Imprecise Decision-Making:
From Choice Functions to Trustworthy Machine Learning

EPIMP 2026, Bristol

Jasper De Bock

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FLip

Foundations Lab
for imprecise probabilities





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imprecise randomness

credal networks

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imprecise stochastic processes
and
imprecise Markov chains


quantum mechanics
with imprecise probabilities


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choice functions

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trustworthy
machine learning

Imprecise Decision-Making: From Choice Functions to Trustworthy Machine Learning

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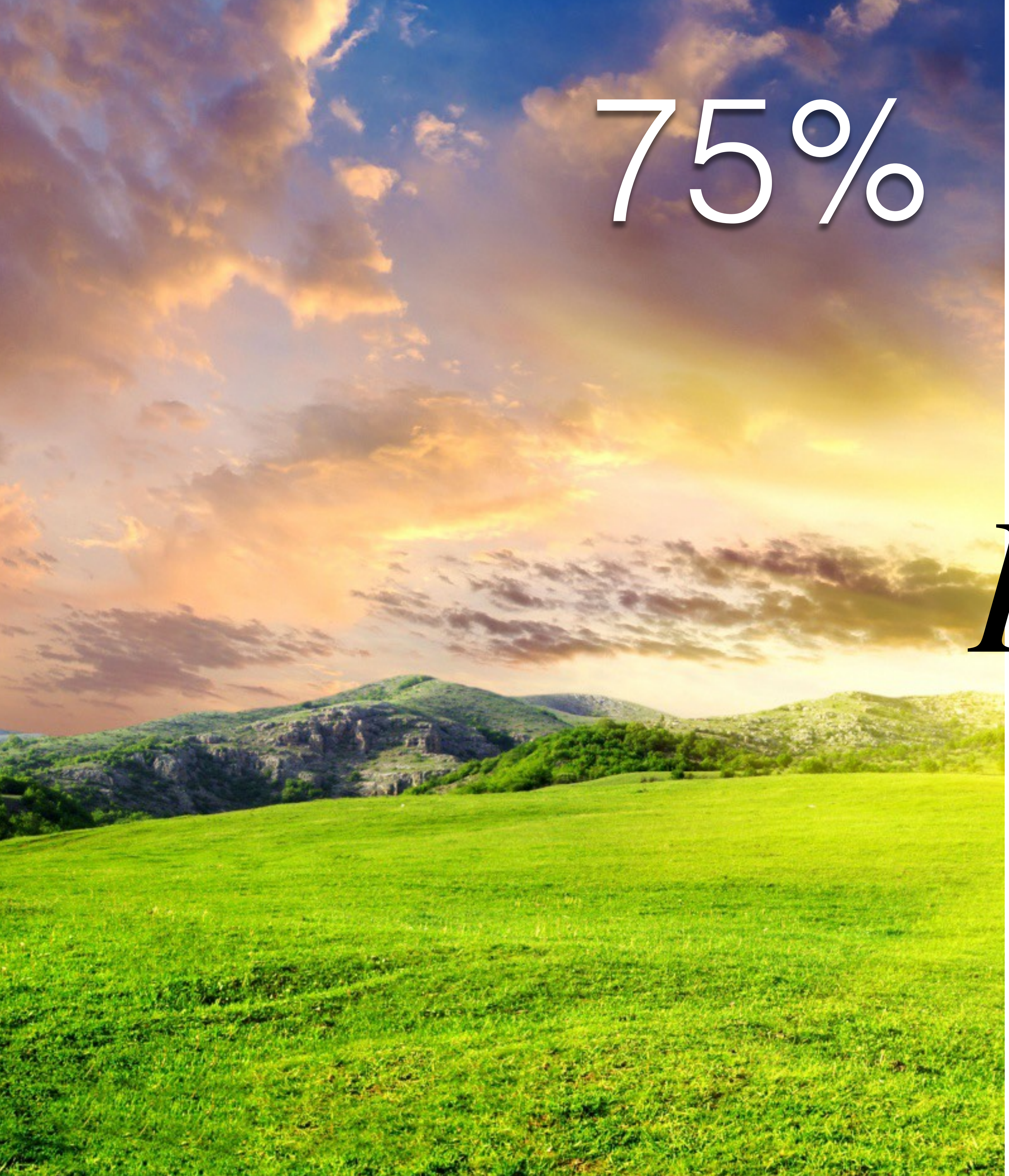
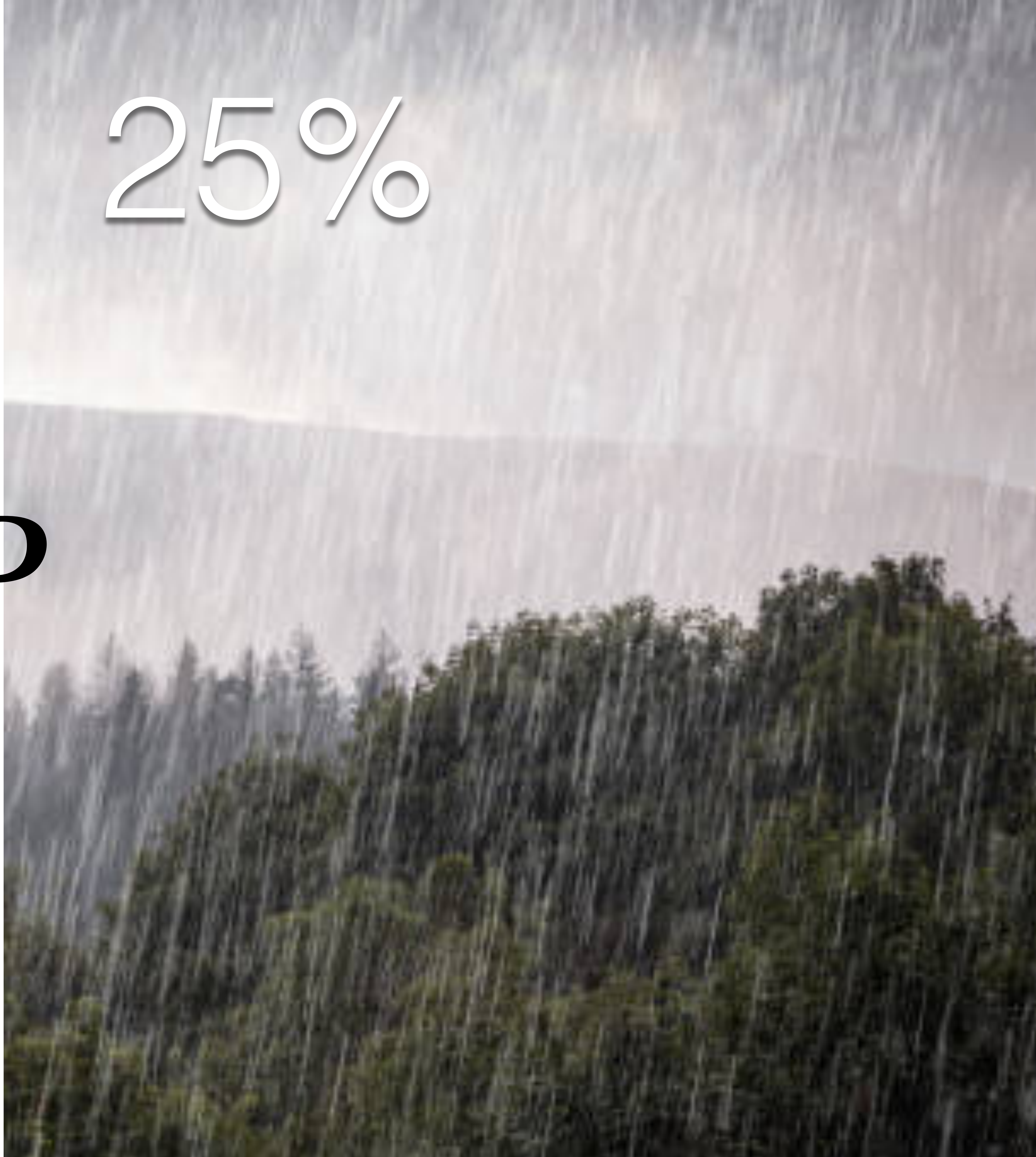
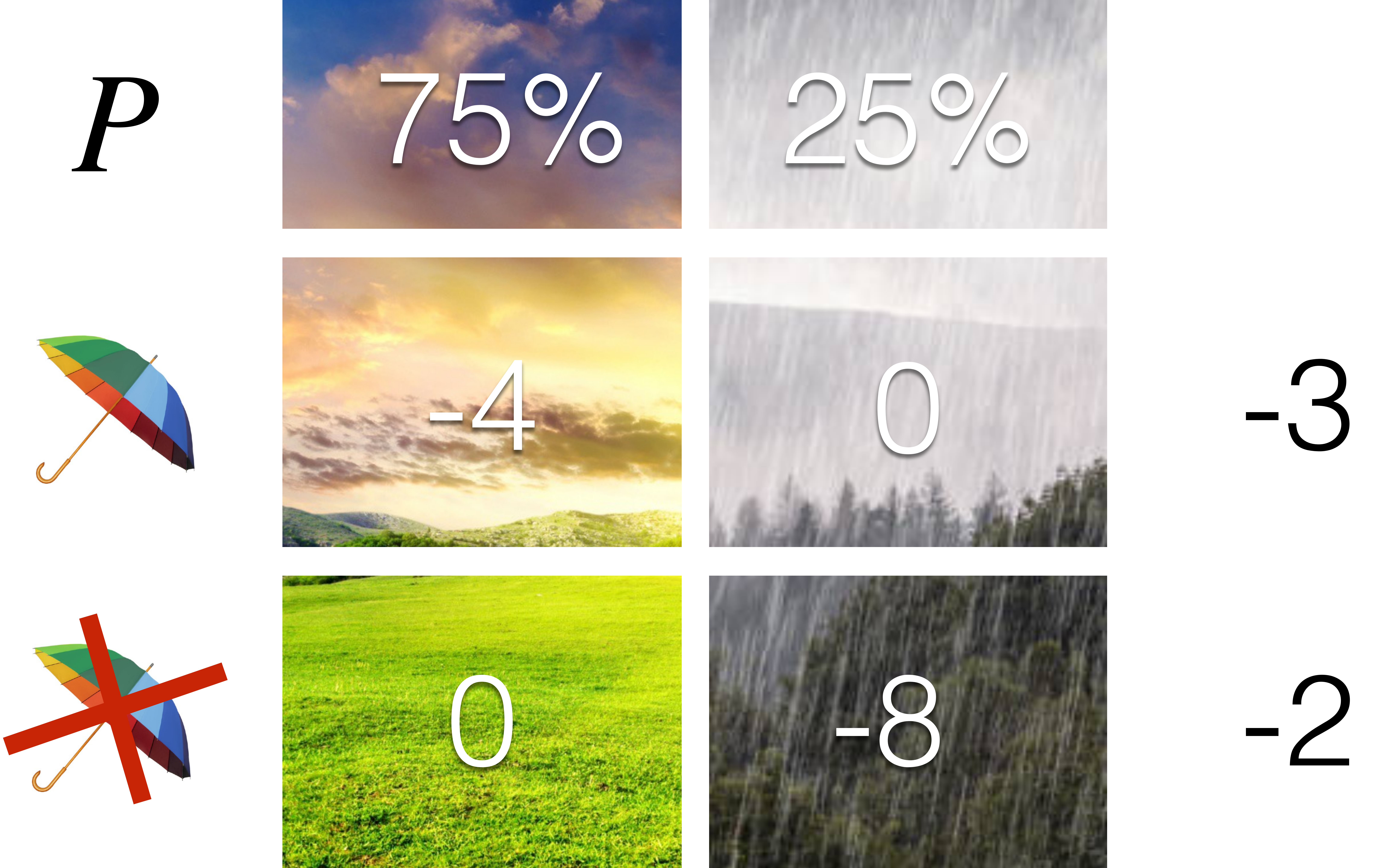
DECISION MAKING

P



P




P
75%
25%
-4
0
-3
0
-8
-2

A set of possible “states” $\mathscr{X}$

The set $\mathscr{G}(\mathscr{X})$ of gambles on $\mathscr{X}$: bounded real-valued functions on $\mathscr{X}$

Given a finite set of gambles $A \subseteq \mathscr{G}(\mathscr{X})$, which one(s) do we “choose” ?

$\mathscr{X} = \{$  ,  $\}$

$A = \{$  ,  $\}$

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MAXIMIZING EXPECTED UTILITY

Consider a probability distribution P on the power set of $\mathscr{X}$

Choose those gambles f in A that maximize $E_P(f)$

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Decision making with a preference order

Consider a preference order $\prec$ on $\mathscr{G}(\mathscr{X})$

Choose those gambles f in A that that are undominated w.r.t. $\prec$

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$$
\begin{array}{ccccc}
 & & d & \prec & e \\
 & & \curlywedge & & \\
a & \prec & b & \prec & c
\end{array}
\qquad\qquad
f \prec g
$$

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Consider a probability distribution P on the power set of $\mathscr{X}$

Define $\prec_P$ as follows: $f \prec_P g \Leftrightarrow E_P(f) < E_P(g)$

Choose those gambles f in A that that are undominated w.r.t. $\prec_P$

$\prec_P$ is not just any preference order

Irreflexive: $a \nprec a$

Transitive: $a \prec b \ \ \& \ \ b \prec c \Rightarrow a \prec c$

$\prec_P$ is not just any preference order

Irreflexive: $a \not\prec a$

Transitive: $a \prec b \;\;\&\;\; b \prec c \Rightarrow a \prec c$

$\left.\begin{array}{l} \\ \\ \end{array}\right\}$ partial order

$\prec_P$ is not just any preference order

Irreflexive: $a \not\prec a$

Transitive: $a \prec b \;\&\; b \prec c \Rightarrow a \prec c$

Transitive incomparability: $a \sim b \;\&\; b \sim c \Rightarrow a \sim c$

$\hookrightarrow$ $a \not\prec b \;\&\; b \not\prec a$

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weak order

$a \nprec b \,\&\, b \nprec a$

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Transitive: $a \prec b$ & $b \prec c \Rightarrow a \prec c$

Transitive incomparability: $a \sim b$ & $b \sim c \Rightarrow a \sim c$

Translation invariance: $a \prec b \Rightarrow a + c \prec b + c$

Scaling invariance: $a \prec b \Rightarrow \lambda a \prec \lambda b$ for $\lambda > 0$

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weak vector order

$\prec_P$ is not just any preference order

$$\left.\begin{array}{l}
\text{Irreflexive: } a \nprec a \\
\text{Transitive: } a \prec b \ \& \ b \prec c \Rightarrow a \prec c \\
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\text{Translation invariance: } a \prec b \Rightarrow a + c \prec b + c \\
\text{Scaling invariance: } a \prec b \Rightarrow \lambda a \prec \lambda b \text{ for } \lambda > 0 \\
\text{Positivity: } \inf a > 0 \Rightarrow 0 \prec a \\
\text{Archimedeanity: } a \prec b \Rightarrow (\exists \epsilon > 0) \ a \prec b - \epsilon
\end{array}\right\} \prec_P$$

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A

d real-valued

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IMPRECISE DECISION MAKING


$\mathscr{P}$
P_1
P_2
P_3
P_4
...

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E-ADMISSIBILITY

Consider a closed set $\mathscr{P}$ of probability distributions

Choose those gambles f in A that maximize $E_P(f)$ for at least one P in $\mathscr{P}$

A set of possible “states” $\mathscr{X}$

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A set of possible "states" $\mathscr{X}$

The set $\mathscr{G}(\mathscr{X})$ of gambles on $\mathscr{X}$: bounded

Given a finite set of gambles $A \subseteq \mathscr{G}(\mathscr{X})$, wh

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Imprecise Decision-Making:
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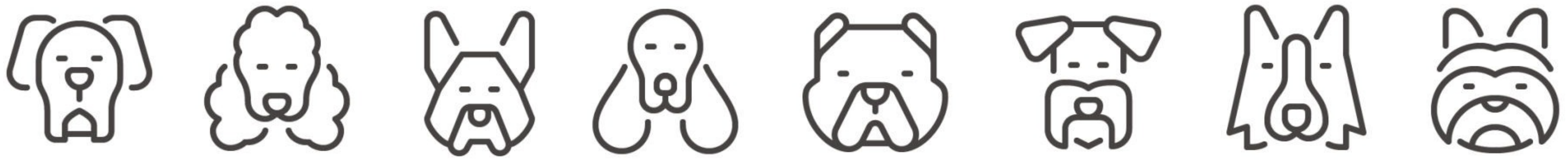
CHOICE FUNCTIONS

A set $\mathscr{T}$ consisting of “things”

Given a finite subset of things $A \subseteq \mathscr{T}$, which one(s) do we “choose” ?

CHOICE FUNCTIONS

$\mathscr{T} = \{$  $\cdots \}$

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A se

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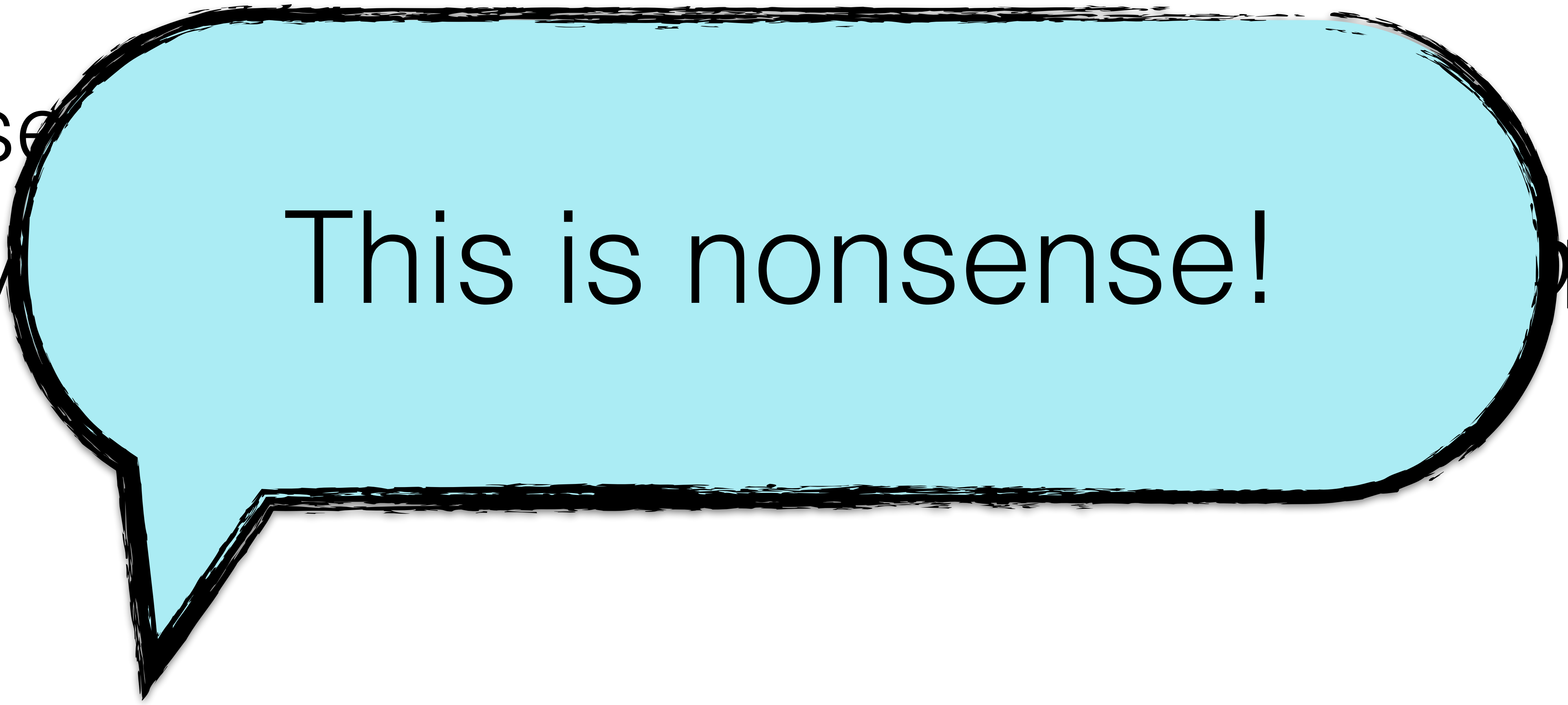

CHOICE FUNCTIONS

 … }

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Given a finite subset of things $A \subseteq \mathscr{T}$, which one(s) do we "choose" ?

CHOICE FUNCTIONS

$\mathscr{T} =$ a vector space

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CHOICE FUNCTIONS

$\mathscr{T} =$ the set $\mathscr{G}(\mathscr{X})$ of all gambles on a state space $\mathscr{X}$

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CHOICE FUNCTIONS

$\mathscr{T} = \{$

$\cdots \}$

A set $\mathscr{T}$ consisting of "things"

Given a finite subset of things $A \subseteq \mathscr{T}$, which one(s) do we "choose" ?

CHOICE FUNCTION C : the things in $C(A) \subseteq A$ are chosen

$\Updownarrow$ $\Updownarrow$

REJECTION FUNCTION R : the things in $R(A) = A \backslash C(A)$ are rejected

$A = \{$  $\}$ $C(A) = \{$  $\}$ $\Leftrightarrow R(A) = \{$  $\}$

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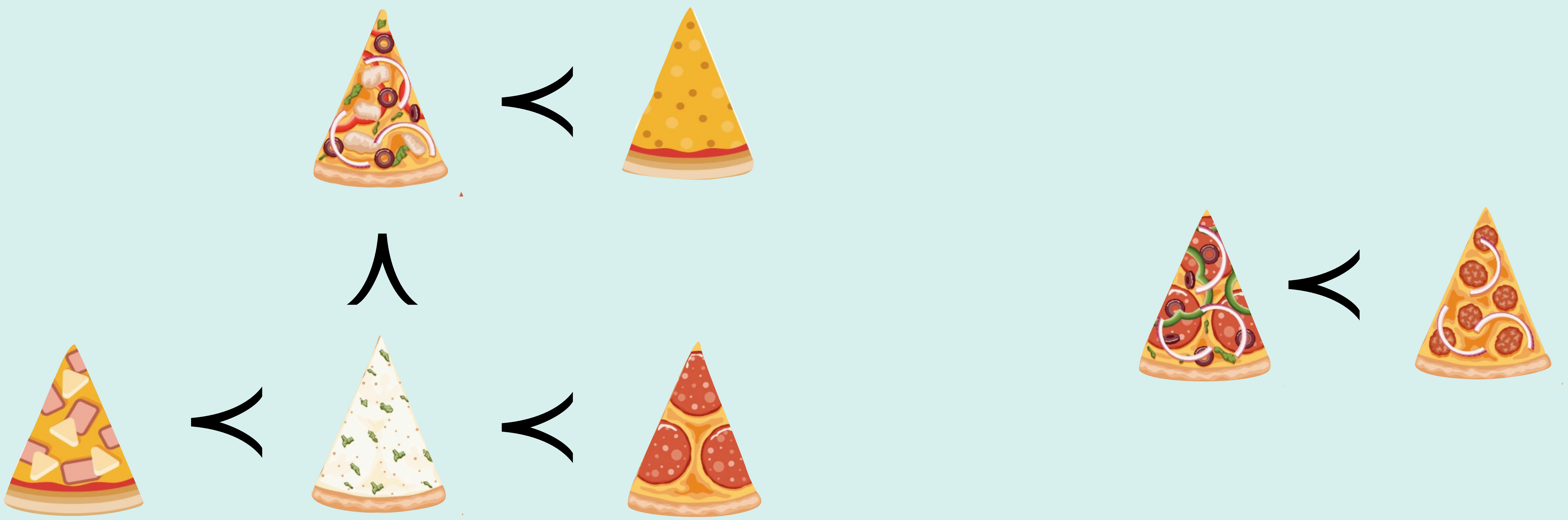

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Given a finite subset of things $A \subseteq \mathscr{T}$, which one(s) do we "choose" ?

Decision making with a set of preference orders

Consider a set $\mathscr{O}$ of preference orders on $\mathscr{T}$

Choose those things a in A that are chosen by at least one $\prec \in \mathscr{O}$

$$C_{\mathscr{O}}(A) = \bigcup_{\prec \in \mathscr{O}} C_{\prec}(A) = \{a \in A : (\exists \prec \in \mathscr{O})(\forall b \in A)\; a \nprec b\}$$

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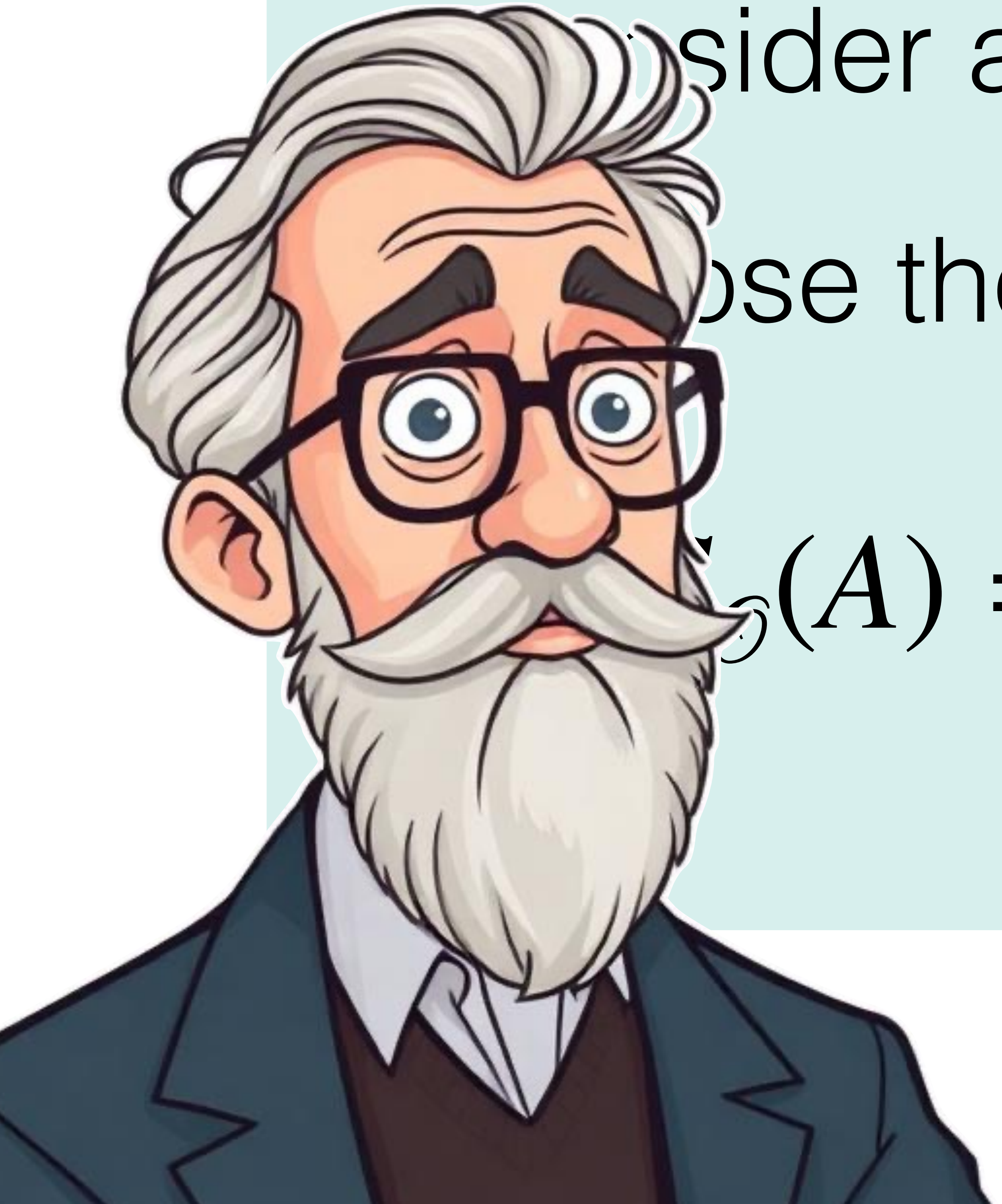

Axioms for C/R

NE $C(A) \neq \varnothing$ (non-emptiness)

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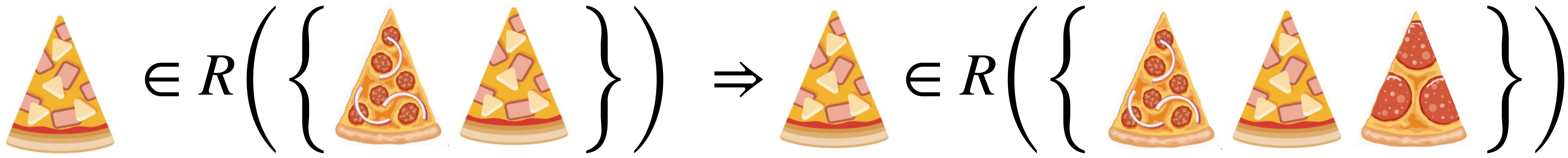

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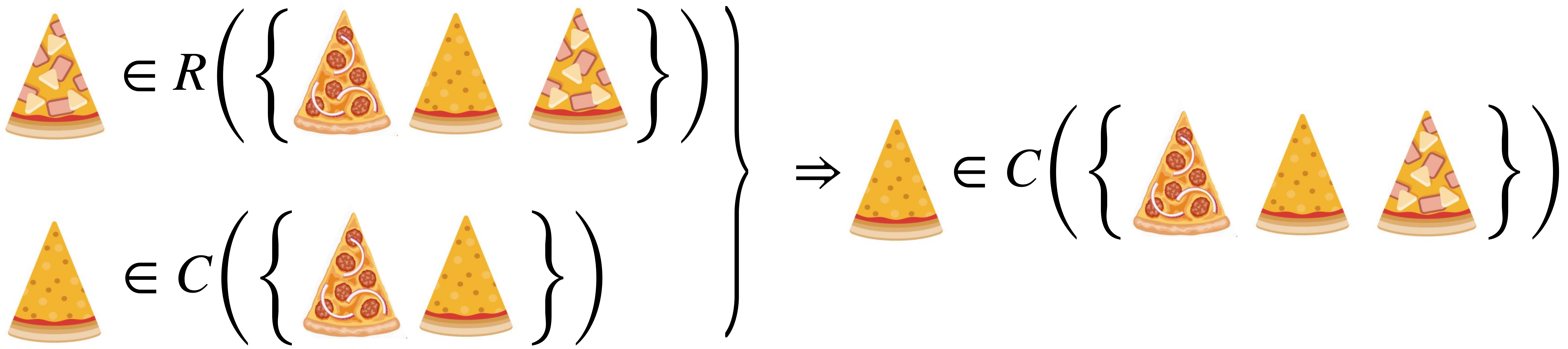

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$$\Leftrightarrow C = C_{\mathcal{O}}$$

with $\mathcal{O}$ a set of partial orders on $\mathcal{T}$

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CHOICE FUNCTIONS

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TI $a \in R(A) \Rightarrow a + b \in R(A + b)$ (translation invariance)

AD $0 \in R(\{0, a\} \cup S)$ & $0 \in R(\{0, b\} \cup S) \Rightarrow 0 \in R(\{0, a + b\} \cup S)$ (add.)

SI $0 \in R(\{0, a\} \cup S) \Rightarrow 0 \in R(\{0, \lambda a\} \cup S)$ for $\lambda > 0$ (scaling inv.)

Axioms for C/R

NE

IIA

Ou

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MI $A \subseteq B \subseteq \mathrm{conv}(A) \Rightarrow C(A) \subseteq C(B)$ (mixingness)

Axioms for C/R

NE
IIA
Ou
TI
AD
SI
MI

$$\Leftrightarrow$$

$$C = C_{\mathcal{O}}$$

with $\mathcal{O}$ a set of weak vector orders on $\mathcal{T}$

A set $\mathscr{T}$ consisting of "things"

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MI $A \subseteq B \subseteq \mathrm{conv}(A) \Rightarrow C(A) \subseteq C(B)$ (mixingness)

PO $\inf a > 0 \Rightarrow 0 \in R(\{0, a\})$ (positivity)

AR $a \in R(\{a\} \cup A) \Rightarrow (\exists \epsilon > 0)\, a \in R(\{a\} \cup (A - \epsilon))$ (archimedeanity)

Axioms for C/R

NE
IIA
Ou
TI
AD
SI
MI
PO
AR

$\Leftrightarrow$

E-ADMISSIBILITY

$$C = C_{\mathscr{O}}$$

with $\mathscr{O} = \{ \prec_P : P \in \mathscr{P} \}$ and $\mathscr{P}$ a closed set of prob. distr.

Imprecise Decision-Making:
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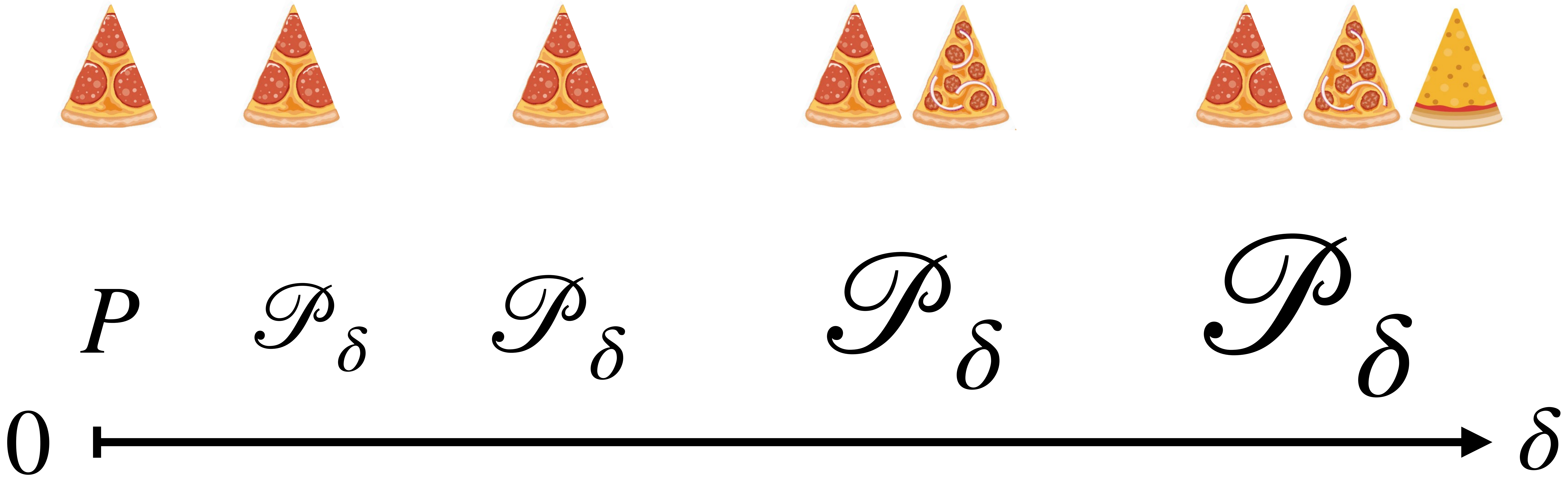
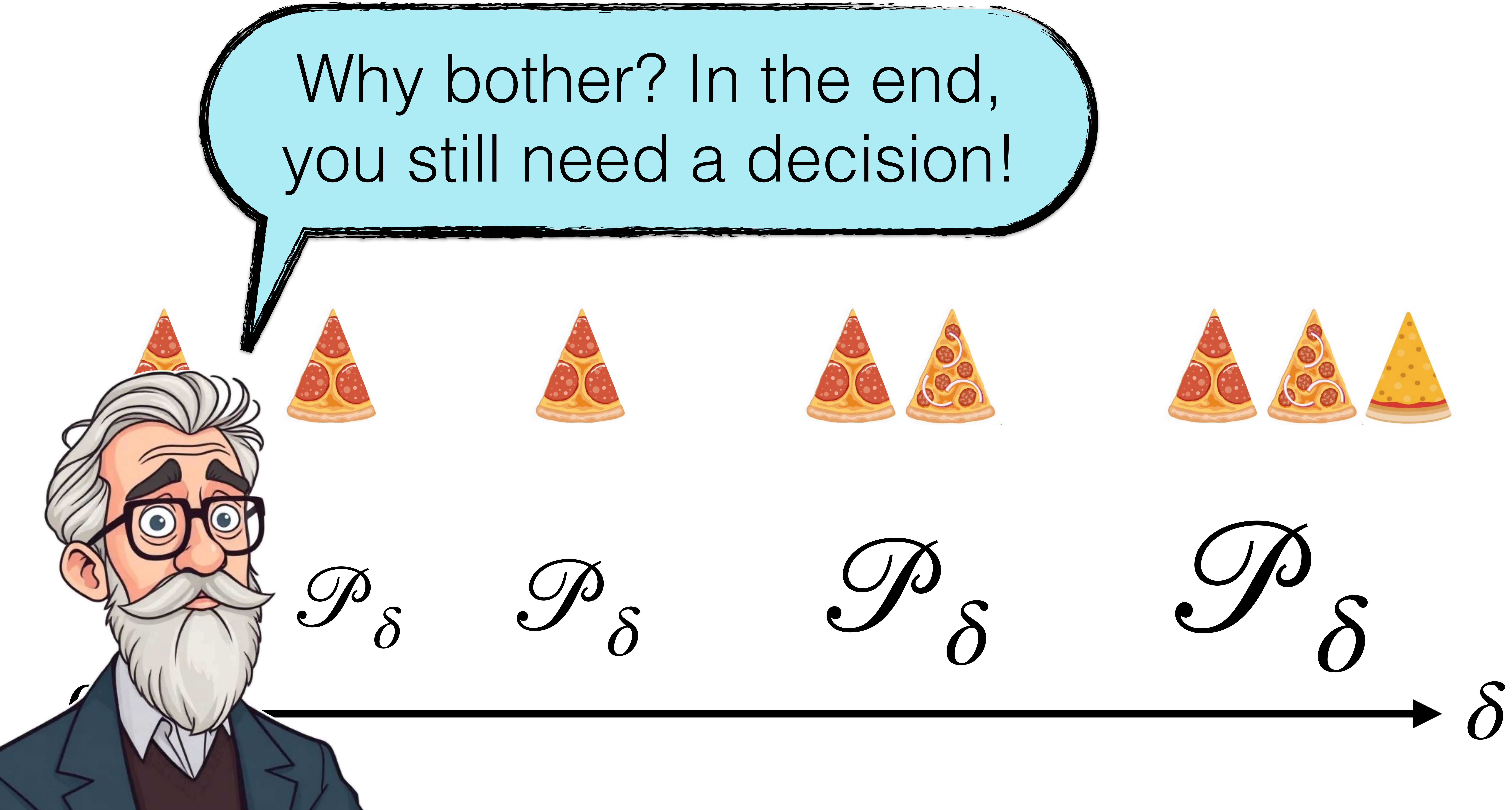
$\mathscr{P}$
P_1
P_2
P_3
P_4
...

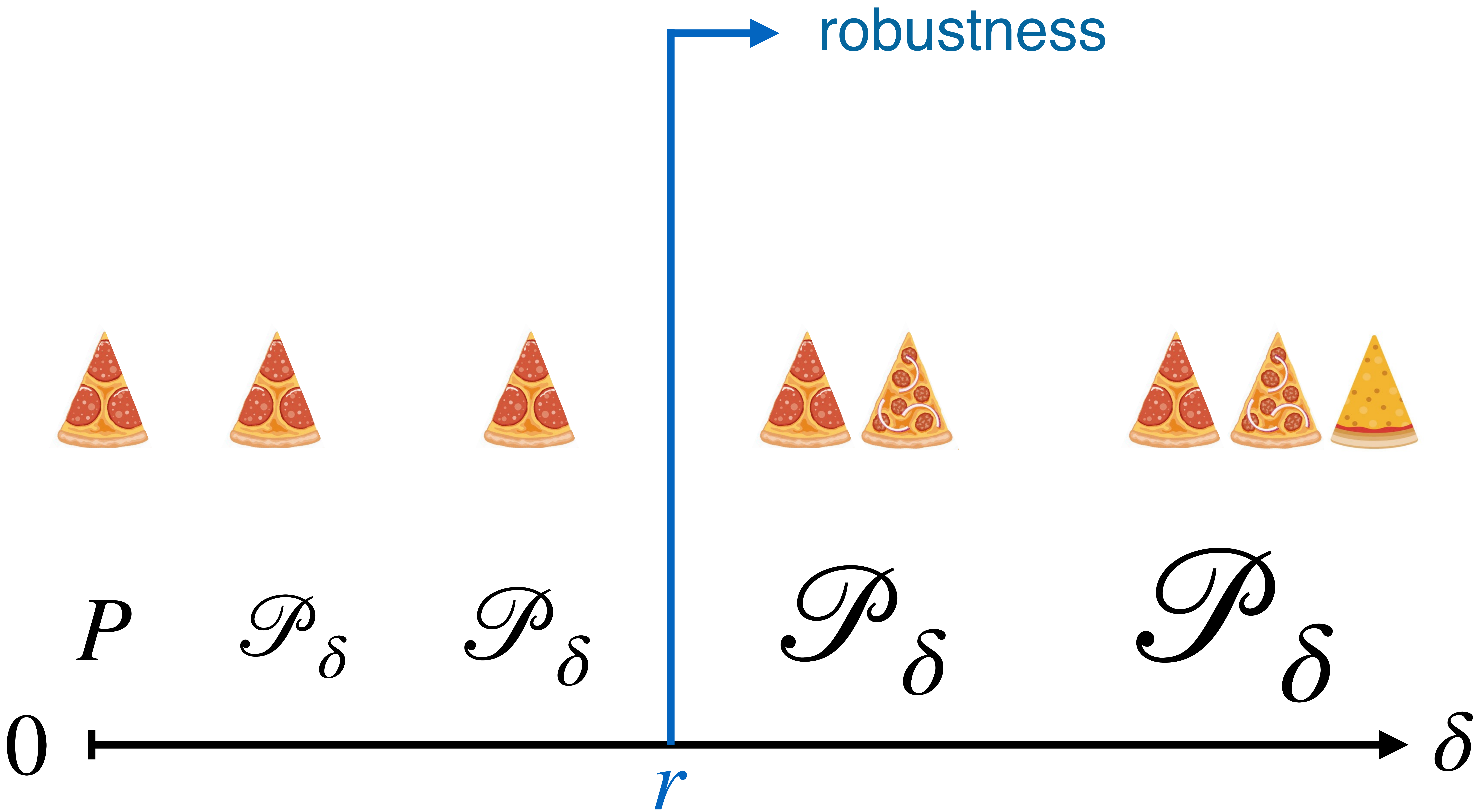

$\mathscr{P}$
P_1
P_2
P_3
P_4
...
Where do these sets come from?

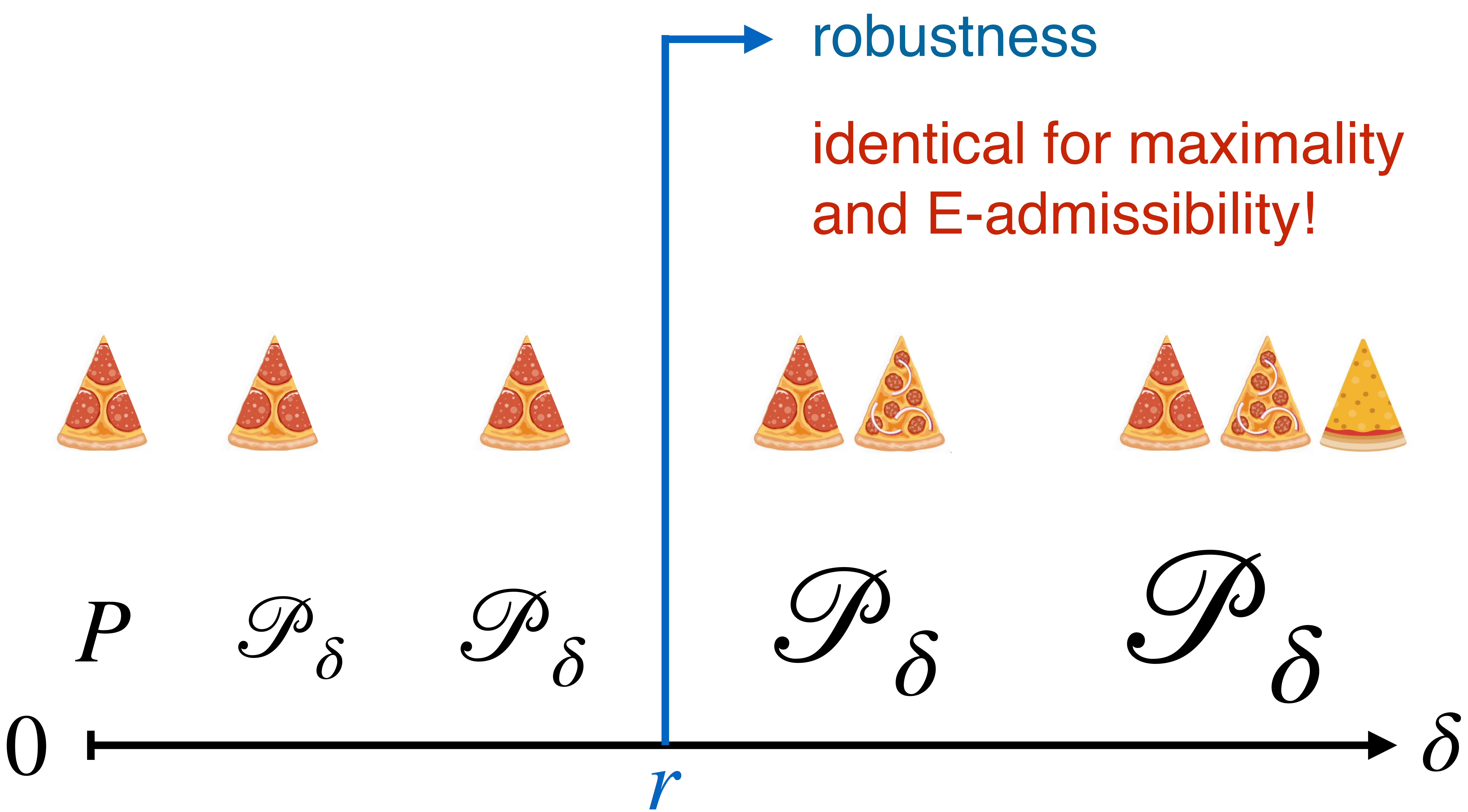
Where do these sets come from?
$\mathscr{P}$
P_1 P_2 P_3 P_4 ...
How imprecise should we be?



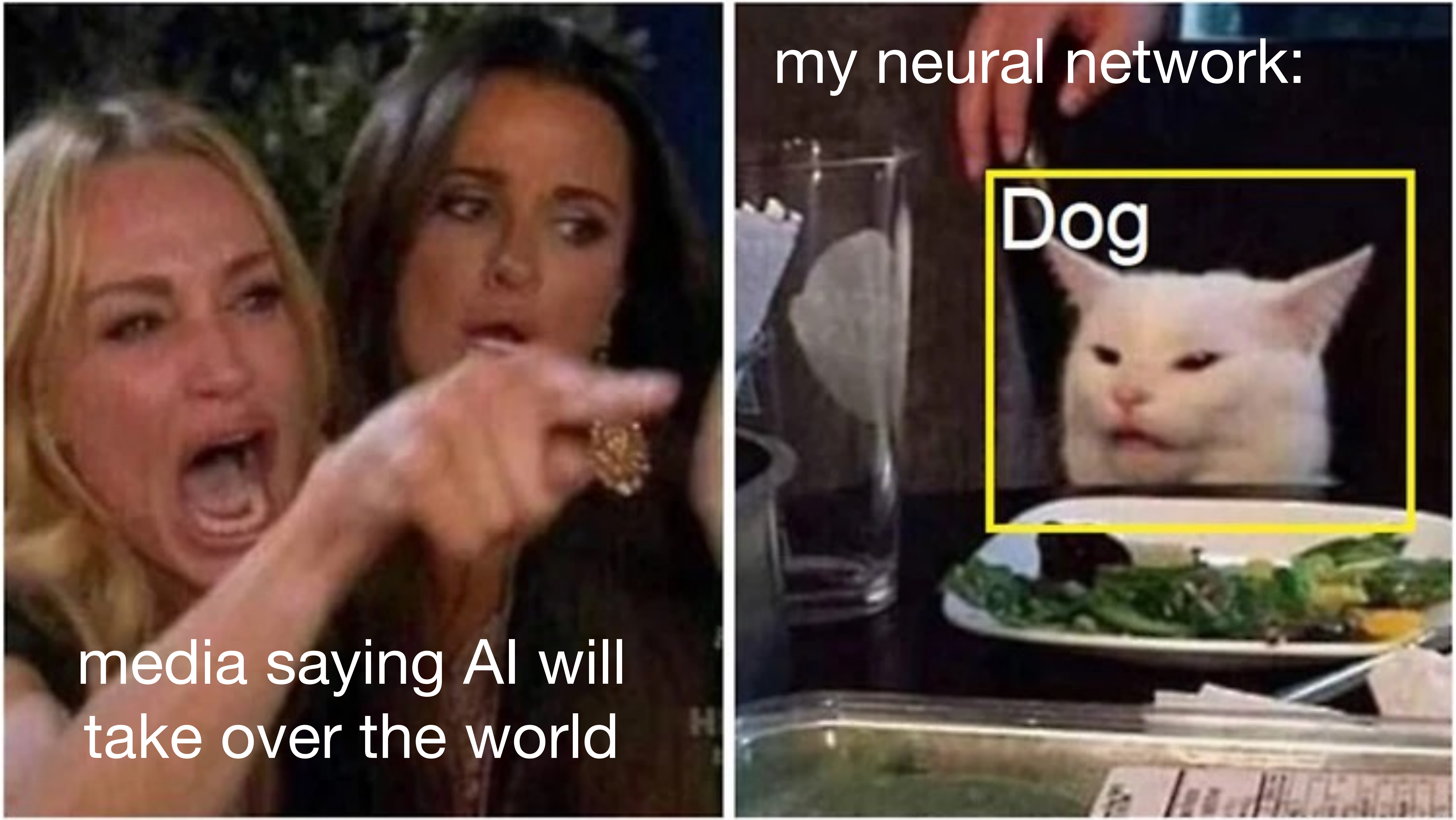
P
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
0
δ


Why bother? In the end, you still need a decision!
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
δ


robustness
P
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
0
r
δ



robustness
identical for maximality
and E-admissibility!
P
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
$\mathscr{P}_\delta$
0
r
δ


media saying AI will take over the world
my neural network:
Dog

CLASSIFICATION

features x

FEATURES

photo
medical data
...

CLASSIFICATION

features x

predicted class $\hat{y} = h(x)$

FEATURES → try to predict → CLASS

photo
medical data
...

CLASSIFIER h

label
best treatment
...

CLASSIFICATION

features x

FEATURES → try to predict → CLASS

predicted class $\hat{y} = h(x)$

photo
medical data
…

PROBABILISTIC CLASSIFIER h

predict the class y that maximizes $P_{\text{classif}}(y \mid x)$

label
best treatment
…

CLASSIFICATION

special case of MAXIMIZING EXPECTED UTILITY

features x

FEATURES

try to predict

predicted class $\hat{y} = h(x)$

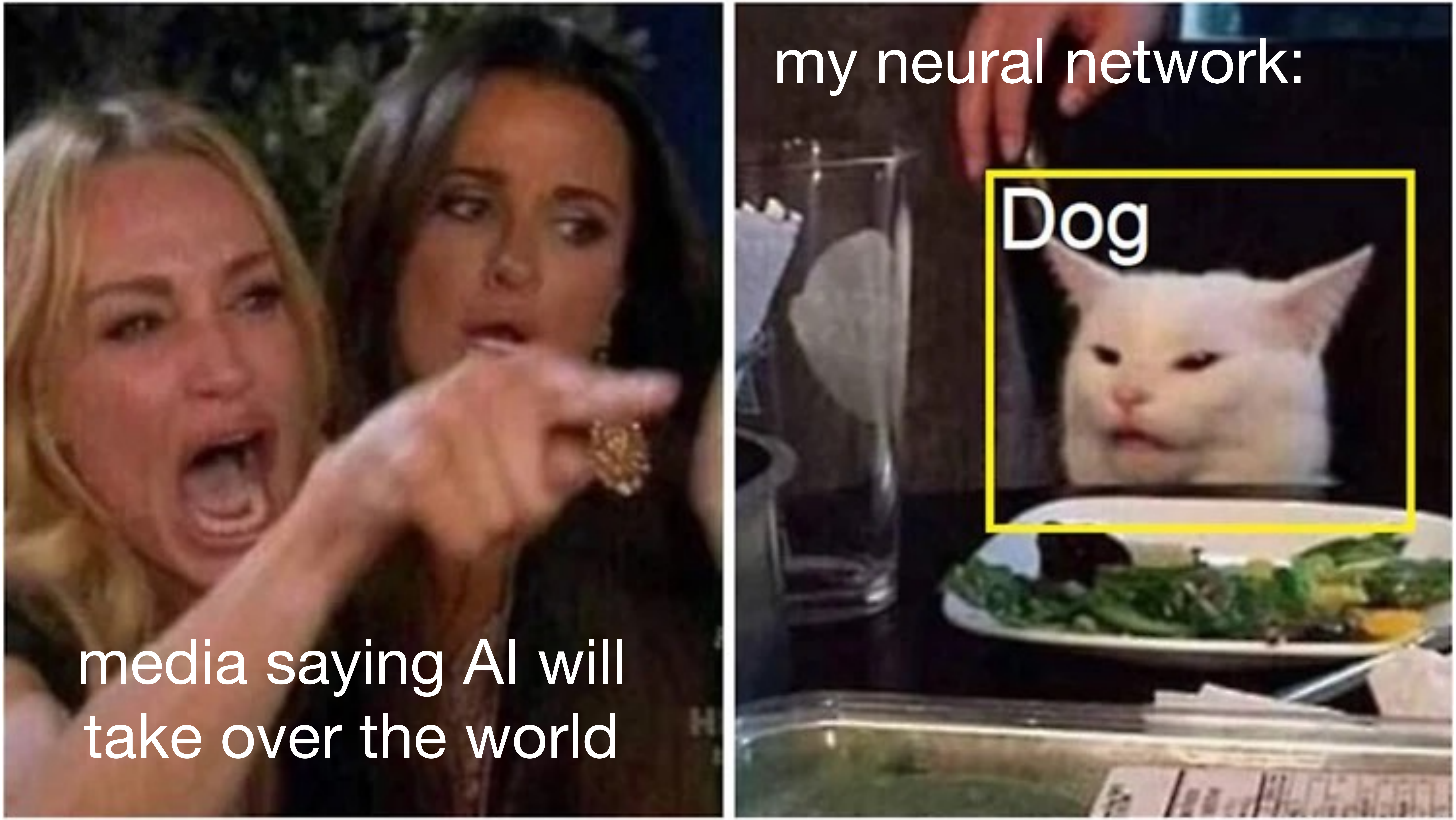
CLASS

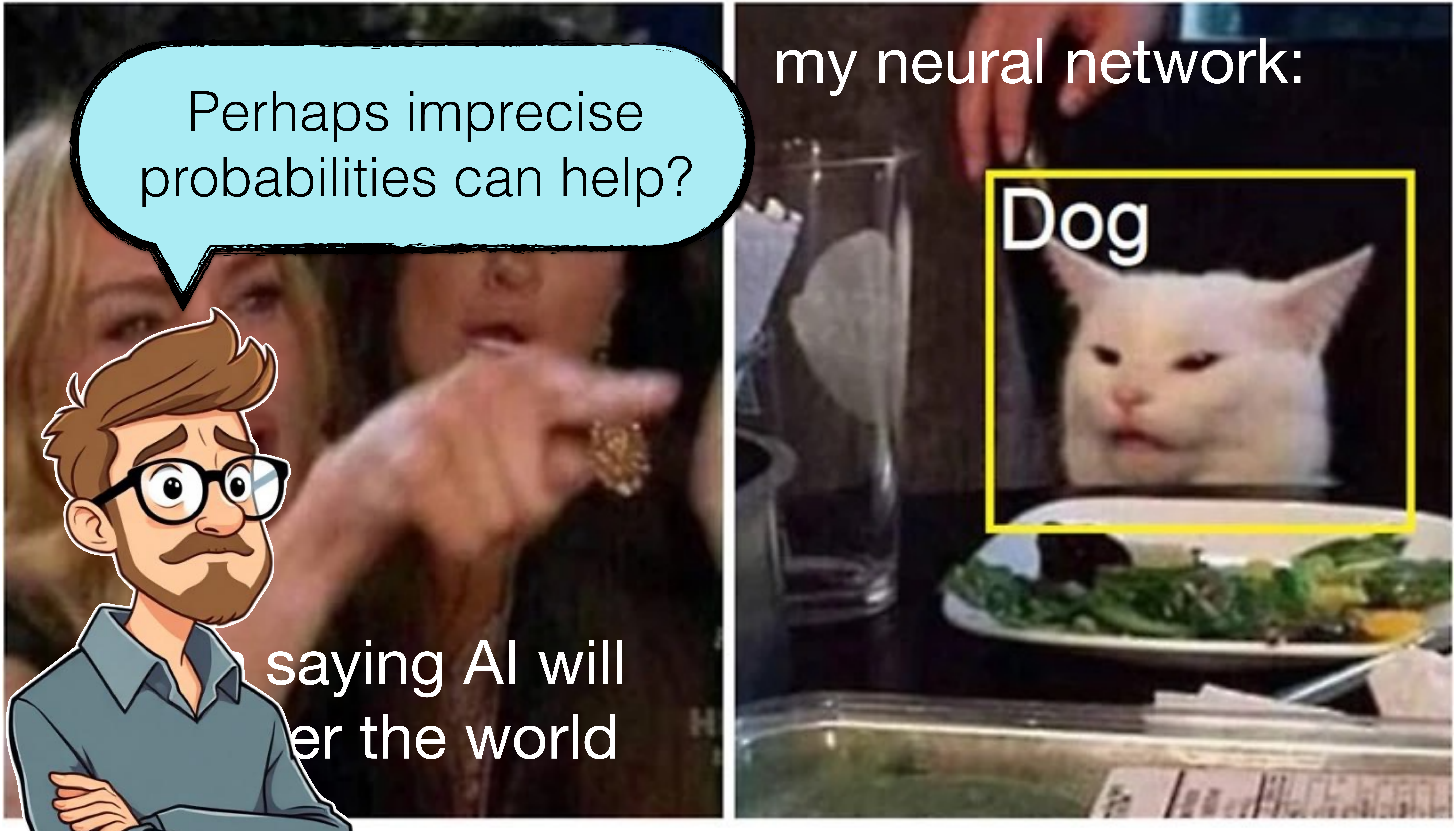
photo
medical data
...

PROBABILISTIC CLASSIFIER h

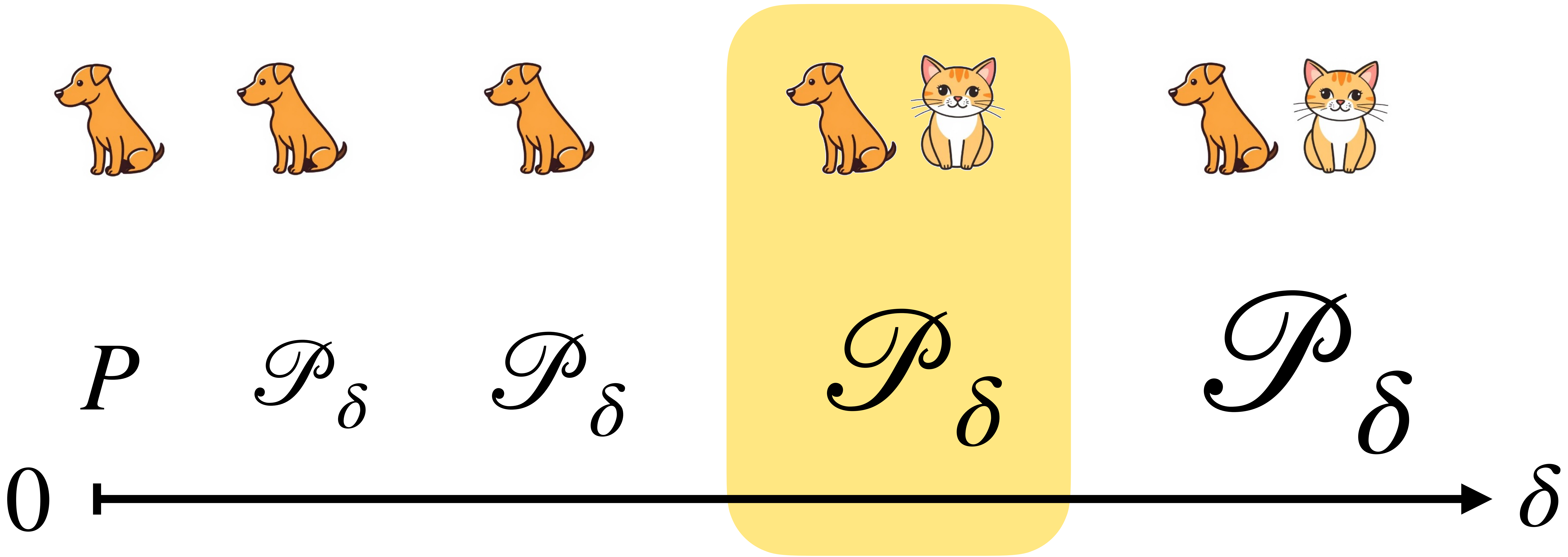
predict the class y that maximizes $P_{\text{classif}}(y \mid x)$

label
best treatment
...

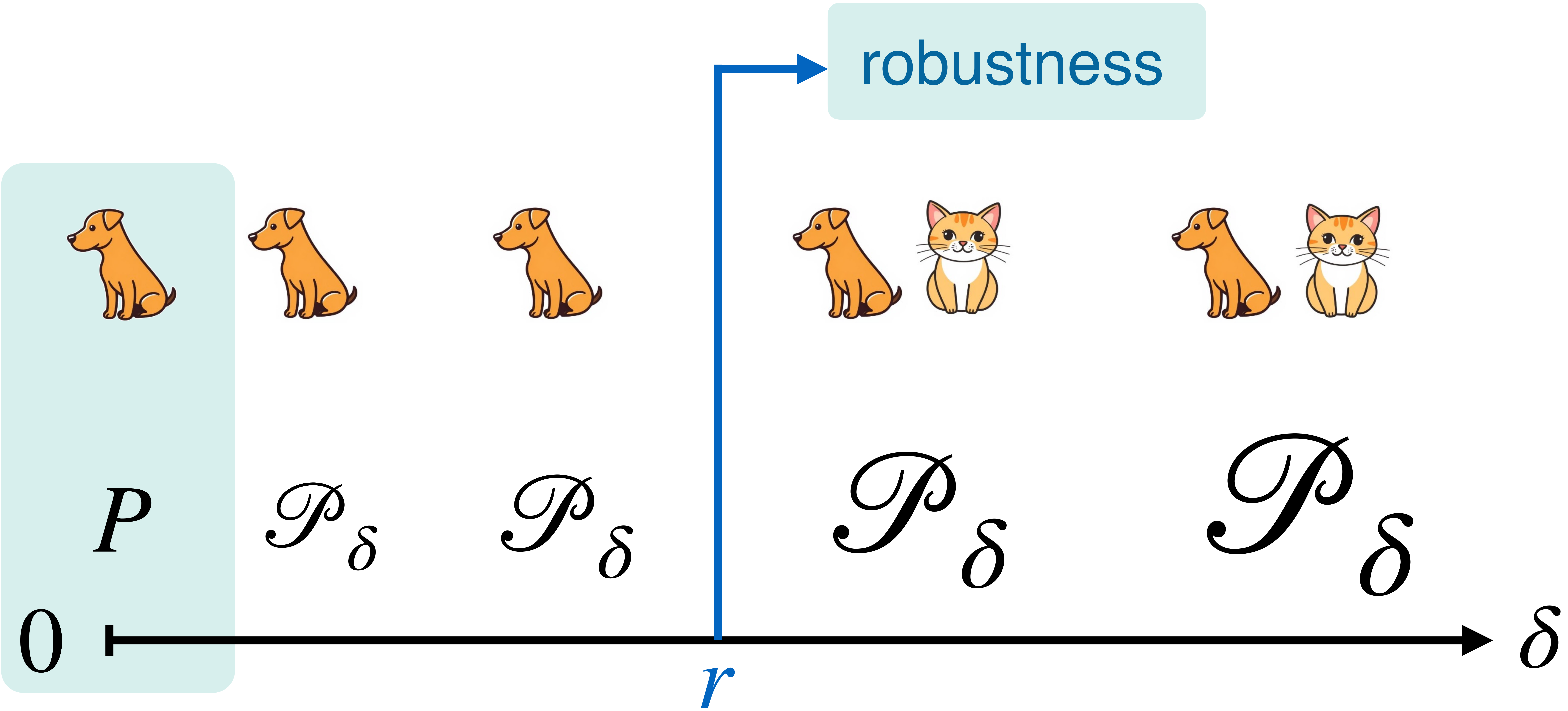

media saying AI will take over the world
my neural network:
Dog


Perhaps imprecise probabilities can help?
saying AI will
er the world
my neural network:
Dog

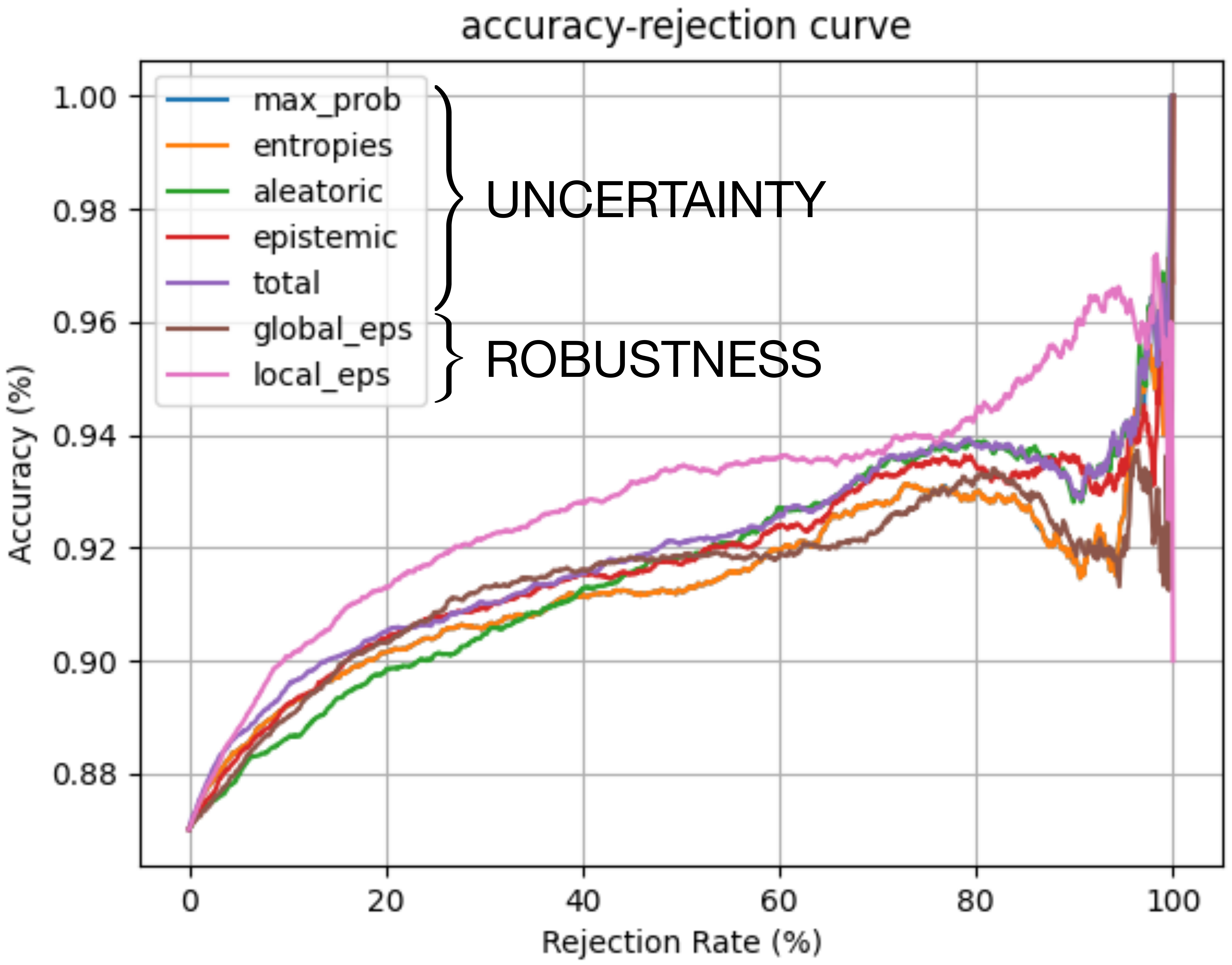
CREDAL CLASSIFICATION

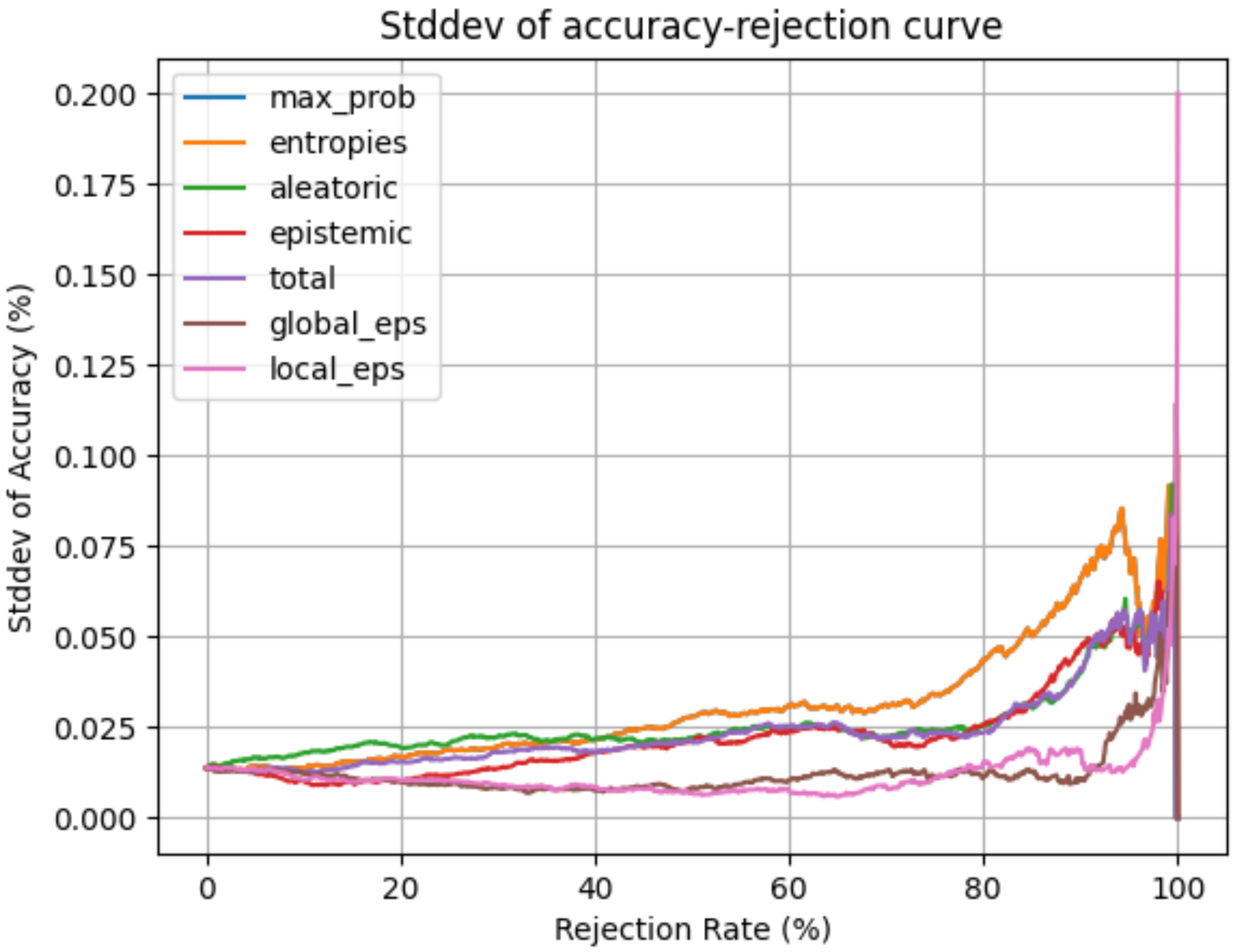


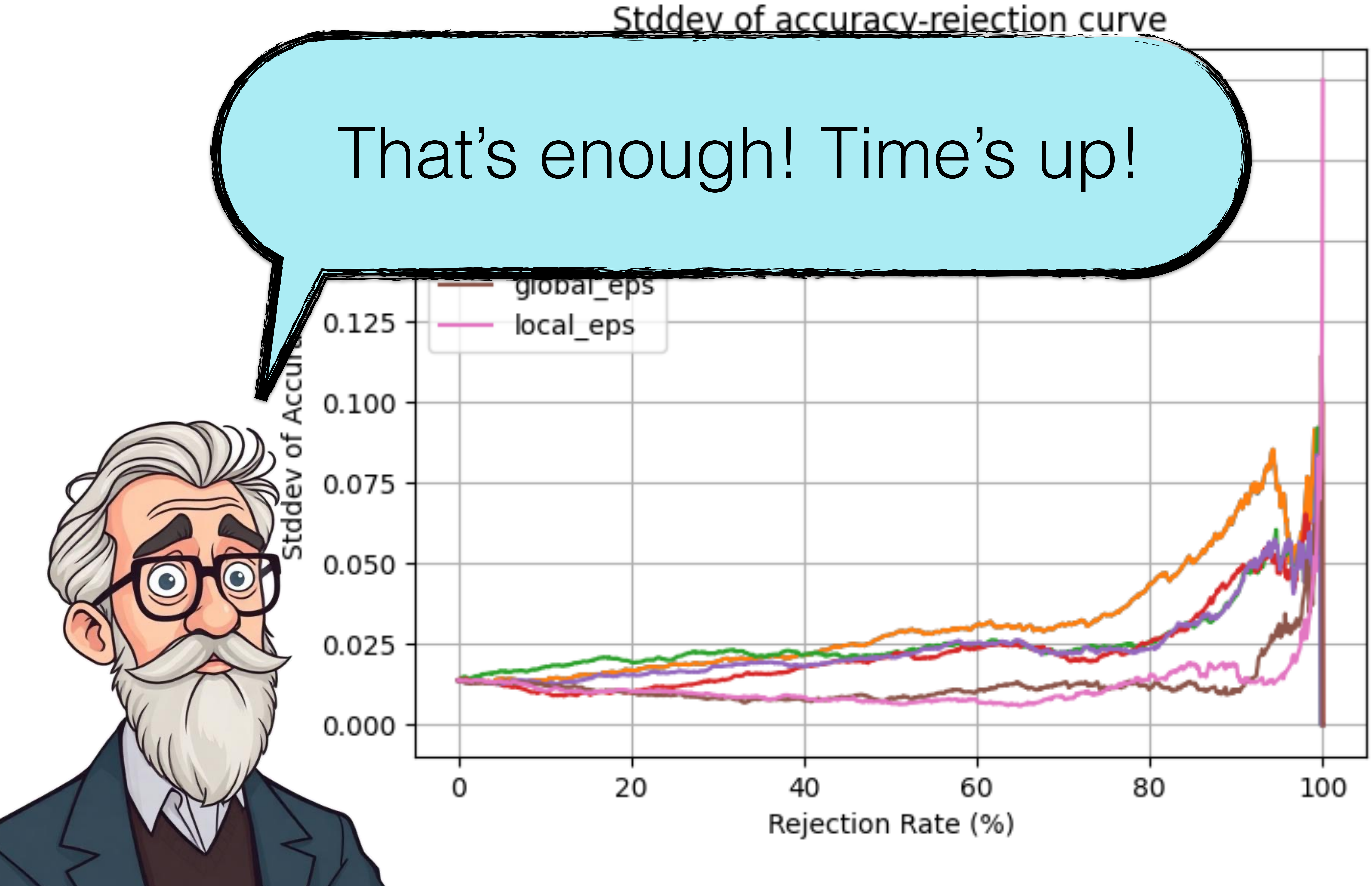
ROBUSTNESS QUANTIFICATION




Does this actually work?
my neural network:
Dog
a saying AI will
over the world


accuracy-rejection curve
max_prob
entropies
aleatoric
epistemic
total
global_eps
local_eps
UNCERTAINTY
ROBUSTNESS
Accuracy (%)
Rejection Rate (%)
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0
20
40
60
80
100


Stddev of accuracy-rejection curve
Stddev of Accuracy (%)
Rejection Rate (%)
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
0
20
40
60
80
100
max_prob
entropies
aleatoric
epistemic
total
global_eps
local_eps



Stddev of accuracy-rejection curve
That's enough! Time's up!
global_eps
local_eps
0.125
0.100
0.075
0.050
0.025
0.000
0
20
40
60
80
100
Rejection Rate (%)