Virtual Seminar on Climate Economics

Federal Reserve Bank of San Francisco

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Carbon prices, preferences, and the timing of uncertainty

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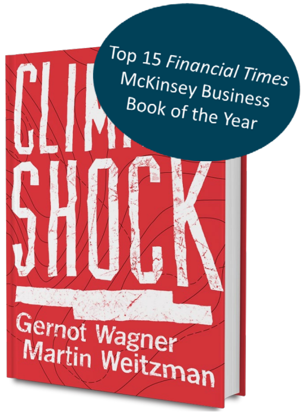

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$50

~$50 Social Cost of CO_2

Based on 3% constant discount rate, and an average of 3 climate-economy models, including DICE

Table ES-1: Social Cost of CO_2, 2020 – 2050 (in 2020 dollars per metric ton of CO_2)[3]

	Discount Rate and Statistic			
Emissions Year	5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	14	51	76	152
2025	17	56	83	169
2030	19	62	89	187
2035	22	67	96	206
2040	25	73	103	225
2045	28	79	110	242
2050	32	85	116	260

~$50 'interim' Biden SC-$CO_2$,
up from $1-7 Trump figure

Source: "Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990" (February 2021).

Eight priorities for calculating the social cost of carbon

Gernot Wagner, David Anthoff, Maureen Cropper, Simon Dietz, Kenneth T. Gillingham, Ben Groom, J. Paul Kelleher, Frances C. Moore & James H. Stock

Advice to the Biden administration as it seeks to account for mounting losses from storms, wildfires and other climate impacts.

One of the first executive orders US President Joe Biden signed in January began a process to revise the social cost of carbon (SCC). This metric is used in cost–benefit analyses to inform climate policy. It puts a monetary value on the harms of climate change, by tallying all future damages incurred globally from the emission of one tonne of carbon dioxide now.

This month, the Biden administration is publishing an interim value of the SCC, which could be used immediately. Within a year, a newly reconstituted Interagency Working Group (IWG) will issue a review of the latest scientific and economic thinking, to inform what it calls a final number. The IWG will be co-led by the Council of Economic Advisers, the Office of Management and Budget and the Office of Science and Technology Policy. The group will also assess the social costs of methane, nitrous oxide and other greenhouse gases, and will provide recommendations for using and revising the SCC.

The time is ripe for this update. Climate science and economics have advanced since 2010, when a working group in the administration of former president Barack Obama first calculated the m

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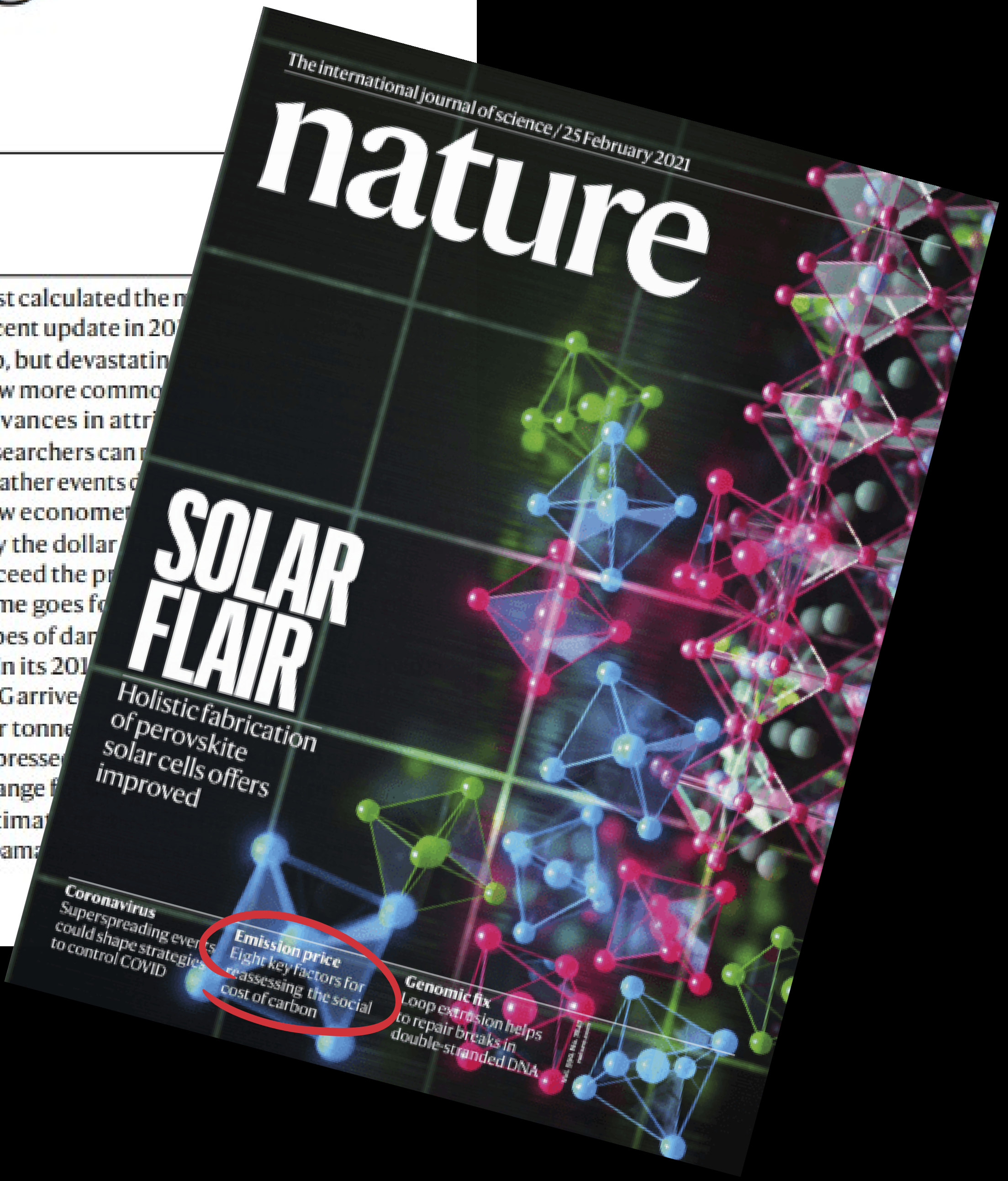

gwagner.com/SCC-8

>$100

>$100:

Climate damage quantification

including tipping points

Tail risks

Discounting

“Proper” preference calibration

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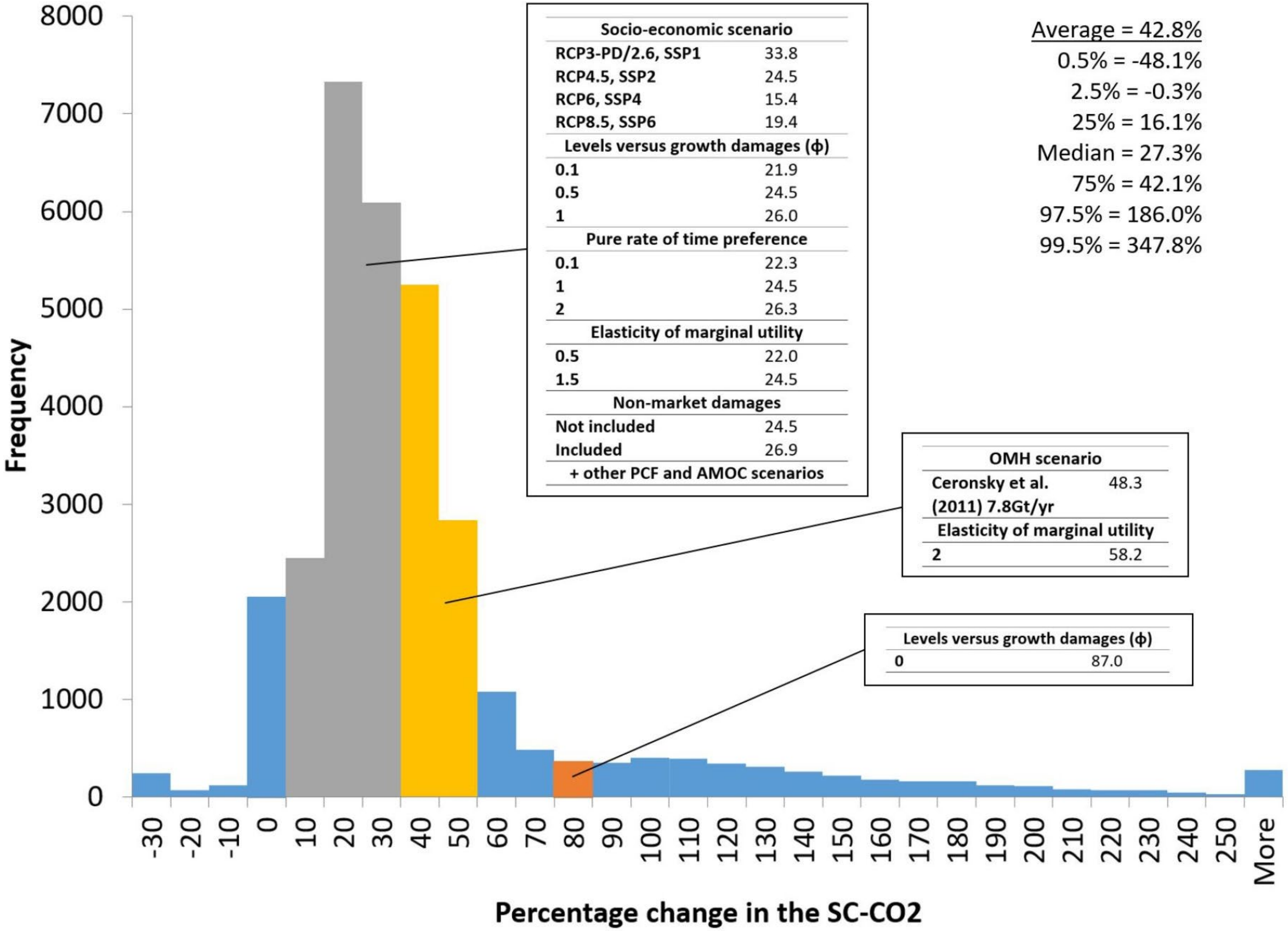
Economic impacts of tipping points in the climate system

Tipping points increase SCC by between ~27-43%, with large distribution



Source: Dietz, Rising, Stoerk & Wagner (working paper), gwagner.com/tipping-economics

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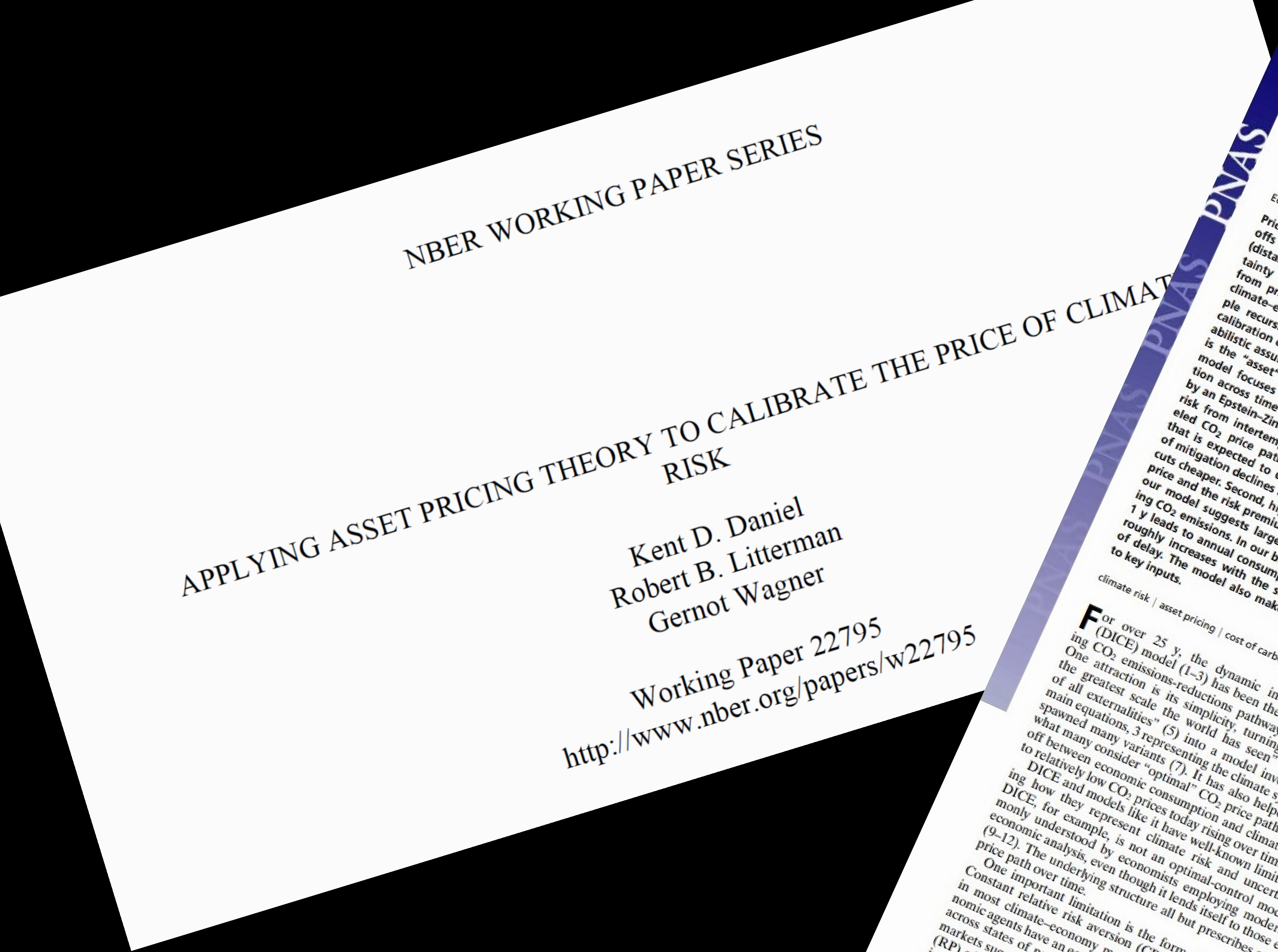

NBER WORKING PAPER SERIES

APPLYING ASSET PRICING THEORY TO CALIBRATE THE PRICE OF CLIMATE RISK

Kent D. Daniel
Robert B. Litterman
Gernot Wagner

Working Paper 22795
http://www.nber.org/papers/w22795

PNAS

Declining CO_2 price paths

Kent D. Daniel[a,b,1], Robert B. Litterman[c,1], and Gernot Wagner[d,1,2,3]

[a]Columbia Business School, New York, NY 10027; [b]National Bureau of Economic Research, Cambridge, MA 02138; [c]Kepos Capital, New York, NY 10018; and [d]Harvard University Center for the Environment, Cambridge, MA 02138

Edited by Jose A. Scheinkman, Columbia University, New York, NY, and approved September 9, 2019 (received for review October 9, 2018)

Pricing greenhouse-gas (GHG) emissions involves making trade-offs between consumption today and unknown damages in the (distant) future. While decision making under risk and uncertainty is the forte of financial economics, important insights from pricing financial assets do not typically inform standard climate–economy models. Here, we introduce EZ-Climate, a simple recursive dynamic asset pricing model that allows for a calibration of the carbon dioxide (CO_2) price path based on probabilistic assumptions around climate damages. Atmospheric CO_2 is the "asset" with a negative expected return. The economic model focuses on society's willingness to substitute consumption across time and across uncertain states of nature, enabled by an Epstein–Zin (EZ) specification that delinks preferences over risk from intertemporal substitution. In contrast to most modeled CO_2 price paths, EZ-Climate suggests a high price today that is expected to decline over time as the "insurance" value of mitigation declines and technological change makes emissions cuts cheaper. Second, higher risk aversion increases both the CO_2 price and the risk premium relative to expected damages. Lastly, our model suggests large costs associated with delays in pricing CO_2 emissions. In our base case, delaying implementation by 1 y leads to annual consumption losses of over 2%, a cost that roughly increases with the square of time per additional year of delay. The model also makes clear how sensitive results are to key inputs.

climate risk | asset pricing | cost of carbon

For over 25 y, the dynamic integrated climate–economy (DICE) model (1–3) has been the standard tool for analyzing CO_2 emissions-reductions pathways, and for good reason. One attraction is its simplicity, turning a "market failure on the greatest scale the world has seen" (4) and "the mother of all externalities" (5) into a model involving fewer than 20 main equations, 3 representing the climate system (6). DICE has spawned many variants (7). It has also helped set the tone for what many consider "optimal" CO_2 price paths. The core trade-off between economic consumption and climate damages leads to relatively low CO_2 prices today rising over time.

DICE and models like it have well-known limitations, including how they represent climate risk and uncertainty (7–15). DICE, for example, is not an optimal-control model, as commonly understood by economists employing modern dynamic economic analysis, even though it lends itself to those extensions (9–12). The underlying structure all but prescribes a rising CO_2 price path over time.

One important limitation is the form of the utility function. Constant relative risk aversion (CRRA) preferences, standard in most climate–economy models (1, 7, 16), assume that economic agents have an equal aversion to variation in consumption across states of nature and over time. Evidence from financial markets suggests that this is not the case (17). The risk premium (RP) of equities over bonds points to a fundamental difference in how much society is willing to pay to substitute consumption risk across states of nature compared to over time (18, 19). Some have explained the discrepancy by allowing for extreme events (20–22), and others have looked to more flexible preferences (23–26) or both (27). Our own preference specification follows Epstein and Zin (EZ) (24, 25).

EZ Preferences

Here, we use EZ preferences and focus on climate uncertainties. We approach climate change as an asset pricing problem with atmospheric CO_2 as the "asset." The value of an investment in reducing CO_2 emissions depends on the state of nature, represented by its fragility θ_t. That, in turn, helps determine the discount rate applied to the damages that would have occurred without the investment.

Our representative agent maximizes a recursive utility U_t based on consumption c_t and expectations E_t over future utility for times $t \in \{0, 1, 2, \ldots, T-1\}$:

$$U_t = \left[(1-\beta)c_t^{\rho} + \beta\left(E_t\left[U_{t+1}^{\alpha}\right]\right)^{\frac{\rho}{\alpha}}\right]^{\frac{1}{\rho}}. \quad [1]$$

Parameters α and ρ measure the agent's willingness to substitute consumption across states of nature and across time, respectively. (See *Methods* for the final-period utility U_T and further derivations.) CRRA preferences are a special case, with $\alpha = \rho$. Unlike with CRRA, Eq. 1 implies that CO_2 prices no longer collapse to zero with increasing risk aversion (RA) and equity risk premia (Fig. 1A). The same goes for the portion of CO_2 prices explained by RA (Fig. 1B).

EZ preferences have since found their way into the climate–economic literature (9–12, 28–35). Some have embedded EZ into DICE (28, 35), and others employ supercomputers to solve (9–12). The complexity typically does not allow for analytic solutions (34). We here follow a simple binomial-tree model with a long history in financial modeling (36). It is precisely this modeling choice—standard in financial economics but novel to climate–economic applications—that leads to our fundamentally differing CO_2 price paths. Mitigating climate risk provides

Significance

Risk and uncertainty are important in pricing climate damages. Despite a burgeoning literature, attempts to marry insights from asset pricing with climate economics have largely failed to supplement—let alone supplant—decades-old climate–economy models, largely due to their analytic and computational complexity. Here, we introduce a simple, modular framework that identifies core trade-offs, highlights the sensitivity of results to key inputs, and helps pinpoint areas for further work.

Author contributions: K.D.D., R.B.L., and G.W. designed research, performed research, contributed new analytic tools, and wrote the paper.

The authors declare no competing interest.

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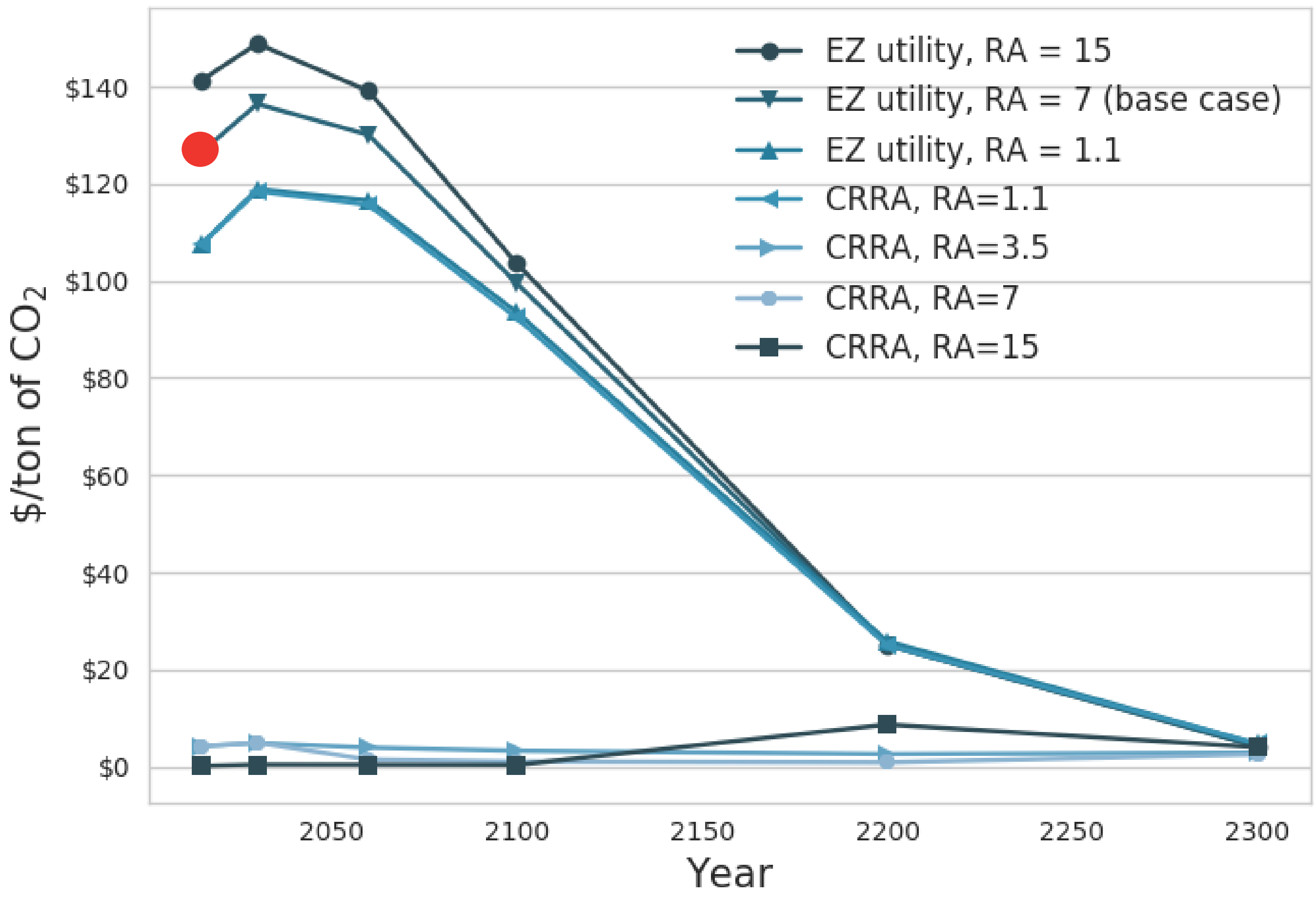
ECONOMIC SCIENCES

www.pnas.org/cgi/doi/10.1073/pnas.1817444116

gwagner.com/ezclimate

Optimal CO_2 price sensitive to utility specification for ‘reasonable’ RA values

No difference between CRRA and EZ utility at RA=1.1, large differences for RA>~3



Source: Daniel, Litterman & Wagner (NBER October 2018)

>$100:

Climate damage quantification

including tipping points

→ Tail risks

→ Discounting

→ "Proper" preference calibration

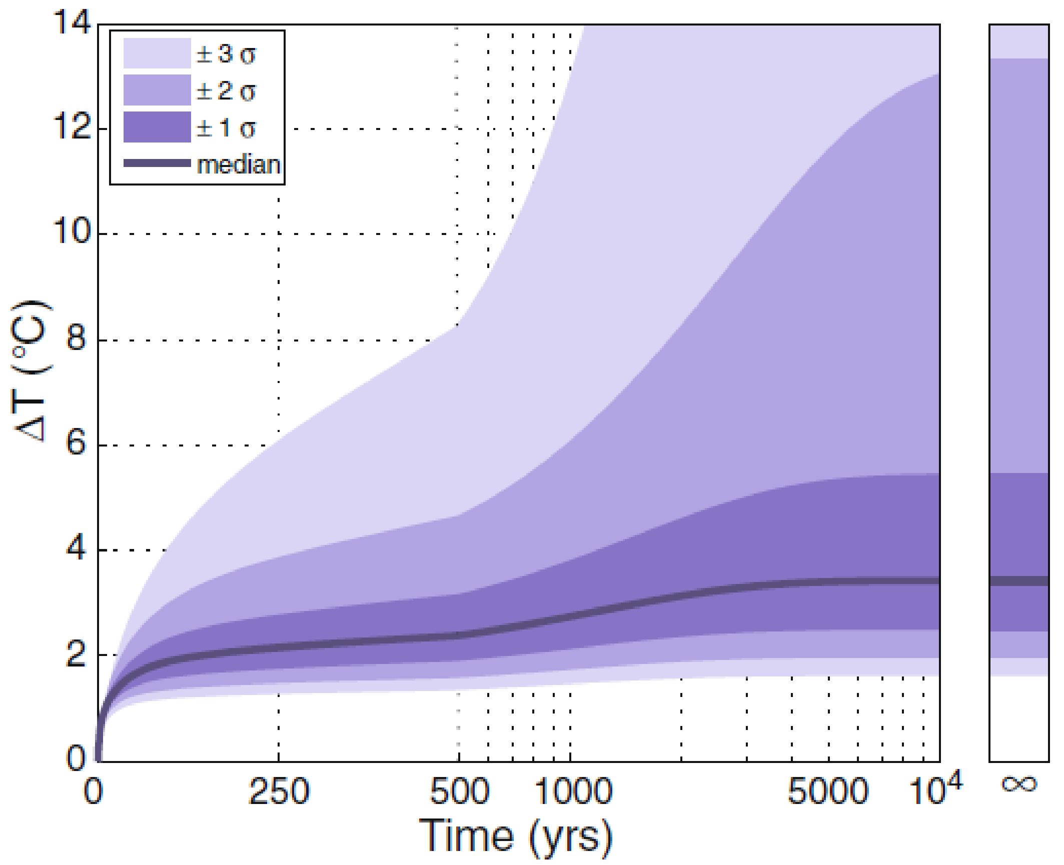
Two critical examinations:

1. Fat tails with “Roe-Bauman” time component
2. Closer look at Epstein-Zin preferences (& discounting)

1 Roe-Bauman critique of "fat tails" argument

"Climate sensitivity: should the climate tail wag the policy dog?"

"**Fig. 2 a** The time evolution of uncertainty in global temperature in response to an instantaneous doubling of CO_2 at t = 0, and for standard parameters. The shading reflects the range of feedbacks considered (symmetric in feedbacks, but not in climate response), as explained in the text. Note the change to a logarithmic x-axis after t = 500 yr. The panel illustrates that **for high climate sensitivity it takes a very long time to come to equilibrium**." (Roe & Bauman, 2013, p. 651)



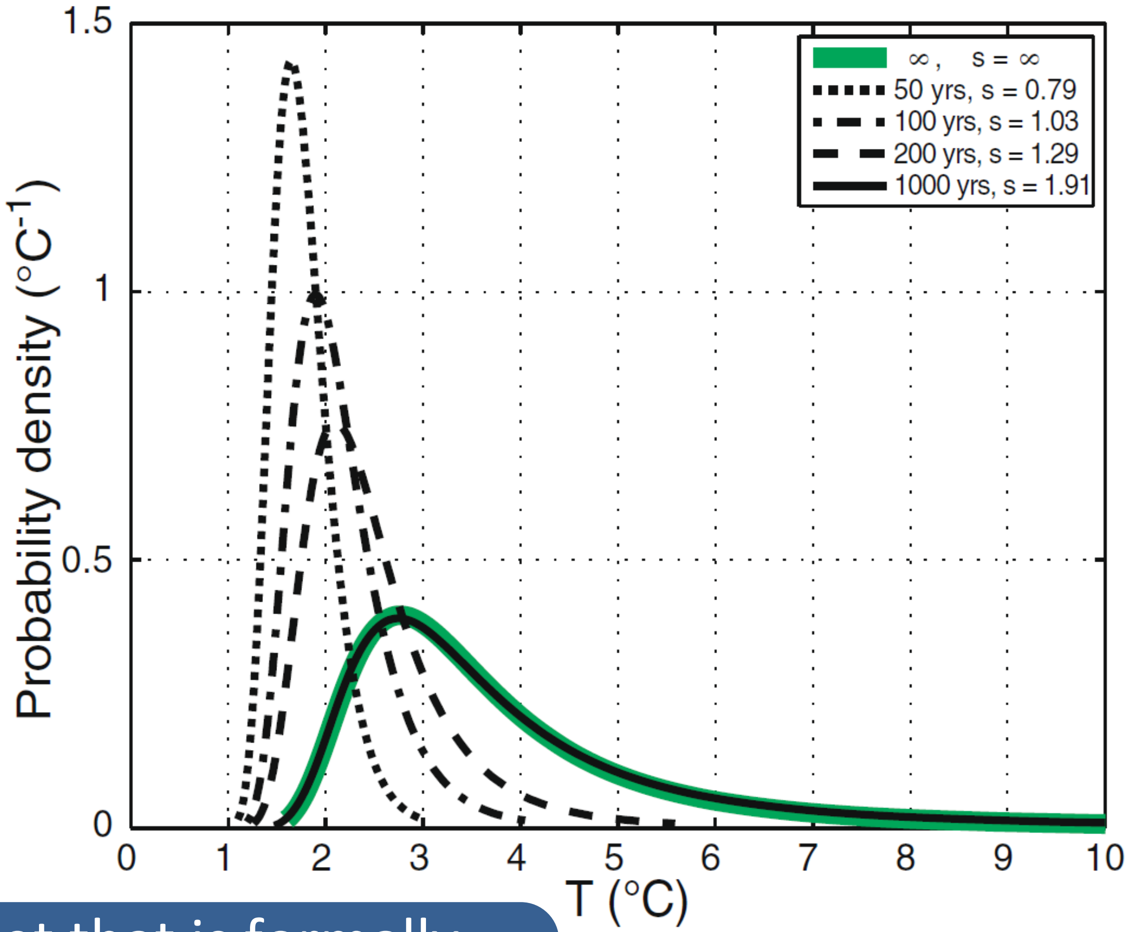
The farther out the climate damage, the more discounting matters

Source: Roe & Bauman (2013); see also e.g.: Baker & Roe (2009)

1 Roe-Bauman critique of "fat tails" argument

"Climate sensitivity: should the climate tail wag the policy dog?"

"**Fig. 2 b** The shape of the [climate sensitivity] distribution at particular times. The skewness of the distributions are also shown in the legend; as described in the text, **the upper bound on possible temperatures is finite at finite time, limiting the skewness**" (Roe & Bauman, 2013, p. 651)



"even for a planet that is formally headed to[ward] oblivion, it can take a very long time to get there"

Source: Roe & Bauman (2013)

Carbon prices, preferences, and the timing of uncertainty

3 questions

1. Does the Roe-Bauman (RB) critique matter?

2. Does the separation of risk and time *a la* Epstein-Zin (EZ) matter?

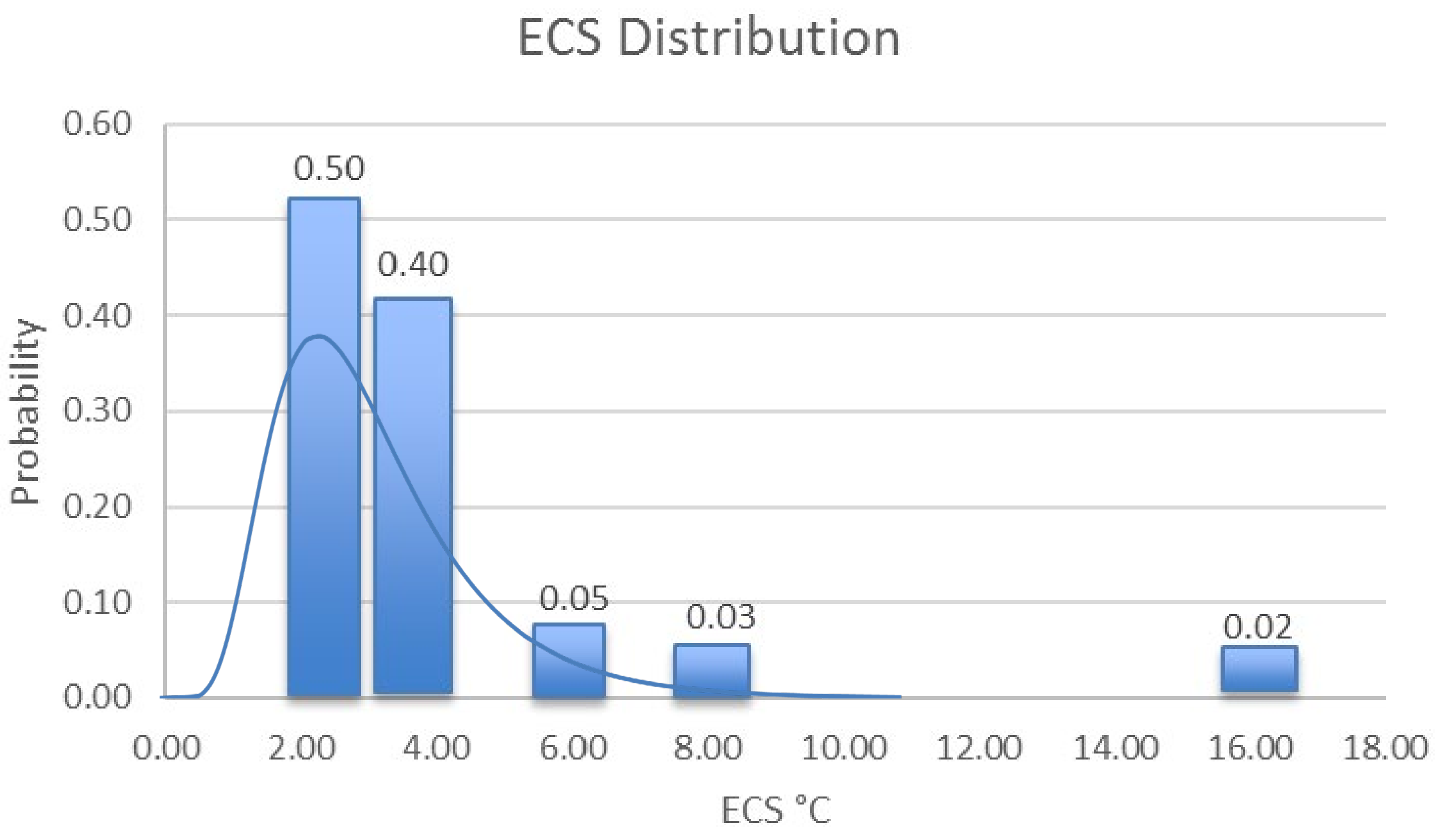
1 & 2 What about the combination of the two?

We build "DICE-EZ-RB" to help answer these questions

Source: Hogan & Wagner (Mimeo)

1 *Rough* Roe-Baker ECS calibration

Recursive DICE-EZ implementation calls for simple scenarios: 5 scenarios, with ECS uncertainty resolved in 50yrs (2065)

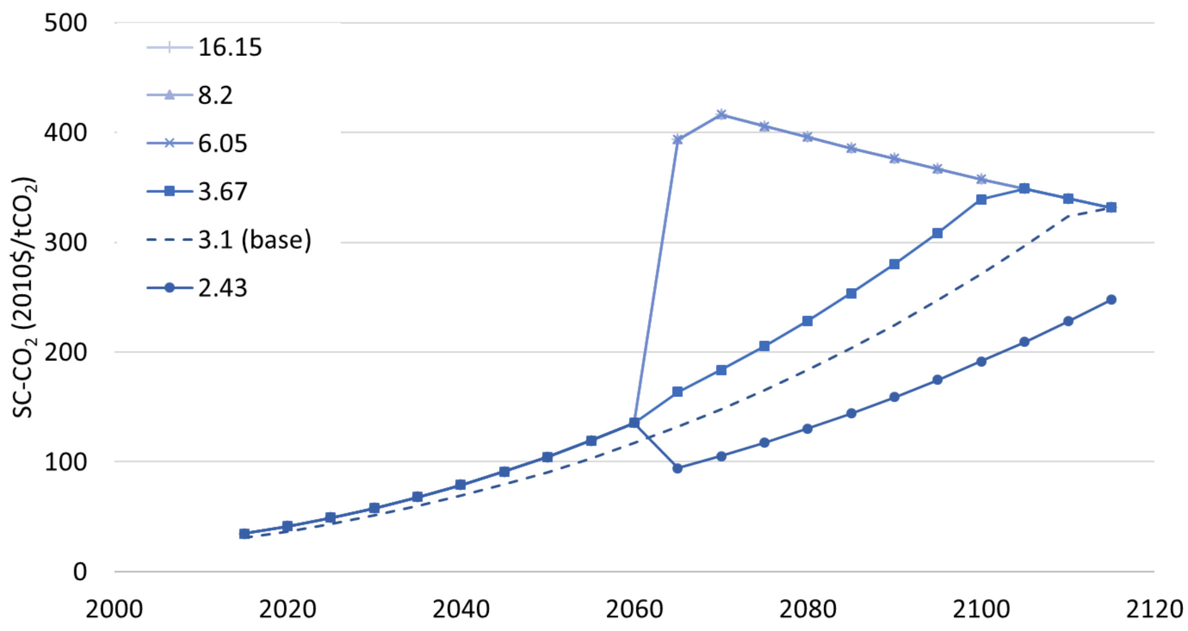


Source: Hogan & Wagner (Mimeo)

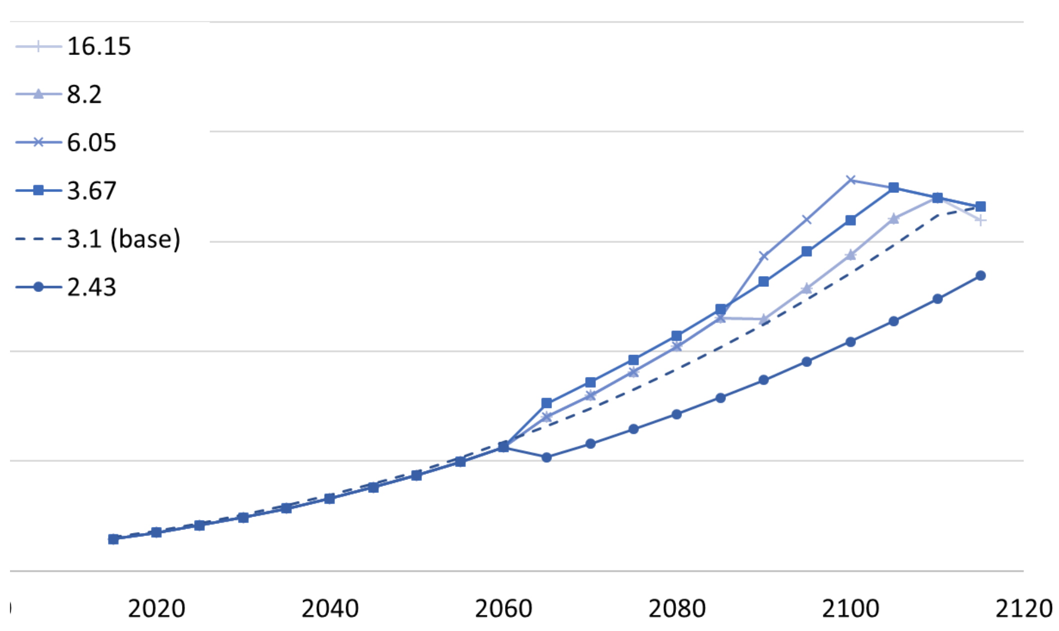
1 Roe-Bauman time dynamics dramatically reduce $SC\text{-}CO_2$ uncertainty

$SC\text{-}CO_2$ smaller in expectations, less uncertain after resolution of uncertainty

DICE with Roe-Baker tail uncertainty



DICE with Roe-Bauman time dynamics



Tail risks much less significant, given time interaction (discounting!)

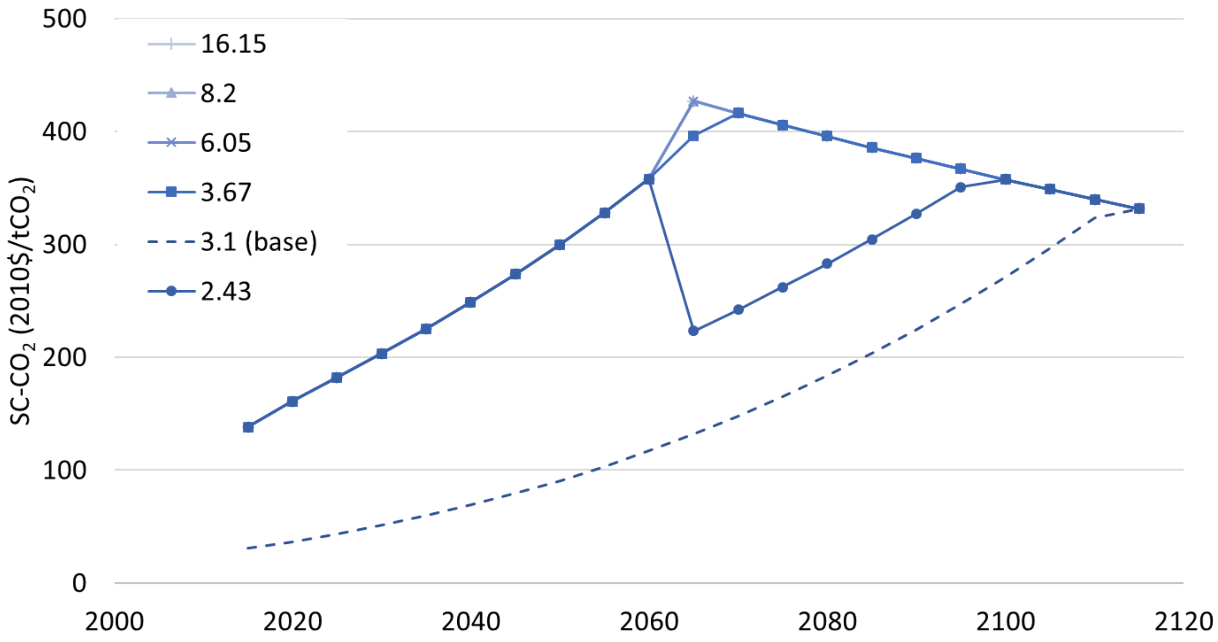
Source: Hogan & Wagner (Mimeo)

1 & 2

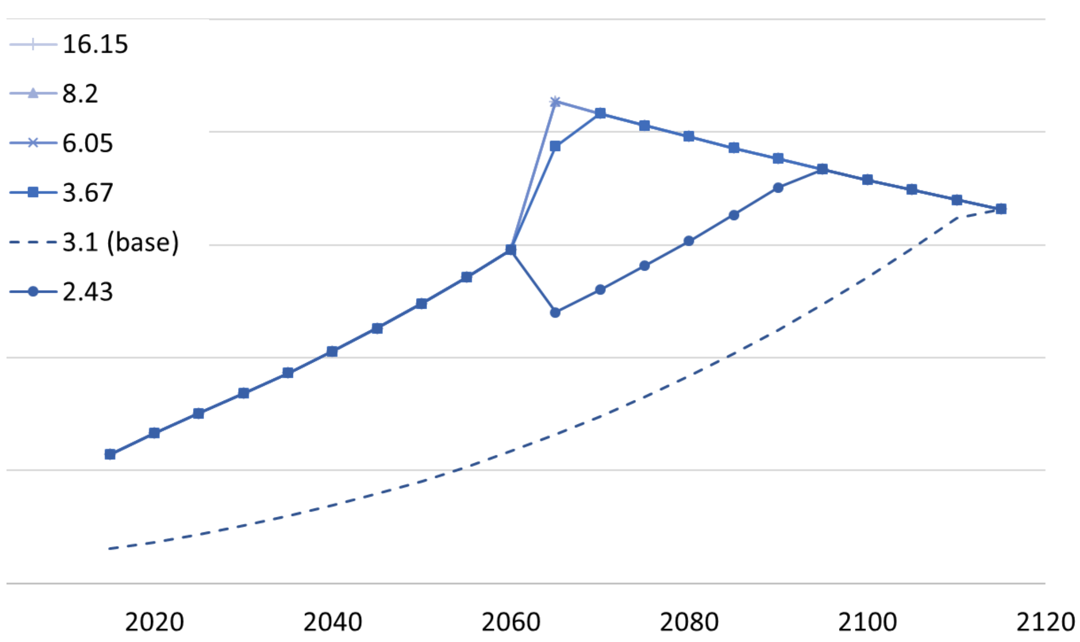
Impact of EZ preferences much larger than RB dynamics

Initial SC-CO_2 jumps to over $100

DICE-EZ



DICE-EZ-RB



Switch to EZ appears to have large impact on SC-CO_2

Source: Hogan & Wagner (Mimeo)

1 & 2

Roe-Bauman (RB) time-delay decreases SCC by >30%

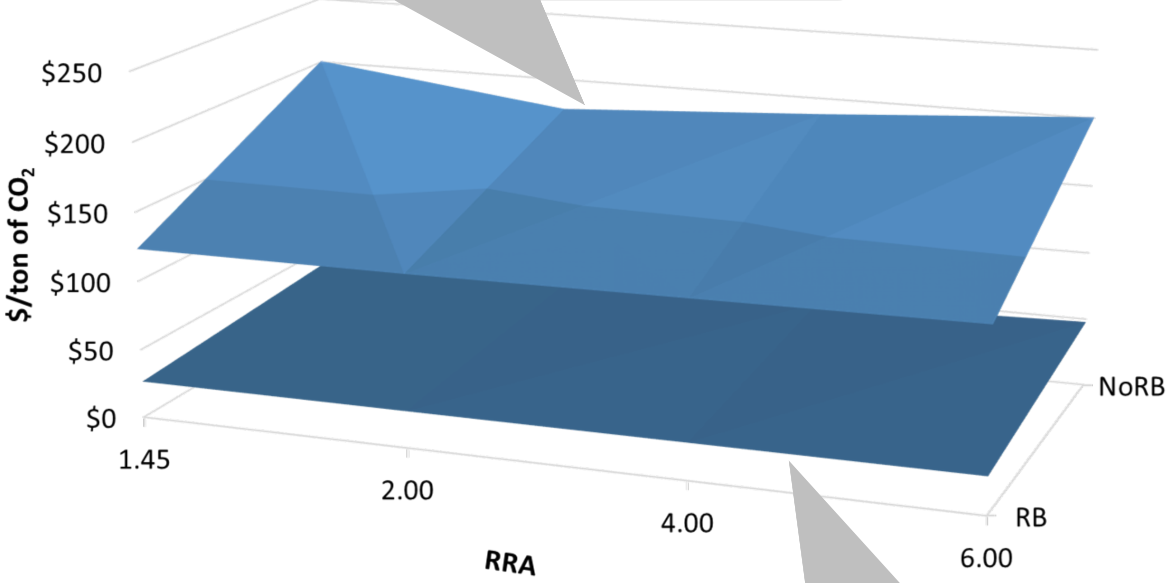
DICE calibration (EIS = 0.69 and RRA = 1.45) changes from $31

DICE calibration (SCC = $31)

EIS =	0.69			
RRA =	1.45	2	4	6
RB	$ 26	$ 26	$ 27	$ 27
no RB	$ 38	$ 39	$ 43	$ 48

EIS =	1.5			
RRA =	1.45	2	4	6
RB	$ 123	$ 124	$ 126	$ 128
no RB	$ 201	$ 177	$ 188	$ 201

Elasticity of Intertemporal Substitution (EIS) = 1.5



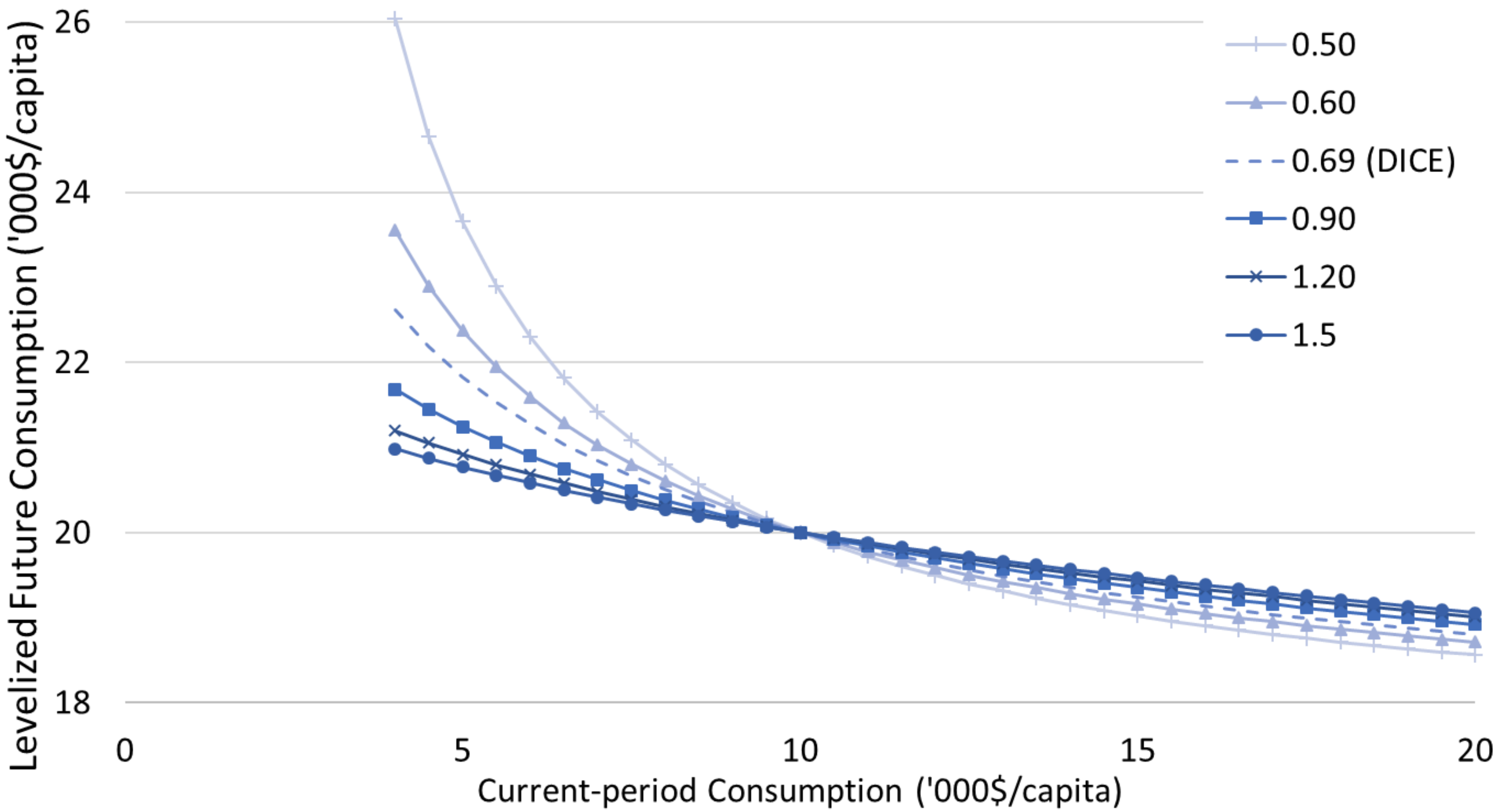
EIS = 0.69

Impact of changes to EIS (far) greater than RB/noRB and RRA

Source: Hogan & Wagner (Mimeo)

Elasticity of Intertemporal Substitution (EIS) drives all

SC-CO_2 very sensitive to EIS parameters; EIS meanwhile, anywhere from ~0.50 to >1.5 (Thimme 2017)



What's the right EIS? aka
There appears to be no escaping economics' philosophical roots.

Source: Hogan & Wagner (Mimeo)

Eight priorities for calculating the social cost of carbon

Gernot Wagner, David Anthoff, Maureen Cropper, Simon Dietz, Kenneth T. Gillingham, Ben Groom, J. Paul Kelleher, Frances C. Moore & James H. Stock

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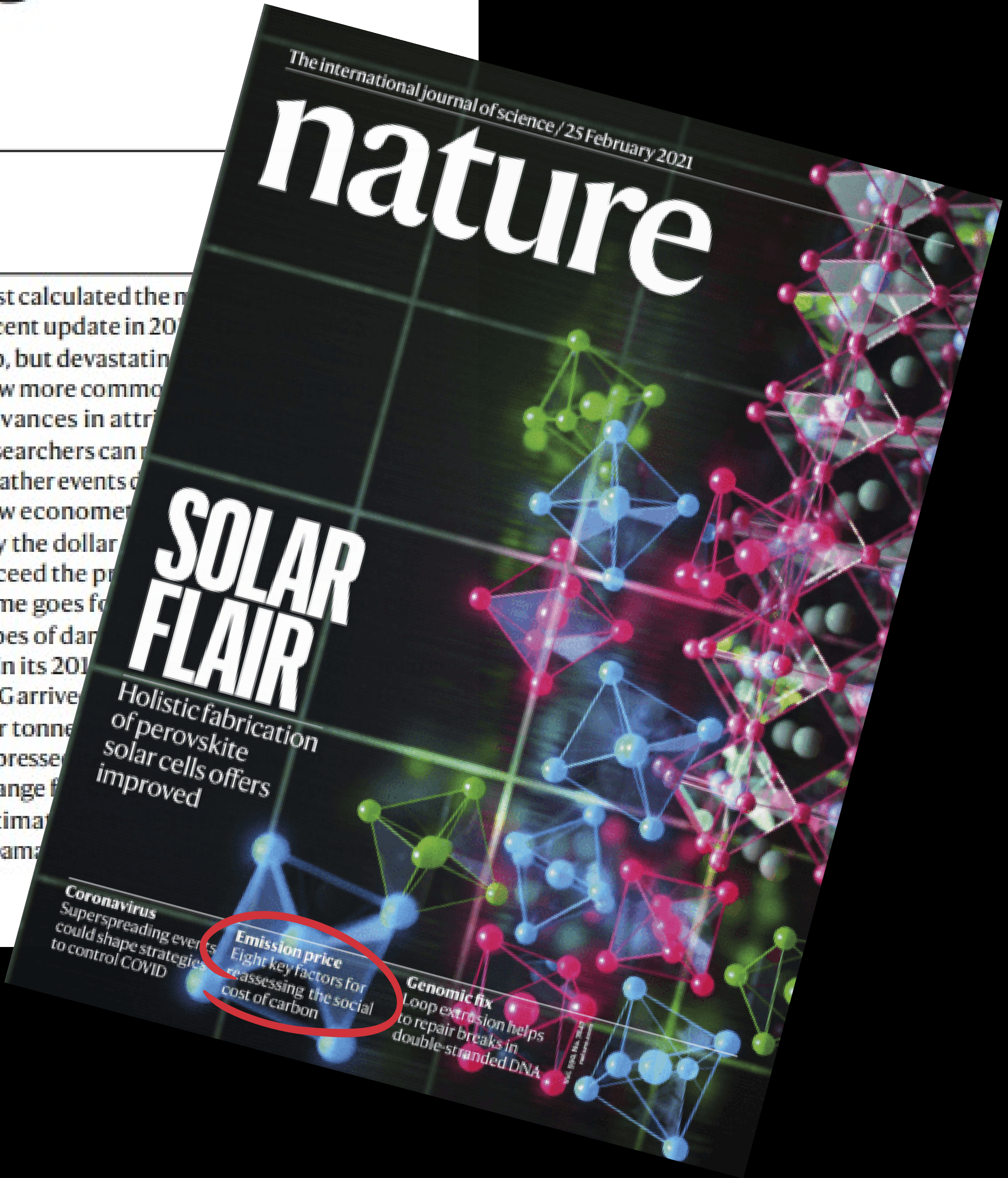

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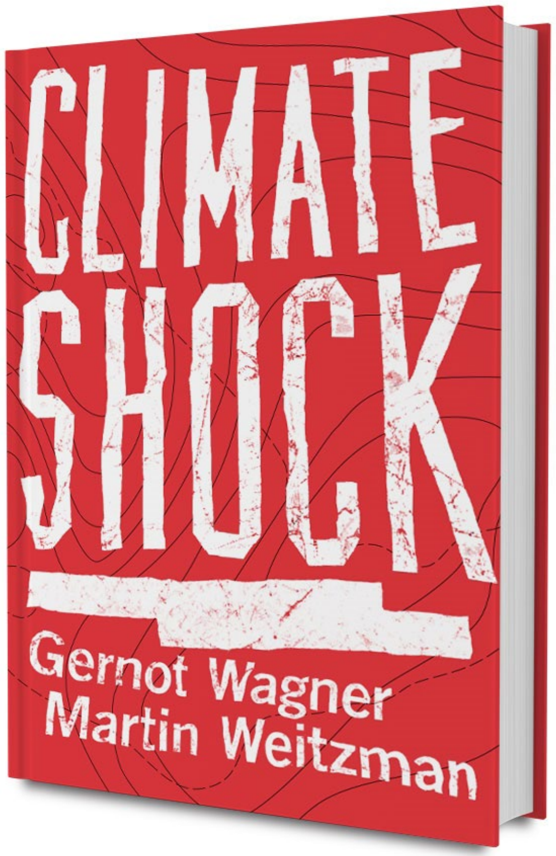

gwagner.com/SLK

EZ Climate

gwagner.com/EZclimate

Tipping Points

gwagner.com/tipping-economics

Prescriptivism

gwagner.com/prescriptivism

8 priorities for SCC

gwagner.com/SCC-8

DICE-EZ-RB

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Backup

"DICE-EZ-RB" based on DICE with modified utility & calibration (1/2)

Based on Ackerman *et al.* (2013) and Roe & Bauman (2013), and Nordhaus (2013, 2016)

Epstein-Zin utility:

$$U_t = \left[(1-\beta) c_t^\rho + \beta \left(\mu_t [U_{t+1}]^\rho \right) \right]^{1/\rho}$$

$$\mu_t [U_{t+1}] = \left(E_t \left[U_{t+1}^\alpha \right] \right)^{1/\alpha}$$

modified to allow for intra-period uncertainty in consumption:

$$U_t = \left[(1-\beta) \mu_t (c_t)^\rho + \beta \left(\mu_t [U_{t+1}]^\rho \right) \right]^{1/\rho}$$

$$\mu_t [U_{t+1}] = \left(E_t \left[U_{t+1}^\alpha \right] \right)^{1/\alpha}$$

$$\mu_t [c_t] = \left(E_t \left[c_t^\alpha \right] \right)^{1/\alpha}$$

Utility of c_t is uncertain in each period, not just in its present value

Source: Hogan & Wagner (Mimeo)

"DICE-EZ-RB" based on DICE with modified utility & calibration (2/2)

Based on Ackerman *et al.* (2013) and Roe & Bauman (2013), and Nordhaus (2013, 2016)

Modify temperature pathway from "ΔT_{DICE}" to "$\Delta T'$" in:

$$T_{AT}(t) = T_{AT}(t-1) + \xi_1 \left\{ F(t) - \xi_2 T_{AT}(t-1) - \xi_3 \left[T_{AT}(t-1) - T_{LO}(t-1) \right] \right\}$$

$$T_{LO}(t) = T_{LO}(t-1) + \xi_4 \left[T_{AT}(t-1) - T_{LO}(t-1) \right].$$

by scaling parameters, *e.g.*:

$$\xi_2' = \xi_2 \left(\frac{\Delta T'}{\Delta T_{DICE}} \right)^{-1} \qquad \xi_3' = \xi_3 \left(\frac{\Delta T'}{\Delta T_{DICE}} \right)^{\lambda_{RB}}$$

We instead scale based on fraction of asymptotic adjustment; i.e. time it takes to get to 1 − 1/e, or ~ 63 %.

→ Choose parameters ξ_1', ξ_3', ξ_4' to minimize squared deviation from DICE parameters:

$$\frac{T(ECS, p)}{T(3.1, p)} = \left(\frac{y}{3.1} \right)^2$$

Source: Hogan & Wagner (Mimeo)

Four novel conclusions:

1. Increased risk aversion *increases* the optimal CO_2 price

   in contrast to most standard models employing power utility functions, where increased risk aversion implies a higher discount rate implies a lower optimal CO_2 price

2. Optimal CO_2 price *declines* over time

   in contrast to most standard models with the exception of Ulph & Ulph (1994) [producer behavior], Acemoglu et al (2012) [shift from "dirty" to "clean"], Lemoine & Rudik (2017) [inertia]

3. Increased risk aversion increases risk premium relative to expected damages

   in contrast to standard models due to their use of power utility functions and (typically) lack of possibility for 'catastrophic' damages

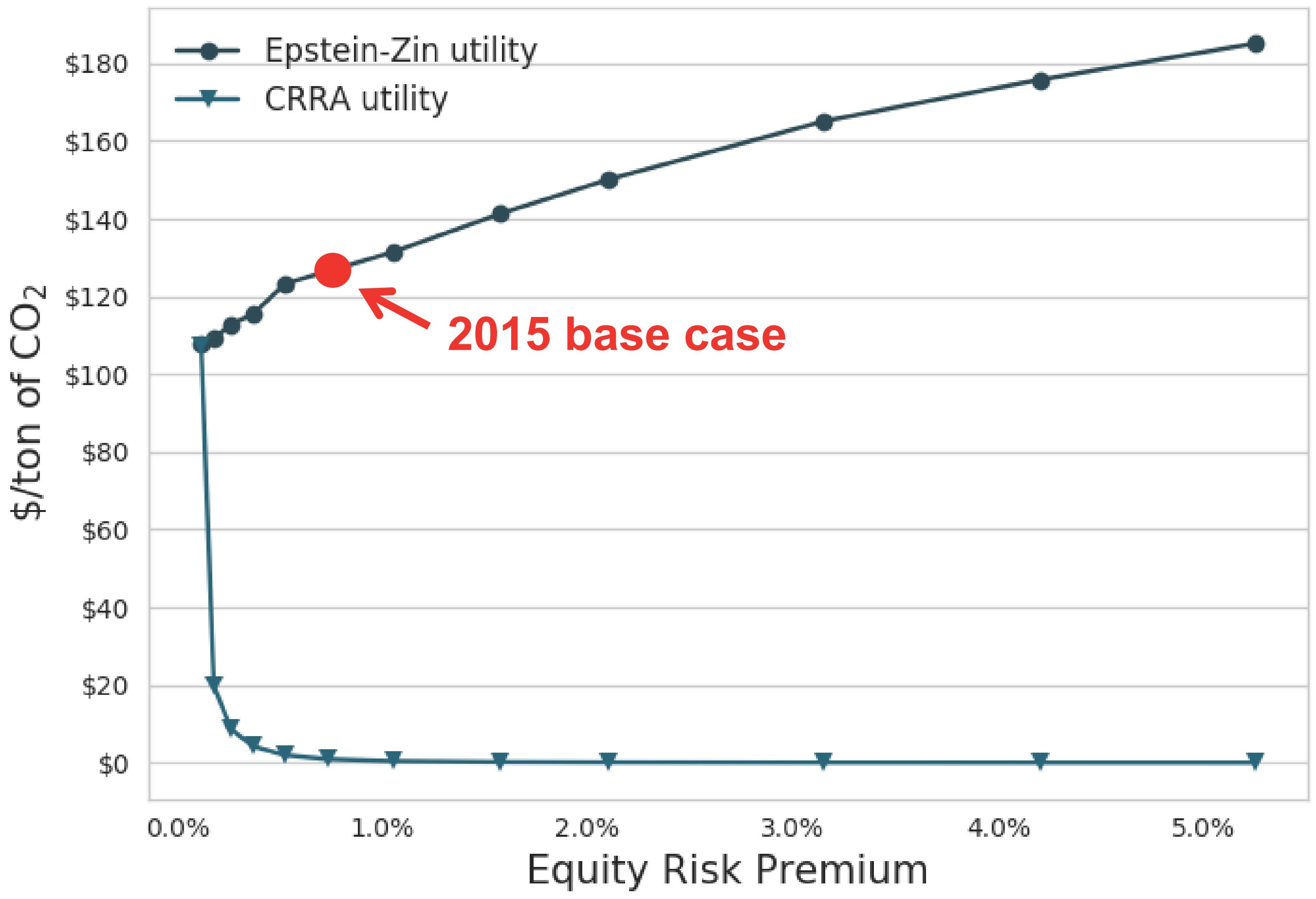
4. Enormous social costs of delay

   in contrast to most standard models, which often estimate cost of delay based on (rising) 'optimal' CO_2 price over time in any given year (e.g. Nordhaus 2017, Changes in the DICE model, 1992 – 2017)

Source: Daniel, Litterman & Wagner (NBER October 2018)

1 Standard utility specifications misrepresent (climate) risk

Constant Relative Risk Aversion (CRRA) utility conflates risk across time and across states of nature



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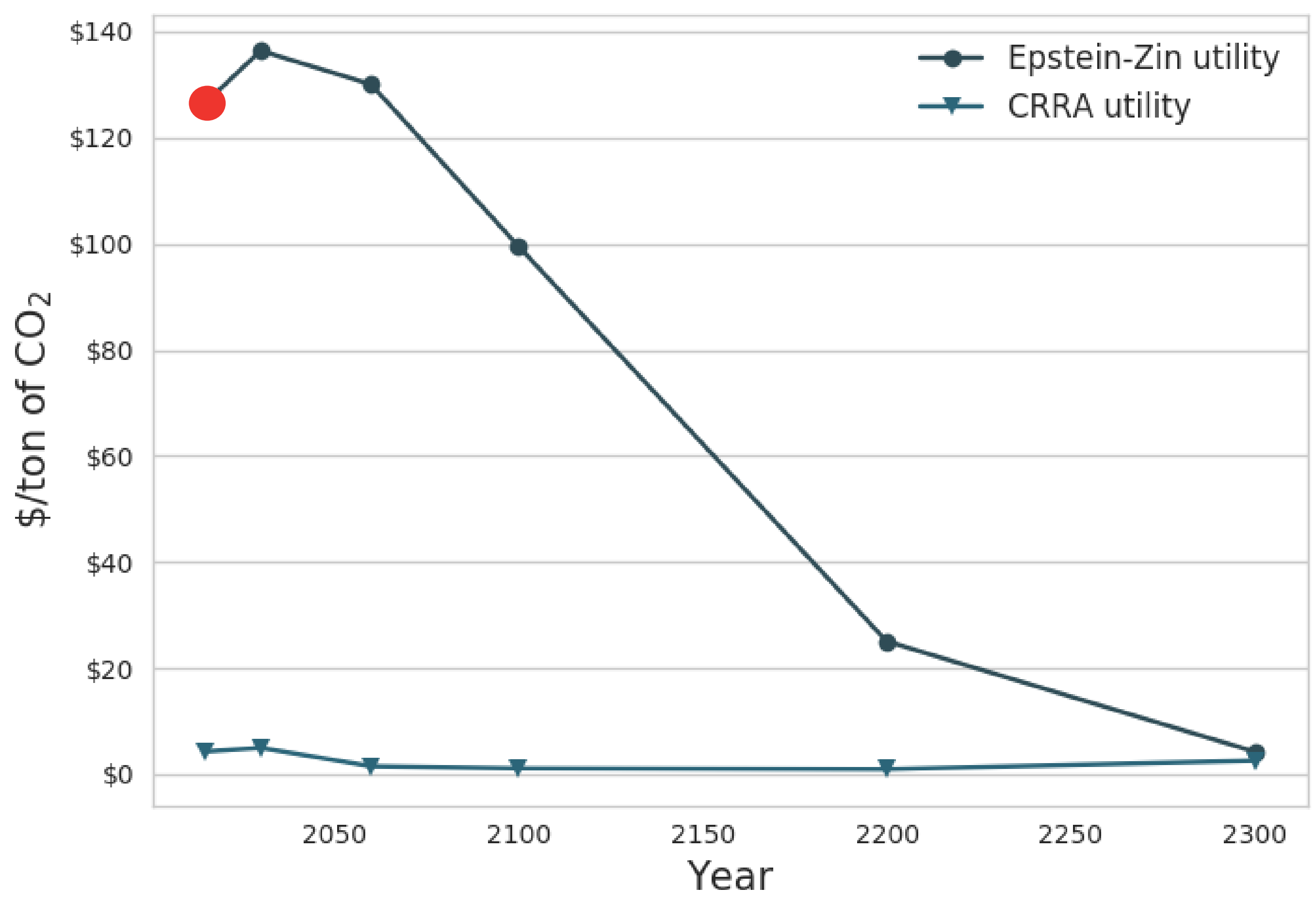
Source: Daniel, Litterman & Wagner (NBER October 2018)

2 Optimal CO_2 price declines over time

Optimal price starts $>100, declines as uncertainties clear up

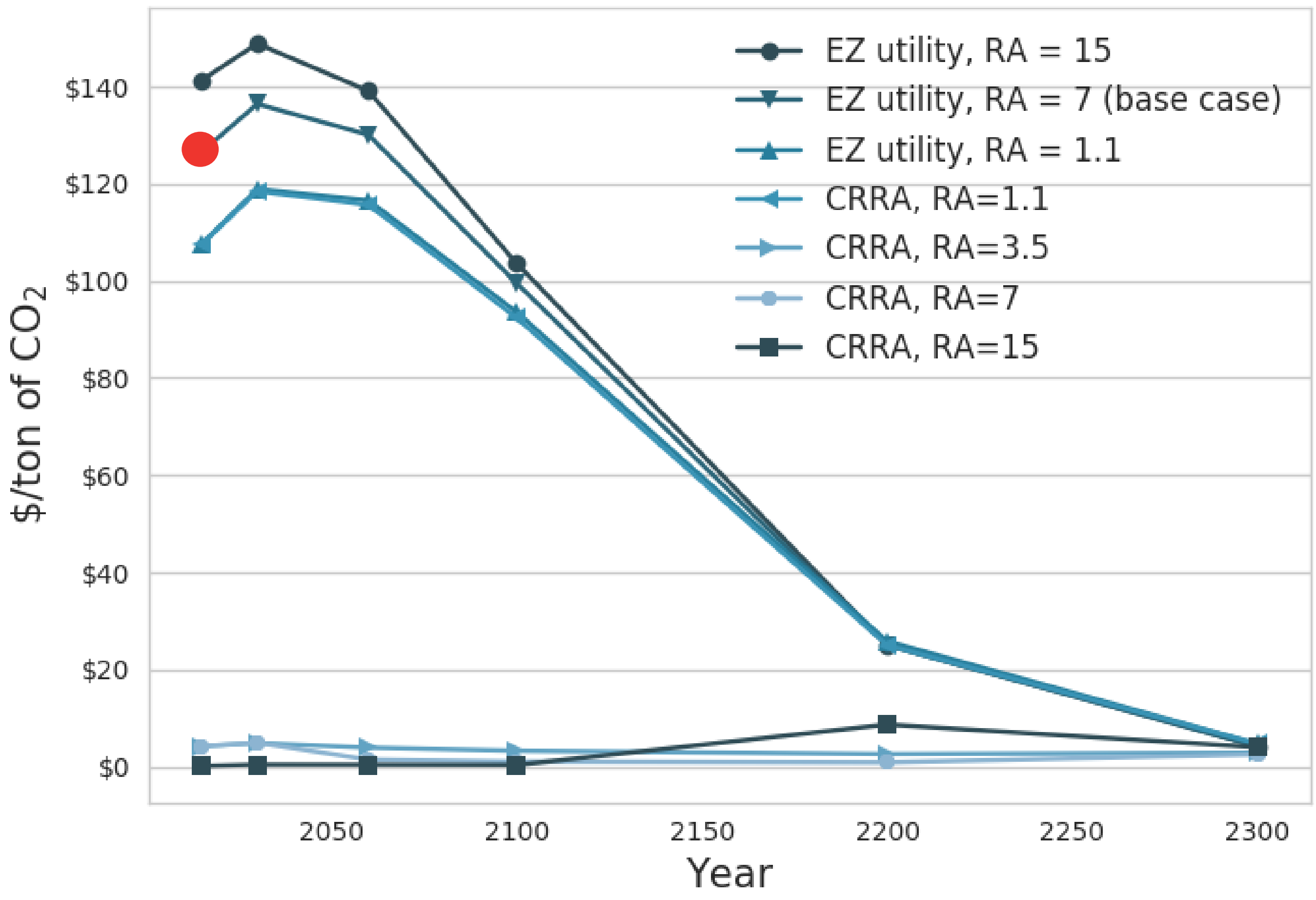


Source: Daniel, Litterman & Wagner (NBER October 2018)

2

Optimal CO_2 price sensitive to utility specification for 'reasonable' RA values

No difference between CRRA and EZ utility at RA=1.1, large differences for RA>~3



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3 We decompose optimal CO_2 price into two components

Optimal CO_2 price = expected damages + risk premium

Optimal CO_2 price reflects future state-dependent damages, $D_{s,t}$, weighted by their probability, $\pi_{s,t}$, and pricing kernel $m_{s,t} = \left(\frac{\partial U}{\partial c_{s,t}}\right) / \left(\frac{\partial U}{\partial c_0}\right)$:

$$\sum_{t=1}^{T} \sum_{s=1}^{S(t)} \pi_{s,t} m_{s,t} D_{s,t} \left(= \sum_{t=1}^{T} E_0\left[\tilde{m}_t \tilde{D}_t\right] \right)$$

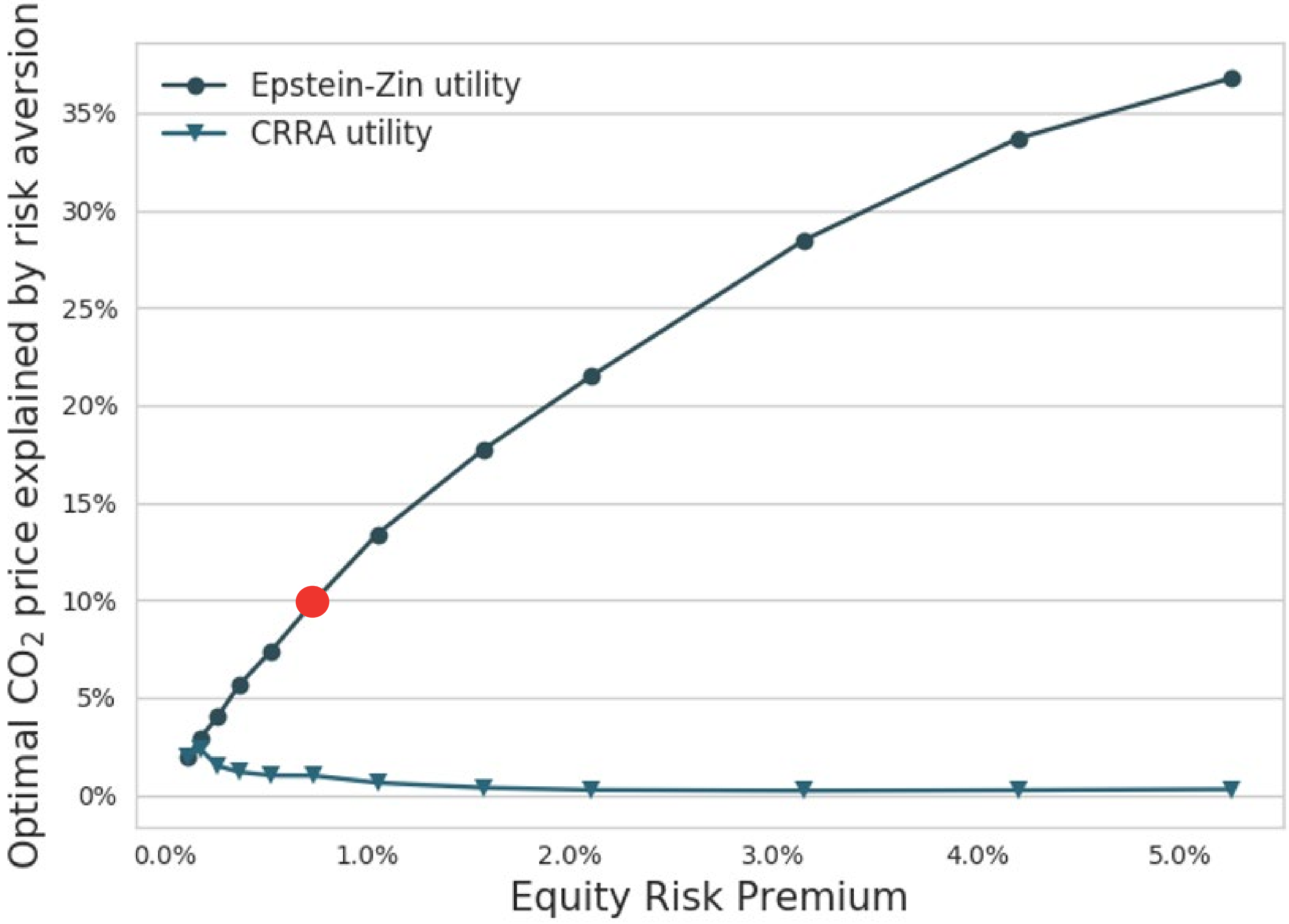
which we rearrange as:

$$\underbrace{\sum_{t=1}^{T} E_0[\tilde{m}_t] \cdot E_0\left[\tilde{D}_t\right]}_{Expected\ Damages} + \underbrace{\sum_{t=1}^{T} cov_0\left(\tilde{m}_t, \tilde{D}_t\right)}_{Risk\ Premium}$$

Source: Daniel, Litterman & Wagner (NBER October 2018)

3 Epstein-Zin utility allows risk premium to play a significant role

Increased risk aversion increases risk premium relative to expected damages



Source: Daniel, Litterman & Wagner (NBER October 2018)

Four novel conclusions:

1. Increased risk aversion *increases* the optimal CO_2 price

   in contrast to most standard models employing power utility functions, where increased risk aversion implies a higher discount rate implies a lower optimal CO_2 price

2. Optimal CO_2 price *declines* over time

   in contrast to most standard models with the exception of Ulph & Ulph (1994) [producer behavior], Acemoglu et al (2012) [shift from "dirty" to "clean"], Lemoine & Rudik (2017) [inertia]

3. Increased risk aversion increases risk premium relative to expected damages

   in contrast to standard models due to their use of power utility functions and (typically) lack of possibility for 'catastrophic' damages

4. Enormous social costs of delay

   in contrast to most standard models, which often estimate cost of delay based on (rising) 'optimal' CO_2 price over time in any given year (e.g. Nordhaus 2017, Changes in the DICE model, 1992 – 2017)

Source: Daniel, Litterman & Wagner (NBER October 2018)

4 Enormous social costs of delay

Cost of delay increases roughly with the square of time

Q: How much additional consumption is required throughout the first period to bring the utility with first-period mitigation set to zero up to the unconstrained level?

First-period length	Annual consumption impact during first period
5 years	11%
10 years	23%
15 years	36%

Each year of delay causes the equivalent consumption loss *over the entire first period* to increase by roughly 2.3%

Source: Daniel, Litterman & Wagner (NBER October 2018)

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