

A detailed **Seismic Modelling**
of the Beta Cephei star **Nu Eri**

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Work performed within the **B**elgian **A**steroseismology **G**roup

Overview

- Introduction
 - ★ Goal
 - ★ Strategy
- Seismic Modelling
 - Case Study 1: Matching 3 Pulsation Modes
 - Case Study 2: Matching 4 Pulsation Modes
- Conclusions

Overview

- **Introduction**

- ★ Goal

- ★ Strategy

- Seismic Modelling

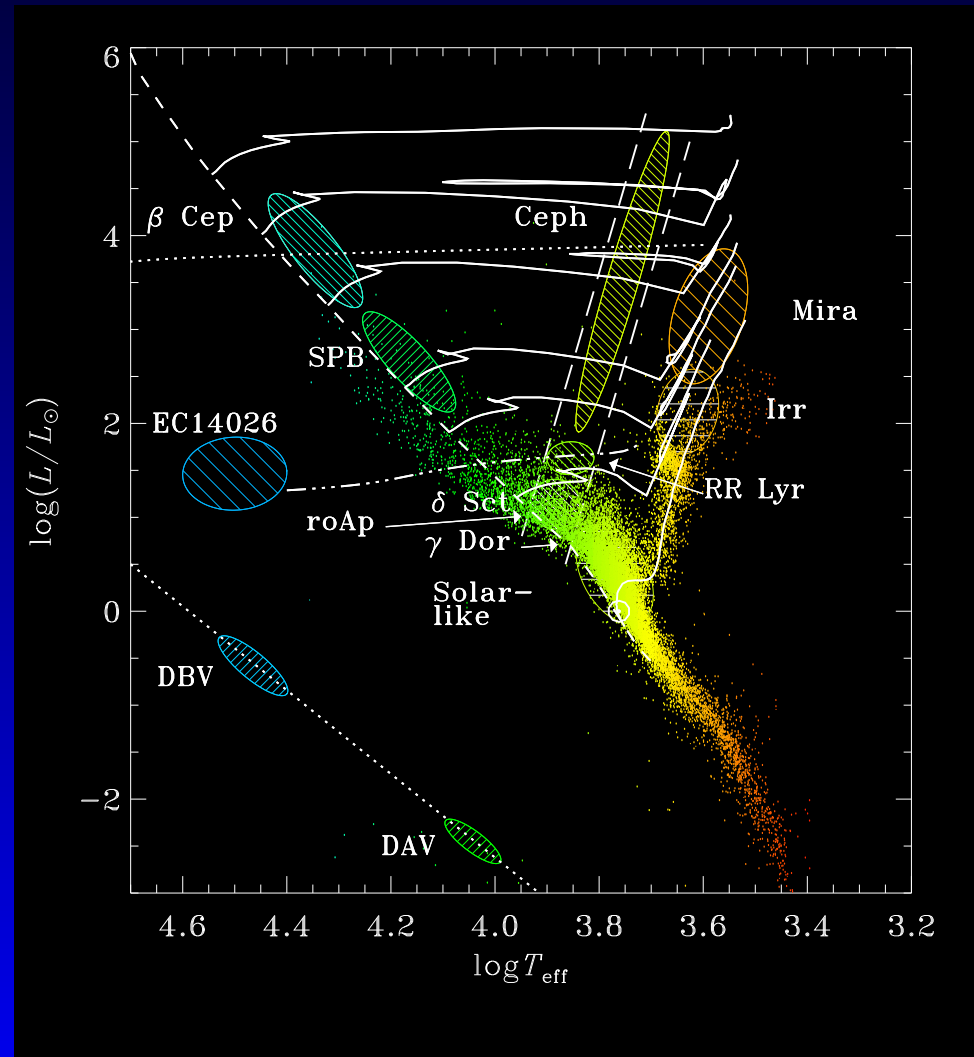
- Case Study 1: Matching 3 Pulsation Modes

- Case Study 2: Matching 4 Pulsation Modes

- Conclusions

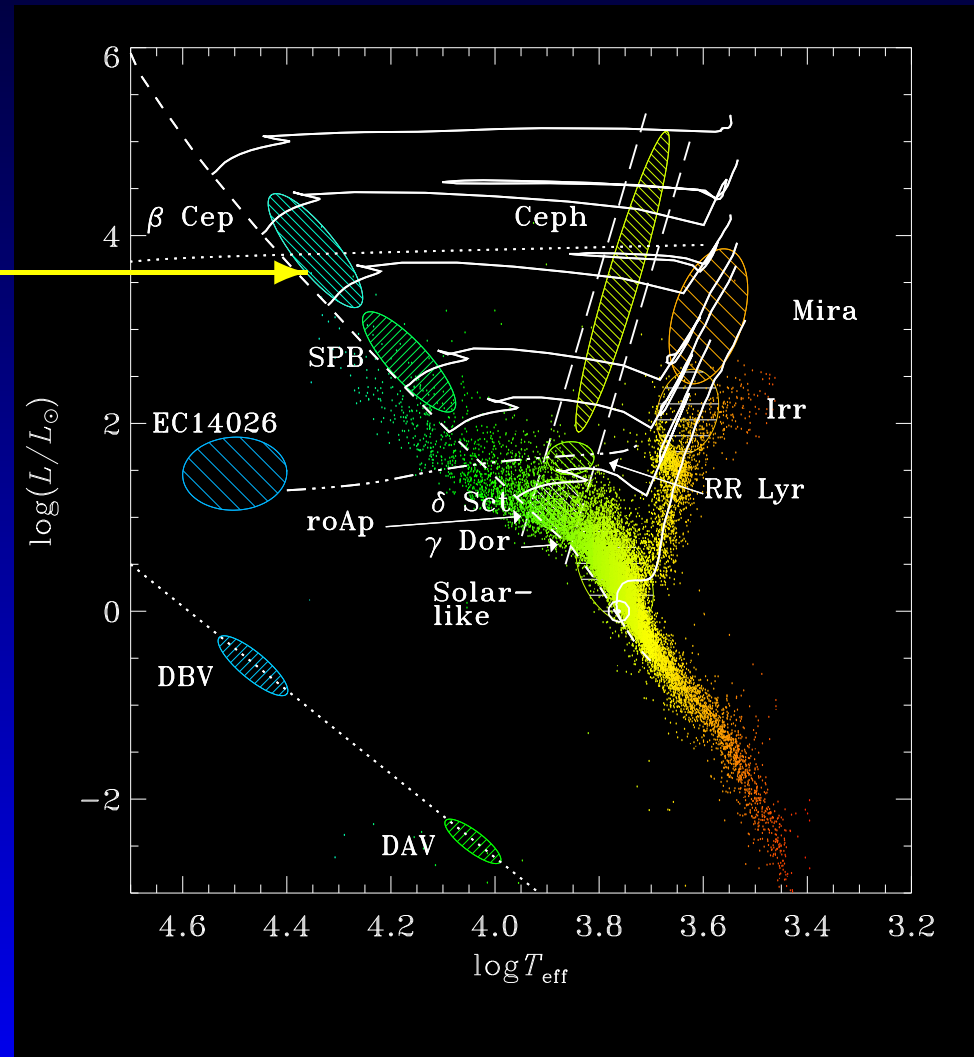
Goal

Asteroseismology of massive main sequence B stars



Goal

Asteroseismology of massive main sequence B stars



Strategy

Theoretical Part

Observational Part

Strategy

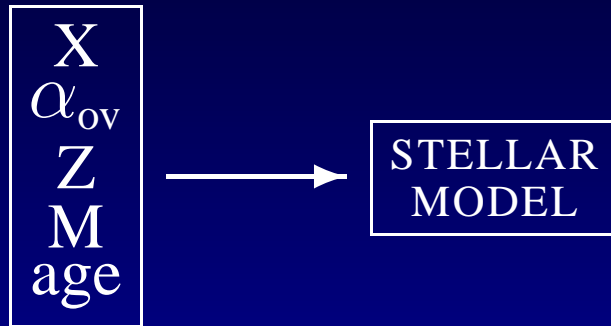
Theoretical Part

X
 α_{ov}
Z
M
age

Observational Part

Strategy

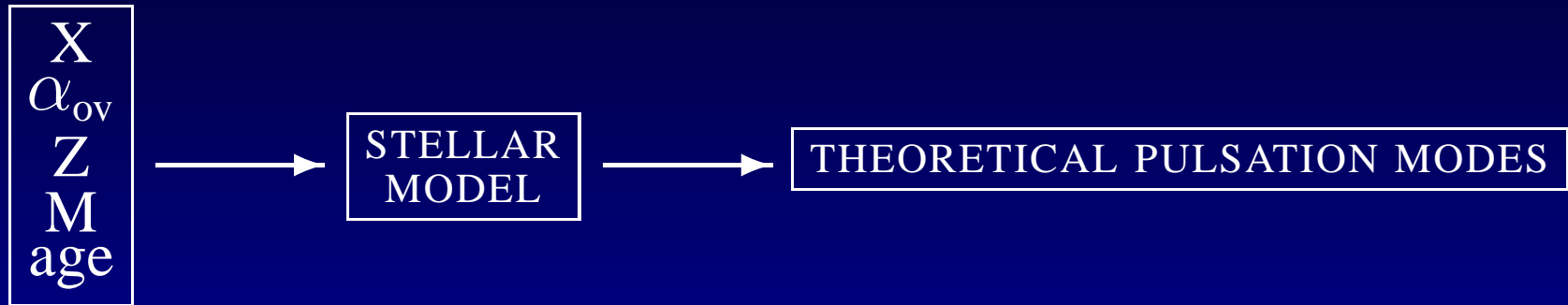
Theoretical Part



Observational Part

Strategy

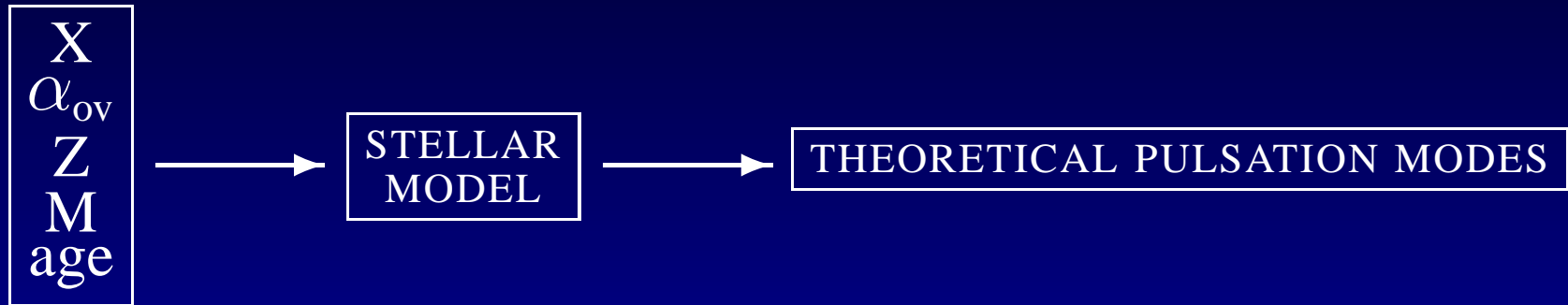
Theoretical Part



Observational Part

Strategy

Theoretical Part

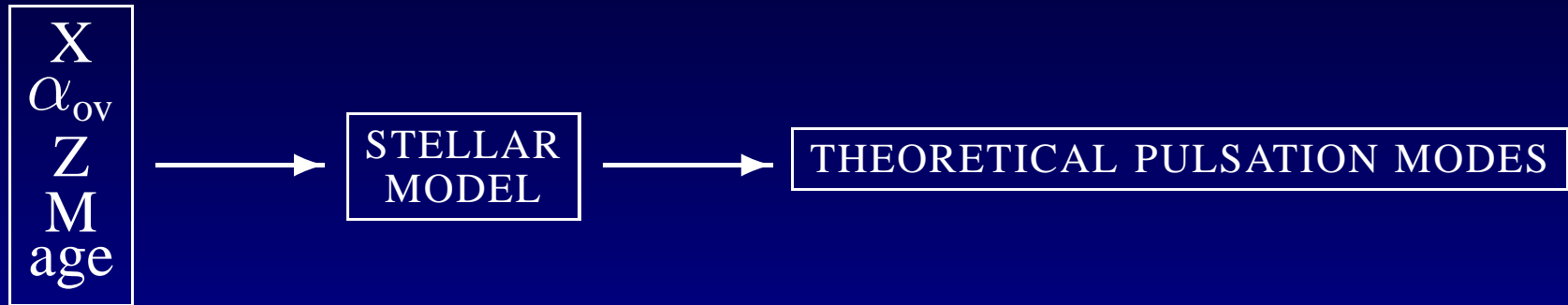


Observational Part

DATA

Strategy

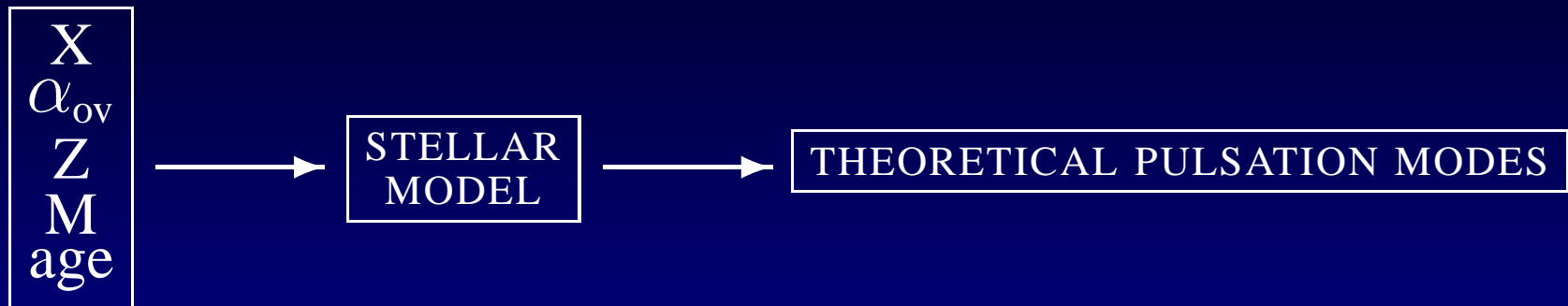
Theoretical Part



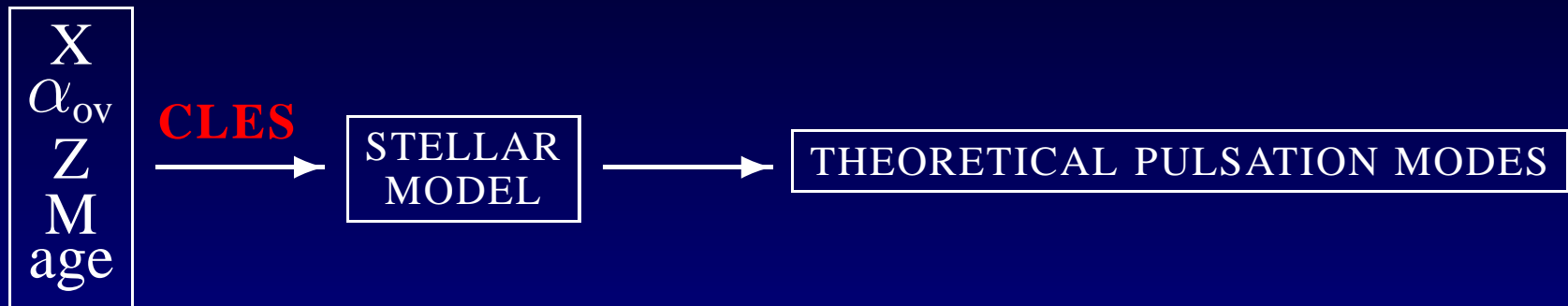
Observational Part



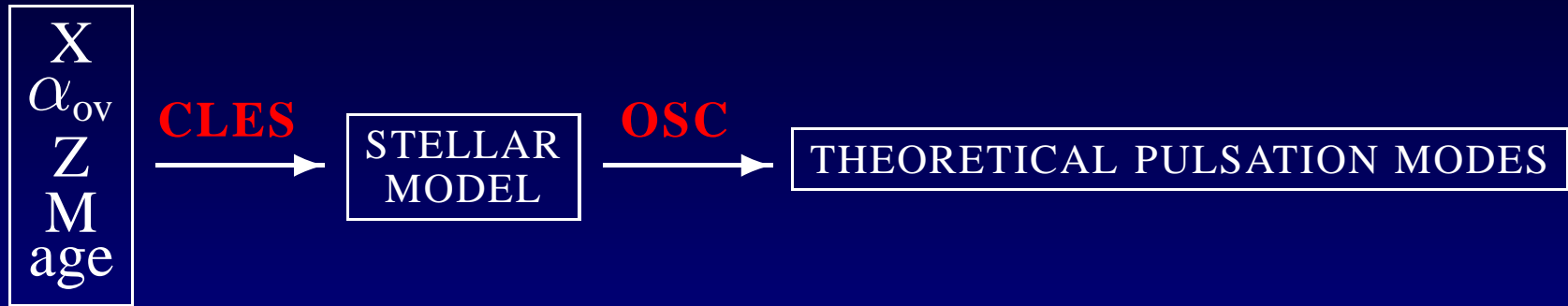
Theoretical Part



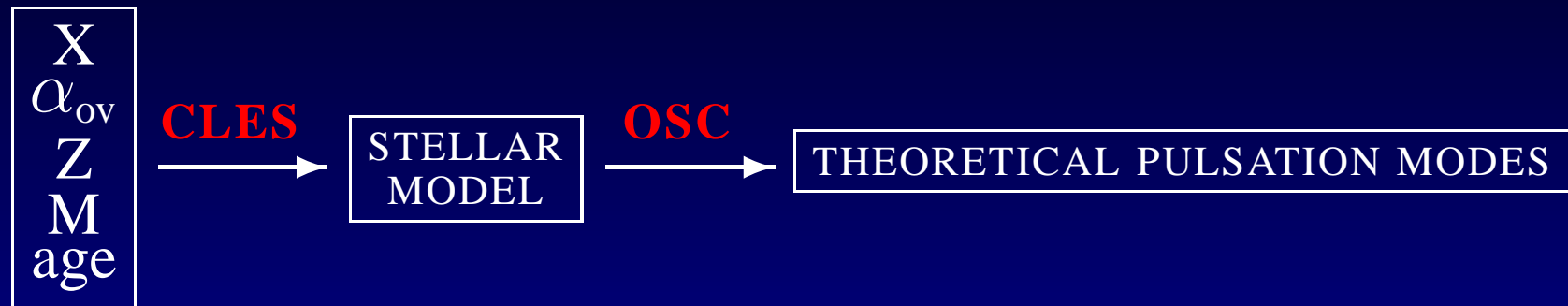
Theoretical Part



Theoretical Part



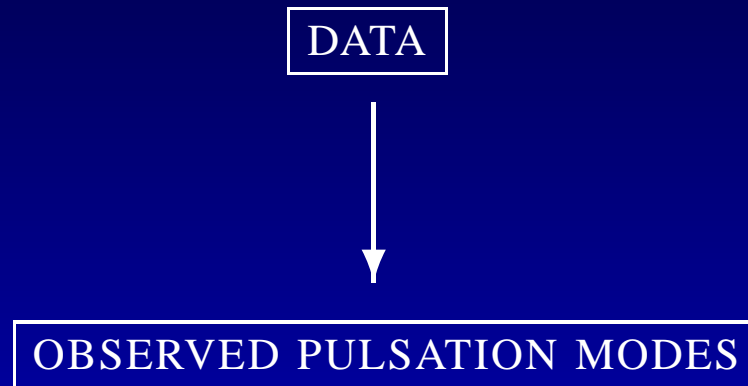
Theoretical Part



GRID

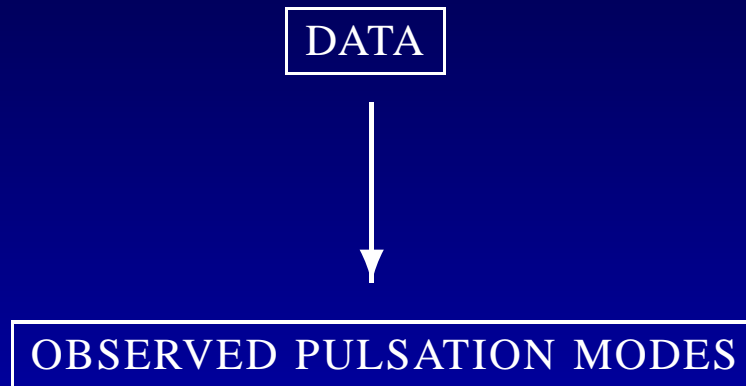
$X = 0.70$
 $\alpha_{ov} = 0.0, 0.1 \text{ and } 0.2$
 $Z = 0.012, 0.014, \dots, 0.030$
 $M = 7.0, 7.1, \dots, 13.0$
 $\text{age} = \text{ZAMS} \longrightarrow \text{TAMS}$

Observational Part



Observational Part

ν Eridani



Observational Part

A 5-month multisite campaign on ν Eridani



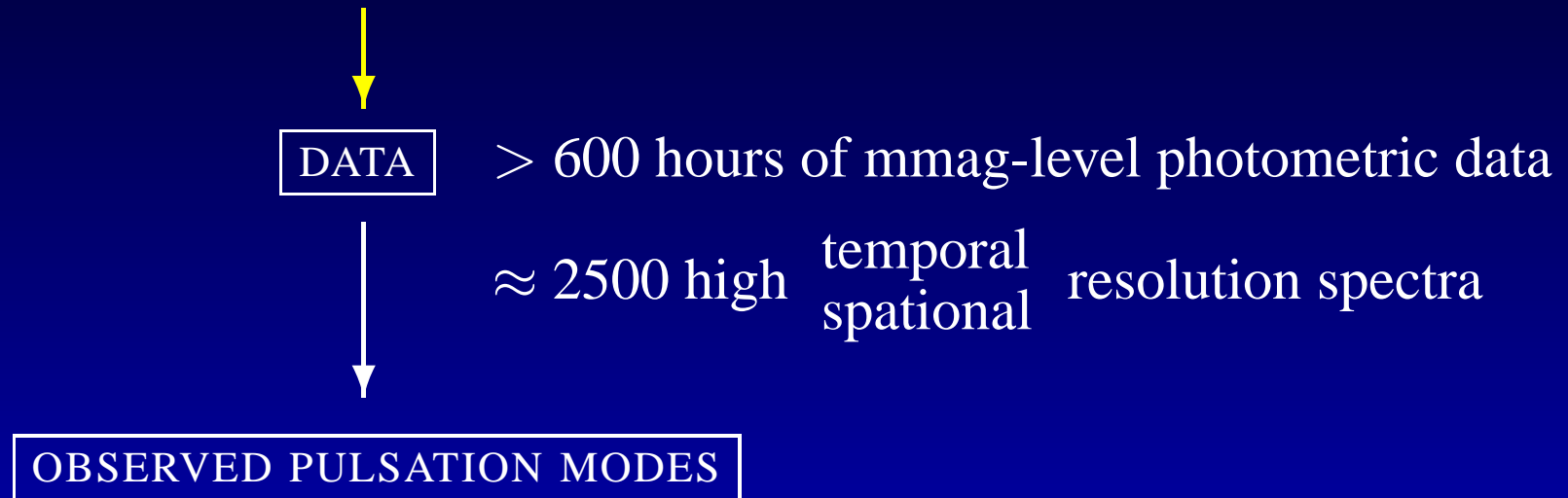
DATA



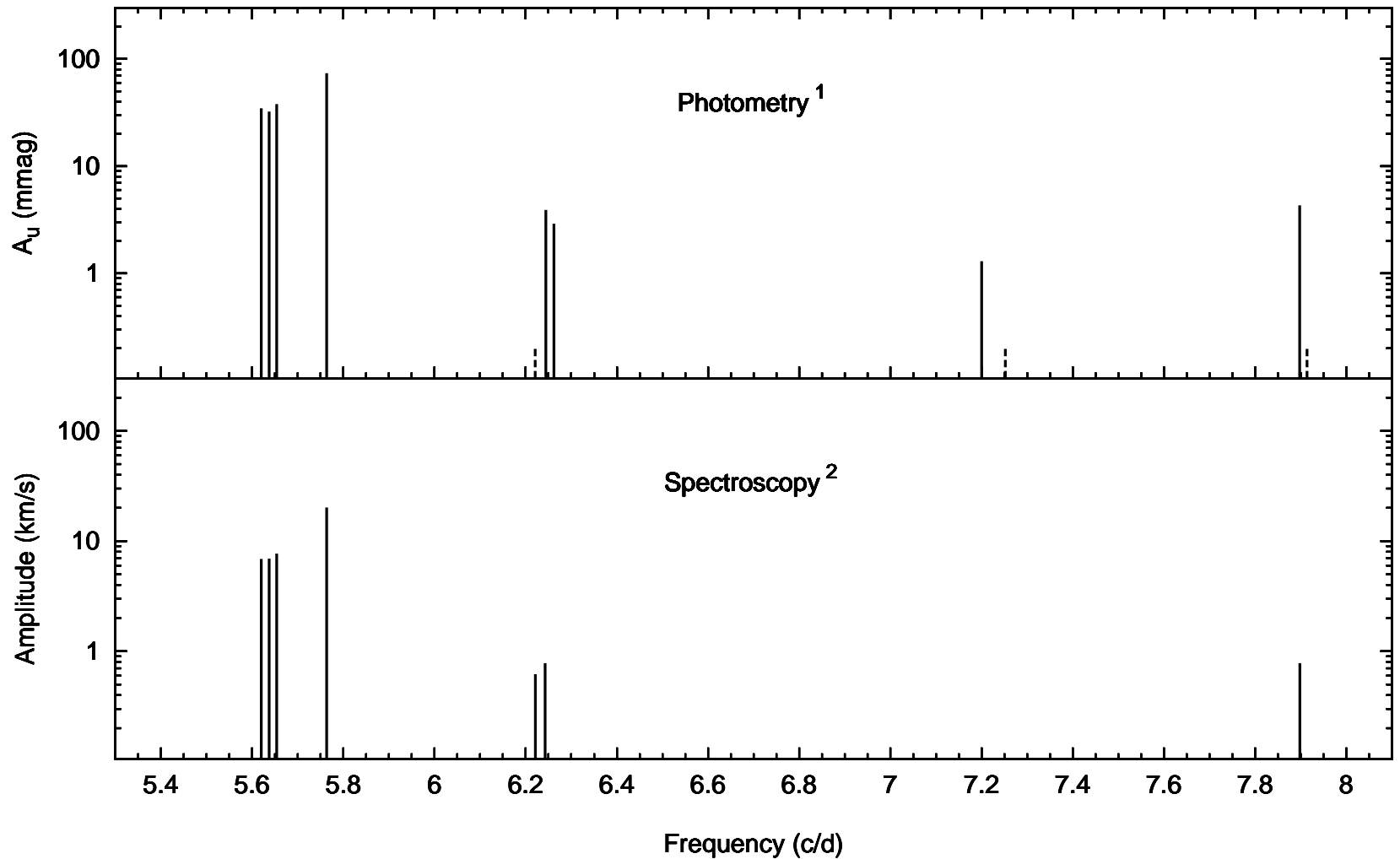
OBSERVED PULSATION MODES

Observational Part

A 5-month multisite campaign on ν Eridani



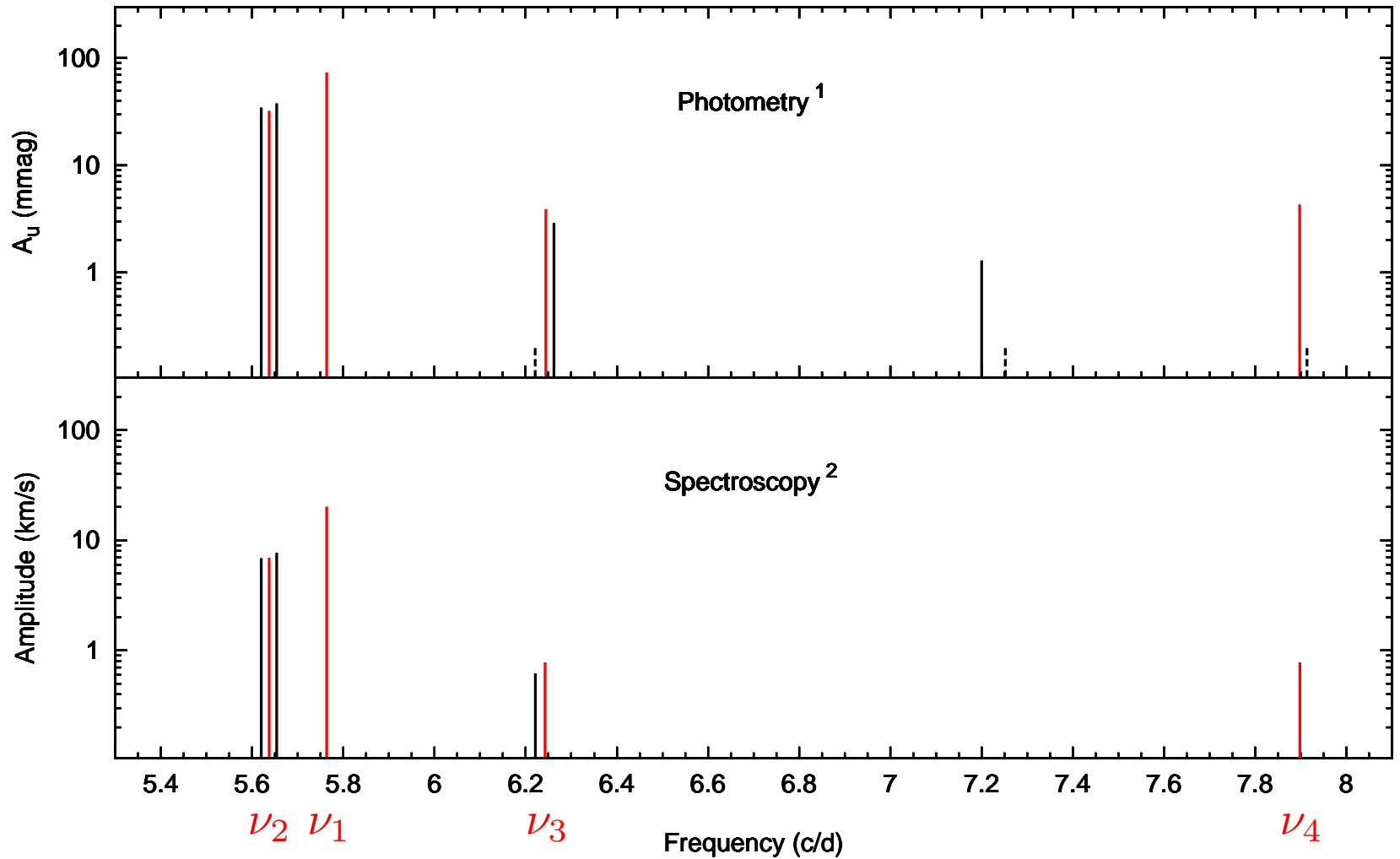
Observed frequency spectrum



¹ Handler G., et al., 2004, MNRAS, 347, 452

² Aerts C., et al., 2004, MNRAS, 347, 463

Observed frequency spectrum

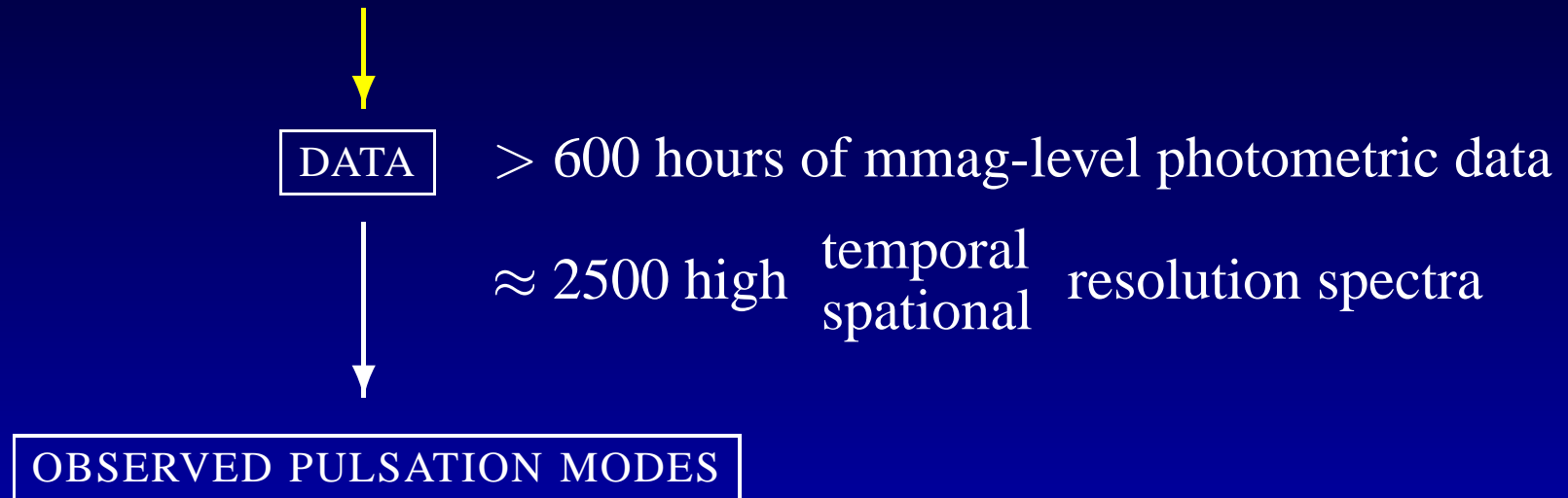


¹ Handler G., et al., 2004, MNRAS, 347, 452

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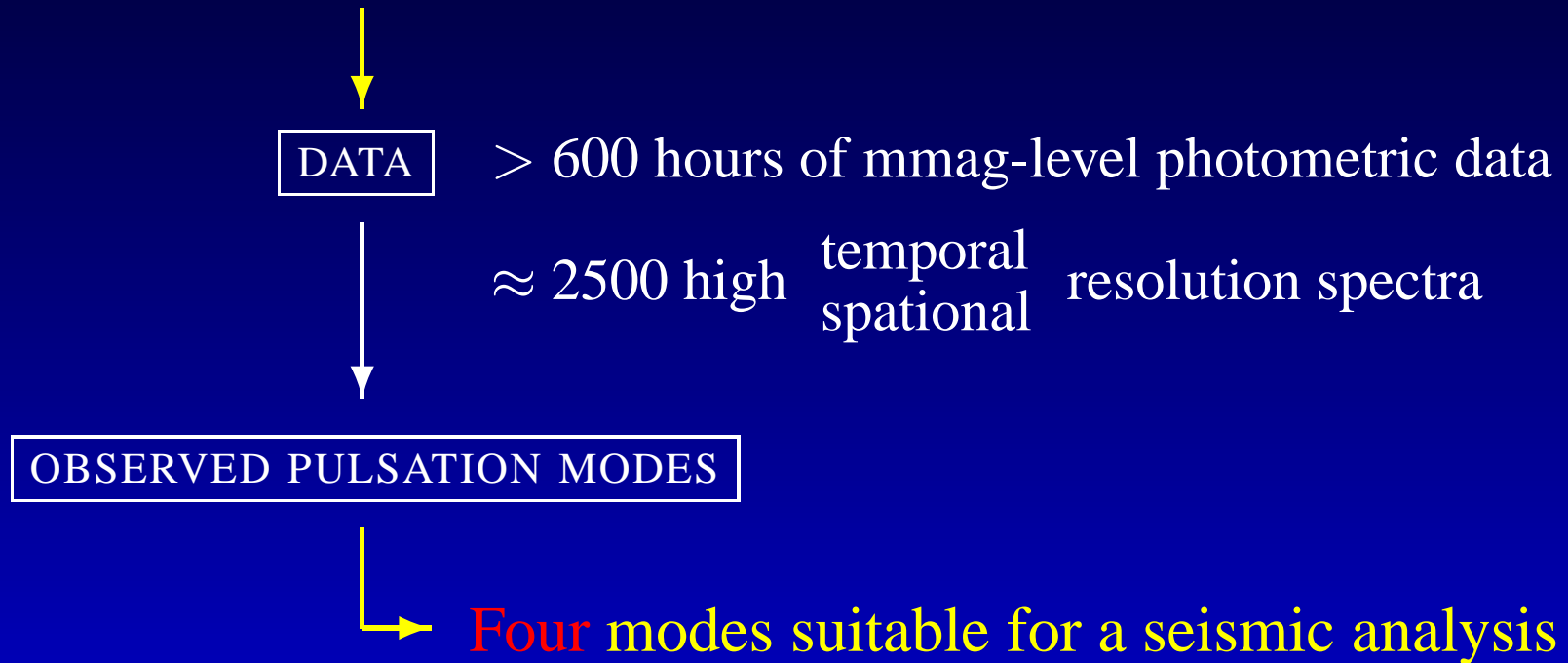
Observational Part

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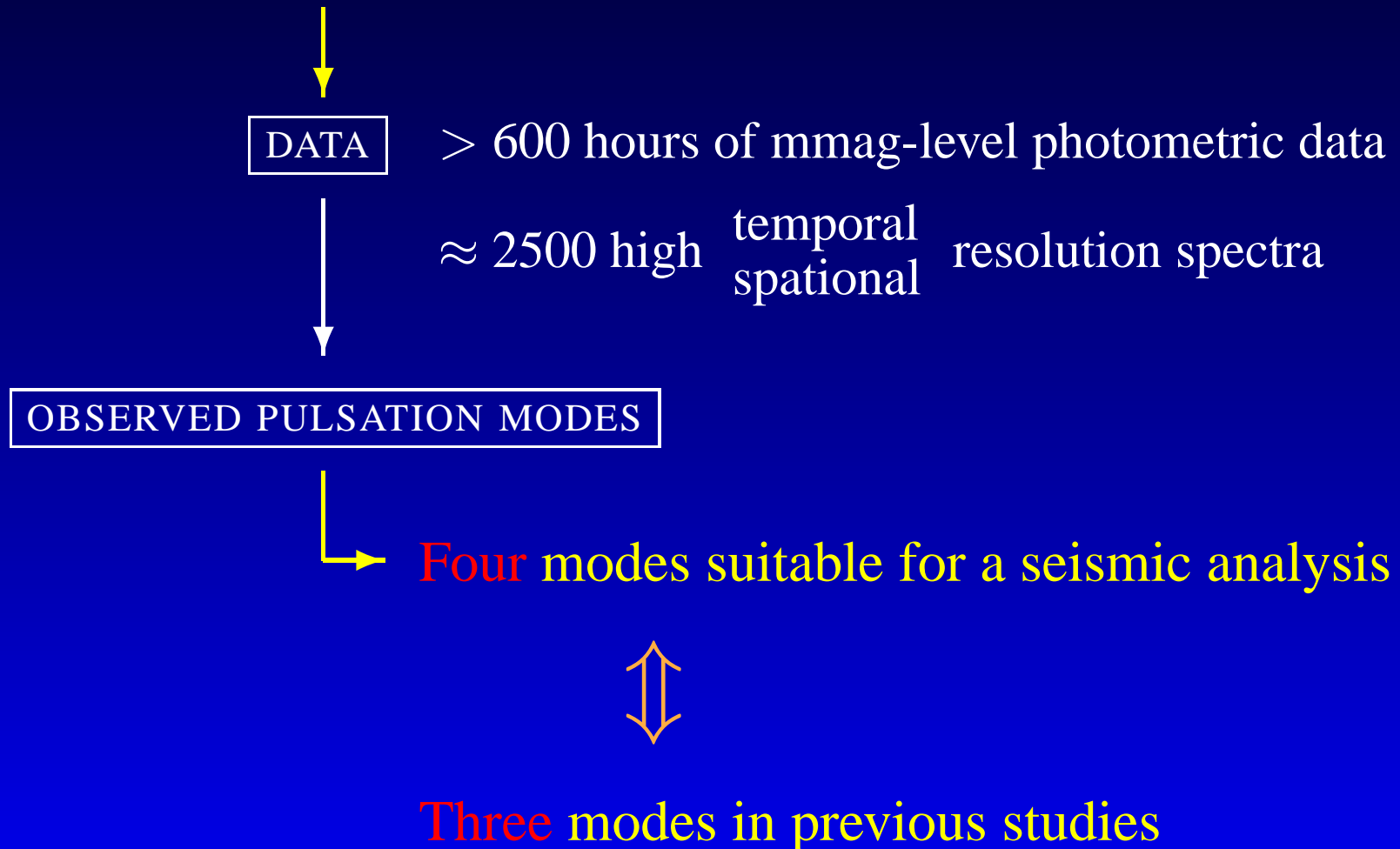
Observational Part

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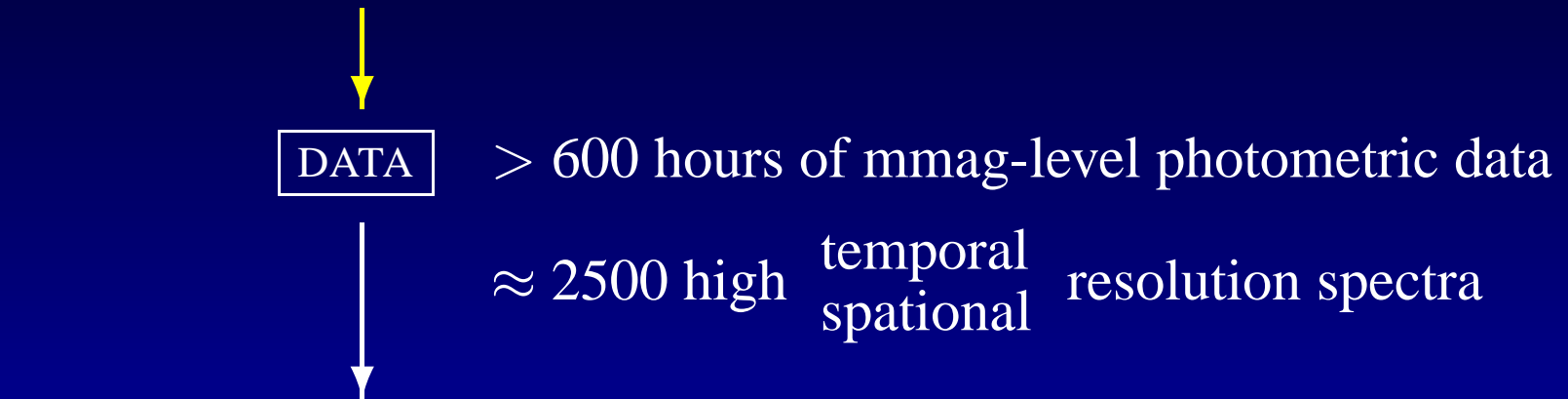
Observational Part

A 5-month multisite campaign on ν Eridani



Observational Part

A 5-month multisite campaign on ν Eridani



OBSERVED PULSATION MODES

Four modes suitable for a seismic analysis



Worth the effort?

Three modes in previous studies

Overview

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- **Seismic Modelling**
 - Case Study 1: Matching 3 Pulsation Modes
 - Case Study 2: Matching 4 Pulsation Modes
- Conclusions

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 - Case Study 1: Matching 3 Pulsation Modes**
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Case Study 1 : Matching 3 Pulsation Modes

X α_{ov} Z M/M $_{\odot}$ age (My)

Case Study 1 : Matching 3 Pulsation Modes

| X | α_{ov} | Z | M/M $_{\odot}$ | age (My) |
|------|---------------|---|----------------|----------|
| 0.70 | 0.0 | | | |

Case Study 1 : Matching 3 Pulsation Modes

| X | α_{ov} | | Z | M/M $_{\odot}$ | age (My) |
|------|---------------|------------|-------|----------------|----------|
| 0.70 | 0.0 | \implies | 0.016 | 9.9 | 15.9 |

Case Study 1 : Matching 3 Pulsation Modes

| X | α_{ov} | | Z | M/M $_{\odot}$ | age (My) |
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ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable?

\rightarrow Non-adiabatic analysis with the code MAD¹

¹ Dupret M.-A., 2002, A&A, 234, 262

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| X | α_{ov} | | Z | M/M $_{\odot}$ | age (My) |
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1. Are the observed modes unstable?

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Case Study 1 : Matching 3 Pulsation Modes

| X | α_{ov} | | Z | M/M $_{\odot}$ | age (My) |
|------|---------------|------------|-------|----------------|----------|
| 0.70 | 0.0 | \implies | 0.016 | 9.9 | 15.9 |

ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable?

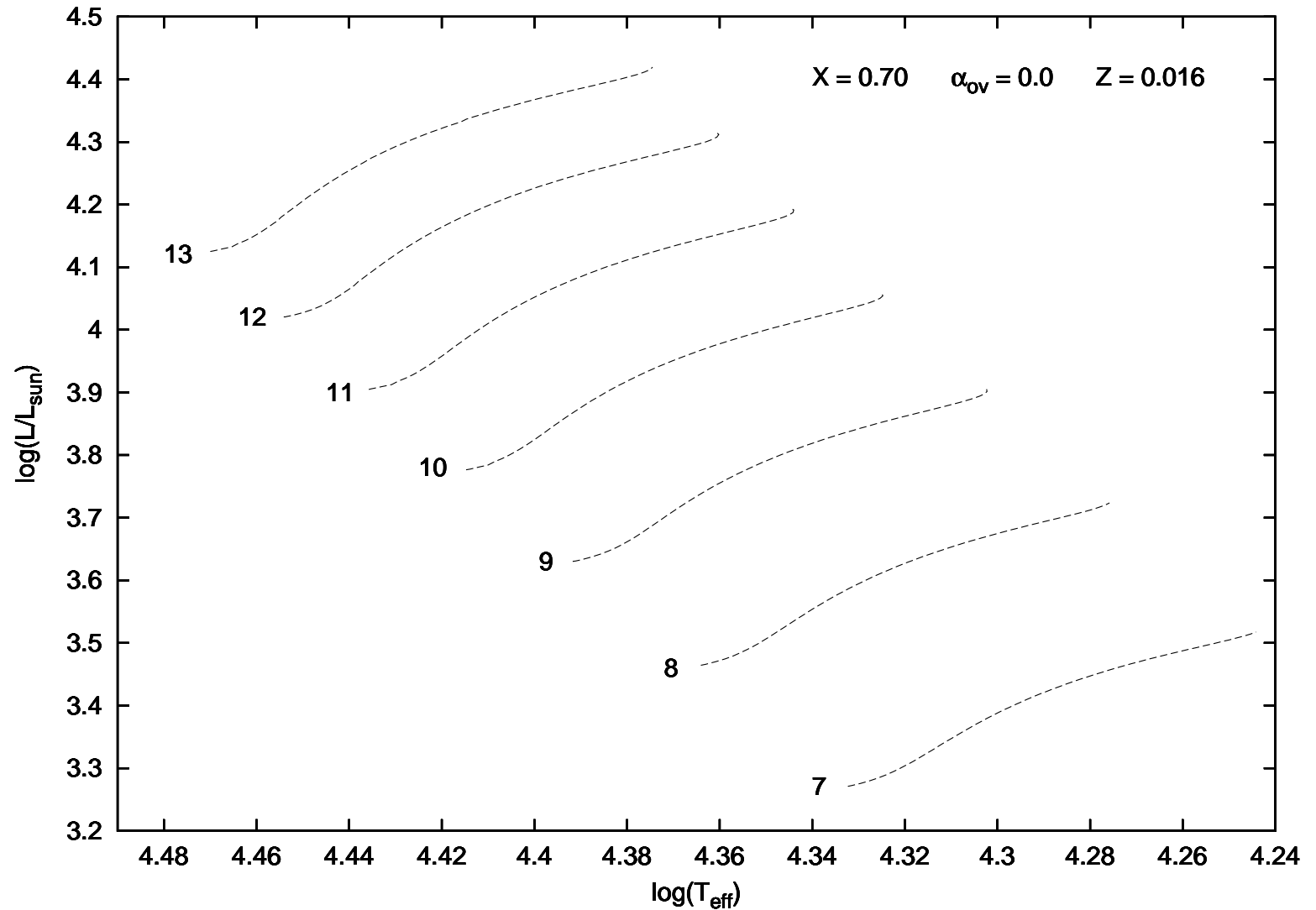
OK

→ Non-adiabatic analysis with the code MAD¹

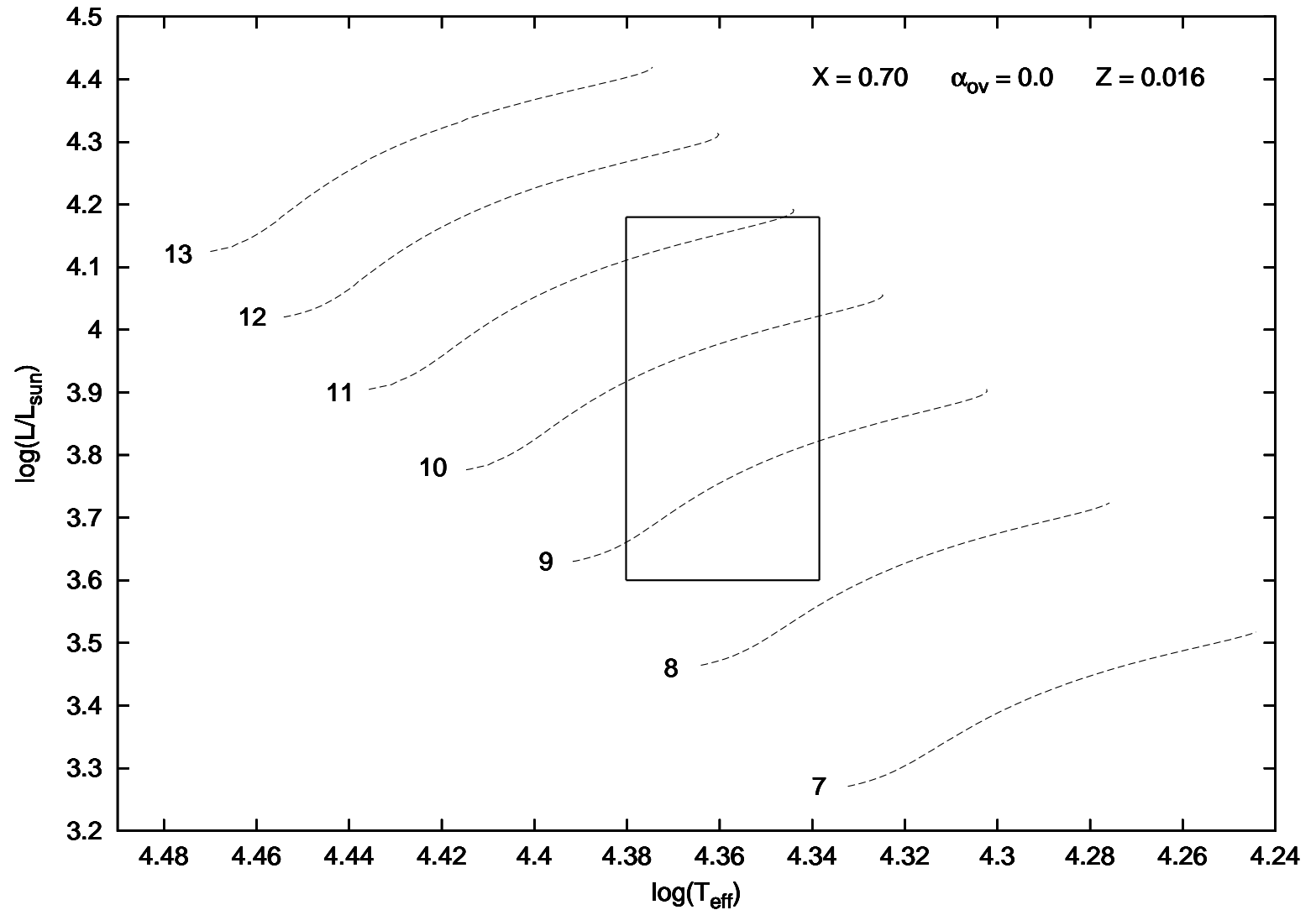
2. Position in HR diagram within error box?

¹ Dupret M.-A., 2002, A&A, 234, 262

Position in HR diagram

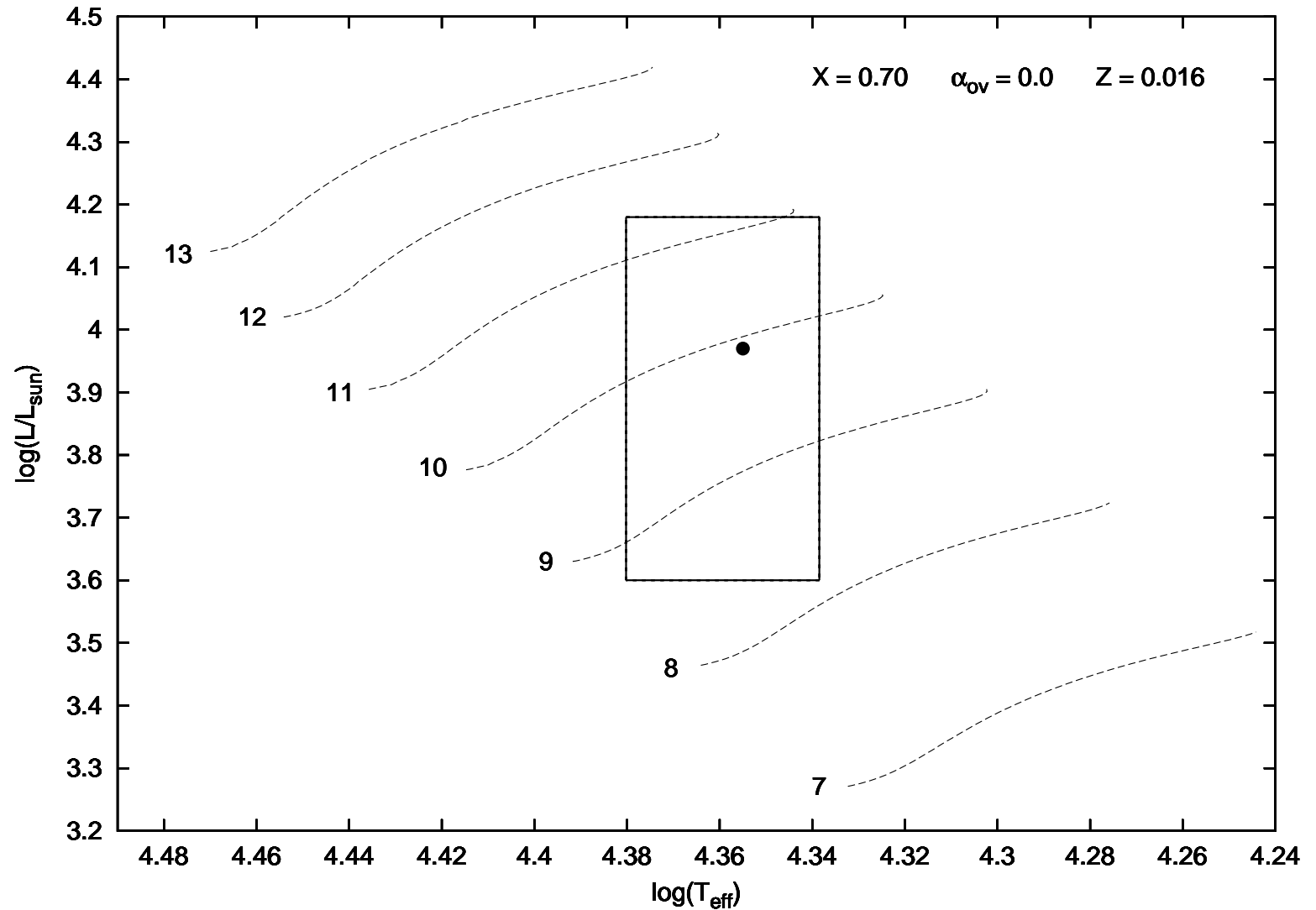


Position in HR diagram



Error box taken from De Ridder J., et al., 2004, MNRAS, (*in press*)

Position in HR diagram



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Case Study 1 : Matching 3 Pulsation Modes

| X | α_{ov} | | Z | M/M $_{\odot}$ | age (My) |
|------|---------------|------------|-------|----------------|----------|
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1. Are the observed modes unstable?

OK

→ Non-adiabatic analysis with the code MAD

2. Position in HR diagram within error box?

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| X | α_{ov} | | Z | M/M $_{\odot}$ | age (My) |
|------|---------------|------------|-------|----------------|----------|
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ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable? *OK*
→ Non-adiabatic analysis with the code MAD
2. Position in HR diagram within error box? *OK*

Case Study 1 : Matching 3 Pulsation Modes

| X | α_{ov} | | Z | M/M $_{\odot}$ | age (My) |
|------|---------------|------------|-------|----------------|----------|
| 0.70 | 0.0 | \implies | 0.016 | 9.9 | 15.9 |

ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable? *OK*
 \rightarrow Non-adiabatic analysis with the code MAD
2. Position in HR diagram within error box? *OK*

\implies A standard stellar model with normal stellar parameter values matches 3 observed pulsation modes and satisfies all other observational constraints.

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 - Case Study 1: Matching 3 Pulsation Modes

 - Case Study 2: **Matching 4 Pulsation Modes**

- Conclusions

Case Study 2 : Matching 4 Pulsation Modes

X

α_{ov}

Z

M/M_⊙

age (My)

Case Study 2 : Matching 4 Pulsation Modes

| X | α_{ov} | Z | M/M $_{\odot}$ | age (My) |
|------|---------------|---|----------------|----------|
| 0.70 | | | | |

Case Study 2 : Matching 4 Pulsation Modes

| X | | α_{ov} | Z | M/M $_{\odot}$ | age (My) |
|------|------------|---------------|--------|----------------|----------|
| 0.70 | \implies | 0.31 | 0.0155 | 7.8 | 29.6 |

Case Study 2 : Matching 4 Pulsation Modes

| X | | α_{ov} | Z | M/M $_{\odot}$ | age (My) |
|------|------------|----------------------|--------|----------------|----------|
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|------|------------|----------------------|--------|----------------|----------|
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ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable?

NO

\rightarrow None of them is unstable!

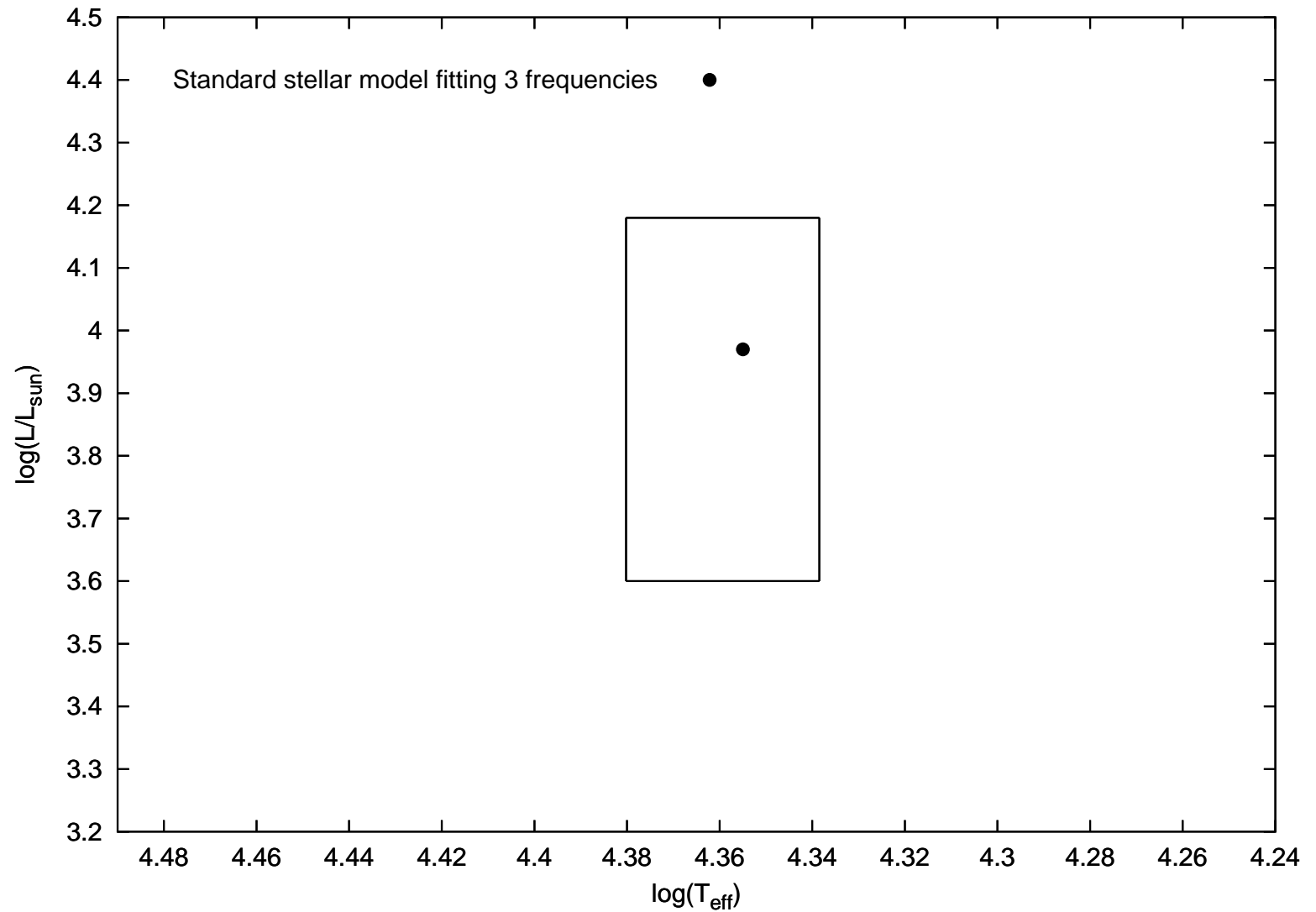
Case Study 2 : Matching 4 Pulsation Modes

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|------|------------|----------------------|--------|----------------|----------|
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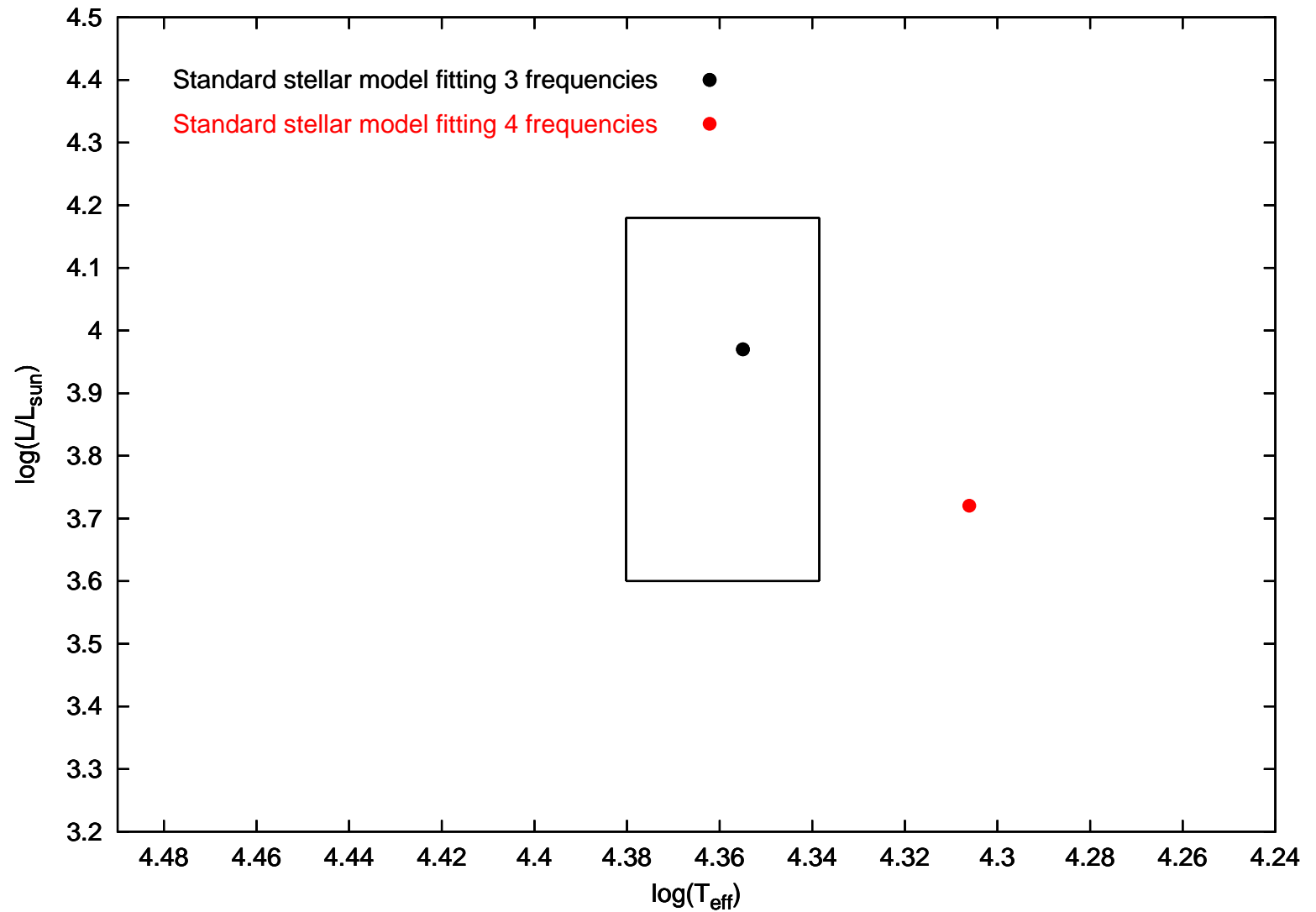
ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable? *NO*
 \rightarrow None of them is unstable!
2. Position in HR diagram within error box?

Position in HR diagram



Position in HR diagram



Case Study 2 : Matching 4 Pulsation Modes

| X | | α_{ov} | Z | M/M $_{\odot}$ | age (My) |
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ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable? *NO*
 \rightarrow None of them is unstable!
2. Position in HR diagram within error box? *NO*

Case Study 2 : Matching 4 Pulsation Modes

| X | | α_{ov} | Z | M/M $_{\odot}$ | age (My) |
|------|------------|----------------------|--------|----------------|----------|
| 0.70 | \implies | 0.31 | 0.0155 | 7.8 | 29.6 |

ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable? *NO*
 \rightarrow None of them is unstable!
2. Position in HR diagram within error box? *NO*

\implies The standard stellar model that matches the 4 selected pulsation modes doesn't satisfy the other observational constraints.

Case Study 2 : Matching 4 Pulsation Modes

| X | | α_{ov} | Z | M/M $_{\odot}$ | age (My) |
|------|------------|----------------------|--------|----------------|----------|
| 0.70 | \implies | 0.31 | 0.0155 | 7.8 | 29.6 |

Case Study 2 : Matching 4 Pulsation Modes

| Fe | X | | α_{ov} | Z | M/M $_{\odot}$ | age (My) |
|---------------|------|------------|---------------|--------|----------------|----------|
| Fe $_{\odot}$ | 0.70 | \implies | 0.31 | 0.0155 | 7.8 | 29.6 |

Case Study 2 : Matching 4 Pulsation Modes

| Fe | X | | α_{ov} | Z | M/M $_{\odot}$ | age (My) |
|---------------|------|------------|---------------|--------|----------------|----------|
| Fe $_{\odot}$ | 0.70 | \implies | 0.31 | 0.0155 | 7.8 | 29.6 |

4 Fe $_{\odot}$

$\frac{1}{4}$ Fe $_{\odot}$

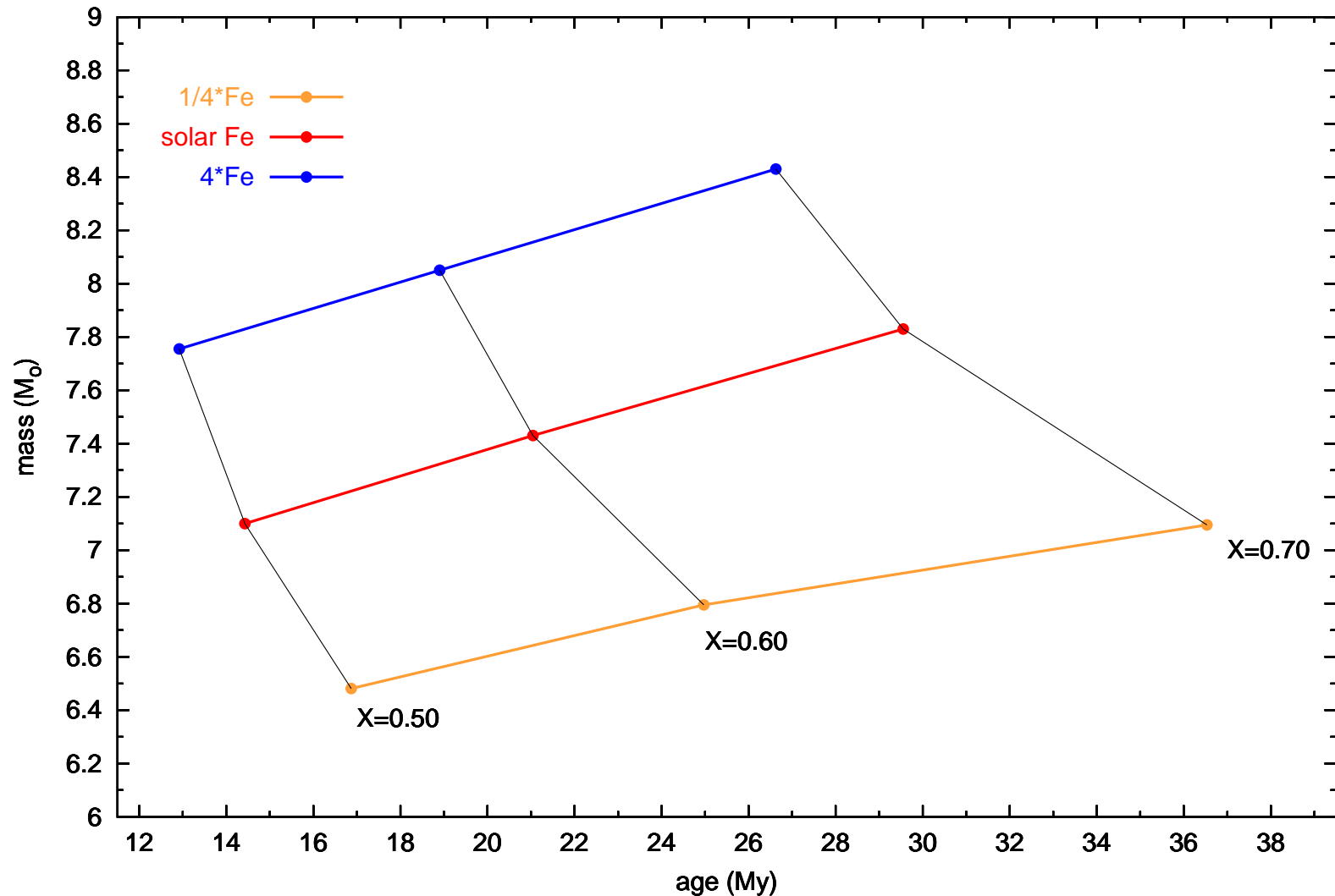
Case Study 2 : Matching 4 Pulsation Modes

| Fe | X | | α_{ov} | Z | M/M $_{\odot}$ | age (My) |
|-----------------------------|------|------------|---------------|--------|----------------|----------|
| Fe $_{\odot}$ | 0.70 | \implies | 0.31 | 0.0155 | 7.8 | 29.6 |
| | 0.60 | | | | | |
| | 0.50 | | | | | |
| 4 Fe $_{\odot}$ | 0.70 | | | | | |
| | 0.60 | | | | | |
| | 0.50 | | | | | |
| $\frac{1}{4}$ Fe $_{\odot}$ | 0.70 | | | | | |
| | 0.60 | | | | | |
| | 0.50 | | | | | |

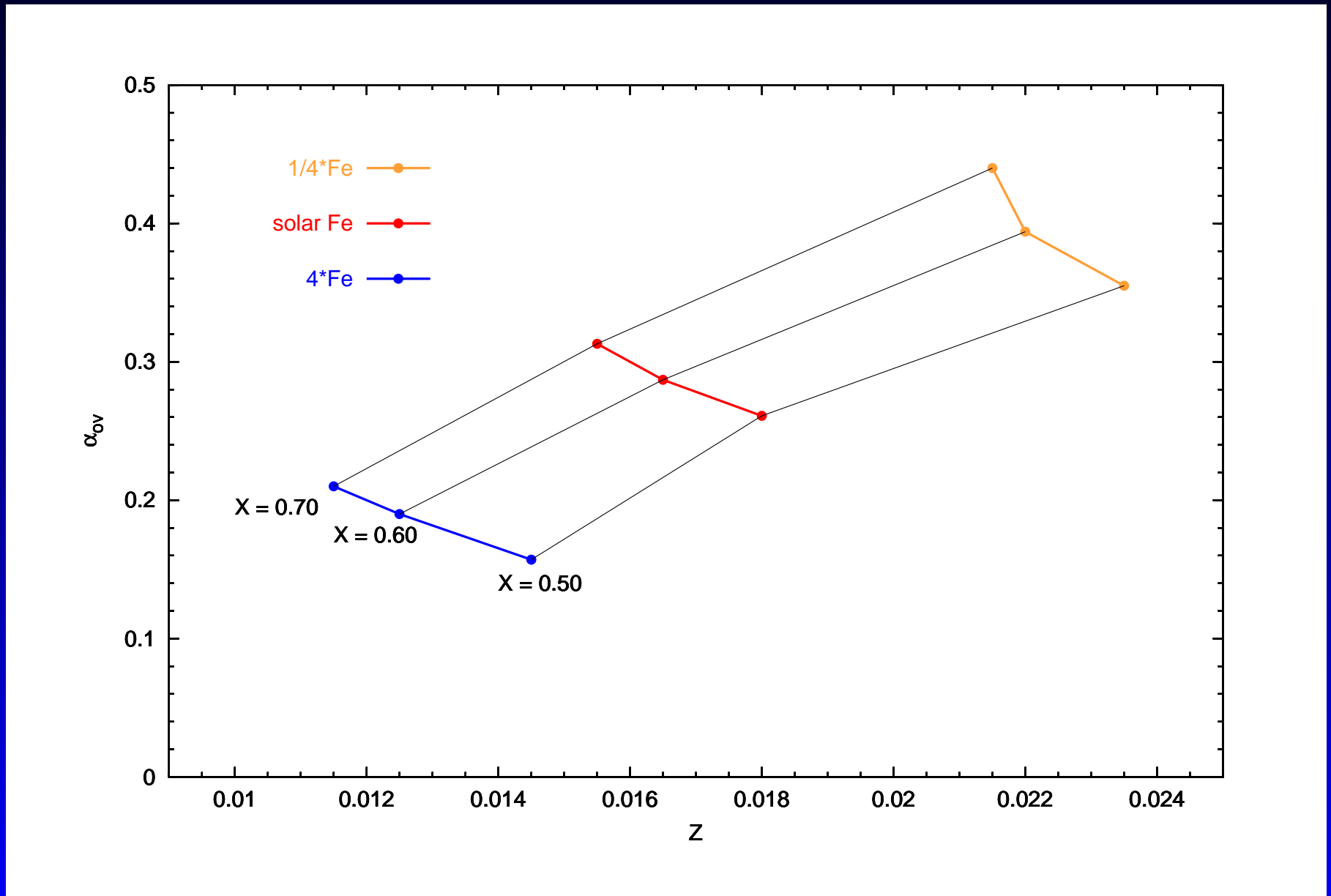
Case Study 2 : Matching 4 Pulsation Modes

| Fe | X | | α_{ov} | Z | M/M $_{\odot}$ | age (My) |
|-----------------------------|------|------------|---------------|--------|----------------|----------|
| Fe $_{\odot}$ | 0.70 | \implies | 0.31 | 0.0155 | 7.8 | 29.6 |
| | 0.60 | \implies | 0.29 | 0.0165 | 7.4 | 21.0 |
| | 0.50 | \implies | 0.26 | 0.018 | 7.1 | 14.4 |
| 4 Fe $_{\odot}$ | 0.70 | \implies | 0.21 | 0.0115 | 8.4 | 26.6 |
| | 0.60 | \implies | 0.19 | 0.0125 | 8.1 | 18.9 |
| | 0.50 | \implies | 0.16 | 0.0145 | 7.8 | 12.9 |
| $\frac{1}{4}$ Fe $_{\odot}$ | 0.70 | \implies | 0.44 | 0.0215 | 7.1 | 36.5 |
| | 0.60 | \implies | 0.39 | 0.022 | 6.8 | 25.0 |
| | 0.50 | \implies | 0.36 | 0.0235 | 6.5 | 16.9 |

Case Study 2 : Matching 4 Pulsation Modes



Case Study 2 : Matching 4 Pulsation Modes



Case Study 2 : Matching 4 Pulsation Modes

ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable?

Case Study 2 : Matching 4 Pulsation Modes

ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable?

$$Fe = Fe_{\odot} \implies X < 0.50$$

Case Study 2 : Matching 4 Pulsation Modes

ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable?

$$\text{Fe} = \text{Fe}_{\odot} \implies X < 0.50$$

$$X = 0.70 \implies \text{Fe} \gtrsim 4 \text{Fe}_{\odot}$$

Case Study 2 : Matching 4 Pulsation Modes

ADDITIONAL CONSTRAINTS:

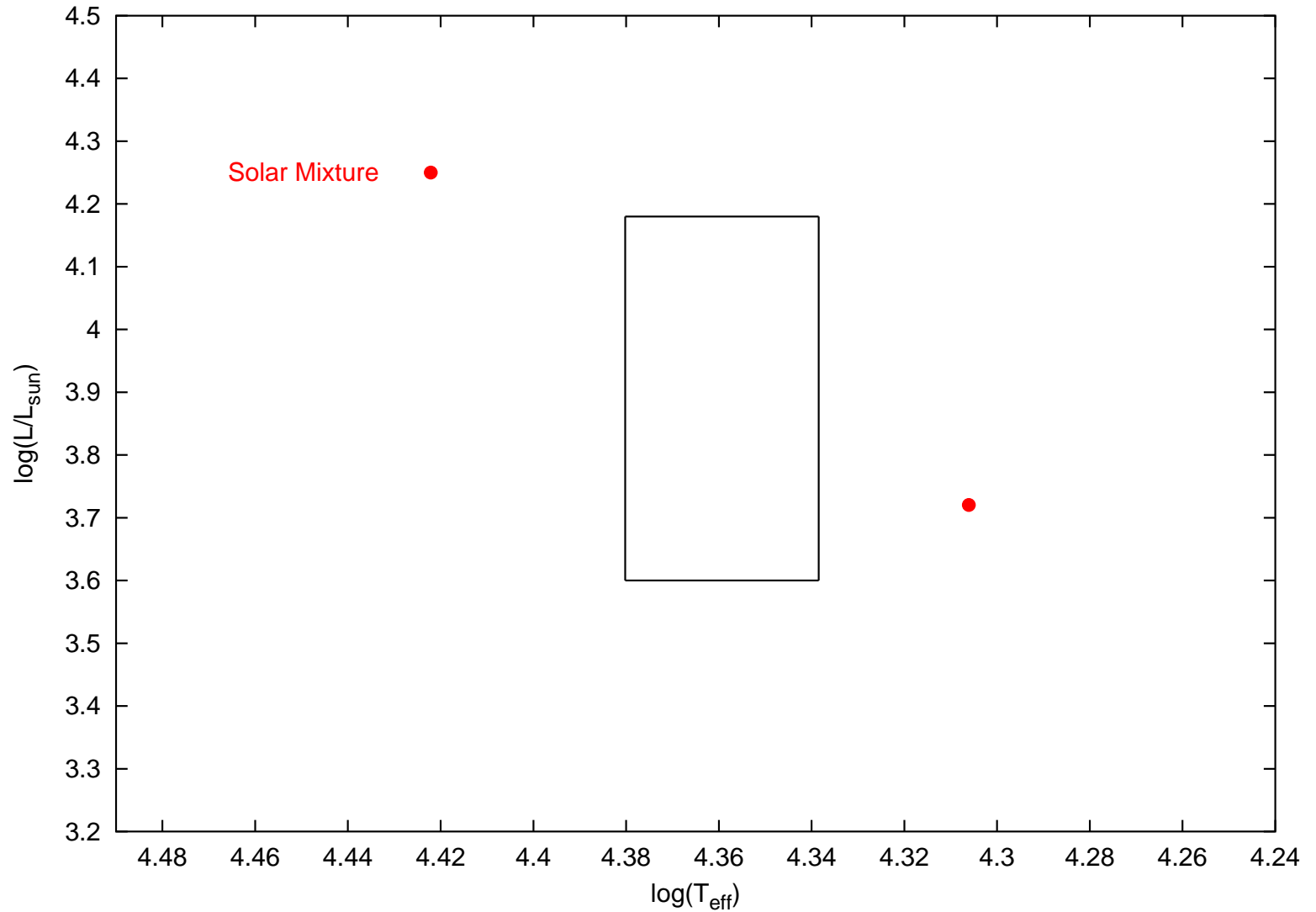
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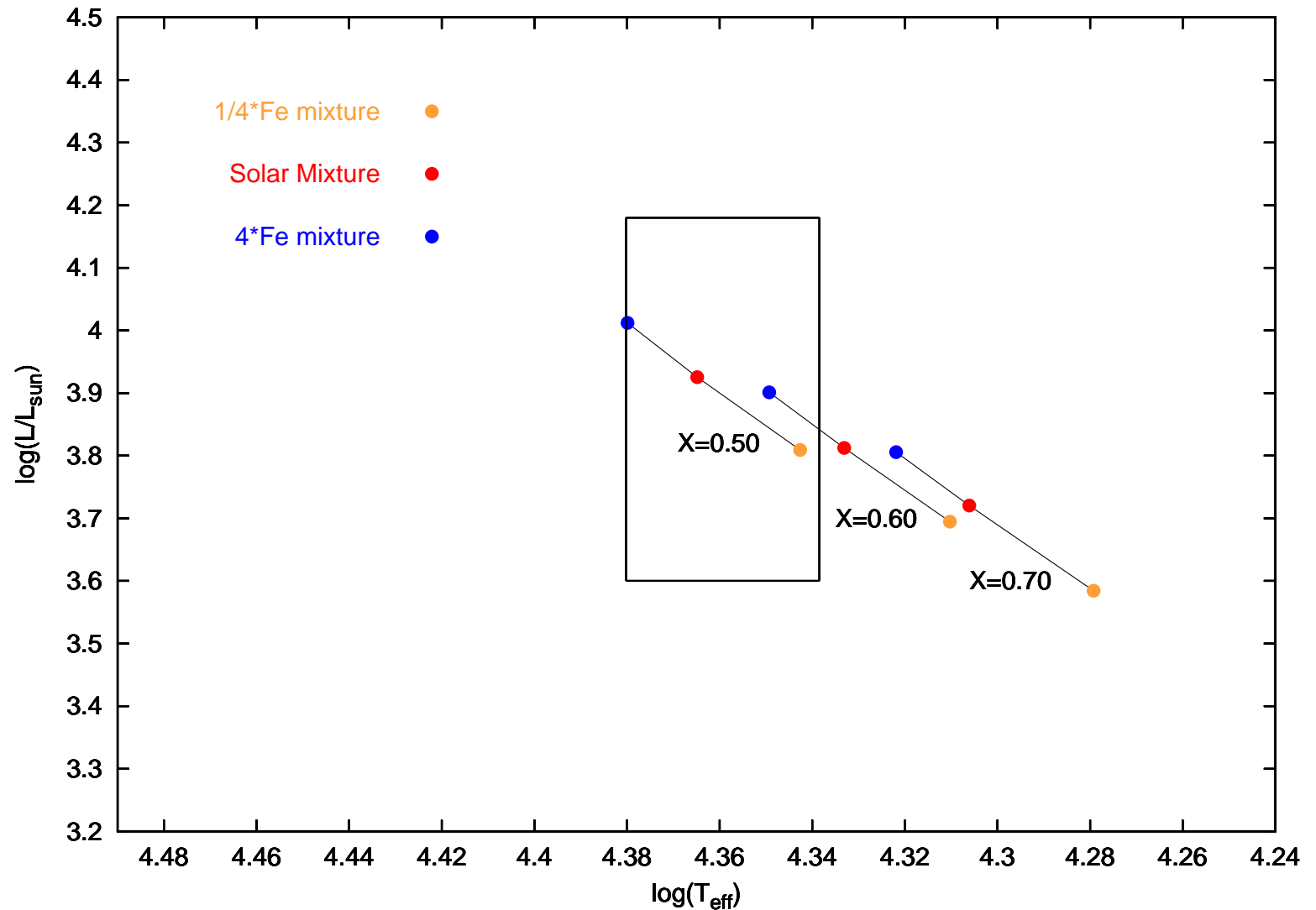
$$X = 0.70 \implies \text{Fe} \gtrsim 4 \text{Fe}_{\odot}$$

2. Position in HR diagram within/near error box?

Position in HR diagram



Position in HR diagram



Case Study 2 : Matching 4 Pulsation Modes

ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable?

$$\text{Fe} = \text{Fe}_{\odot} \implies X < 0.50$$

$$X = 0.70 \implies \text{Fe} \gtrsim 4 \text{Fe}_{\odot}$$

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Case Study 2 : Matching 4 Pulsation Modes

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1. Are the observed modes unstable?

$$\text{Fe} = \text{Fe}_{\odot} \implies X < 0.50$$

$$X = 0.70 \implies \text{Fe} \gtrsim 4 \text{Fe}_{\odot}$$

2. Position in HR diagram within/near error box?

$$\text{Fe} = \text{Fe}_{\odot} \implies X < 0.60$$

Case Study 2 : Matching 4 Pulsation Modes

ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable?

$$\text{Fe} = \text{Fe}_{\odot} \implies X < 0.50$$

$$X = 0.70 \implies \text{Fe} \gtrsim 4 \text{Fe}_{\odot}$$

2. Position in HR diagram within/near error box?

$$\text{Fe} = \text{Fe}_{\odot} \implies X < 0.60$$

$$X = 0.70 \implies \text{Fe} > 4 \text{Fe}_{\odot}$$

Case Study 2 : Matching 4 Pulsation Modes

ADDITIONAL CONSTRAINTS:

1. Are the observed modes unstable?

$$\text{Fe} = \text{Fe}_{\odot} \implies X < 0.50$$

$$X = 0.70 \implies \text{Fe} \gtrsim 4 \text{Fe}_{\odot}$$

2. Position in HR diagram within/near error box?

$$\text{Fe} = \text{Fe}_{\odot} \implies X < 0.60$$

$$X = 0.70 \implies \text{Fe} > 4 \text{Fe}_{\odot}$$

\implies An increase in Fe as well as a decrease in X help to satisfy both additional constraints

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- **Conclusions**

Conclusions

- ★ We have performed **a seismic modelling of** the β Cep star ν **Eridani** with the Liège evolution and pulsation codes
- ★ Several standard stellar models can be found fitting three pulsation modes and satisfying the other observational constraints
- ★ A massive exploration of the 4D parameter space reveals that **no standard stellar model** fits the four clearly detected pulsation modes and **fulfills all** the other **observational constraints**

Conclusions

- ★ We calculated additional models fitting the four pulsation modes for different (X, Fe) sets with

$$X : 0.70, 0.60, 0.50$$

$$Fe : Fe_{\odot}, 4 Fe_{\odot}, \frac{1}{4} Fe_{\odot}$$

- ★ **An increase in Fe and/or a decrease in X** results in stellar models matching the four pulsation modes and help to satisfy all the other observational constraints that are currently available for ν Eri

Conclusions

- ★ We calculated additional models fitting the four pulsation modes for different (X, Fe) sets with

$$X : 0.70, 0.60, 0.50$$

$$\text{Fe} : \text{Fe}_{\odot}, 4 \text{Fe}_{\odot}, \frac{1}{4} \text{Fe}_{\odot}$$

- ★ **An increase in Fe and/or a decrease in X** results in stellar models matching the four pulsation modes and help to satisfy all the other observational constraints that are currently available for ν Eri

⇒ The **4th pulsation mode** puts **much stronger limits** on the acceptable stellar models!

Future

- ★ A seismic analysis of other β Cep stars
→ 12 Lacertae

Future

★ A seismic analysis of other β Cep stars

→ 12 Lacertae

★ Space missions

→ COROT

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