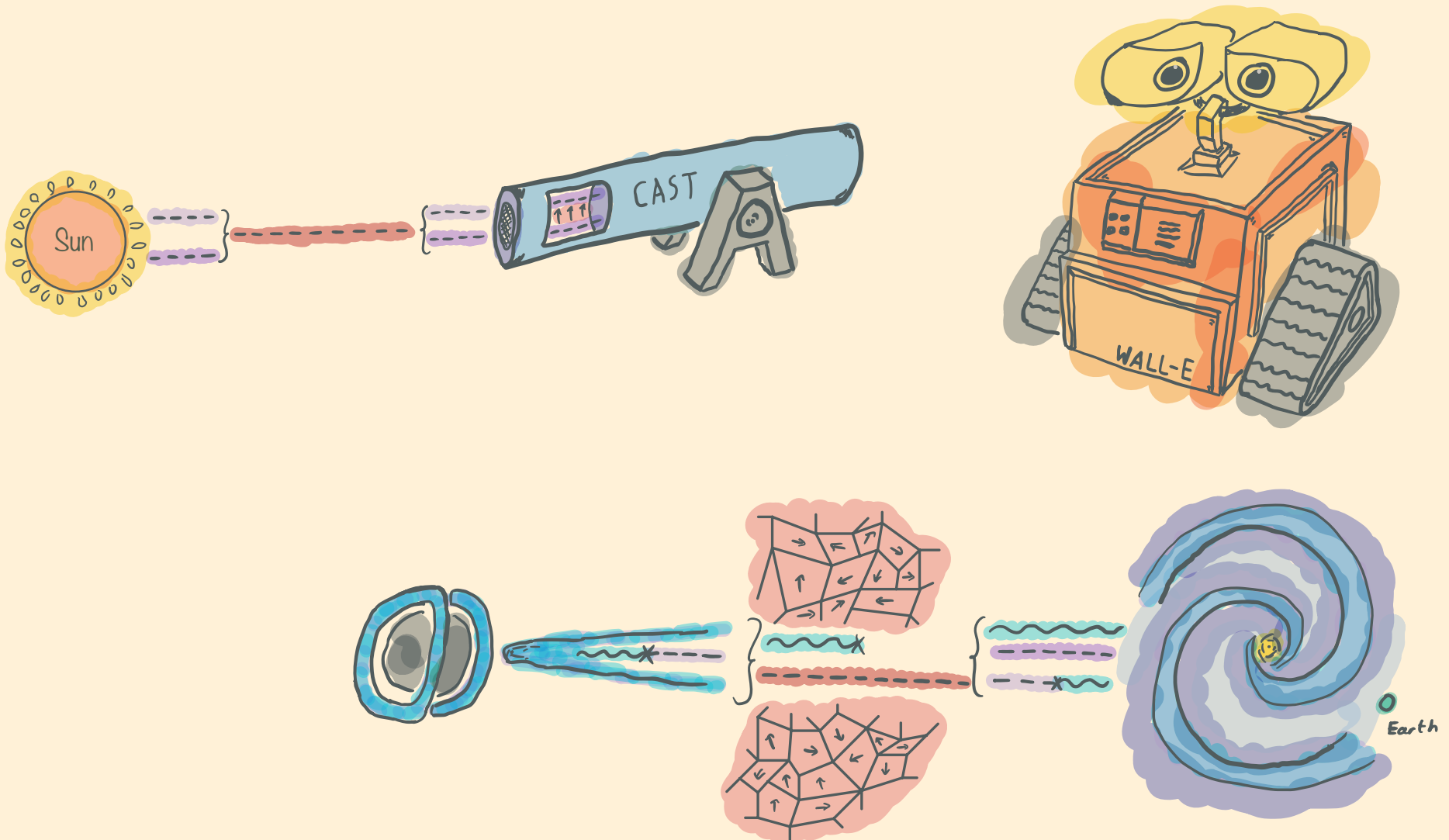


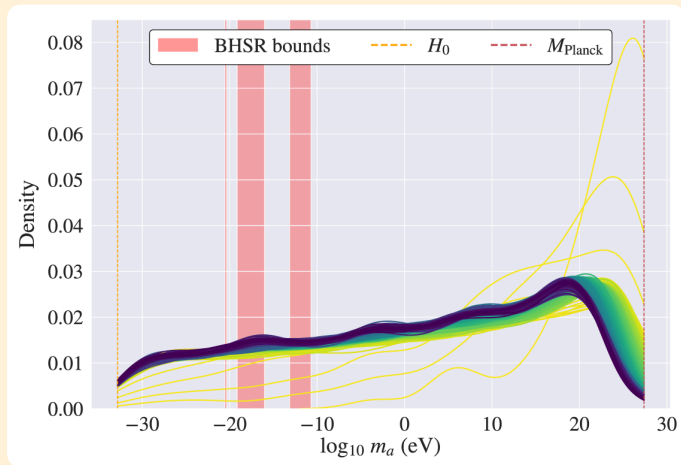
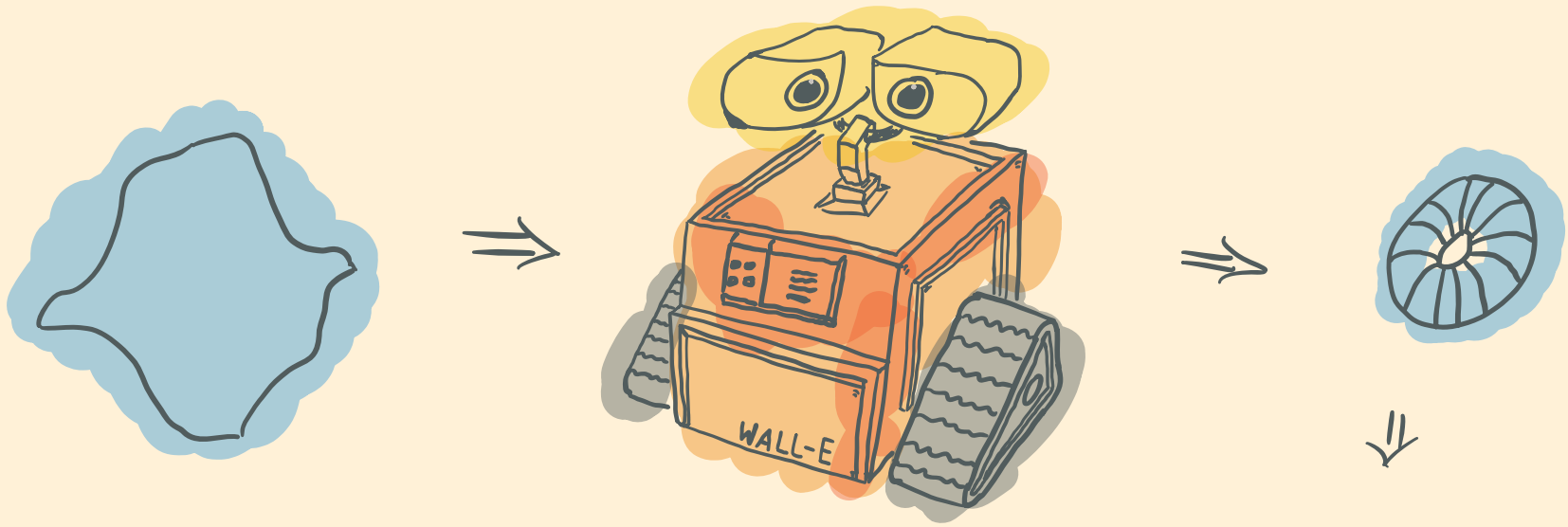
# Astrophysical Searches for the String Axiverse



## Collaborators

Jessica Turner  
Francesca Chadha-Day

# Motivating Many Axions



Up to several hundred axions:

A purple cloud-like shape containing a collection of symbols representing axions. The symbols are arranged in a roughly circular pattern and include  $\phi_{12}$ ,  $\phi_{11}$ ,  $\phi_{10}$ ,  $\phi_1$ ,  $\phi_2$ ,  $\phi_4$ ,  $\phi_3$ ,  $\phi_5$ ,  $\phi_6$ ,  $\phi_{11}$ ,  $\phi_7$ ,  $\phi_8$ ,  $\phi_9$ , and several ellipses ( $\dots$ ) indicating a large number of axions.

# Couplings

EM Basis

$$\mathcal{L} \supset -\sum_i \frac{1}{2} \partial^\mu \phi^i \partial_\mu \phi^i - \sum_{i,j} \frac{1}{2} M_{ij}^\tau \phi^i \phi^j + \sum_i g_i^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi^i - g^\tau \phi^i \tilde{F}^{\mu\nu} F^{\mu\nu}$$

$\Uparrow$   $SO(N)$

Mass Basis

$$\mathcal{L} \supset \sum_{i=1}^N \left( -\frac{1}{2} \partial^\mu \phi^i \partial_\mu \phi^i - \frac{1}{2} m_i^2 (\phi^i)^2 - \overset{\text{EM}}{g_i^\tau \phi^i \tilde{F}^{\mu\nu} F_{\mu\nu}} + \overset{\text{Electronic}}{g_i^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi^i} \right)$$

$\Downarrow$   $SO(N)$

Electronic Basis

$$\mathcal{L} \supset -\sum_i \frac{1}{2} \partial^\mu \phi^i \partial_\mu \phi^i - \sum_{i,j} \frac{1}{2} M_{ij}^e \phi^i \phi^j - \sum_i g_i^\tau \phi^i \tilde{F}^{\mu\nu} F_{\mu\nu} + g^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi^i$$

# Couplings

EM Basis

$$\mathcal{L} \supset -\sum_i \frac{1}{2} \partial^\mu \phi^i \partial_\mu \phi^i - \sum_{i,j} \frac{1}{2} M_{ij}^\tau \phi^i \phi^j + \sum_i g_i^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi^i - g^\tau \phi^i \tilde{F}^{\mu\nu} F^{\mu\nu}$$

$\Uparrow$   $SO(N)$

Mass Basis

$$\mathcal{L} \supset \sum_{i=1}^N \left( -\frac{1}{2} \partial^\mu \phi^i \partial_\mu \phi^i - \frac{1}{2} m_i^2 (\phi^i)^2 - \overset{\text{EM}}{g_i^\tau \phi^i \tilde{F}^{\mu\nu} F_{\mu\nu}} + \overset{\text{Electronic}}{g_i^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi^i} \right)$$

$\Downarrow$   $SO(N)$

Electronic Basis

$$\mathcal{L} \supset -\sum_i \frac{1}{2} \partial^\mu \phi^i \partial_\mu \phi^i - \sum_{i,j} \frac{1}{2} M_{ij}^e \phi^i \phi^j - \sum_i g_i^\tau \phi^i \tilde{F}^{\mu\nu} F_{\mu\nu} + g^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi^i$$

# Couplings

Electromagnetic

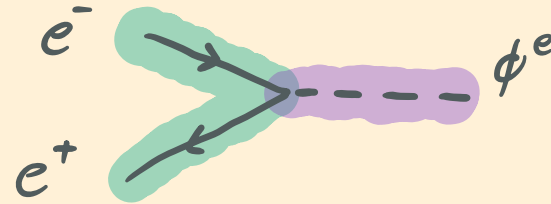
$$g^r \phi^r \tilde{F}^{\mu\nu} F_{\mu\nu}$$



$$\phi^r \neq \phi^e$$

Electronic

$$g^e \bar{\Psi} \gamma^\mu \gamma_5 \Psi \partial_\mu \phi^e$$



Mass Basis

$$\frac{1}{2} m_i^2 (\phi^i)^2$$



# Couplings

Electromagnetic

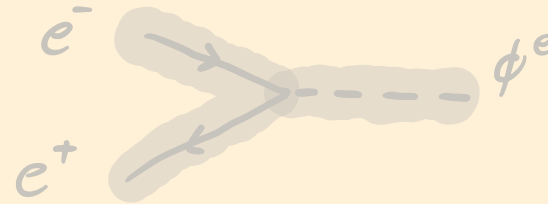
$$g^r \phi^r \tilde{F}^{\mu\nu} F_{\mu\nu}$$



$$\phi^r \neq \phi^e$$

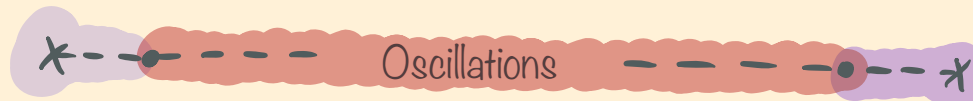
Electronic

$$g^e \bar{\Psi} \gamma^\mu \gamma_5 \Psi \partial_\mu \phi^e$$

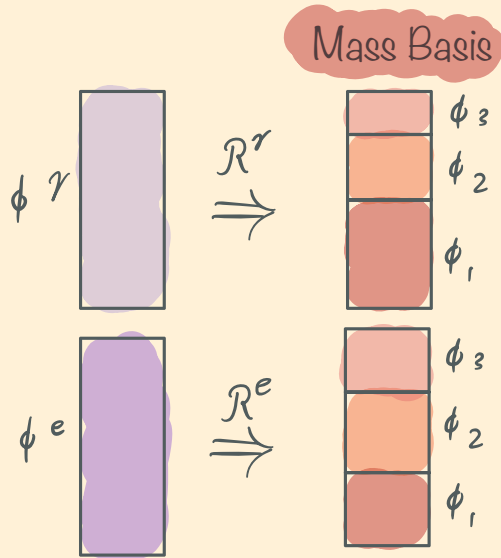


Mass Basis

$$\frac{1}{2} m_i^2 (\phi^i)^2$$



# Rotations and Anarchy

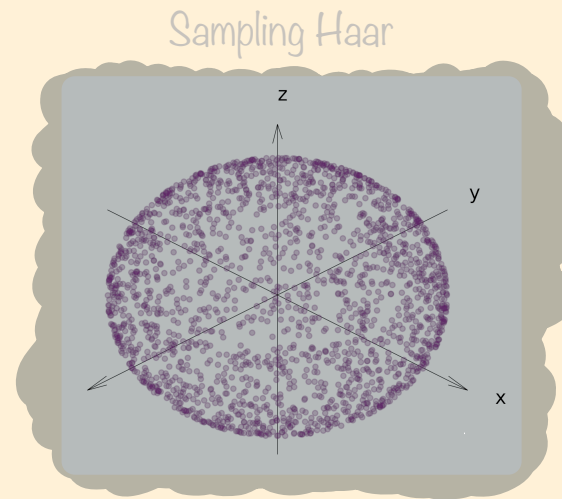
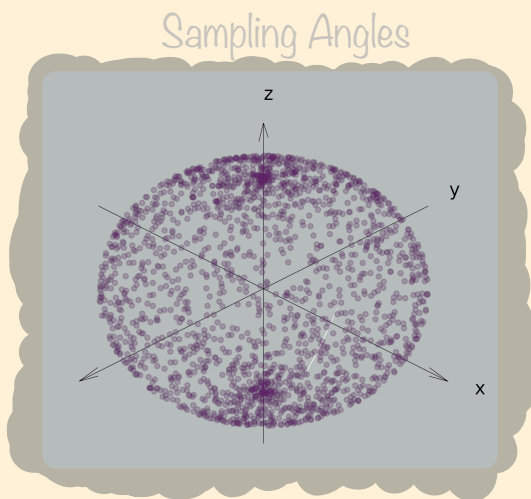


Uniform Sample

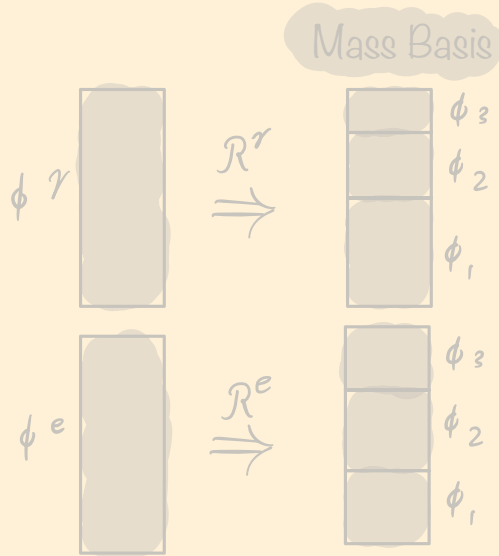
$$\{\mathcal{R}^r\}, \{\mathcal{R}^e\} = U(SO(N))$$

Haar Measure

$$dV = \left( \prod_{1 \leq i < j \leq N-1} \sin^{i-1}(\theta_{ij}) \right) d\theta_{1,1} \dots d\theta_{N-1, N-1}$$



# Rotations and Anarchy



Uniform Sample

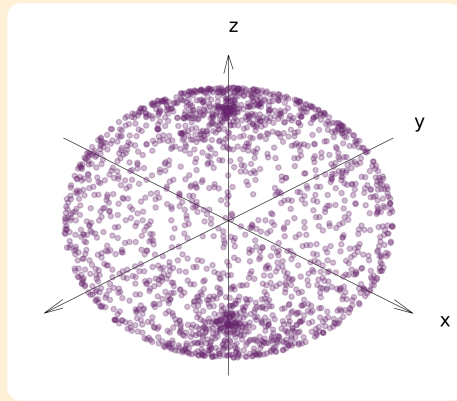
$$\{\mathcal{R}^r\}, \{\mathcal{R}^e\} = U(SO(N))$$

⇓

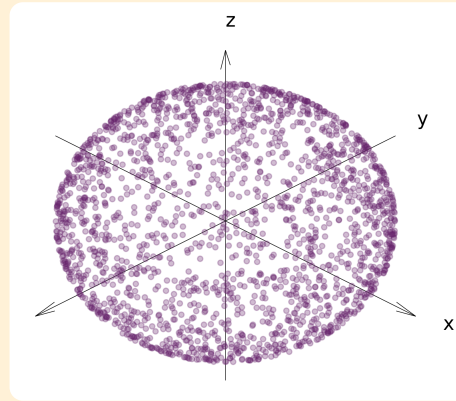
Haar Measure

$$dV = \left( \prod_{1 \leq i < j \leq N-1} \sin^{i-1}(\theta_{ij}) \right) d\theta_{1,1} \dots d\theta_{N-1, N-1}$$

Sampling Angles



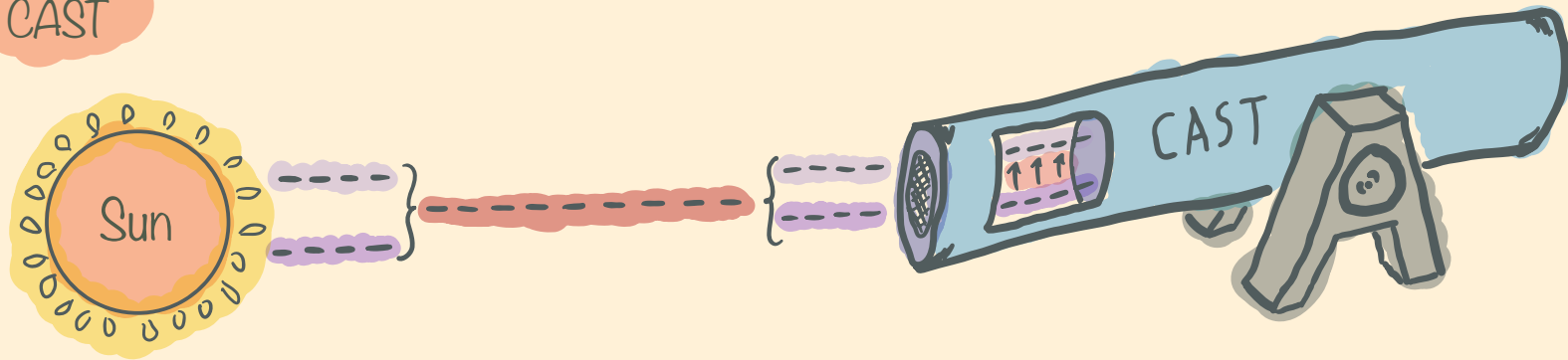
Sampling Haar





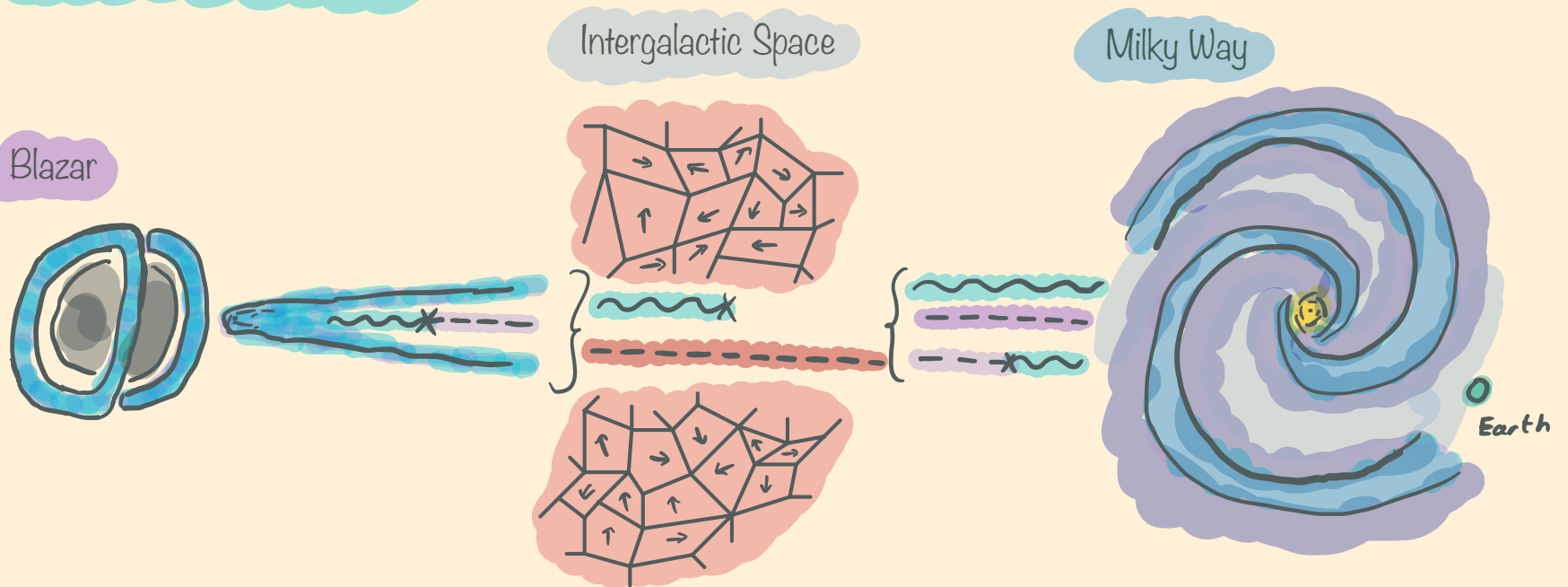
# Astrophysical Searches

CAST



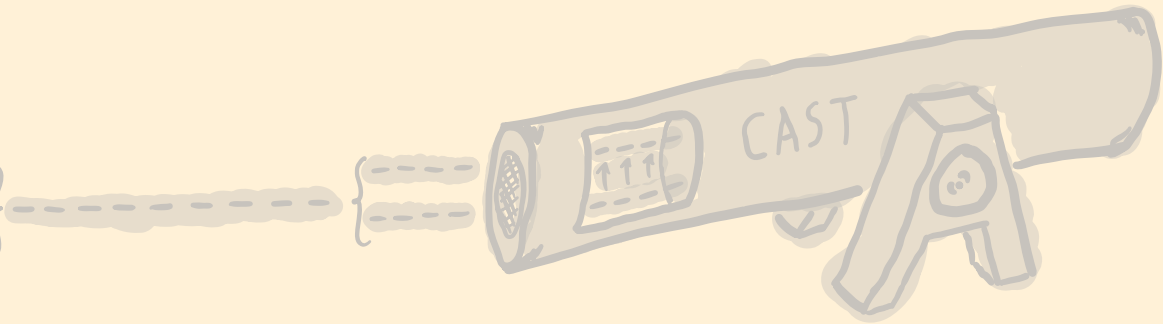
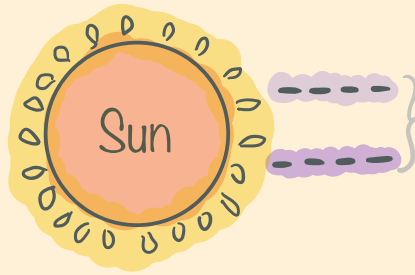
Anomalous Transparency

Blazar

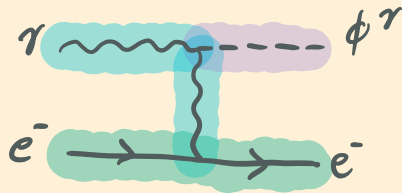


# CAST

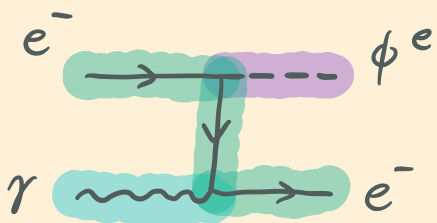
## Production



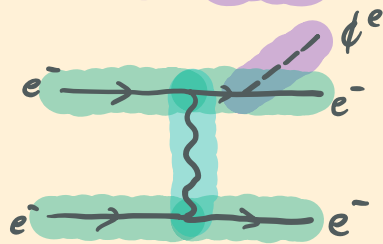
## Primakoff



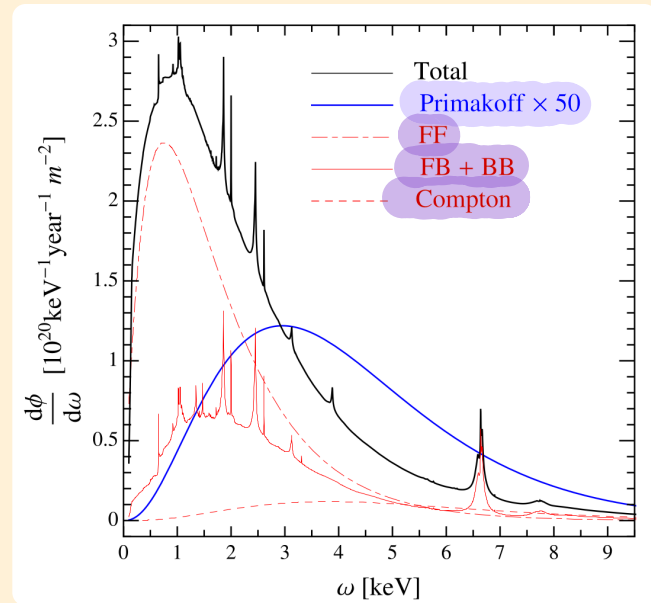
## Compton Scattering



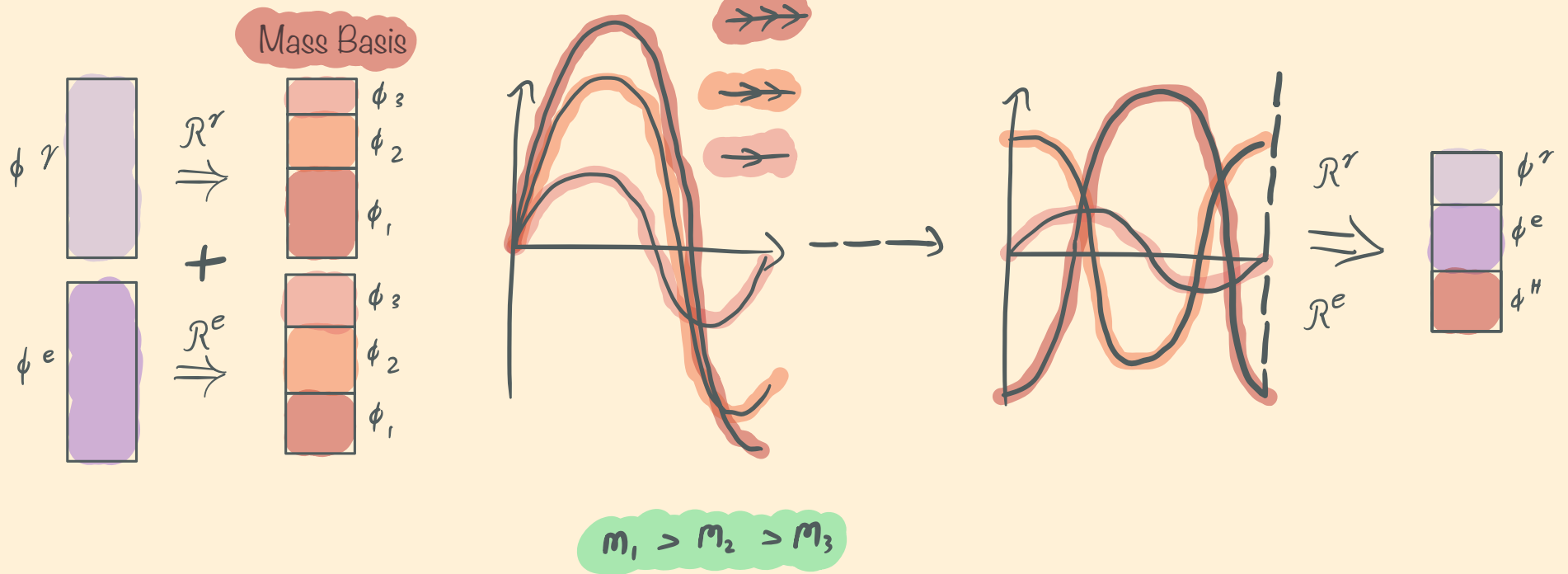
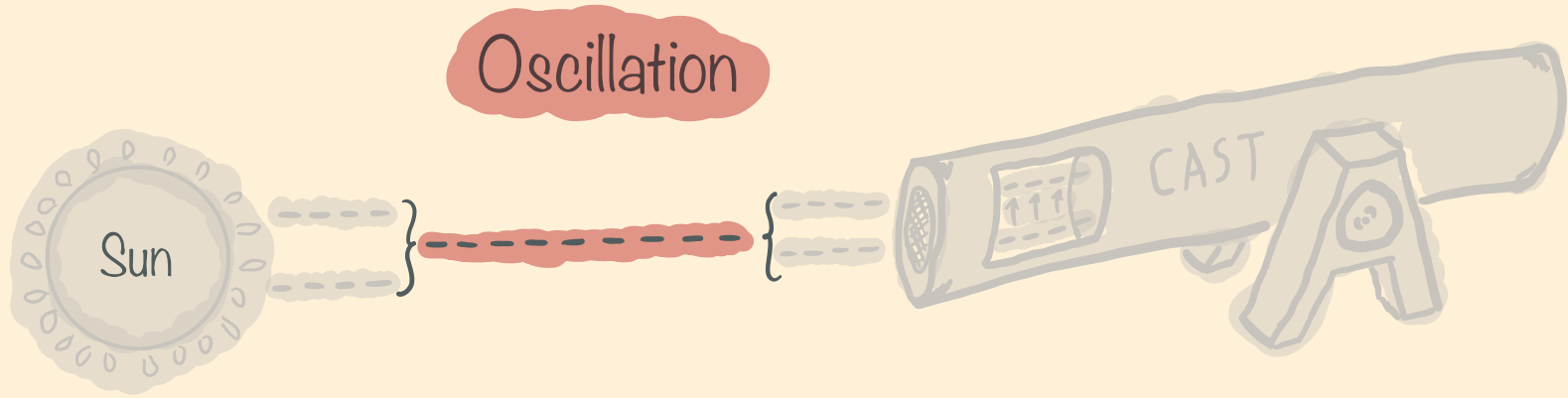
## Bremsstrahlung



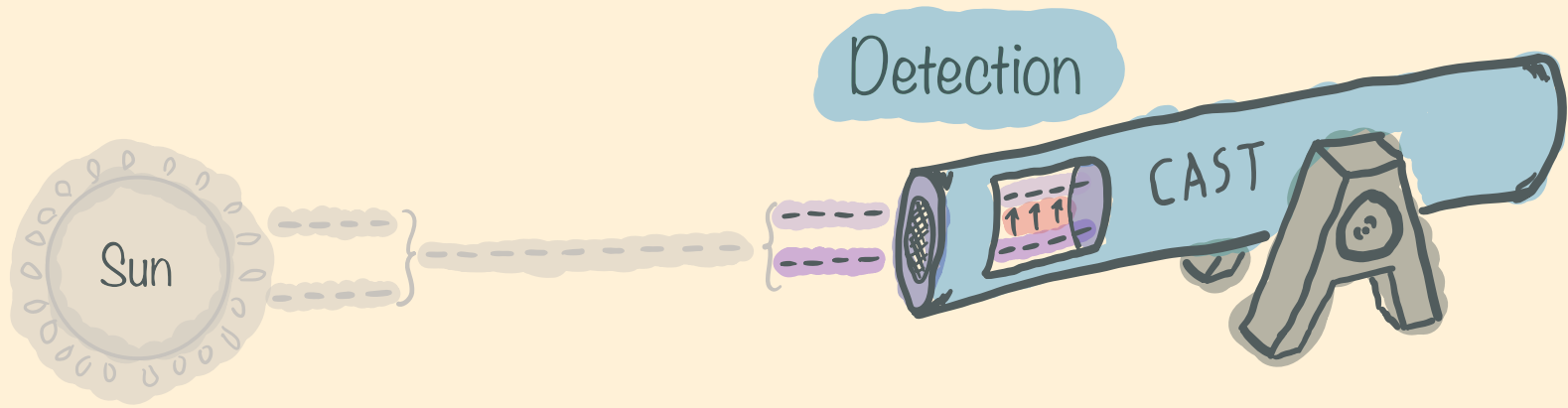
## Characteristic Flux



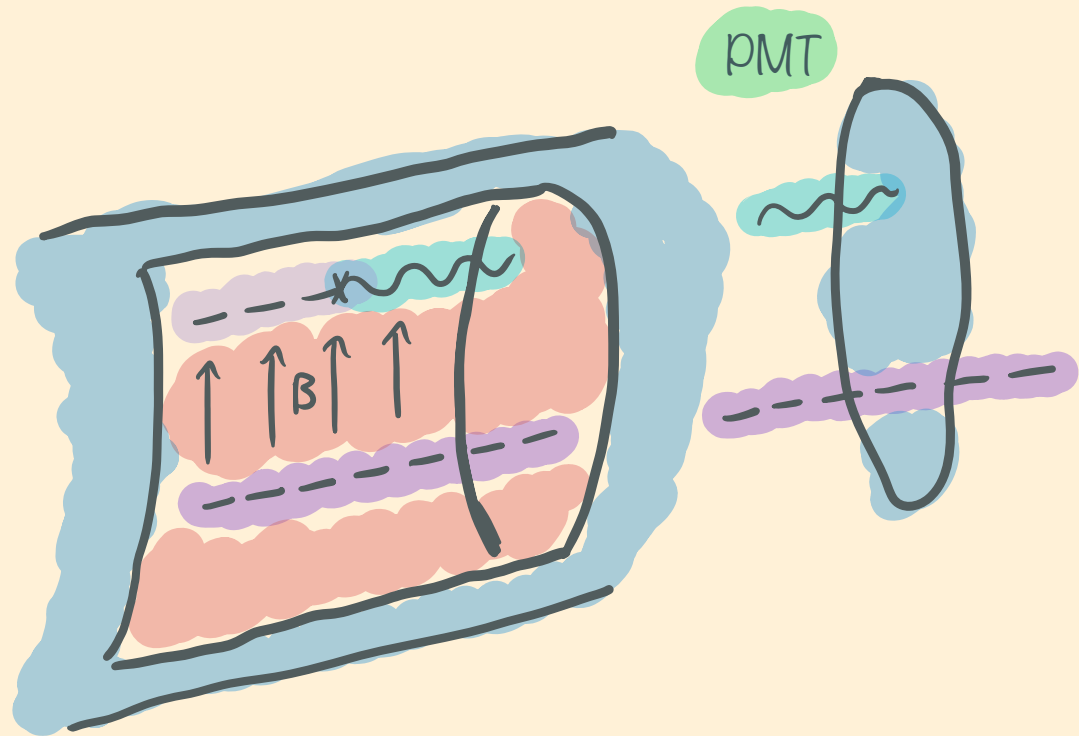
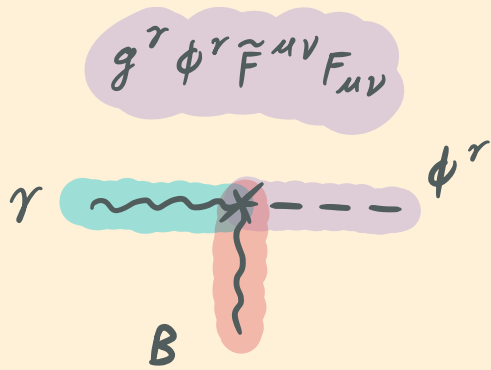
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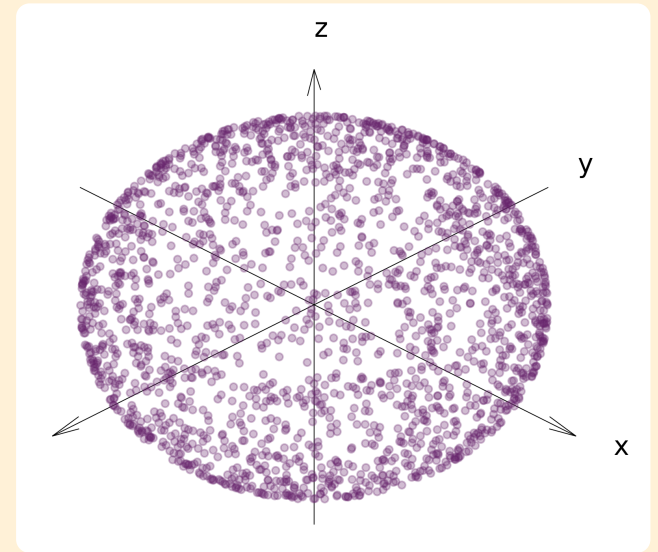
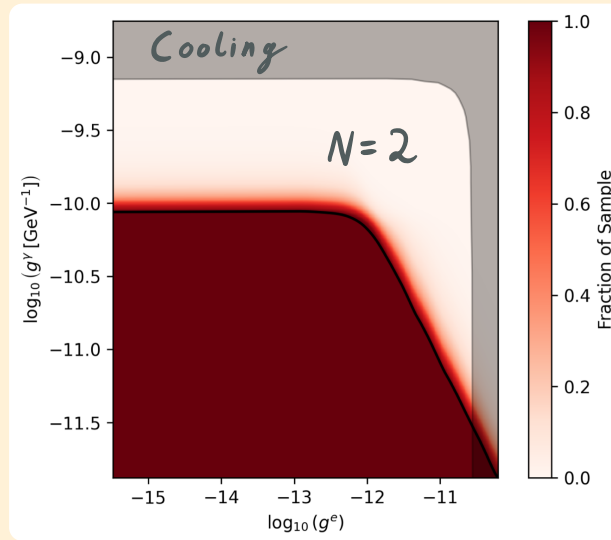
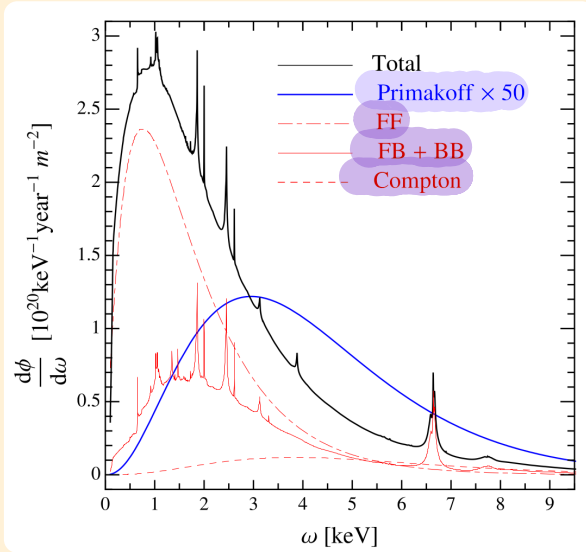
# CAST



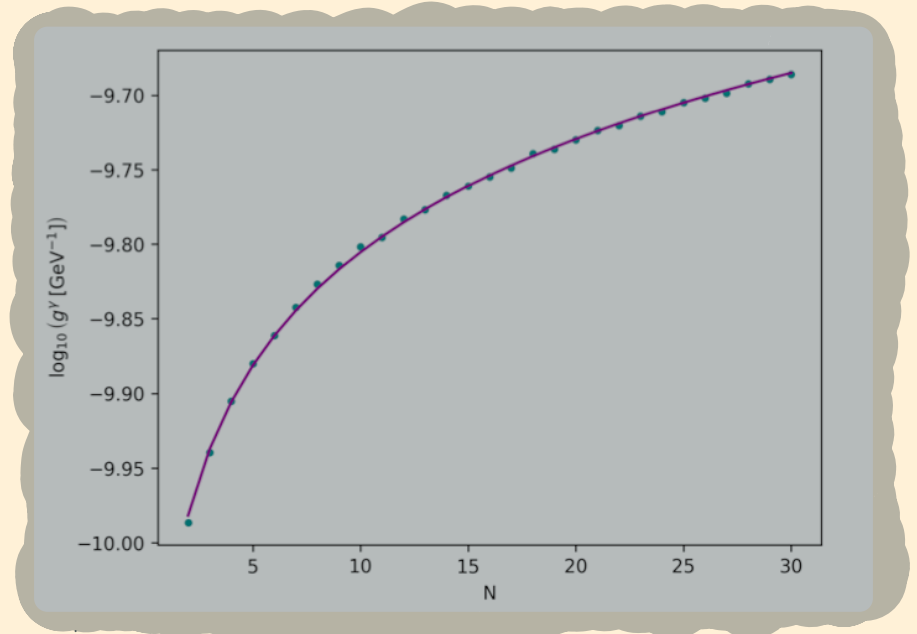
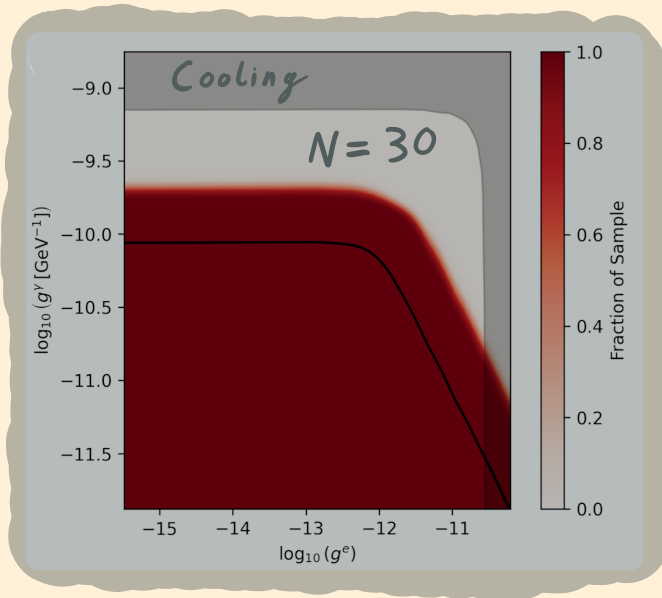
Magnetic Field



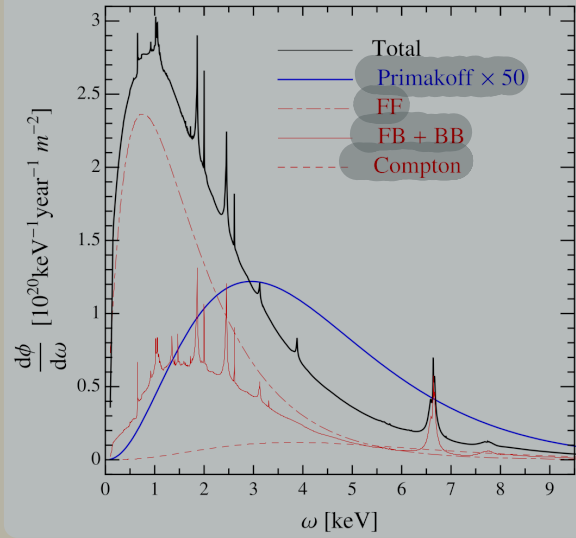
# CAST Results



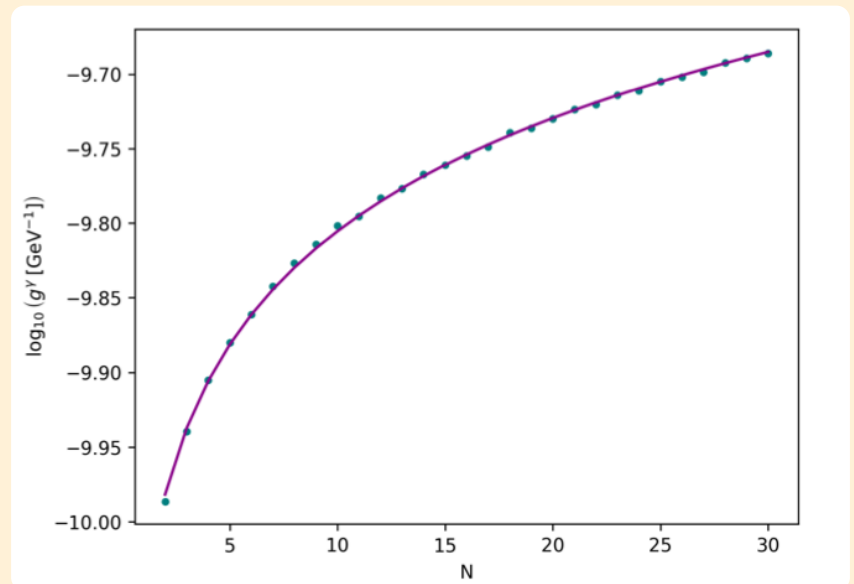
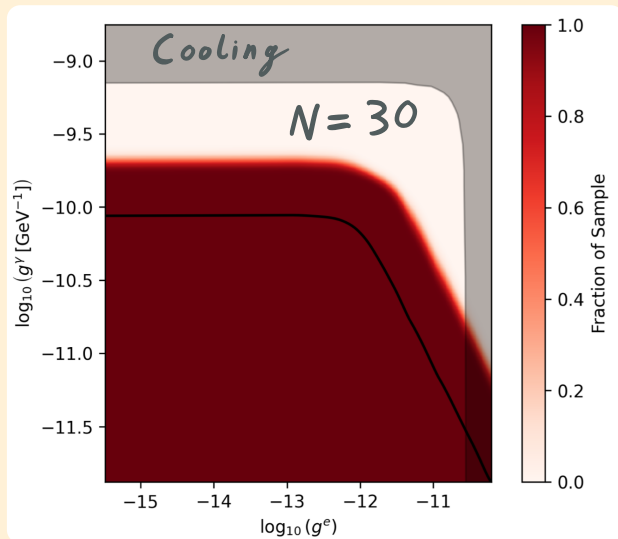
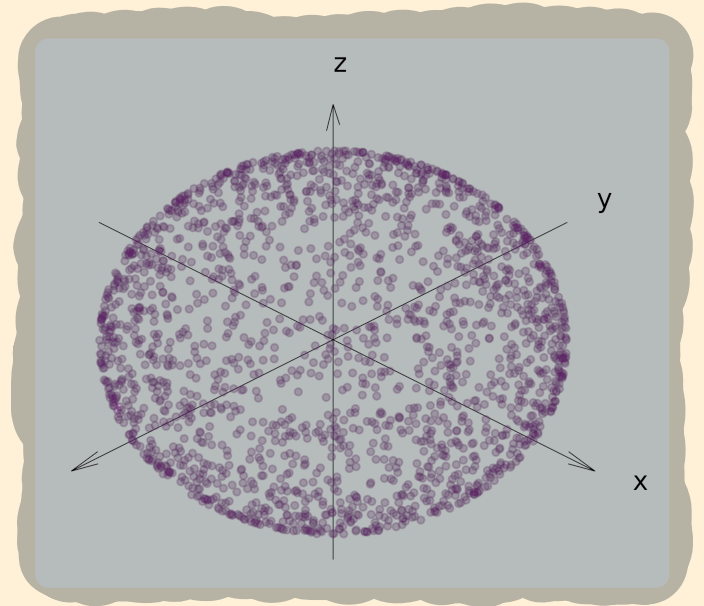
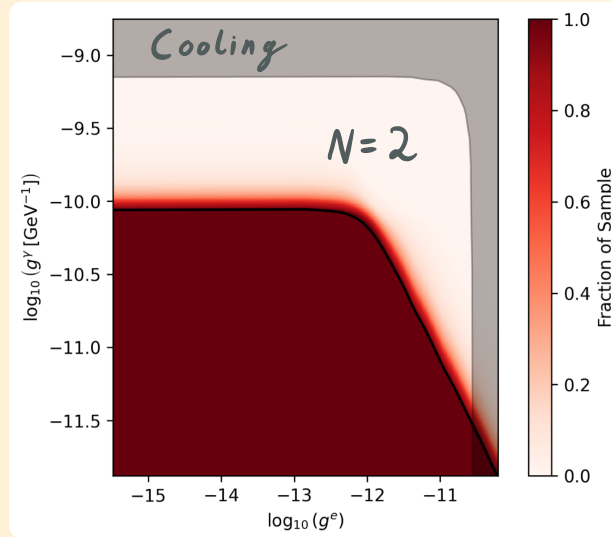
arXiv: 1302.6283



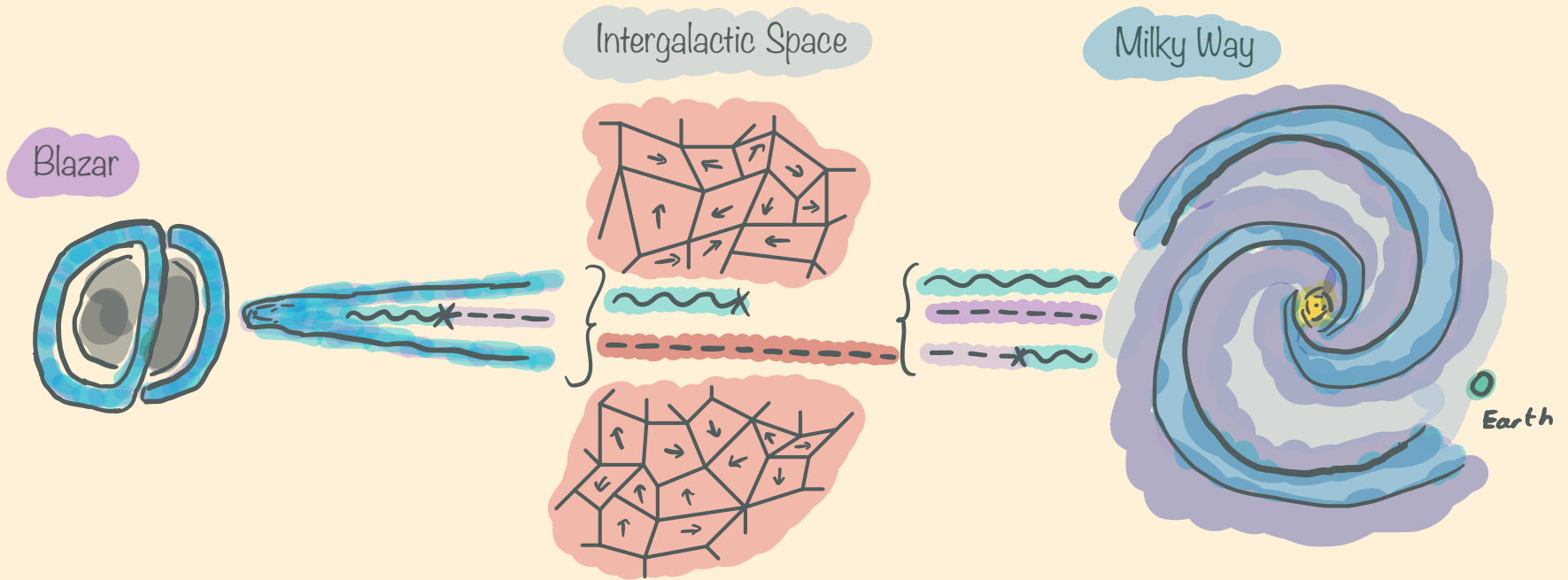
# CAST Results



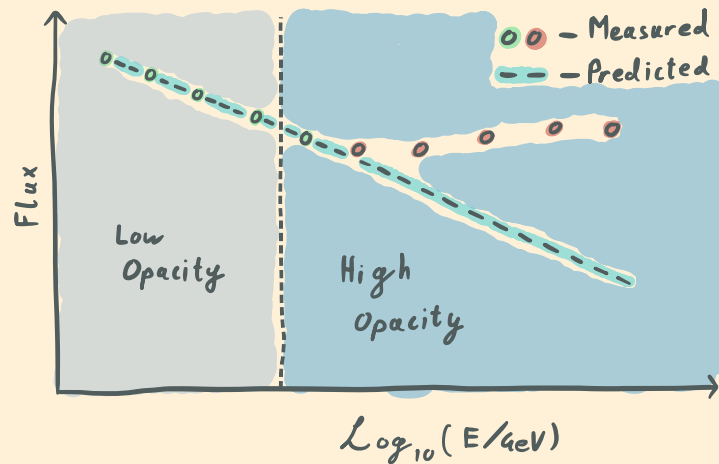
arXiv: 1302.6283



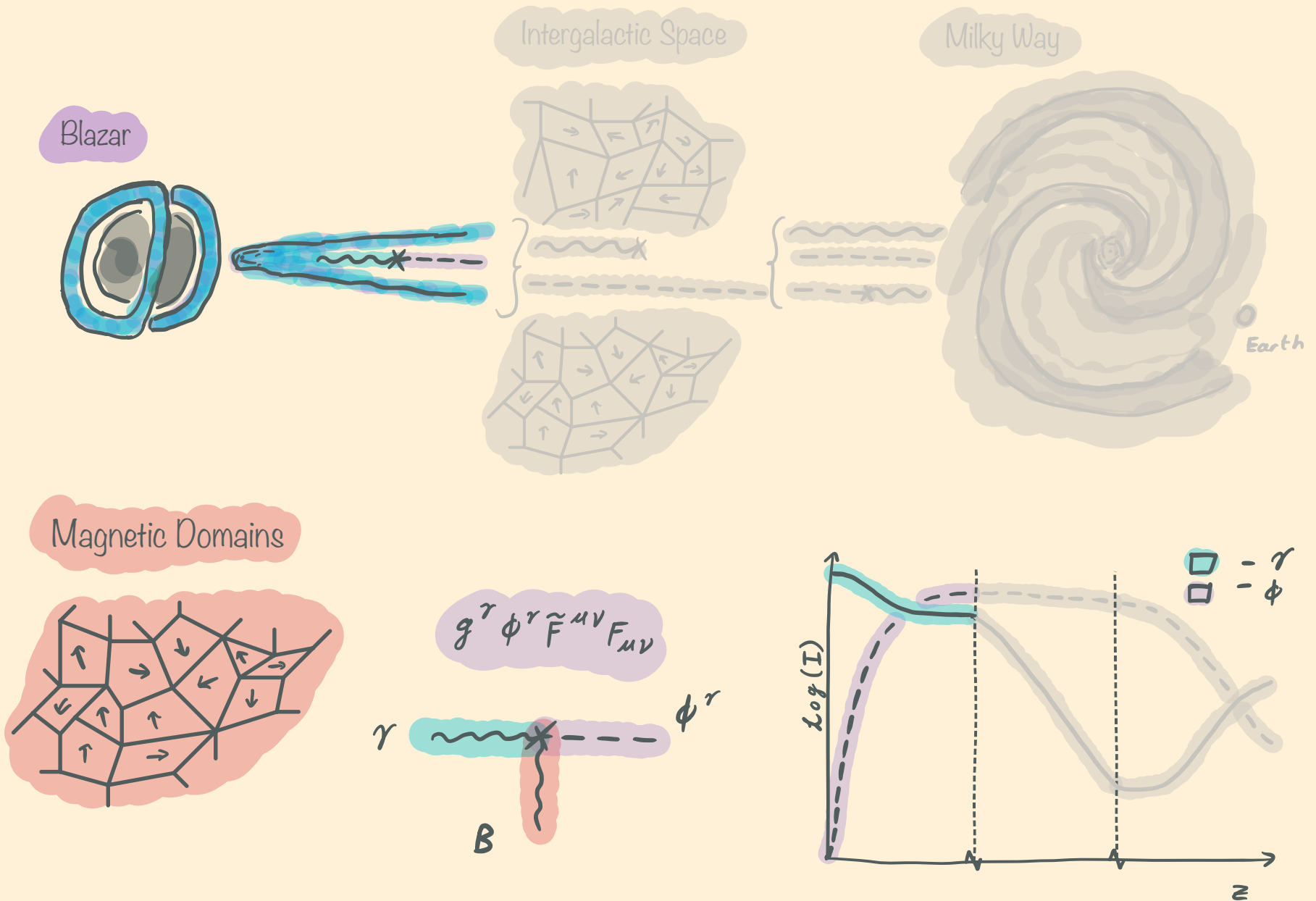
# Anomalous Transparency



Flux on Earth

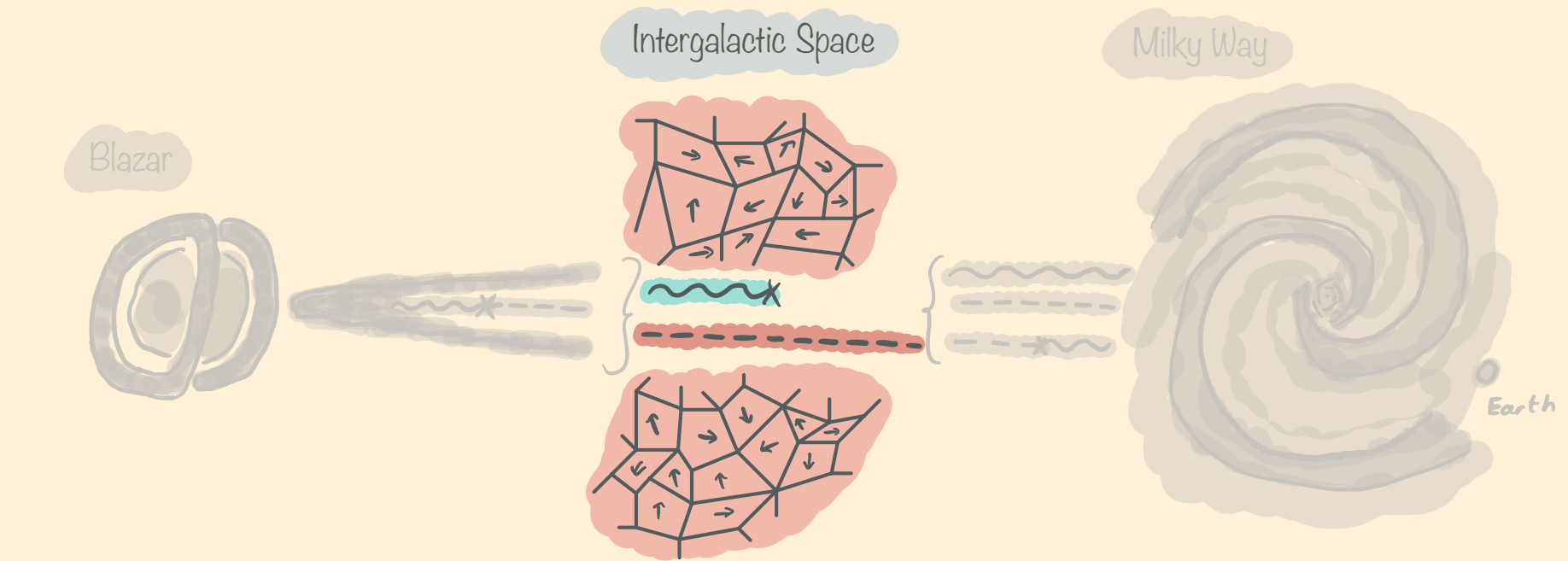


# Anomalous Transparency

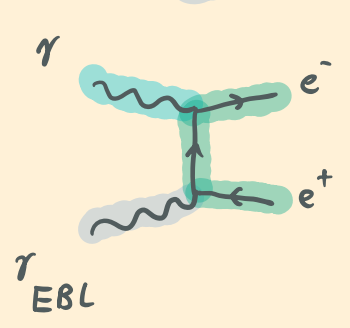




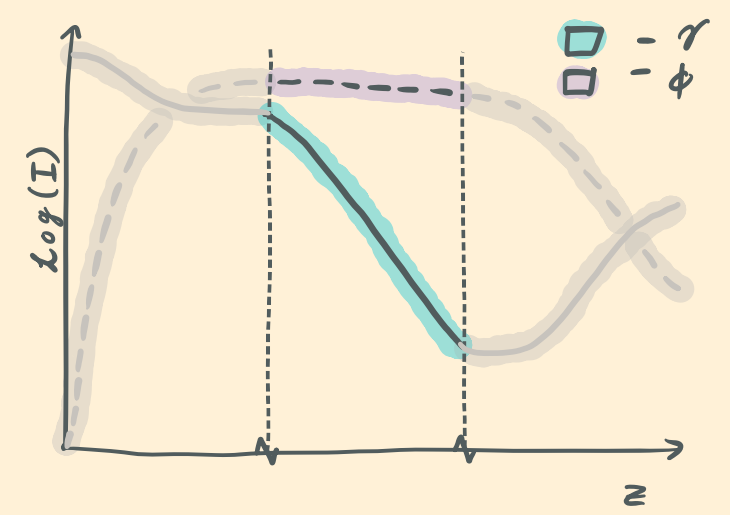
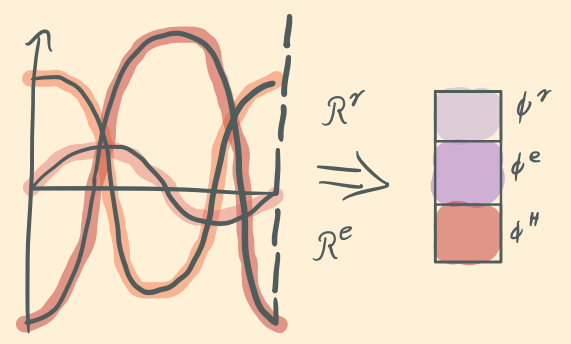
# Anomalous Transparency



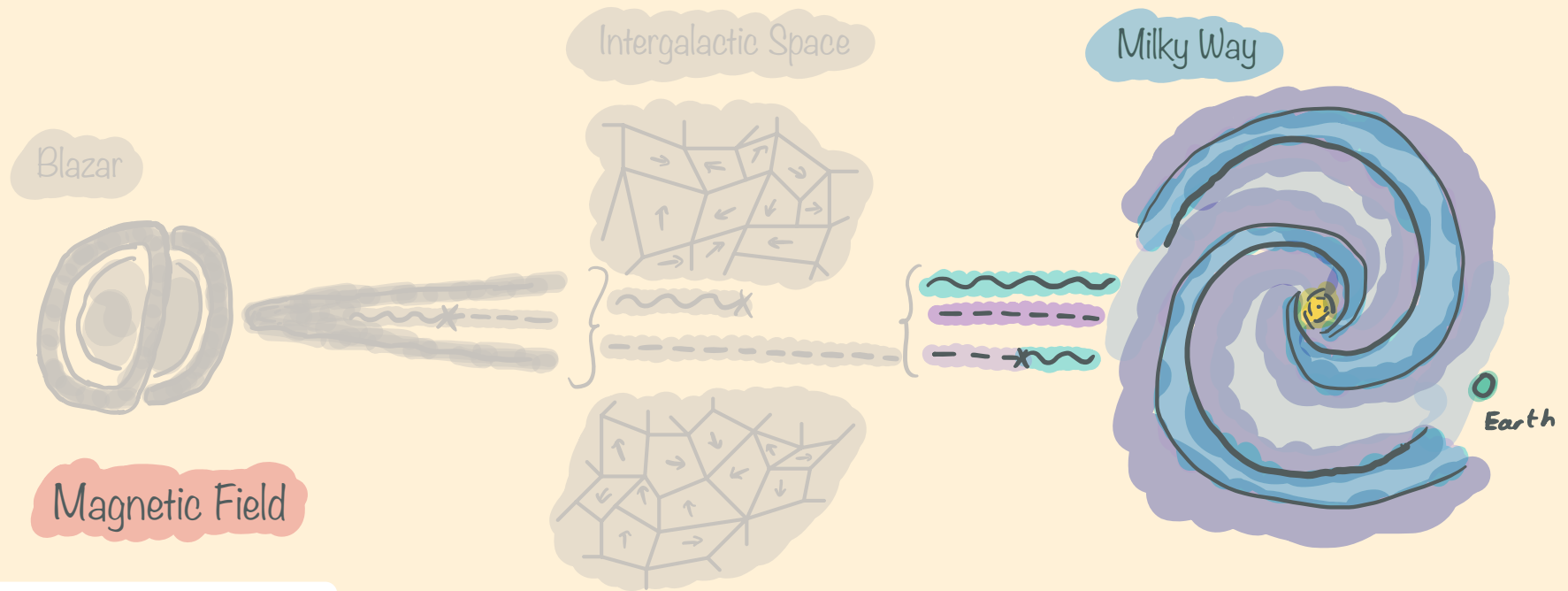
Extragalactic Background Light



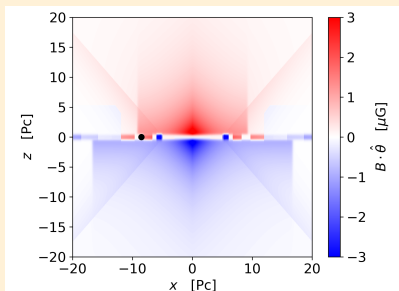
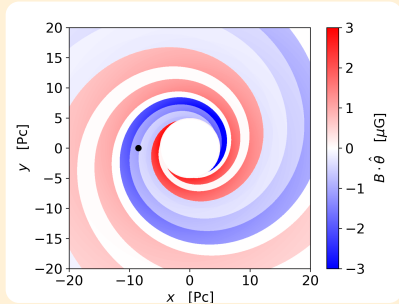
Oscillations



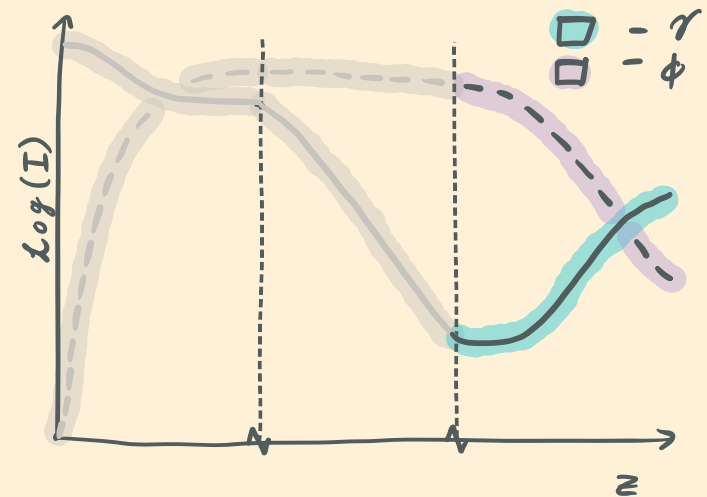
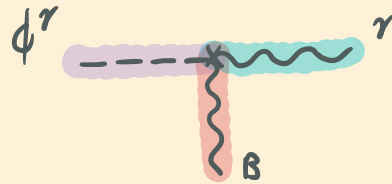
# Anomalous Transparency



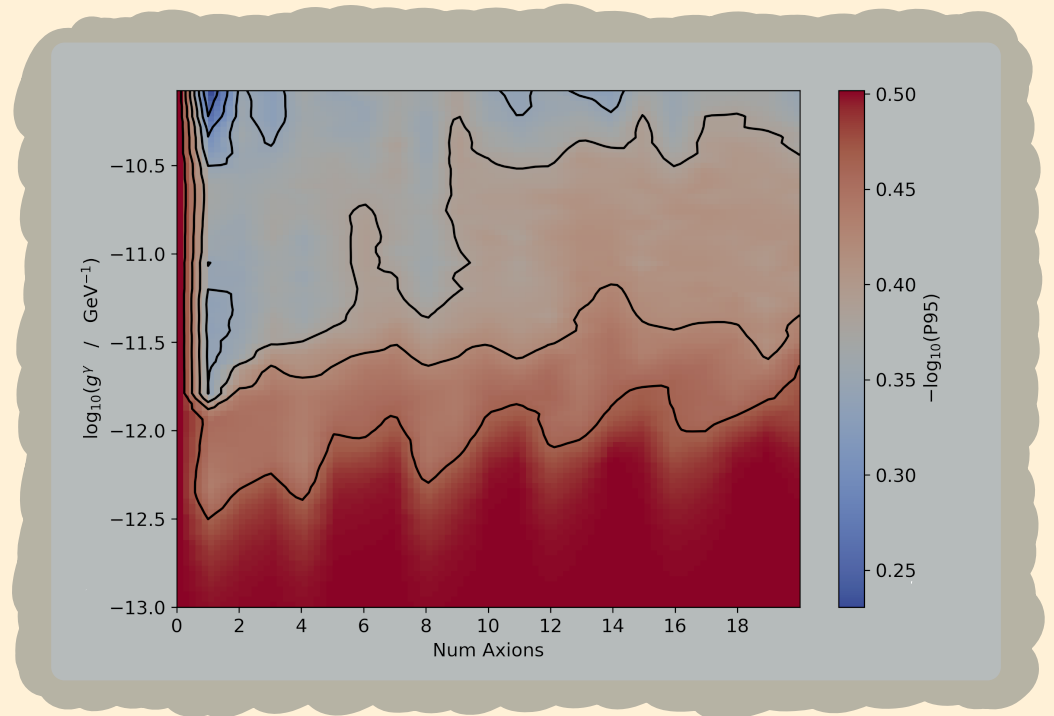
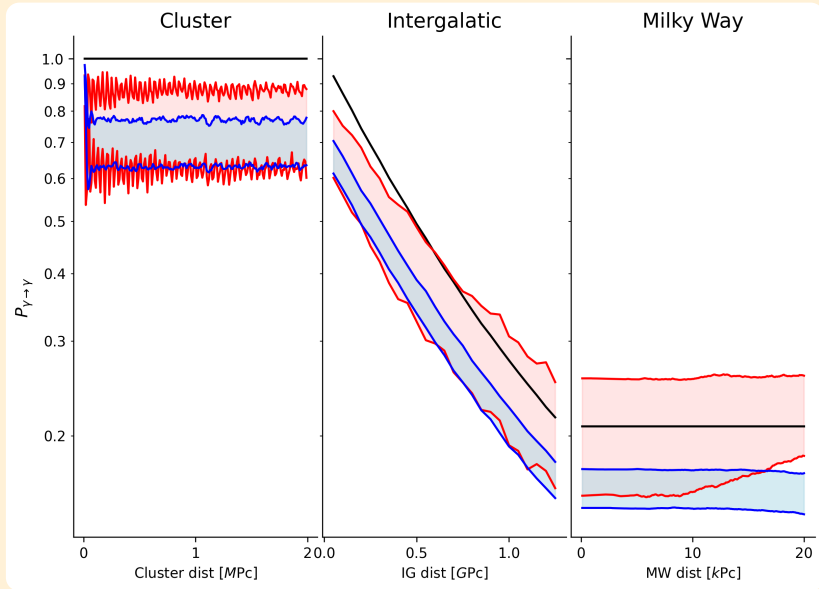
Magnetic Field



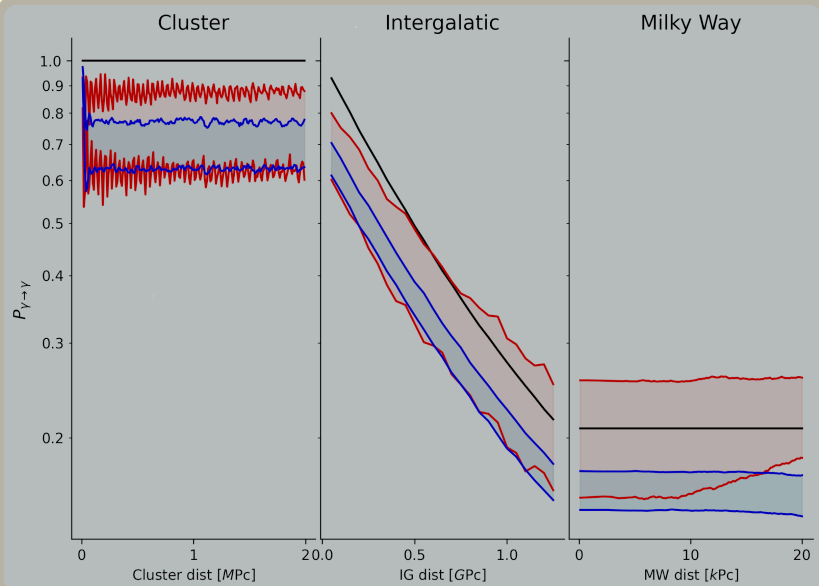
Back Conversion



# Results



# Results

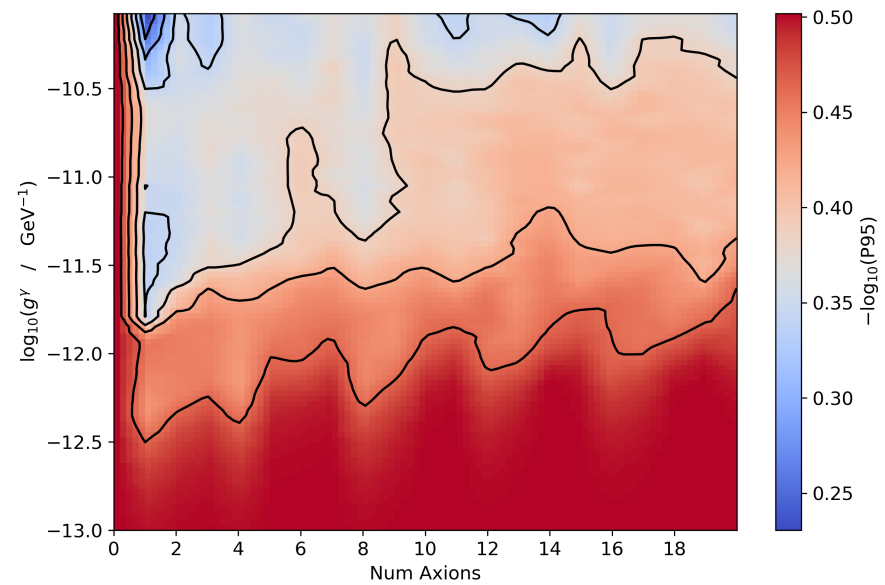


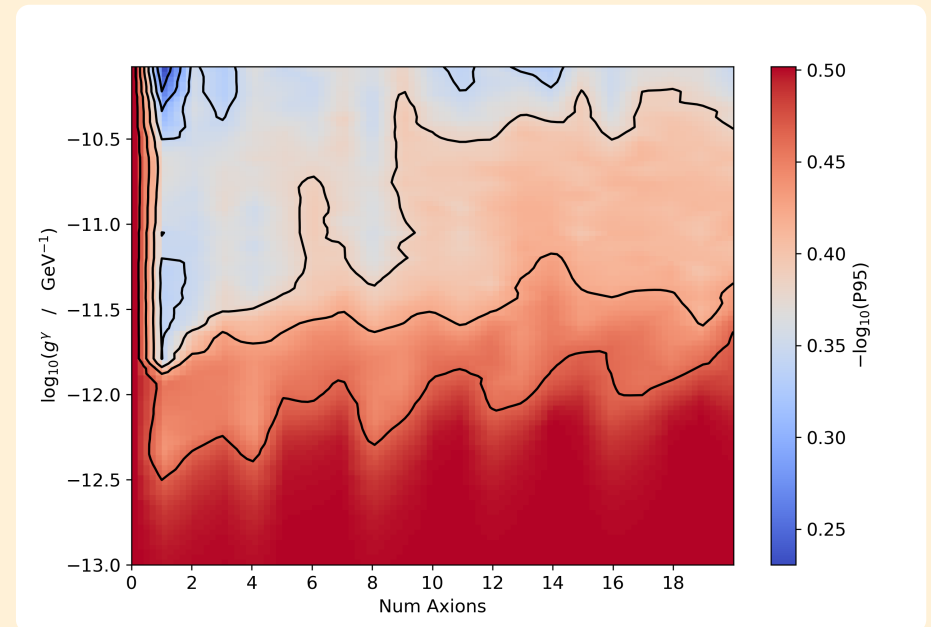
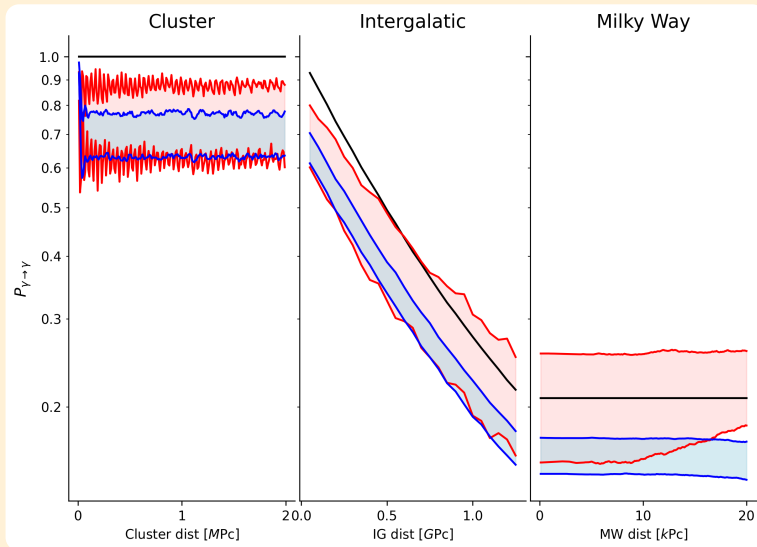
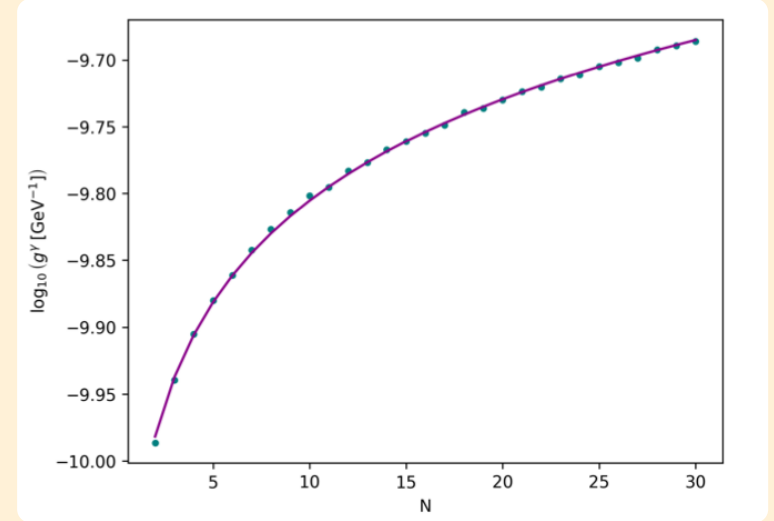
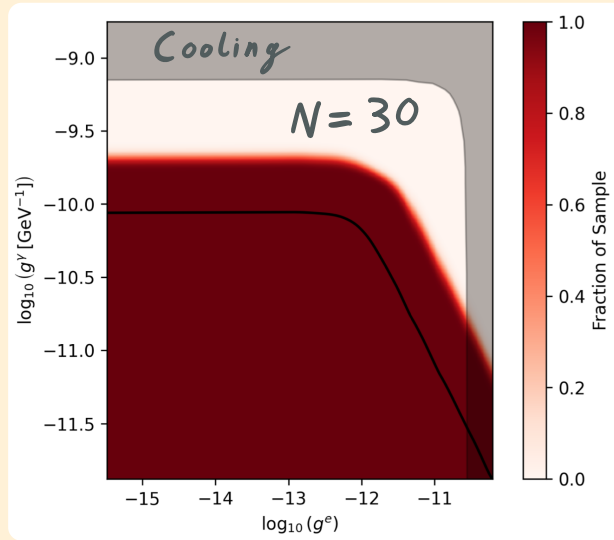
key:

— 0 ALPs

— 1 ALP

— 20 ALPs





Collaborators

Jessica Turner

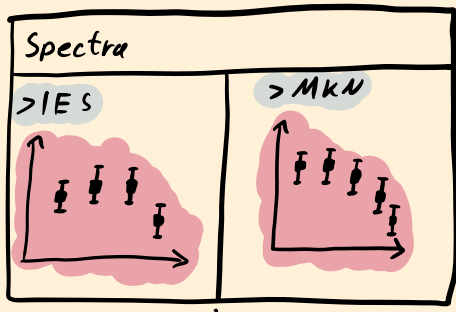
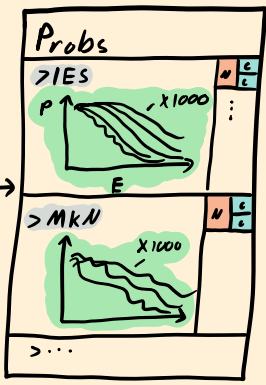
Francesca Chadha-Day

# Spectral Processing

scan Params  
> Couplings  
> N

Blazar Properties  
> IES  
> MKN  
> ...

Grid Scan

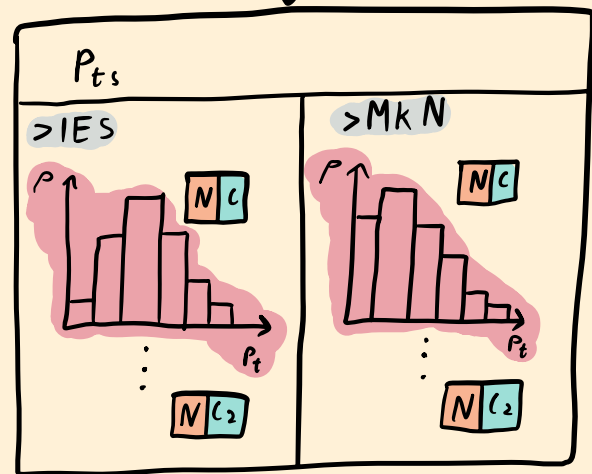


Fit spectra

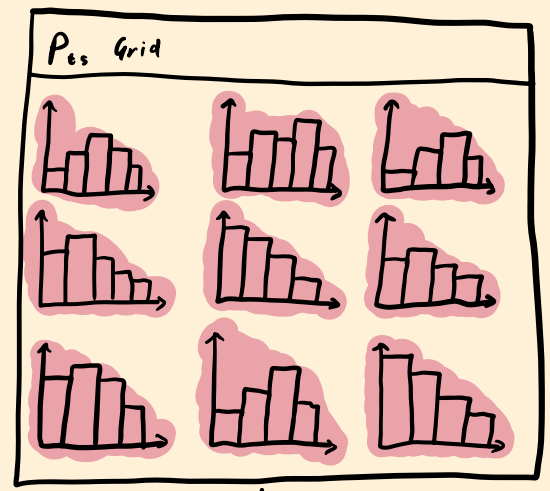
Residuals

	> IES	> MKN														
$N_1$	<table border="1"><tr><td><math>C_1</math></td><td><math>R_1 \dots R_{1000}</math></td></tr><tr><td><math>C_2</math></td><td><math>R_1 \dots R_{1000}</math></td></tr><tr><td><math>C_3</math></td><td><math>R_1 \dots R_{1000}</math></td></tr><tr><td><math>\vdots</math></td><td><math>\vdots</math></td></tr></table>	$C_1$	$R_1 \dots R_{1000}$	$C_2$	$R_1 \dots R_{1000}$	$C_3$	$R_1 \dots R_{1000}$	$\vdots$	$\vdots$	<table border="1"><tr><td><math>C_1</math></td><td><math>R_1 \dots R_{1000}</math></td></tr><tr><td><math>C_2</math></td><td><math>R_1 \dots R_{1000}</math></td></tr><tr><td><math>\vdots</math></td><td><math>\vdots</math></td></tr></table>	$C_1$	$R_1 \dots R_{1000}$	$C_2$	$R_1 \dots R_{1000}$	$\vdots$	$\vdots$
$C_1$	$R_1 \dots R_{1000}$															
$C_2$	$R_1 \dots R_{1000}$															
$C_3$	$R_1 \dots R_{1000}$															
$\vdots$	$\vdots$															
$C_1$	$R_1 \dots R_{1000}$															
$C_2$	$R_1 \dots R_{1000}$															
$\vdots$	$\vdots$															
$N_2$	$\vdots$	$\vdots$														
$\vdots$	$\vdots$	$\vdots$														

Compute Pts



Combine Pts



Compute P95

