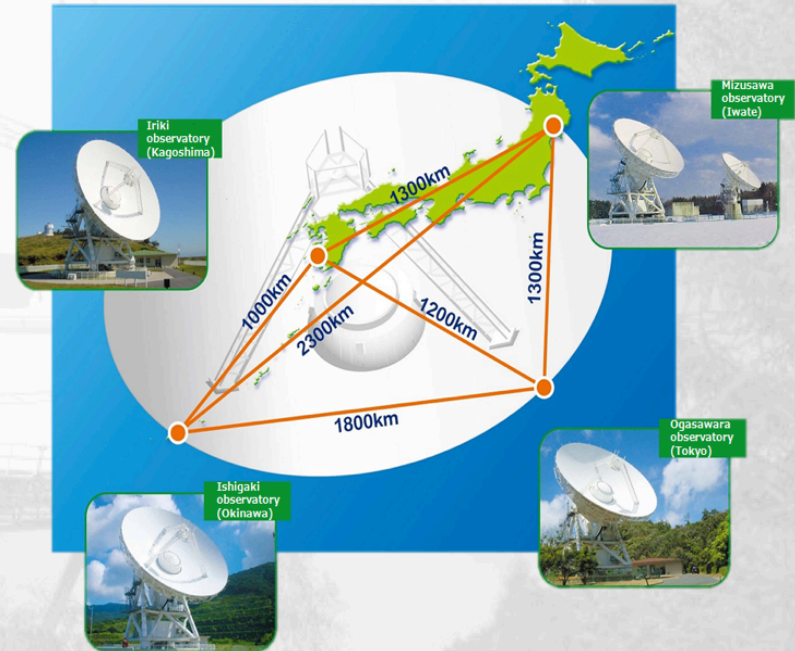
The Very Large Array (VLA) is a collection of 27 radio antennas located at the NRAO site in Socorro, New Mexico. Each antenna in the array measures 25 meters (82 feet) in diameter and weighs about 230 tons. Credit: Alex Savello/NRAO

VLA / ALMA / ATCA “Radio interferometers”

Baselines: ~ 1-100 km
Resolution: ~ 10-100s milliarcsecond

VLBI

Baselines: 1000s of km
Resolution: ~ milliarcsecond

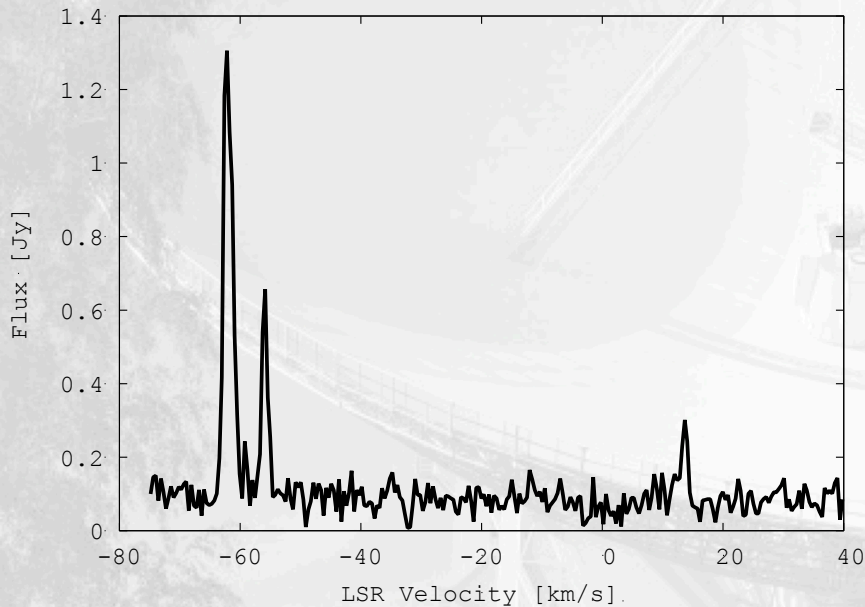


Both provide different but complementary science

Maser observations

Single dish radio telescope

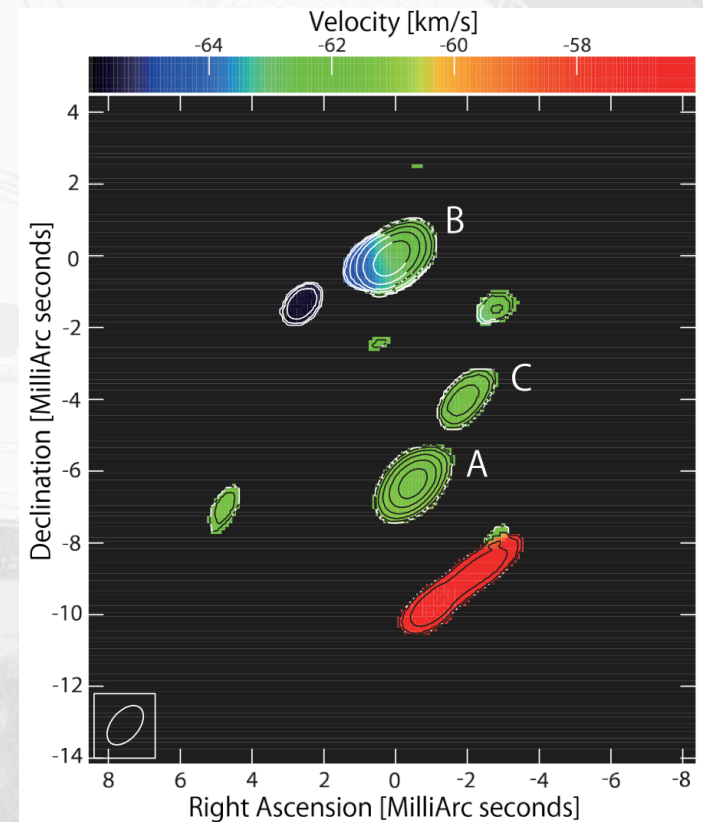
- + Easier to perform observations
- Only measures flux and frequency



Again: Both provide different but complementary science

VLBI / VLA

- Harder technique
- + Measures flux and frequency and sky-plane distribution



The background image is a faded, grayscale photograph of a roller coaster. It shows a large, circular loop of the track. A roller coaster train is positioned at the very top of the loop, appearing to be at the peak of its vertical ascent. The track curves downwards on both sides of the loop. The entire scene is set against a backdrop of trees and a light sky, though the image is intentionally faded to serve as a background for the text.

Proper motions

Multi-epoch VLBI observations



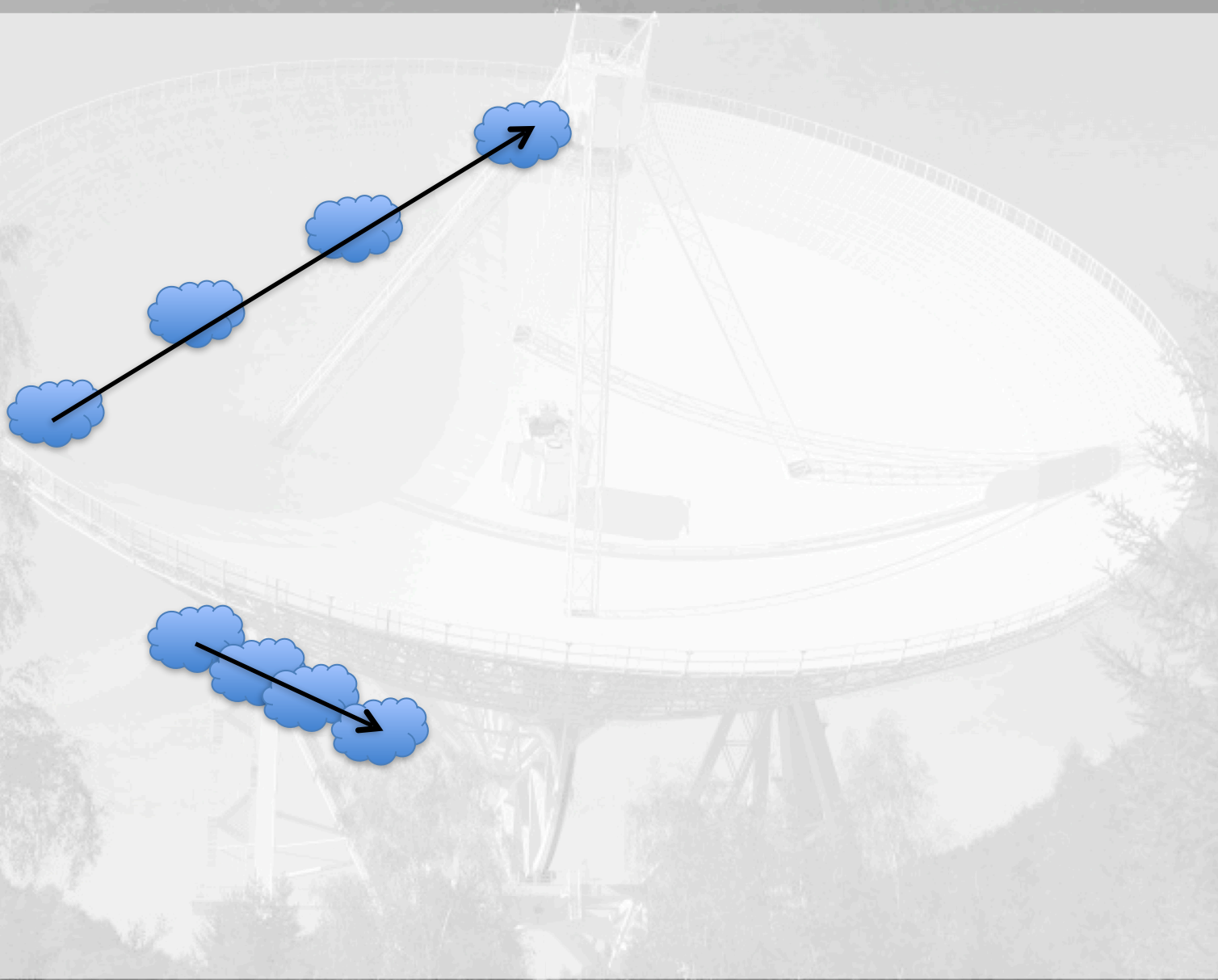
Multi-epoch VLBI observations



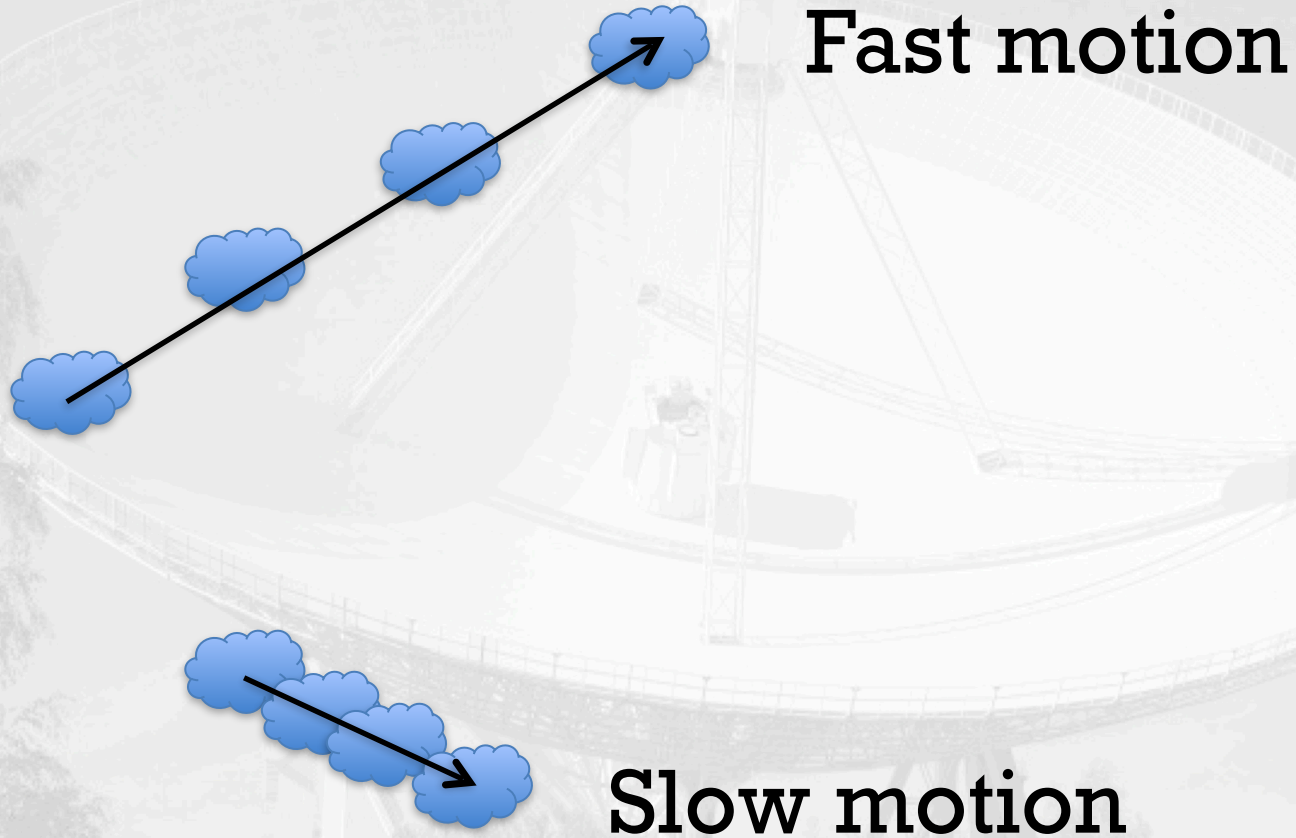
Multi-epoch VLBI observations



Multi-epoch VLBI observations



Multi-epoch VLBI observations

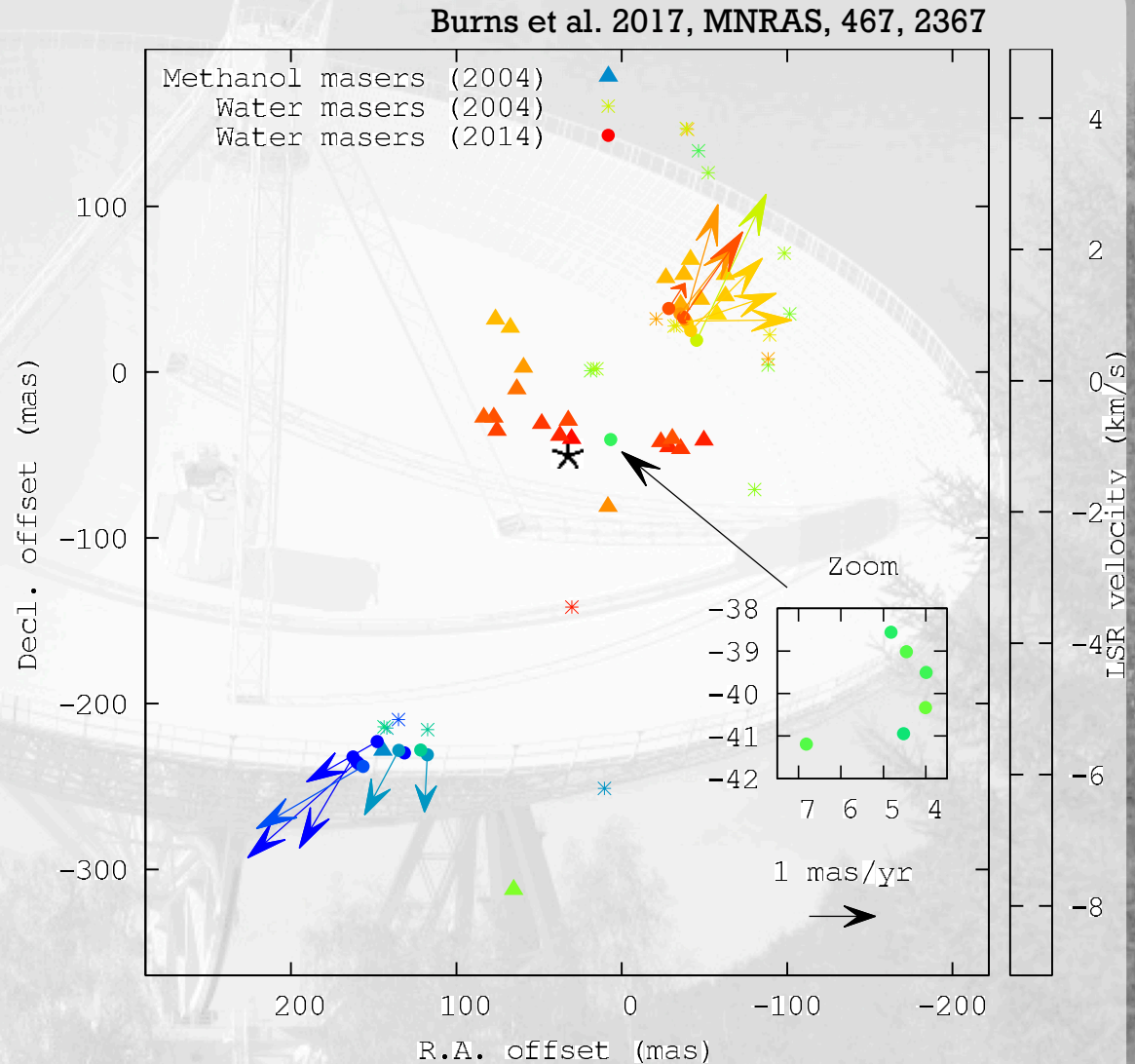


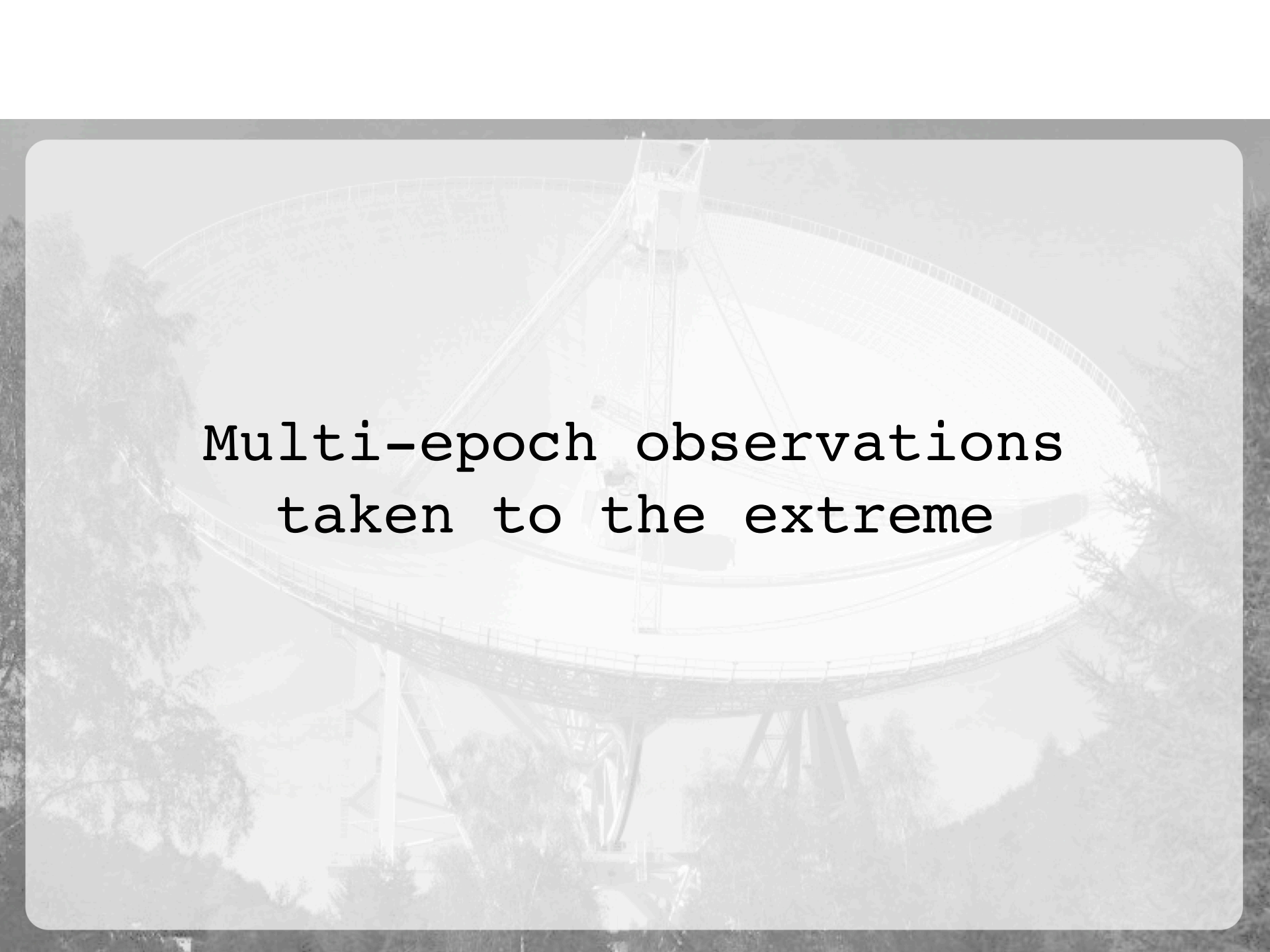
Multi-epoch VLBI observations

Fast motion



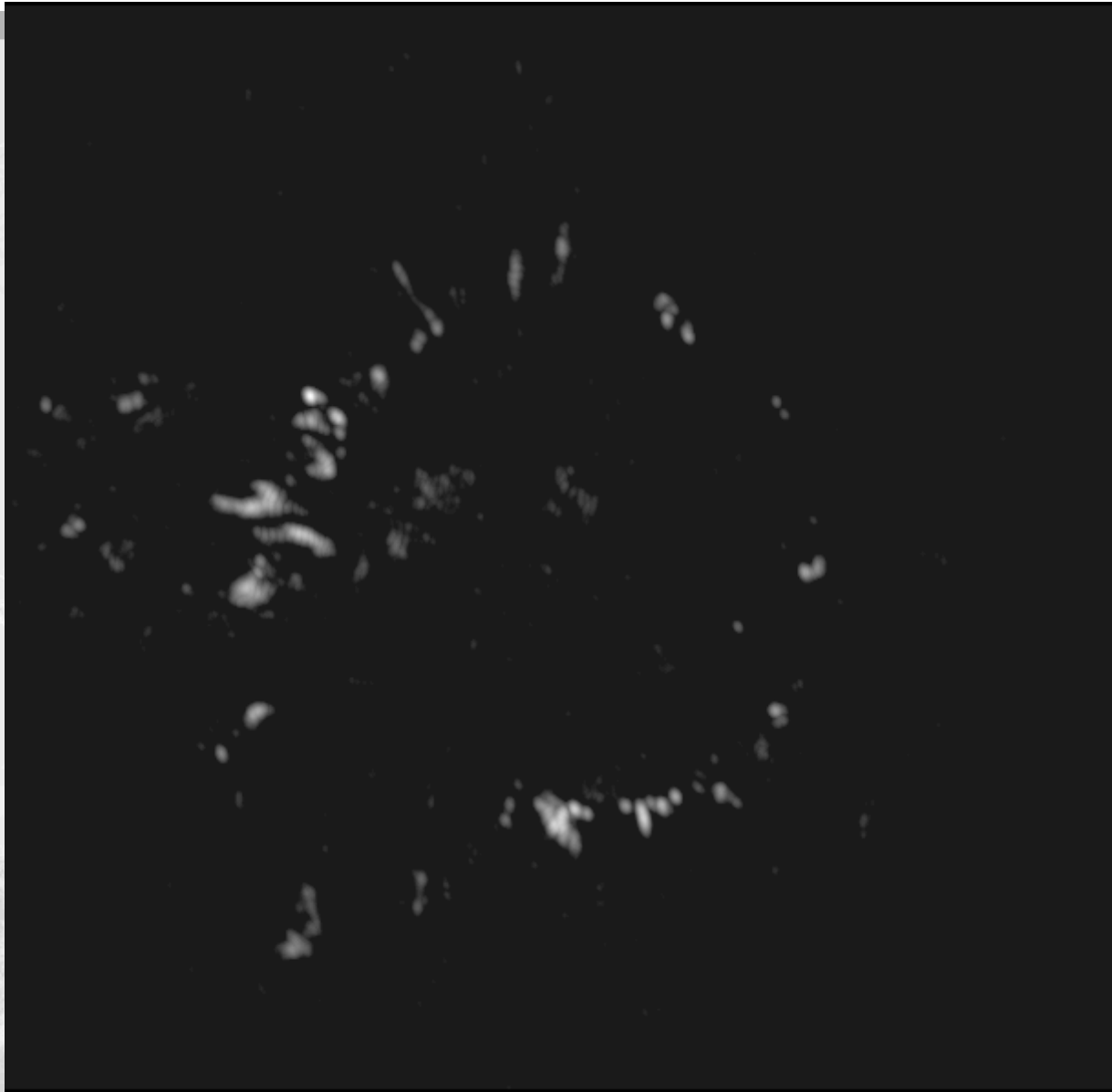
Slow motion



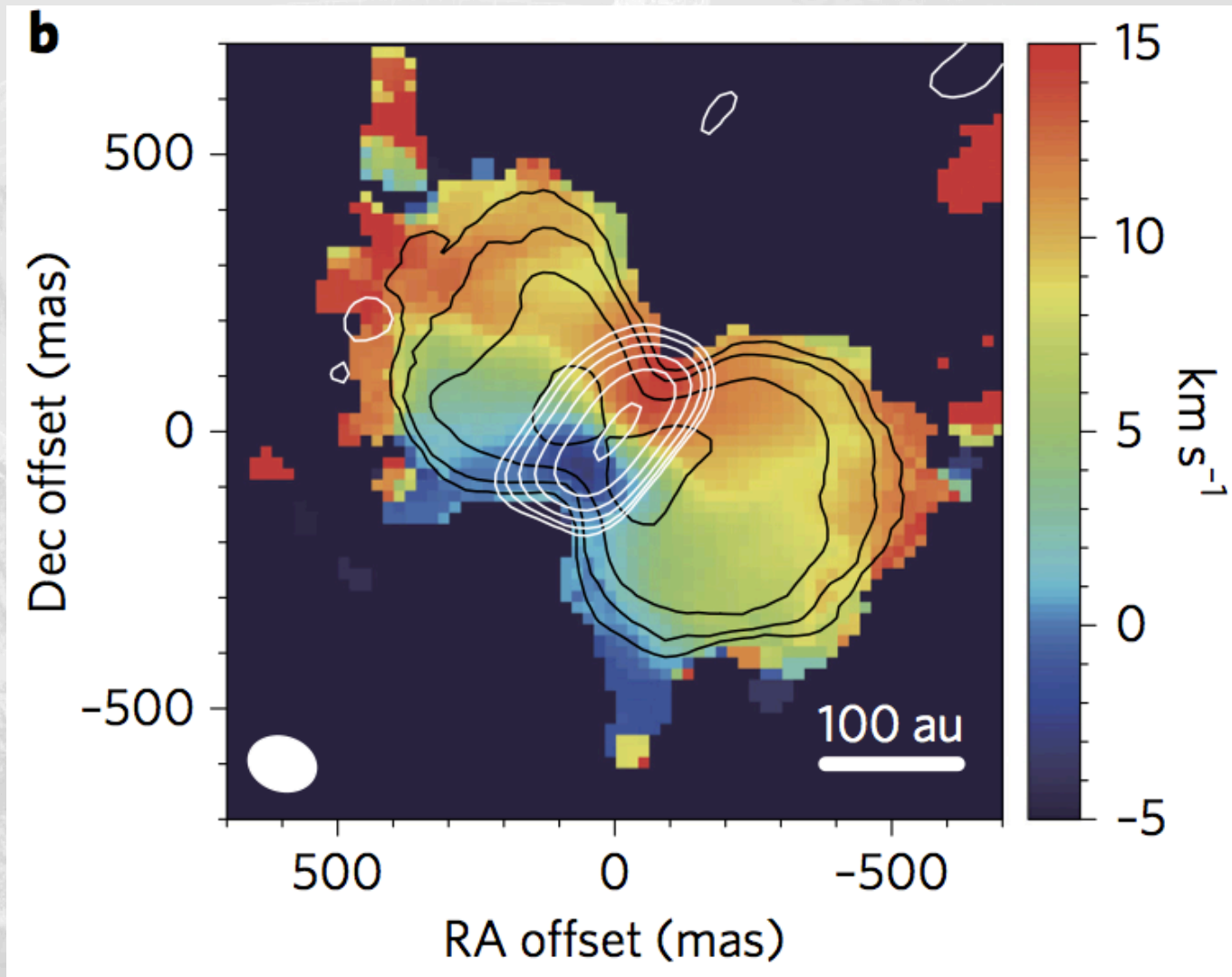
A large radio telescope dish is shown in a forest setting. The dish is a large, curved structure supported by a complex metal framework. It is surrounded by dense trees and foliage. The text "Multi-epoch observations taken to the extreme" is overlaid on the image in a black, monospace font.

Multi-epoch observations
taken to the extreme

Maser movie: AGB



Maser movie: Orion S.I




Maser movie: Orion S.I

2001.21



20 AU



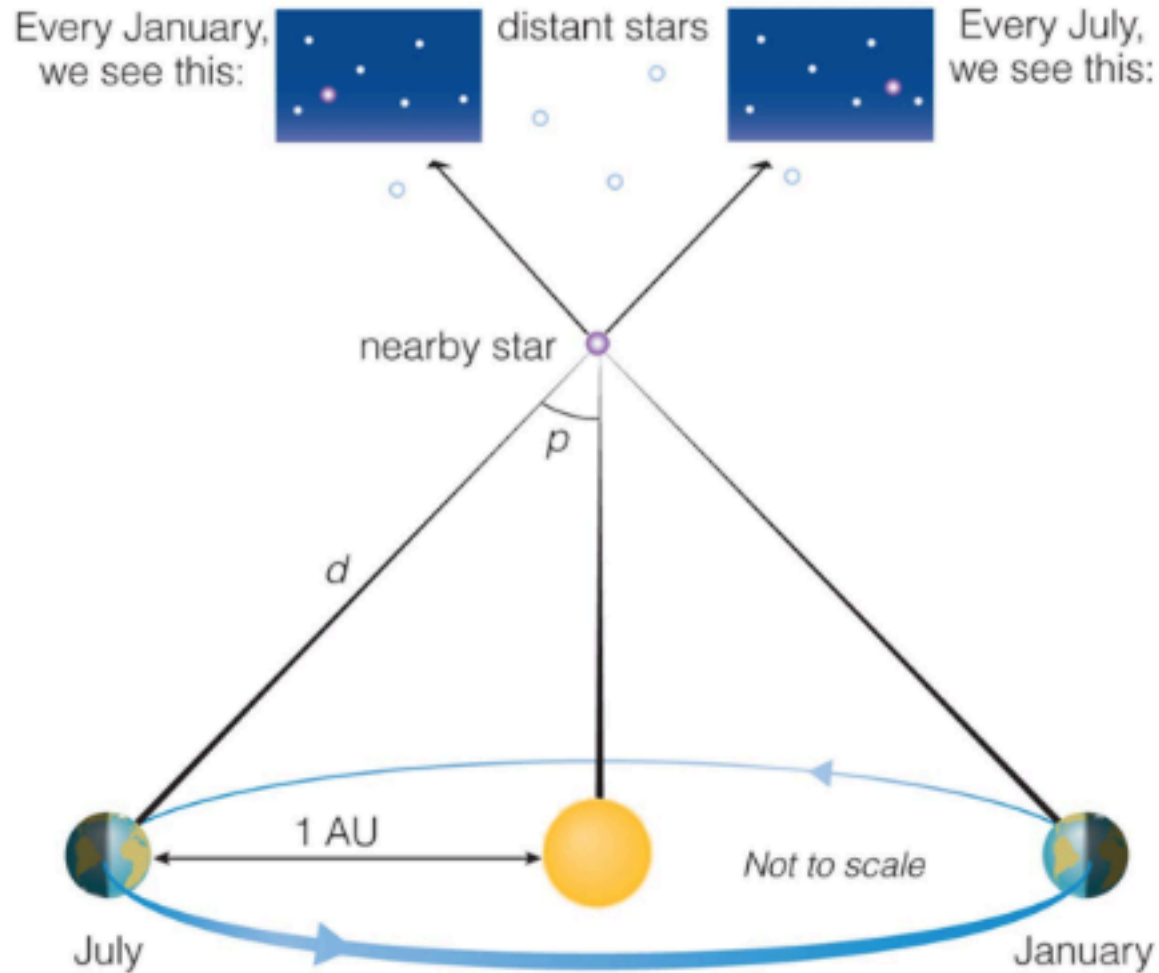


Questions?



Using masers to
map the Galaxy

Annual parallax

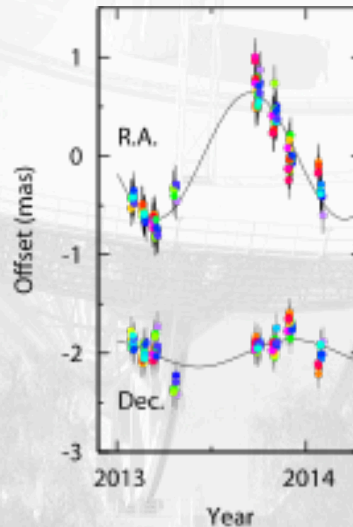


Multi-epoch observations



Astrometry (~ 1 Year)
Make a fit

Sinusoidal component
~~Annual~~
parallax
↓
Distance ✓

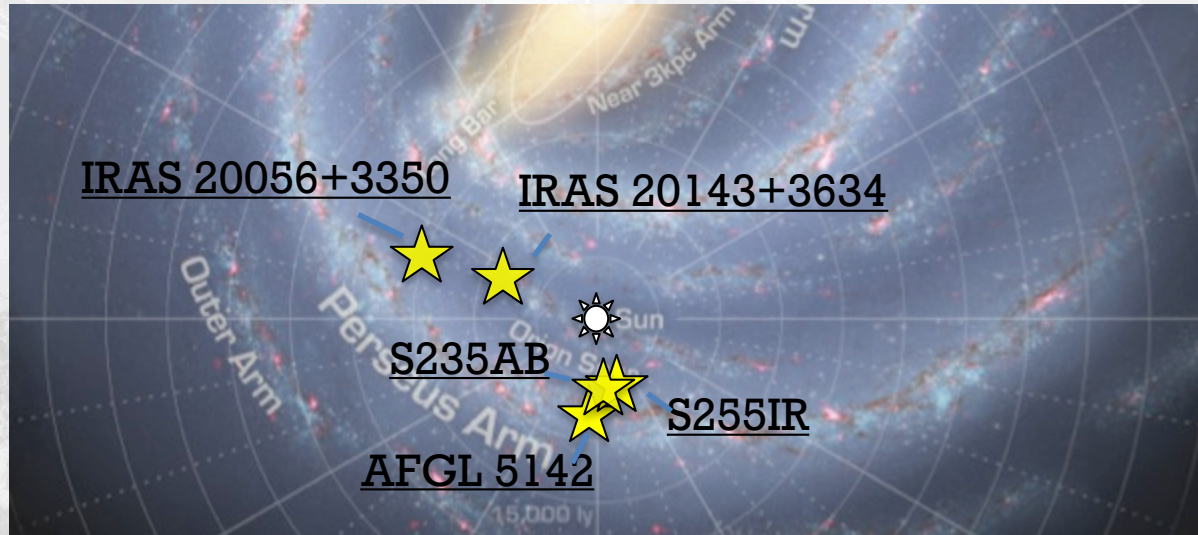
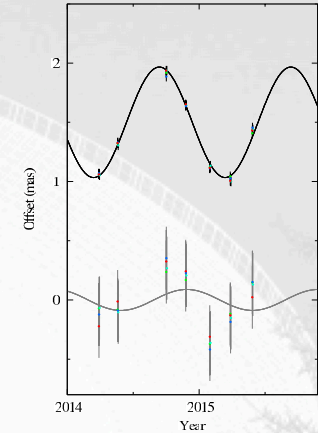
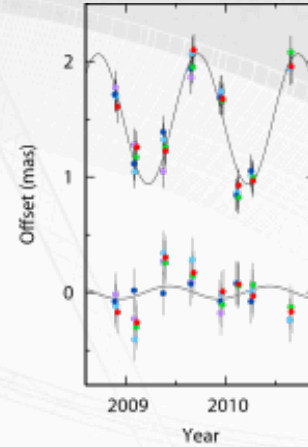
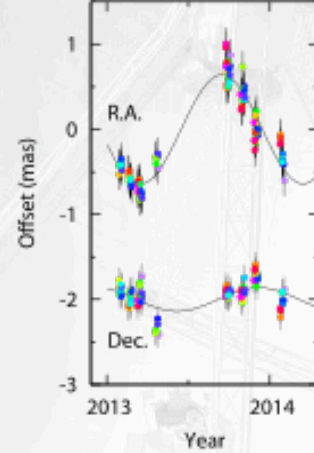
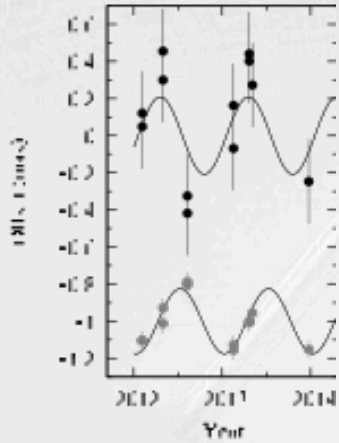
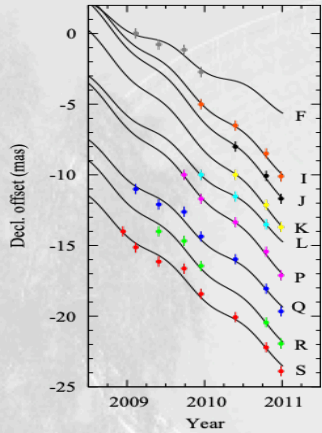


Linear component
• Proper motion

IRAS 20056+3350 S235AB

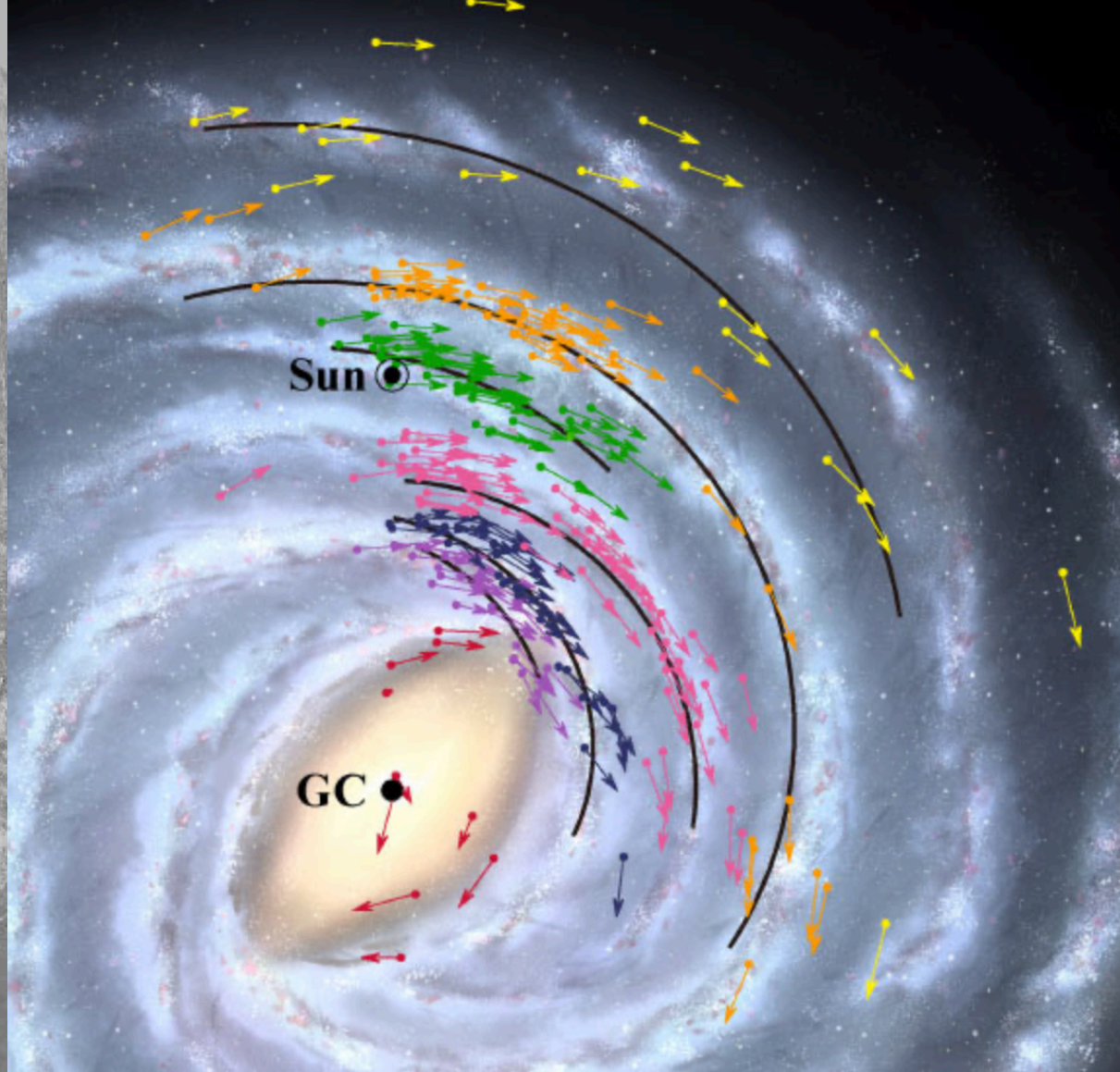
S255IR

AFGL5142



VLBI maser parallaxes circa 2021

VERA collaboration, 2020, PASJ, 72, 4, 50



Galactic structure
by direct distance
measurement

Map the
Spiral Arms

Distance to Galx.
center