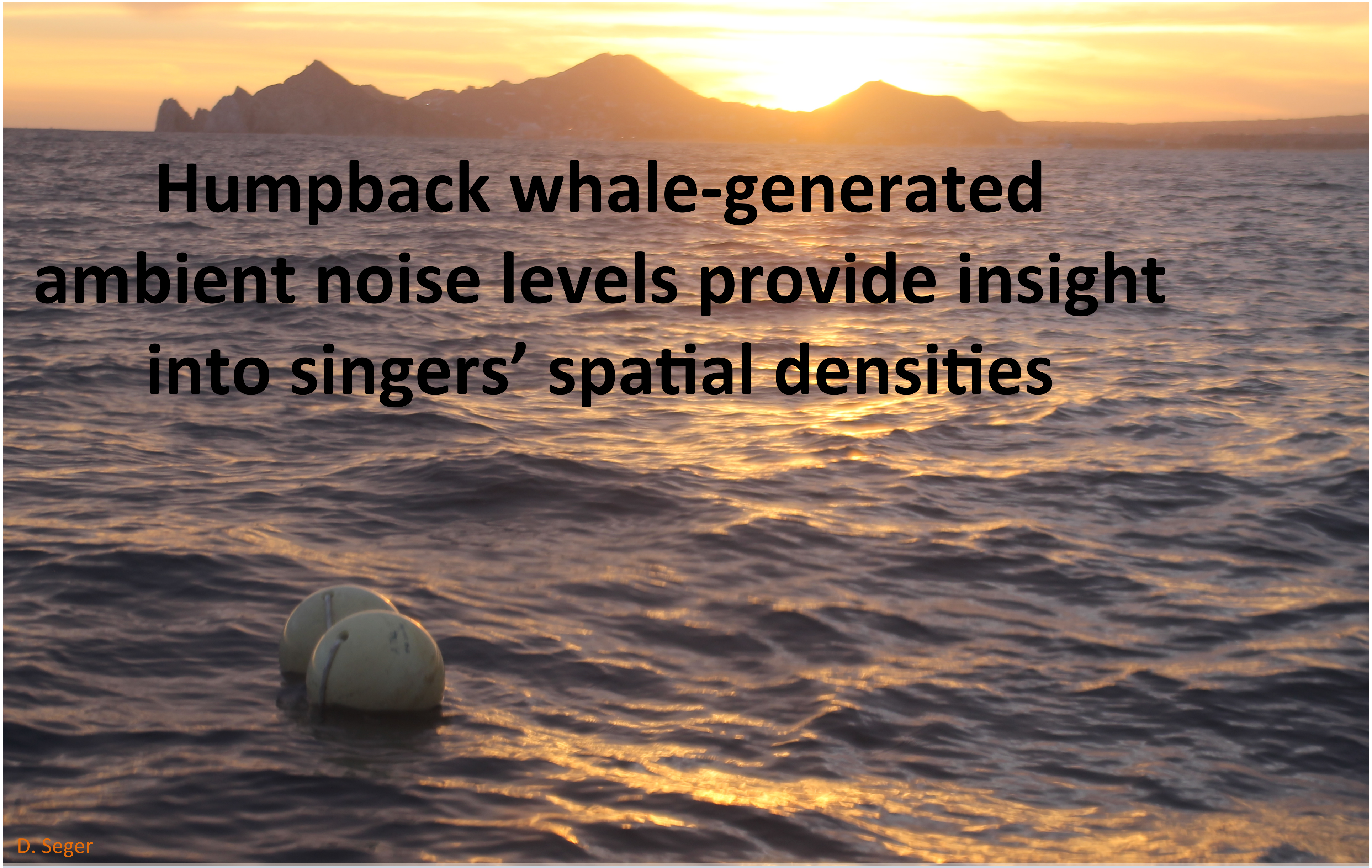
Humpback whale-generated ambient noise levels provide insight into singers' spatial densities



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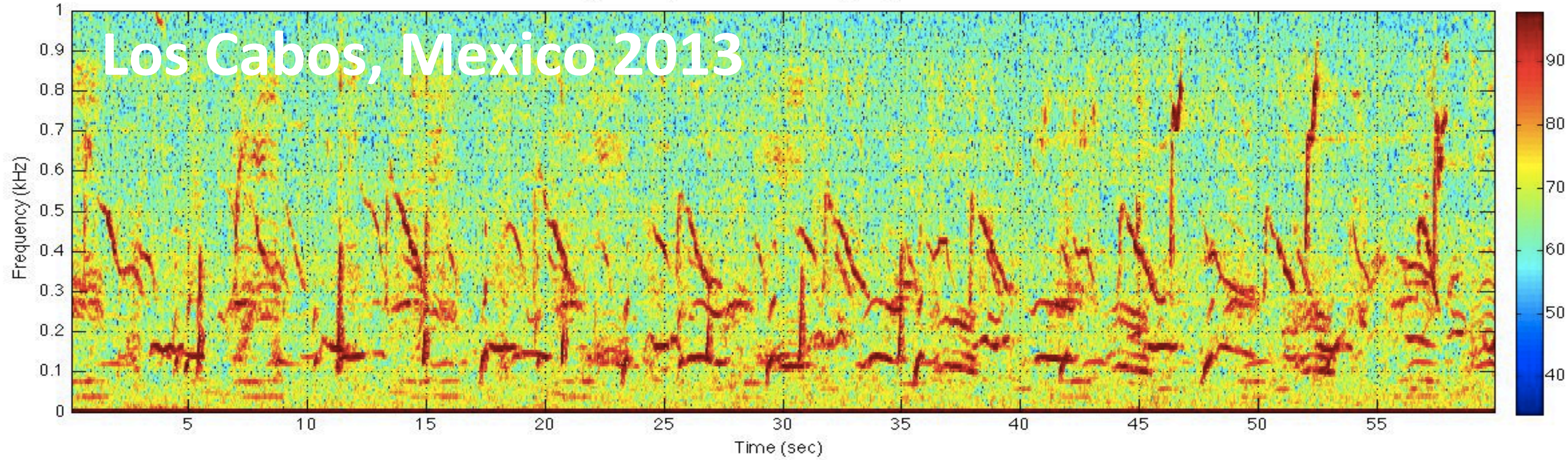
OUTLINE

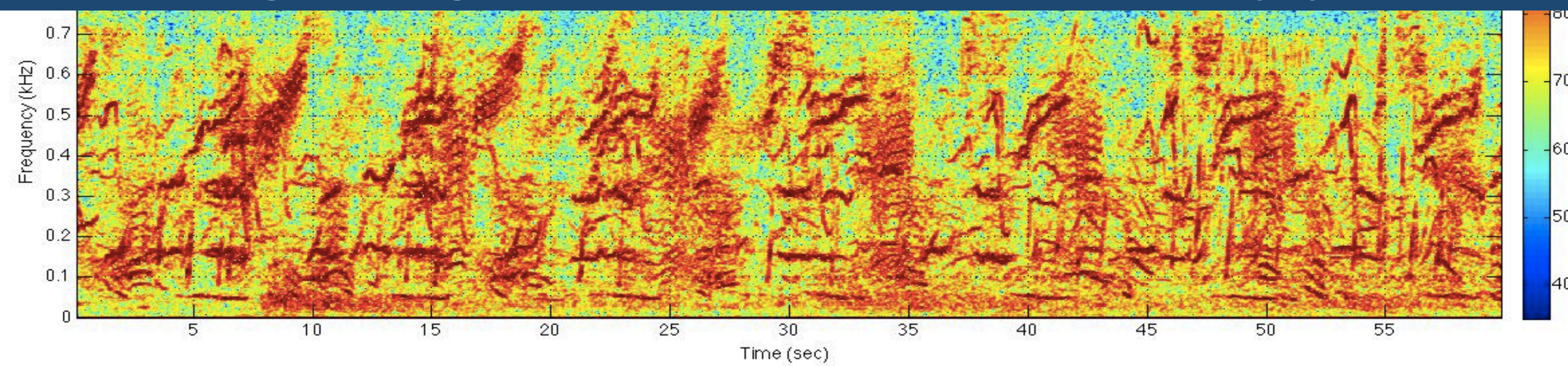
- **Background**
  - **Humpback whales (*Megaptera novaeangliae*) sing profusely and are the dominant sound source in breeding ground soundscapes**
  - **Can this singing "noise" level be related to singer population size?**
- **Theory & Methods**
  - **"KIP" model: models ambient noise generated by random sources**
    - **Our random sources = singing humpback whales**
    - **Caveat → Noise levels highly sensitive to animal source level and other behaviors**
    - **Define "sensitivity" term that is less dependent on SL / behaviors**
  - **Field data collection to test KIP model**
    - **Geography of Los Cabos**
    - **Visual & acoustic surveys**
    - **Control for the diel cycle**
- **Analysis Techniques & Results**
  - **Generalized Linear Model used to measure "sensitivity" & compare to KIP**
  - **"Sensitivity" allows identification of how singing humpback whales pack themselves as population changes**

BACKGROUND

Males sing profusely on the breeding grounds. (Payne & McVay, 1971)



Individual song indistinguishable → Is "NOISE" level related to population size?



Can we model it? → And then empirically test it?

Au *et al*., 2000; Mellinger *et al*., 2009

THEORY – THE KIP MODEL*

*ORGINALLY DEVELOPED FOR RANDOMLY DISTRIBUTED WIND-DRIVEN NOISE

(Kuperman and Ingenito, 1980; Perkins *et al.*, 1993 → "KIP model")

*Not equal to transmission loss

$$I = \frac{Sf}{A(N)/N} P(z_r, z_w, R)$$

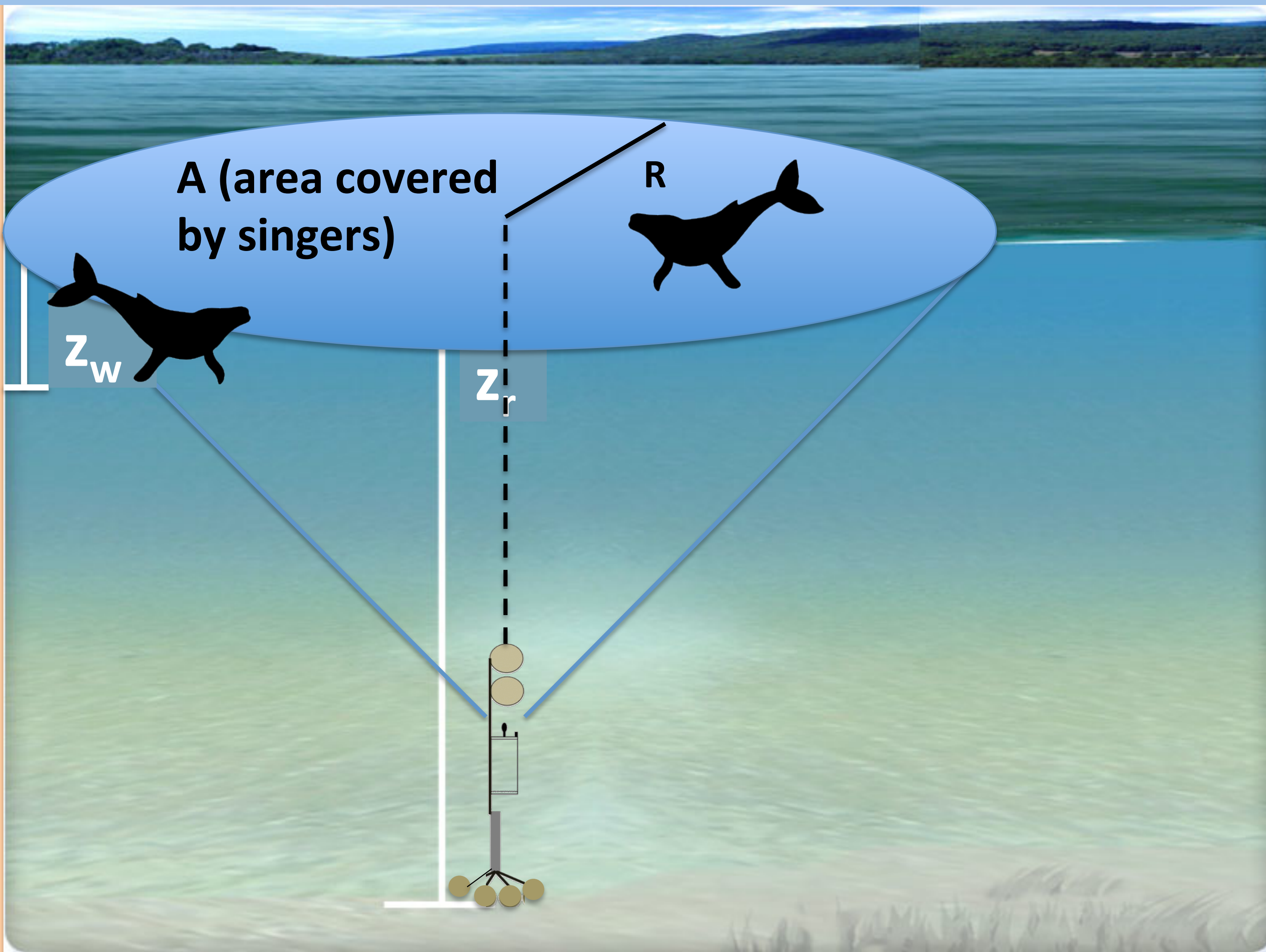
Linear ambient noise intensity (μPa²/Hz)

Source spectral density weighted by fraction of singing time (μPa²/Hz @ 1m)

Spatial density of whales (A = area): function of N

Propagation term: function of whale & receiver depths, and area covered by singing whales

THEORY – EXPLANATION OF PROPAGATION TERMS



THEORY – THE KIP MODEL WITH MORE FAMILIAR dB UNITS

$$I = \frac{Sf}{A(N)/N} P(z_r, z_w, R)$$

$$I_{dB} = S_{dB} + 10\log_{10} f + 10\log_{10} N - 10\log_{10} A + 10\log_{10} P$$

dB noise intensity ($\mu Pa^2/Hz$) measured from receivers

Source spectral density

Fraction of singing time ("duty cycle")

N = number of whales within area A

*Source Level now additive
e.g. a 10 dB increase in singing level = 10 dB increase in ambient din

THEORY – EXAMPLE CALCULATION

$$I = \frac{Sf}{A(N)/N} P(z_r, z_w, R)$$

(80m, *20m*, 20km) in 90m water

105 re 1 µPa (100-1000Hz)

$$I_{dB} = S_{dB} + 10\log_{10} f + 10\log_{10} N - 10\log_{10} A + 10\log_{10} P$$

155 -1.87 -17 -31.13

dB noise intensity (µPa^2/Hz) estimate

Source spectral density = 155 dB re 1 uPa @ 1m (Au *et al.*, 2006)

Fraction of singing time ("duty cycle") = 65% (Payne & Payne, 1985; Mednis, 1991)

Spacing between whales = 4 km
and N = 1
A = 50.26

*Calculations represent a flat spectrum 100-1000 HZ bandwidth

THEORY – EXAMPLE CALCULATION

(80m, 20m, 20km) in 90m water

$$I = \frac{Sf}{A(N)/N} P(z_r, z_w, R)$$

105 re 1 µPa (100-1000Hz)

$$I_{dB} = S_{dB} + 10\log_{10} f + \underbrace{10\log_{10} N - 10\log_{10} A}_{-20.02} + 10\log_{10} P$$

157   -3.01   -20.02   -28.97

dB noise intensity (µPa^2/Hz) estimate

Source spectral density = 157 dB re 1 uPa @ 1m (Au *et al.*, 2006)

Fraction of singing time ("duty cycle") = 50%

Spacing between whales = 8 km
and N = 2
A = 50.26

There are many combinations of model inputs that yield the same answer.
Is a more rigorous test of the model possible?

THEORY – CONCEPT OF "SENSITIVITY" ALLOWS A MORE RIGOROUS TEST

TIME 1: original population N_1

$$I_{dB1} = 155 + 10\log_{10}0.65 + 10\log_{10}N_1 - 10\log_{10}A_1 + 10\log_{10}P_1$$

TIME 2: population changes to N_2

$$- I_{dB2} = 155 + 10\log_{10}0.65 + 10\log_{10}N_2 - 10\log_{10}A_2 + 10\log_{10}P_2$$

$$\Delta I_{dB} = \Delta 10\log_{10}(S*f) + \Delta 10\log_{10}N - \Delta 10\log_{10}A + \Delta 10\log_{10}P$$

Q_{INDIV}

- Q_{INDIV} represents how an single singer changes singing behavior in response to population fluctuation
- Assume Q_{INDIV} is small: removes need for individual behavior parameters.

MEASURE NOISE LEVELS ALONGSIDE VISUAL SURVEYS

$$I_{dB}^{1} = 155 + 10\log_{10}0.65^{1} + 10\log_{10}N^{1} - 10\log_{10}A^{1} + 10\log_{10}P^{1}$$

$$- I_{dB}^{2} = 155 + 10\log_{10}0.65^{2} + 10\log_{10}N^{2} - 10\log_{10}A^{2} + 10\log_{10}P^{2}$$

$$\Delta I_{dB} = Q_{indiv} + \Delta 10\log_{10}N - \Delta 10\log_{10}A + \Delta 10\log_{10}P$$

$$\Delta 10\log_{10}N = \Delta N/N$$

→ Measure CHANGE in RELATIVE POPULATION SIZE

→ We have a measurable quantity: "SENSITIVITY" (δ)

$$\delta = \Delta I_{dB} / \Delta 10\log_{10} N$$

THEORY – definition OF "SENSITIVITY"

$$I_{dB}^{1} = 155 + 10\log_{10}0.65^{1} + 10\log_{10}N^{1} - 10\log_{10}A^{1} + 10\log_{10}P^{1}$$

$$- I_{dB}^{2} = 155 + 10\log_{10}0.65^{2} + 10\log_{10}N^{2} - 10\log_{10}A^{2} + 10\log_{10}P^{2}$$

$$\Delta I_{dB} = Q_{indiv} + \text{survey} - \Delta 10\log_{10}A + \Delta 10\log_{10}P$$

$$\delta \equiv \frac{\partial(I_{dB})}{\partial(10\log_{10}N)} = Q_{indiv} + 1 - \left(\frac{N}{A}\right)\frac{\partial A}{\partial N} + \left(\frac{N}{P}\right)\frac{\partial P}{\partial N}$$

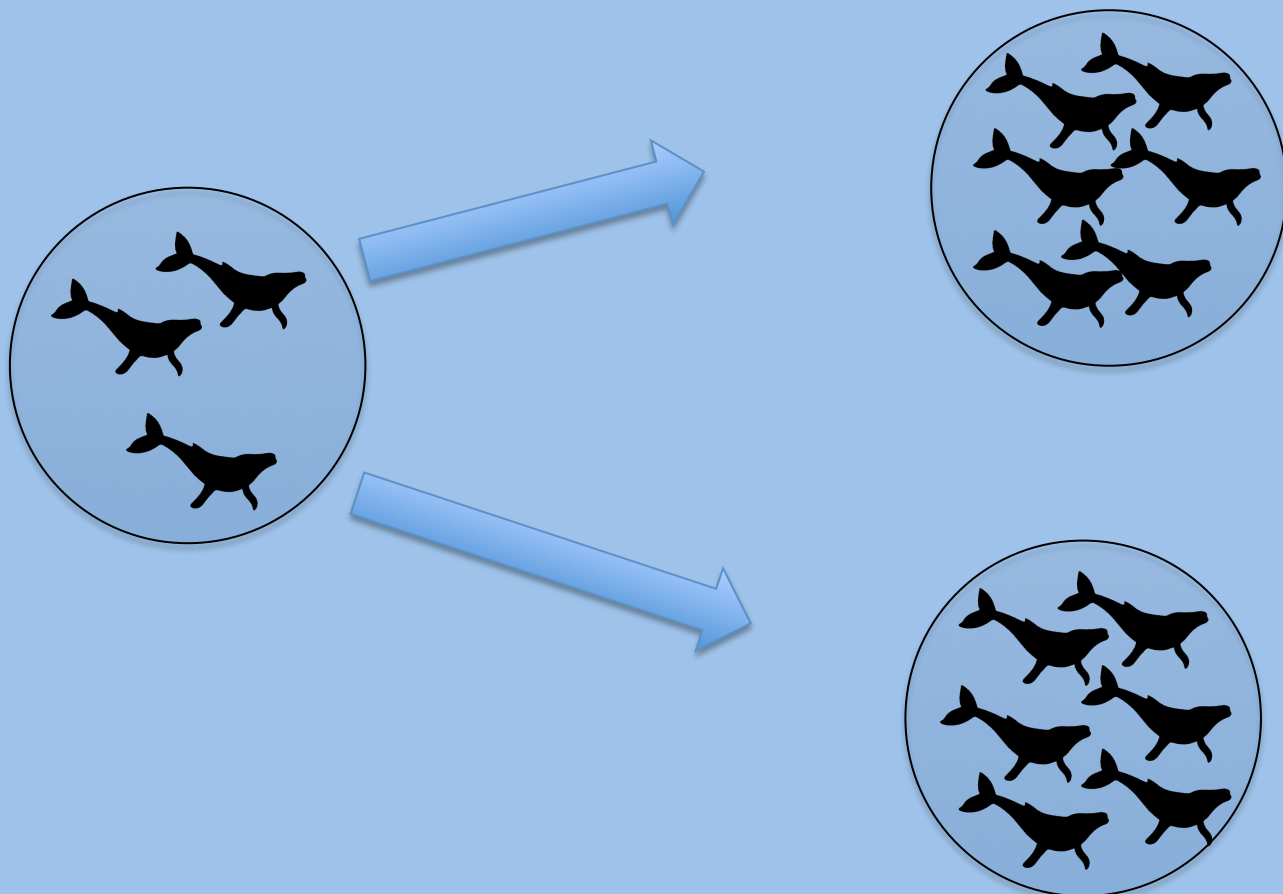
δ becomes dominated by spatial density terms

- → **dependence of *A* on *N***
- → **acoustic propagation factors (the propagation *P* term)**

How to relate A to N?

"PACKING MODELS" – HOW TO RELATE A TO N (AREA TO POP. SIZE)

Winn & Winn, 1978; Tyack, 1981; Frankel *et al.*, 1995



"Constant Density"

Area changes

$\boldsymbol{\nu} = 1$

"Constant Area"

Density changes

$\boldsymbol{\nu} = 0$

If A is proportional to N^{ν}, both scenarios are covered

MEASURING SENSITIVITY PREDICTS WHALE SPACING BEHAVIOR

$$\delta = 1 + Q_{indiv} + v\left[\left(\frac{A}{P}\right)\frac{\partial P}{\partial A} - 1\right]$$

Now we can estimate v from data

SET v = 0

$$1 + Q_{indiv} < \delta_{CA}$$

CONSTANT AREA

Independent of frequency

SET v = 1

$$Q_{indiv} < \delta_{CD} < Q_{indiv} + 0.5$$

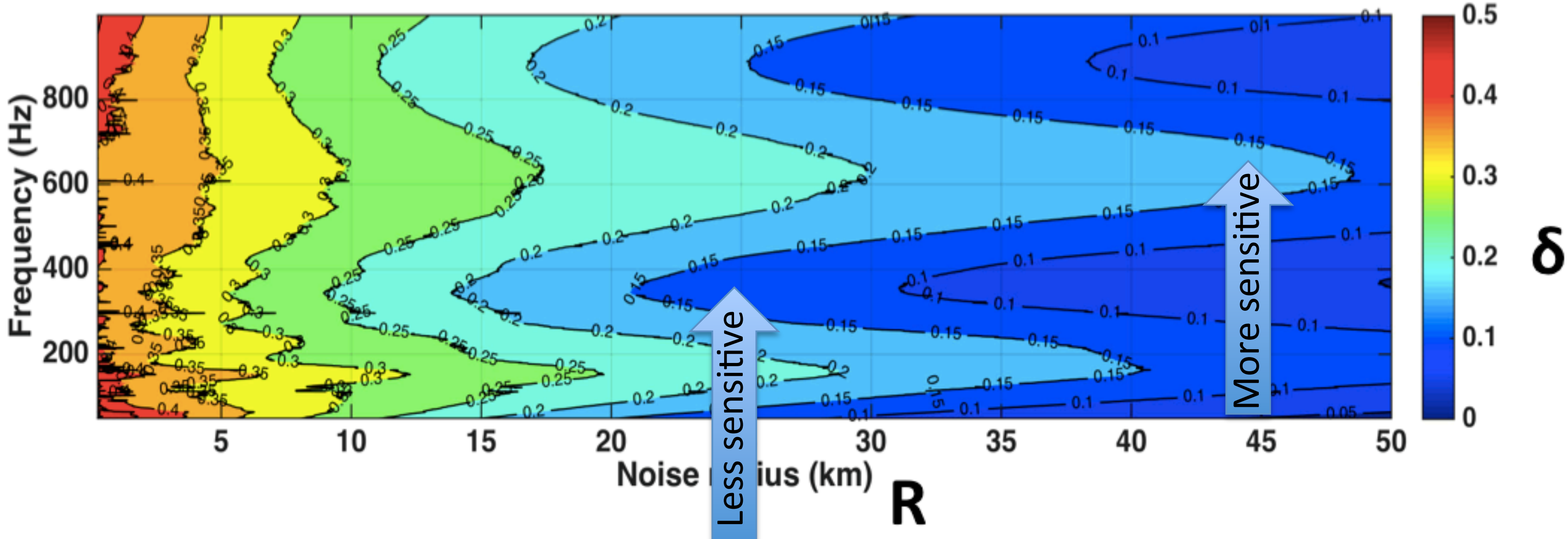
CONSTANT DENSITY

Dependent on frequency (has the P terms)

MODEL PREDICTS SPECIFIC VALUES OF SENSITIVITY WITHOUT REQUIRING BEHAVIORAL ASSUMPTIONS
If we can measure δ, we can gain insight into whether CD or CA is more realistic

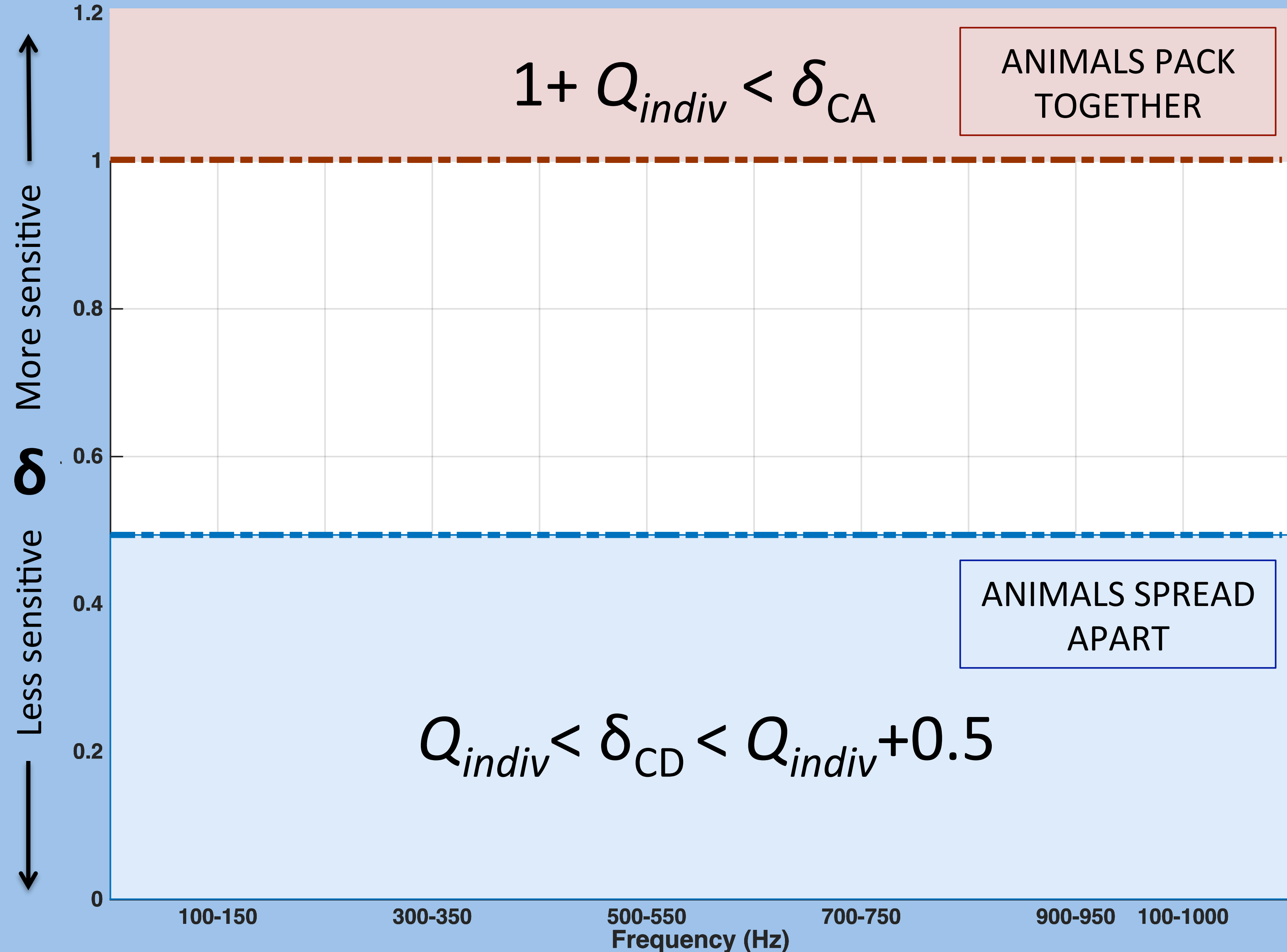
δ IS FREQUENCY DEPENDENT IN A CONSTANT DENSITY SCENARIO REPRESENTATIVE OF LOS CABOS, MEXICO

Expect different sensitivity values for different small bandwidths

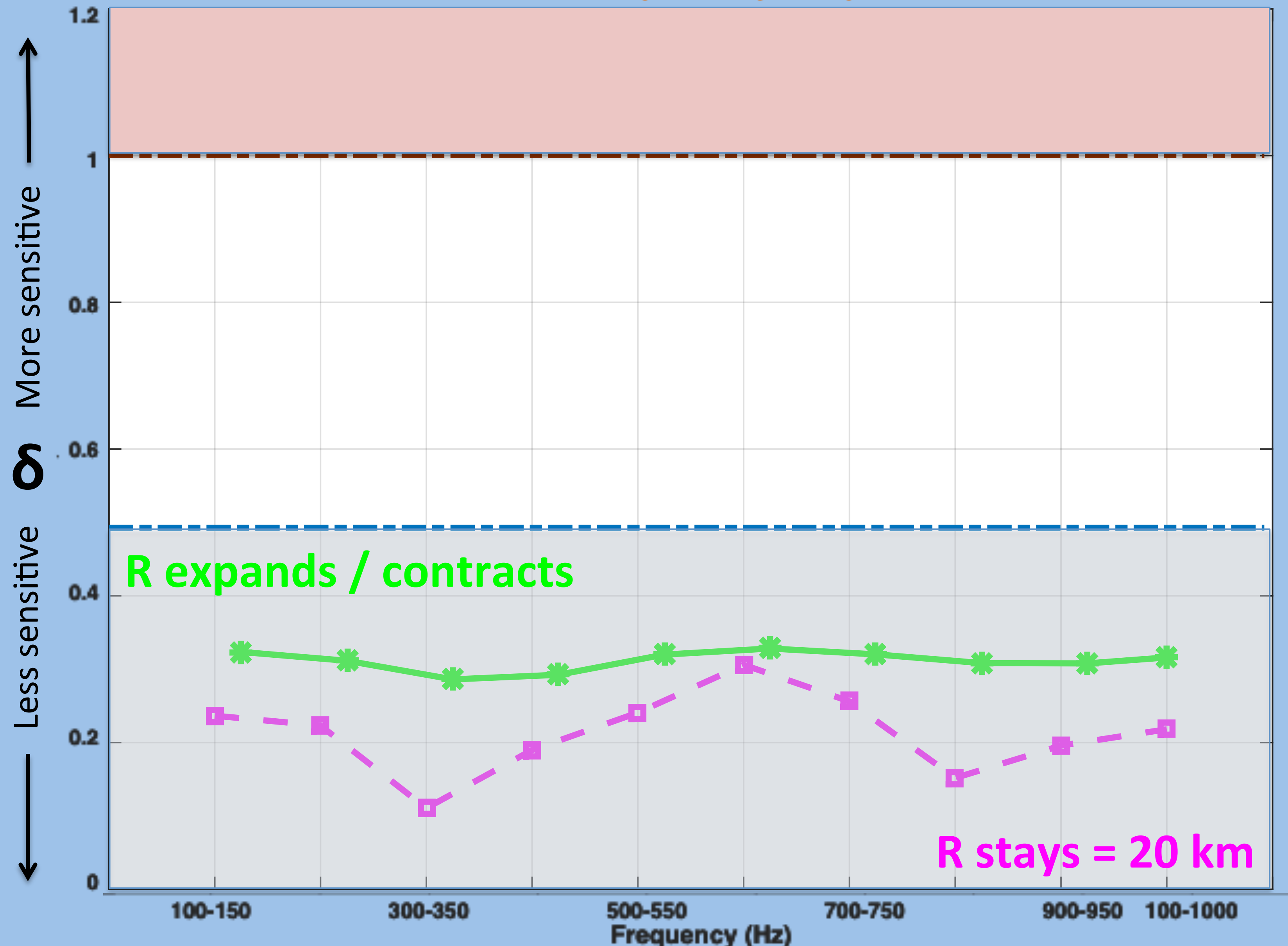


90 m waveguide
80 m receiver
1500 m/s isovelocity profile
Granite overlaid by 25 m sand
Flat bathymetry*

MEASURING SENSITIVITY VS FREQUENCY WILL REVEAL HOW WHALES SPACE THEMSELVES



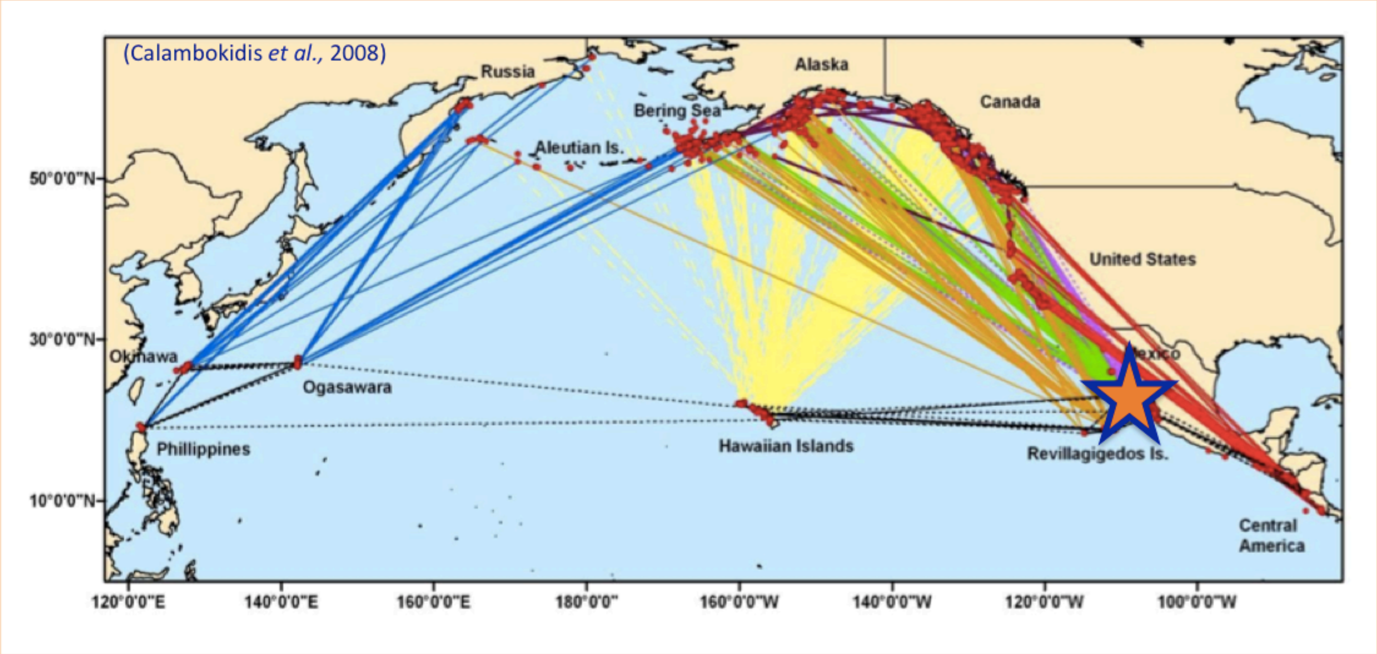
THEORY – Expanding / Contracting Effective Radius Over a Season Smooths out Frequency Dependence



METHODS – TESTING THE MODEL

1. **Choose appropriate location**

North Pacific humpback whales feed at high latitudes and breed off Mexico and Hawai'i.



<u>Our focus</u> → Los Cabos (from SE Alaska and the Aleutians)

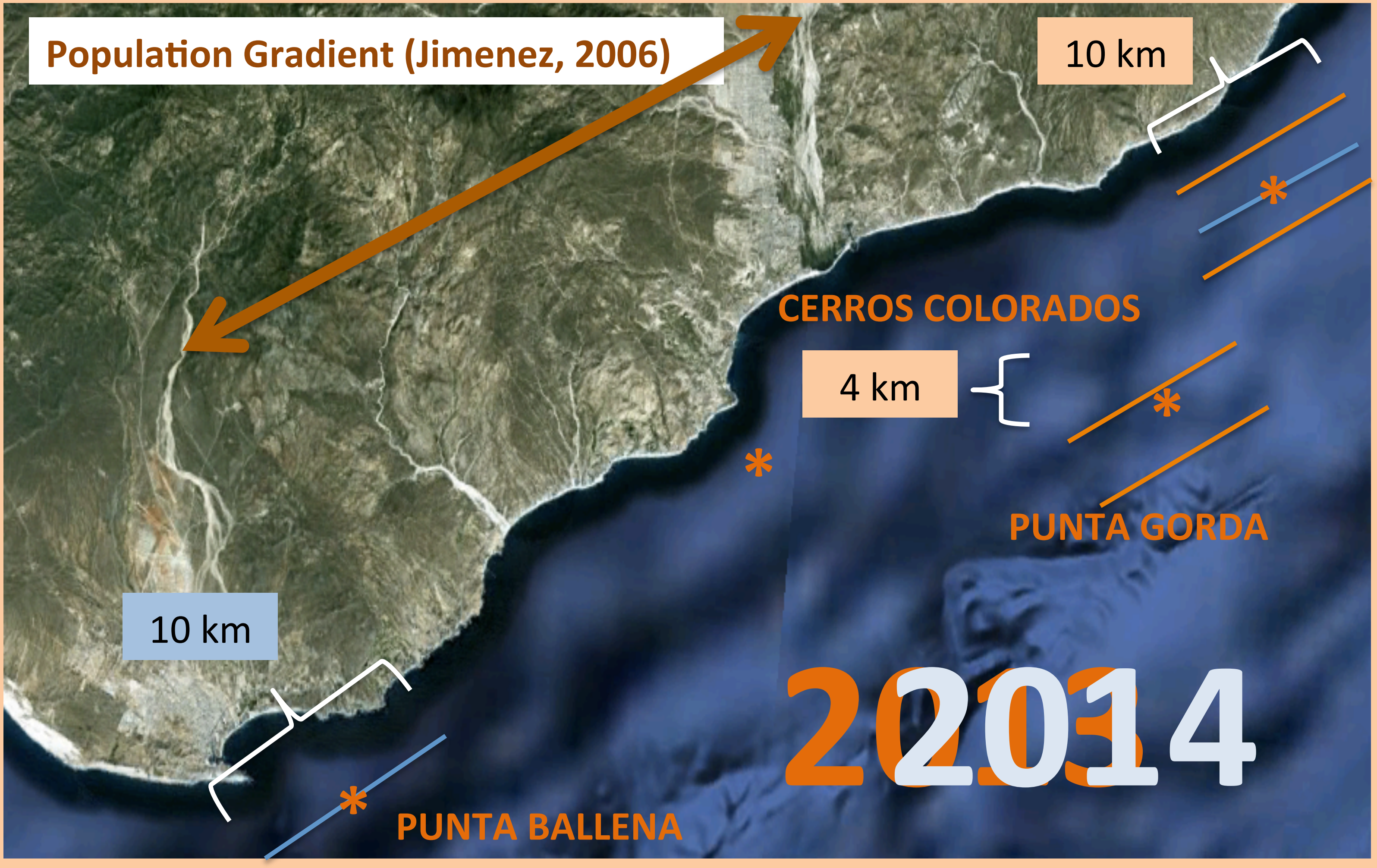
METHODS – TESTING THE MODEL

1. Choose appropriate location
2. **Deploy acoustic recorders**

- 6.25 kHz sampling rate
- HTI-96-MIN (High Tech Inc.)
  - -171 dB re 1 V/µPa sensitivity
- 2013 & 2014 Feb – Mar
- Depths: ~100m
  - Each season, instruments deployed at common depth
  - Common propagation environment
- Duty Cycle: 30 min/hr (2013)
  - Continuous (2014)

METHODS – TESTING THE MODEL

1. Choose appropriate location
2. Deploy acoustic recorders
3. **Conduct visual surveys**



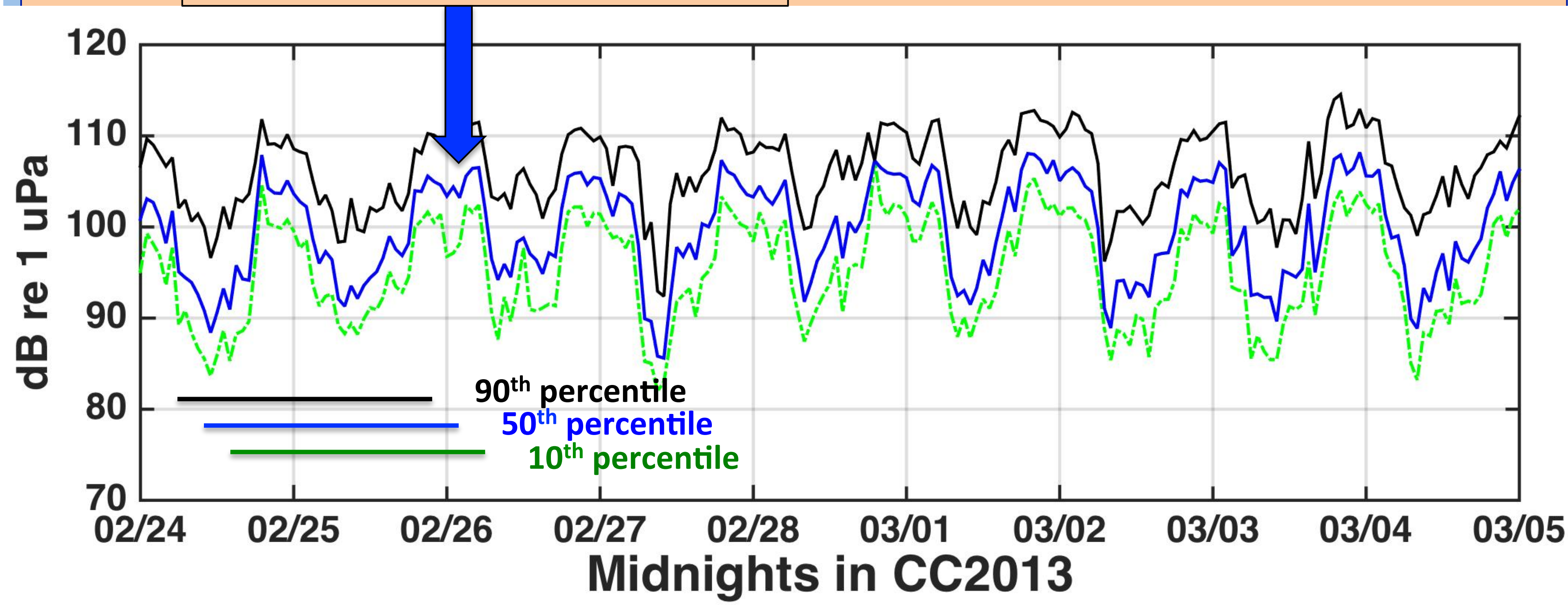
ACOUSTIC RESULTS

A diel cycle in singing behavior exists

(Using the 50th percentile of hourly intensity distributions)

And dominates the ambient environment between 100-1000 Hz

Recall 105 dB re 1 µPa prediction



HOW TO MEASURE SENSITIVITY EMPIRICALLY?

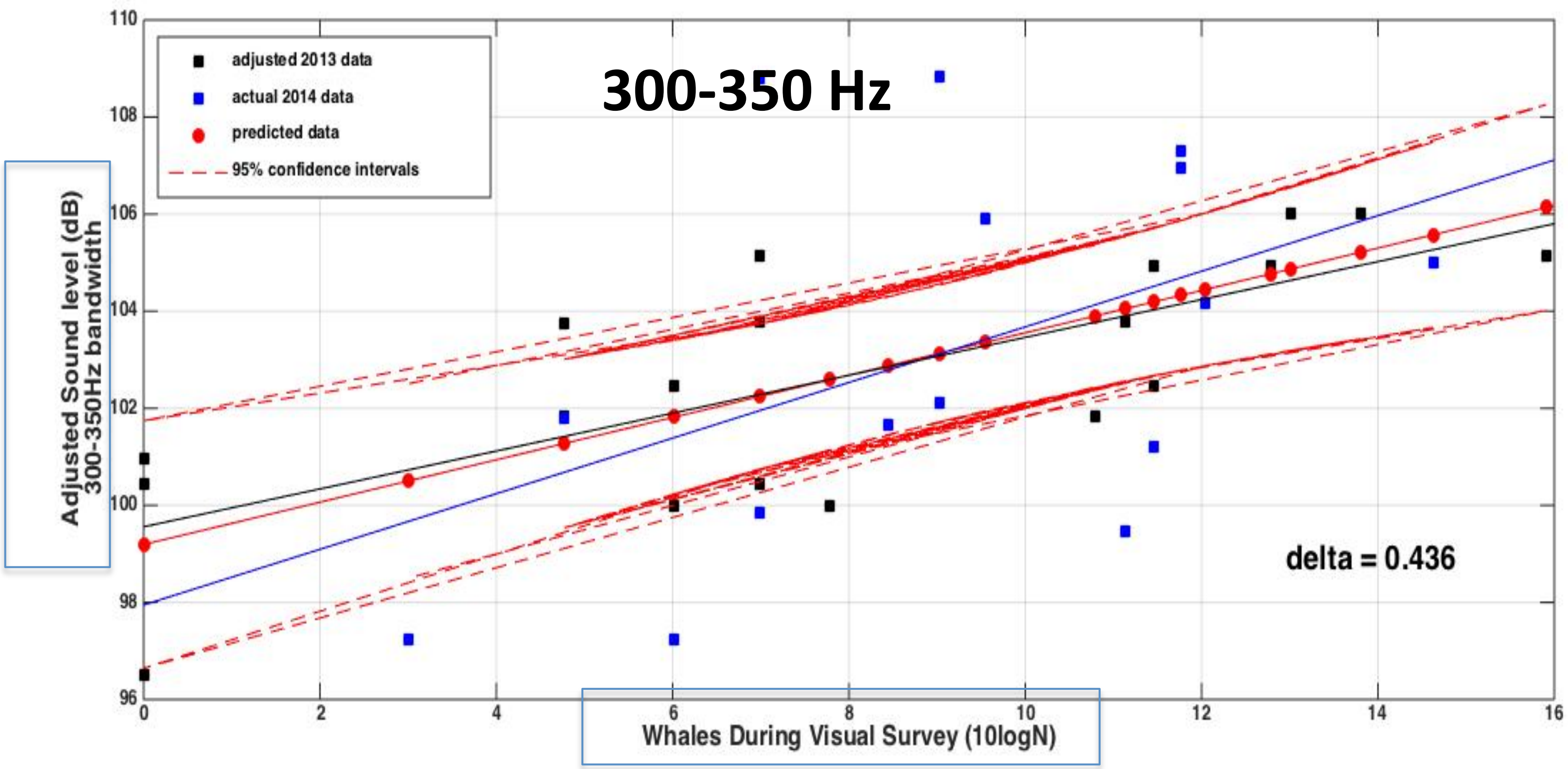
METHODS – DEVELOPING THE GLM

$$\mathrm{I}(dB) = 10\log\beta + \delta(10\log N) + \gamma[Year]$$

- I = average of nightly peaks (dB re 1 uPa)
- N = "all" whales
- Year → categorical to account for methodological differences
- δ = power law coefficient
    - **To compare to KIP model**
    - **Should be equal to theoretical sensitivity**

METHODS – Empirical delta values

$$\mathrm{I}(dB) = 10\log\beta + \delta(10\log N) + \gamma[Year]$$

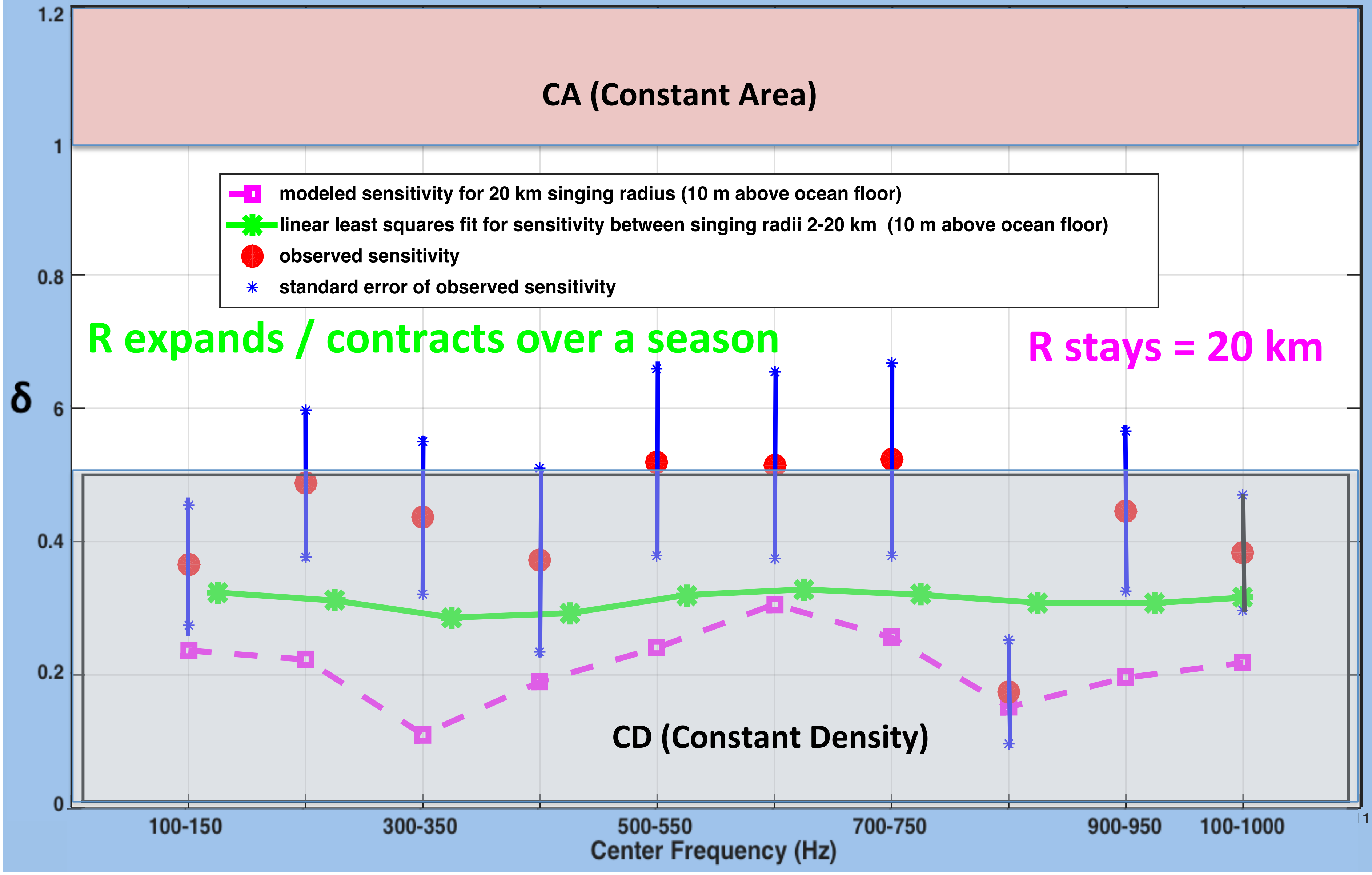


Red → GLM fit & CIs; Blue / black → empirical data

SENSITIVITY = 0.436

Ran GLM over full (100-1000 Hz) and 9 (50-Hz wide) bandwidths

Measured sensitivity is frequency dependent and less than 0.5 →CD

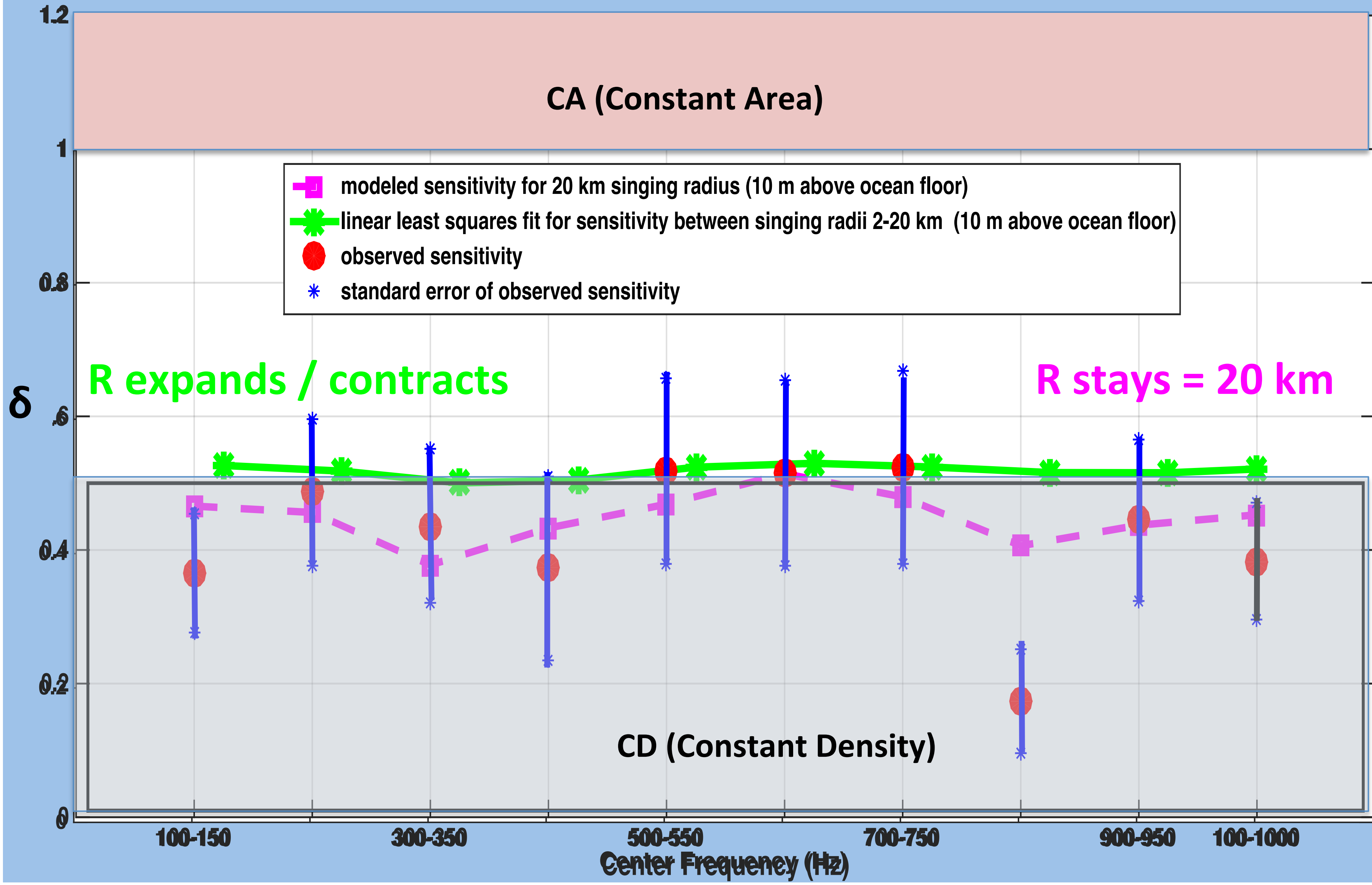


ANALYSIS – WHY IS δ A LITTLE LARGER THAN CD SCENARIO?

Or an intermediate of the two?

1. Animals pack a *little* tighter when the population grows
   - If v=0.7 instead of 1 → spacing decreases ~20% if population doubles

ANALYSIS: ν = X 0.7



ANALYSIS – WHY IS δ A LITTLE LARGER THAN CD SCENARIO?

Or an intermediate of the two?

1. Animals pack a *little* tighter when the population grows
   - If v = 0.7 instead of 1 → spacing decreases ~20% if population doubles

2. Alter (Q_{indiv})
   - Increase source level when other animals are present
   - "speed up" the "tempo" between units, or use units with smaller inter-unit intervals.

3. Bathymetry is not flat; area is not a perfect circle.

4. The male/female mixture may change when more females are present (Nishiwaki, 1959; Tyack, 1981; Baker & Herman, 1984; Au *et al.*, 2000; Darling & Bérubé, 2001).

CONCLUSIONS

- **KIP model predicts:**
  - **Ambient noise levels can be used to estimate N whales & spatial density**
    - **Many combinations give same result**
  - **Need concurrent visual survey and acoustic data to infer the most realistic packing model**

- **GLM tests the KIP model**
  - **Empirical data suggests a constant density scenario**
  - **The more likely CD scenario agrees with earlier research**
    - Winn & Winn, 1978; Tyack, 1981; Frankel *et al.,* 1995

- **Technique can be applied elsewhere and for other species**
  - **Do blue and fin whales follow a constant density scenario when calling? (See Dave's talk at 11:40)**

Thank You!

Juan Carlos Salinas-Vargas

Hiram Rosalez-Nanduca

Carlos Lopez-Montalvo

Robert Glatts

Lorena Viloria

Jit Sarkar

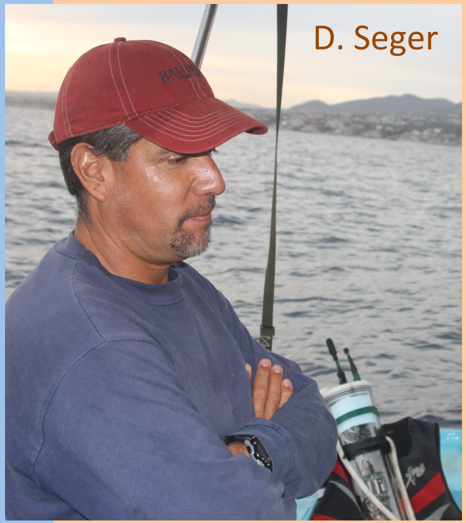
Melania Guerra

Ludovic Tenorio-Halle

Romina Carnero-Huaman

Cedric Arissdakessian

The Los Zacatitos Community



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The Wyer Family

UABCS

IGERT Integrative Graduate Education and Research Traineeship

Questions?

E. Jimenez

If animals are CD, then why didn't we get the same N for every survey?

- Singing is mainly at night, but surveys are during the day (during other behavioral states)
- Behavioral states are not static, and different vocalization states have different densities (packing models / values of *v*)
- Different demographics (sex ratios) have different density patterns
  - Non-singers may have different values of *v*
- *There are not just singers in the survey area: the survey assumes singers are a relative proportion of the overall population*

Three Visual Metrics (for N)

WHALES:

ALL whales counted

Year	Punta B	Punta G	Cerros C
2013	-	51	142
2014	50	-	97

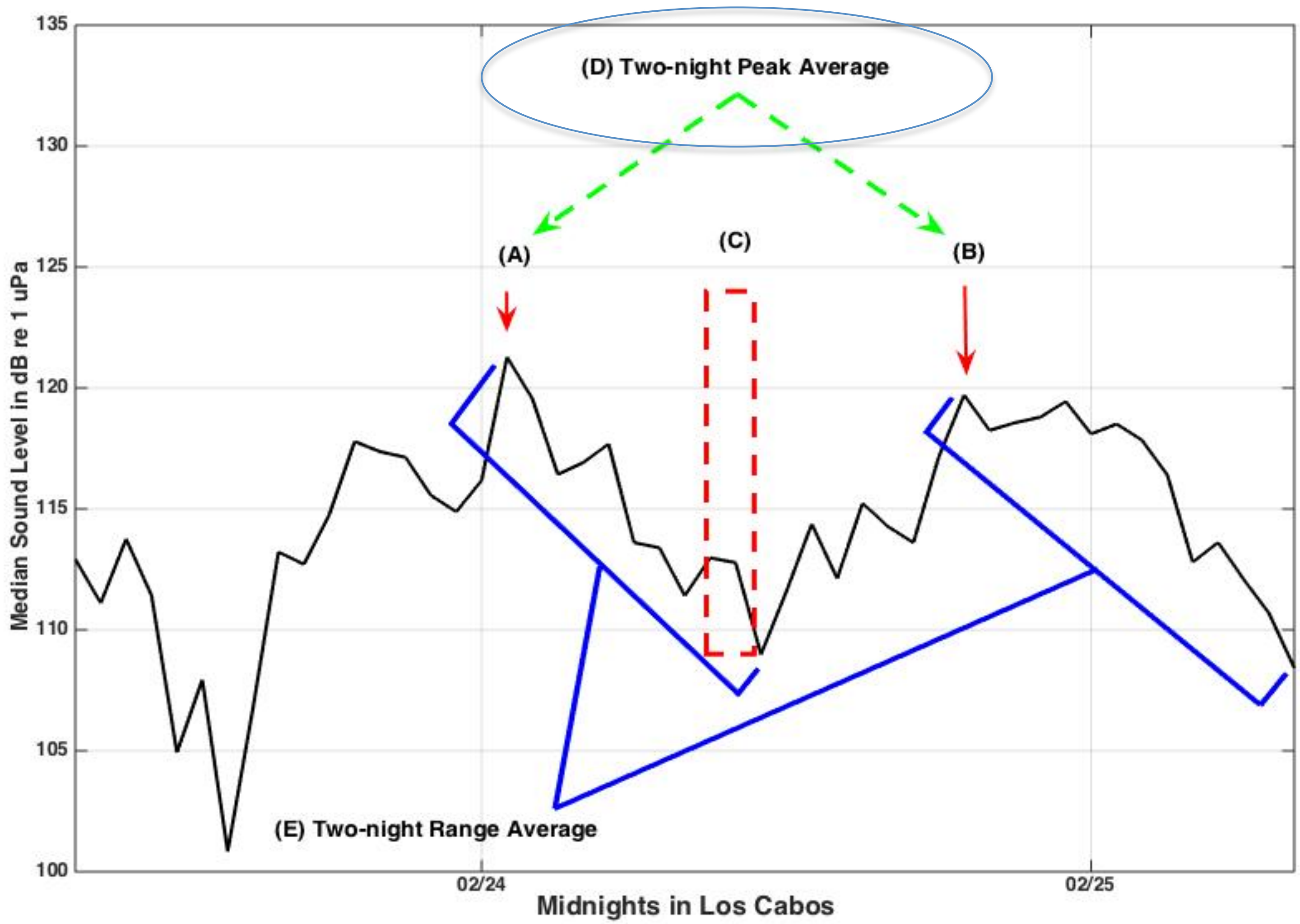
ONLY males (mother/calf pairs excluded)

Year	Punta B	Punta G	Cerros C
2013	-	47	136
2014	46	-	85

ONLY solos

Year	Punta B	Punta G	Cerros C
2013	-	22	58
2014	26	-	34

NOISE METRIC NEEDS TO REMOVE DIEL CYCLE



Thoughts from Tyler's talk

- "Singing jumps" might affect our model
  - But the acoustic metric is averaged over an hour
  - Even if singer stops singing, "jumps", and starts singing relatively quickly, the noise level change back and forth would not "count" the singer twice
- Singing shown at 100m depth
  - Our model is rather robust to whale depth → 10m and 20m singing depths showed negligible variance in δ
  - Depth of the hydrophone above the seabed had a greater effect on δ