Global Warming Mitigation Investments Optimized under Uncertainty

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- The ‘climate problem’:
  Cost Benefit vs. Cost Effectiveness Analysis
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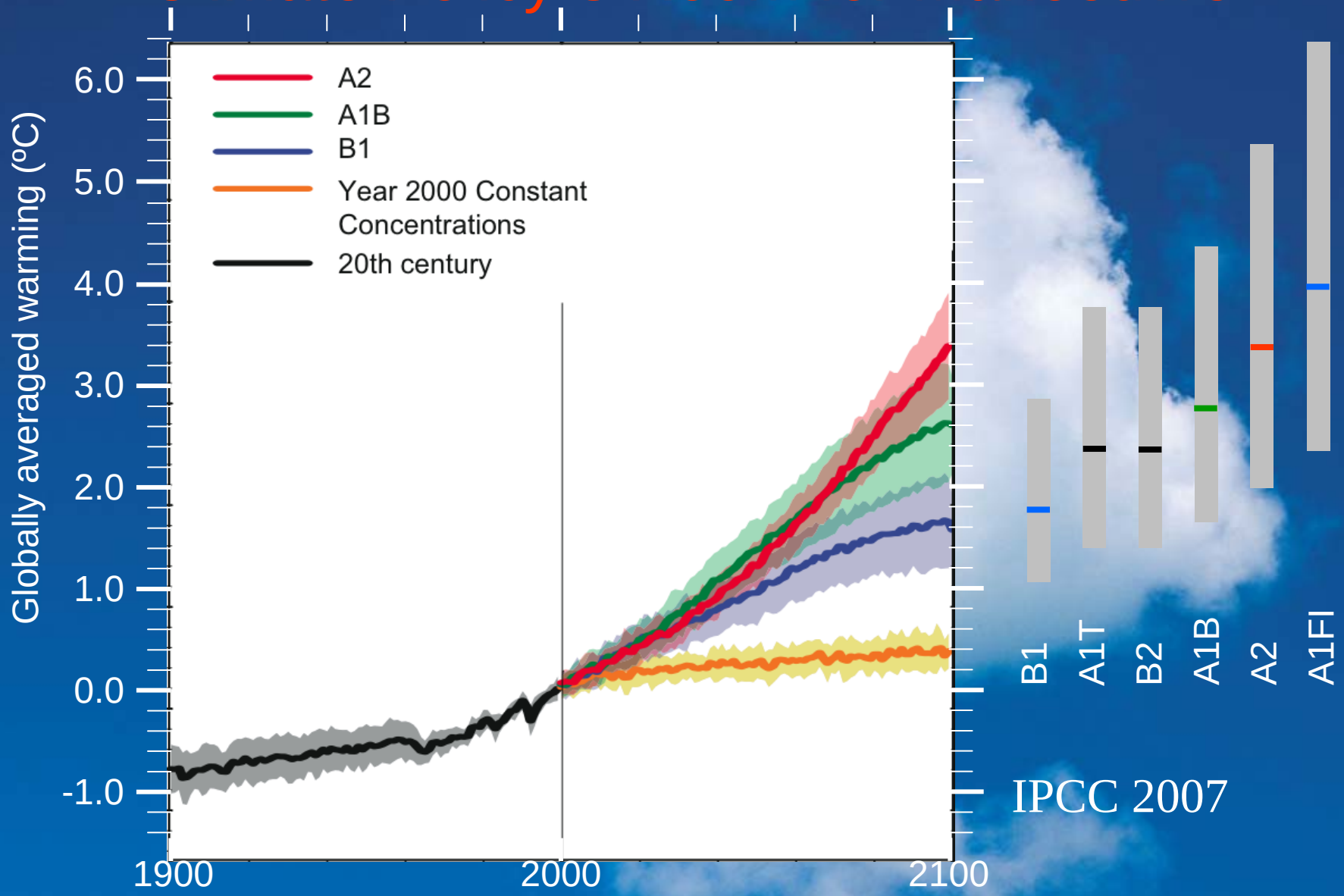
  - Without learning
  - With learning
- Stimulating investments via EIT?

Future Temperature Rise: Climate Policy´s Room for Manoeuvre



IPCC 2007

Extreme Weather Conditions 2007

Floods in England

Forest Fires in Southern Europe

Floods in Southeast Asia

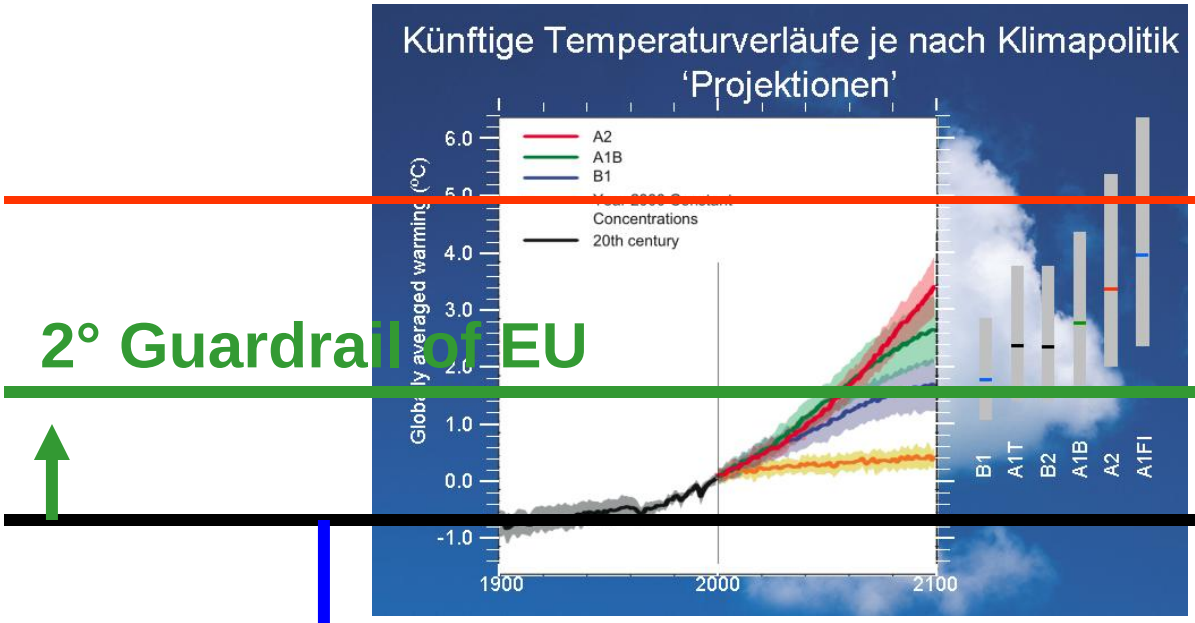
Heavy Storm Kyrill

Typhoon Sepan

Two Lines of Argument behind Global Warming Mitigation Policies

- Explicitly projected impacts of global warming ‘too large’
- Precautionary principle
  - beyond certain regimes knowledge too poor to weigh costs and benefits

Historic Dimension of Temperature Rise



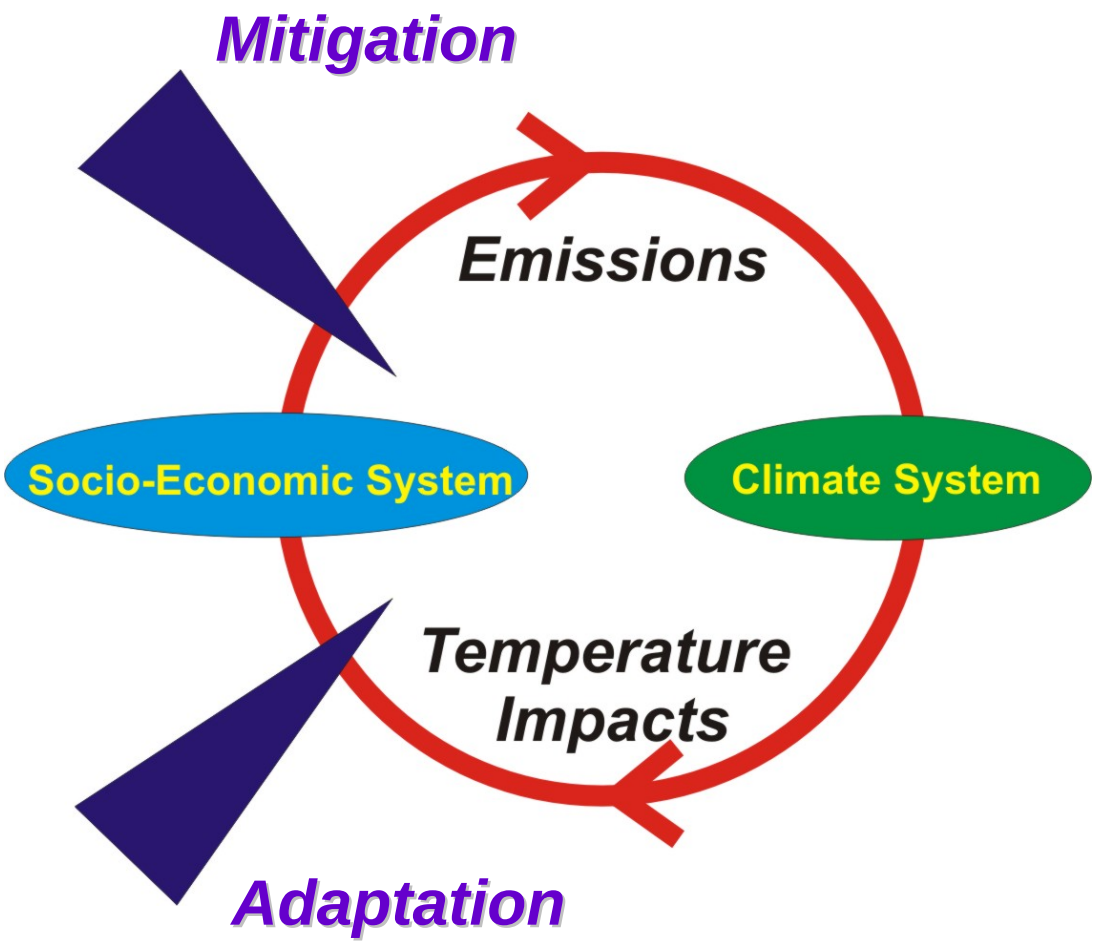
("Hot House"
– at least
55Million years ago)

2° Guardrail of EU

Holocene

Last Ice Age
(until ~10 000 years)

Facing Global Warming:
Two possible Climate Policies



Limits to ‚Adaptation-Only'?

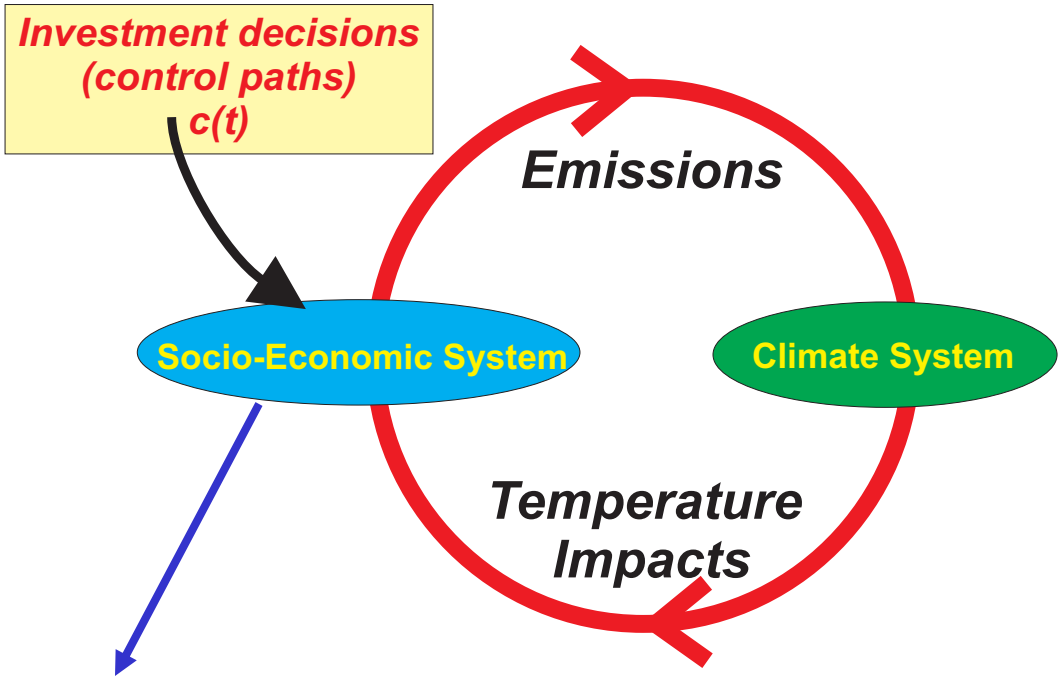
© Bill Hare

When to Invest How Much into which Energy Technology?

Phrasing as a Control Problem

Investments in

- ***Renewables***
- ***Efficiency***
- ***Fossil Fuels***
- ***CCS***



$$\mathrm{Max}_c \; ! \int dt \; \mathrm{Welfare}(t) \; [c(-t_0{}')\ldots c(t)] \;\; \exp(-r\, t);$$

„Cost-Benefit-Mode“

Conceptual Difficulties

- Impacts poorly known
  - Often poor natural science/engineering knowledge (at least today)
  - Need for valuation of goods
- Need to weigh
  - Present mitigation costs … against …
  - Future avoided damages

When to Invest How Much into which Energy Technology?

Phrasing as a Control Problem

Investments in

- ***Renewables***
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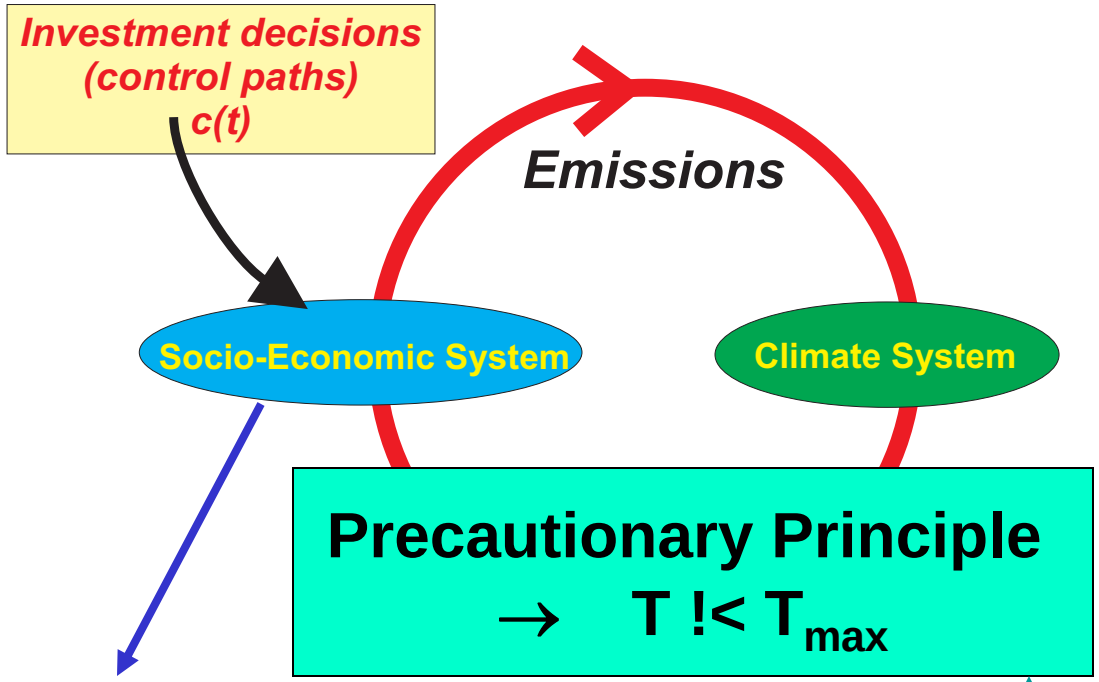


Precautionary Principle

$\rightarrow$ T !< T_{max}

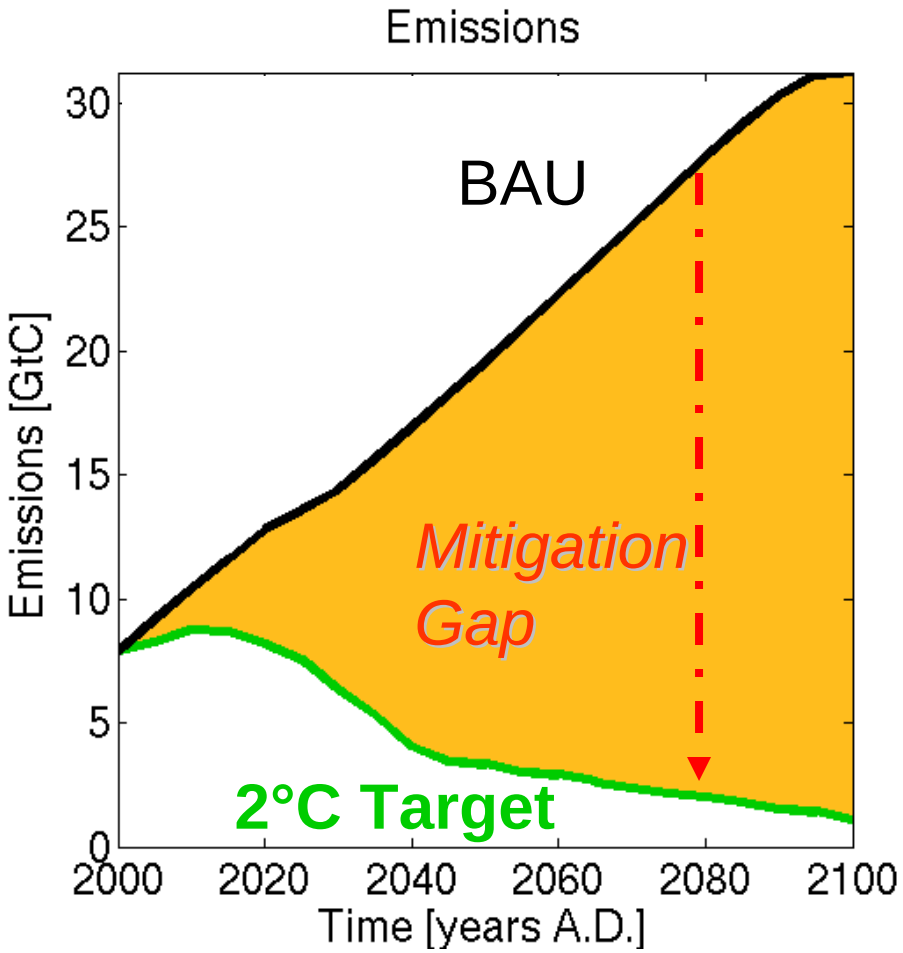
Max_c ! $\int$ dt Welfare(t) [c(-t_0´)...c(t)] exp(-r t);

$\forall$t Temperature(t) [c(-t_0´)...c(t)] within T- guardrail

„Cost-Effectiveness-Mode“

CO_2-Emissions

Business as Usual (BAU) vs EU´s 2°C-Target



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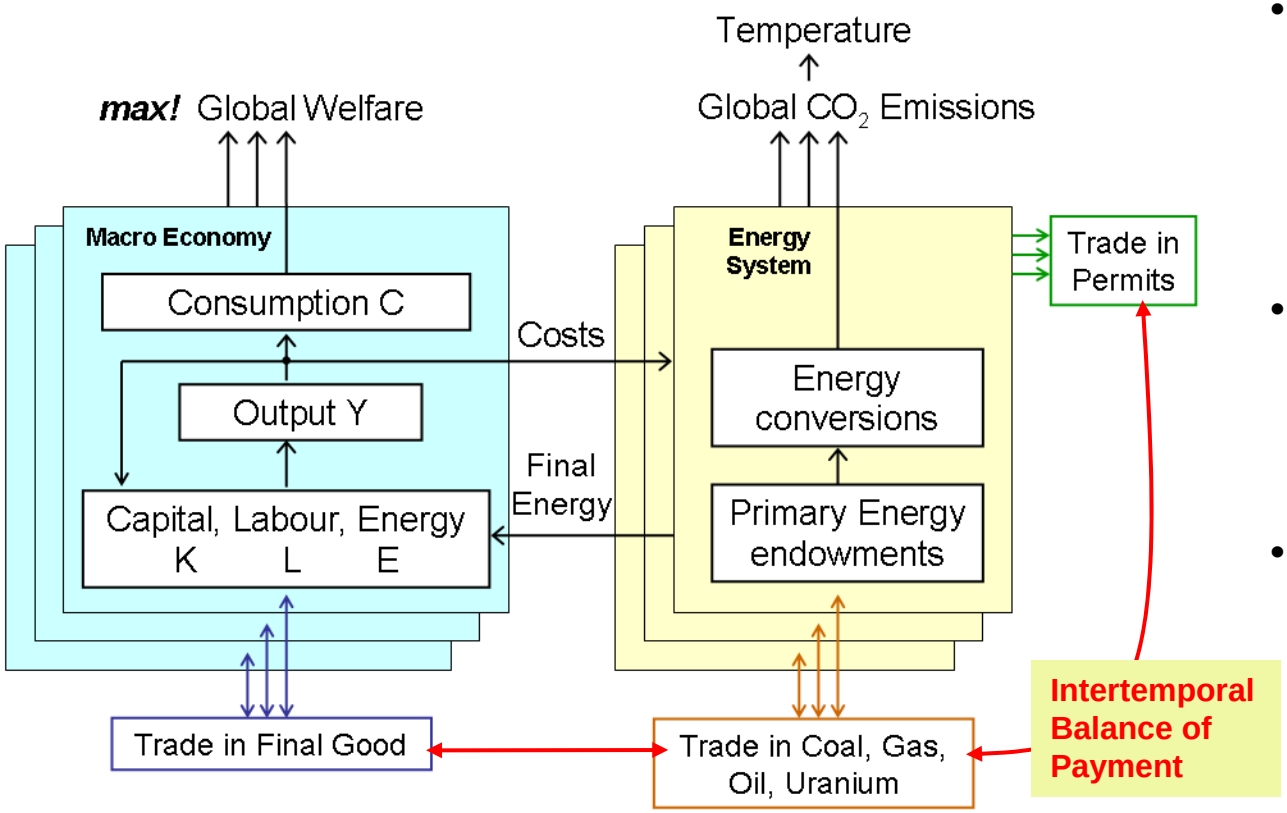
The REMIND-R Model: Basic Characteristics



- Fully coupled macro-economy and energy system (Bauer et al., J. Comp. Mgmt. Sciences 5: 95-117,2008)
- 11 world regions, heterogeneous capital stocks in energy sector, international trade
- Regionally specific fossil fuel endowments and renewable energy potentials

Benchmark (1st best) solution: Includes full when, where, what flexibility

Intertemporal optimization of regional welfare

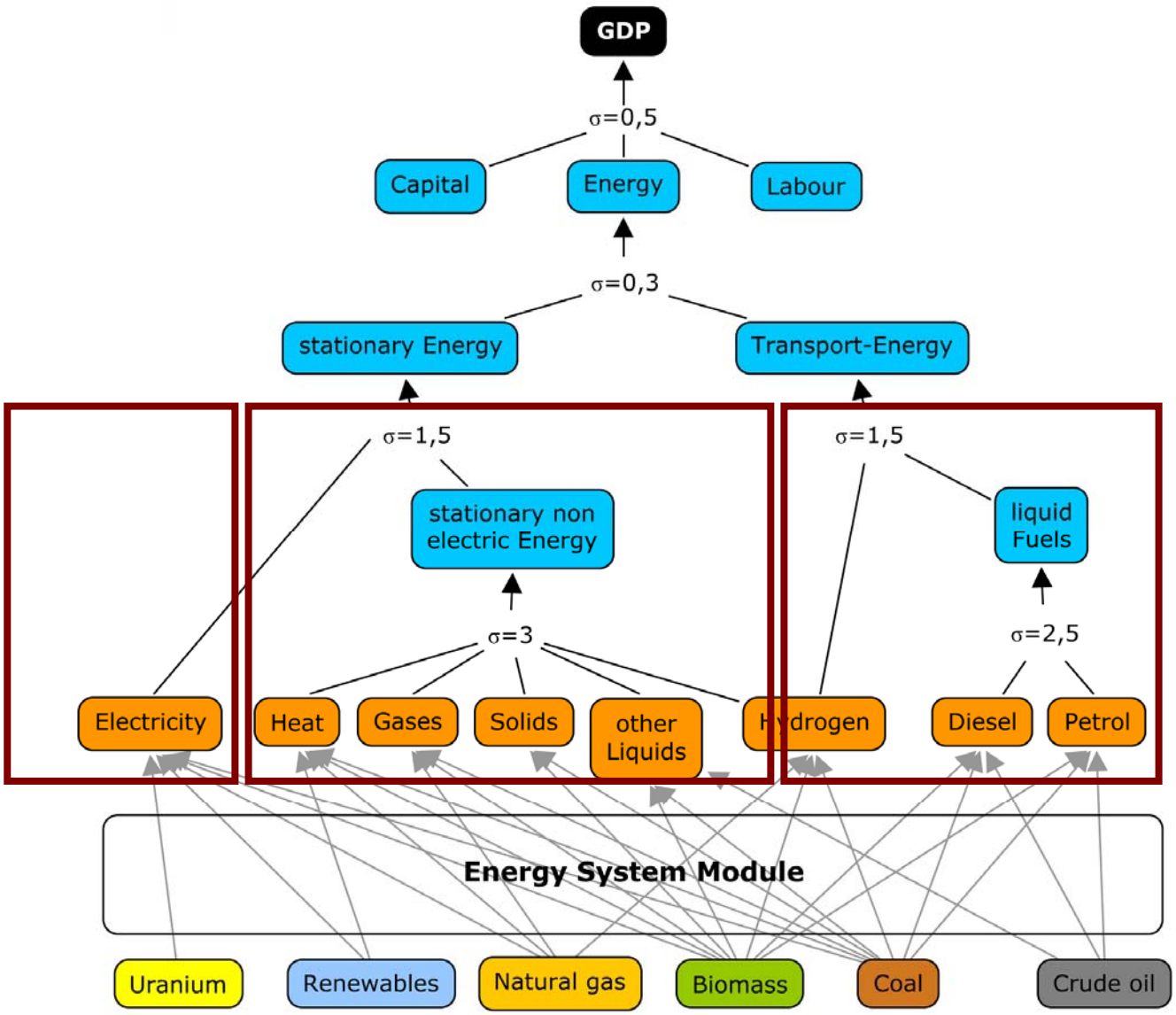
Intertemporal equilibrium of capital, energy and goods markets (Pareto optimum)

2nd best solutions: Implemented by adding constraints

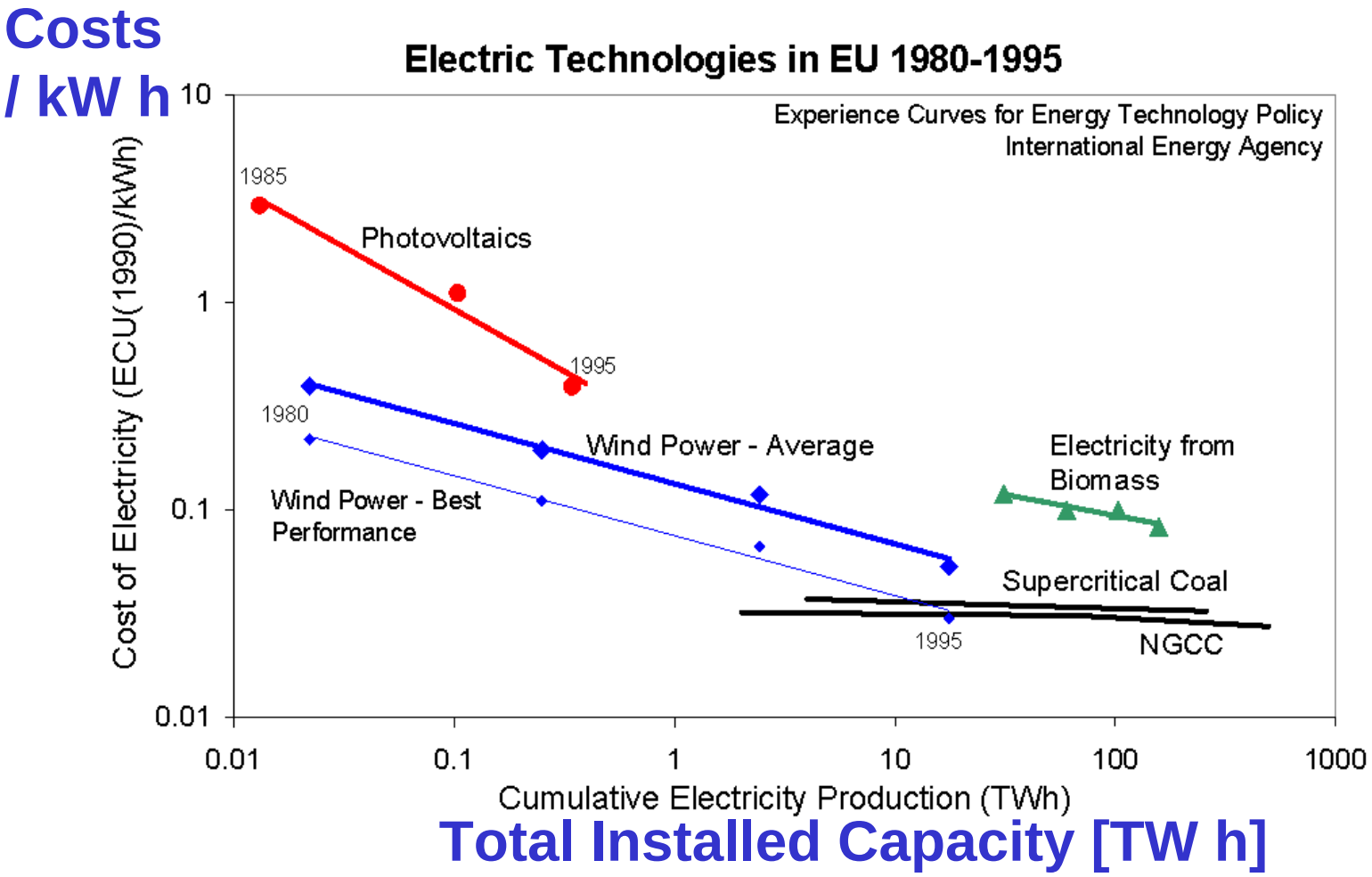
Delayed participation, Limited availability of technologies, …

Edenhofer et al.

The REMIND-R Model: Energy as Production Factor

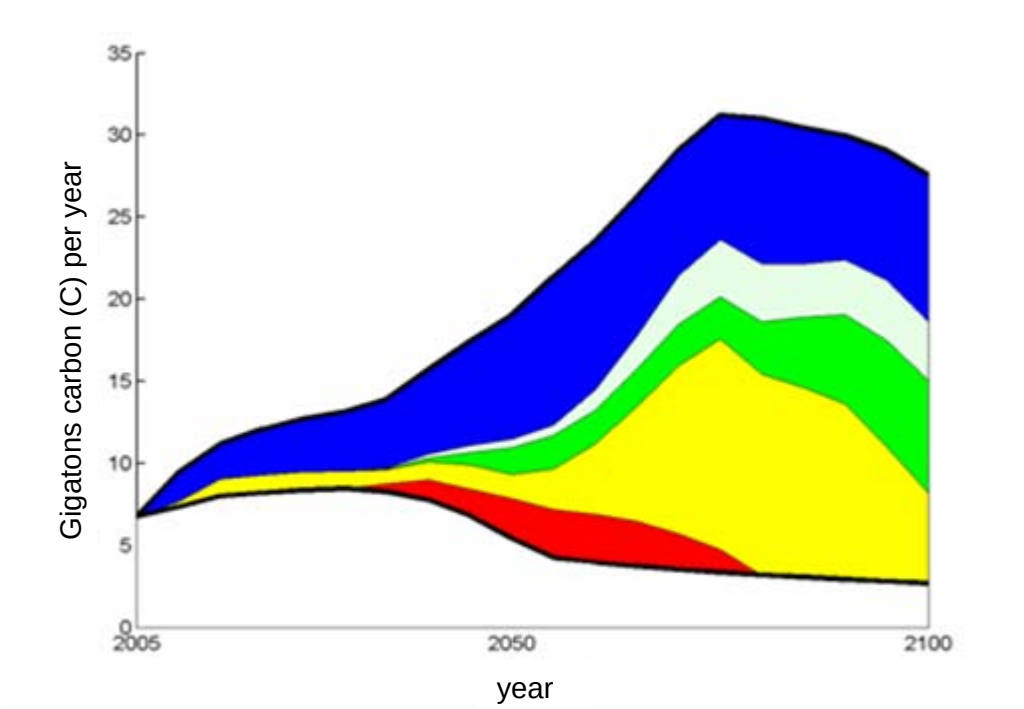


Mass Production lowers Costs



Source: IEA (2000): Experience Curves for Energy Technology Policy; p. 21

Options for CO_2 emissions abatement



Energy-induced emissions

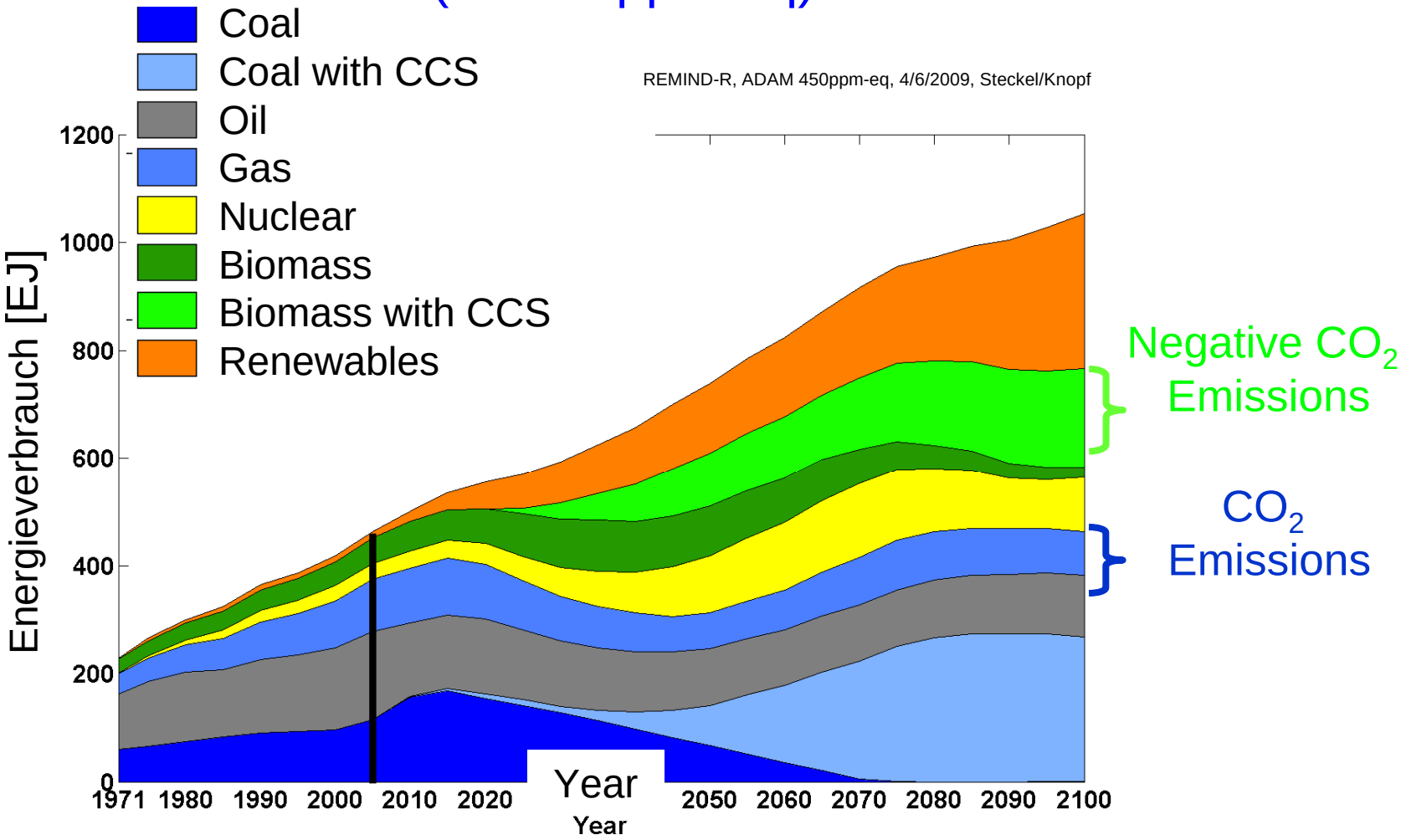
- **nuclear**
- renewables
- biomass + CCS
- fossil + CCS
- efficiency

Bruckner, Edenhofer, Held et. al., 2009

Coal/Oil/Nat.Gas cheap, pure time preference rate 1%, 450ppm target

Higher Resolved Energy System

(for 450ppm-eq)

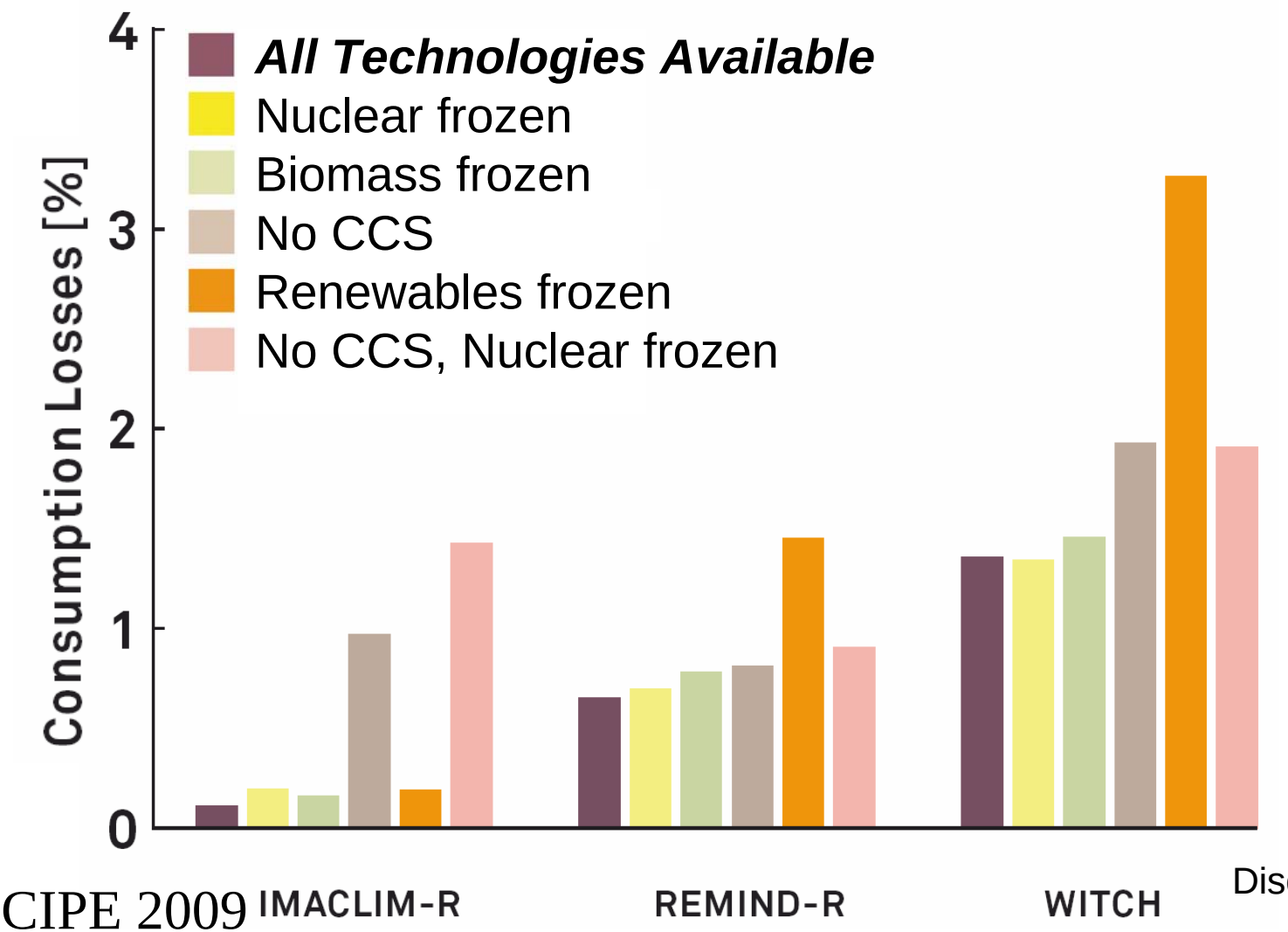


Edenhofer et al.

Based on IEA-Daten (1971-2005) and REMIND-Results for 450ppm-eq (ADAM); Graphics by Jan Steckel (PIK)

Mitigation Costs & Value added by Individual Technologies

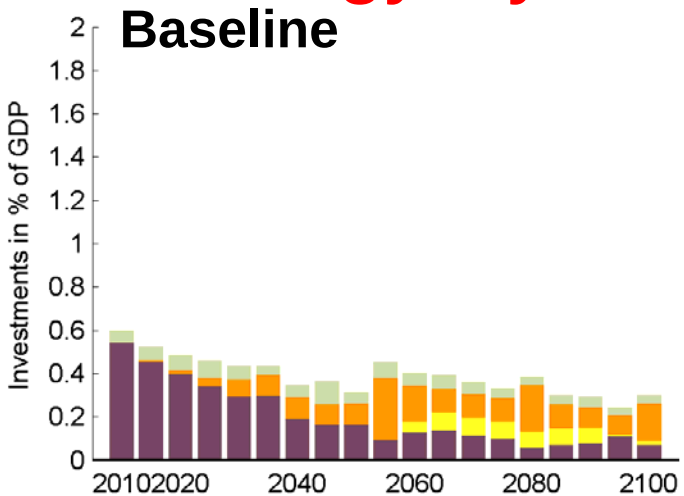
(for 450 ppm (~50% 2°-Target) & 2050 equal per-capita emission rights)

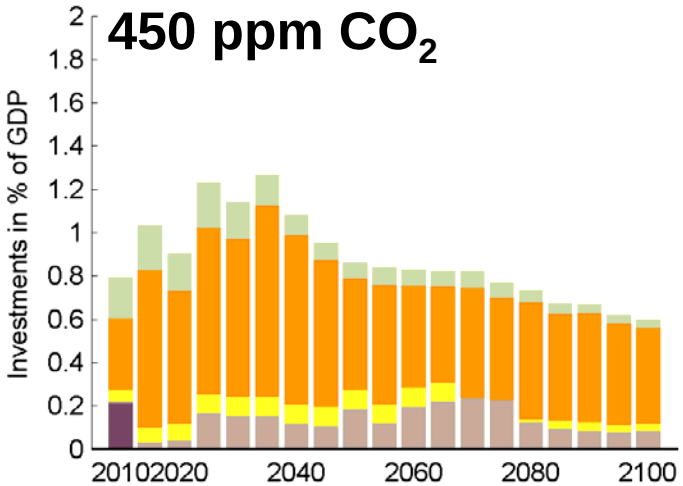


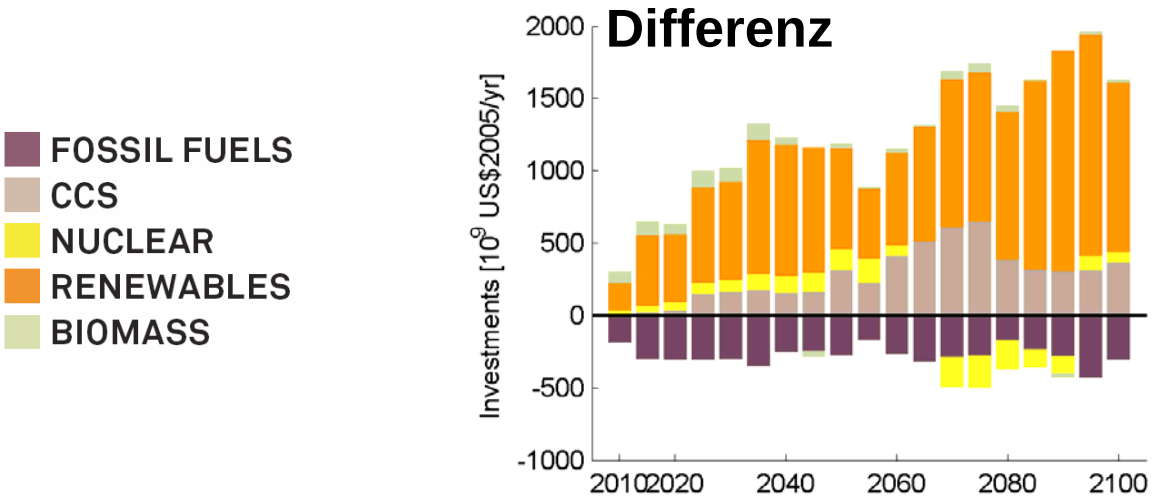
Discounted at 3%

RECIPE 2009

Energy System-Investments







- No investments into conventional fossils after 2015
- ½ … 1% GDP into renewables

RECIPE 2009

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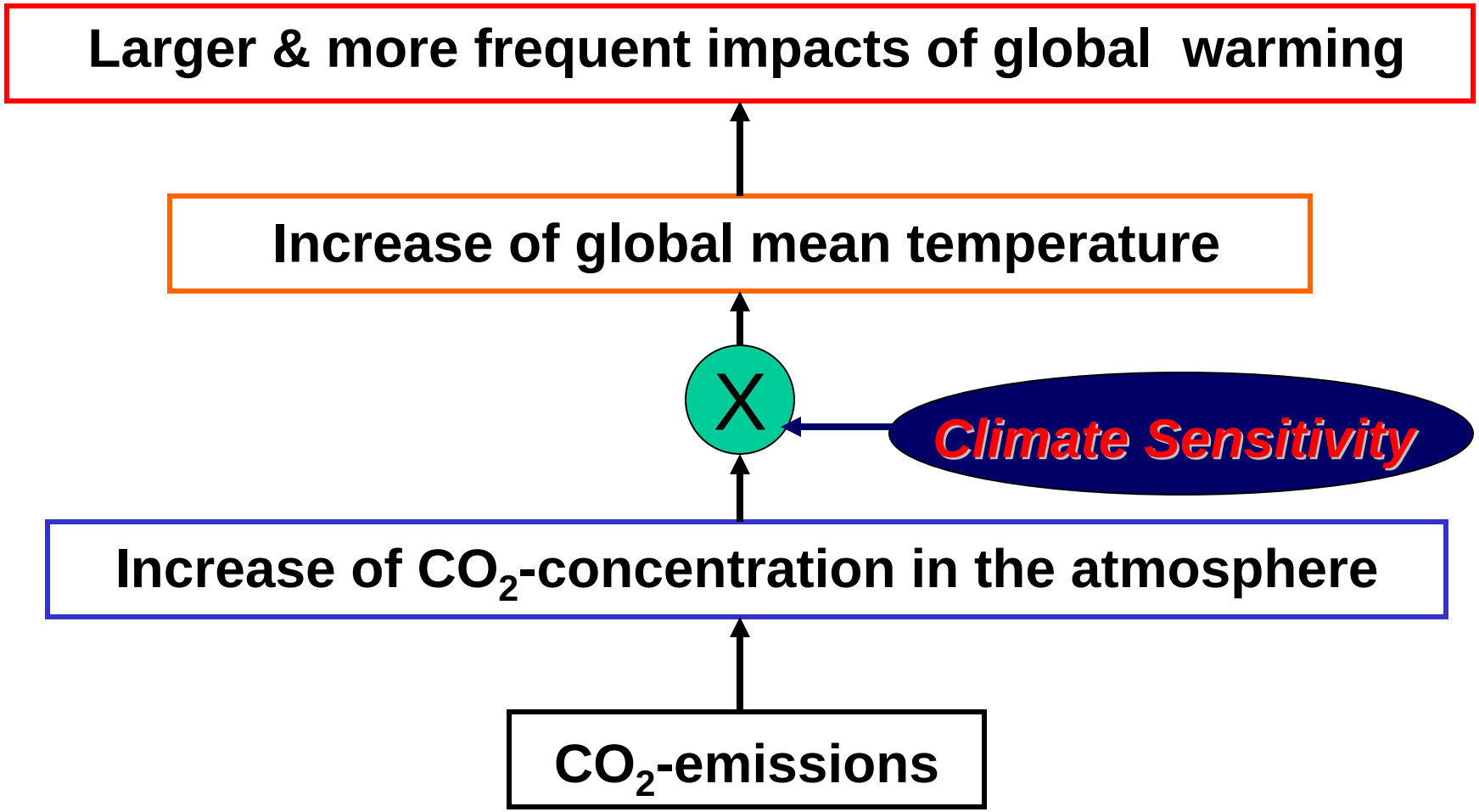
Hedging Strategy needed in view of ‘Irreversibility Effect under Uncertainty‘

- Our actions may have irreversible effects:
  - Investing too early in a specific energy technology or adaptation measures may lead to stranded investments.
  - Waiting too long on mitigation may trigger irreversible climate system or ecological effects.

→ Again an application for optimisation, if uncertainty is reflected in the welfare function.

Key Factor Climate Sensitivity



Definition of Climate Sensitivity

- CS:= Change in global mean surface temperature for doubling pre-industrial CO_2 concentration, i.e.

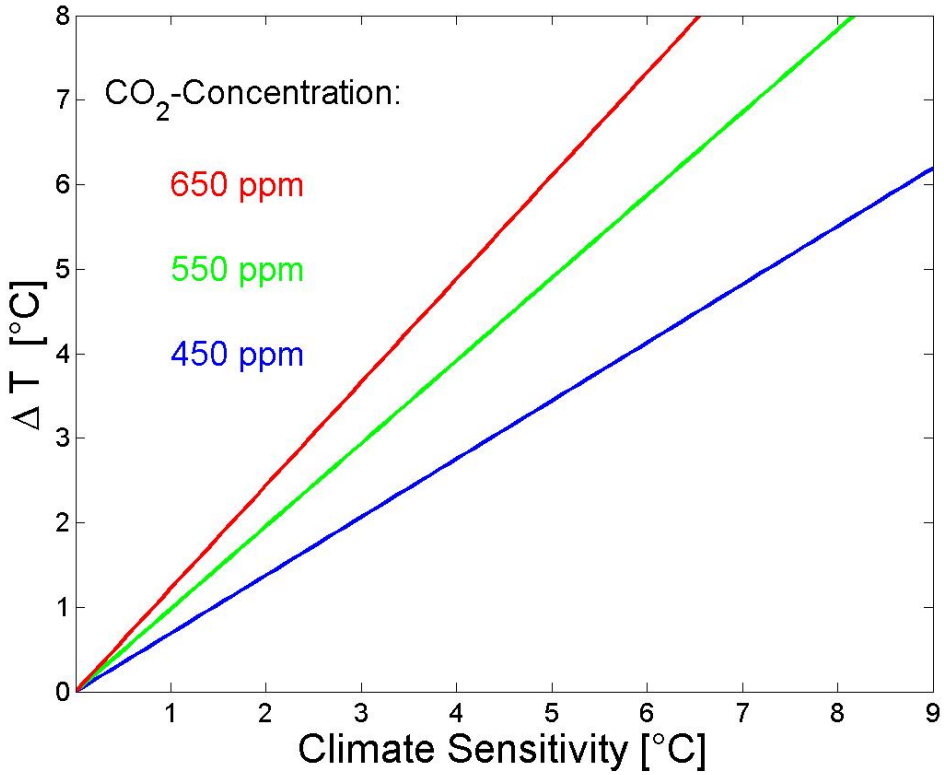
- T(560 ppm CO_2) – T(280 ppm CO_2)

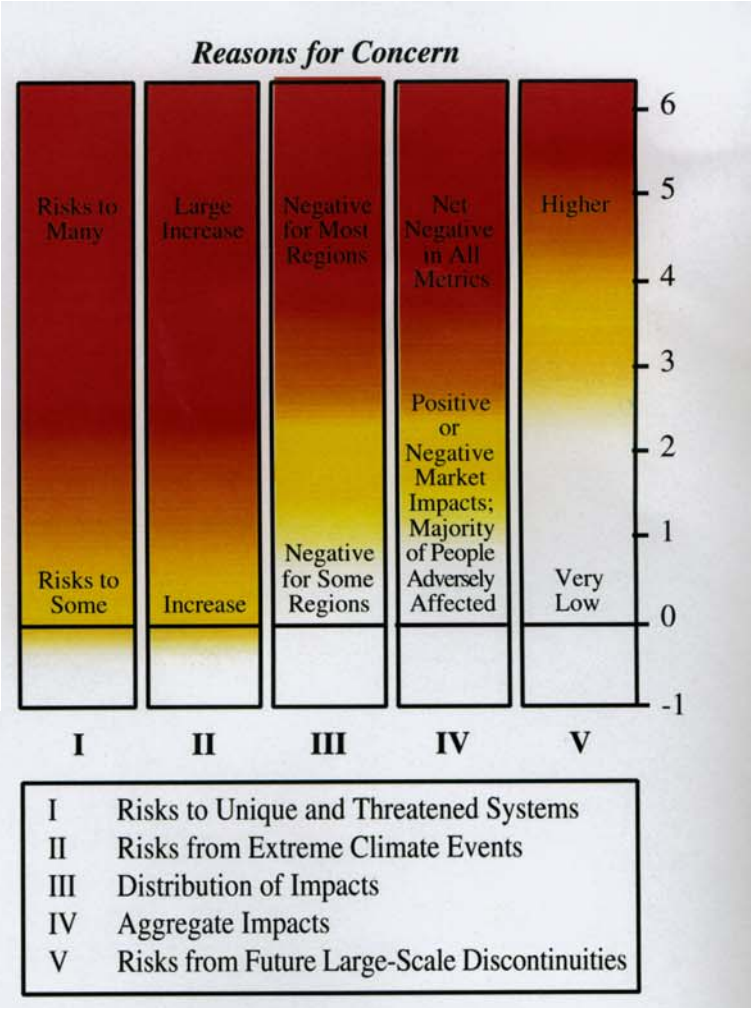
- *Convenient climate system surrogate: Uncertainty in CS explains > 50% of uncertainty in global warming projections*

Perturbing a Second Important Climate Parameter

Climate Sensitivity	$\propto$	Temp ($t \rightarrow \infty$)
Ocean Heat Uptake	$\propto$	Lin. Temp – Response Time Scale

Climate Sensitivity → Impacts





IPCC WG II (2001)

The following graphs are from

- Hermann Held, Elmar Kriegler, Kai Lessmann, Ottmar Edenhofer:

  Efficient Climate Policies under Technology and Climate Uncertainty

  Energy Economics – special issue on induced technological change & uncertainty, 2009

The simplified Model

Simplifications in MIND as against REMIND

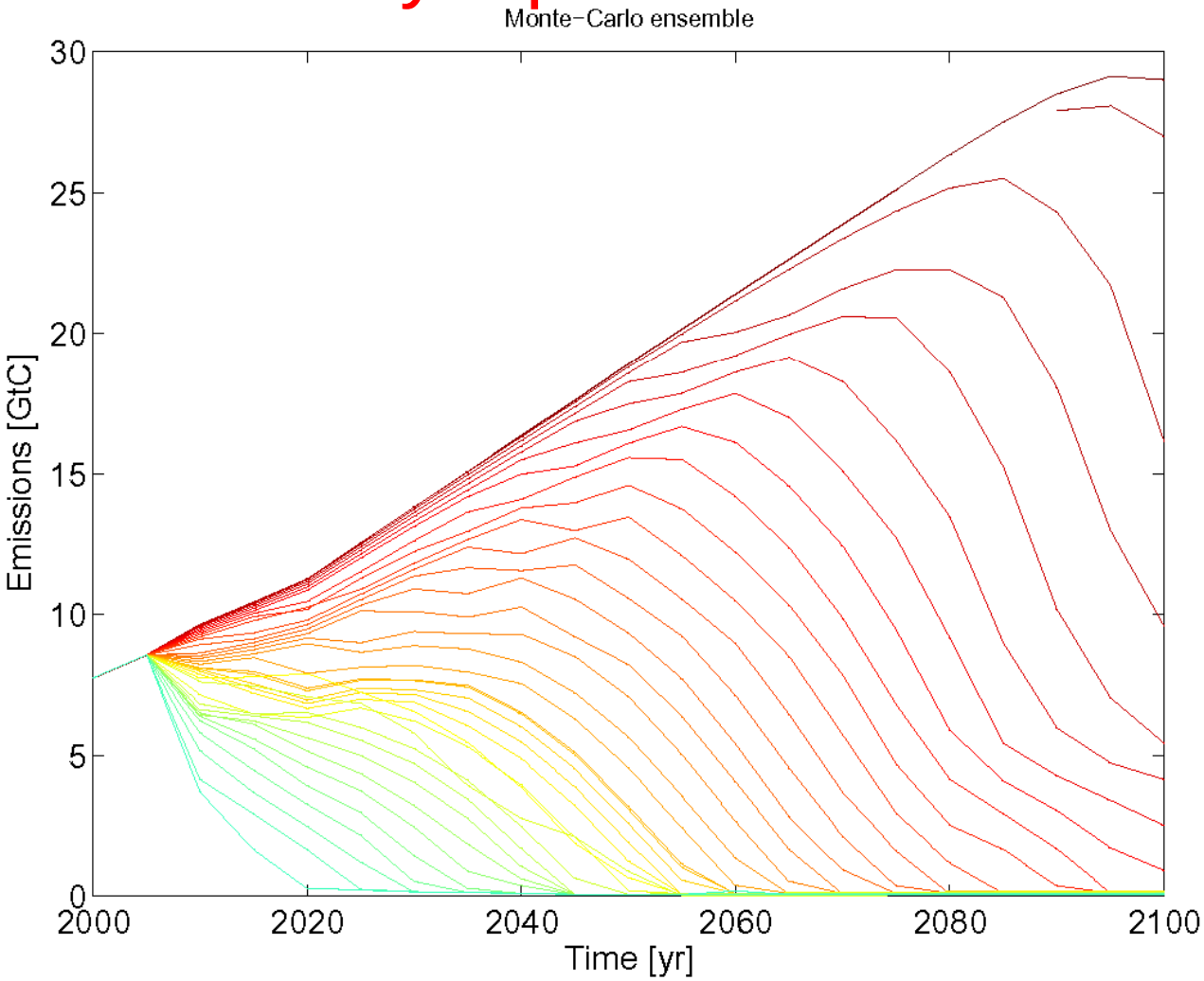
- Endogenous technical change over both learning-by-doing and R&D in labor- and energy-efficiency.

- Crudely resolved energy sector with renewables, fossils, and fossil extraction.

- Starting with

  a series of sensitivity studies…

Strong Influence of Climate Sensitivity on Economically Optimal Emission Paths



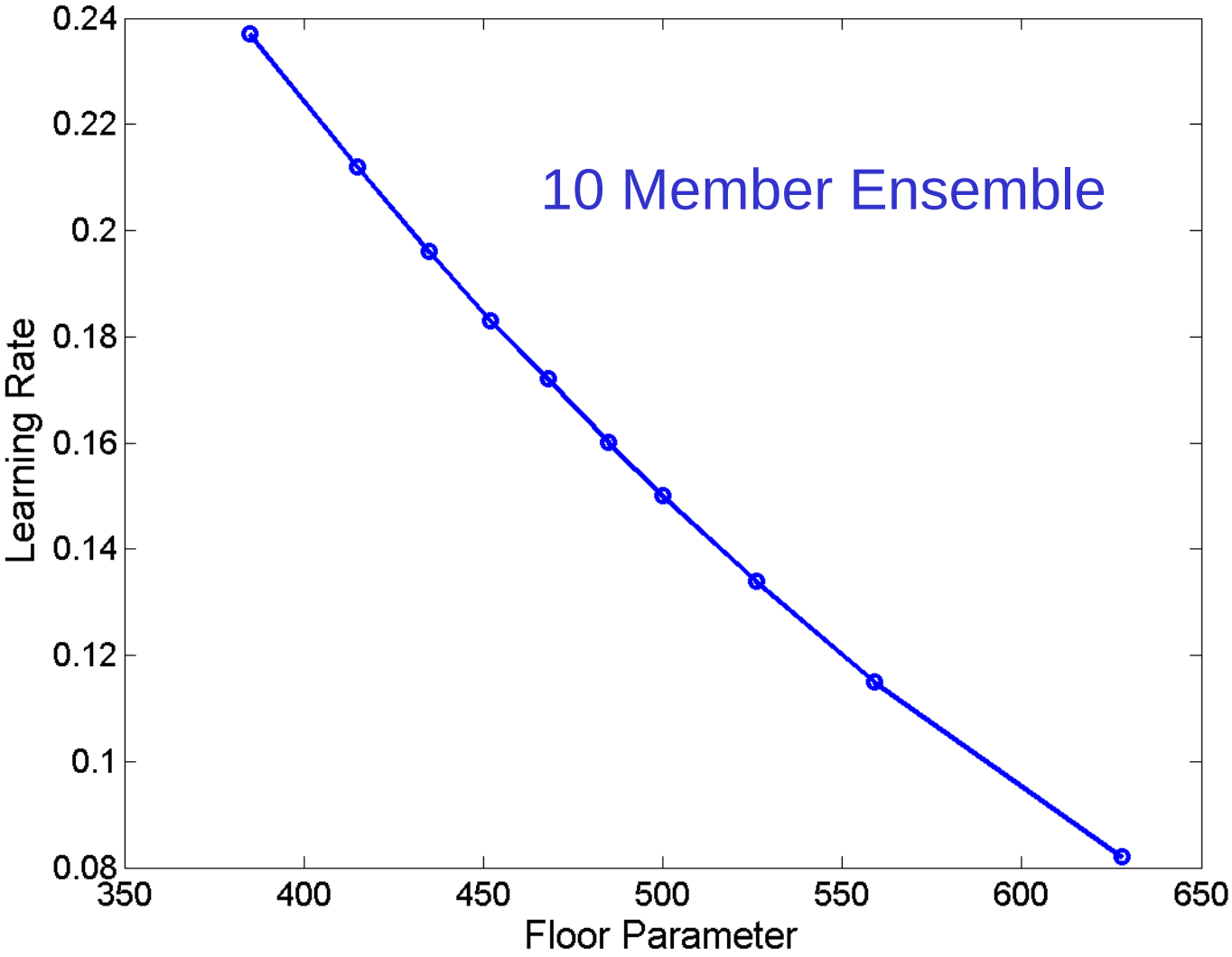
..in MIND

Addressing also Technological Uncertainty

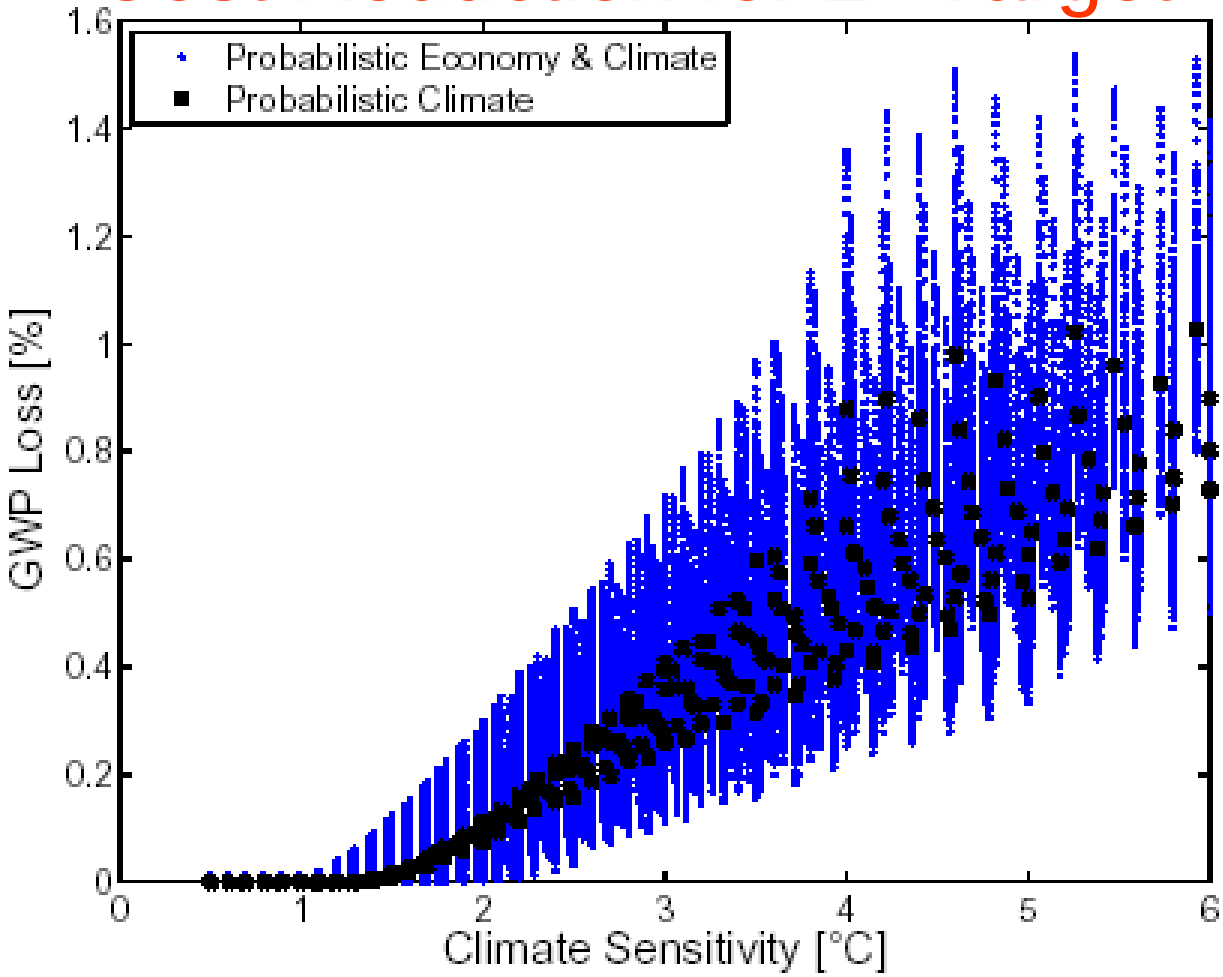
Factorial Design

- 10 Rogner Parameter (fossil resource base)
- X 10 Learning Rate of Renewables
- X 300 Climate (correlated climate sensitivity & ocean heat uptake)
- $\Rightarrow$ 30 000 ‘Parallel Worlds’

Co-Variation of Learning Rate & Floor Parameter



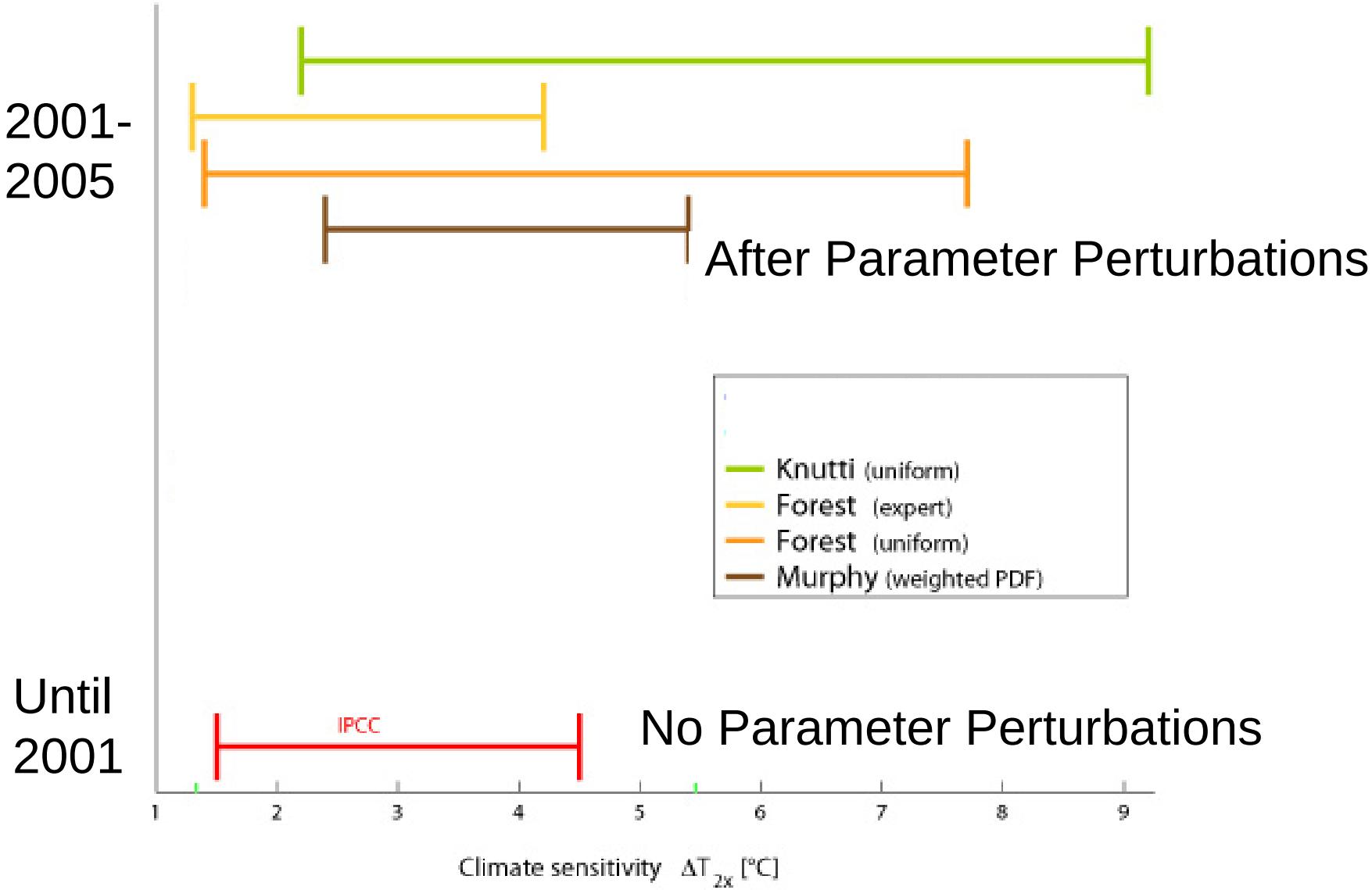
Lower Climate Sensitivity implies Cost Reduction for 2° Target



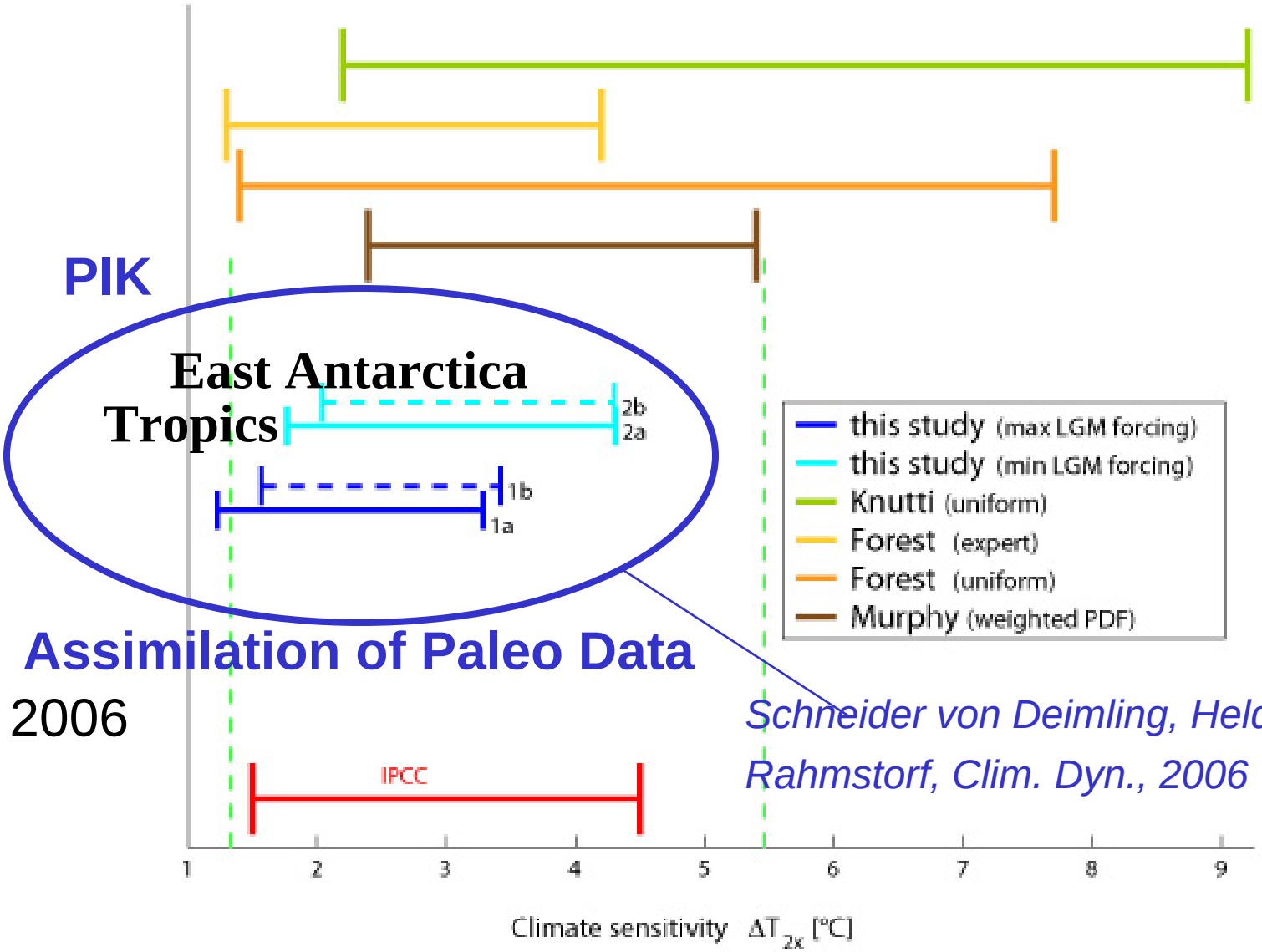
Held et al., Energy Economics (2009)

Climate Science‘s evergreen: Knowledge on CS

5...95% Quantiles



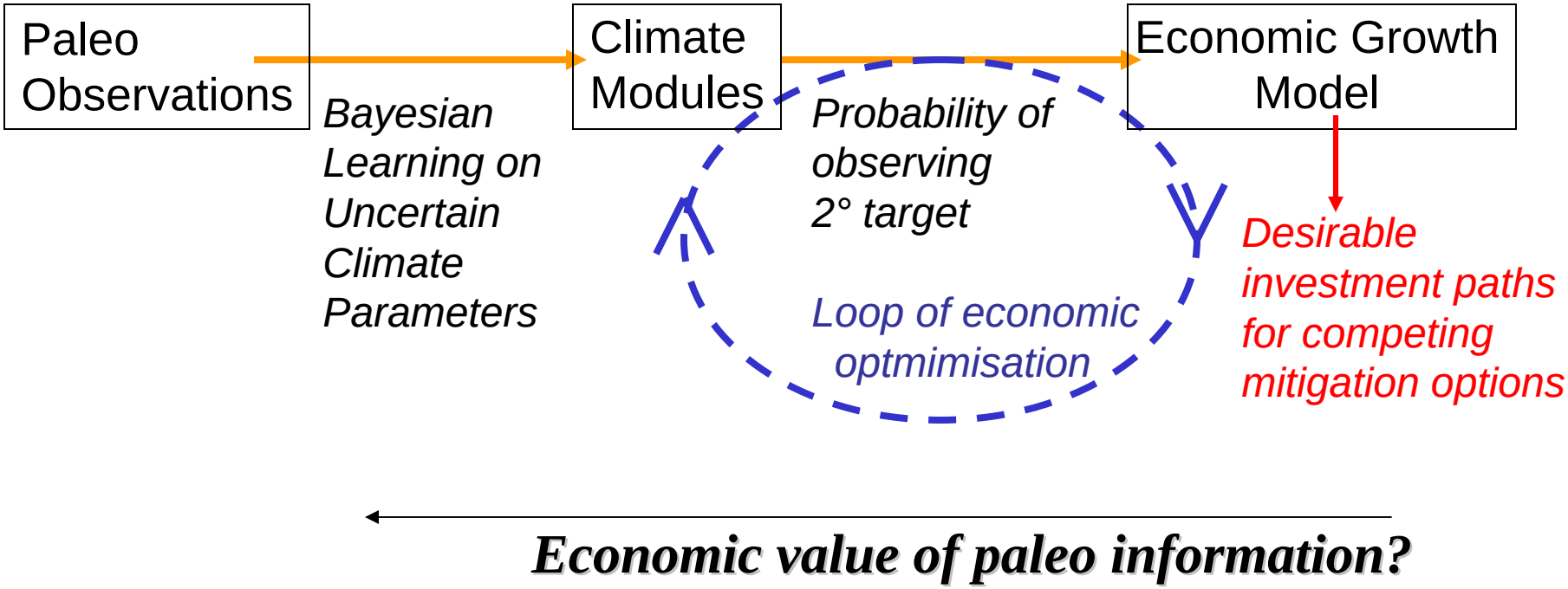
CS: 5...95% Quantiles



Assimilation of Paleo Data

2006

Schneider von Deimling, Held, Ganopolski, Rahmstorf, Clim. Dyn., 2006



Economic value of paleo information?

- ***LGM -> Climate sensitivity (Schneider von Deimling, Held, Ganopolski, Rahmstorf, 2006)***

- ***8k-event -> ocean time scales (Lorenz, Held, Bauer, Schneider; 2010; Heraeus-Prize 2008)***

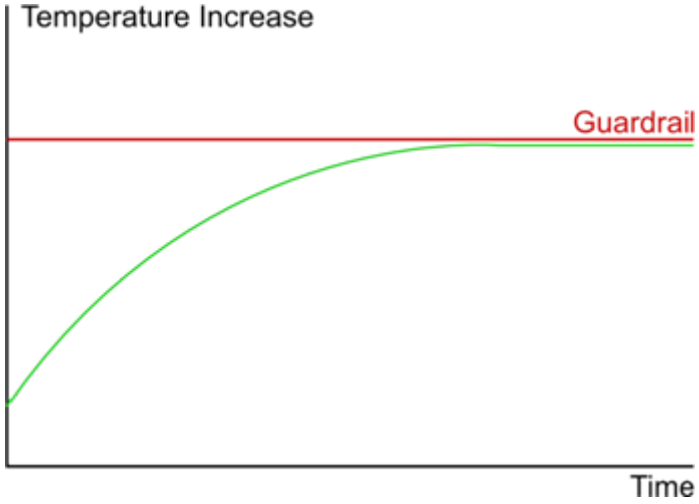
Economic Optimisation internalising Uncertainty

Factorial Design

- 10 Rogner Parameter (fossil resource base)
- X 10 Learning Rate of Renewables
- X 300 Climate (correlated climate sensitivity & ocean heat uptake)
- $\Rightarrow$ 30 000 'Parallel Worlds'

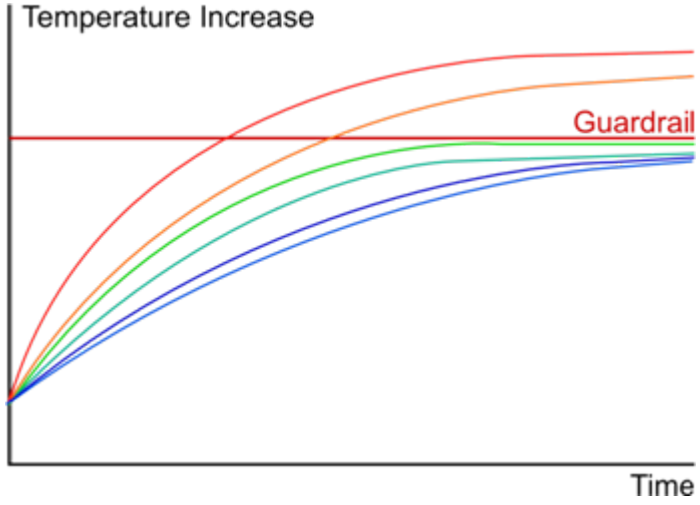
- Optimise Expected Utility
- Under $P(T<2°) = 75\%$ boundary condition

Probabilistic Guardrail
‘Chance Constrained Programming’ (CCP)



<u>Deterministic Guardrail</u>

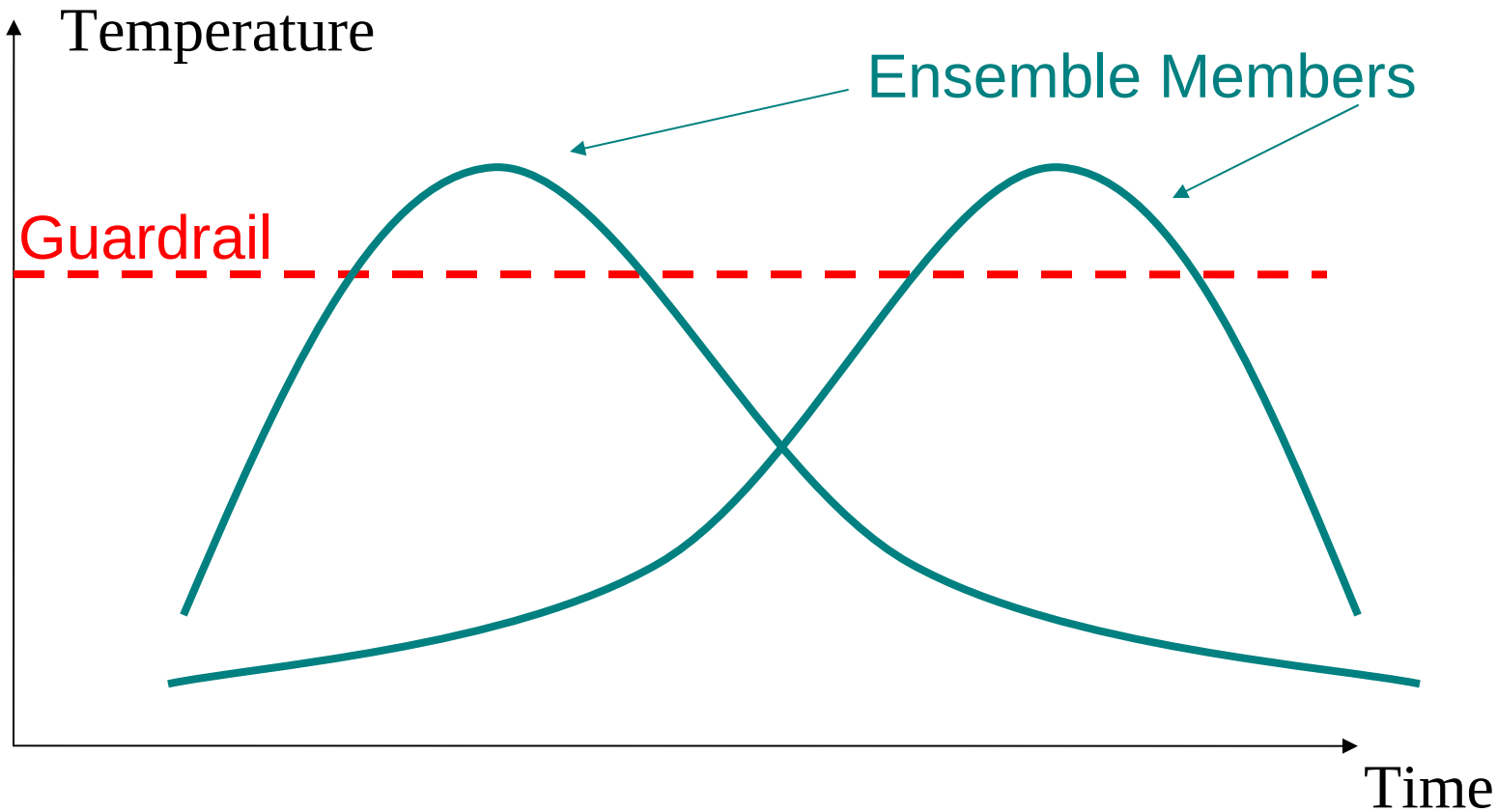
- Single Investment Strategy
- Single Temperature Profile keeping the Guardrail



<u>Probabilistic Guardrail</u>

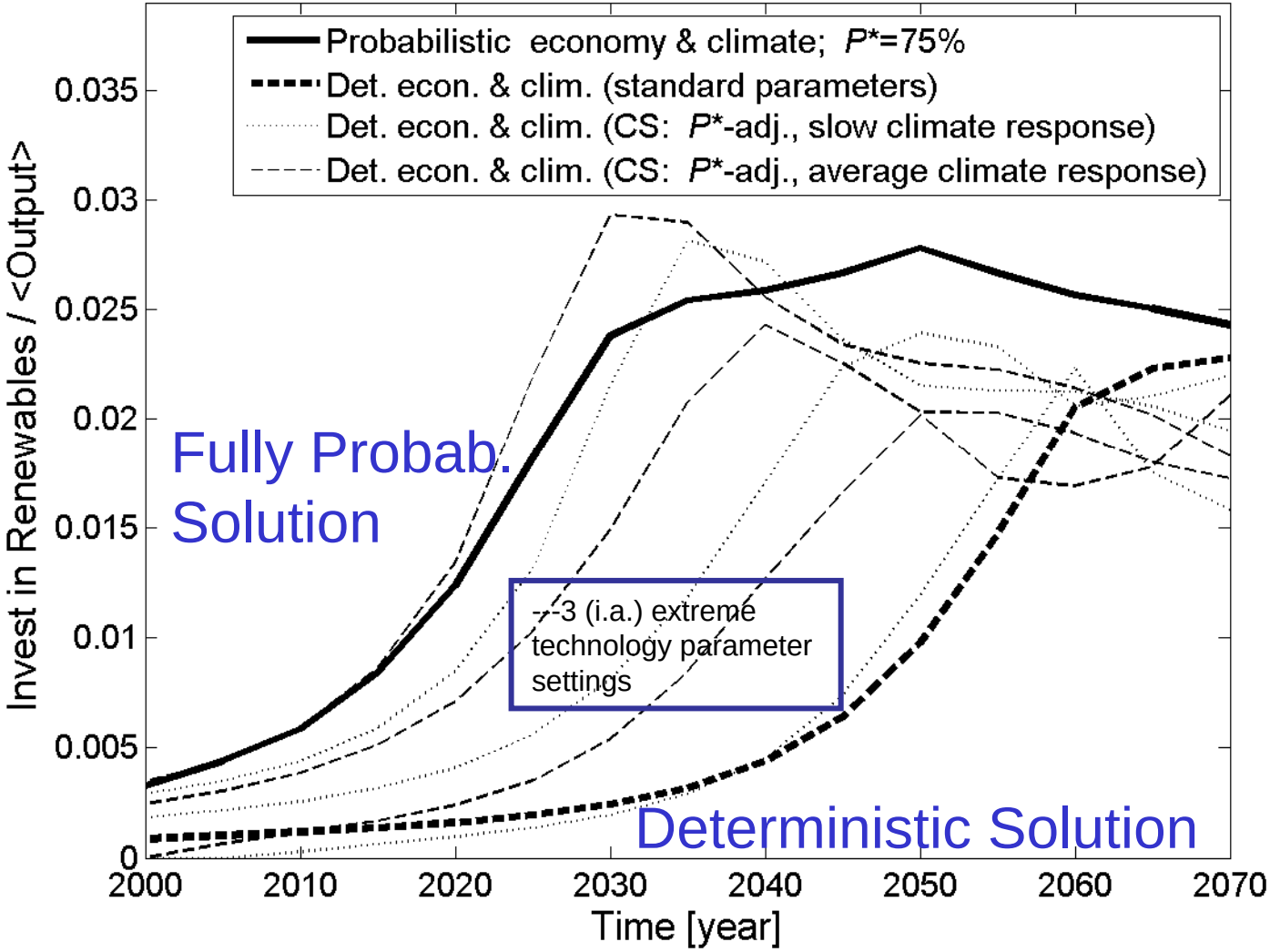
- Single Investment Strategy
- Multiple Temperature Profiles due to Uncertainties
- p% keep the Guardrail
- (1-p)% may exceed the Guardrail

Two Guardrail Versions



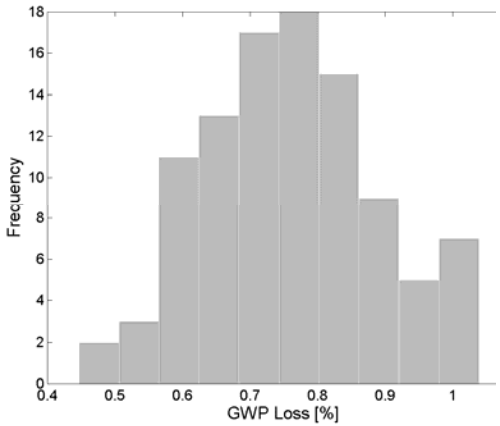
- **Version I: $P(\forall_t \; T(t) \leq T_{max}) = 0$ – stricter condition**
- **Version II: Given t, $P(T(t) \leq T_{max}) = 50\%$ or 100%**
- **Version I observed $\Rightarrow$ Version II observed**

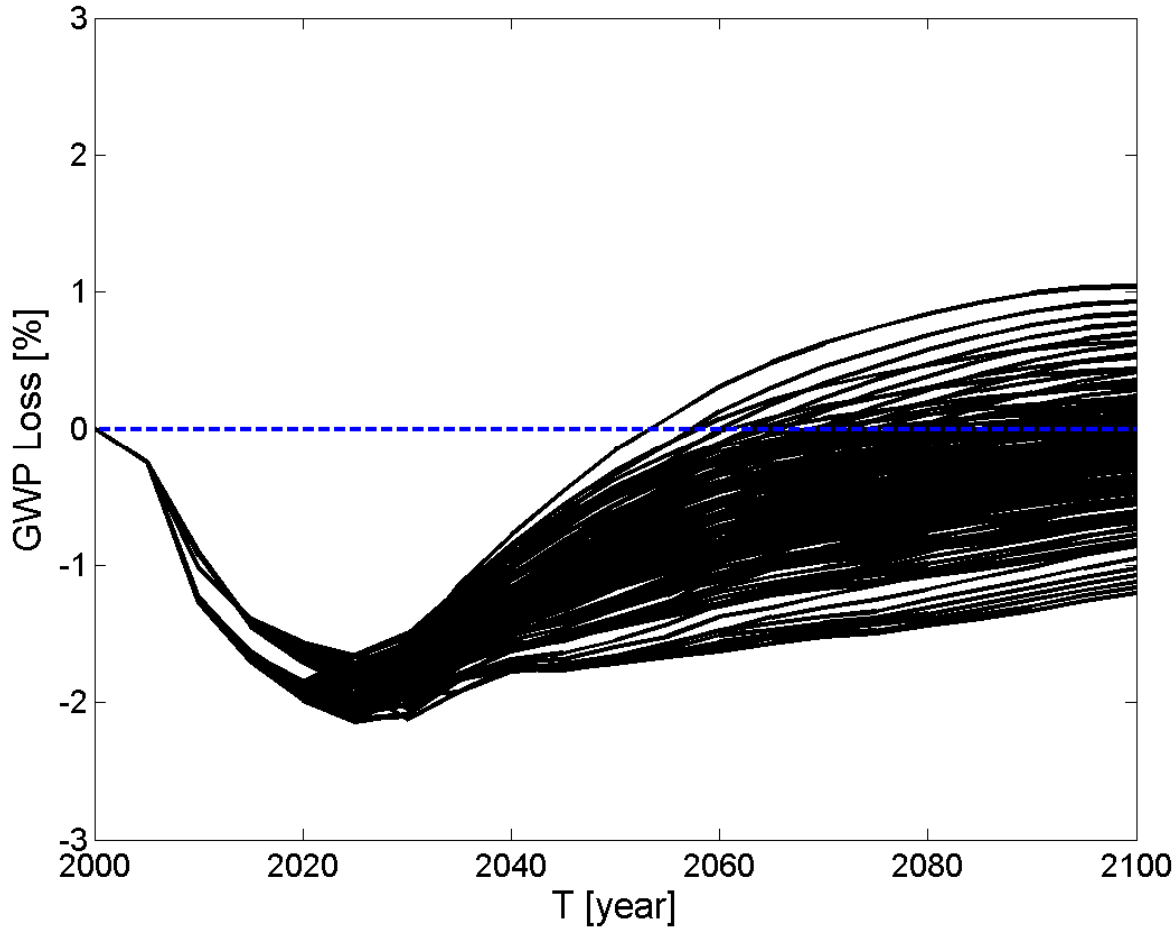
Optimal Investments into Renewable Energy | $P(T<2°) = 75\%$



Held, Kriegler, Lessmann, Edenhofer, Energy Economics, 2009

...disaggregated over time





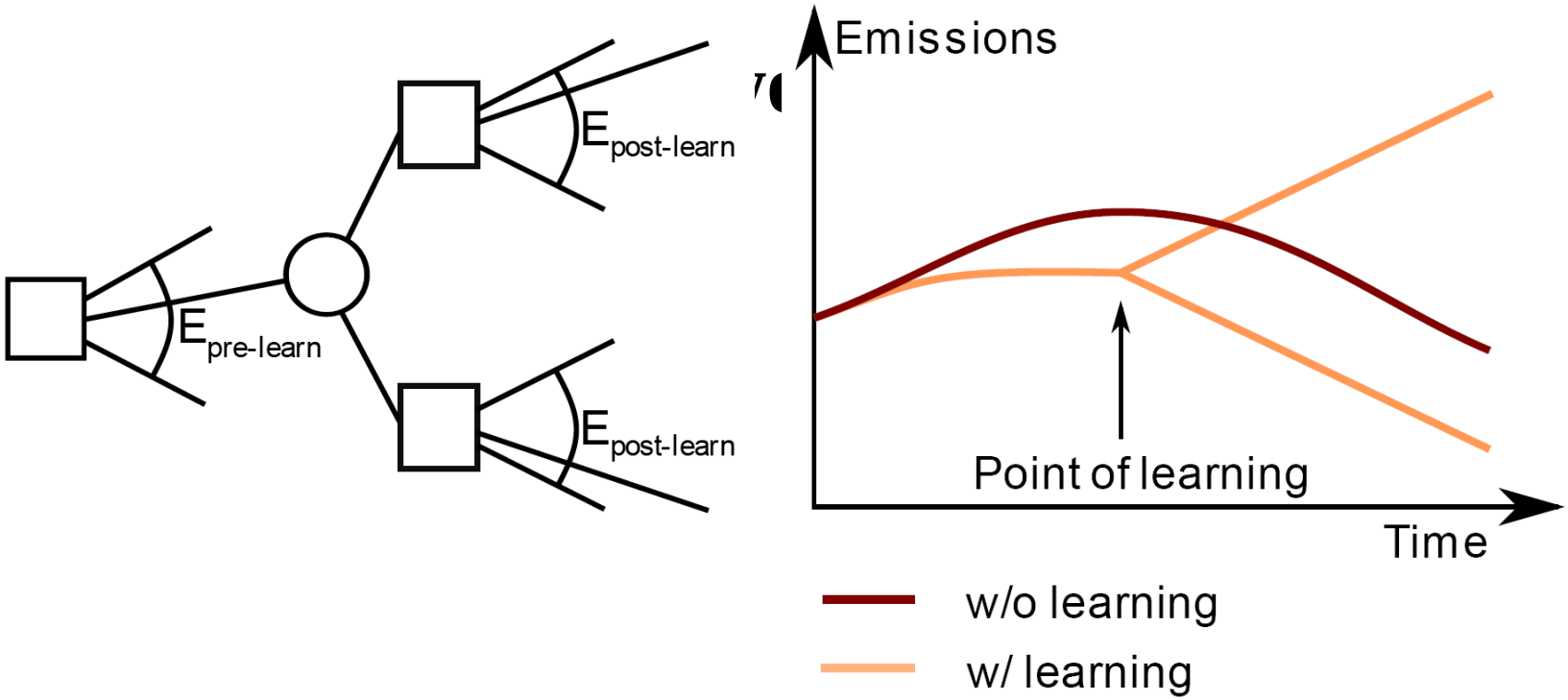
$$\frac{\text{Output.Guardrail}\,(n,t)\,-\,\text{Output.BAU}(n.t)}{\text{Output.BAU}(n.t)}$$

‘Uncertainty under Learning’

Why is studying anticipated learning interesting?

- We are highly uncertain about the climate and economy
- Investments are partly sunk
- Emissions and climate processes are partly irreversible
- We will certainly reduce uncertainty in the future

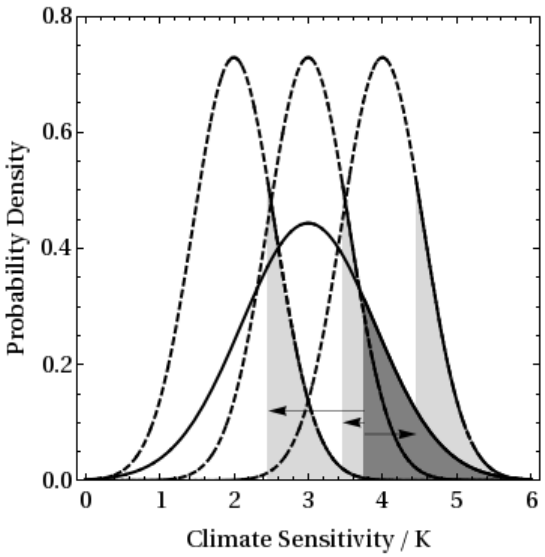
➢ Flexibility and anticipation of learning are valuable.



- Dynamic problem is solved as sequential stochastic optimization problem in GAMS

Learning about climate sensitivity

Optimal emission trajectory



Missing figure

- Strong dependence of optimal emissions on what is learned
- Much stronger emission reductions if learning is anticipated

Schmidt, M., Lorenz, A., Held, H., Kriegler, E. (2010) *Climate targets in an uncertain world*. submitted Clim. Change Lett.

1st Problem with CCP
‘Chance’ of Infeasible Solution

- Large - Climate Sensitivity ‘states of the world’ dominate the prior emission path.

- In order to prepare for the worst case after learning, the allowed cumulative amount of emissions before learning gets too restricted
  - (Cumulative allowed Emissions scale with $\mathbf{(2^{T^*/CS} - 1)}$ in 1st order – Kriegler&Bruckner, Clim. Change, 2004)

2nd Problem with CCP:

- Optimisation under expected learning may not work within chance constrained programming, as damage function is missing & represented as constraint
  - hence EVPI could be negative

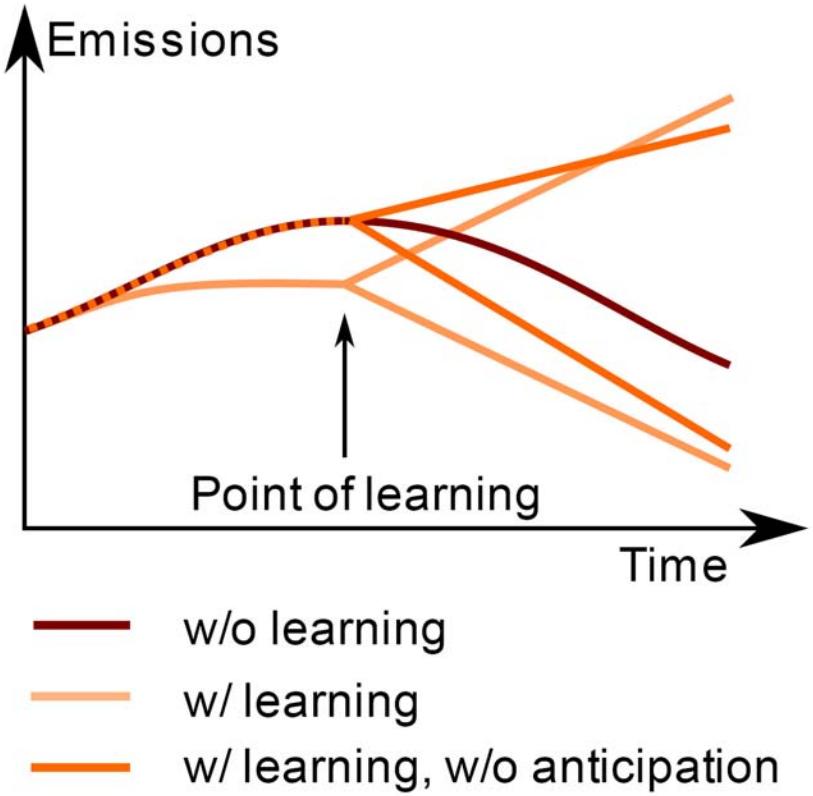
- **Compromise:** Use „Cost Risk Analysis“ (Schmidt, Lorenz, Held, Kriegler, subm.)
  - $U(t) := U_{standard}(t) - a\, P(T>T^*)(t)$
  - Is a utility function
  - Yet avoids having to know all the damages.

- Therefore: We switch to the cost benefit mode for a moment….

- …due to fat-tailed distribution of climate sensitivity and related effects

Terminology

- Expected Value of Information (EVOI): Overall welfare benefits from anticipated learning
- Conditional EVOI (CEVOI): Welfare benefits without anticipation of learning
- Expected Value of anticipation (EVOA): benefits due to anticipation.
  EVOA = EVOI – CEVOI



Additional Model Spec‘s

Further specifications of the MIND model for this study:

- Nordhaus‘s damage function
- Pure rate of time preference of 0.01
- CRRA (constant relative risk aversion) of 2.

Threshold Damages:

- Irreversible, uncertain perpetual damage above T_0[°C] of D_x[% GWP] or 0% with probabilities p and (1-p), such that $E(D_x) = 1.5\%$.
- Uncertain damage D_x is revealed at time t_{lp}.

$$DF_{thresh} = \frac{1}{1 + aT^b + D_x}$$

Learning about

- Climate Sensitivity and Damages
- Threshold damages

We find: Almost No Anticipation Effect
in the Absence of Threshold Damages

Results including Threshold Damages

EVOA, EVOI and Δemi, depending on t_{lp}.

Missing figure

(Lorenz, Schmidt, Kriegler, Held, subm. *J. Envir. Mod. Assess.*)

Outlook on Optimisation under Anticipated Learning

- Better (semi-)analytical understanding
- Inclusion of all ‘major’ uncertainties
- Endogenous learning in the technology sector
  - Society learns through implementation
- Implementation of cost-risk analysis?

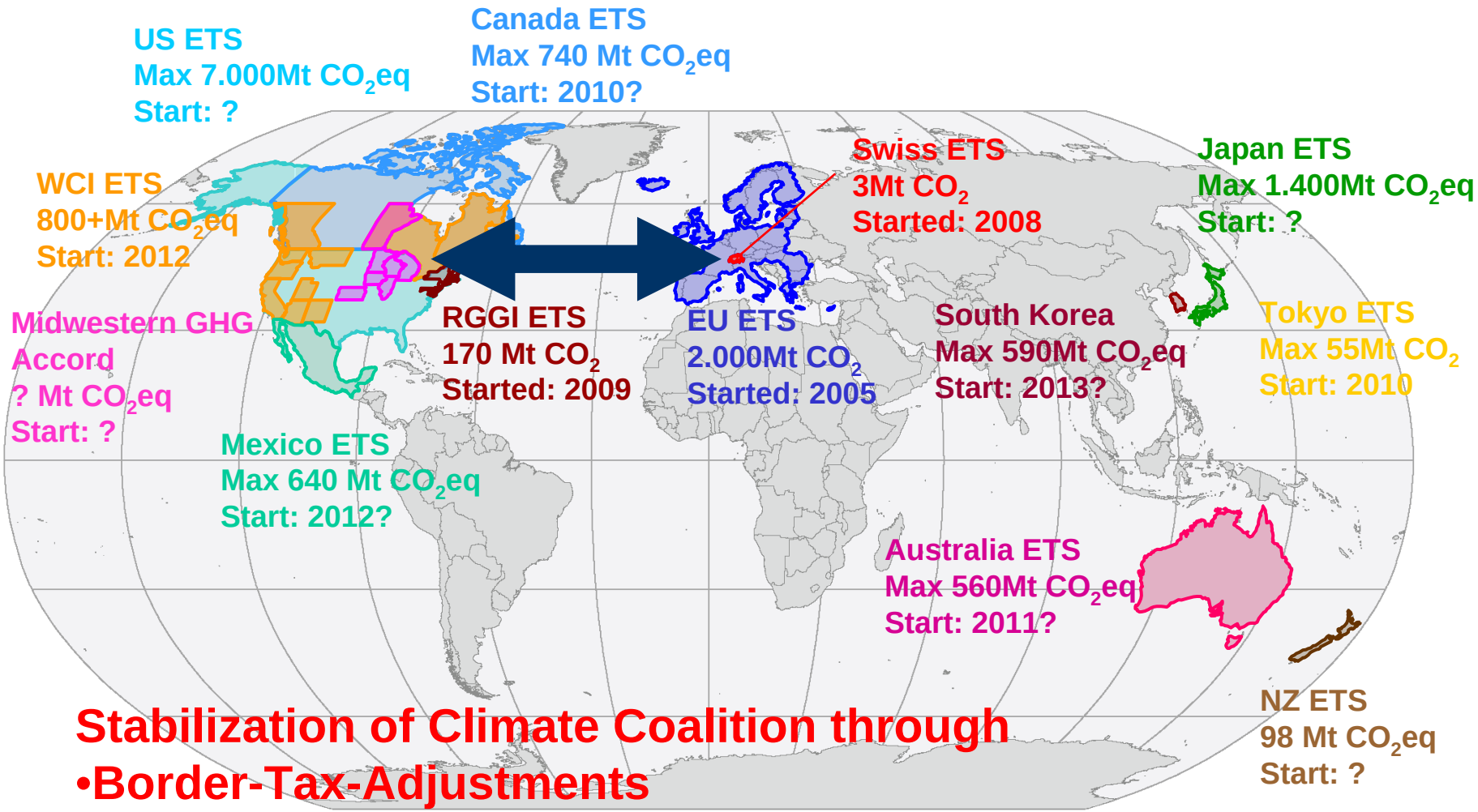
Further Topics

- Early warning systems for bifurcations & their economic value
- Regulation of carbon storage
- Impact functions for the insurance sector & insurability
- Representing uncertainties through imprecise probabilities

Three major Challenges for a Climate Policy

- Diverging views on techno-economic feasibility of mitigation & large-scale adaptation
- Fragmented knowledge on global warming impacts
- Multi-actor effects – free-riding
  - (De-)Stabilisation of coalitions
  - Incoherent pure rate of time preferences

Post Copenhagen: Potential 'Plan B': Linking of Regional CO_2-Trading Systems



Stabilization of Climate Coalition through

- **Border-Tax-Adjustments**
- **Creating ‚Club-Goods' – eg Technology Protocols**

Source: Flachsland, Lessmann et al. (2009)

- Herald Tribune, Friday, January 23rd, 2009

Conclusions

- Costs of transforming the energy system in-line with a 2° target on the order of ½…2% GWP (deterministic analysis)

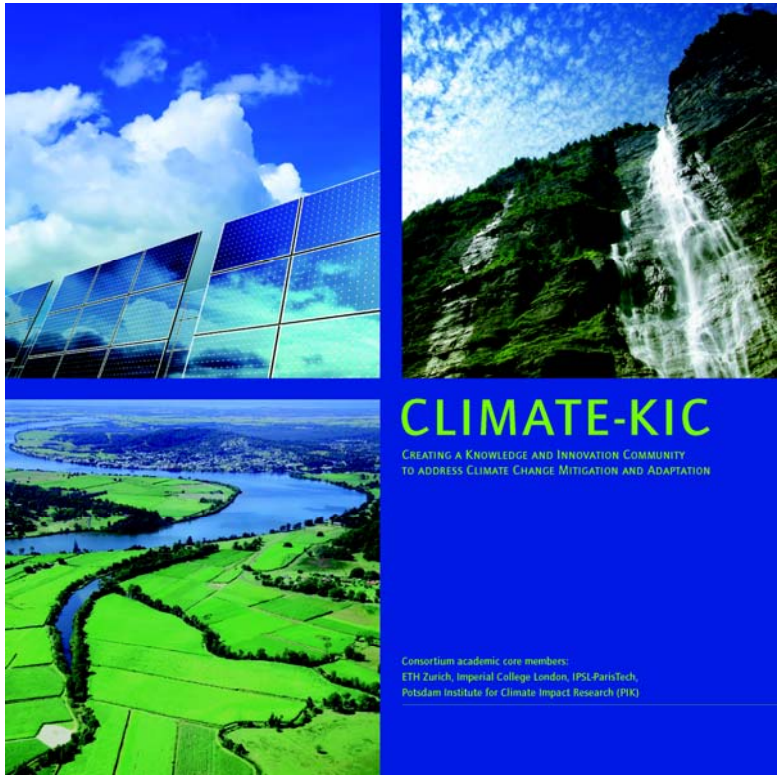
- Inclusion of uncertainty without learning in cost effectiveness analysis suggests decades earlier investments into mitigation technologies
  - Most likely in part triggered by nonlinearities in the technology sector

- Learning about climate sensitivity, climate damage amplitude and threshold damages have considerable value of up ~0.1% GWP.

- Uncertain, irreversible threshold damages are an exception where *anticipation is crucial* and provides up to 99% of the overall value of information.

European Institute for Innovation & Technology (EIT)

3 Virtual Departments (KICs – max 15 years life time)



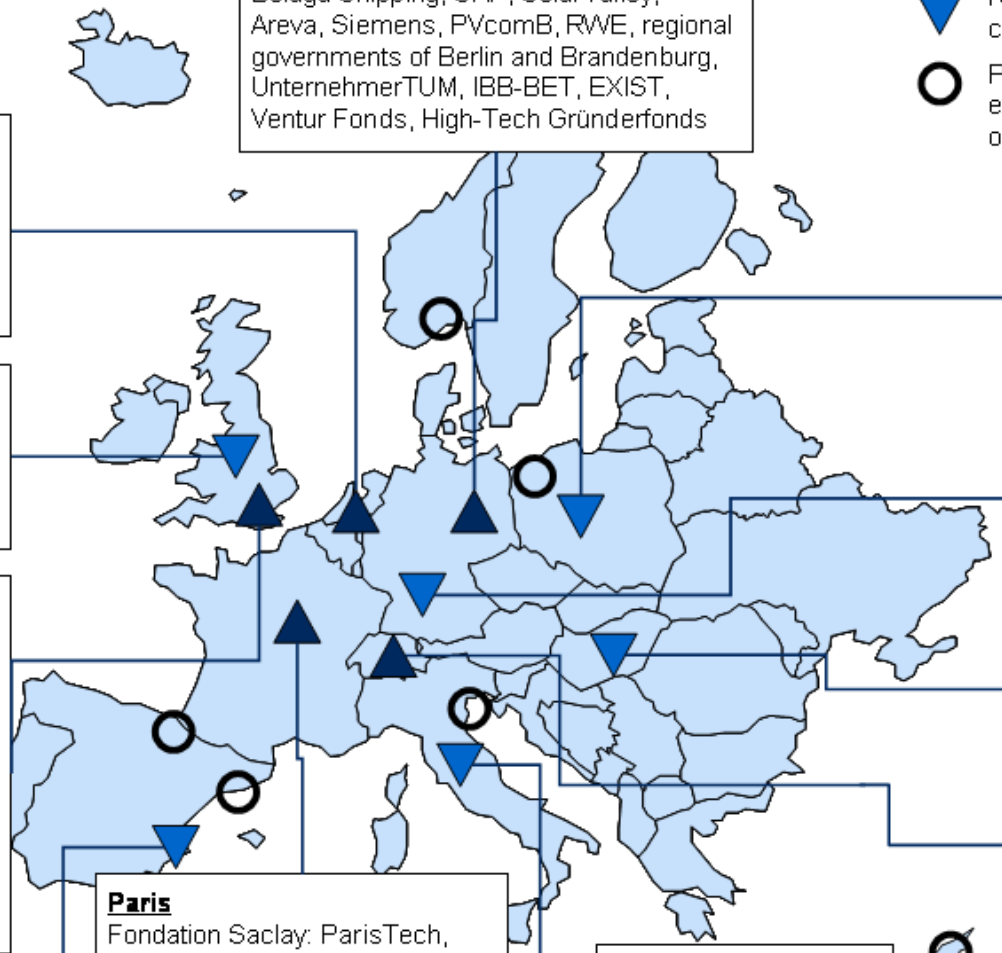
Innovation Stimulus
on
Mitigation
& Adaptation

Proposal for Climate Dep't:

August 2009: 120M€ applied for (2010-2013)

December 2009: Funding approved (albeit reduced amount)

PIK leads Climate KIC on national & EU-Level



Co-location centre

Regional implementation centre

Potential future expansion – dialogue ongoing

Berlin
PIK, TU Berlin, TU München, GFZ, Bayer, Beluga Shipping, SAP, SolarValley, Areva, Siemens, PVcomB, RWE, regional governments of Berlin and Brandenburg, UnternehmerTUM, IBB-BET, EXIST, Ventur Fonds, High-Tech Gründerfonds

Netherlands
Utrecht University, Delft Technical University, Wageningen University, TNO, Deltares, Alterra, Province of Utrecht, Port of Rotterdam, Schiphol Airport, Shell, DSM, ARCADIS

West Midlands
West Midlands Regional Development Agency, Ove Arup, Qinetiq, Birmingham City Council, NISP, 12,000 SMEs

London
Imperial College, Cisco, London Thames Gateway Institute for Sustainability, LSE, NCEO, Porter Alliance, Reading University, UK Met Office, BNSC, Akins Global, Willis Re, Telefonica, ESA, Wheb Partners; Climate Change Capital SME Knowledge Transfer Networks, SMEs e.g., Novacem, Plaxica, Ceres Power, Quantasol

Valencia
Regional Government, IMPIVA, REDIT, Iberdrola, CEAM R&D, 12,000 SMEs

Paris
Fondation Saclay: ParisTech, UVSQ, IPSL, CEA, INRA, Advancity, Meteo France, Thales, EDF, Emertec, OSEO, Incub Alliance SMEs e.g., AriaTech Noveltis NumTech Leospere

Emilia Romagna
Regional government, ASTER, ENEA, LISEA, LEAP Confindustria 15,000 SMEs

Lower Silesia (Wroclaw)
City of Wroclaw, Wroclaw Research Centre (EIT+) KGHM, Fortum, Philips 4,000 SMEs

Hessen
Regional government, TU Darmstadt, Deutsche Bank, HSE, Rittal, Schott, E.on, Infraserv, 15,000 SMEs

Central Hungary
City of Budapest, OBEKK, GITR, ABONY, HANGYA 5,000 SMEs

Zürich
ETH Zürich, MeteoSwiss, Eawag, PSI, WSL, EMPA, IBM, Siemens City of Zürich, Viva!Campus, ETH Transfer, Technopark Zürich, Venture Incubator Partners, CTI Start-Up, Venturelab, Öbu Works for Sustainability

Why should the private sector join?

Missing figure

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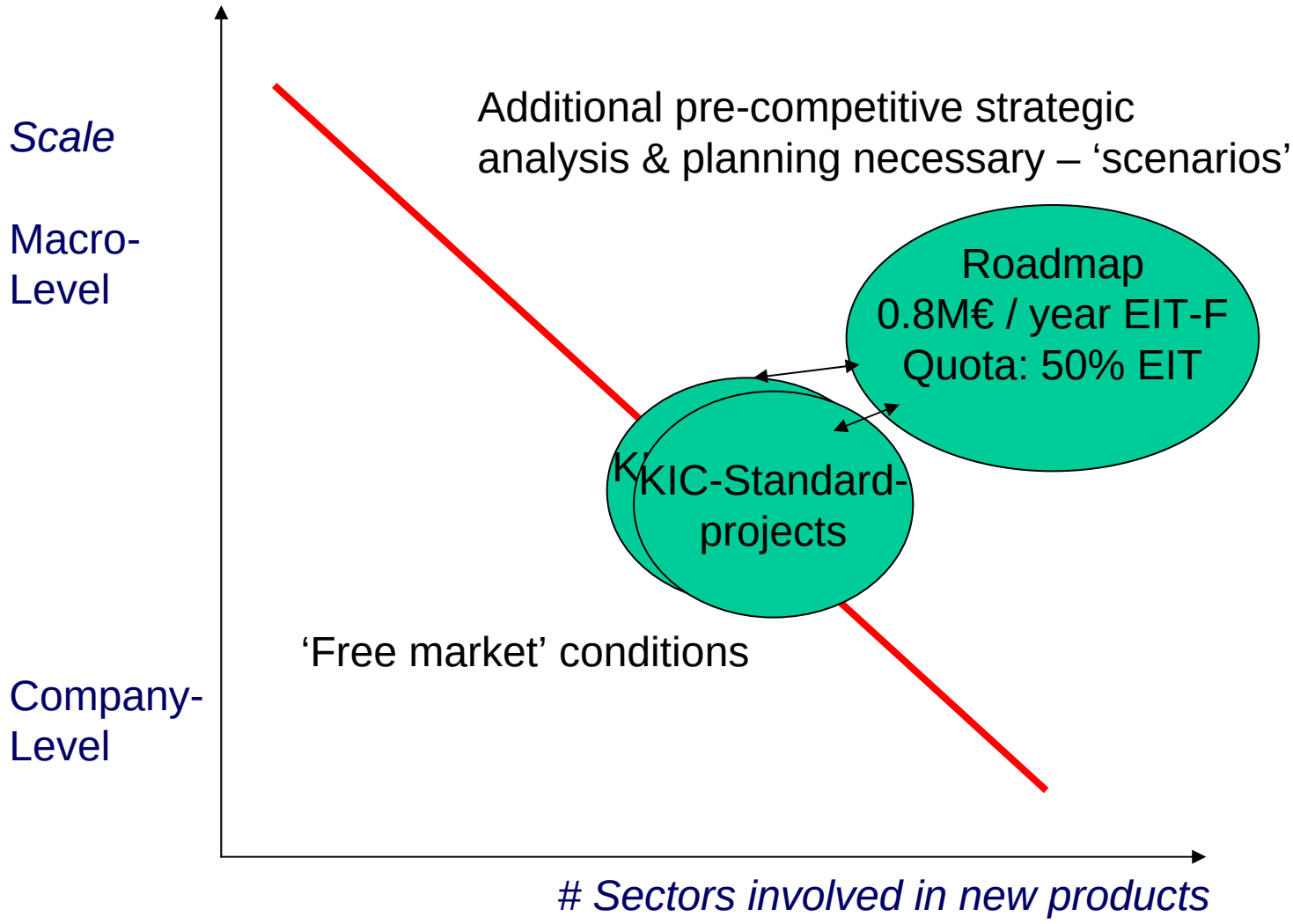
The scale-bridging role of a Roadmap Process: Framing of Innovation



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